International Workshop:Neutrino Research and Thermal Evolution of the Earth

27 October 2016

The Importance of Neutrinos and Some New Experiments to Measure Them

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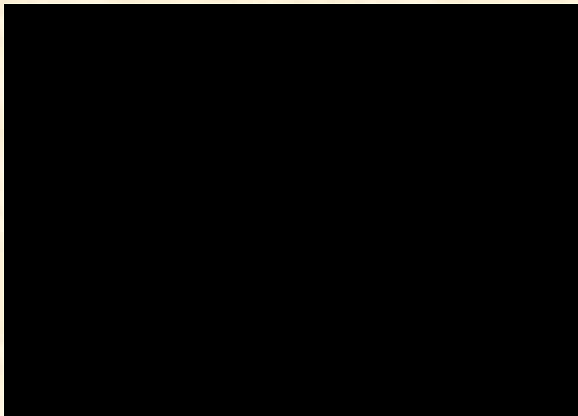
University of Hawaii, Manoa

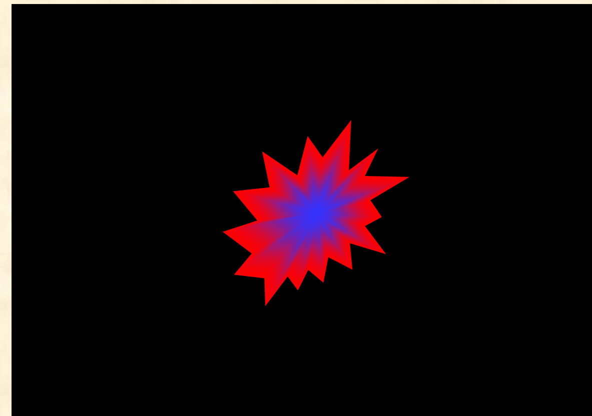
With Many thanks to UH Neutrino Group , KamLAND, mTC, and NuLat Collaboration Colleagues

So, what IS a Neutrino?

This is a Neutrino

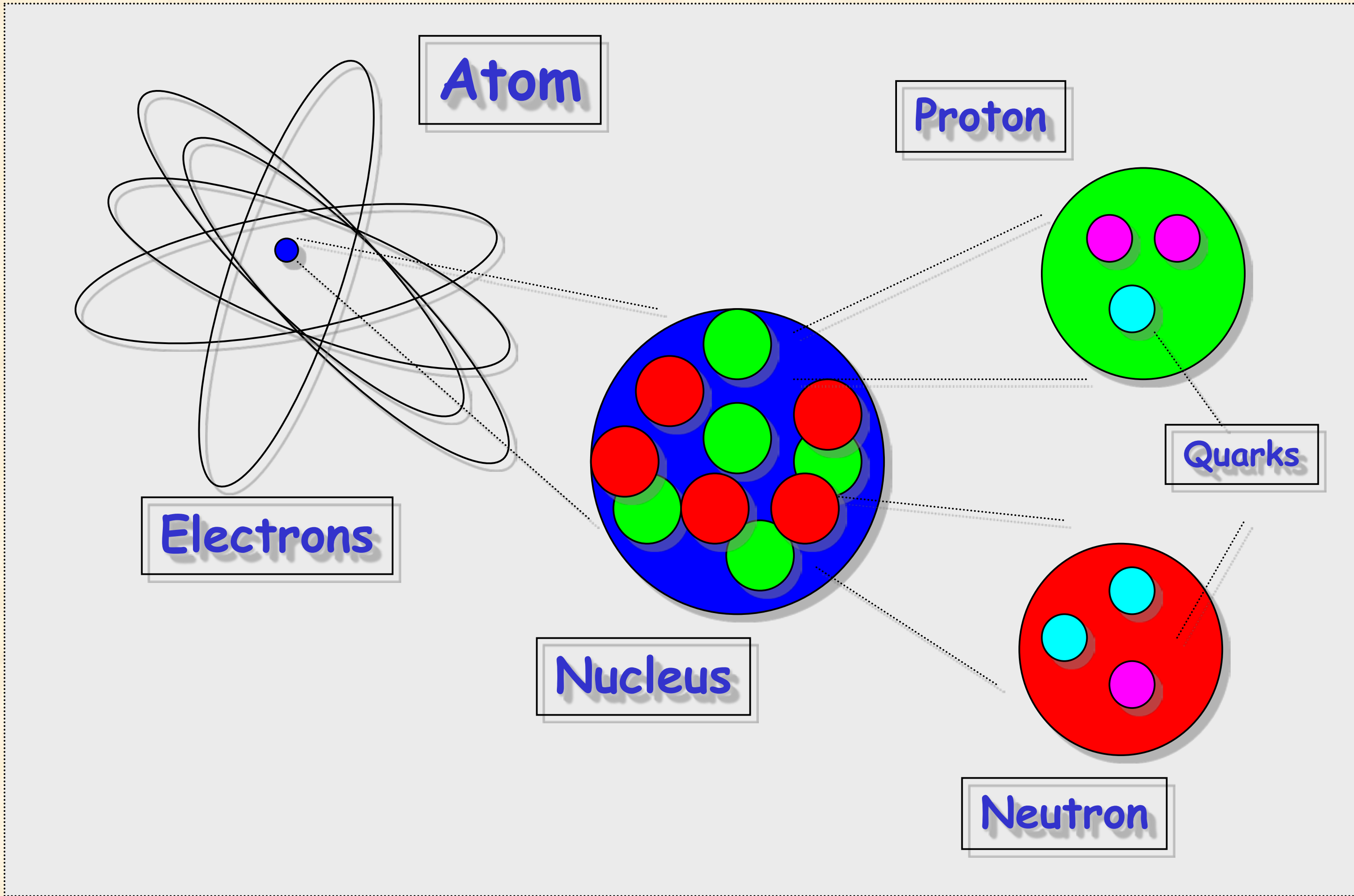


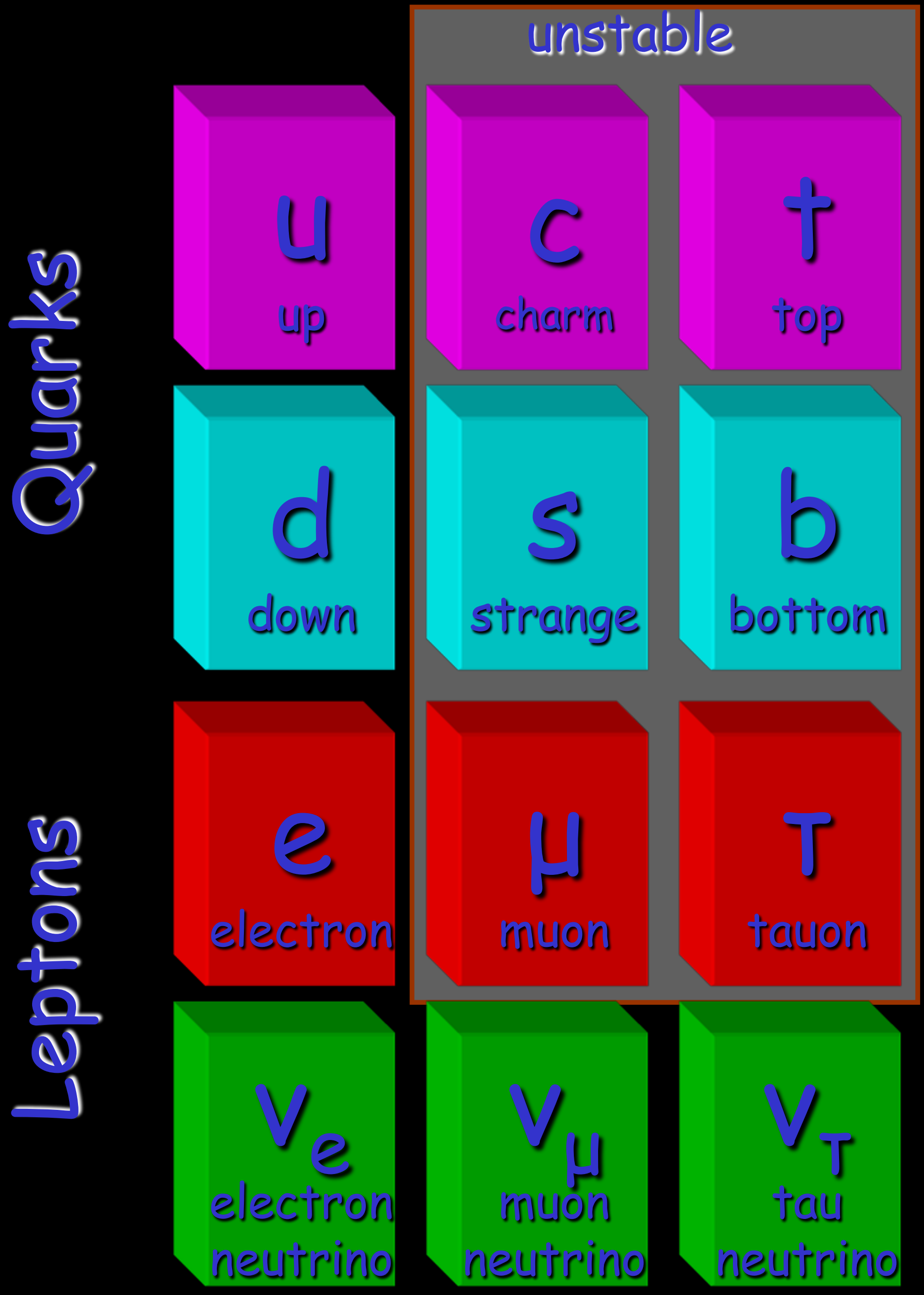
This was a Neutrino



Stable Elementary Particle – 3 of 6 constituents of matter
No electric charge – cannot see it
Very little interaction with matter – goes through the earth unscathed
Has very little mass – less than 1 millionth of electron
Lots of them though – 100 million in your body any time!

Subatomic Structure




unstable
Quarks
Leptons
u
up
c
charm
t
top
d
down
s
strange
b
bottom
e
electron
μ
muon
τ
tauon
νe
electron neutrino
νμ
muon neutrino
ντ
tau neutrino

Where do Neutrinos come from?

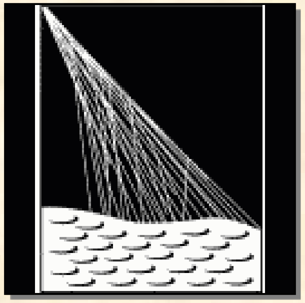
✓ Nuclear Reactors (power stations, ships)

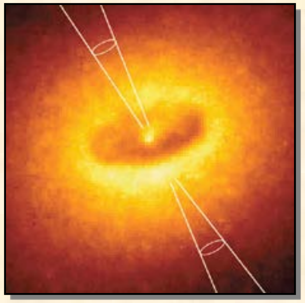
Sun ✓

✓ Particle Accelerator

Supernovae (star collapse)
SN 1987A ✓

✓ Earth's Atmosphere (Cosmic Rays)





Astrophysical Accelerators
IceCube ✓

✓ Earth's Crust (Natural Radioactivity)

Big Bang (here 330 ν/cm³)
Indirect Evidence

So why are neutrinos important?

Anthropic view: Keep physicists busy figuring out why and how….

Very unusual properties… shape shifters, totally unpredicted

Daily use? None! (Yet, but history of electron and many others)

Produced in abundance in Big Bang (associated with excess of matter?)

Supernovae explosions produce nu's in horrendous numbers, and are associated with the production of elements heavier than iron

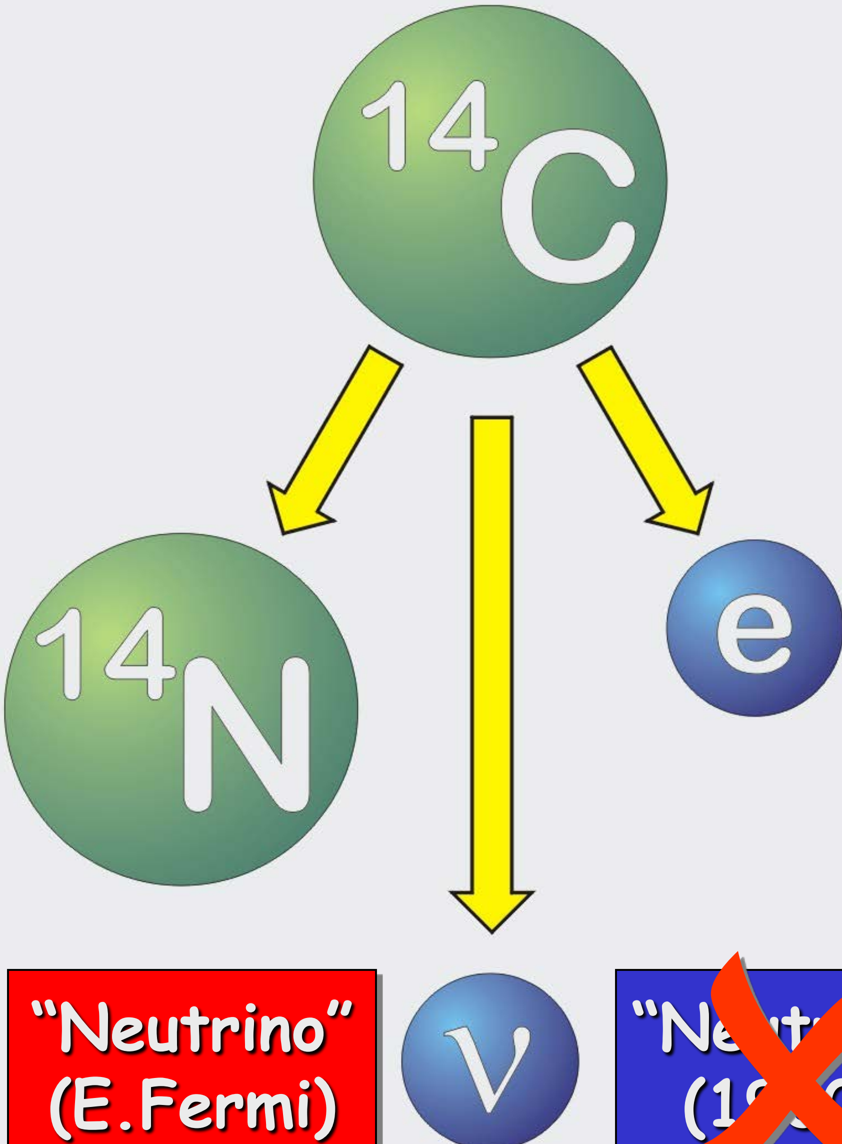
Learning about the interior of sun and earth.

Monitoring nuclear reactors unintrusively and remotely

Communication? Expensive on earth (but crazy fast traders…) Maybe ultimately with ET?

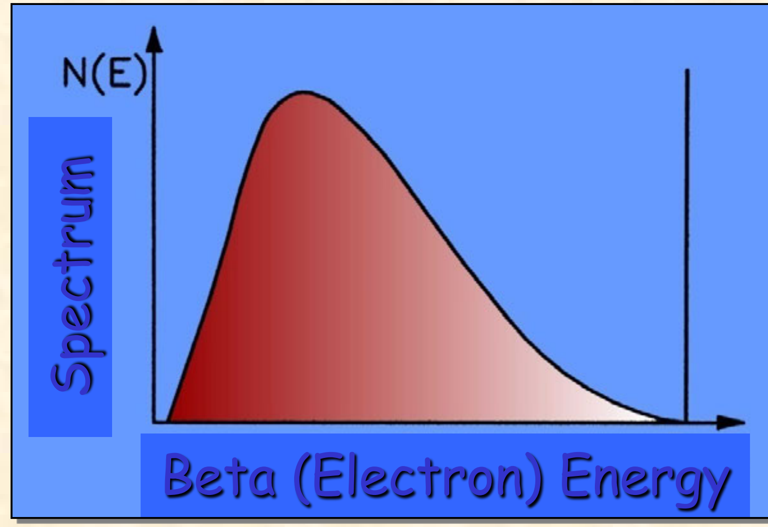
Neutrinos are Fundamental to our existence… and useful too.

How were Neutrinos discovered?



“Neutrino”
(E.Fermi)

~~“Neutron”~~
~~(1930)~~

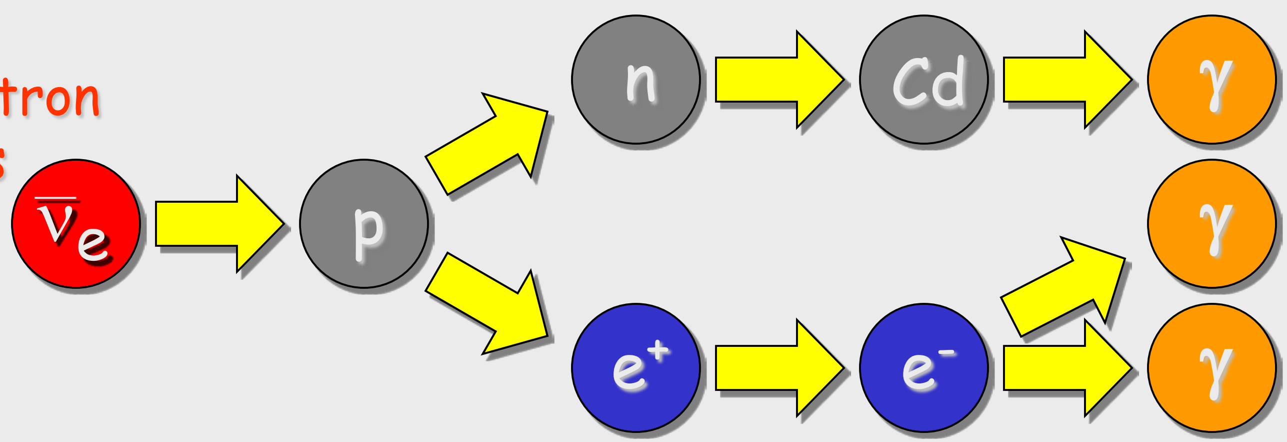


Radioactive Beta Decay

Wolfgang Pauli
(1900-1958)
Nobel Prize 1945

First Detection ! (1954 - 1956)

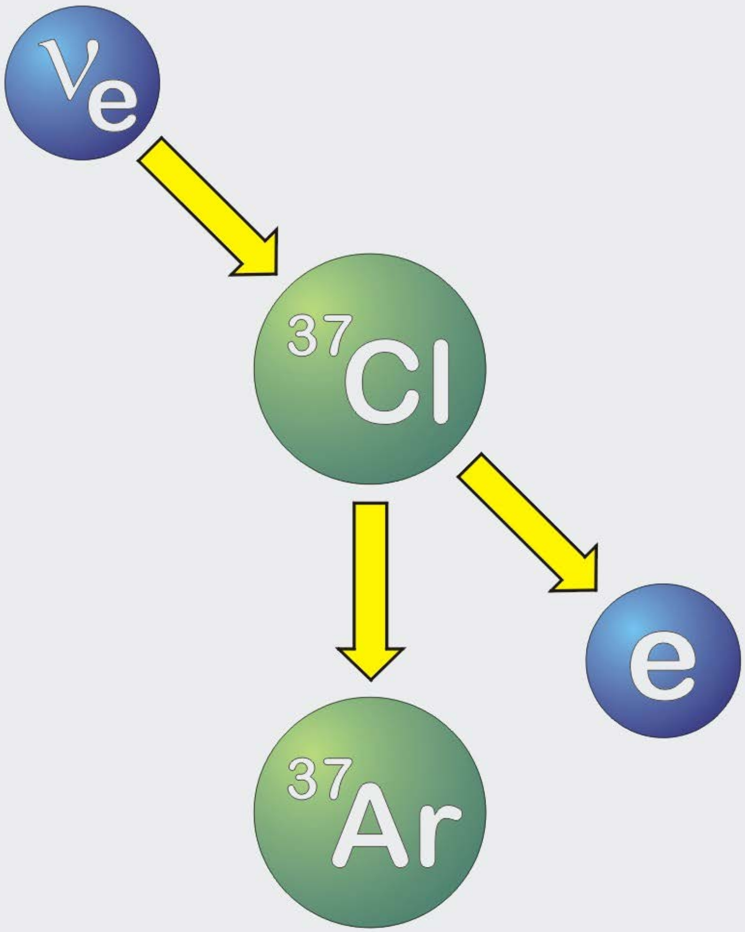
Anti-Electron Neutrinos from Hanford Nuclear Reactor

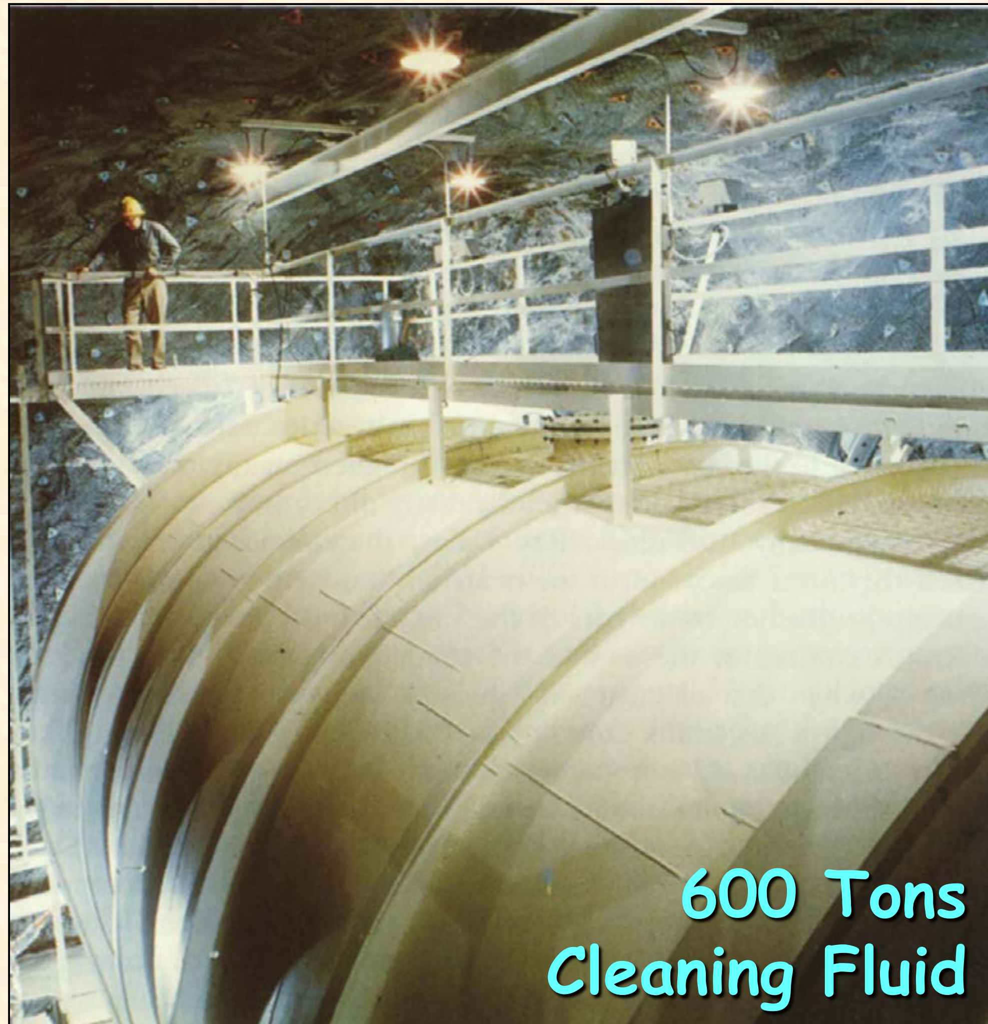


3 gamma quanta in coincidence

First Observation of Solar Neutrinos

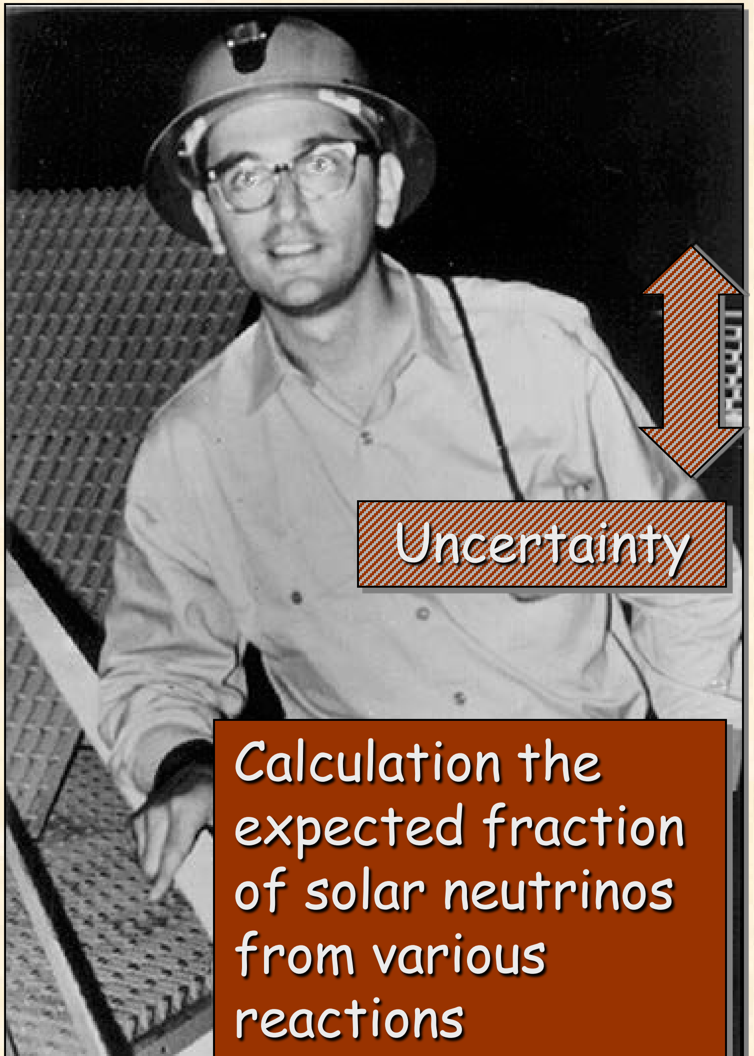
Inverse Beta-Decay ("Neutrino Capture")





Homestake Solar-Neutrino Observatory (since ca.1967)

The Original Solar Neutrino Deficit



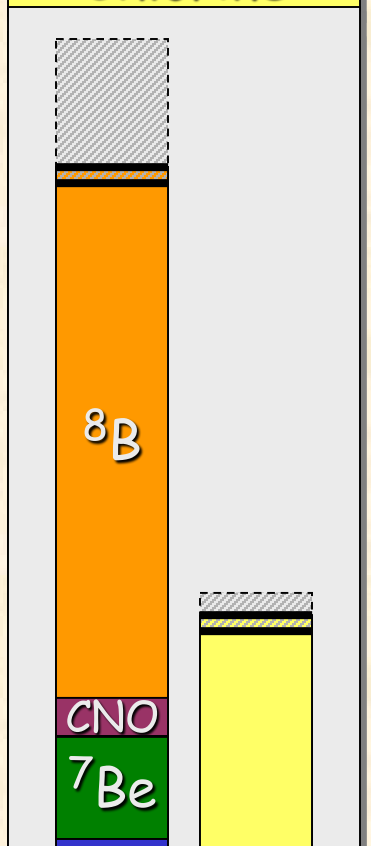
Uncertainty

Calculation the expected fraction of solar neutrinos from various reactions

John Bahcall

Homestake

Chlorine



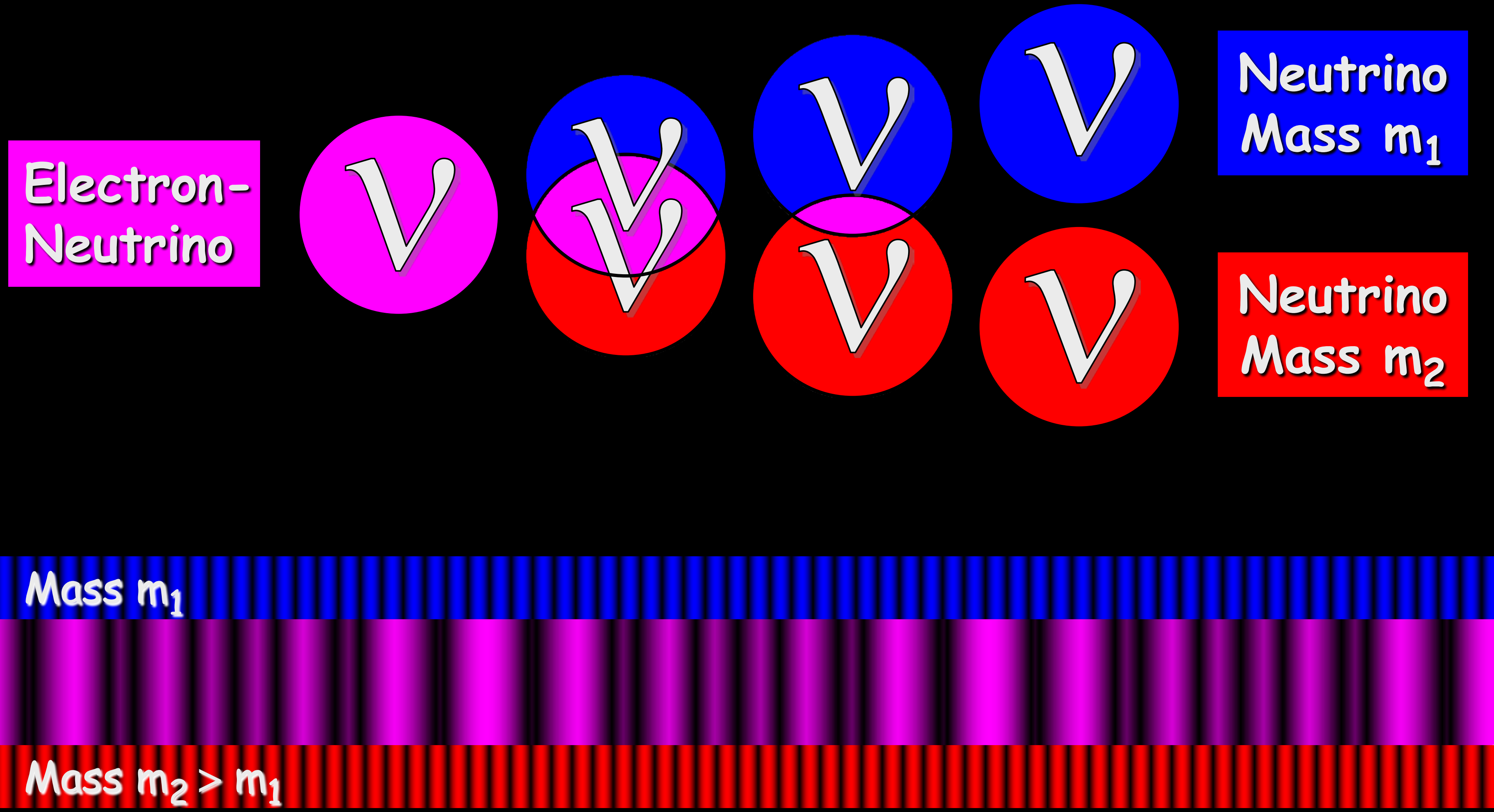
Measured (1967 -1995)

Raymond Davis Jr. Nobel '02

Neutrinos are Shape Shifters!

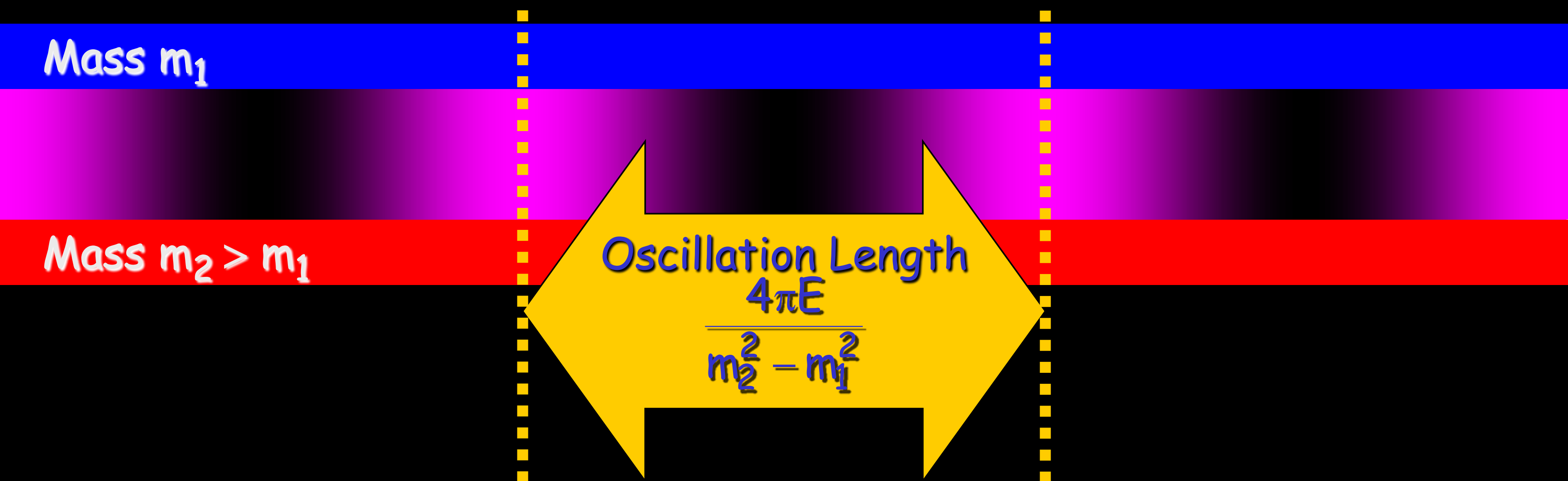
They change from one type (e, mu, tau)
to another (and back again)
as they fly along.

Mixture of Neutrinos of Various Masses

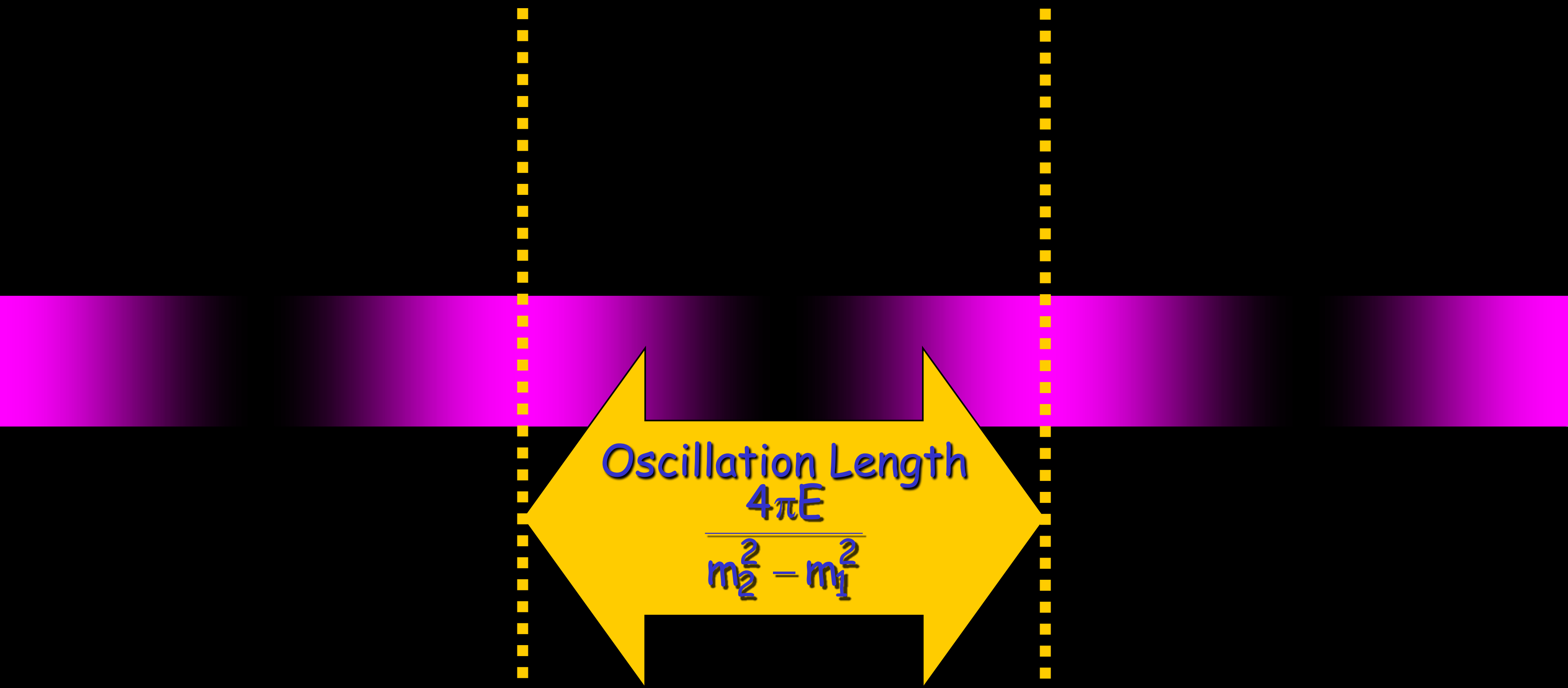


Neutrino oscillation is a wave phenomenon
(Wave-Particle Duality)

Neutrino Oscillations

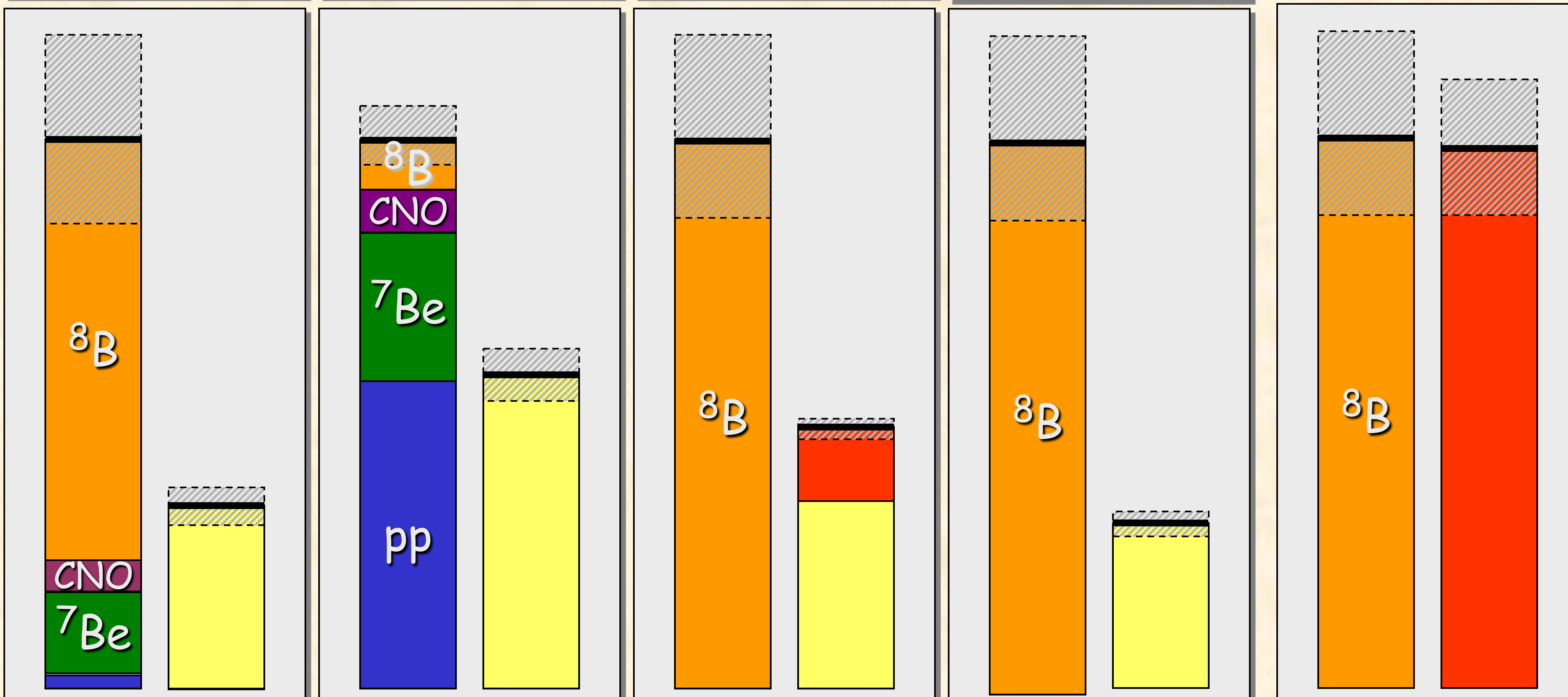


Neutrino Oscillations



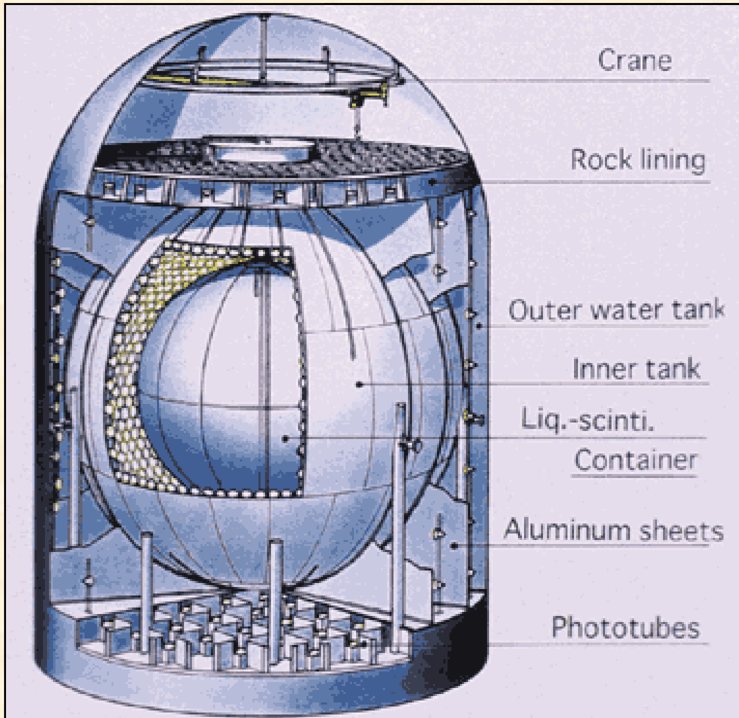
The Solar Neutrino Deficit Resolved

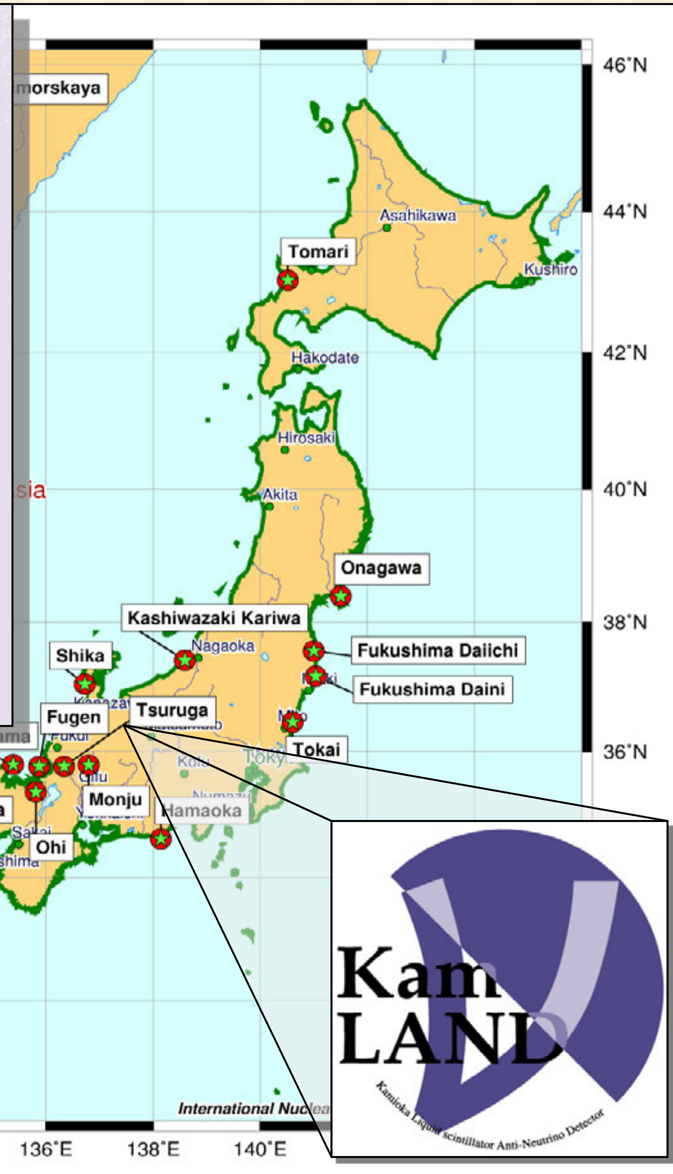
Homestake	Gallex/GNO SAGE	Super-Kamiokande	SNO (Deuterium)	
Chlorine	Gallium	Water	$\nu_e + d \rightarrow p + p + e^-$	$\nu + d \rightarrow p + n + \nu$



Electron-Neutrinos	All Neutrino Types

KamLAND Reactor Neutrino Experiment (Japan)



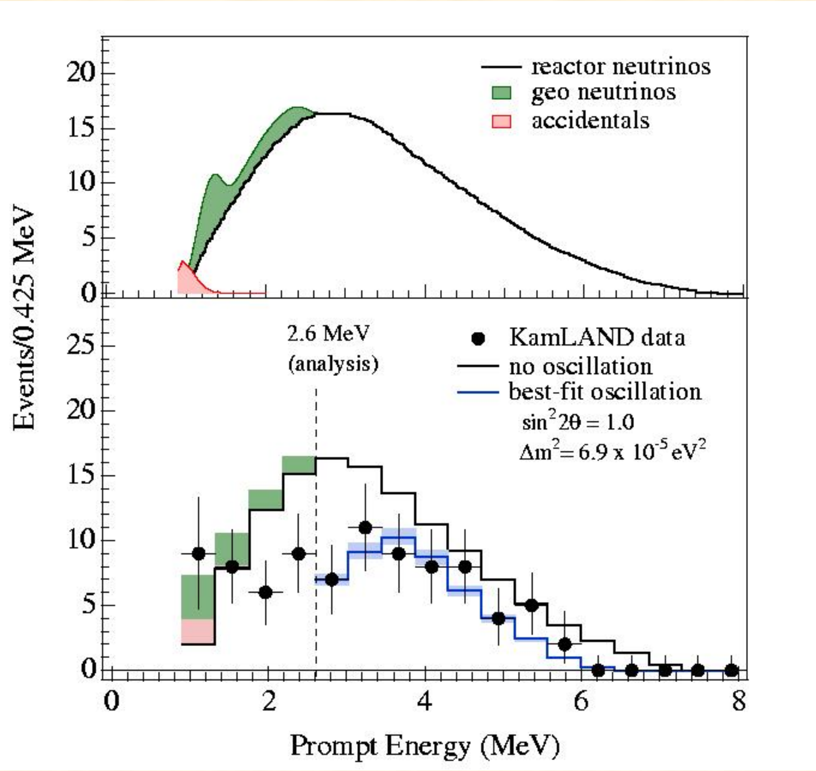


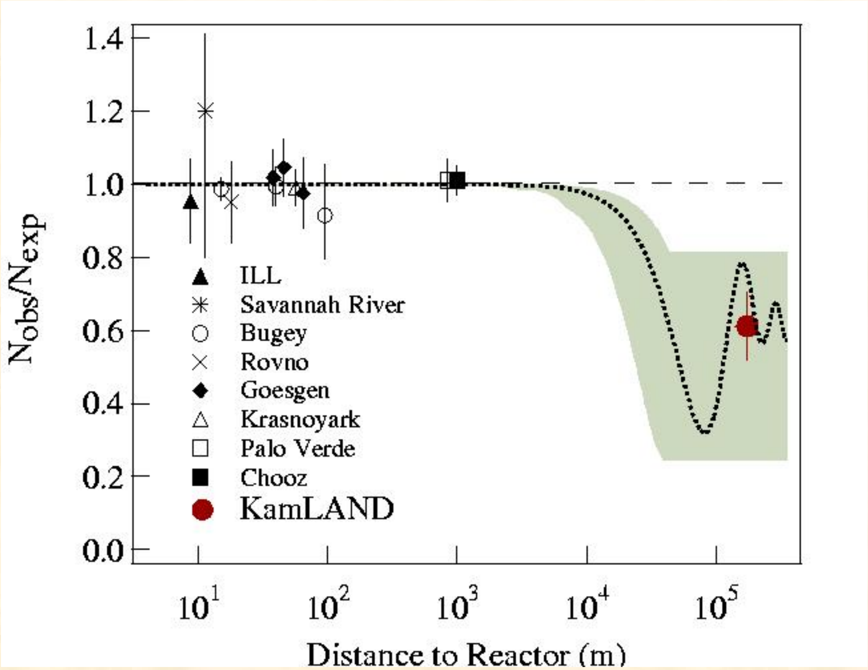
Japanese nuclear reactors 60 GW (20% world total)

- ~1 neutrino capture per day
- Taking data since Jan. '02
- Conclusive Results Fall '02.

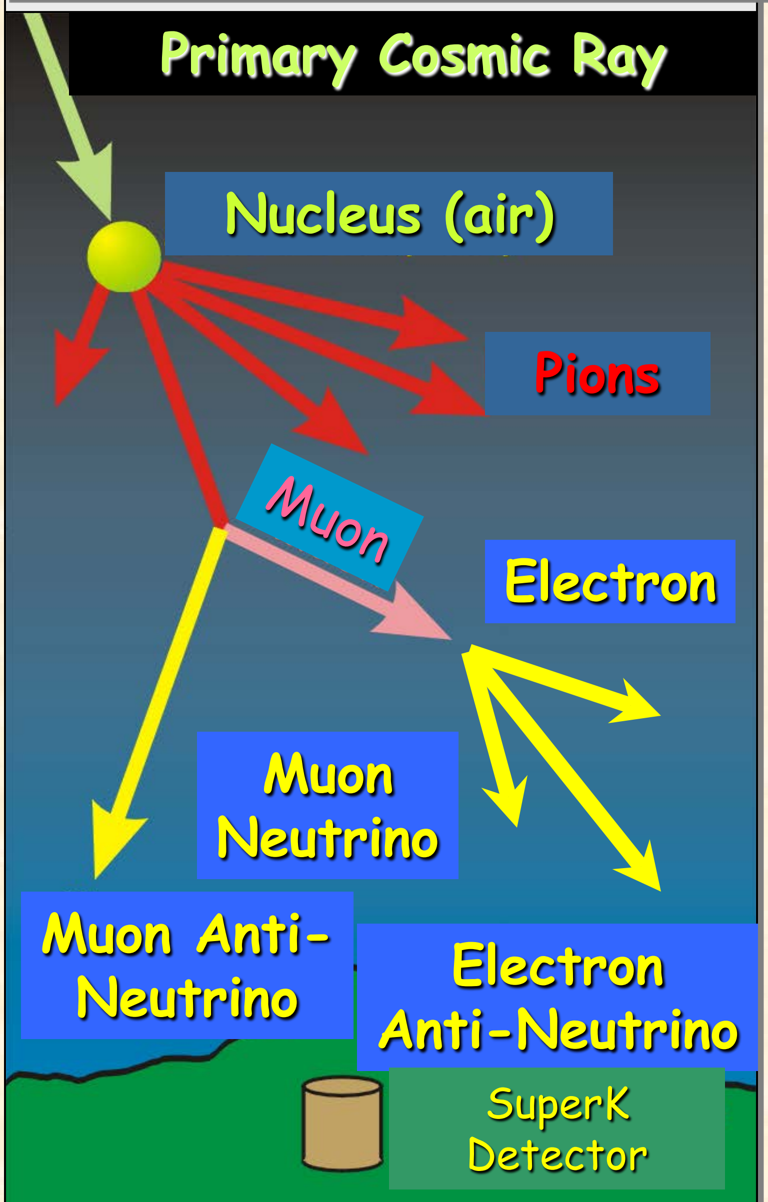
detect ν_e from >100km and observe deficit due to oscillations

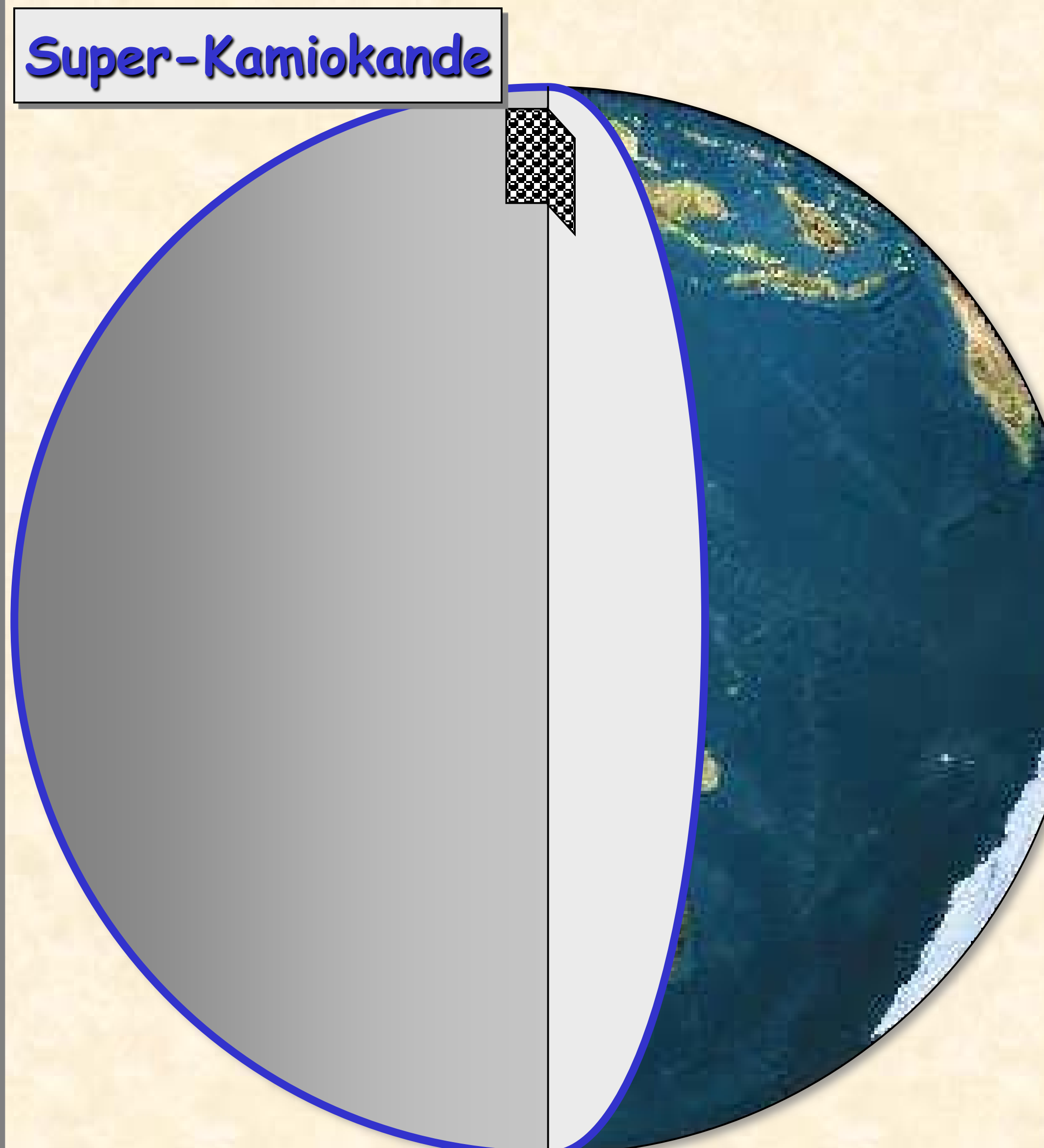
KamLAND Settles the Solar Problem



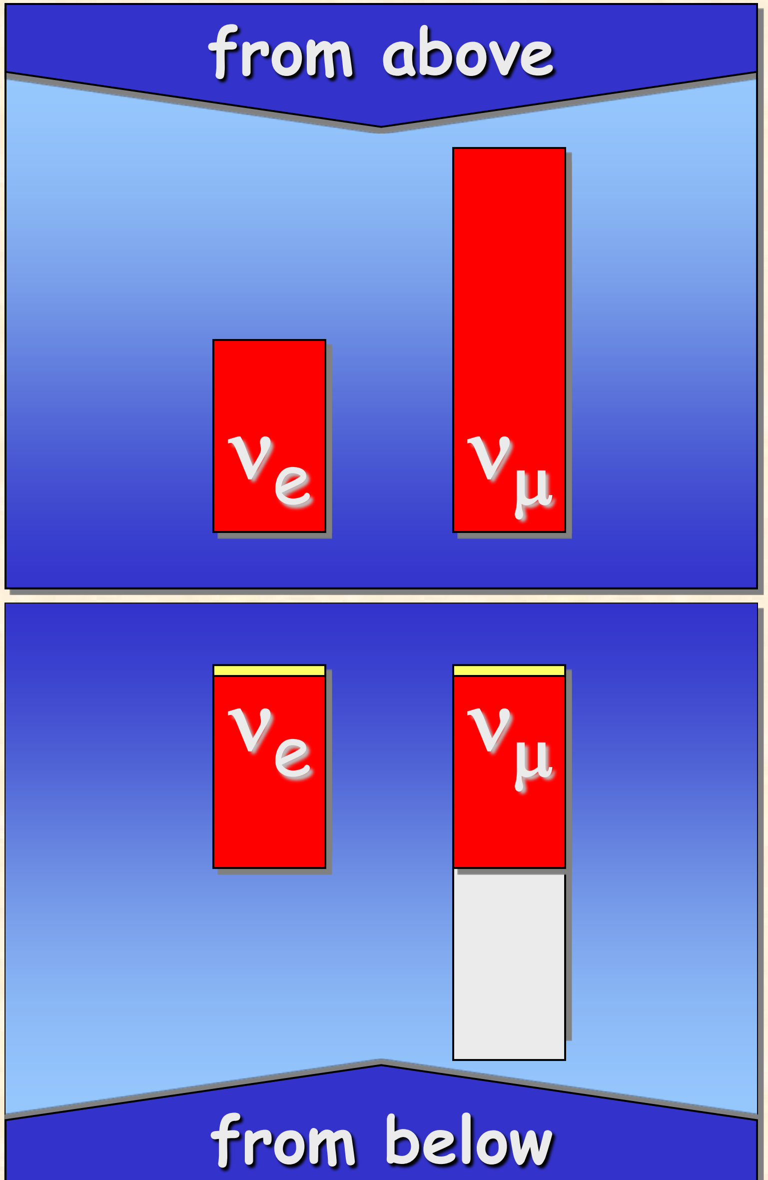


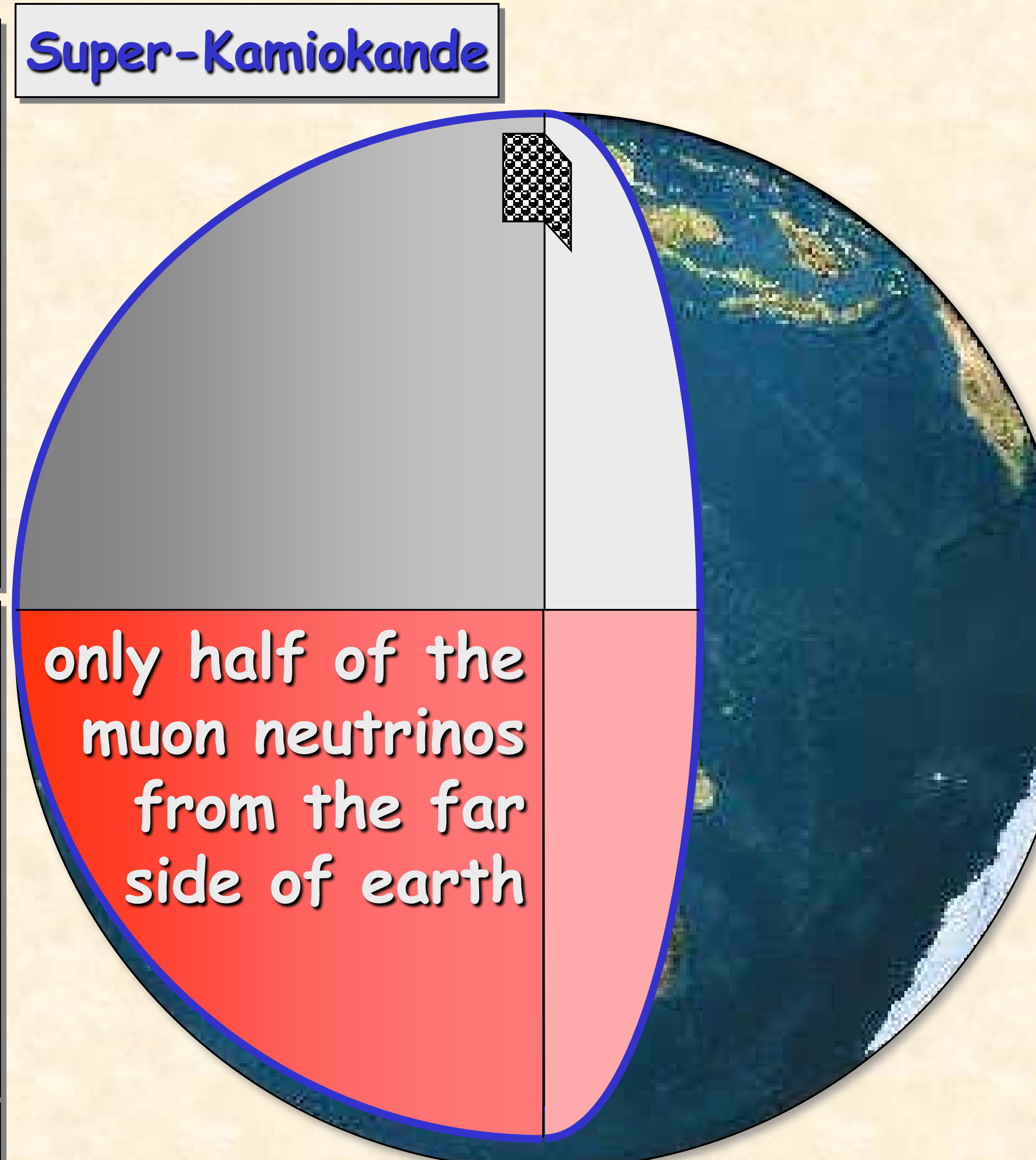
Atmospheric Neutrino Flux



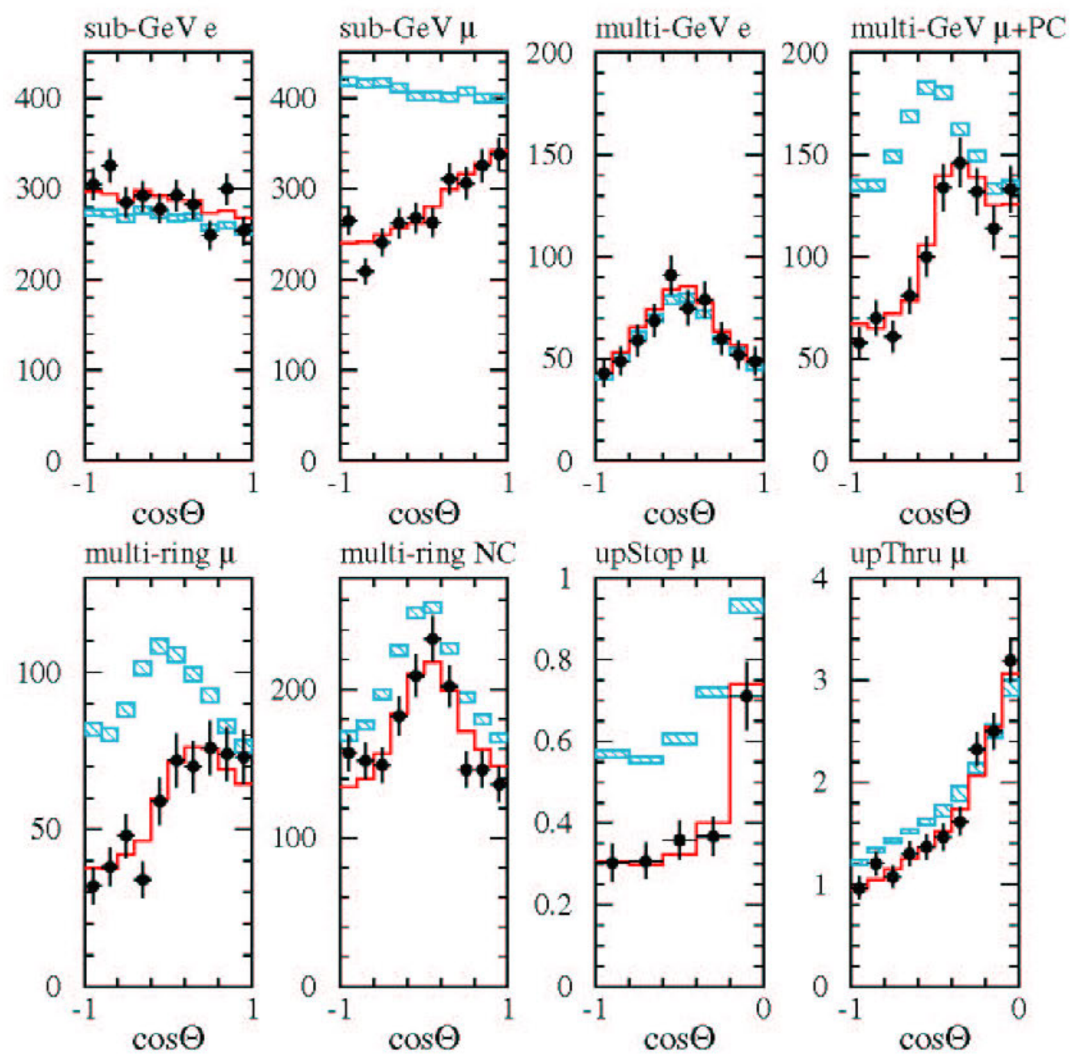


Atmospheric Neutrino Anomaly





Fit to Entire Atmospheric ν Data Set



MC No-Osc

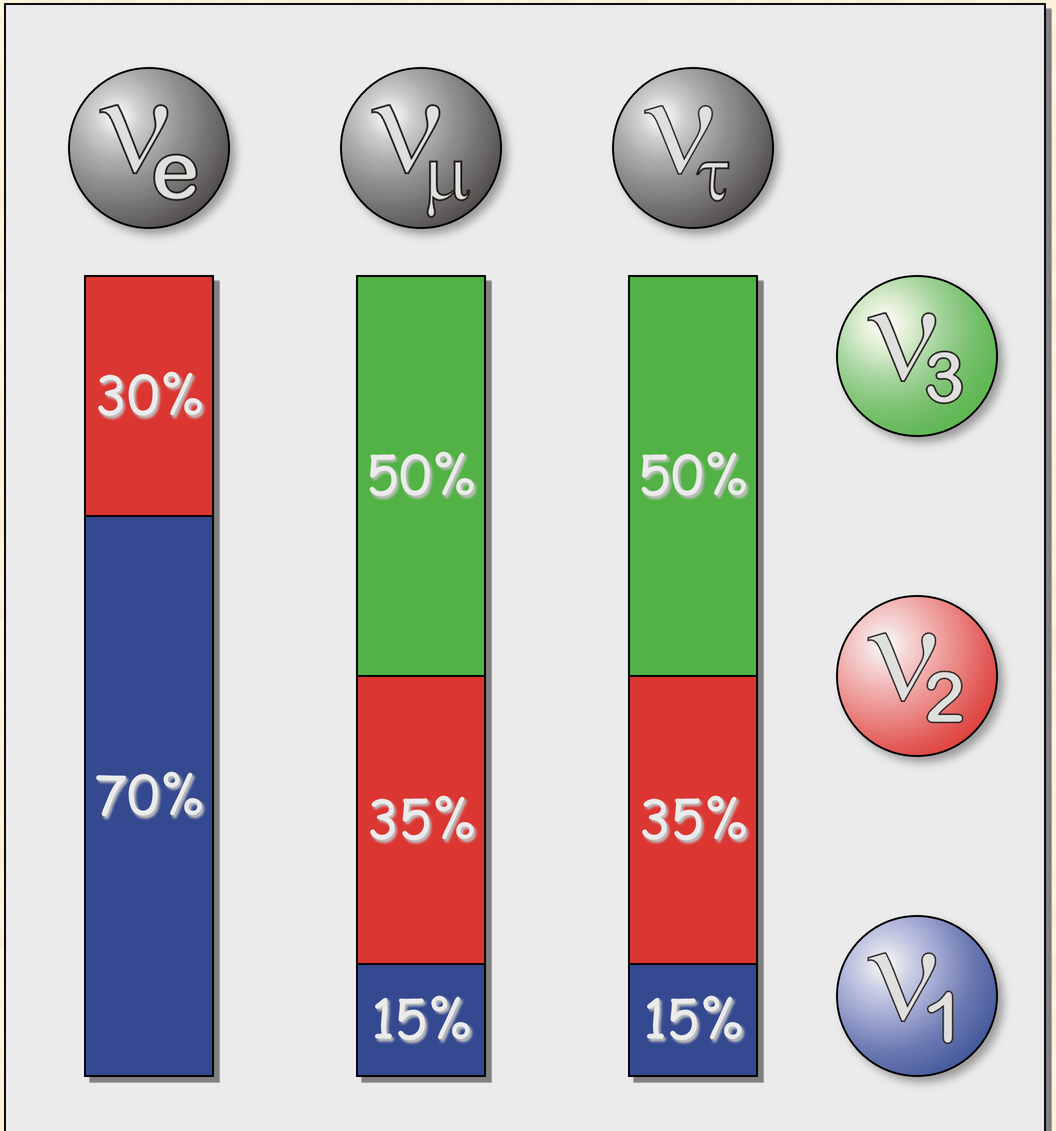
ν_μ-ν_τ

SuperK neutrino oscillations paper now most cited paper in history of experimental particle physics

Phys. Rev. Lett. **81**, 1562 (1998).

Nobel Prize 2015

Neutrino Mass and Composition



Differences of neutrino masses deduced from oscillation experiments.

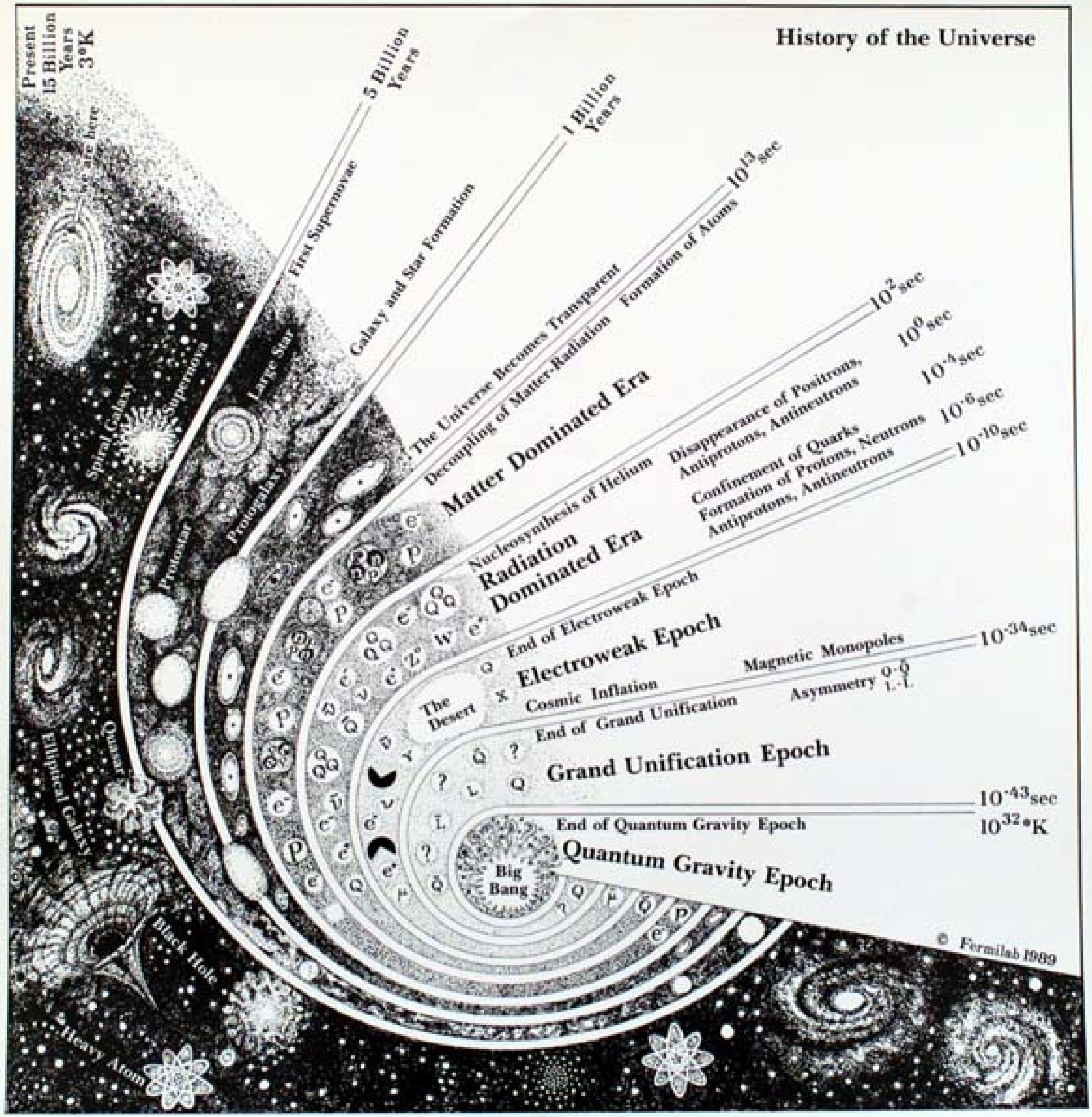
Atmospheric Neutrinos:

$$m_3^2 - m_2^2 = 2 \times 10^{-3}\ eV^2$$

Solar Neutrinos:

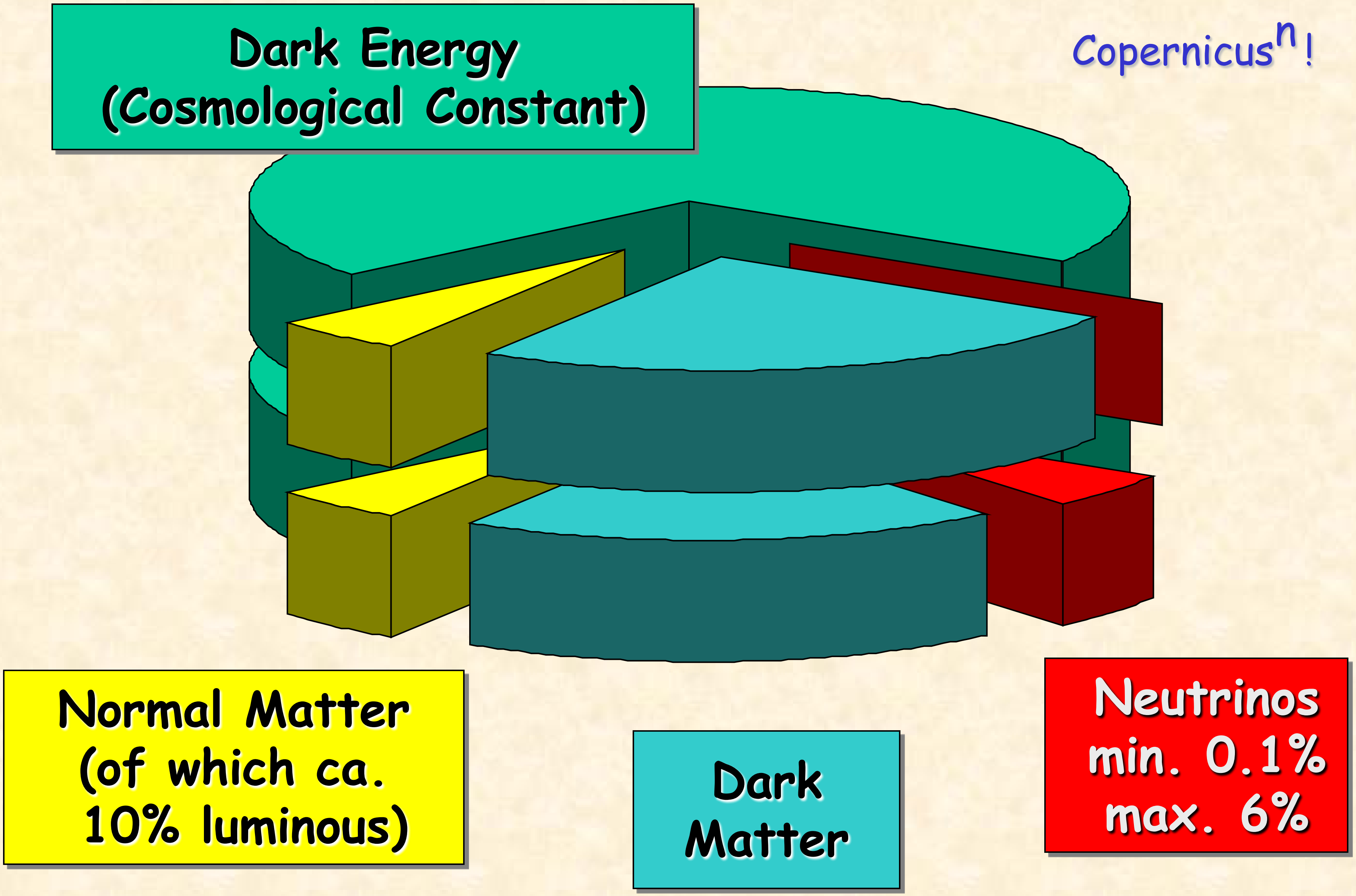
$$m_2^2 - m_1^2 = 7 \times 10^{-5}\ eV^2$$

Mixings peculiarly large,
No theoretical model

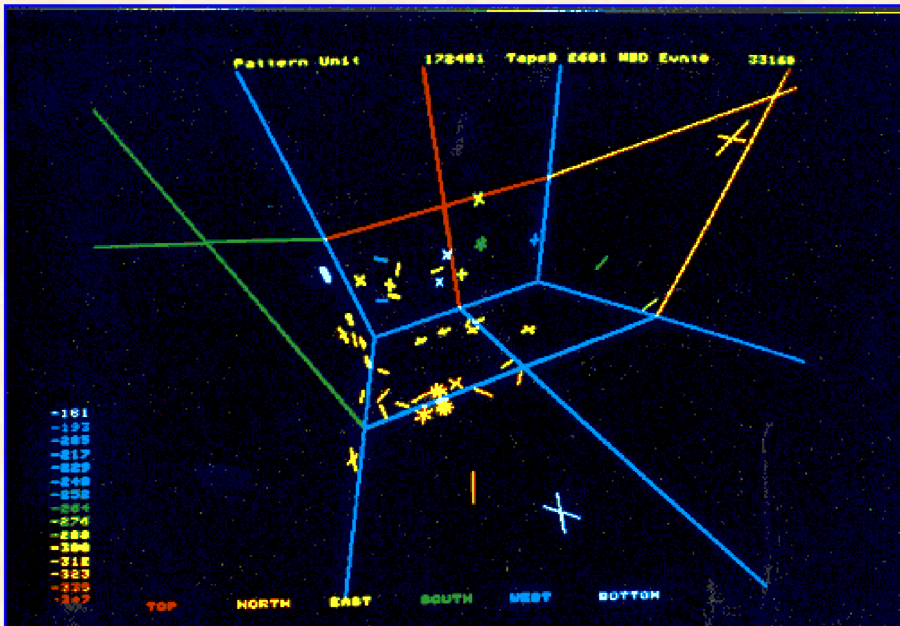


Neutrinos
may play
crucial
role in the
genesis of
excess
matter over
anti-matter
in the
universe…
Hence we
are here!

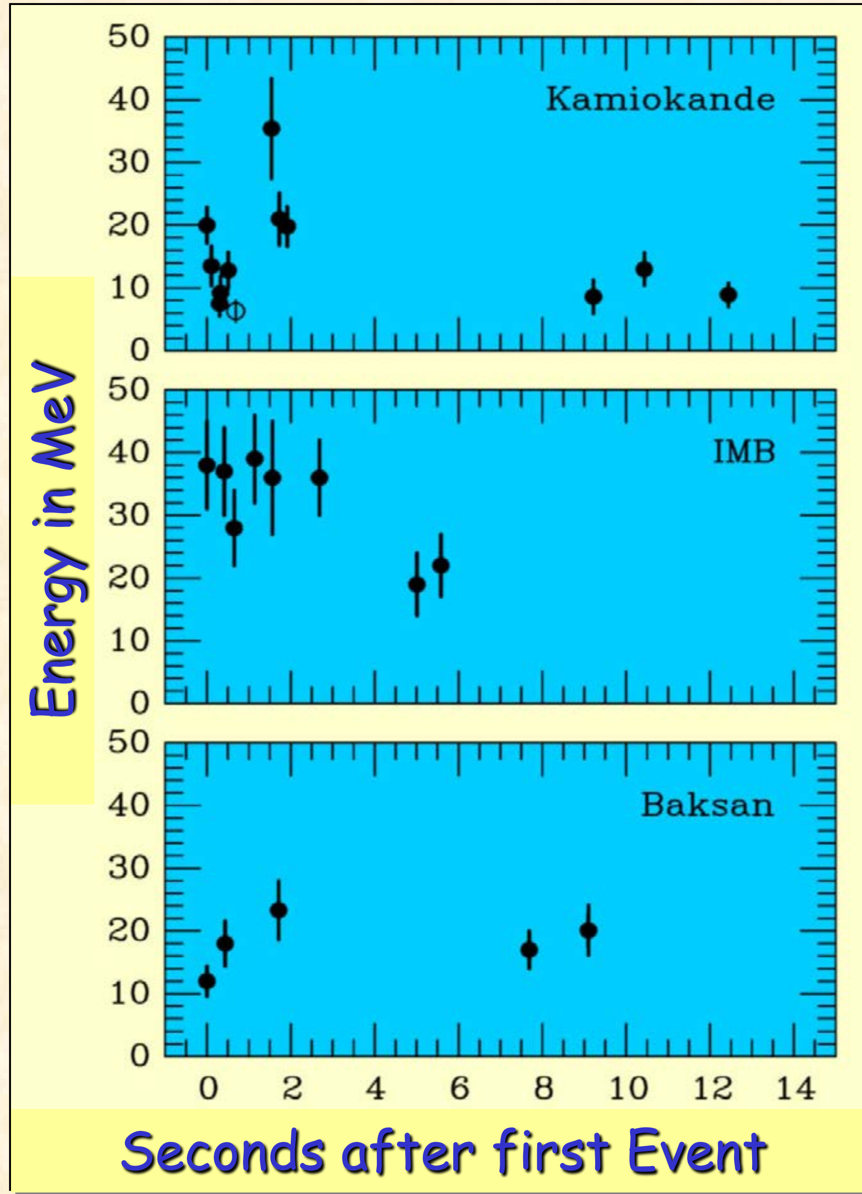
Matter Inventory of the Universe



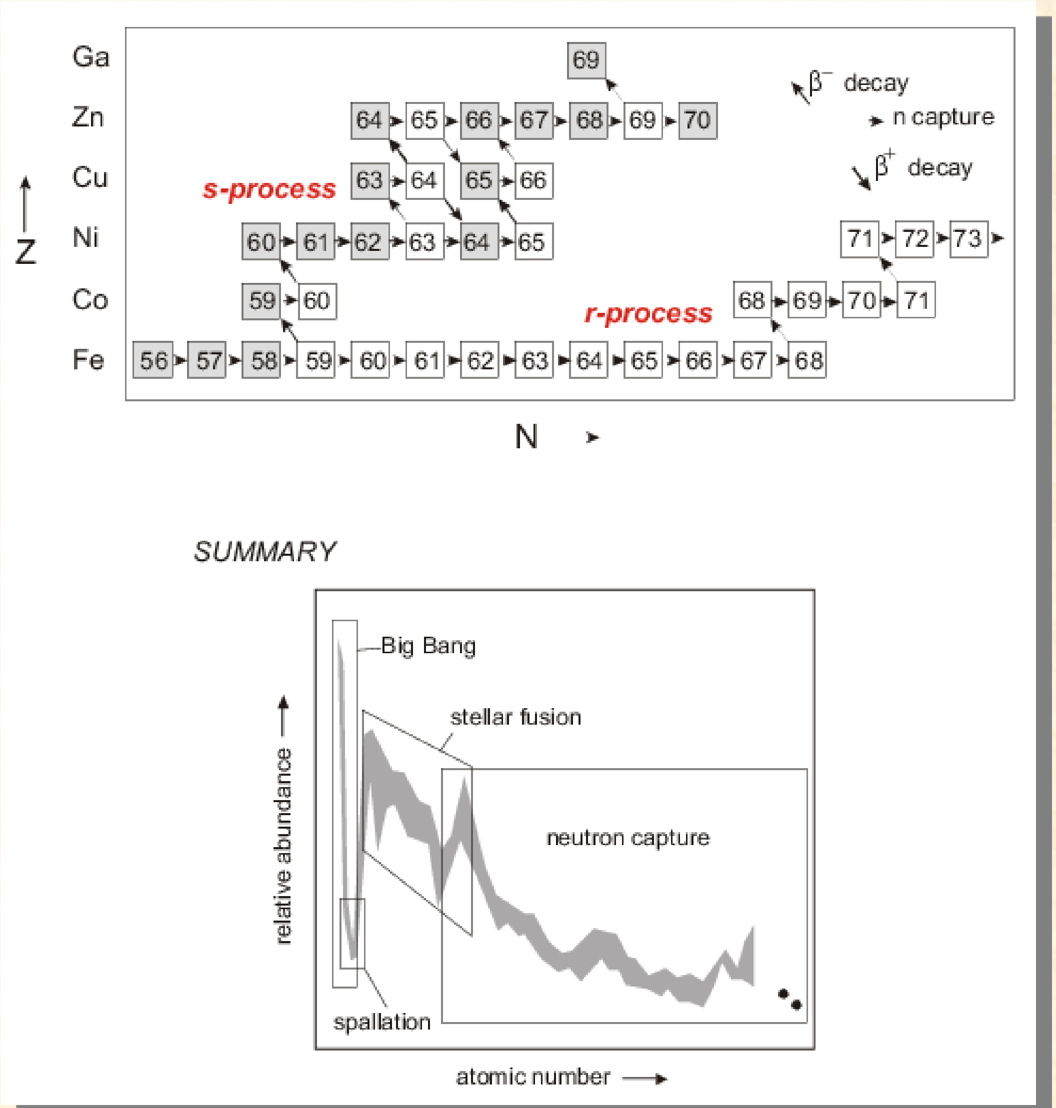
Neutrino Signal from Supernova 1987A



IMB event 33160, 39 MeV



Neutrinos Involved in Making the Heavy Elements

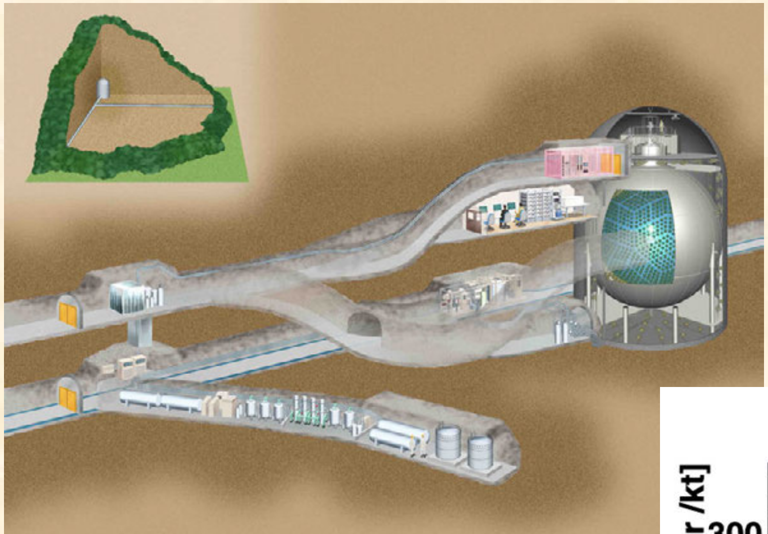


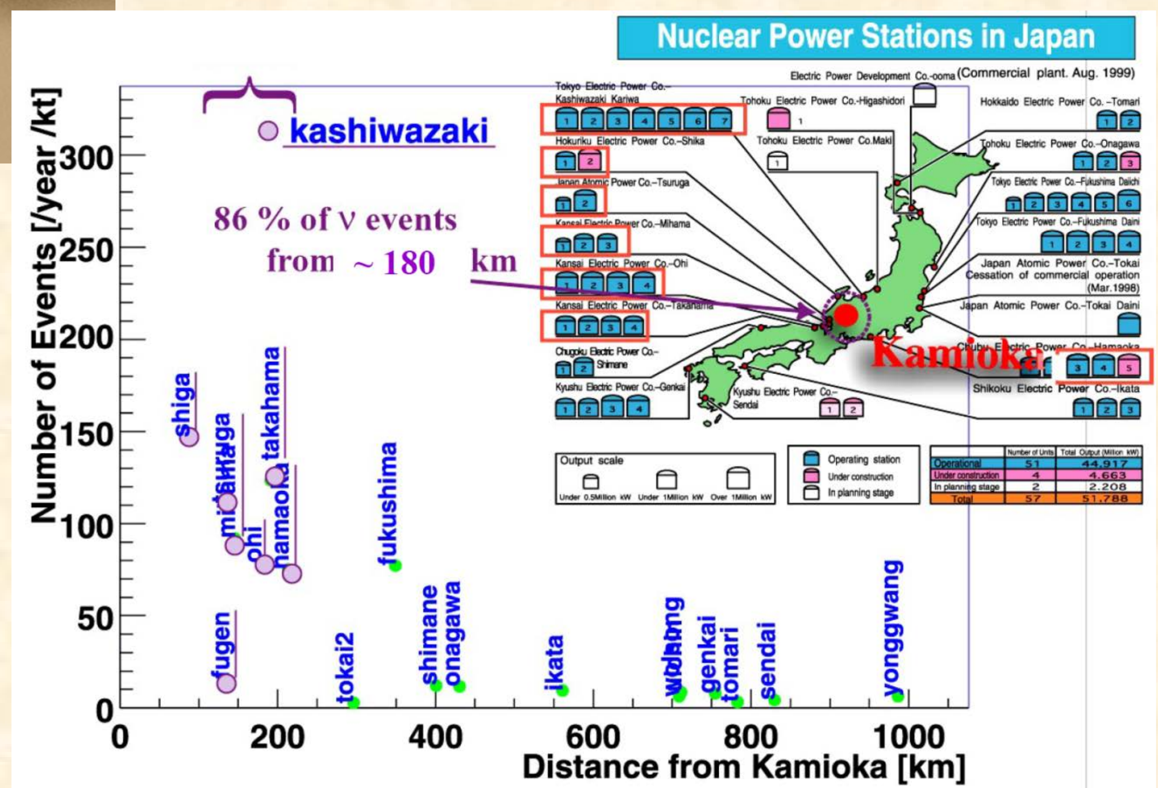
Neutrinos condition the neutron bath in which the atoms accrete mass.

The r-process in supernovae is thought to be the main source of heavy elements.

And, the Fluorine in your toothpaste, for example.

KamLAND sees neutrinos from Japan (and Korea)





KamLAND Observes Neutrino Oscllations

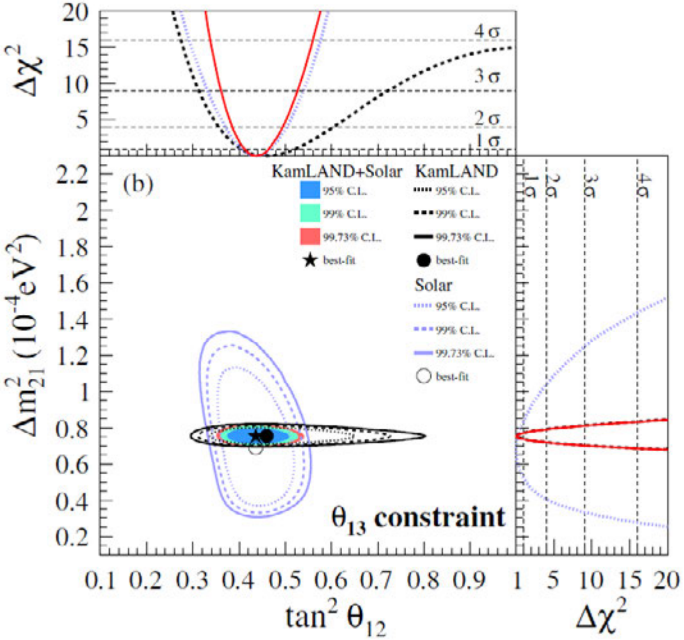


FIG. 4: Allowed regions projected in the $(\tan^2\theta_{12}, \Delta m^2_{21})$ plane, for solar and KamLAND data from the three-flavor oscillation analysis for (a) θ_{13} free and (b) θ_{13} constrained by accelerator and short baseline reactor neutrino experiments. The shaded regions are from the combined analysis of the solar and KamLAND data. The side panels show the $\Delta\chi^2$-profiles projected onto the $\tan^2\theta_{12}$ and Δm^2_{21} axes.

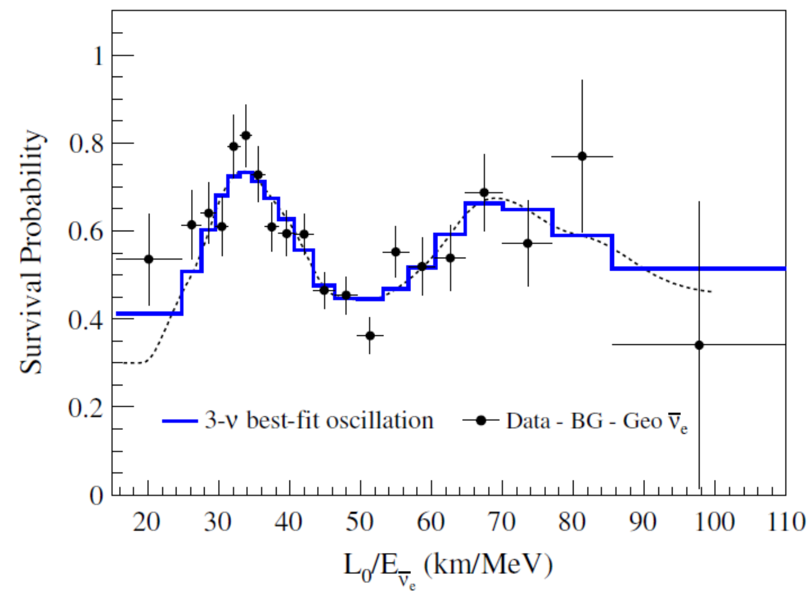


FIG. 5: Ratio of the observed $\overline{\nu}_e$ spectrum to the expectation for no-oscillation versus L_0/E for the KamLAND data. $L_0 = 180$ km is the flux-weighted average reactor baseline. The 3-ν histogram is the expected distributions based on the best-fit parameter values from three-flavor unbinned maximum-likelihood analysis of the KamLAND data.

KamLAND Neutrinos from the earth "GeoNeutrinos"

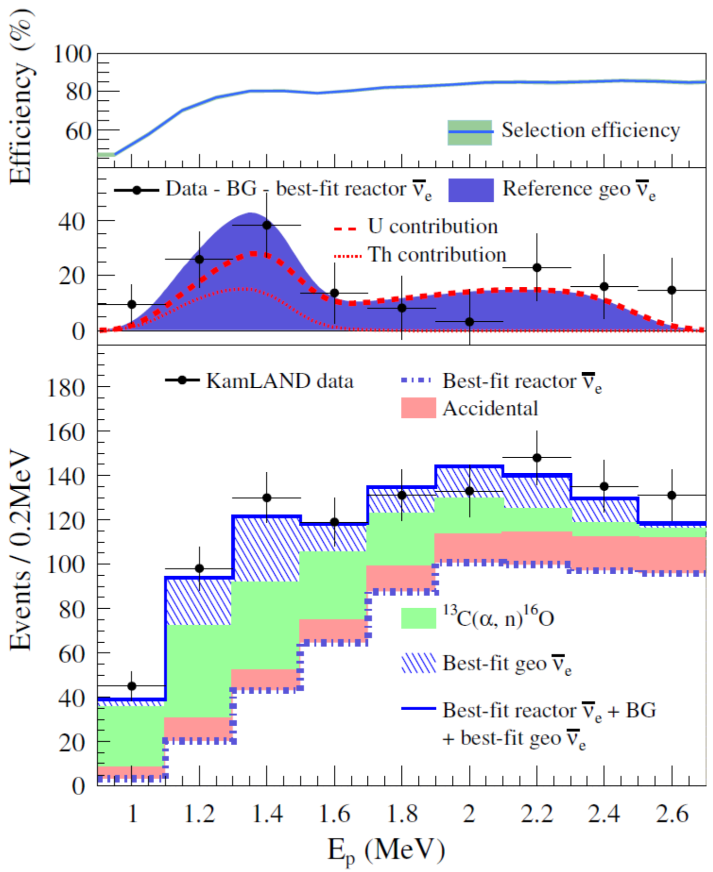


FIG. 6: Prompt energy spectrum of the $\overline{\nu}_e$ events in the low-energy region. Bottom panel, data together with the fitted background and geo $\overline{\nu}_e$ contributions. The shaded background and geo $\overline{\nu}_e$ histograms are cumulative. Middle panel, background and reactor $\overline{\nu}_e$ subtracted data together with the geo $\overline{\nu}_e$'s for the decay chains of U (dashed) and Th (dotted) calculated from a geological reference model [12]. Top panel, the energy-dependent selection efficiency.

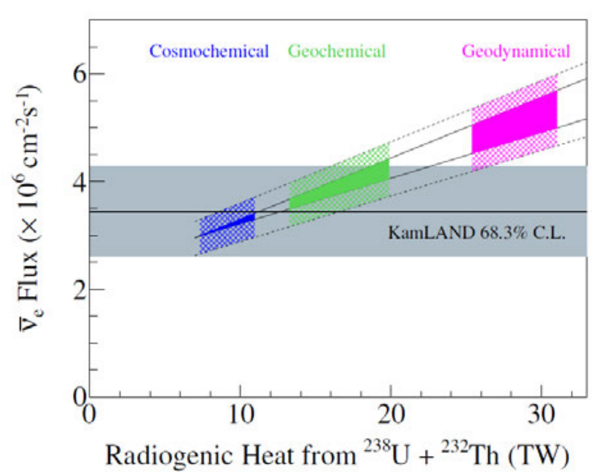


FIG. 8: Geo $\overline{\nu}_e$ flux versus the radiogenic heat production rate from the decay chains of ^{238}U and ^{232}Th. The measured geo $\overline{\nu}_e$ flux (gray band) is compared with the expectations for the different mantle modelsfrom cosmochemical [32], geochemical [5], and geodynamical [33] estimates (color band). The slope starting at 7 TW indicates the response to the mantle $\overline{\nu}_e$ flux, which varies between the homogeneous and sunken-layer hypotheses (solid lines), discussed in the text. The upper and lower slopes (dashed lines) include the uncertainties in the crustal contributions.

Moving on to the Big Picture and the Future needs

The Next Challenges in Big Neutrino Detectors: 50 KT LS - 600 KT WC Detectors?

Motivations (~in energy order):

- Geoneutrinos
- Neutrinoless bb decay
- Solar Neutrinos (HeP, CNO…)
- RAA and Reactor Spectrum Problems
- Search for Sterile Neutrinos
- Relic SN Neutrinos
- Supernova Neutrinos
- Indirect DM Searches
- Other anomalies (LSND, MBOONE)
- Nuclear Counter-Proliferation
- Proton Decay Search
- Long-Baseline Oscillations
- Hierarchy
- CP violation
- Atmospheric Neutrinos
- Earth Tomography
- Cosmic Neutrinos (>100 TeV, >1PeV)

Under Construction

SNO+
JUNO

Rejuvenated Soon?

KamLAND
SuperK
Borexino

Probable (my view)

HyperK, HKK
DUNE (10KT)
JinPing
INO

Also discussed

- USA ("Theia Project")
- Europe ~~LAGUNA~~ (~~LENA~~)

New Physics Challenges, and New Detectors

Several Areas Needing Improvements
- Lower thresholds… big detectors reaching ~1-2 MeV
  - More Pixelation (~1m -> few cm)
  - Timing (<100 ps)
  - Better Scintillator or WBLS (more light, long atten)
  - Great Cleanliness (Borexino or better)
  - Lower CR backgrounds by going deeper than 2KMwe

- Directionality (even a little is good at few MeV)

- Better particle ID in LB experiments (back reconstruction)

Not all are possible in one type of detector

World Nu Community cannot afford Many >$500M Detectors

<u>We must join together to move forwards.</u>
<u>Theia? SuperKamLAND?</u>

What is missing in the world mix?

Assuming extended IceCube and KM3 at high energy + HyperK + SNO+ and JUNO and Jinping…

We need a detector with

- M > 20kt with
- Threshold ~ 1 MeV
- Depth >>2 kmwe
- An accelerator beam pointed at it

JGL's current favorite prospect:

50 KT LS Theia in Homestake

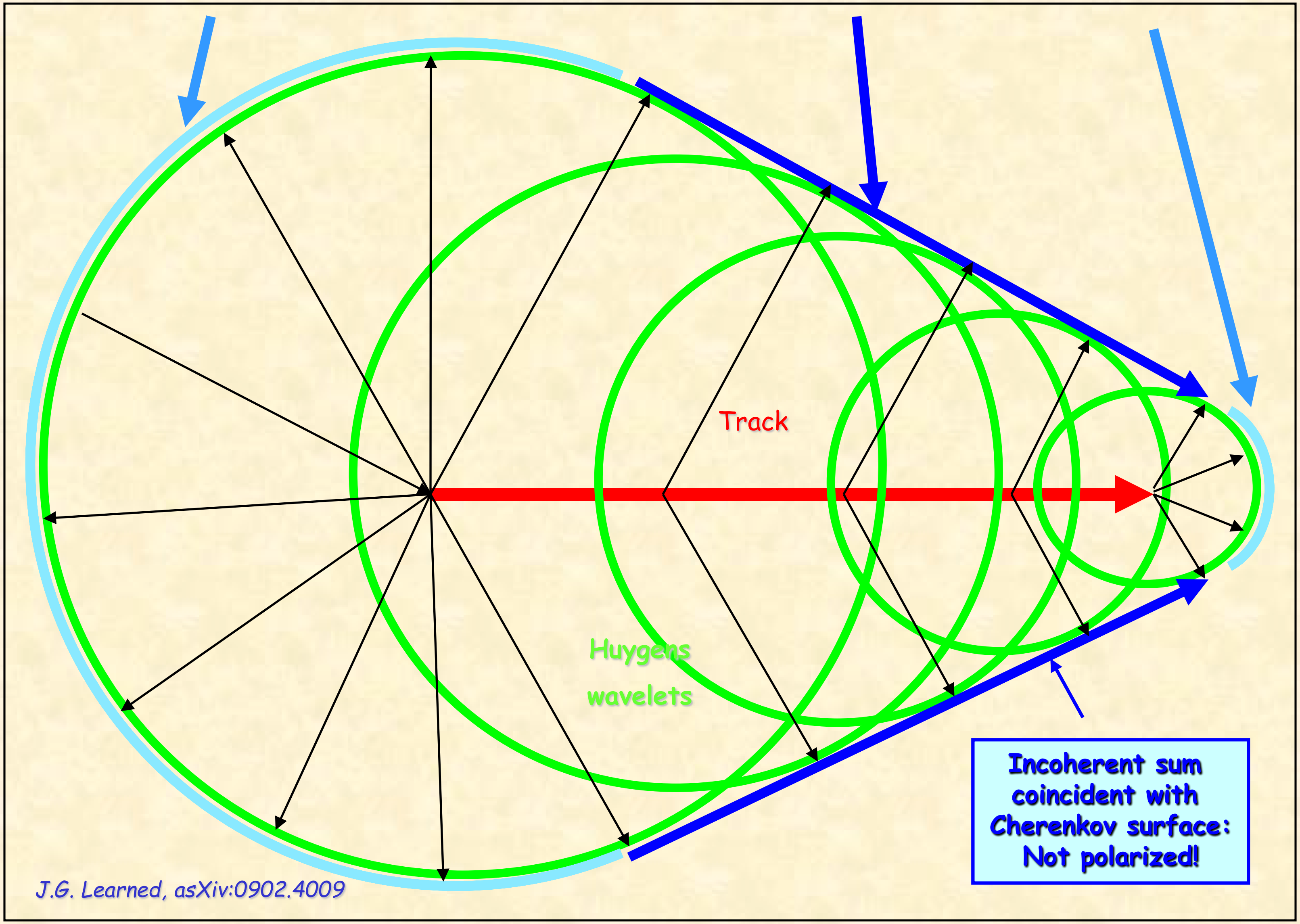
Now discuss some issues related to such development.

Photodetectors are prominent need, not discussed here.

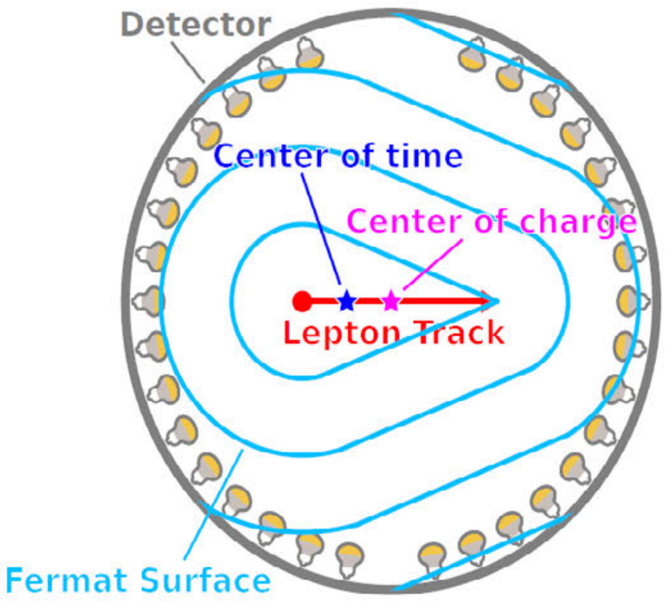
2009 Realization that Liquid Scint Detector Can Reconstruct Events

First light yields topology.

Snapshot of the Fermat Surface for a Single Muon-likeTrack



Fast and Simple Start to Reconstruction



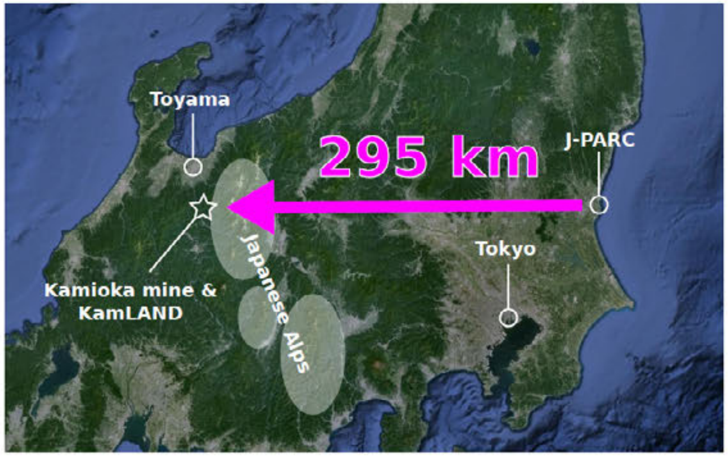
- Center of charge fits middle of track
- **Fermat surface**
  $\equiv$ earliest possible photons
  $\approx$ Cherenkov +
  earliest scintillation
- **Center of time**
  (using Fermat surface photons)
  fits near one end of track
- **And connect dots!**

Sakai thesis, 2016

Fit to 14 Neutrinos in KamLAND from J-Parc

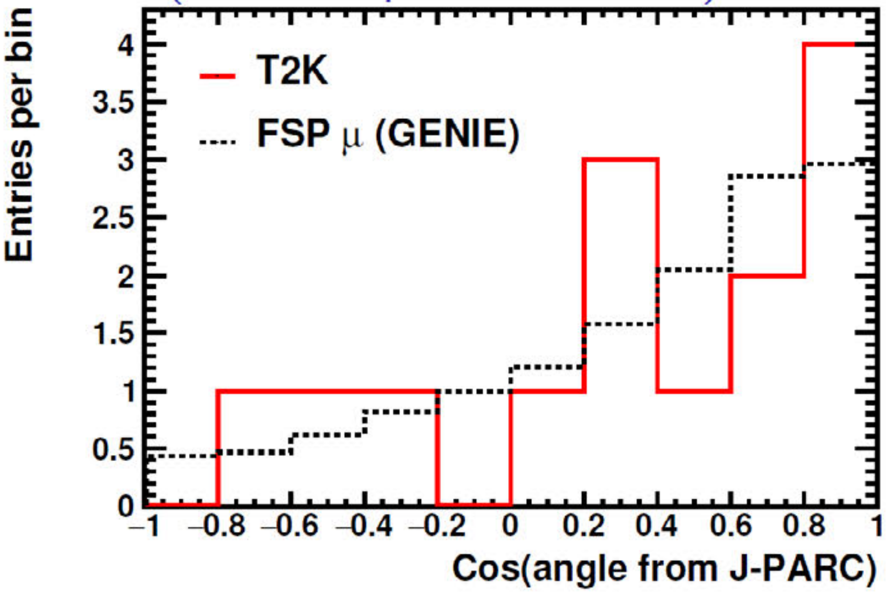
Tag pure beam neutrinos due to having spill times

Map



Agreement with MC

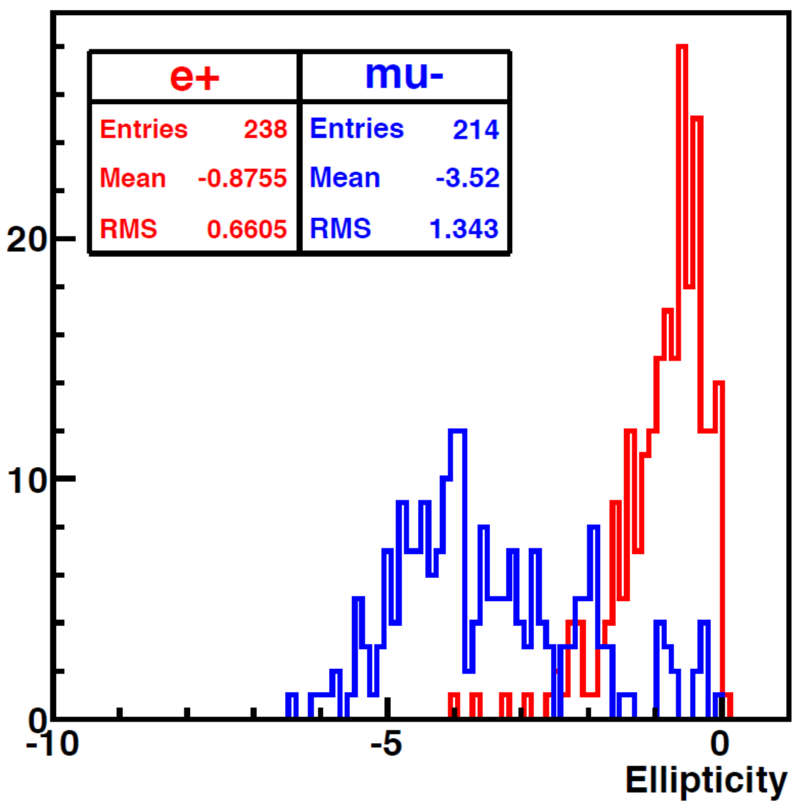
(K-S test p-value = 0.65)



Not official KL result yet

Sakai Thesis

A Simple Ellipticity Particle ID



- Fiducial volume cut:

  $< 3\,\mathrm{m}$ radius
- Event selection efficiency:

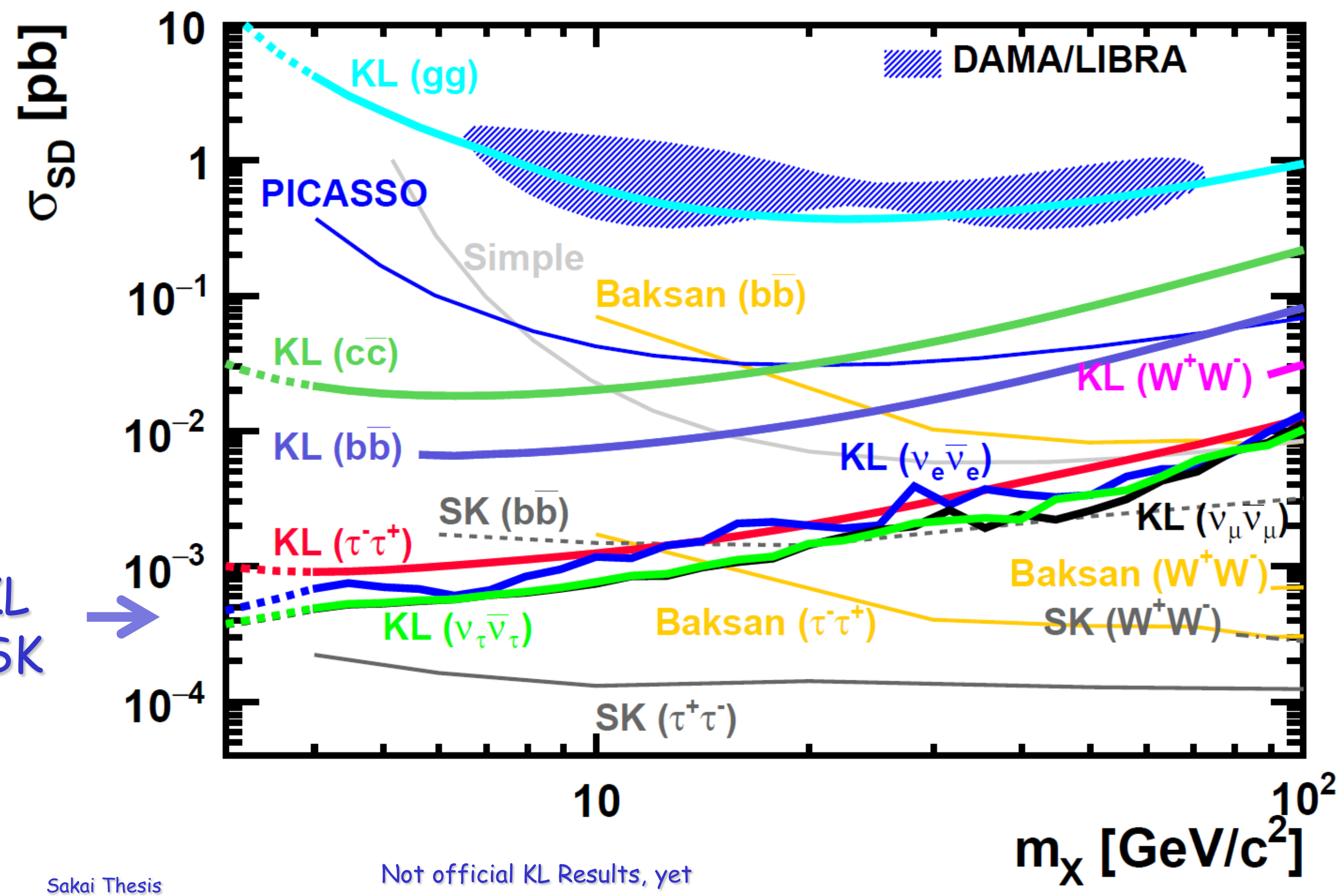
$$e^+ \Longrightarrow 2.4\,\%,$$
$$\mu^- \Longrightarrow 2.1\,\%$$

Sakai Thesis

Probably can do much better in future

Competitive DM Results from This Technique

Sakai Used Back-Propogationtion in KamLAND
to seek Dark Matter Annihilation Neutrinos



<1KT KL
22KT SK

Sakai Thesis

Not official KL Results, yet

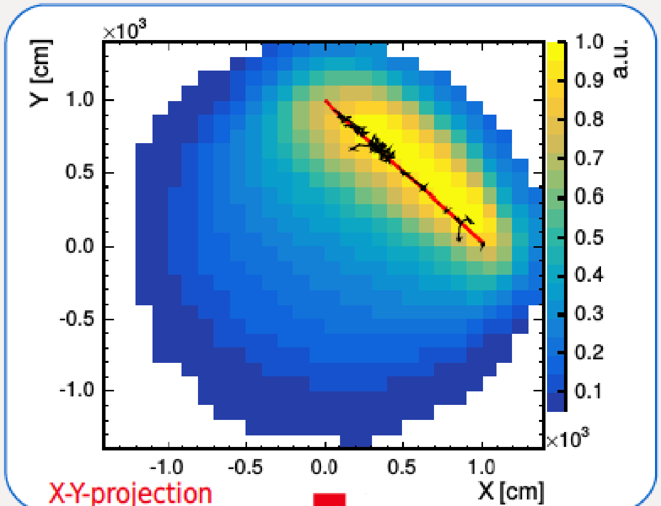
From Sebastian Lorenz's talk at FROST, Mainz

Working Principle of the Topological Reconstruction

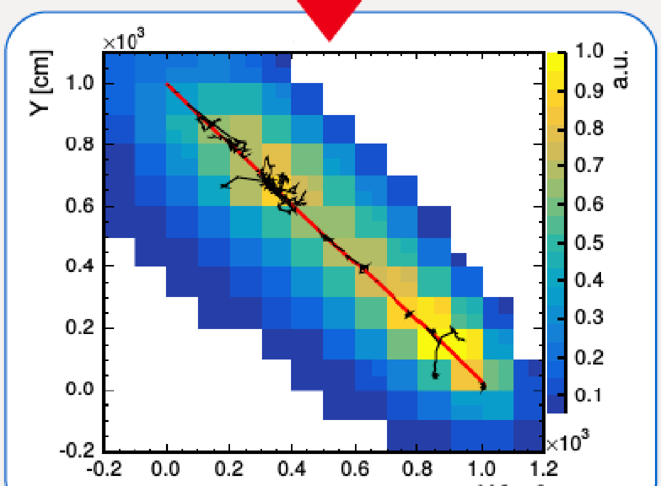
10/22/2016

PRiSMA

- Use all photon hits from all PMTs
- Divide result by local detection efficiency
  - → Number density of emitted photons
- "Connect information" in multiple iterations
  - → Use prior result as "prior information" in next iteration



Decrease cell size



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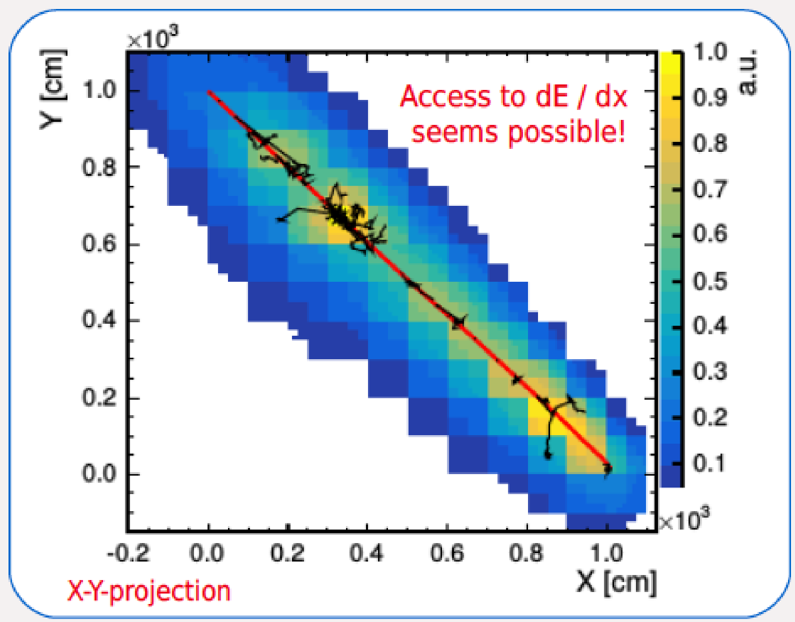


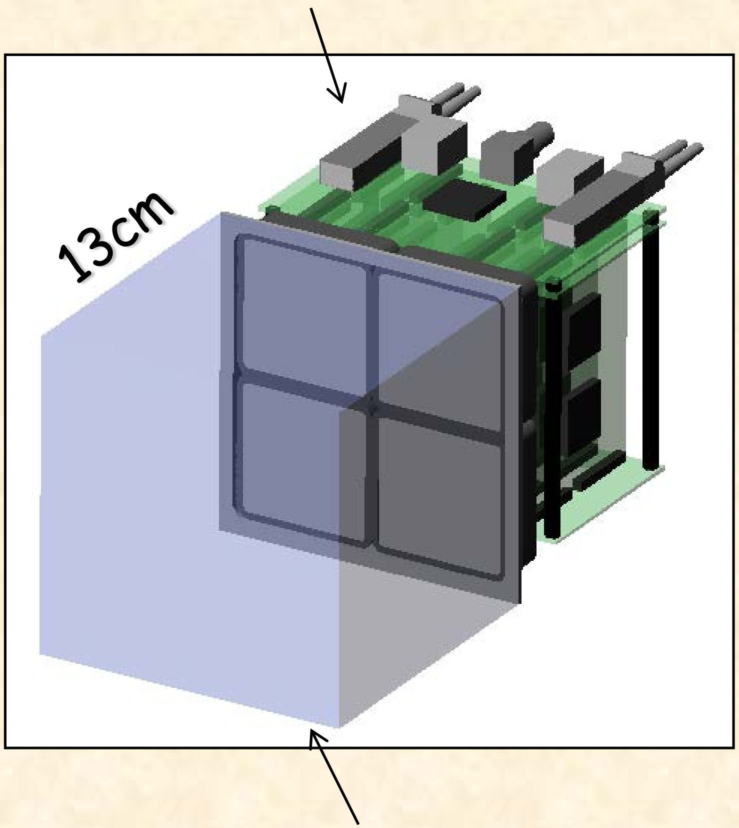
What is the point?

We can have low threshold (MeV)
and we can achieve cm scale resolution at
higher energies (GeV)
to cover a
huge range in energy
and
great reach in physics

in a single large deep scintillation detector

MiniTimeCube Small and Directional Inverse Beta Detector

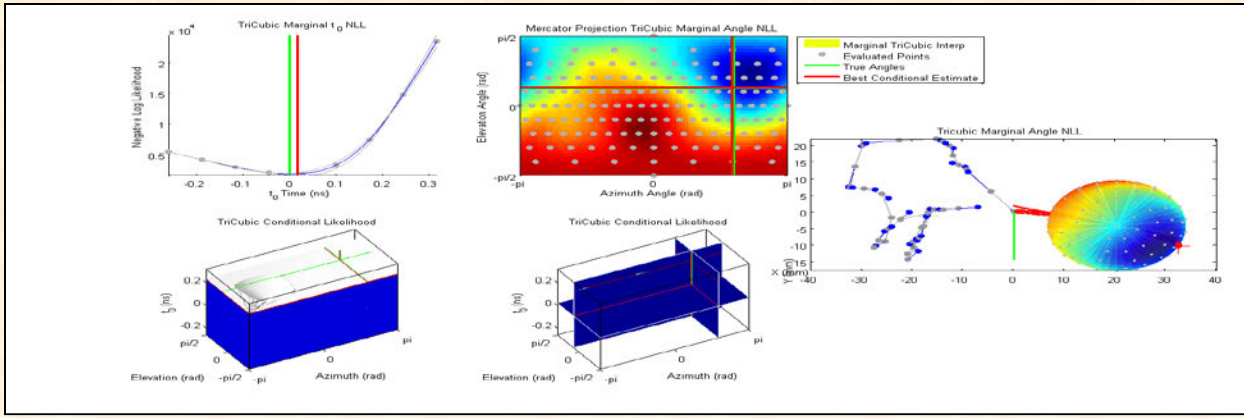
Fast digitizing electronics (x6)

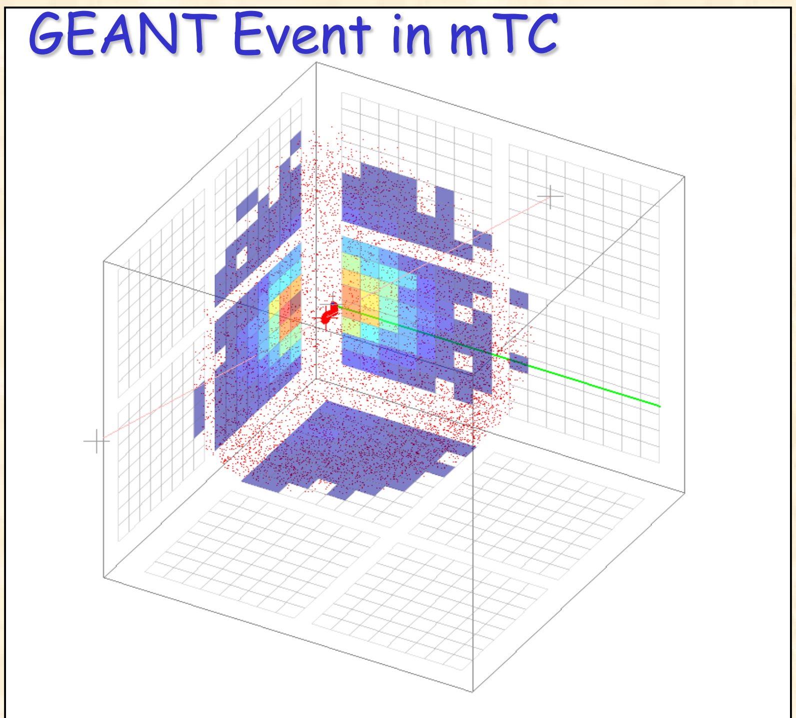


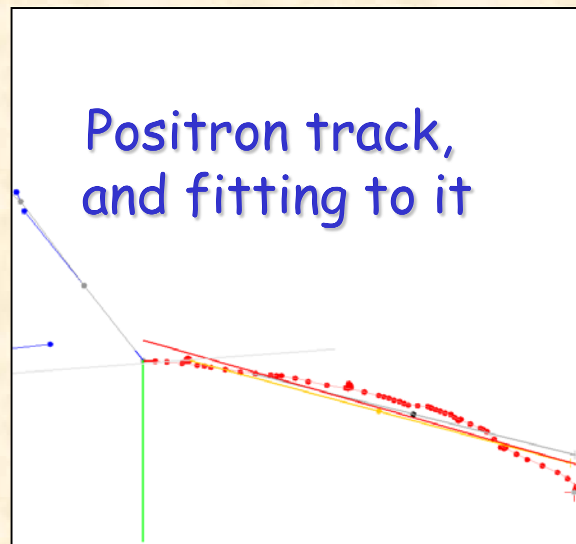
2.2 liter scintillator

- Small portable 2.2 liter scintillating cube with neutron capture doping.
- Contain positron, lose gammas
- Do imaging with fast timing, not optics (time reversal imaging).
- Get some neutrino directionality between positron origin and neutron capture point.
- Reject noise on the fly; no shielding needed (if far from reactor)
- 4 x 6 MCP (x64 pixels each) fast (<100 ps) pixel detectors on surrounding faces
- ~10/day anti-neutrino interactions (inverse beta decay signature) from reactor.
- Data taken at NIST, being analyzed at present

Fitting the Positron Track in mTC







NuLat a new type of 3D pixelated detector

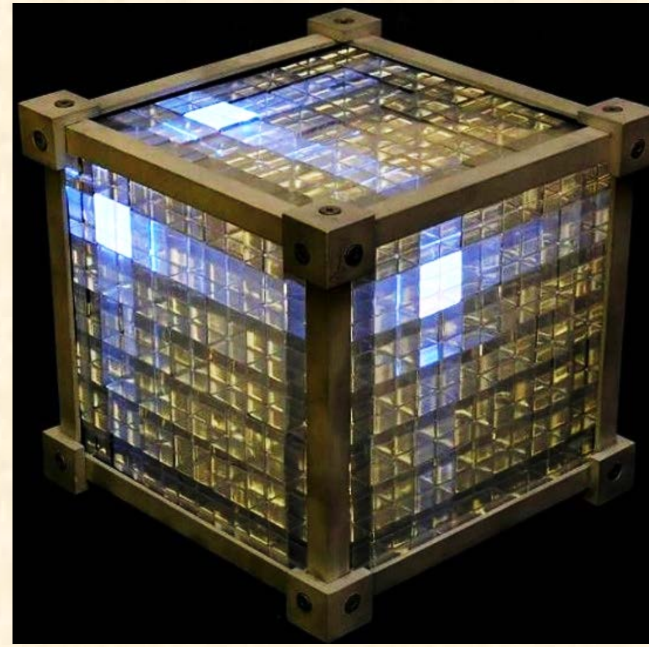
Stack of optically isolated scintillating cubes

Light transmitted largely to 3 directions

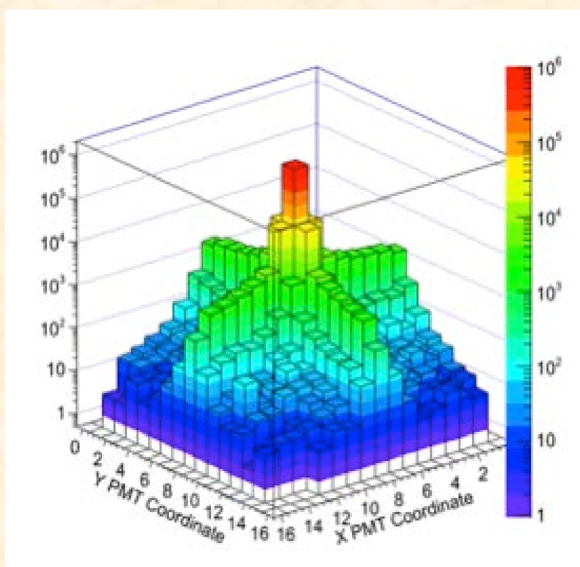
6 PMTs get coincident, strong light

Lithiated plastic cubes now available

Alternate design for large version with LS



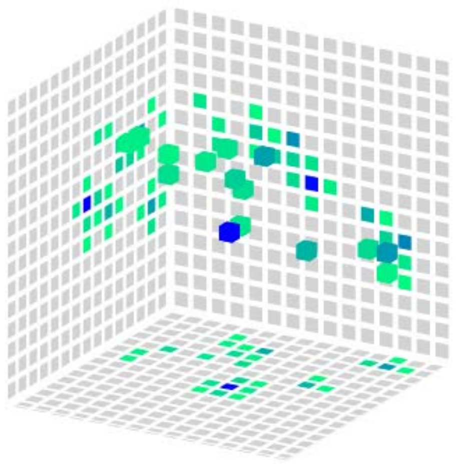
NB, log scale



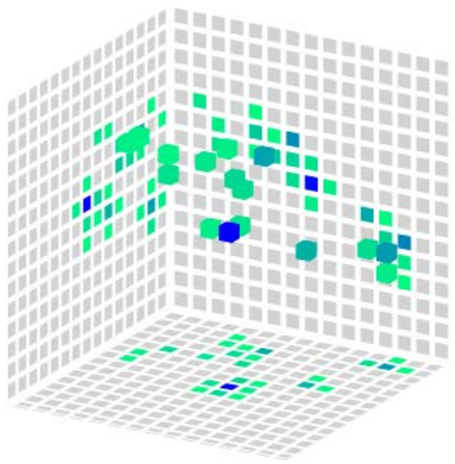
Reconstructing 3D Energy Deposition in NuLat

Allows breaking multi-dimensional degeneracies

Truth



Reconstructed



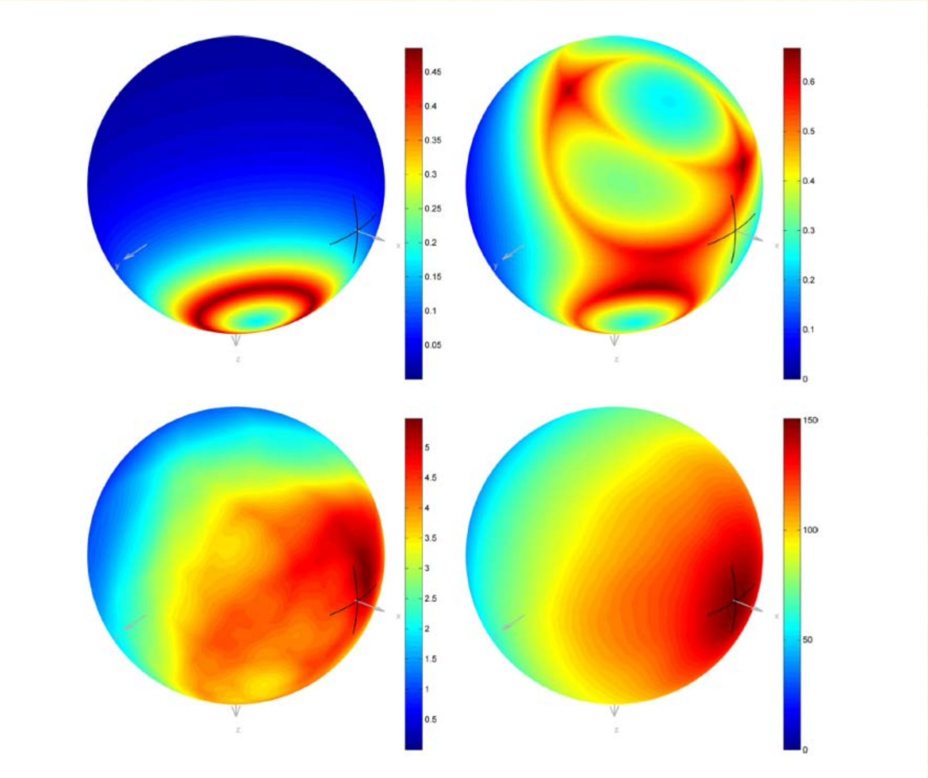
Not the case in 2D or 1 D detectors....

Very importnat in identifying events and eliminating backgrounds

NuLat as a reactor neutrino detector

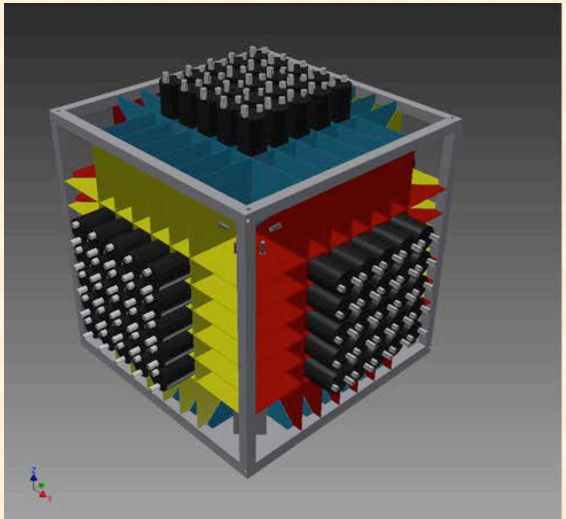
- Reactor power cycles and fuel composition
- New tool in non-proliferation arsenal
- Detection of special nuclear materials
- NuLat whitepaper: arXiv:1501.06935
- See talk at Applied Antineutrino Physics 2015

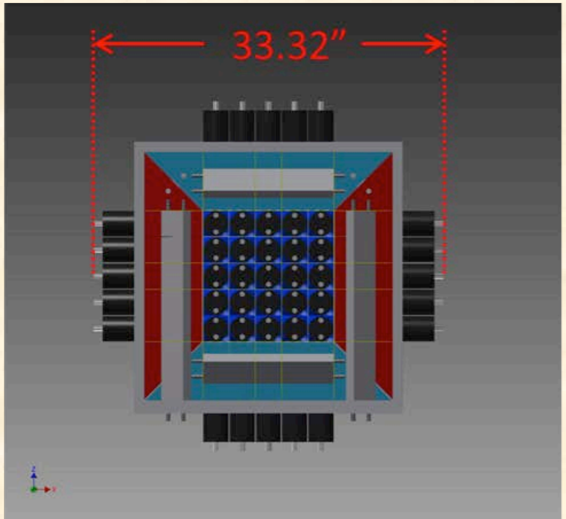
Directionality



NuLat Demonstrator Being Assembled Now

- A 5×5×5 ROL with ^{6}Li-loaded scintillator
- Contract with Eljen for 130 cubes
- Instrumented with 150 PMTs, Spring 2017
- Demonstrate reactor monitoring
  - Deploy at commercial power plant
- Measure backgrounds for NuLat
  - Deploy at NIST in NuLat shielding





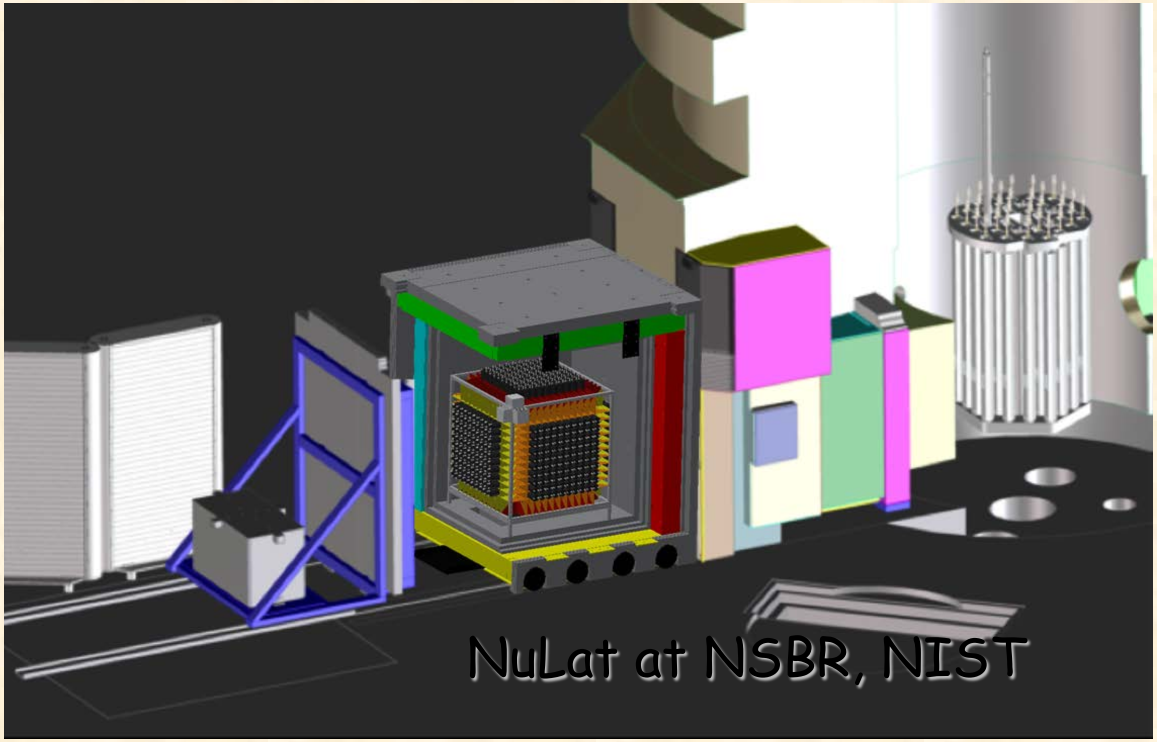
NuLat at a 20MW Reactor

Plan to take to NIST

Same location as mTC

5 m from core

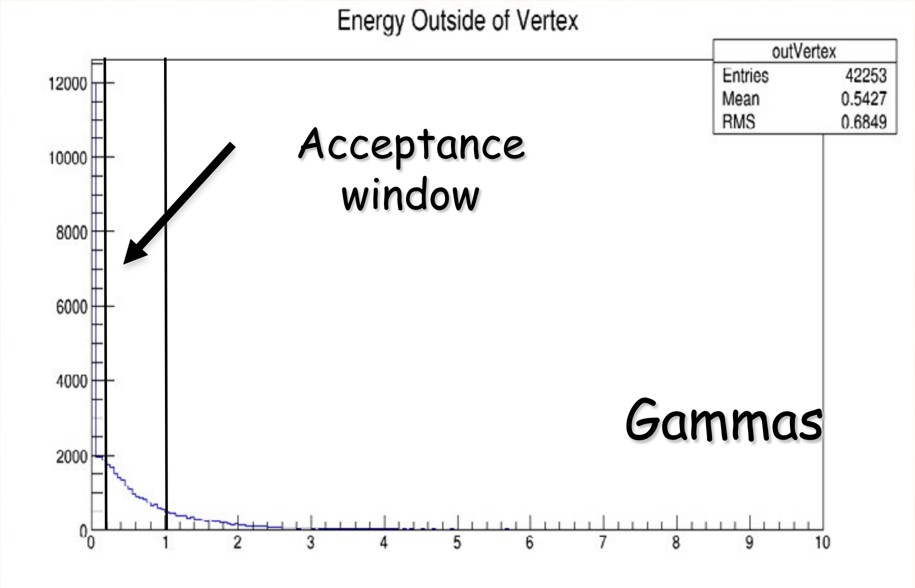
Spring 2017

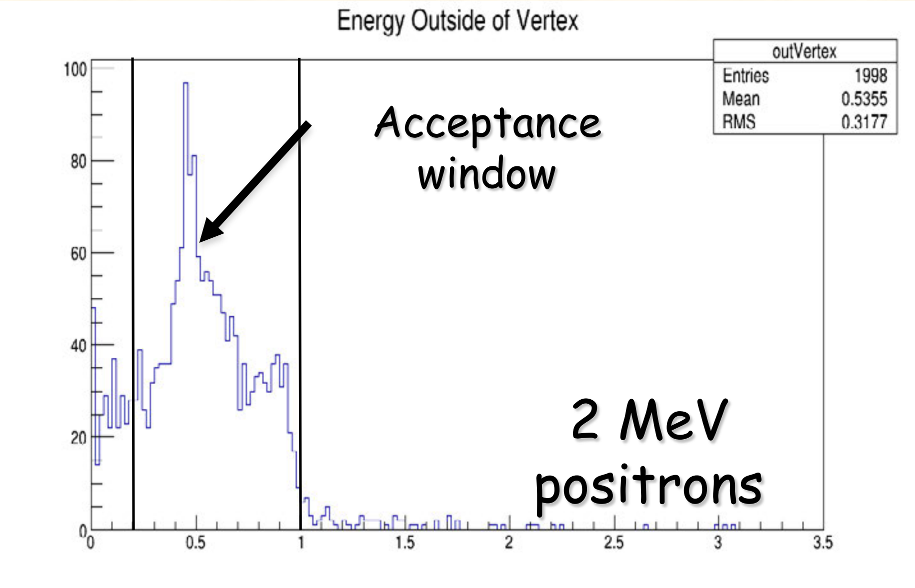


NuLat at NSBR, NIST

Gamma-induced false prompt events

– Multiple Compton scattering: Energy outside of vertex
  – Accept 0.2 MeV < E < 1.0 MeV
  – This alone removes ~ **60%** of gammas

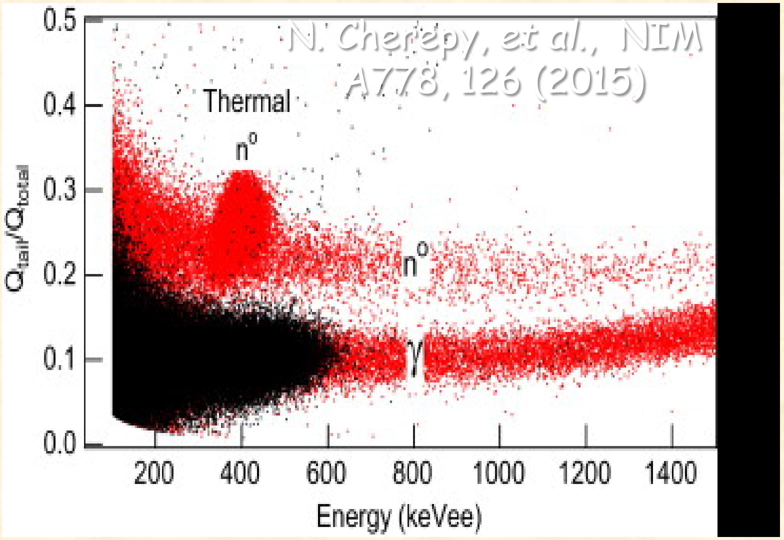


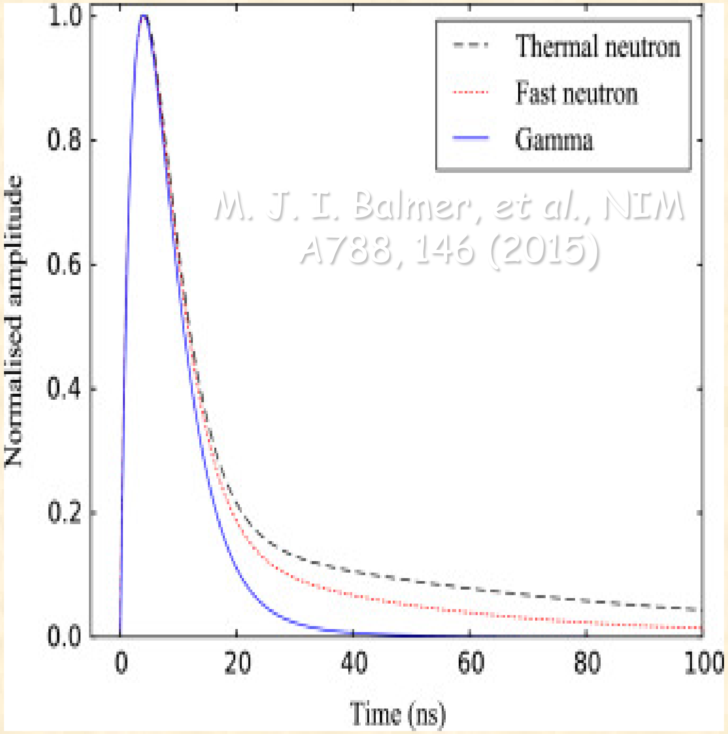


JHU APL

PSD for background rejections

- Pulse shape discrimination
  - Different dE/dx ⇒ different scintillator





Summary

Neutrino studies are mature

We have a good 3 neutrino model

Campaigns progressing for hierarchy, lowest mass, CP violation

A few mysteries and many challenges remain

New detection techniques are being developed… only discussed two which we have been exploring... (mTC and NuLat)

Seems to be growing international desire for a huge scintillation detector at great depth, low threshold, and 10x existing size

Solution: Theia? SuperKamLAND? Other?

Join the fun and stay tuned