The Future of Water Cherenkov Neutrino Detectors

Matthew Malek
The University of Sheffield

Réunion Gdr Neutrino 2015
Laboratoire de Physique Corpusculaire – Clermont-Ferrand
09 June 2015

Outline

I) Introduction:

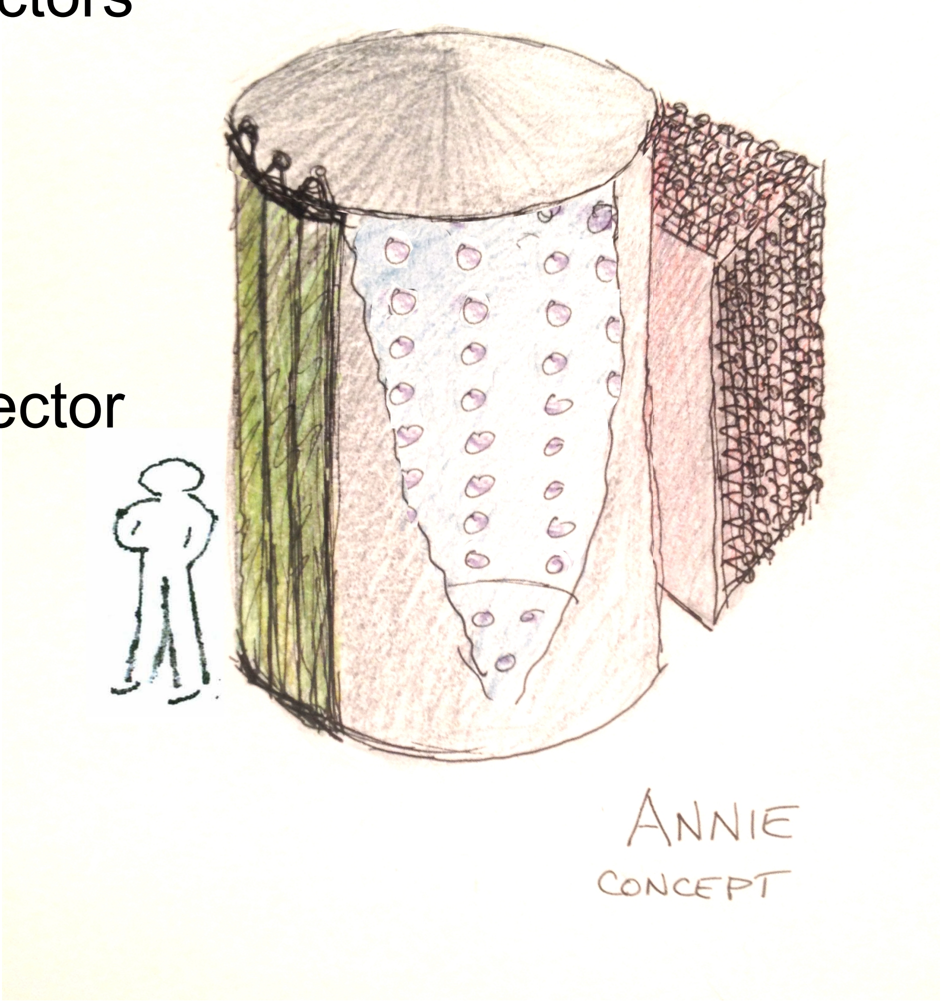
- A Brief History of WC ν detectors
- Open questions

II) Next generation:

- The Hyper-Kamiokande detector
- Beam programme

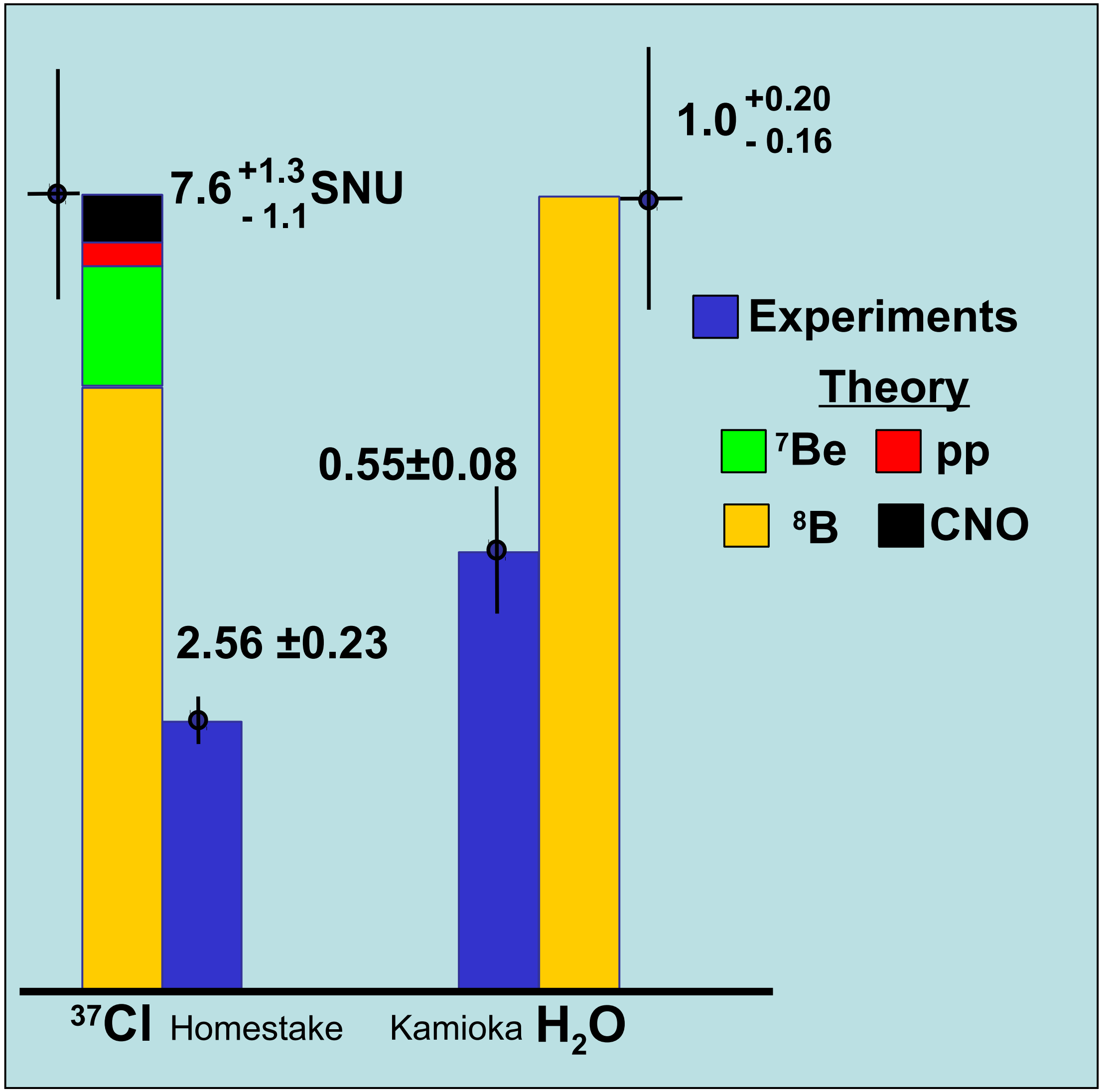
III) Intermediate steps:

- The ANNIE experiment
- Comparisons with LAr

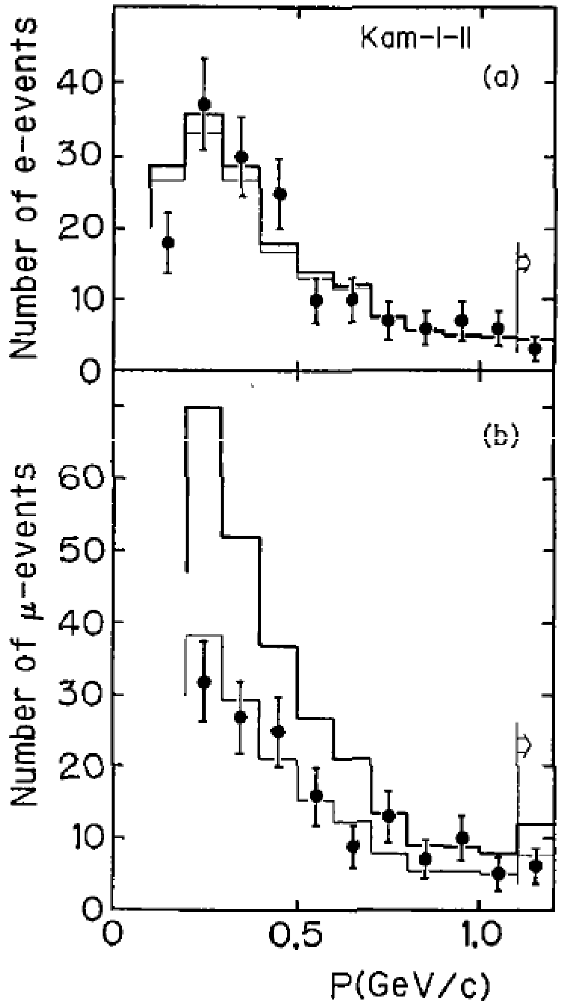


In the Beginning

Solar Neutrinos

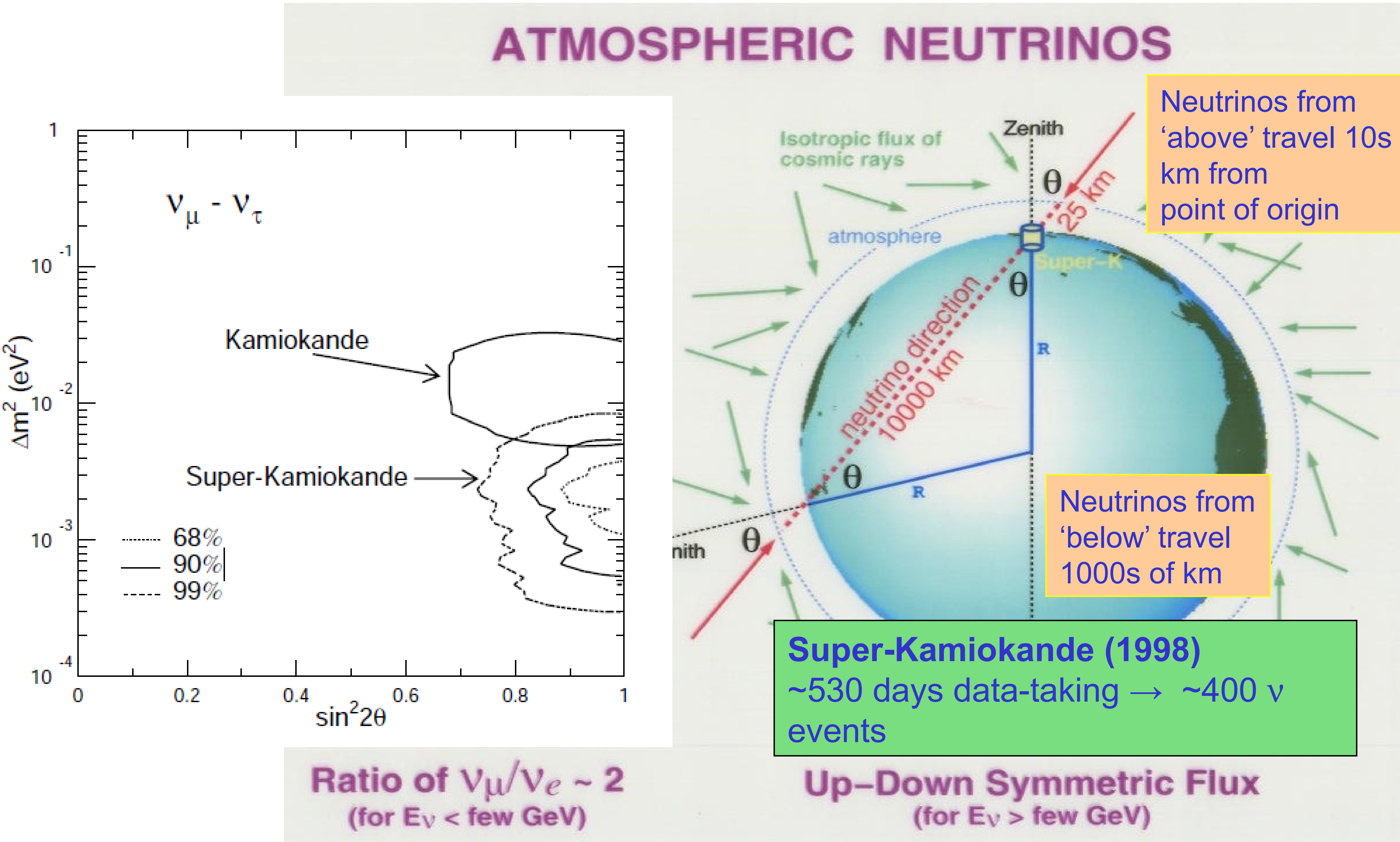


Atmospheric Neutrinos



Kamiokande (1992)

1998: Neutrino Mass!



Neutrinos from 'above' travel 10s of km from point of origin

Neutrinos from 'below' travel 1000s of km

Super-Kamiokande (1998)
~530 days data-taking → ~400 ν events

Where Are We Now?

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- In ν physics, our **starting** point is beyond the Standard Model
  - Arguably our only experimental evidence of BSM physics thus far...

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{pmatrix}1&0&0\\0&\cos\theta_{23}&\sin\theta_{23}\\0&-\sin\theta_{23}&\cos\theta_{23}\end{pmatrix}\times\begin{pmatrix}\cos\theta_{13}&0&\sin\theta_{13}e^{-i\delta}\\0&1&0\\-\sin\theta_{13}e^{i\delta}&0&\cos\theta_{13}\end{pmatrix}\times\begin{pmatrix}\cos\theta_{12}&\sin\theta_{12}&0\\-\sin\theta_{12}&\cos\theta_{12}&0\\0&0&1\end{pmatrix}\times\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

1998 onwards:
Probed with atmospheric neutrinos, long baseline accelerator neutrinos (SK, K2K, MINOS)

$\sin^2(2\theta_{23}) > 0.95$ **(90% C.L.)**
$|\Delta m^2_{32}| = 2.44 \pm 0.13 \times 10^{-3}\ eV^2$

2001 onwards:
Probed with solar neutrinos, long baseline reactor neutrinos (SK, SNO, KamLAND)

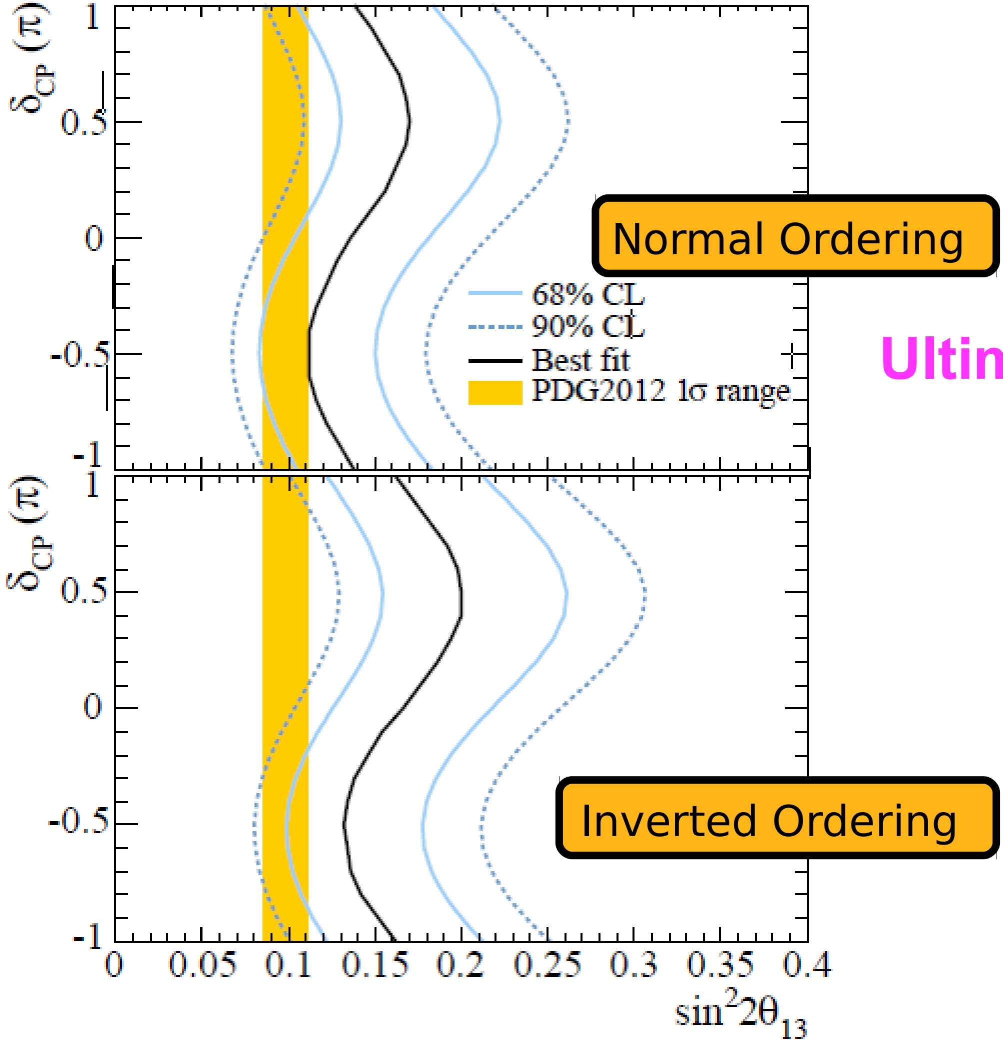
$\sin^2(2\theta_{12}) = 0.846 \pm 0.021$
$\Delta m^2_{12} = 7.53 \pm 0.18 \times 10^{-5}\ eV^2$

First measured recently! (2011 – 2012)
Short baseline reactor neutrinos (Daya Bay, RENO, DoubleChooz);
Long baseline accelerator neutrinos (T2K, MINOS, NOvA)

$\sin^2(2\theta_{13}) = 0.093 \pm 0.008$

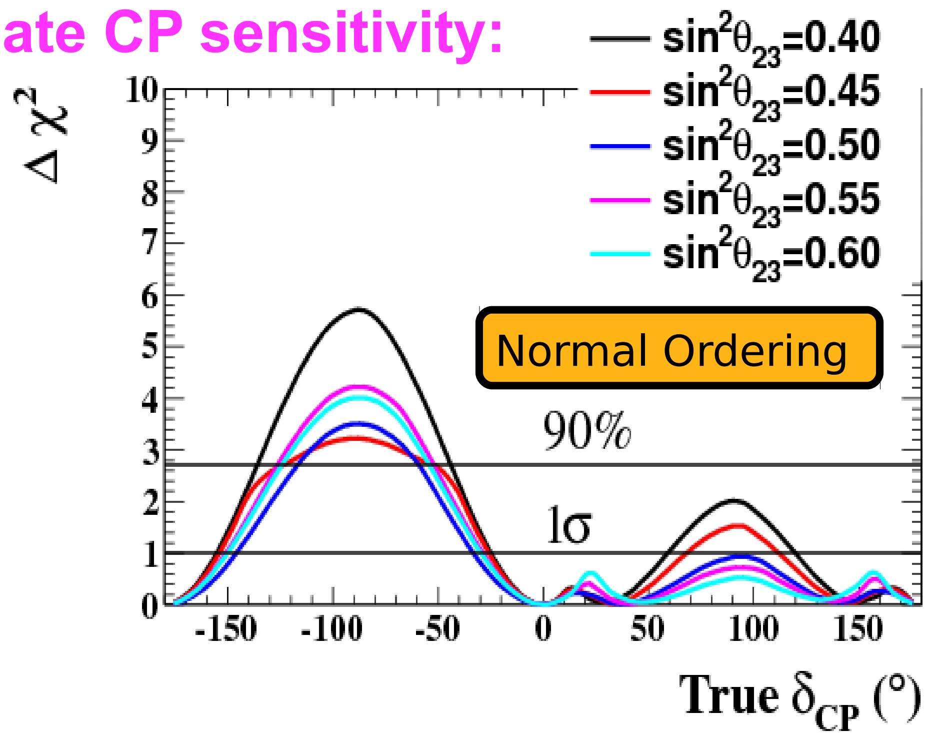
Recent T2K & Reactor

- T2K observes **28 ν_e events** (4.92 ± 0.55 events expected for $\sin^2(2\theta_{13}) = 0$)
- Comparison to null hypothesis gives 7.3σ significance for $\theta_{13} \neq 0$



Tension with θ_{13} measurement at reactors already gives some sensitivity to δ
- Some regions excluded at 90% CL
- $\delta = -\pi/2$ preferred for both hierarchies

Ultimate CP sensitivity:

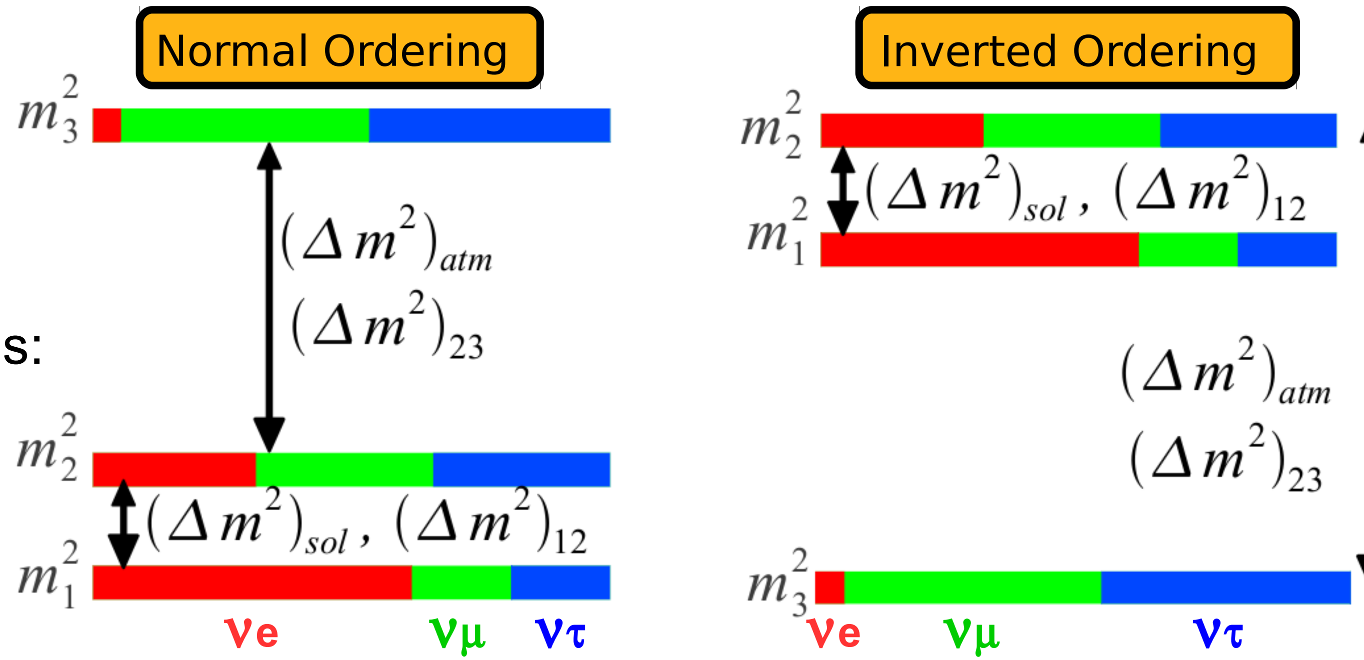


1) What is the CP violating phase δ?
2) What is the mass ordering?

Ambiguity in sign of:

$$m_3^2 - m_2^2$$

Two possible mass orderings:



3) Is θ_{23} maximal? (*i.e.*, 45°) If not, what octant does it lie in?

Also, whilst not directly oscillation physics, we want to know:

4) What is the nature of the neutrino? Dirac or Majorana?
5) Neutrino interaction cross-sections (currently not well understood)

Our Matter-Dominated Universe

A priori, we expect equal amounts of matter and anti-matter to have formed in the Big Bang.

Today (13.8 Gyears later): **Not true!**

Measured asymmetry parameter:

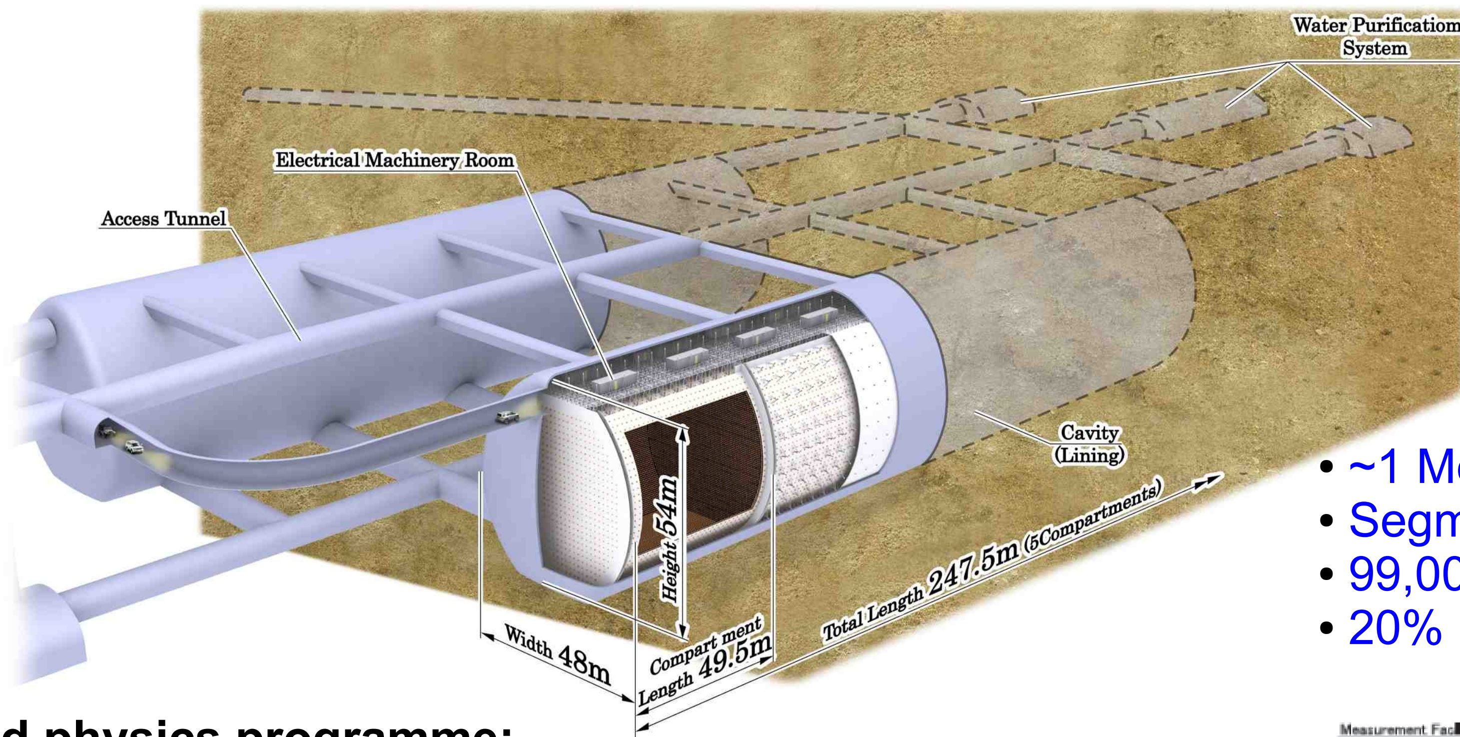
$$\eta_B = \frac{(n_B - n_{\bar{B}})}{n_\gamma} \approx \frac{n_B}{n_\gamma} \approx 6 \times 10^{-10}$$

(Using observations from D/H ratio, CMB, etc.)

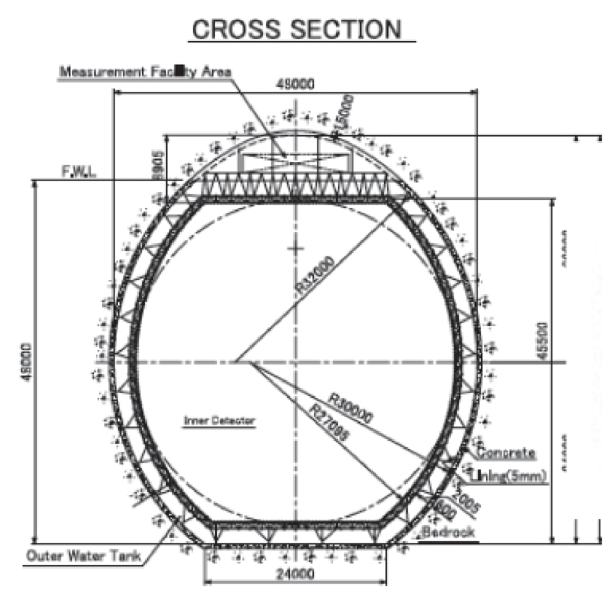
Leptogenesis provides possible solution if:

- Neutrinos are Majorana particles (*i.e.*, $\nu = \bar{\nu}$)
- CP violation in the neutrino sector (creates L asymmetry)
- Non-perturbative processes in the early universe (converts L → B asymmetry)

Hyper-Kamiokande



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

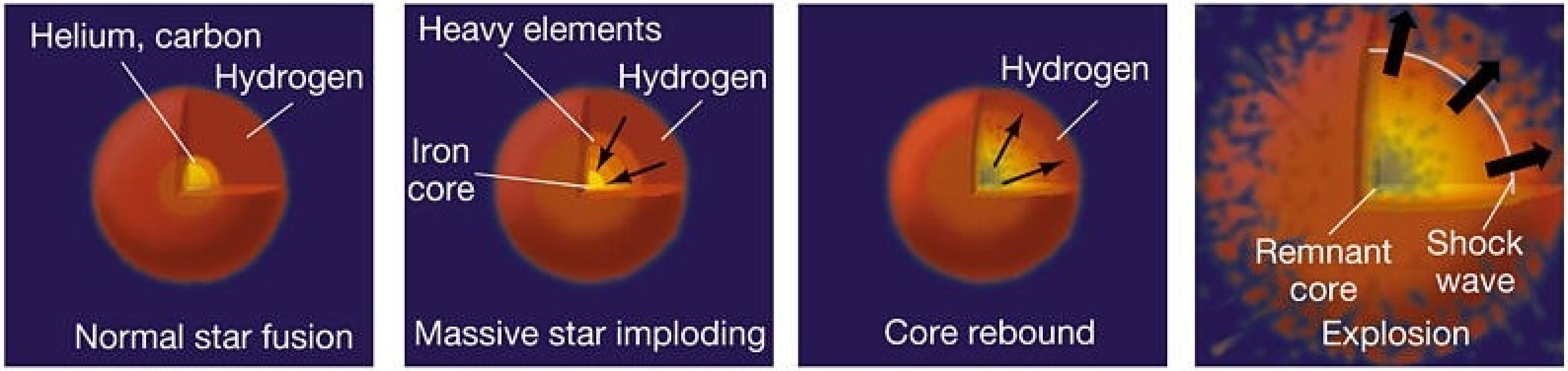


Broad physics programme:

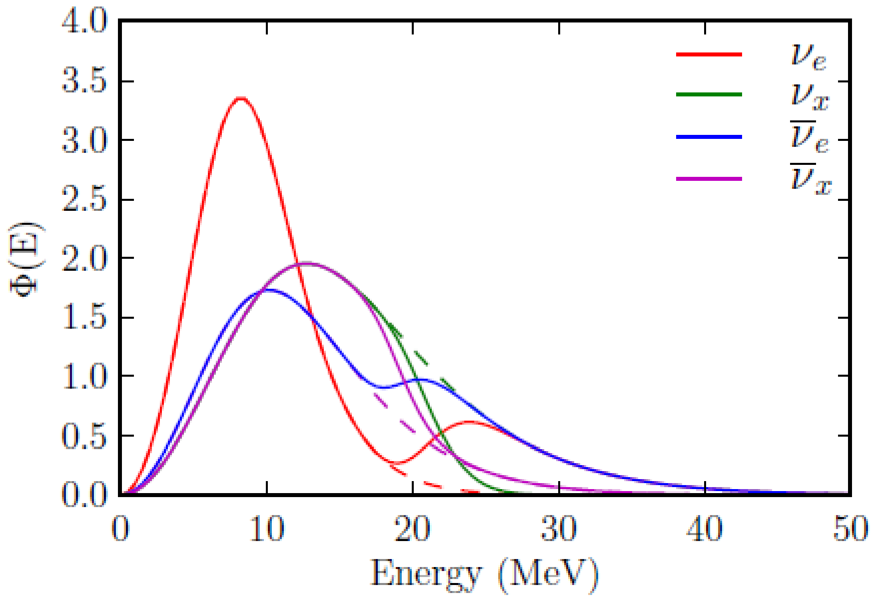
- Neutrino oscillation:
  - Atmospheric neutrinos (still statistics limited!)
  - **Accelerator neutrinos**
  - Solar neutrinos
- **Proton decay**
- Neutrino astrophysics
  - **Supernova burst** (~250,000 events expected @ 10 kpc)
  - **Supernova relic neutrinos**
- Various other physics (indirect WIMP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

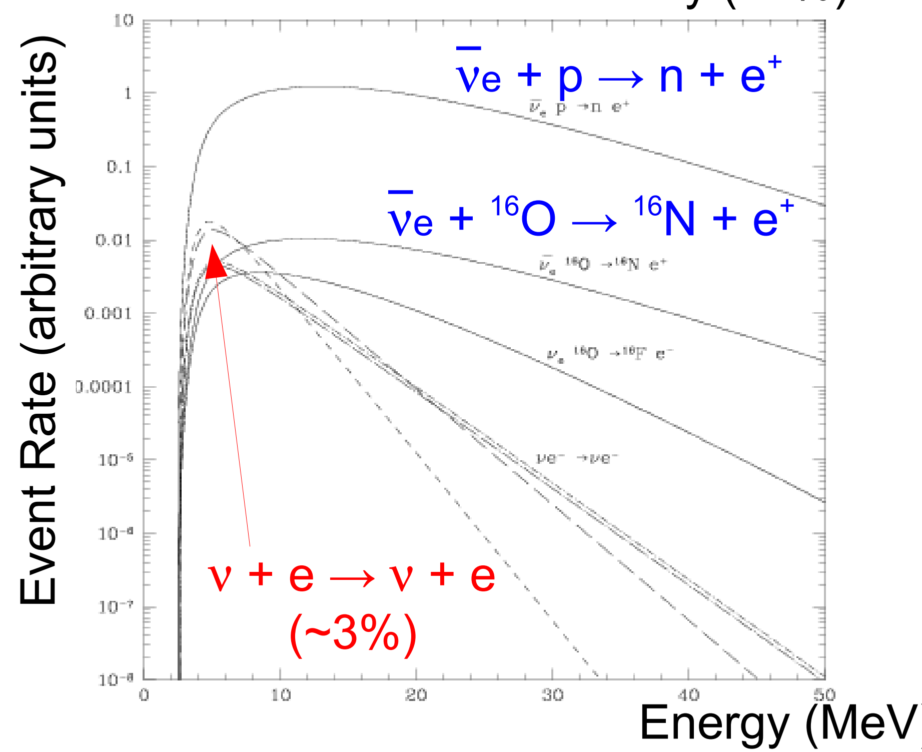
Supernova Neutrino Burst

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 $\bar{\nu}_e$ 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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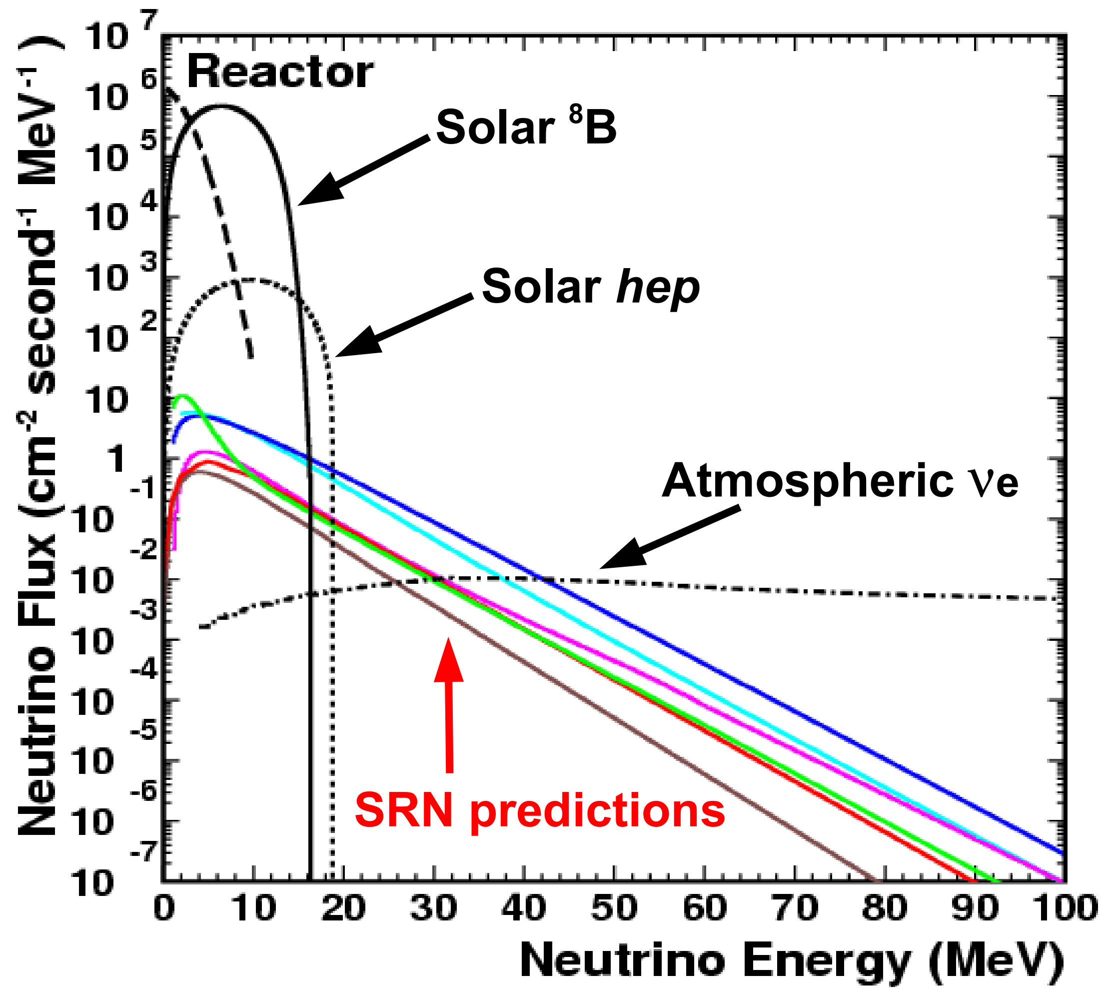
In 1987, neutrinos were detected from a SN burst in Large Magellanic Cloud (Sanduleak -69^o 292 → SN1987a)

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

Even today, Super-Kamiokande would detect **~10,000** neutrinos from SN burst in galactic centre. (**250,000** in Hyper-K)

A SN burst in Andromeda would produce **25 – 50** neutrinos in Hyper-K.

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.



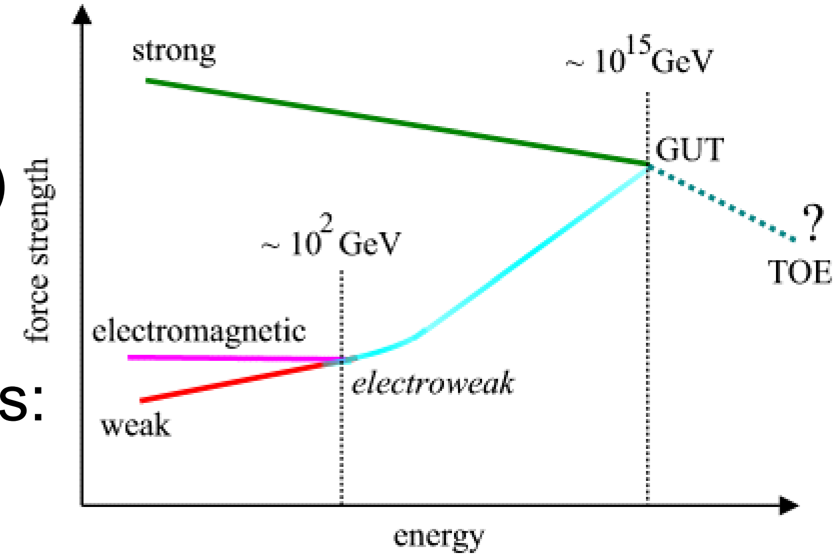
Searches for these "Supernova Relic Neutrinos" (SRN) are currently background limited; understanding neutron yield could help separate the signal from various backgrounds

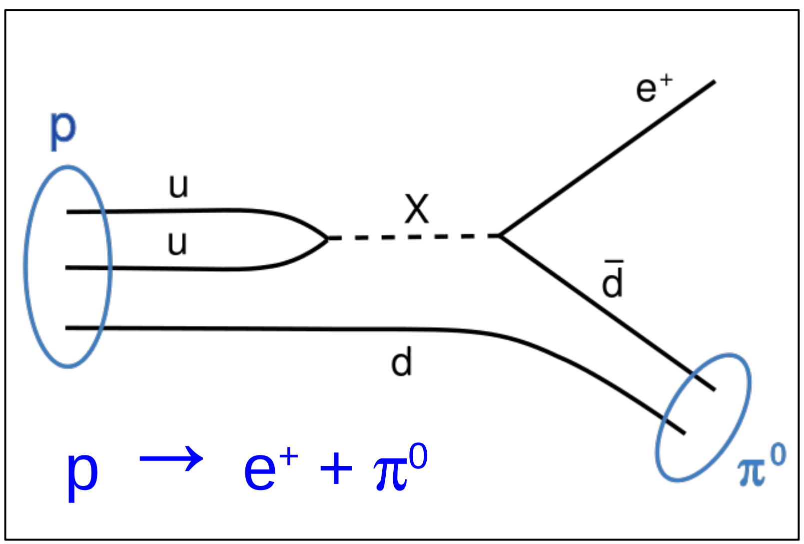
Proton Decay

Possible "grand unification" of strong & electroweak forces not directly testable due to energy scale involved (~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 ~10^{29} years.

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

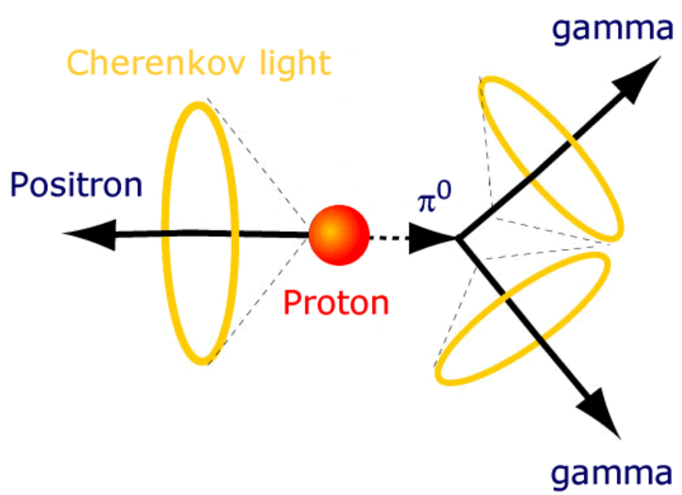
Modern GUTs predict lifetimes of $10^{35\text{-}36}$ years.

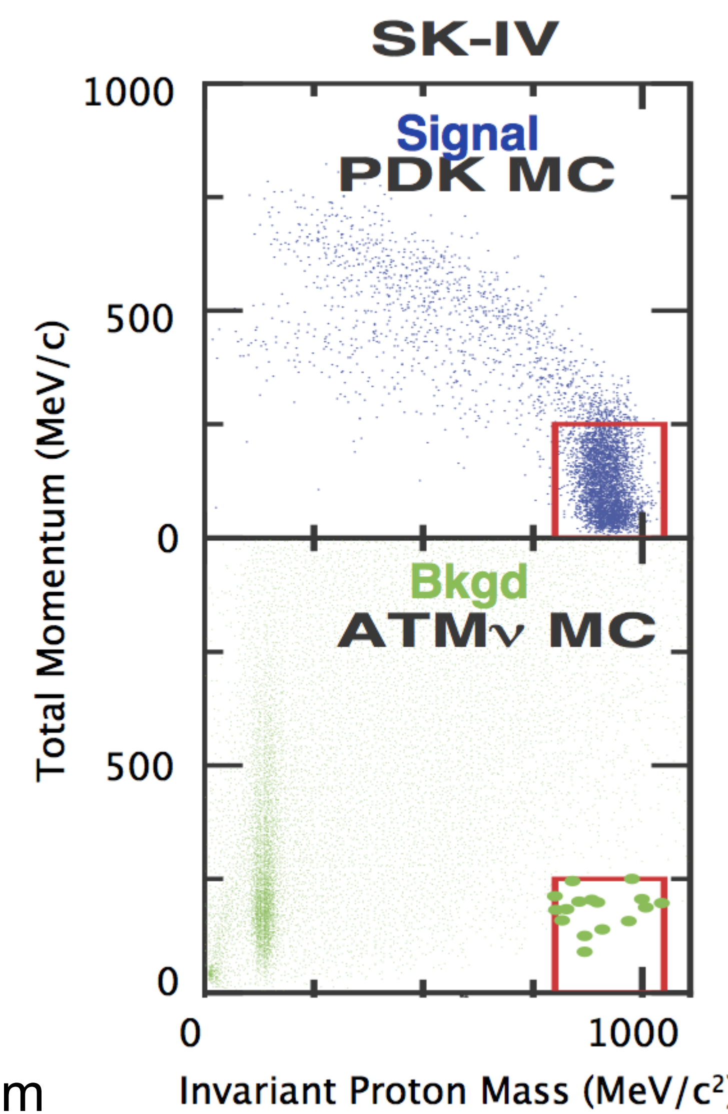
Proton Decay

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

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

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



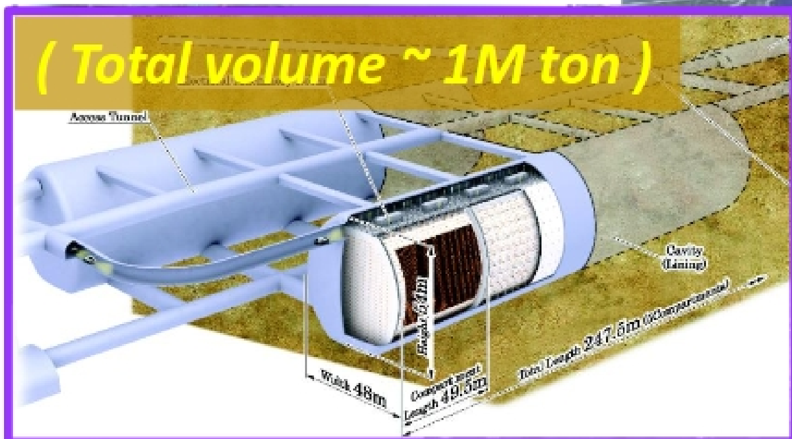


Modern GUTs predict lifetimes of $10^{35\text{-}36}$ years.

→ Hyper-Kamiokande will probe this region

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

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)

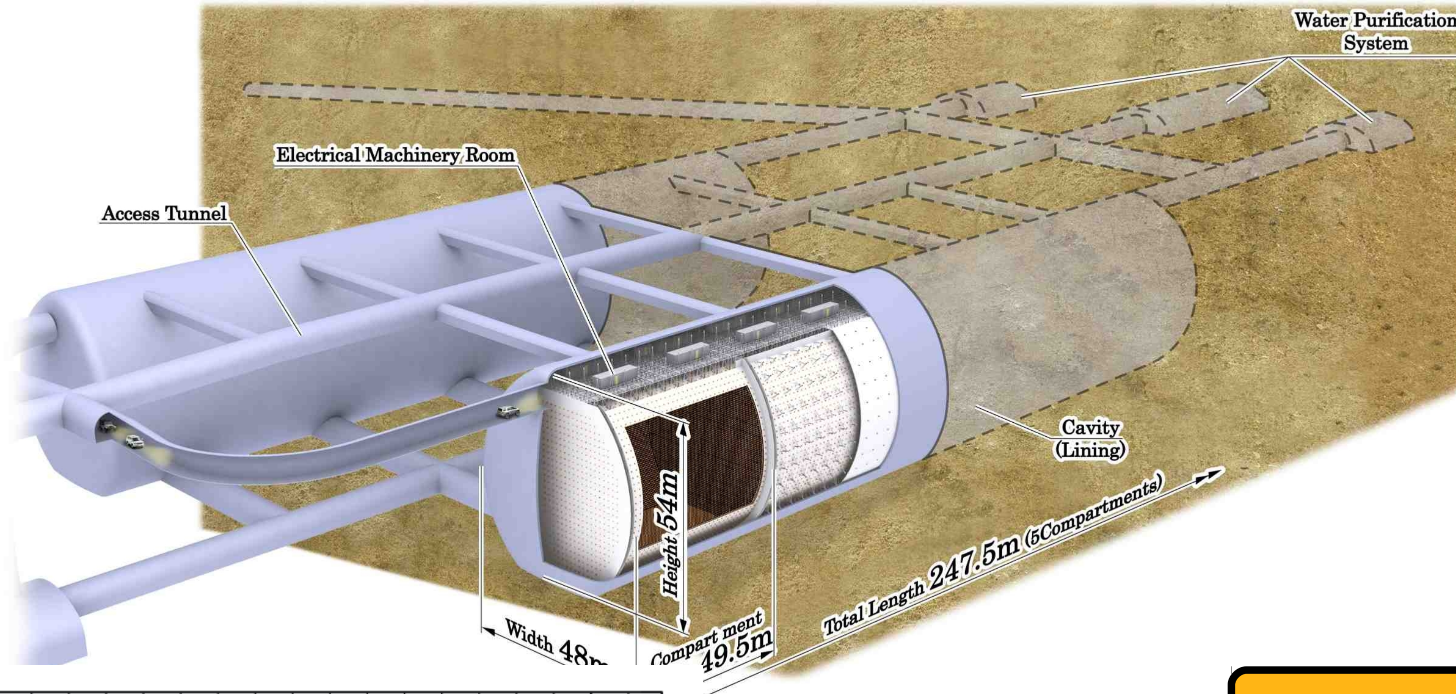
	Signal ($\nu\mu \rightarrow \nu e$ CC)	Wrong sign appearance	$\nu\mu/\bar{\nu}\mu$ CC	beam $\nu e/\bar{\nu}e$ contamination	NC
ν	3,016	28	11	523	172
$\bar{\nu}$	2,110	396	9	618	265

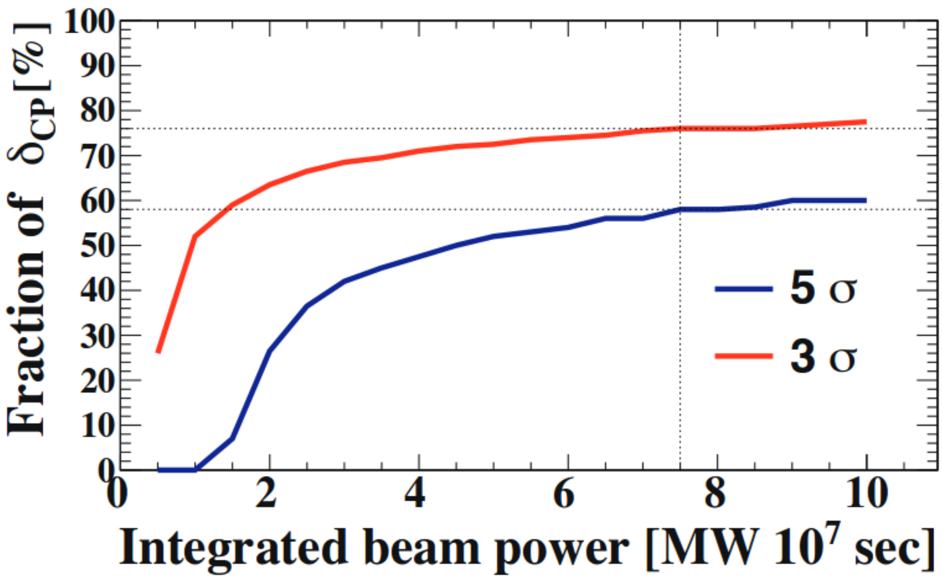
From Hayato (Neutrino 2014)

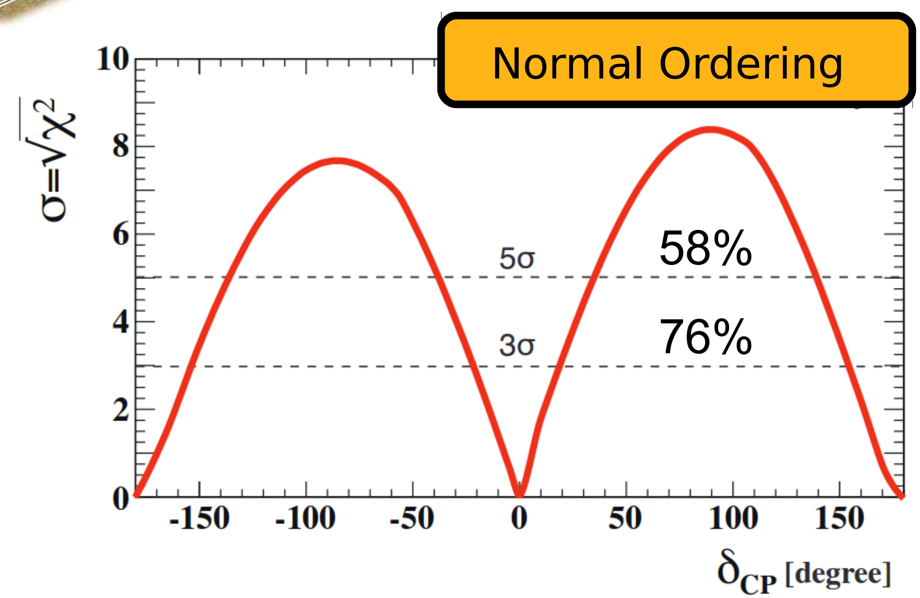
Significantly larger statistics merit better systematics:

New near detector(s)!

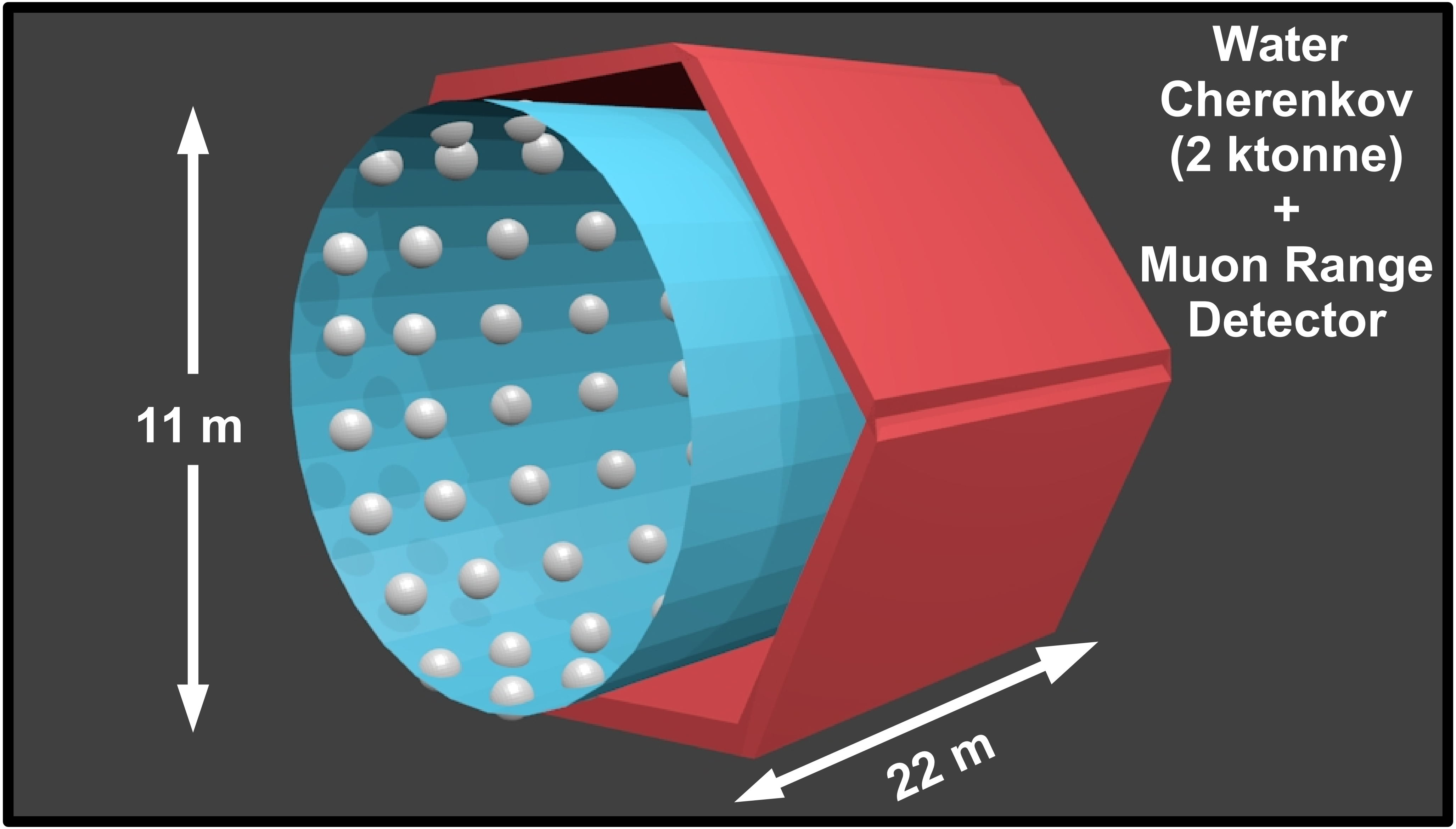
HK Sensitivity to CPV







TITUS



TITUS Overview

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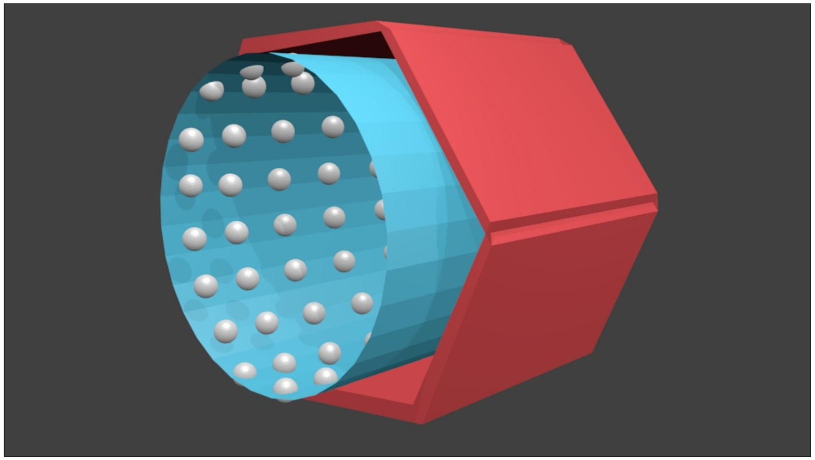
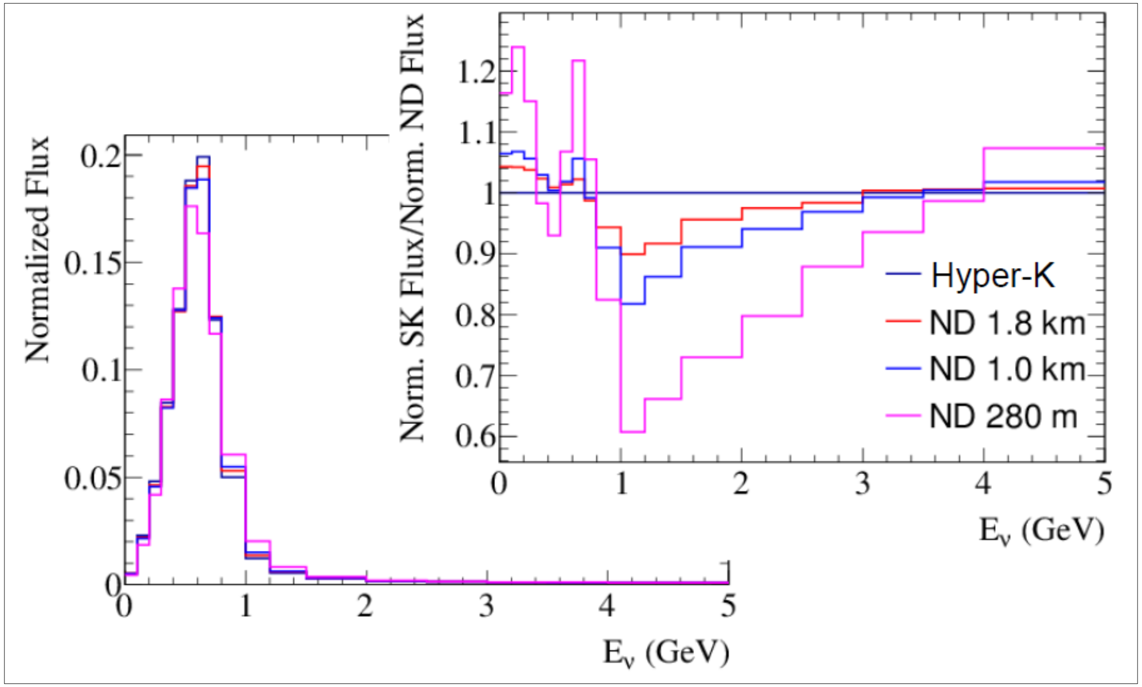
TITUS: The Tokai Intermediate Tank w/ Unoscillated Spectrum



- To be located ~2 km from J-PARC neutrino beam
- Next-generation 2 kt water Cherenkov, includes:
  - 0.1% Gadolinium-doping
  - Partly enclosed by Muon Range Detector
    - 1.5 Tesla magnetic field
  - Large Area Picosec. Photo-Detectors (LAPPDs)
    - < 100 psec t_{res} ; ~1 cm $\mathbf{X}_{res}$

- Same target nuclei as Hyper-K
  - H_2O (and maybe Gd)
- Nearly same target angle and neutrino energy spectrum
- Many systematics cancel out in Far/Near ratio



Next-Gen Water Cherenkov

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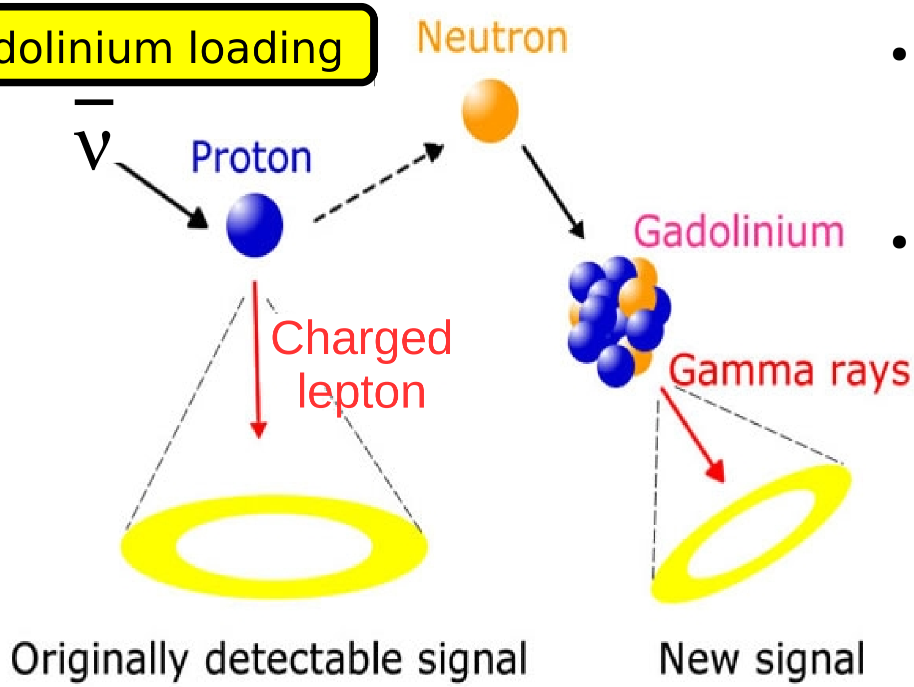
Gadolinium loading



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

  CCQE for $\bar{\nu}$: $\bar{\nu} + p \rightarrow l^+ + n$
- Coincident signal from Gd allows:
  - ν vs. $\bar{\nu}$ discrimination
  - Sensitivity to ν interaction mode

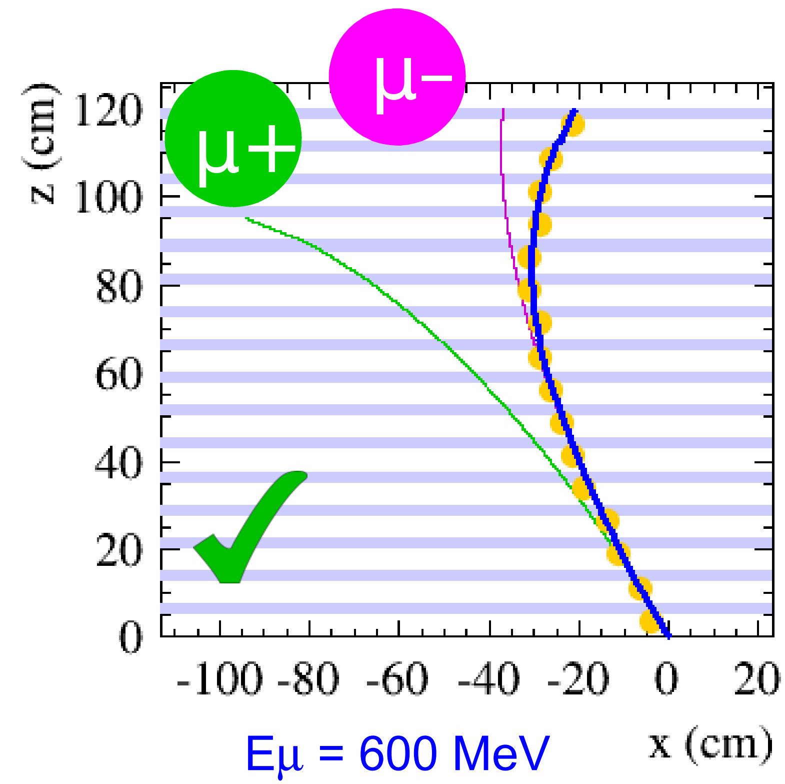
Magnetised MRD

Three main benefits:

(1) Increased statistics via calorimetry by μ range
- Include μ which exit the WC tank but range out in MRD
- N.B. This does NOT require magnetic field

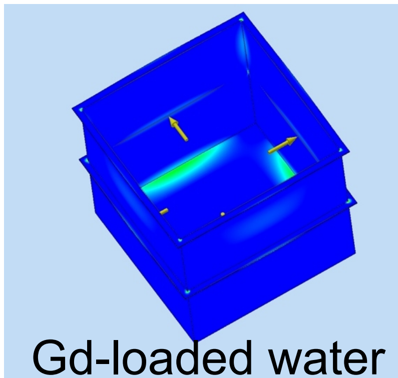
(2) Direct constraint on wrong-sign contamination
- <u>Pro:</u> Well understood physics & high recon. efficiency
- <u>Con:</u> Sample limited to which exit the WC tank

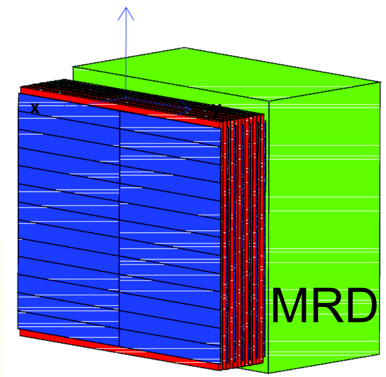
(3) Validation of gadolinium performance
- Gd-loaded water is a new analysis technique
- Cross-checking with **(2)** will provide confidence to exploit it

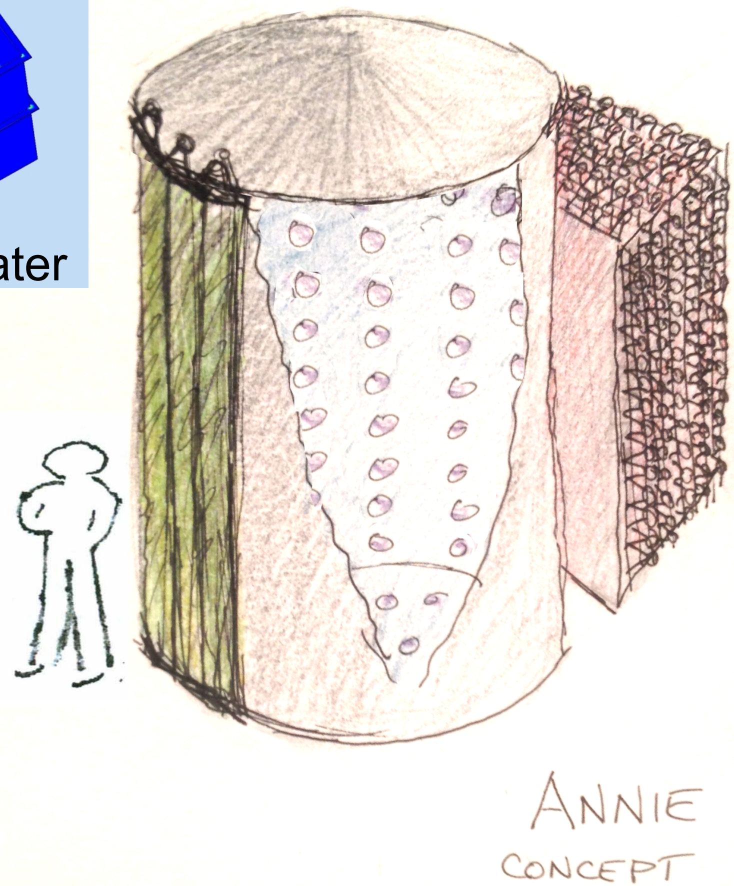


In The Meantime: ANNIE

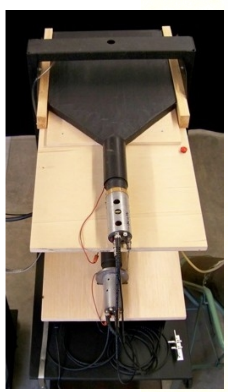
ANNIE: **A**ccelerator **N**eutrino-**N**ucleus **I**nteraction **E**xperiment







Upstream
μ veto

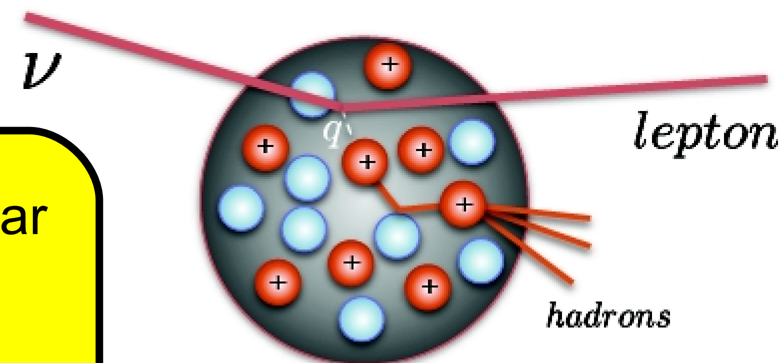


Note: ANNIE is effectively a 1% scale model for TITUS!

ANNIE Motivation

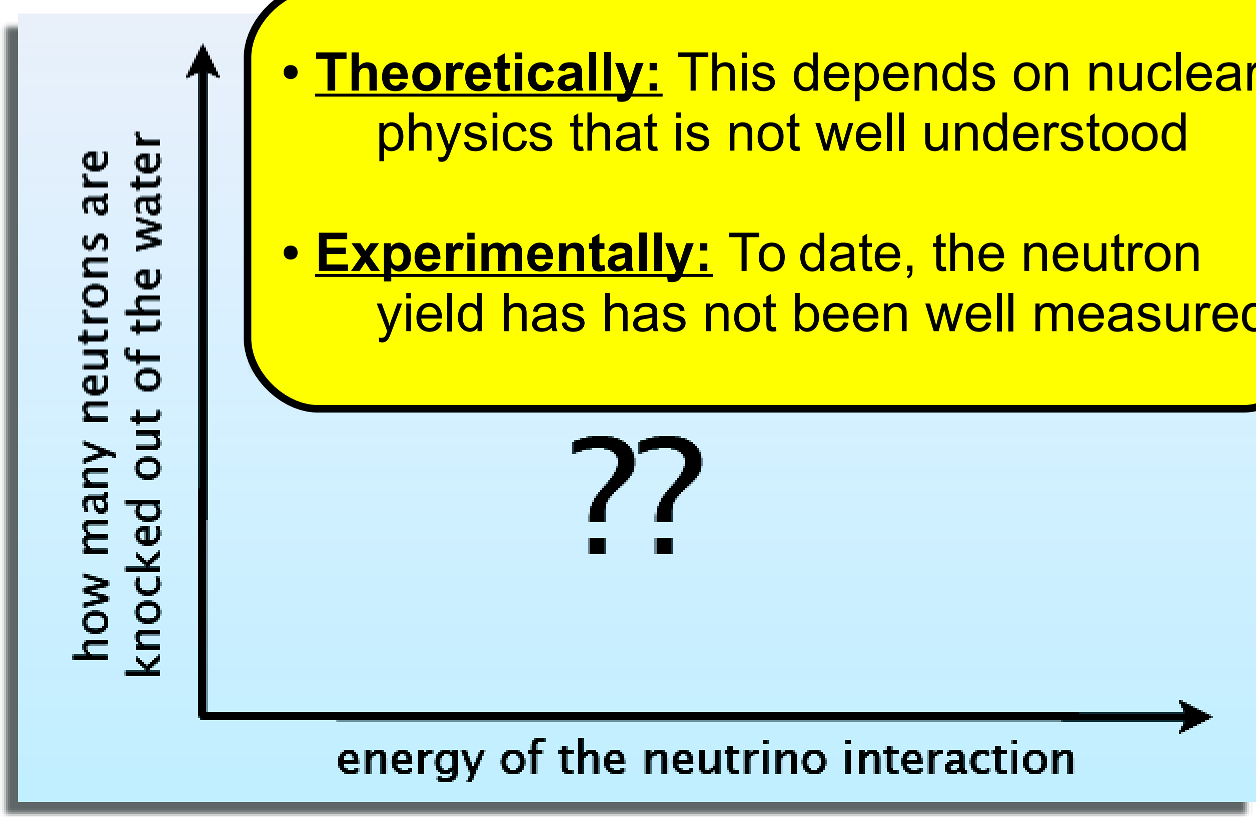
Primary physics objective:

– 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

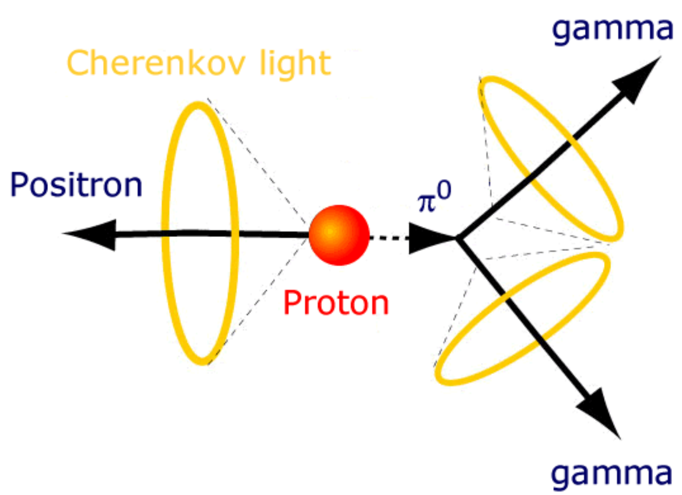


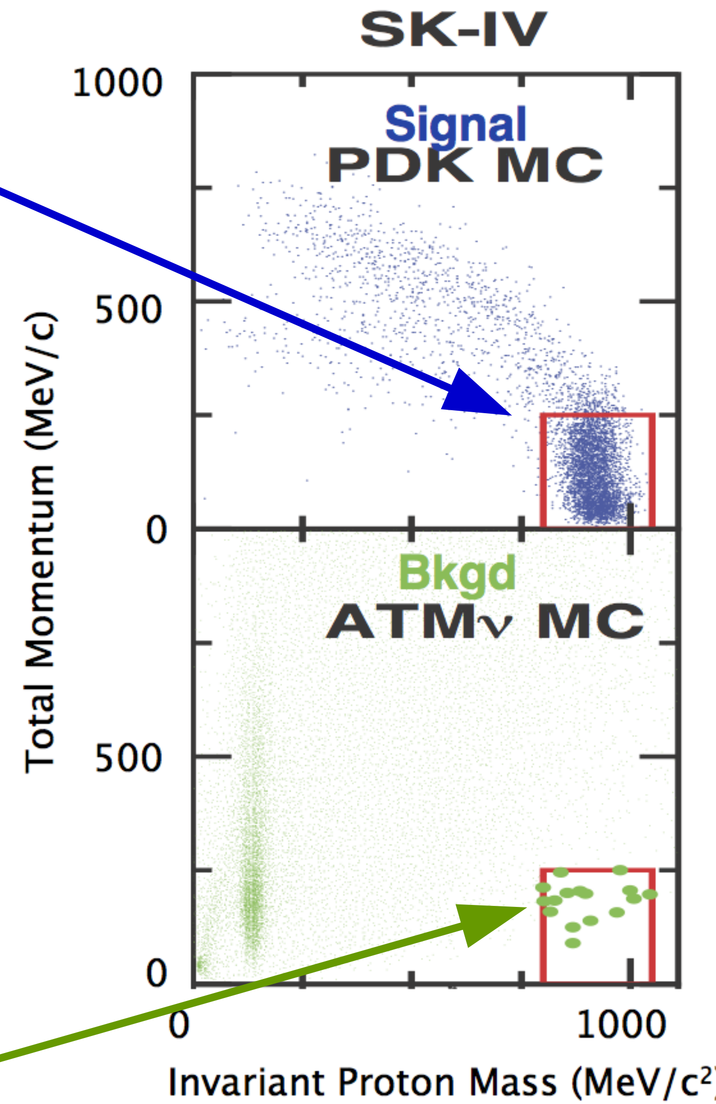
Proton Decay

Q: How can ANNIE help?

Proton decay events only rarely produce neutrons in the final state

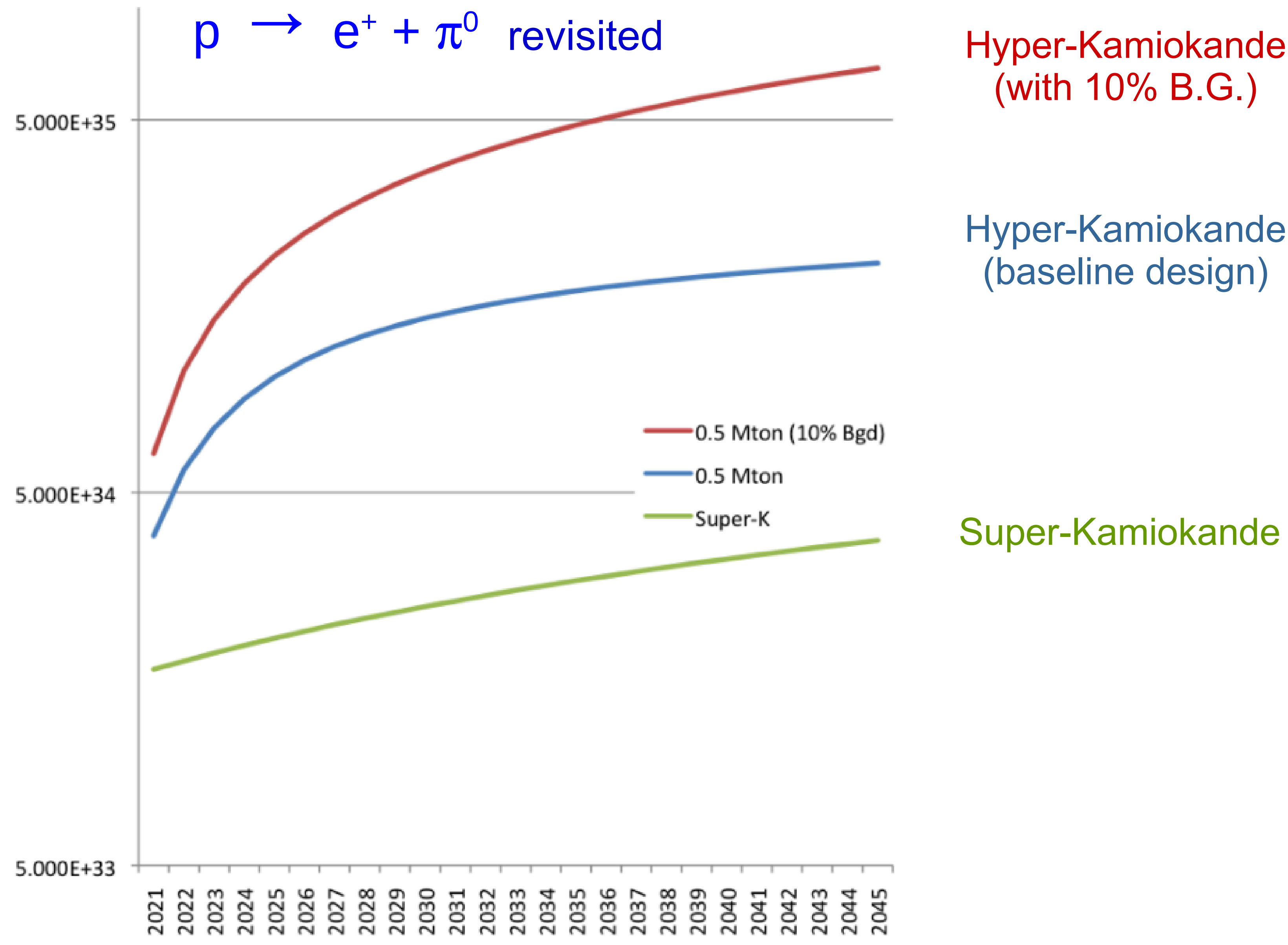
$p \rightarrow e^{+} + \pi^{0}$



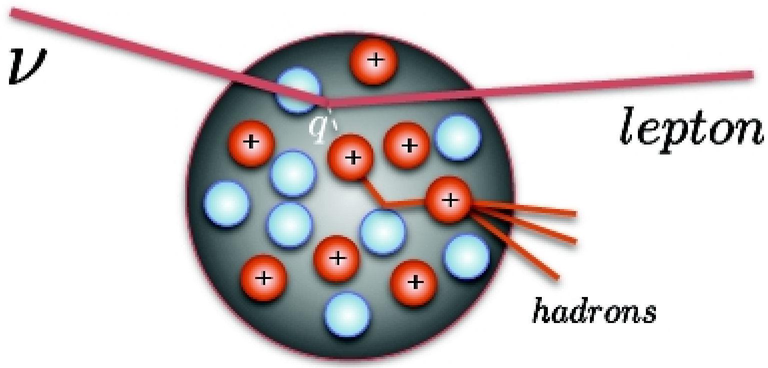


Atmospheric neutrino interactions frequently produce final state neutrons

Hyper-K Proton Decay



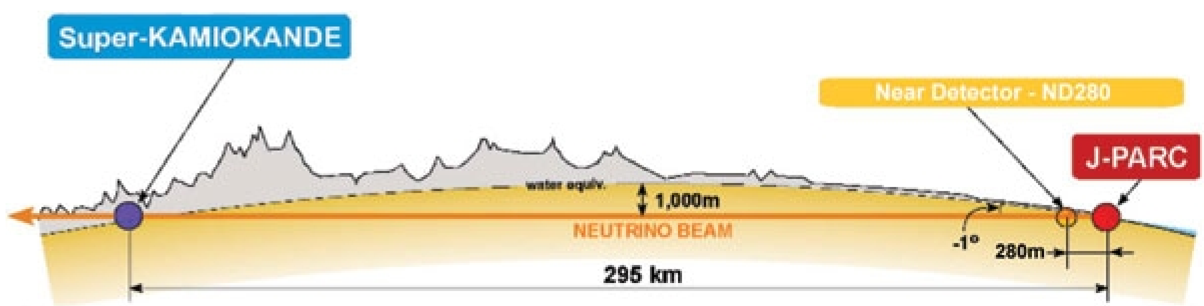
Neutrino Interactions



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.

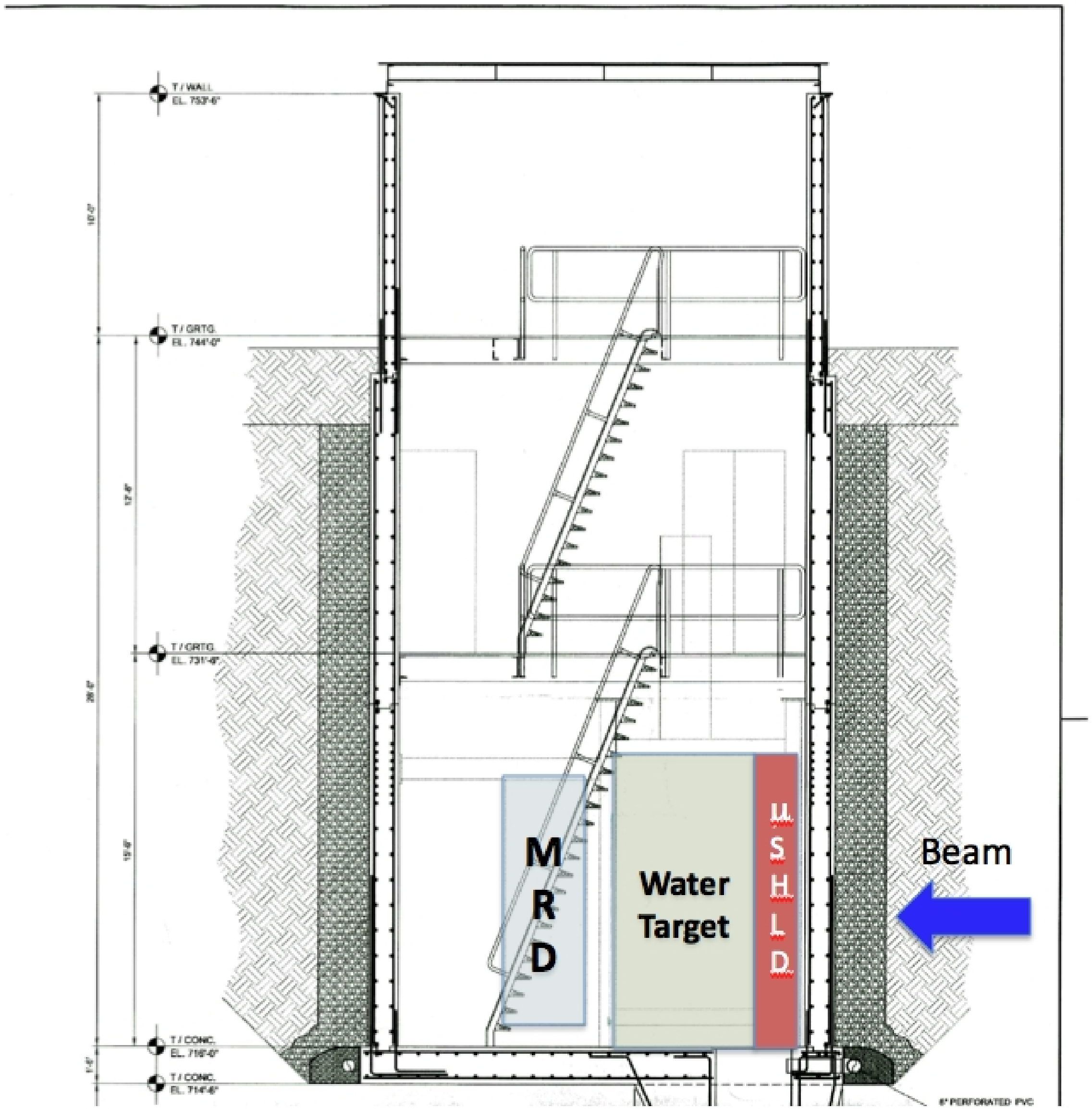
Precision neutrino oscillation measurements:



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.

Neutrino Beam



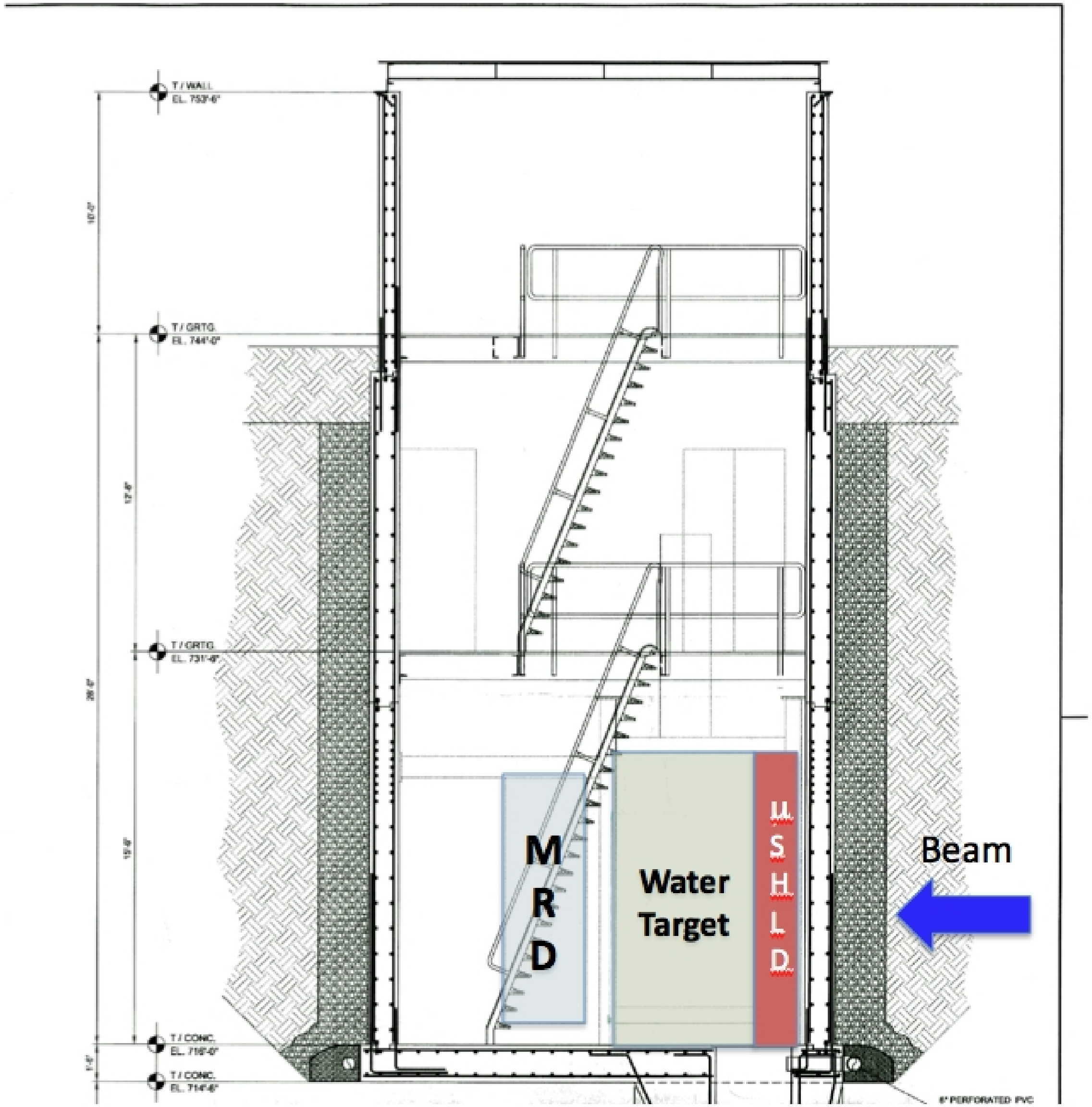
ANNIE is designed to run in the Booster Neutrino Beam (BNB) at Fermilab.

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 ν_μ (in neutrino mode)

Neutrino Beam



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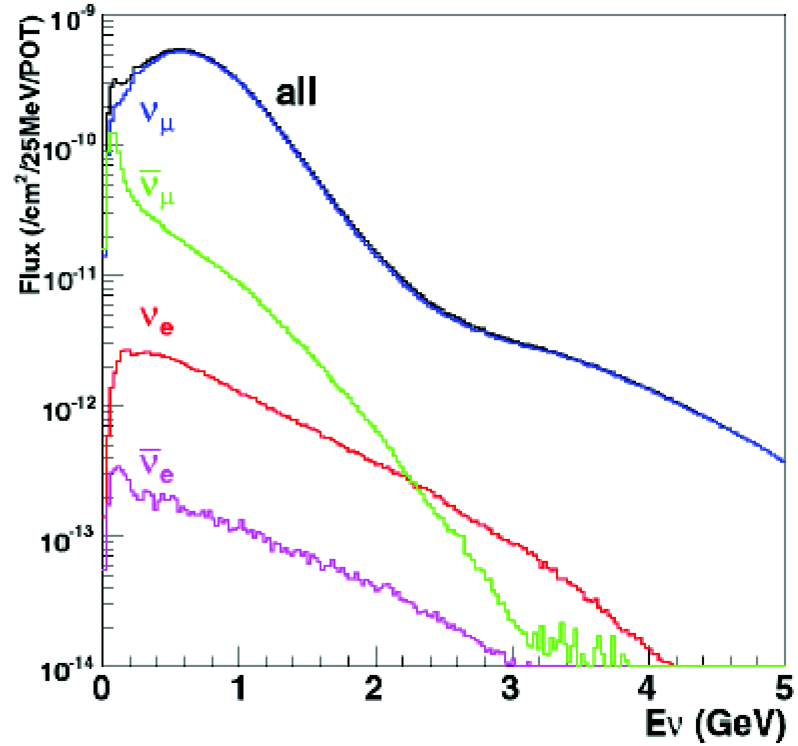
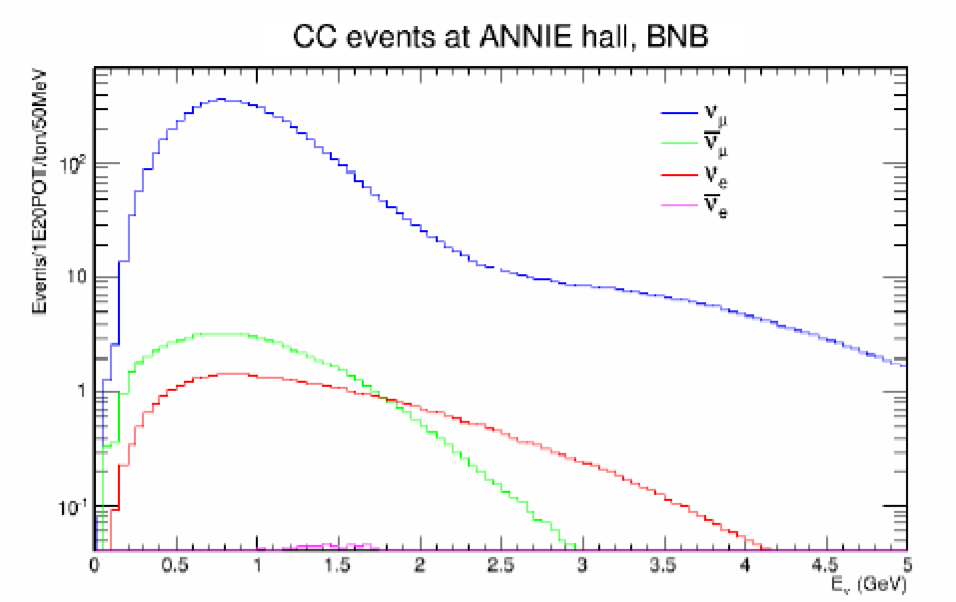
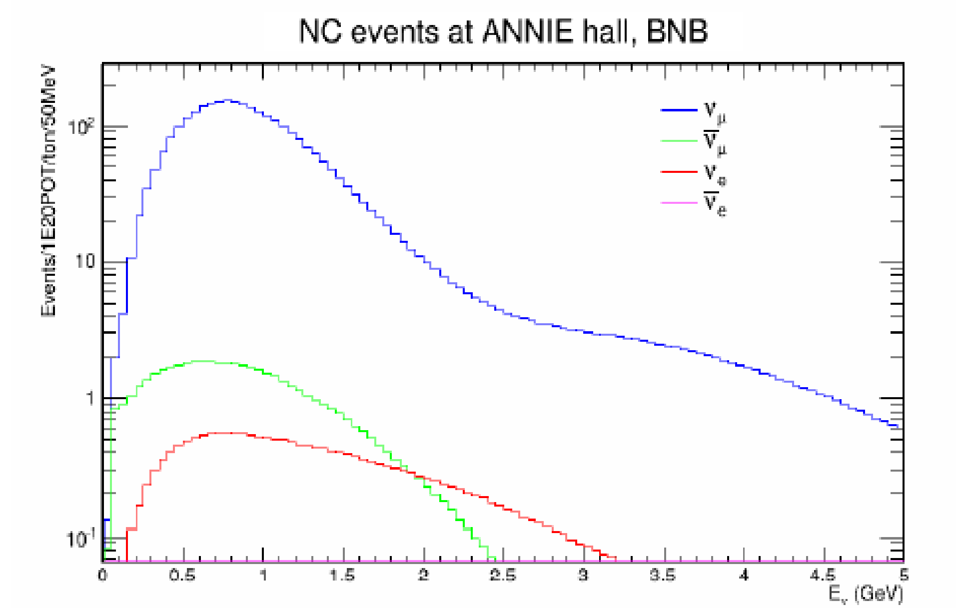
Fluxes at this site:



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

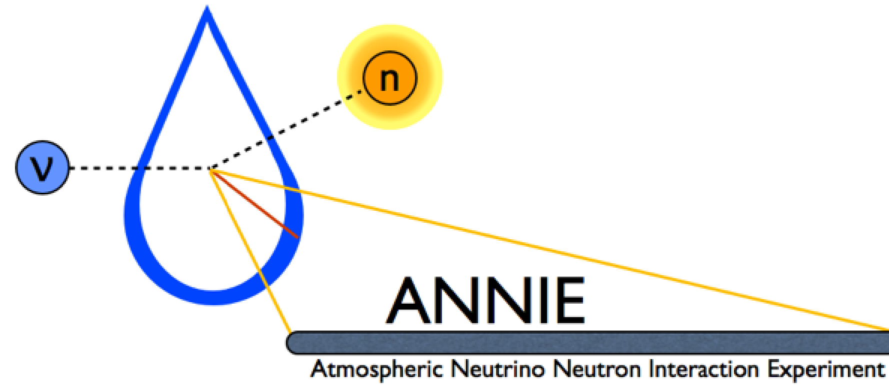
ANNIE Phase I

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

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<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:

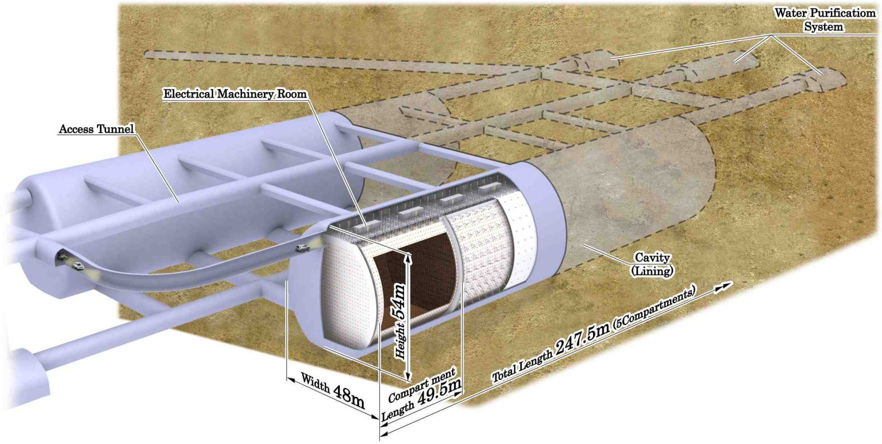
- ~20 tonnes of Gd-doped water
- ~150 PMTs
- 10 – 20 LAPPDs
- MRD (possibly magnetised)

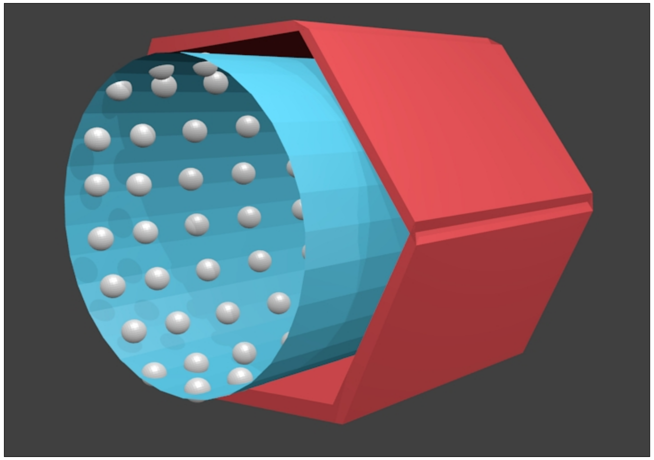
– Physics goals include proper neutron yield measurements, and CC-inclusive measurement of ν_μ on water

– Technical goals include first running of LAPPDs in water

Conclusions

- **Hyper-Kamiokande is the next step in the water Cherenkov detectors**
  - Broad neutrino programme, including oscillation physics and neutrino astrophysics
  - Also will have leading sensitivity for proton decay
- **New technologies for WC include:**
  - Gd-doping for neutron tagging
  - Advanced photosensors (LAPPDs)
- **ANNIE will test these in the Fermilab Booster Neutrino Beam**
  - Will commence running later this year in SciBooNE hall
  - 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 (TITUS) modelled similar to ANNIE
  - Proton decay analysis may increase sensitivity by order of magnitude





Thank you for listening!