

Title: Neutrinos - The x-files of physics

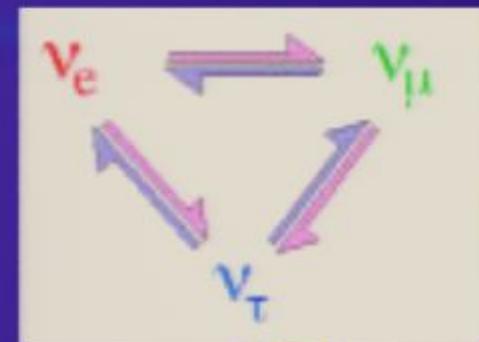
Date: Apr 05, 2006 02:00 PM

URL: <http://pirsa.org/06040003>

Abstract: Neutrinos are the big unknown in Particle Physics. Since their very beginning they behaved strangely. However, in the last decade experiments were able to solve some of their secrets. The talk will review the current experimental status of neutrino experiments and give an outlook on future activities.



# The X-files of Particle Physics



# Neutrinos

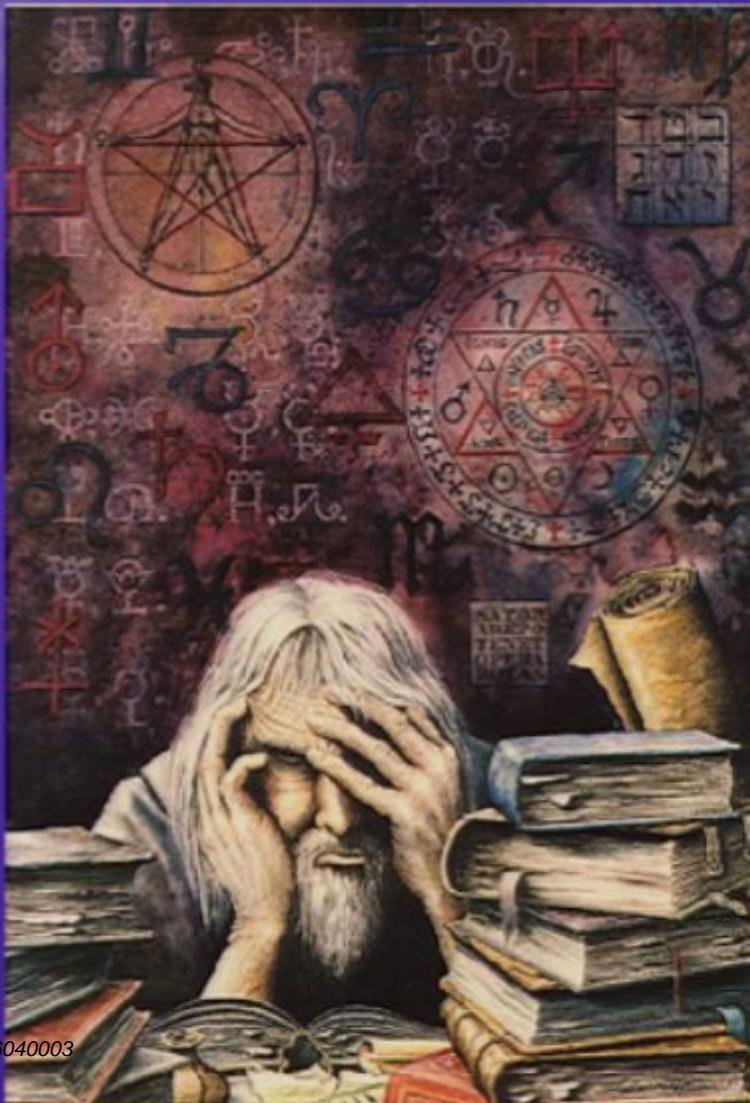




# How to explain absolutely everything about neutrino physics in 50 mins



# Contents

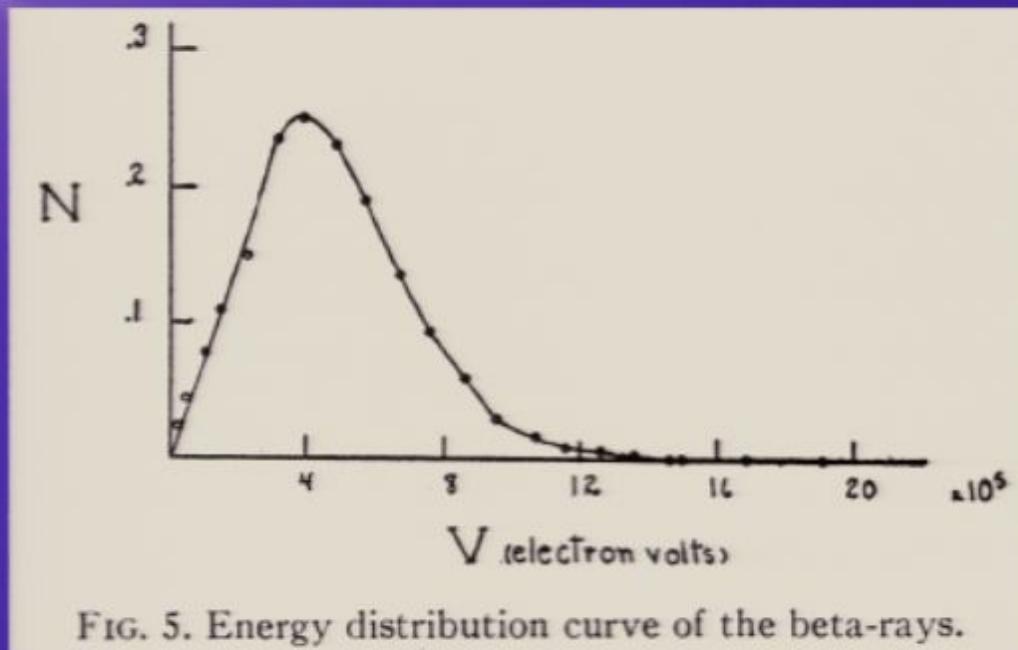


- Introduction
- Solar neutrinos and the Sudbury Neutrino Observatory (SNO)
- Double beta decay and the COBRA experiment
- Outlook and summary



# Why neutrinos?

F. A. Scott, *Phys. Rev.* **48**, 391 (1935)

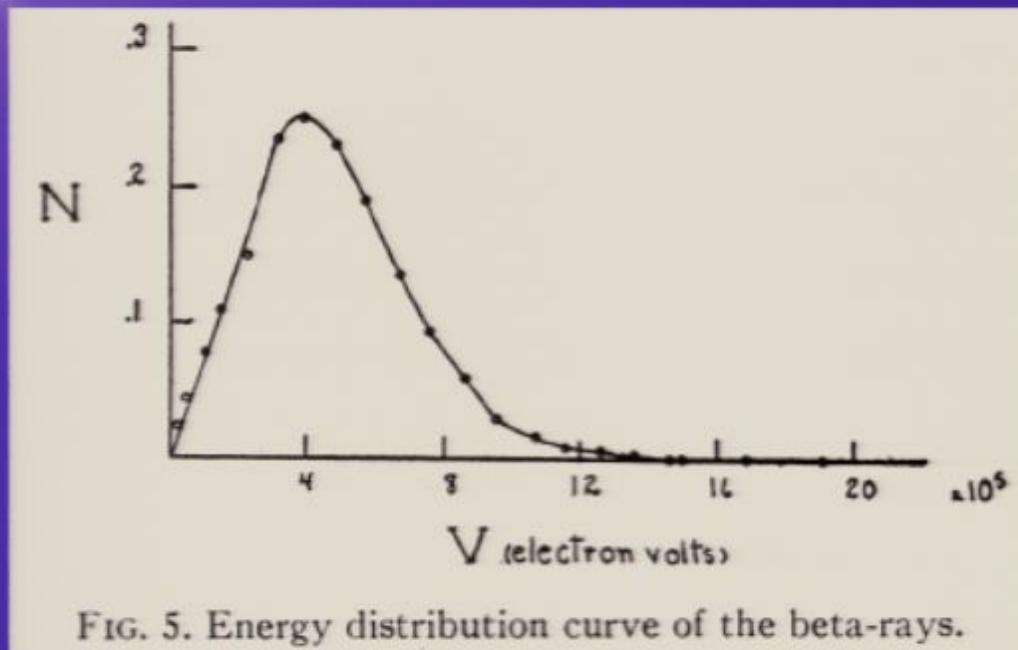


Why do electrons from nuclear beta decay show a continuous electron energy spectrum?



# Why neutrinos?

F. A. Scott, *Phys. Rev.* **48**, 391 (1935)



Why do electrons from nuclear beta decay show a continuous electron energy spectrum?

FIG. 5. Energy distribution curve of the beta-rays.

Bohr: *At the present stage of atomic theory, however, we may say that we have no argument, either empirical or theoretical, for upholding the energy principle in the case of  $\beta$ -ray disintegrations*



# The solution?

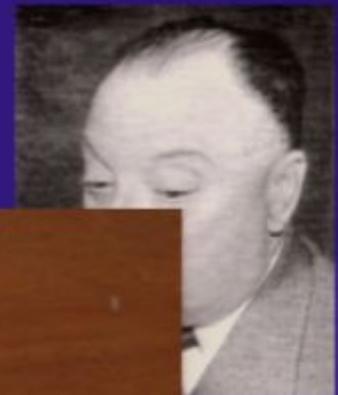
4th December 1930



Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and Li<sup>6</sup> nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons, which have spin 1/2 and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant.

The solution?





# The discovery

C. Cowan, F. Reines 1953,1956

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

Herr Auge

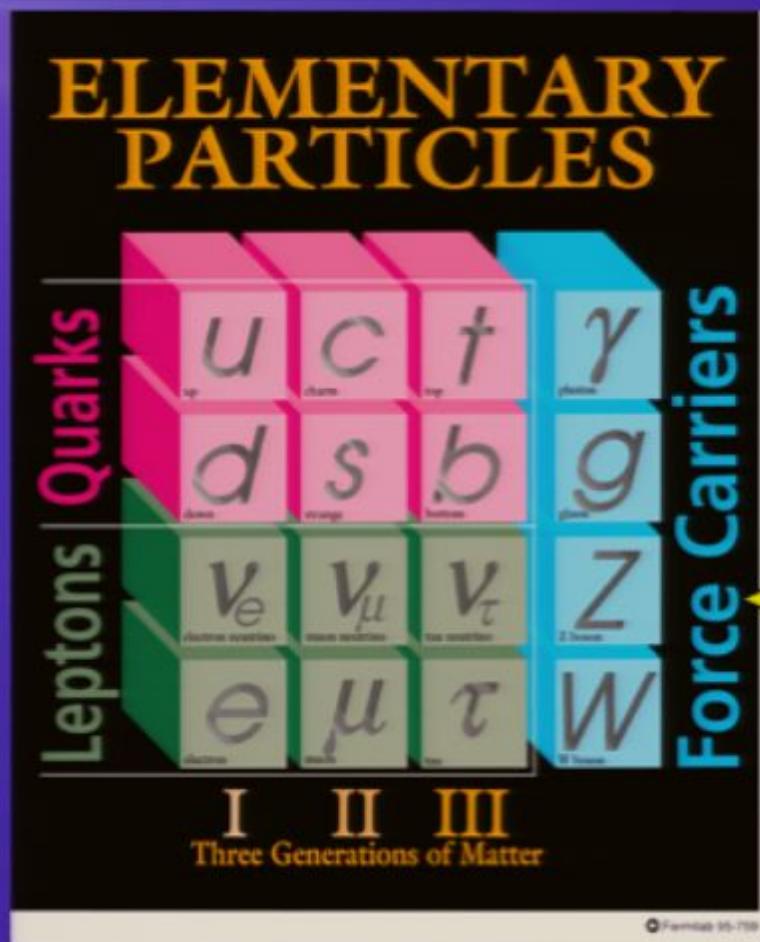


Project Poltergeist



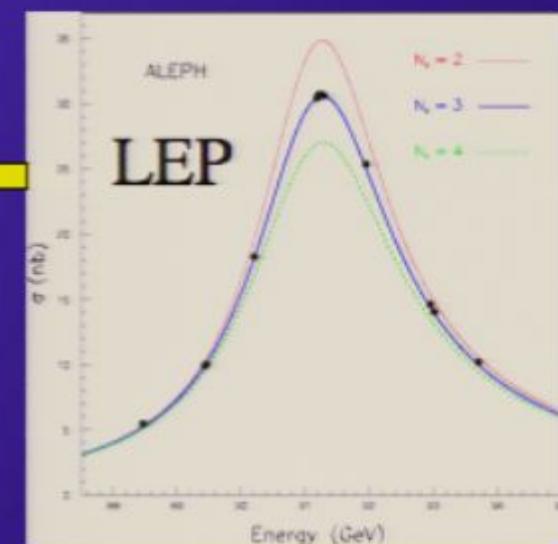


# The Standard Model



1952:  $m_\nu < 10 \text{ keV}$

Within Standard Model  
neutrinos are massless



+ Higgs boson



The fundamental question

**Do neutrinos have a  
non vanishing rest mass?**

Physics beyond the Standard Model



Beta decay  
Double beta

Oscillations  
Z - width

Nuclear  
physics

Particle  
physics

$\nu$  Type Mass Numbers

Astrophysics

Sun  
Supernovae

Cosmology

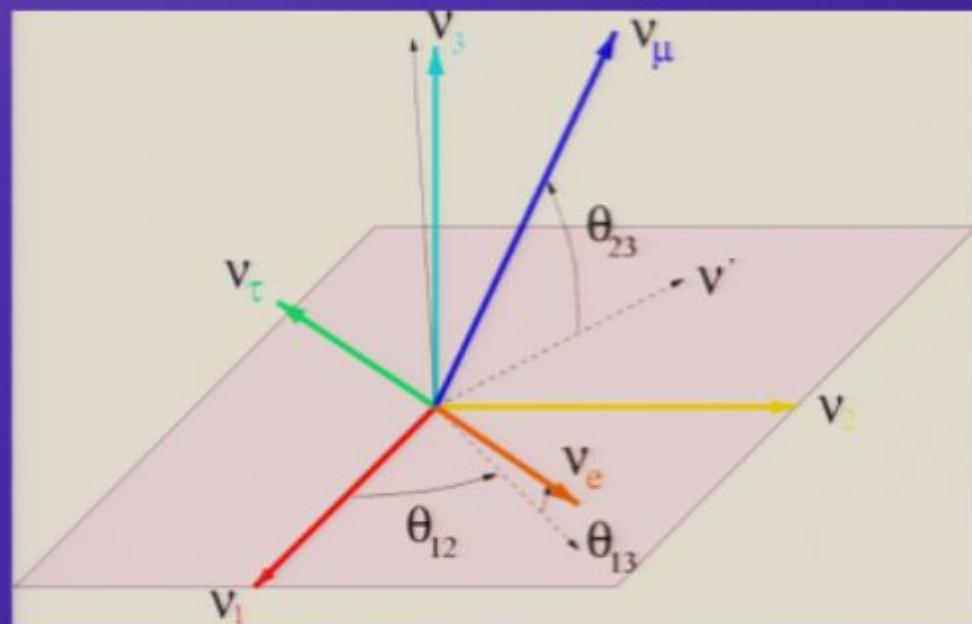
BBN-He4  
Dark matter



# Neutrino Oscillations I

Mass-eigenstates can be different from flavour-eigenstates

*In complete analogy to quark sector*



$$|v_\alpha\rangle = U_{\alpha i} |v_i\rangle$$

*2 flavour scenario*

$$U = \begin{pmatrix} \cos\Theta & \sin\Theta \\ -\sin\Theta & \cos\Theta \end{pmatrix}$$

*3 flavour scenario*

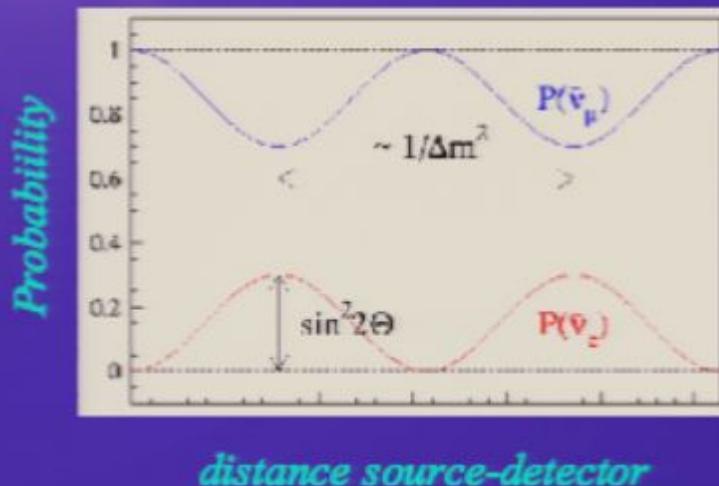
$$U = \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\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



# Neutrino Oscillations II

*Oscillation probability:*

$$P(|\nu_\alpha\rangle \rightarrow |\nu_\beta\rangle) = \sin^2 2\Theta \sin^2(1.27\Delta m^2 \frac{L}{E})$$



*with*

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

*Sensitivity*

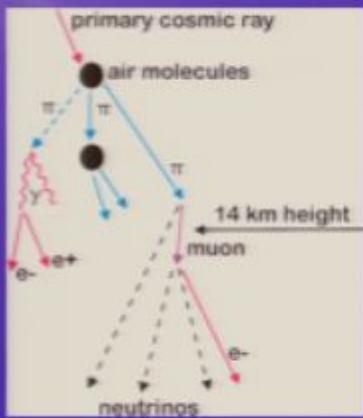
$$\Delta m^2 \propto \frac{E}{L}$$

2 unknown parameters:  $\sin^2 2\theta, \Delta m^2$

**NO absolute neutrino mass measurement!**



# Neutrino sources



Nuclear power plants  $\bar{\nu}_e$



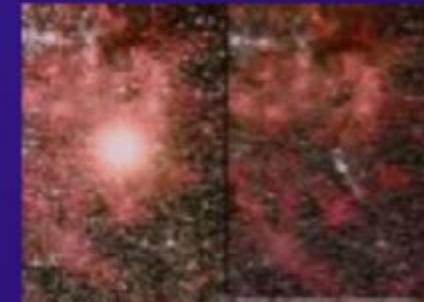
Accelerators

Earth radioactivity  $\bar{\nu}_e$

The atmosphere



The Sun  $\nu_e$

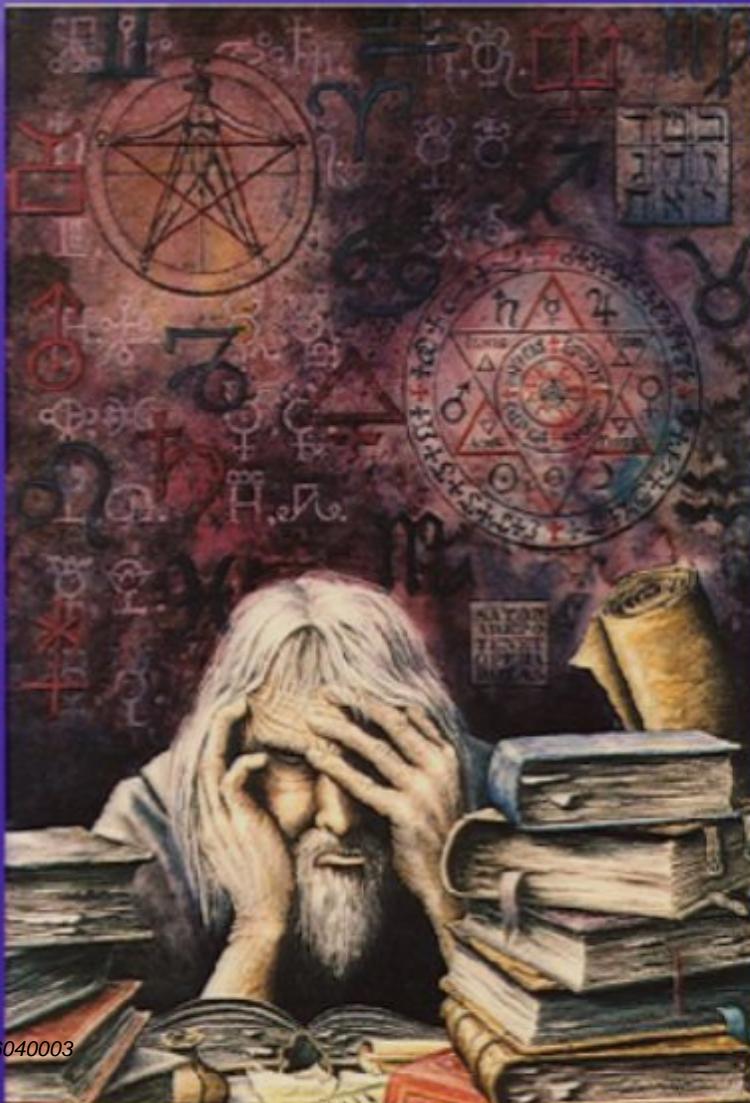


Supernova

The Big Bang



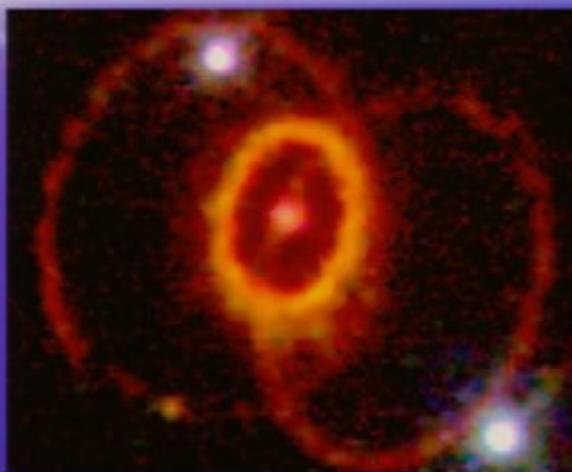
# Contents



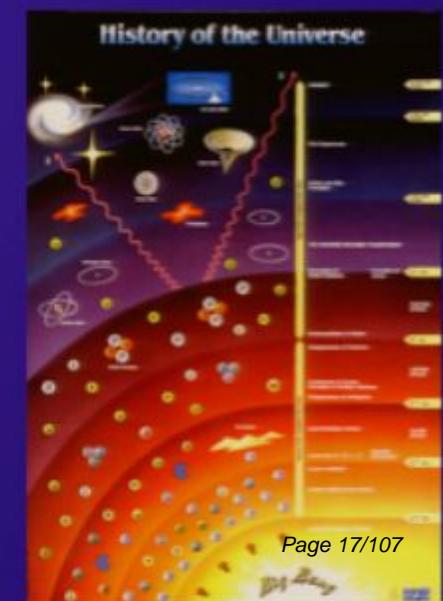
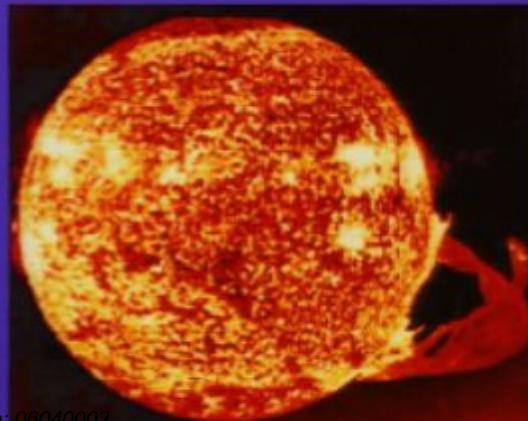
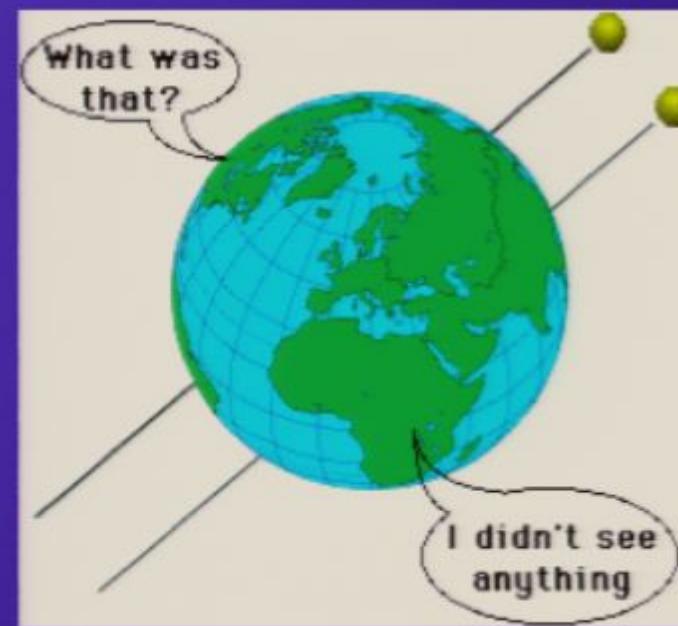
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# Neutrino Astrophysics



The problem...





## Solar neutrinos

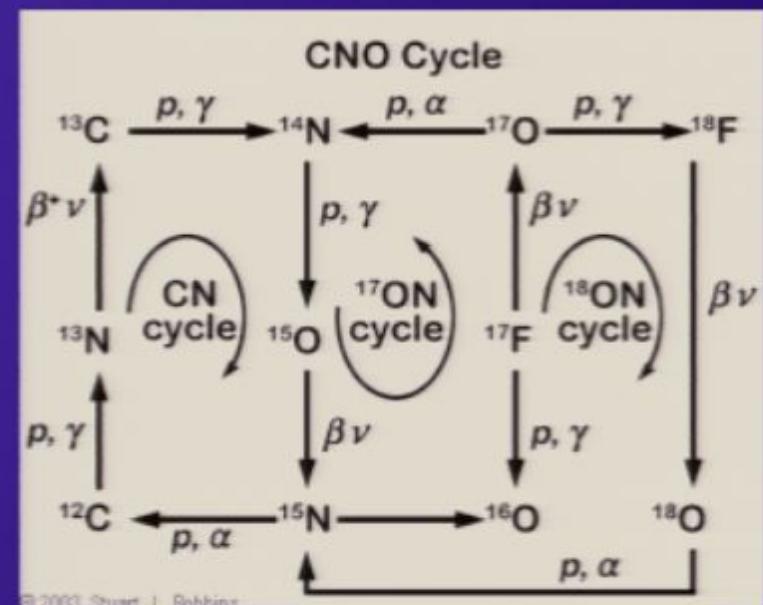
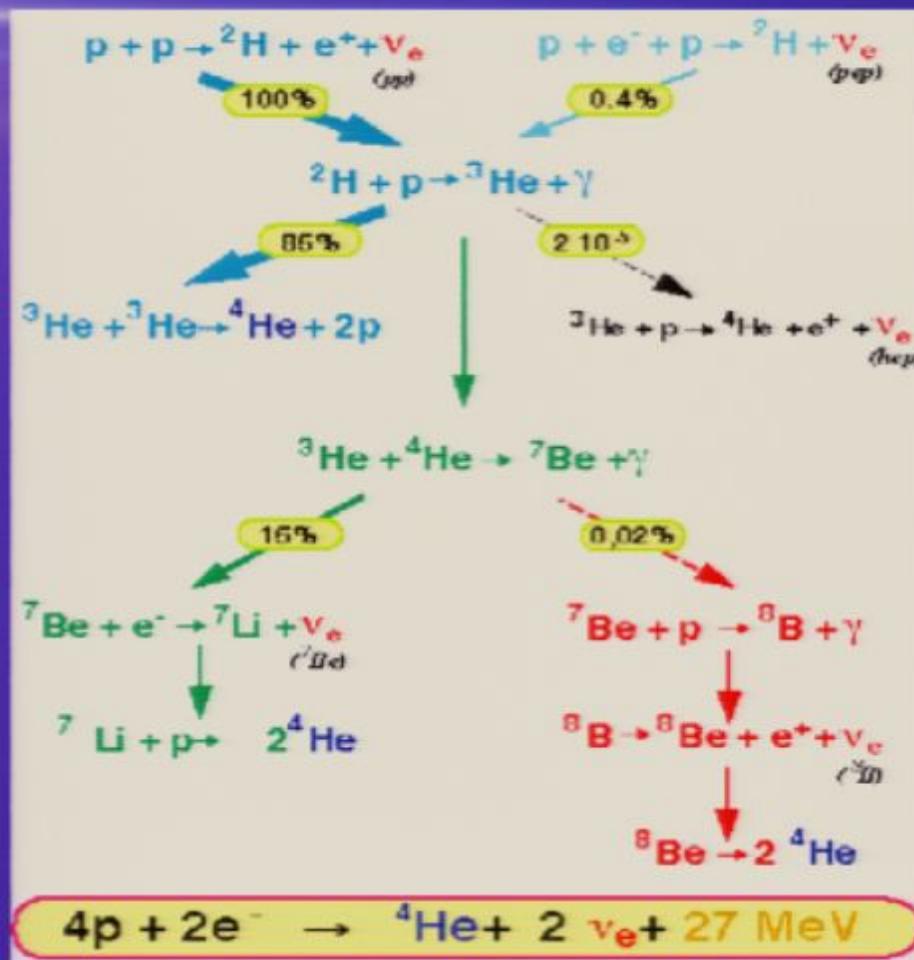
How does the sun produce its energy?



- Crucial for understanding stellar evolution and thus for stellar astrophysics
- Unique view into the Interior of the Sun
- Contribution of two cycles (pp and CNO-cycle)
- Unique neutrino source, 150 million km distance, only electron neutrinos



# Solar energy production

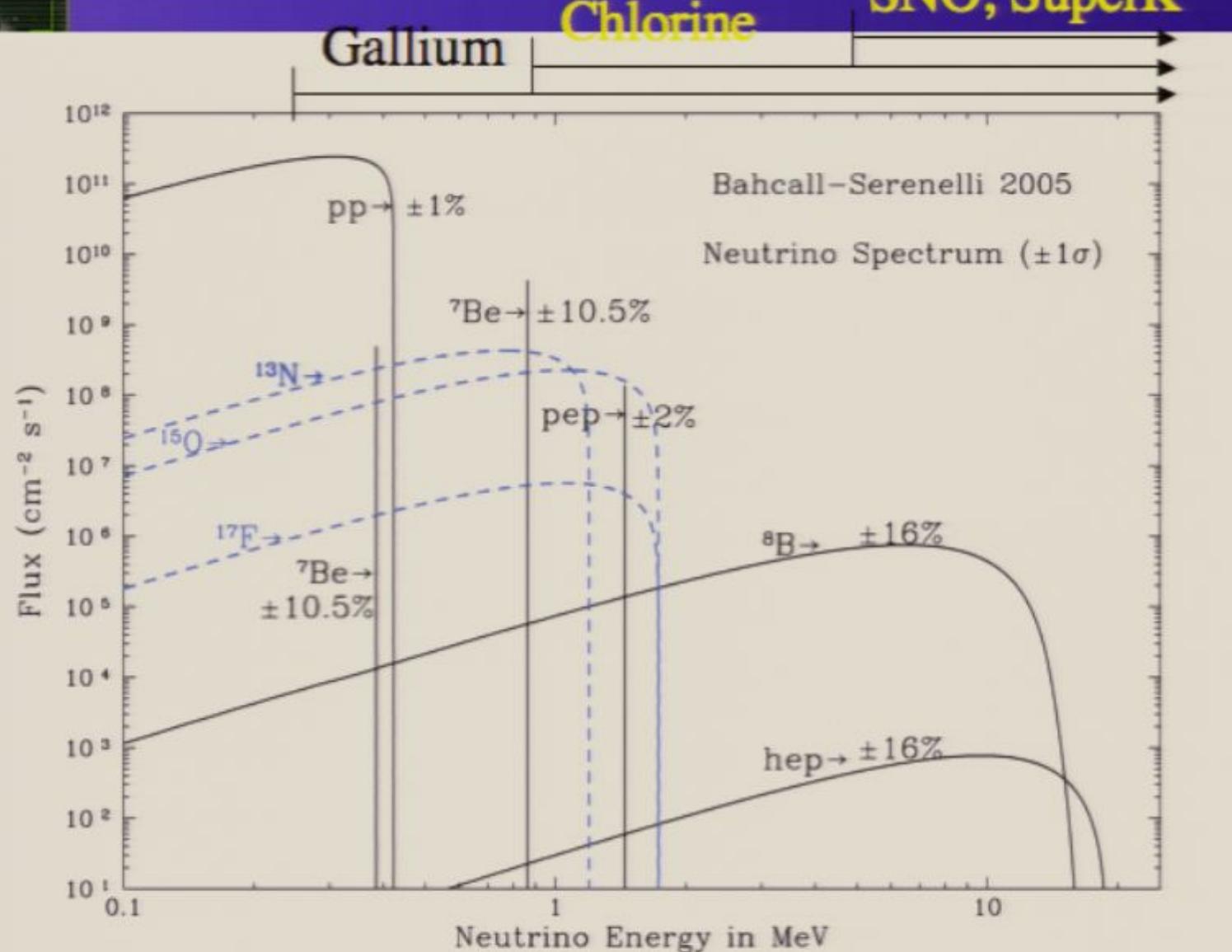


Flux at Earth:  $6 \cdot 10^{10} \text{ cm}^{-2}\text{s}^{-1}$



# The Solar Neutrino Spectrum

SNO, SuperK

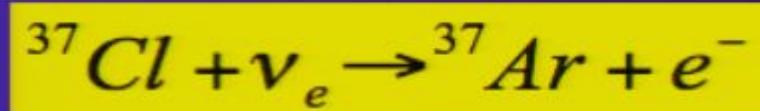




# 30 years of solar neutrinos

## Homestake Experiment

Result:  $2.56 \pm 0.23$  SNU



Theory:  $7.6 \pm 1.2$  SNU

## Gallex/GNO and SAGE

Result:  $68.1 \pm 3.75$  SNU



Theory:  $127 \pm 10$  SNU

## Super-Kamiokande

Result:  $= 2.35 \pm 0.10 * 10^6 \text{ cm}^{-2}\text{s}^{-1}$



Theory =  $5.1 \pm 0.2 * 10^6 \text{ cm}^{-2}\text{s}^{-1}$



# Who is responsible?

Sun

Core temperature

$$\phi(^8B) \propto T^{18}$$

composition

Magnetic field

Cosmions

cross sections

Astrophysicists:

5% change in

temperature is too much

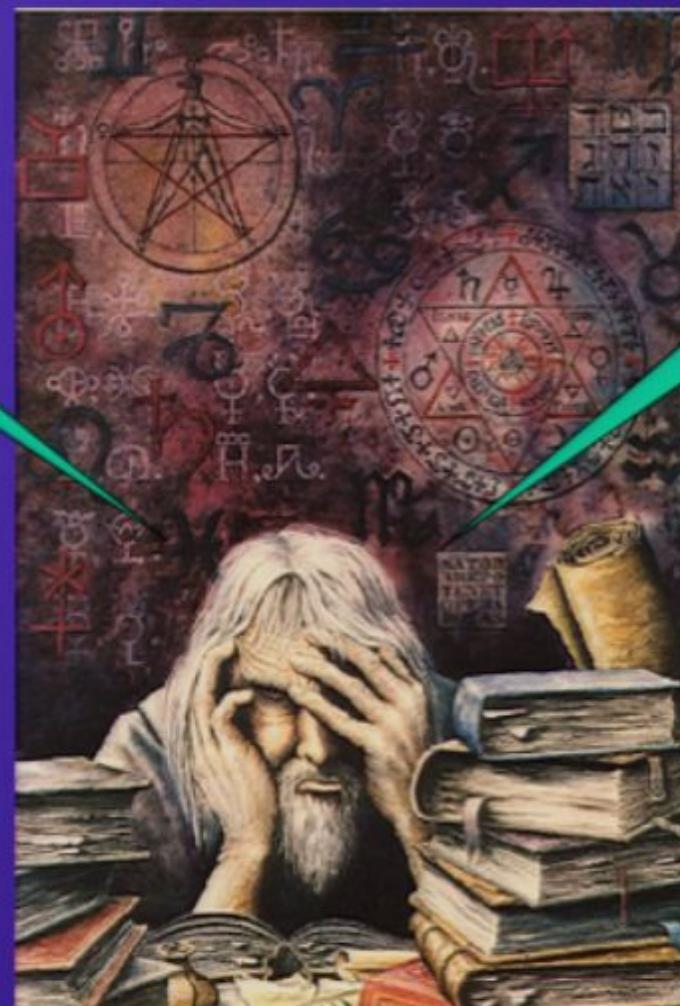
Neutrino

Vacuum  
oscillations

Matter oscillations

Magnetic  
moment

Neutrino decay



All require neutrino mass

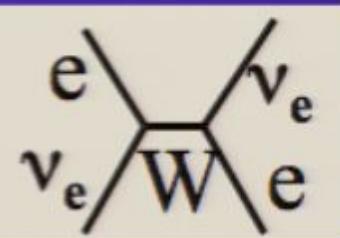
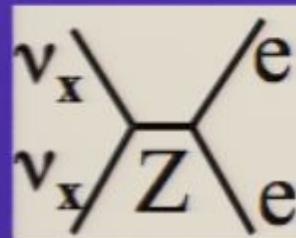


# Oscillations-Solutions

Vacuum oscillations:

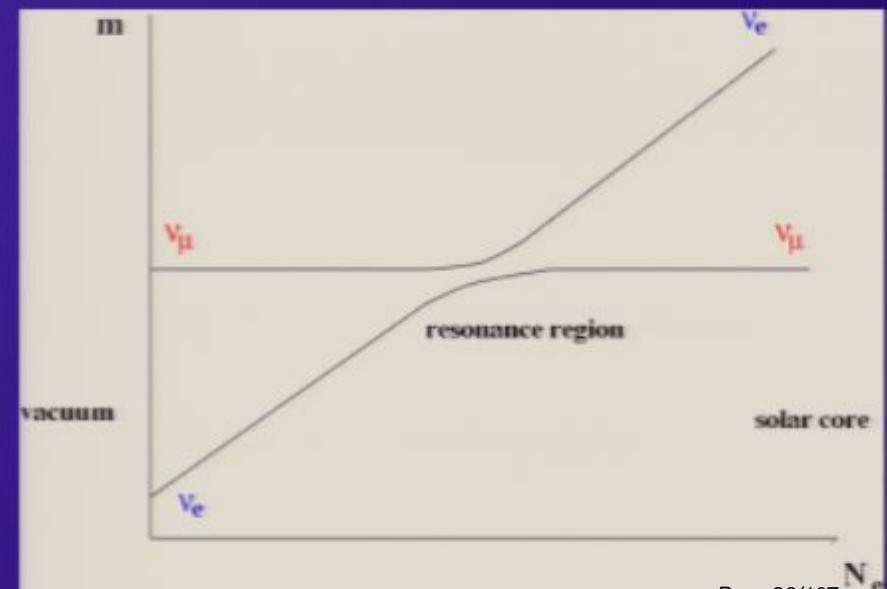
$$\Delta m^2 \approx \frac{E}{L} \approx \frac{1 \text{ MeV}}{10^{11} \text{ m}} = 10^{-11} \text{ eV}^2$$

Matter oscillations (MSW-Effect)



Results in an “effective mass” for  $\nu_e$  in matter proportional to electron density  $N_e$

Resonant amplification of oscillations if  $N_e = G_f \cdot \Delta m^2 / E$





# Matter-Oscillations

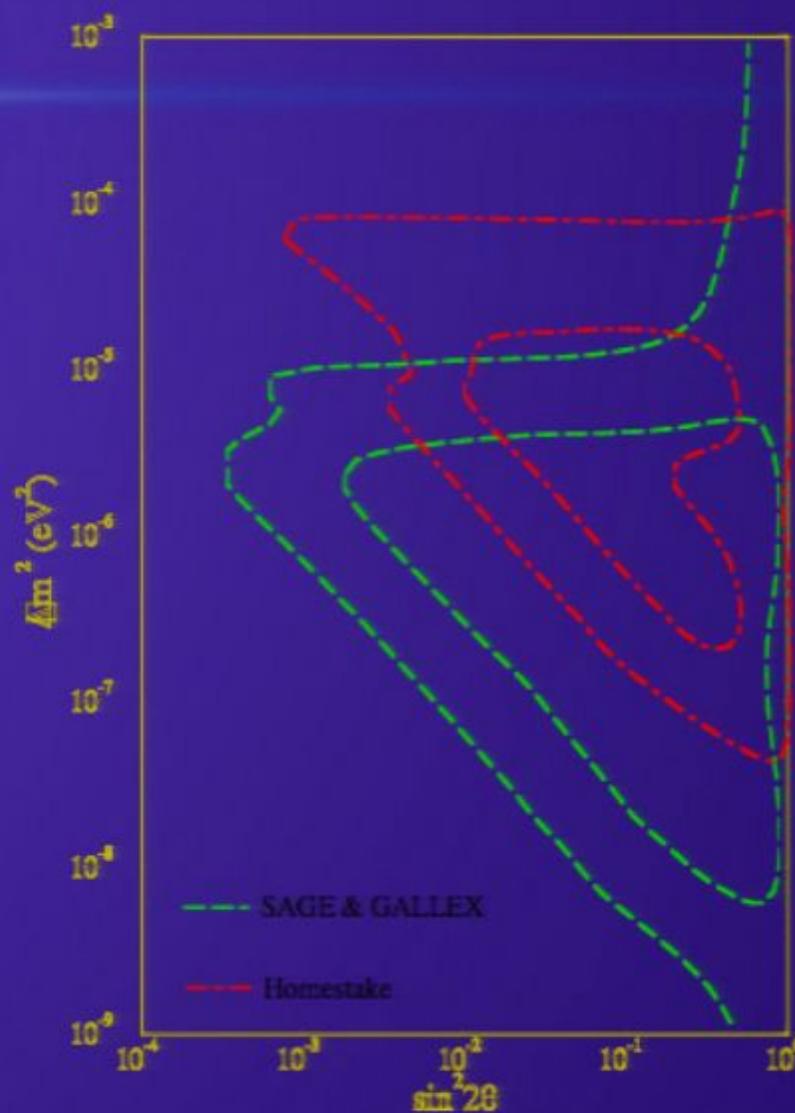
MSW results in a  
enlarged range of  
allowed  $\Delta m^2$  regions





# Matter-Oscillations

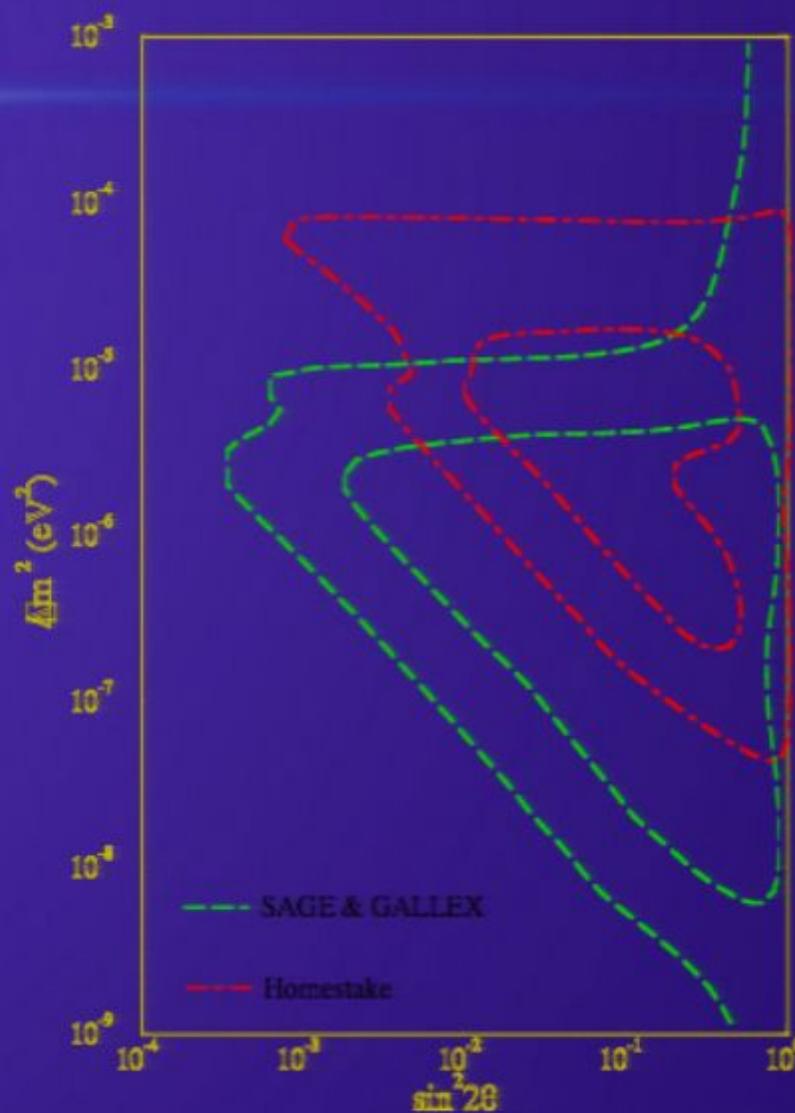
MSW results in a  
enlarged range of  
allowed  $\Delta m^2$  regions





# Matter-Oscillations

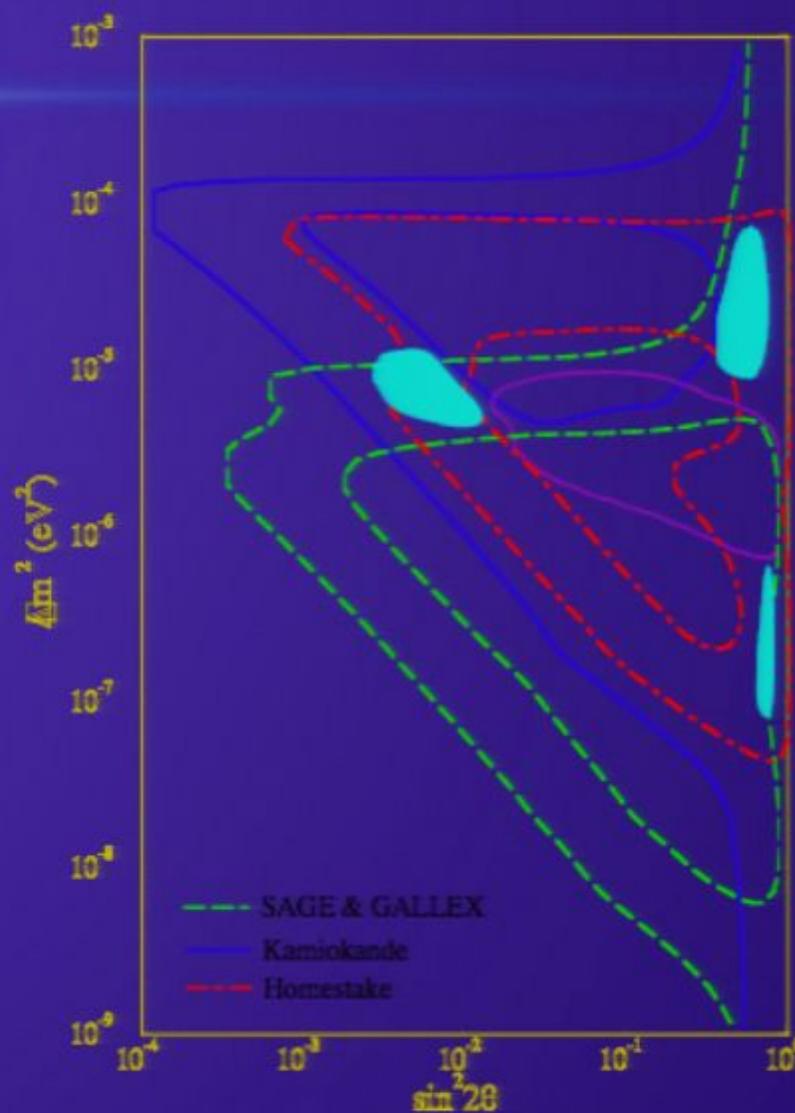
MSW results in a  
enlarged range of  
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# Matter-Oscillations

MSW results in a  
enlarged range of  
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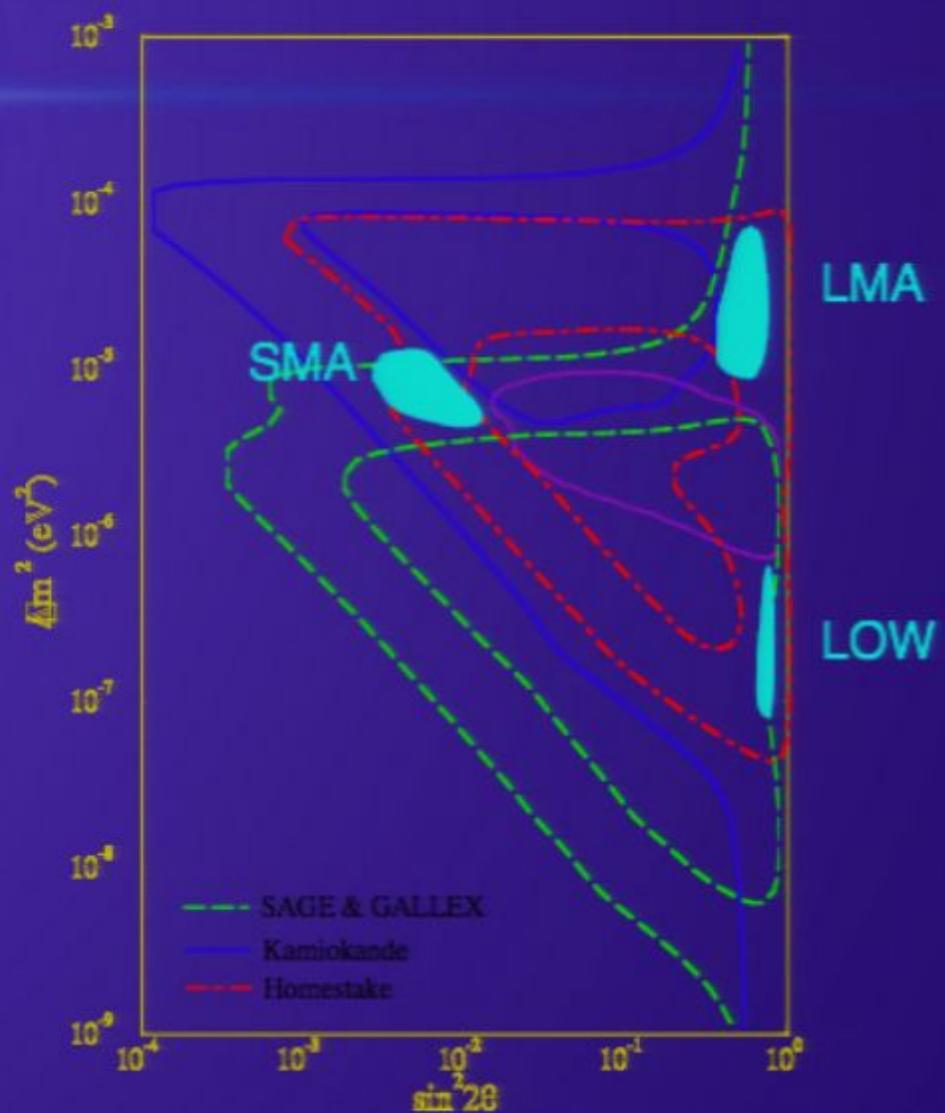


# Matter-Oscillations

MSW results in a  
enlarged range of  
allowed  $\Delta m^2$  regions

Only "weak" evidence

- Needs prove
- Independent of SSM

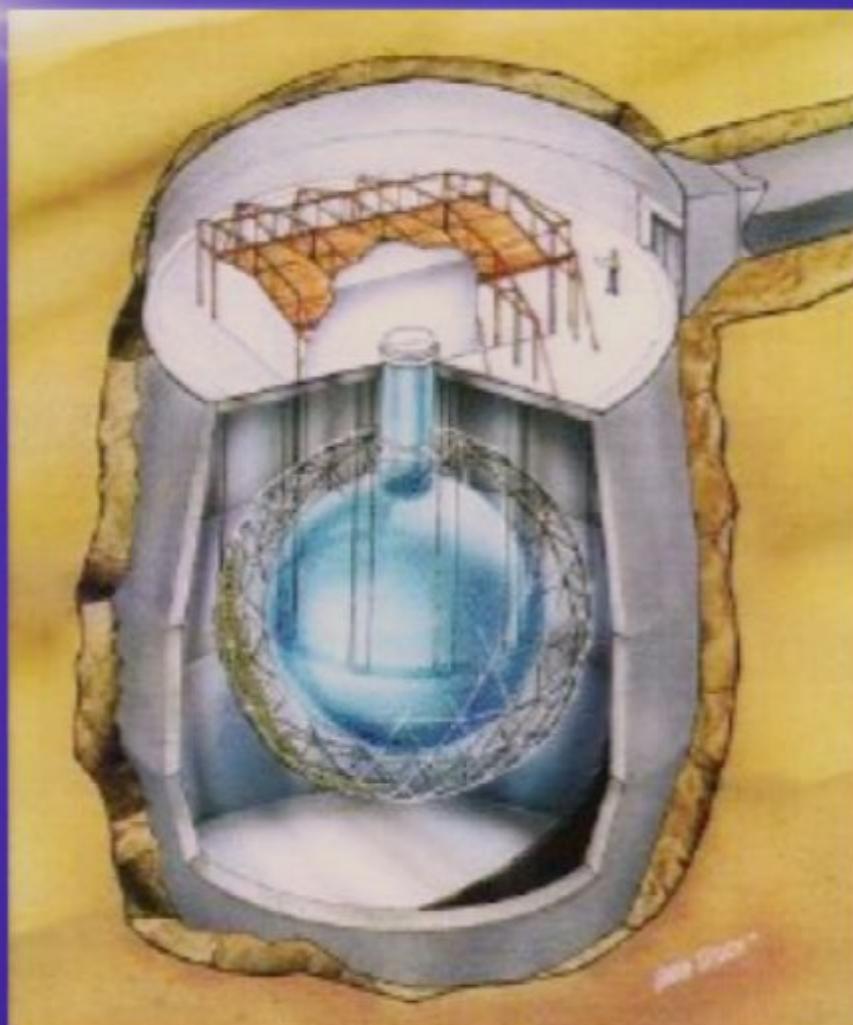




# The Sudbury Neutrino Observatory (SNO)

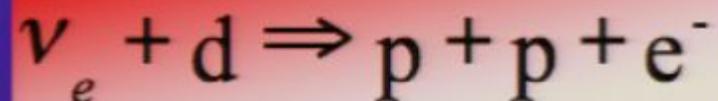


# SNO – The smoking gun

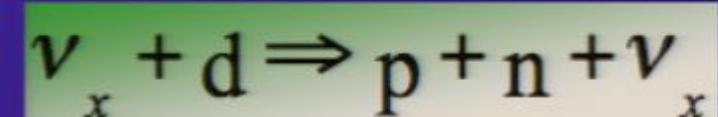


1000 t heavy water ( $D_2O$ )

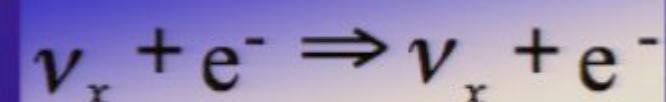
cc



NC



ES



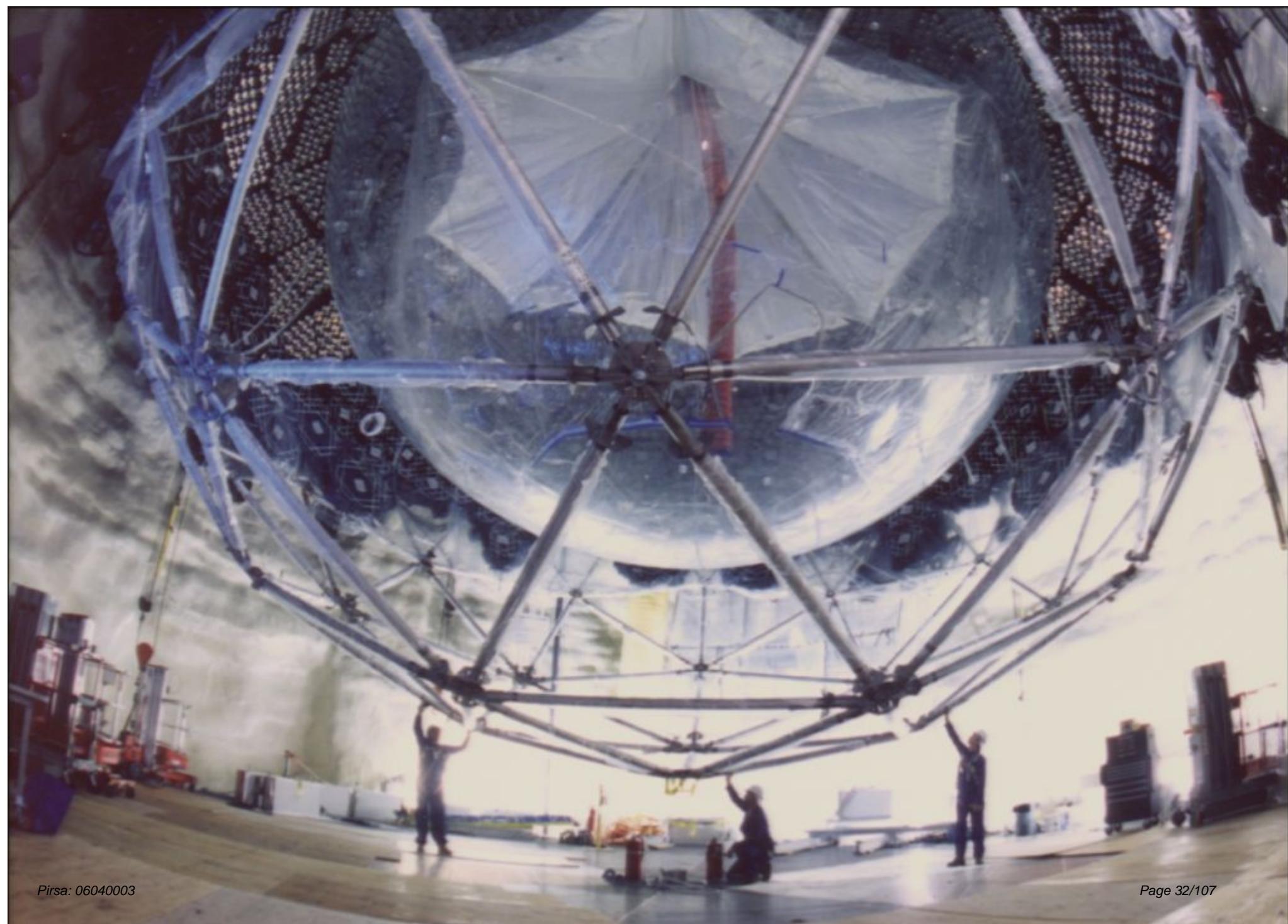
$$\frac{CC}{ES} = \frac{\nu_e}{\nu_e + 0.14(\nu_\mu + \nu_\tau)}$$

$$\frac{CC}{NC} = \frac{\nu_e}{\nu_e + \nu_\mu + \nu_\tau}$$

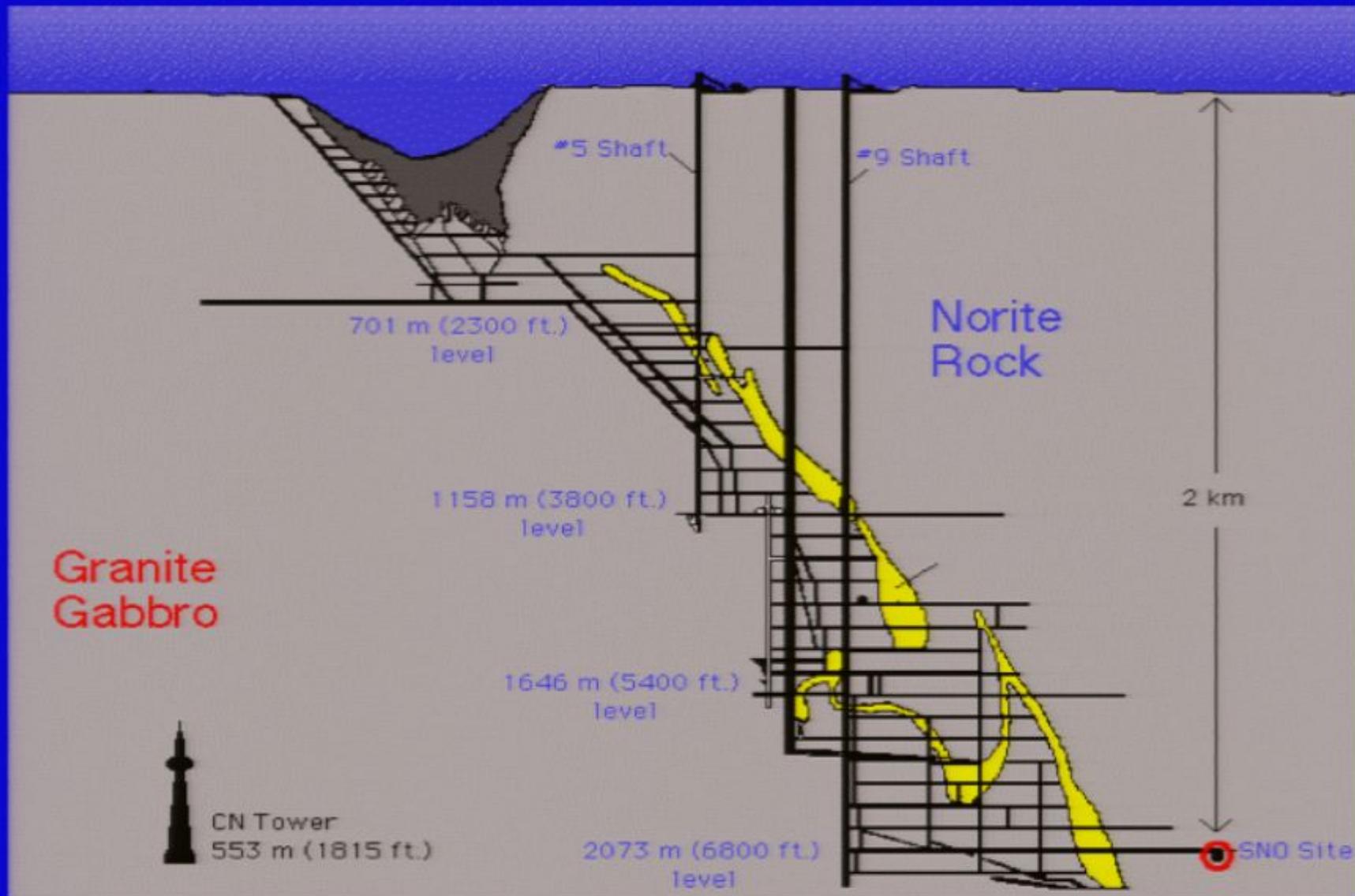


# SNO 2005





# The SNO Detector





# A SNO - day

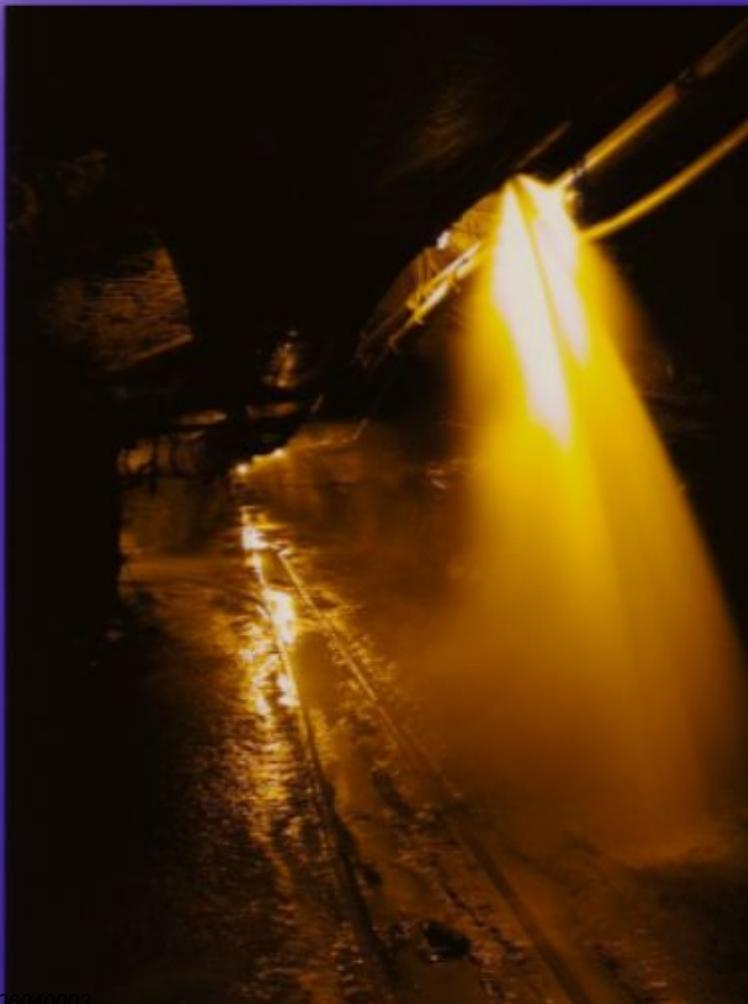


# A SNO - day



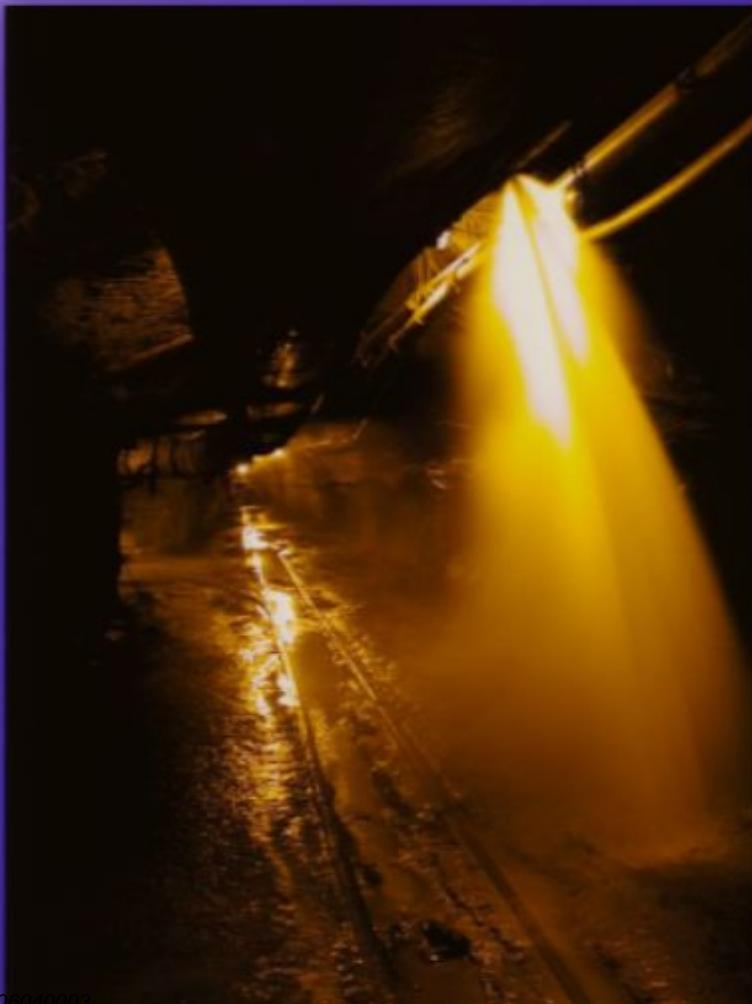


# A SNO - day





# A SNO - day



Pirsa: 06040003



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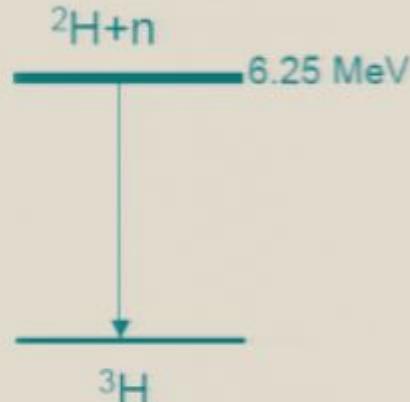


# SNO Run Sequence

## Phase I ( $D_2O$ )

Nov. 99 - May 01

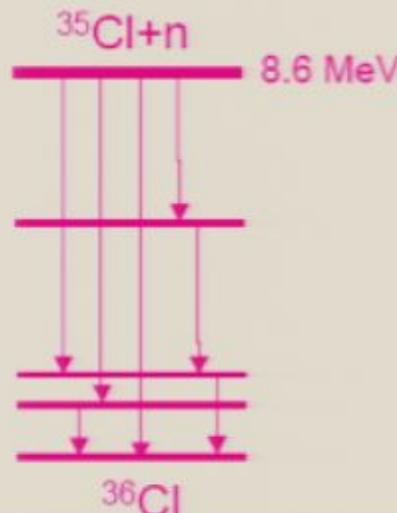
n captures on  
 $^2H(n, \gamma)^3H$   
 $\sigma = 0.0005 \text{ b}$   
Observe 6.25 MeV  $\gamma$   
PMT array readout  
Good CC



## Phase II (salt)

July 01 - Sep. 03

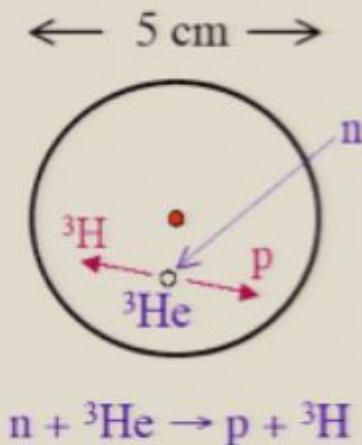
2 t NaCl. n captures on  
 $^{35}Cl(n, \gamma)^{36}Cl$   
 $\sigma = 44 \text{ b}$   
Observe multiple  $\gamma$ 's  
PMT array readout  
Enhanced NC



## Phase III ( $^3He$ )

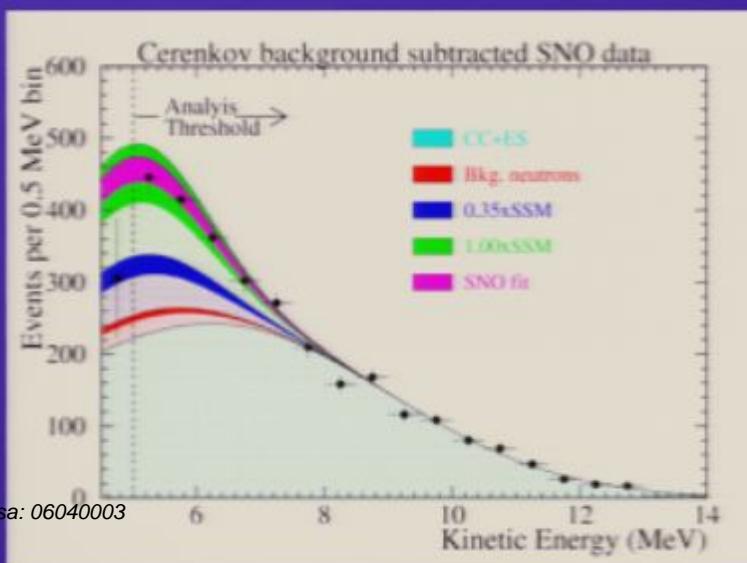
Summer 04 - Dec. 06

40 proportional counters  
 $^3He(n, p)^3H$   
 $\sigma = 5330 \text{ b}$   
Observe p and  $^3H$   
PC independent readout  
Event by Event Det.

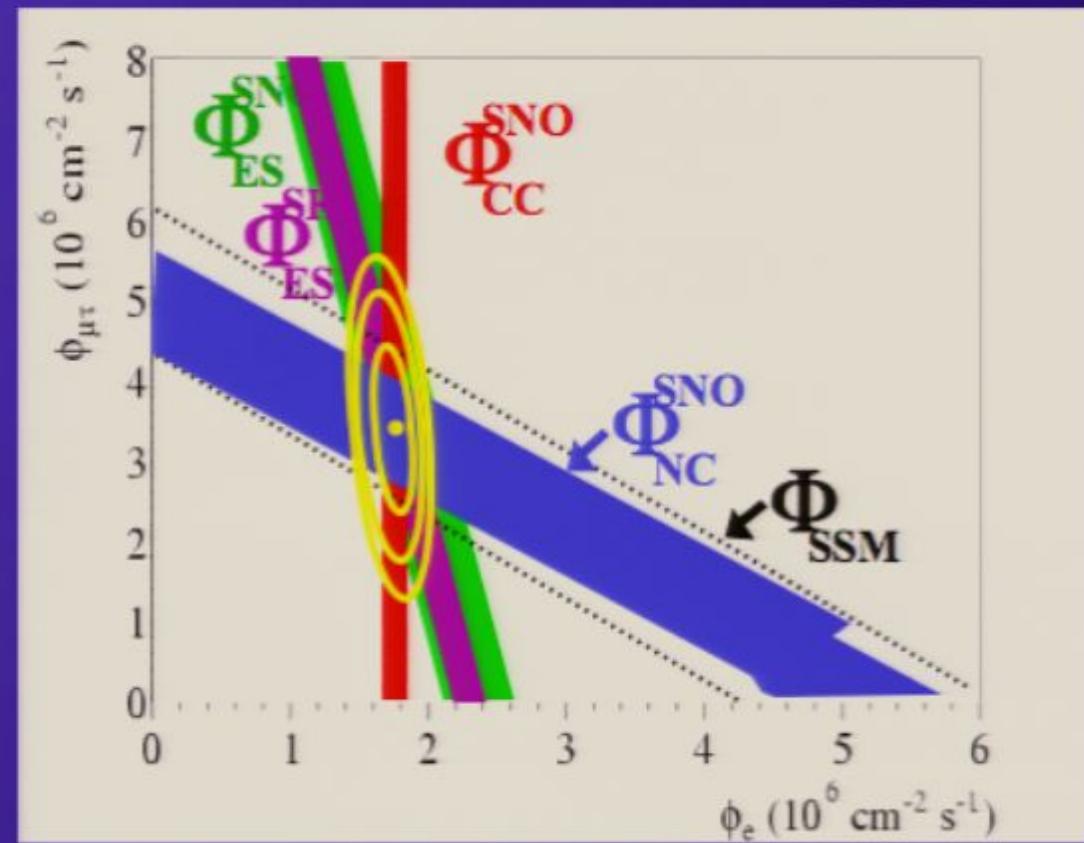


# #EVENTS

<b>CC</b>	<b>1967.7</b>	$^{+61.9}_{-60.9}$
<b>ES</b>	<b>263.6</b>	$^{+28.6}_{-28.6}$
<b>NC</b>	<b>576.5</b>	$^{+49.5}_{-48.9}$



# SNO Spectrum - D<sub>2</sub>O phase

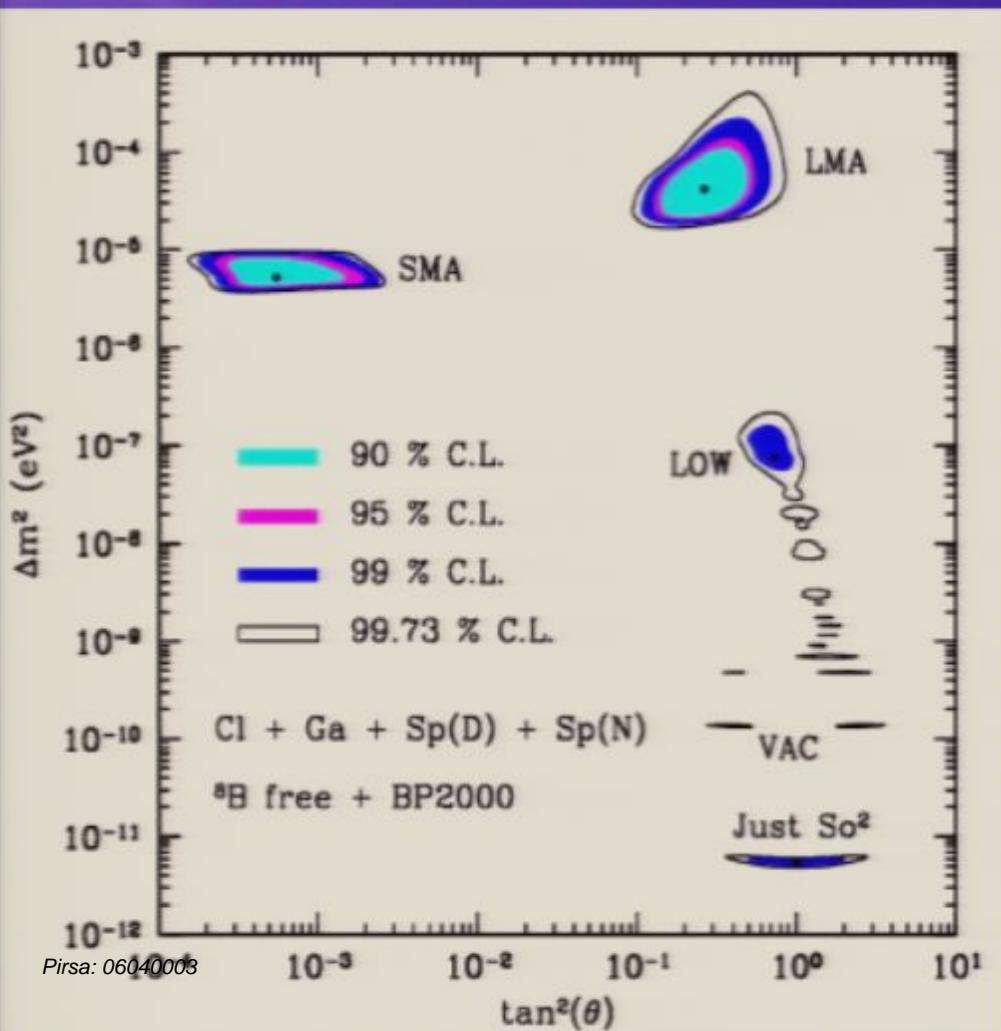


Full solar neutrino flux measured !  
Not missing but wrong neutrinos !



# SNO - Impact

## Before SNO

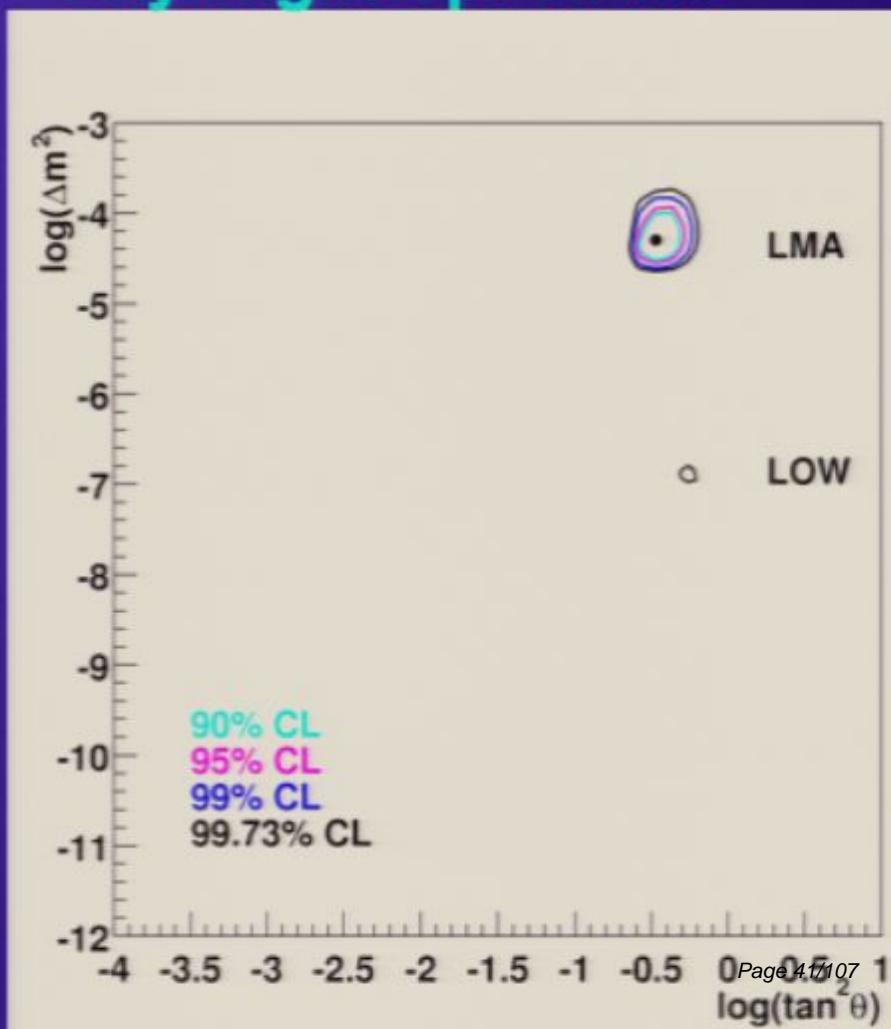
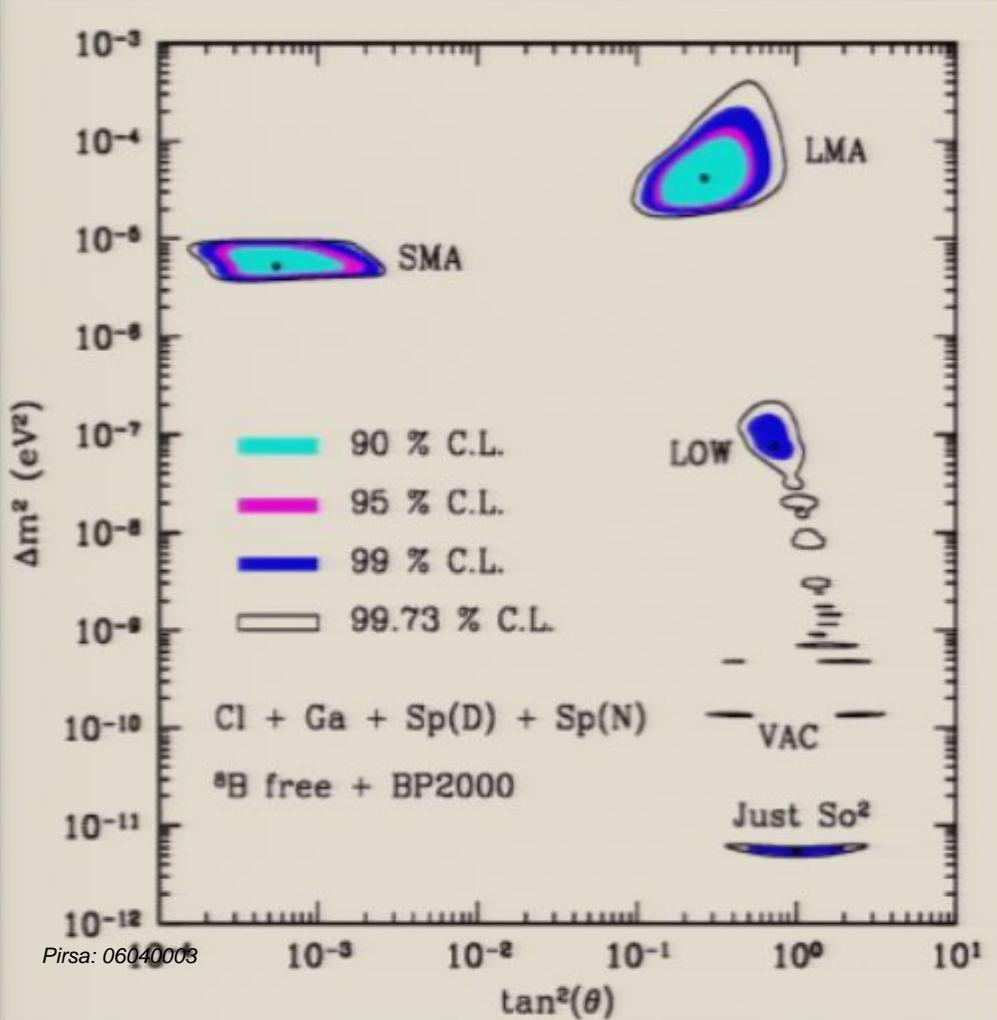




# SNO - Impact

## Before SNO

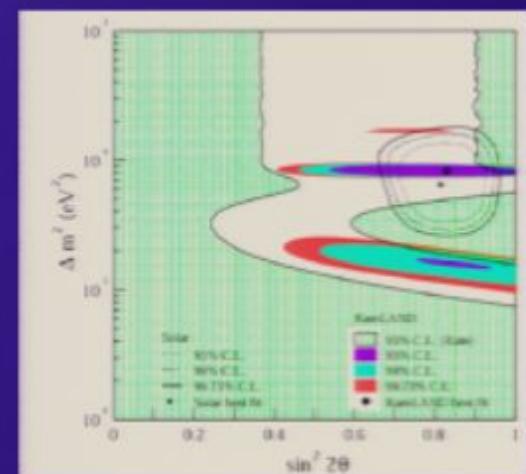
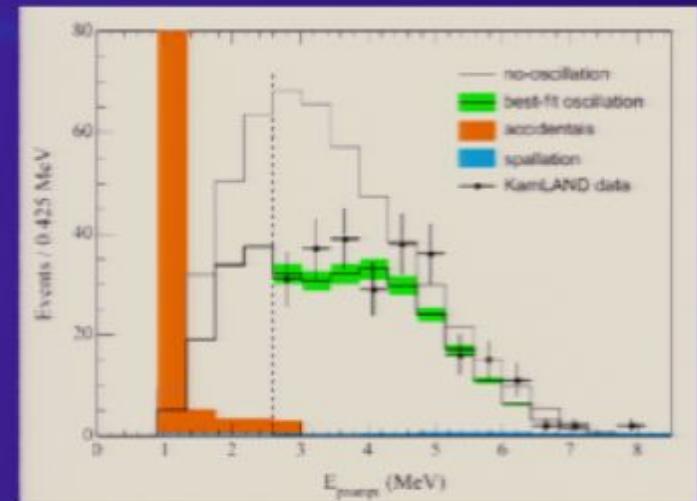
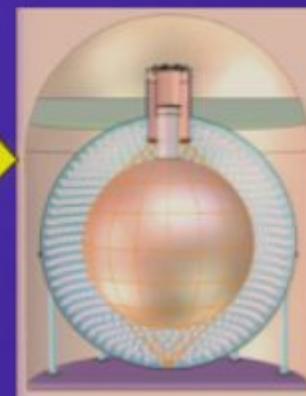
With SNO, NC/CC,  
Day-Night Spectrum





# KamLAND - Results

$365 \pm 24$  events expected,  
258 observed



LMA solution is correct



## 391-day salt results

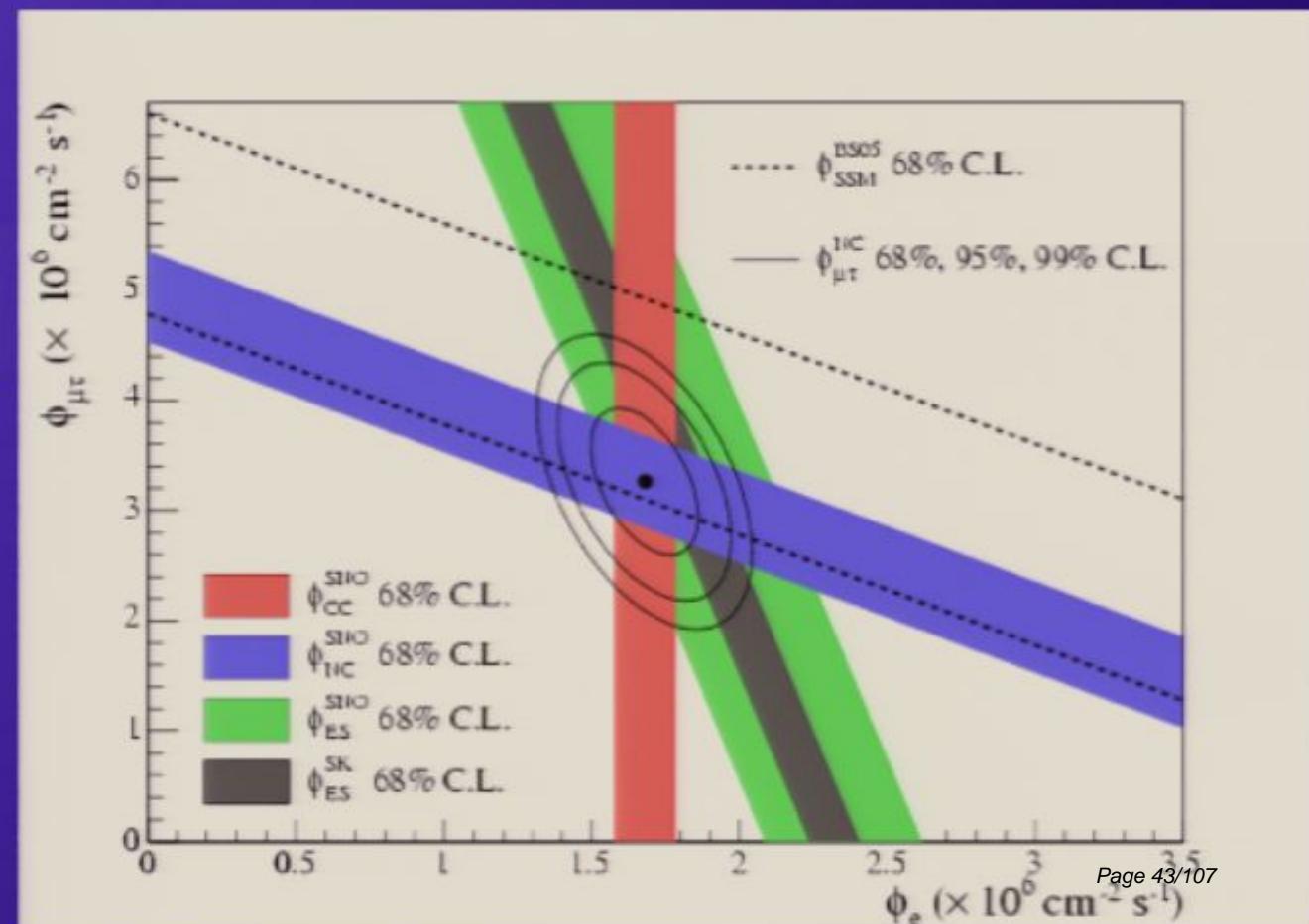
$$\phi_{CC} = 1.68 \quad {}^{+0.06}_{-0.06} (\text{stat.}) \quad {}^{+0.08}_{-0.09} (\text{syst.})$$

$$\phi_{NC} = 4.94 \quad {}^{+0.21}_{-0.21} (\text{stat.}) \quad {}^{+0.38}_{-0.34} (\text{syst.})$$

$$\phi_{ES} = 2.35 \quad {}^{+0.22}_{-0.22} (\text{stat.}) \quad {}^{+0.15}_{-0.15} (\text{syst.})$$

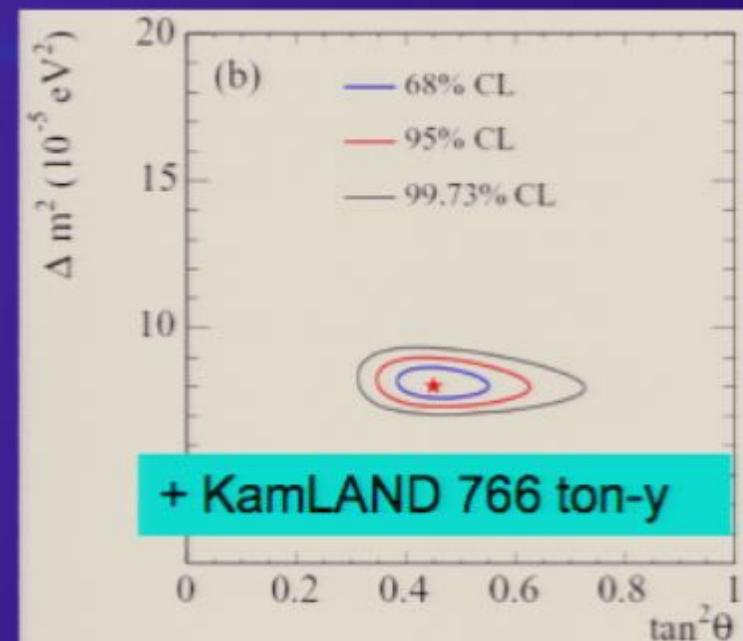
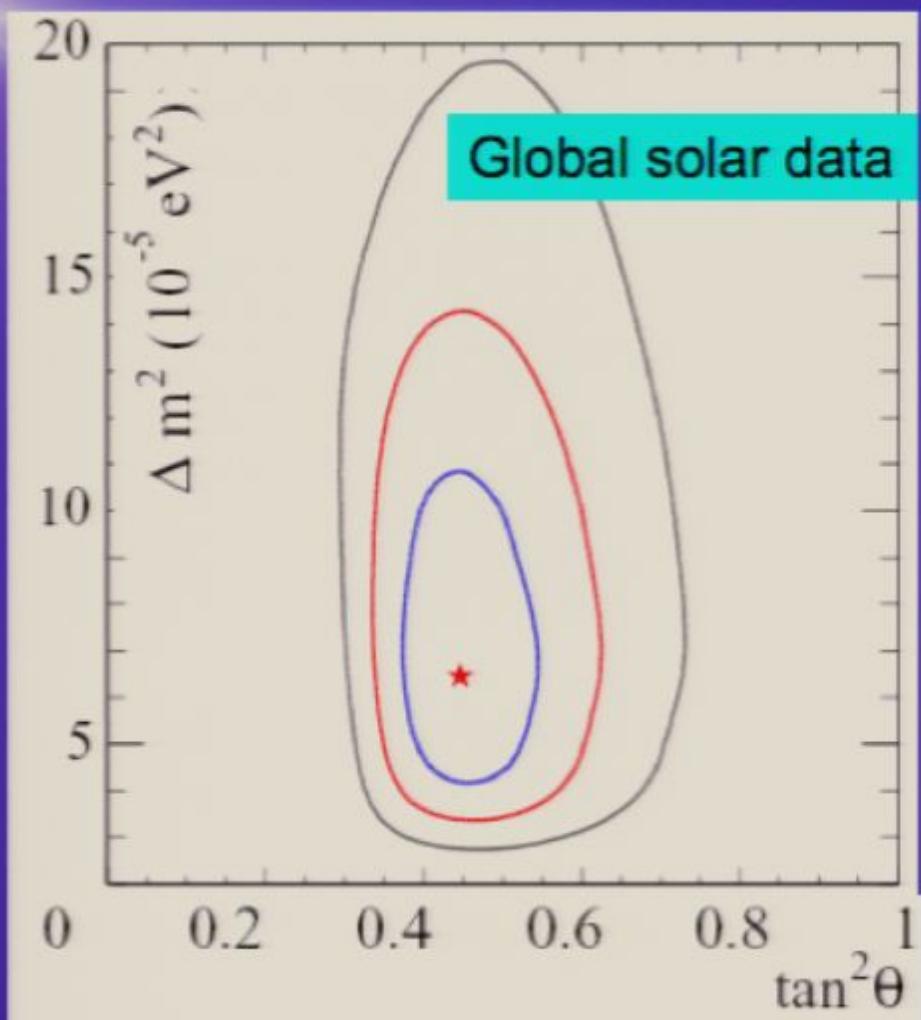
(In units of  
 $10^6 \text{ cm}^{-2} \text{s}^{-1}$ )

$$\begin{aligned}\phi_{CC} &= 0.340 \pm 0.023 (\text{stat.}) \quad {}^{+0.029}_{-0.031} \\ \phi_{NC} &\end{aligned}$$





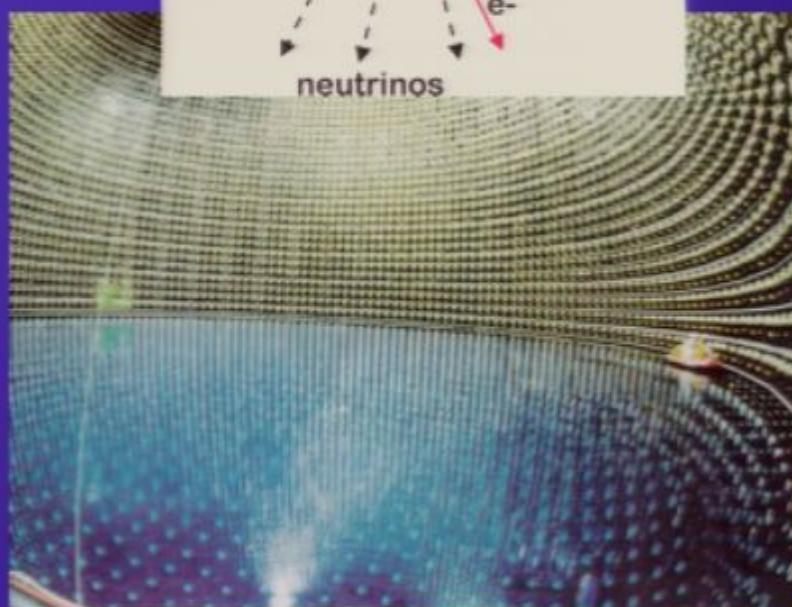
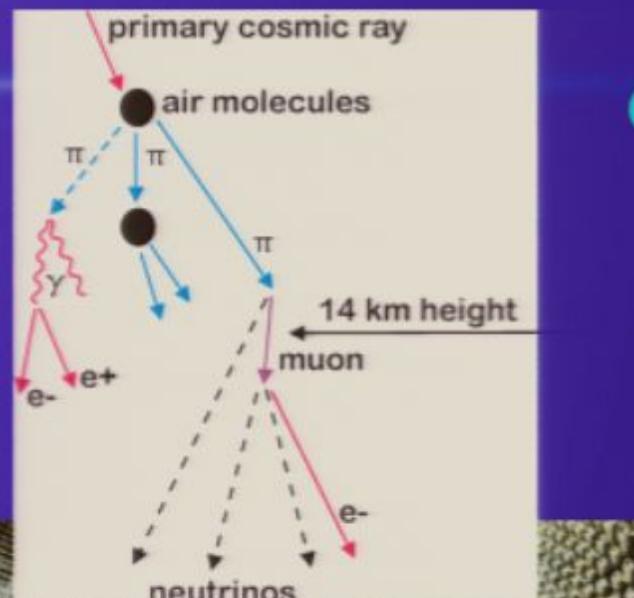
## SNO data fixes $\theta$ , KamLAND fixes $\Delta m^2$



$$\begin{aligned}\Delta m^2 &= 8.0^{+0.6}_{-0.4} \times 10^{-5} \text{ eV}^2 \\ \theta &= 33.9^{+2.4}_{-2.2} \text{ degrees}\end{aligned}$$



# Atmospheric neutrinos



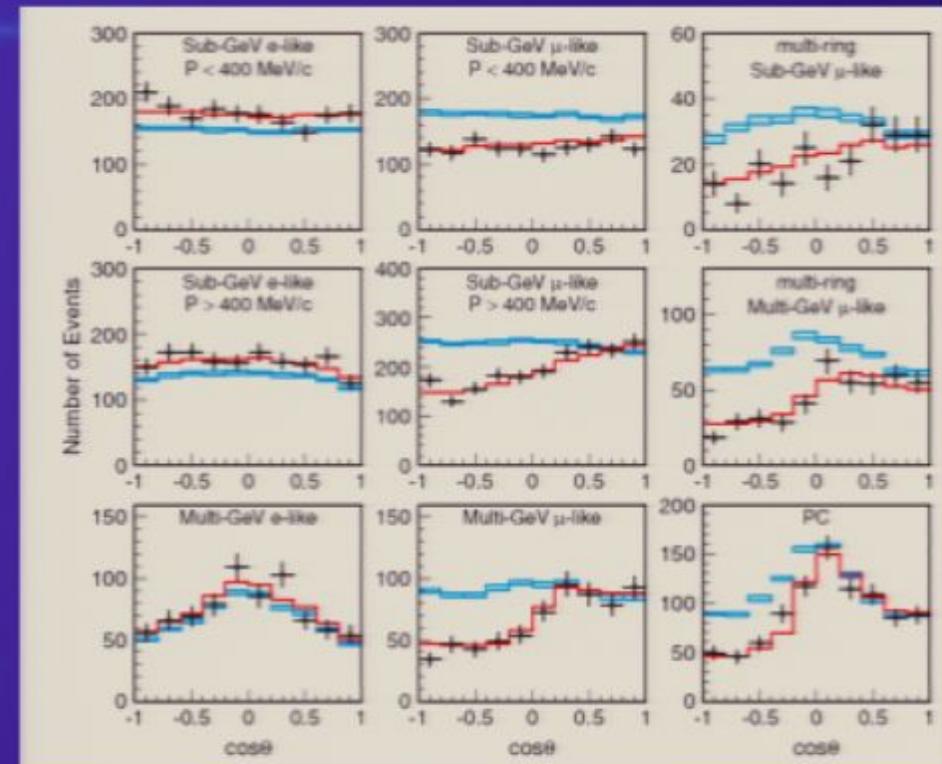
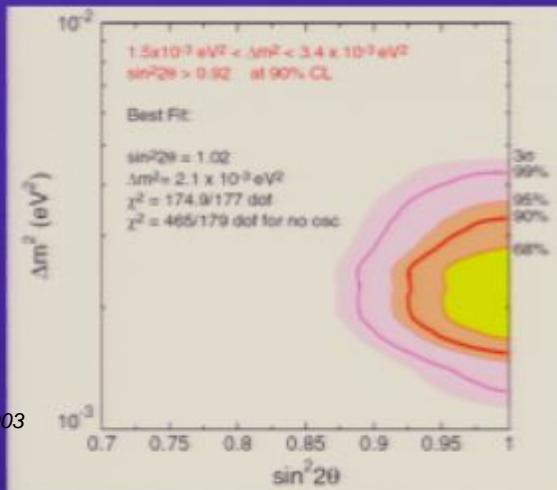
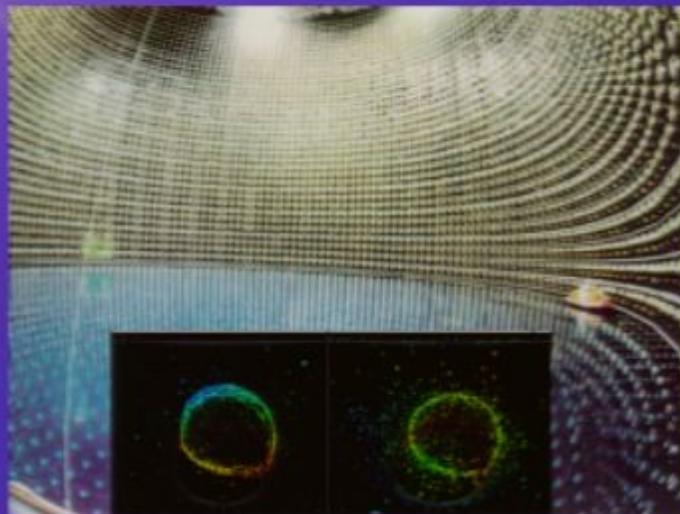
Cosmic proton beam

Target = N, O

$$\nu_\mu, \nu_e$$



# SK-Zenith angle dependence



Deficit in upward going muons



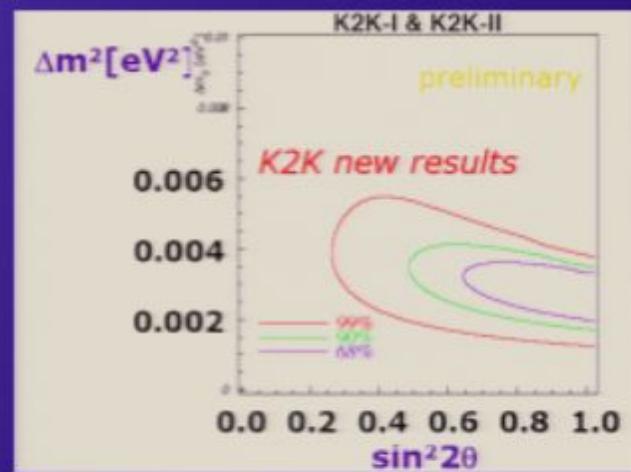
# K2K



Analysis based on  $8.9 \times 10^{19}$  pot

Best fit value in physical region :  $\sin^2 2\theta = 1.00$  ,  $\Delta m^2 = 2.73 \times 10^{-3} \text{ eV}^2$

K2K-alll (K2K-I, K2K-II)	DATA (K2K-I, K2K-II)	MC (K2K-I, K2K-II)
FC 22.5kt	<b>108</b> (56, 52)	<b>150.9</b> (79.1*, 71.8)
1ring	<b>66</b> (32, 34)	<b>93.7</b> (48.6, 45.1 )
$\mu$ -like for $E_{rec}$	<b>57 (56)</b> (30, 27)	<b>84.8</b> (44.3, 40.5)
e-like	<b>9</b> (2, 7)	<b>8.8</b> (4.3, 4.5)
Multi Ring	<b>42</b> (24, 18)	<b>57.2</b> (30.5, 26.7)



Oscillations confirmed at  $3.9 \sigma$



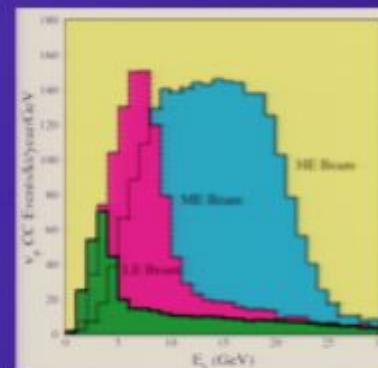
# MINOS



732 km

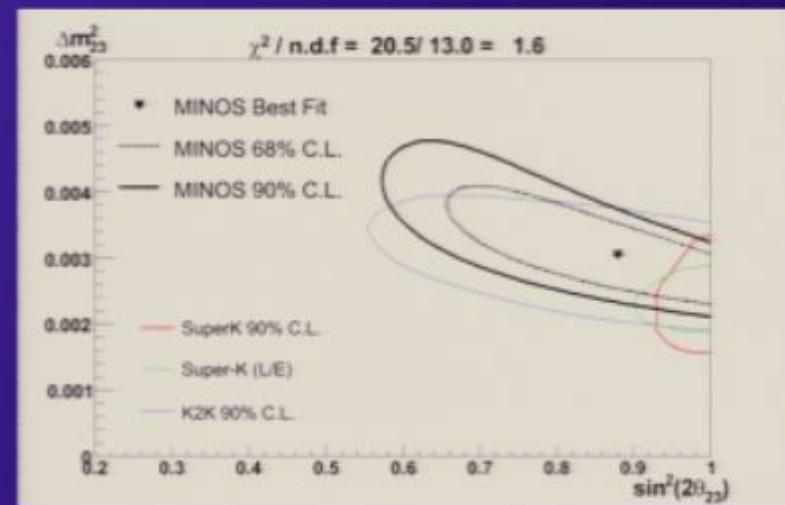


5.4 kt magnetized  
iron spectrometer



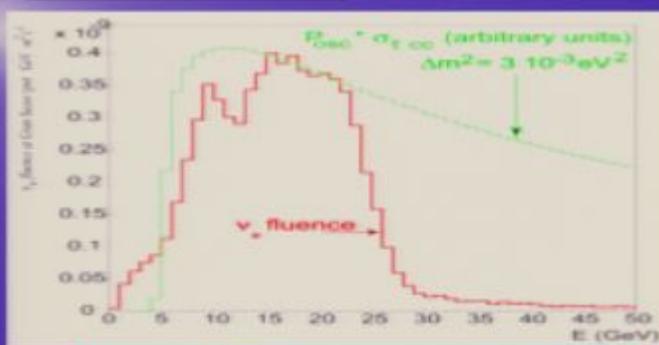
Near detector under  
construction

First results  
(last week)



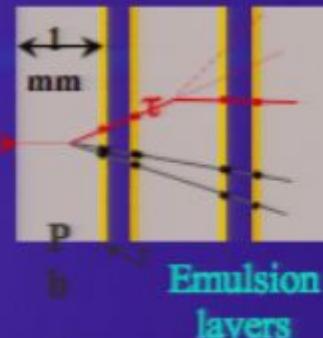


# CERN - Gran Sasso (CNGS)

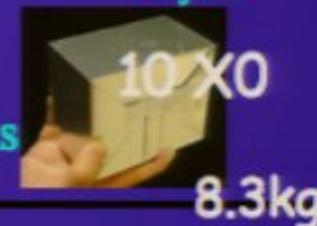


OPERA

lead-emulsion  
sandwich



about 206 000 blocks



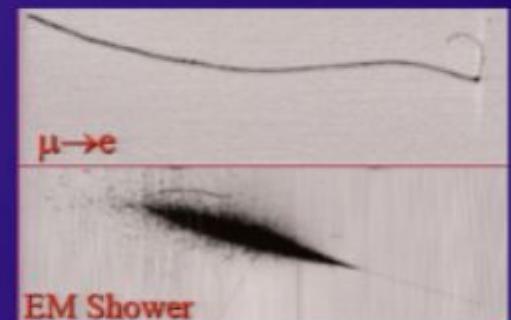
ICARUS

LAr TPC

T 600  
at LNGS



(electronic bubble chamber)

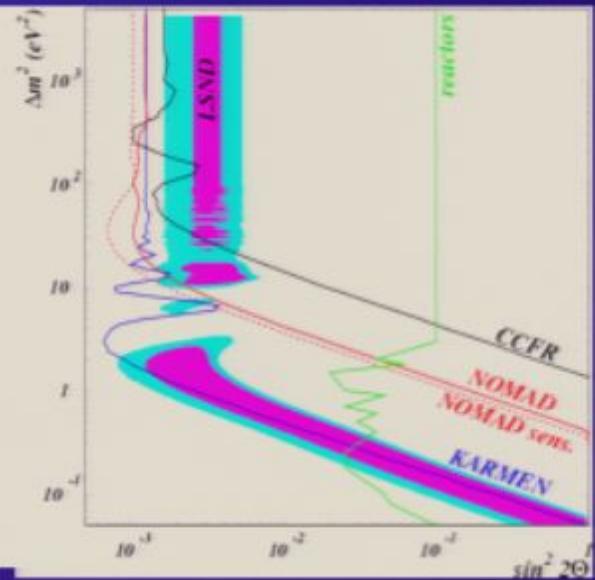
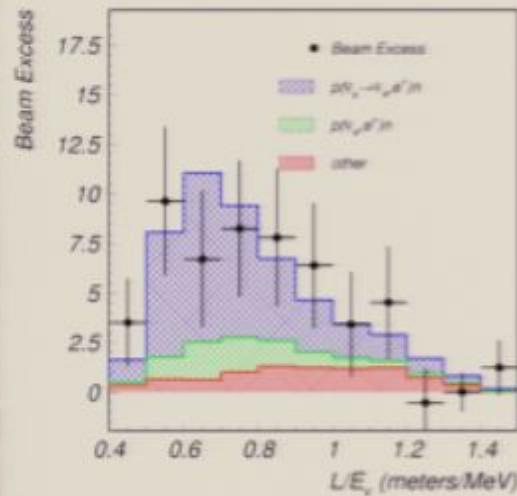
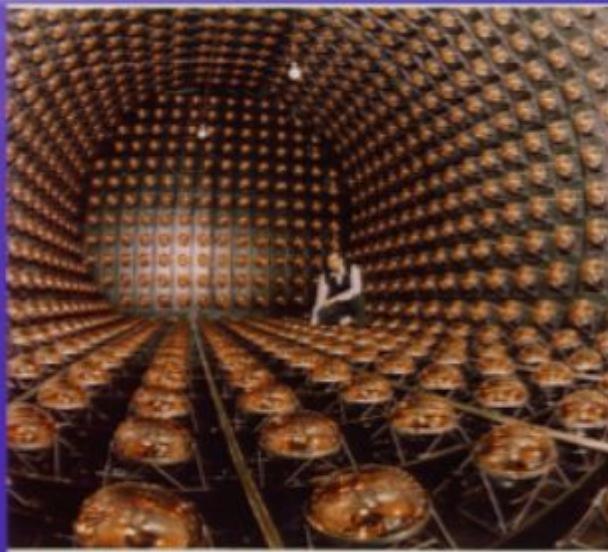


Beam this year

Expect about a dozen  $\tau$ -events in both experiments



# The LSND Evidence



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

A. Aguilar et al,  
PRD 64, 112007 (2001)

$87.9 \pm 22.4 \pm 6.0$  events  
above background, about  
 $4\sigma$  evidence

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = \\ (0.264 \pm 0.067 \pm 0.045)\%$$

Most of allowed parameters  
in contradiction with  
KARMEN and NOMAD

Combined analysis of  
KARMEN and LSND  
(E.D. Church et al,  
PRD 66, 013001 (2002))



# Oscillation evidences

depends on  $\Delta m^2 = m_2^2 - m_1^2$  No absolute mass measurement

LSND

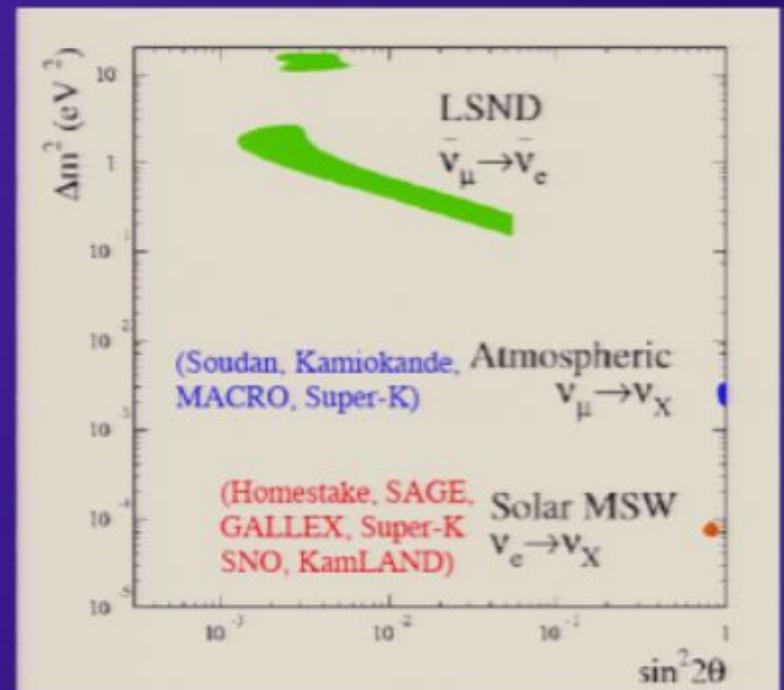
$$\sin^2 2\theta = 10^{-1} - 10^{-3}, \Delta m^2 = 0.1 - 6 \text{ eV}^2$$

Atmospheric

$$\sin^2 2\theta = 1.00, \Delta m^2 = 2.1 \times 10^{-3} \text{ eV}^2$$

Solar + reactors

$$\sin^2 2\theta = 0.81, \Delta m^2 = 8.2 \times 10^{-5} \text{ eV}^2$$



If all three are correct... we need more (sterile ones)



# Oscillation evidences

depends on

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

No absolute mass measurement

LSND

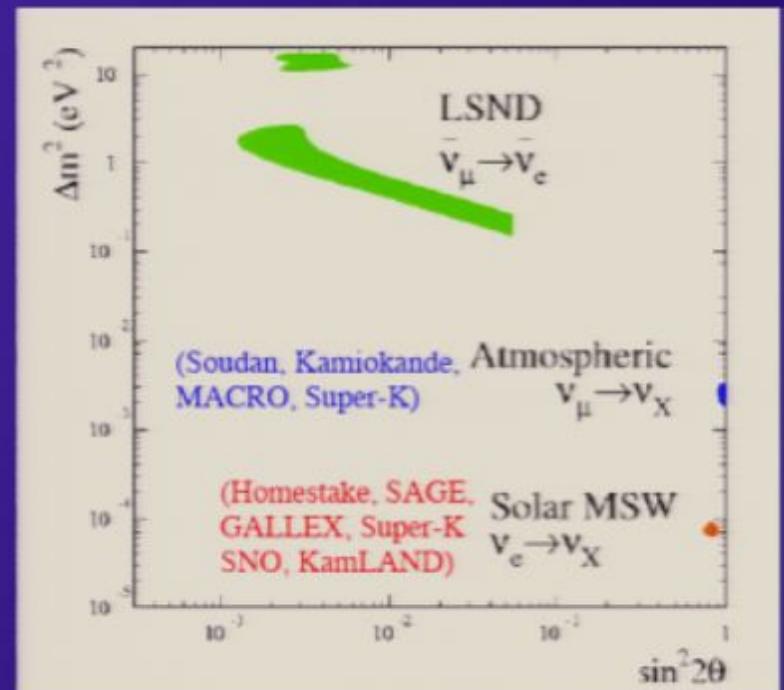
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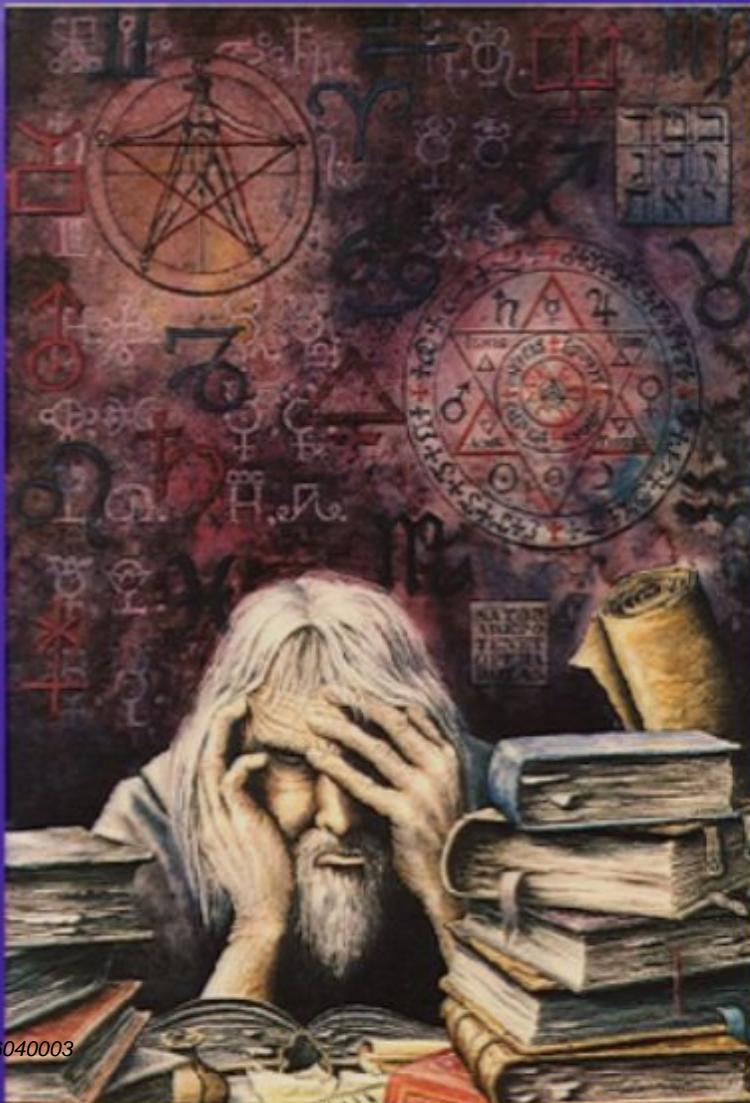
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# Contents

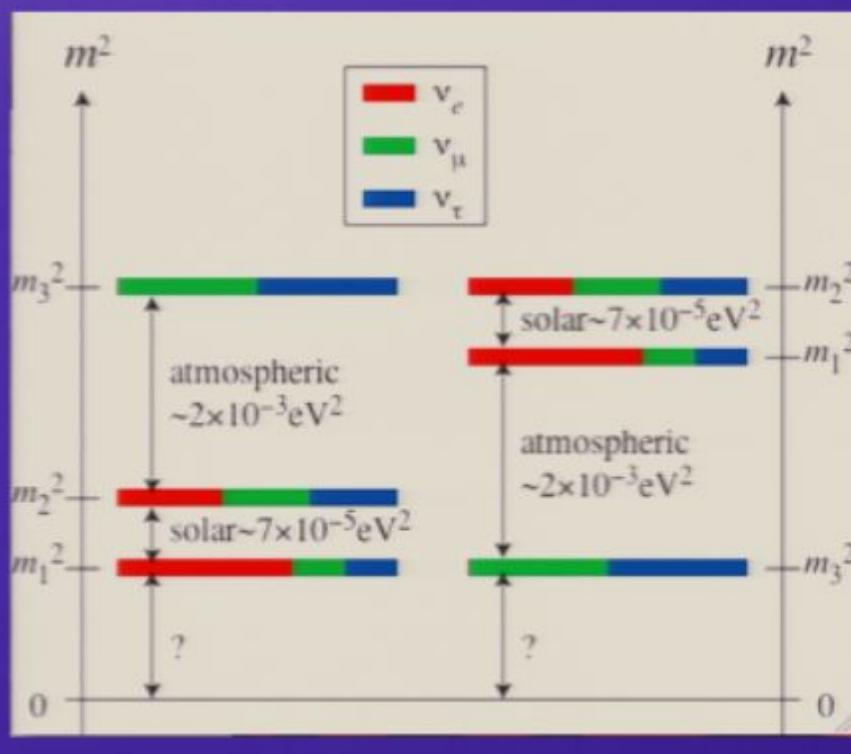


- Introduction
- Solar neutrinos and the Sudbury Neutrino Observatory (SNO)
- Double beta decay and the COBRA experiment
- Outlook and summary



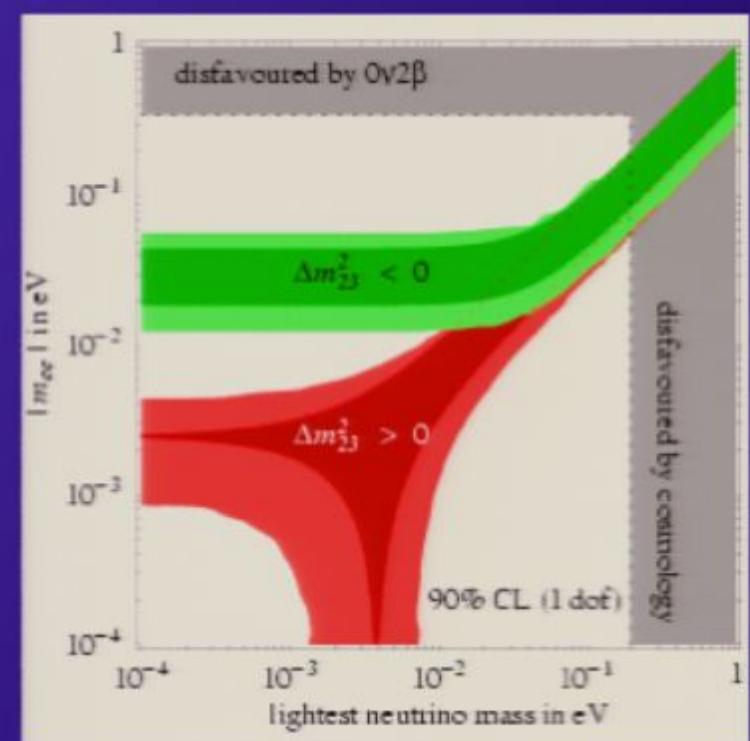
# Neutrino mass schemes

- almost degenerate neutrinos  $m_1 \approx m_2 \approx m_3$
- hierarchical neutrino mass schemes



normal

inverted



Benchmark number to discriminate  
between hierarchical models:  $m = 50 \text{ meV}$



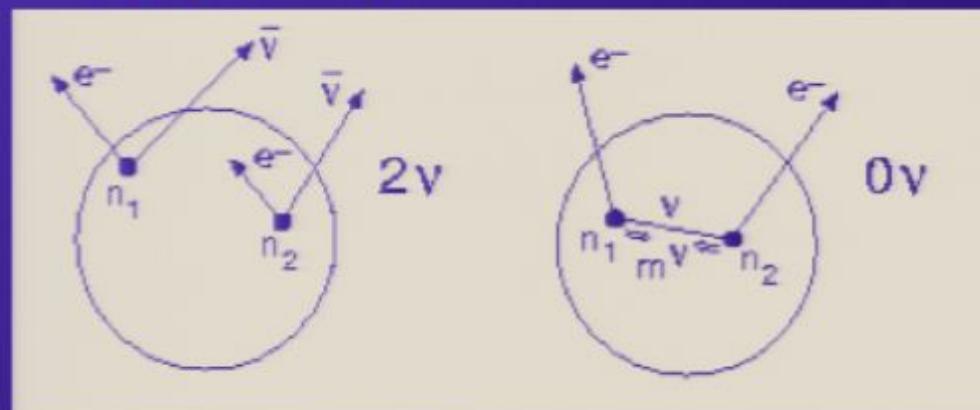
# Beta and double beta decay

## Beta decay

- $(A, Z) \rightarrow (A, Z+1) + e^- + \bar{\nu}_e$   **$\beta$ -decay**
- $n \rightarrow p + e^- + \bar{\nu}_e$

## Double beta decay

- $(A, Z) \rightarrow (A, Z+2) + 2 e^- + 2\bar{\nu}_e$   **$2\nu\beta\beta$**
- $(A, Z) \rightarrow (A, Z+2) + 2 e^-$   **$0\nu\beta\beta$**



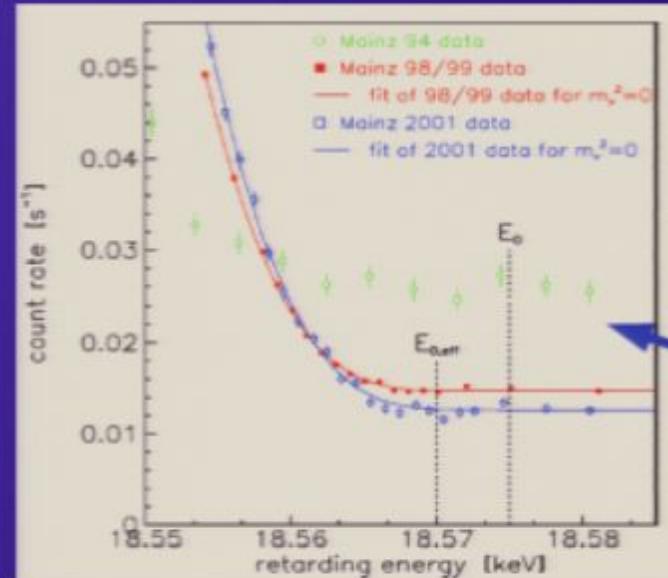
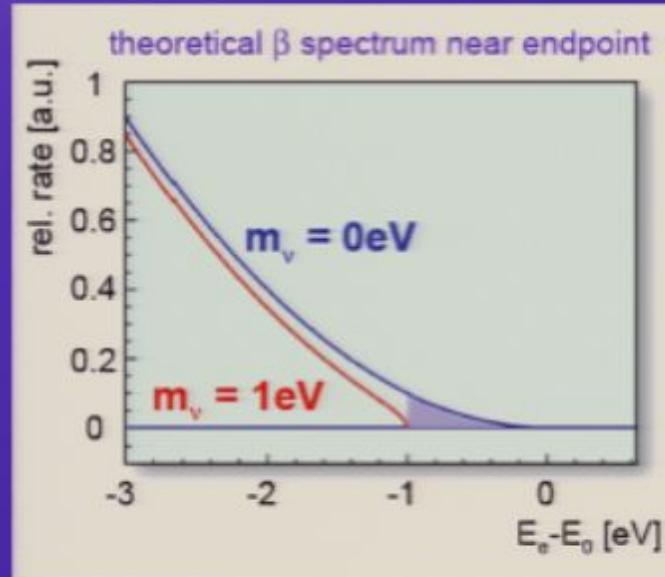


# Beta decay - Current status ( ${}^3\text{H}$ )

## Electron energy spectrum

$$\frac{dN}{dE} = K \cdot F(E, Z) \cdot p \cdot E_{\text{tot}} \cdot (E_0 - E_e) \cdot \sum |U_{eii}|^2 [ (E_0 - E_e)^2 - m(v_i)^2 ]^{1/2}$$

Theory



Mainz:  $m_{\nu e} < 2.3\text{ eV}$  (95% CL)

Troitsk:  $m_{\nu e} < 2.05\text{ eV}$  (95% CL)

C. Kraus et al., Eur. Phys. J. C 40, 447 (2005)

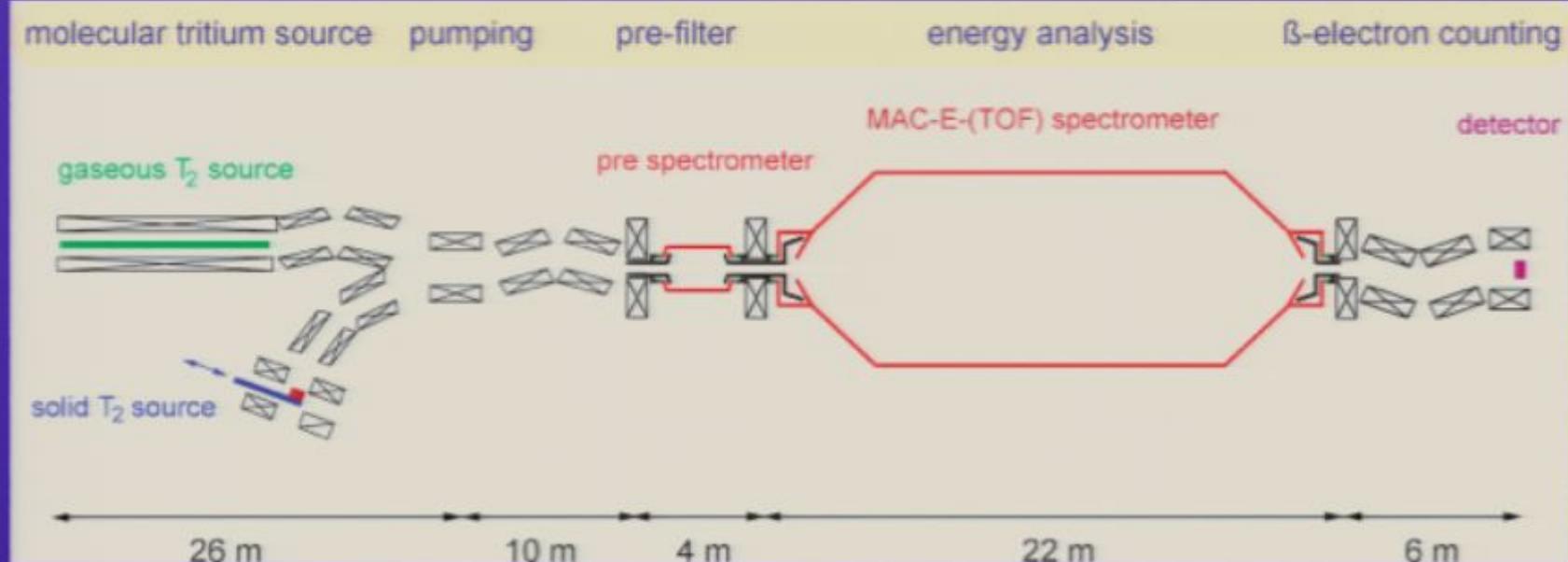
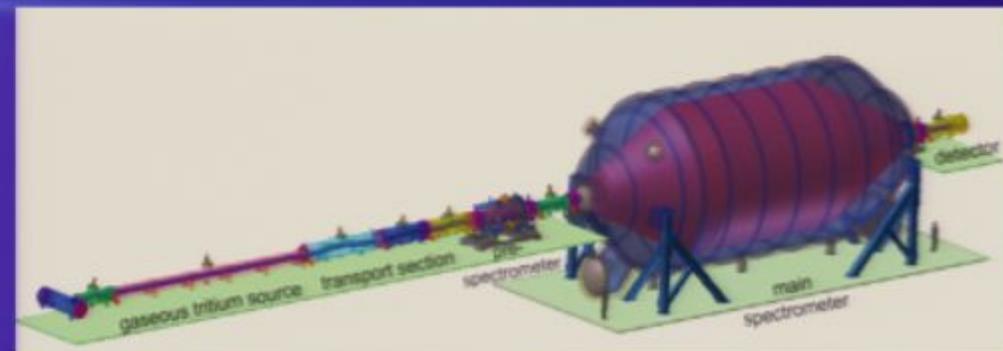
V. M. Lobashev, Nucl. Phys. A 719, 153c (2003)

Alternative approach:  ${}^{187}\text{Re}$  cryogenic bolometers (bounds 15-26 eV)



# KATRIN-

## The ultimate beta-decay experiment



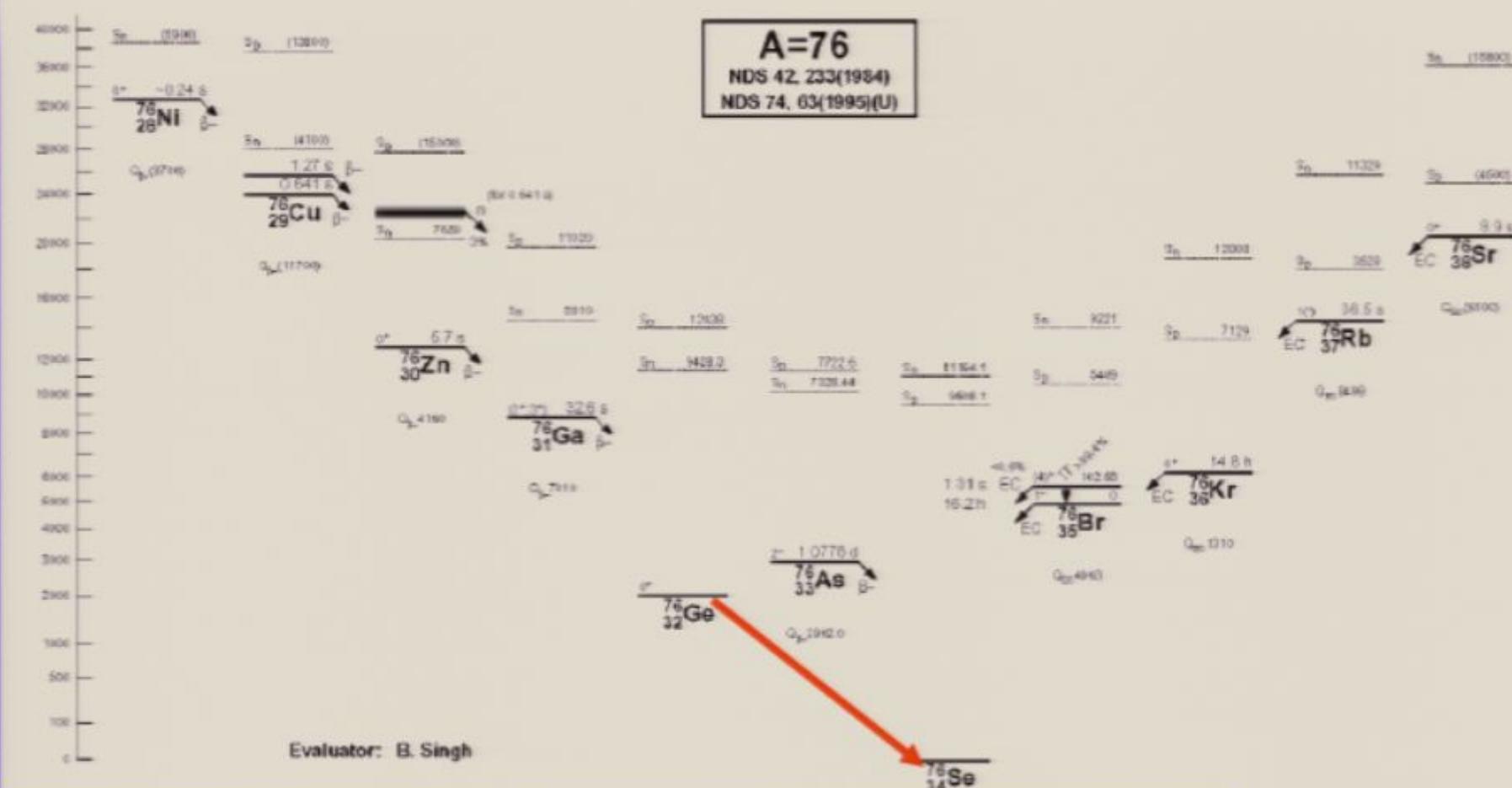
Discovery potential  $m_{\nu_e} = 0.35 \text{ eV}$  at  $5\sigma$

Sensitivity  $m_{\nu_e} < 0.2 \text{ eV}$  (90% CL)

Commissioning in 2008



# Example - Ge76



Neutrinoless mode requires: a) Neutrinos are Majorana particles  
b) a non-vanishing mass



# Phase space

$0\nu\beta\beta$  decay rate scales with  $Q^5$

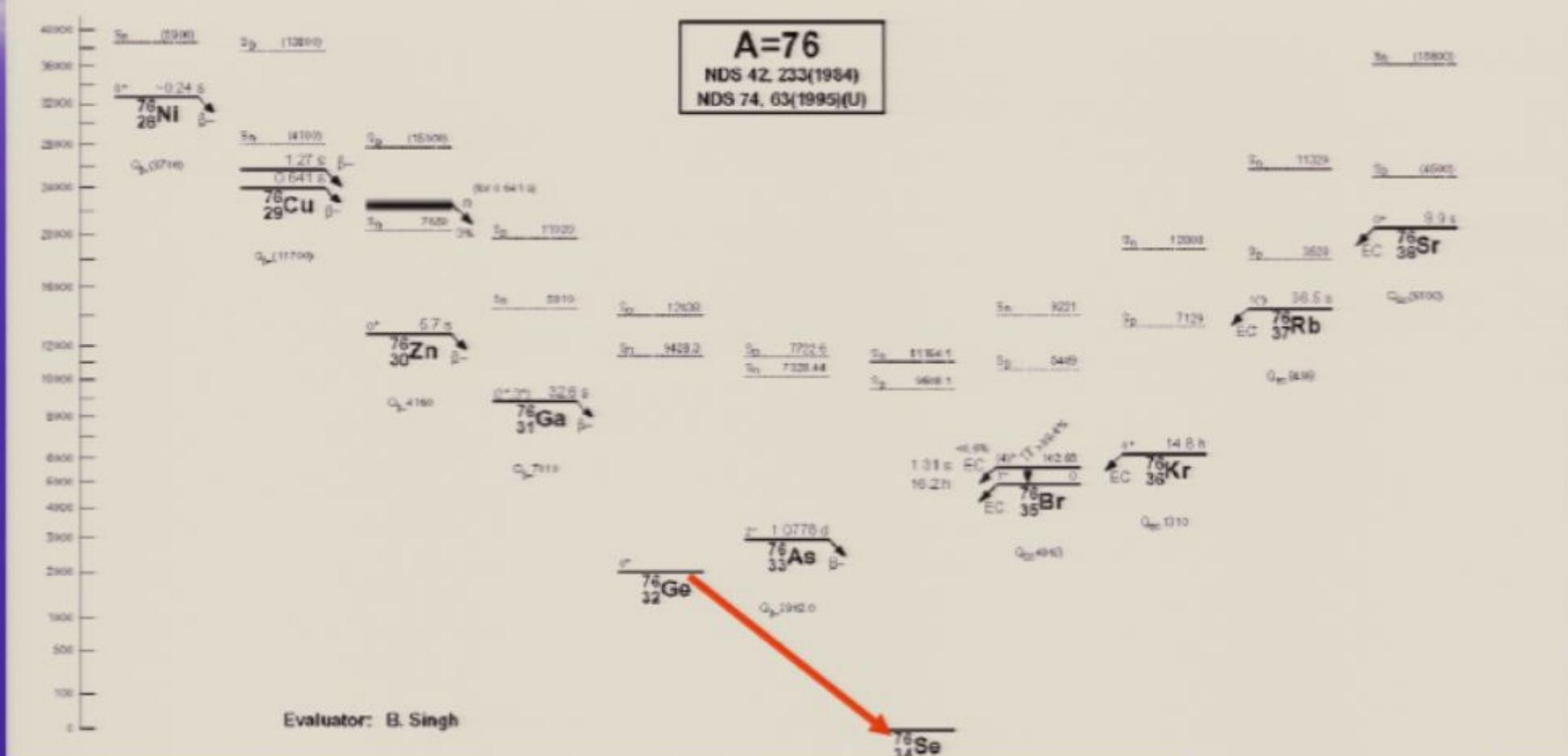
$2\nu\beta\beta$  decay rate scales with  $Q^{11}$

<i>Isotope</i>	<i>Q-value (keV)</i>	<i>Nat. abund. (%)</i>	$(PS \ 0\nu)^{-1}$ $(\text{yrs} \times eV^2)$	$(PS \ 2\nu)^{-1}$ (yrs)
----------------	--------------------------	----------------------------	--	-----------------------------

<b>Ca 48</b>	<b>4271</b>	<b>0.187</b>	<b>4.10E24</b>	<b>2.52E16</b>
<b>Ge 76</b>	<b>2039</b>	<b>7.8</b>	<b>4.09E25</b>	<b>7.66E18</b>
<b>Se 82</b>	<b>2995</b>	<b>9.2</b>	<b>9.27E24</b>	<b>2.30E17</b>
<b>Zr 96</b>	<b>3350</b>	<b>2.8</b>	<b>4.46E24</b>	<b>5.19E16</b>
<b>Mo 100</b>	<b>3034</b>	<b>9.6</b>	<b>5.70E24</b>	<b>1.06E17</b>
<b>Pd 110</b>	<b>2013</b>	<b>11.8</b>	<b>1.86E25</b>	<b>2.51E18</b>
<b>Cd 116</b>	<b>2802</b>	<b>7.5</b>	<b>5.28E24</b>	<b>1.25E17</b>
<b>Sn 124</b>	<b>2288</b>	<b>5.64</b>	<b>9.48E24</b>	<b>5.93E17</b>
<b>Te 130</b>	<b>2529</b>	<b>34.5</b>	<b>5.89E24</b>	<b>2.08E17</b>
<b>Xe 136</b>	<b>2479</b>	<b>8.9</b>	<b>5.52E24</b>	<b>2.07E17</b>
<b>Nd 150</b>	<b>3367</b>	<b>5.6</b>	<b>1.25E24</b>	<b>8.41E15</b>



# Example - Ge76



Neutrinoless mode requires: a) Neutrinos are Majorana particles  
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$2\nu\beta\beta$  decay rate scales with  $Q^{11}$

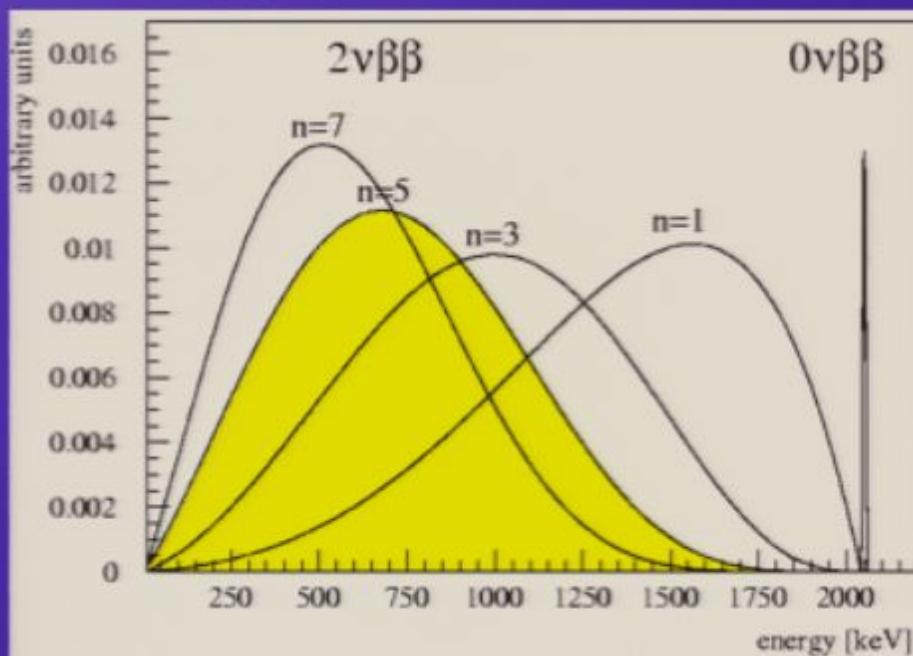
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# Spectral shapes

$0\nu\beta\beta$ : Peak at Q-value of nuclear transition



Sum energy spectrum of both electrons

Measured quantity: Half-life

Dependencies (BG limited)

$$T_{1/2} \propto a \cdot \epsilon \cdot (M \cdot t / \Delta E \cdot B)^{1/2}$$

link to neutrino mass

$$1/T_{1/2} = PS * ME^2 * (m_\nu / m_e)^2$$

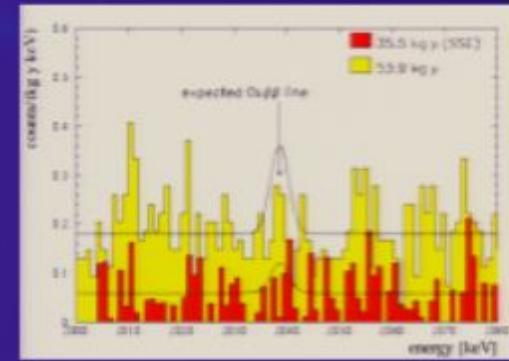
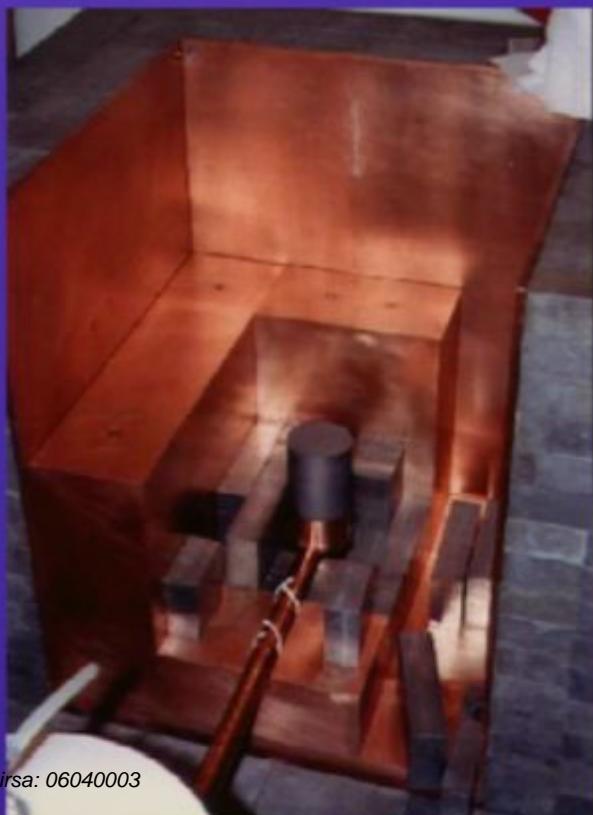
Nuclear physics  
input needed !



# Heidelberg -Moscow

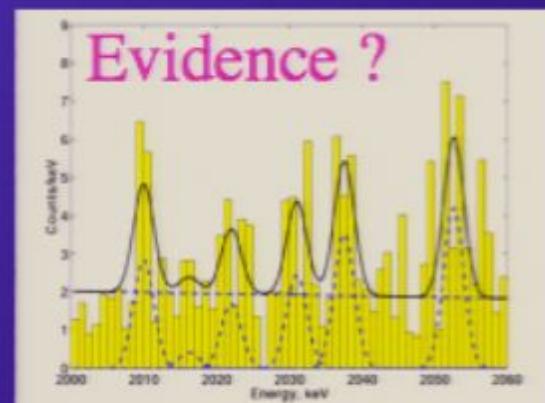


- Five Ge Diodes (mass 10.9 kg)  
Isotopically enriched ( 86%) in  $^{75}\text{Ge}$   
lead shield and nitrogen purging  
Peak at 2039 keV



H.V. Klapdor-Kleingrothaus et al,  
Europ. Phys. J. A 12, 147 (2001)

$$T_{1/2} > 1.9 \times 10^{25} \text{ yr} \text{ (90\% CL)} \rightarrow m < 0.35 \text{ eV}$$



Subgroup of collaboration

$$T_{1/2} = 0.6 - 8.4 \times 10^{25} \text{ yr} \rightarrow m = 0.17 - 0.63 \text{ eV}$$

H.V. Klapdor-Kleingrothaus et al,  
Phys. Lett. B 586, 198 (2004)



# COBRA

Use large amount of  
CdZnTe  
Semiconductor Detectors



Array of  $1\text{cm}^3$   
CdZnTe detectors



## Advantages

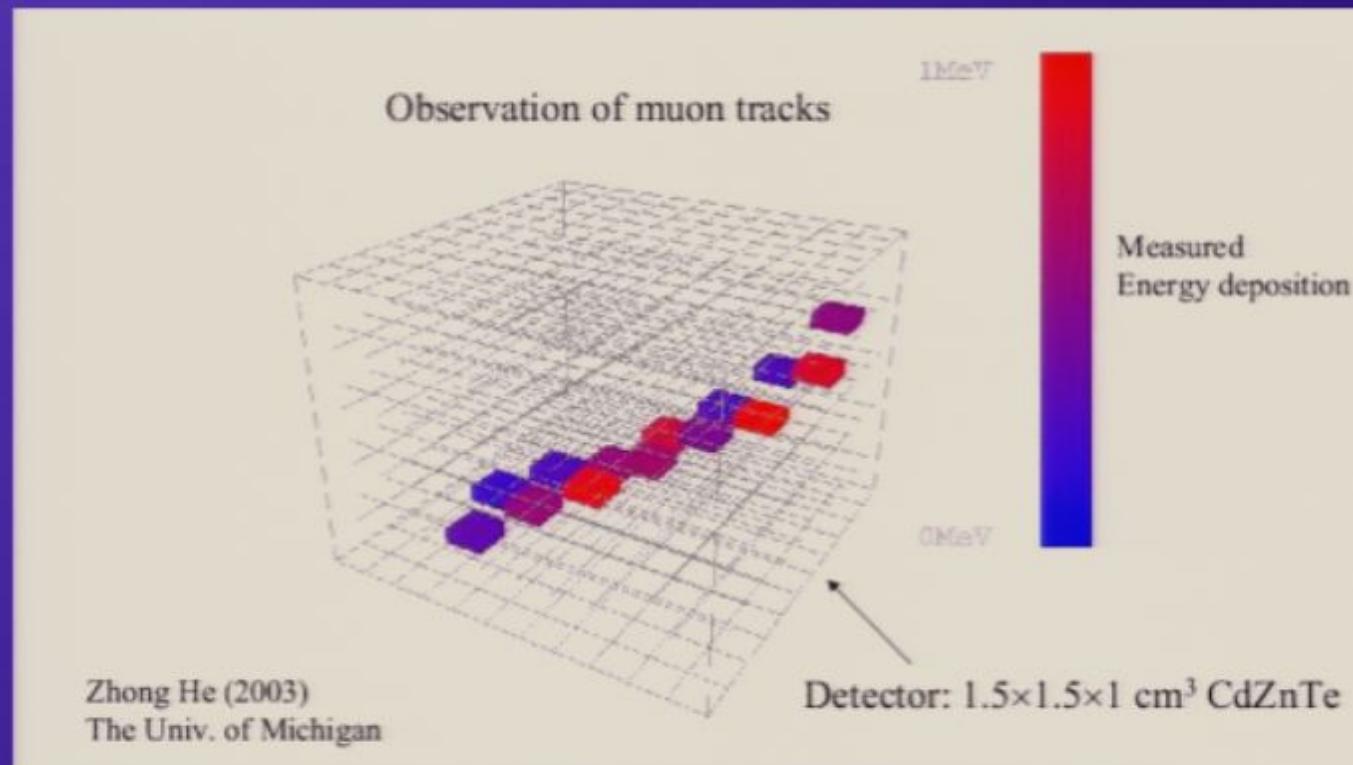
- Source = detector
- Semiconductor (Good energy resolution, clean)
- Room temperature (safety)
- Modular design (Coincidences)
- Two isotopes at once
- Industrial development of CdTe detectors
  - $^{116}\text{Cd}$  above 2.614 MeV
- Tracking („Solid state TPC“)

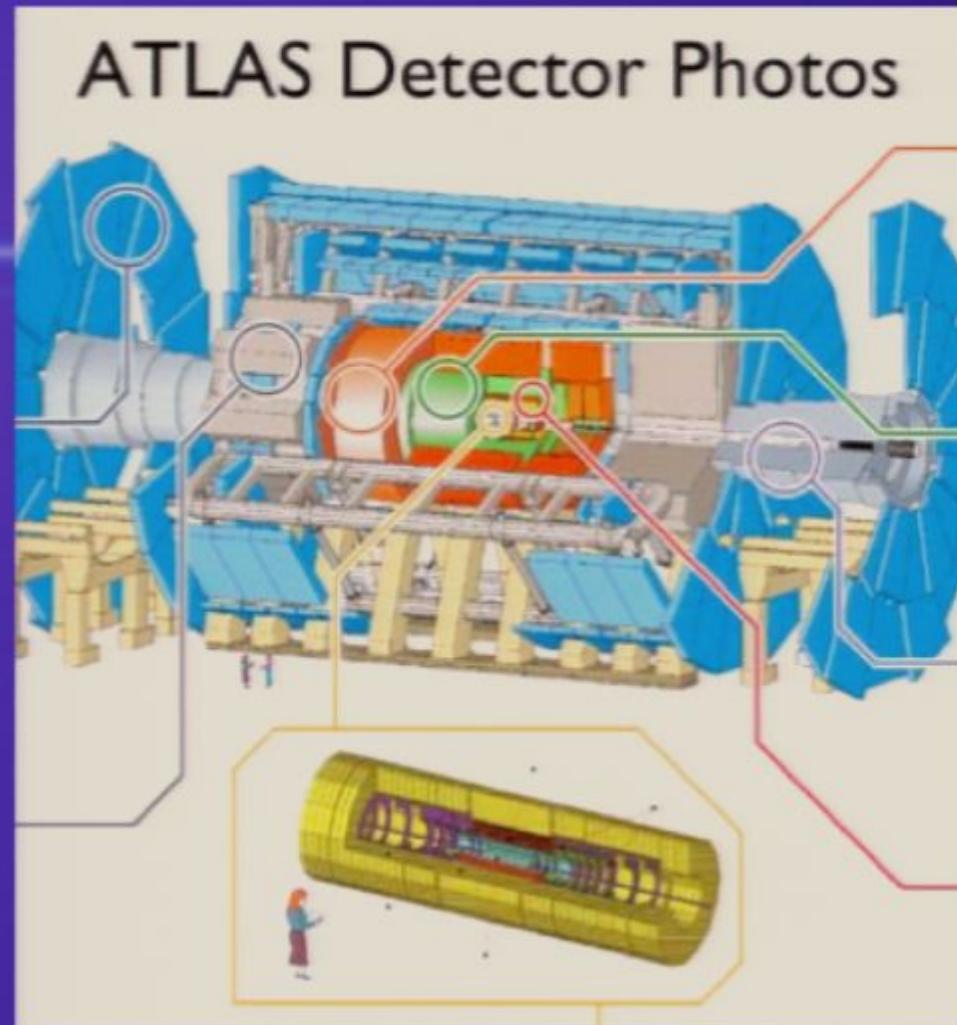


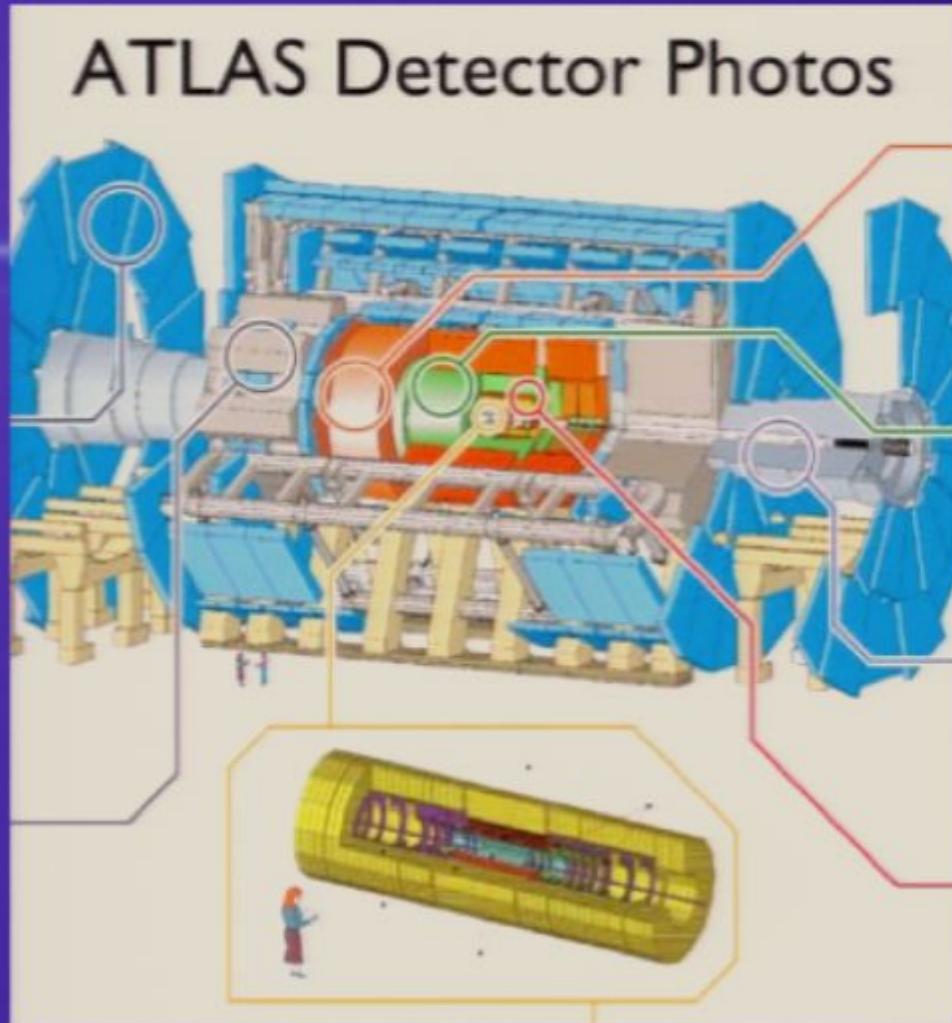
# Pixellated detectors

## Solid state TPC

### 3D - Pixelisation:







**Nobody said it was going to be easy, and nobody was right**

**George W. Bush**



## Back of the envelope

$$T_{1/2} = \ln 2 \cdot a \cdot N_A \cdot M \cdot t / N_{\beta\beta} \quad (\tau \gg T) \quad (\text{Background free})$$

50 meV implies half-life measurements of  $10^{26-27}$  yrs  
1 event/yr you need  $10^{26-27}$  source atoms

This is about 1000 moles of isotope, implying 100 kg

Now you only can loose: nat. abundance, efficiency, background, ...



# Future projects



CARVEL	Ca-48	100 kg $^{48}\text{CaWO}_4$ crystal scintillators
COBRA	Te-130	10 kg CdTe semiconductors
DCBA	Nd-150	20 kg Nd layers between tracking chambers
NEMO	Mo-100, Various	10 kg of $\beta\beta$ isotopes (7 kg of Mo), expand to superNEMO
CAMEO	Cd-114	1 t $\text{CdWO}_4$ crystals
CANDLES	Ca-48	Several tons $\text{CaF}_2$ crystals in liquid scint.
CUORE	Te-130	750 kg $\text{TeO}_2$ bolometers
EXO	Xe-136	1 ton Xe TPC (gas or liquid)
GEM	Ge-76	1 ton Ge diodes in liquid nitrogen
GENIUS	Ge-76	1 ton Ge diodes in liquid nitrogen
GERDA	Ge-76	~30-40 kg Ge diodes in LN, expand to larger masses
GSO	Gd-160	2 t $\text{Gd}_2\text{SiO}_5:\text{Ce}$ crystal scint. in liquid scint.
Majorana	Ge-76	~180 kg Ge diodes, expand to larger masses
MOON	Mo-100	Mo sheets between plastic scint., or liq. scint.
Xe	Xe-136	1.56 t of Xe in liq. Scint.
XMASS	Xe-136	10 t of liquid Xe

small scale ones will expand, very likely not a complete list...



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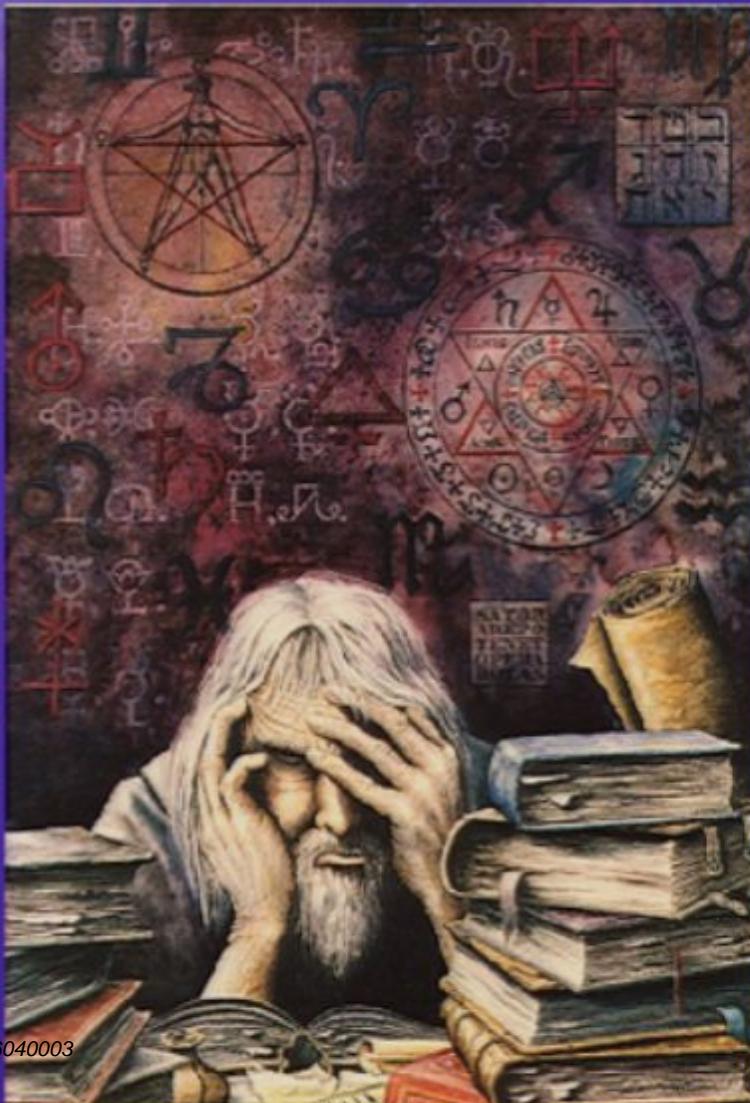


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# Contents



- Introduction
- Solar neutrinos and the Sudbury Neutrino Observatory (SNO)
- Double beta and the COBRA experiment
- Outlook and summary



## The twofold way....

- Precision determination of mixing matrix elements (PMNS), CP violation
- Absolute neutrino mass measurement





## Where do we go - Masses

- KATRIN beta decay experiment, start 2008, sensitivity down to 0.2 eV
- Improved cosmological data (CMB, new large scale-structure surveys)
- Neutrinoless double beta decay

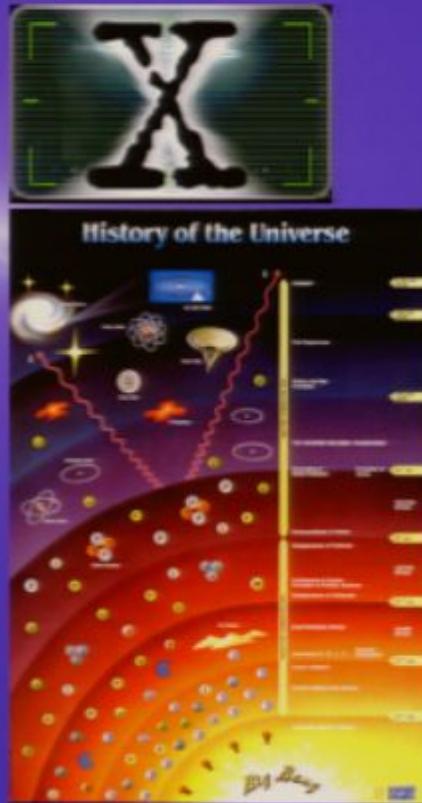


# Where do we go - Oscillations

- MINOS has just reported first results, more to come
- MiniBooNE is running, significant results in 2006
- CERN-Gran Sasso beam operational in 2006
- T2K approved, start in 2009, Nova pre-approved, start around 2009 possible
- High precision nuclear reactor experiment, start around 2008 possible (Double Chooz)
- Low energy real time solar neutrinos (Borexino, KamLand, SNO+,...)
- Superbeam, Beta-beams (under study)
- Ultimate accelerator project: The neutrino factory

# Apologies

and everything else I have not mentioned...



Neutrinos in  
Cosmology  
Relic 1.96 K  
neutrino  
background



UHE neutrinos

- Baikal
- Nestor
- Antares
- Amanda
- Icecube
- Auger

Supernova  
neutrinos

- Low energy  
real -time  
experiments
- Borexino
- KamLAND
- CLEAN
- Xmass
- LENS
- MOON

Precision  
measurements  
in vN scattering

- Weinberg  
angle
- Structure  
functions
- ...



# Summary

- Neutrino physics made major step forward in the last decade by establishing a non-vanishing rest mass
- Solar neutrino problem solved as being due to matter effects, with SNO as a major player, continues to be so, SNO+ would be an obvious straightforward follow-up
- Double beta decay is the gold plated channel to probe the fundamental character of neutrinos
- Taking current evidences from oscillation data it is likely to be the only way to fix the absolute neutrino mass
- COBRA rather new idea, but now a real existing experiment
- Several new projects in the future with the neutrino factory as the ultimate accelerator facility

# A lot to do ...



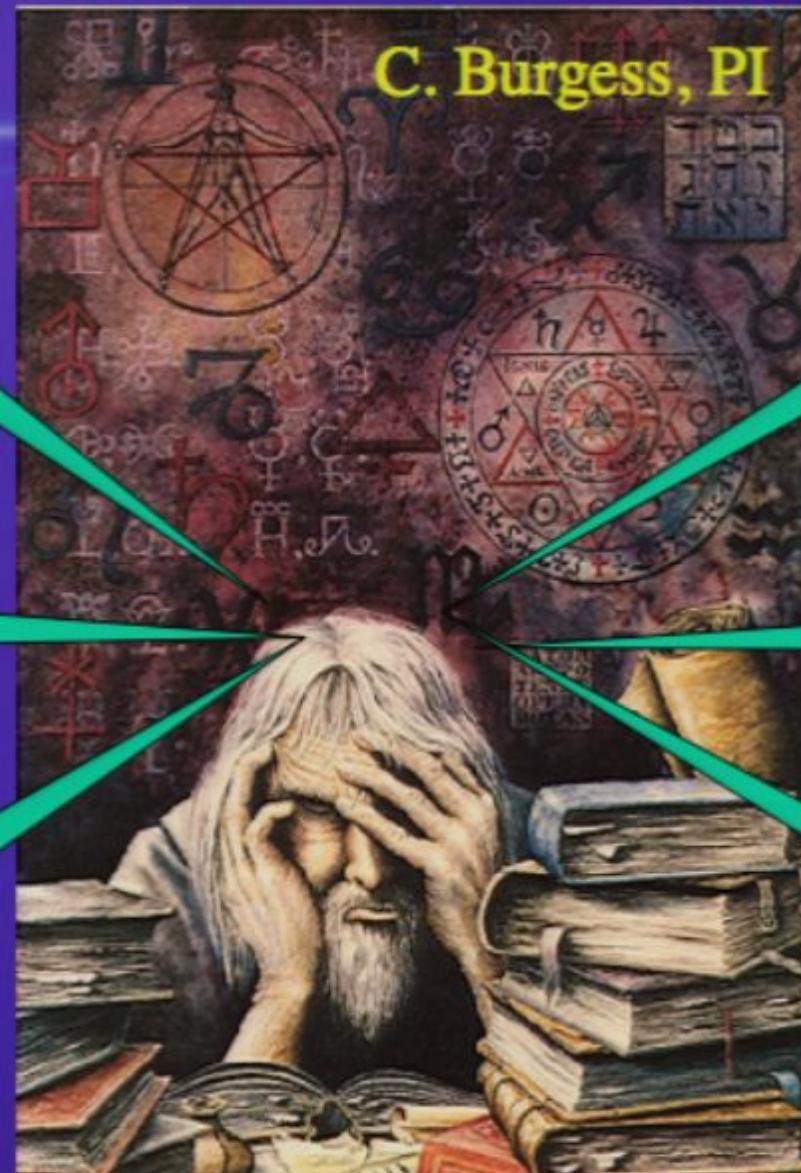
$\theta_{13}$

PMNS

$\beta\beta$ -decay

mass hierarchy

leptonic  
CPV



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46 47 48 49 50

46: 

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56 57 58 59 60

56: Where do we go - Masses

57: Where do we go - Oscillations

58: Apologies

59: Summary

60: A lot to do ...

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71 72 73 74 75

76 77 78 Superbeams Results

79 80

81 Neutrino factories 82 High Resolution L/E Analysis 83 Mainz and Troitsk 84 85

86 The neutrino program - II 87 The future - SNO+

Pisa: 06040003 Page 82/107

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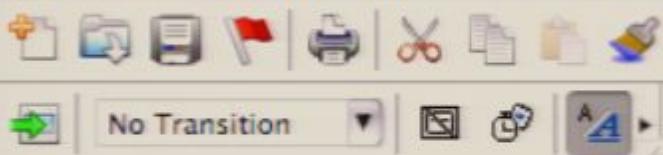
71 72 73 74 75

76 77 78 79 80

81 82 83 84 85

Pista: 06040003 Page 84/107

The presentation consists of 15 slides, each containing a screenshot of a software interface. The slides are numbered 66 through 85. The software interfaces show various types of data analysis and visualization, likely related to particle physics or similar scientific fields. The data includes plots of energy vs. time, signal information, radar data, and maps. The software interfaces have a purple background.



last.kumacold  
lfv

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66%

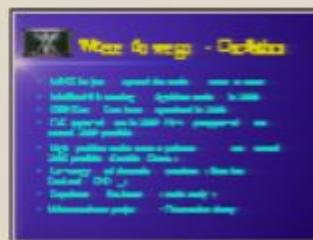


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56



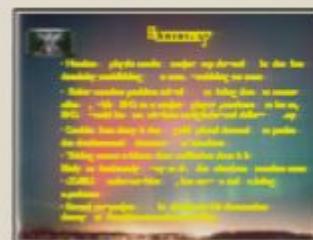
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58



59



60



61



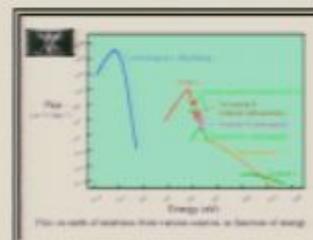
62



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67



68



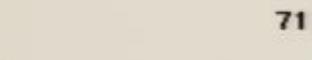
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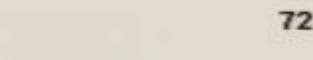
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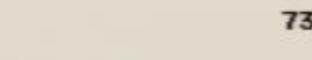
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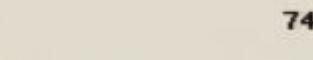
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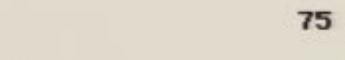
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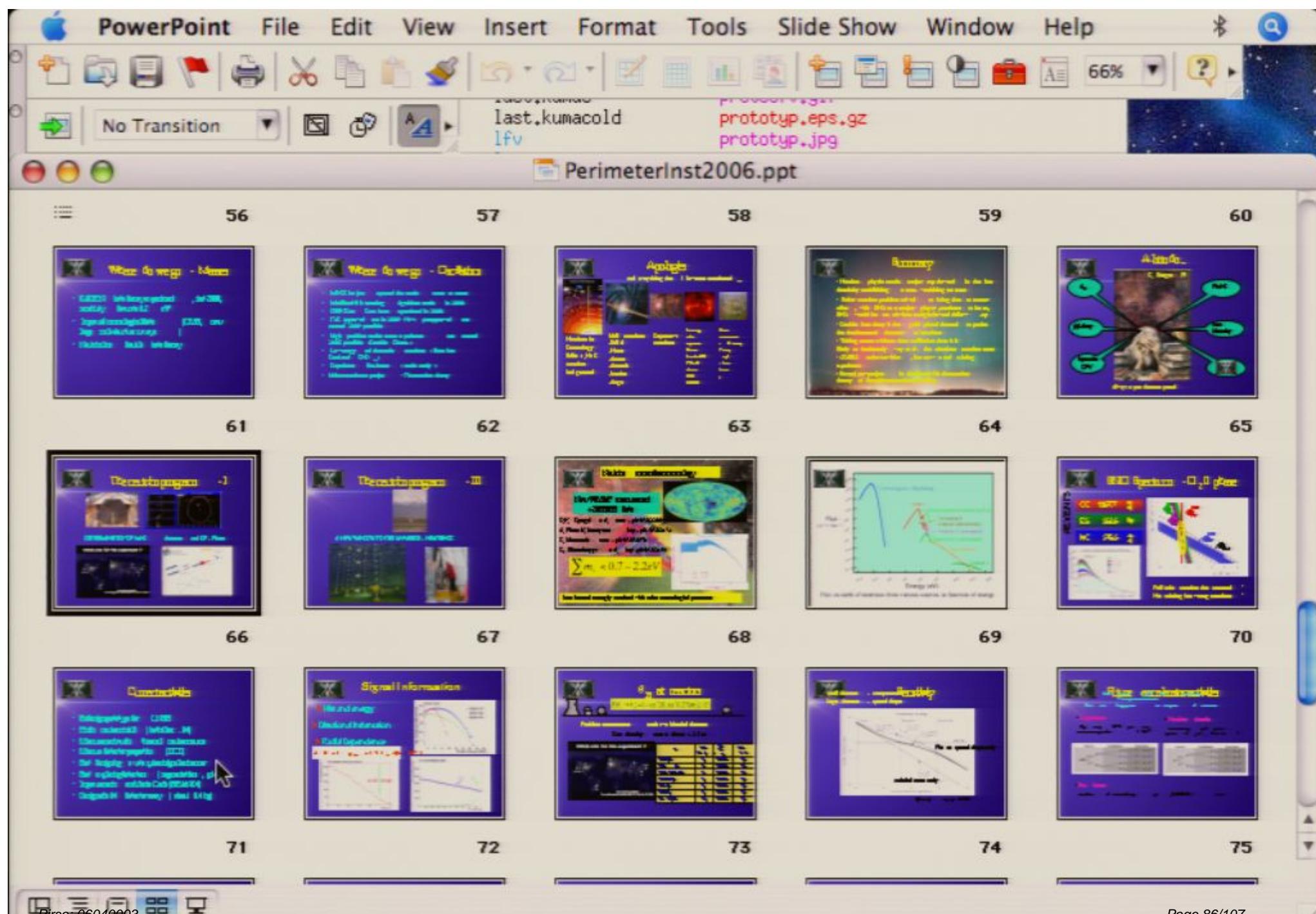


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75

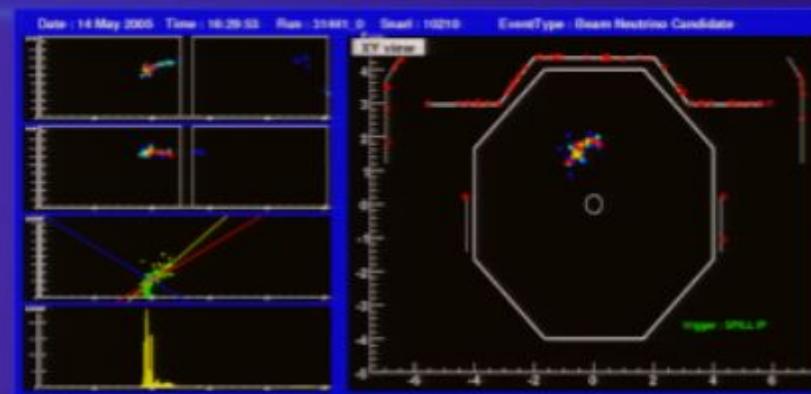




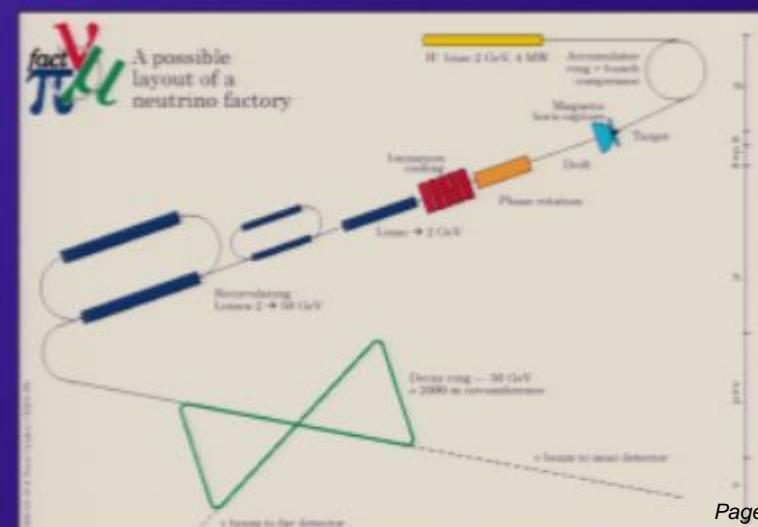




# The neutrino program - I



## DETERMINATION OF MNS elements and CP - Phase

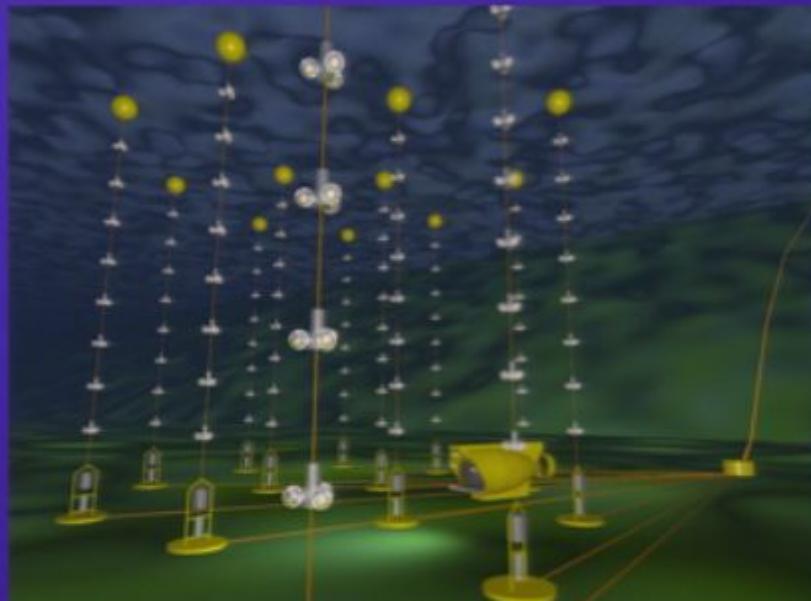




# The neutrino program - III

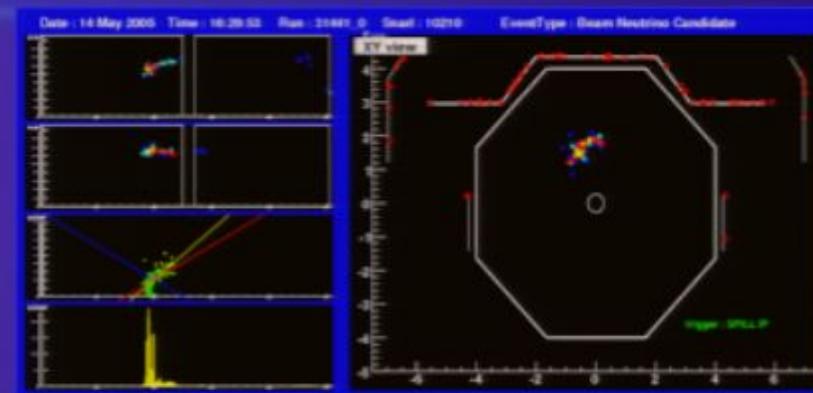


A NEW WINDOW TO THE UNIVERSE - NEUTRINOS

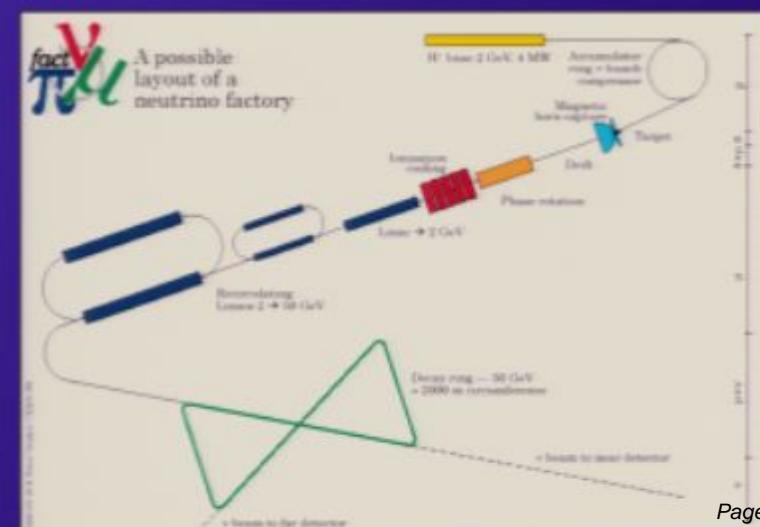


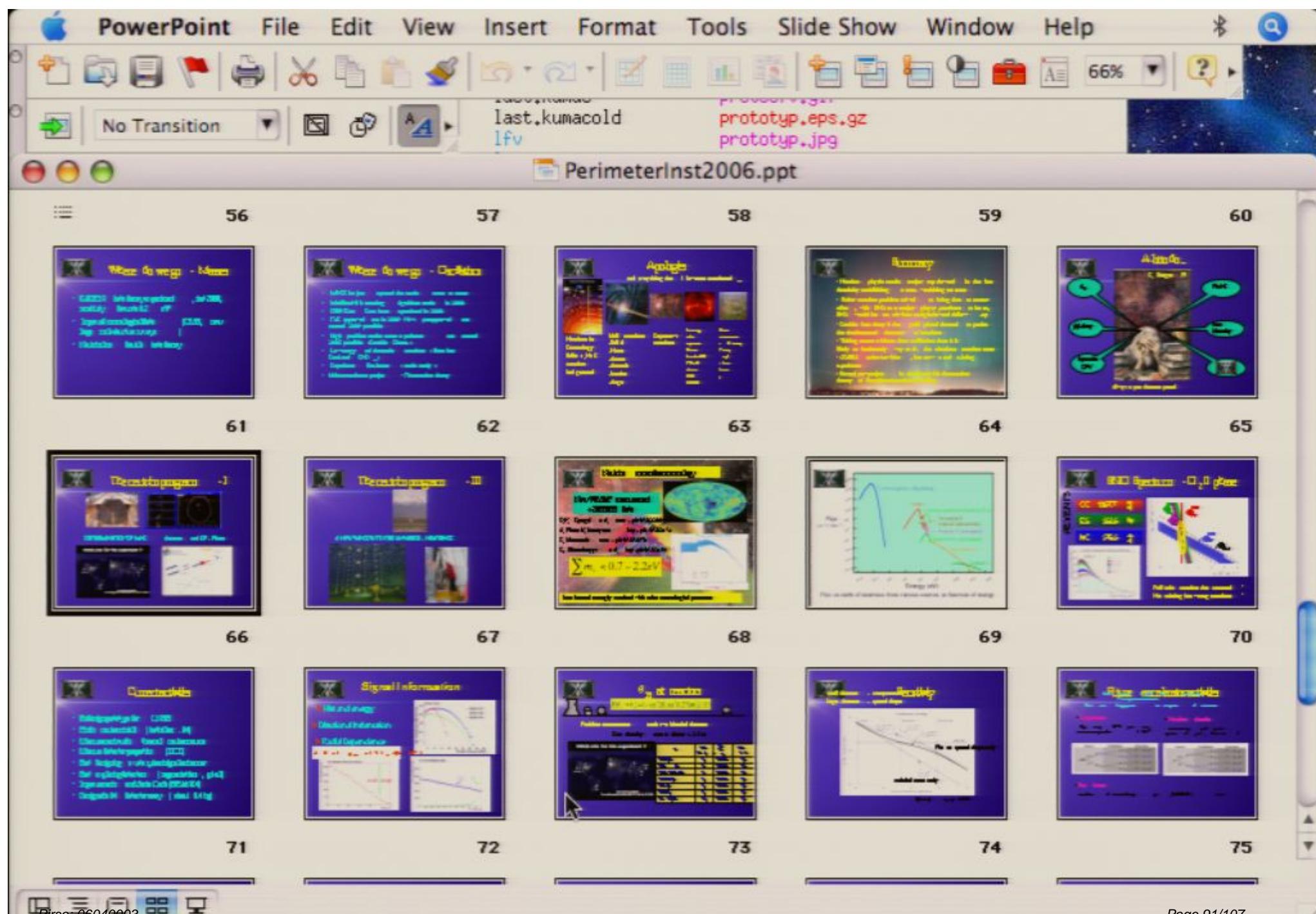


# The neutrino program - I



## DETERMINATION OF MNS elements and CP - Phase





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PerimeterInst2006.ppt

36 37 38 39 40

36  
Definition of detector types:

- Geiger-Mueller tube
- Ionization chamber
- Proportional counter
- Semiconductor detector

37  
Detector:

- Indirect
- DR detector will be Elley White Discovery 2002
- Dual technology of the DR detector
- Geiger-Mueller tube

38  
Nucleus coincidence

39  
Geiger-Mueller - Beta Decay

40  
Beta Decay - Compton (18)

41 42 43 44 45

41  
EASIPR - The other branching detector

42  
Example - Geiger

43  
Phase space

Angle	Energy	Intensity
0°	100	100
10°	100	100
20°	100	100
30°	100	100
40°	100	100
50°	100	100
60°	100	100
70°	100	100
80°	100	100
90°	100	100
100°	100	100
110°	100	100
120°	100	100
130°	100	100
140°	100	100
150°	100	100
160°	100	100
170°	100	100
180°	100	100

44  
Spectrograph

45  
3D Spectrograph (PMT)

46 47 48 49 50

46  
High-Background detector

47  
Si-28

48  
Advantages

- Good resolution
- Semiconductor (low noise detector, ...)
- Room temperature (room)
- High energy resolution (good)
- Relatively low cost
- Useful endpoint of Ge detectors
- ~ Ge 100-1000 keV
- Yield (100-1000 keV)

49  
The Ge detector

50  
Plotted Detection

51 52 53 54 55

51  
High-Background detector

52  
Si-28

53  
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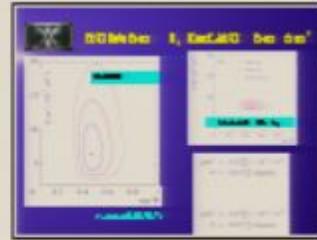
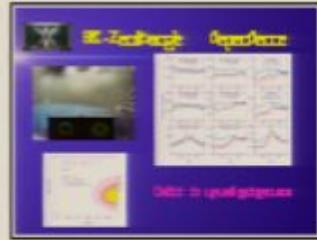
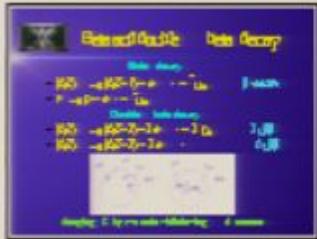
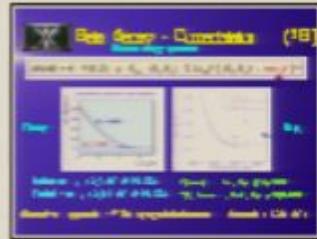
54  
The Ge detector

55  
Plotted Detection

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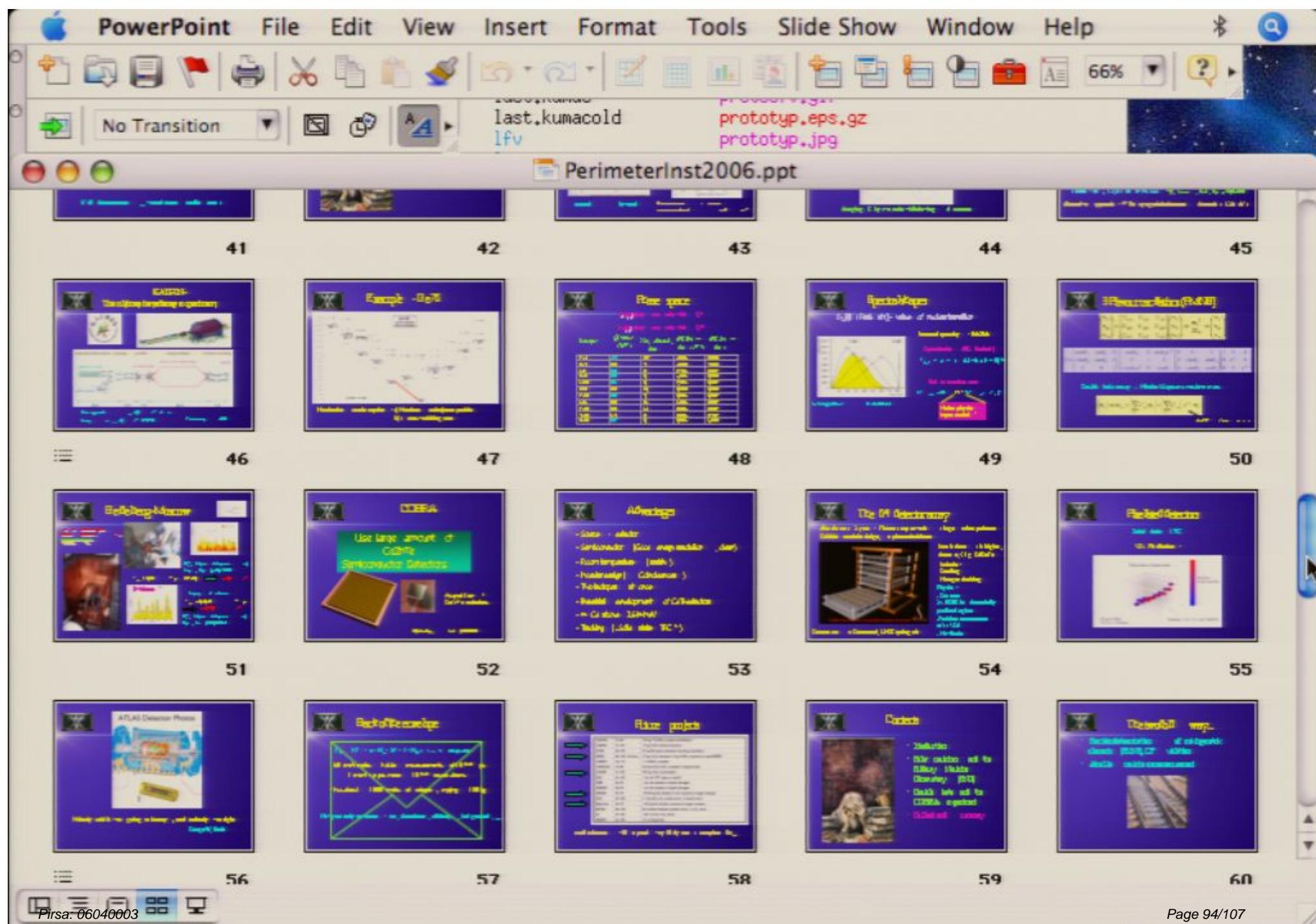
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31	32	33	34	35
		CERN - Gran Sasso (CNGS)	The LSND Evidence	MiniBooNE
36	37	38	39	40
				
41	42	43	44	45
				

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## 3 Flavour oscillations (PMNS)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \Rightarrow \frac{m_i^2}{2E_\nu} \Rightarrow \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$$

$$U = \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\beta_1} & 0 \\ 0 & 0 & e^{i\beta_2} \end{pmatrix}$$

Double beta decay: Effective Majorana neutrino mass

$$\langle m_\nu \rangle \equiv m_{ee} = \left| \sum_k U_{ek}^2 m_k \right| = \left| \sum_k |U_{ek}|^2 e^{i\alpha_{ek}} m_k \right|$$



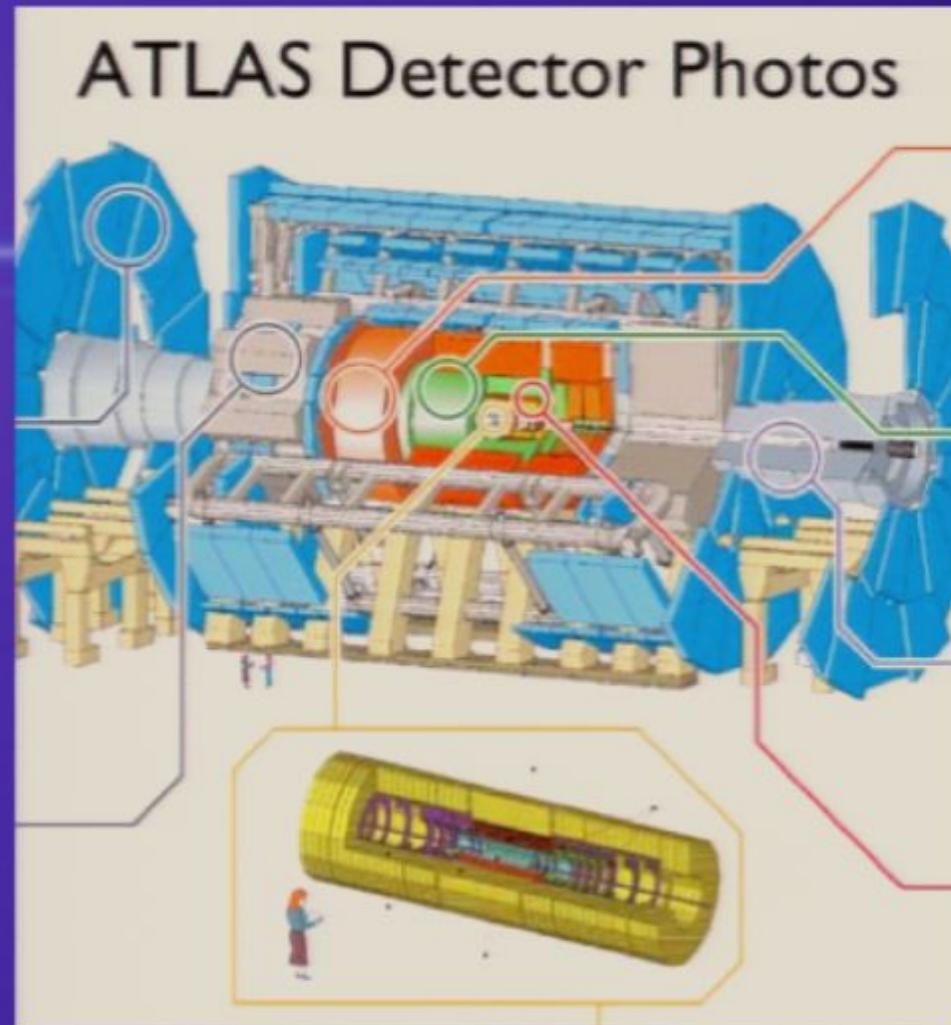
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**Nobody said it was going to be easy, and nobody was right**

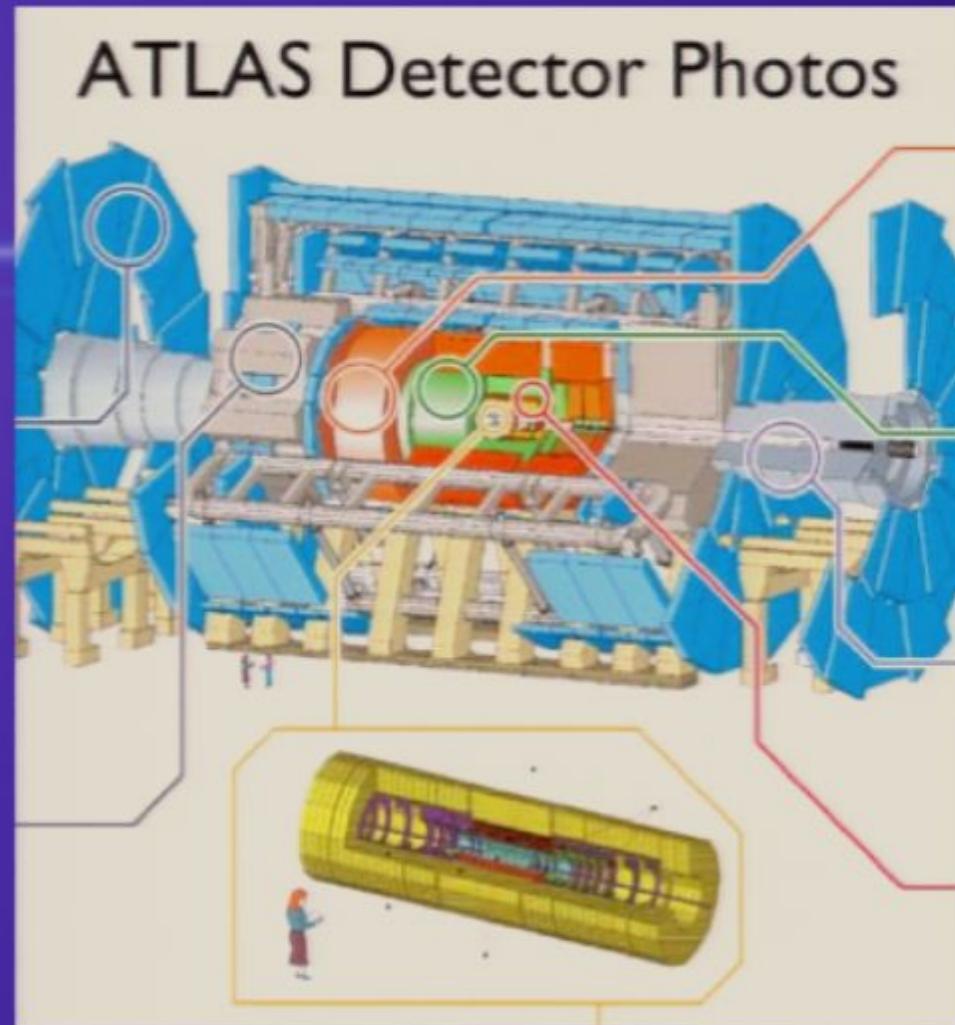


# Future projects



CARVEL	Ca-48	100 kg $^{48}\text{CaWO}_4$ crystal scintillators
COBRA	Te-130	10 kg CdTe semiconductors
DCBA	Nd-150	20 kg Nd layers between tracking chambers
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CAMEO	Cd-114	1 t $\text{CdWO}_4$ crystals
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small scale ones will expand, very likely not a complete list...



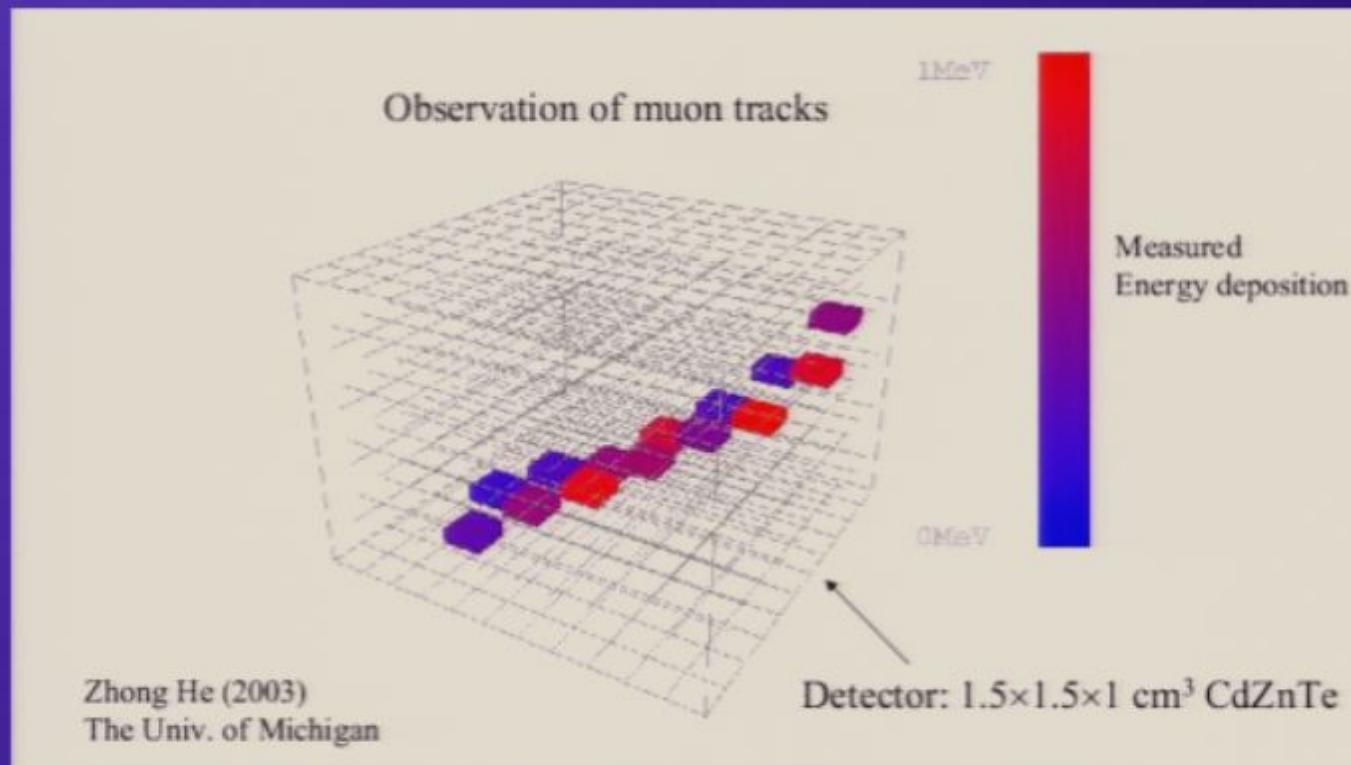
**Nobody said it was going to be easy, and nobody was right**



# Pixellated detectors

## Solid state TPC

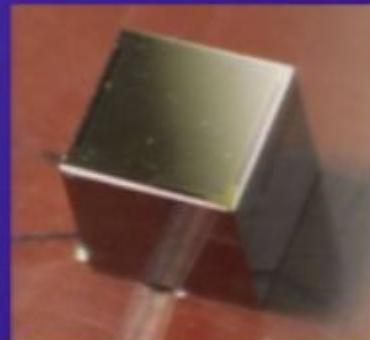
### 3D - Pixelisation:





# COBRA

Use large amount of  
CdZnTe  
Semiconductor Detectors



Array of  $1\text{cm}^3$   
CdZnTe detectors



## 3 Flavour oscillations (PMNS)

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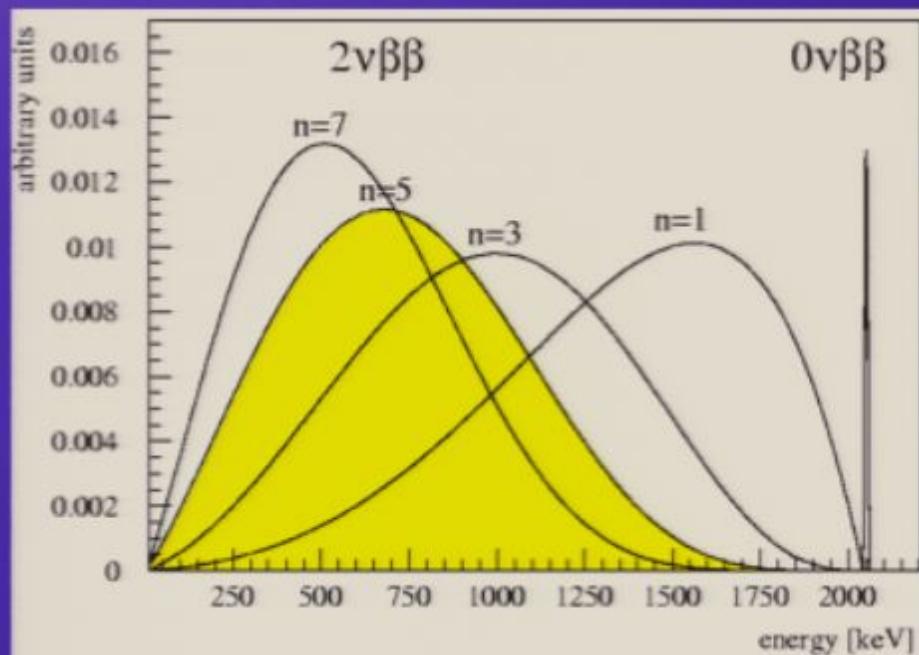
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# Spectral shapes

$0\nu\beta\beta$ : Peak at Q-value of nuclear transition



Sum energy spectrum of both electrons

Measured quantity: Half-life

Dependencies (BG limited)

$$T_{1/2} \propto a \cdot \epsilon \cdot (M \cdot t / \Delta E \cdot B)^{1/2}$$

link to neutrino mass

$$1 / T_{1/2} = PS * ME^2 * (m_\nu / m_e)^2$$

Nuclear physics  
input needed !



# Phase space

$0\nu\beta\beta$  decay rate scales with  $Q^5$

$2\nu\beta\beta$  decay rate scales with  $Q^{11}$

<i>Isotope</i>	<i>Q-value (keV)</i>	<i>Nat. abund. (%)</i>	$(PS \ 0\nu)^{-1}$ $(\text{yrs} \times eV^2)$	$(PS \ 2\nu)^{-1}$ (yrs)
----------------	--------------------------	----------------------------	--	-----------------------------

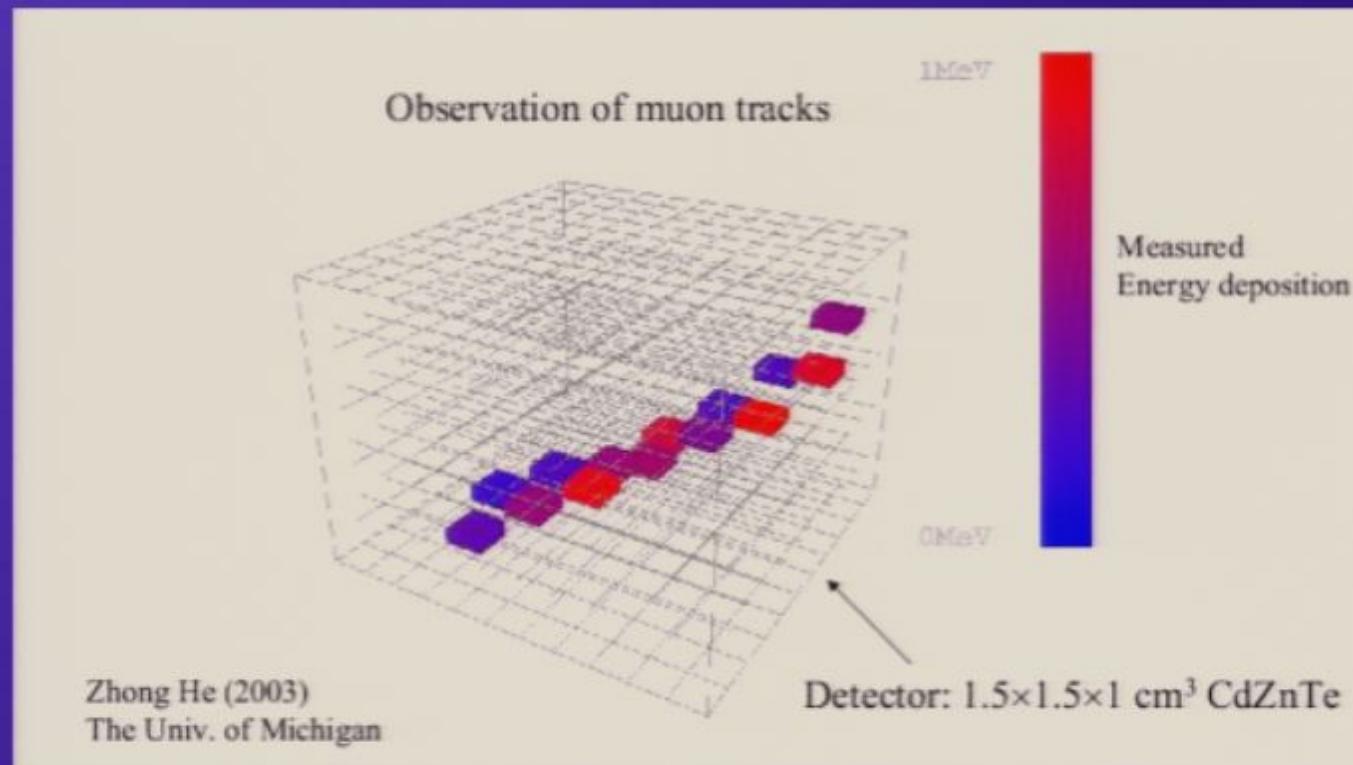
<b>Ca 48</b>	<b>4271</b>	<b>0.187</b>	<b>4.10E24</b>	<b>2.52E16</b>
<b>Ge 76</b>	<b>2039</b>	<b>7.8</b>	<b>4.09E25</b>	<b>7.66E18</b>
<b>Se 82</b>	<b>2995</b>	<b>9.2</b>	<b>9.27E24</b>	<b>2.30E17</b>
<b>Zr 96</b>	<b>3350</b>	<b>2.8</b>	<b>4.46E24</b>	<b>5.19E16</b>
<b>Mo 100</b>	<b>3034</b>	<b>9.6</b>	<b>5.70E24</b>	<b>1.06E17</b>
<b>Pd 110</b>	<b>2013</b>	<b>11.8</b>	<b>1.86E25</b>	<b>2.51E18</b>
<b>Cd 116</b>	<b>2802</b>	<b>7.5</b>	<b>5.28E24</b>	<b>1.25E17</b>
<b>Sn 124</b>	<b>2288</b>	<b>5.64</b>	<b>9.48E24</b>	<b>5.93E17</b>
<b>Te 130</b>	<b>2529</b>	<b>34.5</b>	<b>5.89E24</b>	<b>2.08E17</b>
<b>Xe 136</b>	<b>2479</b>	<b>8.9</b>	<b>5.52E24</b>	<b>2.07E17</b>
<b>Nd 150</b>	<b>3367</b>	<b>5.6</b>	<b>1.25E24</b>	<b>8.41E15</b>

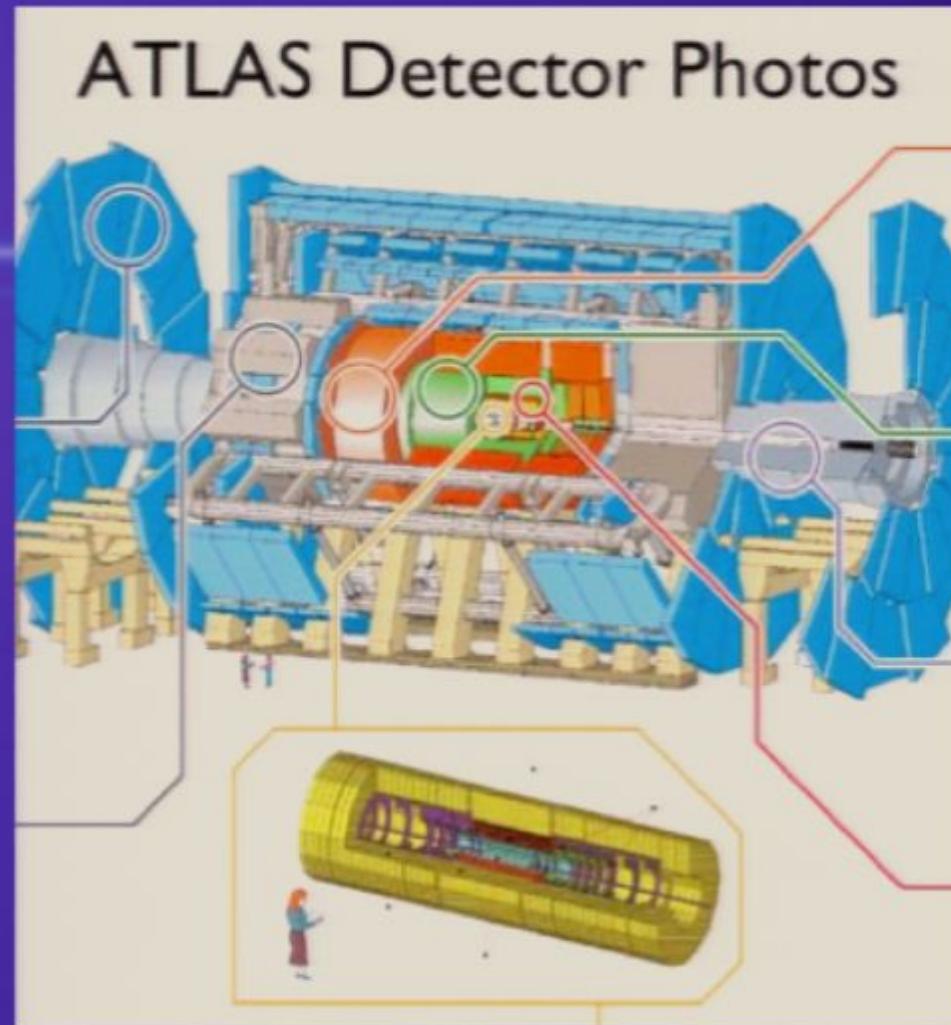


# Pixellated detectors

## Solid state TPC

### 3D - Pixelisation:

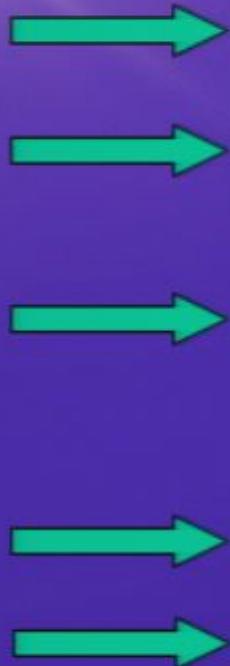




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