Neutrino Physics in 2020

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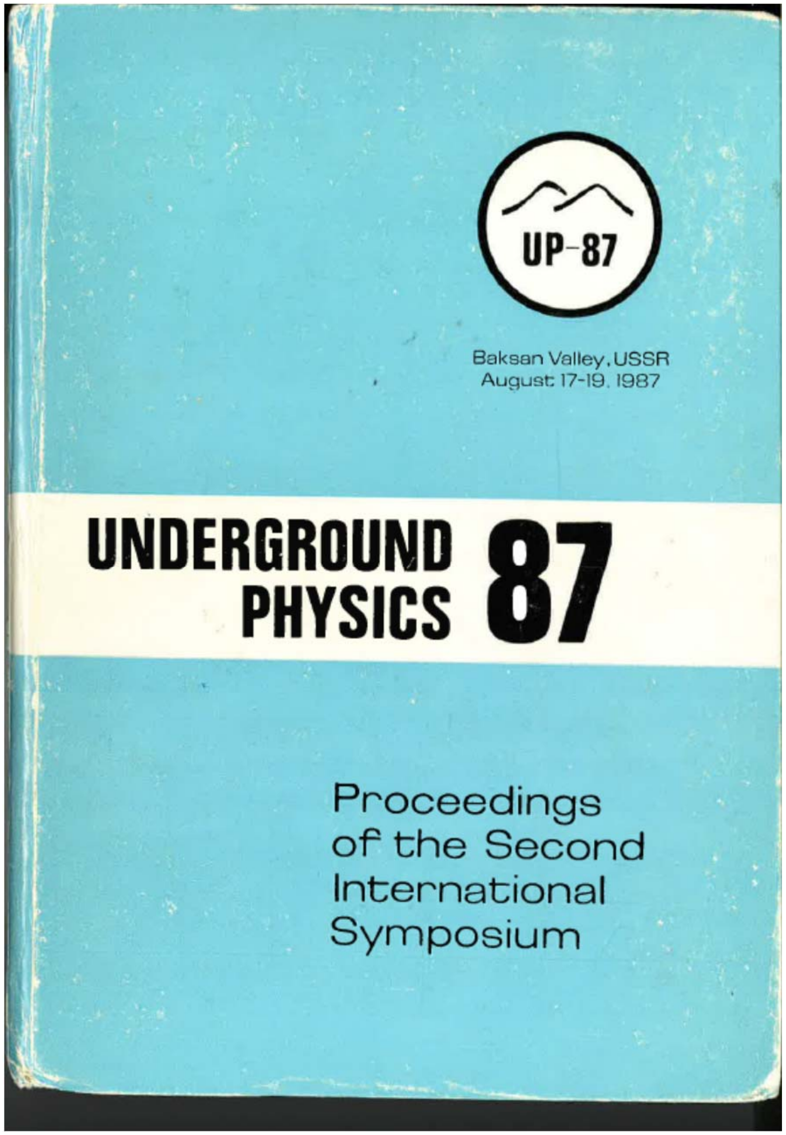
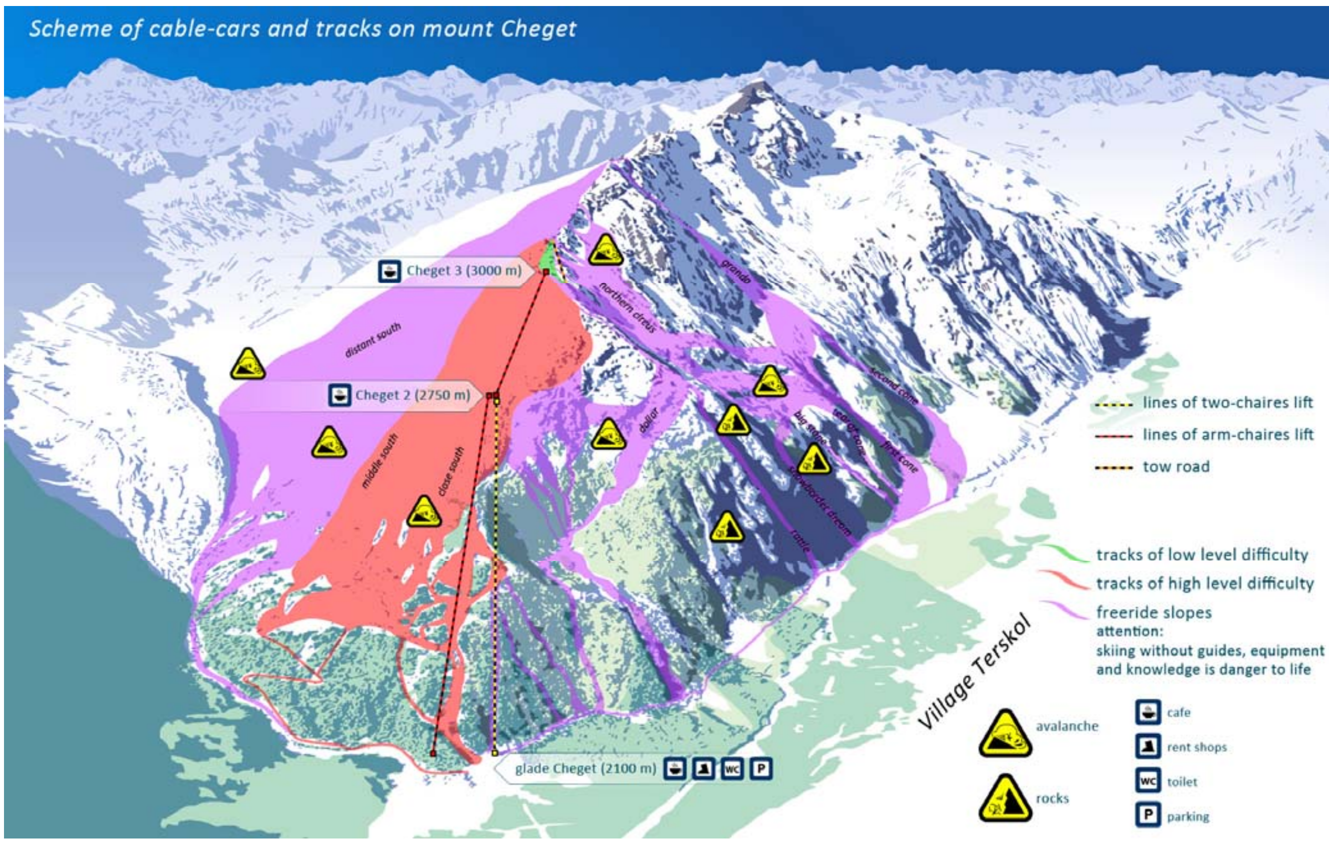
Outline/Purpose

- A review of the ν future.
- Won't tell you anything you don't know
- I'll give some opinions on how neutrino physics will develop.
- Ideally provoke some discussions during coffee breaks



Pontecorvo, Shapiro, Cheget



ν particles - 21[st] century

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin =1/2

Flavor	Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	$(0-0.13)\times10^{-9}$	0
e electron	0.000511	–1
ν_M middle neutrino*	$(0.009-0.13)\times10^{-9}$	0
μ muon	0.106	–1
ν_H heaviest neutrino*	$(0.04-0.14)\times10^{-9}$	0
τ tau	1.777	–1

Quarks spin =1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.002	2/3
d down	0.005	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	173	2/3
b bottom	4.2	–1/3

change 20th – 21st century

$\nu_e\ \nu_\mu\ \nu_\tau$ $\quad$ $\nu_1\ \nu_2\ \nu_3$

Neutrino Physics
2013

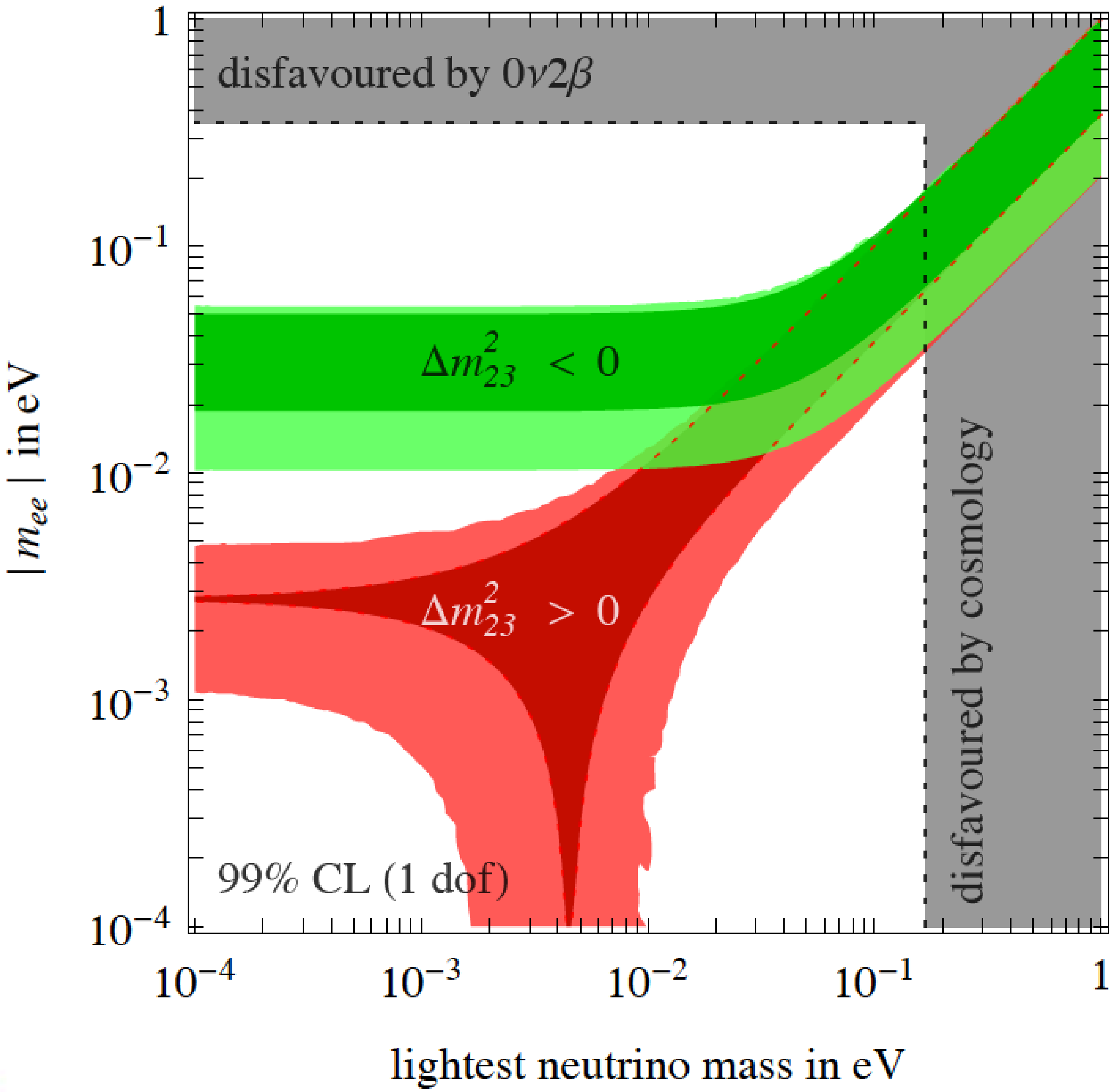
A notation issue

- θ_{12}, θ_{13}, θ_{23} are labels,
- Δm^2_{jk} are ordered (sign)
- Only 2 are independent
- We know the sign of Δm^2_{21} but not $\Delta m^2_{32} \sim \Delta m^2_{31}$

$$\Delta m^2_{12} \equiv m_1^2 - m_2^2$$
$$\Delta m^2_{21} \equiv m_2^2 - m_1^2$$
$$\Delta m^2_{13} \equiv m_1^2 - m_3^2$$
$$\Delta m^2_{31} \equiv m_3^2 - m_1^2$$
$$\Delta m^2_{23} \equiv m_2^2 - m_3^2$$
$$\Delta m^2_{32} \equiv m_3^2 - m_2^2$$

$$\Delta m^2_{21} + \Delta m^2_{32} + \Delta m^2_{13} = 0$$

Who cares?



- Either

They define

$\Delta m^2_{ij} \equiv m_j^2 - m_i^2$

opposite PDG

$\Delta m^2_{ij} \equiv m_i^2 - m_j^2$

- Or

mistake

PMNS matrix in The 3 ν paradigm

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

PDG 2013

$\sin^2(2\theta_{12}) = 0.857 \pm 0.024$

$\Delta m^2_{21} = (7.50 \pm 0.20) \times 10^{-5}\ \mathrm{eV}^2$

$\sin^2(2\theta_{23}) > 0.95$

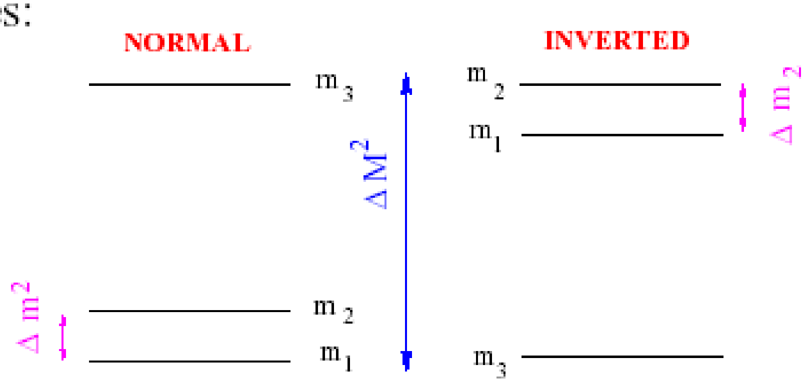
$\Delta m_{32}^2 = 2.32 + 0.08 - 0.12 \times 10^{-3}\ \mathrm{eV}^2$

$\sin^2(2\theta_{13}) = 0.098 \pm 0.013$

– U: 3 angles, 1 CP-phase + (2 Majorana phases)

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

– Two schemes:



If masses are hierarchical

$m_{heavy} = 48$ meV

$m_{light} = 9$ meV

but $\Sigma(m_\nu) < 300$ meV

1 meV (milli eV)= 10^{-3} eV

3ν paradigm

- All of these numbers are in the 3 neutrino paradigm
- In other words, they were calculated using formulae assuming that there are 3 and only 3 neutrinos, and that they interact normally
- If this isn't true, the numbers may be wrong or meaningless, or just approximations
- One way to test the paradigm, is to measure the numbers different ways

The *remaining* World Neutrino Experimental Program

- Parameter Measurement
  - θ_{23} Octant (>, < 45°)
  - Mass hierarchy
  - Mass scale
  - CP violation δ
  - Dirac or Majorana?
  - More accuracy for θ_{12}, θ_{23}, θ_{13}, Δm^2_{32}, Δm^2_{21}

Questions with answers

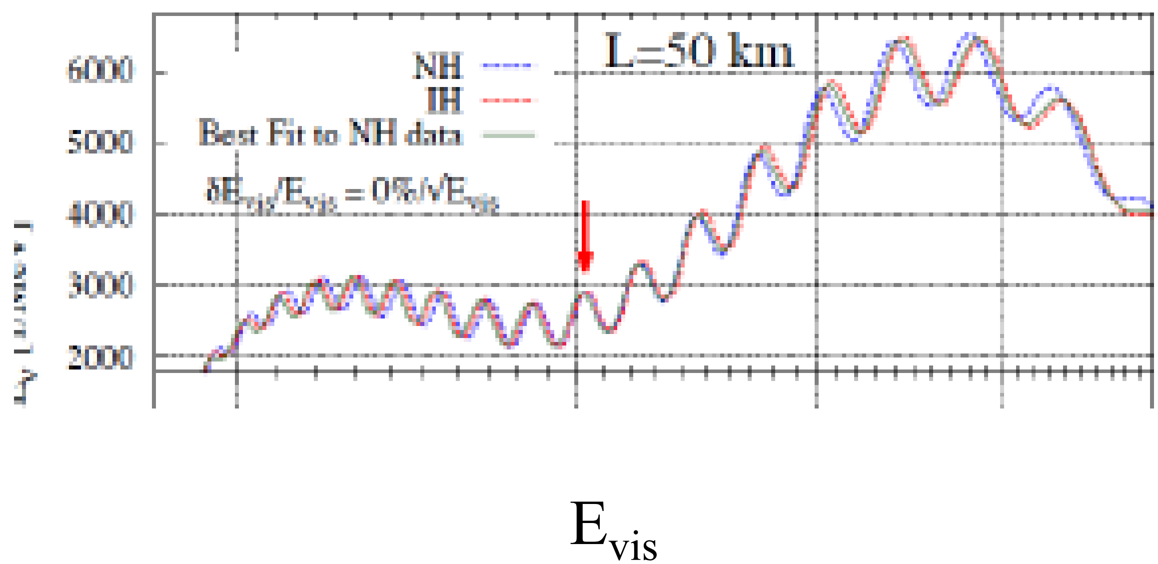
- Paradigm testing
  - Sterile neutrinos?
  - Non standard Interactions?
  - Lorentz violation?
  - CPT violation?
  - Non-Unitarity of MNS matrix?
  - velocity

Questions which might or might not have answers

How do we find the neutrino mass hierarchy

There are many ways

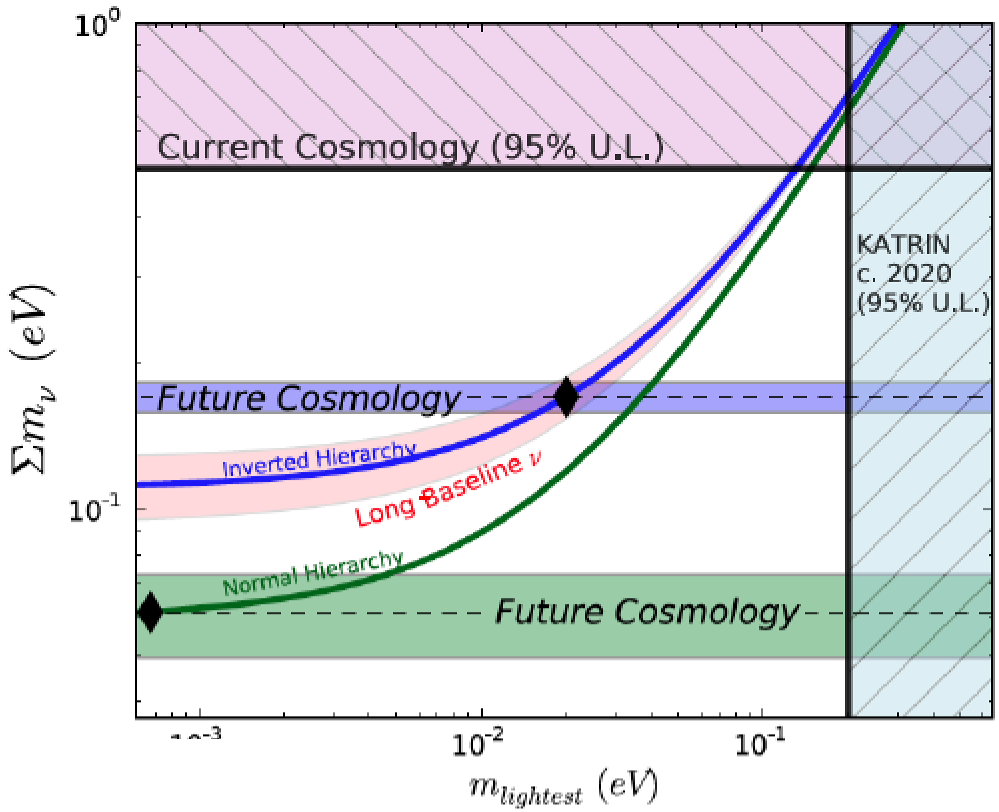
1. accurate measurements of Δm^2_{32} and Δm^2_{31}
2. reactor neutrinos
   ↳ JUNO/RENO50
   a large detector
   ~50 km from
   reactors with good
   energy resolution



Hierarchy from cosmology

3. Cosmological fits
   - ❖ $\Sigma m_\nu \geq$ 55 meV normal
   - ❖ $\Sigma m_\nu \geq$ 105 meV inverted
   - ❖ $\delta(\Sigma m_\nu)$ ~ 50 meV South Pole Telescope 2019

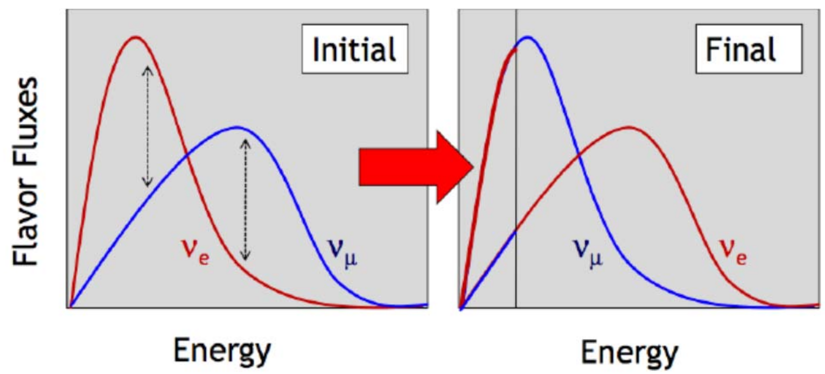
$\Sigma m_\nu <$ 300 meV Planck, March 2013



Projected Reach:
2013-2016: Σm_ν ~0.1 eV
2016-2020: Σm_ν ~ 0.06 eV
2020-2025: Σm_ν ~ 16 meV

More ways to learn the ν mass hierarchy

4. Supernova neutrinos.
   - spectrum swap:



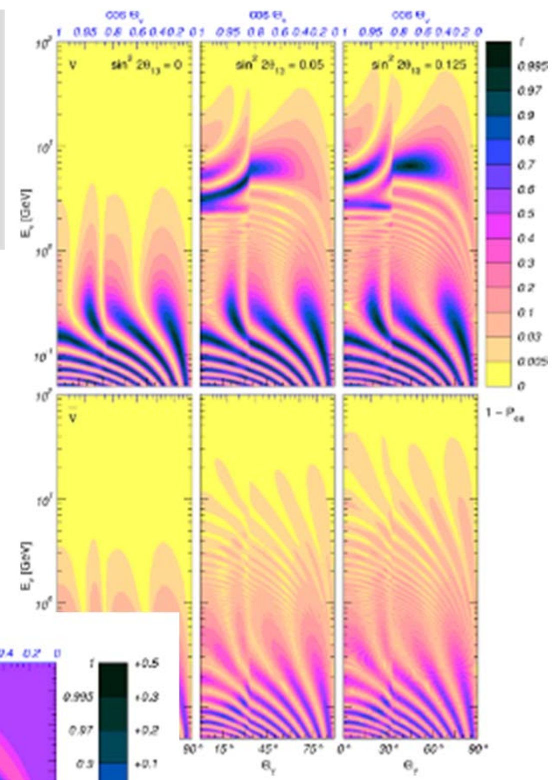
5. Atmospheric neutrino measurements
6. Long-baseline neutrino measurements

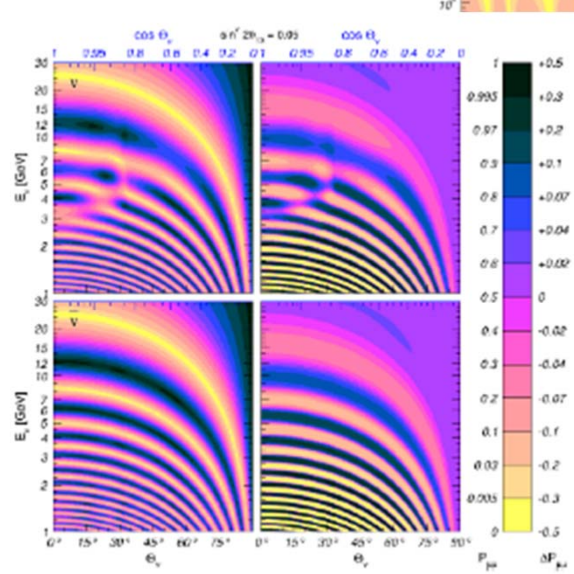
Atmospheric Neutrinos

Handles on the mass hierarchy from atmospheric neutrinos:

1. Due to enhanced matter effects in $\nu_\mu \rightarrow \nu_e$ OR $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$, the angular distribution of ν_es will differ for normal and inverted hierarchy.
2. Due to enhanced matter effects in $\nu_\mu \rightarrow \nu_e$ OR $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$, the angular distribution of the μ^+/μ^- ratio (from ν) will differ for normal and inverted hierarchy.

ν_e





ν_μ

How do we find the neutrino mass hierarchy in long-baseline experiments?

At an accelerator
$P(\nu_\mu \rightarrow \nu_e)$ (in Vacuum)

$$P(\nu_\mu \rightarrow \nu_e) = P_1 + P_2 + P_3 + P_4$$

- $P_1 = \sin^2(\theta_{23}) \sin^2(2\theta_{13}) \sin^2(1.27\, \Delta m_{31}^2\, L/E)$
- $P_2 = \cos^2(\theta_{23}) \sin^2(2\theta_{12}) \sin^2(1.27\, \Delta m_{21}^2\, L/E)$
- $P_3 = \ -/+\ J \sin(\delta) \sin(1.27\, \Delta m_{31}^2\, L/E)$
- $P_4 = J \cos(\delta) \cos(1.27\, \Delta m_{31}^2\, L/E)$

where $J = \cos(\theta_{13}) \sin(2\theta_{12}) \sin(2\theta_{13}) \sin(2\theta_{23})$ x

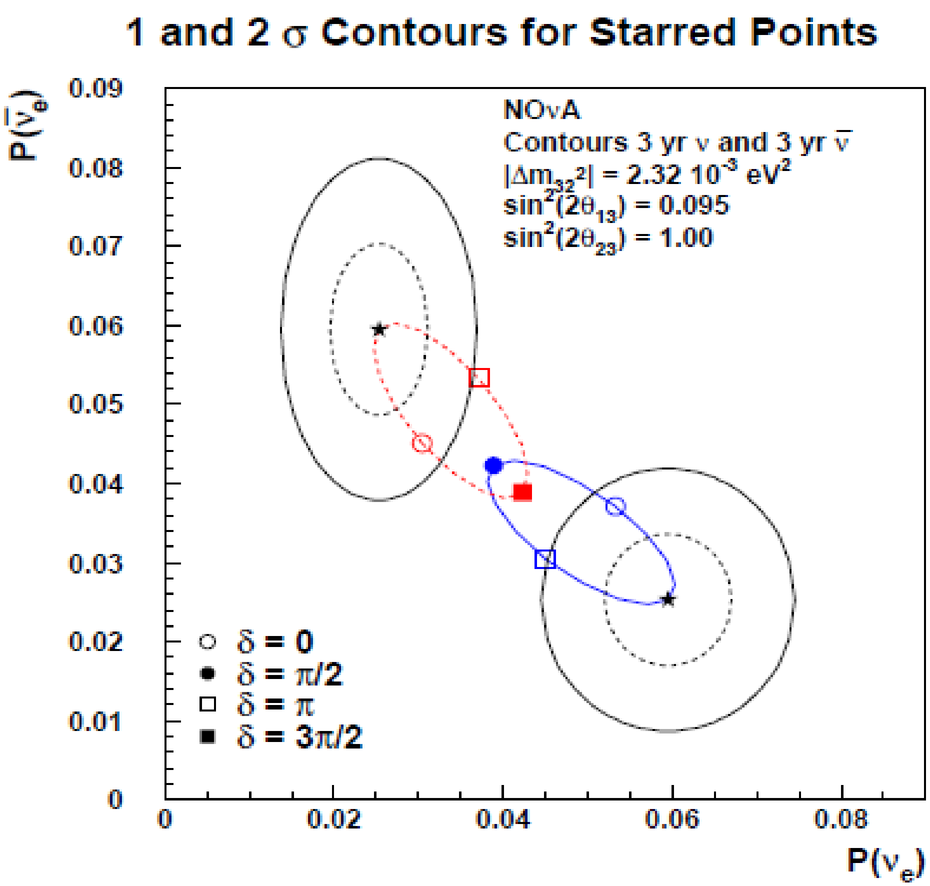
$\sin(1.27\, \Delta m_{31}^2\, L/E) \sin(1.27\, \Delta m_{21}^2\, L/E)$

Matter effects

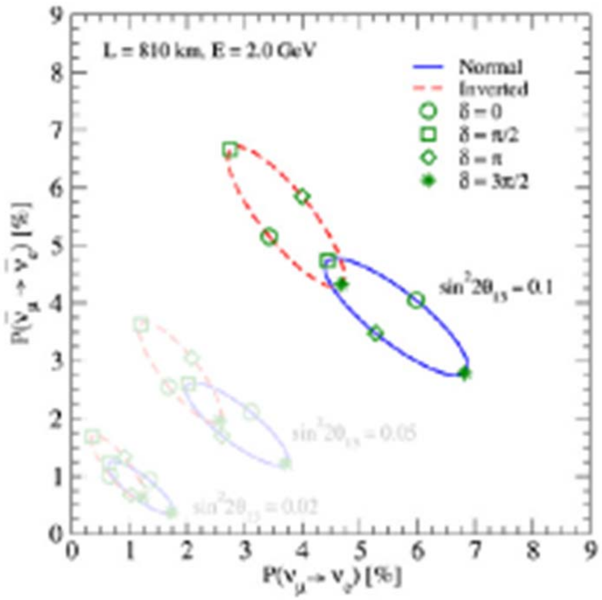
- Oscillations in matter
  - $P=P(\theta,\theta,\theta,\Delta m^2,\Delta m^2,\delta,n_e,\text{hierarchy})$

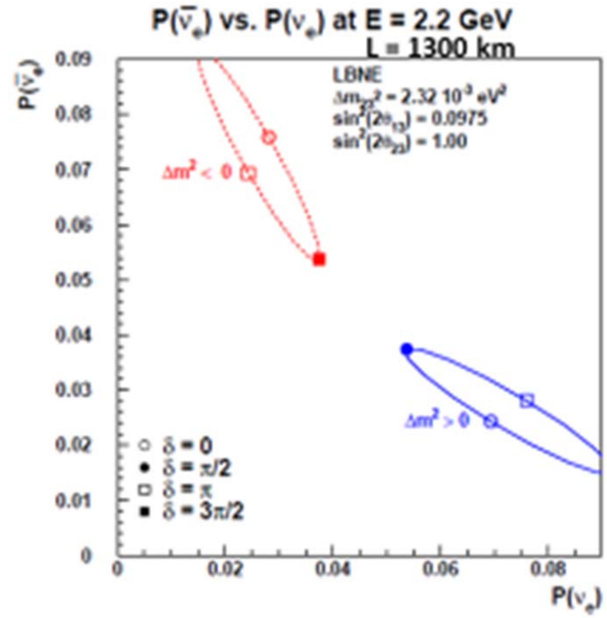
- Enhance oscillations for neutrinos in the normal hierarchy
- Enhance oscillations for antineutrinos in the inverted hierarchy

ν, $\bar{\nu}$ oscillation probabilities



More Distance

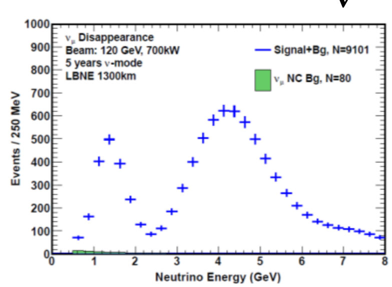




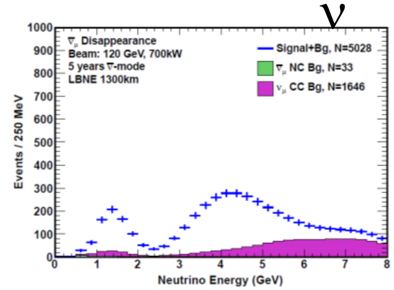
Comparison of 800 km to 1300 km

Spectra

ν



$\bar{\nu}$



Can we measure the CP parameter δ without running antineutrinos?

- Yes, we can compare

$P_{\mathbf{1}}(\theta,\theta,\theta,\Delta m^2,\Delta m^2,\delta,n_e,\text{hierarchy},\mathbf{L_1})$ & $P_{\mathbf{2}}(\theta,\theta,\theta,\Delta m^2,\Delta m^2,\delta,n_e,\text{hierarchy},\mathbf{L_2})$

- This measures δ assuming the 3 ν paradigm

  as does any measurement.

- Of course comparing oscillations for both neutrinos and antineutrinos is one of the most obvious and important paradigm tests we can do.

How do we determine if the neutrino is Dirac or Majorana?

DIRAC/MAJORANA?

- Something about a Lagrangian
- There can be Dirac terms, there can be Majorana terms
- As I understand it, if there are both Dirac and Majorana terms, the neutrino is Majorana (rewriting things)

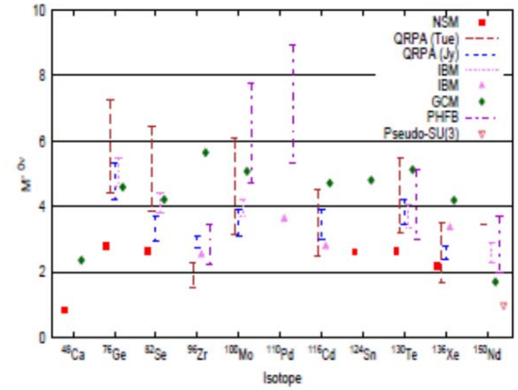
- If the neutrino is Majorana:
  - Neutrinoless double beta decay happens at predictable rates

    depends on masses, mixing angles, matrix elements
- If the neutrino is Dirac:
  - Neutrinoless double beta decay does not happen

$0\nu\beta\beta$ rates

Decay rate is given by the golden rule and depends on an effective Majorana mass. It requires knowledge of nuclear physics quantities.

M



$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu} \cdot \left|M^{0\nu}\right|^2 \cdot \langle m_{\beta\beta}\rangle^2$$

Phase space

Matrix element

$$\left\langle m_{\beta\beta} \right\rangle^2 = \left| \sum_{i=1}^{3} \eta_i \cdot U_{ei}^2 \cdot m_i \right|^2$$

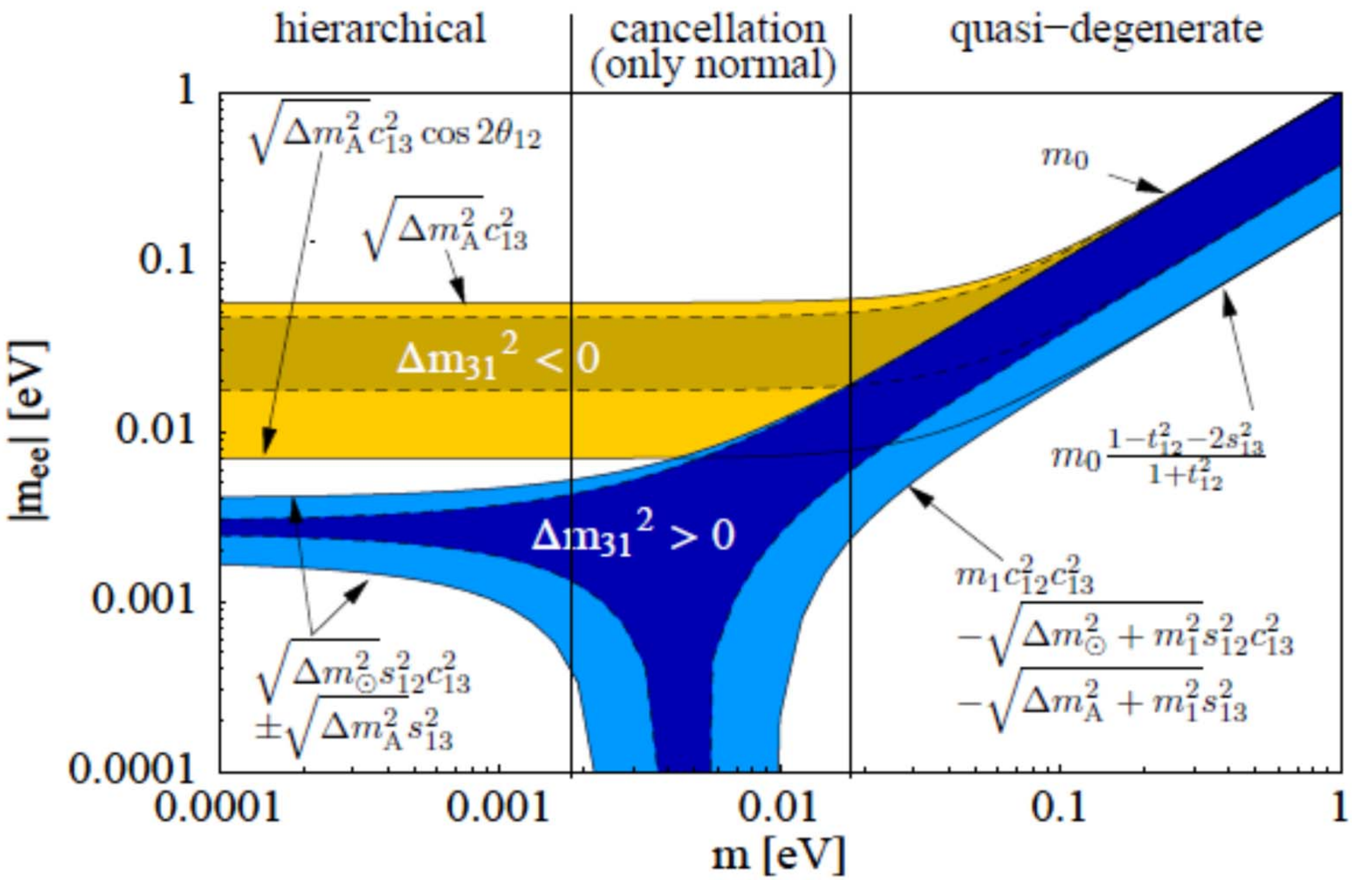
CP-phases: ±1

Elements upper row of MNS-matrix

Neutrino masses

CP-phases can lead to cancellation. But how much? Replace masses by two possible choices of minimal mass m_1 or m_3 and add knowledge of mixing and mass splitting from oscillations.

Allowed m_{ee} =$m_{\beta\beta}$ values



Discovery matrix for $0\nu\beta\beta$

	Dirac	Majorana
Normal Hierarchy	✘ NO	✘ **Not anytime soon**
Inverted Hierarchy	✘ NO	✓ Feasible

Leading factors for $0\nu\beta\beta$ and Direct mass

For the Normal mass hierarchy ($m_3 > m_2$)
and non-degenerate or hierarchical structrure ($m_2 > m_1$)

- $0\nu\beta\beta$
  - $U_{e3}^2 m_3 \pm U_{e2}^2 m_2 \pm U_{e1}^2 m_1$
  - $\pm$1.19 meV + 2.47 meV + 0
    - Dominated by m_2
- Tritium Beta Decay
  - $U_{e3}^2 m_3^2 \pm U_{e2}^2 m_2^2 \pm U_{e1}^2 m_1^2$
  - 50 meV^2 $\pm$ 21 meV^2 + 0
    - Dominated by m_3

Beyond the 3ν paradigm "anomolies"

- Sterile Neutrinos
- Lorentz Violation
- Non-Standard Interactions
- Neutrino velocity
- Non-unitary MNS matrix
- CPT violation

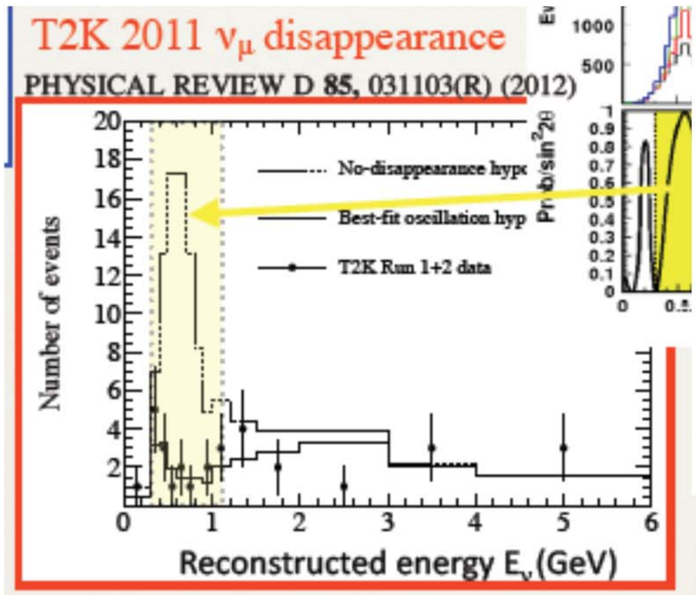
"...there are an infinite number of tests of the null hypothesis" MCG

- Sterile ν hints
  - LSND
  - MiniBooNE
  - Reactor ν anomaly
  - Chromium anomaly

"Almost any problem in a neutrino experiment can be interpreted as a sterile neutrino." MCG

The current world neutrino program

T2K

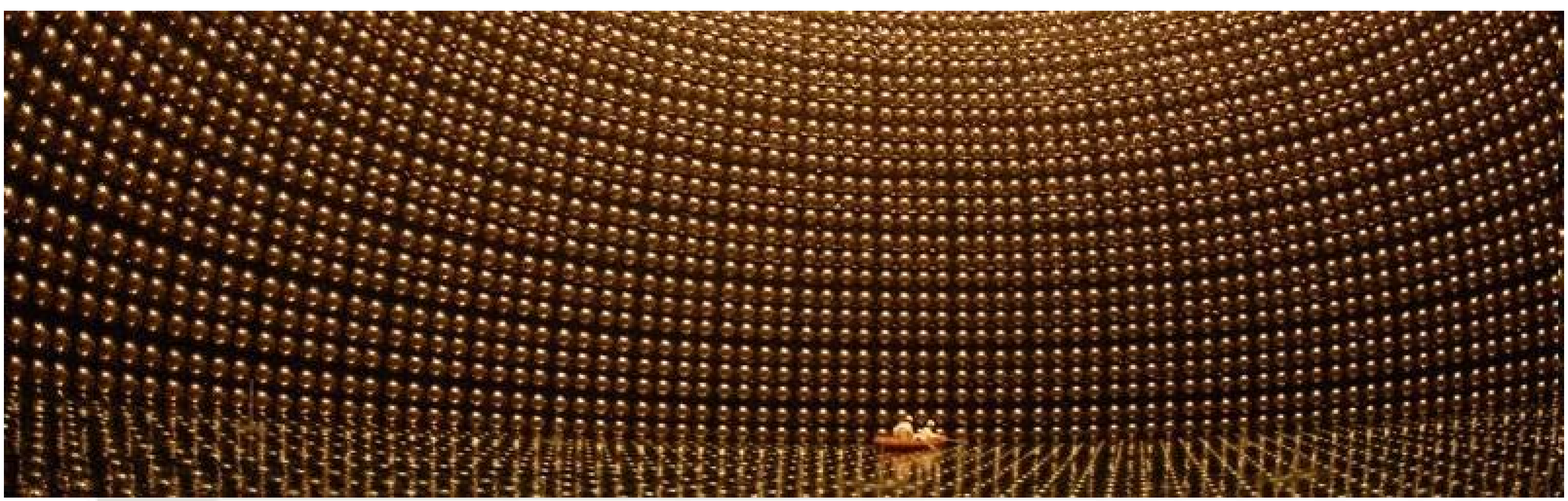


ν_e appearance

~~10~~ events so far

28!

- ~8E20 POT (2013) → ~1.2E21 POT (2014) → ~1.8E21 POT (2015)



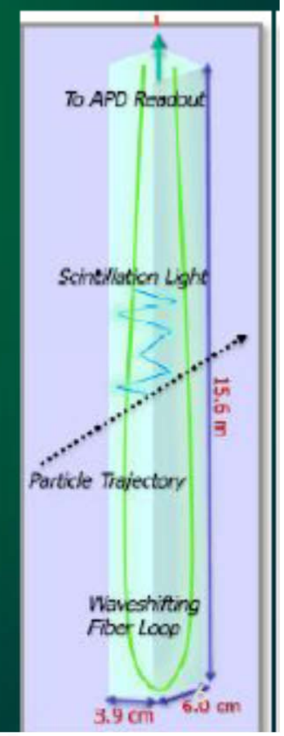
NOvA

The NOvA detectors

- 14 kton Far Detector
  - >70% active detector.
  - 360,000 detector cells read by APDs.
- 0.3 kton Near Detector
  - 18,000 cells (channels).
- Each plane just 0.15 X_0. Great for e^- vs π^0 .

32-pixel APD

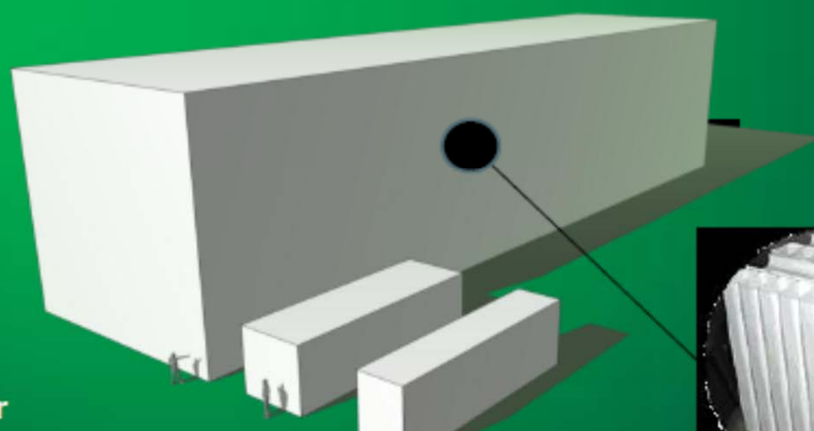
Both ends of a fiber to one pixel



Far detector
14 kton
928 planes

Near detector
0.3 kton

Prototype detecor
0.2 kton



Friday talk by Kravtsov

Other stuff

- Minerva
- NuSTORM
- Neutrino Telescopes
- MicroBooNE
- India-Based Neutrino Observatory INO

- Other Long- and Short-Baseline ideas
  ...
- Lots of ideas for Snowmass white papers
  - More NOvA
  - CHIPS
  - Lake Superior
  - GLADE
  - RADAR
  - Daedalus

Future accelerator experiments

Long-Baseline Neutrino Experiments

LBNE

LBNO

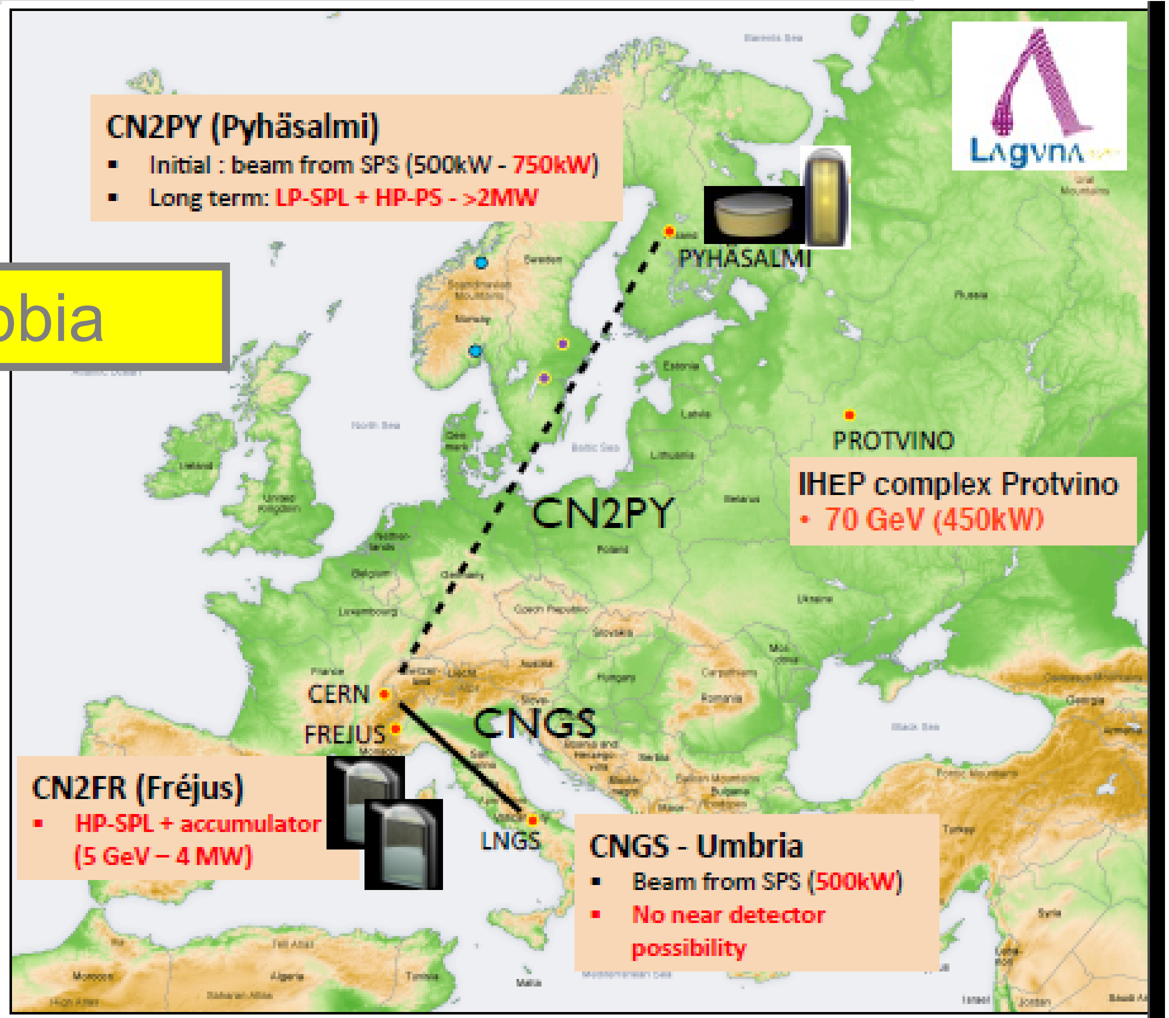
Hyper-Kamiokande

LBNE
Long-Baseline Neutrino Experiment

Talk today by Urheim

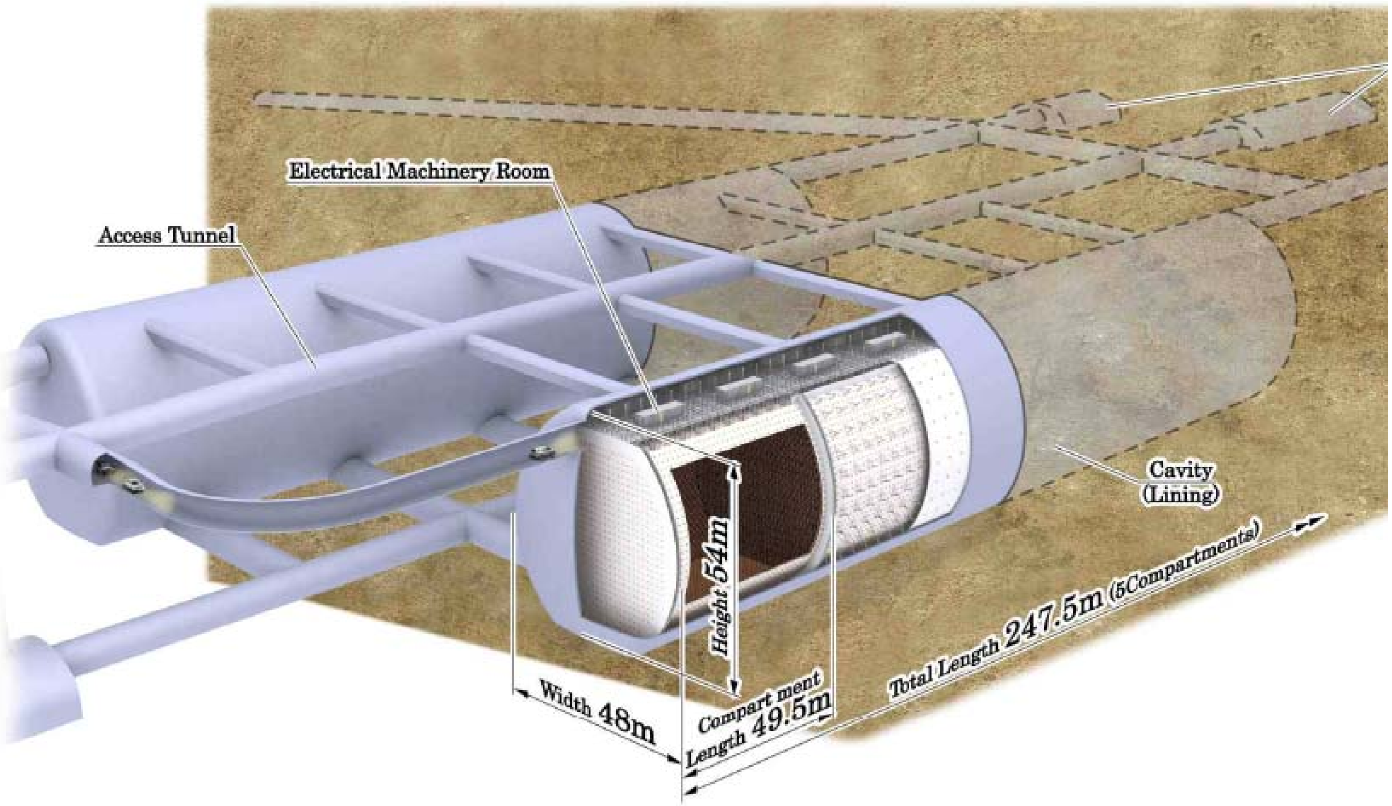
Laguna/LBNO
Long-Baseline Neutrino Oscillations

- Talk today by Rubbia



- **Detector options:** 20, 50, 100 kton LAr; 50 kton LSc and 540 kton WCD

Hyper-Kamiokande



Monday talk by Yokayama

"SNOWMASS on the Mississippi" 2013
for planning the future US program

Snowmass Summary Talks

Neutrino Oscillations

Intensity Frontier

The U.S. with the Long-Baseline Neutrino Experiment (LBNE) and a future multi-megawatt beam from Project-X is uniquely positioned to lead an international campaign to test the 3-flavor paradigm, measure CP violation and go beyond.

An underground location for a far detector significantly enhances the physics breadth & allows for the study of atmospheric ν' s, nucleon decay, & precision measurement of ν' s from a galactic supernova explosion

This is now considered phase I

- Shoutout to LBNE in summary of **Cosmic Frontier** Talk by Steve Ritz (now chair of P5)

Cosmic Frontier

On Electroweak Symmetry Breaking

The LHC has revealed that the minimum SM prescription for electroweak … the one Higgs double model — is at least approximately … at have to do with neutrinos?

Energy Frontier

1. Neutrinos talk to the Higgs boson very, very weakly (Dirac neutrinos);
2. Neutrinos talk to a different Higgs boson – there is a new source of electroweak symmetry breaking … neutrinos);

Beautiful NOvA and LBNE programs might very well influence the Higgs Program.

- While there are several paths to the mass hierarchy, only the long-baseline accelerator experiments, and to a lesser extent the atmospheric neutrino experiments, are sensitive to the CP δ parameter
- One or more of these experiment will be starting around 2020.

Theory comment I

Challenge for our theorists here

- We will soon measure the hierarchy.
- Quarks and charged leptons have what we would call a normal hierarchy.
- If we measure the inverted hierarchy, would that be:
  - New?
  - Surprising?
  - Tell us something qualitative about the nature of neutrinos?
- or;
  - Would it just rule out half of a semi-infinite number of models?

Statistics Rant

- A standard criterion for a discovery (but a wrong one in my opinion) is 5 σ.

Physicists can set up an experiment and do an a-priori test of a hypothesis. When we see an unexpected result, we can calculate an a-posteriori probability for that result.

  - The probability calculations we do in these two cases are *identical*
  - The meaning is *totally different*

For measurements, the PDG quotes $\pm 1\sigma$. The mass hierarchy determination, in my opinion, is a measurement, not a discovery. When we know it with 99% CL, I won't think another long expensive experiment is important.

When we measure θ_{13}, m_H, $B(B^+ \rightarrow \text{anything})$, ... we often want to measure them better. When we measure the mass hierarchy, there is nothing to measure better.

Theory comment II

- We rely on theoretical motivation for experiments more than we are willing to admit.
- We may not have a theoretical prediction for something that we are trying to measure, but we always have a theoretical context.
- Bethe told us mixing angles were small. He was wrong, but
- Pontecorvo gave us

$$P = \sin^2(2\theta)\,\sin^2(1.27\Delta m^2 L/E)$$

and it has served us well for over 50 years.

As our field to moves to fewer more expensive and longer experiments, I would like the theoretical community to play a more active role in helping us make the tough choices. "Do everything" will not be the answer.

2020

My guess by 2020

- Parameter Measurement
  - θ_{23} Octant (>, < 45°) ✓
  - Mass hierarchy ✓
  - Mass scale ✓
  - CP violation δ ±60°
  - Dirac or Majorana? not yet
  - More accuracy for θ_{12}, θ_{23}, θ_{13}, Δm^2_{32}, Δm^2_{21} ✓

Questions with answers

- Paradigm testing
  - Sterile neutrinos?
  - Non standard Interactions?
  - Lorentz violation?
  - CPT violation?
  - Non-Unitarity of MNS matrix?
  - velocity

Questions which might or might not have answers

The program in 2020

- Parameter Measurement
  -
  -
  -
  - CP violation δ $\pm\sim 60° \rightarrow \pm\sim 20°$ in LBNE/LBNO/HyperK
  - Dirac or Majorana? **will be determinable if inverted hierarchy**
  - More accuracy for θ_{12}, θ_{23}, θ_{13}, Δm^2_{32}, Δm^2_{21} **even better**

Questions with answers

In 2020, Maybe

- We'll know these parameters with no paradigm shifts, but theoretically we'll be where we are now; then
  - ➲ I see no strong argument for a new or continued $B scale program.
- Or there will be strong theoretical progress an we'll want to know parameters even better, then
  - ➲ We'll press on with better larger long-baseline experiments.
- Or something outside the 3ν paradigm shows up, then
  - ➲ We'll need new experiments, but don't know what those might be.

Intelligent Design of Neutrino Parameters?

(from S. Wojcicki)

- The optimum choice for Δm^2_{21}?

Such as to give resonant transition (MSW effect) in the middle of solar energy spectrum -, $\Delta m^2_{21} = 8.2 \times 10^{-5}$ eV^2

- The optimum choice for $\sin\theta_{12}$?

Big enough for oscillations to be seen in KamLAND - ~0.8

- The optimum choice for Δm^2_{32}?

Such as to give full oscillation in the middle of the range of possible distances that atmospheric ν's travel to get to the detector - $\Delta m^2_{32} = 2.3 \times 10^{-3}$ eV^2

- The optimum choice for $\sin\theta_{23}$?

Big enough so that oscillations could be seen easily - $\theta_{23} \sim \pi/4$

- The optimum choice for $\sin\theta_{13}$?

Small enough so as not to confuse interpretation of the above - $\theta_{13} < 10^0$

- **But the acid test - will θ_{13} be big enough to see CP violation and determine mass hierarchy?**

In 2020

- Suppose parameters are such that the "Intelligent Design" arguments can get longer?
  - $\delta \sim \pi/2$
    - to most quickly determines the hierarchy
    - to get large CP violation & answer the CP violation question
  - The inverted hierarchy, so we can tell Dirac/Majorana & maybe beta decay endpoint
  - Majorana, which seems to be more interesting so that some of our theorists will be happy (seesaw, etc.)

Conclusion

- Neutrino Physics is currently in an excellent position:
  - Much recent progress
  - Questions that have answers
  - Many will be answered in the next decade
  - We'll have a program of long-baseline accelerator experiments and $0\nu\beta\beta$ decay that can answer the remaining ν questions of 2020.

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- Free monthly neutrino rumor newsletter sent to 1900--~100 lines, send "subscribe" to maury.goodman@anl.gov or see http://www.hep.anl.gov/ndk/longbnews/
  - Newsletter will continue till at least 2020
    - it started in 1992
- Neutrino Oscillation Industry Web Page http://www.neutrinooscillation.org/