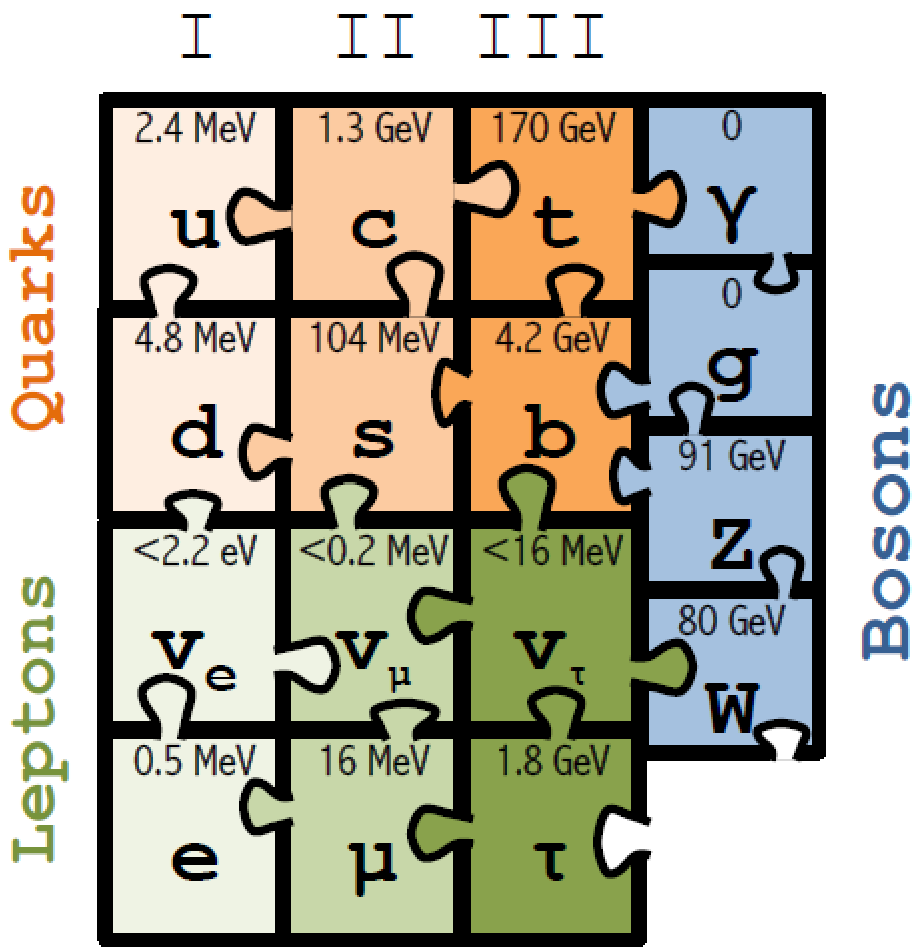
What is next in particle physics?

Alain Blondel

1994-1999: top mass predicted (LEP, mostly Z mass&width)
top quark discovered (Tevatron)
t'Hooft and Veltman get Nobel Prize

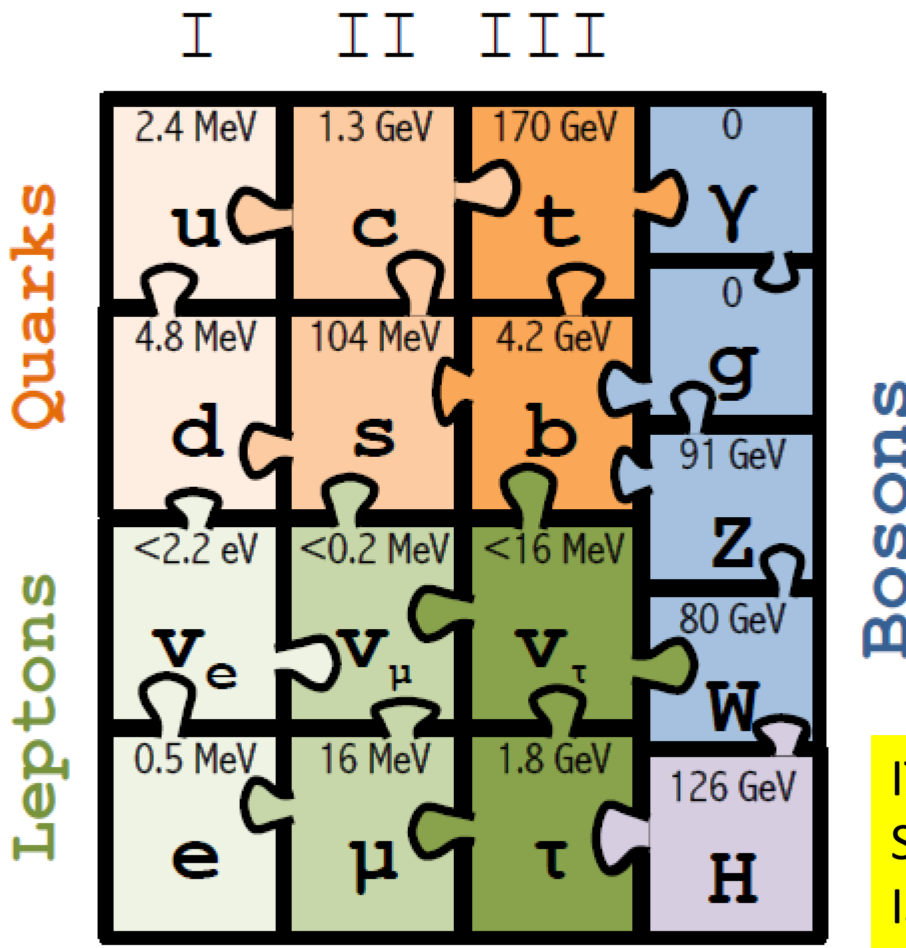


(c) Sfyrla

1997-2013 Higgs boson mass cornered (LEP H, M_Z etc +Tevatron m_t , M_W)

Higgs Boson discovered (LHC)

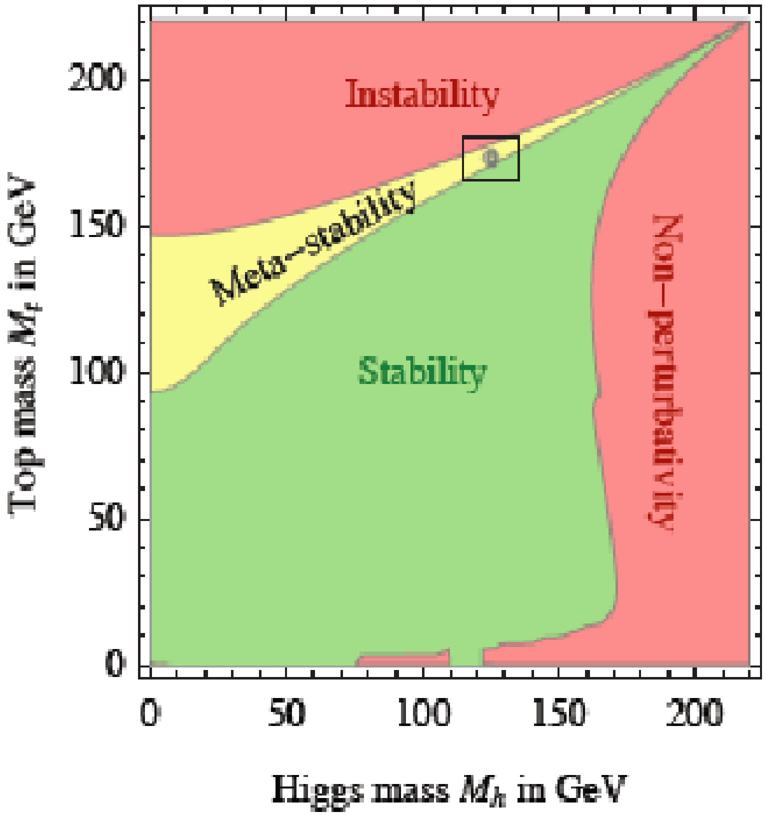
Englert and Higgs get Nobel Prize



IT LOOKS LIKE THE STANDARD MODEL IS COMPLETE.....

(c) Sfyrla

Is it the end?


Instability
Meta−stability
Stability
Non−perturbativity
Top mass M_t in GeV
Higgs mass M_h in GeV
0
50
100
150
200
0
50
100
150
200

Is it the end?

Certainly not!

-- Dark matter

-- Baryon Asymmetry in Universe

-- Neutrino masses

are **experimental proofs** that there is more to understand.

We must continue our quest

HOW?

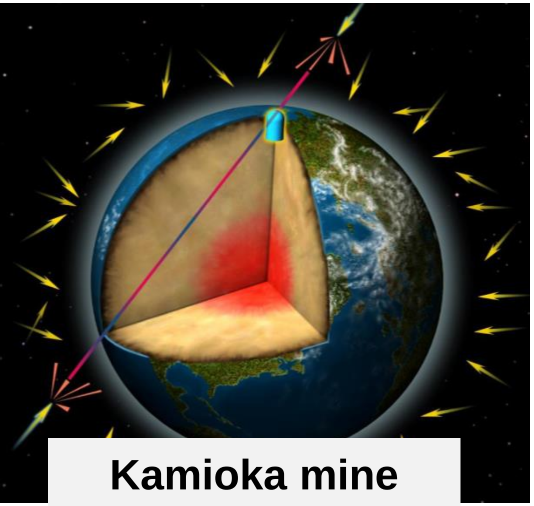
Direct observation of new particles (but not only!)

New phenomena (Neutral currents, CP violation, neutrino oscillations…)

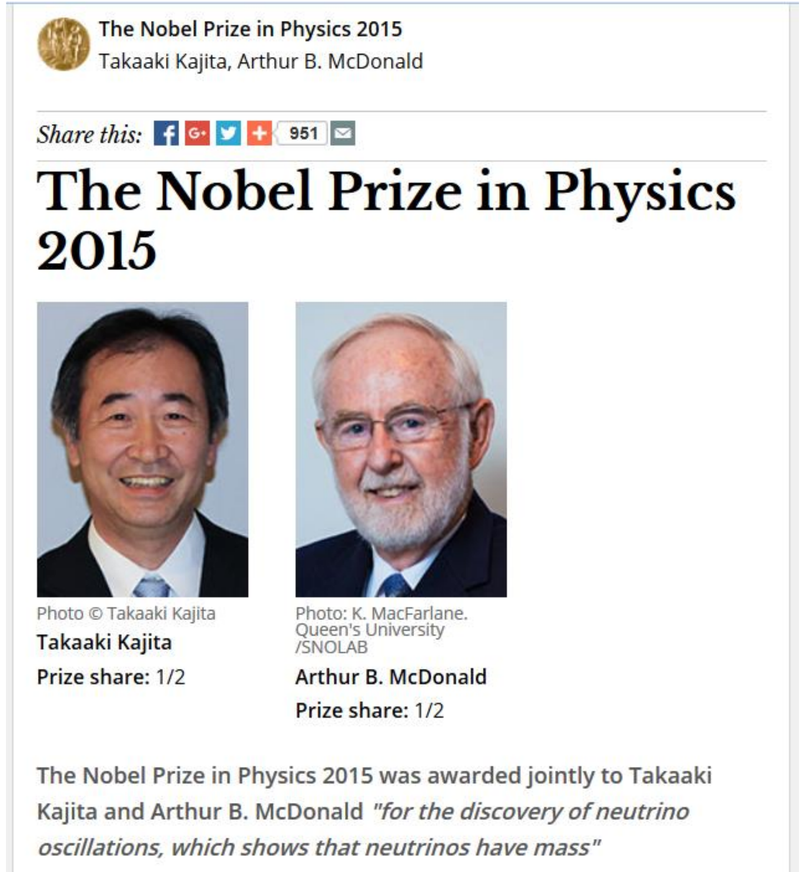
Deviations from precise predictions

(ref. Uranus to Neptune, top and Higgs preds from LEP/SLC/Tevatron/B factories, g-2, violation of unitarity, lepton number violation etc…)

1998 Experimental birth of .. Beyond the Standard Model



Kamioka mine detectors


The Nobel Prize in Physics 2015
Takaaki Kajita, Arthur B. McDonald

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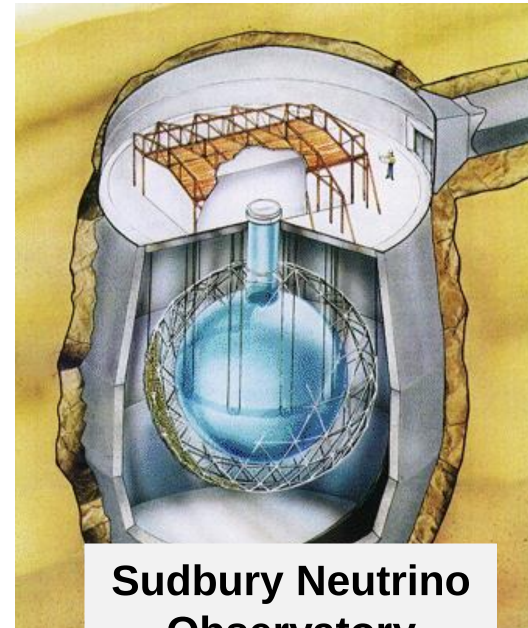
The Nobel Prize in Physics 2015

Photo © Takaaki Kajita
Takaaki Kajita
Prize share: 1/2

Photo: K. MacFarlane. Queen's University /SNOLAB
Arthur B. McDonald
Prize share: 1/2

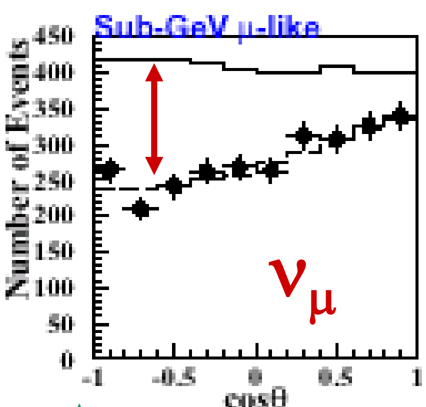
The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*



Sudbury Neutrino Observatory

1000 ton of heavy water $D_2 0$
12 m diam. 9456 PMTs

Determine that all neutrinos reach the earth but only 1/3 remain of same flavour as produced in the sun



from under

from above

The discovery of neutrino oscillations shows that neutrinos have mass

Neutrinos having mass and mixing…..
1. → there shall be CP violation (just like in quarks)
2. → there should be right-handed neutrinos.

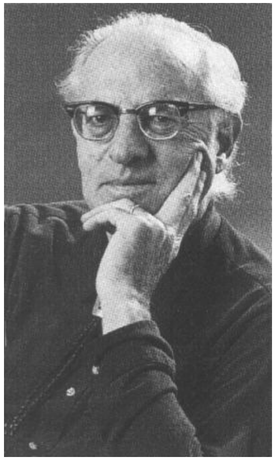
Neutrinos: *detection of neutrino interactions*

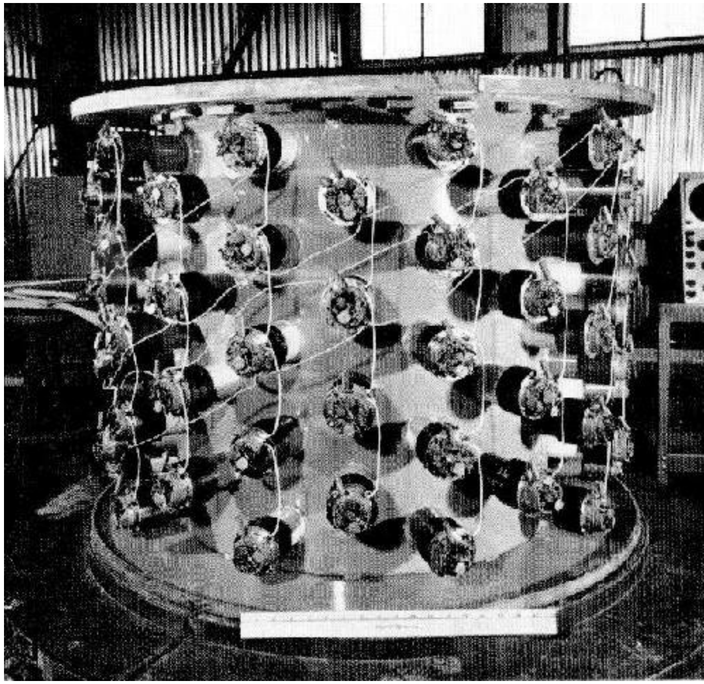
Reines and Cowan **1953**

The anti-neutrino coming from the nuclear reactor interacts with a proton of the target, giving a positron and a neutron.

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

The target is made of about 400 liters of water mixed with cadmium chloride





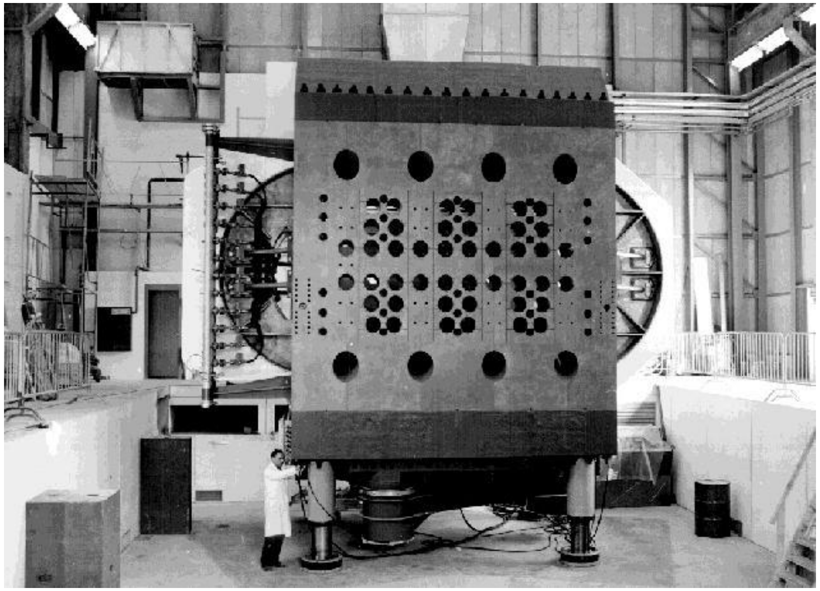
The positron annihilates with an electron of target and gives two simultaneous photons ($e^+ + e^- \rightarrow \gamma\gamma$) .
The neutron slows down before being eventually captured by a cadmium nucleus, that gives the emission of 2 photons about 15 microseconds after those of the positron.

All those 4 photons are detected and the 15 microseconds identify the "neutrino" interaction.

4-fold delayed coincidence

Neutrinos

the weak neutral current



Gargamelle Bubble Chamber
CERN

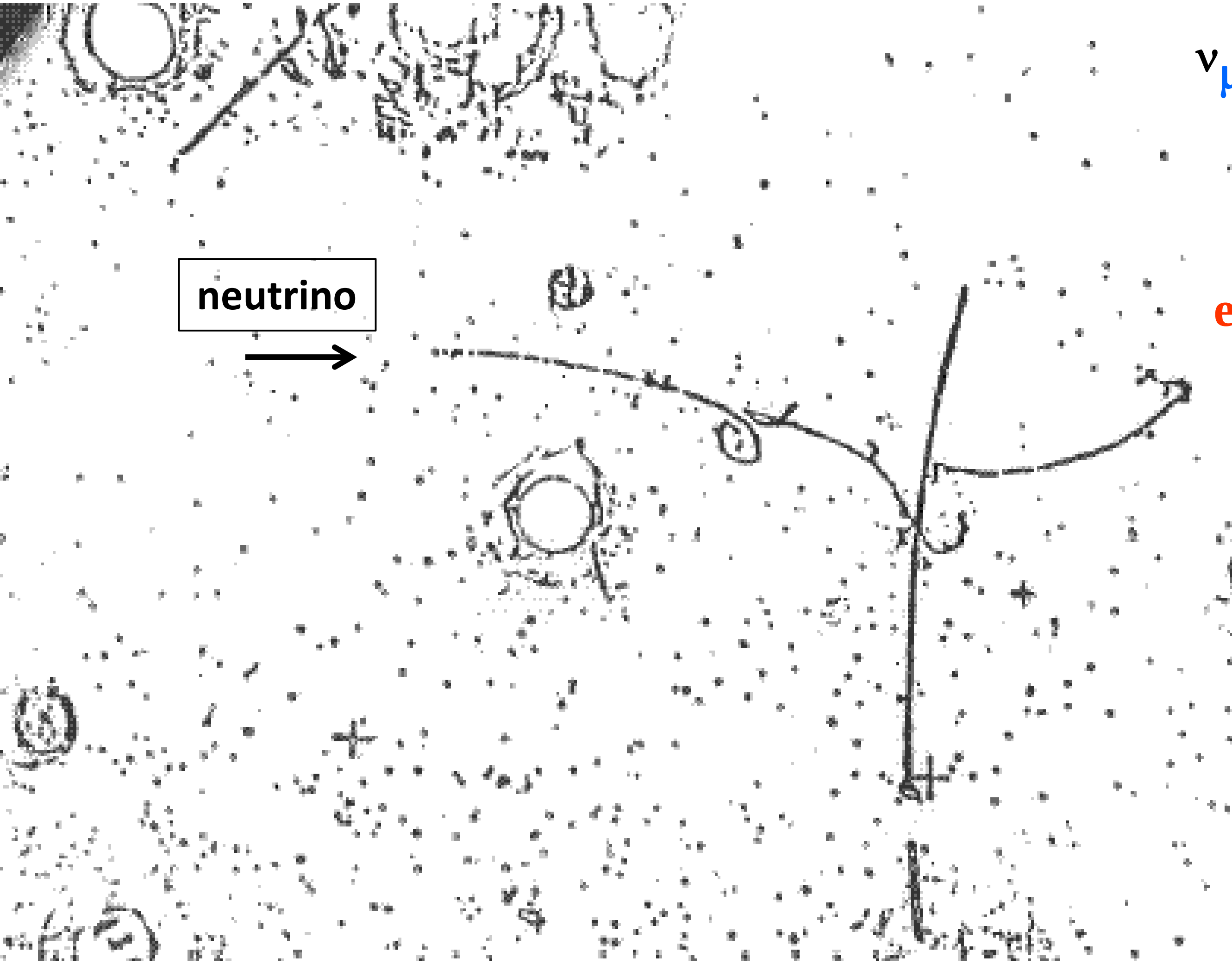
Discovery of weak neutral current

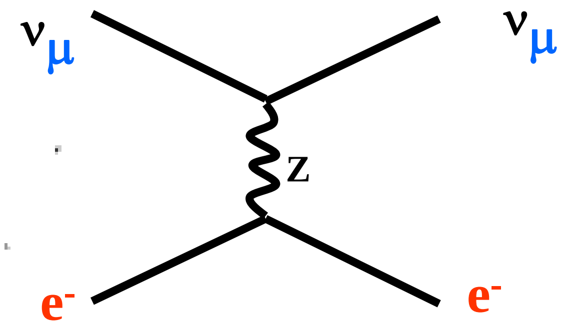
$\nu_\mu + e \rightarrow \nu_\mu + e$

$\nu_\mu + N \rightarrow \nu_\mu + X$ **(no muon)**

previous searches for neutral currents had been performed in particle decays (e.g. $K^0 \rightarrow \mu\mu$) leading to extremely stringent limits (10^{-7} or so)

early neutrino experiments had set their trigger on final state (charged) lepton!





elastic scattering of neutrino
off electron in the liquid freon

1973 Gargamelle

experimental birth of the Standard model

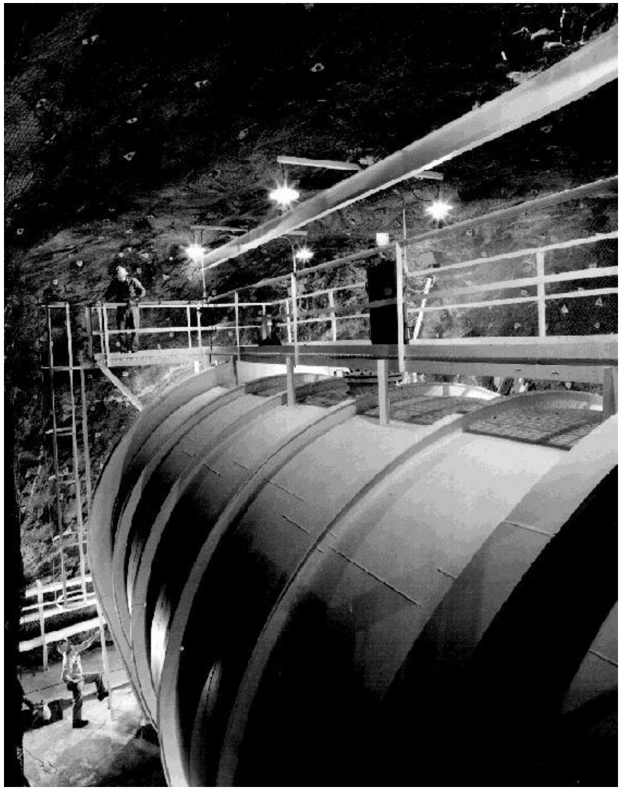
Neutrinos

astrophysical neutrinos

Ray Davis

since ~1968

Homestake Detector



Solar Neutrino Detection
600 tons of chlorine.

- Detected neutrinos E> 1MeV

- fusion process in the sun

solar : $pp \rightarrow pn\ e^+\ \nu_e$ (then D gives He etc…)

these ν_e do $\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$

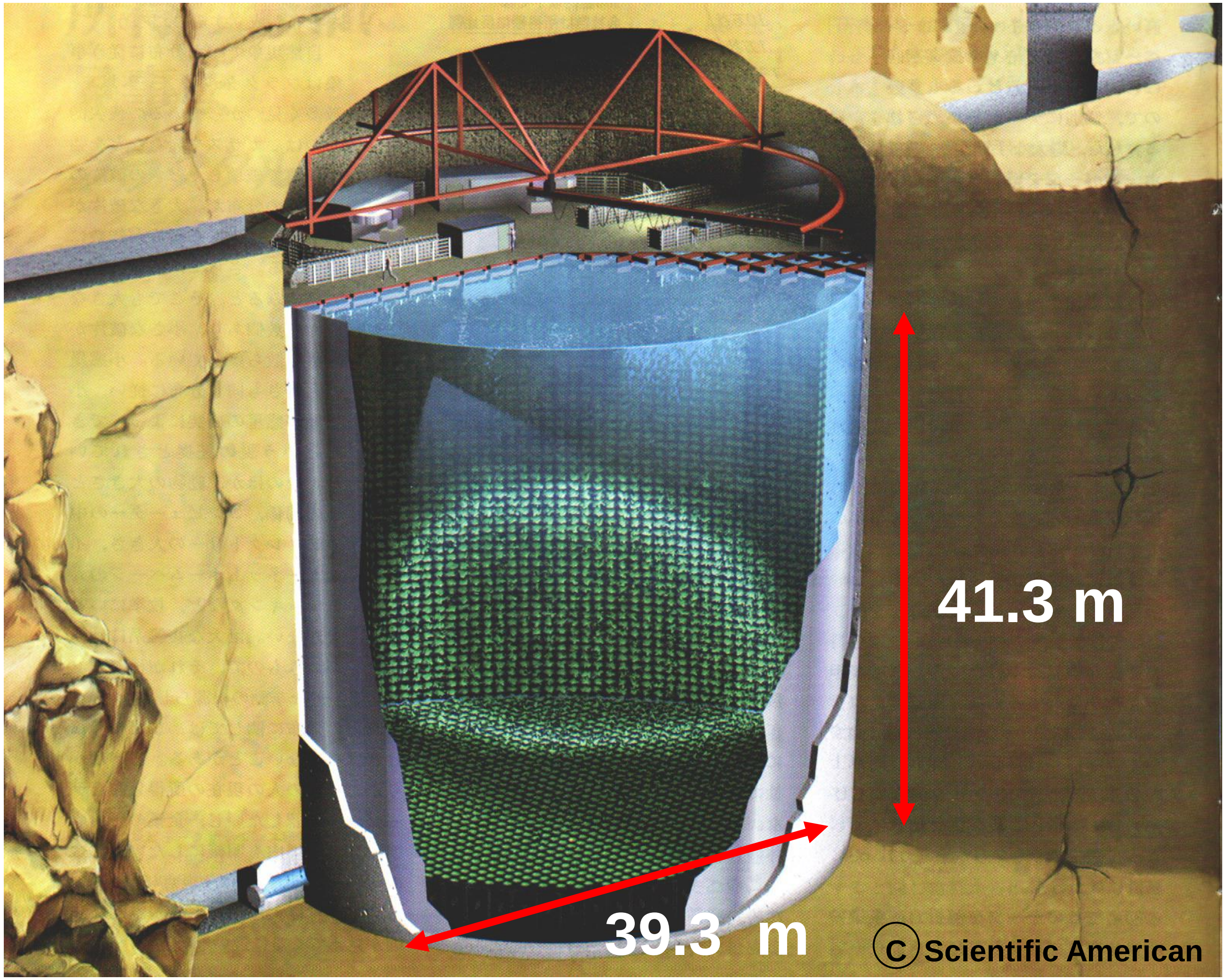
they are neutrinos

- The rate of neutrinos detected is **three** times less than predicted!

solar neutrino 'puzzle' since 1968-1975!

solution: 1) solar nuclear model is wrong or 2) neutrino oscillate

Super-K detector



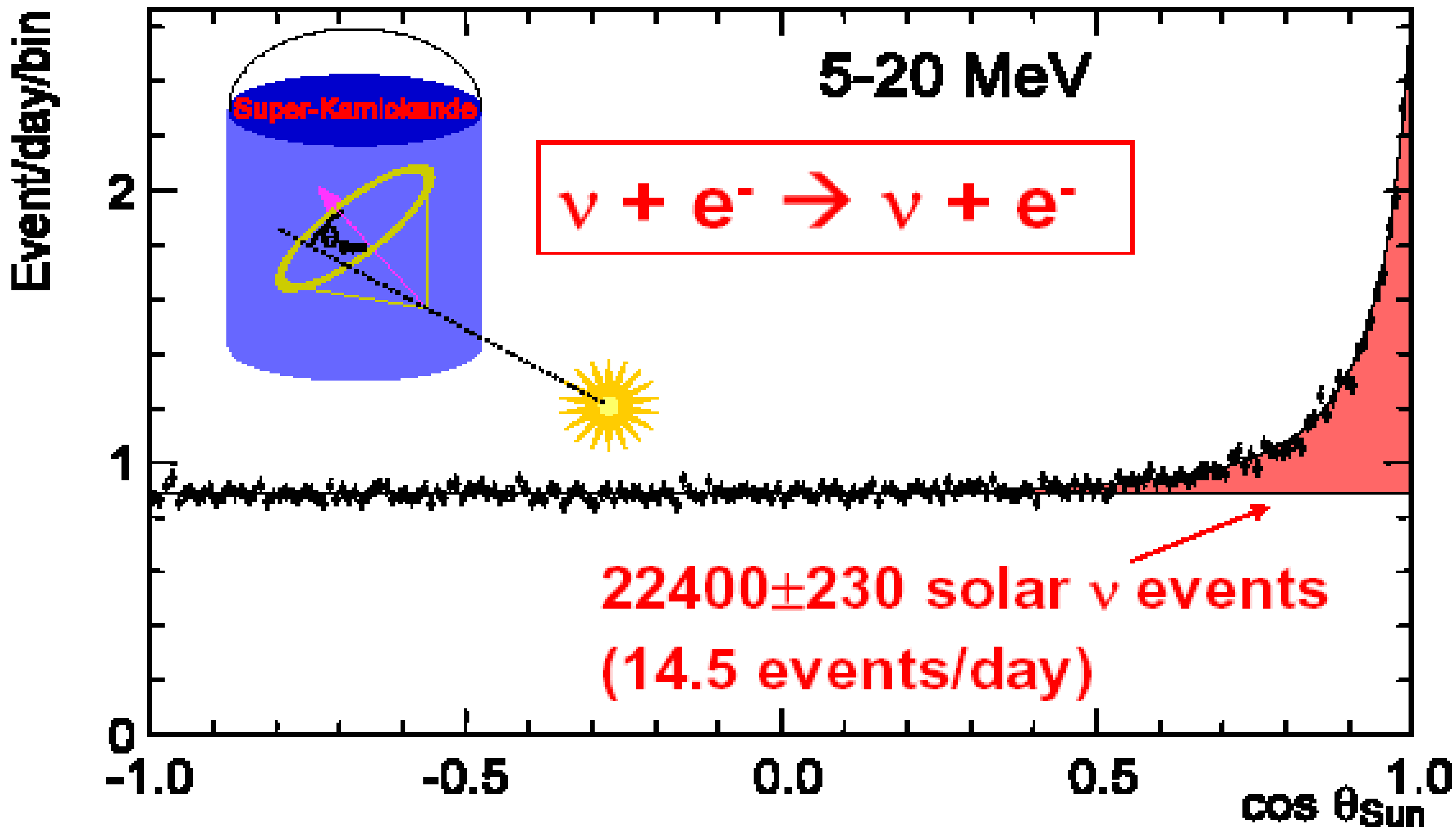
Water Cerenkov detector

50000 tons of pure light water

≈10000 PMTs

Super-Kamiokande-I solar neutrino data

May 31, 1996 – July 13, 2001 (1496 days)



^{8}B flux : $2.35 \pm 0.02 \pm 0.08$ [x 10^6 /cm^2/sec]

$$\frac{\text{Data}}{\text{SSM(BP2004)}} = 0.406 \pm 0.004 \, {}^{+0.014}_{-0.013}$$

(Data/SSM(BP2000) = 0.465 ±0.005 +0.016/-0.015)

neutrino definitions

the electron neutrino is present in association with an electron (e.g. beta decay)

the muon neutrino is present in association with a muon (pion decay)

the tau neutrino is present in association with a tau ($W \rightarrow \tau\nu$ decay)

these flavor-neutrinos are not (as we know now) quantum states of well defined mass (neutrino mixing)

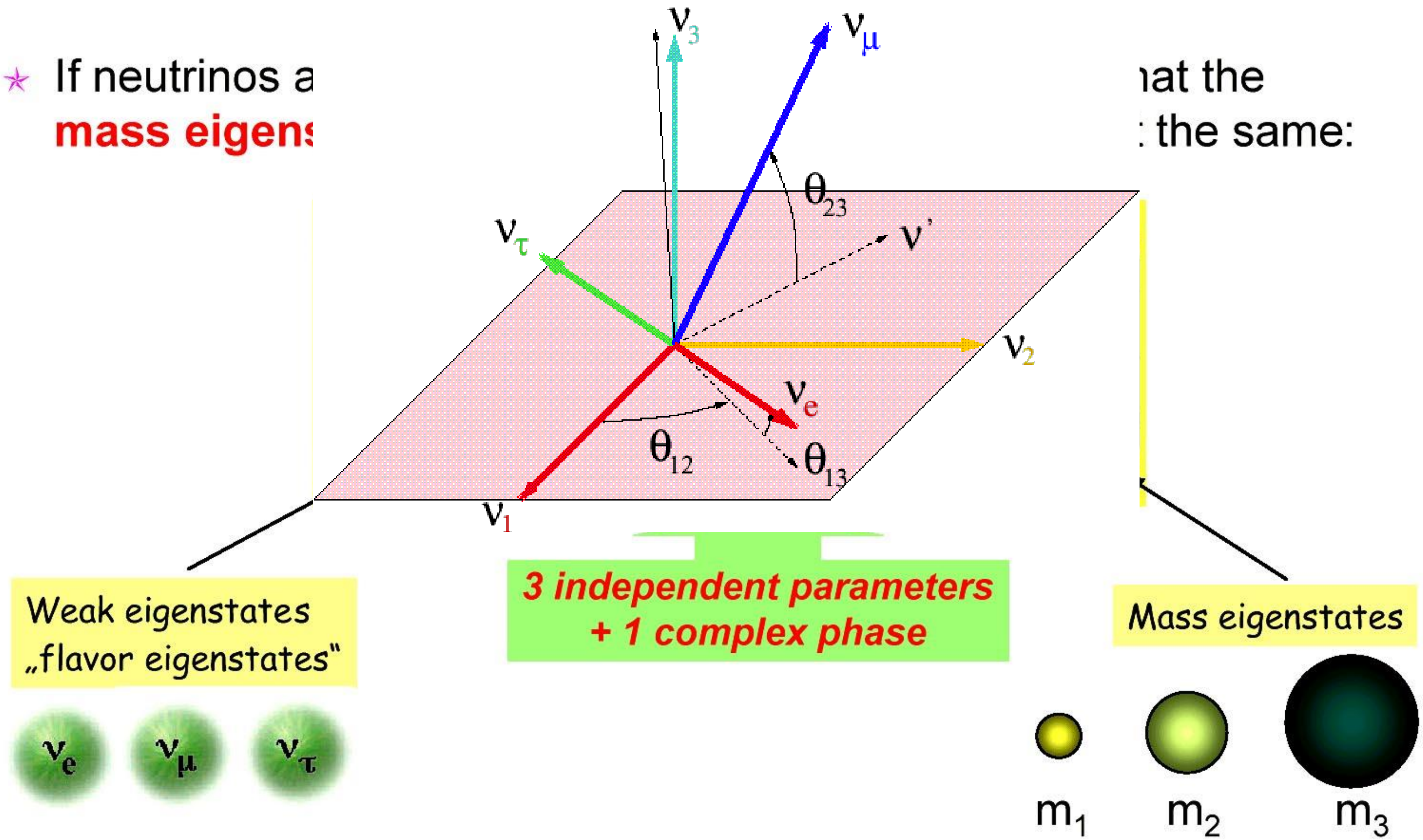
the mass-neutrino with the highest electron neutrino content is called ν_1

the mass-neutrino with the next-to-highest electron neutrino content is ν_2

the mass-neutrino with the smallest electron neutrino content is called ν_3

Lepton Sector Mixing

★ If neutrinos a … hat the
mass eigens … the same:



Pontecorvo 1957

NB This is a ridiculous picture:
the size is inversely proportional
to the mass (energy)

Oscillation Probability

- The case with two neutrinos:
  - → A mixing angle: θ
  - → A mass difference:

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$\Delta m^2 = m_2^2 - m_1^2$$

- The oscillation probability is:

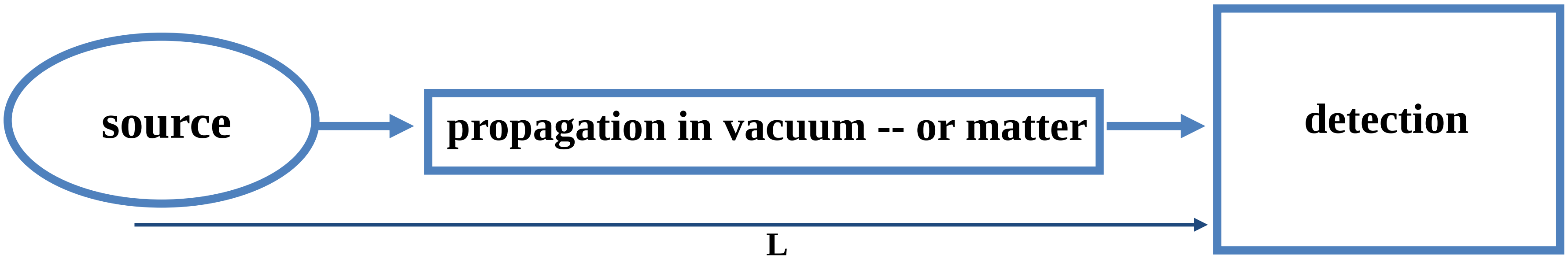
Dm2 en ev2
L en km
E en GeV

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2\left(1.27 \Delta m^2 \frac{L}{E}\right)$$

where L = distance between source and detector
E = neutrino energy

Hamiltonian= E = sqrt($p^2 + m^2$) = p + $m^2 / 2p$
for a given momentum, eigenstate of propagation in free space are the mass eigenstates!

Neutrino Oscillations (Quantum Mechanics lesson 5)



weak interaction produces 'flavour' neutrinos

e.g. pion decay $\pi \to \mu\nu$

$|\nu_\mu\rangle = \alpha\,|\nu_1\rangle + \beta\,|\nu_2\rangle + \gamma\,|\nu_3\rangle$

Energy (i.e. mass) eigenstates propagate

$$|\nu(t)\rangle = \alpha\,|\nu_1\rangle \exp(i E_1 t) + \beta\,|\nu_2\rangle \exp(i E_2 t) + \gamma\,|\nu_3\rangle \exp(i E_3 t)$$

t = proper time $\propto$ L/E

weak interaction: (CC)

$\nu_\mu\ N \to \mu^-\ X$

or $\nu_e\ N \to e^-\ X$

or $\nu_\tau\ N \to \tau^-\ X$

$$P(\nu_\mu \to \nu_e) = |\langle \nu_e | \nu(t)\rangle|^2$$

α is noted $U_{1\mu}$

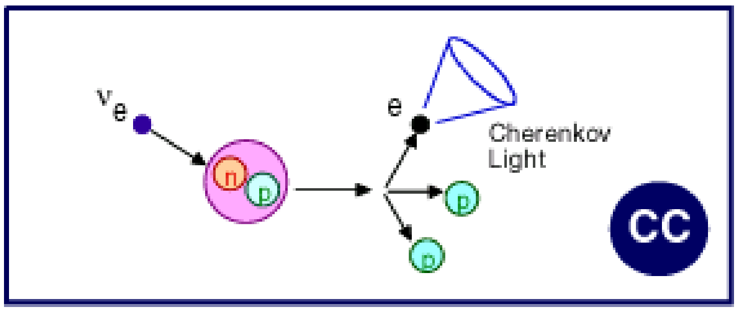
β is noted $U_{2\mu}$

γ is noted $U_{3\mu}$ etc….

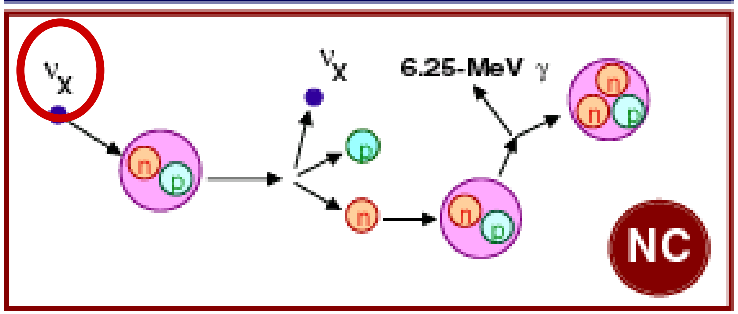
SNO detector

Aim: measuring non ν_e neutrinos in a pure solar ν_e beam

How? Three possible neutrino reaction in heavy water:

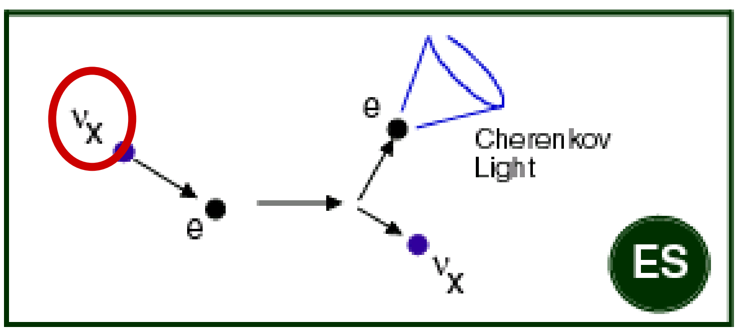


only ν_e



equally

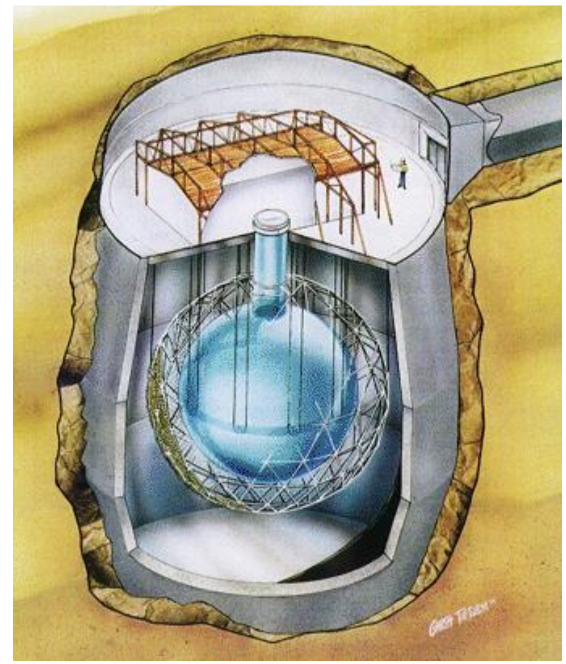
$\nu_e + \nu_\mu + \nu_\tau$



in-equally

$\nu_e +$

$0.1\ (\nu_\mu + \nu_\tau)$

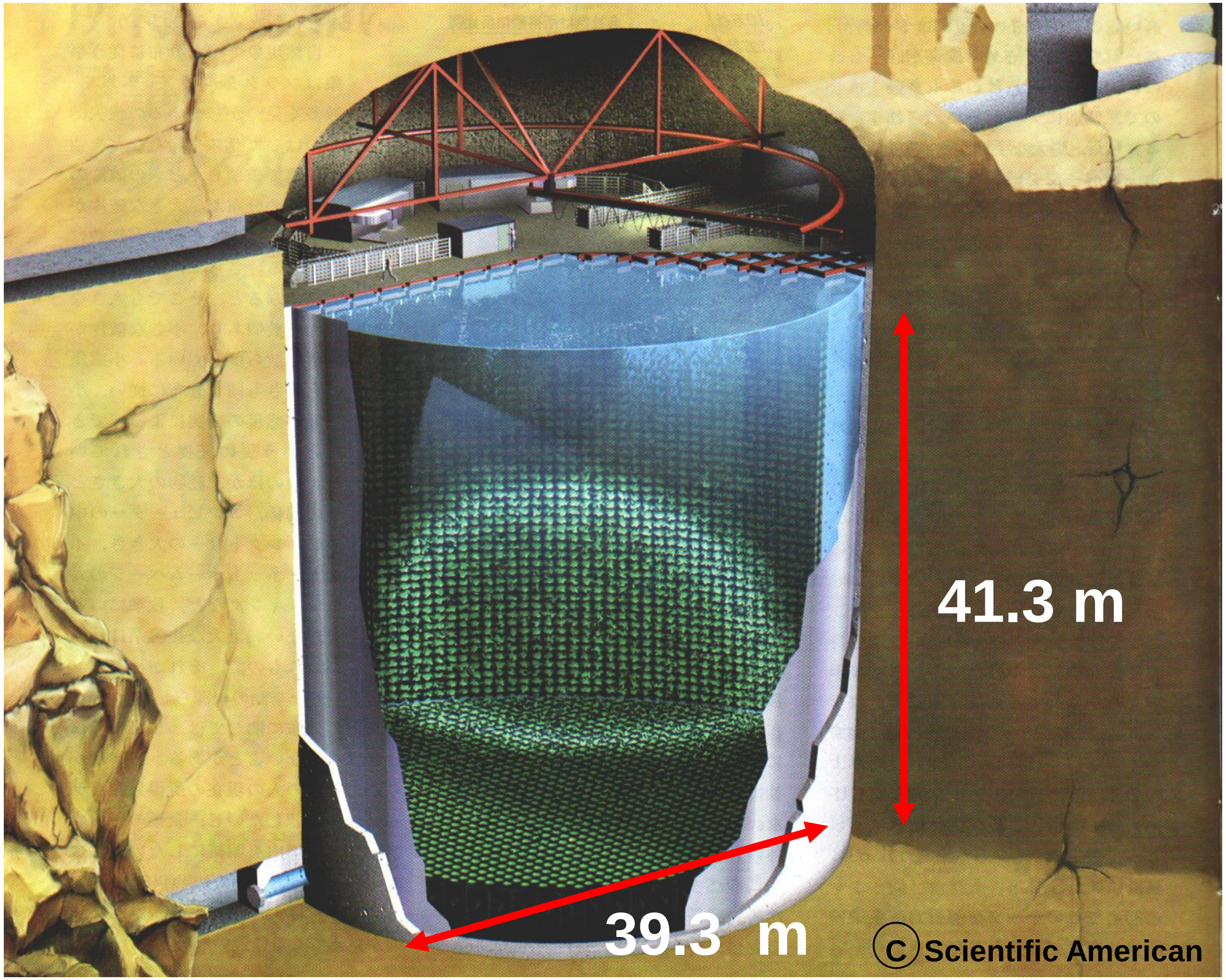


1000 ton of $D_2 0$

12 m diam.

9456 PMTs

Super-K detector

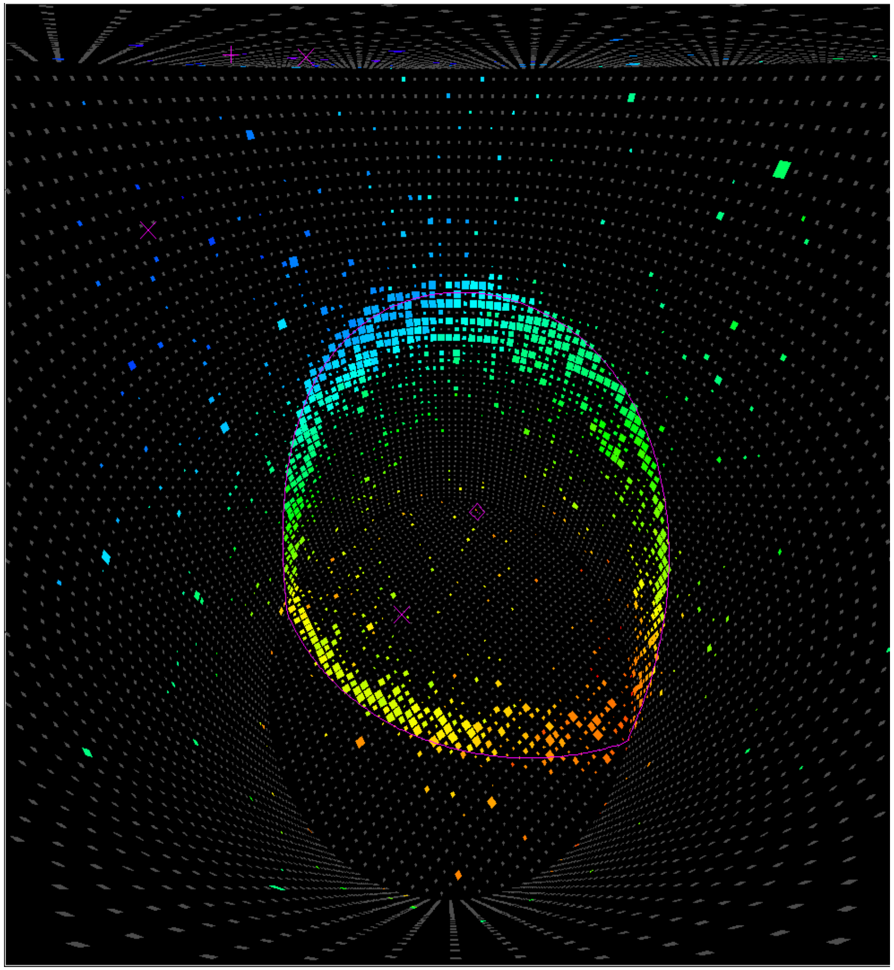


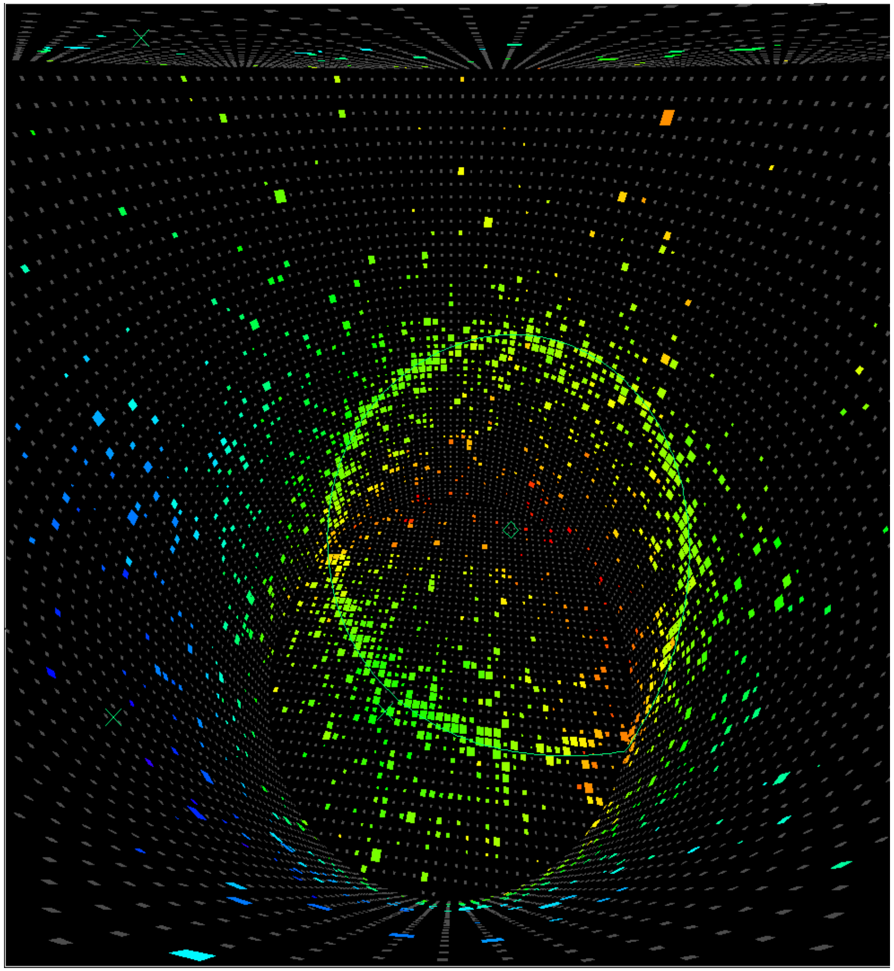
- Water Cerenkov detector
- 50000 tons of pure light water
- ≈10000 PMTs

μ/e Background Rejection

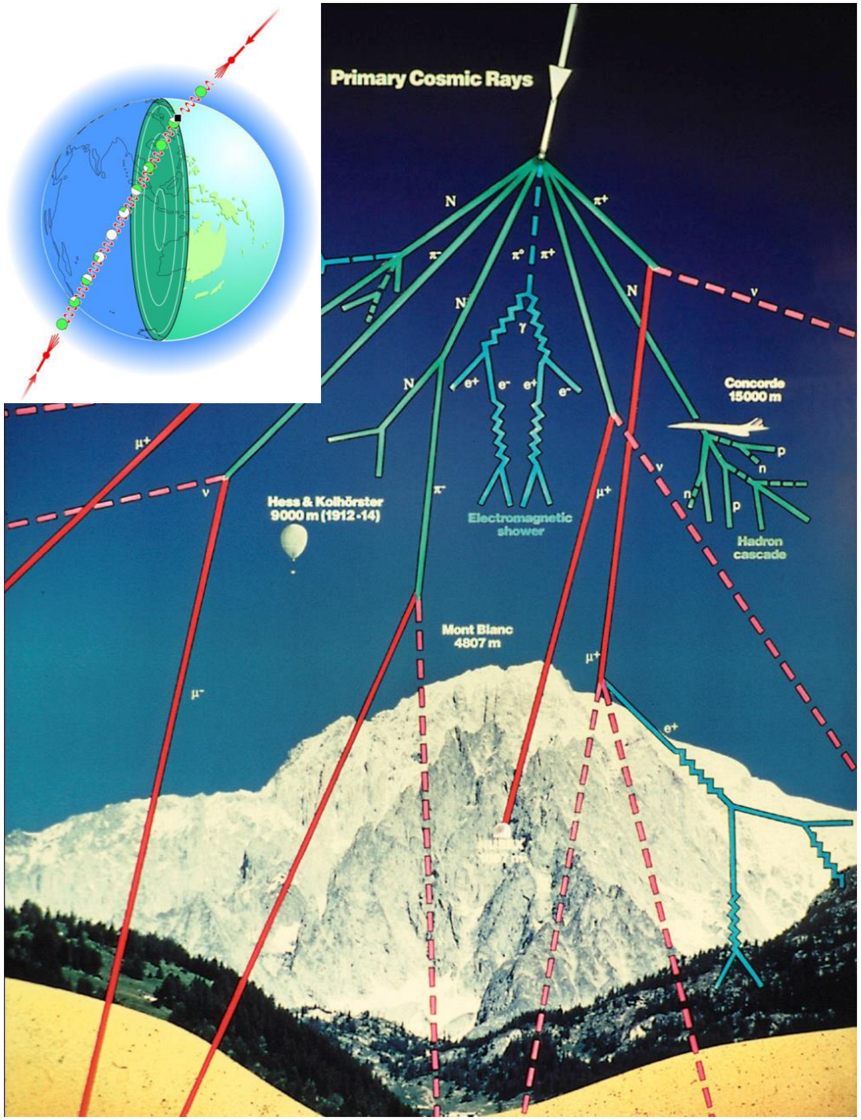
e/mu separation directly related to granularity of coverage.

Limit is around 10^{-3} (mu decay in flight) SKII coverage OKOK, less maybe possible



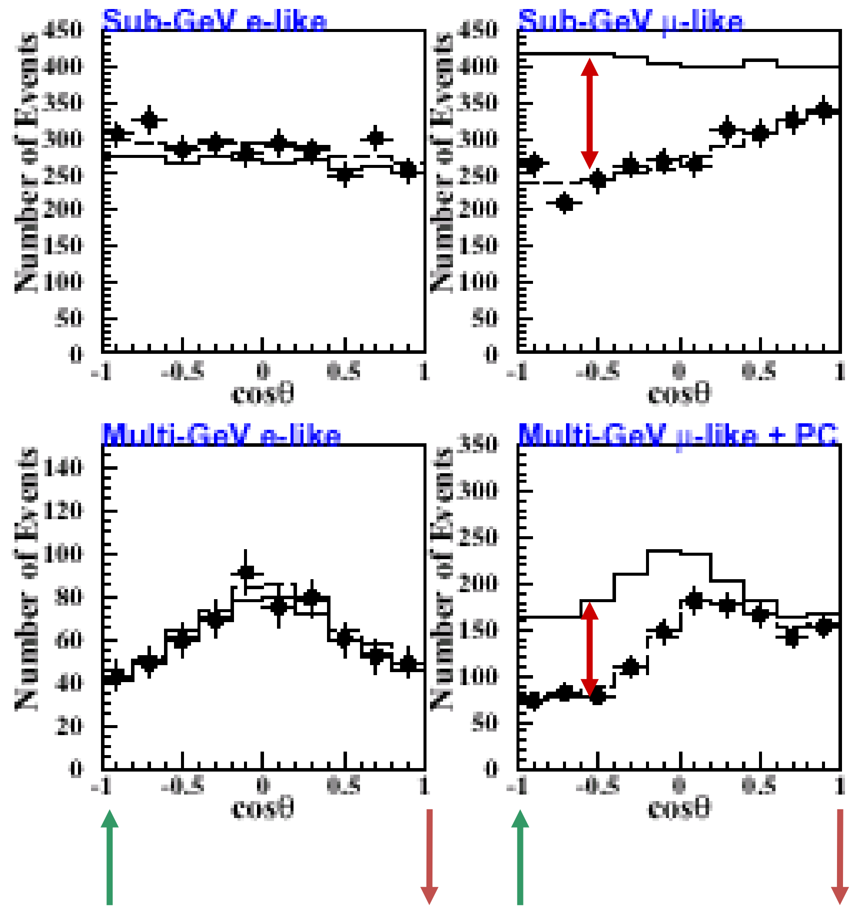


Atmospheric ν : up-down asymmetry



Super-K results

ν_e ν_μ



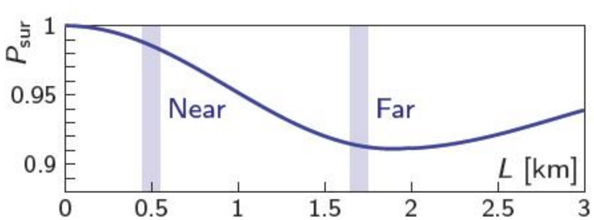
up down

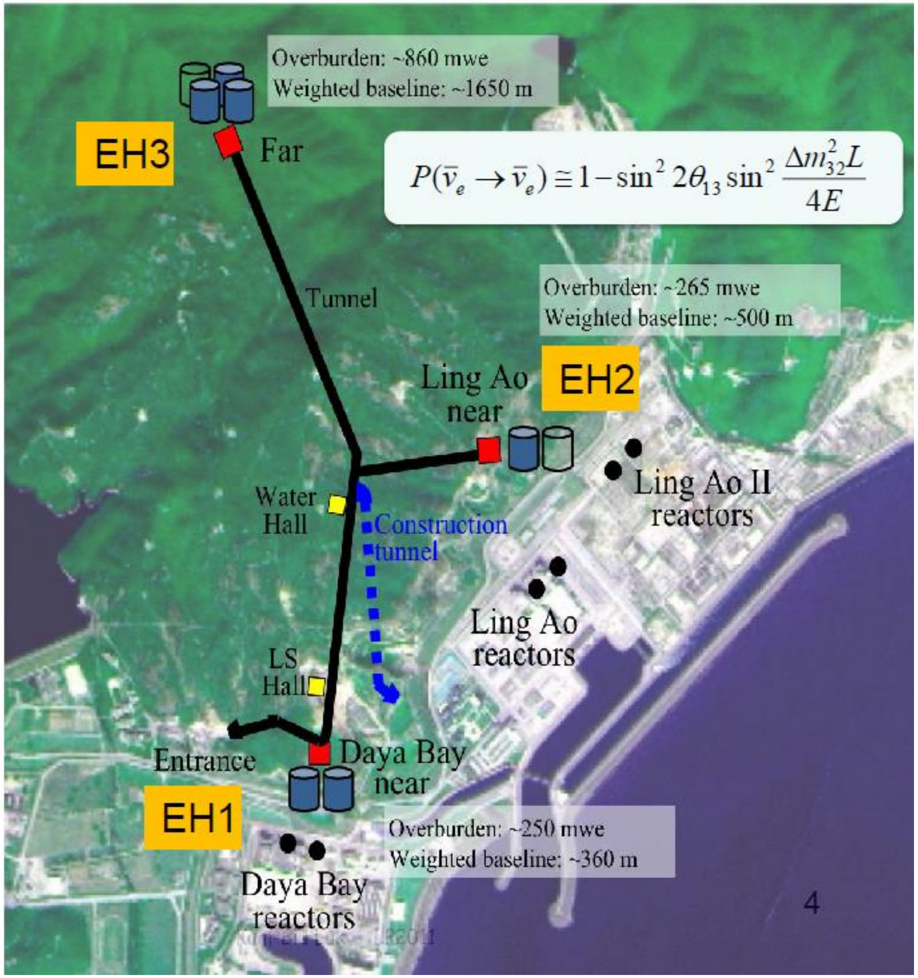
Daya Bay Experiment Layout

- 6 reactor cores, 17.6GW_{th} total power
- Relative measurement
  - 2 near sites, 1 far site
- Multiple detector modules
- Good cosmic ray shielding

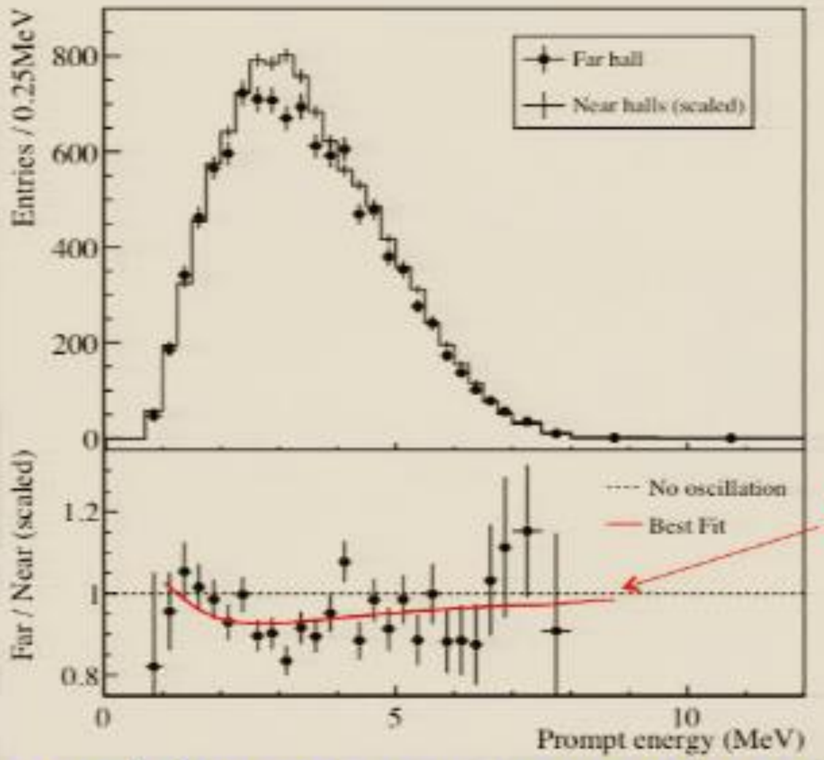
TABLE I. Vertical overburden (m.w.e.), muon rate R_μ (Hz/m^2), and average muon energy E_μ (GeV) of the three EHs, and the distances (m) to the reactor pairs.

	Overburden	R_μ	E_μ	D1,2	L1,2	L3,4
EH1	250	1.27	57	364	857	1307
EH2	265	0.95	58	1348	480	528
EH3	860	0.056	137	1912	1540	1548





Far vs. Near Comparison : Spectrum



$\sin^2 2\theta_{13} = 0.092$

Spectral distortion consistent with oscillation.

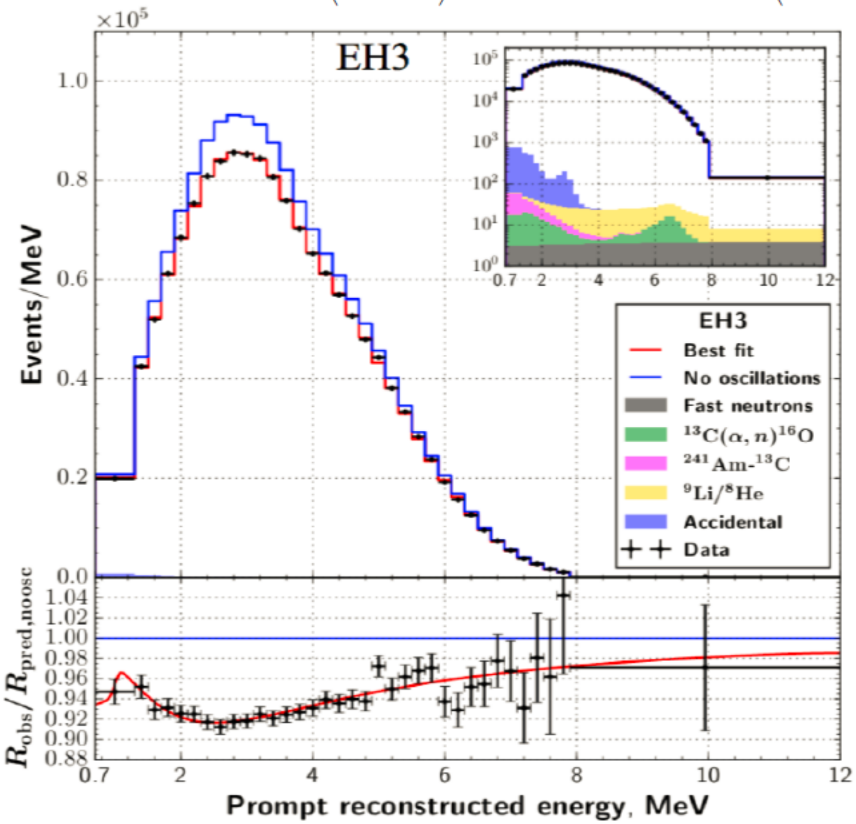
$\sin^2 2\theta_{13} = 0.092 \pm 0.016\ (\text{stat}) \pm 0.005\ (\text{syst})$

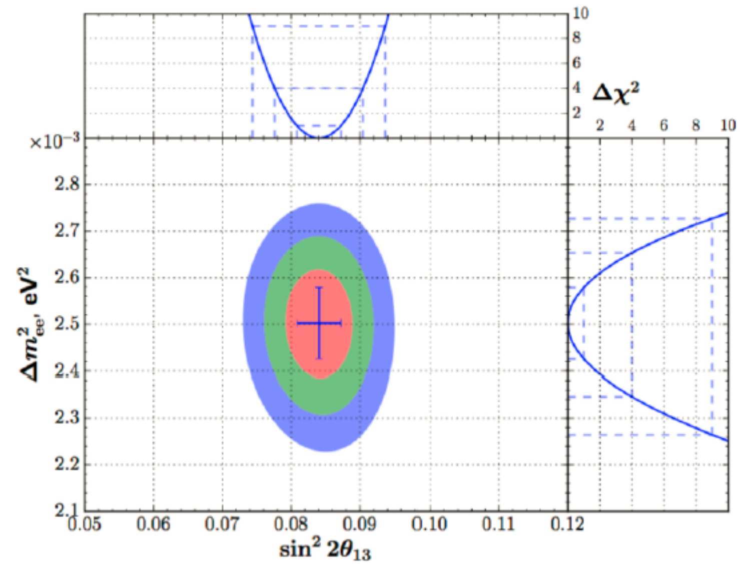
$\sin^2 2\theta_{13} = 0$ excluded at 5.2σ

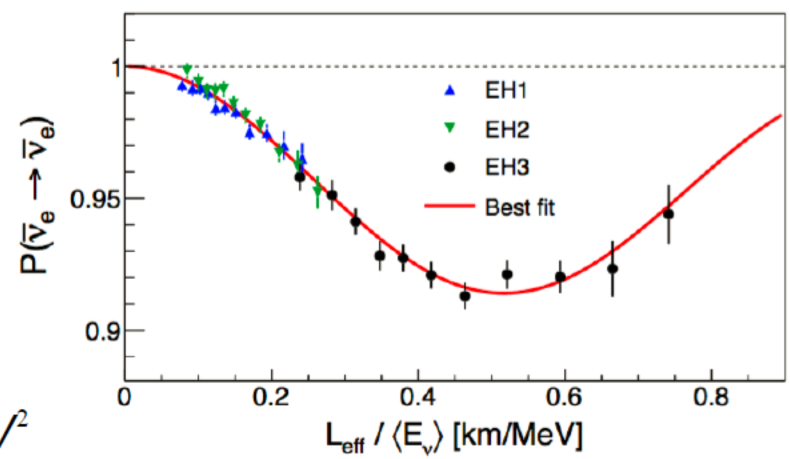
8 Mars 2012

Daya Bay: the Latest Results

$$P_{ee} = 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{ee} L}{4E}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)$$





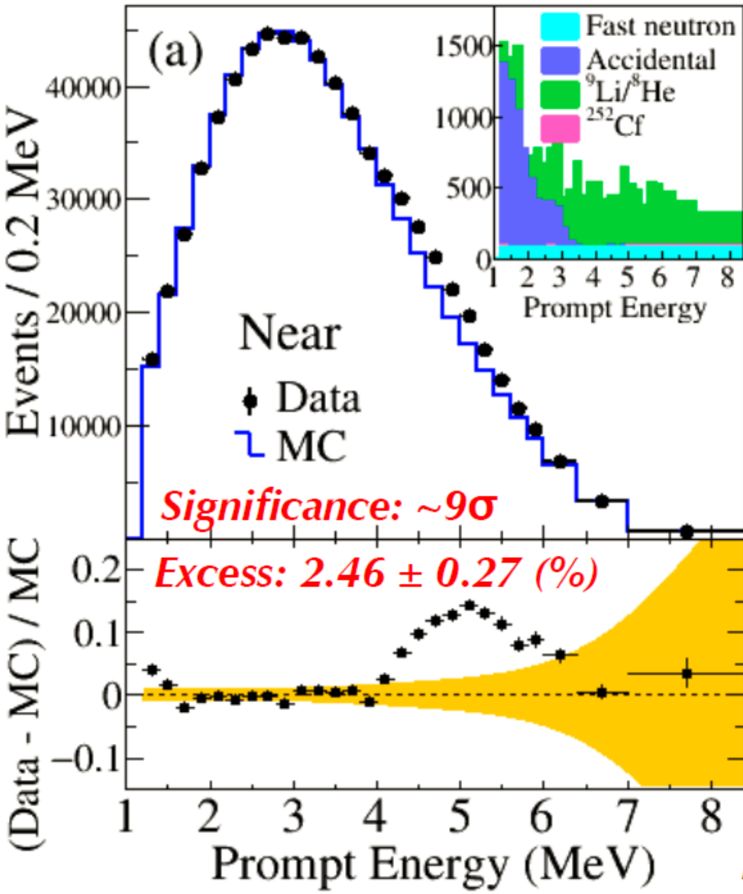


$$\sin^2 2\theta_{13} = 0.0841 \pm 0.0027(stat.) \pm 0.0019(syst.)$$

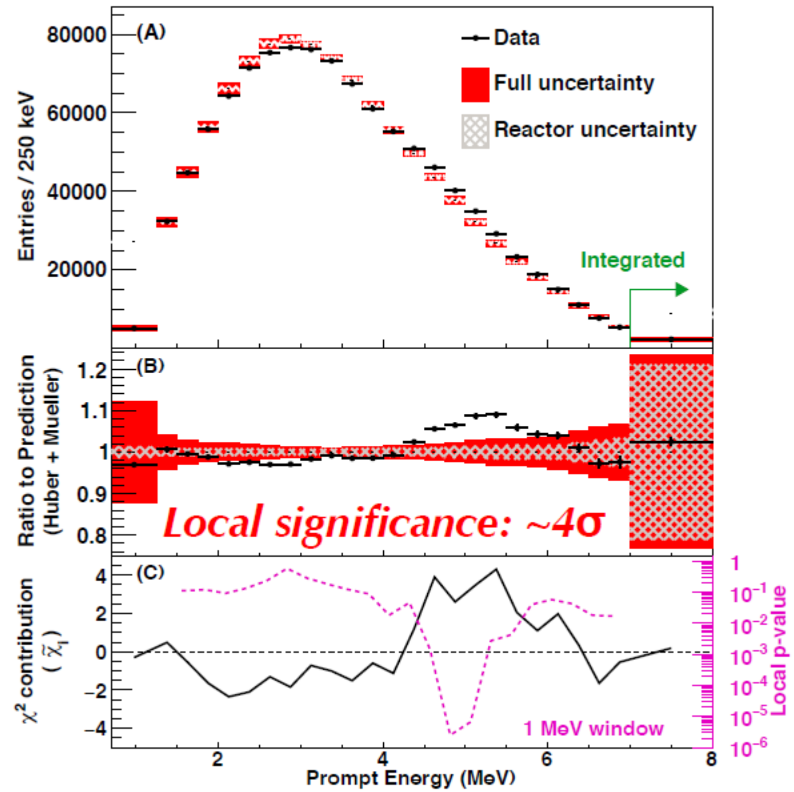
$$|\Delta m^2_{ee}| = [2.50 \pm 0.06(stat.) \pm 0.06(syst.)] \times 10^{-3}\, eV^2$$

The Reactor Flux Spectrum Discrepancy

RENO preliminary



Daya Bay CPC

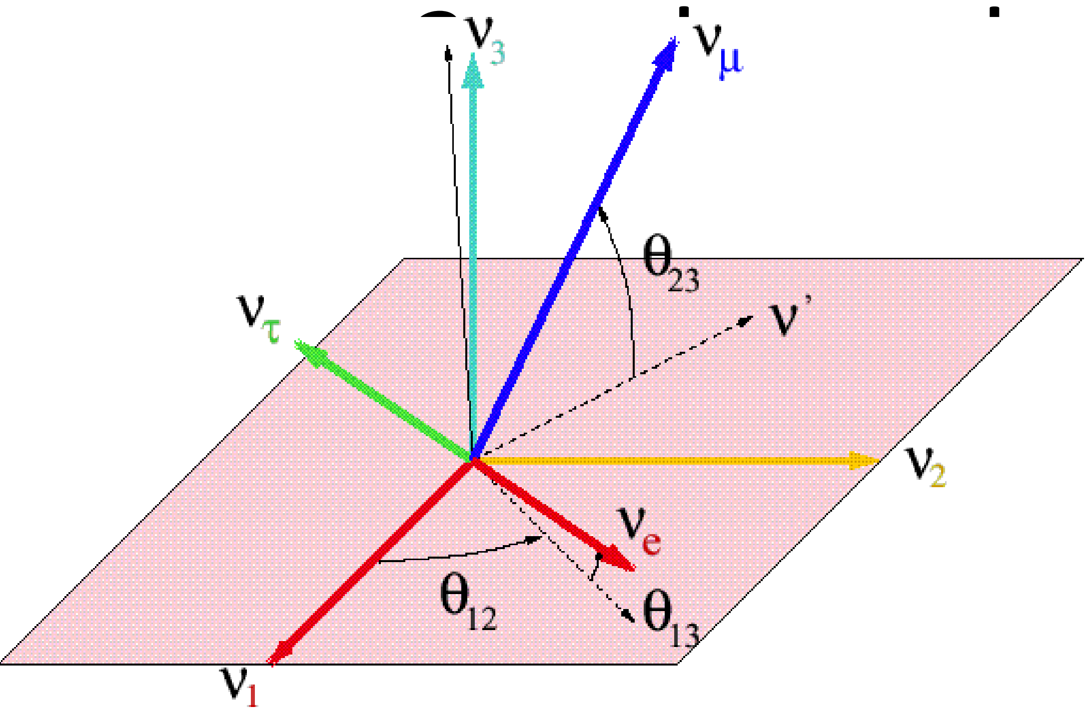


Blaming fission isotope beta decay calculation/data?

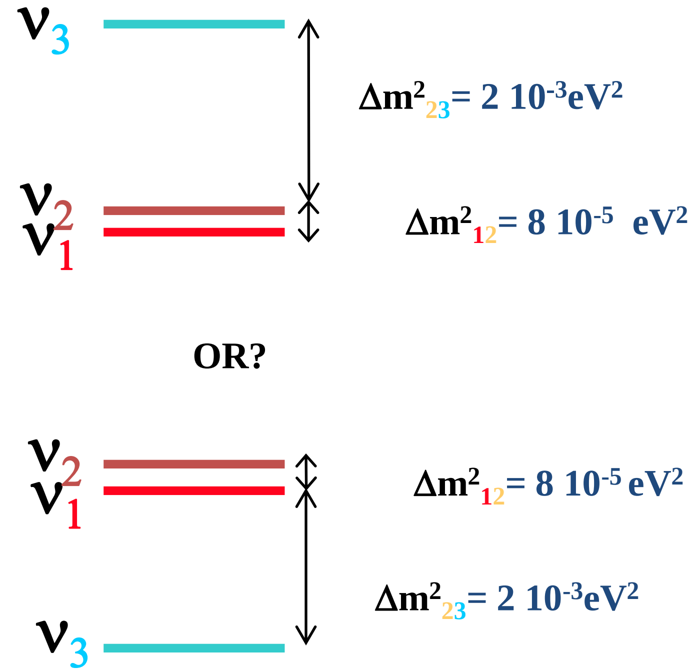
For example, see: Dwyer & Langford, PRL114 (2015)012502; Hayes et al, PRL112 (2014) 202501

reactor experiments allow investigation of reactor calculations! (and… badly off)

The neutrino mixing matrix:
phase δ



θ_{23} (atmospheric) = 45^0 , θ_{12} (solar) = 32^0 , θ_{13} (Chooz) < 13^0



$$U_{MNS}: \begin{pmatrix} \sim \frac{\sqrt{2}}{2} & \sim -\frac{\sqrt{2}}{2} & \sin\theta_{13}\, e^{i\delta} \\ \sim \frac{1}{2} & \sim \frac{1}{2} & \sim -\frac{\sqrt{2}}{2} \\ \sim \frac{1}{2} & \sim \frac{1}{2} & \sim \frac{\sqrt{2}}{2} \end{pmatrix}$$

Unknown or poorly known today phase δ , sign of Δm_{13}^2

Oscillation maximum $1.27\ \Delta m^2\ L / E = \pi/2$

Atmospheric $\Delta m^2 = 2.5\ 10^{-3}$ eV^2 L = 500 km @ 1 GeV
Solar $\Delta m^2 = 7\ 10^{-5}$ eV^2 L = 18000km @ 1 GeV

Consequences of 3-family oscillations:

I There will be $\nu_\mu \leftrightarrow \nu_e$ oscillation at L_{atm}
(discovered by T2K)

$$P(\nu_\mu \leftrightarrow \nu_e)_{max} =\sim \tfrac{1}{2}\ \sin^2 2\theta_{13} + \ldots \text{(small)}$$

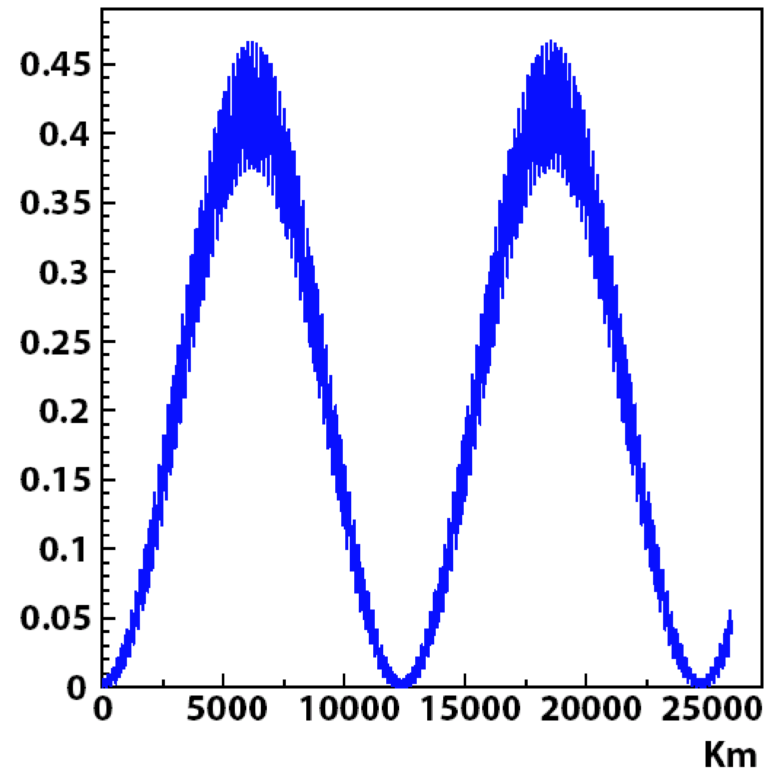
II There will be CP violation

CP: $P(\bar{\nu}_\mu \leftrightarrow \bar{\nu}_e) \neq P(\nu_\mu \leftrightarrow \nu_e)$

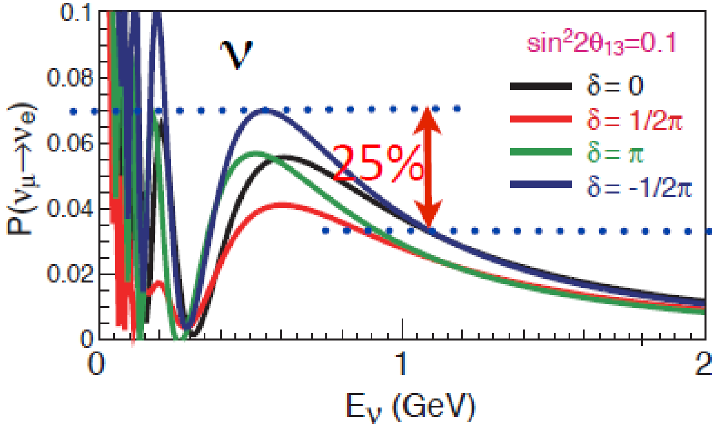
III we do not know if the neutrino ν_1 which contains more ν_e is
the lightest one (natural?)
or not (inverted)

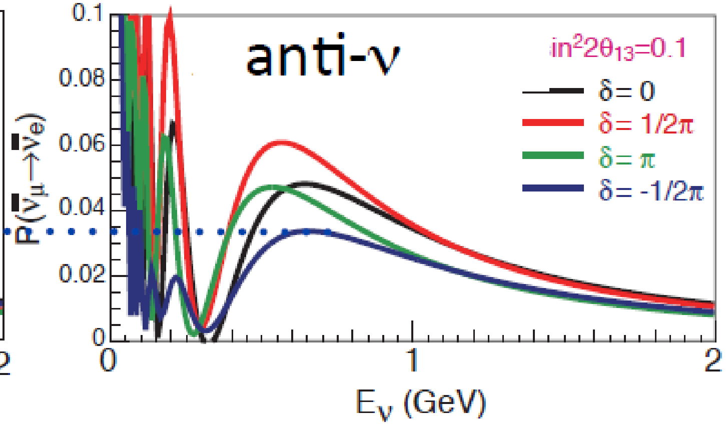
Oscillations of 250 MeV neutrinos;

$P(\nu_\mu \leftrightarrow \nu_e)$



ν_e appearance





for $P(\overline{\nu}_\mu \to \overline{\nu}_e)$

- $\delta \to -\delta$
- $a \to -a$

$$P(\nu_\mu \to \nu_e) =$$

$$4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2 \frac{\Delta m_{13}^2 L}{4E}\left(1+\frac{2a}{\Delta m_{13}^2}\left(1-2s_{13}^2\right)\right)$$

θ_{13}(Leading term)

$$+8c_{13}^2 s_{12} s_{13} s_{23}\left(c_{12}c_{23}\cos\delta - s_{12}s_{13}s_{23}\right)\cos\frac{\Delta m_{23}^2 L}{4E}\sin\frac{\Delta m_{13}^2 L}{4E}\sin\frac{\Delta m_{21}^2 L}{4E}$$

CPC

$$-8c_{13}^2 c_{12}c_{23}s_{12}s_{13}s_{23}\sin\delta\sin\frac{\Delta m_{23}^2 L}{4E}\sin\frac{\Delta m_{13}^2 L}{4E}\sin\frac{\Delta m_{21}^2 L}{4E}$$

CPV

$$+4s_{12}^2 c_{13}^2\left(c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12}c_{23}s_{12}s_{23}s_{13}\cos\delta\right)\sin\frac{\Delta m_{21}^2 L}{4E}$$

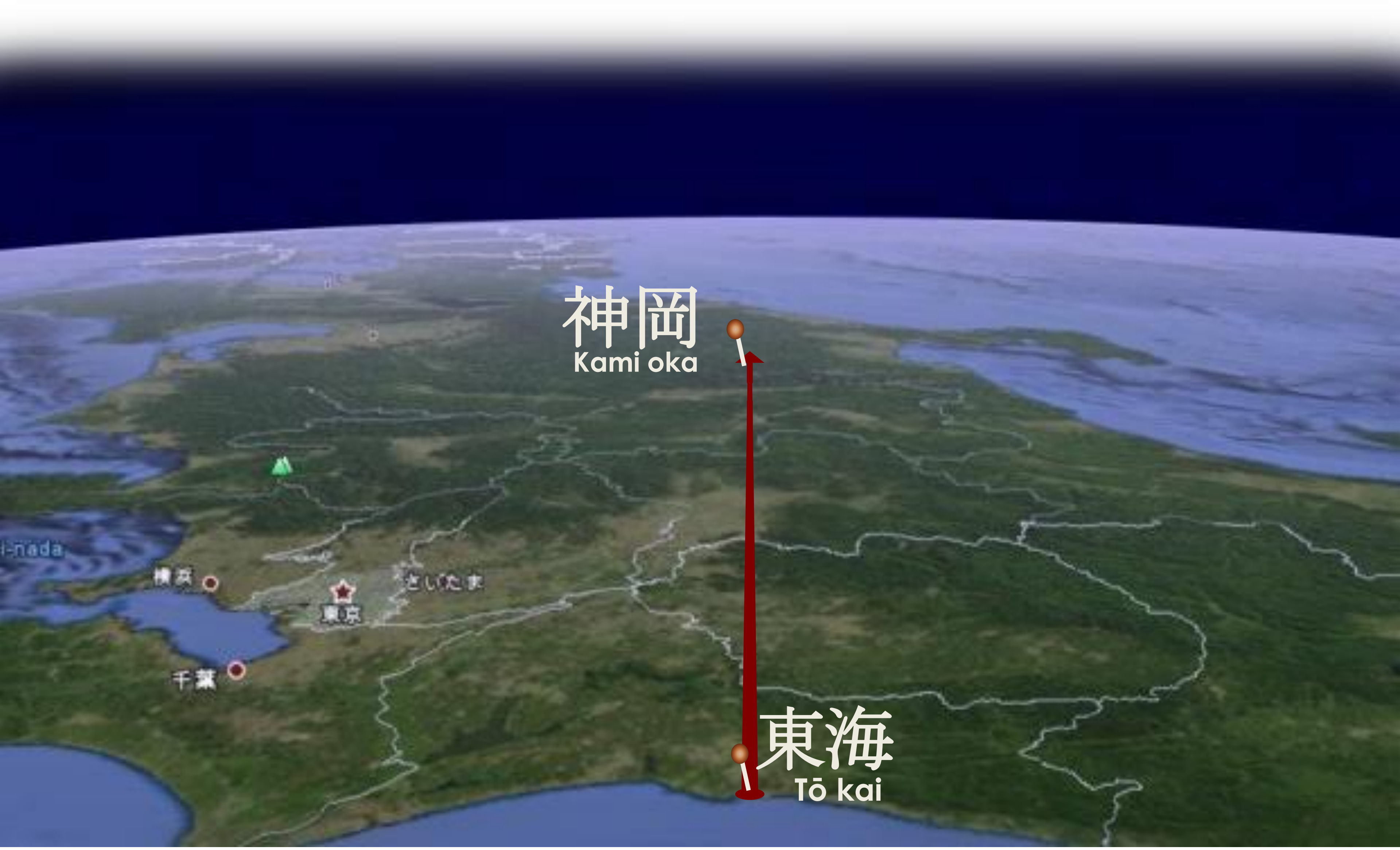
Solar

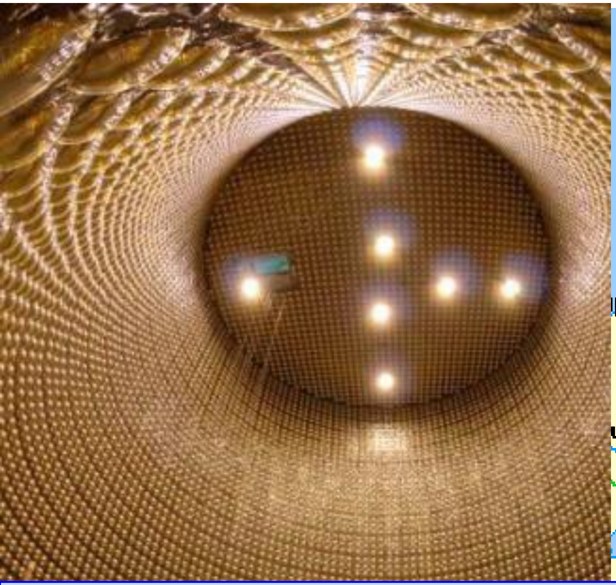
$$-8c_{13}^2 s_{13}^2 s_{23}^2\cos\frac{\Delta m_{23}^2 L}{4E}\sin\frac{\Delta m_{13}^2 L}{4E}\frac{aL}{4E}\left(1-2s_{13}^2\right)$$

Matter effect

since I am coming back from Japan…

T2K, T2K-II and HyperK





Idea of T2K was born 1999-2001 hep-ex/0106019 combining:

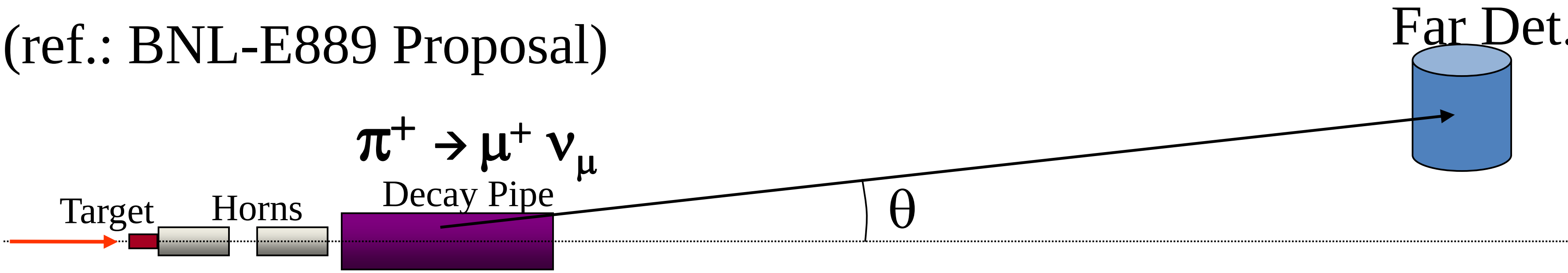
-- existing SuperKamiokande detector (50kton W.Č., 22.5 kton fiducial)

-- JAERI-KEK Japanese Proton Accelerator Research Complex (JPARC) at TOKAI including a high power, 0.75MW/30GeV Proton Synchrotron neutrino beam from pion decay $\pi^+ \rightarrow \mu^+ \nu_\mu$

-- baseline 295 km ➔ neutrino energy for first maximum is ~650 MeV achievable by pion-decay beam at 2.5 degrees off-axis

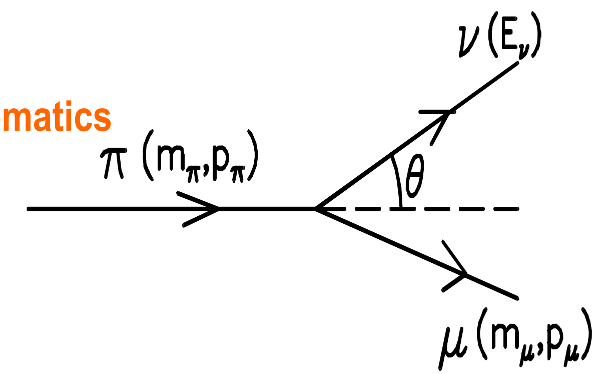
Off Axis Beam (another NBB option)

(ref.: BNL-E889 Proposal)

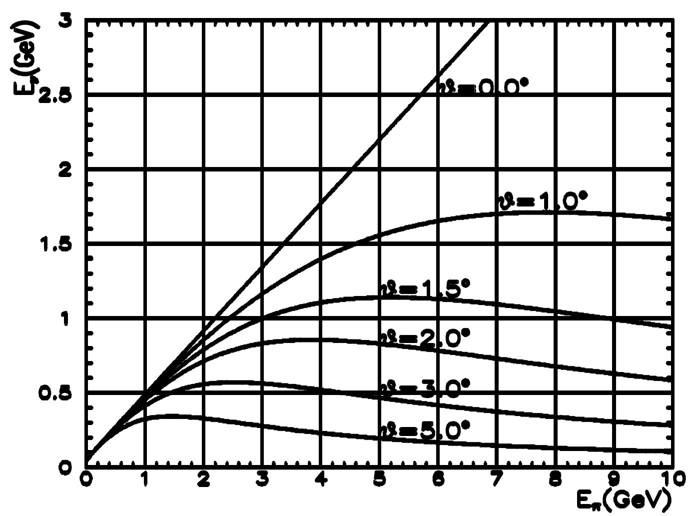


WBB w/ intentionally misaligned beam line from det. axis

Decay Kinematics

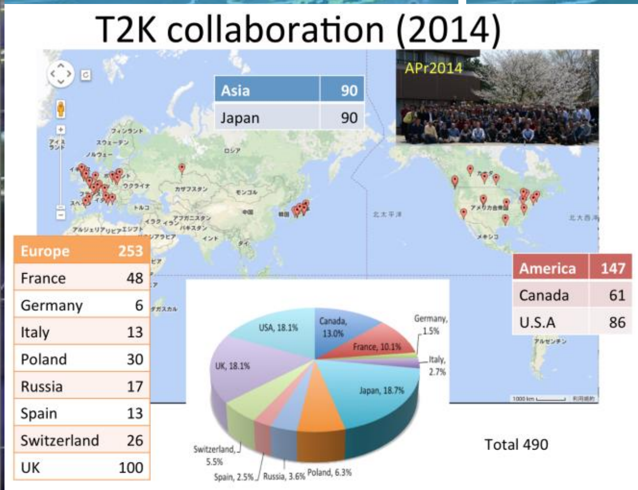


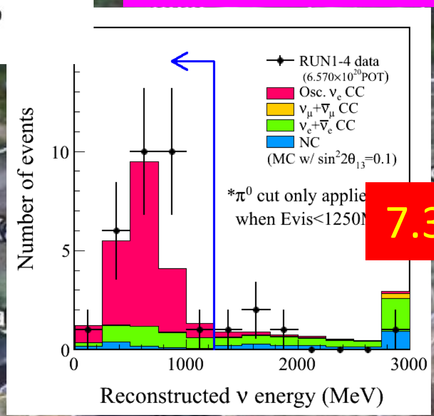
$$E_\nu = \frac{m_\pi^2 - m_\mu^2}{2(E_\pi - p_\pi \cos\theta)}$$

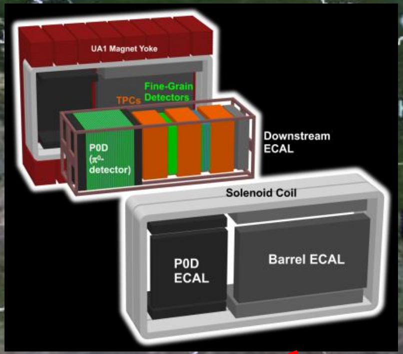


Quasi Monochromatic Beam with energy determined by beam geometry!

T2K Long Baseline Neutrino Oscillation Experiment



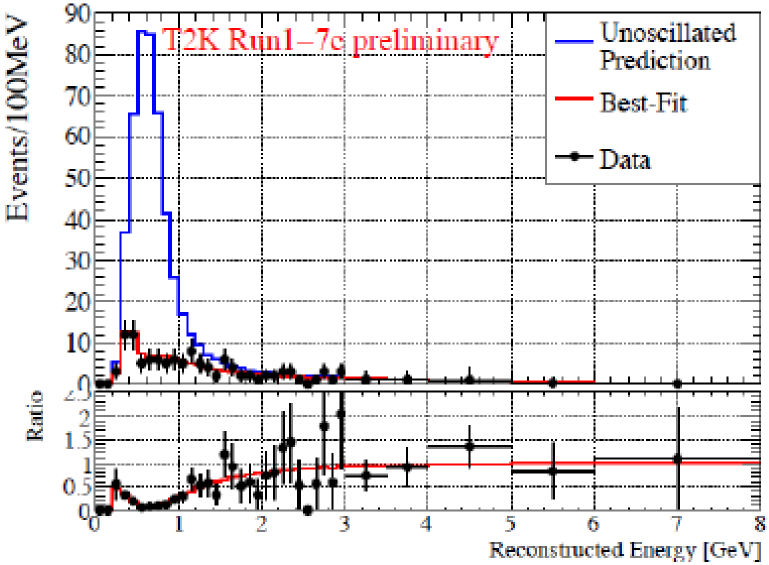




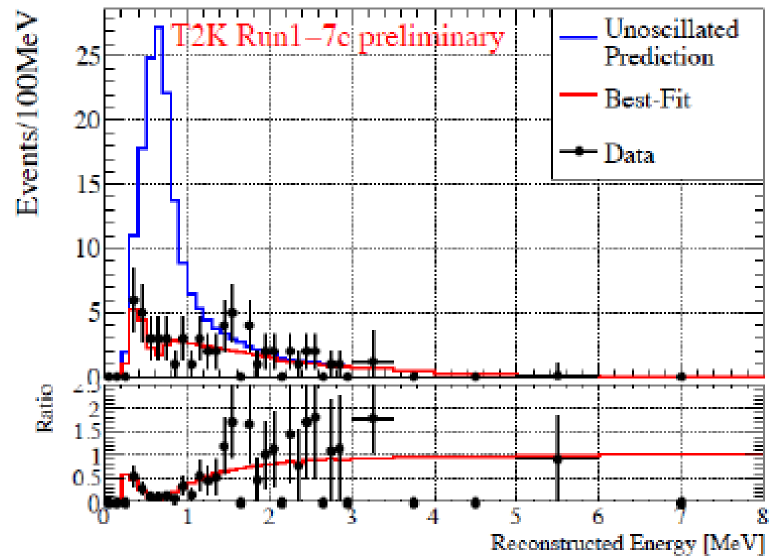
- T2K collaboration ~500 collaborators from 59 institutions, 11 countries
- Funded in FY2004, Started measurements in 2010
- First discovery of ν_e appearance in ν_μ beam
- Best measurement of ν_μ disappearance
- Opens the door for CP violation measurements
  - Could be the key to matter in the universe!

$\nu_\mu \rightarrow \nu_\mu$ and $\overline{\nu_\mu} \rightarrow \overline{\nu_\mu}$ disappearance

Neutrino



Antineutrino



$\Delta m^2_{32} = [2.34, 2.75]\times10^{-3} eV^2 (NH)$ at 90% CL

$\sin^2\theta_{23} = [0.42, 0.61] (NH)$ at 90% CL

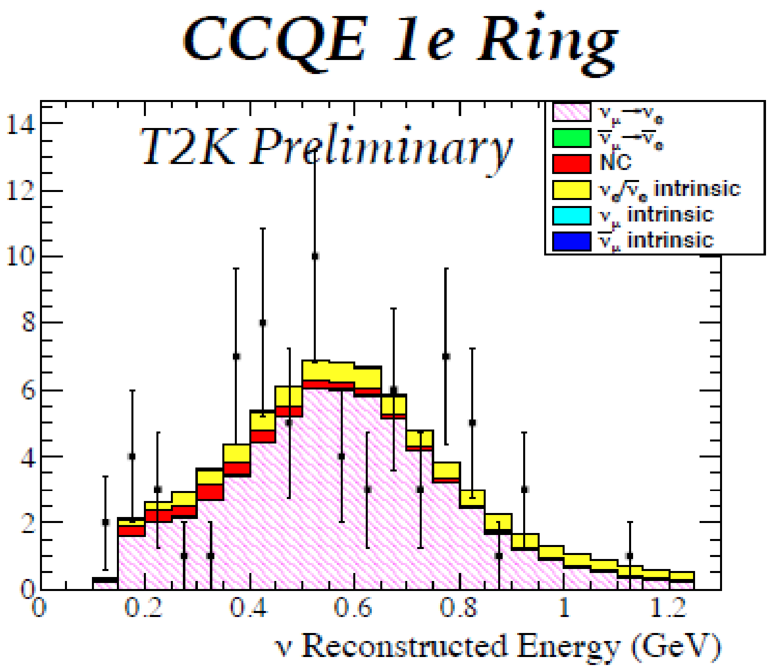
$\Delta \overline{m}^2_{32} = [2.16, 3.02]\times10^{-3} eV^2 (NH)$ at 90% CL

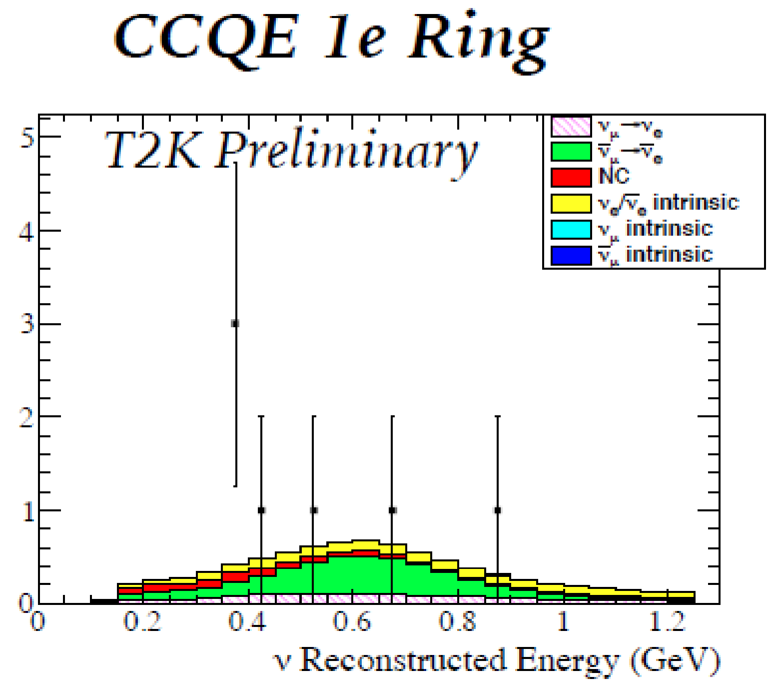
$\sin^2\overline{\theta}_{23} = [0.32, 0.70] (NH)$ at 90% CL

Neutrino and antineutrino parameters are consistent

No evidence of CPT violation, NSI, etc

ν_e and $\bar{\nu}_e$ appearance





75 events (89 if one adds the CCe 1π)

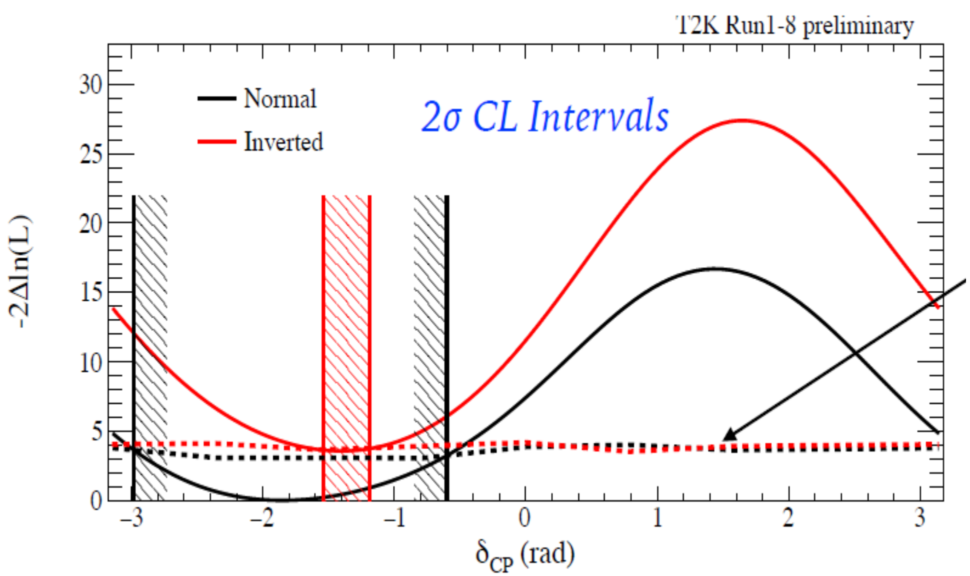
7 events

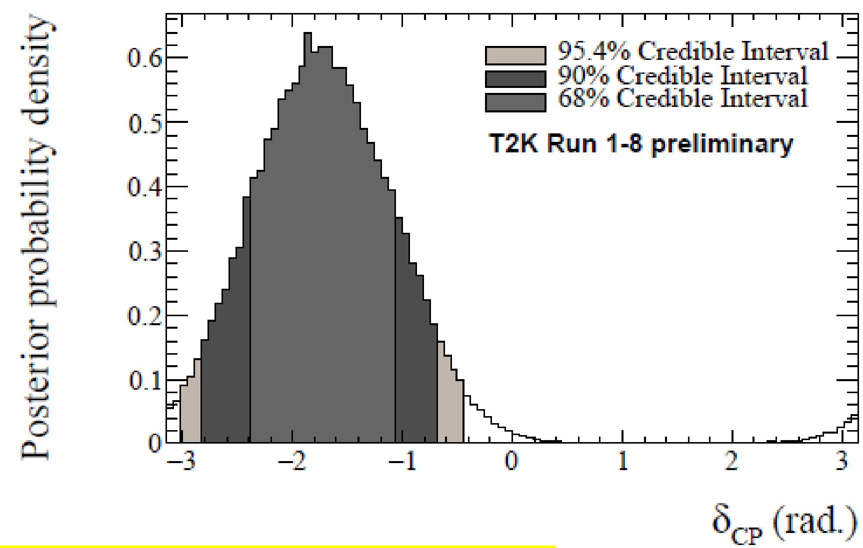
NEUTRINO

ANTINEUTRINO

PREDICTED AND OBSERVED EVENT RATES

	Predicted Rates				Observed
Sample	$\delta_{cp}=-\pi/2$	$\delta_{cp}=0$	$\delta_{cp}=\pi/2$	$\delta_{cp}=\pi$	Rates
CCQE 1-Ring e-like FHC	73.5	61.5	49.9	62.0	74
CC1π 1-Ring e-like FHC	6.92	6.01	4.87	5.78	15
CCQE 1-Ring e-like RHC	7.93	9.04	10.04	8.93	7
CCQE 1-Ring μ-like FHC	267.8	267.4	267.7	268.2	240
CCQE 1-Ring μ-like RHC	63.1	62.9	63.1	63.1	68

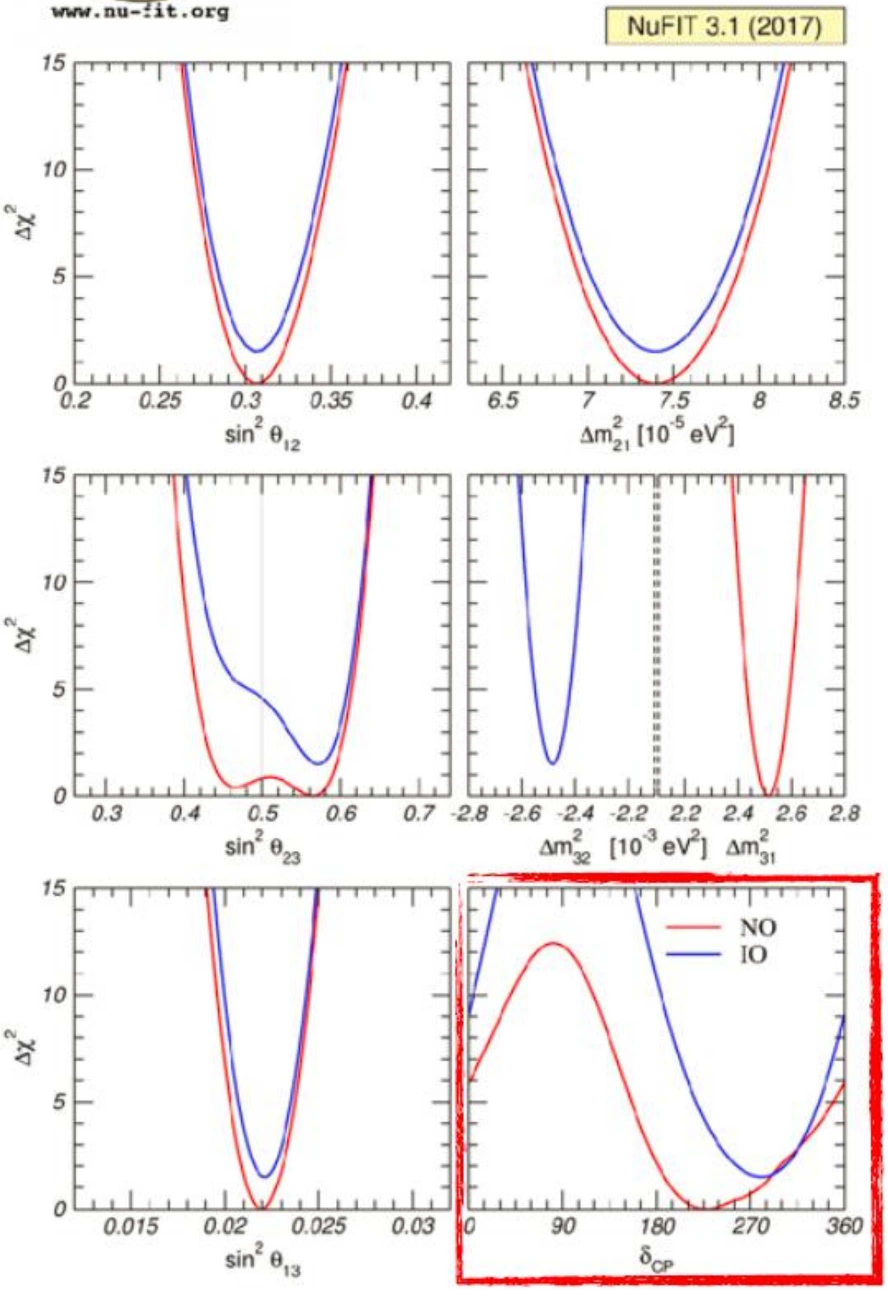




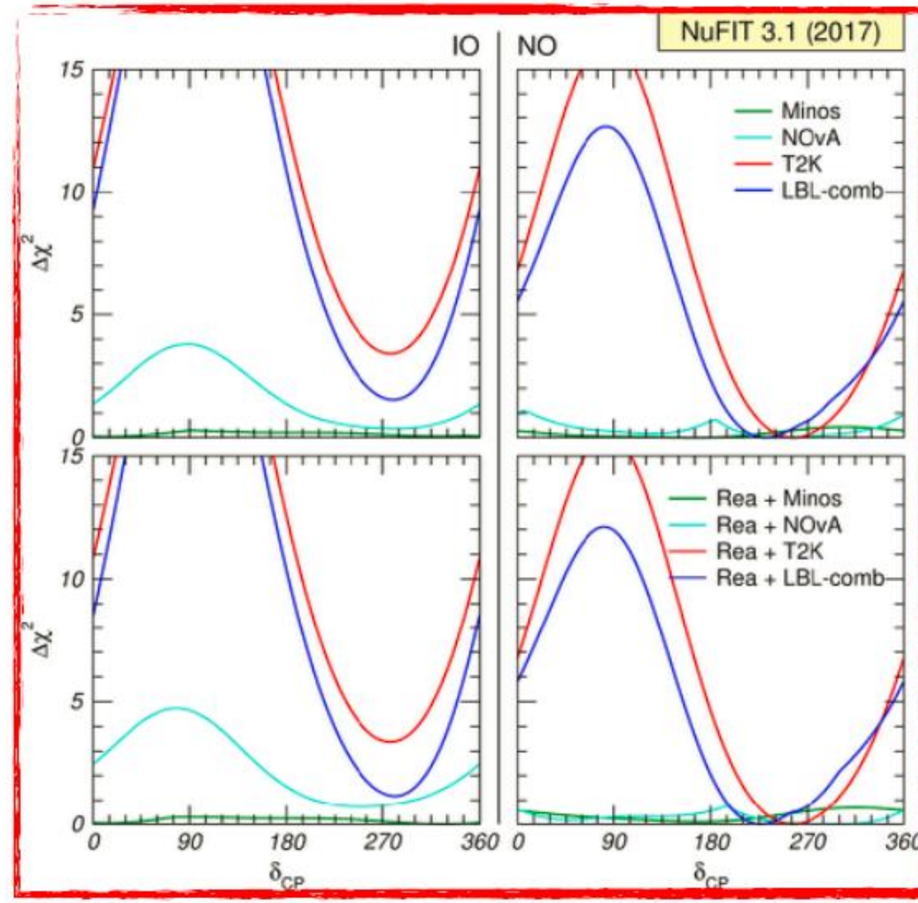
CP symmetry excluded at more than 95% C.L.

www.nu-fit.org

Neutrino Oscillation parameters in 2017



δ_{CP}

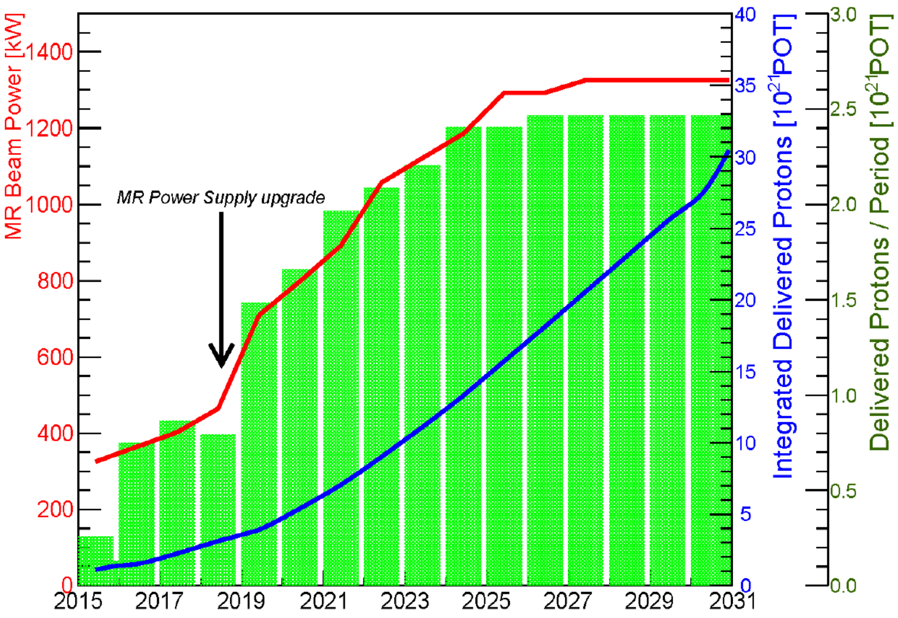


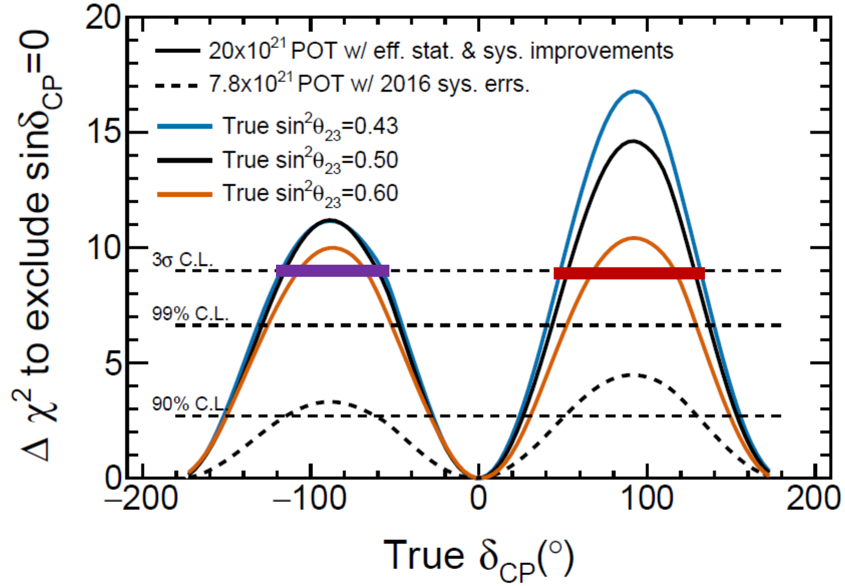
The T2K result constrains the range of δ_{CP}

CPV ~2σ MH uncertain.

Proposal for an Extended Run of T2K to 20×10^{21} POT

«T2K-II»





(b) Assuming the MH is known – measured by an outside experiment.

Approved upgrade of T2K intensity up to 1.3 MW beam power.

Not trivial but no show stoppers

3σ over 40% of 2π
(will grow with time…)

Include upgrade of near detector to reduce systematics

Obviously need something bigger!

KEK Preprint 2016-21
ICRR-Report-701-2016-1

Hyper-Kamiokande

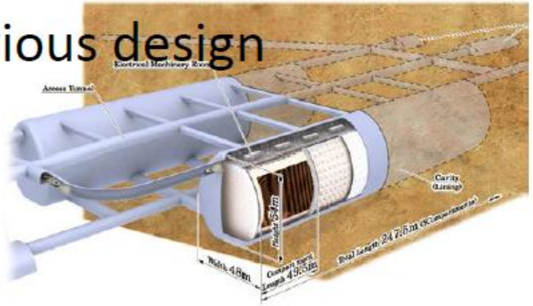
Design Report

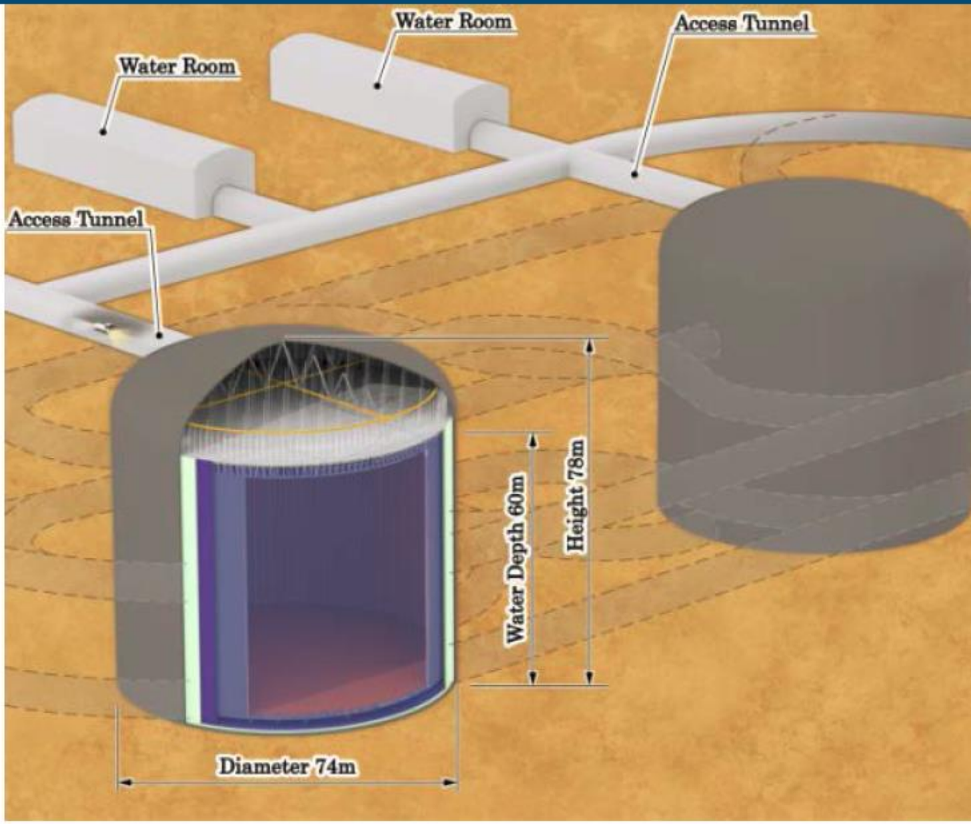
(Februry 7, 2016)

https://lib-extopc.kek.jp/preprints/PDF/2016/1627/1627021.pdf

Present design of Hyper-K

Previous design





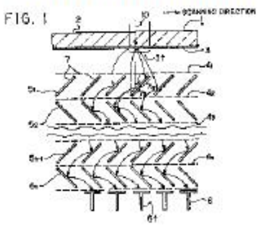
- ✓ Super-K-like structure
- ✓ 2 tanks with staging
  (2[nd] tank assumed to be ready 6 years later)
- ✓ 1 tank will be;
  - 60m(H)×74m(D)
  - Total volume: 260 kton
  - Fiducial volume(FV): 190 kton
    ~10 x Super-K FV
  - PMT coverage 40%, 40,000 ID-PMT, 6,700 OD-PMT
- ✓ The candidate site is ~8km south of SK (2.5 degree off axis beam, L=295km)

Photosensor Improvements

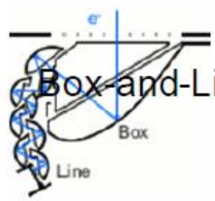
Photo Multipliers (PMTs)

Super-K PMT

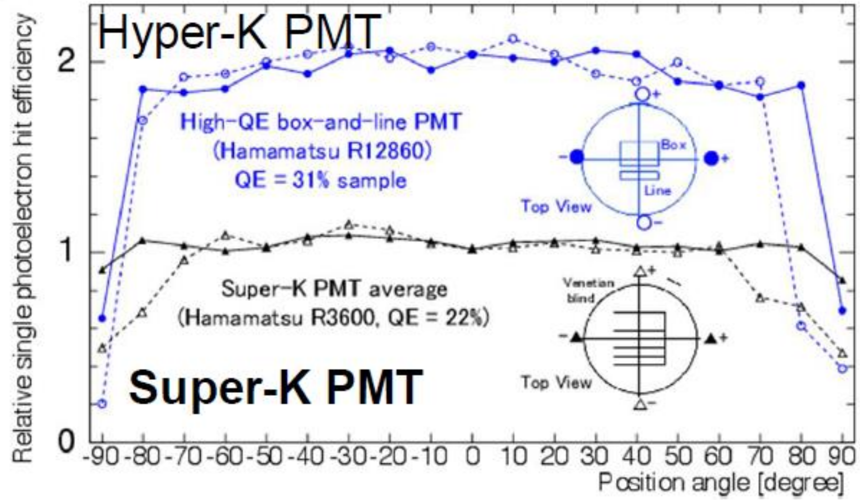
Venetian Blind



50cm HQE Box&Line PMT

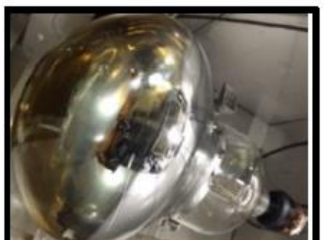


- Efficiency x 2, Timing resolution x 1/2
  Pressure tolerance x 2 (>100m)
  Enhance p→$\bar{\nu}K^+$ signal, solar ν, neutron signature of np→d+γ(2.2MeV),..

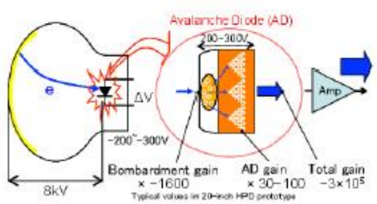


Other Developments:

Hybrid Photo Detectors (HPDs)

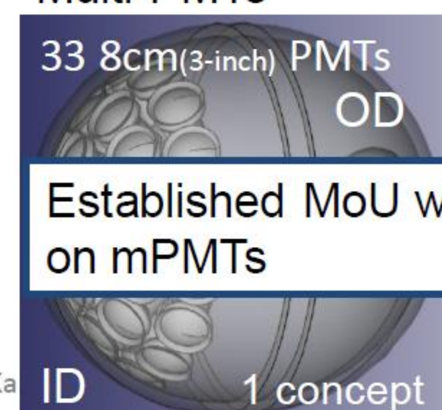


50cm HQE HPD w/ 20mm ϕ AD



Under viability study

Multi-PMTs



Working concept from KM3NeT but:
- peripheral ID/OD
- ultrapure water.

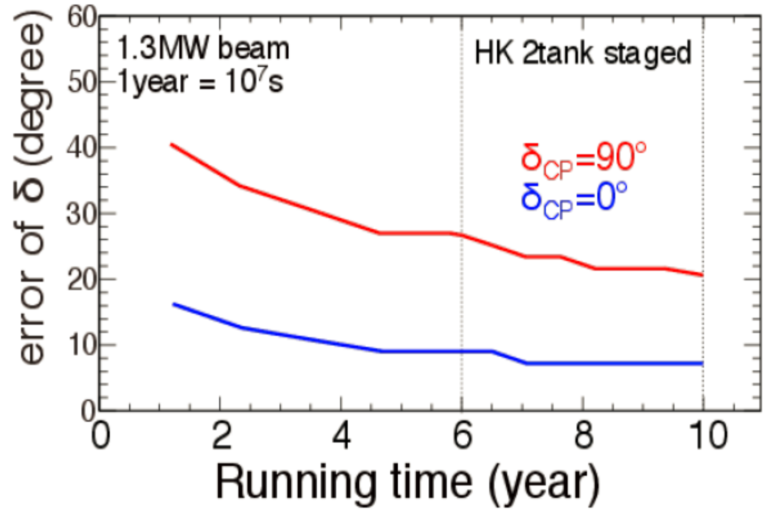
International contribut.

Established MoU with KM3Net to collaborate on mPMTs

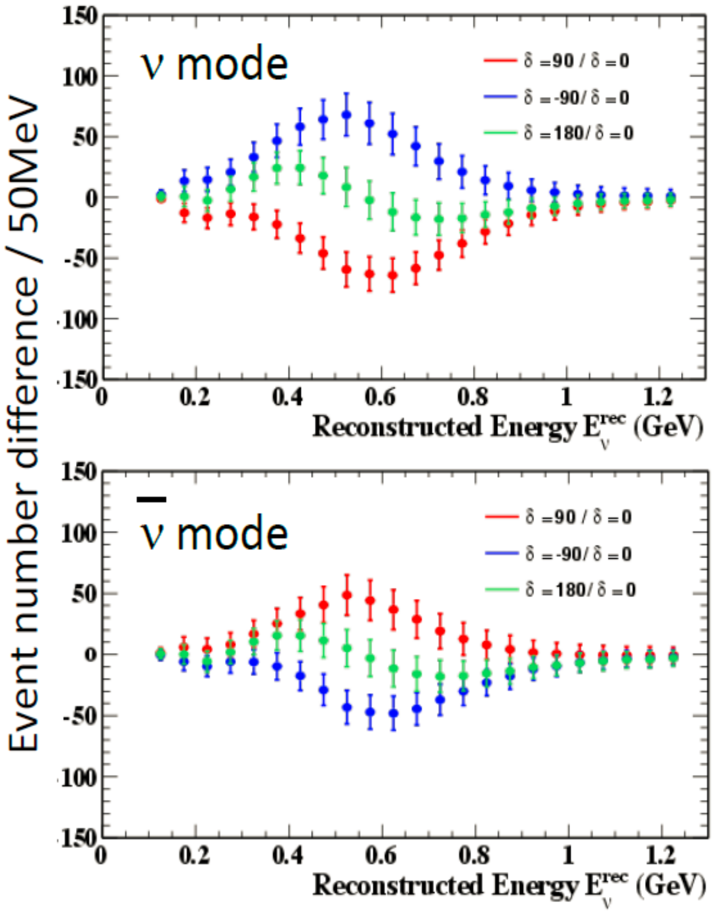
Hamamatsu new plant for mass production

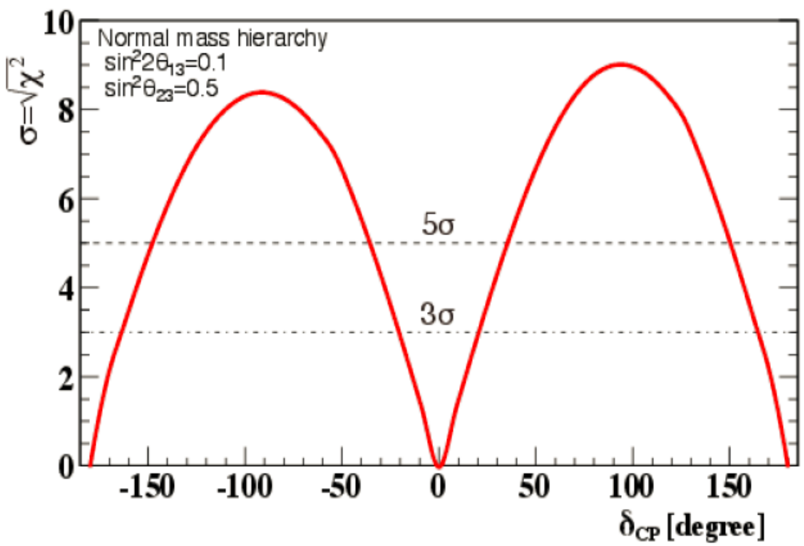
- **New large plant for mass production for HK built by Hamamatsu.**
- The PMT division is moving there.
- Around 6 years for mass production.

δ_{CP} sensitivity

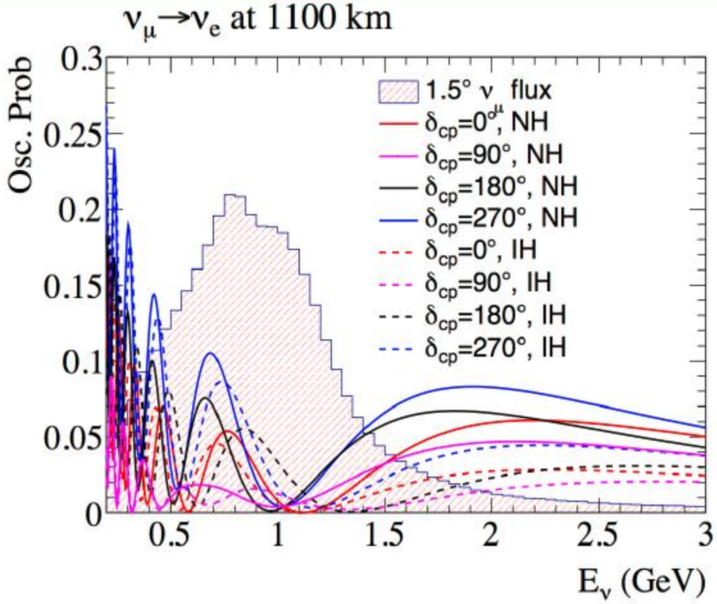


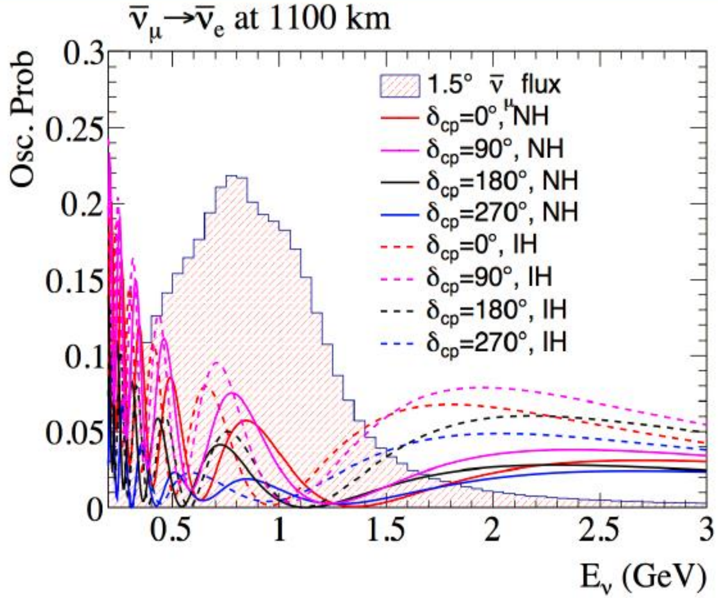
Difference from δ_{CP}=0



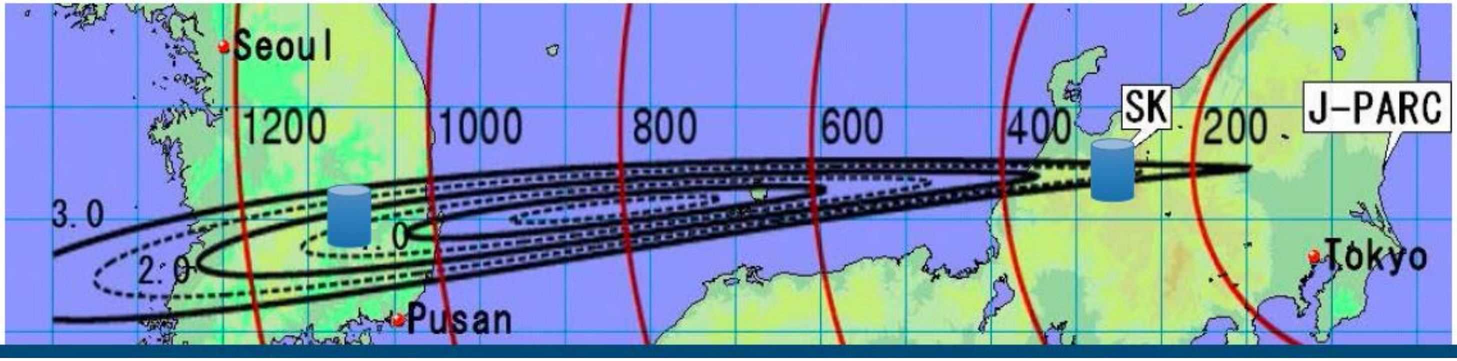


2^{nd} Hyper-K detector in Korea ?





Phys.Rev.D72:033003,2005
Phys.Lett.B637:266-273,2006
Phys. Rev. D81, 093001, 2010



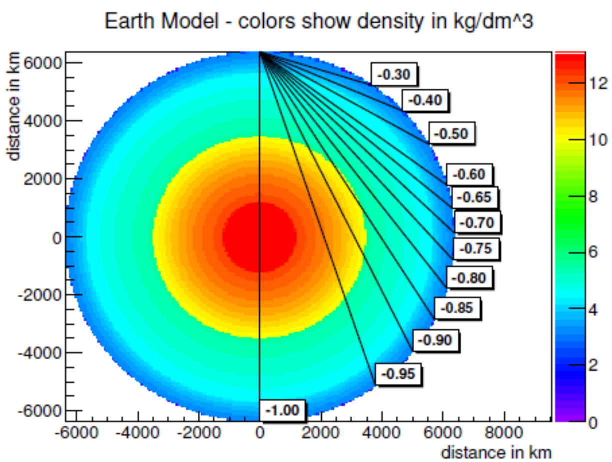
- The 2^{nd} HK tank can be located some other place.
- About 10 years ago, this possibility was discussed.
- Now this possibility is revisited...

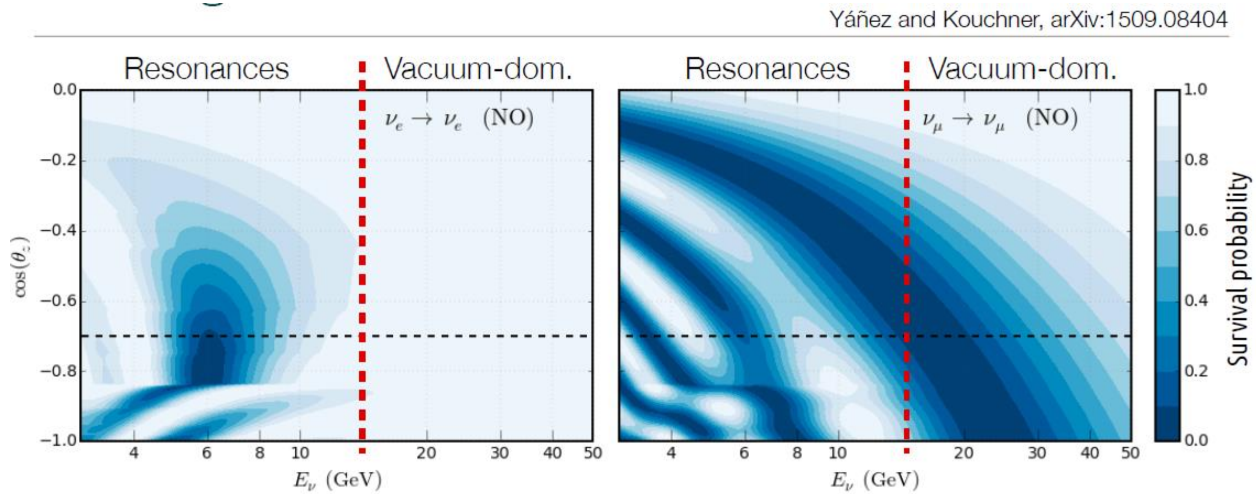
ORCA and PINGU atmospheric neutrinos

Determination of mass hierarchy with matter effect

Very large effect : up to ~100% asymmetry $\nu_e \rightarrow \nu_e$ vs. $\bar{\nu}_e \rightarrow \bar{\nu}_e$, different for ν_μ

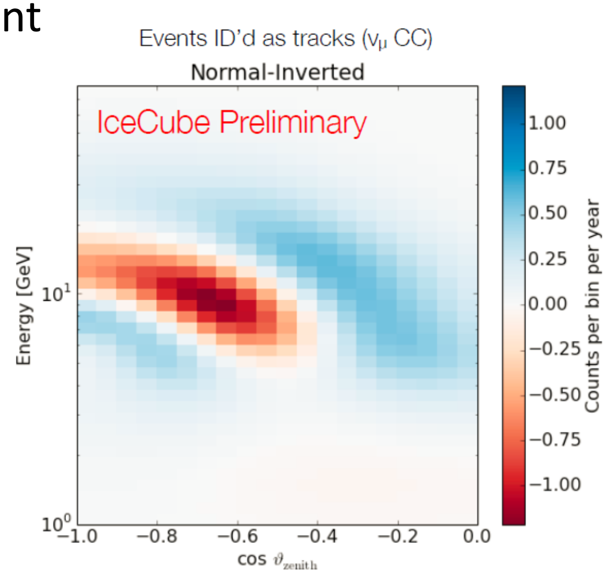
diluted by charge, PID, lepton angle energy reconstruction

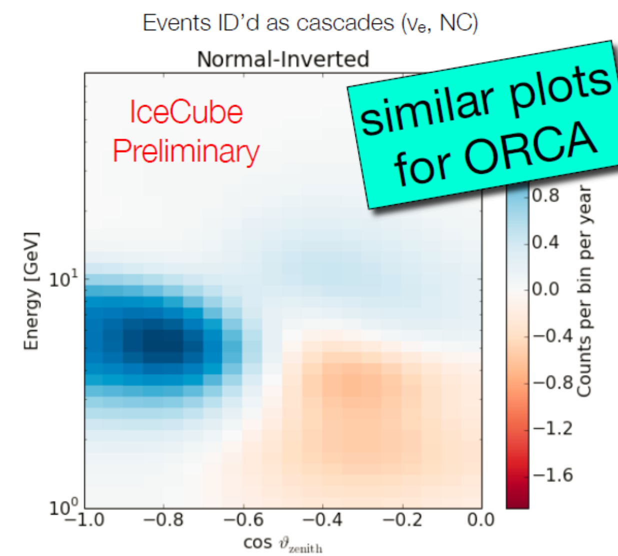




Optimum region for measurement
Is around 10 GeV and 7000km

Dilution and systematics due to ν flux, cross-sections and angle smearing… but effect is large; little sensitivity to δ_{CP}

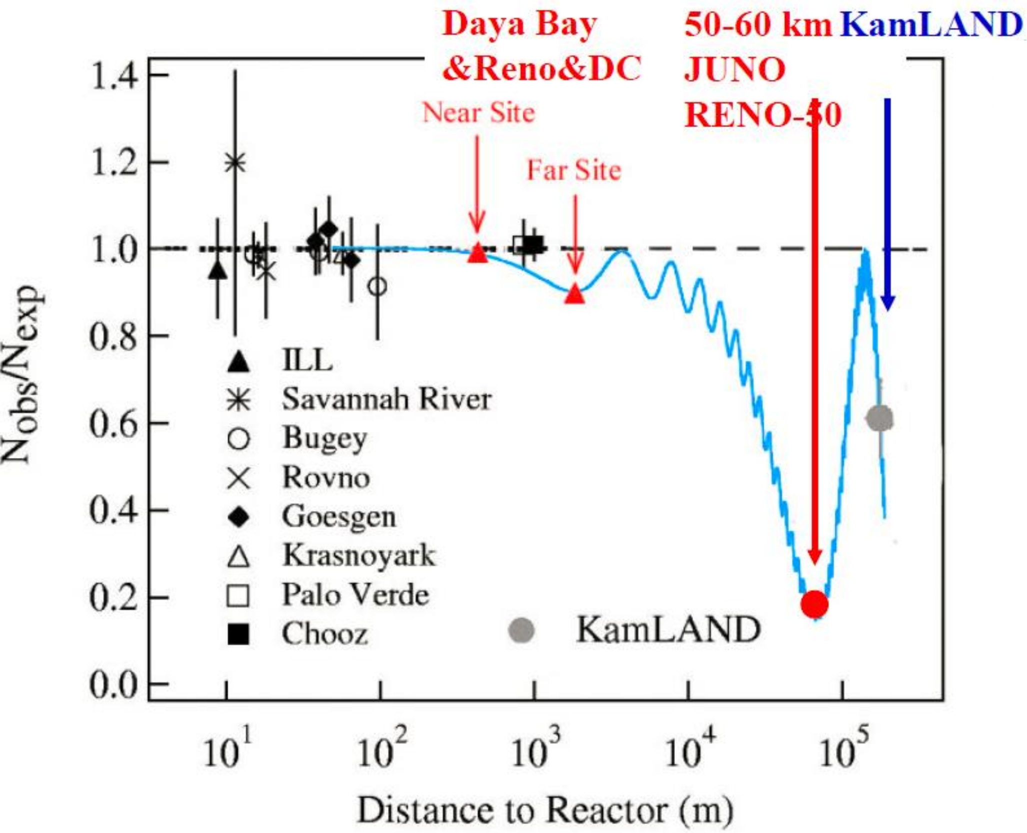


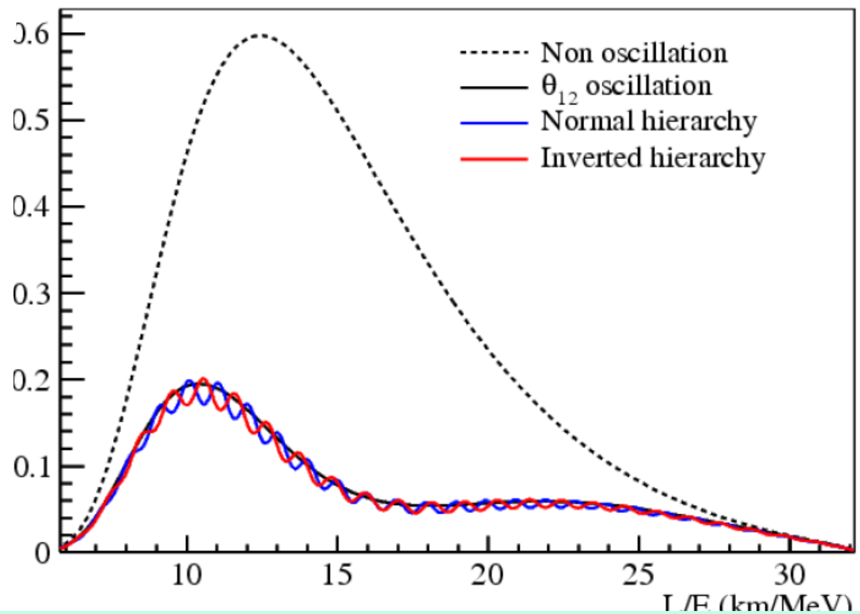


JUNO (RENO50)

$\bar{\nu}_e$ disappearance from reactor.

$$P_{ee}(L/E) = 1 - P_{21} - P_{31} - P_{32}$$
$$P_{21} = \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21})$$
$$P_{31} = \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31})$$
$$P_{32} = \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32})$$





Locate 20kton, 75% coverage liq. scintillator detector at 1st solar disappearance max (50km) use interference between solar and atmospheric terms which is sensitive to the **sign of Δm^2_{23}**

Since disappearance is used, no sensititivity to δ_{CP} .

<u>Challenge from energy scale/linearity/resolution!</u>

Yellow Book

Neutrino Physics with JUNO

The Jiangmen Underground Neutrino Observatory (JUNO), a 20 kton multi-purpose underground liquid scintillator detector, was recently proposed with the determination of the neutrino mass hierarchy as a primary physics goal. The excellent energy resolution and the large fiducial volume anticipated for the JUNO detector offer exciting opportunities for addressing many important topics in neutrino and astro-particle physics. In this document, we present the physics motivations and the anticipated performance of the JUNO detector for various proposed measurements.

arXiv: 1507.05613

- Reactor neutrino physics
  - Mass hierarchy, precision measurements, (geo-neutrino),…
- Astro-particle physics
  - Supernova neutrino, diffused supernova neutrino background, solar neutrino
- High energy events
  - Atmospheric neutrino, nucleon decays, …

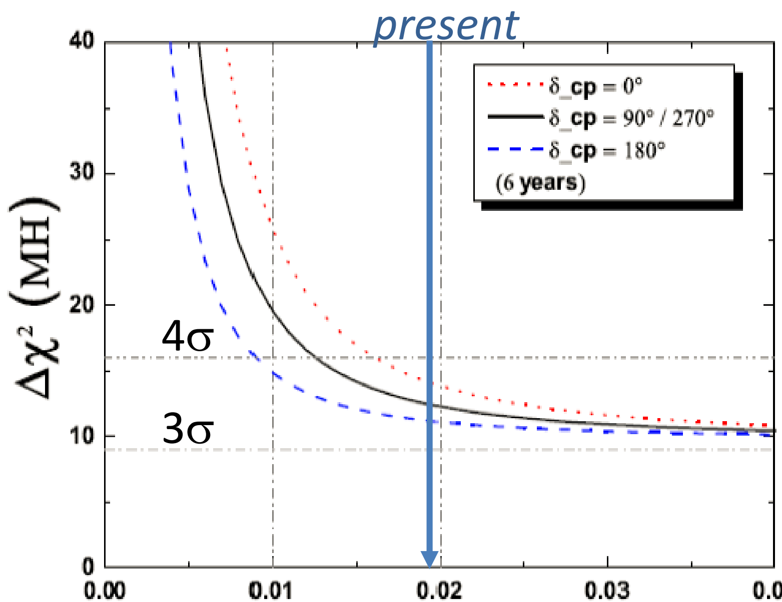
1. **Statistical error-->Target Mass: 20 ktons, biggest LS Detector**
2. **Best Energy Resolution for LS Detector: 3%**

   → ~75% PMT: coverage

   → Photon Detection Efficience double 30% **Quantum Effi. + 90% Collection Efficience of PMT**

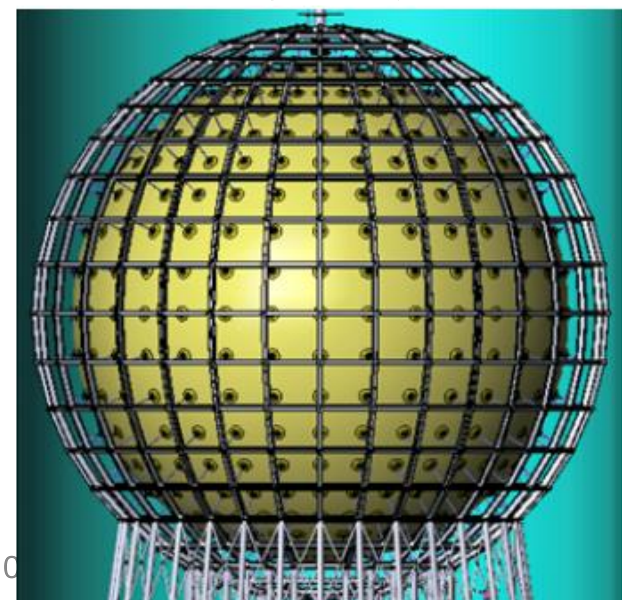
   →Transparent LS
3. **Energy and Vertex reconstruction and correction:**
   symmetrical structure, time and charge measurement by PMT
4. **Energy range and linearity: PMT response and electronics**
5. **Background Radiation Rate, fiducial volume cut, Material, Clean consideration**

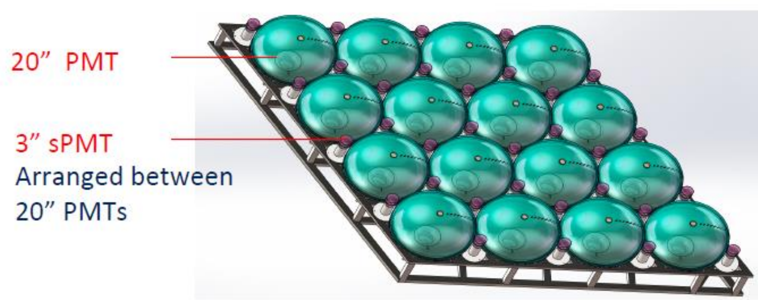
JUNO sensitivity to Mass Hierarchy :
«more than 3 σ in 6 years»



Relative error on $\sigma(\Delta m^2_{\mu\mu})$ (external input)

	Current	JUNO
Δm^2_{12}	3%	0.6%
Δm^2_{23}	5%	0.6%
$\sin^2\theta_{12}$	6%	0.7%
$\sin^2\theta_{23}$	20%	N/A
$\sin^2\theta_{13}$	5%	~ 15%
δ_{CP}		N/A





20'000 PMTs 15k from China 5k from Japan

Civil construction underway → complete 2018

Data taking date: early 2020.

JUNO (RENO50)

Crossing point with DUNE & HyperK

Many physics topics

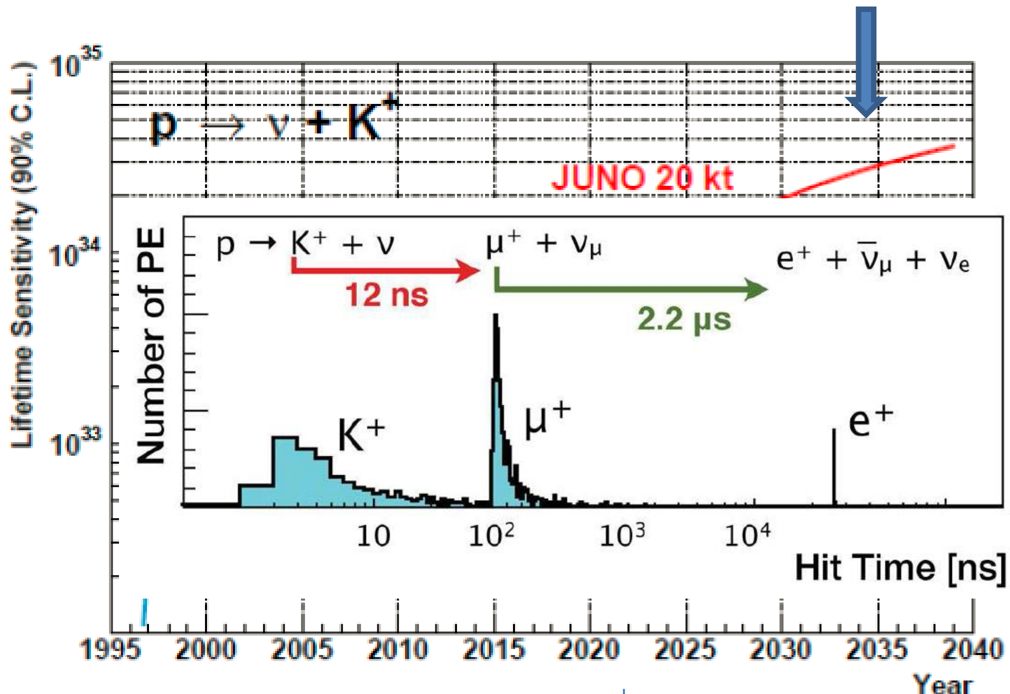
Some overlap with DUNE/HyperK

-- p→ νK →

-- SuperNovae

Some specific

-- geoneutrinos



700m deep

Supernova neutrinos

- Less than 20 events observed so far
- Assumptions:
  - **Distance: 10 kpc (our Galaxy center)**
  - **Energy: 3×10^{53} erg**
  - **L_ν the same for all types**
  - **Tem. & energy**

$T(\bar{\nu}_e)$ = 3.5 MeV, $\langle E(\bar{\nu}_e)\rangle$ = 11 MeV

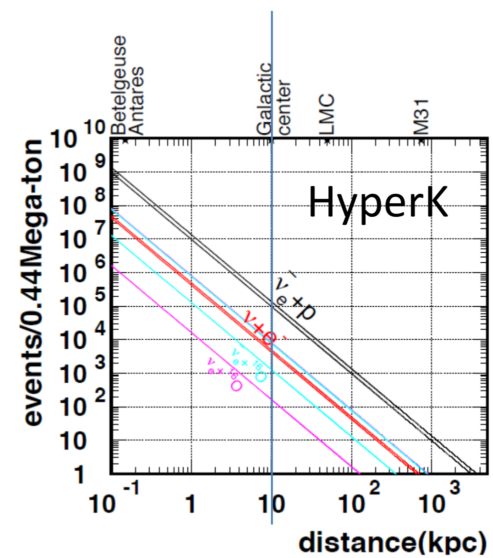
$T(\nu_e)$ = 5 MeV, $\langle E(\nu_e)\rangle$ = 16 MeV

$T(\nu_x)$ = 8 MeV, $\langle E(\nu_x)\rangle$ = 25 MeV

- Many types of events:
  - **$\bar{\nu}_e + p \rightarrow n + e^+$, ~ 3000 correlated events**
  - **$\bar{\nu}_e + {}^{12}C \rightarrow {}^{12}B^* + e^+$, ~ 10-100 correlated eve**
  - **$\nu_e + {}^{12}C \rightarrow {}^{12}N^* + e^-$, ~ 10-100 correlated eve**
  - **$\nu_x + {}^{12}C \rightarrow \nu_x + {}^{12}C^*$, ~ 600 correlated events**
  - **$\nu_x + p \rightarrow \nu_x + p$, single events**
  - **$\nu_e + e^- \rightarrow \nu_e + e^-$, single events**
  - **$\nu_x + e^- \rightarrow \nu_x + e^-$, single events**

Water Cerenkov detectors can not see these correlated events

Energy spectra & fluxes of all types of neutrinos

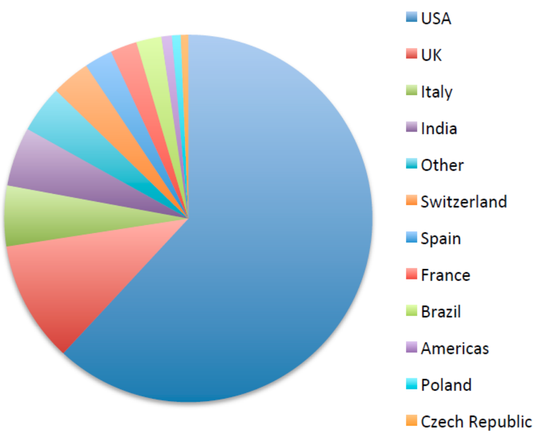


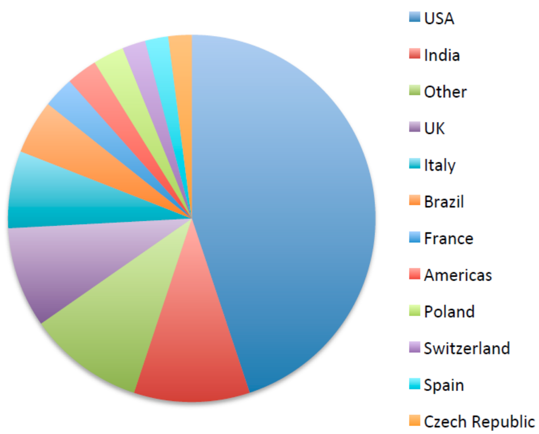
The DUNE Collaboration

Based on Liquid Argon Technology.

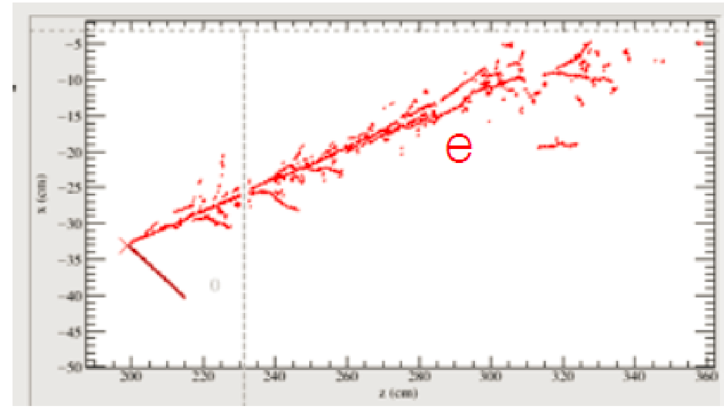
As of today: from

1001 Collaborators **144 Institutes**





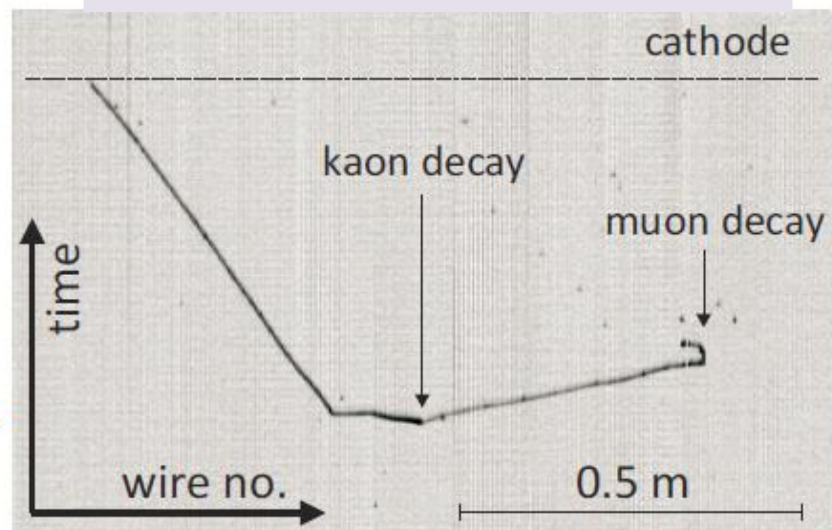
DUNE Primary Science Program



Focus on fundamental open questions in particle physics and astro-particle physics:

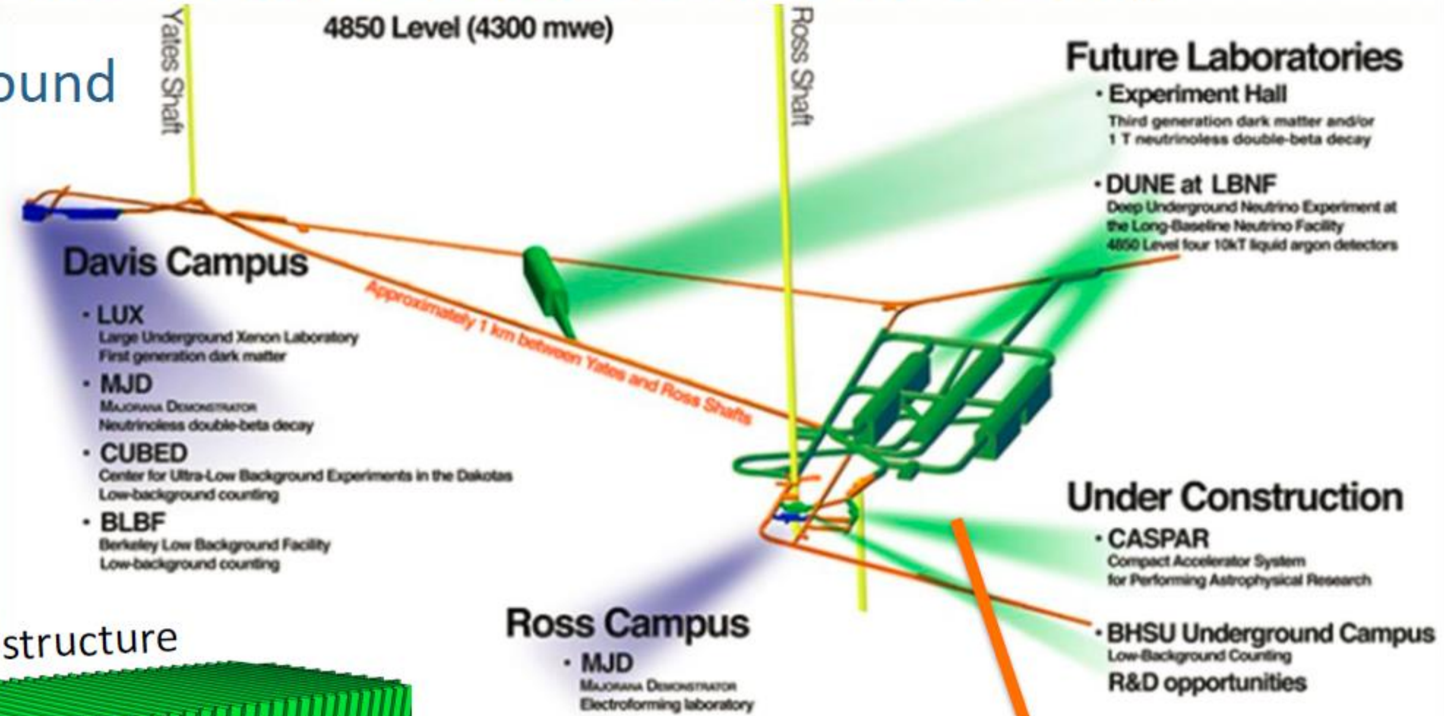
- **1) Neutrino Oscillation Physics**
  - CPV in the leptonic sector
  - Definitive determination of the Mass Hierarchy
  - Precision Oscillation Physics (θ_{23} octant, …) & testing the 3-flavor paradigm
- **2) Nucleon Decay**
  - Targeting SUSY-favored modes, e.g. $p \rightarrow K^{+}\overline{\nu}$
- **3) Supernova burst physics & astrophysics**
  - Galactic core collapse supernova, sensitivity to ν_e

Very clean signals for Kaon decay.

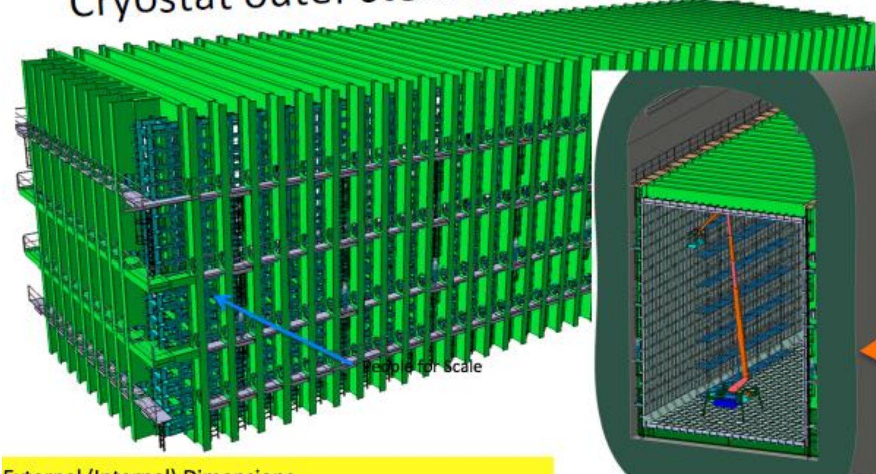


DUNE Far Detector at SURF

Location:
Sanford Underground Research Facility

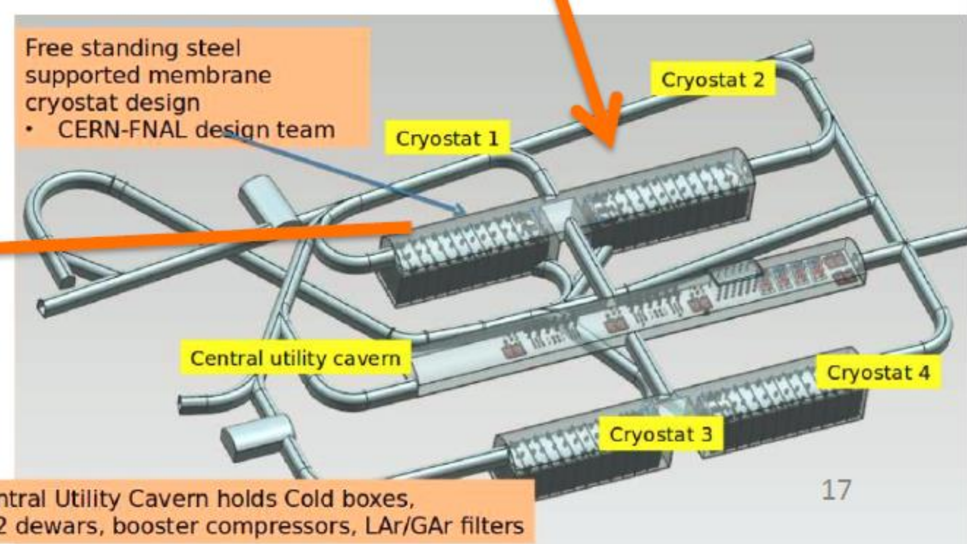


Cryostat outer steel structure



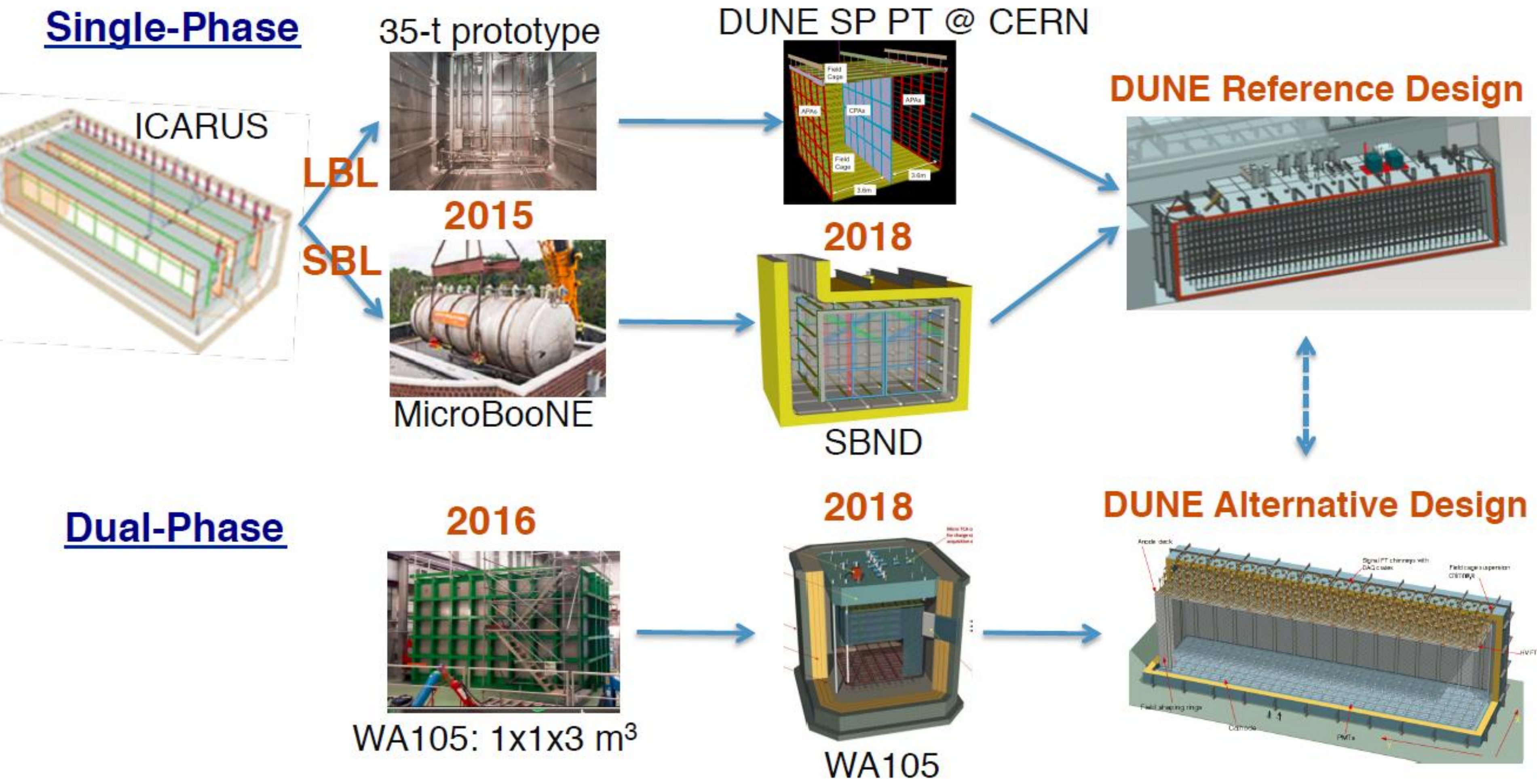
External (Internal) Dimensions
19.1m (16.9m) W x 18.0m (15.8m) H x 66.0m (63.8m) L

Can accommodate single and dual-phase LAr detectors



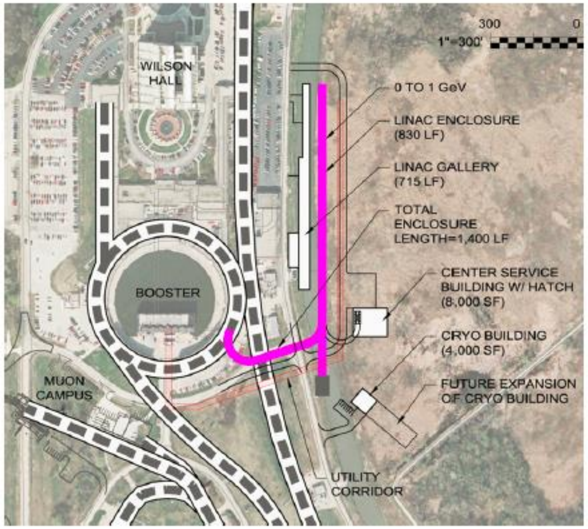
LArTPC Development Path

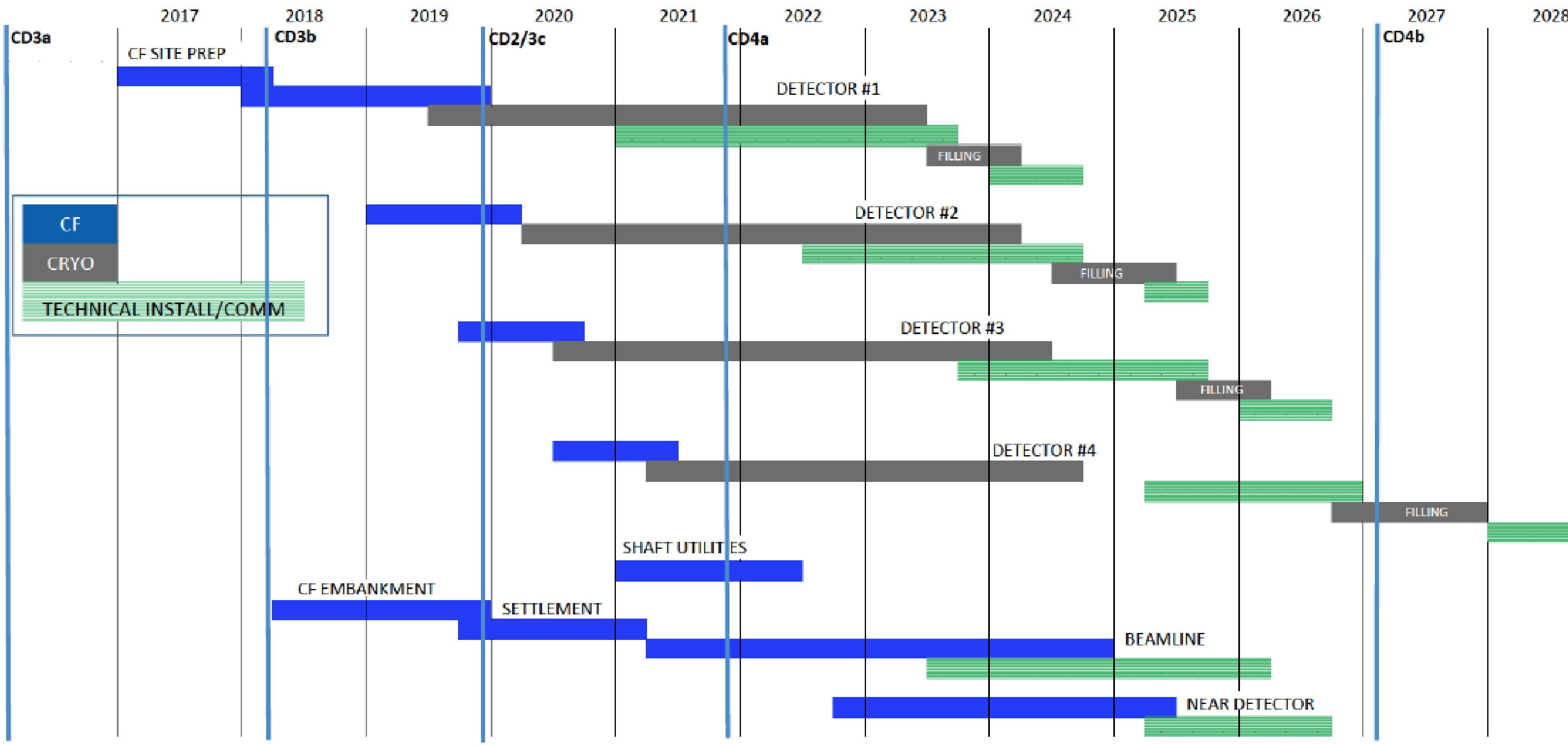
Fermilab SBN and CERN neutrino platform provide a strong **LArTPC** development and prototyping program



LBNF and PIP-II

- ★ In beam-based long-baseline neutrino physics:
  - beam power drives the sensitivity
- ★ LBNF will be the world's most intense high-energy ν beam
  - Build on strong Fermilab track record (BNB & NuMI)
  - 1.2 MW from day one (end 2026)
    - NuMI (MINOS) <400 kW
    - NuMI (NOVA) ultimately ~700 kW
  - upgradable to 2.4 MW After 6 years
- ★ Requires PIP-II (proton-improvement plan)
  - $0.5B upgrade of FNAL accelerator infrastructure
  - Replace existing 400 MeV LINAC with 800 MeV SC LINAC

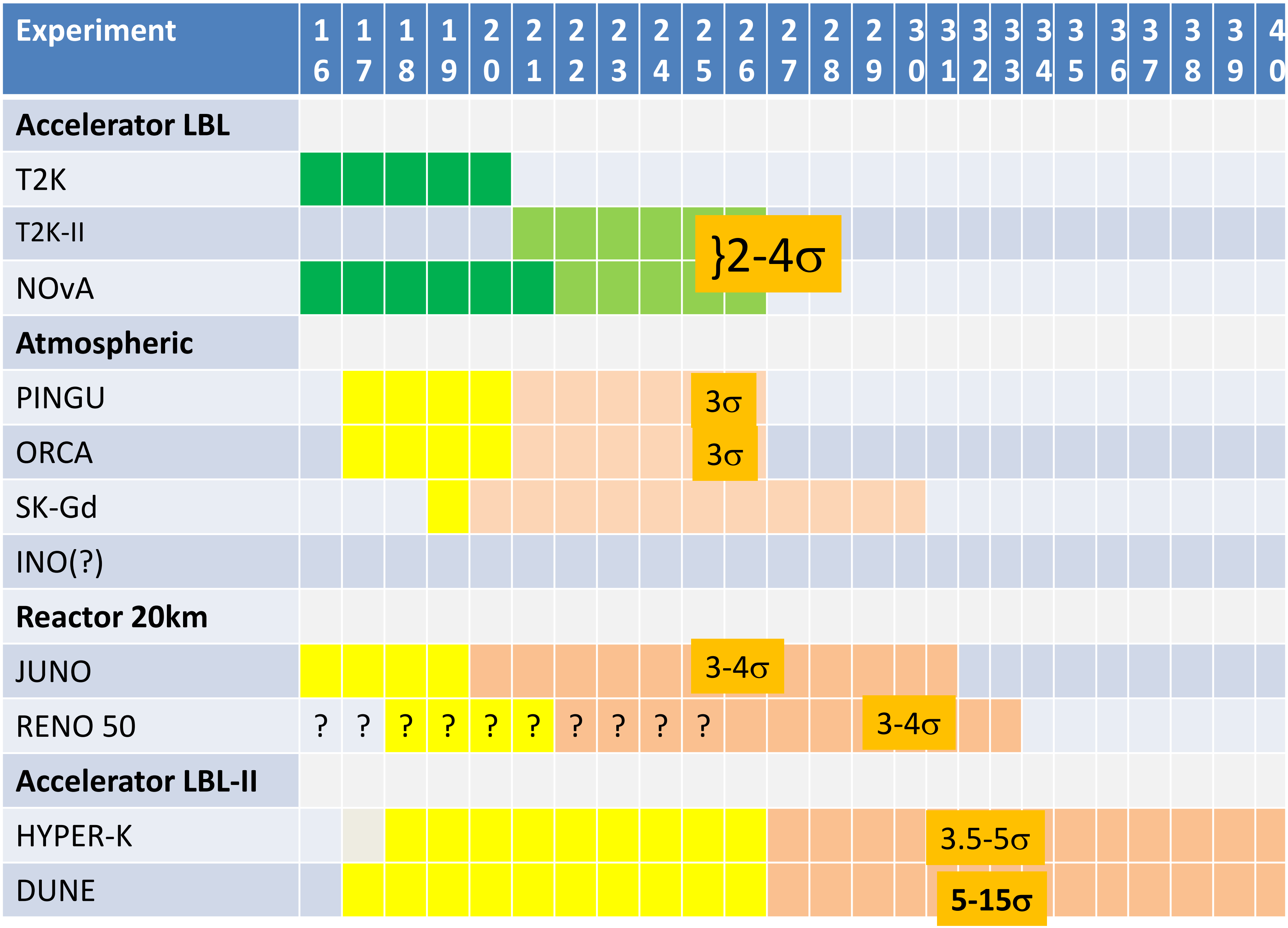




DUNE Schedule as of CDR http://arxiv.org/abs/1601.05471

Beam starts (with 1.2 MW capability) in 2026 with 2 detectors, upgrade to 2.4Mw ~6 yrs later.

The players Mass Ordering



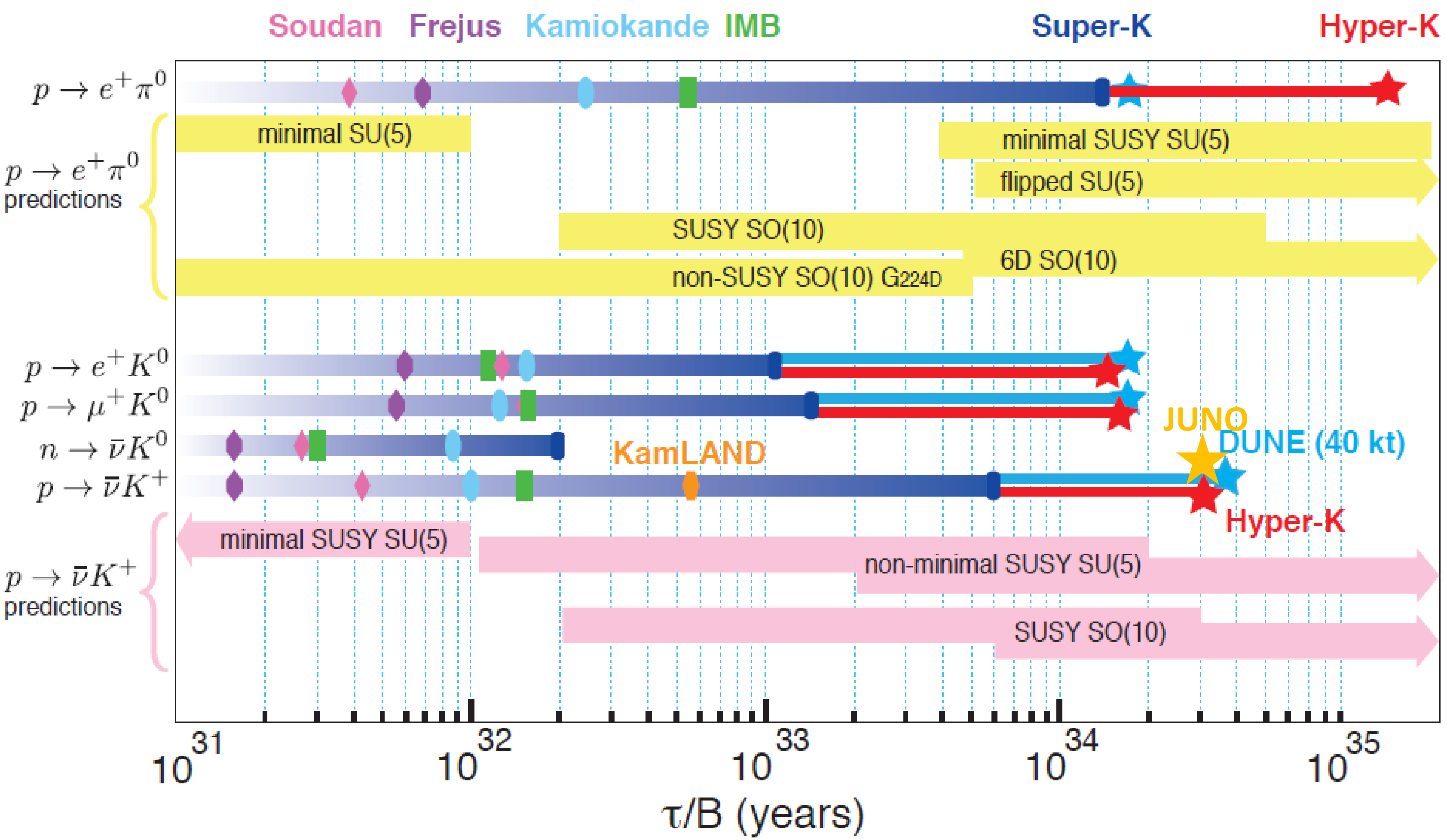
The players CP Violation fraction at 3σ /5σ /(1σ error at δ=0)

Experiment	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
Accelerator LBL																									
T2K																									
T2K-II																									
NOvA																									
Atmospheric																									
PINGU																									
ORCA																									
SK-Gd																									
INO(?)																									
Reactor 20km																									
JUNO																									
RENO 50	?	?	?	?	?	?	?	?	?	?															
Accelerator LBL-II																									
HYPER-K																									
DUNE																									

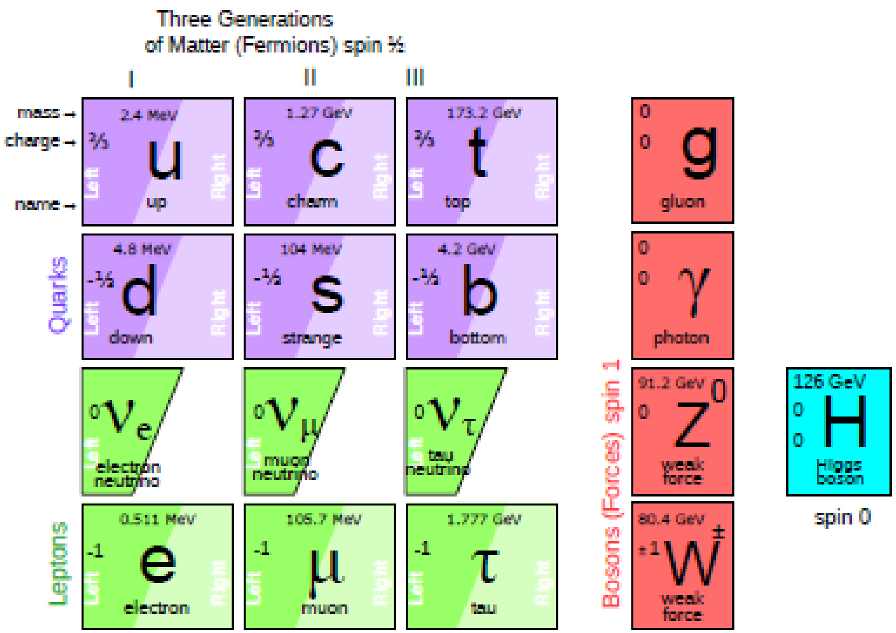
40%/0/<20º

78%/62%/7º

75%/50%/7º

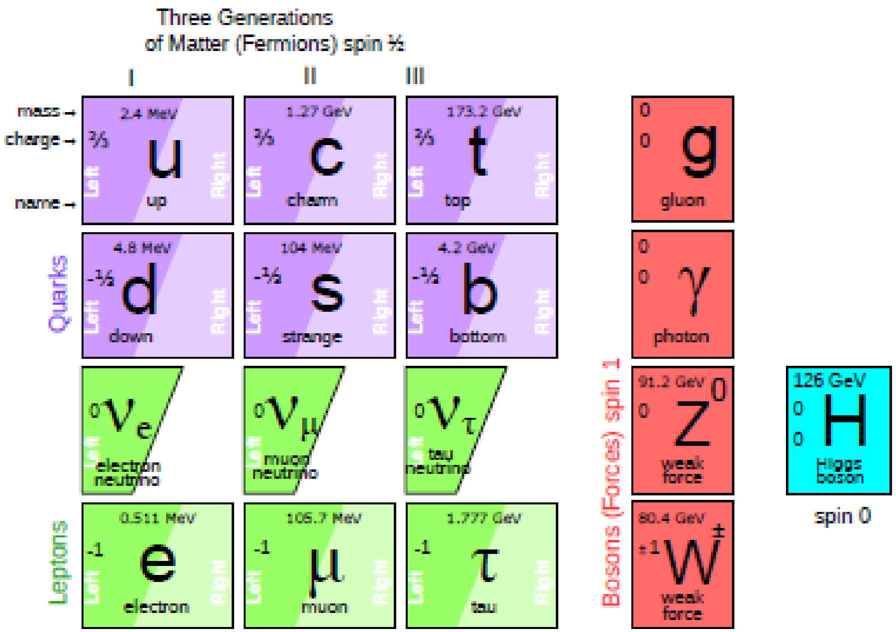

Soudan Frejus Kamiokande IMB Super-K Hyper-K
$p \to e^+\pi^0$
$p \to e^+\pi^0$ predictions
minimal SU(5)
minimal SUSY SU(5)
flipped SU(5)
SUSY SO(10)
6D SO(10)
non-SUSY SO(10) G224D
$p \to e^+K^0$
$p \to \mu^+K^0$
$n \to \bar{\nu}K^0$
$p \to \bar{\nu}K^+$
KamLAND
JUNO
DUNE (40 kt)
Hyper-K
$p \to \bar{\nu}K^+$ predictions
minimal SUSY SU(5)
non-minimal SUSY SU(5)
SUSY SO(10)
10^{31} 10^{32} 10^{33} 10^{34} 10^{35}
τ/B (years)

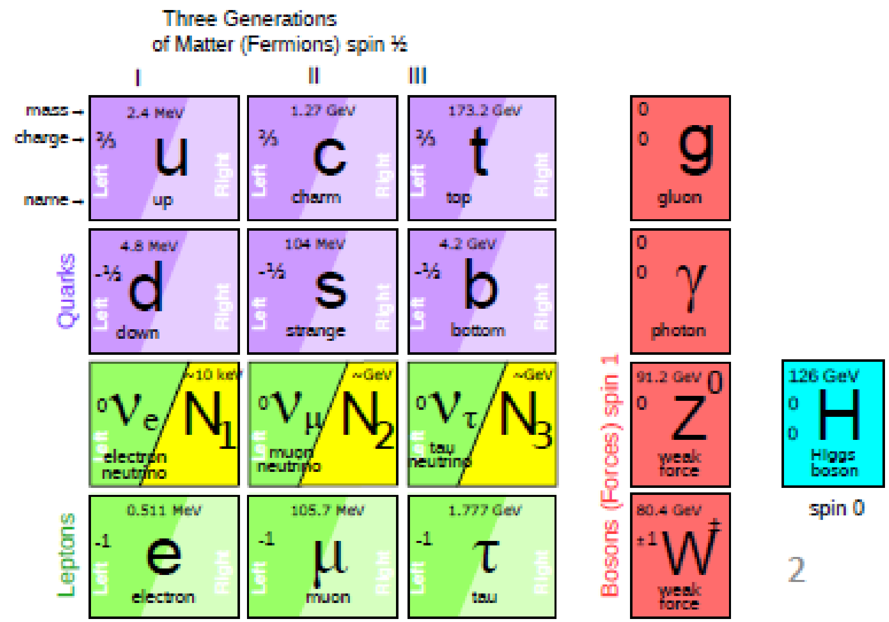
at least 3 pieces are still missing



We know since 1957 : **(anti)neutrinos are Left(Right)-handed**.
Since 1998 it is established that neutrinos have mass
and this very probably implies new degrees of freedom
simplest solution: right-handed neutrinos.

at least 3 pieces are still missing

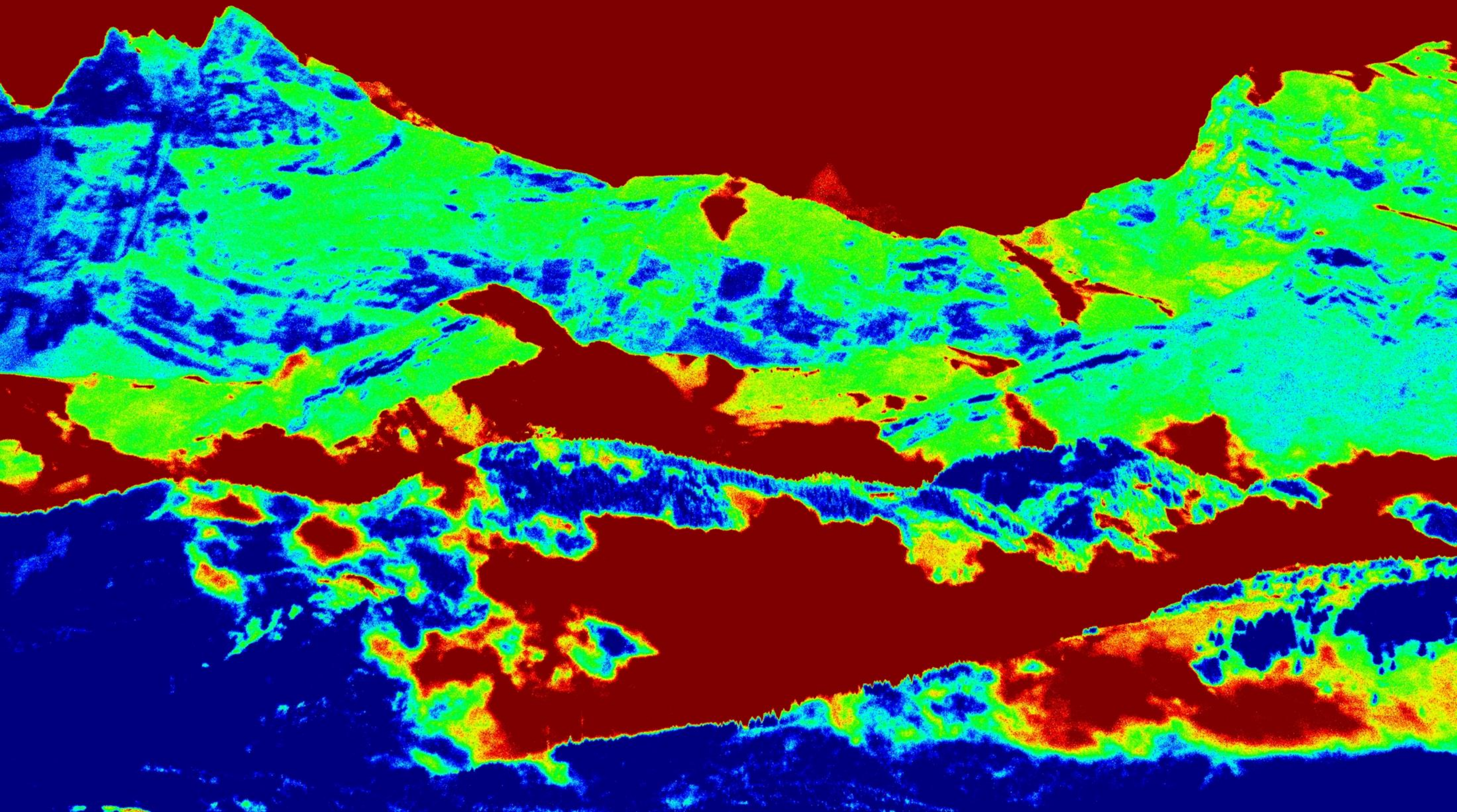




2

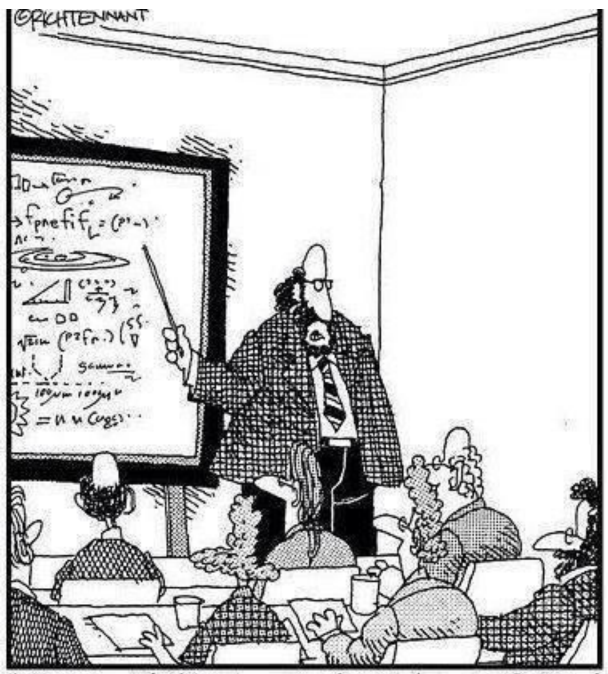
Since 1998 it is established that neutrinos have mass
and this very probably implies new degrees of freedom
such as right handed neutrinos
➔ «sterile», very small coupling to known particles
completely unknown masses (eV to ZeV), nearly impossile to find.
.... but could perhaps explain all: DM, BAU,ν-masses

The Search for the Right-Handed Neutrinos



Electroweak eigenstates

I = 1/2	I = 0	
$\begin{pmatrix} e \\ \nu_e \end{pmatrix}_L \quad \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}_L \quad \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}_L$	$(e)_R \quad (\mu)_R \quad (\tau)_R$	Q= -1
	$(\nu_e)_R \quad (\nu_\mu)_R \quad (\nu_\tau)_R$	Q= 0



"Along with 'Antimatter,' and 'Dark Matter,' we've recently discovered the existence of 'Doesn't Matter,' which appears to have no effect on the universe whatsoever."

Right handed neutrinos are singlets
no weak interaction
no EM interaction
no strong interaction

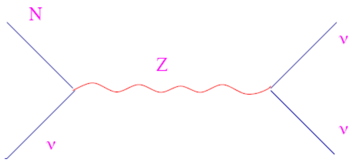
can't produce them
can't detect them
-- so why bother? –

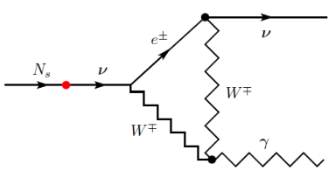
Also called 'sterile'

Search Processes (I)

m_N Below m_π:

$N \rightarrow 3\nu$; $N \rightarrow \nu\gamma$ w $E_\gamma = m_N/2$

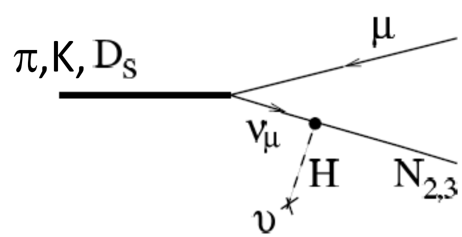


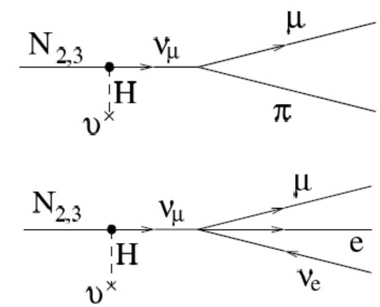


$$\tau_{N_1} = 10^{14}\,\text{years}\left(\frac{10\,\text{keV}}{M_N}\right)^5\left(\frac{10^{-8}}{\theta_1^2}\right)$$

Long life, dark matter candidate
Equilibrium with neutrinos
produced in the stars
➔ Search for gamma emission line
(such as 3.5 keV line)
Drewes et al; arXiv:1602.04816v1

Meson decay (π,K: neutrino beams) examples:





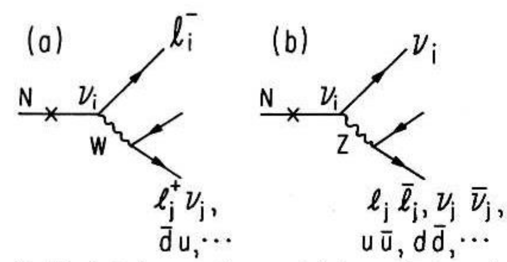


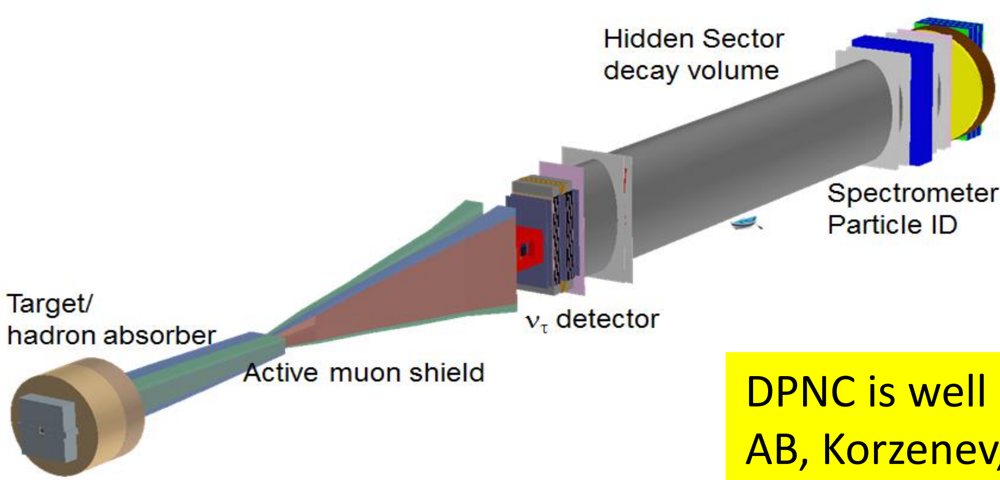
FIG. 2. Typical decays of a neutral heavy lepton via (a) charged current and (b) neutral current. Here the lepton l_i

$$L \approx \frac{3}{|U|^2\,(m_{\nu_m}(\mathrm{GeV}/c^2))^6} \times \frac{P_\nu}{45GeV/c}$$

Decay via W gives at least two charged particles, and amounts to ~60% of decays.
Searches for long lived decays in neutrino beams
PS191, NuTeV, CHARM; SHIP and DUNE proposals

Experiment	PS191	NuTeV	CHARM	SHiP
Proton energy (GeV)	19.2	800	400	400
Protons on target ($\cdot 10^{19}$)	0.86	0.25	0.24	20
Decay volume (m^3)	360	1100	315	1780
Decay volume pressure (bar)	1 (He)	1 (He)	1 (air)	10^{-6} (air)
Distance to target (m)	128	1400	480	80-90
Off beam axis (mrad)	40	0	10	0

Next generation heavy neutrino search experiment SHIP
-- focuses on neutrinos from charm to cover 0.5 – 2 GeV region
-- uses beam dump to reduce background from neutrino interactions from pions and Kaons and bring the detector as close as possible to source.
-- increase of beam intensity and decay volume
status: proposal, physics report and technical report exist. R&D phase approved at CERN



arXiv:1504.04855
arXiv:1504.04956

DPNC is well and truly there!
AB, Korzenev, Mermod, etc.

Future Circular Collider Study - SCOPE
CDR and cost review for the next ESU (2018)

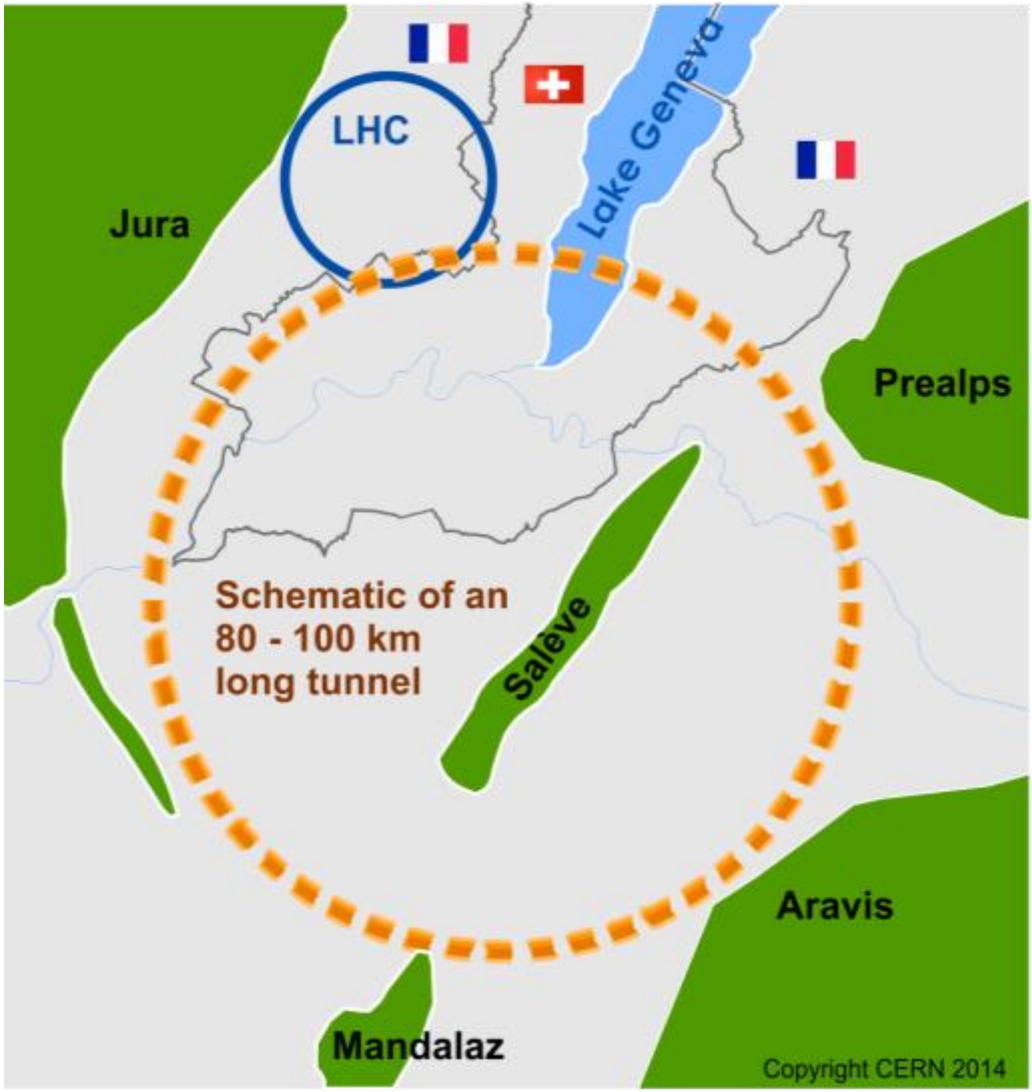
Forming an international collaboration to study:

- *pp*-collider (*FCC-hh*)

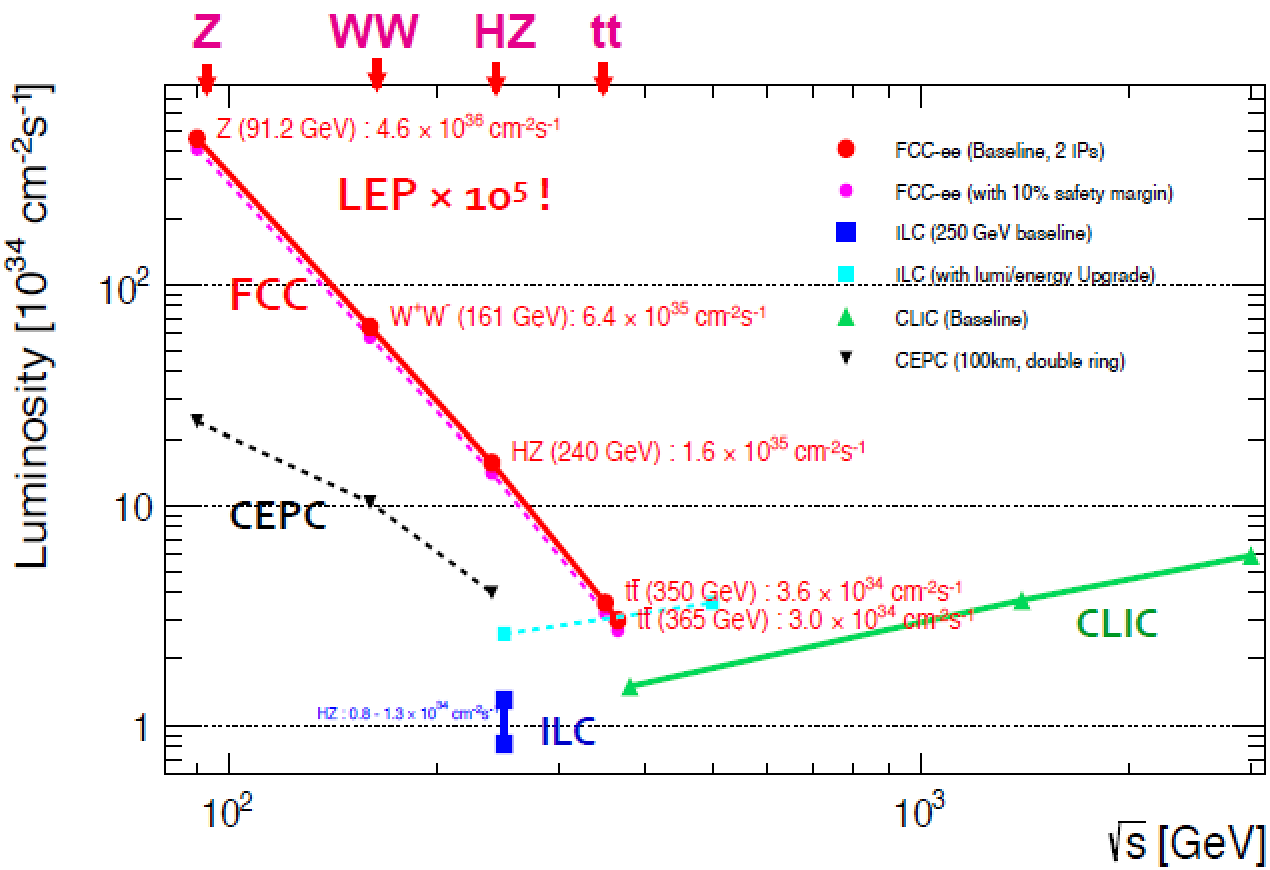
~16 T ⇒ 100 TeV *pp* in 100 km

→ ultimate goal defining infrastructure requirements

- e^+e^- collider (*FCC-ee*) as potential first step ECM=90-400 GeV
- *p-e* (*FCC-he*) option
- 80-100 km infrastructure in Geneva area



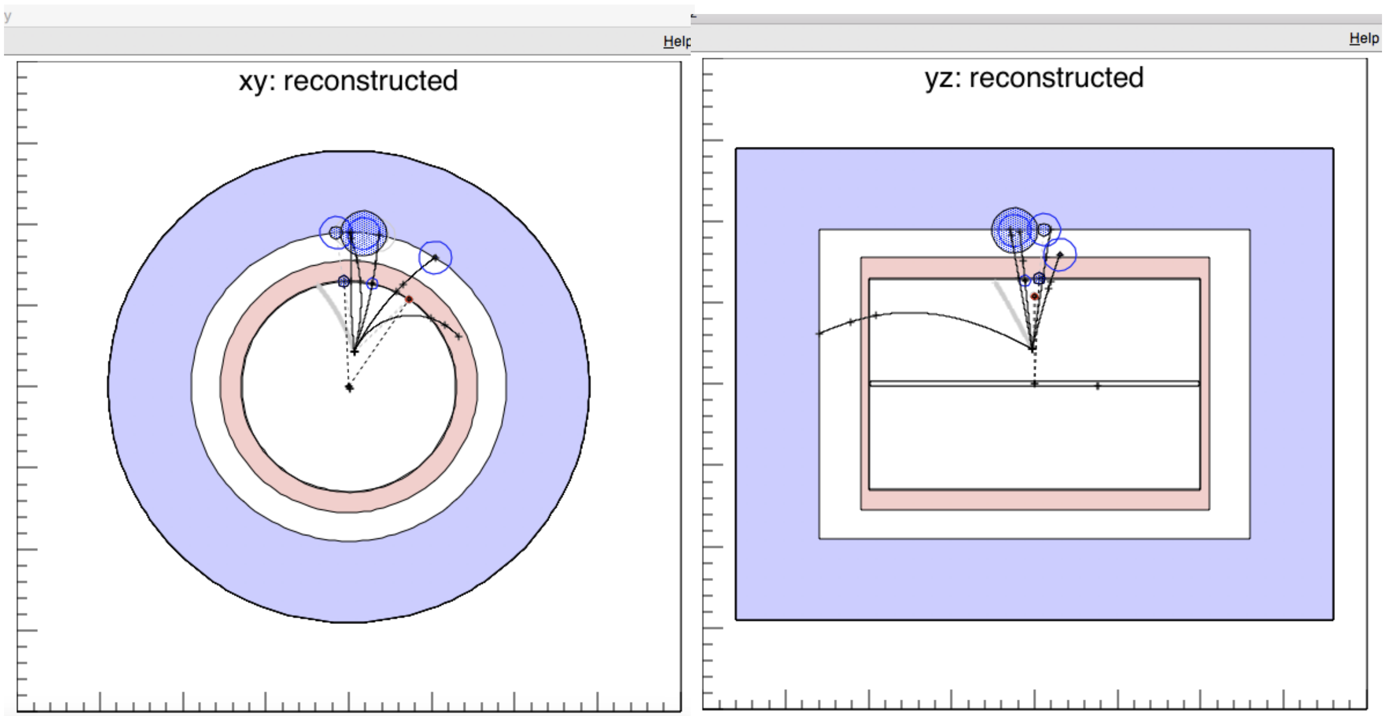
FCC-ee highest possible luminosity from Z to tt by exploiting b-factory technologies:

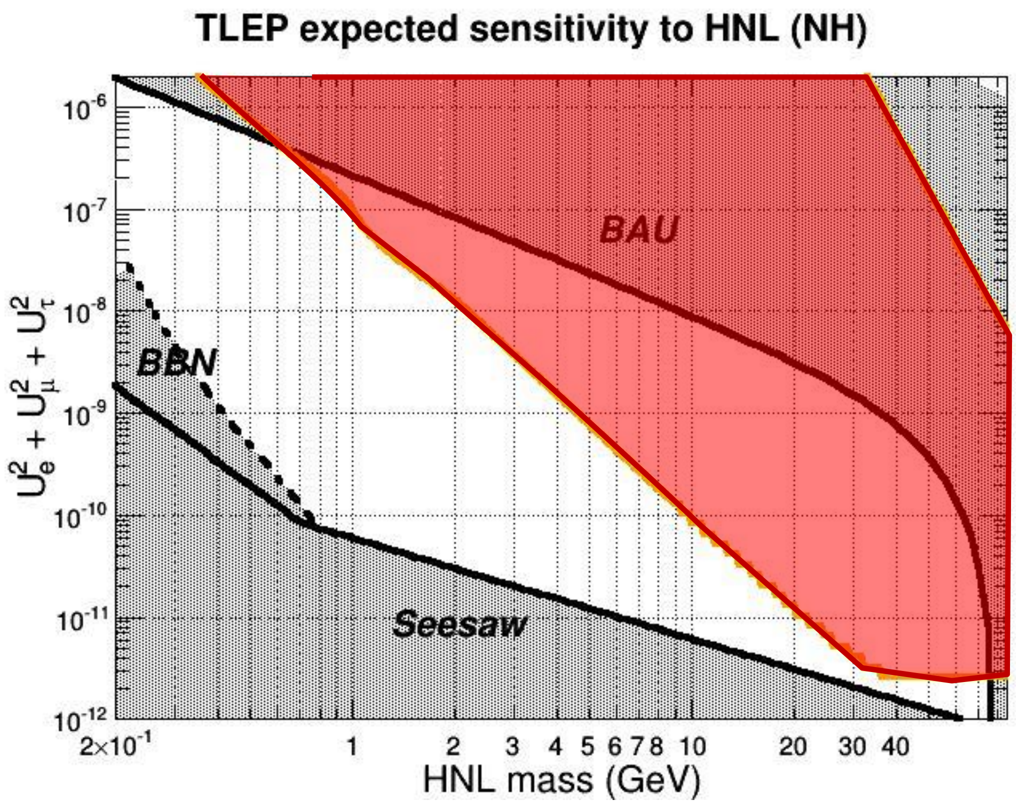


Event statistics :

Z peak	E_{cm} : 91 GeV	$5\ 10^{12}$ e+e- → Z	LEP x 10^5
WW threshold	E_{cm} : 161 GeV	10^8 e+e- → WW	LEP x 2.10^3
ZH threshold	E_{cm} : 240 GeV	10^6 e+e- → ZH	Never done
tt threshold	E_{cm} : 350 GeV	10^6 e+e- → tt	Never done

Simulation of heavy neutrino decay in a FCC-ee detector





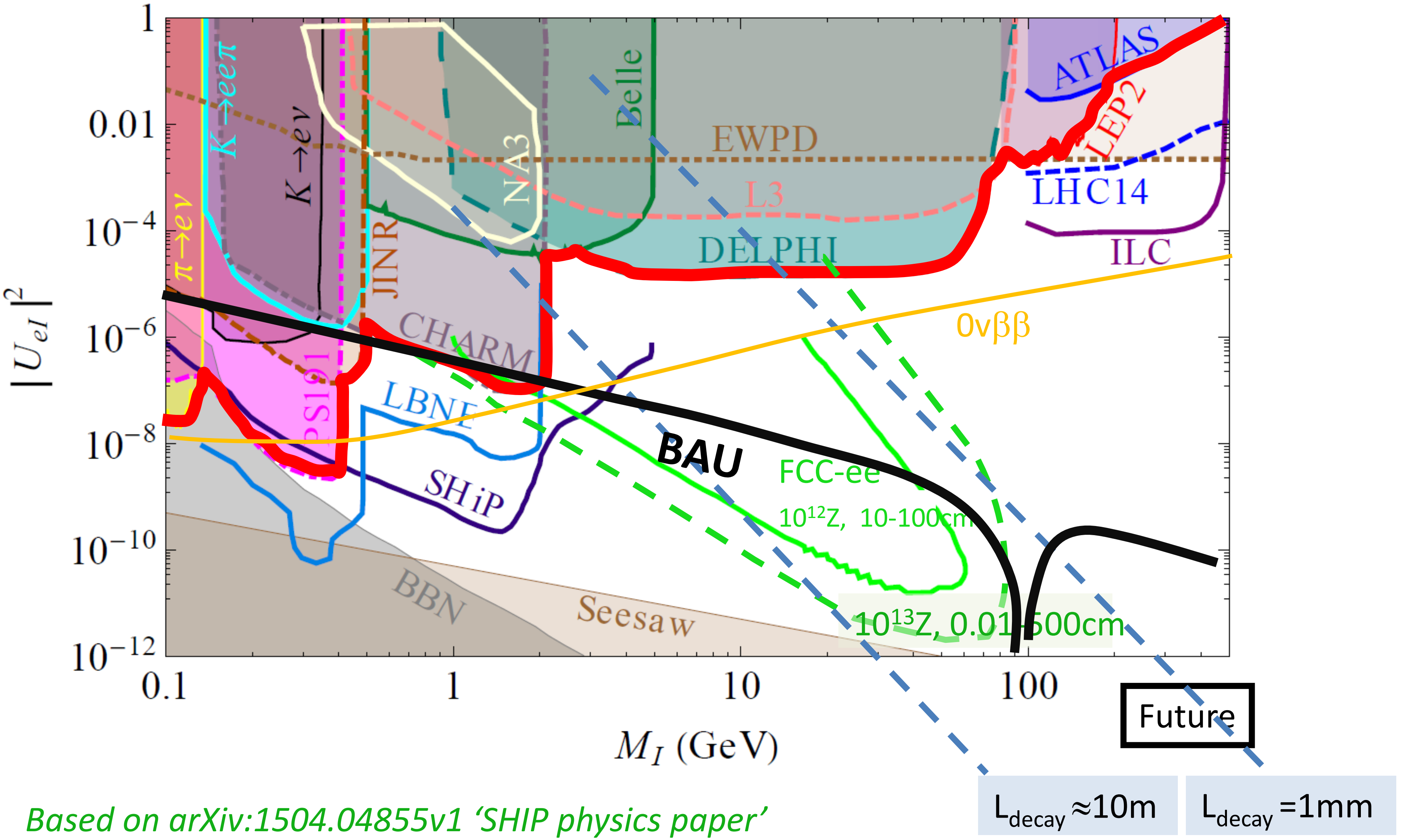
$N_Z = 10^{13}$ $100\mu m$ <L<5m

region of interest

FCC-ee sensitivity

presently studying the feasibility of ddetector with tracking volume of 8m radius for both FCC-ee and FCC-hh

Present limits



Based on arXiv:1504.04855v1 'SHIP physics paper'
And Pilar Hernandez, HEP-EPS Vienna

CONCLUSIONS

Neutrinos offer so far the only Particle Physics signal beyond the Standard Model

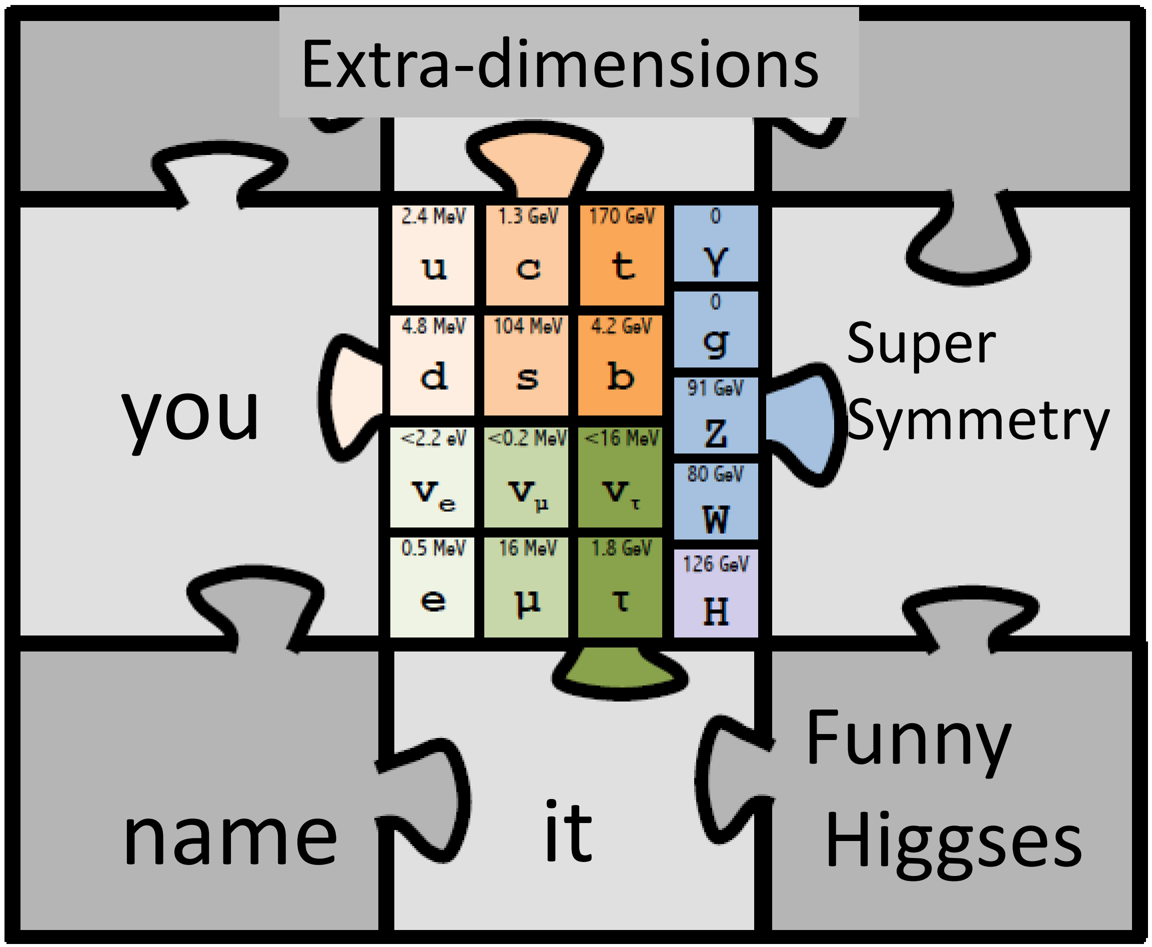
The activities involve long baseline experiments with a strong program in US and Japan of
-- Giant detector construction (HyperK, DUNE, also JUNO)
-- increase of (pulsed) proton beam power to 1.2 to 2.4 MW,
well beyond the best achieved so far (700kW at Fermilab 500 at JPARC)

This should lead to the discovery of CP violation and the solution of the mass hierarchy in the next decade (2020-2035)

In parallel the search for the heavy right handed neutrinos
(and other signs of a Majorana mass for neutrinos violating fermion number) will go full steam with
-- search for neutrinoless double beta decay (ultrpure reaching 100 or 1000 tons)
-- direct search for heavy right handed neutrinos
beam dump expt/SHIP ....
and the Future Circular Colliders (at CERN or in China)

We may thus understand the origin of neutrino masses, but also be given solutions for the Baryon Asymmetry of the Universe and even Dark Matter

or perhaps new world(s) of SM replicas



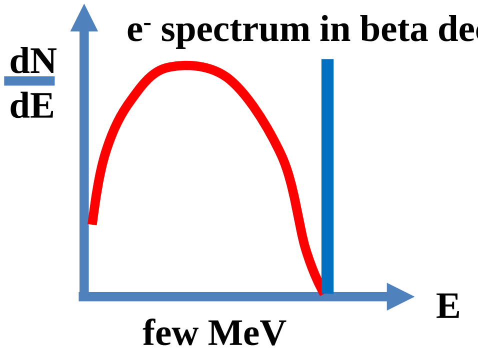

But Where Is Everybody?
Nima
At higher masses -- or at smaller couplings?

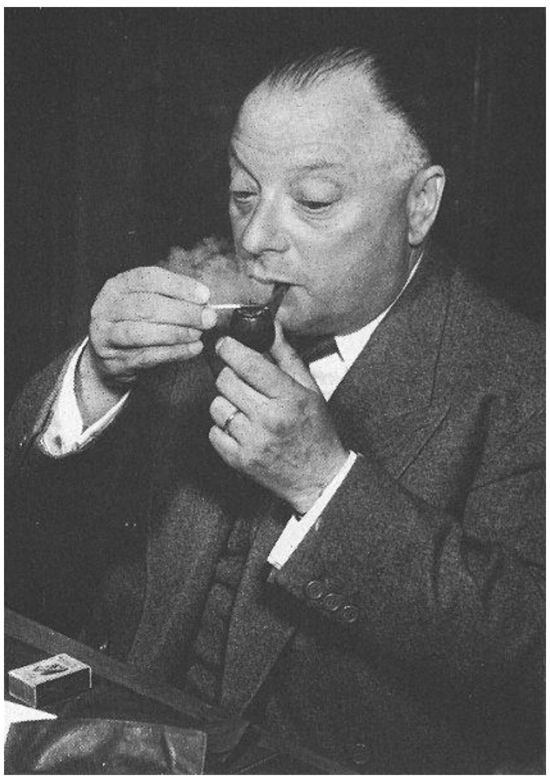
1930 Neutrinos: *the birth of the idea*

Pauli's letter of the 4th of December 1930

Consider $^{6}He^{++} \to {}^{6}Li\ \bar{\nu}_e\ e^-$

Q=3.5078 MeV T/2 ≈ 0.8067 s





Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and Li6 nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons, which have spin 1/2 and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant...

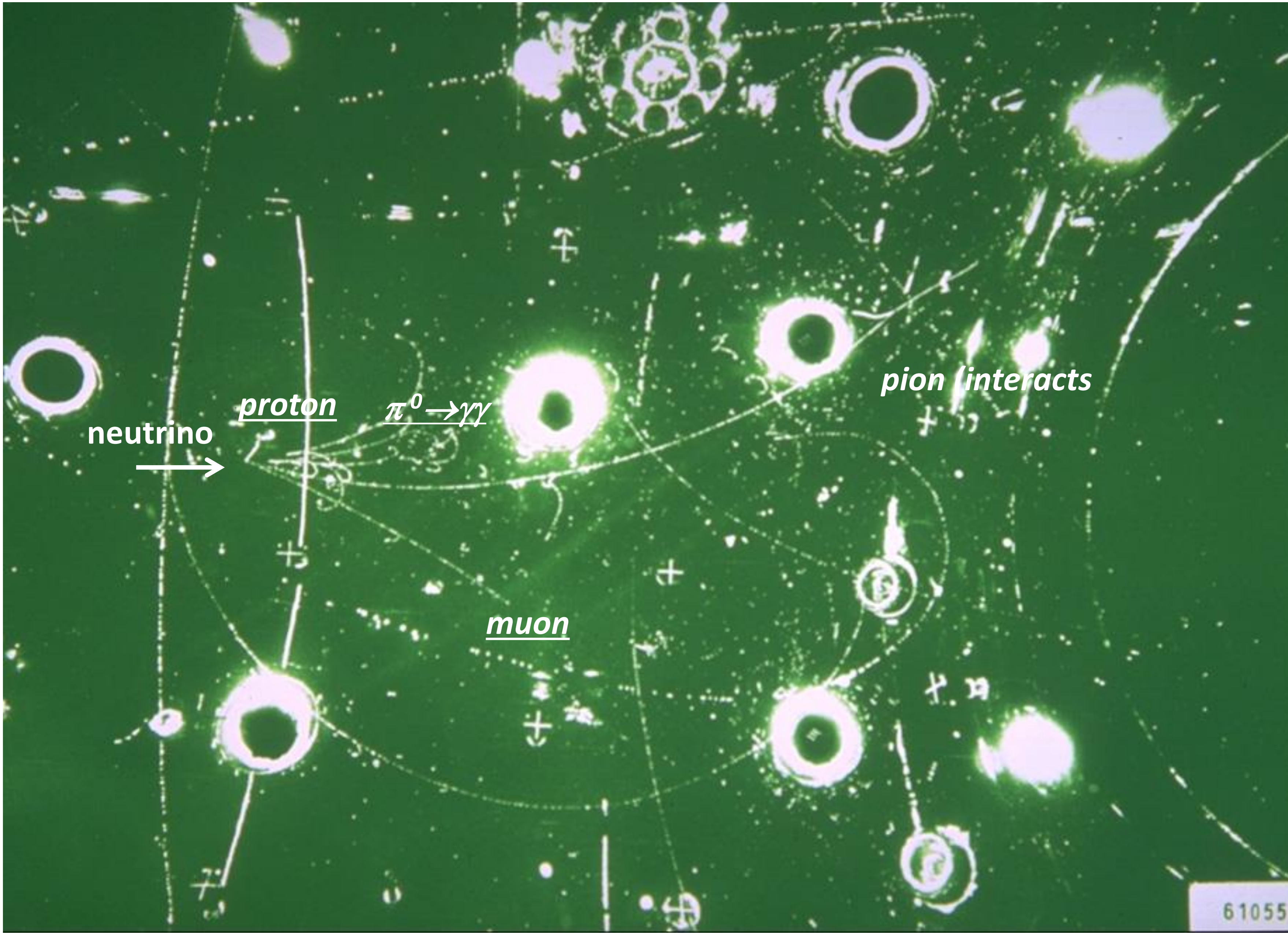
I agree that my remedy could seem incredible because one should have seen those neutrons very earlier if they really exist. But only the one who dare can win and the difficult situation, due to the continuous structure of the beta spectrum, is lighted by a remark of my honoured predecessor, Mr Debye, who told me recently in Bruxelles: "Oh, It's well better not to think to this at all, like new taxes". From now on, every solution to the issue must be discussed. Thus, dear radioactive people, look and judge.

Unfortunately, I cannot appear in Tubingen personally since I am indispensable here in Zurich because of a ball on the night of 6/7 December. With my best regards to you, and also to Mr Back.

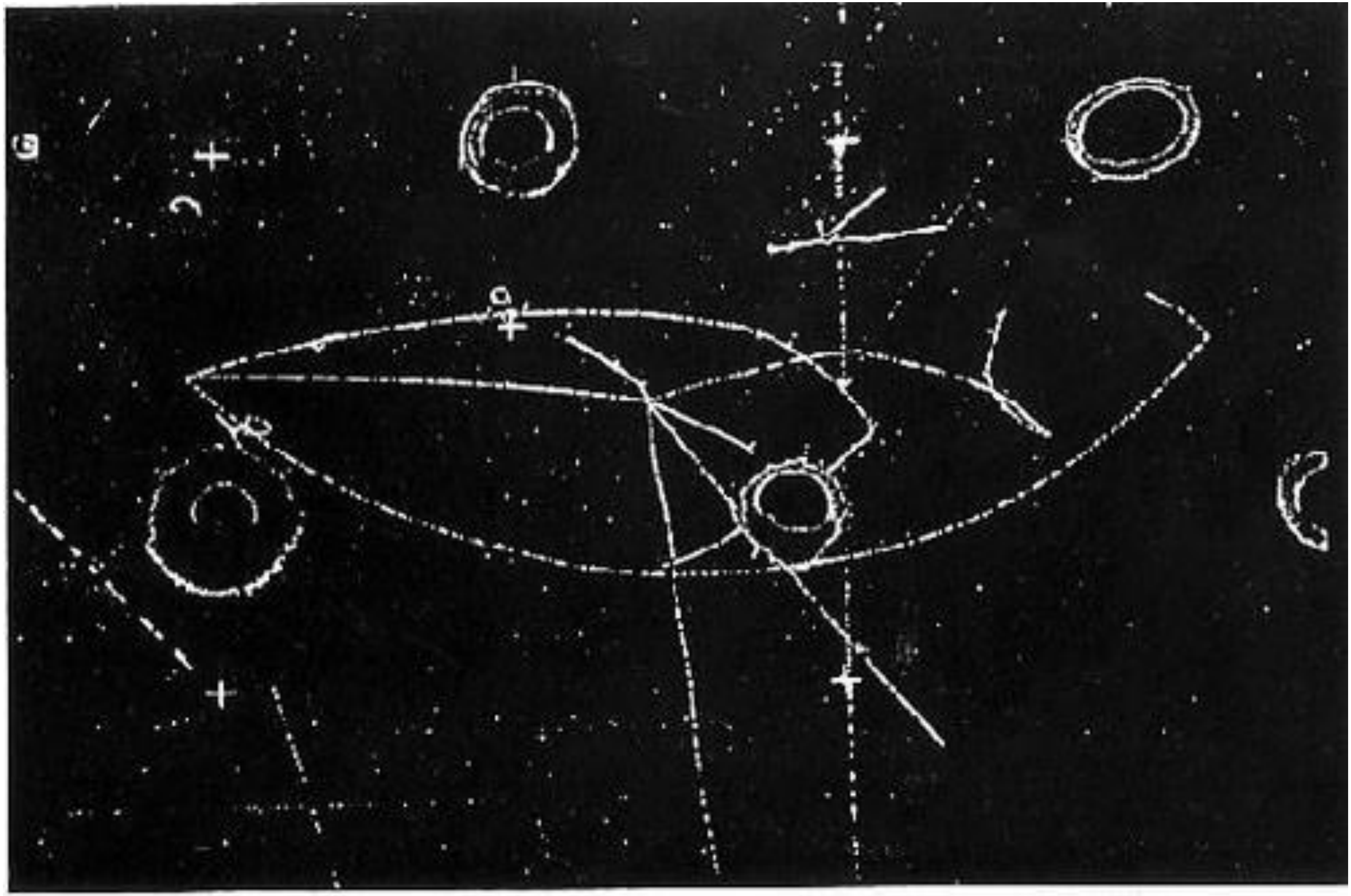
Your humble servant

. W. Pauli

Wolfgang Pauli

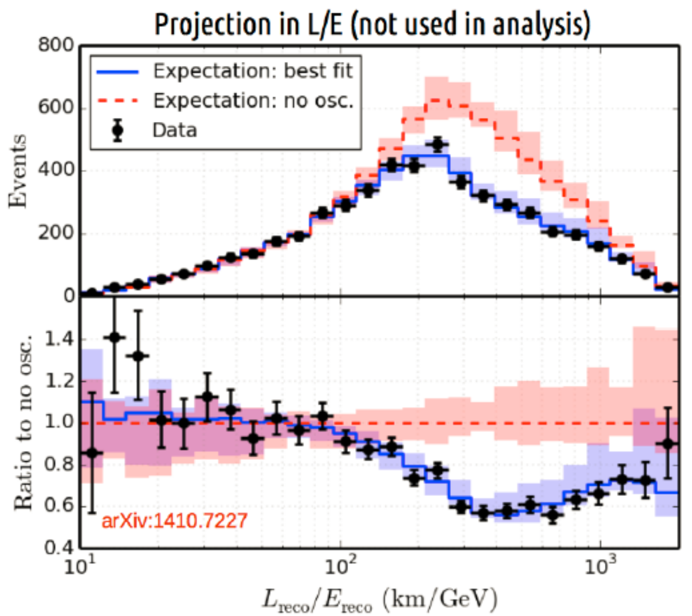


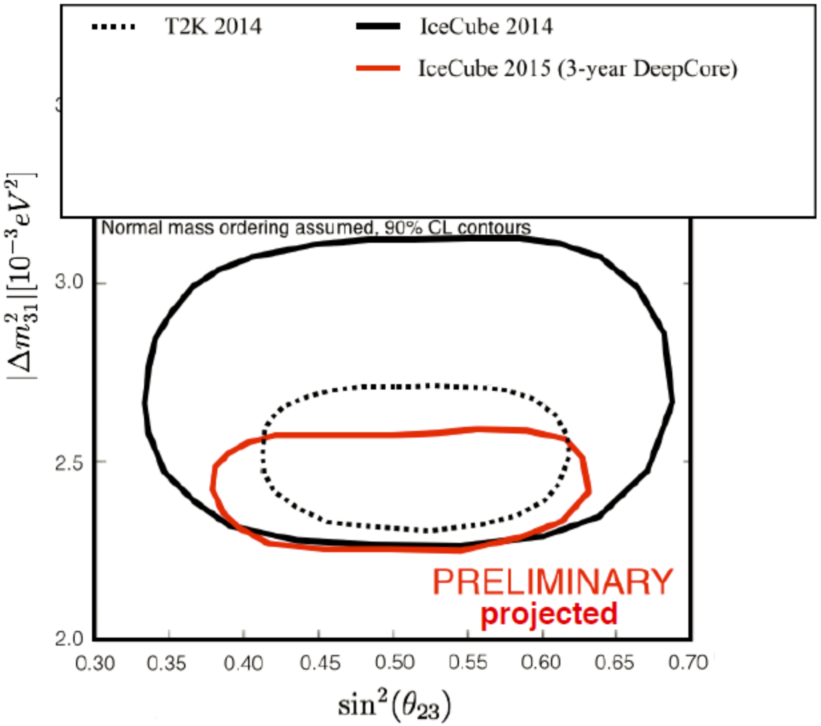
Gargamelle Charged Current event

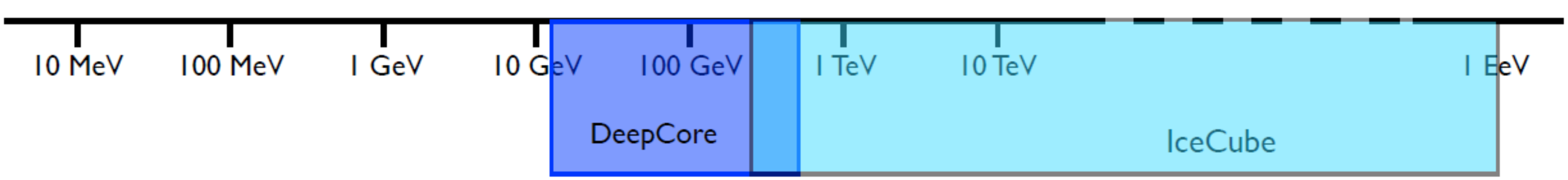


Gargamelle neutral current event (all particles are identified as hadrons)

Atmospheric neutrino oscillations with DeepCore

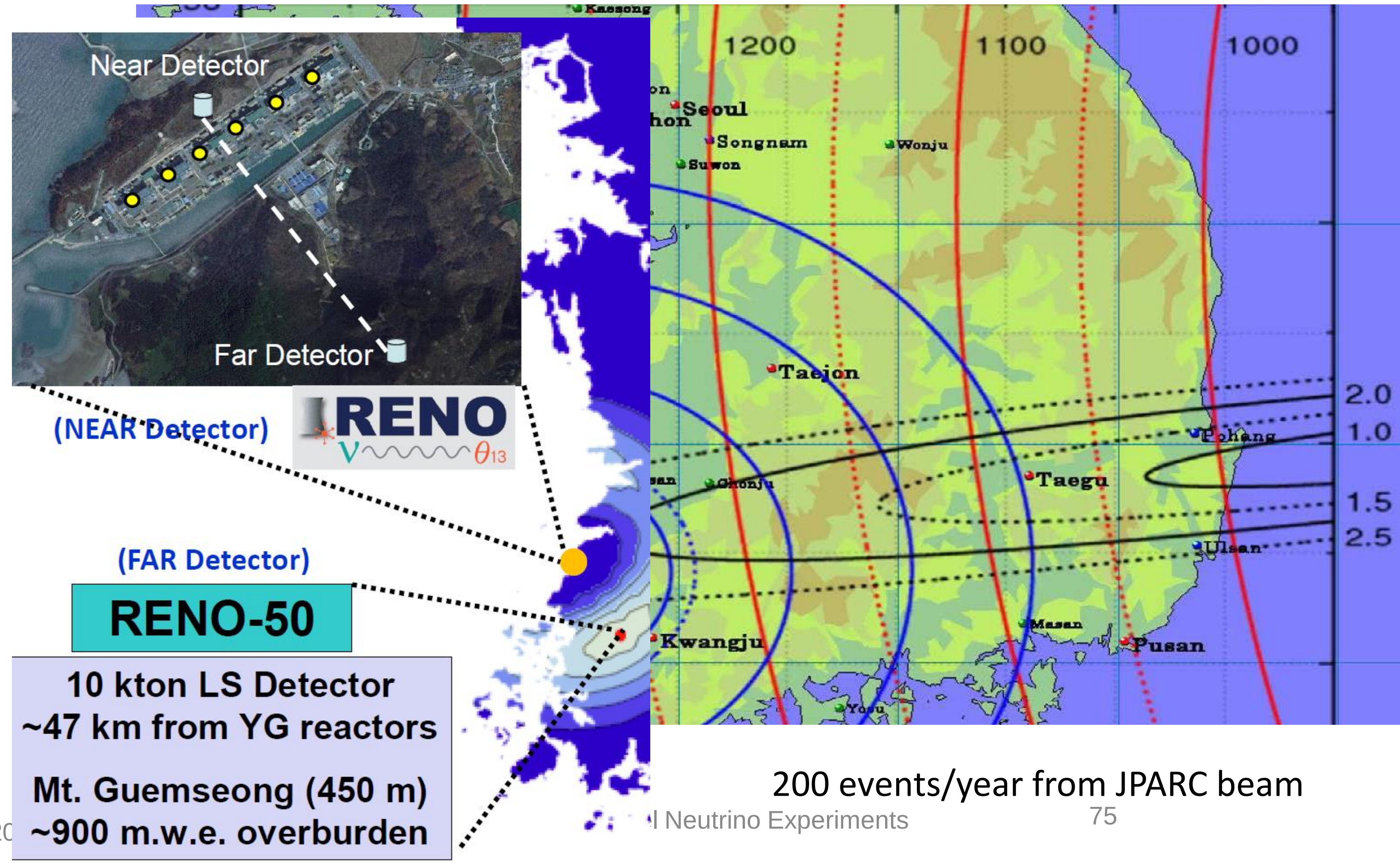






A word on RENO50 (17kton, 60% coverage, 100M$)

-- R&D funding (US $2M for 2015-2017)
from the Samsung Science & Technology Foundation.
R&D is in progress to produce TDR.
-- A proposal has been submitted to obtain full funding.



200 events/year from JPARC beam

A STUDY OF THE DECAY $\tau^- \to \pi^- \nu_\tau$☆

C.A. BLOCKER [1], J.M. DORFAN, G.S. ABRAMS, M.S. ALAM [2], A. BLONDEL [3], A.M. BOYARSKI, M. BREIDENBACH, D.L. BURKE, W.C. CARITHERS, W. CHINOWSKY, M.W. COLES [4], S. COOPER [4], W.E. DIETERLE, J.B. DILLON, J. DORENBOSCH [5], M.W. EATON, G.J. FELDMAN, M.E.B. FRANKLIN, G. GIDAL, G. GOLDHABER, G. HANSON, K.G. HAYES [5], T. HIMEL [5], D.G. HITLIN [6], R.J. HOLLEBEEK, W.R. INNES, J.A. JAROS, P. JENNI [5], A.D. JOHNSON, J.A. KADYK, A.J. LANKFORD, R.R. LARSEN, M. LEVI [1], V. LÜTH, R.E. MILLIKAN, M.E. NELSON, C.Y. PANG, J.F. PATRICK, M.L. PERL, B. RICHTER, A. ROUSSARIE, D.L. SCHARRE, R.H. SCHINDLER [5], R.F. SCHWITTERS [1], J.L. SIEGRIST, J. STRAIT, H. TAUREG [5], M. TONUTTI [7], G.H. TRILLING, E.N. VELLA, R.A. VIDAL, I. VIDEAU [3], J.M. WEISS and H. ZACCONE [8]

Lawrence Berkeley Laboratory and Department of Physics, University of California, Berkeley, CA 94720, USA and Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94305, USA

Received 19 October 1981

We present a high statistics measurement of the branching ratio for the decay $\tau^- \to \pi^-\nu_\tau$ using data obtained with the Mark II detector at the SLAC e^+e^- storage ring SPEAR. We have used events from the center-of-mass energy region 3.52 to 6.7 GeV to determine that $B(\tau^- \to \pi^-\nu_\tau) = 0.117 \pm 0.004 \pm 0.018$. From electron–muon events in the same data sample, we have determined that $B(\tau^- \to \pi^-\nu_\tau)/B(\tau^- \to e^-\bar{\nu}_e\nu_\tau) = 0.66 \pm 0.03 \pm 0.11$. We present measurements of the mass and spin of the τ and the mass of the τ neutrino based, for the first time, on a hadronic decay mode of the τ.

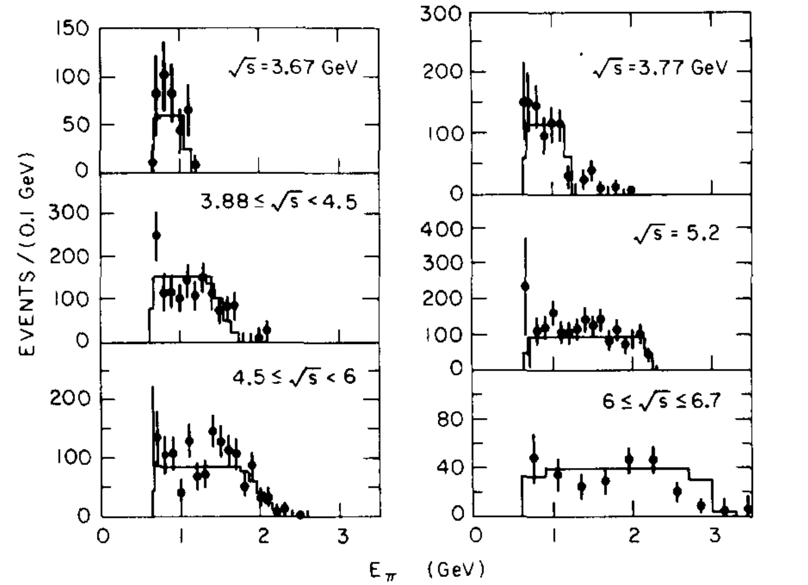


Fig. 3. Pion energy spectrum for π–X events with bin-by-bin background subtraction and efficiency corrections. The curves are the expected spectra for $m_\tau = 1.782$ GeV/c^2, $m_\nu = 0$, and $B_\pi = 0.117$.

Two body decay $\tau^- \to \pi^- \nu_\tau$ with $m(\nu_\tau) < 250$ MeV

The ratio $B(\tau^- \to \pi^-\nu_\tau)/B(\tau^- \to e^-\bar{\nu}_e\nu_\tau) = 0.66 \pm 0.03 \pm 0.11.$ is consistent with the tau being coupled to the hadronic weak axial-vector current

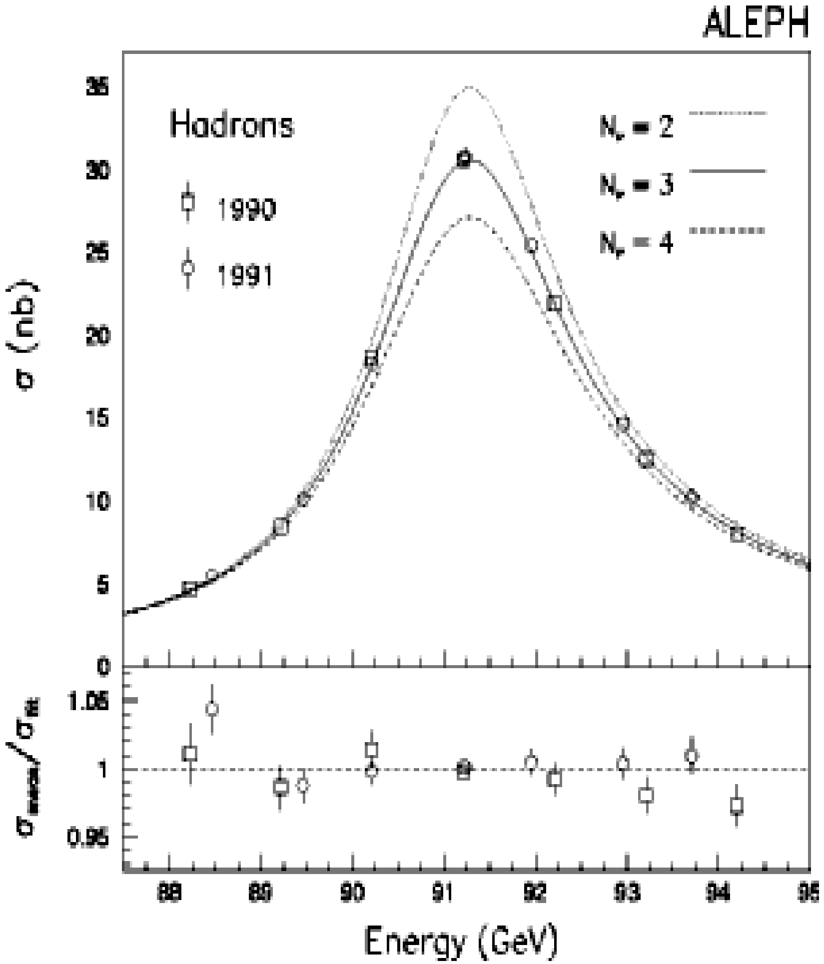
… and the life time of the tau is consistent with the emitted neutrino being >90% the isospin partner of the tau

The tau neutrino was discovered in e+ e- experiments

1989 The Number of Neutrinos

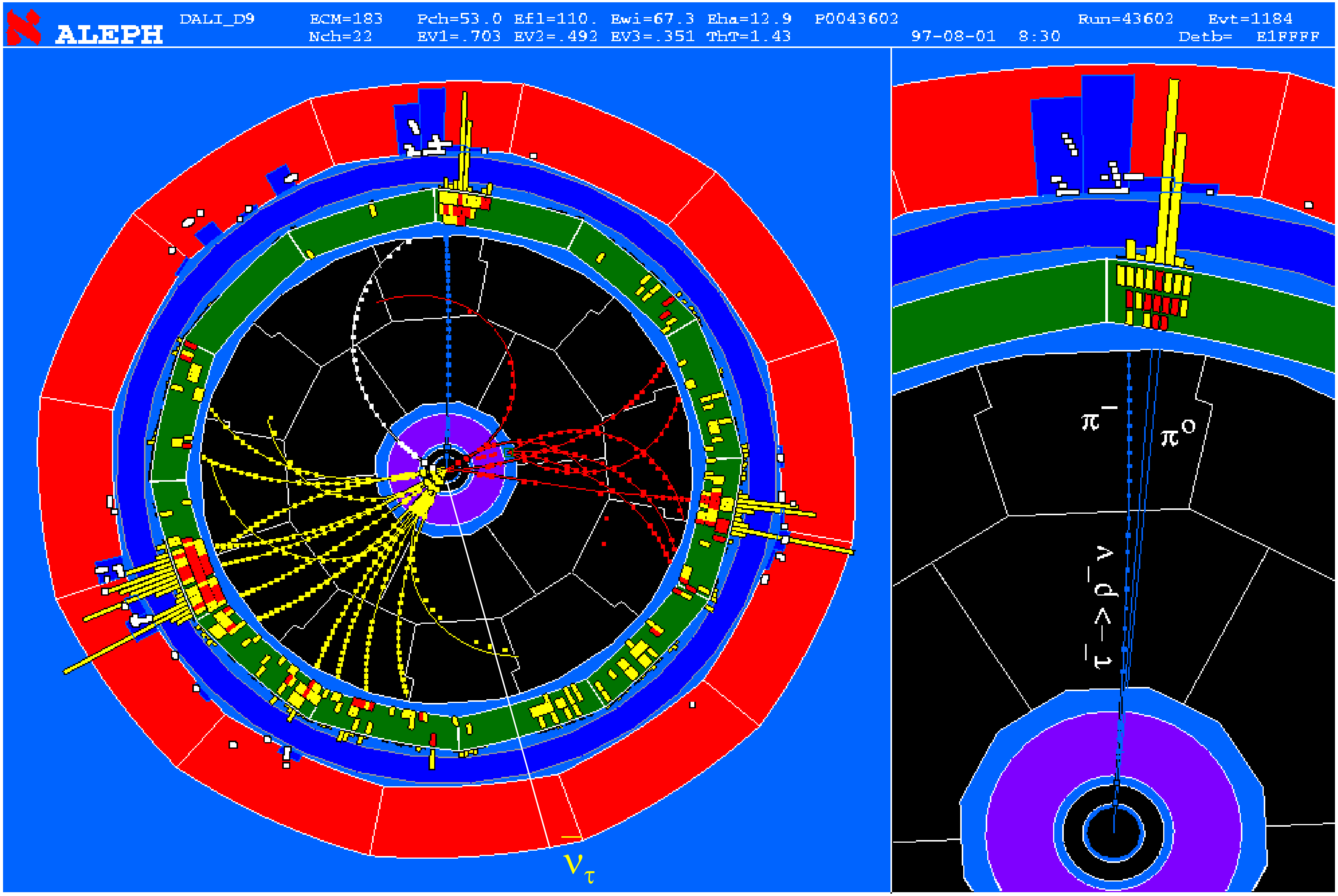
collider experiments: LEP

- **N_ν determined from the visible Z cross-section at the peak (most of which are hadrons):**
the more decays are invisible the fewer are visible:
hadron cross section decreases by 13% for one more family of neutrinos



in 2001: N_ν = 2.984 ±0.008

Number of active (left-handed) neutrinos with mass < 45 GeV



Observation of tau-neutrino in ALEPH at LEP (183 GeV E_{cm})

e+e- → W+ W- → $(hadrons)^+$ + $\bar{\nu}_\tau \tau^-$ (→ $\rho\ \nu_\tau$)

Observation of Tau Neutrino Interactions

DONUT Collaboration
K. Kodama[1], N. Ushida[1], C. Andreopoulos[2], N. Saoulidou[2],
G. Tzanakos[2], P. Yager[3], B. Baller[4], D. Boehnlein[4],
W. Freeman[4], B. Lundberg[4], J. Morfin[4], R. Rameika[4],
J.C. Yun[4], J.S. Song[5], C.S. Yoon[5], S.H.Chung[5], P. Berghaus[6],
M. Kubanstev[6], N.W. Reay[6], R. Sidwell[6], N. Stanton[6],
S. Yoshida[6], S. Aoki[7], T. Hara[7], J.T. Rhee[8],
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R. Schwienhorst[9], J. Sielaff[9], J. Trammell[9], J. Wilcox
K. Hoshino[10], H. Jiko[10], M. Miyanishi[10], M. Komatsu[10], M. Na
T. Nakano[10], K. Niwa[10], N. Nonaka[10], K. Okada[10],
O. Sato[10], T. Akdogan[11], V. Paolone[11], C. Rosenfeld
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[3] *University of California/Davis, Davis, California*
[4] *Fermilab, Batavia, Illinois 60510*
[5] *Gyeongsang University, Chinju, Korea*
[6] *Kansas State University, Manhattan, Kansas*
[7] *Kobe University, Kobe, Japan*
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[10] *Nagoya University, Nagoya 464-8602, Japan*
[11] *University of Pittsburgh, Pittsburgh, Pennsylvania 15260*
[12] *University of South Carolina, Columbia, South Carolina*
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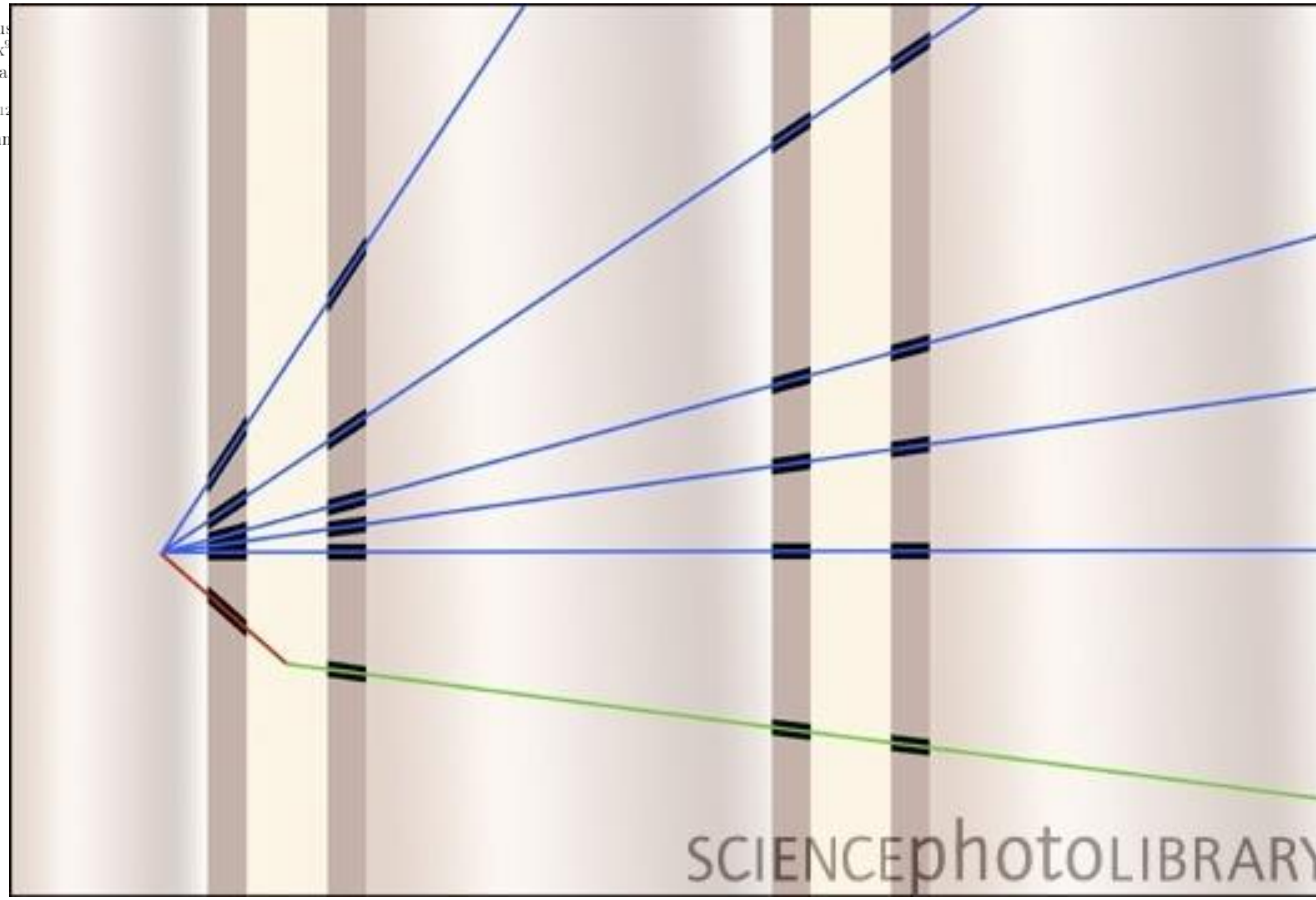
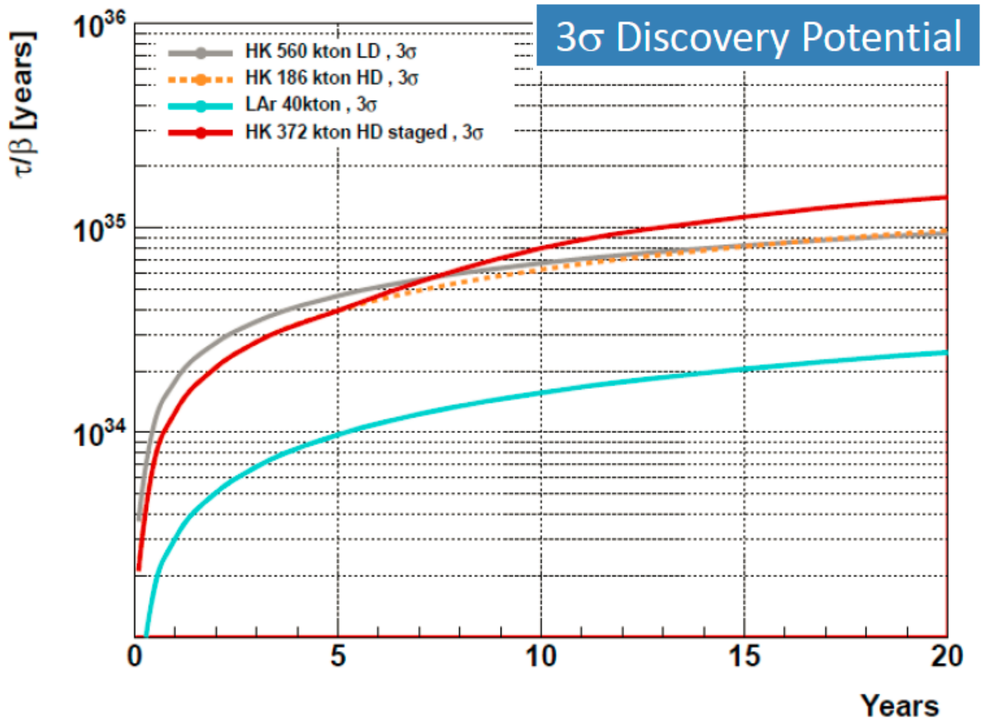
December 14, 2000

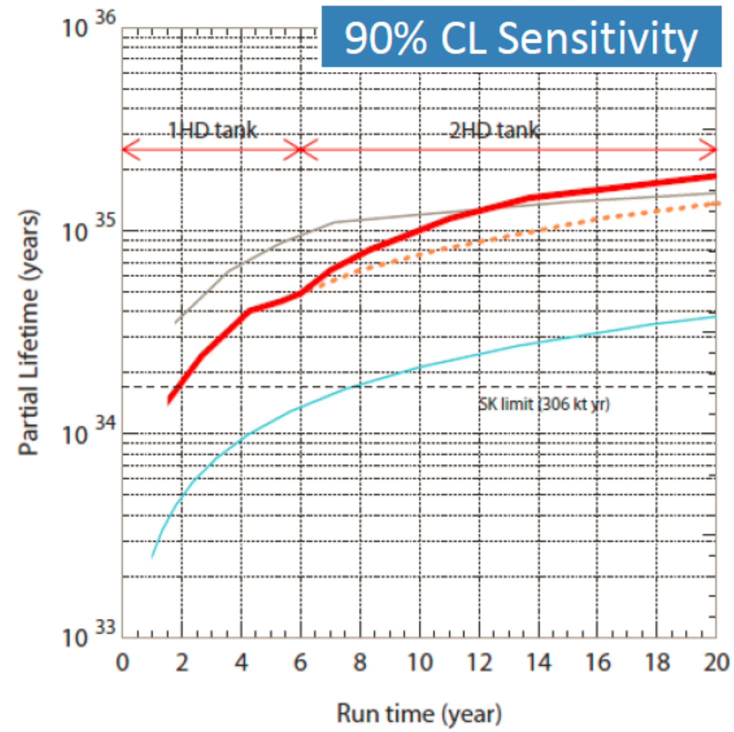


Tau Neutrino interaction in DONUT experiment (Fermilab) 2000

Proton decay

$P \rightarrow e^+ \pi^0$: sensitivity



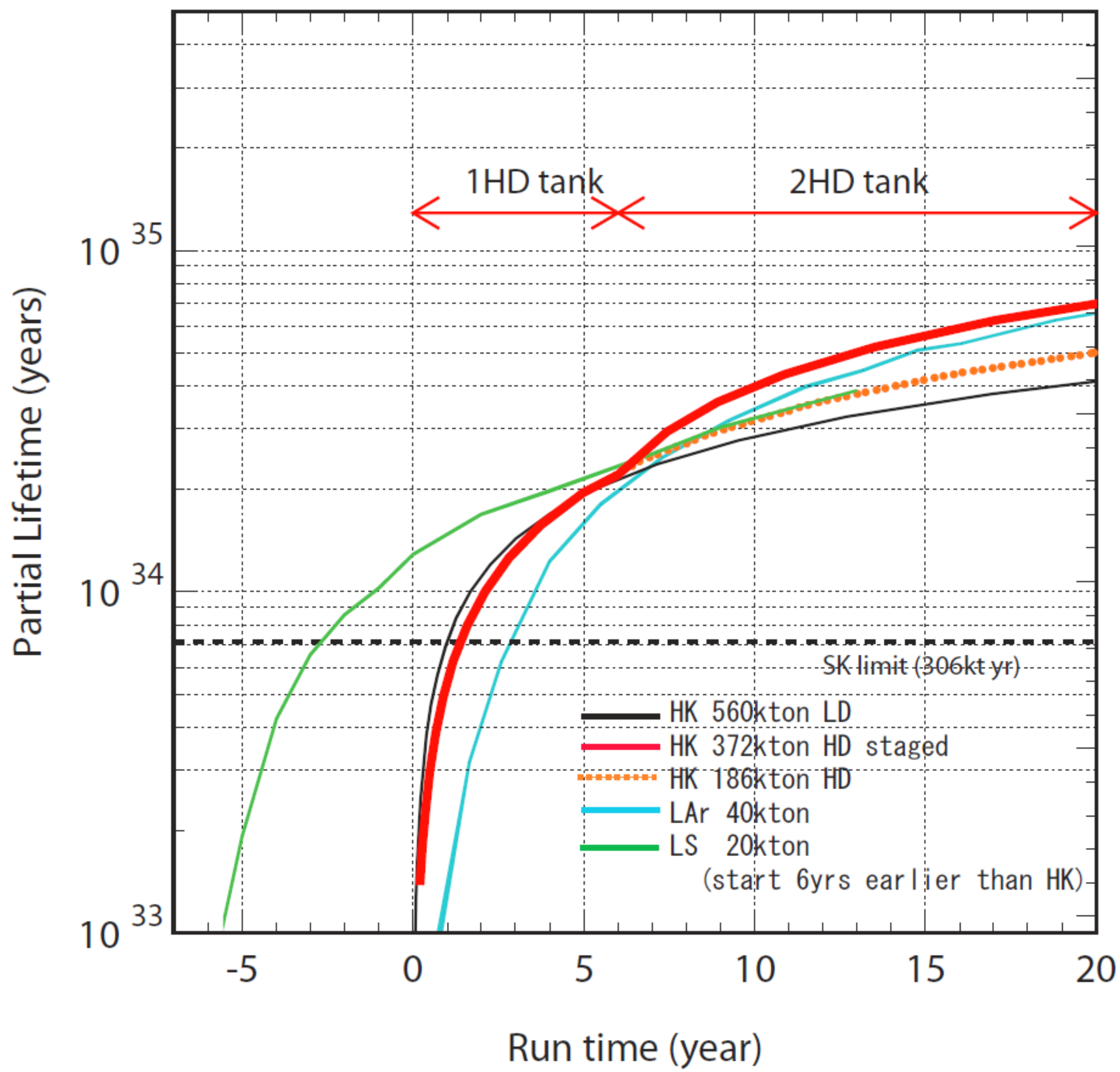


- > 1×10^{35} years after 2.7 Mton yr (90%CL) or 3σ discovery with 4.0 Mtonyr.
- If proton lifetime is near the current Super-K limit of 1.7×10^{34} years Hyper-K will observe a positive signal at 8.9σ in 2.7 Mtonyr exposure.

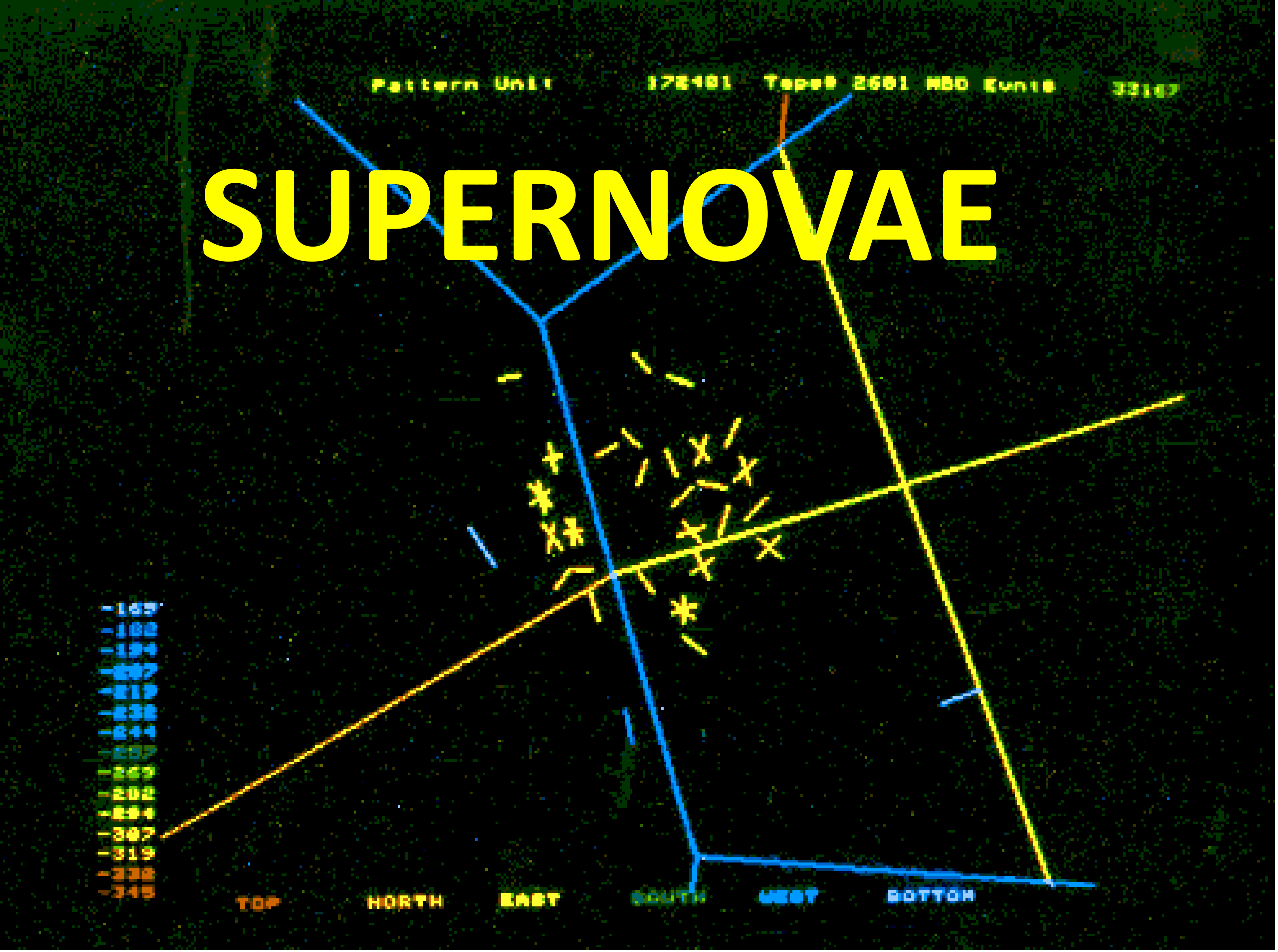
(Lines for the liquid argon experiment have been generated based on numbers in the literature (efficiency: 45% bkg: 1 event/Mtonyr).)

$p \rightarrow K^{+} \nu$ sensitivity

Here, JUNO expt (liquid Scintillator (LS) is competitive and will be earlier.



SUPERNOVAE



Galactic SN Burst Neutrino Events

Neutrino source	1 Tank HD	2 Tank HD	LOI
$\bar{\nu}_e + p$	49,000～68,000	98,000～136,000	165,000～230,000
$\nu_e + e^-$	2,100～2,500	4,200～5,000	7,000～8,000
$\nu_e + {}^{16}O$ CC	80～4,100	160～8,200	300～14,000
$\bar{\nu}_e + {}^{16}O$ CC	650～3,900	1,300～7,800	2,000～13,000
NC γ	～2,500	～5,000	～7,500
$\nu_e + e^-$ (Neutronization)	6～40	12～80	20～130
Total events.	52,000～79,000	104,000～158,000	170,000～260,000

Energy threshold is 5MeV in all cases.

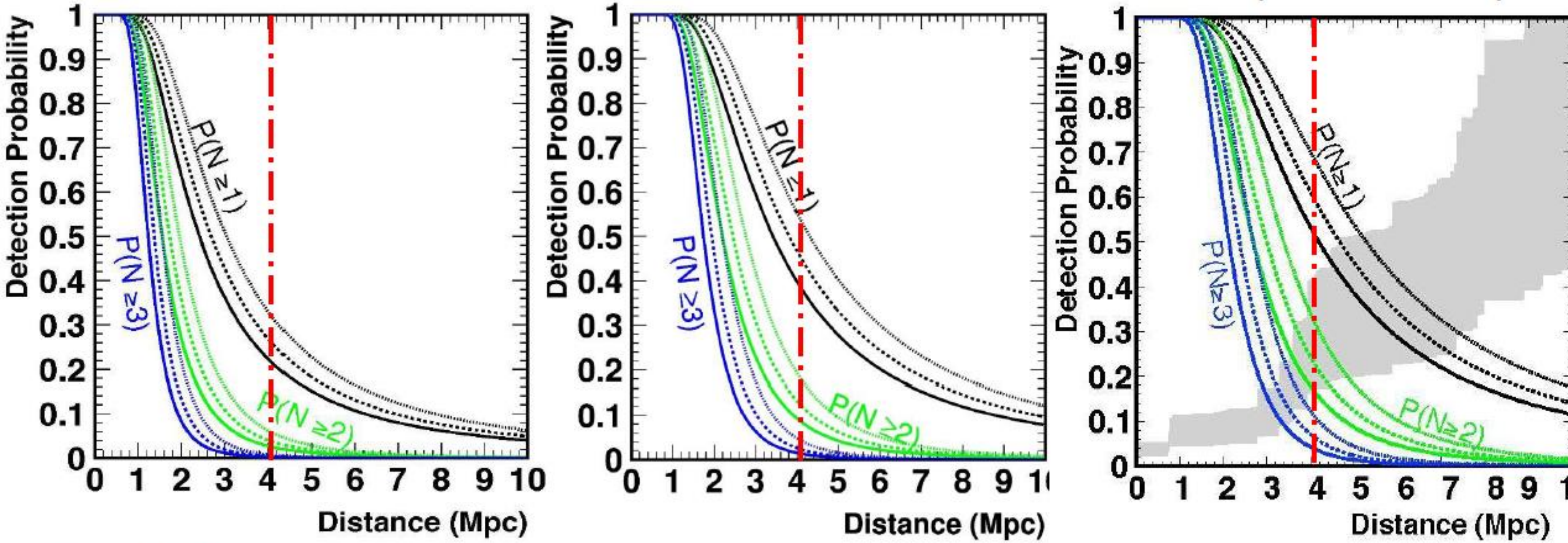
NC is roughly scaled from Langanke et al. PRL 76 2629, 1996

10kpc, Livermore model

Large statistics will make it possible to study SN mechanism in detail

ν detection probability for ~Mpc SN

1 tank (0.19Mt FV) | 2tank staged (0.37Mt FV) | LOI (0.56Mt FV)



For 4Mpc supernova

3-6% for P(N >= 2) | 10-20 % for P(N >= 2) | 17-32% for P(N >=2)

Conditions:

- Livermore simulation
- 10MeV threshold
- # range for no osc., N.H. and I.H.

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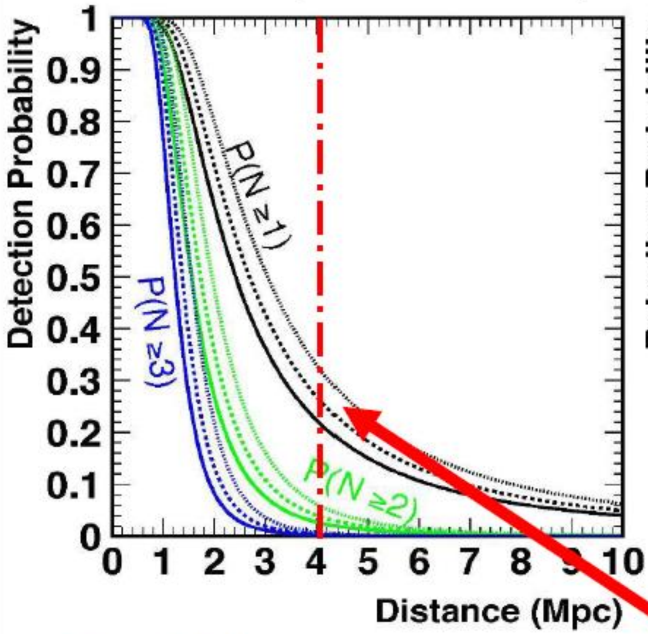
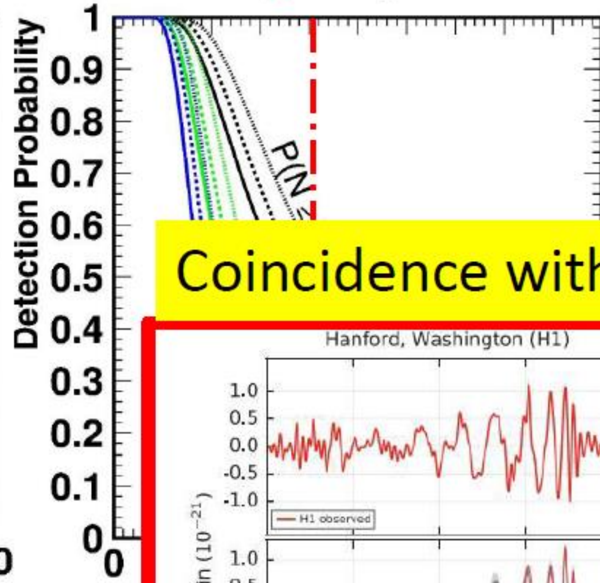
ν detection probability for ~Mpc SN

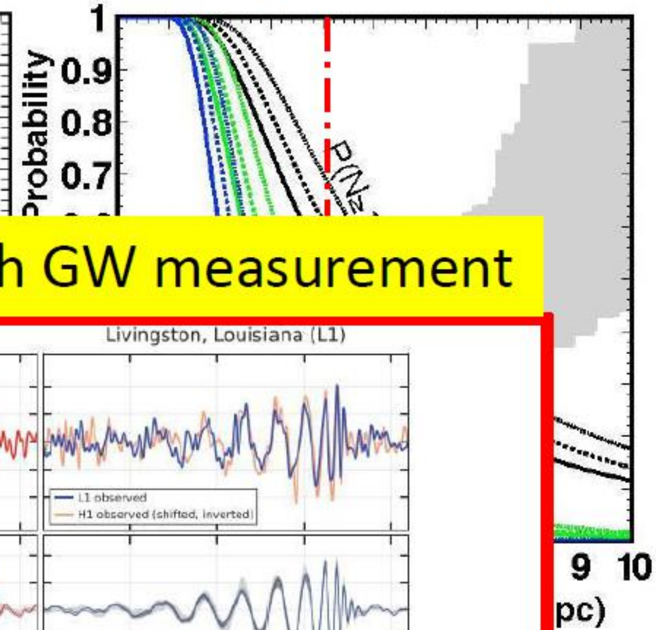
1 tank (0.19Mt FV)



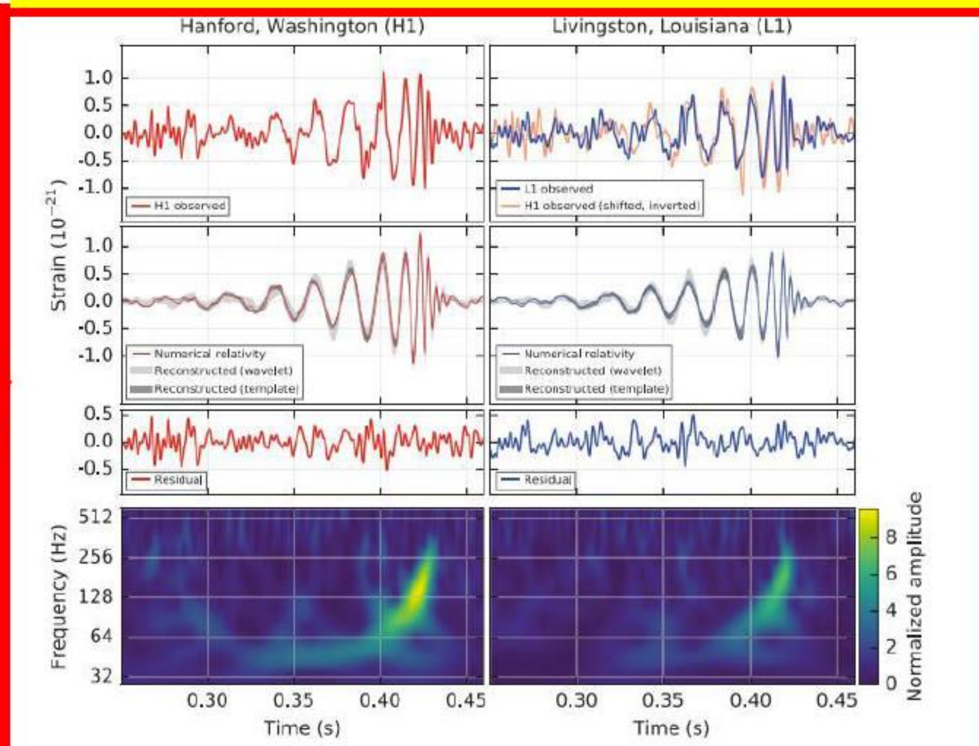
2tank staged (0.37Mt FV)



LOI (0.56Mt FV)



Coincidence with GW measurement



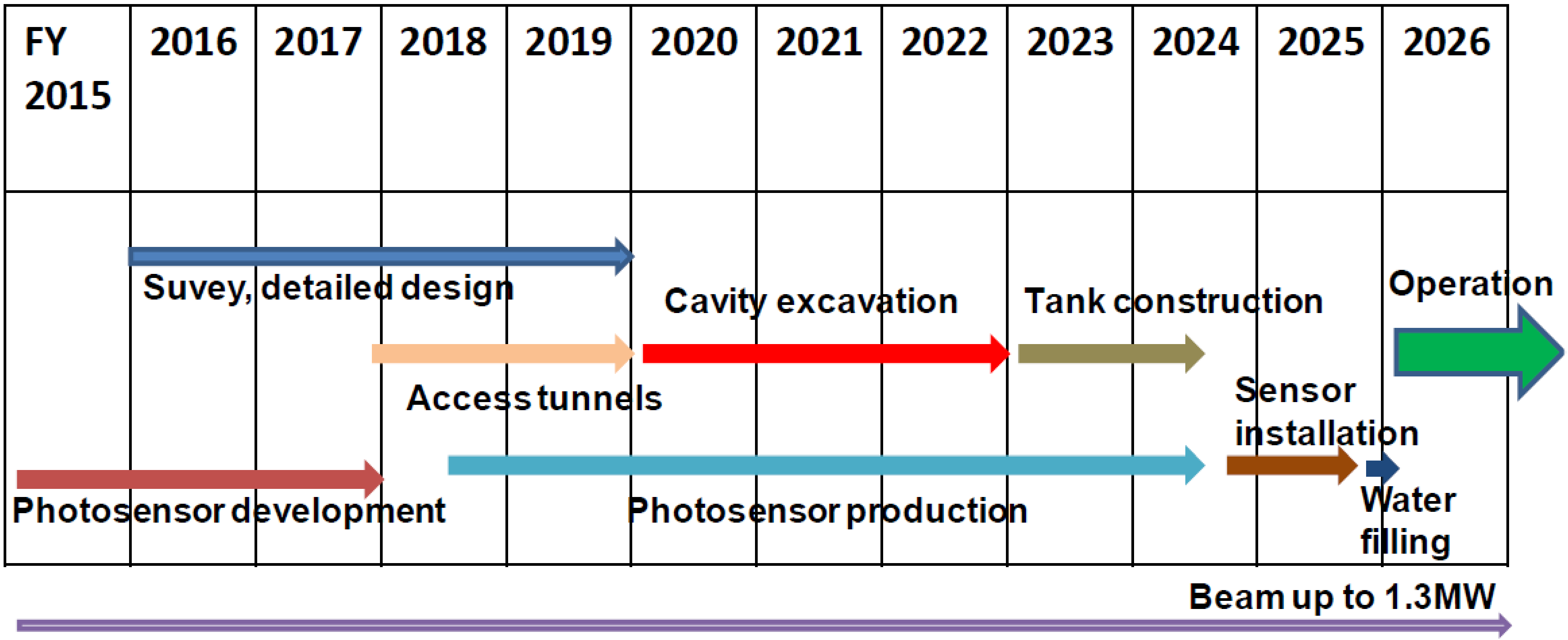
For 4Mpc supernova

3-6% for P(N >= 2) 10-2)

Conditions:

- Livermore simulation
- 10MeV threshold
- # range for no osc., N.H. and I.H.

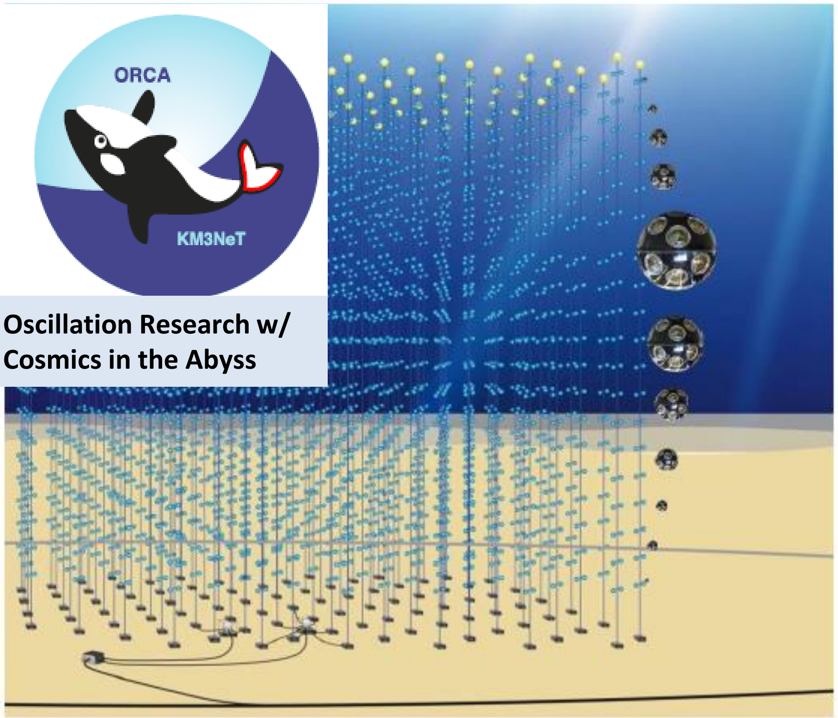
The Hyper-Kamiokande Timeline



- 2018 - 2025 HK construction
- 2026 onwards CPV study, Atm, Solar, Supernova ν study, Proton decay searches

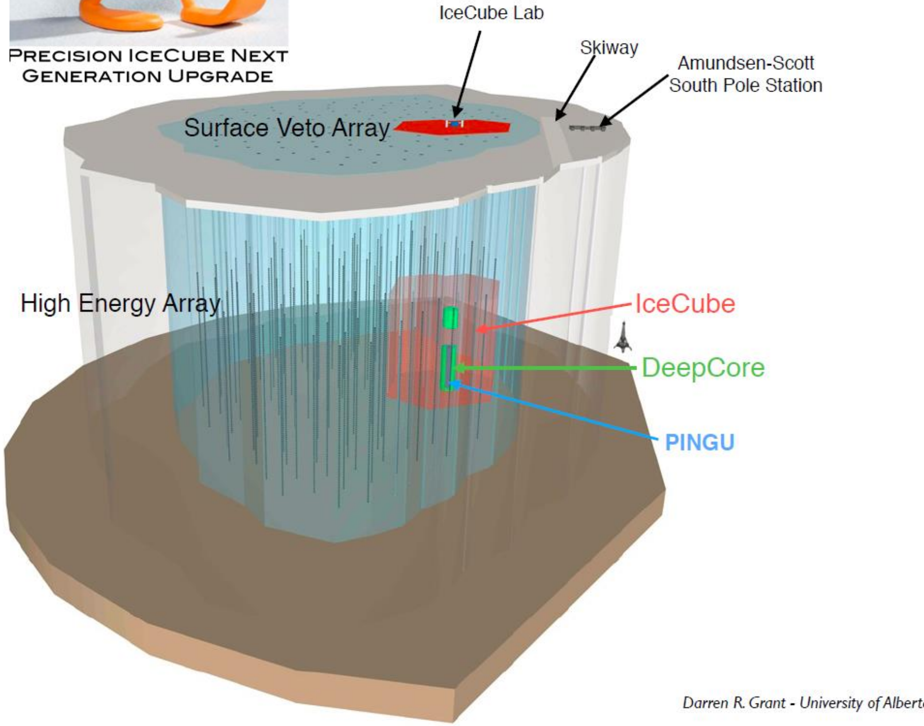
The second (identical) tank start starts operation 6y after the first one.

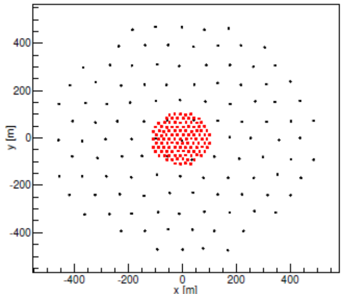
ORCA and PINGU



Artist's impression of a KM3NeT building block: 115 strings of 18 DOMs.

PRECISION ICECUBE NEXT GENERATION UPGRADE





ORCA: 3.8 Mton

Both experiments are in <u>proposal</u> phase.
ORCA: deployment 2018-2021
PINGU: aim at completion in 2022.
Both: 4 years for MH determination at 3 sigma

Asymptotic safety of gravity and the Higgs boson mass

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12 January 2010

Abstract

There are indications that gravity is asymptotically safe. The Standard Model (SM) plus gravity could be valid up to arbitrarily high energies. Supposing that this is indeed the case and assuming that there are no intermediate energy scales between the Fermi and Planck scales we address the question of whether the mass of the Higgs boson m_H can be predicted. For a positive gravity induced anomalous dimension $A_\lambda > 0$ the running of the quartic scalar self interaction λ at scales beyond the Planck mass is determined by a fixed point at zero. This results in $m_H = m_{\min} = 126$ GeV, with only a few GeV uncertainty. This prediction is independent of the details of the short distance running and holds for a wide class of extensions of the SM as well. For $A_\lambda < 0$ one finds m_H in the interval $m_{\min} < m_H < m_{\max} \simeq 174$ GeV, now sensitive to A_λ and other properties of the short distance running. The case $A_\lambda > 0$ is favored by explicit computations existing in the literature.

Key words:
Asymptotic safety, gravity, Higgs field, Standard Model
PACS: 04.60.-m 11.10.Hi 14.80.Bn

Detecting the Higgs scalar with mass around 126 GeV at the LHC could give a strong hint for the absence of new physics influencing the running of the SM couplings between the Fermi and Planck/unification scales.

$$P(\nu_e \to \nu_\mu) = |A|^2 + |S|^2 + 2\,A\,S\ \sin\delta$$

$$P(\bar{\nu}_e \to \bar{\nu}_\mu) = |A|^2 + |S|^2 - 2\,A\,S\ \sin\delta$$

$$\frac{P(\nu_e \to \nu_\mu) - P(\bar{\nu}_e \to \bar{\nu}_\mu)}{P(\nu_e \to \nu_\mu) + P(\bar{\nu}_e \to \bar{\nu}_\mu)} = A_{CP}\ \alpha\ \frac{\sin\delta\ \ \sin(\Delta m^2_{12} L/4E)\ \ \sin\theta_{12}\sin\theta_{13}}{\sin^2 2\theta_{13} + \text{solar term}\ldots}$$

… need large values of $\sin\theta_{12}$, Δm^2_{12} (LMA) but *not* large $\sin^2\theta_{13}$

… need APPEARANCE … $P(\nu_e \to \nu_e)$ is time reversal symmetric (reactors or sun are out)

… can be large (30%) for suppressed channel (one small angle vs two large)

at wavelength at which ‘solar’ = ‘atmospheric’ and for $\nu_e \to \nu_\mu$, ν_τ

… asymmetry is opposite for $\nu_e \to \nu_\mu$ and $\nu_e \to \nu_\tau$