IceCube Dedication Symposium, Madison, Wisconsin
29 April 2011

Non-Accelerator Neutrinos
And the State of Neutrino Studies

John G. Learned
University of Hawaii, Manoa

With Many thanks to UH Neutrino Colleagues:
P. Gorham, J. Kumar, S. Matsuno, A. McDonald, J. Murillo, S. Pakvasa,
M. Rosen, M. Sakai, S. Smith, G. Varner, and more….
+ slides from T. Lasserre, R. Raffelt, T. Schwetz

“Talking to the neighbors”

SETI with Neutrinos

“A modest proposal for an interstellar communications network”
Economist, 7 April 2011

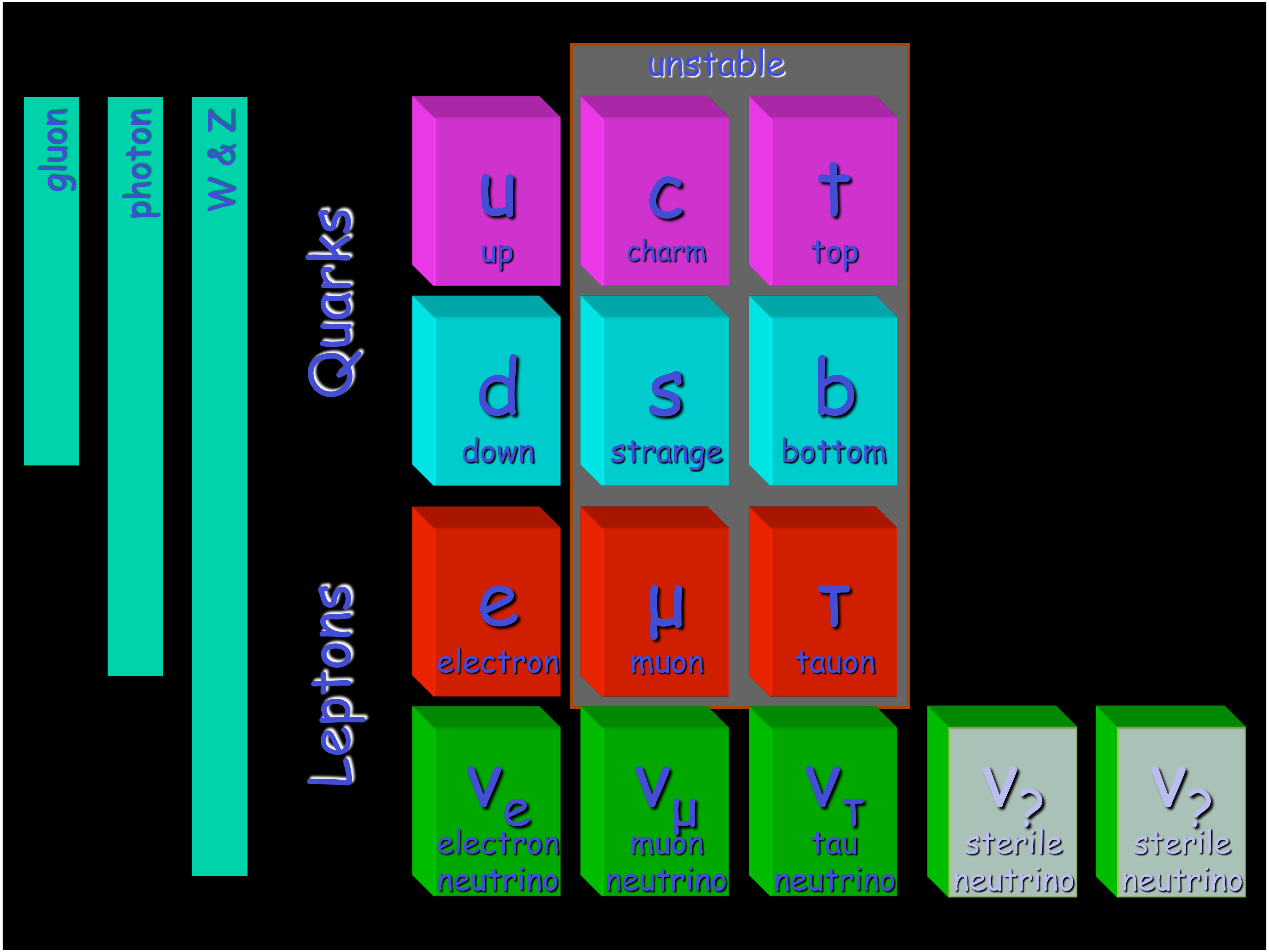
Not what this talk is about….

http://www.economist.com/PrinterFriendly.cfm?story_id=18526871

Breakfast Nus?

Neutrino Contents about 0.000000000000000000002 kCal

Thanks Joshua Murillo



gluon

photon

W & Z

Quarks

Leptons

unstable

u
up

c
charm

t
top

d
down

s
strange

b
bottom

e
electron

μ
muon

τ
tauon

ν_e
electron neutrino

ν_μ
muon neutrino

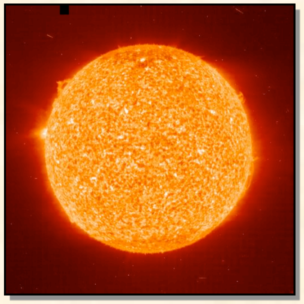
ν_τ
tau neutrino

$\nu_?$
sterile neutrino

$\nu_?$
sterile neutrino

Where do Neutrinos come from?

✓ Nuclear Reactors
(power stations, ships)

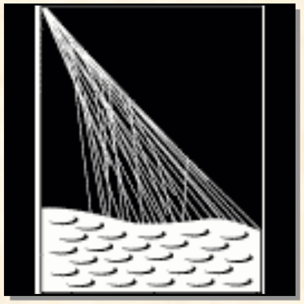


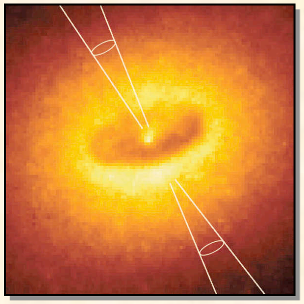
Sun ✓

✓ Particle Accelerator

Supernovae
(star collapse)
SN 1987A ✓

✓ Earth's Atmosphere
(Cosmic Rays)

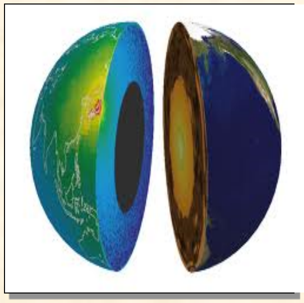




Astrophysical Sources

Soon ?

✓ Bulk Earth
(U/Th Radioactivity)



Big Bang
(here 330 /cm^3)
Indirect Evidence

What do we know well about neutrinos?

- No electric charge.
- Little or no electric/magnetic dipole moment.
- Essentially point particles.
- Very small mass compared to other fermions.
- Participates only in SM weak interaction.
- Falls under gravity (SN1987A).
- Produced in only left-handed helicity state (nubar = righthanded)
- Comes in three flavors, e, μ and τ
- Lepton number is conserved (but not lepton flavor)
- No known lifetime (but…).
- Has nothing to decay to amongst known particle zoo (but v_m-> v_n OK)
- SM processes produce neutrinos as superposition of mass states
- Mass states' relative phases change with flight time,
  producing morphing between interaction states ("v oscillations").
- Three mass states explains all accepted data, but room for new things.
- *Almost* surely we are living in a bath of undetectable ~600nu/cm^3
  left from Big Bang, which travel ~300 km/s.

Unanswered Neutrino Questions

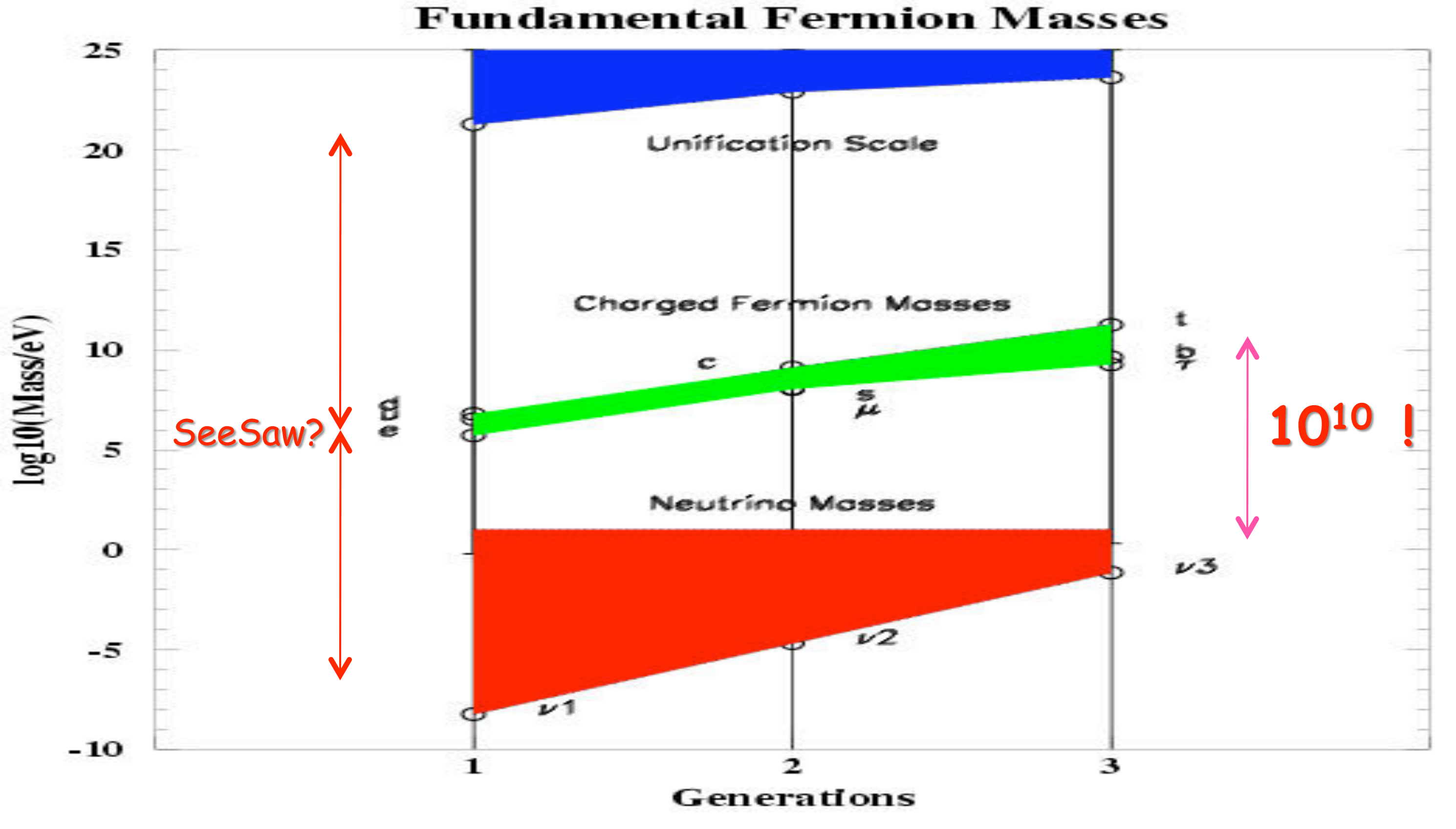
1) Who needed them anyway? Only uncharged fundamental fermion.
2) Why are masses so small?
3) What is the absolute mass scale?
4) What is the mass order?
5) Why is mixing matrix so different from quarks? (Why not?)
6) What is $|\theta_{13}|$? Is mixing tri-bimax ($\theta_{13} = 0$)?
7) Is there CP violation as with quarks?
8) Are there heavy (TeV - GUT scale) right handed neutrinos?
9) Are neutrinos Majorana or Dirac particles?
10) Are there any light (eV scale) sterile neutrinos?
11) Are heavy right handed neutrinos responsible for leptogenesis?
12) What role do neutrinos play in heavy element production in SN?

We have no guidance from a unified theory…
almost all prior theory guesses/biases were wrong…

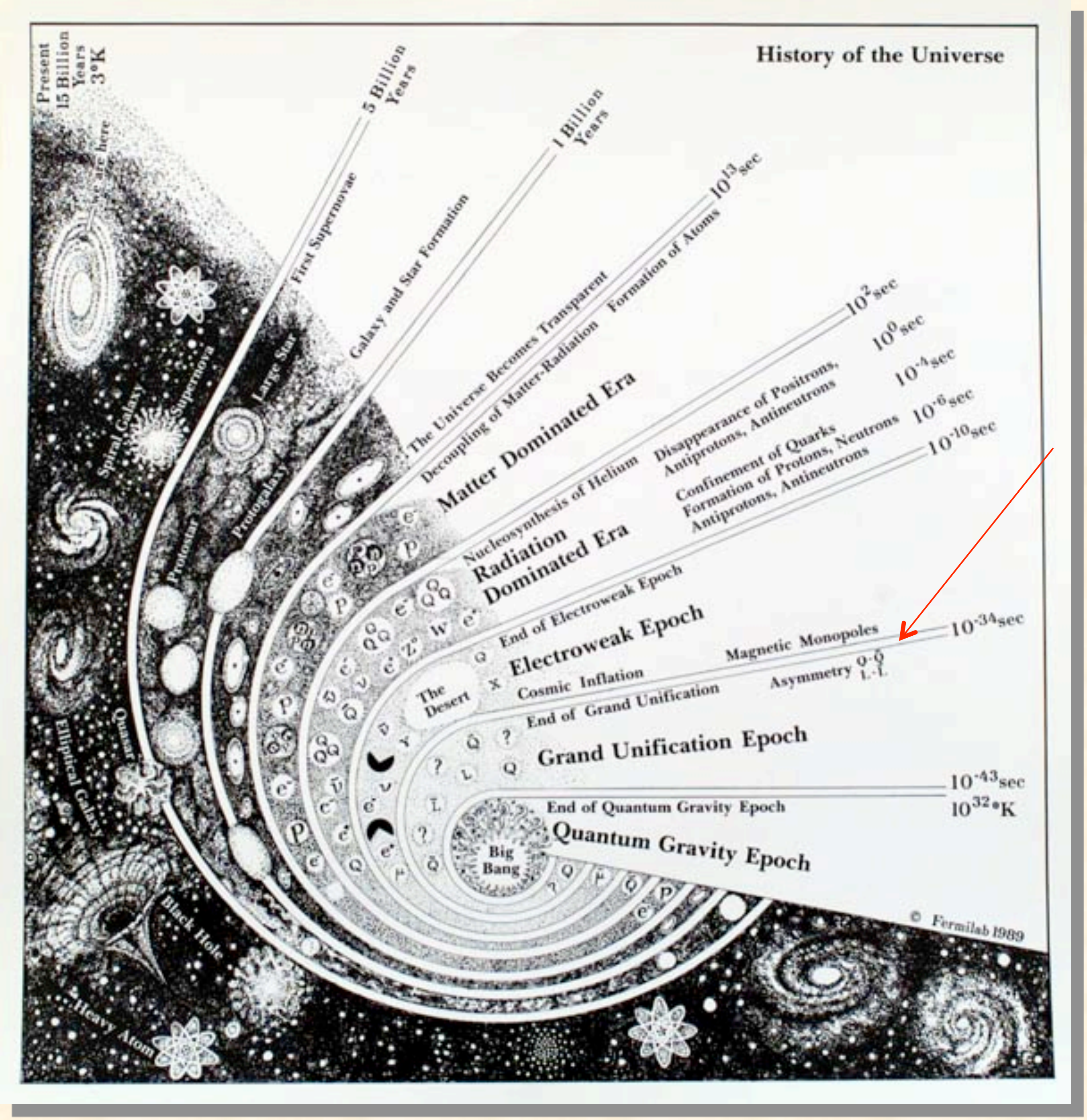
It is an experimentalists game.

Neutrinos as Key To
Grand Unification?

Fermion Mass Puzzle



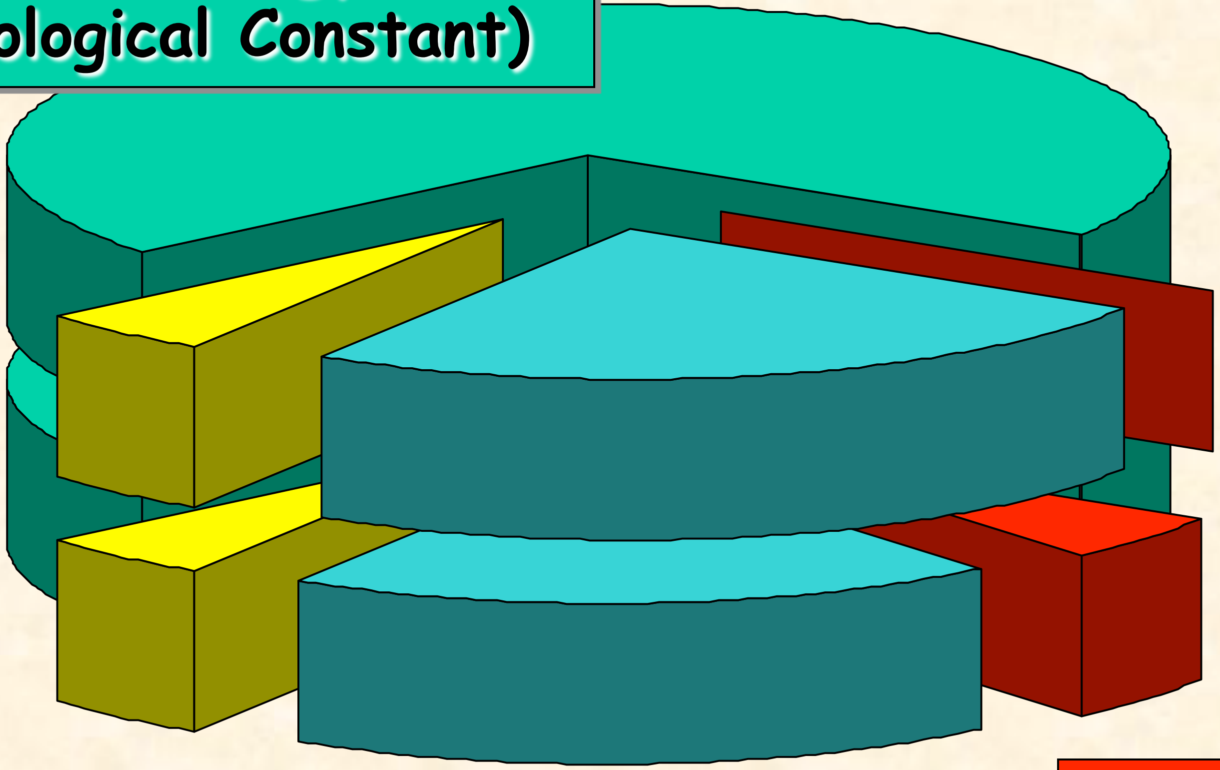
CP and CPT Violation Possible in ν Sector: Could be Key?



Leptogenesis

Neutrinos may play crucial role in the genesis of excess matter over anti-matter in the universe.

Matter Inventory of the Universe



Dark Energy
(Cosmological Constant)

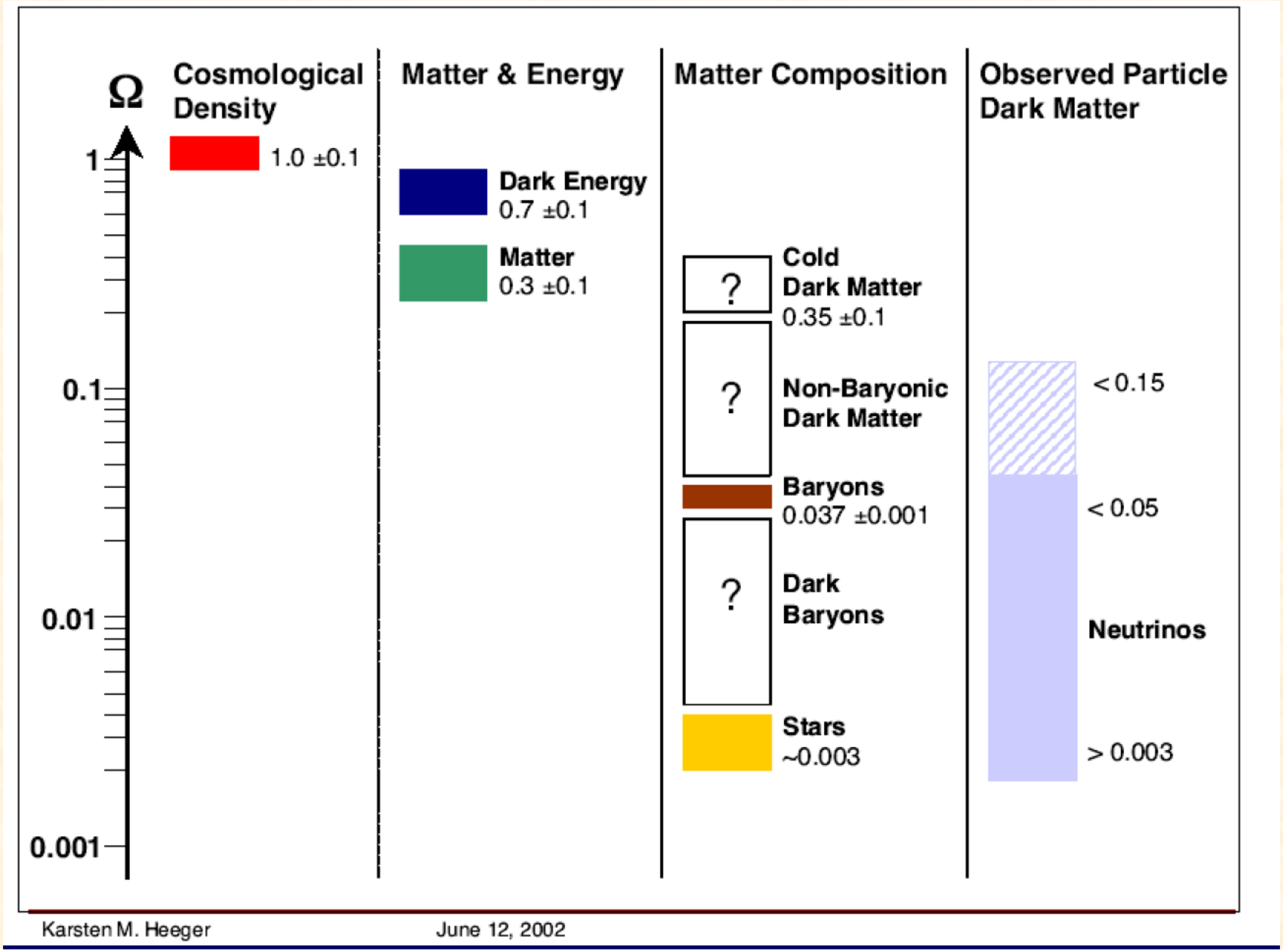
Copernicus^n!

Normal Matter
(of which ca.
10% luminous)

Dark
Matter

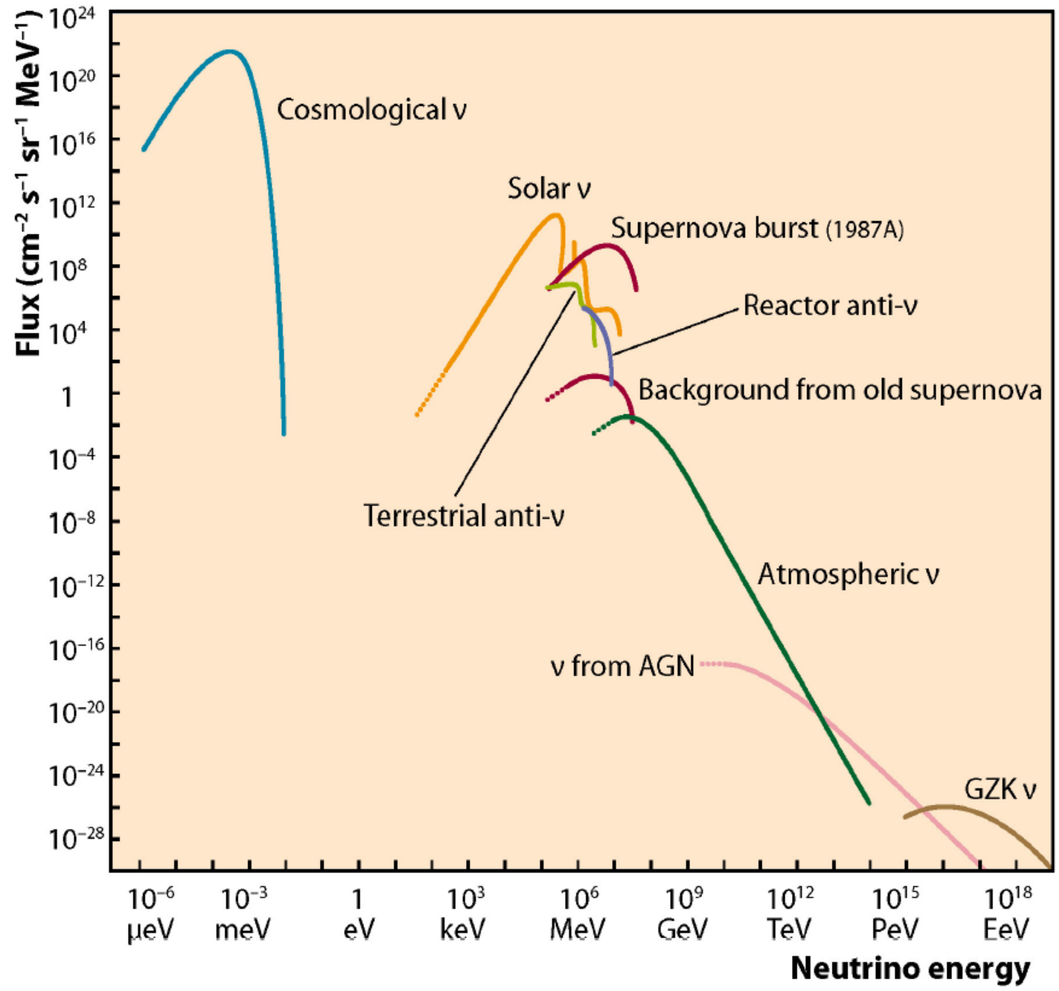
Neutrinos
min. 0.1%
max. 6%

Neutrinos in the Mass-Energy of the Universe



Karsten M. Heeger June 12, 2002

… and vast lands to be explored: one should be open to unexpected results



A synoptic view of neutrino fluxes. (from ASPERA roadmap)

Astrophysical Neutrino Sources… not yet found

High and Ultra-high energy neutrinos?

Supernova neutrinos from GSC in our galactic neighborhood?

Neutrinos associated with Gamma Ray Bursts?

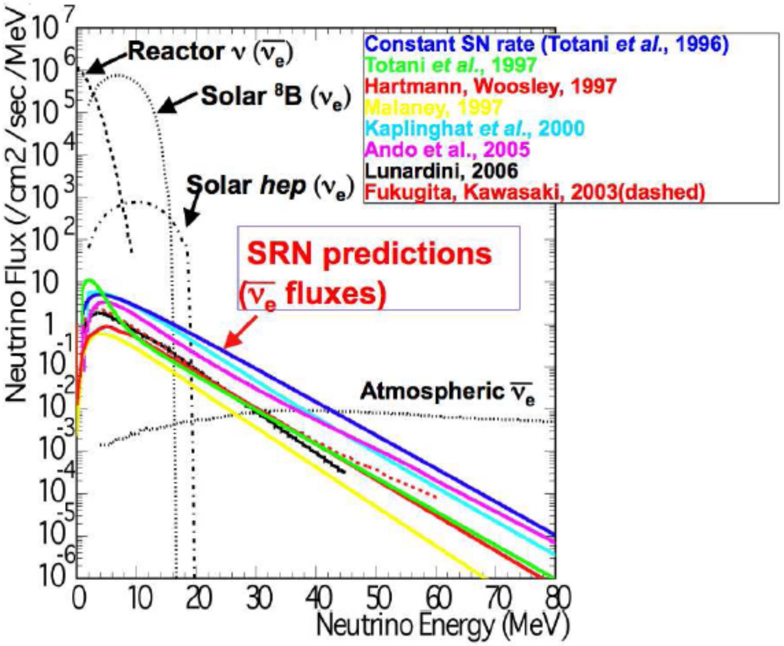
Relic SN neutrinos?

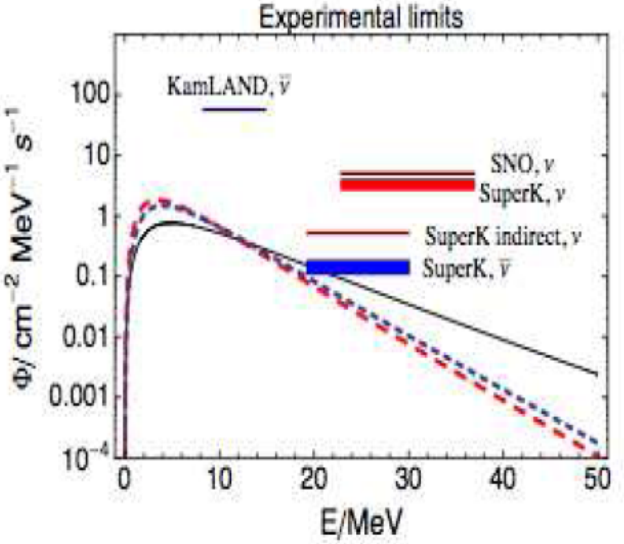
Neutrinos from Dark Matter annihilations in earth, sun or galactic center?

Who knows?

Lesson of history… the latter may be most probable!

Neutrinos from Earlier Supernovae



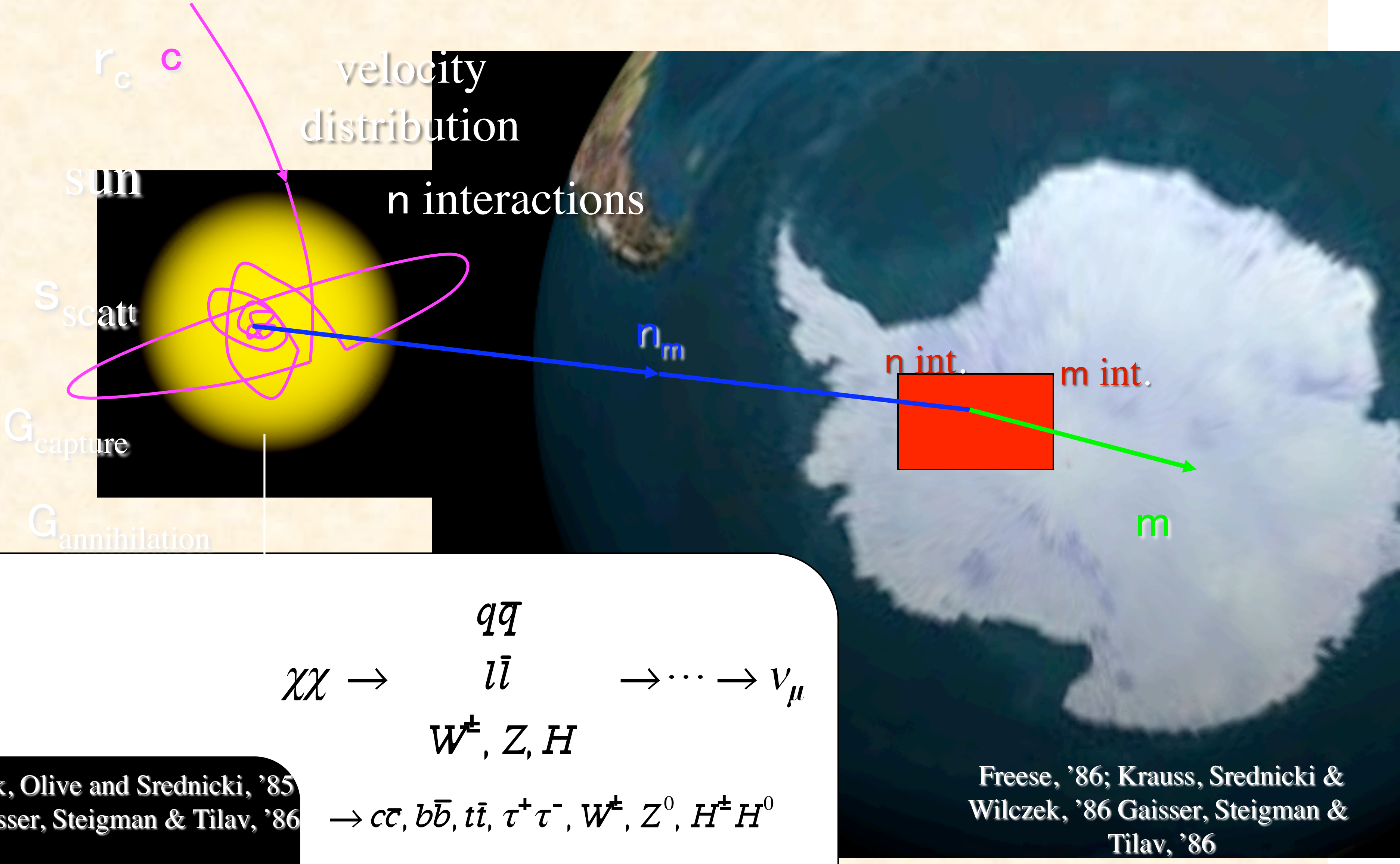


Reference Configuration	Expected Annual SRN Signal (events/year)	Expected Annual Background (events/year)	Years of LBNE Data Needed for a 3.0-σ Signal Assuming Maximum/Minimum SRN Flux
300kt WCD 30%	5 – 52	320	1.3/144
300kt WCD 30% + Gd	13 – 74	64	0.13/0.9
100kt WCD + 100kt WCD-Gd + 17kt LAr	5 – 39	114	0.35/3
100kt WCD-Gd + 34 kt LAr	4 – 27	21	0.32/3

Mary Bishai at NuTel 2011

neutralino capture and annihilation

See "Indirect Detection" of Dark Matter in Laura Baudis' talk



$$\chi\chi \to \begin{matrix} q\bar{q} \\ l\bar{l} \\ W^{\pm}, Z, H \end{matrix} \to \cdots \to \nu_{\mu}$$

$$\to c\bar{c}, b\bar{b}, t\bar{t}, \tau^{+}\tau^{-}, W^{\pm}, Z^{0}, H^{\pm}H^{0}$$

Silk, Olive and Srednicki, '85
Gaisser, Steigman & Tilav, '86

Freese, '86; Krauss, Srednicki & Wilczek, '86 Gaisser, Steigman & Tilav, '86

New Window on Universe? Expect Surprises

Telescope	*User*	*Date*	*Intended Use*	*Actual use*
Optical	**Galileo**	**1608**	**Navigation**	**Moons of Jupiter**
Optical	**Hubble**	**1929**	**Nebulae**	**Expanding Universe**
Radio	**Jansky**	**1932**	**Noise**	**Radio galaxies**
Micro-wave	**Penzias, Wilson**	**1965**	**Radio-galaxies, noise**	**3K cosmic background**
X-ray	**Giacconi …**	**1965**	**Sun, moon**	**neutron stars accreting binaries**
Radio	**Hewish, Bell**	**1967**	**Ionosphere**	**Pulsars**
γ-rays	**military**	**1960?**	**Thermonuclear explosions**	**Gamma ray bursts**
Water-Cherenkov	**IMB, Kamioka**	**1987**	**Nucleon Decay**	**ν's from SN1987A**
Water-Cherenkov	**SuperK**	**1998**	**Nucleon Decay**	**$\nu_\mu \leftrightarrow \nu_\tau$ mixing ν mass**
Solar Neutrino	**Homestake, SuperK, SNO**	**2001**	**Solar Burning**	**ν_e Oscillations**

Some Neutrino Experimental Peculiarities

1) Flux calcs always under-predict observed rate both at accelerators, and from atmospheric cosmic ray interactions. (Known but may be boring, or not?)
2) SN1987A events pointed too well…. Need another SN
3) Where are the very high energy cosmic neutrinos? (Later today…)
4) MINOS finds apparent CPT violation hints in two different runs?

5) LSND anomaly… $\bar{\nu}_e$ appear from stopped pion target (1991).
6) MiniBOONE… unexplained bumps in both nu and antinu runs, but not at same E
7) Revised reactor neutrino flux calcs exceed measurements taken over many years in experiments from 10-2000 m distance.
8) Solar Gallium experiments radioactive source calibrations came out a little low in 4 trials
9) Cosmological neutrino counting coming in high by +1 or +2

Mike Shaevitz will cover #5-9 shortly….

Step back…

- Quick historical tour
- Small tutorial on oscillations

Neutrino Timeline

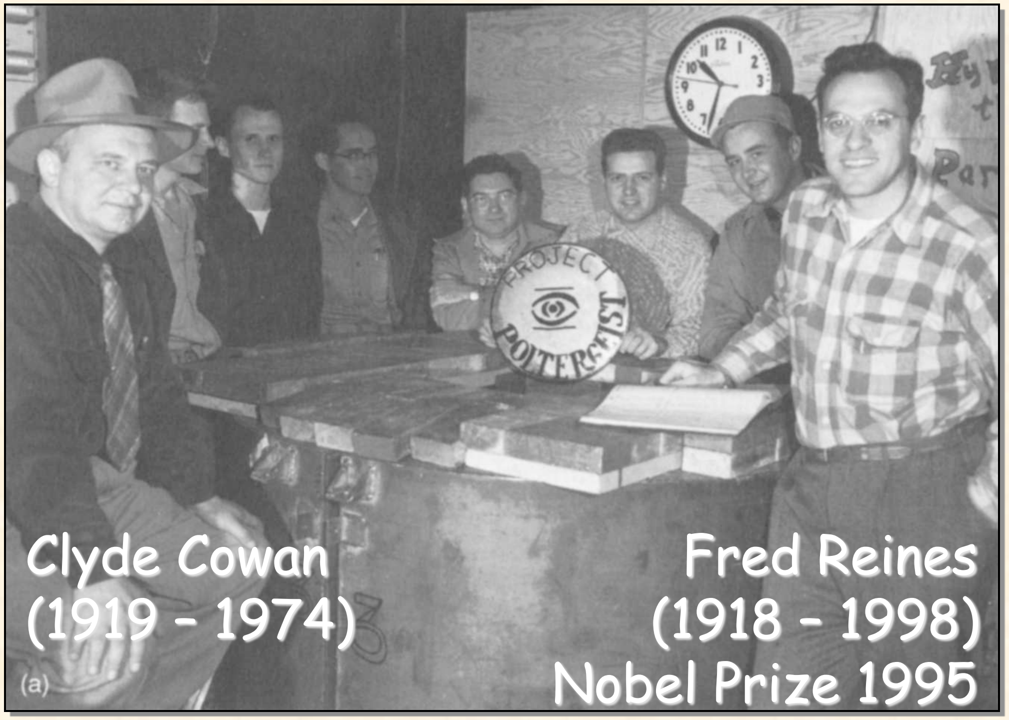
- 1920-1927 Charles Drummond Ellis (along with James Chadwick and colleagues) establishes clearly that the beta decay spectrum is really continous, ending all controversies.
- 1930 Wolfgang Pauli hypothesizes the existence of neutrinos to account for the beta decay energy conservation crisis.
- 1932 Chadwick discovers the neutron.
- 1933 Enrico Fermi writes down the correct theory for beta decay, incorporating the neutrino.
- 1946 Shoichi Sakata and Takesi Inoue propose the pi-mu scheme with a neutrino to accompany muon. (There is a long story about the confusion of mu for pi etc. They were the first to straighten it out and get the spins right, and write down the correct decay scheme completely: pi -> mu + nu_mu, mu -> e + nu_e + nu_mu, and noticed that both nu_mu and nu_e are light, and neutral with spin 1/2, and suggested that they might be "different".)
- 1956 Fred Reines and Clyde Cowan discover (electron anti-) neutrinos using a nuclear reactor.
- 1957 Neutrinos found to be left handed by Goldhaber, Grodzins and Sunyar.
- 1957 Bruno Pontecorvo proposes neutrino-antineutrino oscillations analogously to K0-K0bar, leading to what is later called oscillations into sterile states.
- 1962 Ziro Maki, Masami Nakagawa and Sakata introduce neutrino flavor mixing and flavor oscillations.
- 1962 Muon neutrinos are discovered by Leon Lederman, Mel Schwartz, Jack Steinberger and colleagues at Brookhaven National Laboratories and it is confirmed that they are different from nu_e's.
- 1964 John Bahcall and Ray Davis propose feasibility of measuring neutrinos from the sun.
- 1965 The first natural neutrinos are observed by Reines and colleagues in a gold mine in South Africa, and by Goku Menon and colleagues in Kolar Gold fields in India, setting first astrophysical limits.
- 1968 Ray Davis and colleagues get first radiochemical solar neutrino results using cleaning fluid in the Homestake Mine in North Dakota, leading to the observed deficit known thereafter as the "solar neutrino problem".
- 1976 The tau lepton is discovered by Martin Perl and colleagues at SLAC in Stanford, California. After several years, analysis of tau decay modes leads to the conclusion that tau is accompanied by its own neutrino nutau which is neither nue nor numu.
- 1976 Designs for a new generation neutrino detectors made at Hawaii workshop, subsequently leading to IMB, HPW and Kamioka detectors .
- 1980s The IMB, the first massive underground nucleon decay search instrument and neutrino detector is built in a 2000' deep Morton Salt mine near Cleveland, Ohio. The Kamioka experiment is built in a zinc mine in Japan.
- 1983 The "atmospheric neutrino anomaly" is observed by IMB and later by Kamiokande.
- 1986 Kamiokande group makes first directional counting observation solar of solar neutrinos and confirms deficit.
- 1987 The Kamiokande and IMB experiments detect burst of neutrinos from Supernova 1987A, heralding the birth of neutrino astronomy, and setting many limits on neutrino properties, such as mass.
- 1988 Lederman, Schwartz and Steinberger awarded the Nobel Prize for the discovery of the muon neutrino.
- 1989 The LEP accelerator experiments in Switzerland and the SLC at SLAC determine that there are only 3 light neutrino species(electron, muon and tau).
- 1991-2 SAGE (in Russia) and GALLEX (in Italy) confirm the solar neutrino deficit in radiochemical experiments.
- 1995 Frederick Reines and Martin Perl get the Nobel Prize for discovery of electron neutrinos (and observation of supernove neutrinos) and the tau lepton, respectively.
- 1996 Super-Kamiokande, the largest ever detector at 50 kilotons gross, begins searching for neutrino interactions on 1 April at the site of the Kamioka experiment, with Japan-US team (led by Yoji Totsuka).
- 1998 After analyzing more than 500 days of data, the Super-Kamiokande team reports finding oscillations and, thus, mass in muon neutrinos. After several years these results are widely accepted and the paper becomes the top cited experimental particle physics paper ever.
- 2000 The DONUT Collaboration working at Fermilab announces observation of tau particles produced by tau neutrinos, making the first direct observation of the tau neutrino.
- 2000 SuperK announces that the oscillating partner to the muon neutrino is not a sterile neutrino, but the tau neutrino.
- 2001 and 2002 SNO announces observation of neutral currents from solar neutrinos, along with charged currents and elastic scatters, providing convincing evidence that neutrino oscillations are the cause of the solar neutrino problem.
- 2002 Masatoshi Koshiba and Raymond Davis win Nobel Prize for measuring solar neutrinos(as well as supernova neutrinos).
- 2002 KamLAND begins operations in January and in November announces detection of a deficit of electron anti-neutrinos from reactors at a mean distance of 175 km in Japan. The results combined with all the earlier solar neutrino results establish the correct parameters for the solar neutrino deficit.
- 2004 SuperKamiokande and KamLAND present evidence for neutrino disappearance and reappearance, eliminating non-oscillations models
- 2005 KamLAND announces first detection of neutrino flux from the earth and makes first measurements of radiogenic heating from the earth.

Pakvasa & Learned, 2005

Non-Accelerator Neutrino History Survey

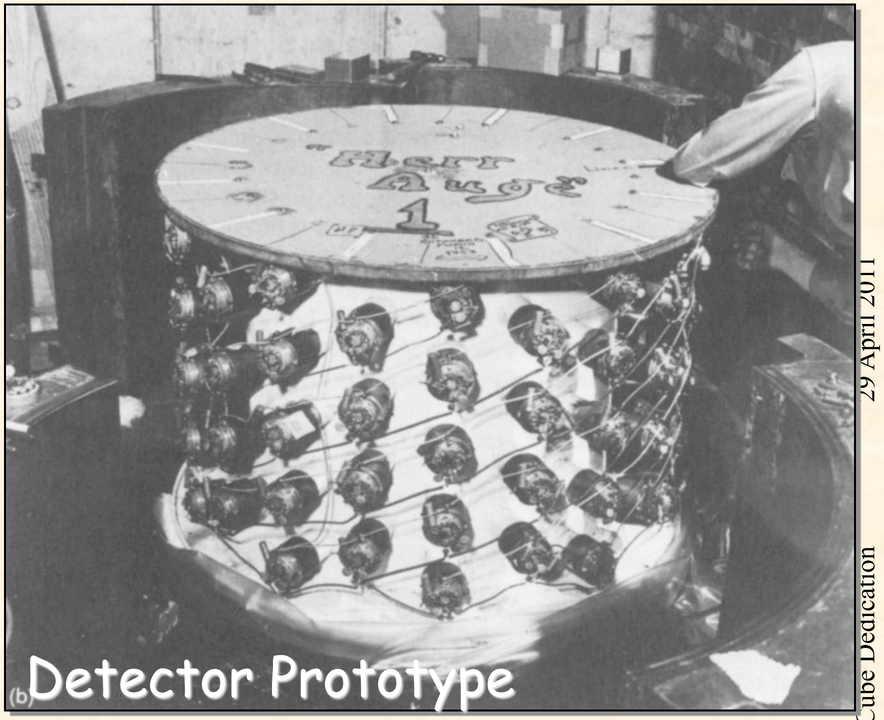
- Neutrinos were proposed in 1930 as solution to missing energy in beta decays.
- Said to be undetectable, but….

First Detection ! (1954 - 1956)



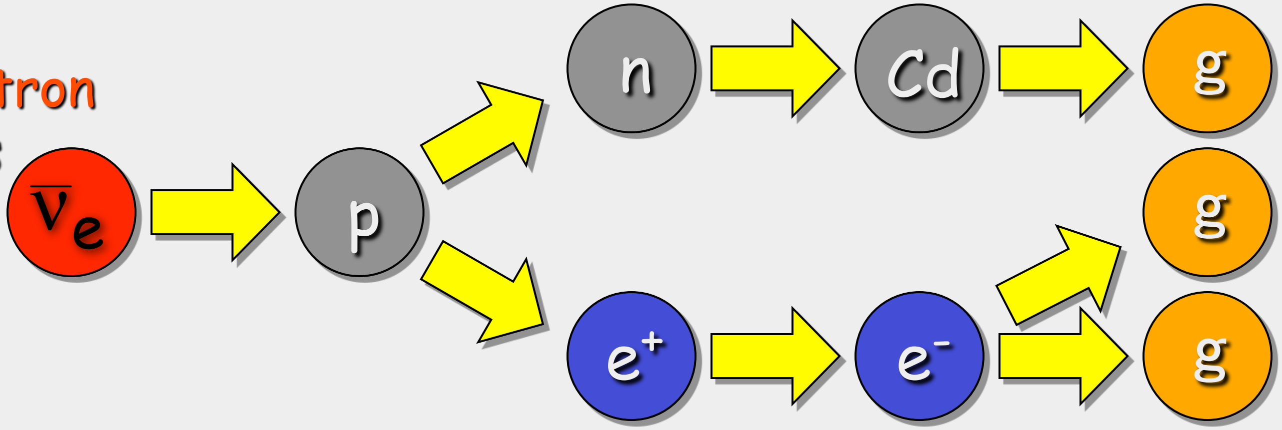
Clyde Cowan
(1919 – 1974)

Fred Reines
(1918 – 1998)
Nobel Prize 1995



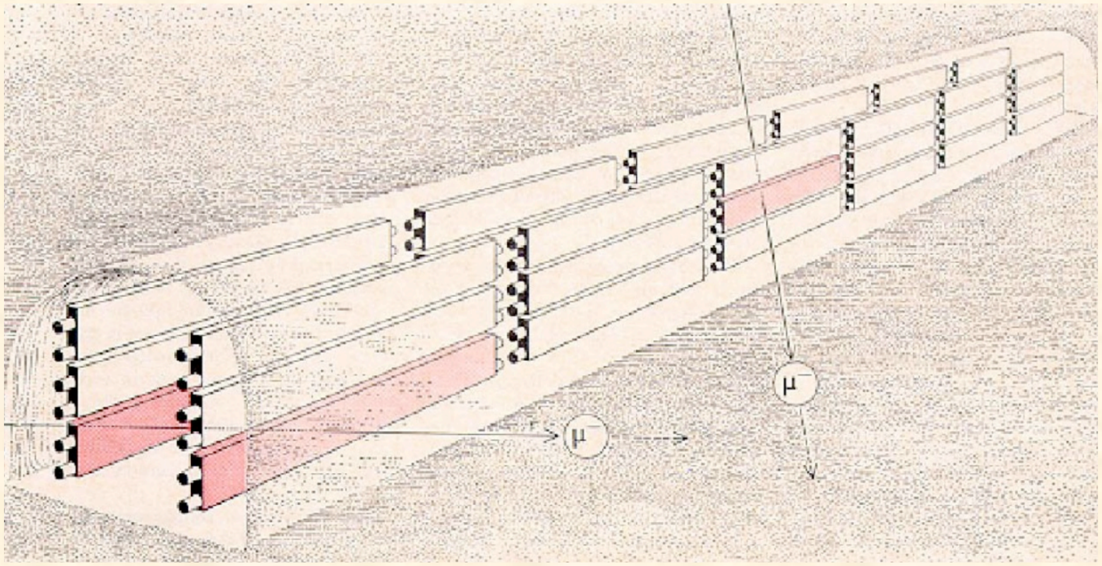
Detector Prototype

Anti-Electron Neutrinos from Hanford Nuclear Reactor

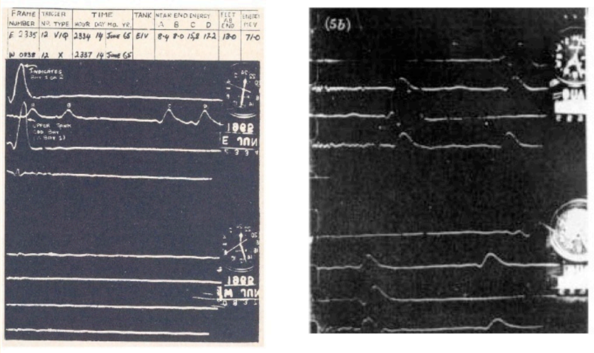


3 gamma quanta in coincidence

First Natural Cosmic Ray Neutrinos, 1965



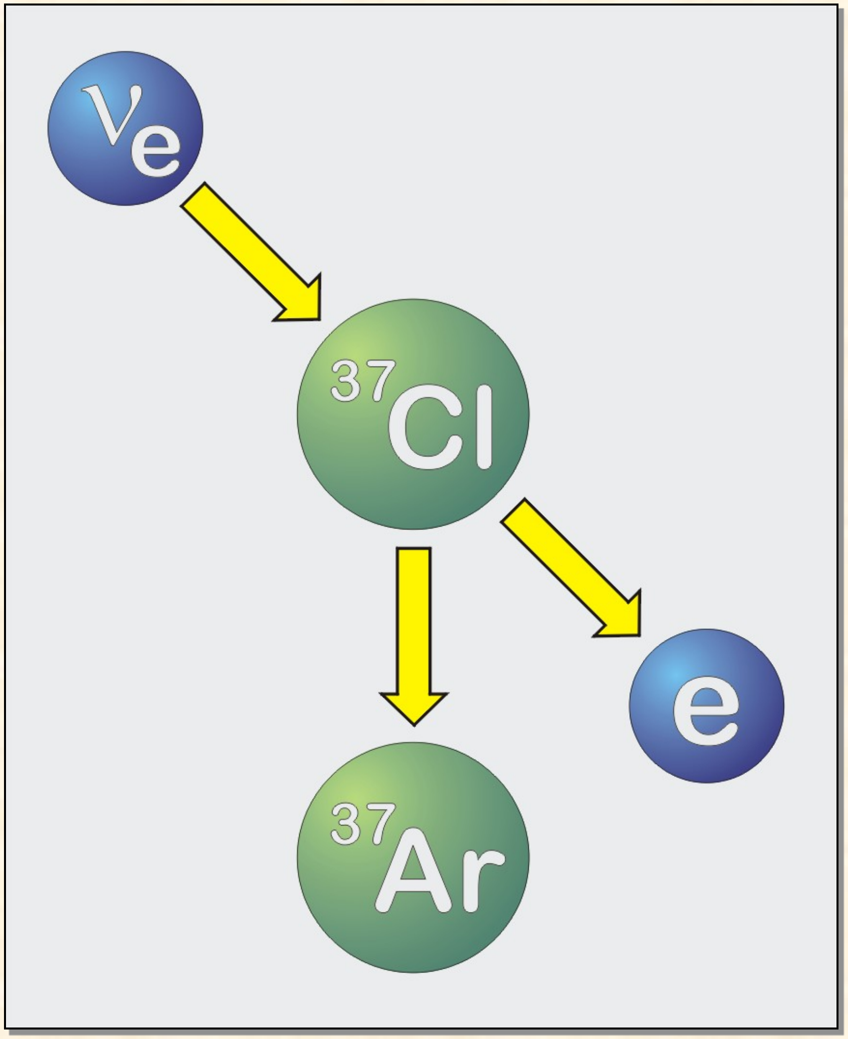
Reines and company in South Africa,
and Gaku Menon and company
in Kolar Gold Fields, India

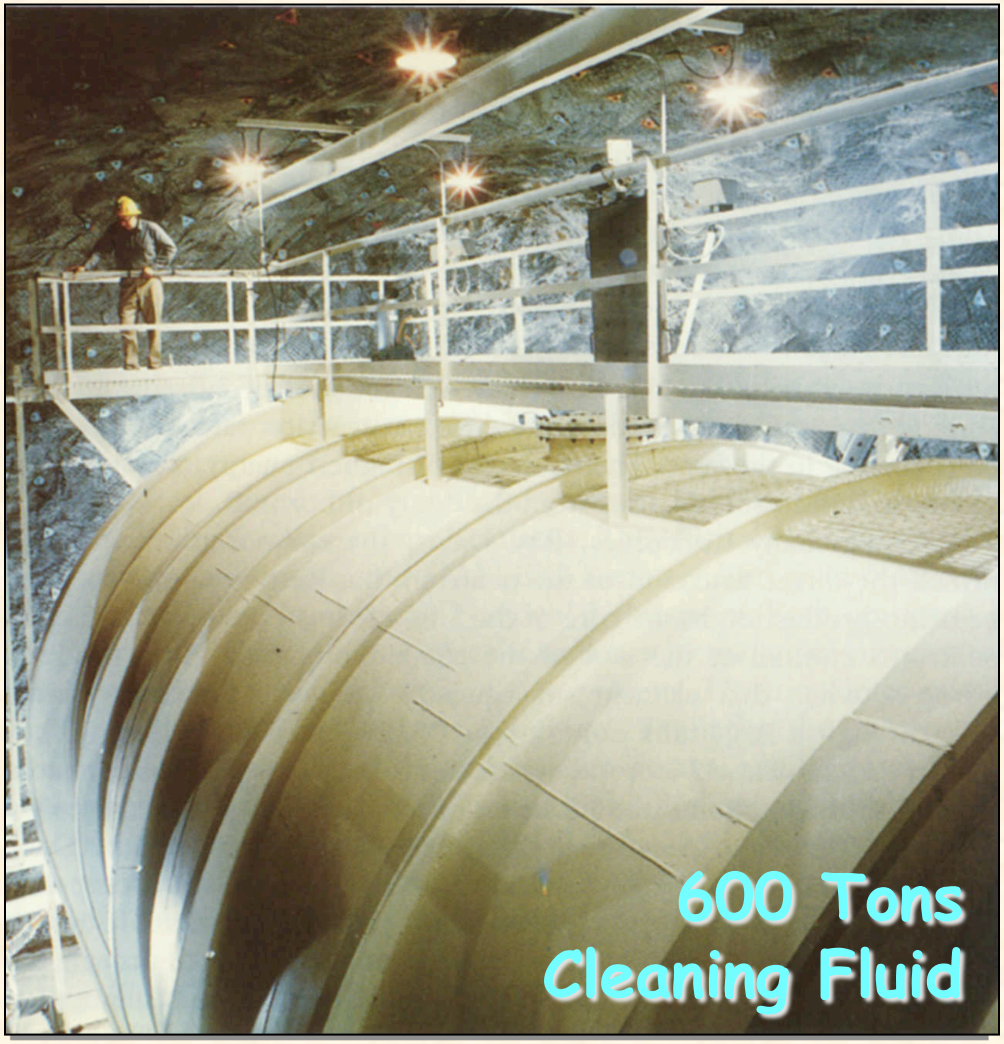


FRAME NUMBER	TRIGGER NO.	TRIGGER TYPE	TIME HOUR	TIME DAY	TIME MO. YR.	TANK	NEAR END ENERGY A	B	C	D	FEET AB END	ENERGY MEV
E 2335	12	V/φ	2334	14	June 65	E/V	8·4	8·0	15,8	17·2	13·0	71·0
W 0938	12	X	2337	14	June 65							

First Observation of Solar Neutrinos

Inverse Beta-Decay
("Neutrino Capture")





600 Tons
Cleaning Fluid

Homestake Solar-Neutrino Observatory (since ca. 1967)

1980's

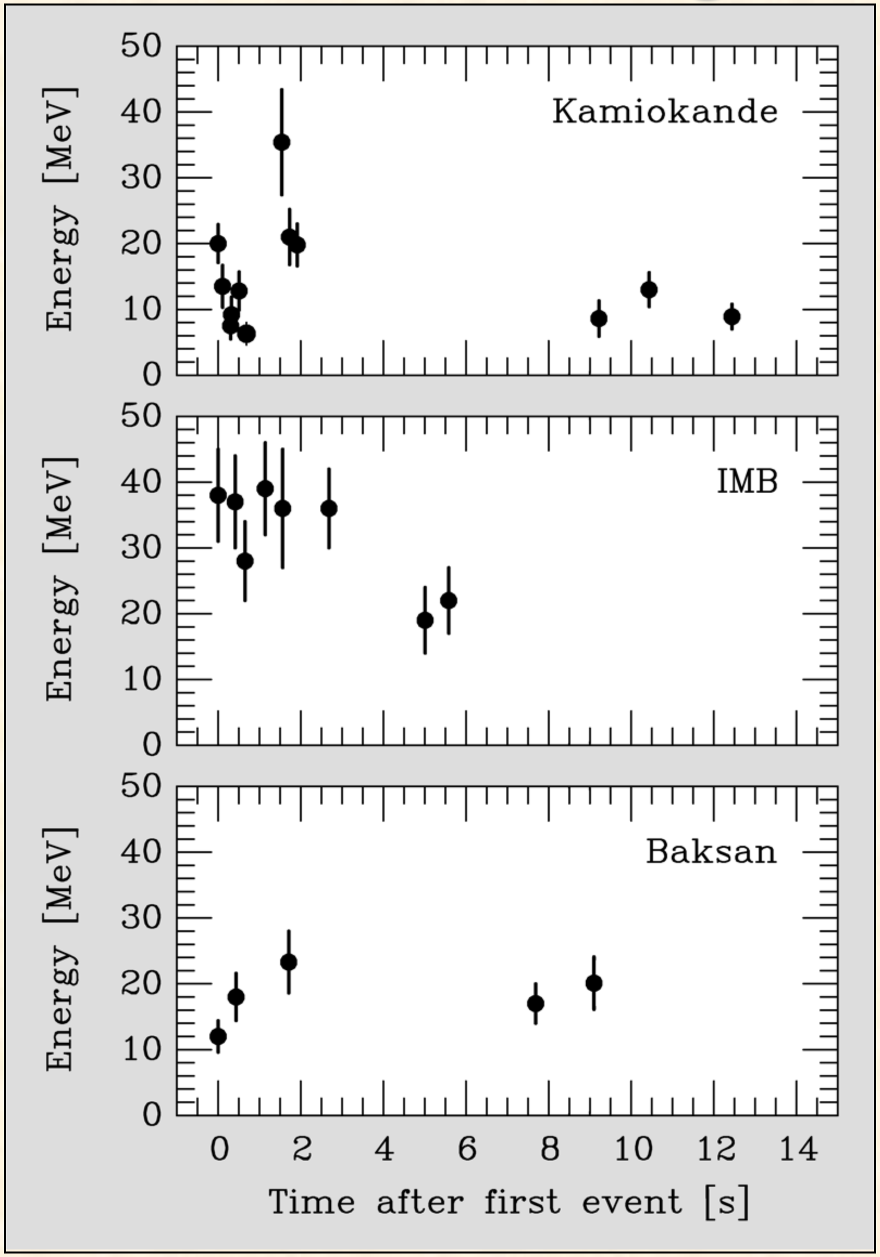
Solar neutrino experiments not seeing predicted rates… blame game between solar modelers and experimentalists. Theory provides a few possible explanations, including oscillations.

Underground cosmic ray neutrino detectors built to search for nucleon decay, but find peculiar deficit of muon/electron neutrinos in US and Japan ("muon neutrino anomaly"), but not in Europe.

Lots of confusion, finger pointing, enthusiasm, but only ambiguous conclusions.

But then one great highlight, resulting in hundreds of papers:

Neutrino Signal of Supernova 1987A



Kamiokande (Japan)
Water Cherenkov detector
Clock uncertainty 1 min

Irvine-Michigan-Brookhaven (US)
Water Cherenkov detector
Clock uncertainty 50 ms

Baksan Scintillator Telescope
(Soviet Union)
Clock uncertainty +2/-54 s

Within clock uncertainties, signals are contemporaneous

Neutrino Fever Hits in the 1990's

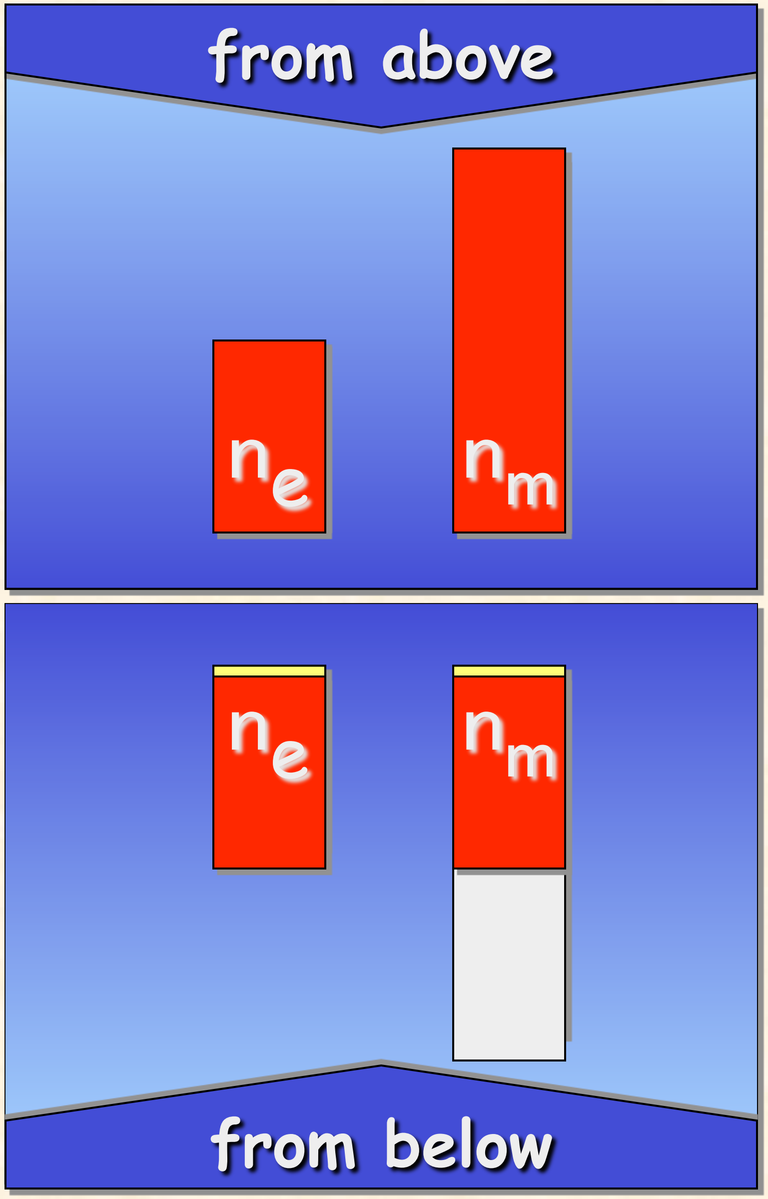
Kamiokande detects solar electron neutrinos, with directionality! (Eliminates question as to whether radiochemical expts actually detecting solar neutrinos)

Solar rates observed in 4 experiments 1/3-1/2 models… suspicions of electron neutrino oscillations, but other solutions not ruled out.

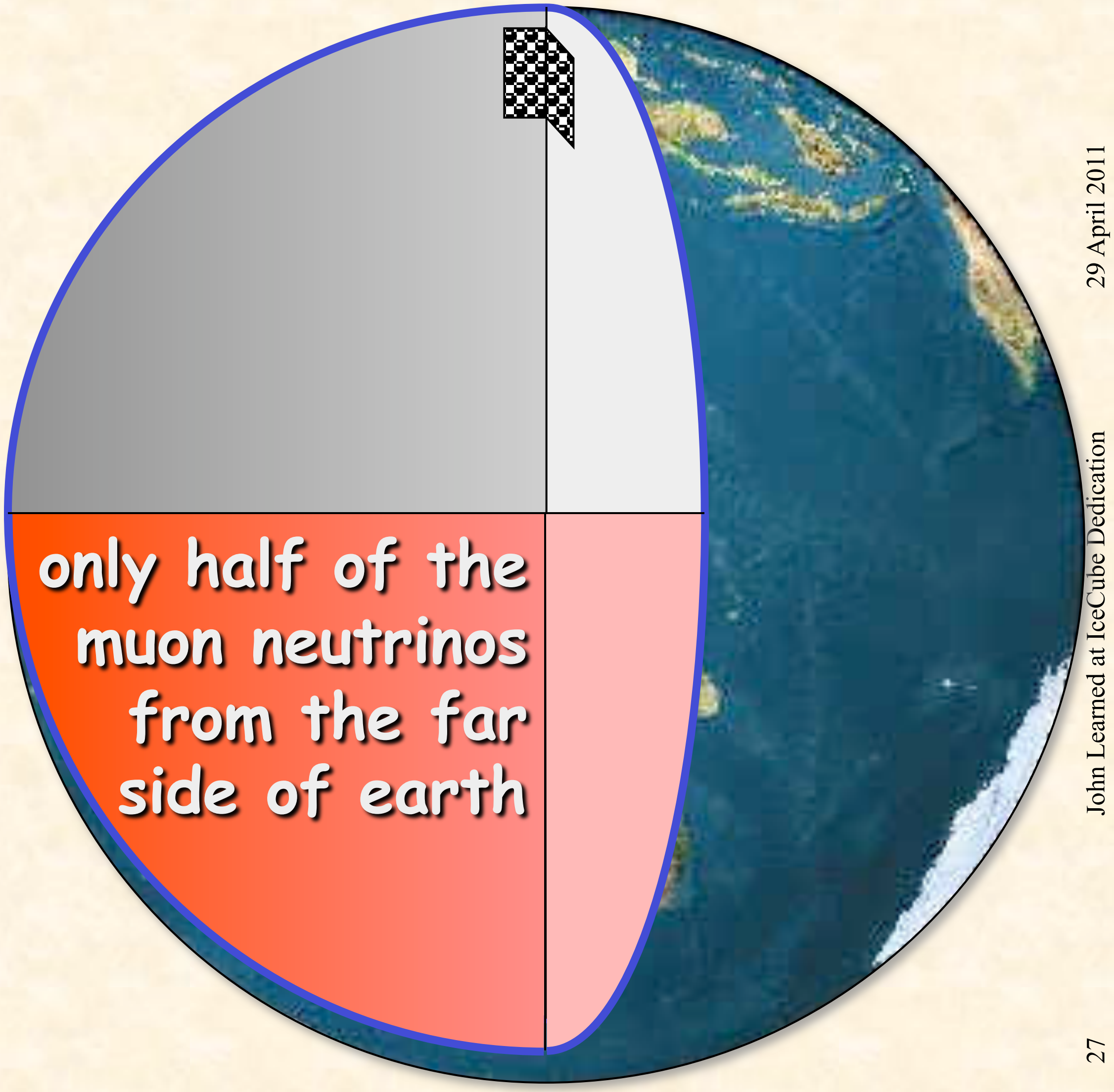
Early 1990's LSND finds peculiar nu_e appearance, claim oscillations. Almost ruled out by other experiments. People generally suspicious of result, but nobody finds smoking gun of problem. (More on this in next talk).

In 1996 the 50 kiloton SuperKamiokande detector starts, and by 1997 some things are beginning to become clear…

Atmospheric Neutrino Anomaly

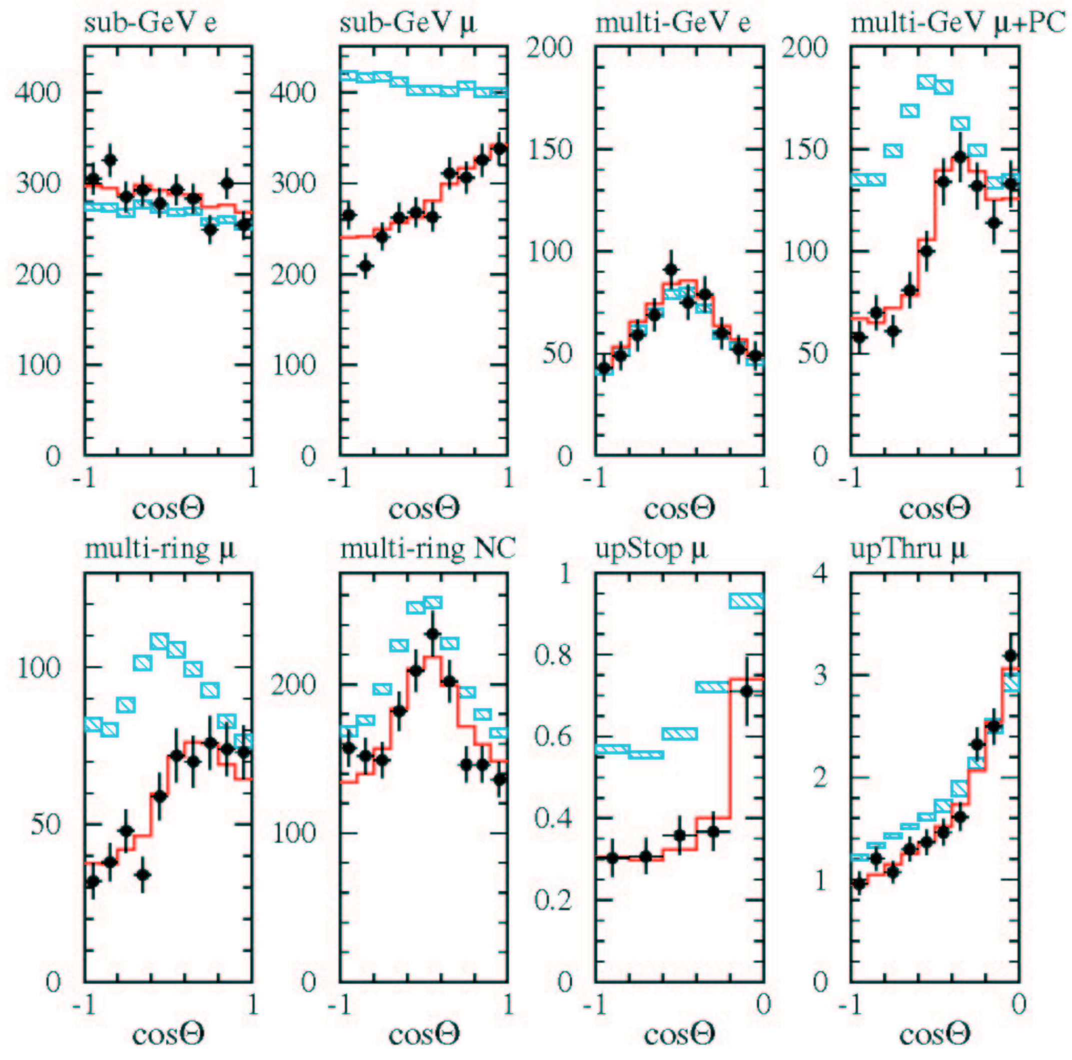


Super-Kamiokande



only half of the muon neutrinos from the far side of earth

Fit to Entire Atmospheric ν Data Set



MC No-Osc

$\nu_\mu - \nu_\tau$

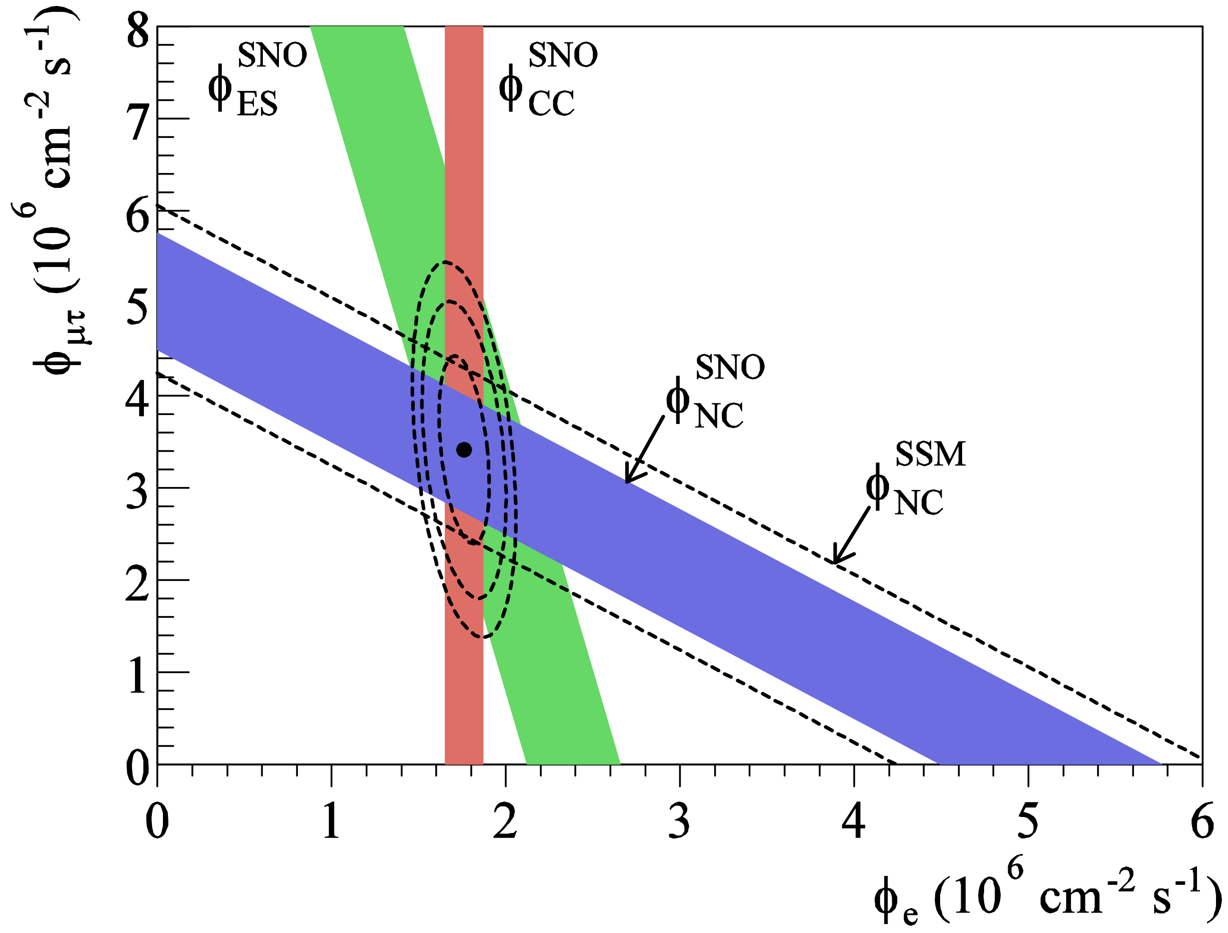
SuperK neutrino oscillations paper now most cited paper in history of experimental particle physics

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

Consistency Between Measurements

$\Phi_{ssm} = 5.05^{+1.01}_{-0.81}$ $\Phi_{sno} = 5.09^{+0.44}_{-0.43}{}^{+0.46}_{-0.43}$

$\Phi_{\mu\tau}$ is 5.3 σ from zero



SNO Settles the Solar Neutrino Problem

Homestake

Gallex/GNO
SAGE

Super-
Kamiokande

SNO (Deuterium)

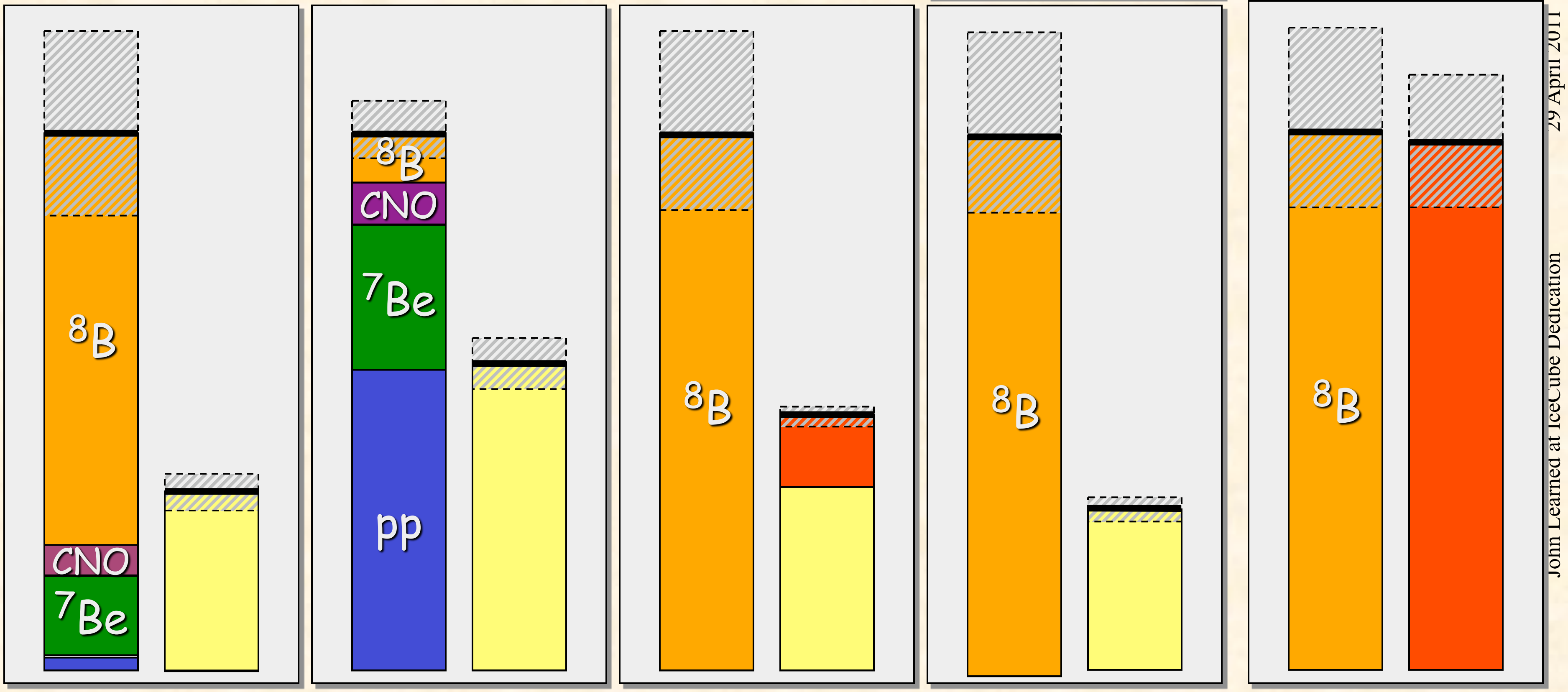
Chlorine

Gallium

Water

n$_e$+d p+p+e$^-$

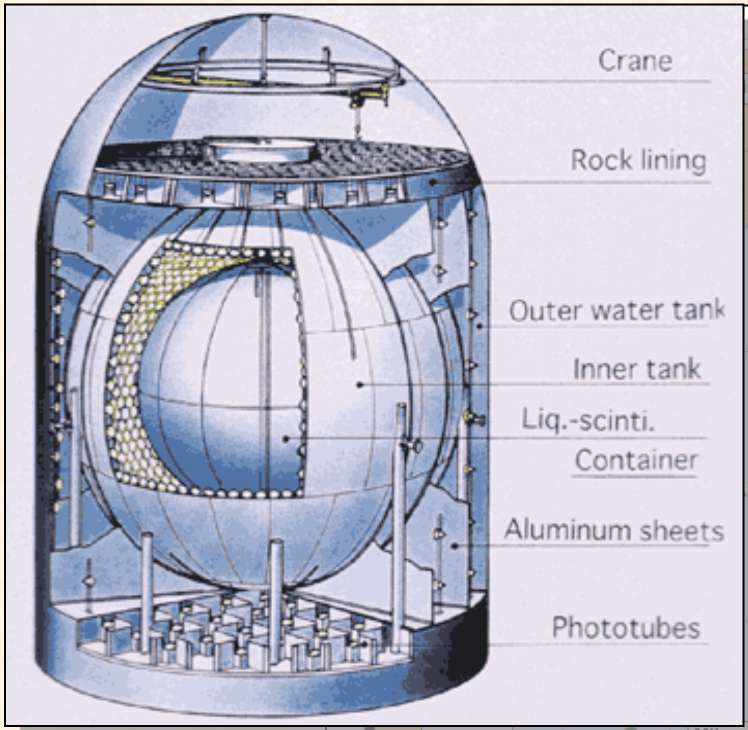
n + d p + n + n

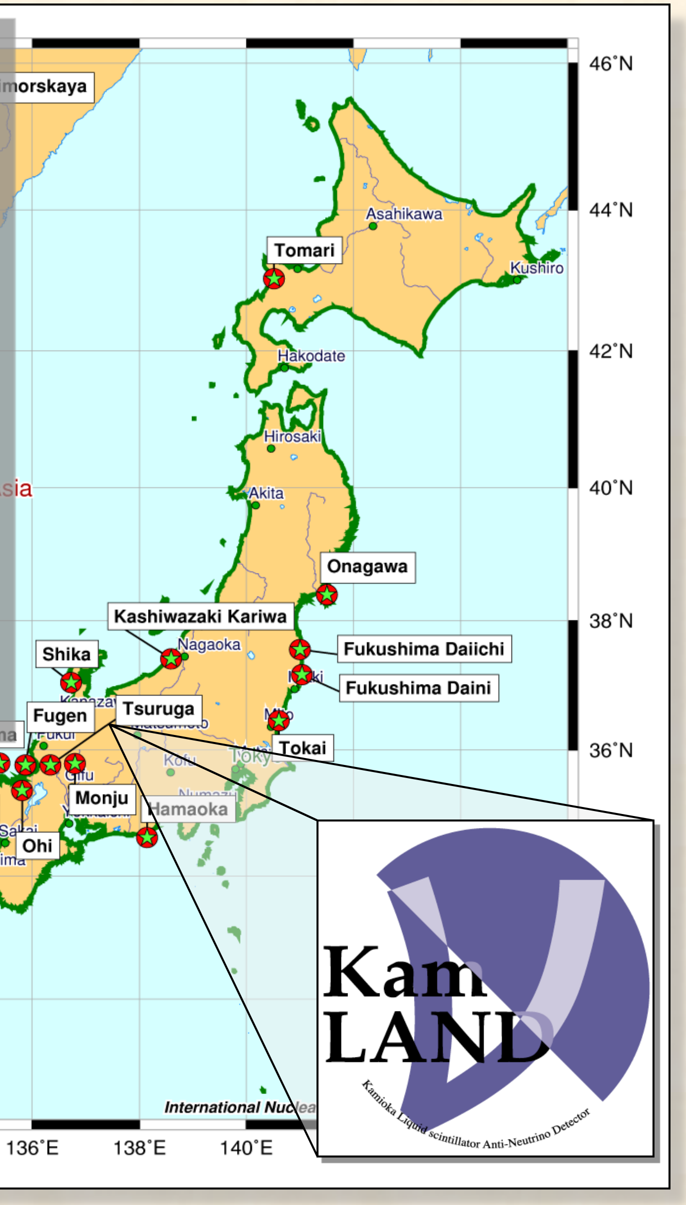


Electron-Neutrinos

All Neutrino Types

KamLAND Reactor Neutrino Experiment (Japan)





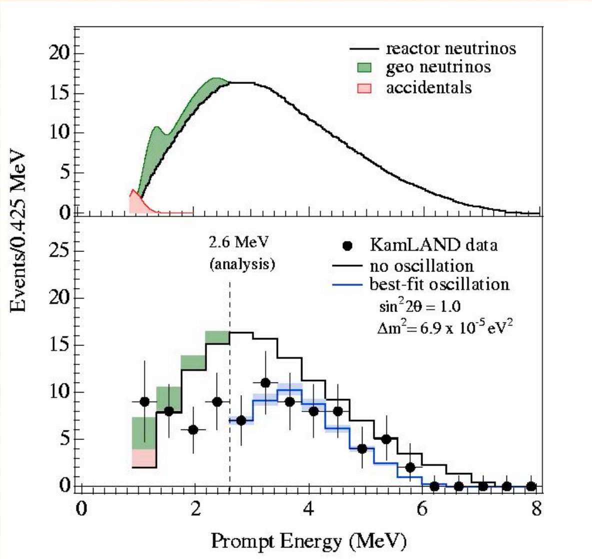
Japanese nuclear reactors 60 GW (20% world total)

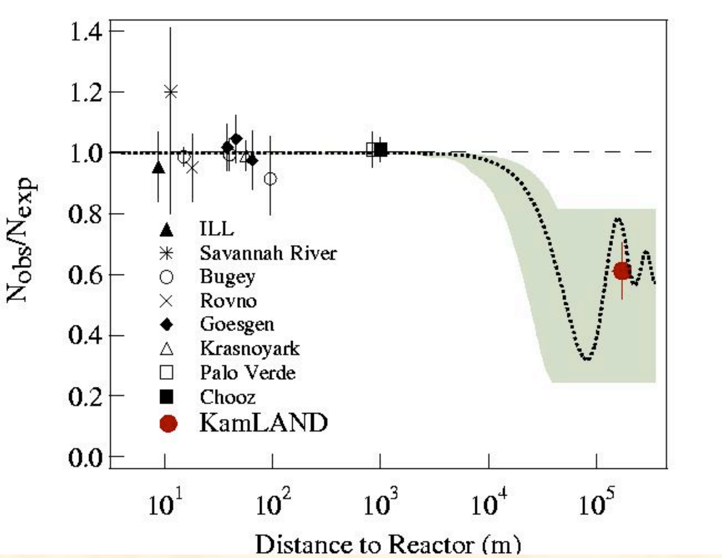
detect ν_e from >100km and observe deficit due to oscillations

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

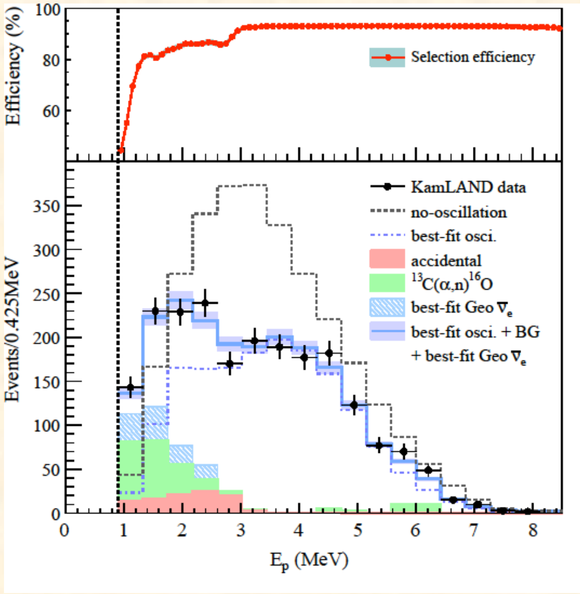
KamLAND … no escaping oscillations

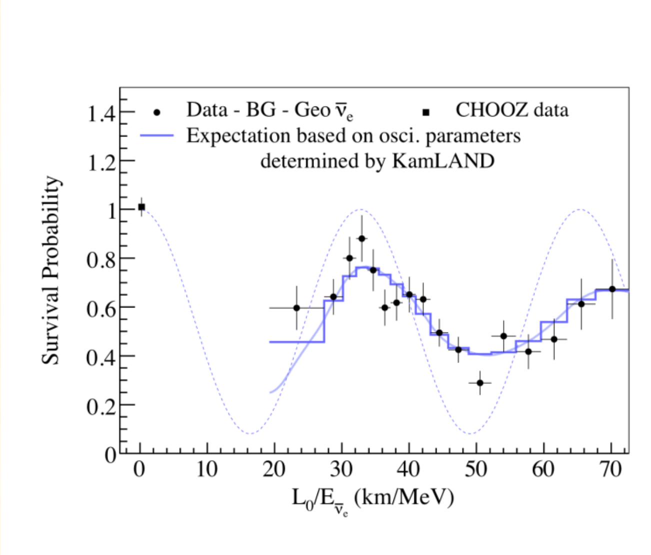
2003



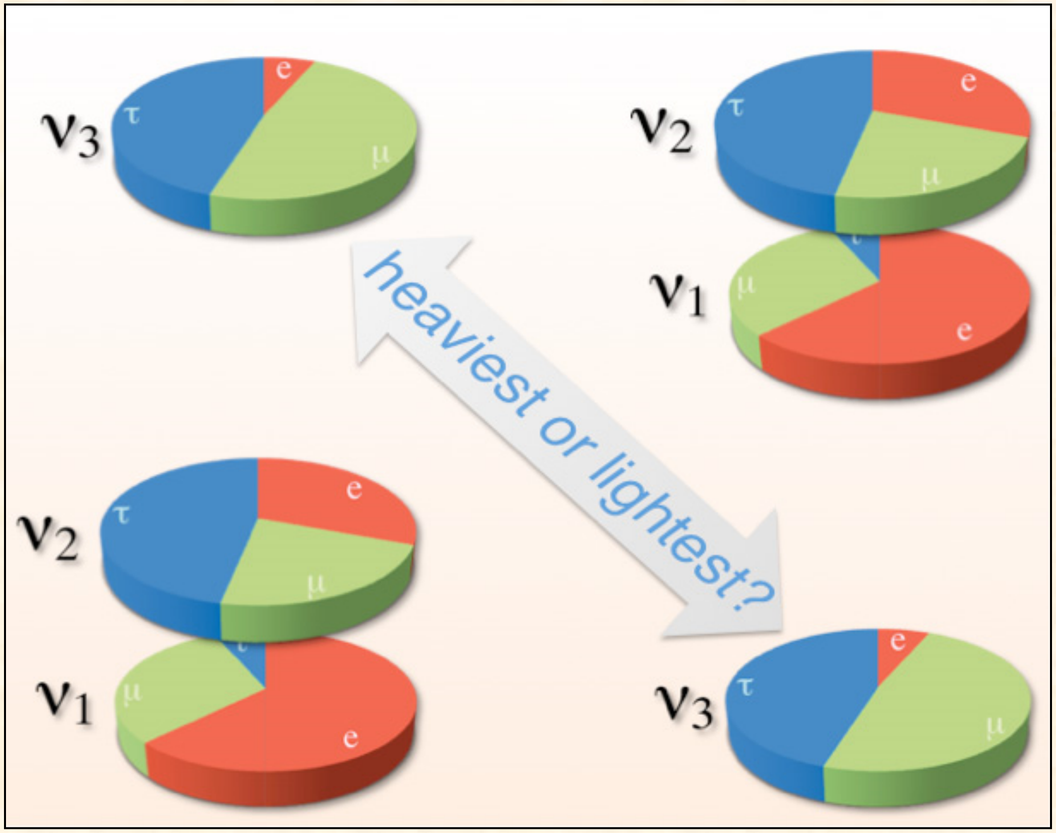


2010





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

Neutrino Oscillation Mixing Matrix

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

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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

Neutrinos

$$U_{MNSP} \sim \begin{pmatrix} 0.8 & 0.5 & ? \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

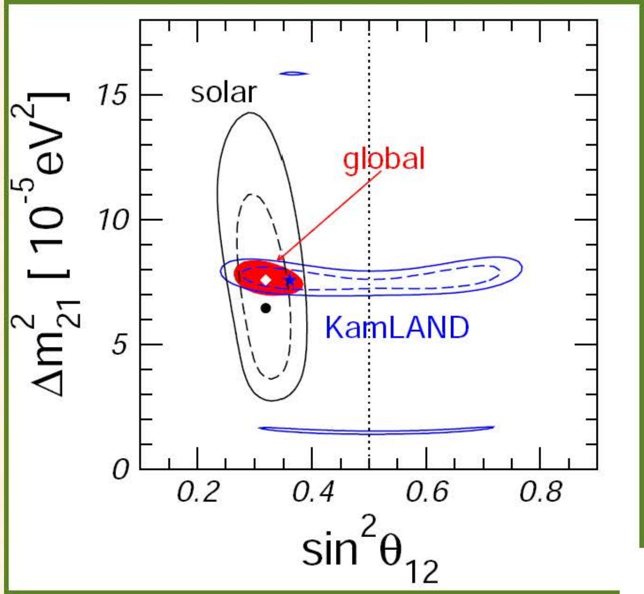
Quarks

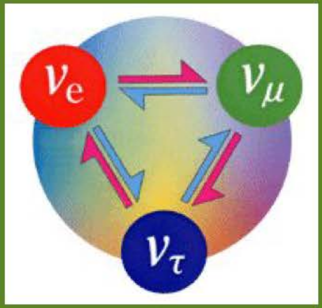
Very Different

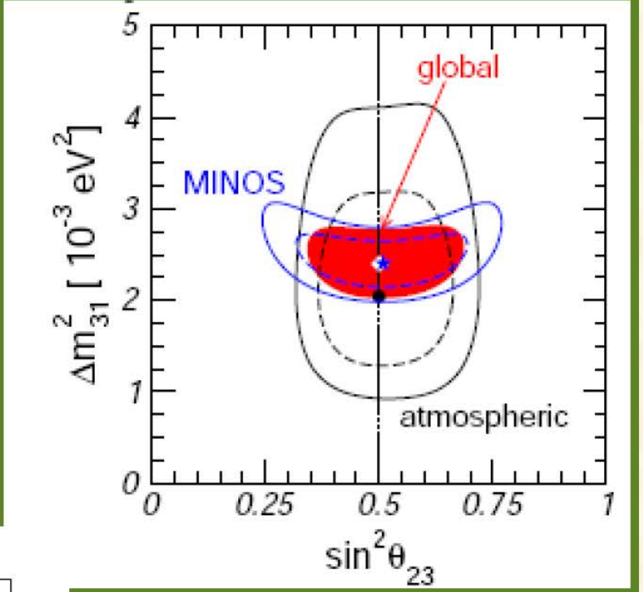
$$V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.005 \\ 0.2 & 1 & 0.04 \\ 0.005 & 0.04 & 1 \end{pmatrix}$$

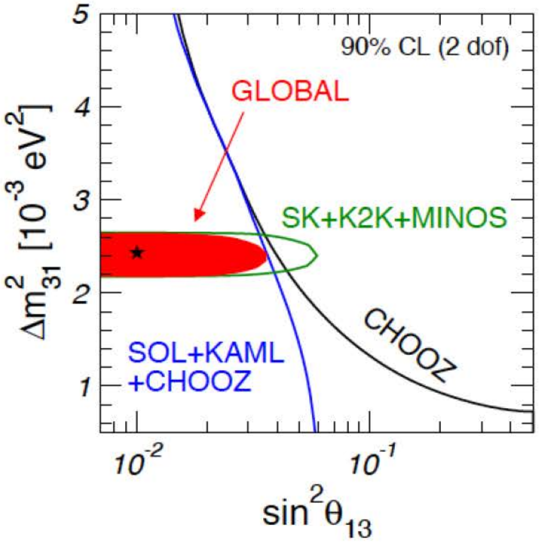
Three Neutrinos Fits Almost all Data

Update of Schwetz et al, NJP 10 (2008) 113011 [rev. Maltoni et al, NJP 6 (2004) 122]









Homestake, SAGE
GALLEX/GNO,
Super-K, SNO-leta, SSM
Borexino
KamLAND (180 Km)

... Super-K

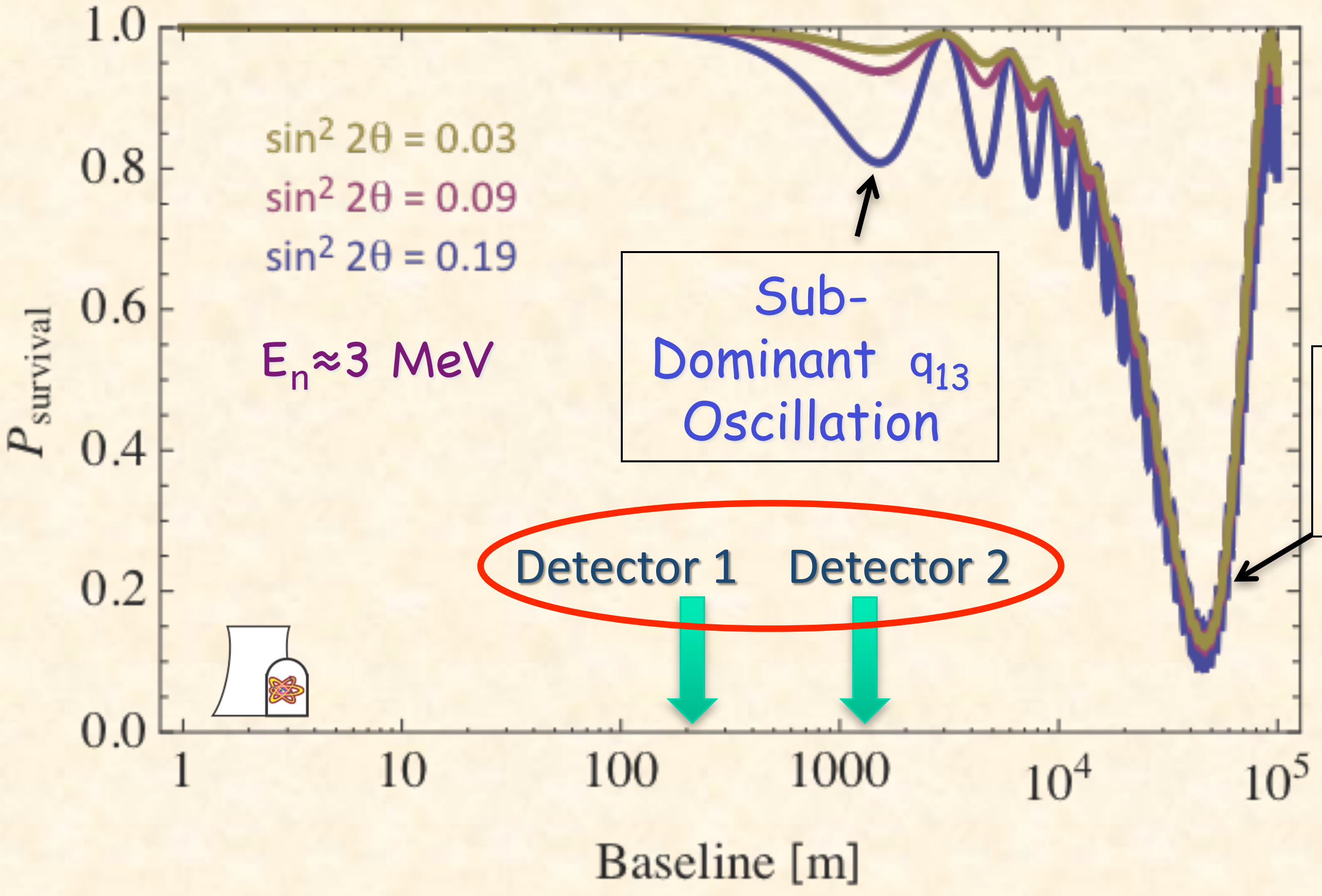
K2K (250 Km)
MINOS latest app
(735 Km)

Valle Nu2010

Precision Reactor Experiments for q_{13}

L. Mikaelyan, arXiv:hep-ex/0008046v2 (Krasnoyarsk)

Not sensitive to CP violation, so clean measurement



Sub-Dominant q_{13} Oscillation

Dominant q_{12} Oscillation

Detector 1 Detector 2

build nearly identical detectors with nearly identical efficiency

Kearns NUFACT09

Three New Reactor Experiments Starting

- Double CHOOZ in France
- Daya Bay in China
- RENO in Korea

- DC starting with one detector now
- DB to start in a year or two
- RENO claims start in June!

Will be interesting horse race!
(more in next talk)

What next in Neutrino Measurements?

Skip detailed comments on indirect Dark Matter measurements via neutrinos: much to be said, no evidence yet… may be heating up with hints at direct DM detection now. NB… direct detection only sees a scatter. Indirect sees annihilation products.

- A quick tour of absolute neutrino mass measure and double beta decay (now about half dozen experiments)…

Neutrinos mass: status and perspectives

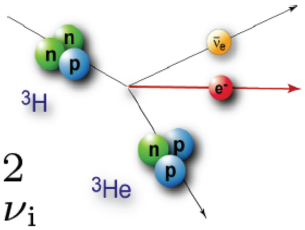
status and potential of
neutrino masses
in lab experiments

kinematics of ß-decay
absolute ν_e-mass: m_ν

search for 0νßß
eff. Majorana mass $m_{ßß}$

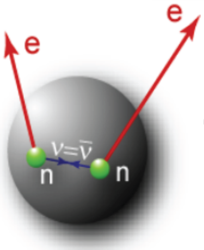
model-independent

squared neutrino mass:



$$m^2_{\nu_e} = \sum_i |U_{ei}|^2 \cdot m^2_{\nu_i}$$

- direct, from kinematics
- status: $m_\nu < 2.3$ eV
- potential: $m_\nu = 200$ meV
- MARE, Project 8, KATRIN



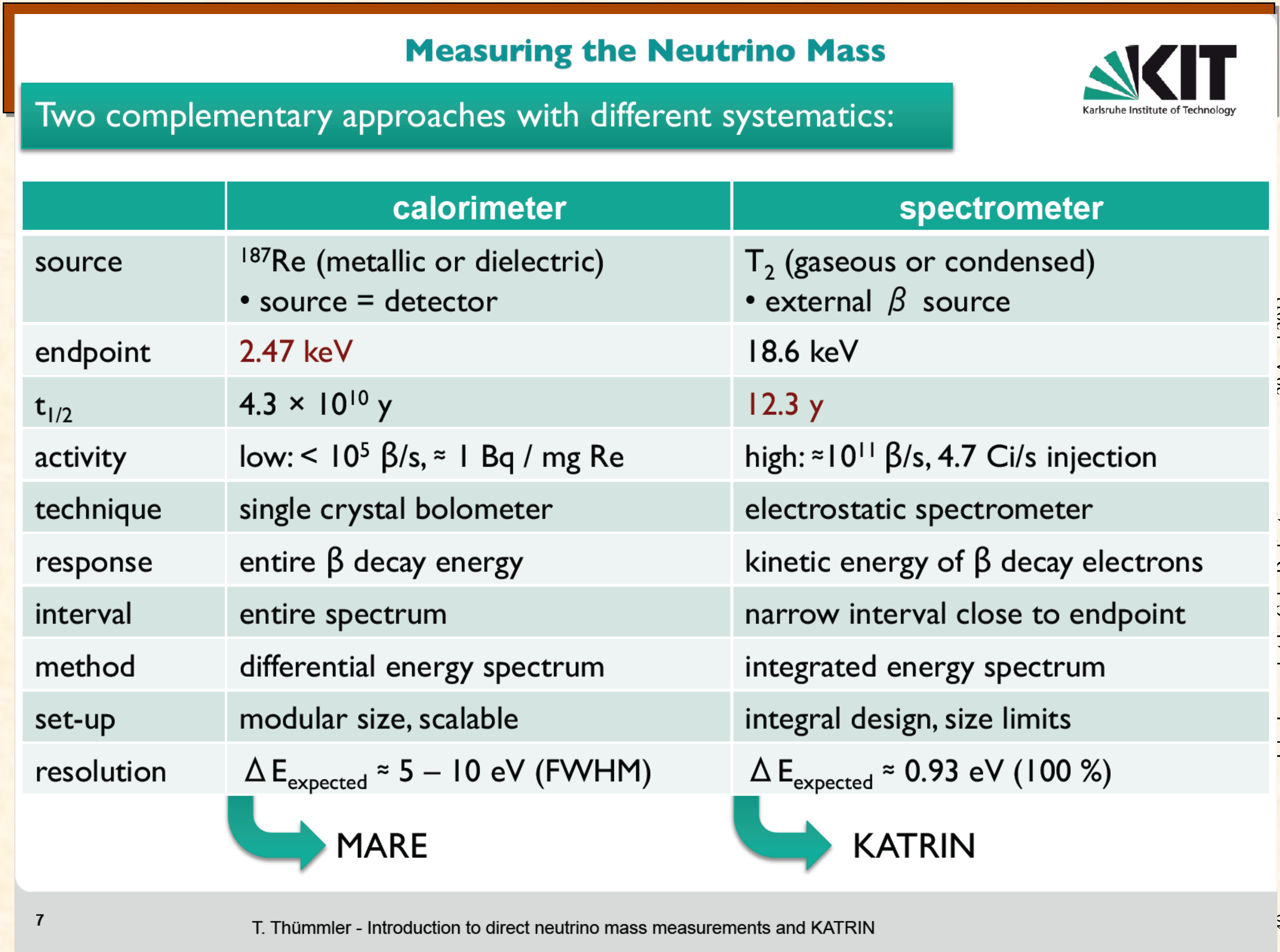
model-dependent (CP-phases)

effective Majorana mass:

$$m_{\beta\beta} = \left|\sum_i U^2_{ei} \cdot m_{\nu_i}\right|$$

- probe ν as Majorana particle: $\nu = \bar{\nu}$?
- status: $m_{ßß} < 0.35$ eV, evidence?
- potential: $m_{ßß} = 20\text{-}50$ meV
- GERDA, SNO+, EXO, CUORE

Talks by: Rodejohann/Pavan/Dolinski/Nakamura
F. Simkovic (Session II / Friday)



Measuring the Neutrino Mass

Karlsruhe Institute of Technology

Two complementary approaches with different systematics:

	calorimeter	spectrometer
source	^{187}Re (metallic or dielectric) • source = detector	T_2 (gaseous or condensed) • external β source
endpoint	2.47 keV	18.6 keV
$t_{1/2}$	4.3×10^{10} y	12.3 y
activity	low: $< 10^5$ β/s, ≈ 1 Bq / mg Re	high: $\approx 10^{11}$ β/s, 4.7 Ci/s injection
technique	single crystal bolometer	electrostatic spectrometer
response	entire β decay energy	kinetic energy of β decay electrons
interval	entire spectrum	narrow interval close to endpoint
method	differential energy spectrum	integrated energy spectrum
set-up	modular size, scalable	integral design, size limits
resolution	$\Delta E_{expected} \approx 5 - 10$ eV (FWHM)	$\Delta E_{expected} \approx 0.93$ eV (100 %)

→ MARE

→ KATRIN

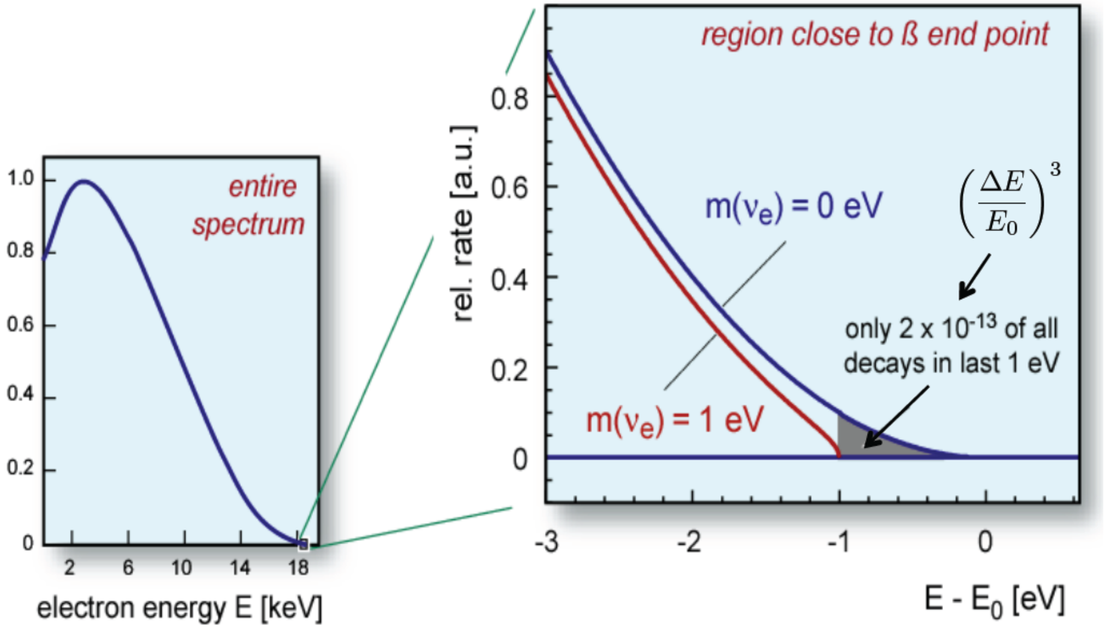
Measuring the Neutrino Mass

$m(\nu_e)$ from β decay: model-independent, based on kinematics and energy conservation

$$m(\nu_e) = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 \cdot m_i^2}$$

$$\frac{d\Gamma_i}{dE} = C \cdot p \cdot (E + m_e) \cdot (E_0 - E) \cdot \sqrt{(E_0 - E)^2 - m_i^2} \cdot F(E,Z) \cdot \theta(E_0 - E - m_i)$$

(ν– mass)^2

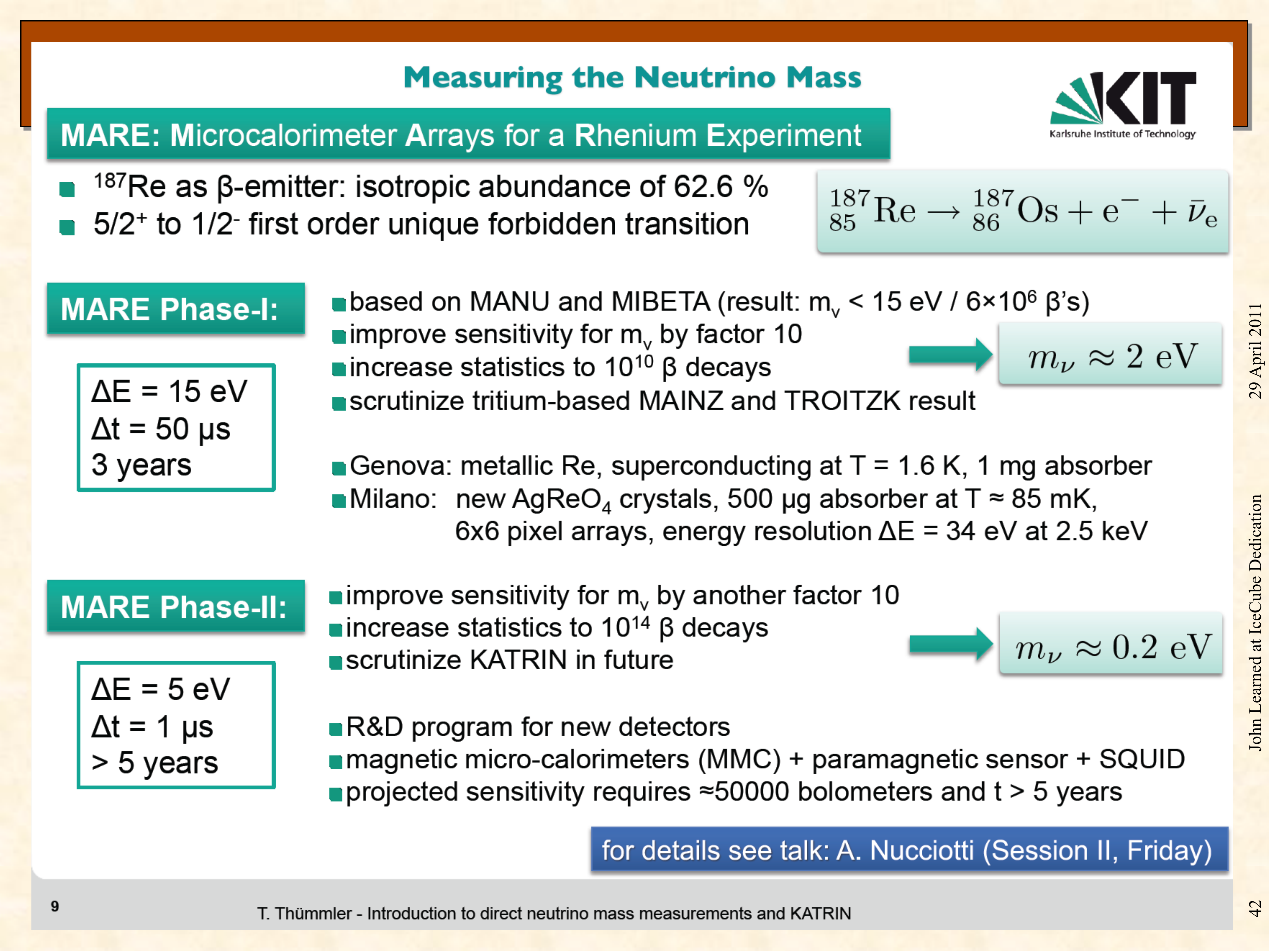


$m_\nu \neq 0$ influence:

- shift of E_0
- changed shape
- shape to be analysed!

key requirements:

- low endpoint β source
- high count rate
- high energy resolution
- extremely low background



Measuring the Neutrino Mass

MARE: Microcalorimeter Arrays for a Rhenium Experiment

- ^{187}Re as β-emitter: isotropic abundance of 62.6 %
- 5/2$^+$ to 1/2$^-$ first order unique forbidden transition

$$^{187}_{85}\mathrm{Re} \longrightarrow {}^{187}_{86}\mathrm{Os} + \mathrm{e}^- + \bar{\nu}_\mathrm{e}$$

MARE Phase-I:

ΔE = 15 eV
Δt = 50 μs
3 years

- based on MANU and MIBETA (result: m_ν < 15 eV / 6×10^6 β's)
- improve sensitivity for m_ν by factor 10
- increase statistics to 10^{10} β decays
- scrutinize tritium-based MAINZ and TROITZK result

→ $m_\nu \approx 2$ eV

- Genova: metallic Re, superconducting at T = 1.6 K, 1 mg absorber
- Milano: new $AgReO_4$ crystals, 500 μg absorber at T ≈ 85 mK,
  6x6 pixel arrays, energy resolution ΔE = 34 eV at 2.5 keV

MARE Phase-II:

ΔE = 5 eV
Δt = 1 μs
> 5 years

- improve sensitivity for m_ν by another factor 10
- increase statistics to 10^{14} β decays
- scrutinize KATRIN in future

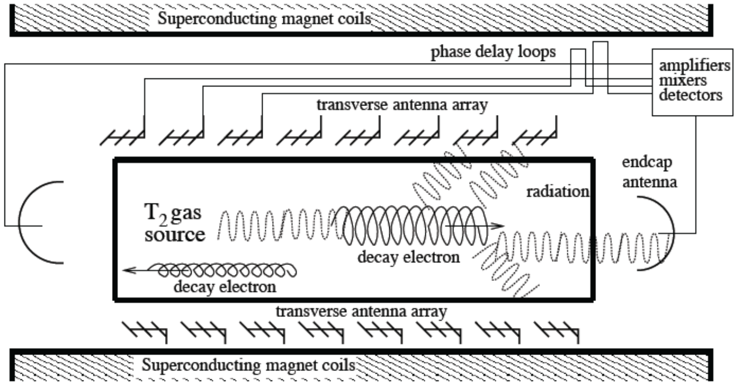
→ $m_\nu \approx 0.2$ eV

- R&D program for new detectors
- magnetic micro-calorimeters (MMC) + paramagnetic sensor + SQUID
- projected sensitivity requires ≈50000 bolometers and t > 5 years

for details see talk: A. Nucciotti (Session II, Friday)

Measuring the Neutrino Mass

3rd approach, proposed recently: Project 8



- source: gaseous T_2
- technique: radio-frequency spectroscopy of coherent cyclotron radiation of β decay electrons
- more details: arXiv:0904.2860v1 [nucl-ex]

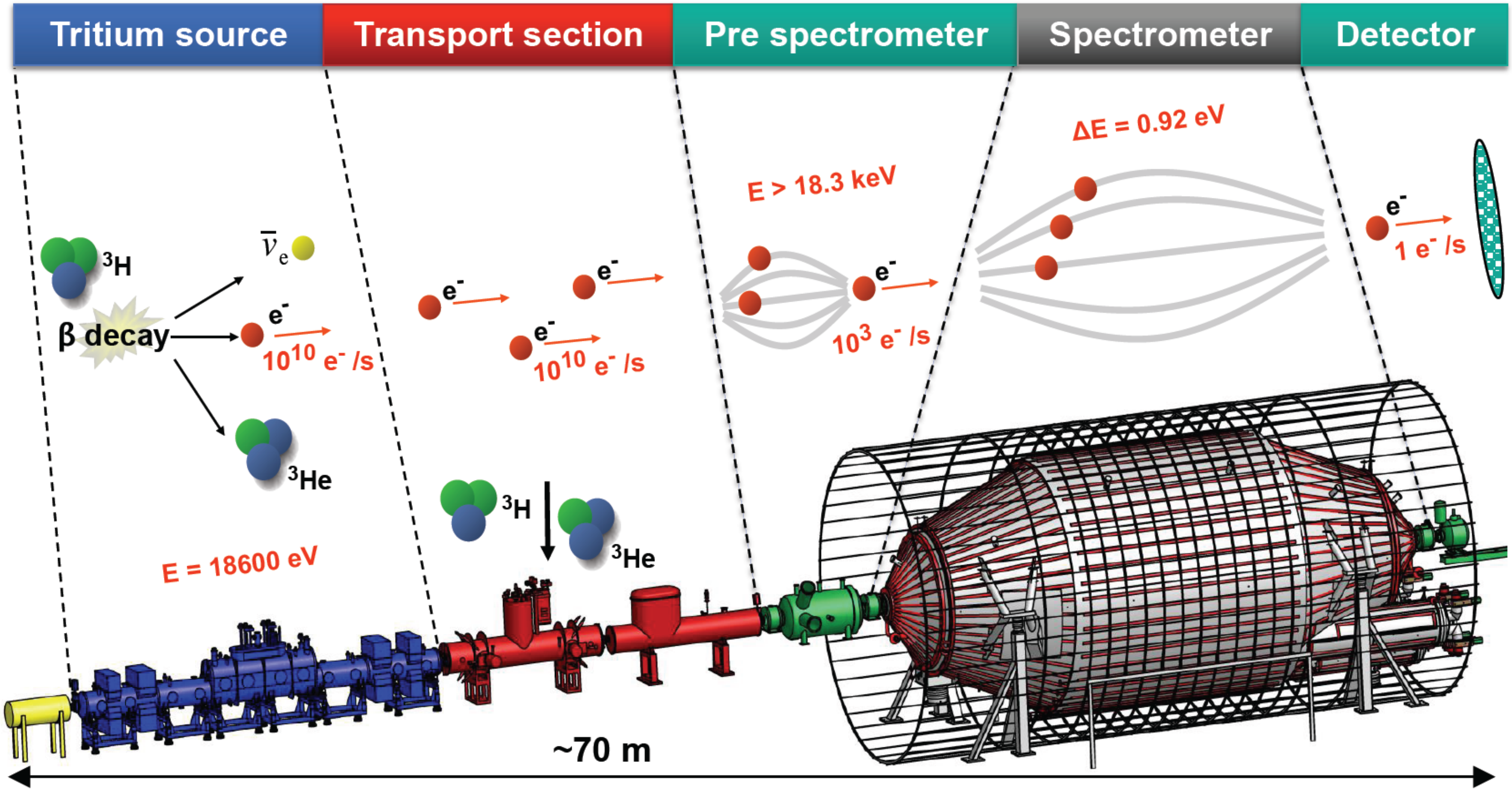
- design values: projected energy resolution: 1 eV
  estimated sensitivity on $m(\nu_e)$: 0.1 eV

- status: preparations for a proof-of-principle experiment

Talk: J. Formaggio, Session II, Saturday

The KATRIN Setup

Karlsruhe Institute of Technology



Doube Beta Decay

ββ2ν: two simultaneous β decays

$$(Z,A) \to (Z+2,A) + e_1^- + e_2^- + \overline{\nu}_{e_1} + \overline{\nu}_{e_2}$$

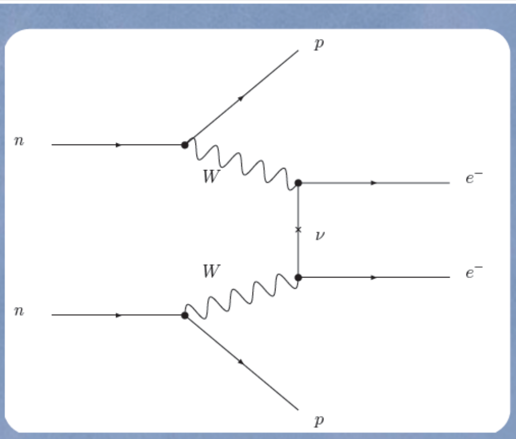
$$\frac{1}{T_{1/2}^{2\nu}} = G^{2\nu}(Q,Z)|M^{2\nu}|^2$$

ββ0ν: requires massive Majorana neutrinos. Non-SM process.

$$(Z,A) \to (Z+2,A) + e_1^- + e_2^- \cancel{+ \overline{\nu}_{e_1} + \overline{\nu}_{e_2}}$$

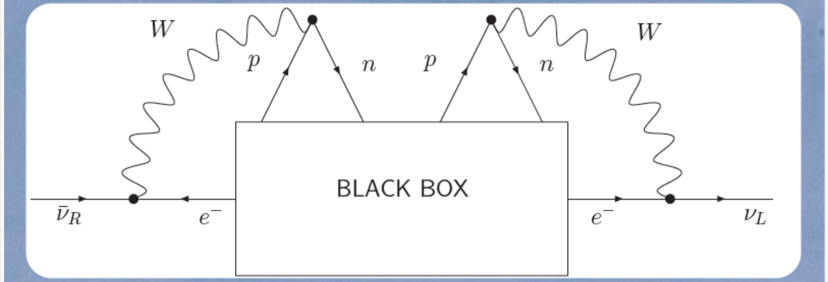
$$(\Delta L = 2)$$

$$\frac{1}{T_{1/2}^{0\nu}} = G^{0\nu}(Q,Z)|M^{0\nu}|^2\langle m_{\beta\beta}\rangle^2$$



Exchange of light Majorana neutrinos

Other mechanisms are possible, but all of them imply a Majorana neutrino mass.

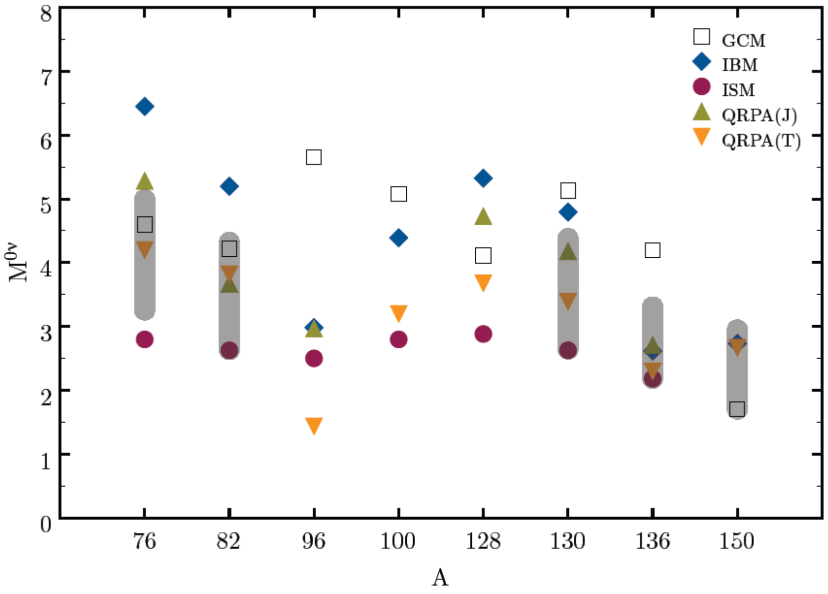


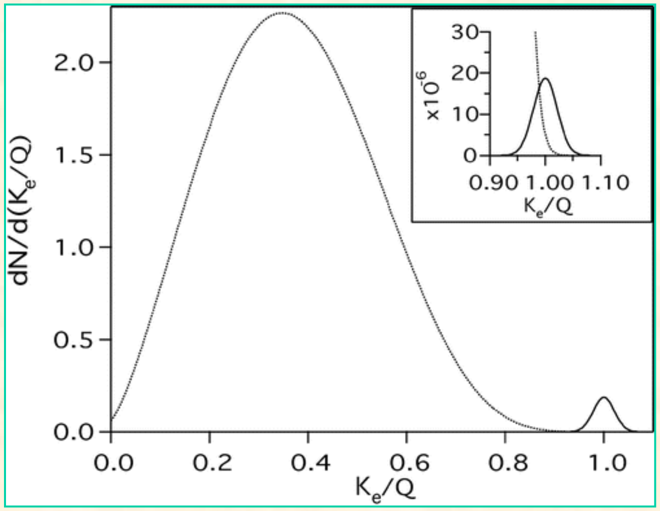
J.J. Gomez-Cadenas, Neutel 2011

Observing DBD is not the same as measuring neutrino mass

$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu}(Q_{\beta\beta}, Z)\left|M_{0\nu}\right|^2 m^2_{\beta\beta}$$

$$m_{\beta\beta} = \left|\sum_i U^2_{ei} m_i\right|$$

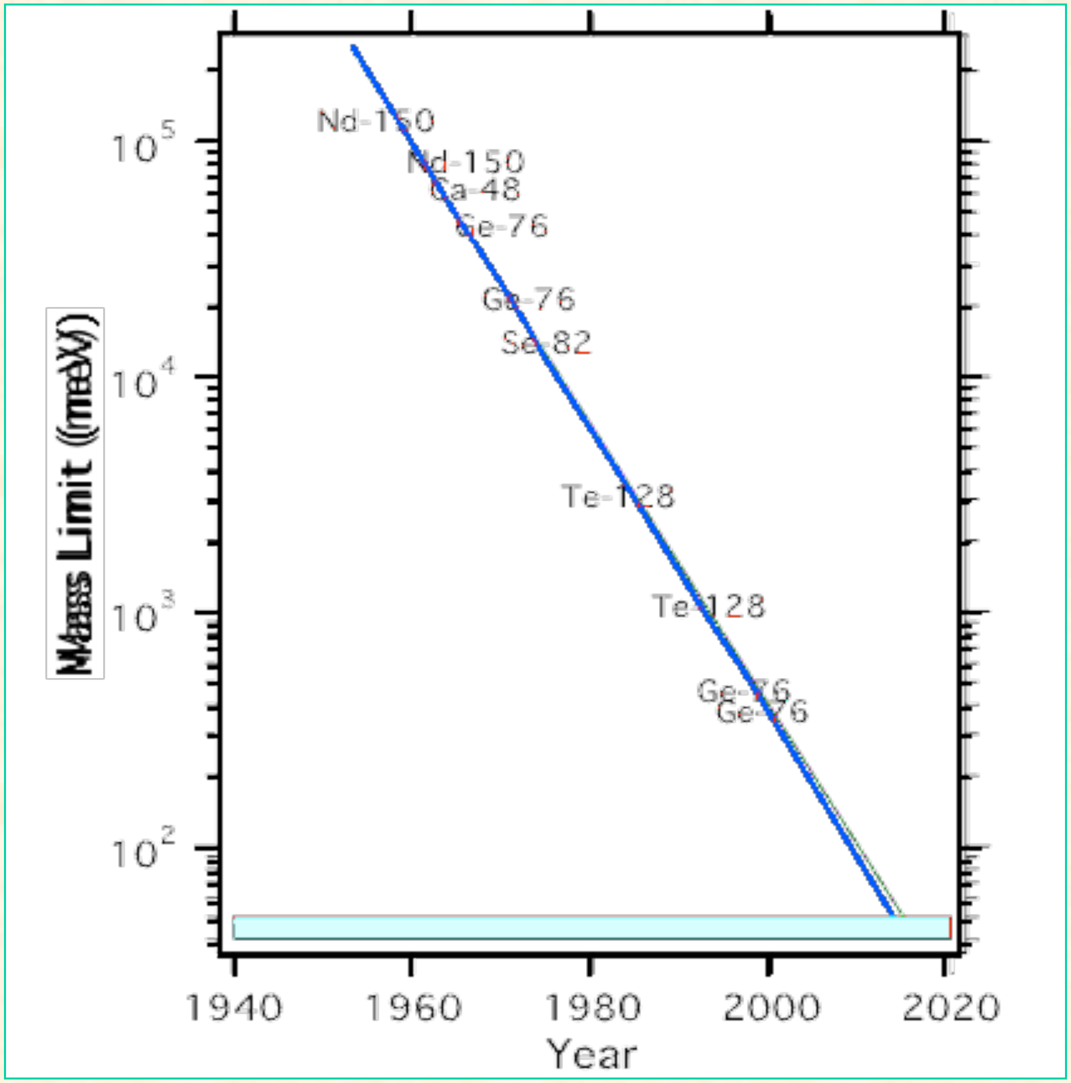




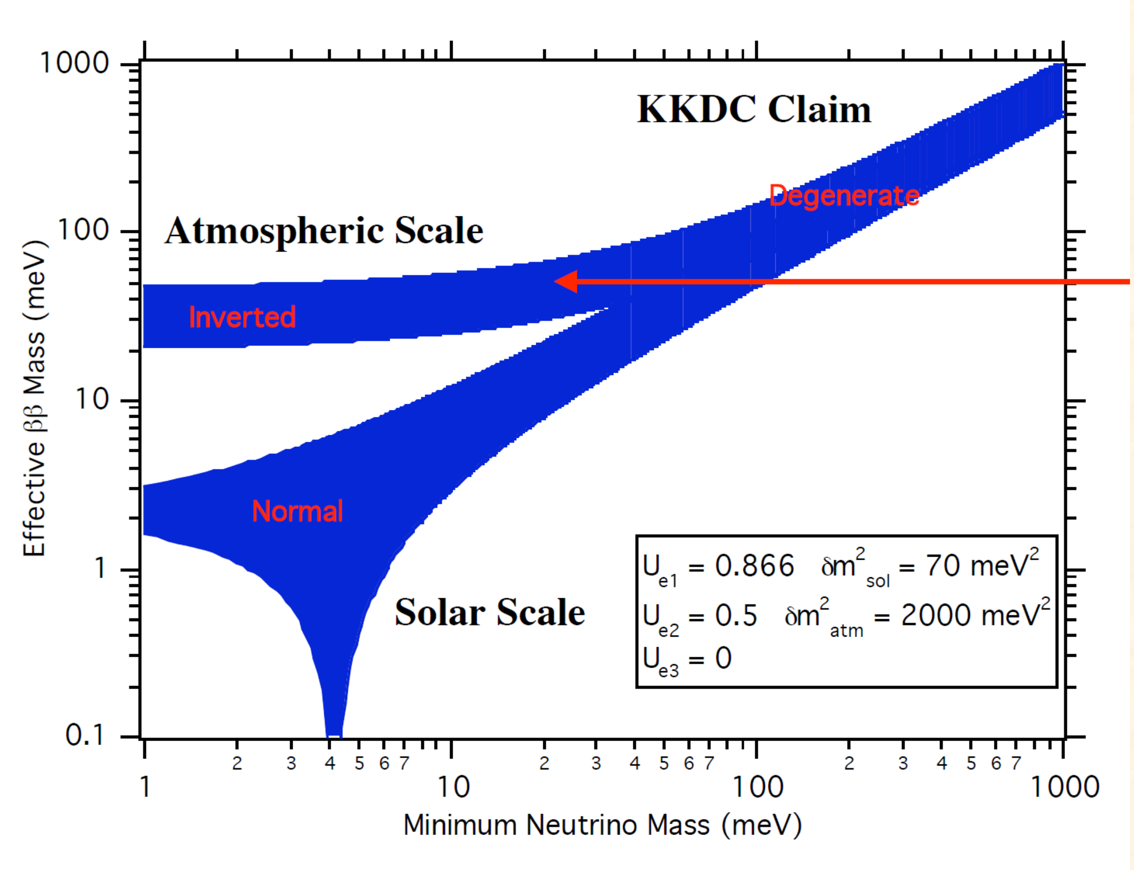
Past Results

^{48}Ca	>1.4x10^{22} y	<(7.2-44.7) eV
^{76}Ge	>1.9x10^{25} y	<0.35 eV
^{76}Ge	>1.6x10^{25} y	<(0.33-1.35) eV
^{76}Ge	=1.2x10^{25} y	=0.44 eV
^{82}Se	>2.1x10^{23} y	<(1.2-3.2) eV
^{100}Mo	>5.8x10^{23} y	<(0.6-2.7) eV
^{116}Cd	>1.7x10^{23} y	<1.7 eV
^{128}Te	>7.7x10^{24} y	<(1.1-1.5) eV
^{130}Te	>3.0x10^{24} y	<(0.41-0.98) eV
^{136}Xe	>4.5x10^{23} y	<(1.8-5.2) eV
^{150}Nd	>1.2x10^{21} y	<3.0 eV

Elliott & Vogel
Annu. Rev. Part. Sci. 2002 52:115



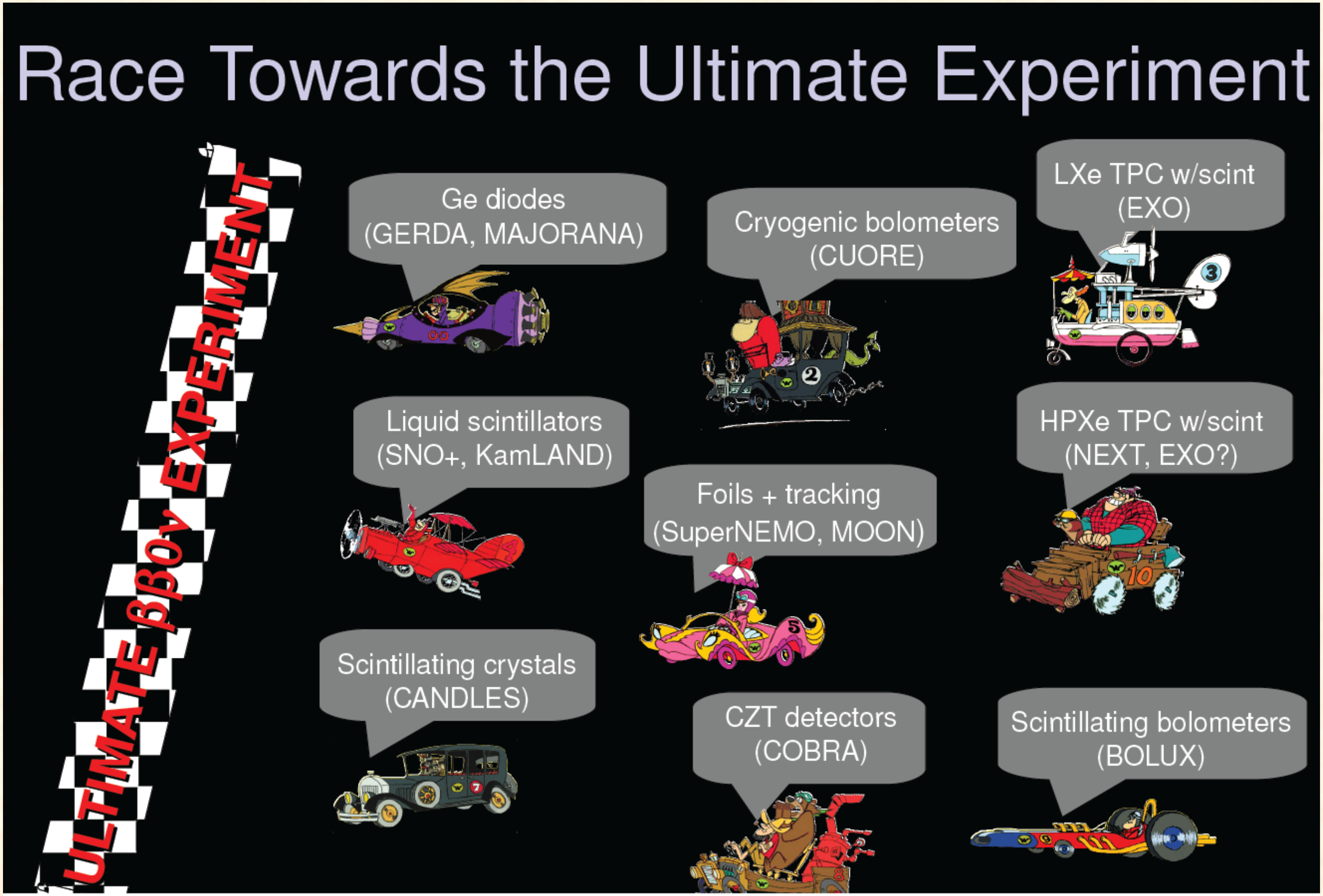
Effective DB Mass Could be Vanishingly Small



Atm dm2

Steve Elliott, LANL

Many Experiments in Motion!



Race Towards the Ultimate Experiment

ULTIMATE $\beta\beta0\nu$ EXPERIMENT

Ge diodes
(GERDA, MAJORANA)

Liquid scintillators
(SNO+, KamLAND)

Scintillating crystals
(CANDLES)

Cryogenic bolometers
(CUORE)

Foils + tracking
(SuperNEMO, MOON)

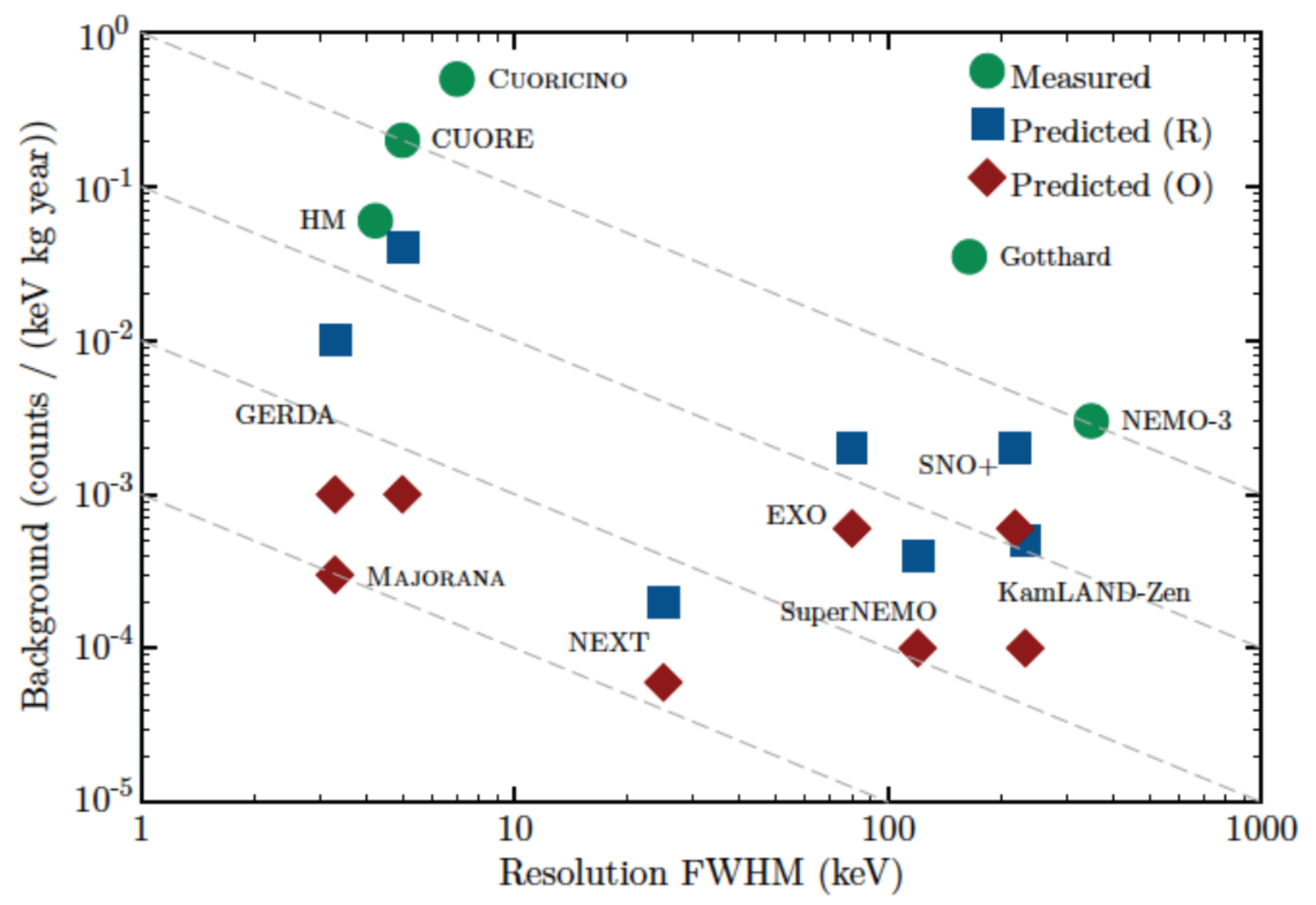
CZT detectors
(COBRA)

LXe TPC w/scint
(EXO)

HPXe TPC w/scint
(NEXT, EXO?)

Scintillating bolometers
(BOLUX)

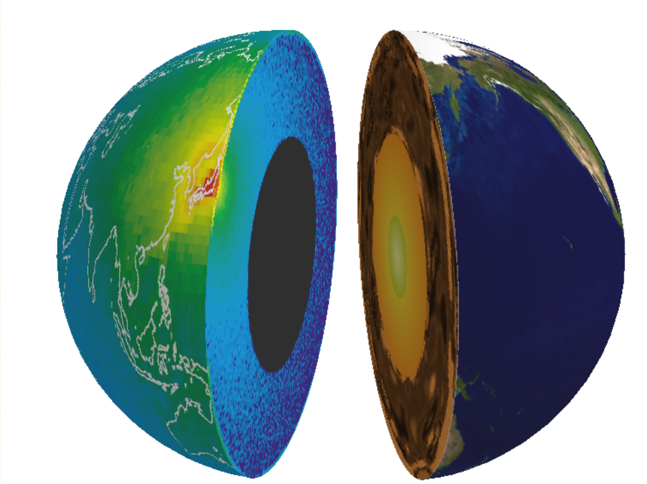
Sensitivity depends upon Background and Resolution



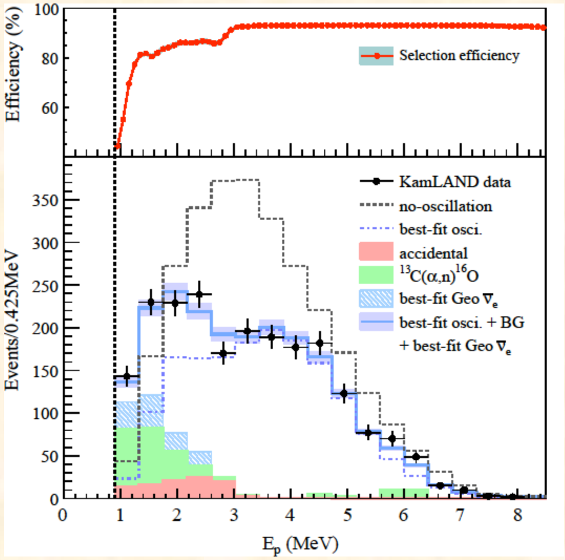
And now for something different, but related…

- We have been studying large and in some versions portable electron anti-neutrino detectors for three applications:
  - More detailed oscillations studies
  - Development of remote reactor monitoring
  - Study of geoneutrinos

Geoneutrinos: An Emerging Field



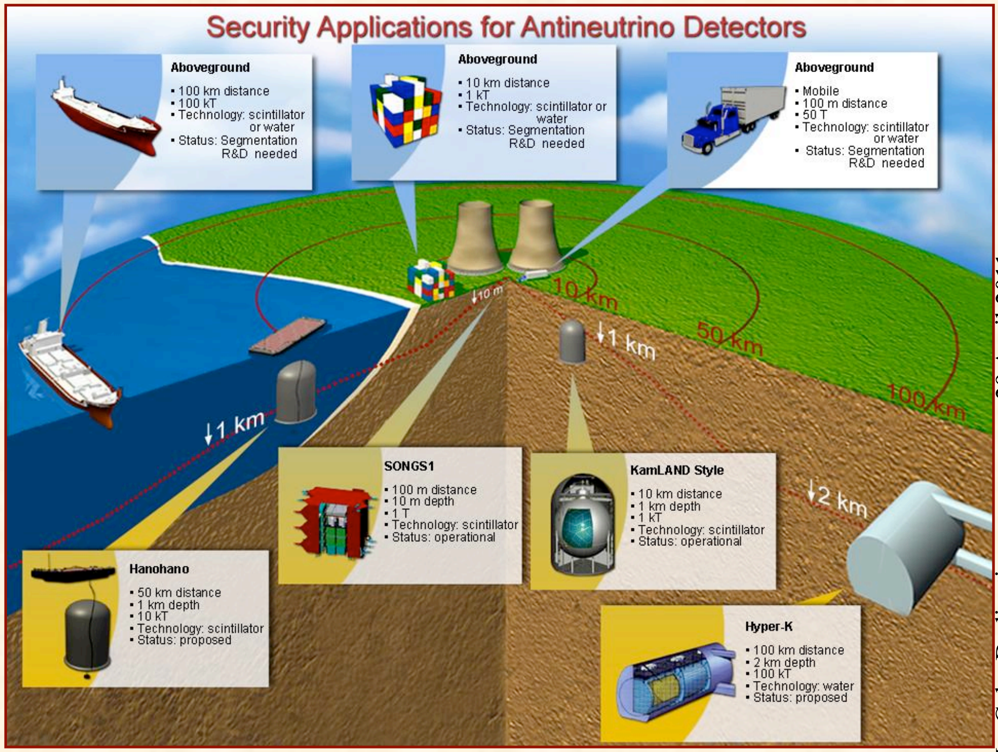
Geophysics with Neutrinos

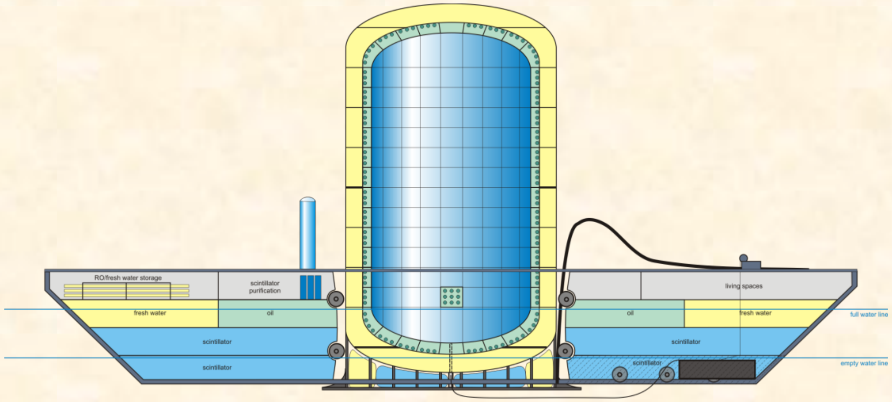


- Neutrinos from U and Th chains thought to be major source of earth internal heat, and geodynamics (crustal motions, earthquakes, volcanoes),
- Much debate about how much total and here it originates. Major question in geology, and no other way to access information than neutrinos.
- KamLAND detected U/Th decay neutrinos from whole earth in 2005, updated in 2009. Borexino too in 2009.
- Results indicate earth heat probably no totally radiogenic. Also no indication (yet) of major natural reactor source.
- This is a budding field… but needs large detectors, and in ocean to discern below local crust.
- A number of workshops, talks at major neutrino meetings, and papers. Nice Geonu meeting Gran Sasso 10/10

Nuclear Reactor Monitoring for Anti-Proliferation

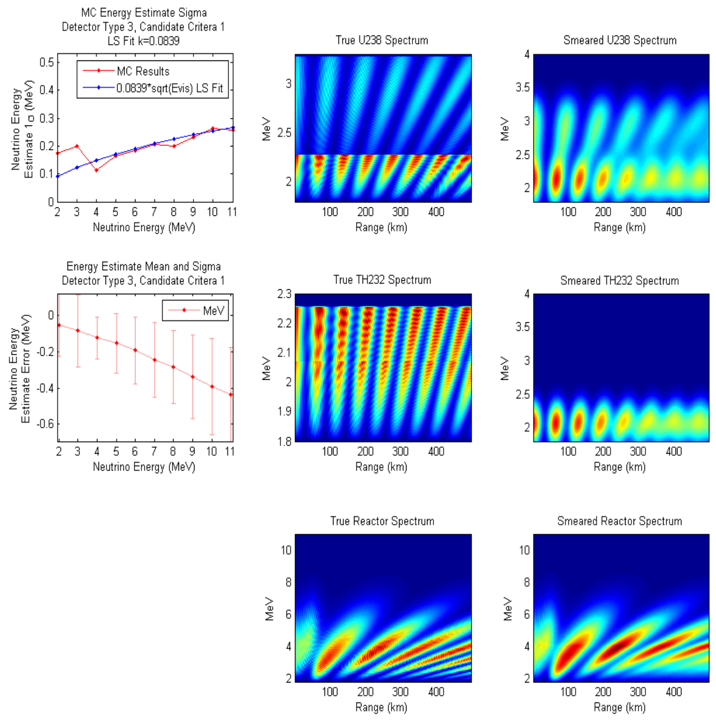
- Series of Workshops over last seven years about reactor monitoring (Hawaii, Palo Alto, Paris, Livermore, Maryland, Japan, Italy).
- Several major (p)review papers (arXiv:0908.4338 , arXiv:1011.3850 , one in preparation)
- Near: ~1m^3, ~20m, cooperative site, IAEA application
- Demonstrations a San Onofre Calif., and other places. Efforts in US, France, Russia, Japan, Brazil, Italy, and more.
- Far: 1-1000 km, possibly clandestine reactor, look at location and operation patterns, huge detectors needed at long dist. (1/r^2 inescapable)
- Developing new techniques to utilize all possible information from multiple detectors.

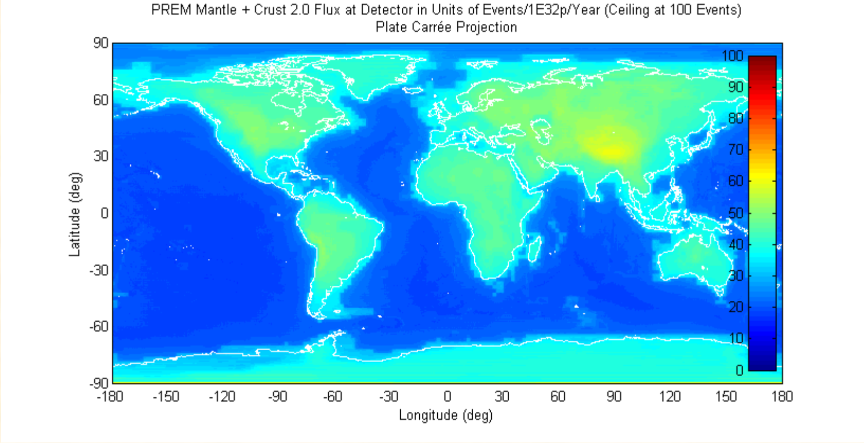


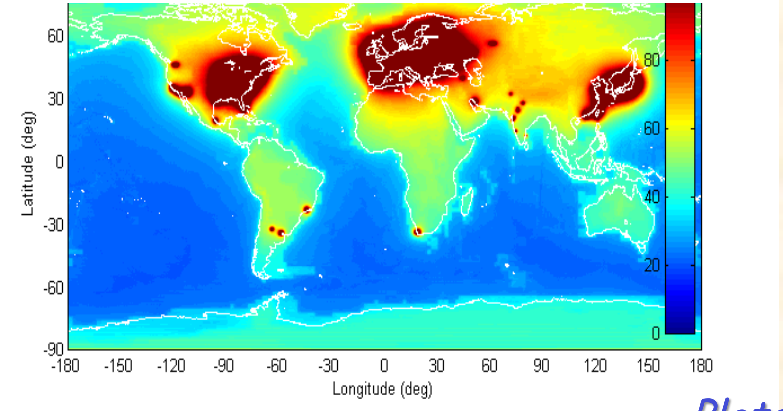


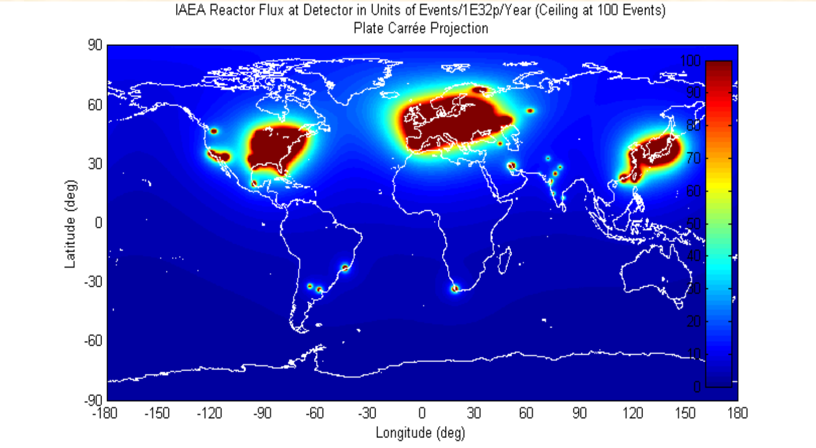
Hanohano Detector

Doing Detailed Modeling of Reactor Backgrounds



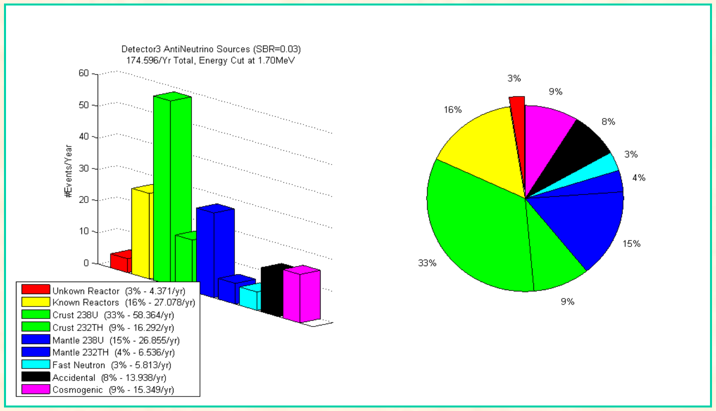




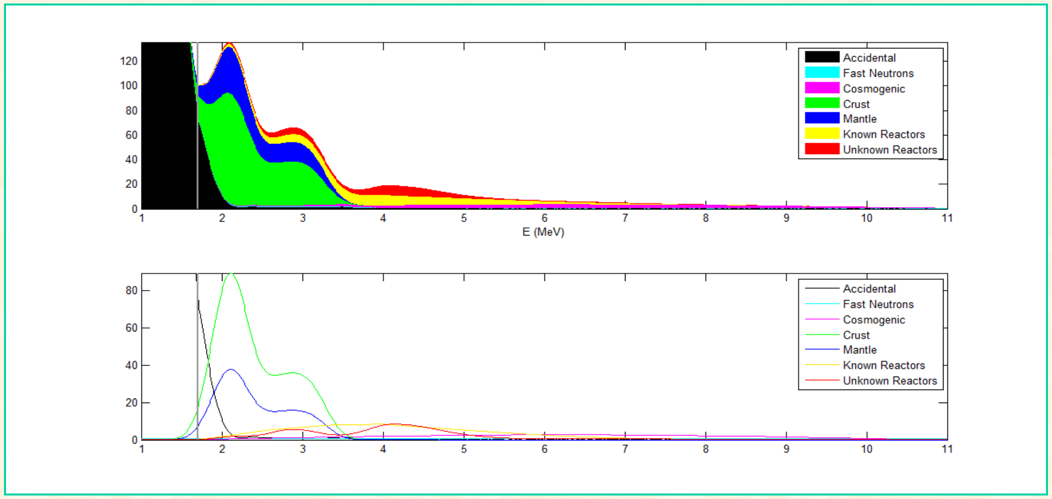


Plots from Glenn Jocher, Integrity ApplicationsInc

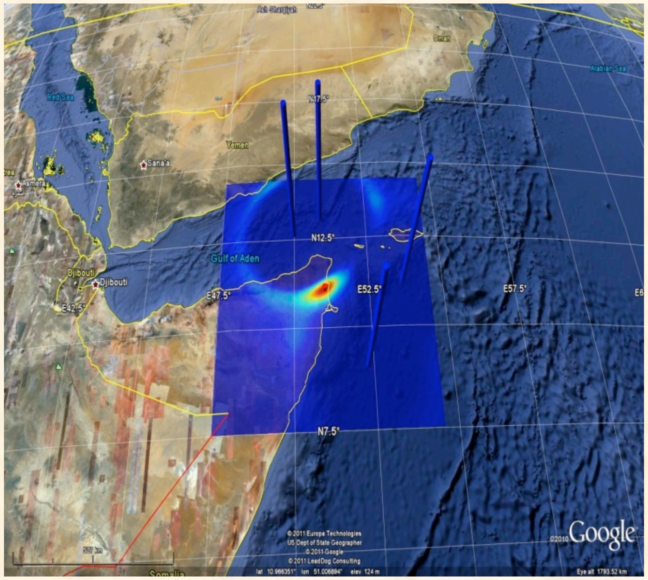
More on Detailed Modeling

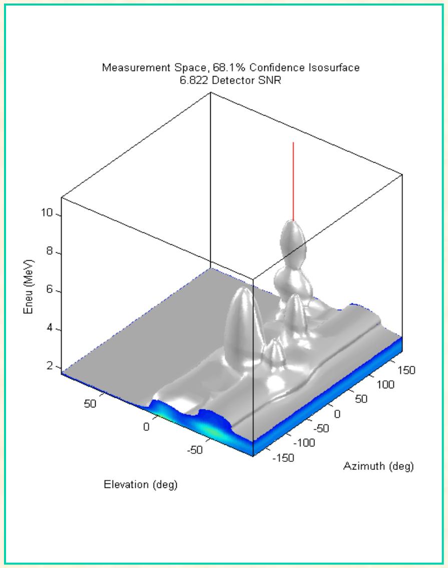


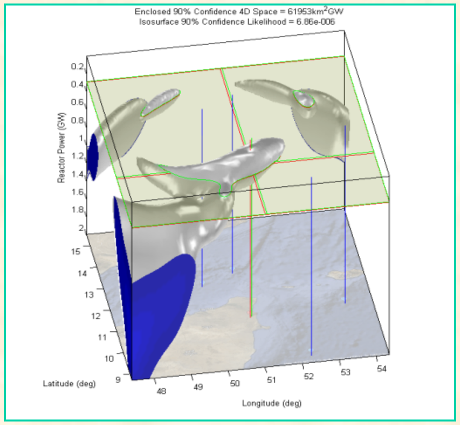
We have a program allowing arbitrary placement of detectors, including depth and calculations of all backgrounds (based on KamLAND and Borexino experience)

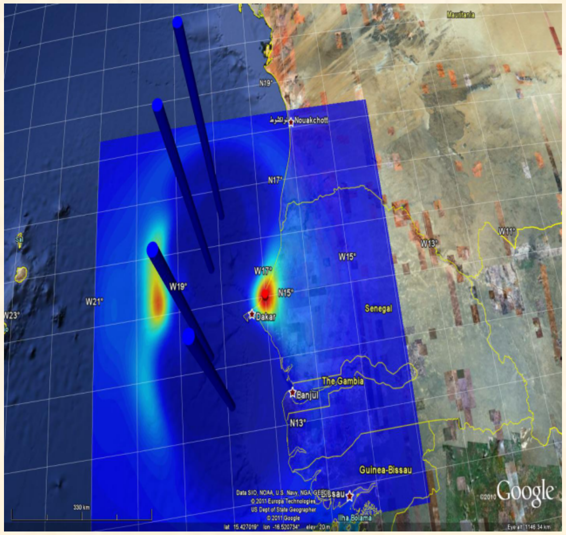


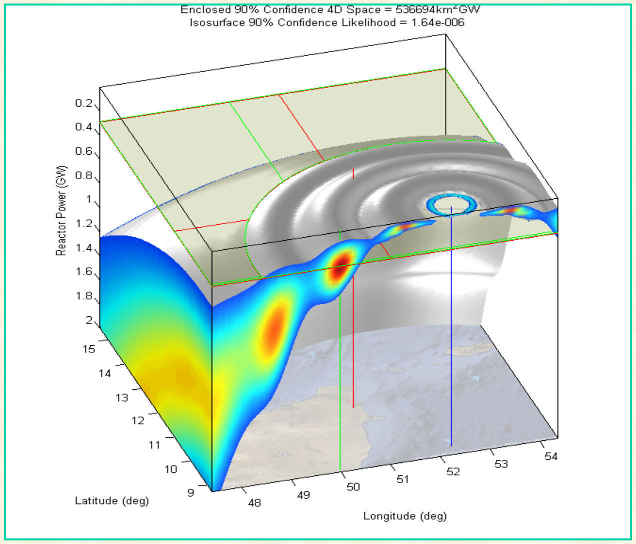
Finding and Measuring Remote Reactors











Glenn Jocher, IAI

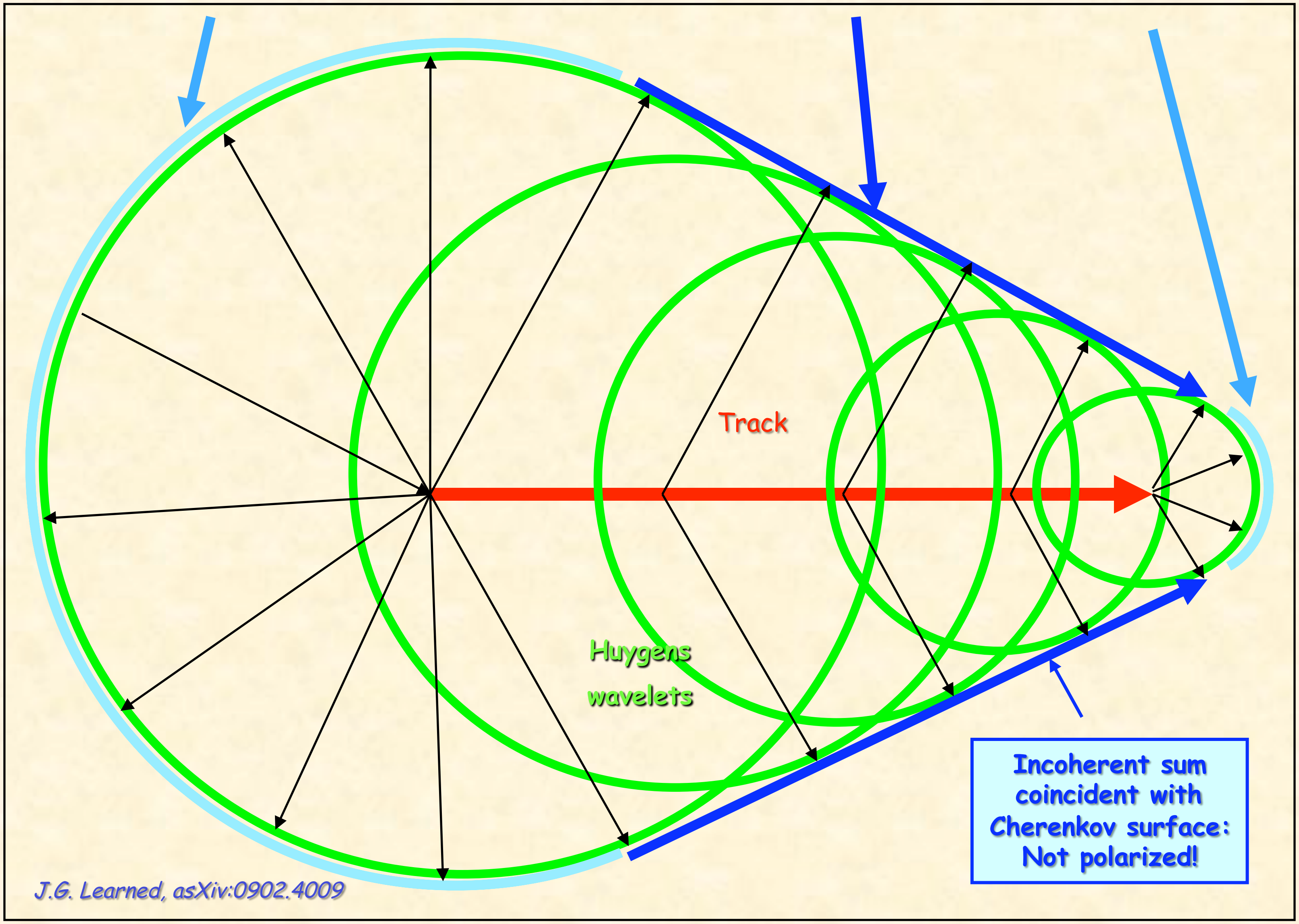
Change Gears and Talk about New Detectors

- Intro to new means of reconstructing events in liquid scintillator, where tracks radiate light isotropically
- (not like Cherenkov radiation in water as in SuperK)

2009 Realization that Liquid Scint Detector Can Reconstruct Events

First light yields topology. Now important part of LENA project proposal.

Snapshot of the Fermat Surface for a Single Muon-likeTrack



Incoherent sum coincident with Cherenkov surface: Not polarized!

J.G. Learned, asXiv:0902.4009

Application in 50 Kiloton LS LENA Detector

FIG. 1: Artist's view of the LENA detector.

LENA is major project proposed for
Europe, probably Finland
(1/3 of LAGUNA initiative)

Much nice physics to be done with such.

Major White Paper on Web today

Most interesting for this talk, is ability to do long baseline GeV neutrino studies Using the Fermat trick.

(Michinari Sakai working on testing with KamLAND data.)

LENA Simulation of Muon Event

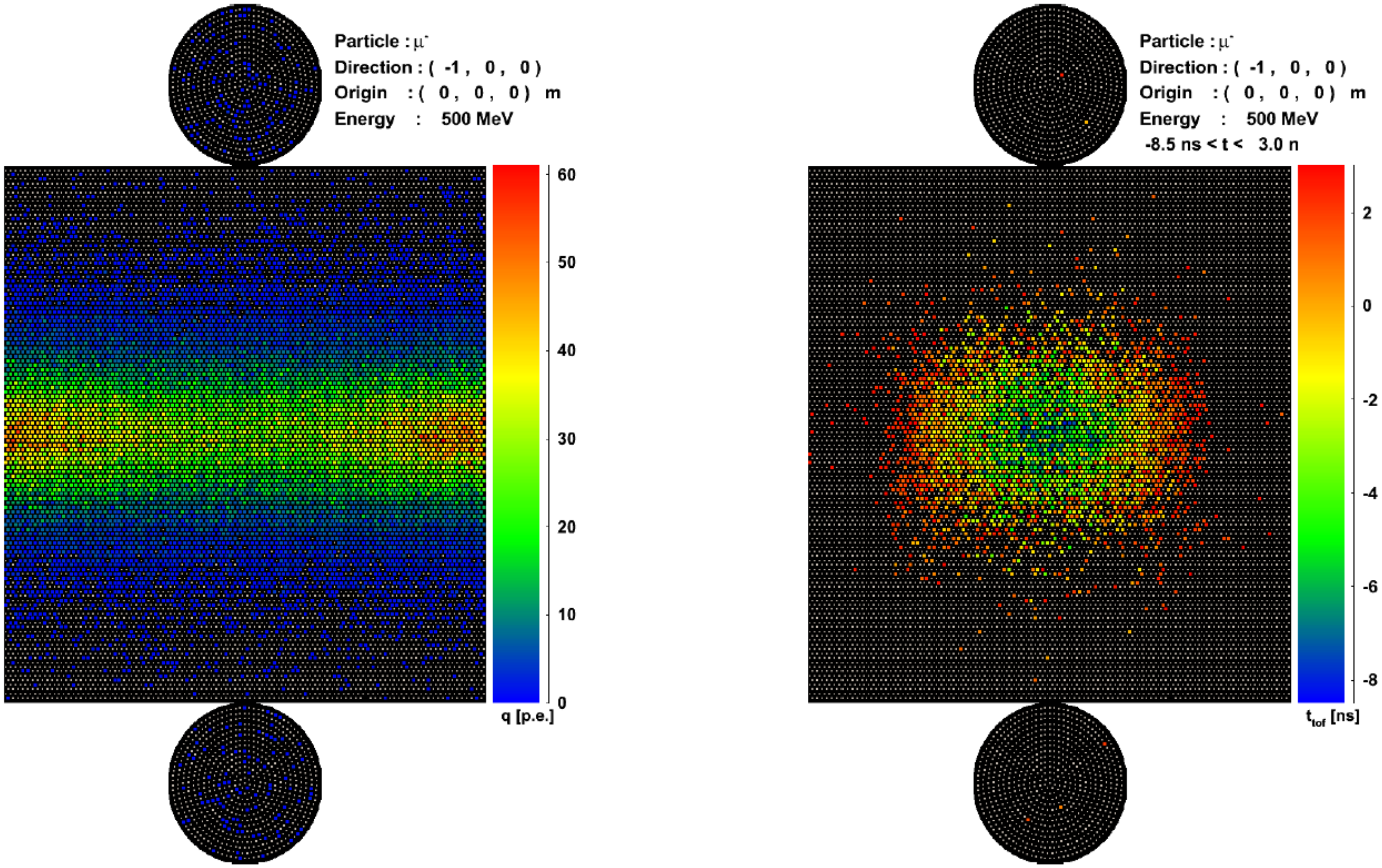


FIG. 18: A 500 MeV muon in LENA. On the left, the color coded information is the charge seen by each PMT, while the hit time of the first photon at each PMT is shown on the right, applying a time of flight correction with respect to the charge barycenter of the track.

Muons Reconstructed Very Well

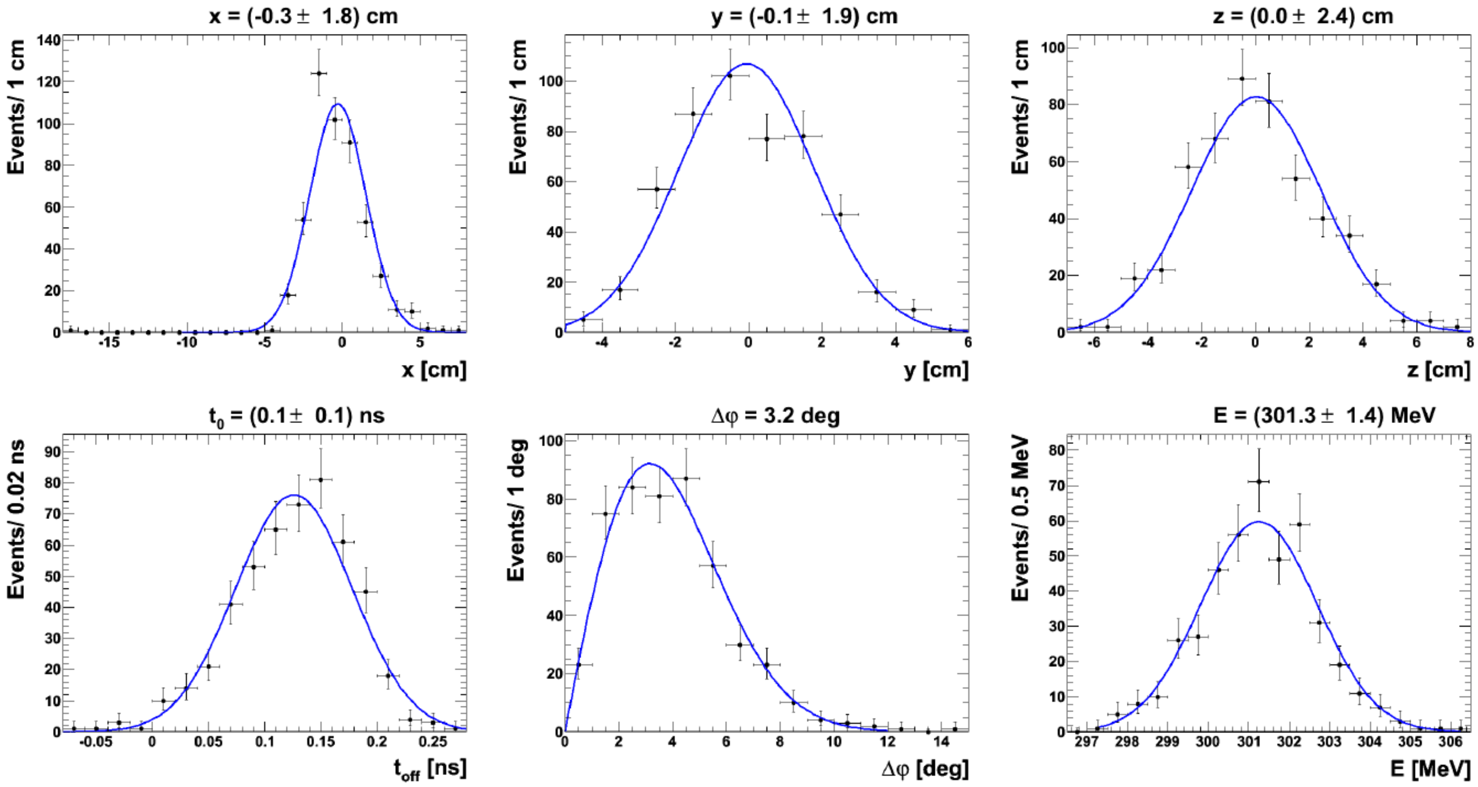
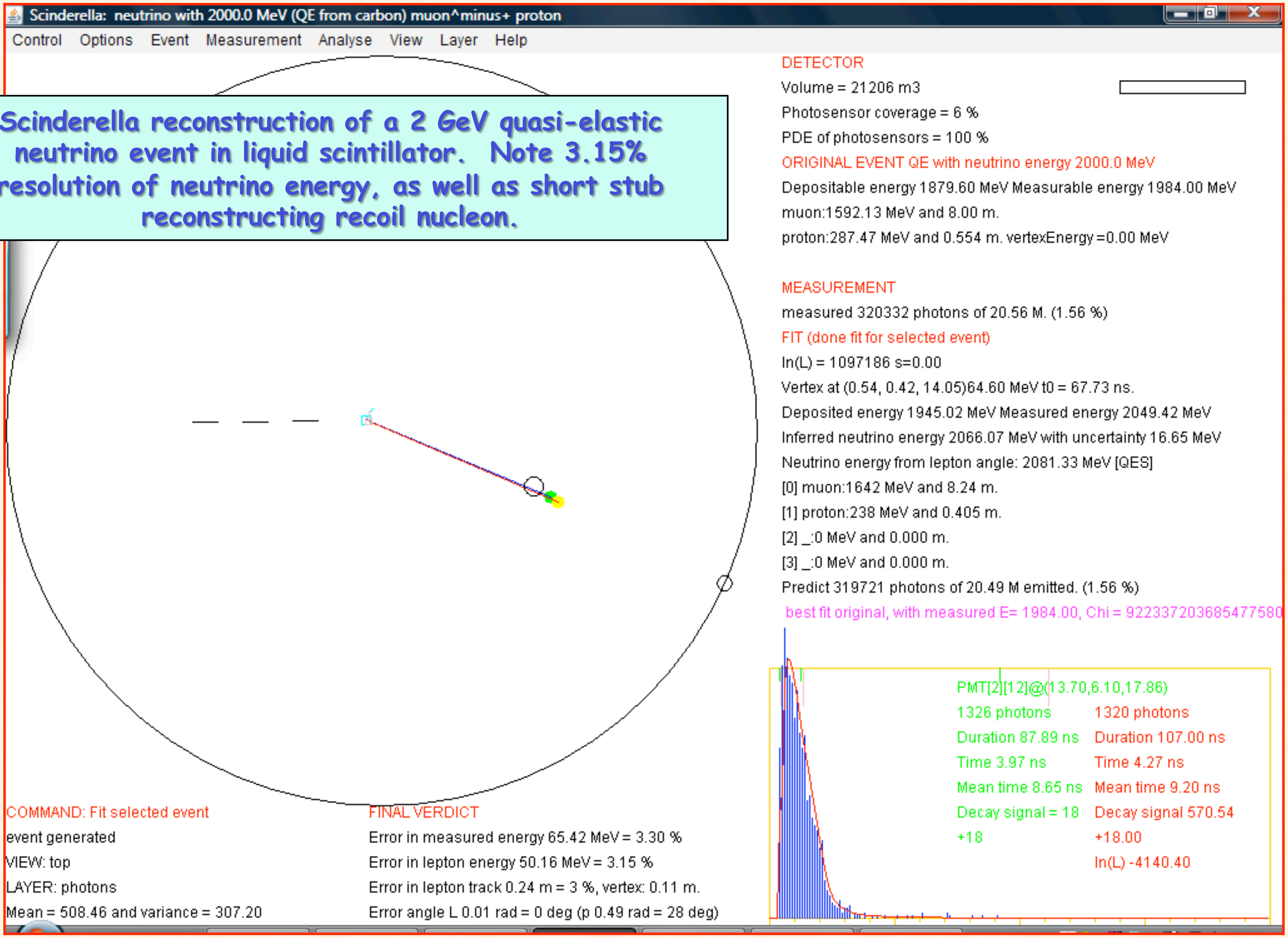


FIG. 19: Results obtained by reconstructing 300 MeV muons created in the center of the detector and traveling in negative x direction (500 events). The upper row shows the results for the start point of the track, the lower row shows the reconstructed start time (left), the angular deviation of the reconstructed track from the Monte Carlo truth (center) and the kinetic energy of the muon (right).

If one can employ the full waveforms…

Scinderella reconstruction of a 2 GeV quasi-elastic neutrino event in liquid scintillator. Note 3.15% resolution of neutrino energy, as well as short stub reconstructing recoil nucleon.



```
DETECTOR
Volume = 21206 m3
Photosensor coverage = 6 %
PDE of photosensors = 100 %
ORIGINAL EVENT QE with neutrino energy 2000.0 MeV
Depositable energy 1879.60 MeV Measurable energy 1984.00 MeV
muon:1592.13 MeV and 8.00 m.
proton:287.47 MeV and 0.554 m. vertexEnergy =0.00 MeV

MEASUREMENT
measured 320332 photons of 20.56 M. (1.56 %)
FIT (done fit for selected event)
ln(L) = 1097186 s=0.00
Vertex at (0.54, 0.42, 14.05)64.60 MeV t0 = 67.73 ns.
Deposited energy 1945.02 MeV Measured energy 2049.42 MeV
Inferred neutrino energy 2066.07 MeV with uncertainty 16.65 MeV
Neutrino energy from lepton angle: 2081.33 MeV [QES]
[0] muon:1642 MeV and 8.24 m.
[1] proton:238 MeV and 0.405 m.
[2] _:0 MeV and 0.000 m.
[3] _:0 MeV and 0.000 m.
Predict 319721 photons of 20.49 M emitted. (1.56 %)
 best fit original, with measured E= 1984.00, Chi = 92233720368547758
```

```
PMT[2][12]@(13.70,6.10,17.86)
1326 photons          1320 photons
Duration 87.89 ns     Duration 107.00 ns
Time 3.97 ns          Time 4.27 ns
Mean time 8.65 ns     Mean time 9.20 ns
Decay signal = 18     Decay signal 570.54
+18                   +18.00
                      ln(L) -4140.40
```

```
COMMAND: Fit selected event
event generated
VIEW: top
LAYER: photons
Mean = 508.46 and variance = 307.20
```

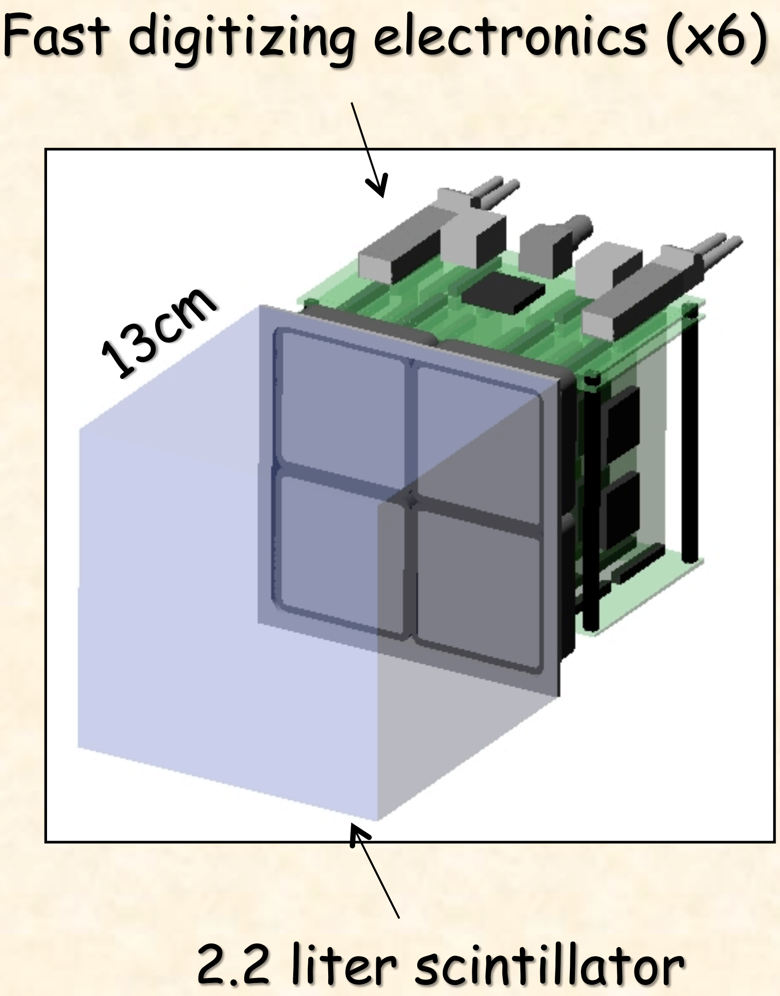
```
FINAL VERDICT
Error in measured energy 65.42 MeV = 3.30 %
Error in lepton energy 50.16 MeV = 3.15 %
Error in lepton track 0.24 m = 3 %, vertex: 0.11 m.
Error angle L 0.01 rad = 0 deg (p 0.49 rad = 28 deg)
```

Juha Peltoniemi, arXiv:0909.4974

Back to UH for our miniTimeCube

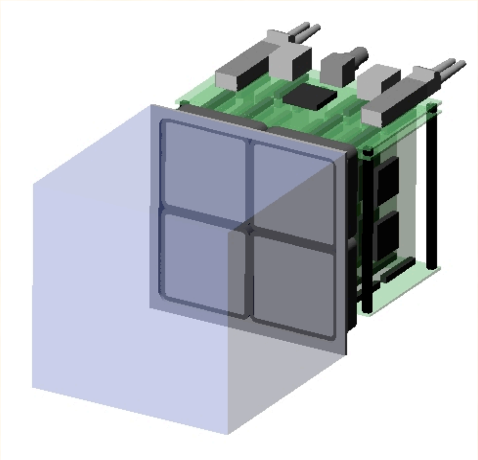
Springboarding from this and wanting to develop a way to get directionality for electron antineutrinos we came up with a new type of detector, with time replacing optics.

Idea for Small and Directional Inverse Beta Detector

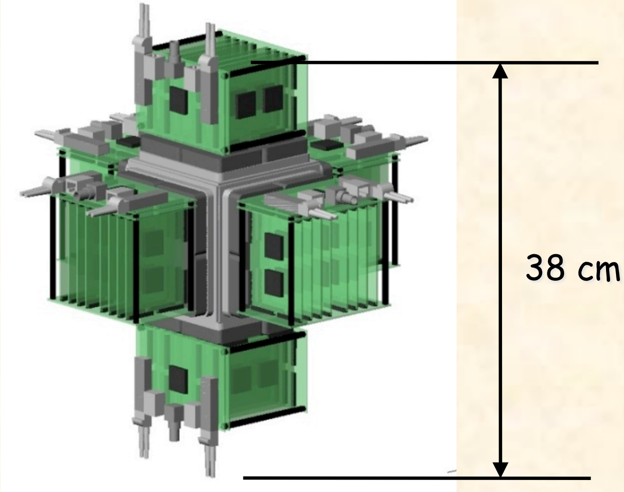


- Small portable 2.2 liter scintillating cube with neutron capture doping.
- Contain positron, lose gammas
- Do imaging with fast timing, not optics (time reversal imaging).
- Get some neutrino directionality between positron origin and neutrino capture point.
- Reject noise on the fly; no shielding needed
- 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.

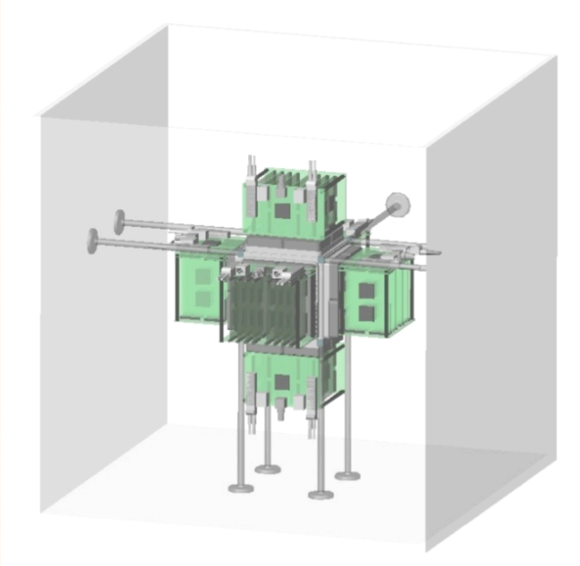
Mini Time Cube Based On 13cm^3 Boron Loaded Plastic Scintillator



MTC with read-out electronics on one face



MTC fully populated with read-out UH-ID electronics



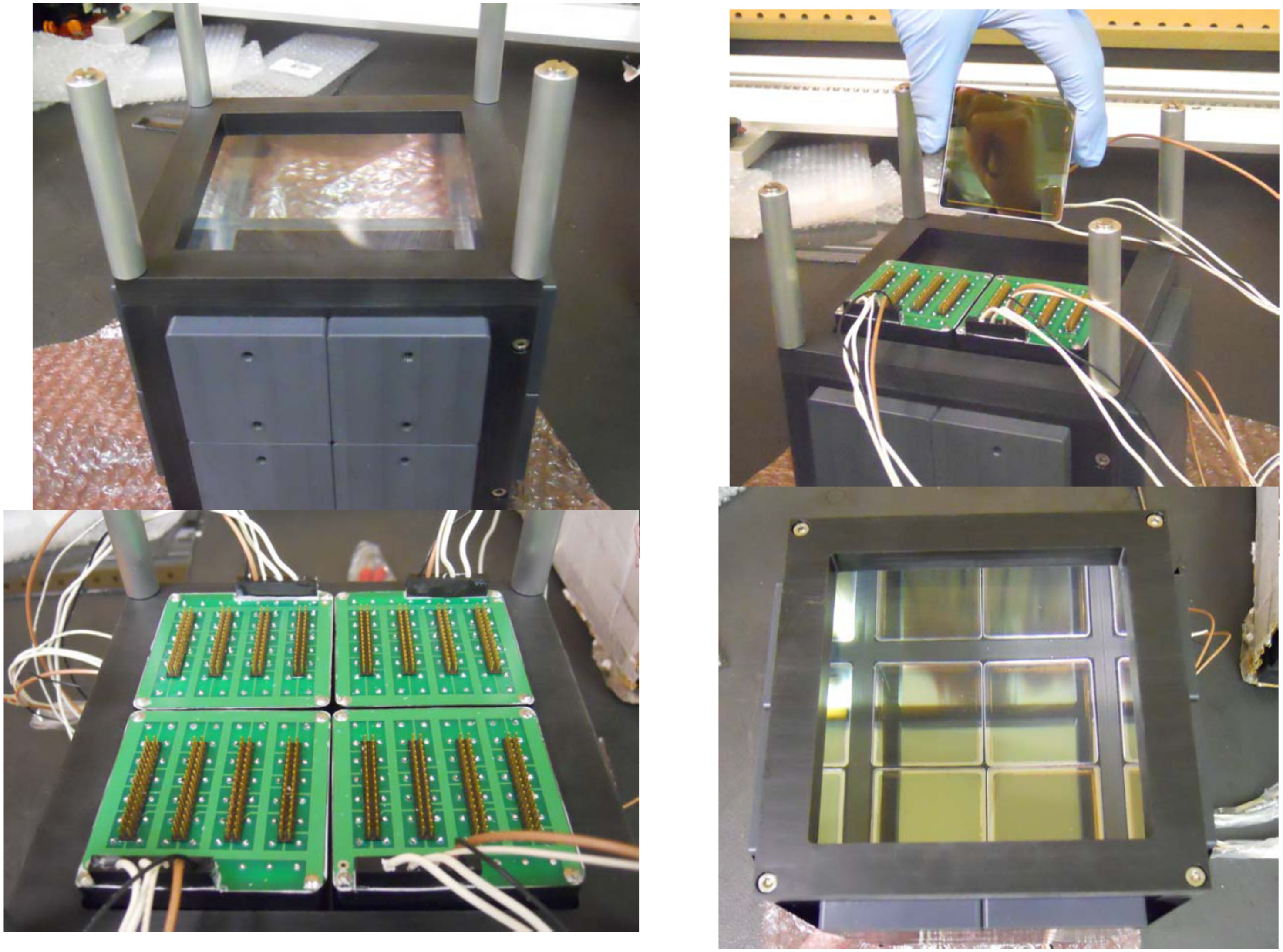
MTC within 2ft^3 enclosure

DAQ fits upper case

Detector fits lower case

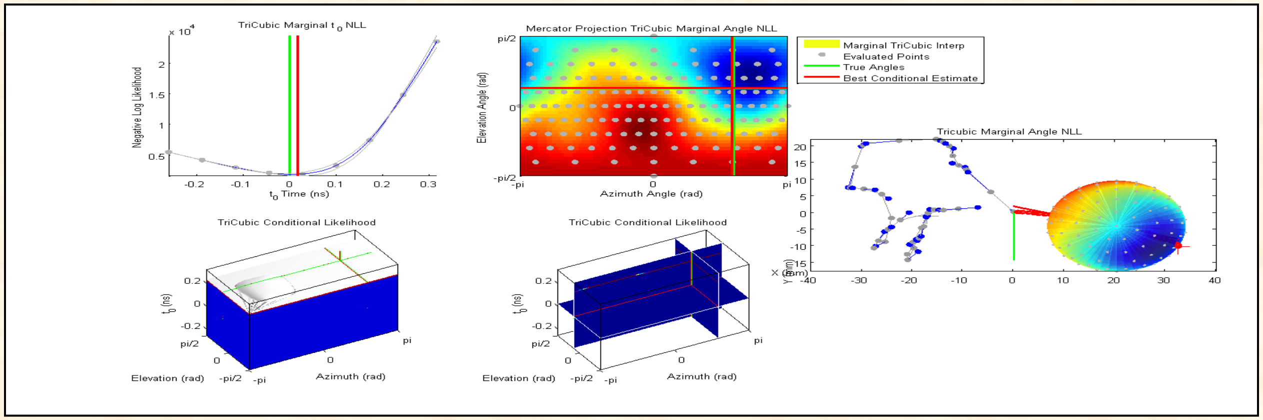
Stackable transport cases

First Installation of Tubes on mTC

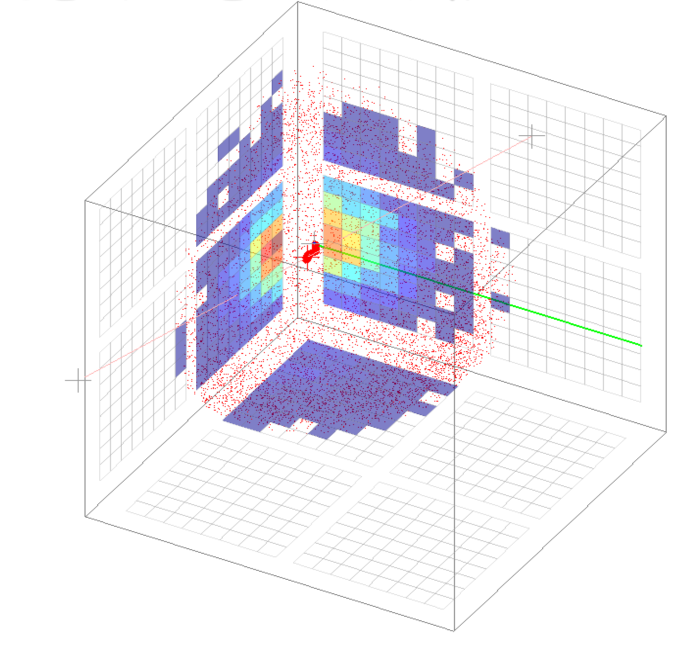


Starting Counting of Muons in Lab

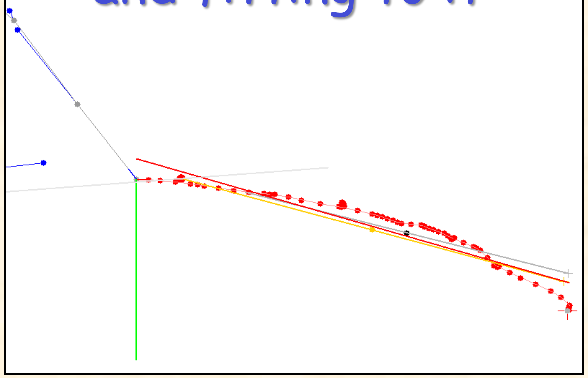
Fitting the Positron Track in mTC



GEANT Event in mTC



Positron track, and fitting to it



Glenn Joshcer, IAI

mTC Virtues, Summary

- Small size avoids gammas which smear resolution (X ~42 cm)
- Fast pixel timing (<100ps) and fast processing of waveforms rejects background in real time, resulting in
- Lack of need for shielding (unlike other detectors).
- Feasible even in high noise environment, near reactor vessel, at surface (eg. in a truck).
- Neutrino directionality via precision measure of positron production and neutron absorption locations.
- Challenges: build one and demonstrate, scale up, make more economically.
- Question under present study: Can we attack RANA with this?

Conclusion: Much Fun to be Had Untangling the Secrets of the Neutrinos

- Probably a hundred neutrino projects, large and small, underway around the world.
- This talk does no justice to the scope of the programs at accelerators, and with reactors and natural sources.
- Hopefully you get the sense of adventure as we look for the newest twists and surprises from the wiley neutrino