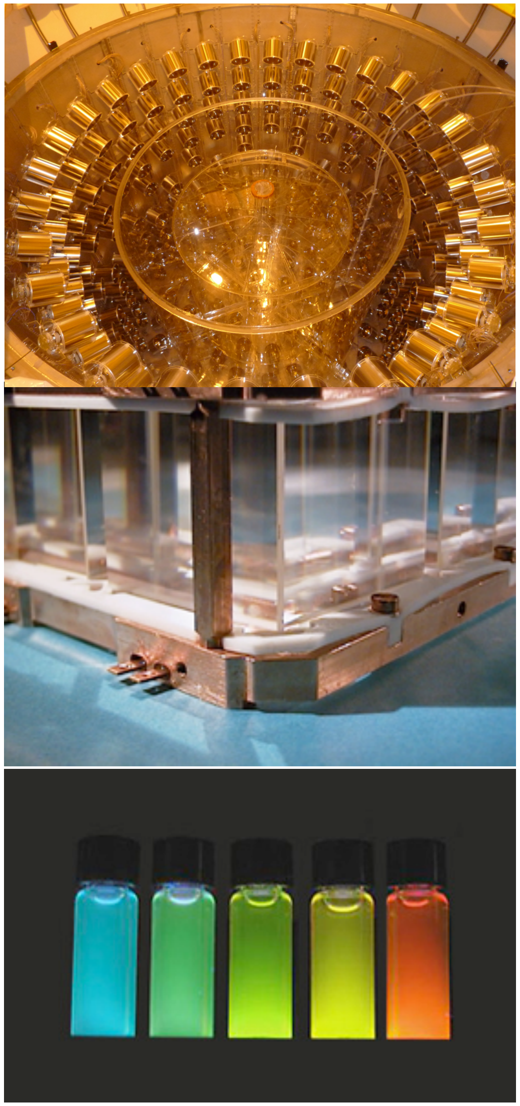
reVolution



Neutrino Oscillation and Beyond

Lindley Winslow
Massachusetts Institute of Technology

Past: Neutrinos have mass.

On the Verge: θ_{13} is Large!

Next: Neutrinos are Majorana?

Revolution

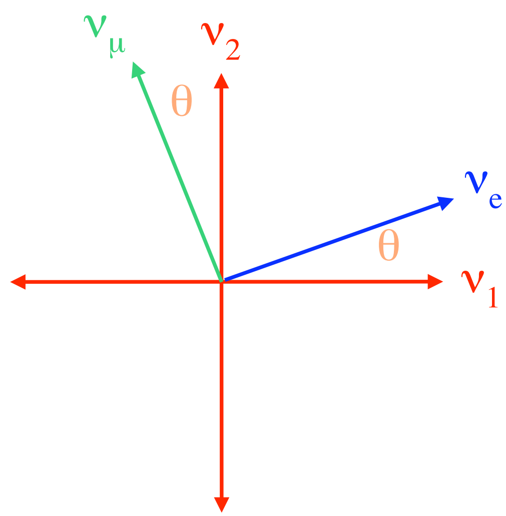
Pronunciation: /ˌrevəˈluːʃ(ə)n/

Fundamental change in the way of
thinking about or visualizing something.

Neutrinos have mass!

Remember:
When I started graduate school neutrinos were believed to be massless.

Let's hypothesize that neutrinos have tiny masses and some flavor mixing:



For Two Neutrinos....

flavor mass

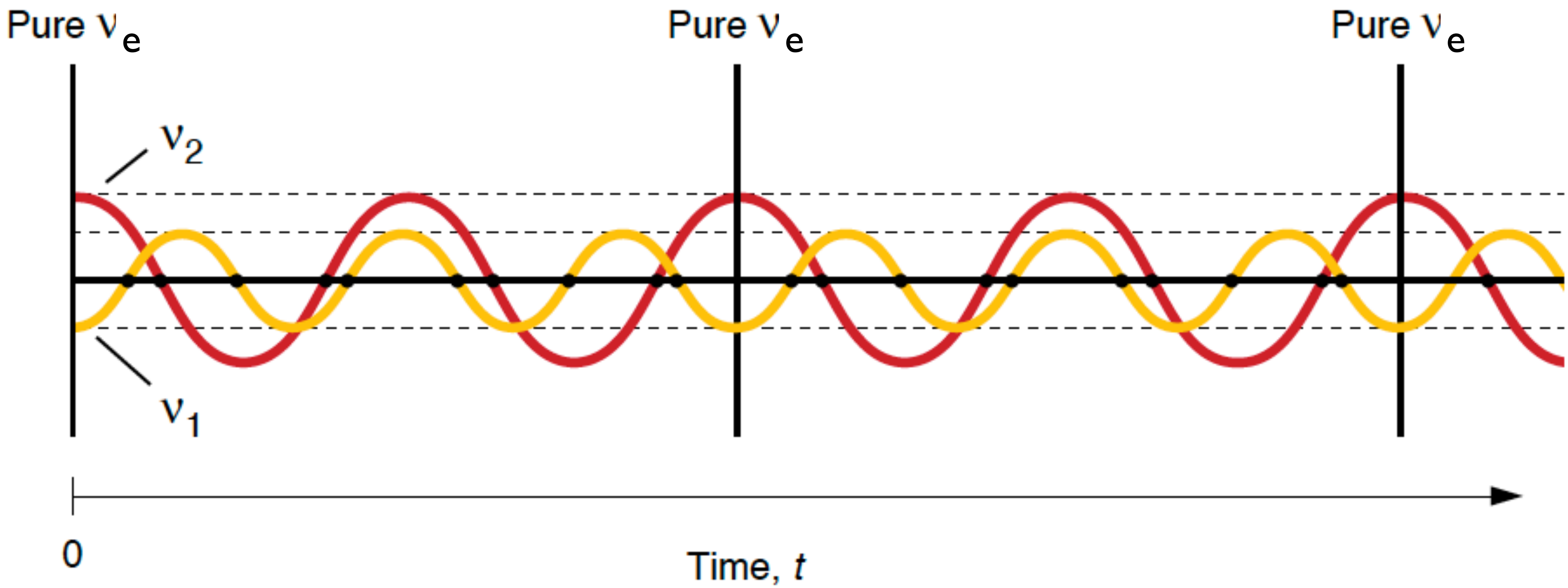
$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

The mixing of the states is expressed by a rotation matrix.

$$|\nu_e\rangle = \cos\theta\,|\nu_1\rangle + \sin\theta\,|\nu_2\rangle$$

$$|\nu_\mu\rangle = -\sin\theta\,|\nu_1\rangle + \cos\theta\,|\nu_2\rangle$$

Neutrinos are produced and detected via their flavor states...



From Celebrating the Neutrino, LANL

but it's their mass states that propagate through space...

Neutrino Oscillation

$$P_{osc} = \sin^2 2\theta \sin^2 \left(\frac{1.27 \Delta m^2 L}{E} \right)$$

Neutrino Oscillation

$$P_{osc} = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$

↑

The Mixing Angle determines the amplitude.

Neutrino Oscillation

$$P_{osc} = \sin^2 2\theta \sin^2 \left(\frac{1.27 \Delta m^2 L}{E} \right)$$

Distance between your source and detector.
Units are km.

Neutrino Oscillation

$$P_{osc} = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$

Energy of the neutrinos
Units are GeV

Neutrino Oscillation

$$P_{osc} = \sin^2 2\theta \sin^2 \left(\frac{1.27 \Delta m^2 L}{E} \right)$$

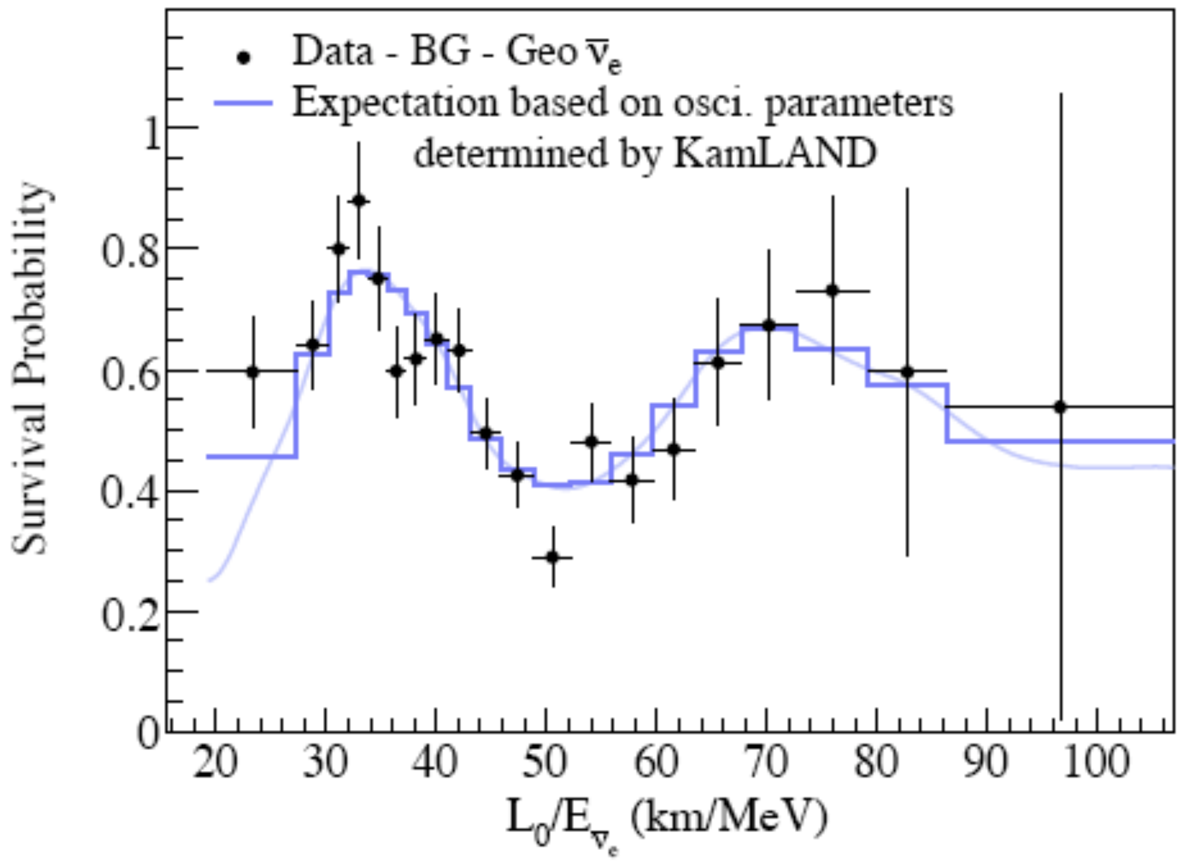
Mass Squared Difference

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

Units are eV^2

KamLAND Data:

$$P_{survival} = 1 - \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$



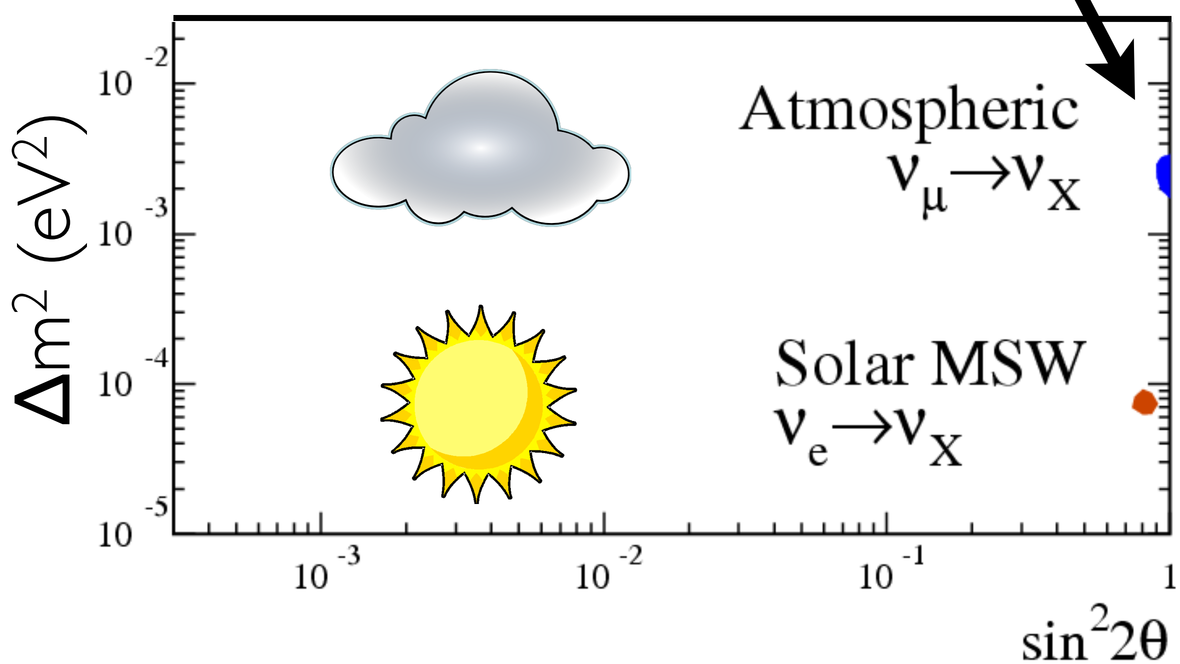
"Solar" (because solar ν experiments saw it first)

Δm^2=7.5x10^{-5} eV^2

Results > 5 sigma in 2001

$>$ 5 sigma **NOW!**

Look how tiny!



reVolution

You say you want a revolution
Well, you know
we all want to change the world.

Revolution

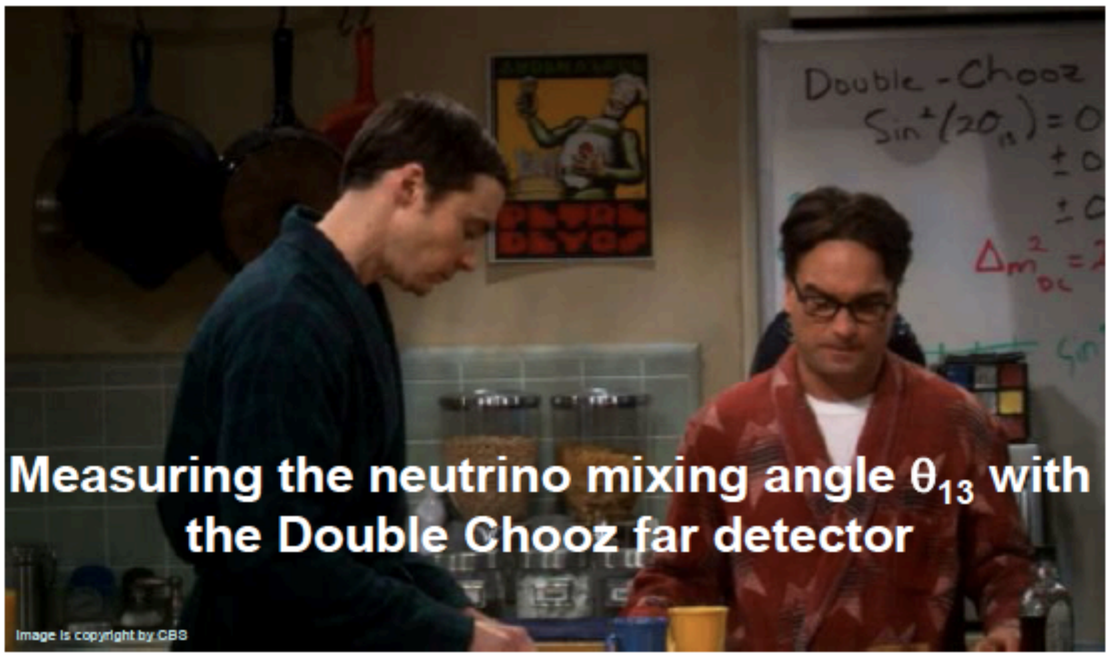
Pronunciation: /ˌrevəˈluːʃ(ə)n/

A change in daily life especially related to technology.

θ_{13} is Large!

In January:

Igor presented to you the first results from Double Chooz,



Igor Ostrovskiy

1

From November:

The first results from Double Chooz found,

$\sin^2 2\theta_{13} = 0.08 \pm 0.04$ (stat) ± 0.03 (sys).

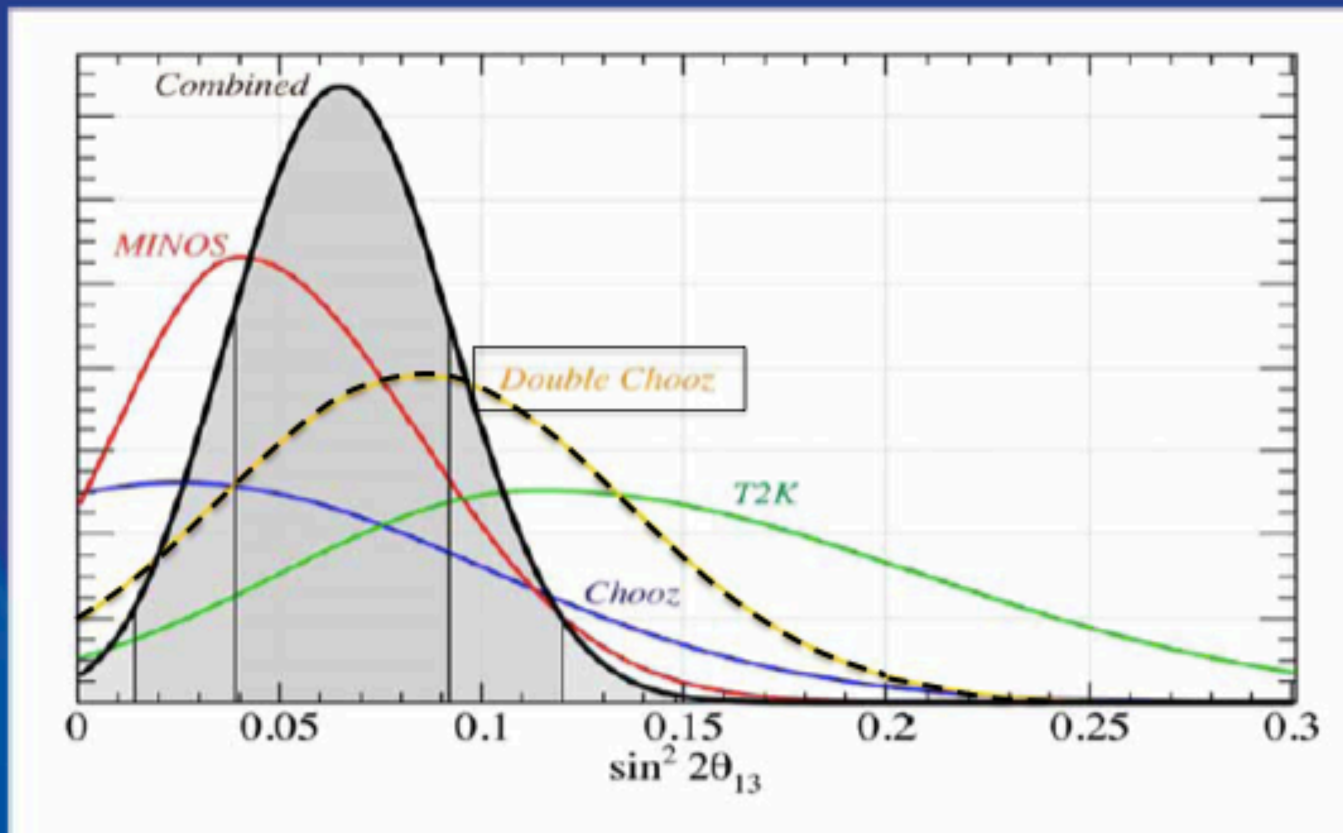
This is not significant by itself...

Why do I think we are on the verge of a technical revolution?

Because of what it brings to the global fits.

From Pier Oddone's LBNE Presentation two weeks ago

The gate is likely open: $\sin^2 2\theta_{13} > 0$



Current knowledge of $\sin^2 2\theta_{13}$ from T2K, MINOS and Double Chooz. Current reactor experiments like Daya Bay, T2K and NOvA will measure $\sin^2 2\theta_{13}$ for all values > 0.01

From November:

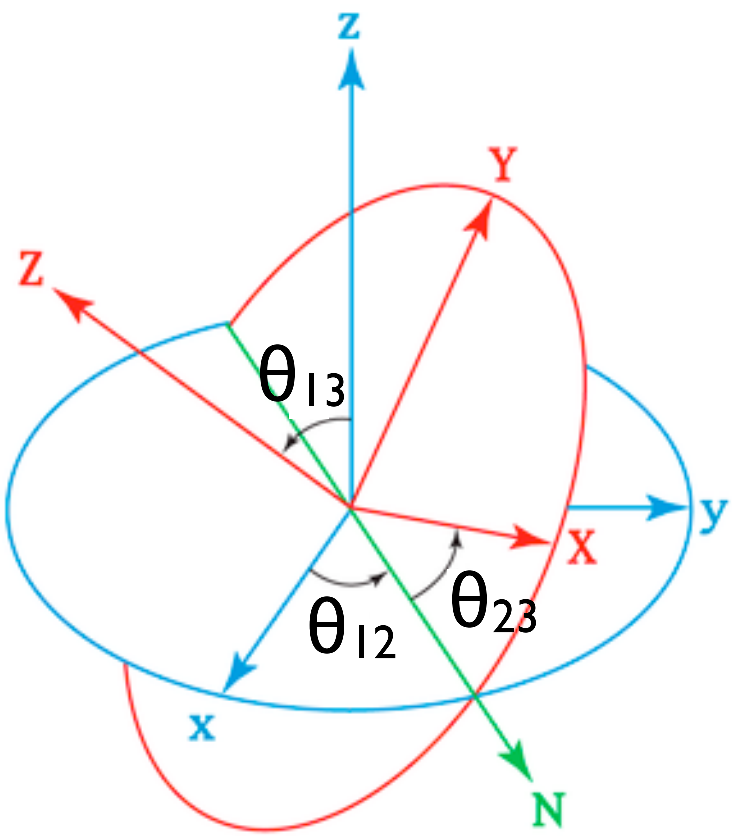
The first results from Double Chooz found,

$\sin^2 2\theta_{13} = 0.08 \pm 0.04\ (\text{stat}) \pm 0.03\ (\text{sys})$.

This is not significant by itself...
Why do I think we are on the verge of a technical revolution?

Because of what it brings to the global fits.

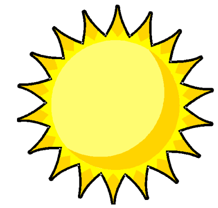
I. What we used to think.
II. The measurement from Double Chooz.
III. The global view and future directions.



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Three neutrino mixing will be defined by three mixing angles and two independent mass differences.

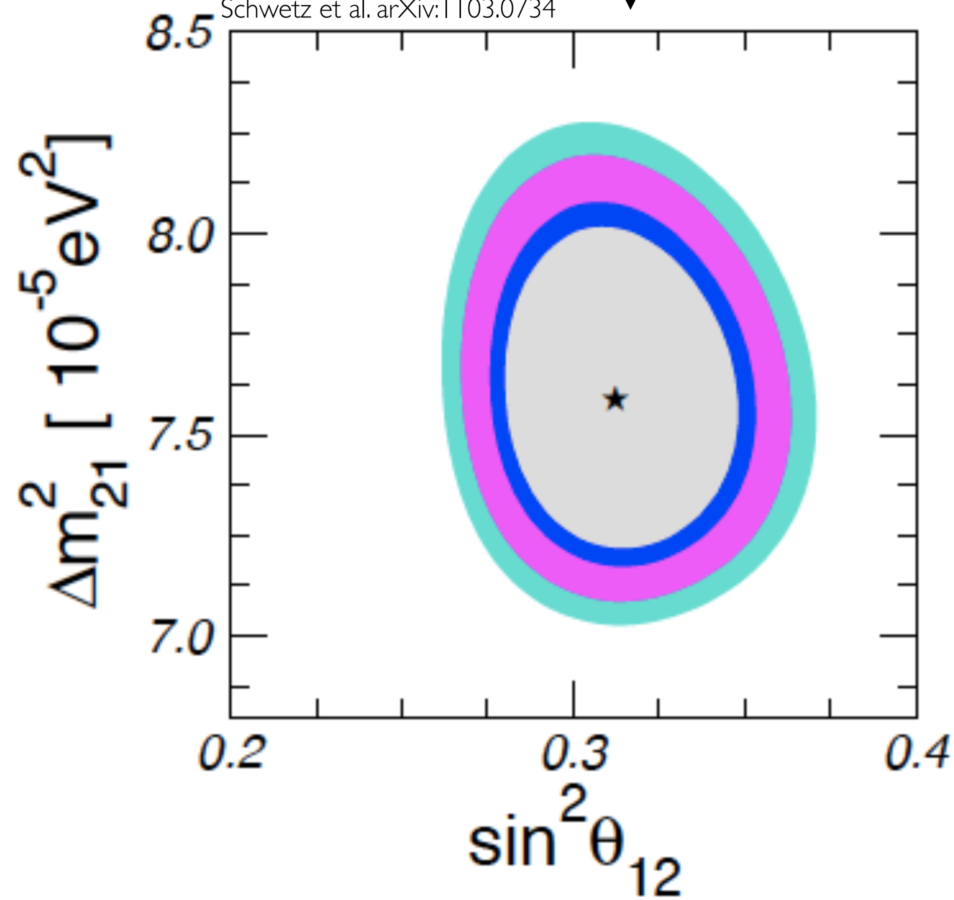
$$U_{\alpha j} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c\theta_{23} & s\theta_{23} \\ 0 & -s\theta_{23} & c\theta_{23} \end{pmatrix} \begin{pmatrix} c\theta_{13} & 0 & s\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s\theta_{13}e^{i\delta} & 0 & c\theta_{13} \end{pmatrix} \begin{pmatrix} c\theta_{12} & s\theta_{12} & 0 \\ -s\theta_{12} & c\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$



Solar/KamLAND

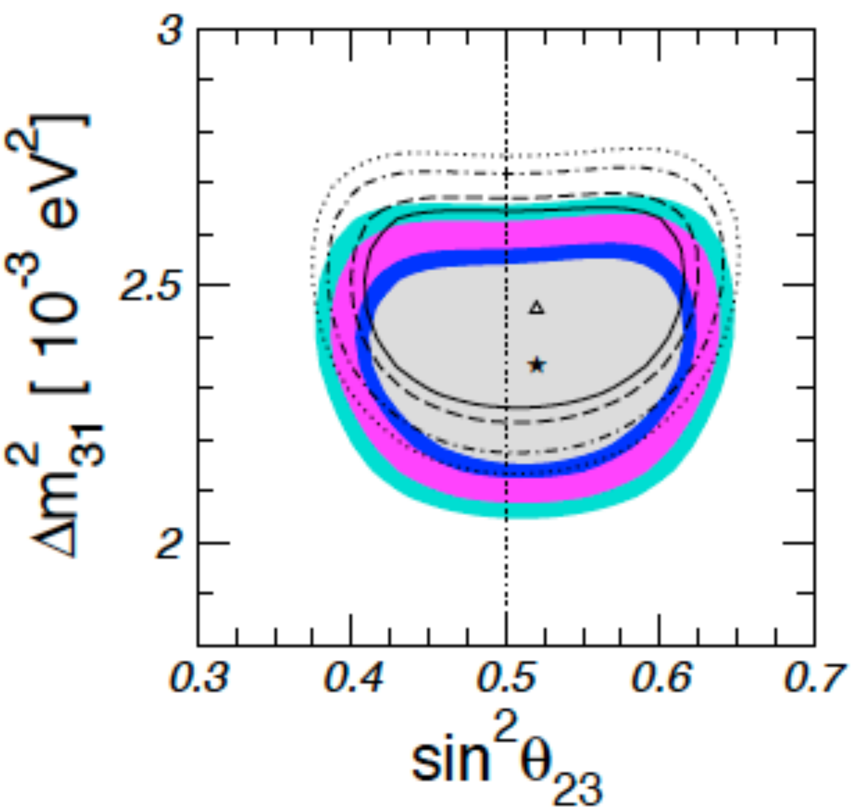
Here is the mixing and Δm^2 which is measured by the Solar neutrino experiments and KamLAND.

Schwetz et al. arXiv:1103.0734



$$U_{\alpha j} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c\theta_{23} & s\theta_{23} \\ 0 & -s\theta_{23} & c\theta_{23} \end{pmatrix} \begin{pmatrix} c\theta_{13} & 0 & s\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s\theta_{13}e^{i\delta} & 0 & c\theta_{13} \end{pmatrix} \begin{pmatrix} c\theta_{12} & s\theta_{12} & 0 \\ -s\theta_{12} & c\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Schwetz et al. arXiv:1103.0734



Atmospheric/Accelerator

This mixing and Δm^2 which is measured by the Accelerator experiments like MINOS/T2K and Super-K's atmospheric neutrino measurements.

$$U_{\alpha j} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c\theta_{23} & s\theta_{23} \\ 0 & -s\theta_{23} & c\theta_{23} \end{pmatrix} \begin{pmatrix} c\theta_{13} & 0 & s\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s\theta_{13}e^{i\delta} & 0 & c\theta_{13} \end{pmatrix} \begin{pmatrix} c\theta_{12} & s\theta_{12} & 0 \\ -s\theta_{12} & c\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

↓

?

Everyone is excited by **δ** the CP violating phase.

What is CP Violation?

$$P(a \rightarrow b) \neq P(\bar{a} \rightarrow \bar{b})$$

or

$$P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$$

If observed this would be a revolution.

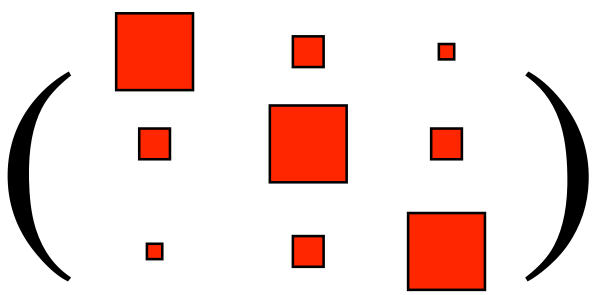
$$U_{\alpha j} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c\theta_{23} & s\theta_{23} \\ 0 & -s\theta_{23} & c\theta_{23} \end{pmatrix} \begin{pmatrix} c\theta_{13} & 0 & s\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s\theta_{13}e^{i\delta} & 0 & c\theta_{13} \end{pmatrix} \begin{pmatrix} c\theta_{12} & s\theta_{12} & 0 \\ -s\theta_{12} & c\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$\downarrow$$

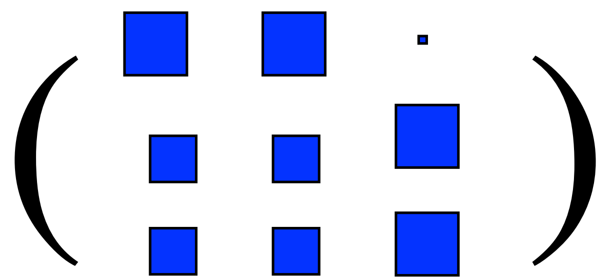
?

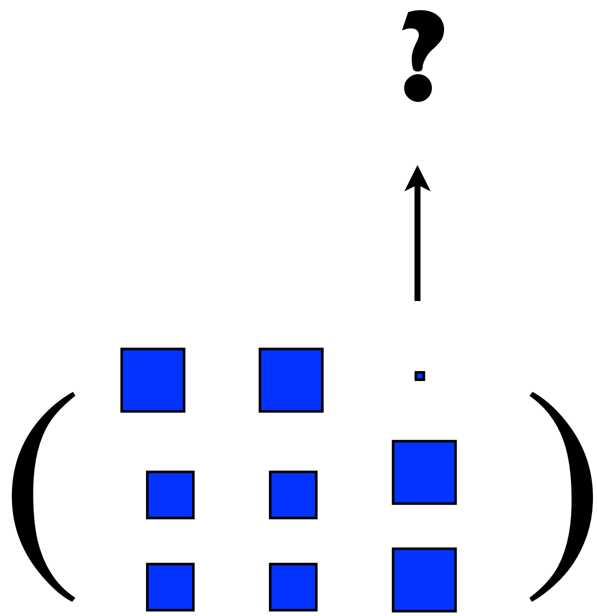
But I would argue the last mixing angle is interesting all in itself.

This is Quark Mixing



This is Neutrino Mixing





It is a fundamental parameter that contributes to many calculations involving electron neutrinos.

Theory favors small $\sin^2 2\theta_{13}$:

Theory	Order of Magnitude Prediction
L_e-L_μ-L_τ	0.00001
SO(3)	0.00001
S3 and S4	0.001
A4 Tetrahedral	0.001
Texture Zero	0.001
RH Dominance	0.01
SO(10) with Sym/Antisym Contributions	0.01
SO(10) with lopsided masses	0.1

Model Review by Albright et. al. ArXiv:0803.4176

Neutrino Factory Dreams (line drawn below SO(3))

Modern Design (line drawn below Texture Zero)

It looks like we are here! (line drawn below SO(10) with Sym/Antisym Contributions)

The most talked about beam designs:

Beta Beams

Super Beams

Neutrino Factories

- These are particularly needed if θ_{13} is small.
- These are **enormous** investments.
- We may still want one but they are not critical.


It’s Chooz Time!

arXiv:1112.6353
Submitted to PRL

Double Chooz Collaboration!

Brazil
CBPF
UNICAMP
UFABC

France
APC
CEA/DSM/IRFU:
- SPP
- SPhN
- SEDI
- SIS
- SENAC

CNRS/IN2P3:
- Subatech
- IPHC

ULB/VUB

Germany
EKU Tübingen
MPIK Heidelberg
RWTH Aachen
TU München
U. Hamburg

Japan
Tohoku U.
Tokyo Inst. Tech.
Tokyo Metro. U.
Niigata U.
Kobe U.
Tohoku Gakuin U.
Hiroshima Inst Tech.

Russia
INR RAS
IPC RAS
RRC Kurchatov

Spain
CIEMAT-Madrid

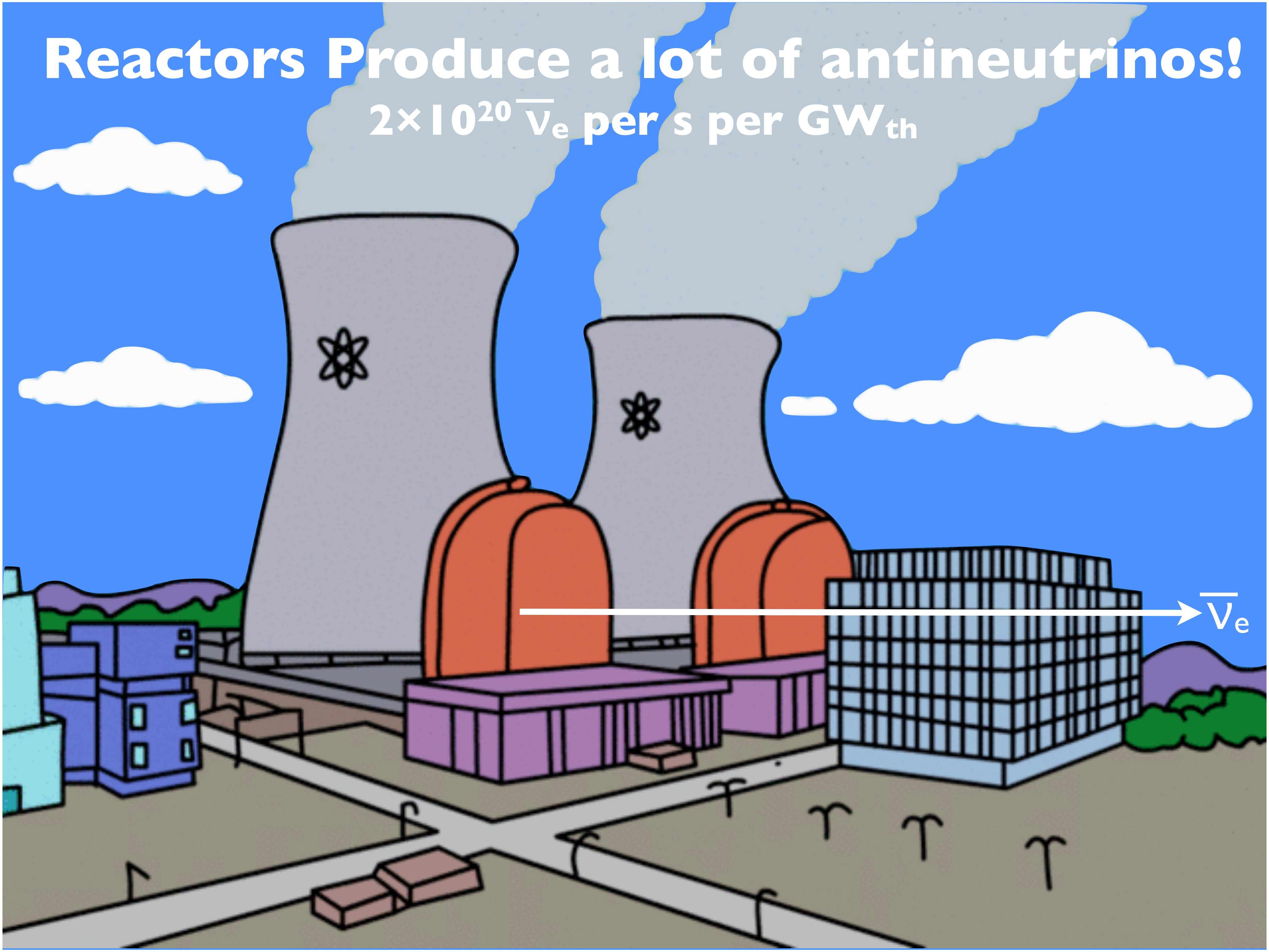
UK
Sussex

USA
U. Alabama
ANL
U. Chicago
Columbia U.
UCDavis
Drexel U.
IIT
KSU
LLNL
MIT
U. Notre Dame
Sandia National Laboratories
U. Tennessee

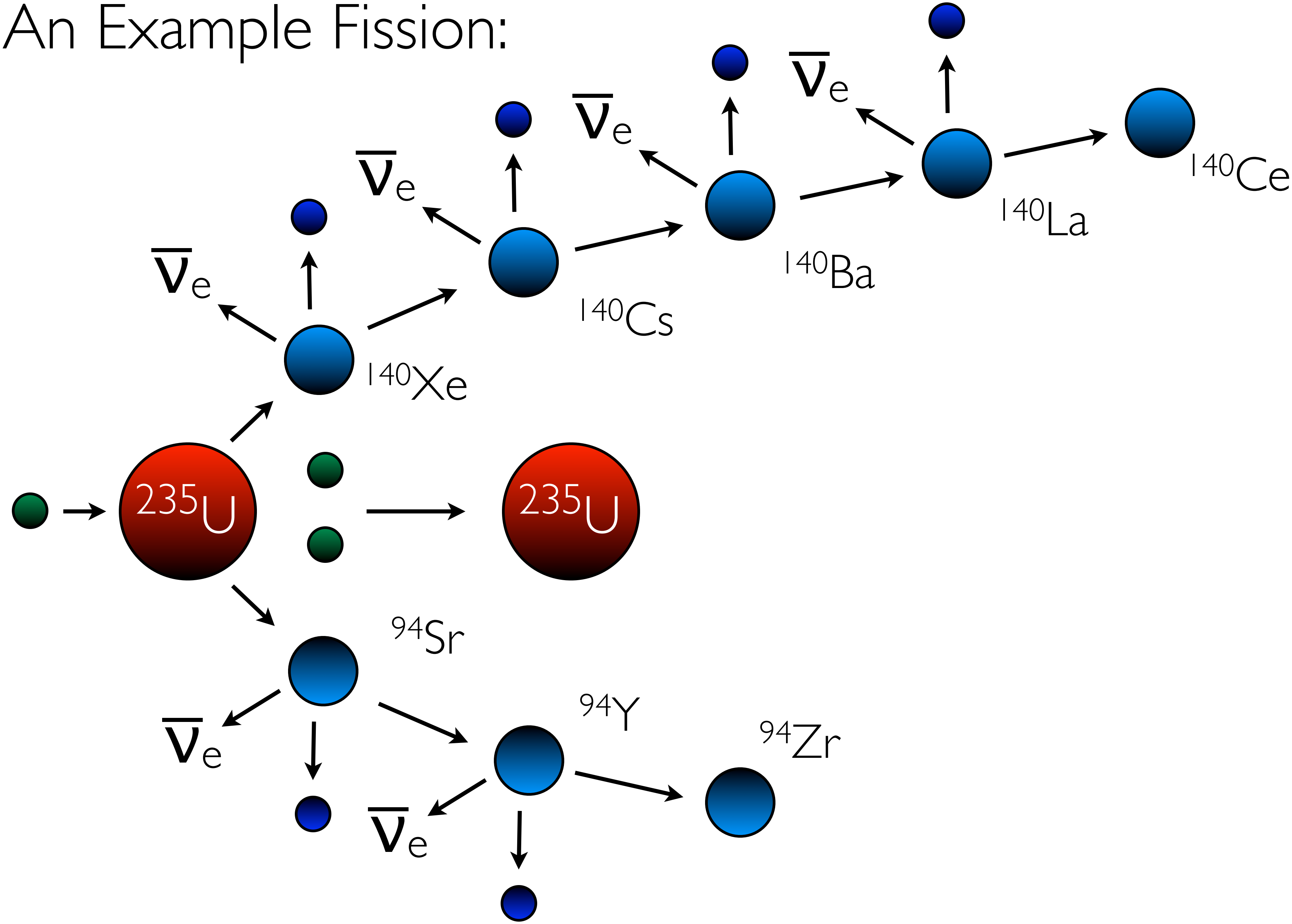
Spokesperson: H. de Kerret (IN2P3)
Project Manager: Ch. Veyssière (CEA-Saclay)

Web Site: www.doublechooz.org/

Double Chooz is an antineutrino disappearance experiment.

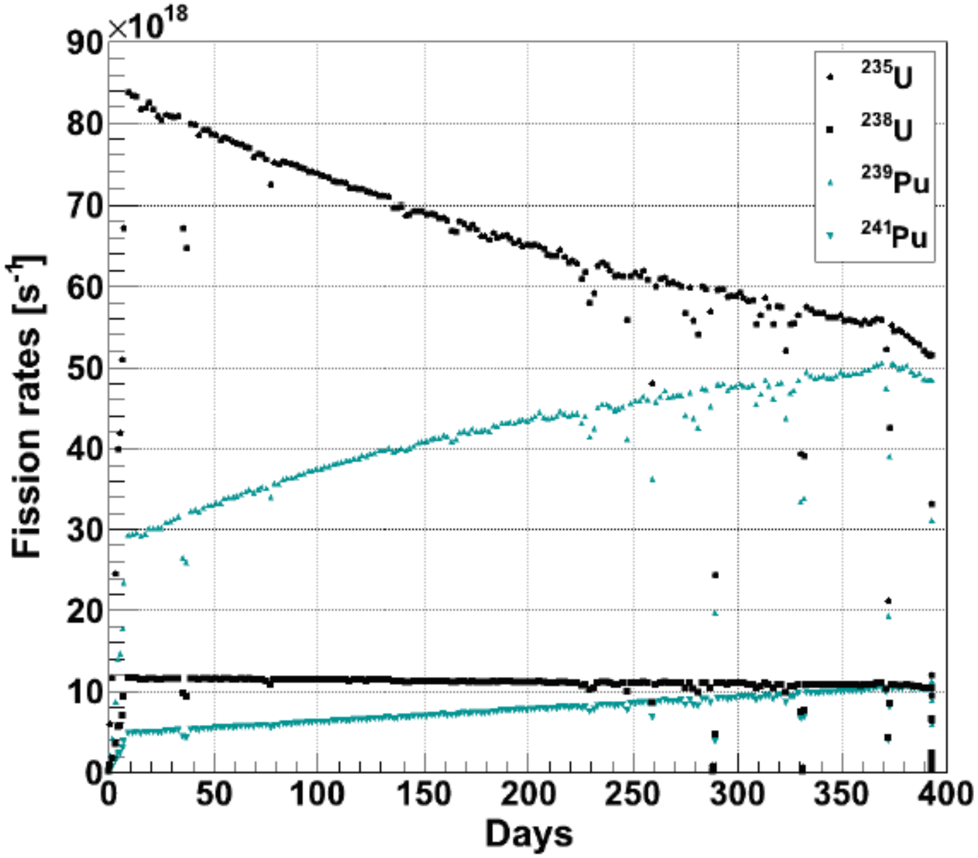

Reactors Produce a lot of antineutrinos!
$2\times10^{20}\ \overline{\nu}_e$ per s per GW_{th}
$\overline{\nu}_e$

An Example Fission:



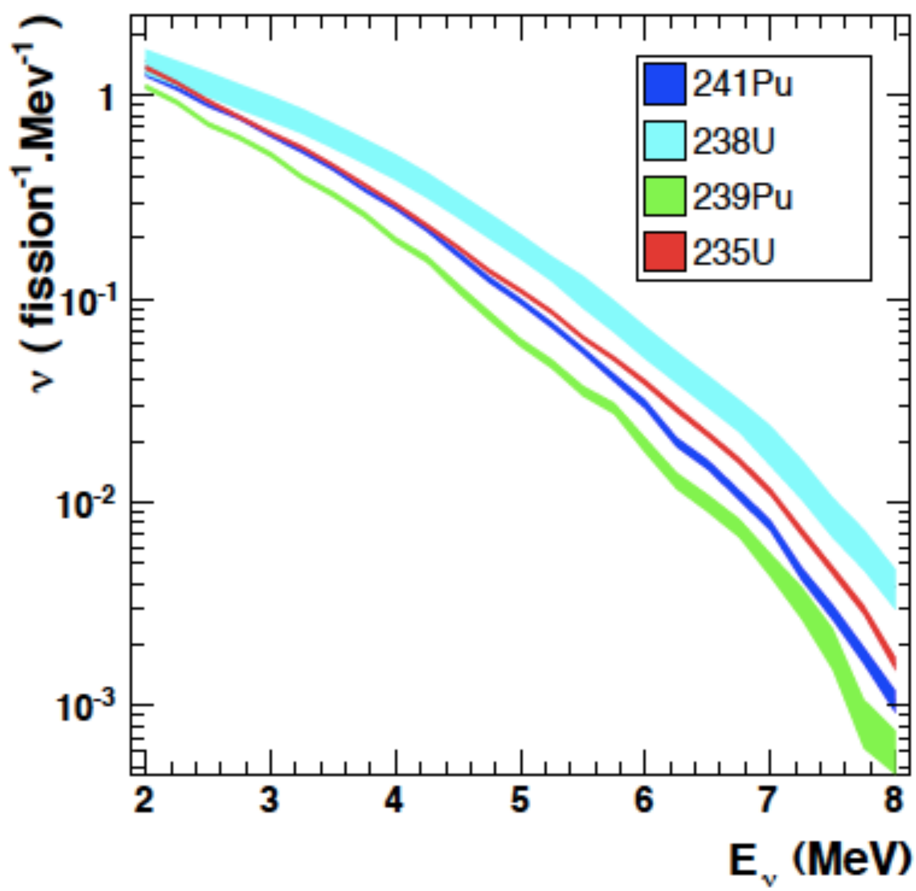
The Prediction:

Fission Rates

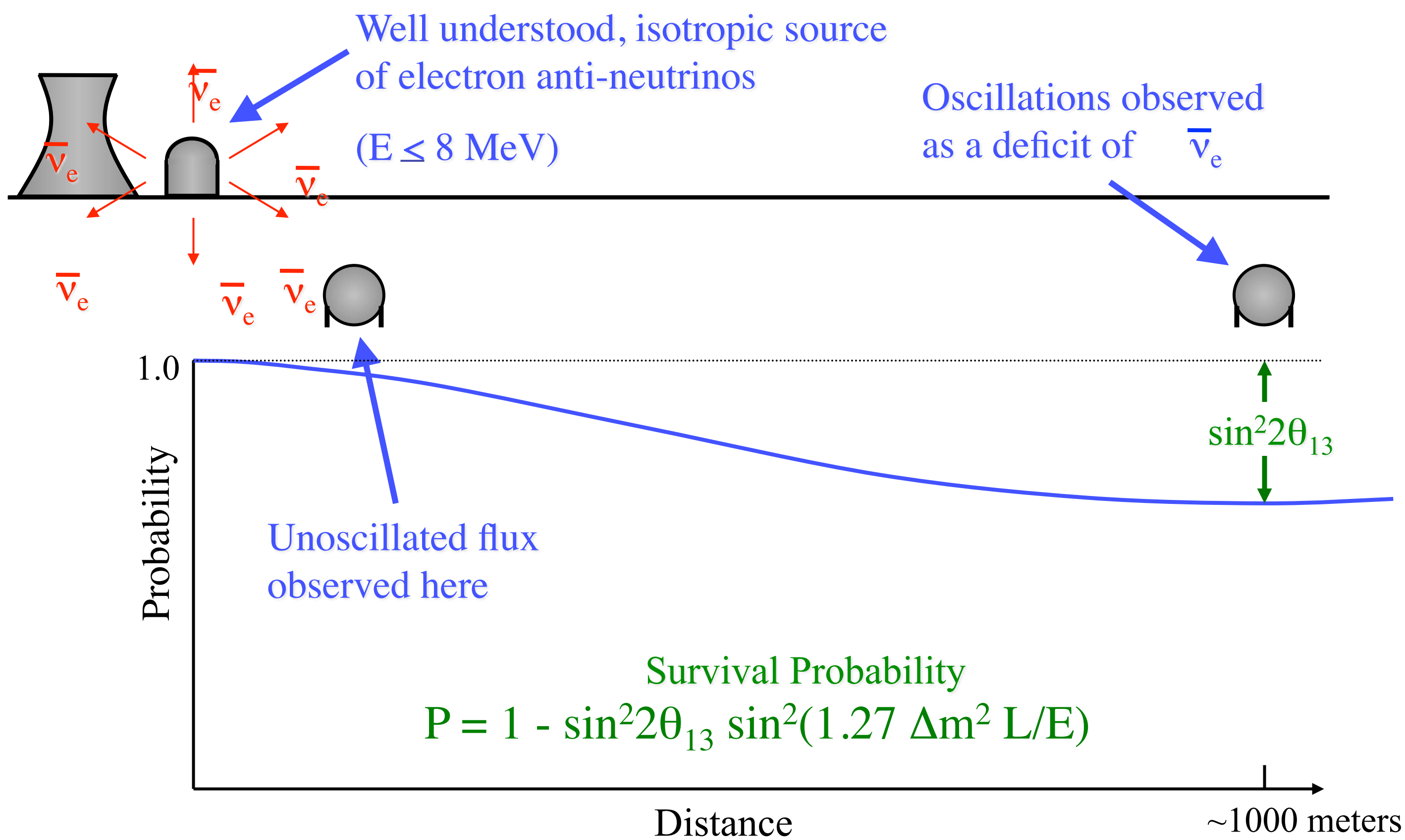


×

Spectra per Fission

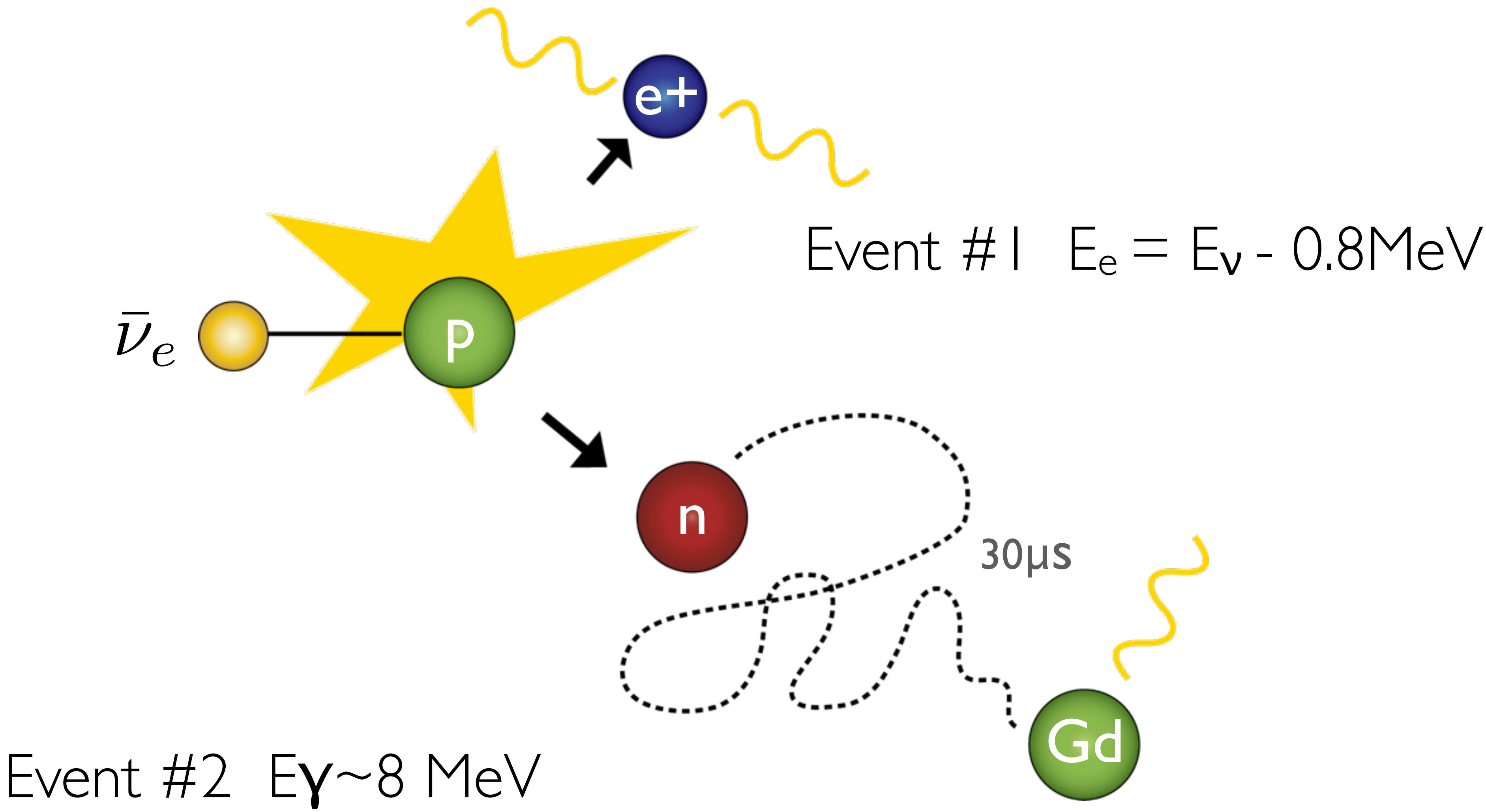


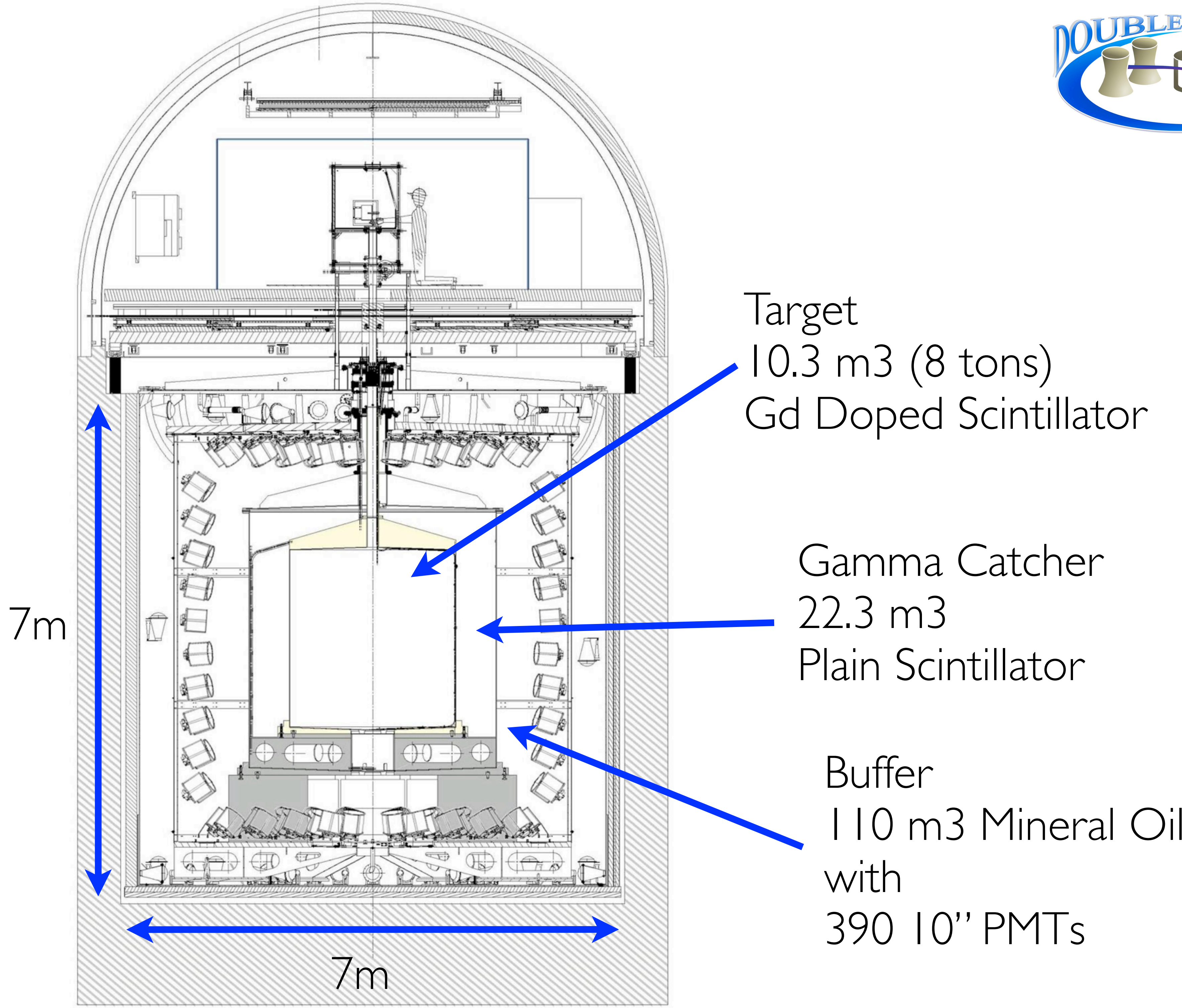
See arXiv:1109.5379

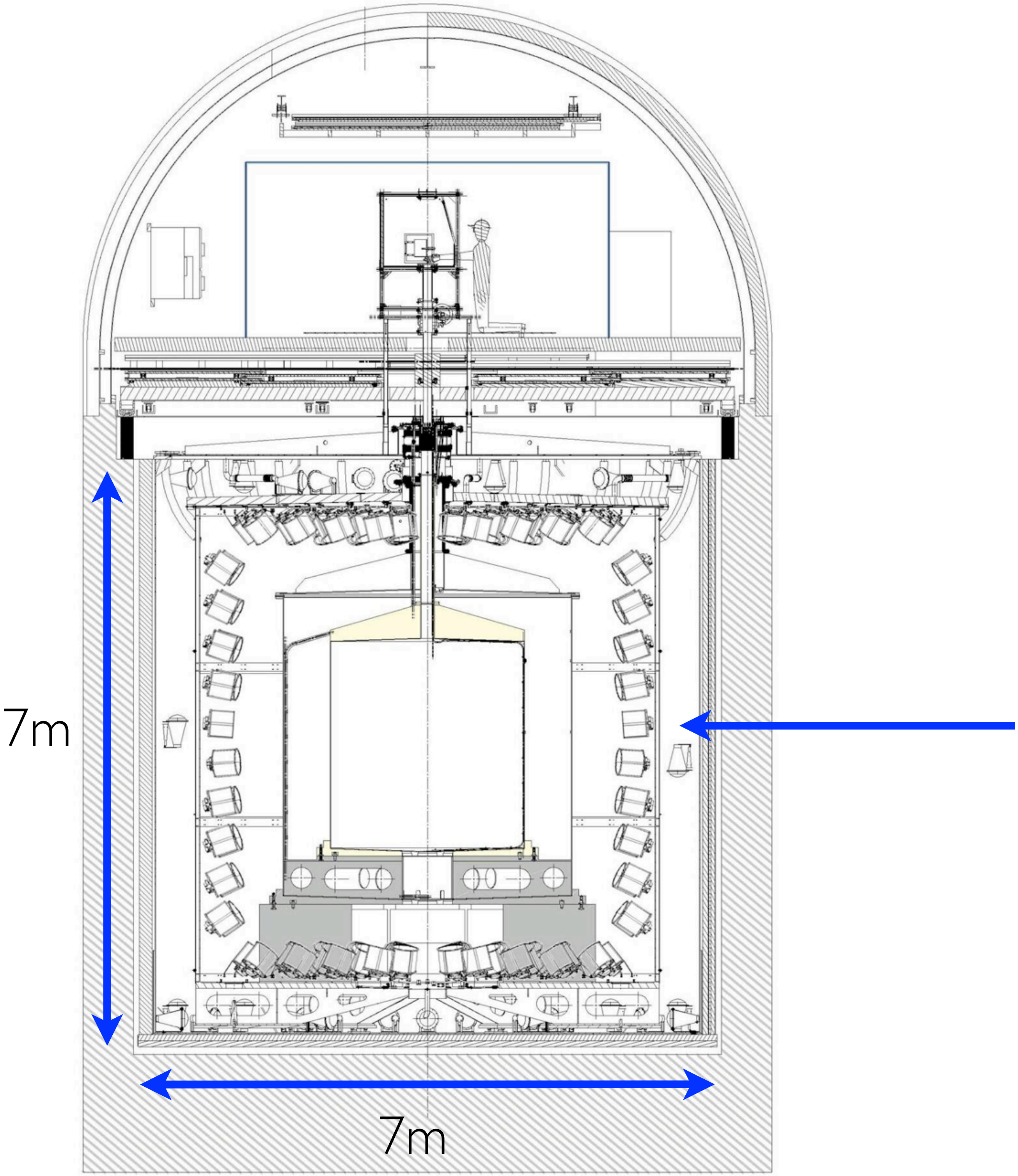


Drawing by A. Kaboth

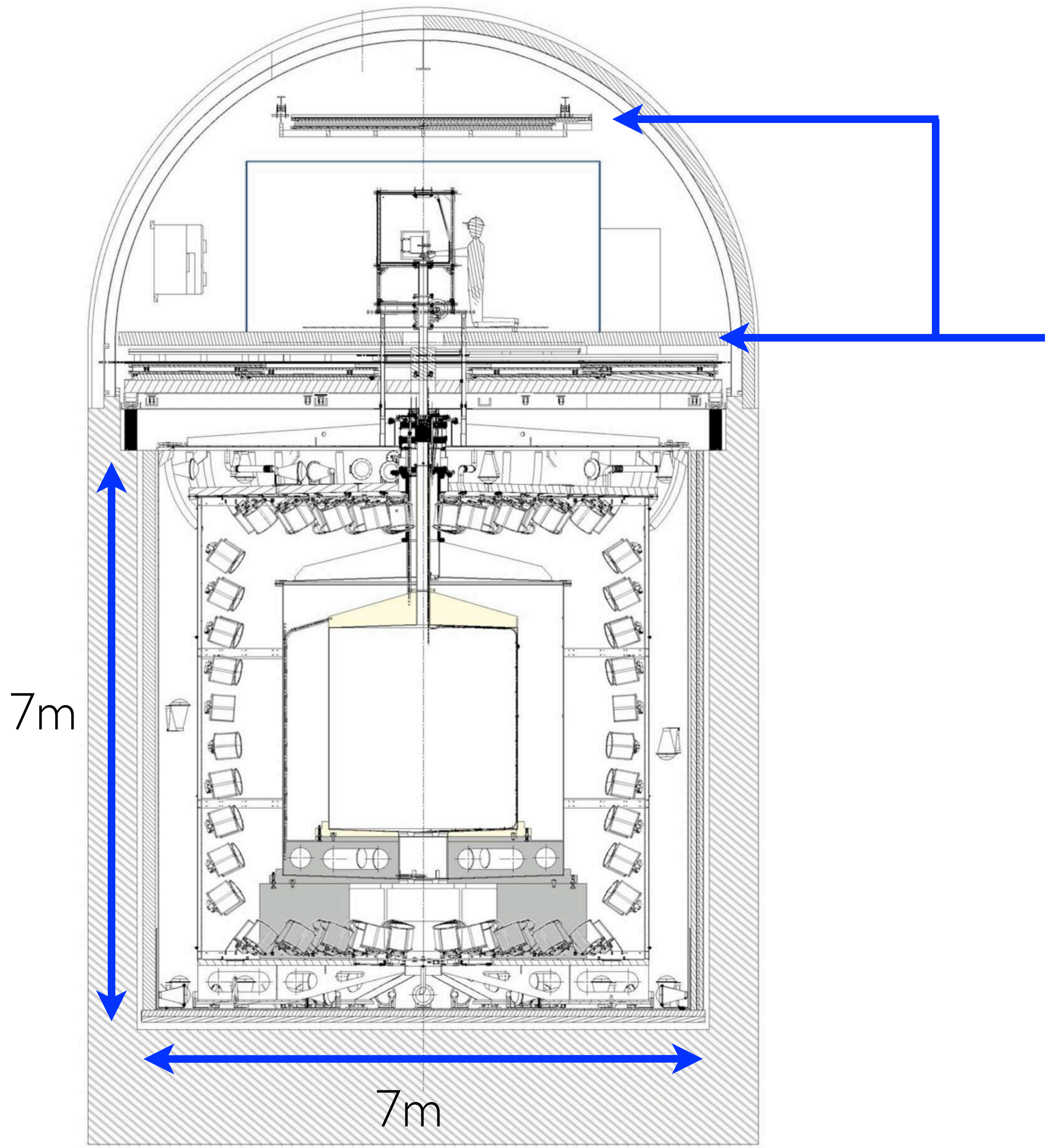
The Signal: Inverse Beta Decay



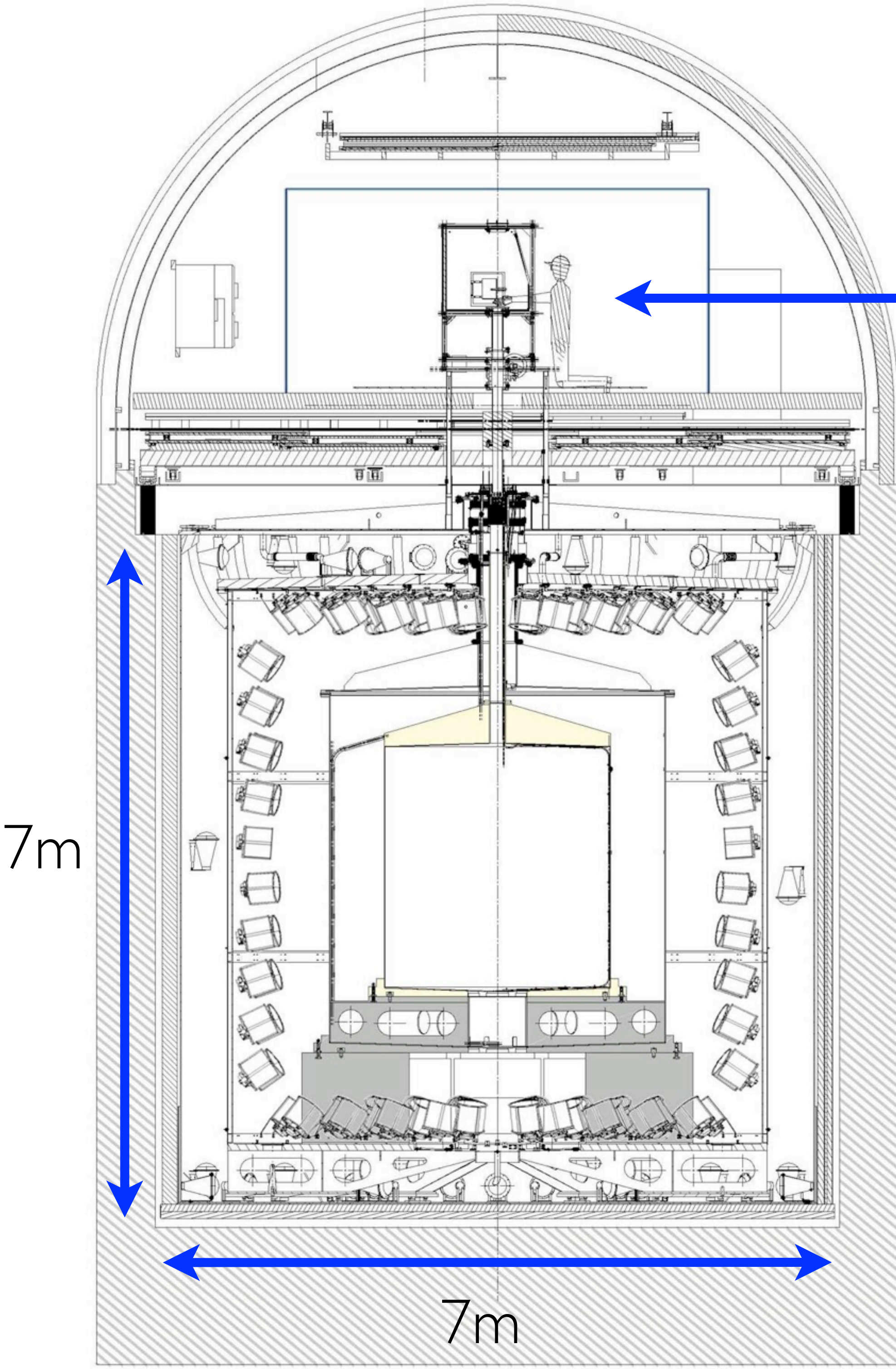

Target
10.3 m3 (8 tons)
Gd Doped Scintillator
Gamma Catcher
22.3 m3
Plain Scintillator
Buffer
110 m3 Mineral Oil
with
390 10'' PMTs
7m
7m



Inner Veto
90 m3 LAB Scintillator
with
78 8'' PMTs



Outer Veto
Precision muon tracking with plastic scintillator readout with fibers and multi-anode PMTs.

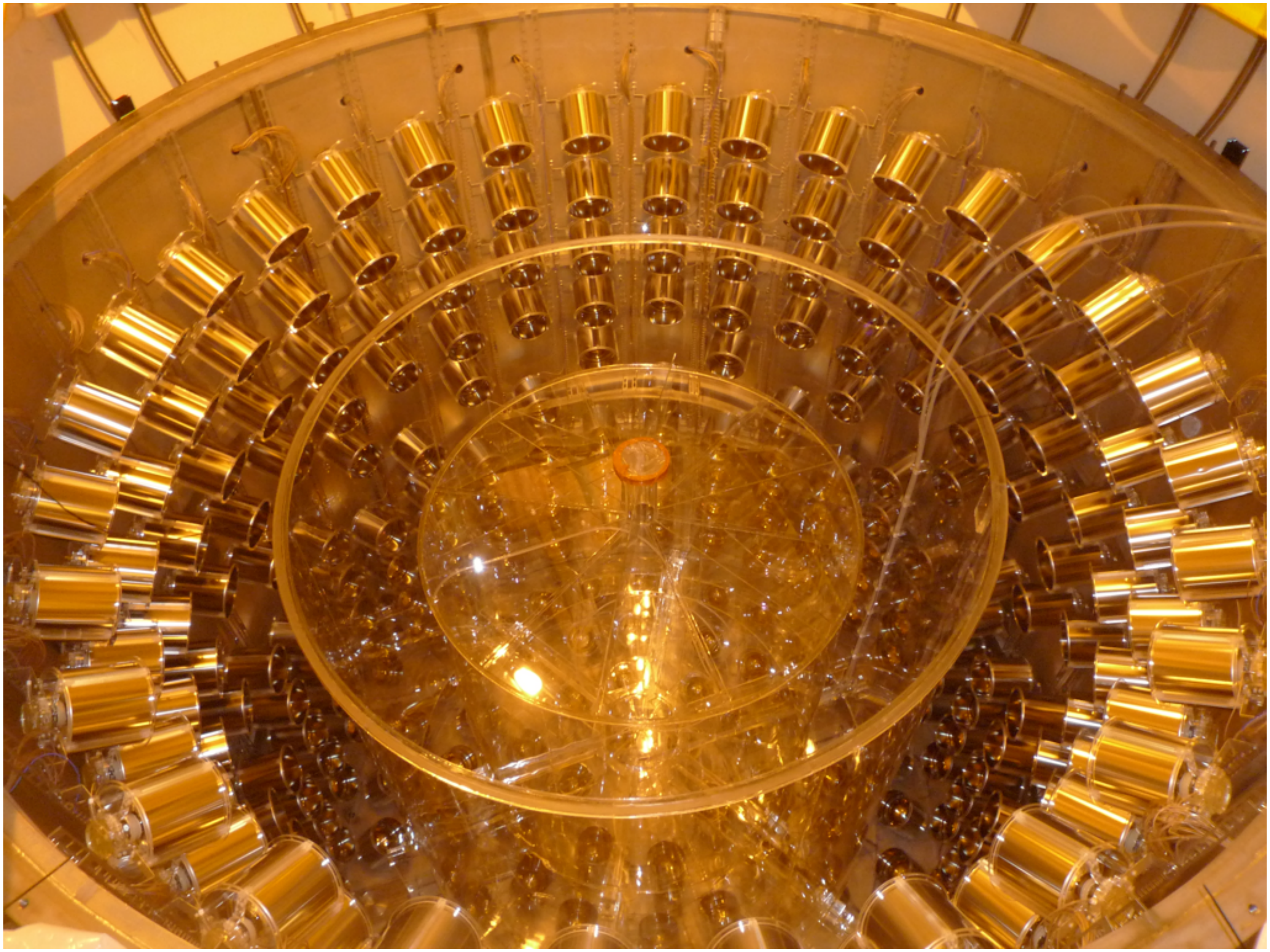


Calibration Systems

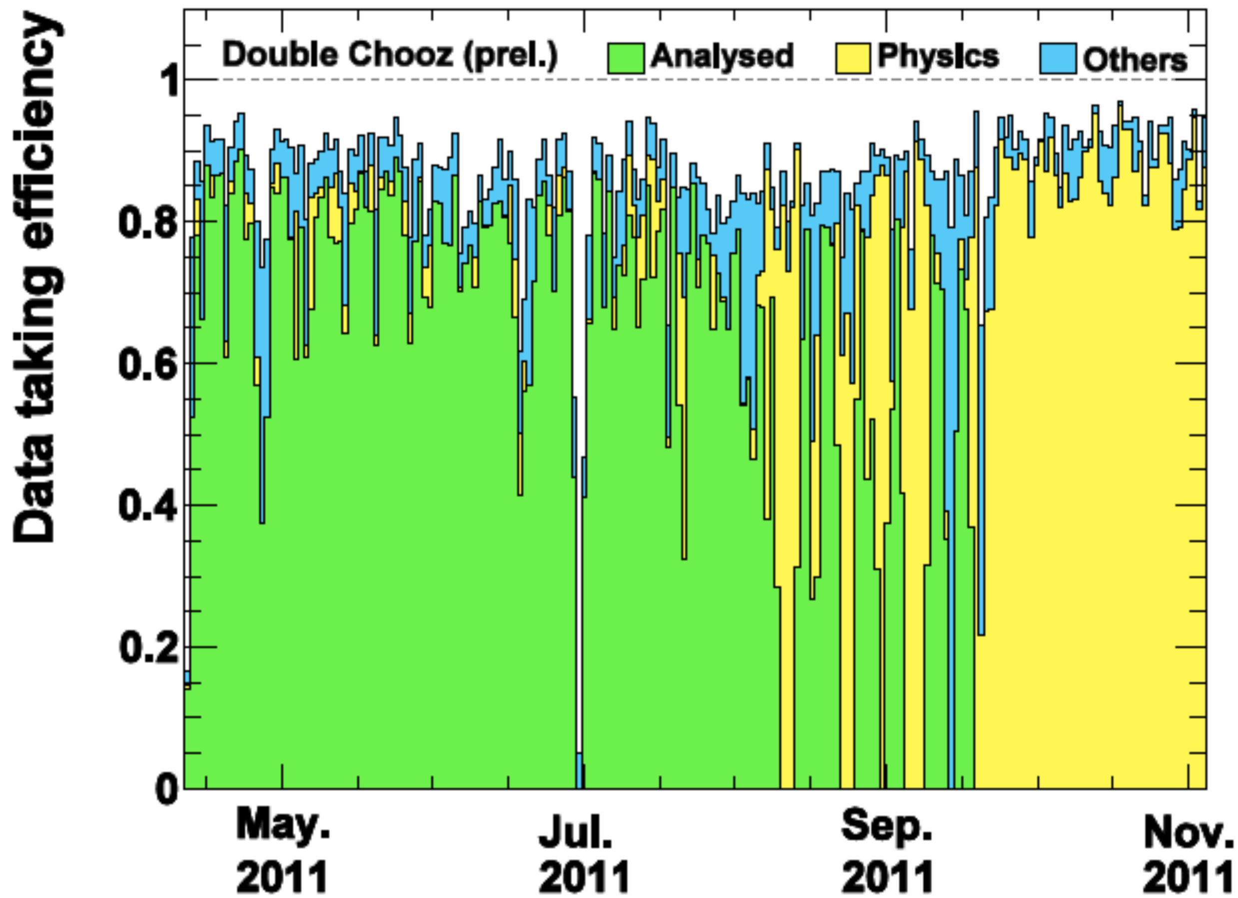
- Z-Axis
- Guide Tube in Gamma Catcher
- Buffer Tube
- Articulated Arm

Most robust calibration plan among the reactor experiments.

View of the Acrylic Vessels:



Collecting Data Since April 13:

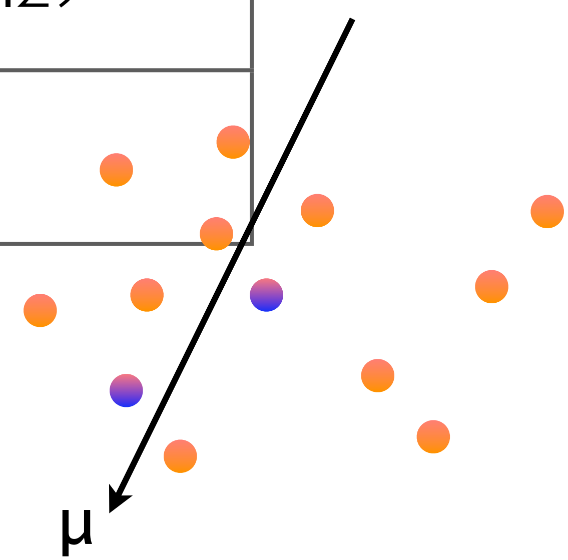


We see **4121** candidates in **96.8** live days.

Background Summary:

	Events per Day
^{9}Li	2.3±1.2
Fast-N + Stopped Muons	0.83±0.38
Accidental	0.33±0.03
Total	3.46±1.29
Candidates	42.6

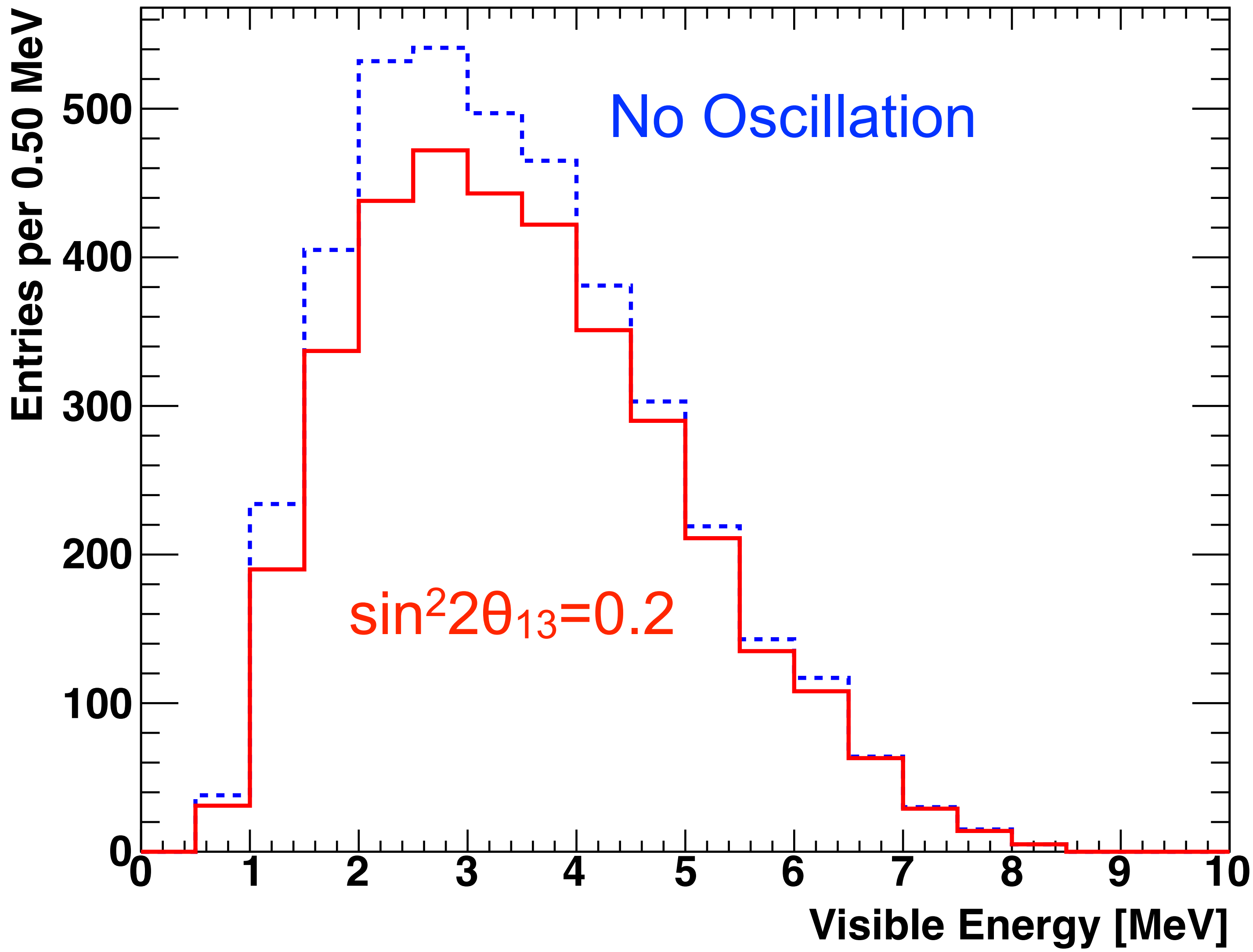
We have 3.0% uncertainty due to the backgrounds, but they can be constrained in a Rate + Shape analysis.



Reactor Off-Off,
great verification for first result!

Statistics 1.6%
Reactor 1.7%
Detector 1.1%
Energy Scale 1.8%
Backgrounds 3.0%

Example Prediction:



Two ways to do the analysis:
Rate
or
Rate+Shape

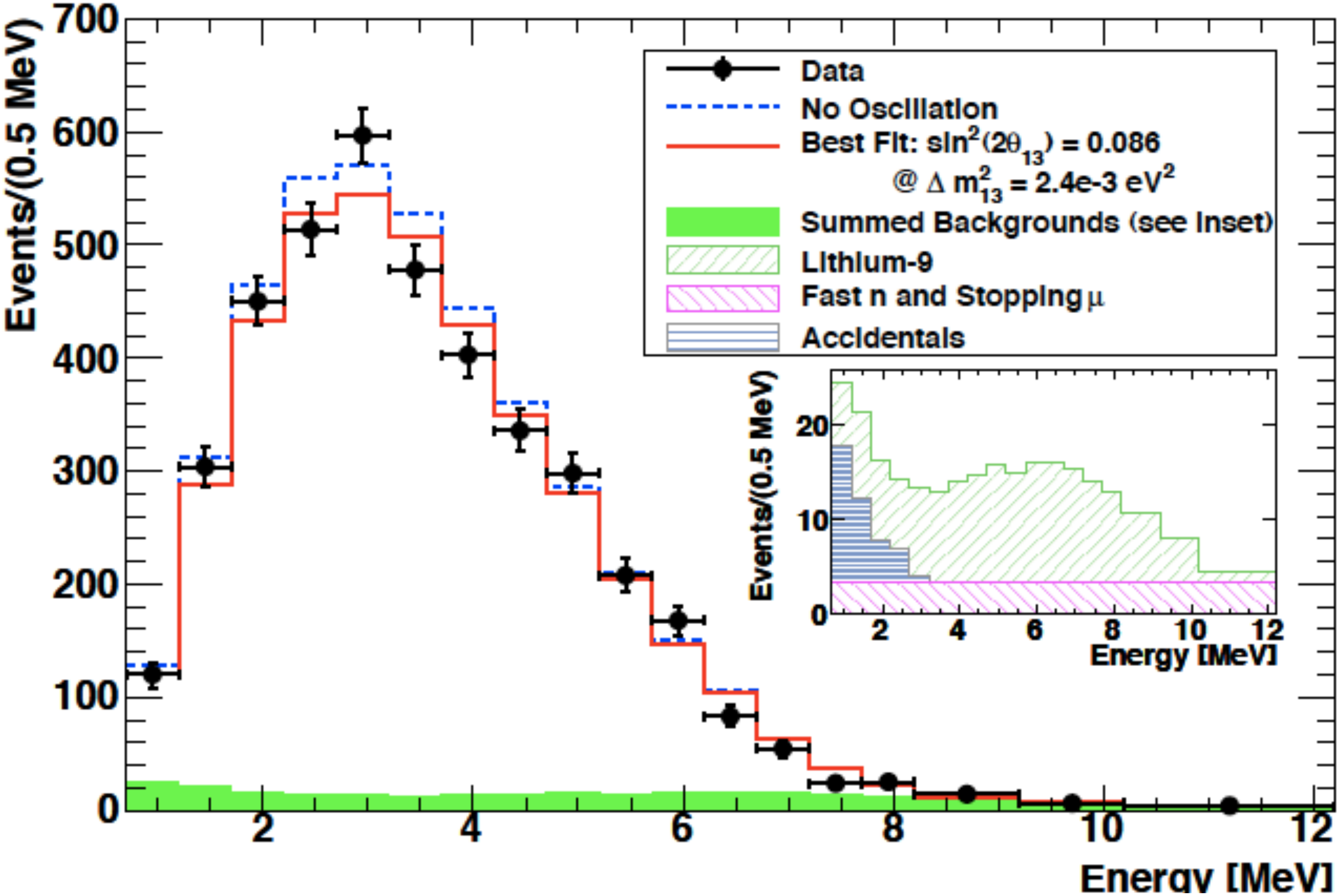
Rate Only:

$\sin^2 2\theta_{13} = 0.104 \pm 0.081$

Rate + Shape

$\sin^2 2\theta_{13}$ = 0.086 ± 0.051

χ^2/NDF = 23.7/17



The other way is...

Appearance

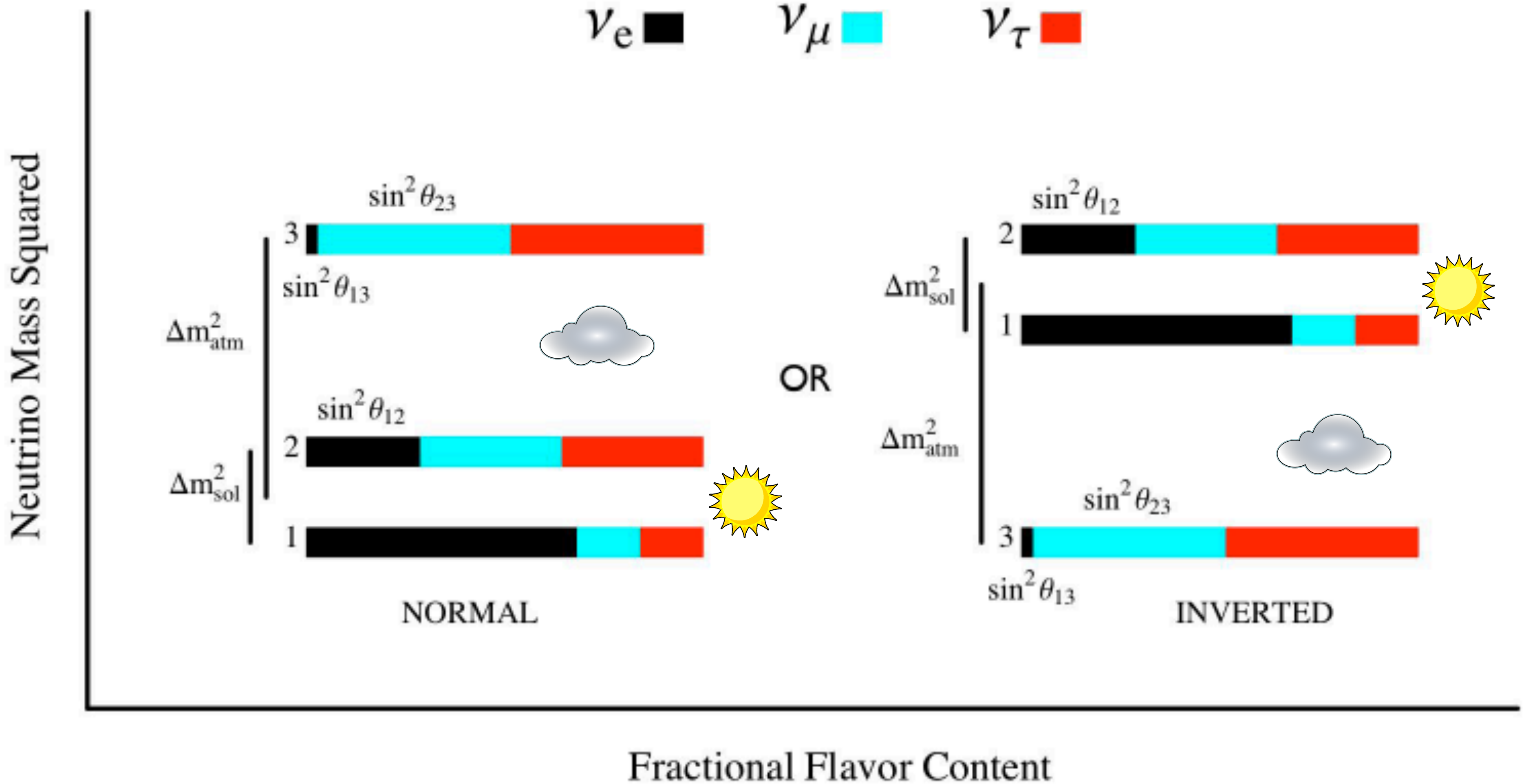
$\nu_\mu \rightarrow \nu_e$

$$
\begin{aligned}
P_{\mathrm{mat}} \quad =& \\
& \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}\mp aL)}{(\Delta_{31}\mp aL)^2}\Delta_{31}^2 \\
& \mp \sin\delta\sin 2\theta_{13}\sin 2\theta_{23}\sin 2\theta_{12}\sin\Delta_{31}\frac{\sin(\Delta_{31}\mp aL)}{(\Delta_{31}\mp aL)}\Delta_{31}\frac{\sin(aL)}{(aL)}\Delta_{21} \\
& + \cos\delta\sin 2\theta_{13}\sin 2\theta_{23}\sin 2\theta_{12}\cos\Delta_{31}\frac{\sin(\Delta_{31}\mp aL)}{(\Delta_{31}\mp aL)}\Delta_{31}\frac{\sin(aL)}{(aL)}\Delta_{21} \\
& + \cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2.
\end{aligned}
$$

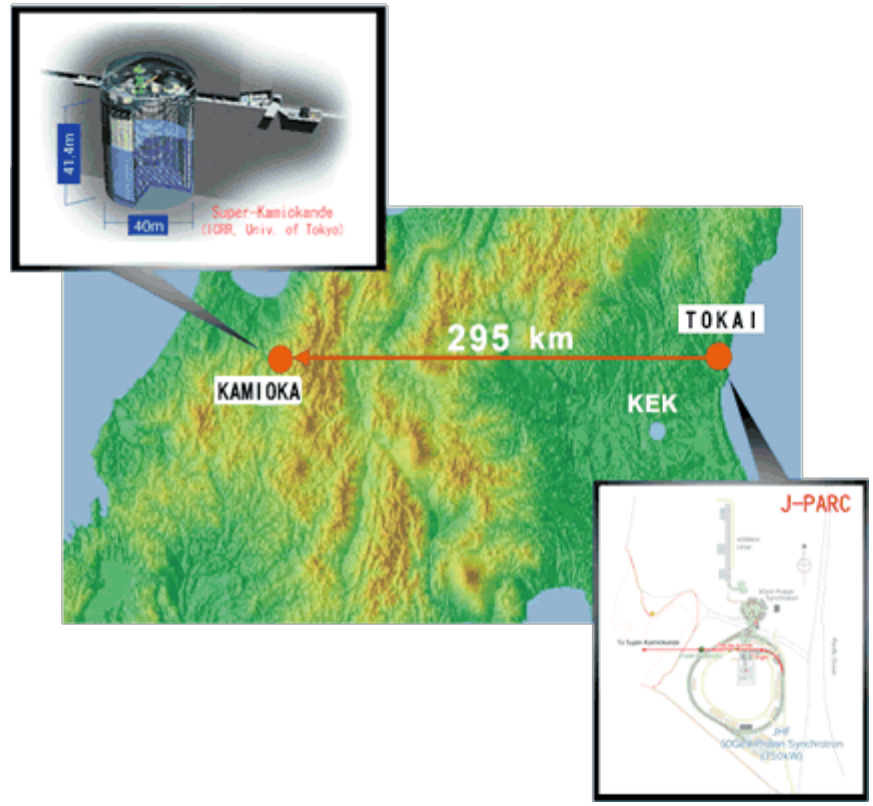
θ_{13}, CP Violation, Mass Hierarchy, Oh My!

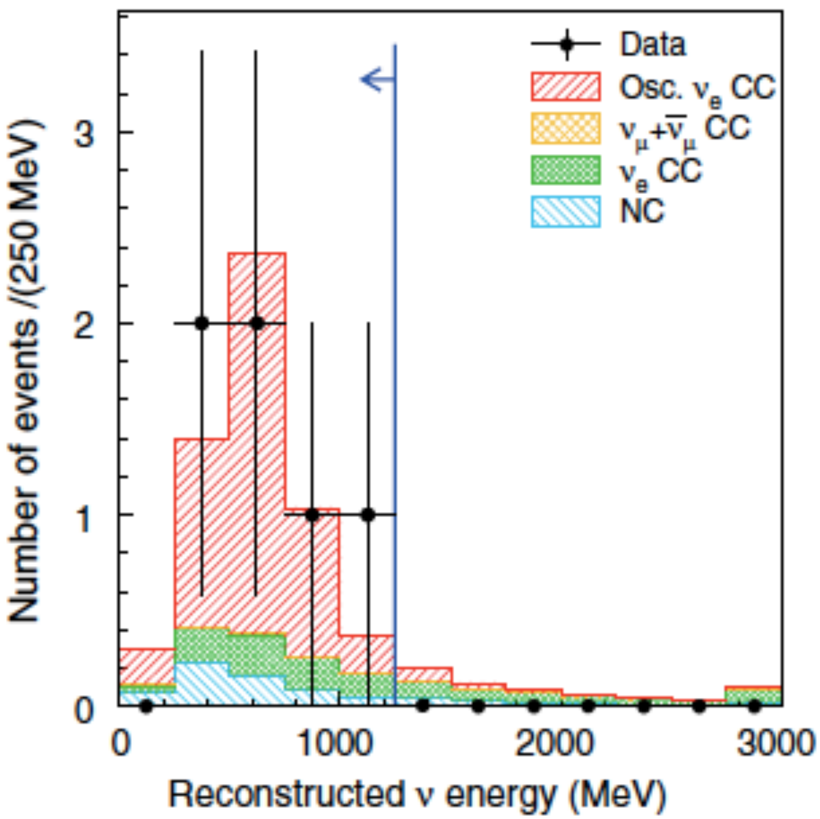
Mass Hierarchy?

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

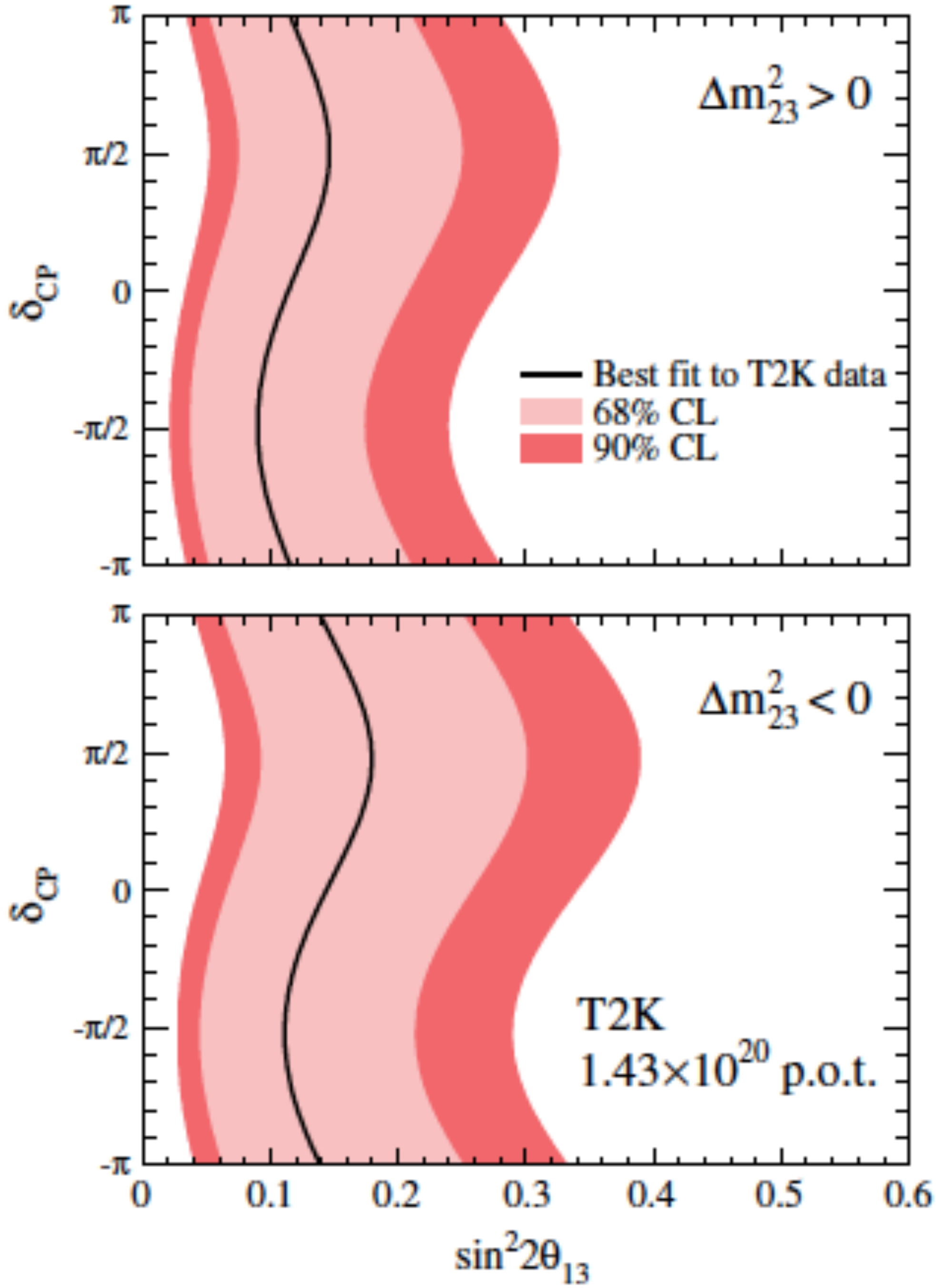


We are the strongest disappearance result to date. The strongest appearance result is from T2K.





Plotting the T2K Result:

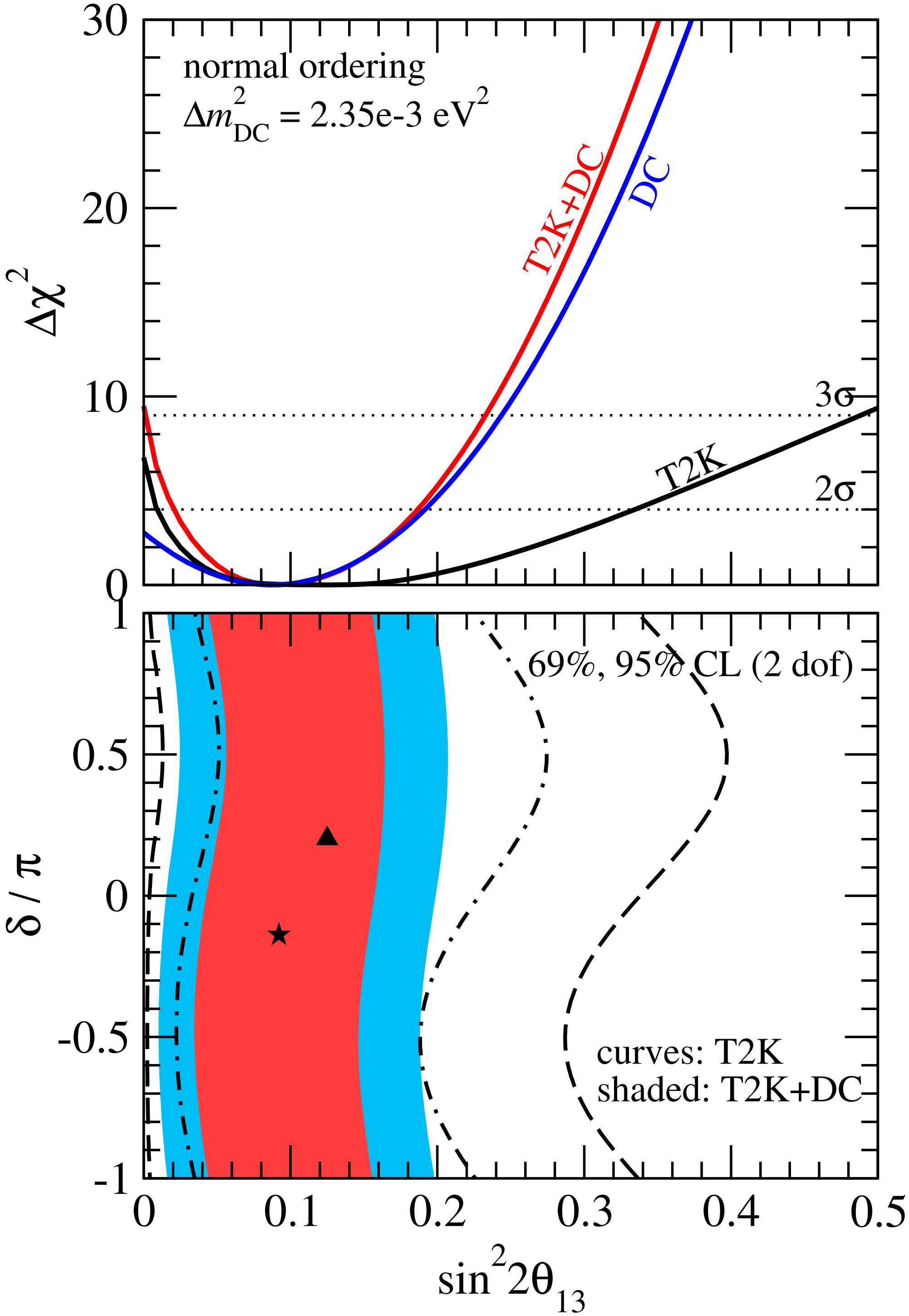


Normal hierarchy, allowed parameter space for mixing angle and CP phase.

Inverted hierarchy, allowed parameter space for mixing angle and CP phase.

From now on, I will just show normal hierarchy....

There are NO systematics in common between T2K and Double Chooz.

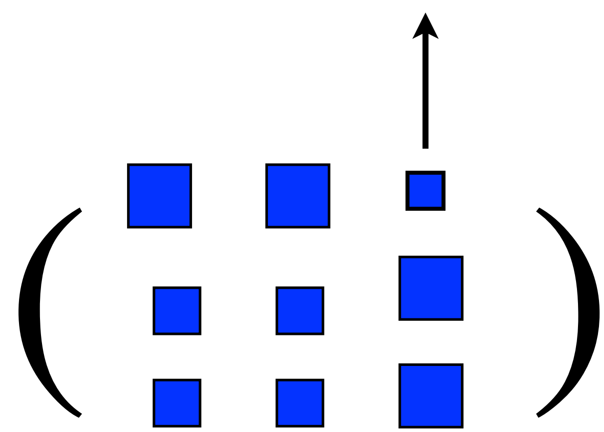


With just T2K+DC, $\sin^2 2\boldsymbol{\theta}_{13} = 0$ is ruled out at > 3**σ**.

Impact of the Double Chooz first result

- First in the new generation of reactor experiments.
- Provides strong bound at high $\sin^2 2\theta_{13}$.
- Compliments T2K's bound at low $\sin^2 2\theta_{13}$.
- When combined with T2K, pushes global fit to non-zero at 3σ.
- For the first time, values for entries of this mixing matrix.

Bigger than we thought!




Summer 2012
Construction Begins!
CLOSE DETECTOR 400 m
DISTANT DETECTOR
1 km
WEST REACTOR
EAST REACTOR

The MIT Double Chooz Group: Analyses Today!

Lindley - Analysis of 300 day data sample

Josh - Lorentz violation analysis

Kazu - Analysis expanding the fiducial volume using nH captures

Chris - Writing his thesis on the reactor flux prediction

reVolution

You say you want a revolution
Well, you know
we all want to change the world.

You ask me for a contribution
Well, you know
We are all doing what we can

Revolution

Pronunciation: /ˌrevəˈluːʃ(ə)n/

Overthrow in favor of a new system.

Neutrinos are there own anti-particle i.e. Majorana?

The Majorana Neutrino Revolution:

I. Double Beta Decay

II. CUORE - My Next Experiment

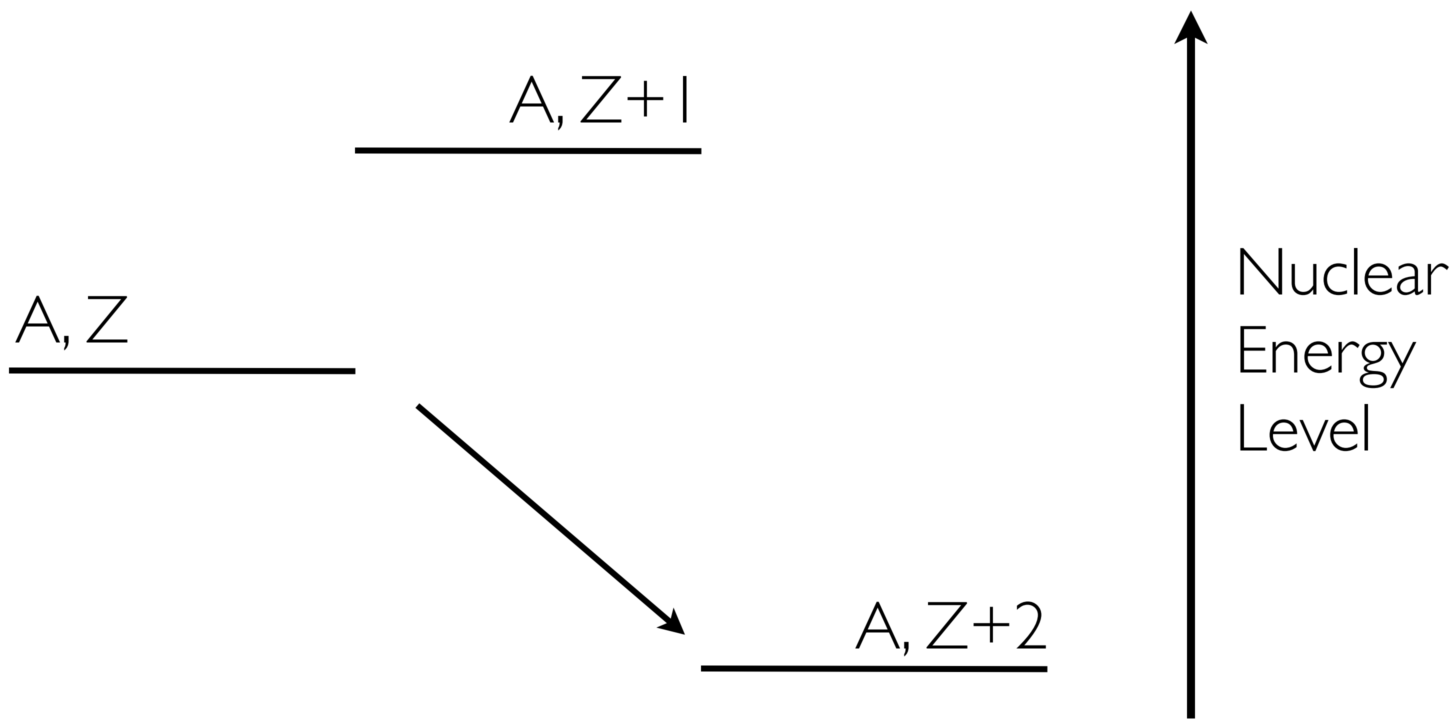
III. The Next Generation? - First results from quantum dots!

There is one process that is feasible for determining the Majorana nature of the neutrino.

Neutrinoless Double Beta Decay

Double Beta Decay

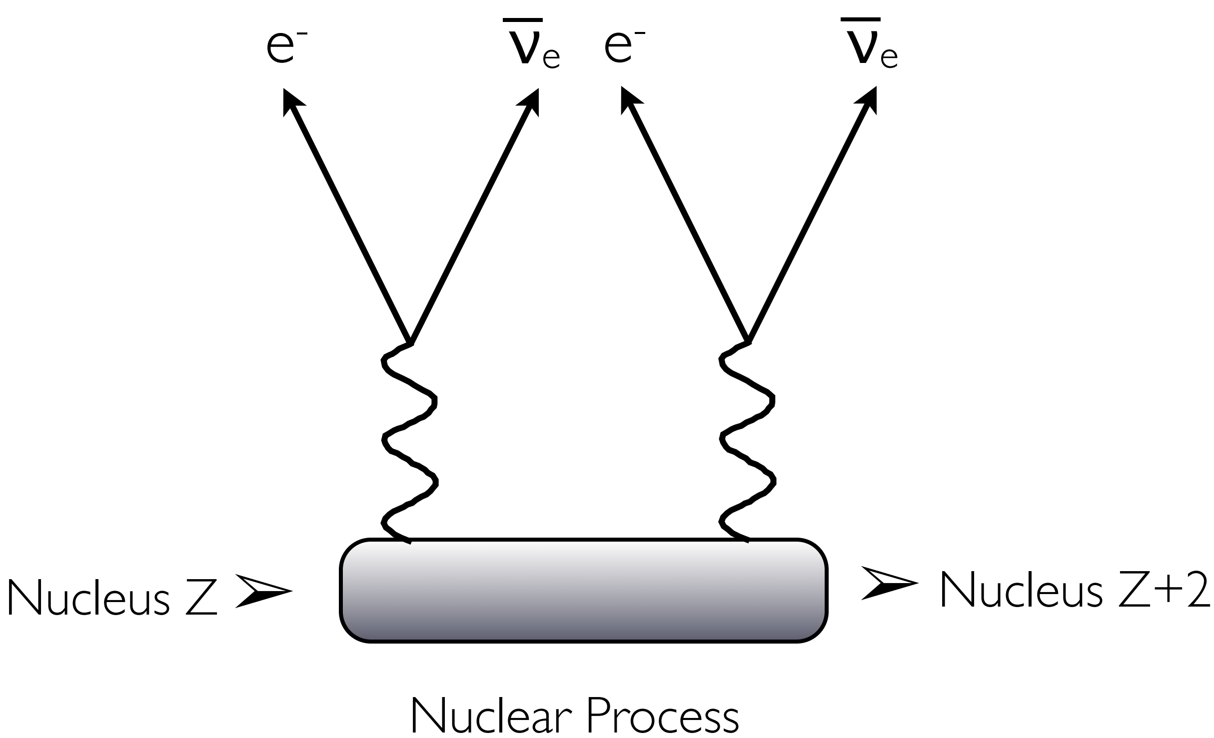
Due to energy conservation some nuclei can't decay to their daughter nucleus, but can skip to their granddaughter nucleus.



Just a few isotopes!

The Standard Model Process

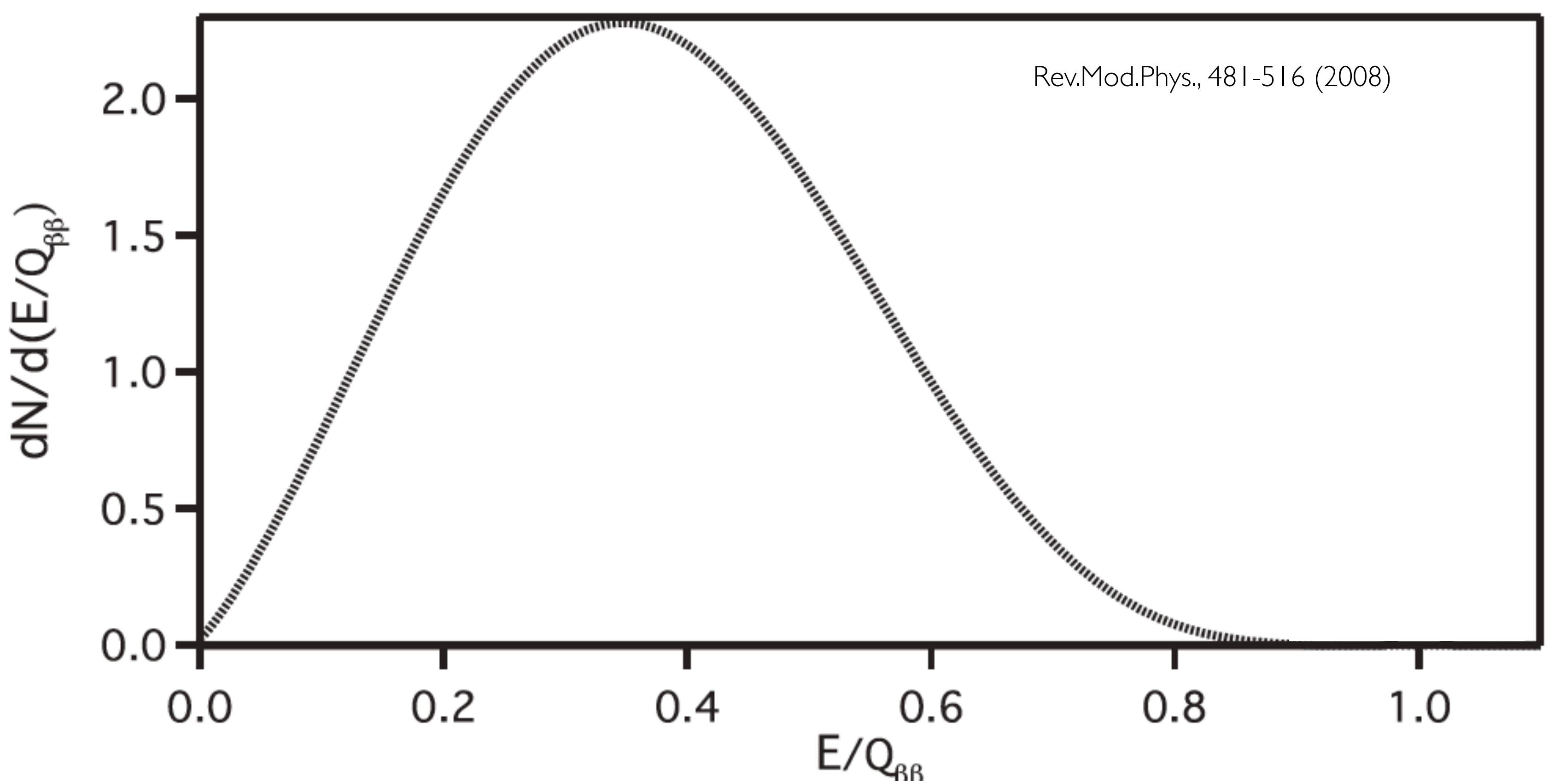
This process is completely allowed and the rate was first calculated by Maria Goeppert-Mayer in 1935.



Phys. Rev. 48, 512-516 (1935)

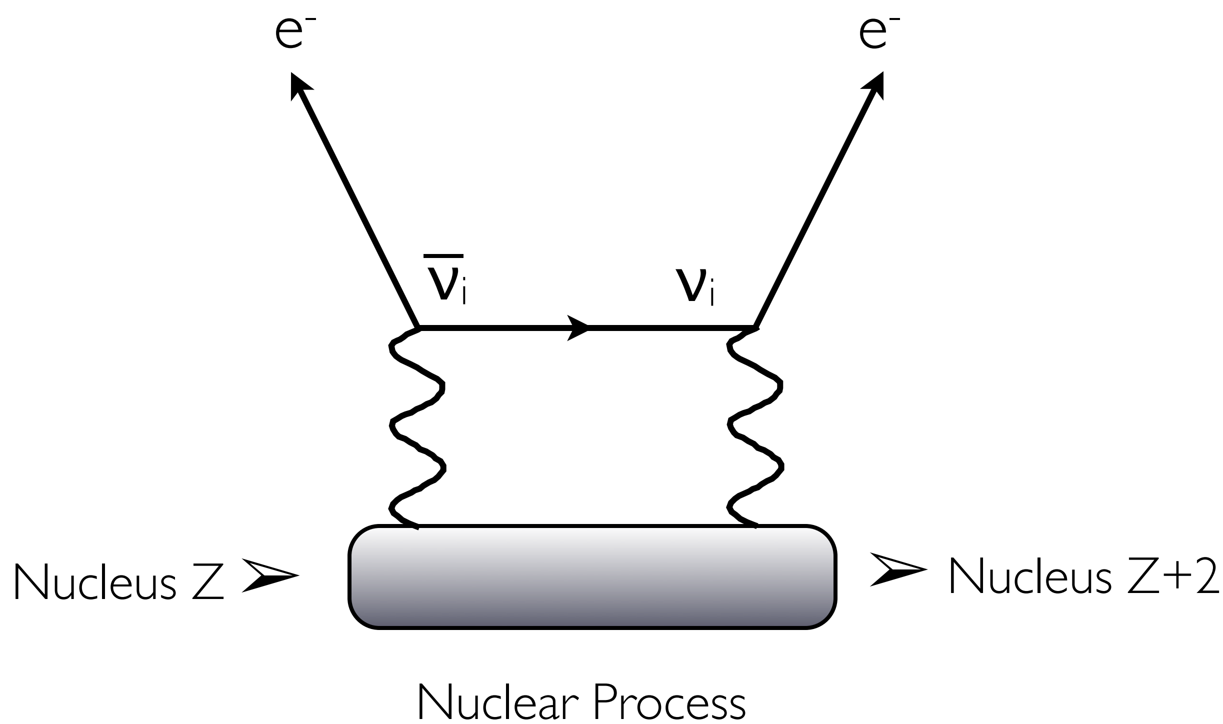
Double Beta Decay

The sum of the electron energies gives a spectrum similar to the standard beta decay spectrum.



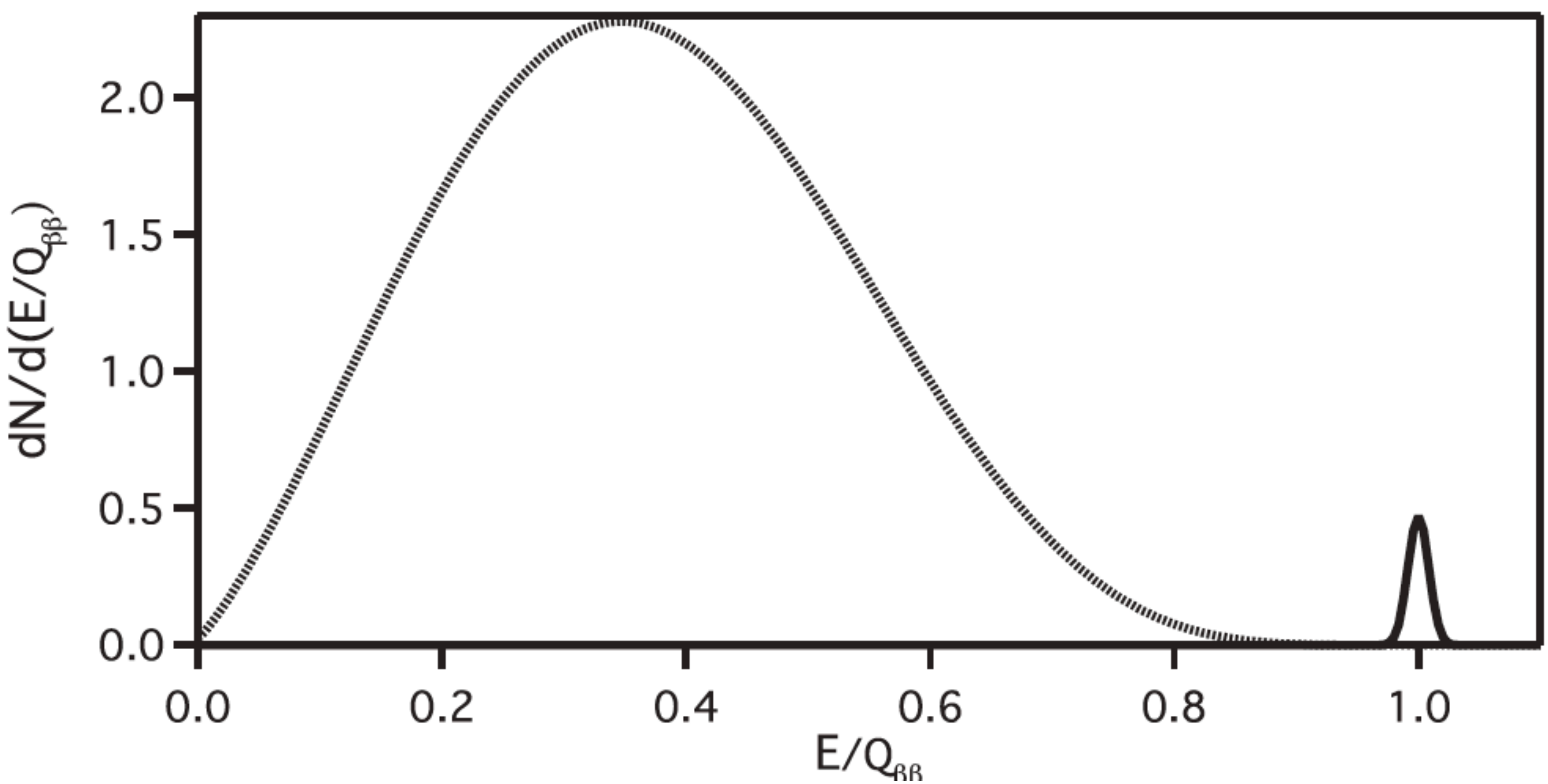
This has been observed in isotopes such as ^{130}Te and ^{116}Cd.

Neutrinoless Double Beta Decay



Neutrinoless Double Beta Decay

The sum of the electron energies gives a spike at the endpoint of the "neutrino-full" double beta decay.



What is measured is a half-life...

The half-life of the neutrinoless decay:

$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu}(Q_{\beta\beta}, Z)|M_{0\nu}|^2 \langle m_{\beta\beta} \rangle^2$$

Phase space factor
Notice higher endpoint means faster rate.

What is measured is a half-life:

$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu}(Q_{\beta\beta}, Z)|M_{0\nu}|^2 \langle m_{\beta\beta} \rangle^2$$

↑ Nuclear Matrix Element

This is a difficult calculation with large errors and substantial variation between isotopes...motivates searches with multiple isotopes.

What is measured is a half-life:

$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu}(Q_{\beta\beta}, Z)|M_{0\nu}|^2\langle m_{\beta\beta}\rangle^2$$

Effective Majorana Mass of the neutrino

Effective Majorana Mass:

$$m_{ee} = \sum_i V_{ei}^2\, m_i = \cos^2\theta_{13}(m_1 e^{2i\beta}\cos^2\theta_{12} + m_2 e^{2i\alpha}\sin^2\theta_{12}) + m_3\sin^2\theta_{13}$$

ooh... look θ_{13} !

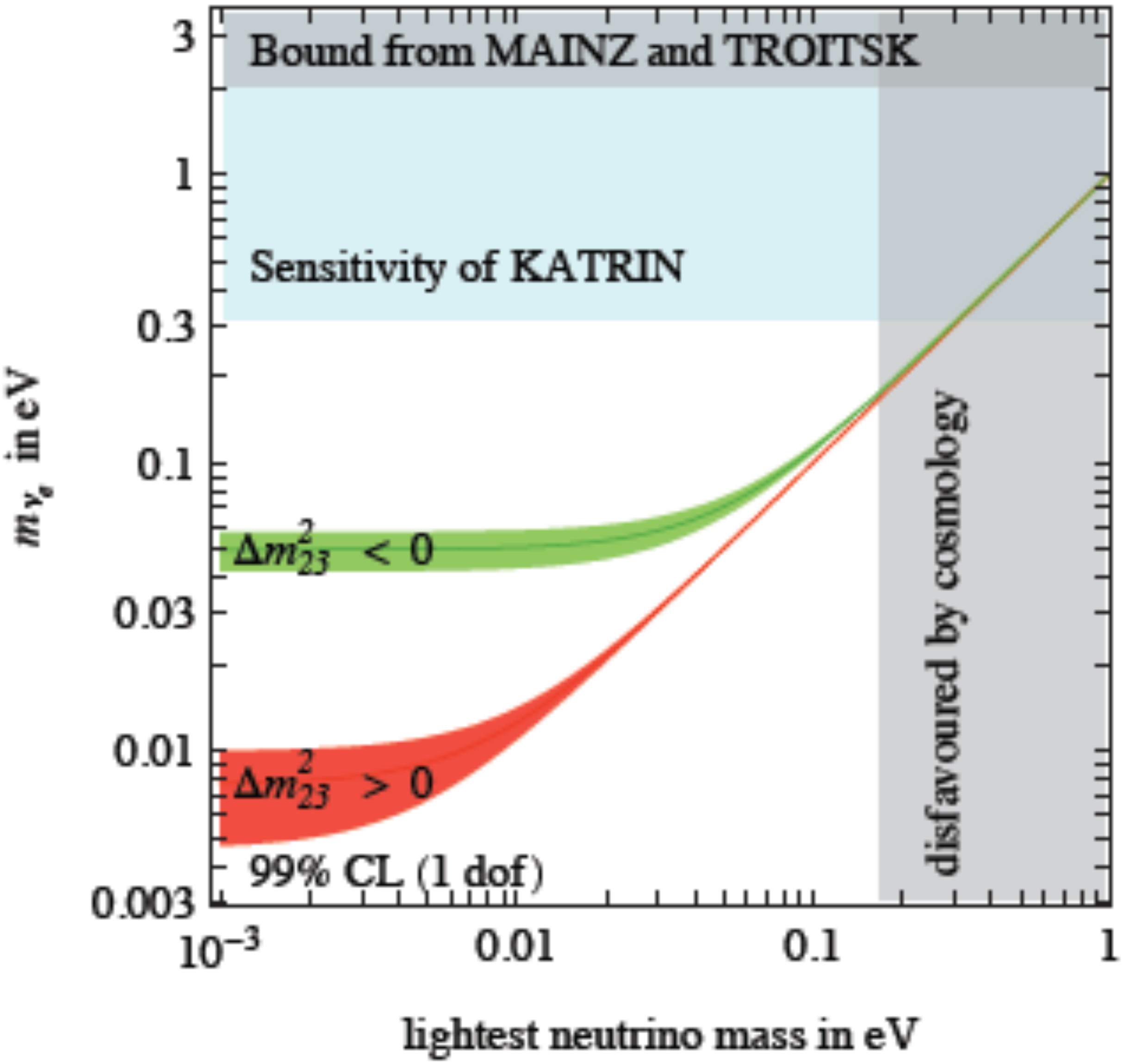
Electron Neutrino Mass:

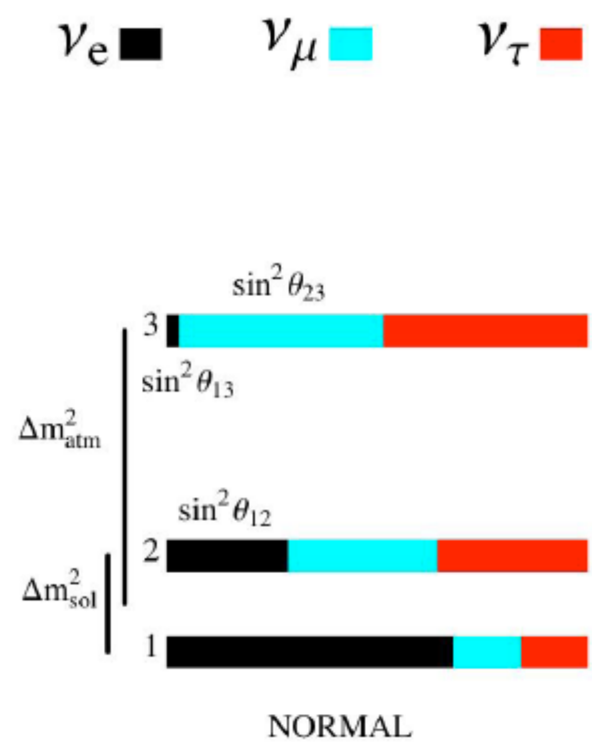
$$m_{\nu_e}^2 \equiv \sum_i |V_{ei}^2| m_i^2 = \cos^2\theta_{13}(m_1^2\cos^2\theta_{12} + m_2^2\sin^2\theta_{12}) + m_3^2\sin^2\theta_{13}$$

measured by KATRIN

Visualizing the Equations:

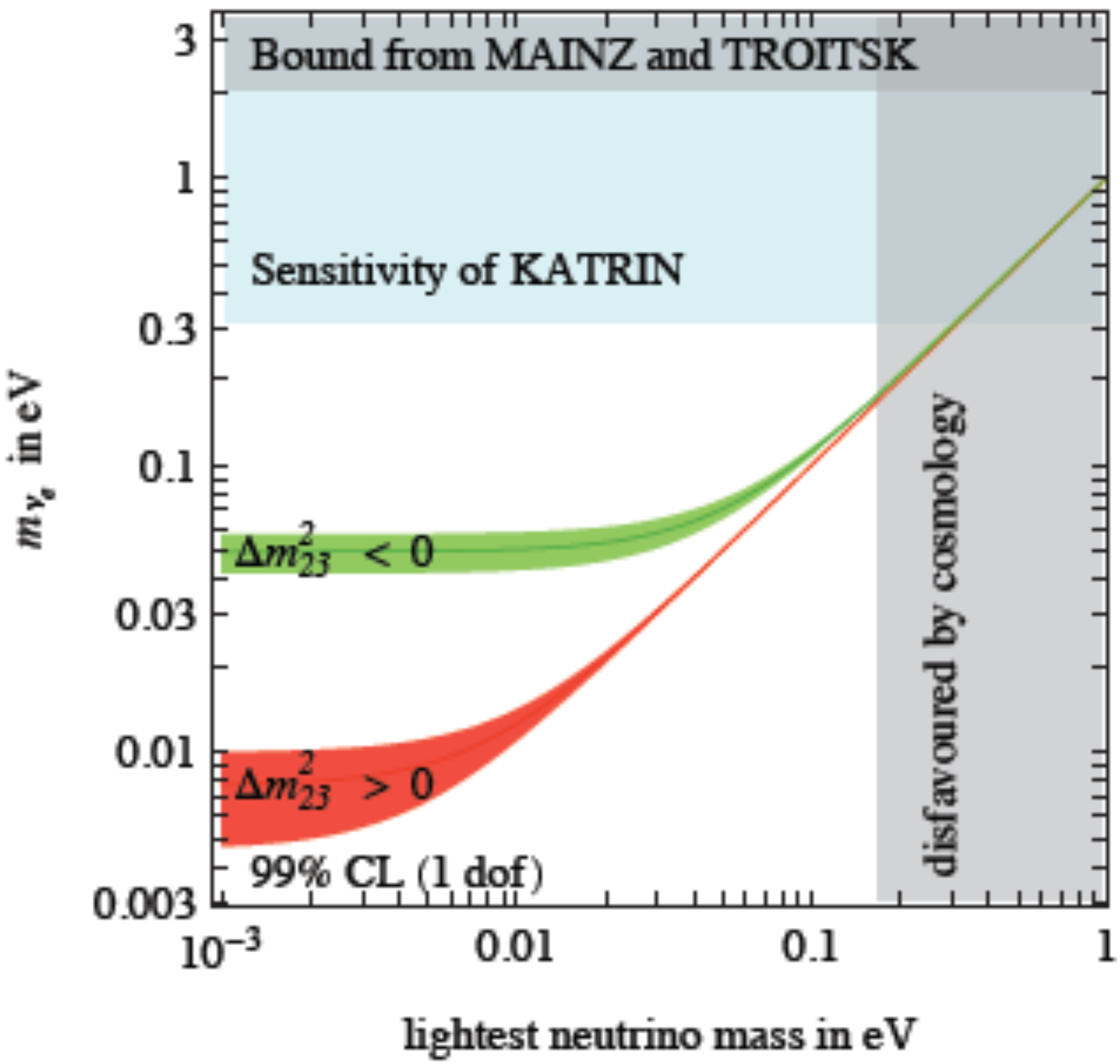
$$m_{\nu_e}^2 \equiv \sum_i |V_{ei}^2| m_i^2 = \cos^2\theta_{13}(m_1^2\cos^2\theta_{12} + m_2^2\sin^2\theta_{12}) + m_3^2\sin^2\theta_{13}$$

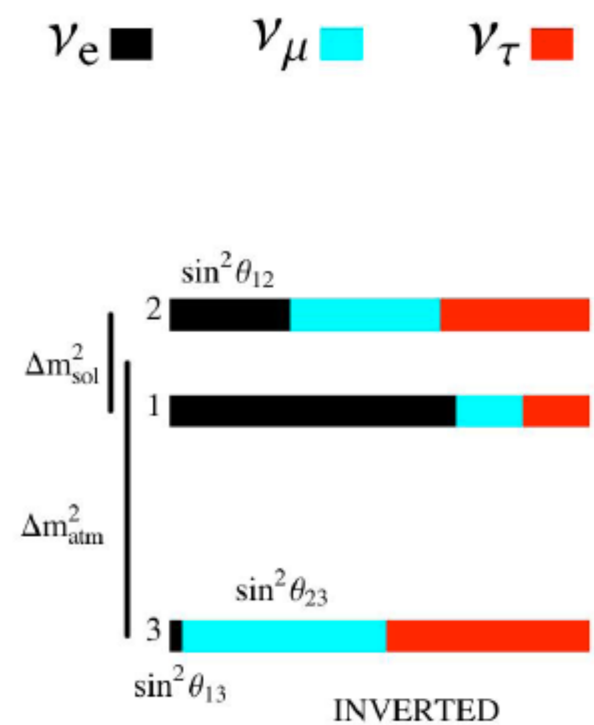




Visualizing the Equations:

$$m_{\nu_e}^2 \equiv \sum_i |V_{ei}^2| m_i^2 = \cos^2\theta_{13}(m_1^2\cos^2\theta_{12} + m_2^2\sin^2\theta_{12}) + m_3^2\sin^2\theta_{13}$$

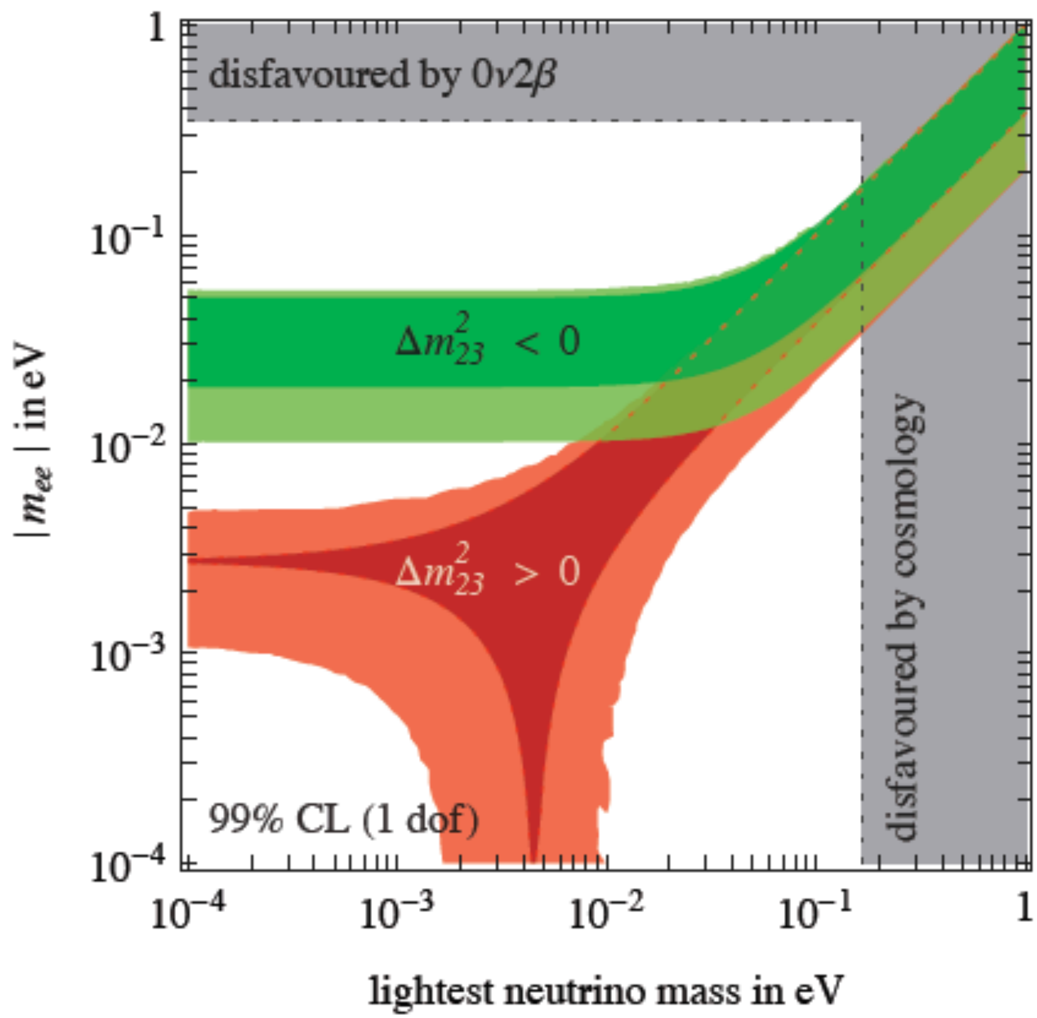




Double Beta Decay Visualizing the Equations:

$$m_{ee} = \sum V_{ei}^2 \, m_i = \cos^2\theta_{13}(m_1 e^{2i\beta}\cos^2\theta_{12} + m_2 e^{2i\alpha}\sin^2\theta_{12}) + m_3\sin^2\theta_{13}$$

arXiv:hep-ph/0606054v3



Design Issues:

Size

- Natural Abundance
- Detector technology

Backgrounds

(2.6 MeV is the highest energy U/Th gamma ray)

- Energy of endpoint
- Cleanliness
- Particle/Event identification

Energy resolution

Pick your favorite candidate isotope......

Isotope	Endpoint	Abundance
^{48}Ca	4.271 MeV	0.0035%
^{150}Nd	3.367 MeV	5.6%
^{96}Zr	3.350 MeV	2.8%
^{100}Mo	3.034 MeV	9.6%
^{82}Se	2.995 MeV	9.2%
^{116}Cd	2.802 MeV	7.5%
^{130}Te	2.533 MeV	34.5%
^{136}Xe	2.479 MeV	8.9%
^{76}Ge	2.039 MeV	7.8%
^{128}Te	0.868 MeV	31.7%

Pick your favorite candidate isotope......

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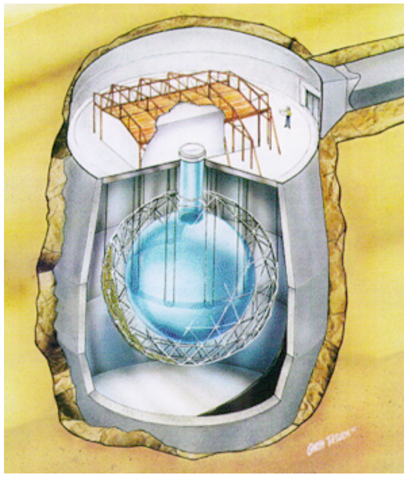
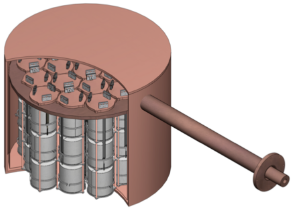
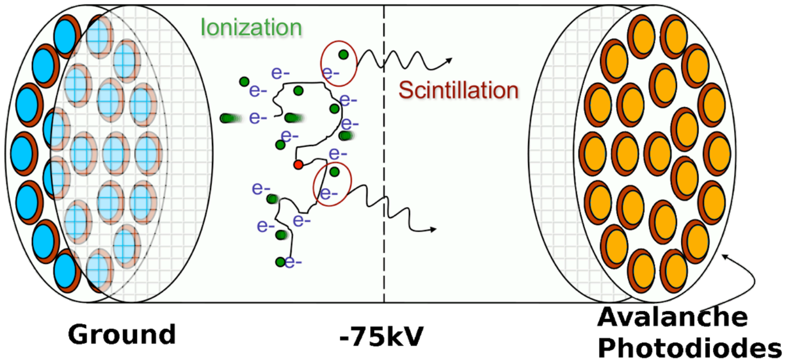
^{128}Te	0.868 MeV	31.7%

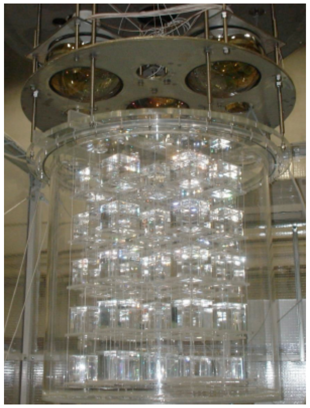
Lower Background!

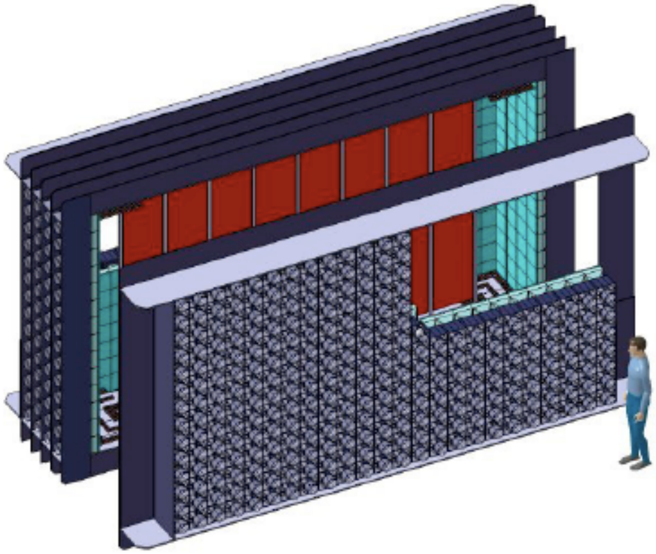
An explosion of technology!

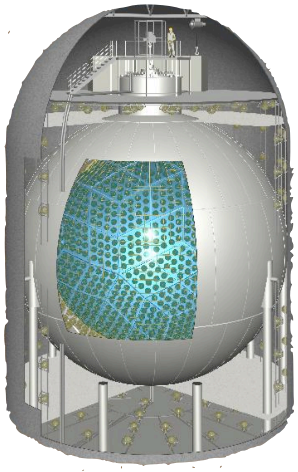






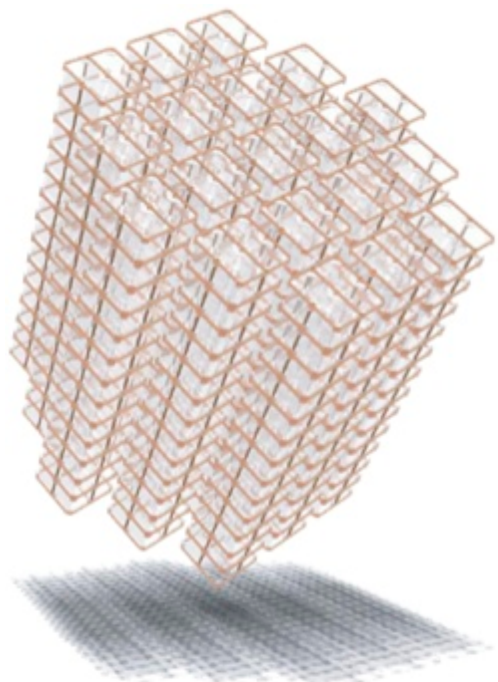






Because of the sensitivity needed almost all experiments have the source = detector.

CUORE



Super Cool and a Big Deal

Super cool

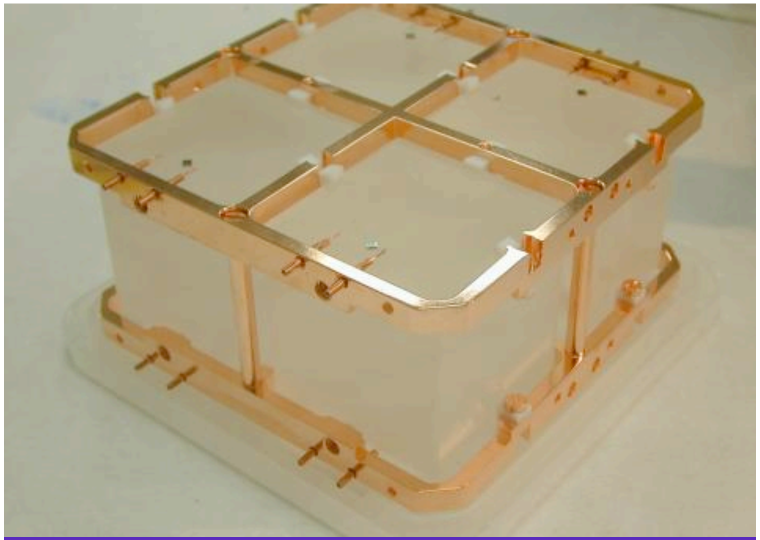
TeO_2 crystals operated as bolometers in a dilution refrigerator at approximately ~10mK.

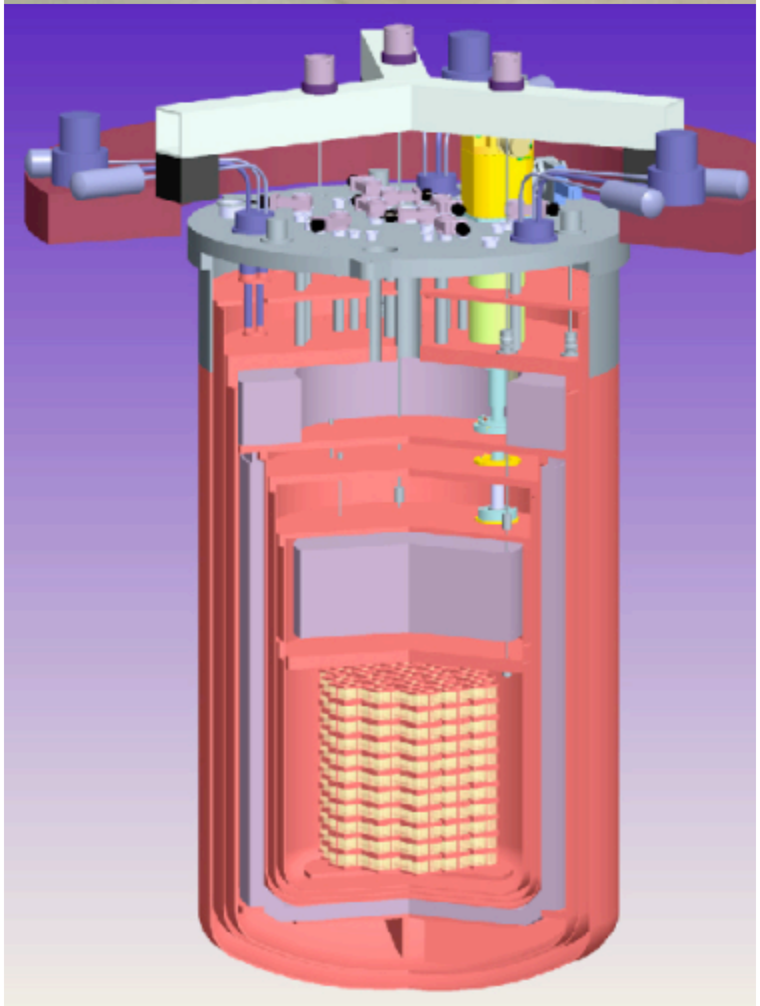
bolometer = temperature measurement

Big Deal

Largest detector currently under construction, 750kg with 206 kg of ^{130}Te.

Next largest are EXO and KamLAND Xen with140kg and 129kg of ^{136}Xe respectively.

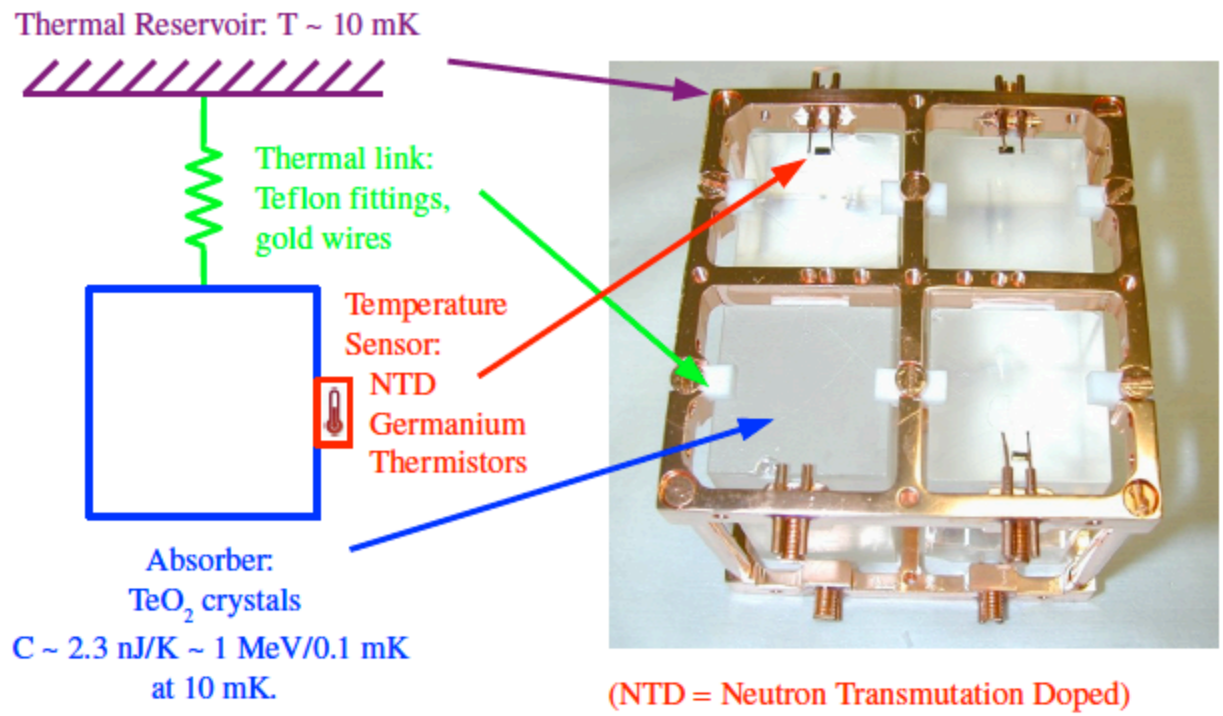


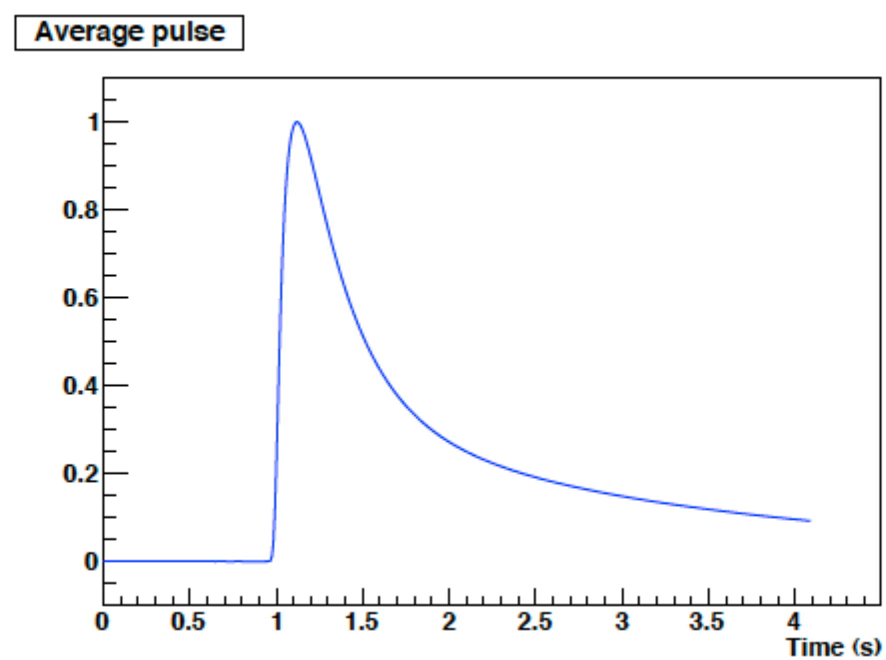


TeO_2 crystals are in a dilution refrigerator at approximately ~10mK.

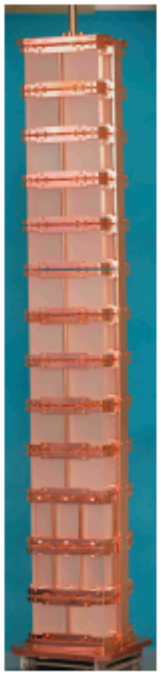
A very sensitive thermometer glued onto the crystal is used to measure the heat generated by the energy deposition.

The peak pulse height is proportional to the energy, but it's not very fast.

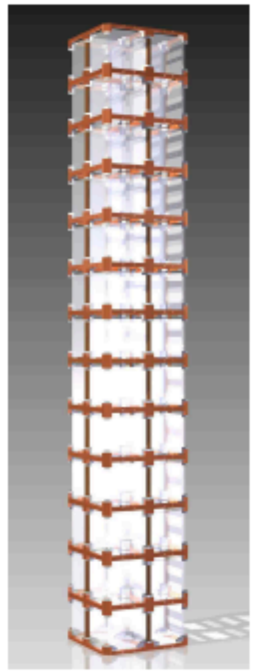




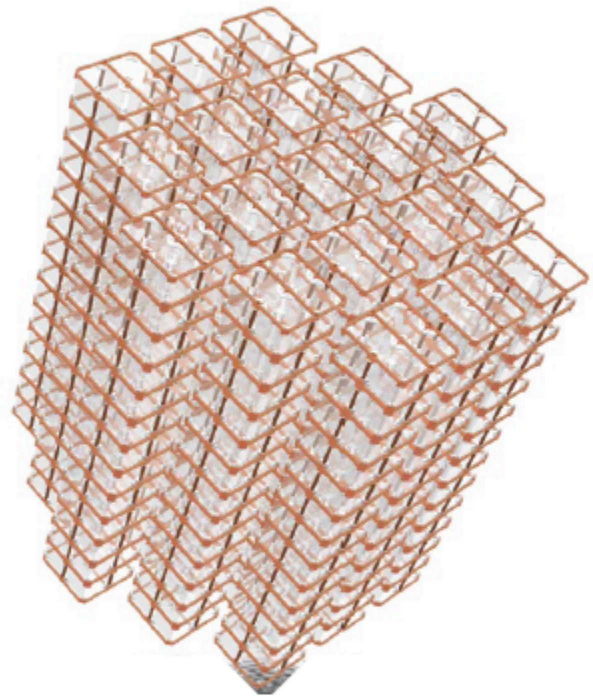
The Next Generation of Bolometer Experiments:



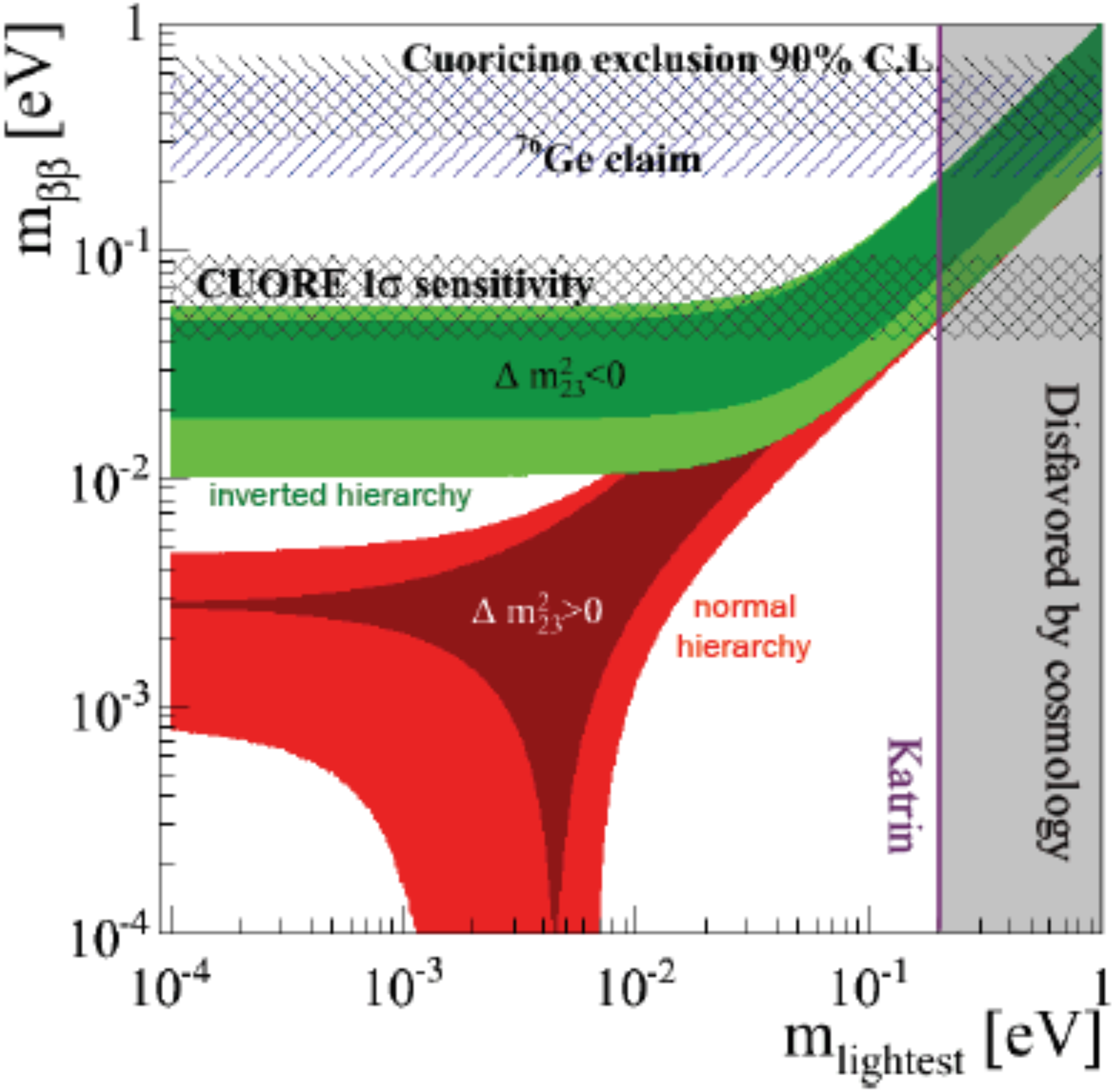
Cuoricino
2003–2008
11 kg ^{130}Te



CUORE-0
2012–2014
11 kg ^{130}Te



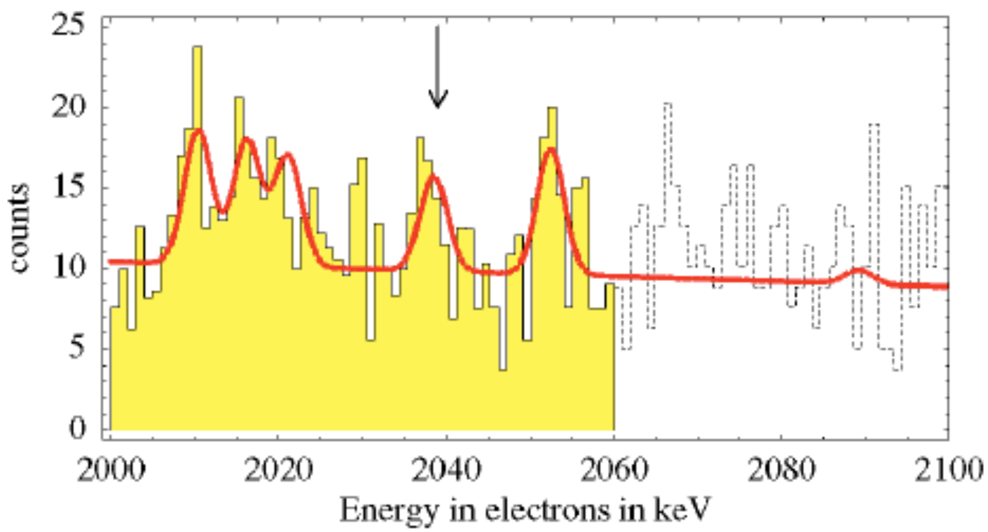
CUORE
2013–2018
206 kg ^{130}Te



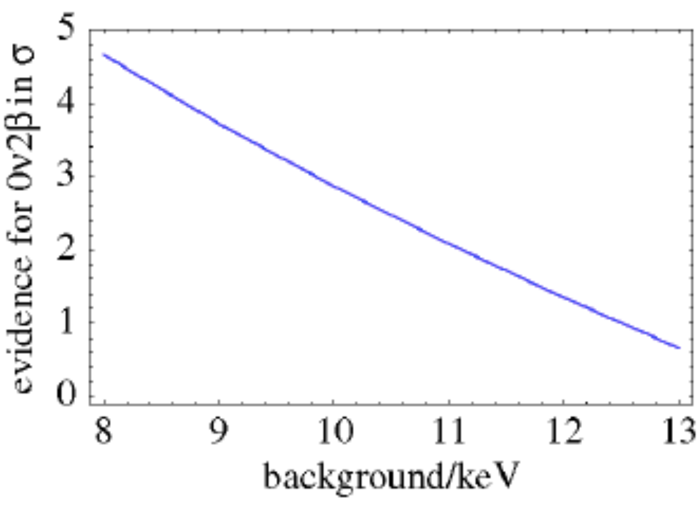
This is the only experiment currently under construction that pushes into the inverted hierarchy.

The Controversial Signal

Heidelberg-Moscow Experiment using ^{76}Ge......

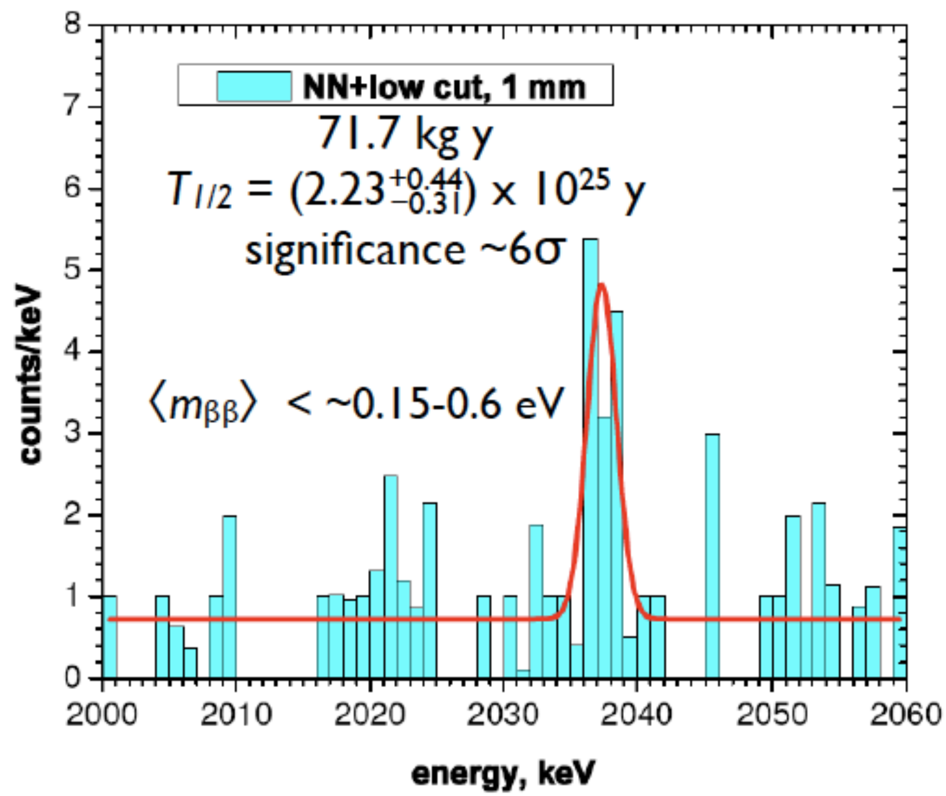


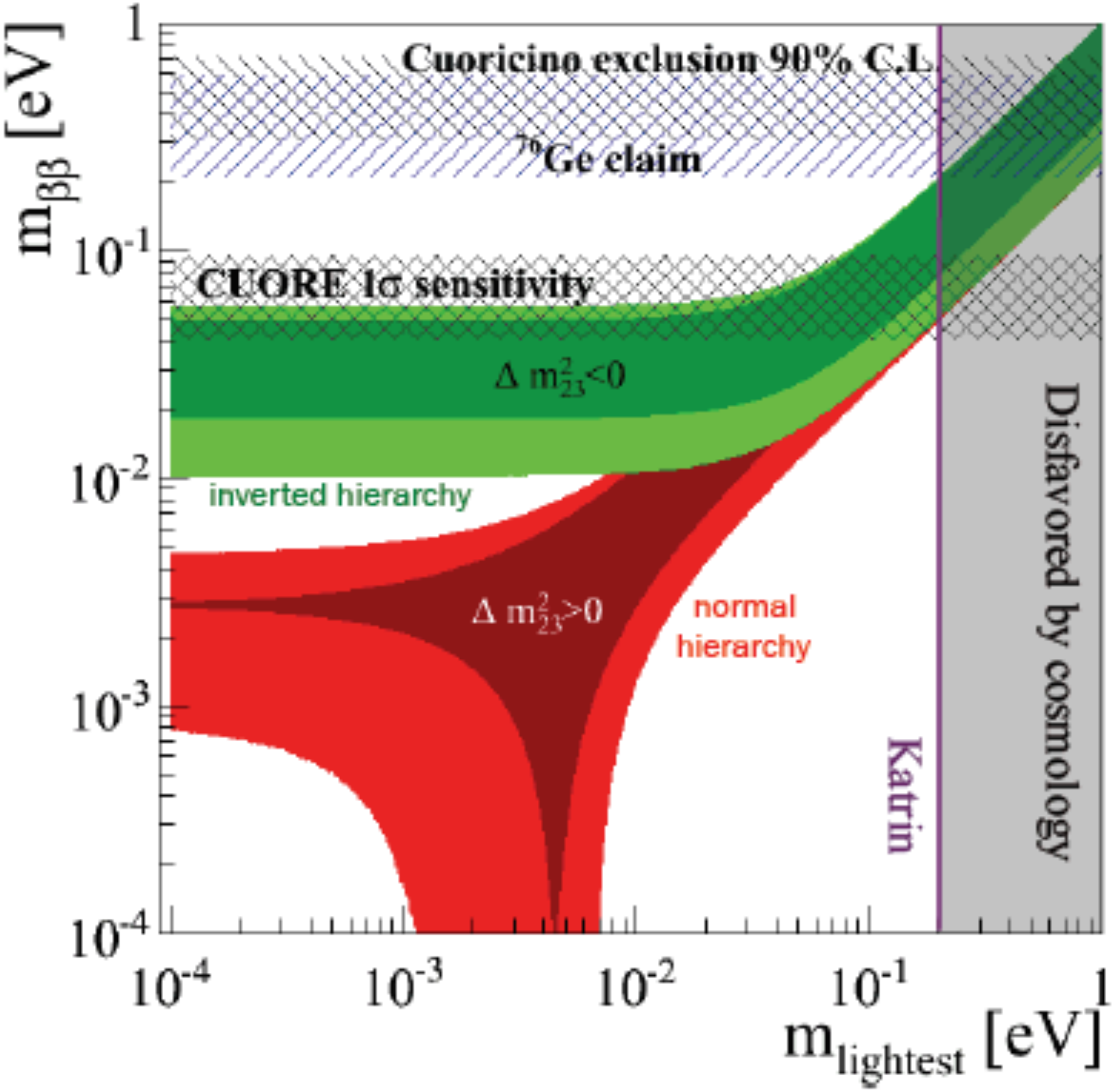
From: Nuclear Physics B 726 (2005) 294–316



Final Analysis of the data using more advanced techniques makes the measurement almost background free.

Klapdor Kleingrothaus *et al.*, Mod. Phys. Lett. A **21** (2006) p 1547.





This is the only experiment currently under construction that pushes into the inverted hierarchy.

If CUORE sees something by 2020

Go after more rare processes to determine whether its the "vanilla" standard model or new physics.

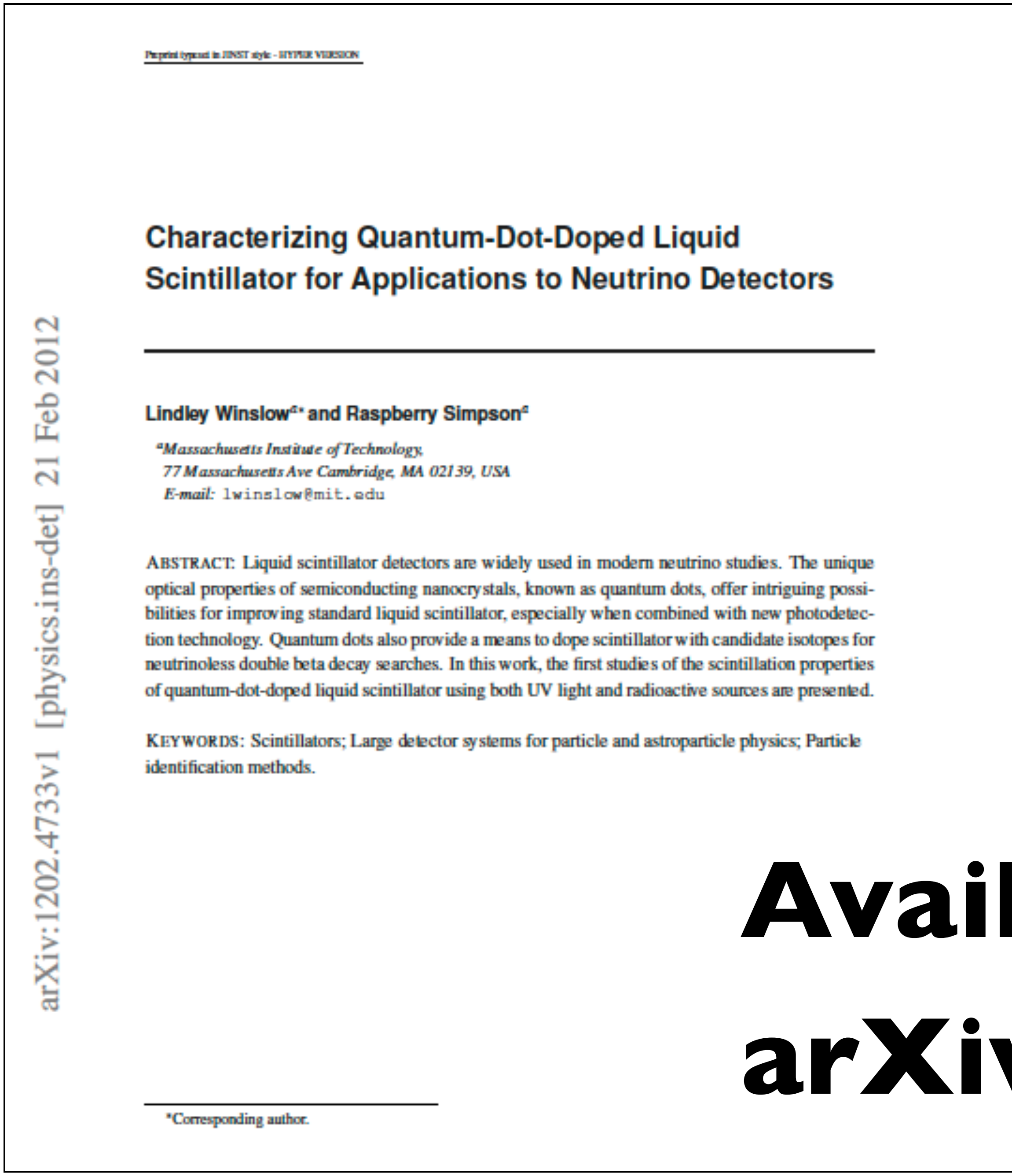
If another experiment sees something and CUORE doesn't

If no experiments see a signal.

Bigger Cleaner Better Detector

First Results from ν

Because ν's are worth it.


Preprint typeset in JINST style - HYPER VERSION

Characterizing Quantum-Dot-Doped Liquid Scintillator for Applications to Neutrino Detectors

Lindley Winslow[a*] **and Raspberry Simpson**[a]

[a] *Massachusetts Institute of Technology, 77 Massachusetts Ave Cambridge, MA 02139, USA*
E-mail: `lwinslow@mit.edu`

ABSTRACT: Liquid scintillator detectors are widely used in modern neutrino studies. The unique optical properties of semiconducting nanocrystals, known as quantum dots, offer intriguing possibilities for improving standard liquid scintillator, especially when combined with new photodetection technology. Quantum dots also provide a means to dope scintillator with candidate isotopes for neutrinoless double beta decay searches. In this work, the first studies of the scintillation properties of quantum-dot-doped liquid scintillator using both UV light and radioactive sources are presented.

KEYWORDS: Scintillators; Large detector systems for particle and astroparticle physics; Particle identification methods.

*Corresponding author.

Available at arXiv:1202.4733

What are Quantum Dots?

Quantum Dots are semiconducting nanocrystals.

Most of the time a shell of organic molecules is used to suspend them in an organic solvent (toluene) or water.

Why are they so popular?

Because of their small size, their electrical and optical properties are more similar to atoms than bulk semiconductors.

In fact, the optical properties of quantum dots with diameter <10nm is completely determined by their size.

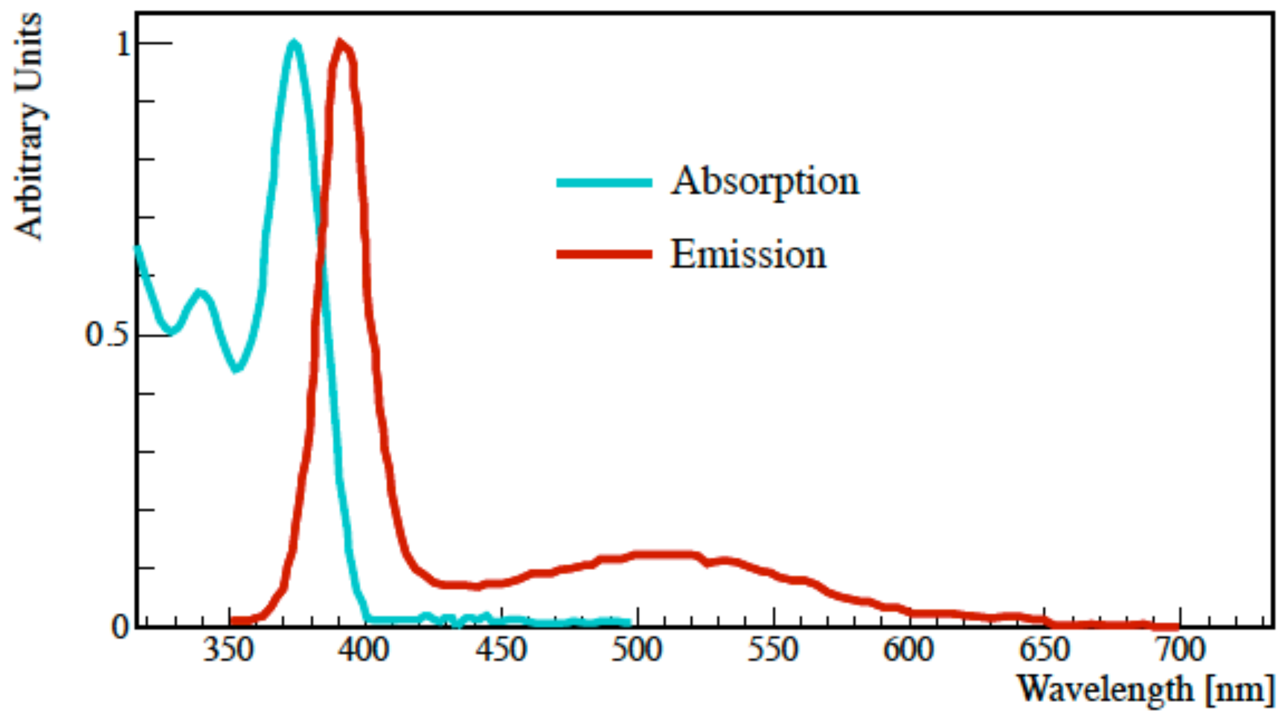
Finally:

Their synthesis allows precise control of the size of the quantum dots.

Can use them to make any wavelength of light that you want!

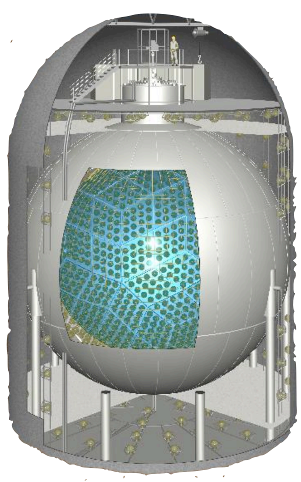
Example CdS Quantum Dot Spectra:

These are 400nm dots made from CdS. They absorb all light shorter than 400nm and re-emit it in a narrow resonance around this wavelength.



Other types of quantum dots include CdSe, CdTe, and ZnS....

What can quantum dots do for neutrino experiments especially neutrinoless double beta decay?



Reminder: liquid scintillator makes light when charged particles go through it, and we know how to make very large liquid scintillator detectors.

What can quantum dots do?

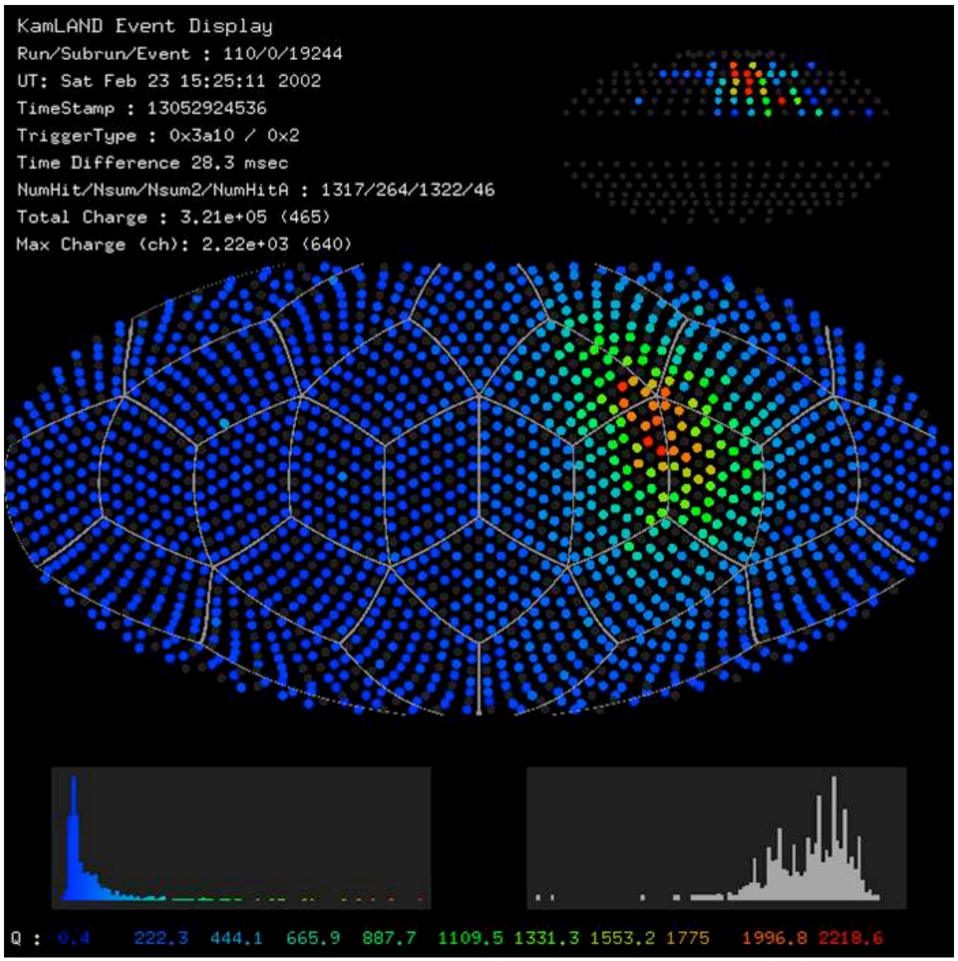
Perfectly tune the wavelength of your scintillator's emission

- Increases total light collected by photomultiplier tubes.
- Match photo-cathode efficiency of new devices.

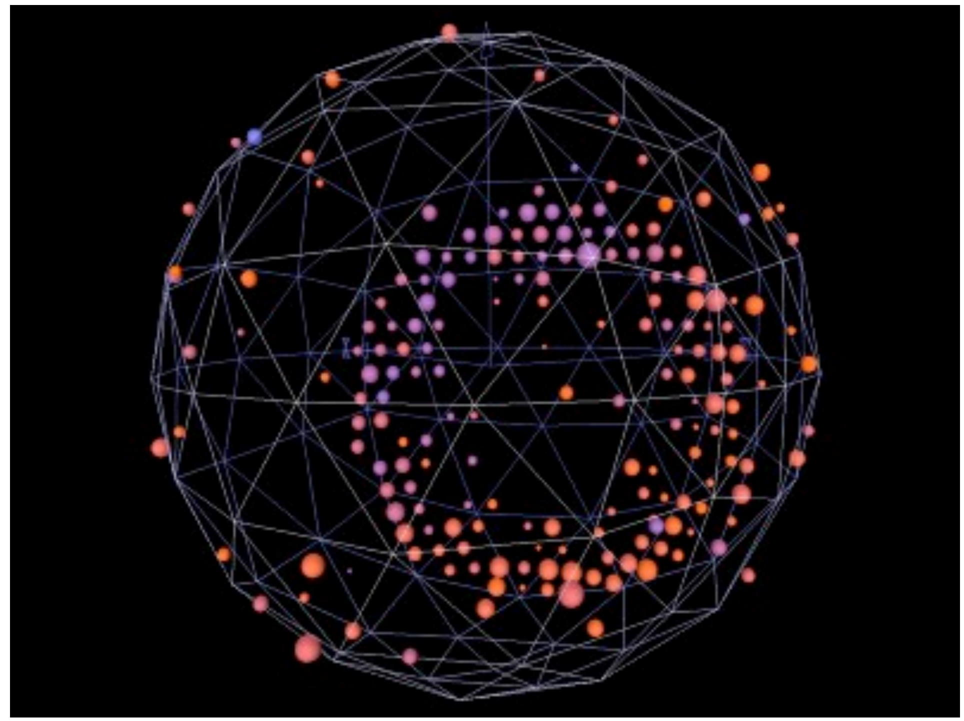
An example of a new devices being design by the LAPPD collaboration (Large Area Picosecond Photodetectors). Such a device could be made cheaper than a PMT, covers more area, and improves timing resolution by an order of magnitude.

Remember:

Scintillator detectors still have Cerenkov light it just gets overwhelmed by the scintillation light.

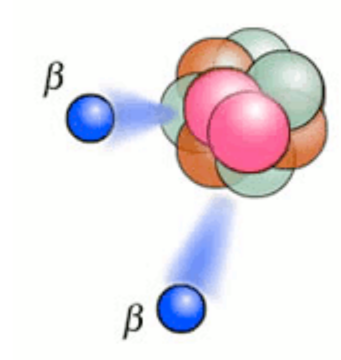


Scintillation: A KamLAND Muon

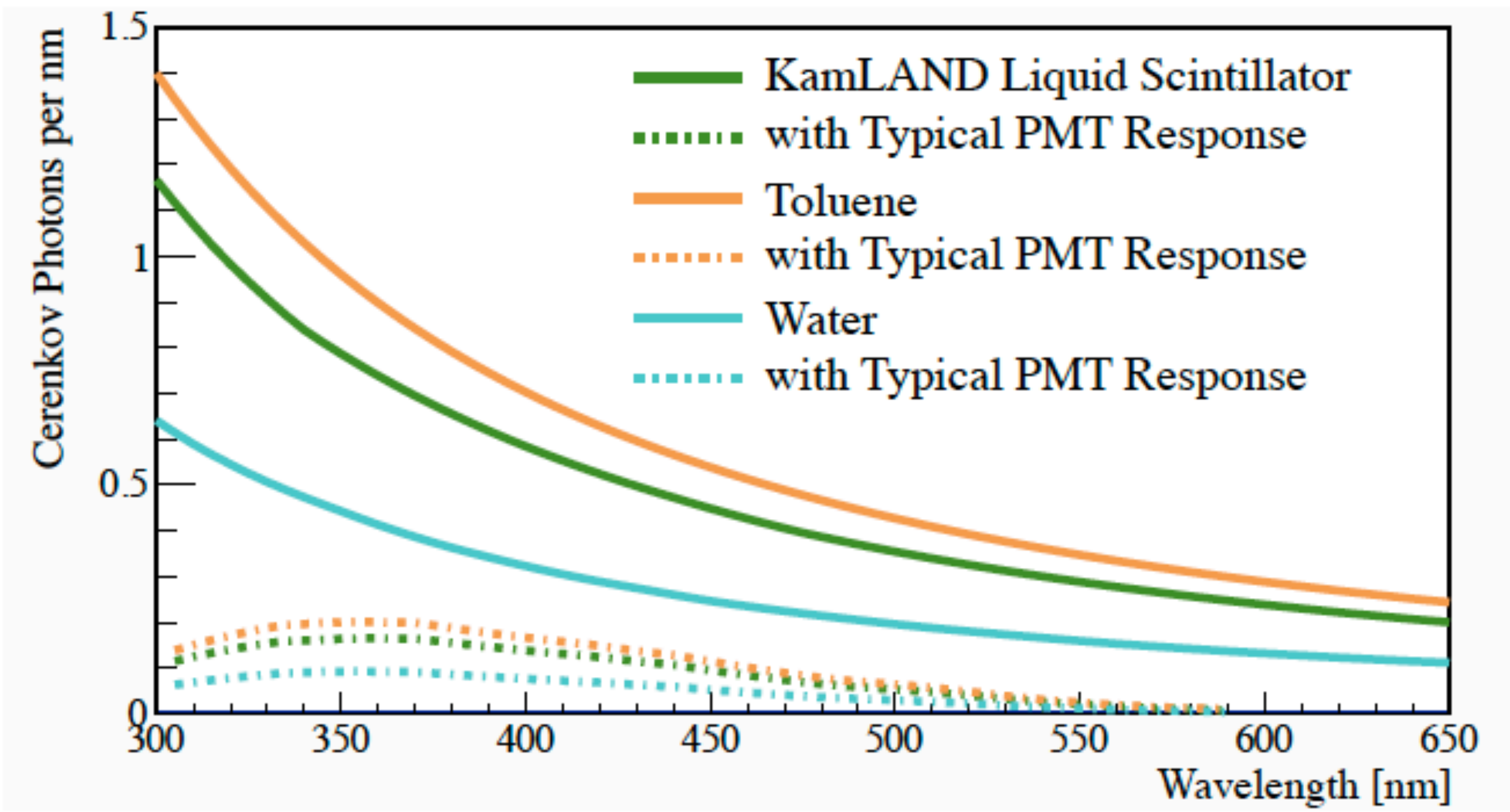


Cerenkov: A MiniBooNE Muon

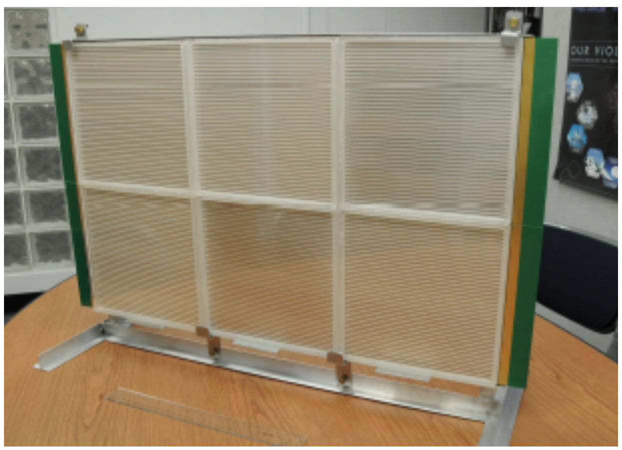
Event Topology:



- Some fraction of the Cerenkov light is produced above the scintillation absorption cut-off.
- Cerenkov light travels to PMTs faster.
- Use quantum dots to tune the absorption cut-off.



This application is perfect for the LAPPD's.



First **P** is for picosecond.

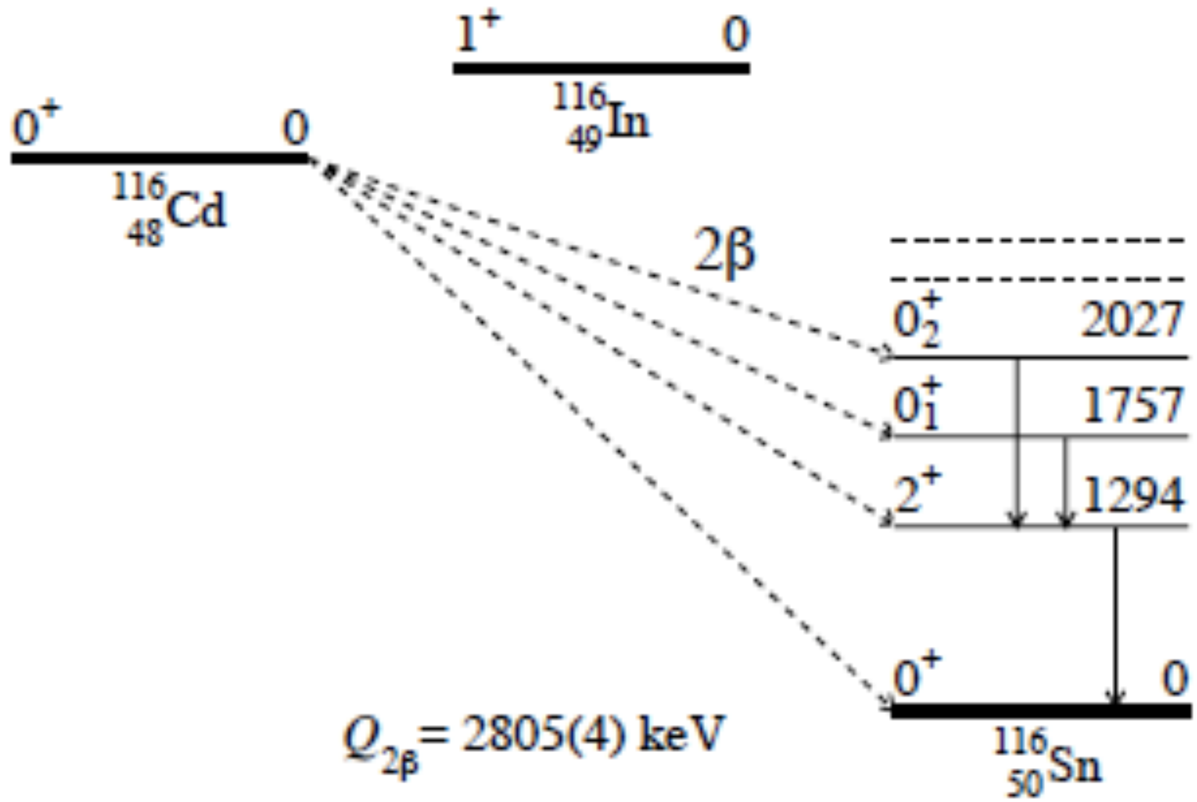
What can quantum dots do?

They provide you a robust way to dope liquid scintillator with heavy metals.... especially Cd!

Why do we like Cd so much?

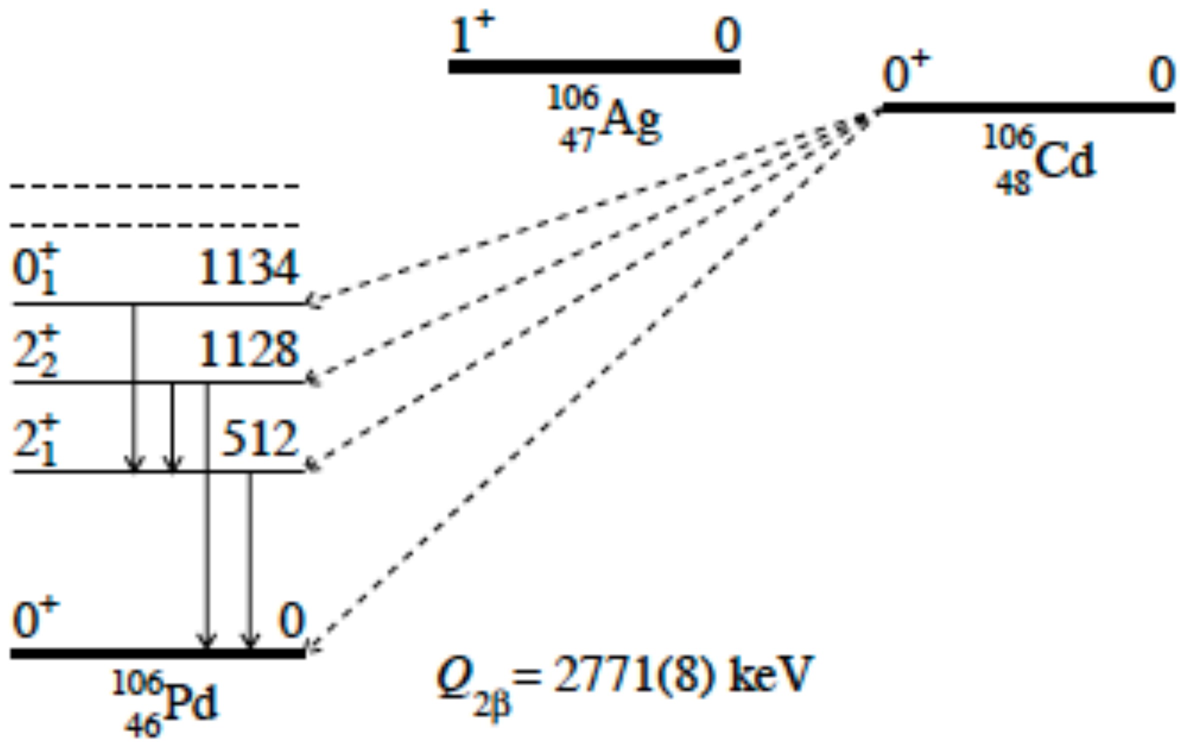
Double Beta Decay Candidate!

Danevich et al. PHYSICAL REVIEW C **68**, 035501 !2003"



Also Double Positron + Electron Capture Decay Candidate!

Danevich et al. PHYSICAL REVIEW C **68**, 035501 !2003"

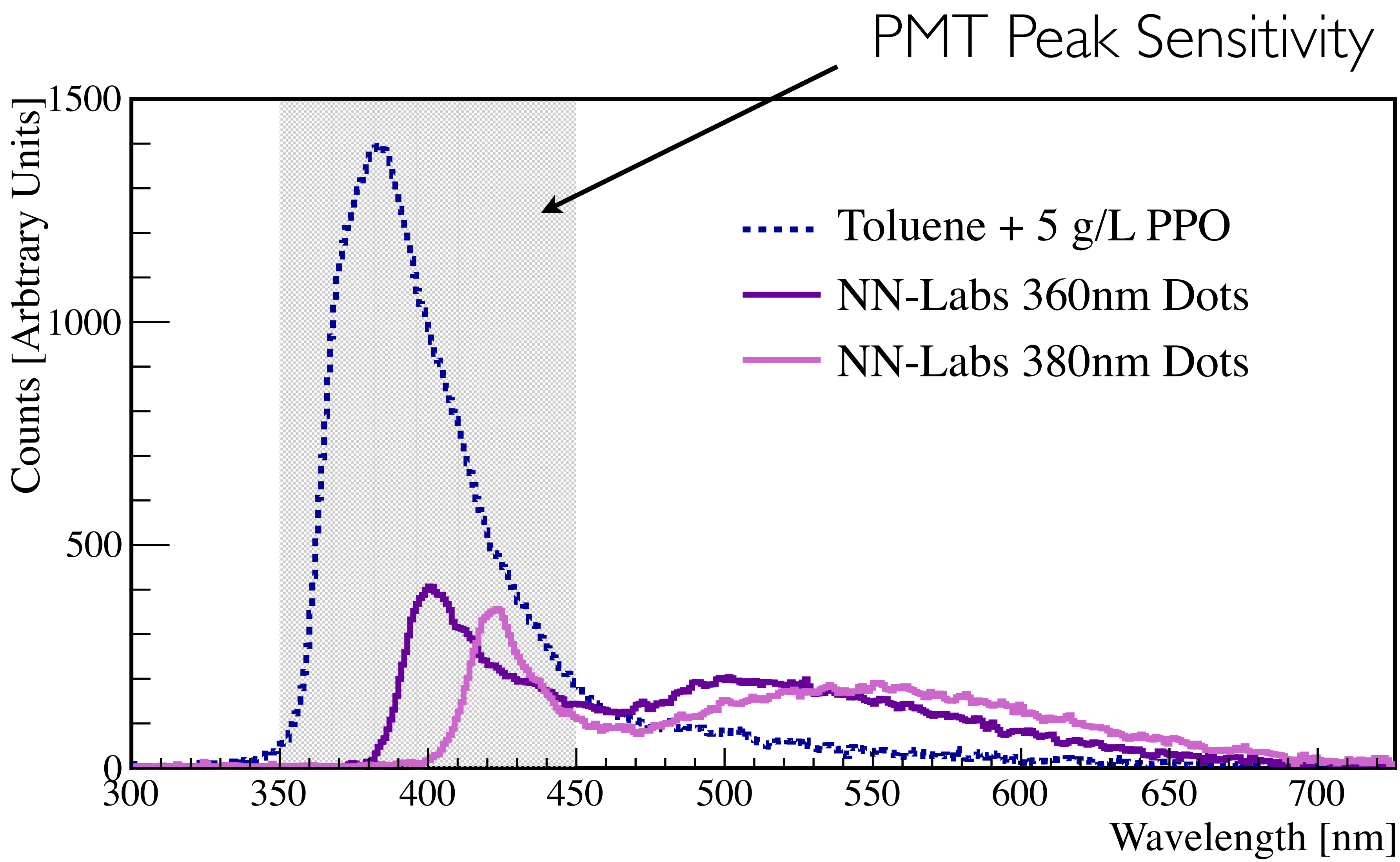


Now for some basic measurements

(Because no one has done this before!)

How much light?

Excite the scintillator with a 280nm LED.



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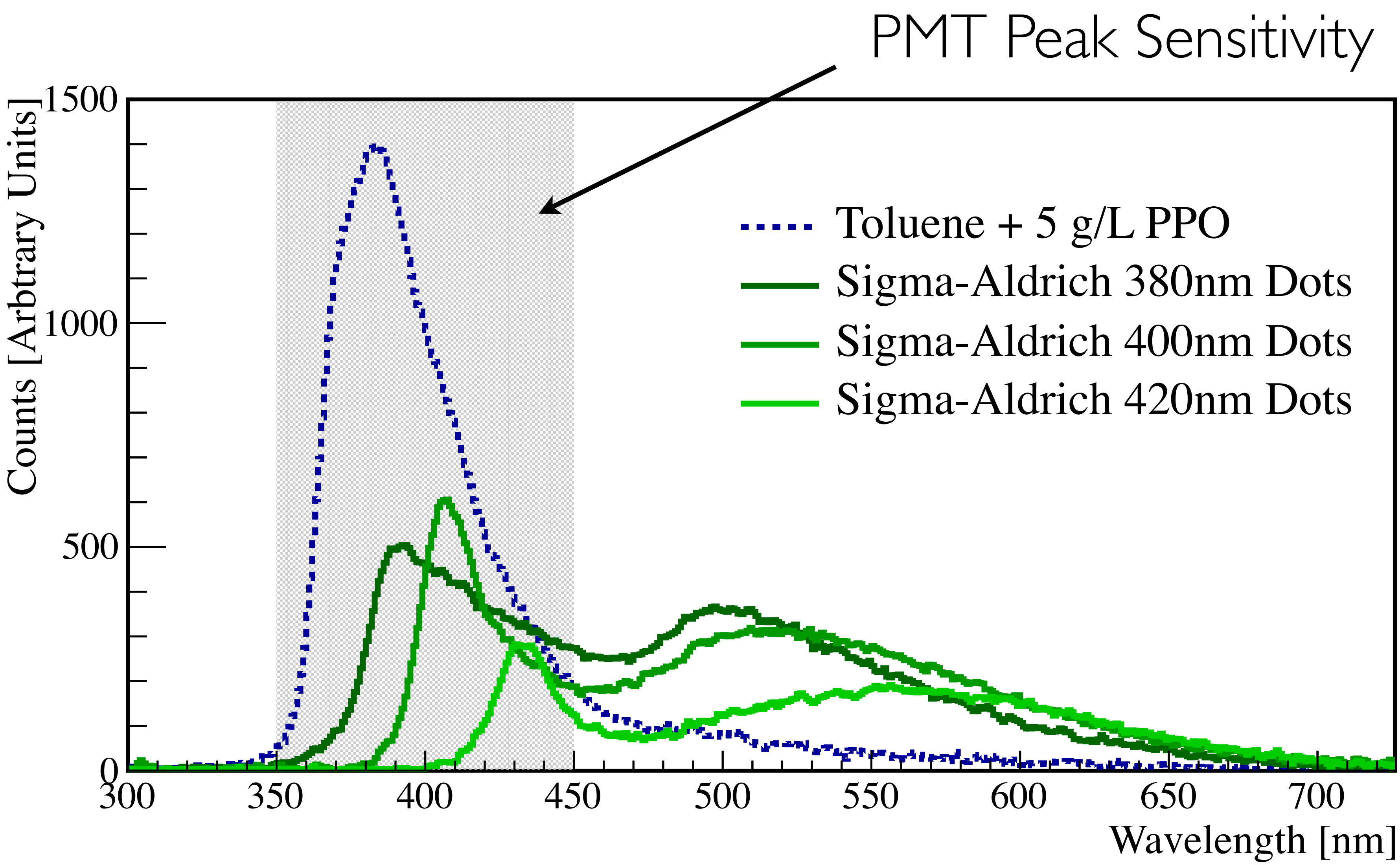
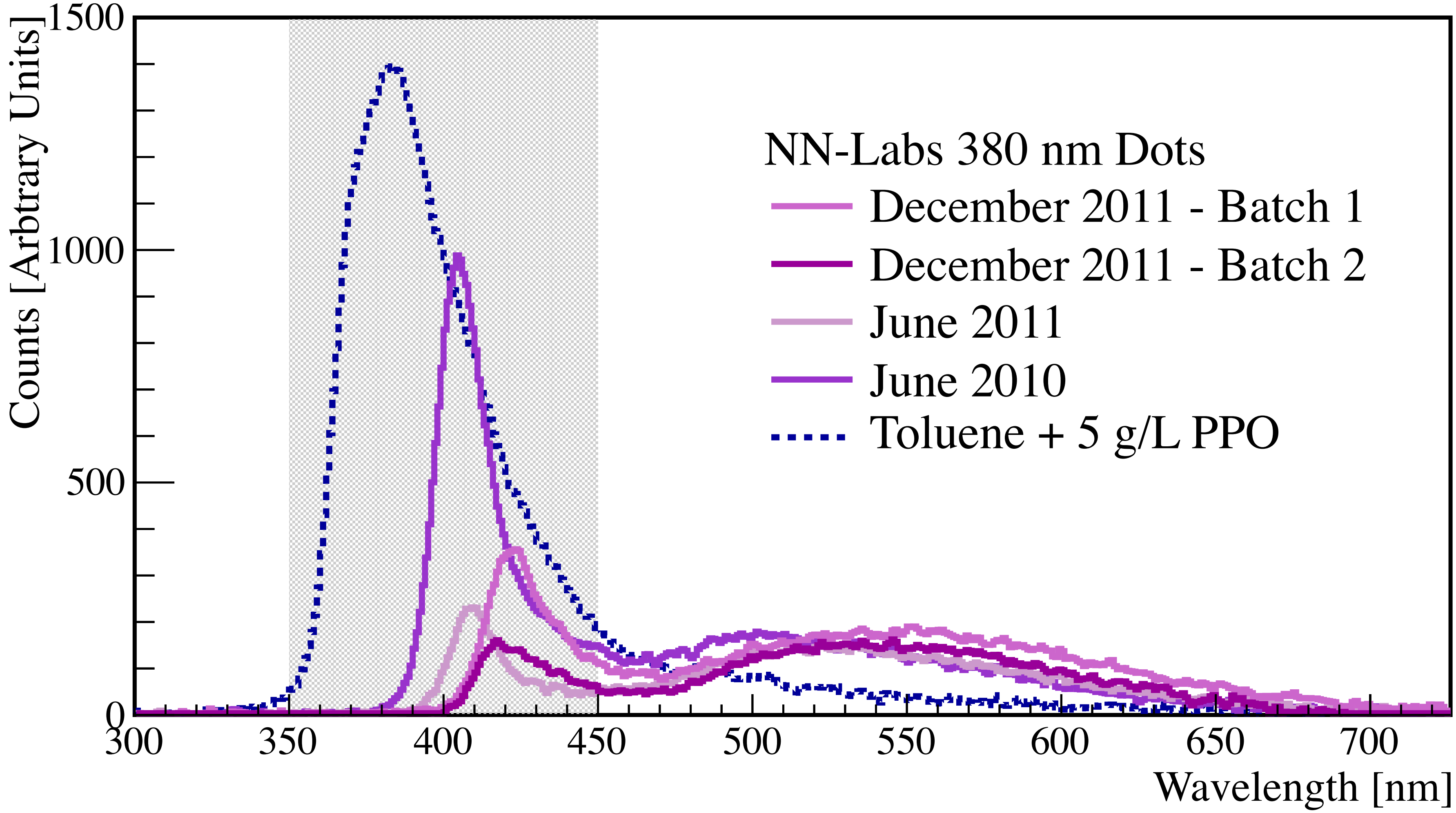
Excite the scintillator with a 280nm LED.



Do Quantum Dots Age?

One of the NSF reviewers asked if this was an issue.

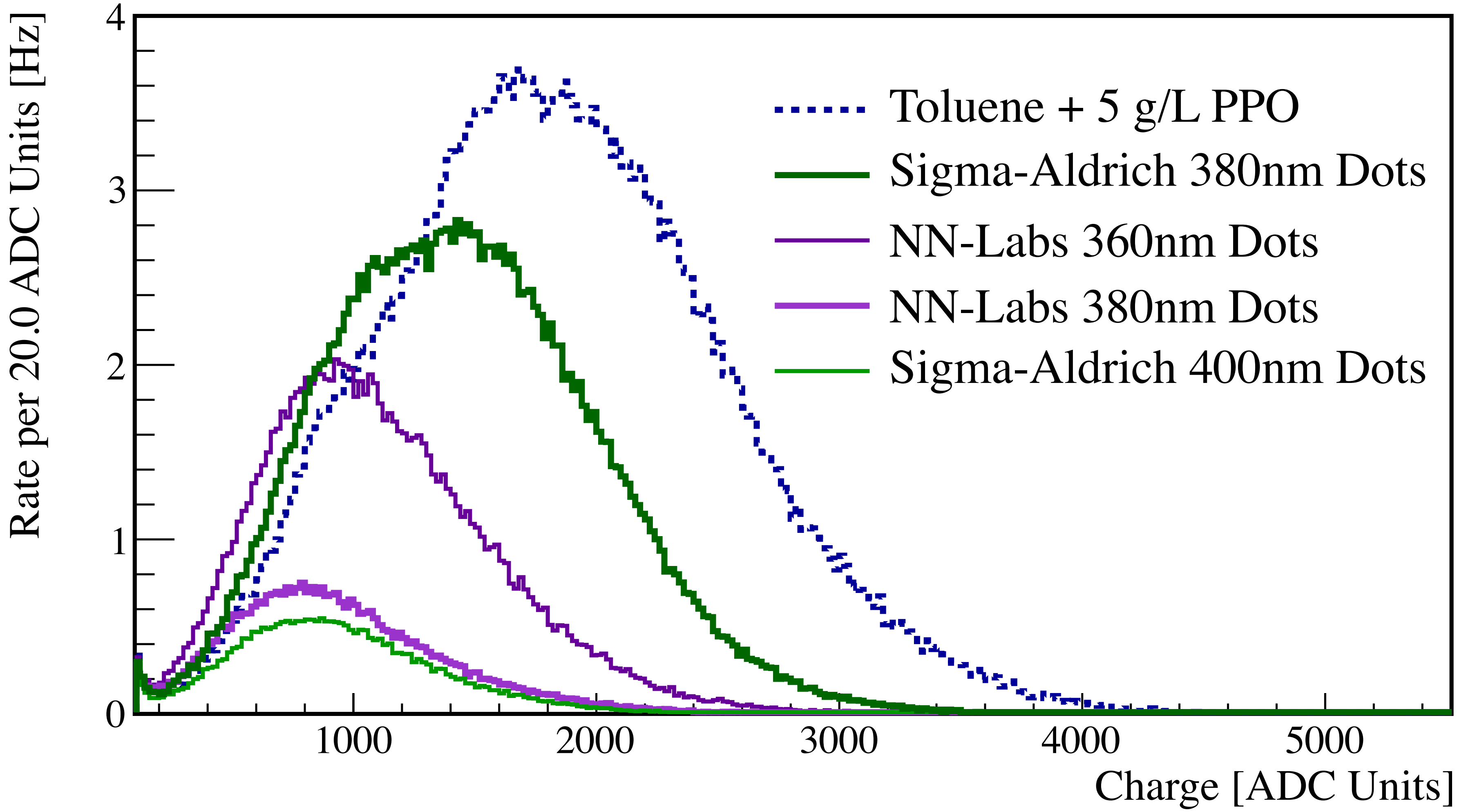


No evidence for aging.

The bigger issue for us seems to be batch to batch variations.

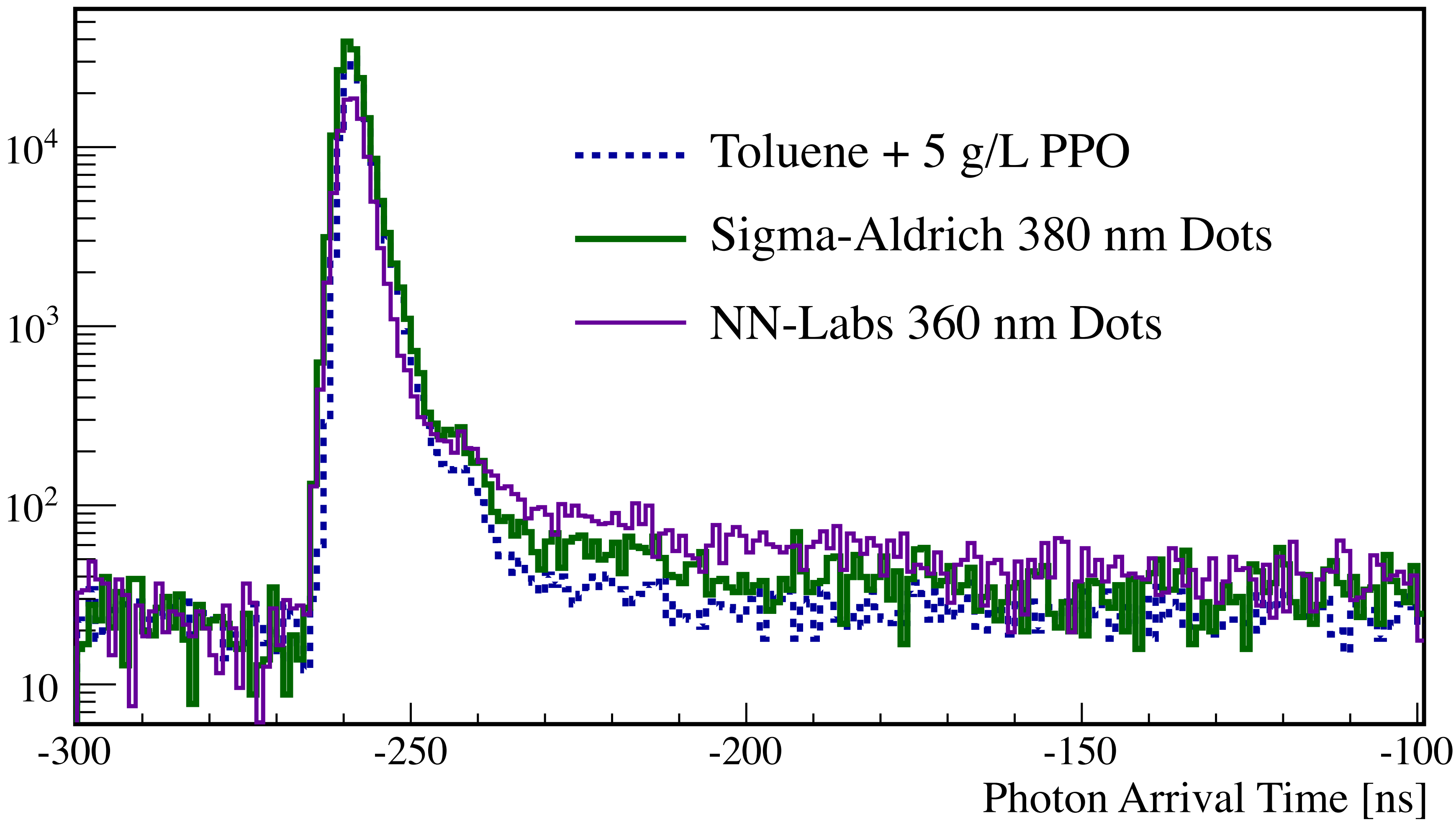
Does the scintillator still scintillate?

Study the scintillator with a ^{90}Sr beta source.



The light yield is reduced compared to the standard scintillator

Do they change the timing characteristics of the scintillator?



The answer is no, though the quantum dot scintillator seems to have a slightly larger late light component.

Next Steps:

ν

1L Detector - This Summer

- More quality control of the dots before using.
- Nitrogen purging for better light yield
- Larger quantum quantities
- Attenuation length measurements

1m³ Detector

- Make use of knowledge from 1L detector
- Perhaps collaborate with LAPPD collaboration
- Make measurement of two neutrino double beta decay in ^{116}Cd.

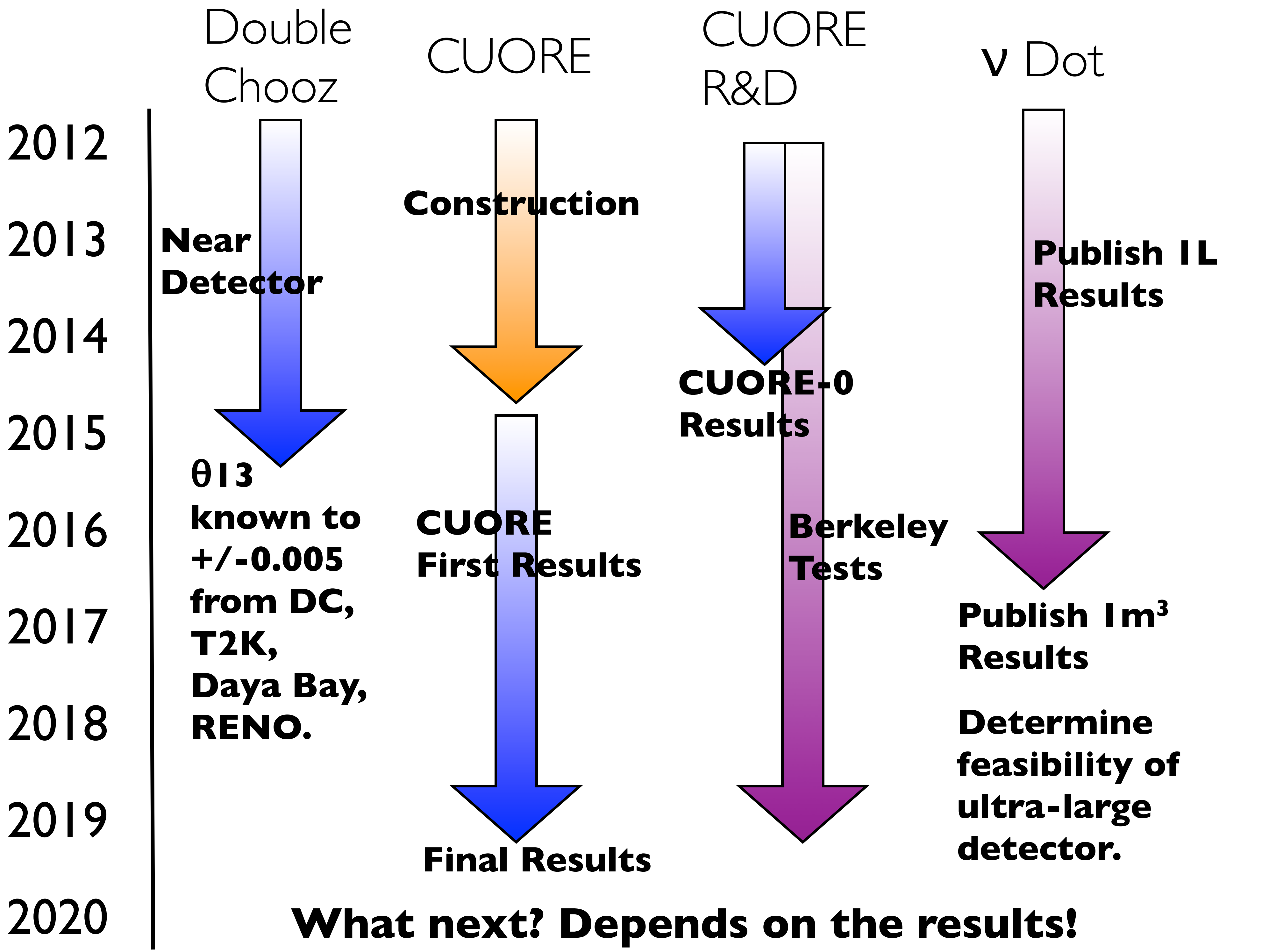
With 10g of 116Cd, I expect 1000 events in 6 months.

reVolution

You say you want a revolution
Well, you know
we all want to change the world.

You ask me for a contribution
Well, you know
We are all doing what we can

You say we want a real solution
Well, you know
We'd all love to see the plan


Double Chooz
CUORE
CUORE R&D
ν Dot
2012
2013
2014
2015
2016
2017
2018
2019
2020
Near Detector
θ13 known to +/-0.005 from DC, T2K, Daya Bay, RENO.
Construction
CUORE First Results
Final Results
CUORE-0 Results
Berkeley Tests
Publish 1L Results
Publish 1m³ Results
Determine feasibility of ultra-large detector.
What next? Depends on the results!

The Neutrino Revolution

Don't you know its gonna be alright!

Many apologies to the Beatles and the OED.