Tohoku University
Global COE Program
Weaving Science Web beyond Particle-Matter Hierarchy
物質階層を紡ぐ科学フロンティアの新展開

Prospects and Challenges in Elementary Particle Physics

March 6, 2009

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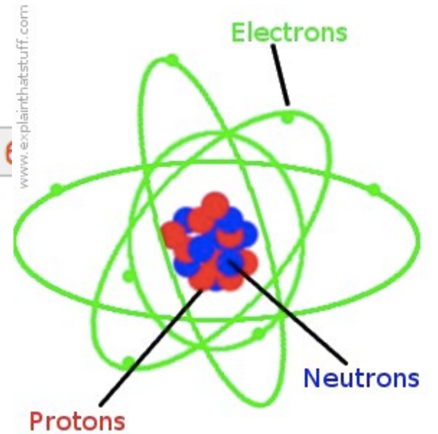
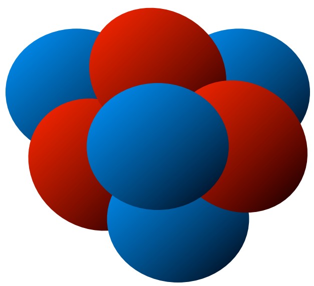
Periodic Table of the Elements



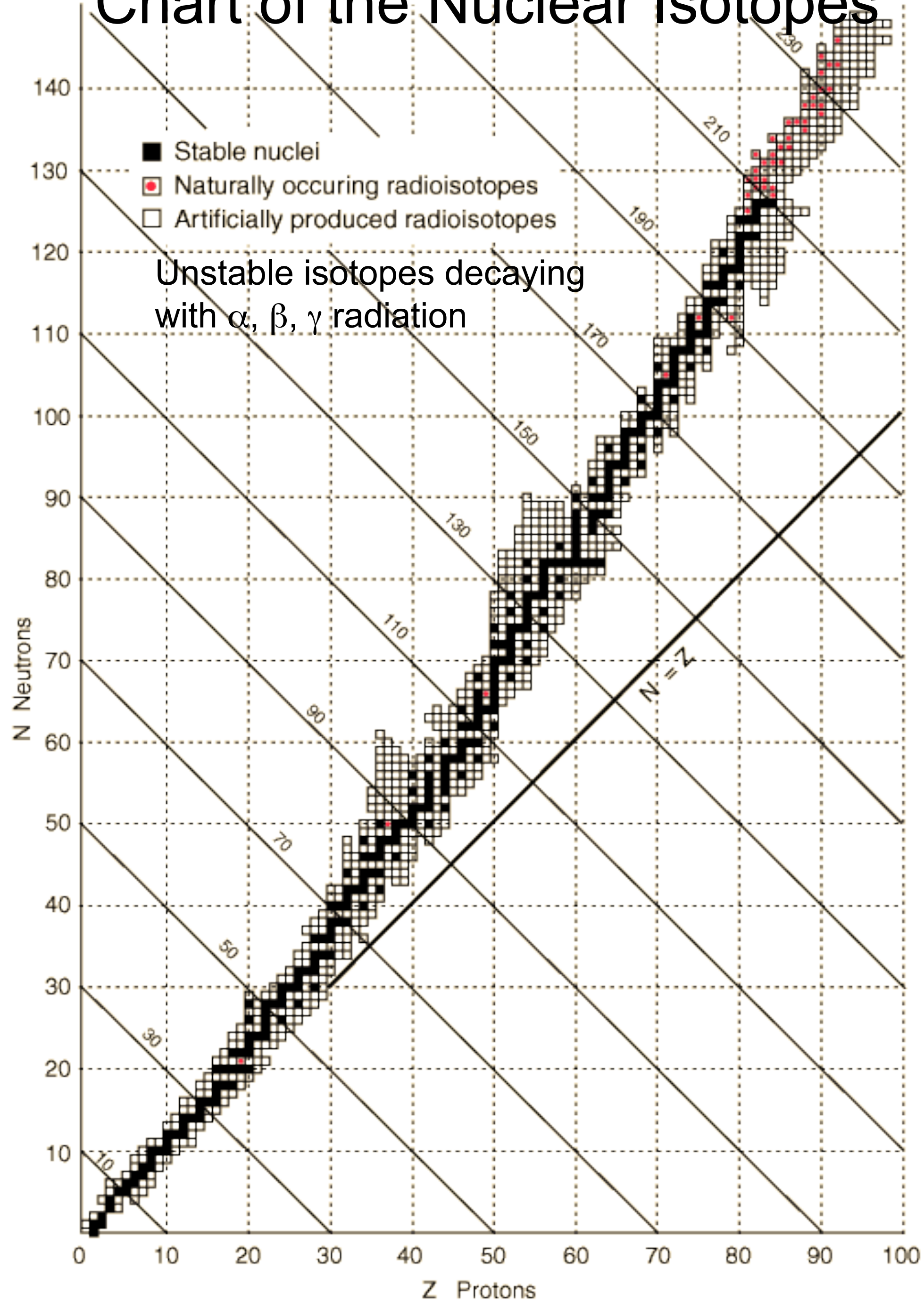
Group	1	2		3	4	5	6					11	12	13	14	15	16	17	18
Period																			
1	1 H																		2 He
2	3 Li	4 Be												5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg												13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca		21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr		39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	*	71 Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	**	103 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Uub	113 Uut	114 Uuq	115 Uup	116 Uuh	117 Uus	118 Uuo

*Lanthanoids	*	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb
**Actinoids	**	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No

Chart of the Nuclear Isotopes



Nucleus



Line for nuclei with equal number of protons and neutrons

The Importance of Broken Symmetries

PHYSICAL REVIEW VOLUME 104, NUMBER 1 OCTOBER 1, 1956

Question of Parity Conservation in Weak Interactions*

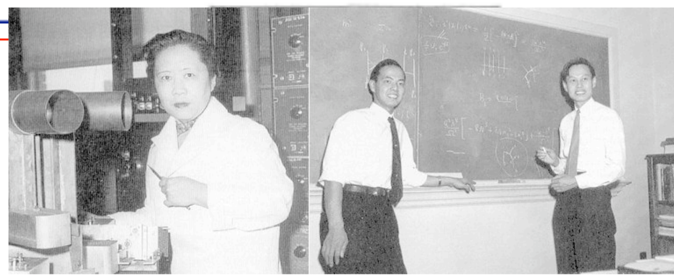
T. D. Lee, *Columbia University, New York, New York*

AND

C. N. Yang,† *Brookhaven National Laboratory, Upton, New York*

(Received June 22, 1956)

The question of parity conservation in β decays and in hyperon and meson decays is examined. Possible experiments are suggested which might test parity conservation in these interactions.



C. S. Wu T. D. Lee C. N. Yang

Experimental Test of Parity Conservation in Beta Decay*

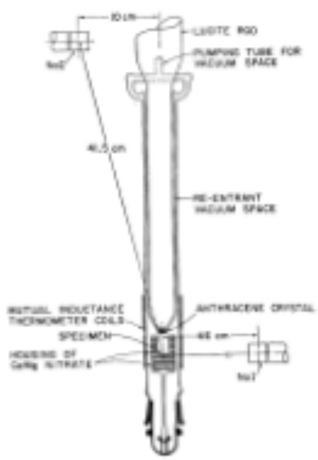
C. S. Wu, *Columbia University, New York, New York*

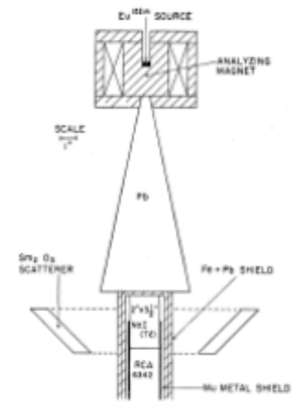
AND

E. Ambler, R. W. Hayward, D. D. Hoppes, and R. P. Hudson, *National Bureau of Standards, Washington, D. C.*

(Received January 15, 1957)

In a recent paper[1] on the question of parity in weak interactions, Lee and Yang critically surveyed the experimental information concerning this question and reached the conclusion that there is no existing evidence either to support or to refute parity conservation in weak interactions. They proposed a number of experiments on beta decays and hyperon and meson decays which would provide the necessary evidence for parity conservation





Helicity of Neutrinos*

M. Goldhaber, L. Grodzins, and A. W. Sunyar
Brookhaven National Laboratory, Upton, New York

(Received December 11, 1957)

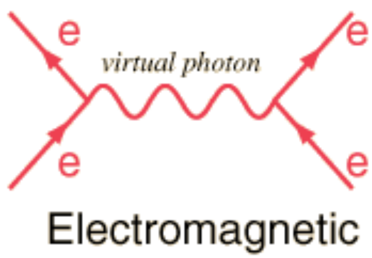
A combined analysis of circular polarization and resonant scattering of γ rays following orbital electron capture measures the helicity of the neutrino. We have carried out such a measurement with Eu^{152m}, which decays by orbital electron capture. If we assume the most plausible spin-parity assignment for this isomer compatible with its decay scheme,[1] 0−, we find that the neutrino is "left-handed," i.e., $\sigma_\nu \cdot \hat{p}_\nu = -1$ (negative helicity).

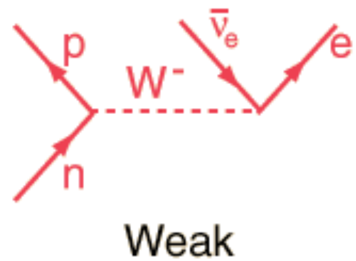
Quantum Field Theory -- Spontaneous Symmetry Breaking

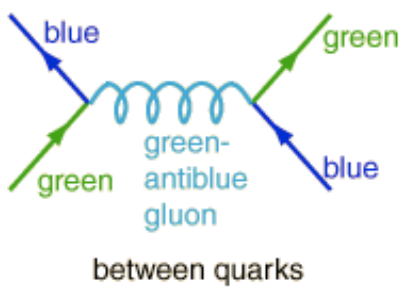
Yukawa

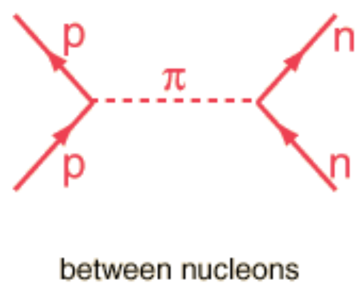
Nambu

Glashow-Salam-Weinberg









Strong Interaction

Standard Model Lagrangian

$$-\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu +$$
$$\frac{1}{2}ig_s^2(\bar{q}^\sigma_i \gamma^\mu q^\sigma_j)g^a_\mu + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu -$$
$$M^2 W^+_\mu W^-_\mu - \frac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \frac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2}\partial_\mu H \partial_\mu H -$$
$$\frac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2\phi^+\phi^- - \frac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0 - \frac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h[\frac{2M^2}{g^2} +$$
$$\frac{2M}{g}H + \frac{1}{2}(H^2+\phi^0\phi^0+2\phi^+\phi^-)] + \frac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu\partial_\nu W^-_\mu -$$
$$W^-_\nu\partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu\partial_\nu W^-_\mu -$$
$$W^-_\mu\partial_\nu W^+_\mu) + A_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - \frac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu +$$
$$\frac{1}{2}g^2 W^+_\mu W_\nu W^+_\mu W_\nu + g^2c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W_\nu - Z^0_\mu Z^0_\mu W^+_\nu W_\nu) +$$
$$g^2 s_w^2(A_\mu W^+_\mu A_\nu W_\nu - A_\mu A_\mu W^+_\nu W_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W_\nu -$$
$$W^+_\nu W_\mu) - 2A_\mu Z^0_\mu W^+_\nu W_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi] -$$
$$\frac{1}{8}g^2\alpha_h[H^4+(\phi^0)^4+4(\phi^+\phi^-)^2+4(\phi^0)^2\phi^+\phi^-+4H^2\phi^+\phi^-+2(\phi^0)^2H^2]-$$
$$gMW^+_\mu W^-_\mu H - \frac{1}{2}g\frac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \frac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) -$$
$$W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \frac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ -$$
$$\phi^+\partial_\mu H)] + \frac{1}{2}g\frac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\frac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) +$$
$$igs_wMA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\frac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) +$$
$$igs_wA_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \frac{1}{4}g^2W^+_\mu W^-_\mu[H^2+(\phi^0)^2+2\phi^+\phi^-] -$$
$$\frac{1}{4}g^2\frac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2+(\phi^0)^2+2(2s_w^2-1)^2\phi^+\phi^-] - \frac{1}{2}g^2\frac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- +$$
$$W^-_\mu\phi^+) - \frac{1}{2}ig^2\frac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \frac{1}{2}g^2s_wA_\mu\phi^0(W^+_\mu\phi^- +$$
$$W^-_\mu\phi^+) + \frac{1}{2}ig^2s_wA_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\frac{s_w}{c_w}(2c_w^2-1)Z^0_\mu A_\mu\phi^+\phi^- -$$
$$g^1 s_w^2 A_\mu A_\mu\phi^+\phi^- - \bar{e}^\lambda(\gamma\partial+m_e^\lambda)e^\lambda - \bar\nu^\lambda\gamma\partial\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial+m_u^\lambda)u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial+$$
$$m_d^\lambda)d^\lambda_j + igs_wA_\mu[-(\bar{e}^\lambda\gamma e^\lambda) + \frac{2}{3}(\bar{u}^\lambda_j\gamma u^\lambda_j) - \frac{1}{3}(\bar{d}^\lambda_j\gamma d^\lambda_j)] + \frac{ig}{4c_w}Z^0_\mu[(\bar\nu^\lambda\gamma^\mu(1+$$
$$\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2-1-\gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(\frac{4}{3}s_w^2-1-\gamma^5)u^\lambda_j) +$$
$$(\bar{d}^\lambda_j\gamma^\mu(1-\frac{8}{3}s_w^2-\gamma^5)d^\lambda_j)] + \frac{ig}{2\sqrt{2}}W^+_\mu[(\bar\nu^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(1+$$
$$\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \frac{ig}{2\sqrt{2}}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1+\gamma^5)u^\lambda_j)] +$$
$$\frac{ig}{2\sqrt{2}}\frac{m_e^\lambda}{M}[-\phi^+(\bar\nu^\lambda(1-\gamma^5)e^\lambda) + \phi\ (\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)] - \frac{g}{2}\frac{m_e^\lambda}{M}[H(\bar{e}^\lambda e^\lambda) +$$
$$i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt{2}}\phi^+[-m_d^\kappa(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m_u^\lambda(\bar{u}^\lambda_j C_{\lambda\kappa}(1+$$
$$\gamma^5)d^\kappa_j] + \frac{ig}{2M\sqrt{2}}\phi^-[m_d^\lambda(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m_u^\kappa(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j] -$$
$$\frac{g}{2}\frac{m_u^\lambda}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \frac{g}{2}\frac{m_d^\lambda}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \frac{ig}{2}\frac{m_u^\lambda}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) - \frac{ig}{2}\frac{m_d^\lambda}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) +$$
$$\bar{X}^+(\partial^2-M^2)X^+ + \bar{X}^-(\partial^2-M^2)X^- + \bar{X}^0(\partial^2-\frac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2 Y +$$
$$igc_wW^+_\mu(\partial_\mu\bar{X}^0X^- - \partial_\mu\bar{X}^+X^0) + igs_wW^+_\mu(\partial_\mu\bar{Y}X^- - \partial_\mu\bar{X}^+Y) +$$
$$igc_wW_\mu(\partial_\mu\bar{X}\ X^0 - \partial_\mu\bar{X}^0X^+) + igs_wW_\mu(\partial_\mu\bar{X}\ Y - \partial_\mu\bar{Y}X^+) +$$
$$igc_wZ^0_\mu(\partial_\mu\bar{X}^+X^+ - \partial_\mu\bar{X}^-X^-) + igs_wA_\mu(\partial_\mu\bar{X}^+X^+ - \partial_\mu\bar{X}^-X^-) -$$
$$\frac{1}{2}gM[\bar{X}^+X^+H + \bar{X}\ X\ H + \frac{1}{c_w^2}\bar{X}^0X^0H] + \frac{1-2c_w^2}{2c_w}igM[\bar{X}^+X^0\phi^+ -$$
$$\bar{X}\ X^0\phi\ ] + \frac{1}{2c_w}igM[\bar{X}^0X\ \phi^+ - \bar{X}^0X^+\phi\ ] + igMs_w[\bar{X}^0X\ \phi^+ -$$
$$\bar{X}^0X^+\phi\ ] + \frac{1}{2}igM[\bar{X}^+X^+\phi^0 - \bar{X}\ X\ \phi^0]$$

Simple?

FERMIONS

matter constituents
spin = 1/2,

Leptons spin =1/2

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

Quarks spin =1/2

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

BOSONS

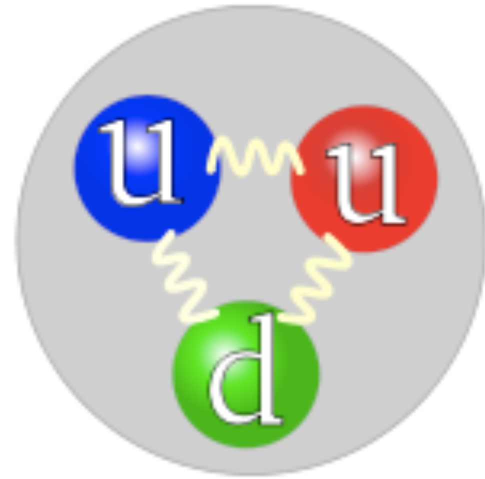
force carriers
spin = 1

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.39	−1
W^+ W bosons	80.39	+1
Z^0 Z boson	91.188	0

Strong (color) spin =1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

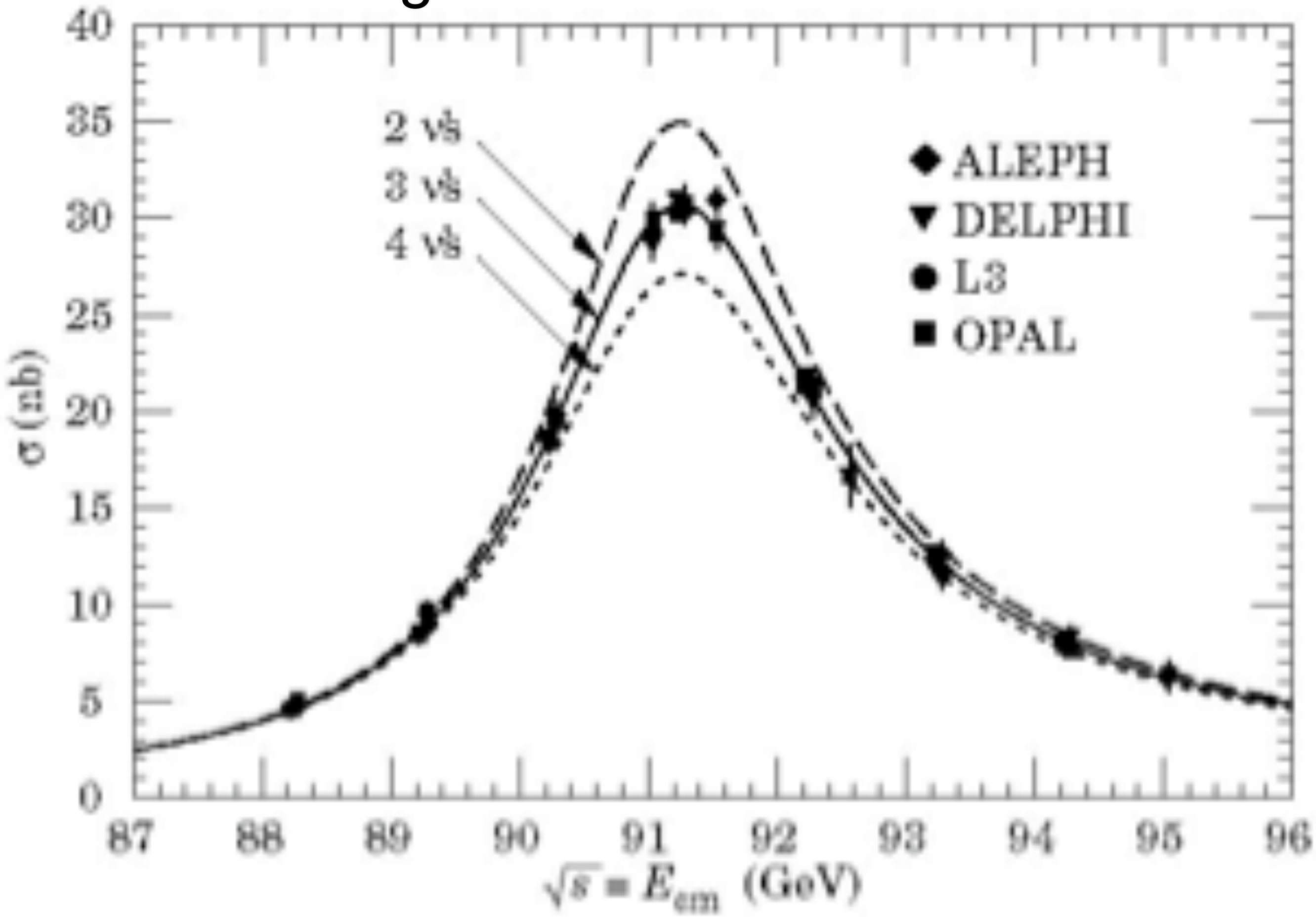


Proton

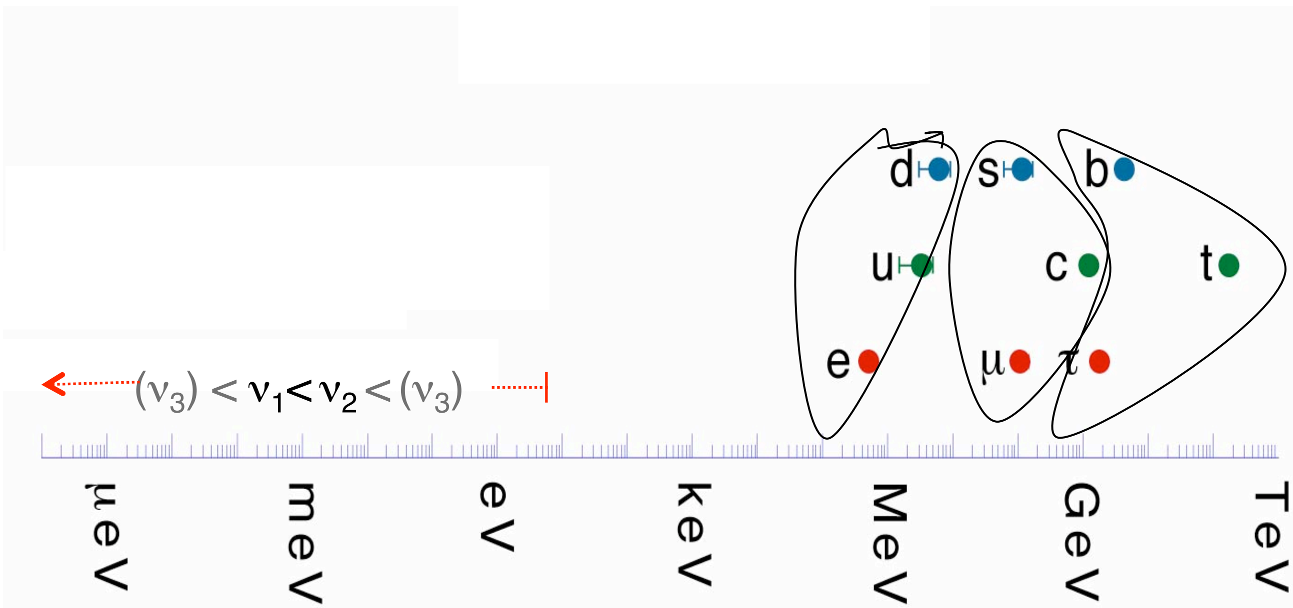
"The Standard Model"

$Z^o \longrightarrow q\bar{q},\ e\bar{e},\ \mu\bar{\mu},\ \tau\bar{\tau},\ \nu\bar{\nu}$

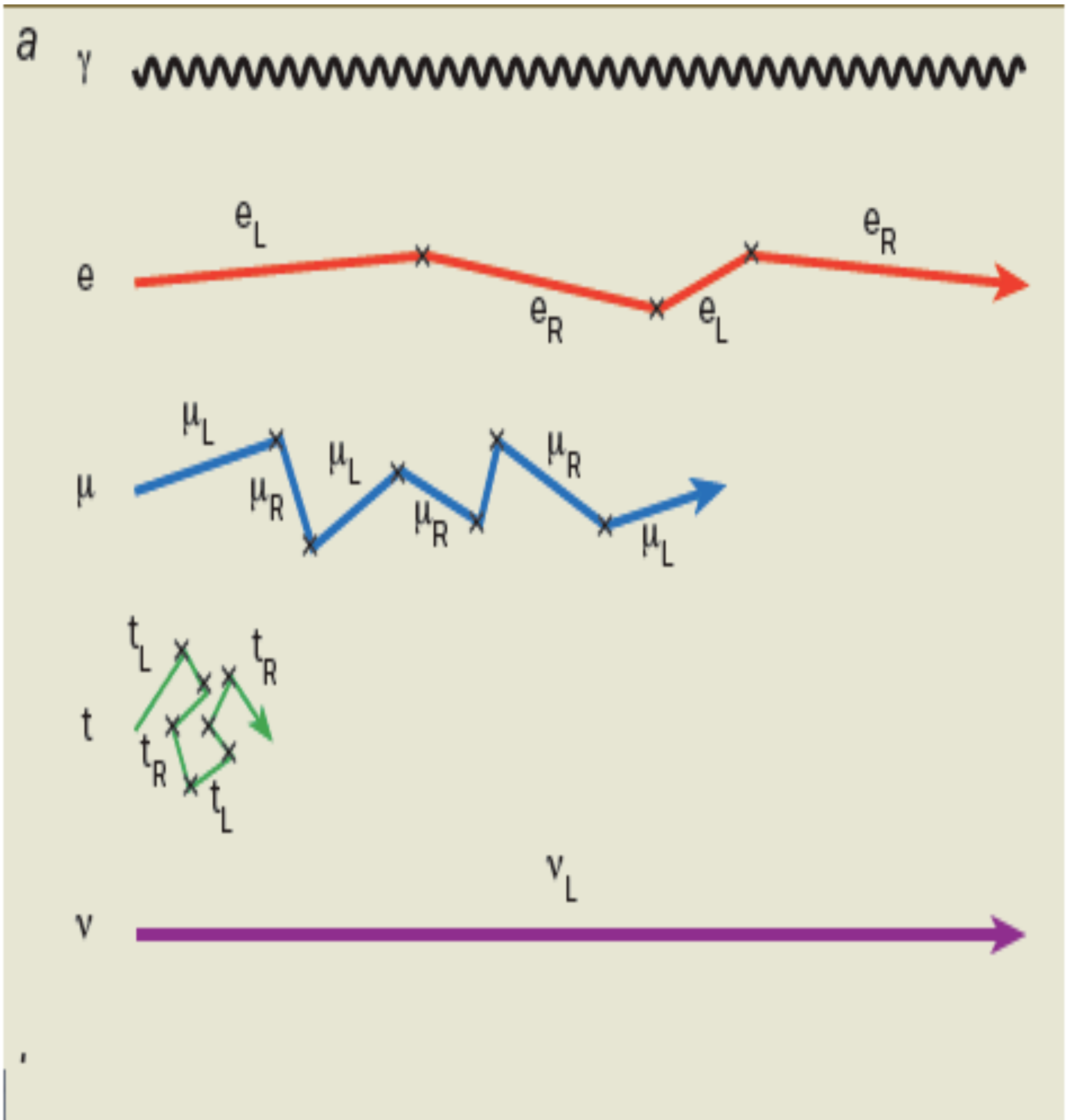
Measuring the width of the Z
Counting the number of Generations



Masses of the Constituents



Mass Comes from Interactions with the Higgs Field



Mass in the Standard Model

CKM Phenomenology

Quarks

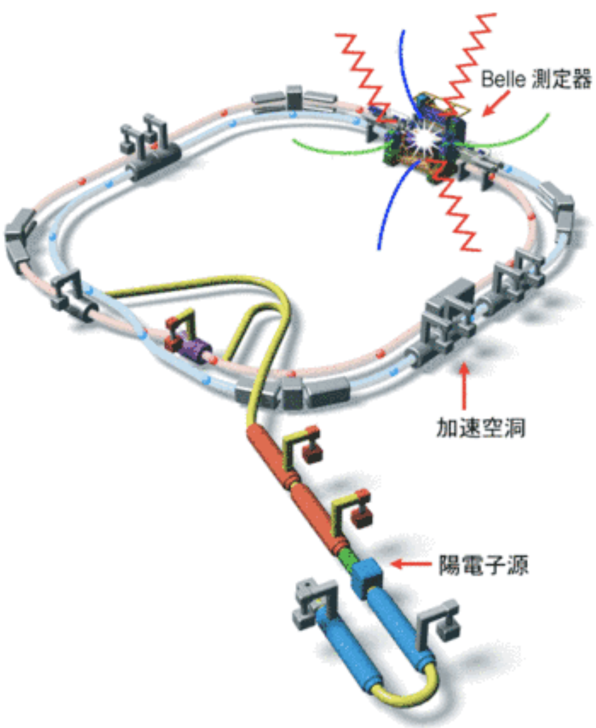
$$\begin{pmatrix} u_L \\ d'_L \end{pmatrix} \quad \begin{pmatrix} c_L \\ s'_L \end{pmatrix} \quad \begin{pmatrix} t_L \\ b'_L \end{pmatrix}$$

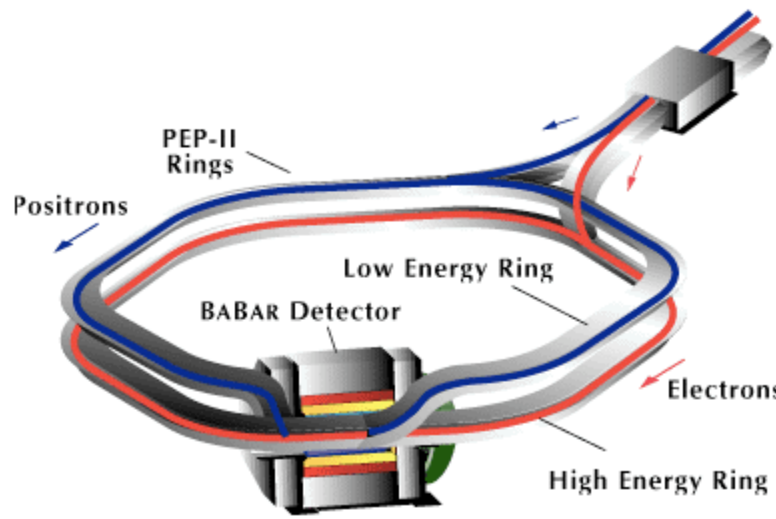
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$$|d'_L> = V_{ud}\,|d_L> + V_{us}\,|s_L> + V_{ub}\,|b_L>$$

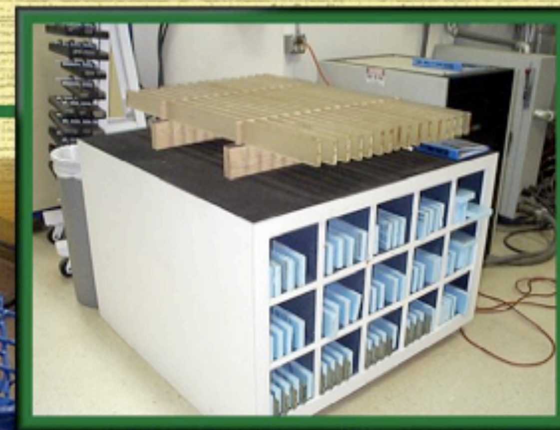
Verifying the Standard Model

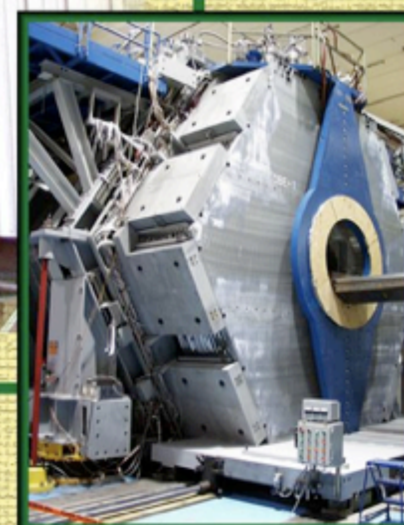




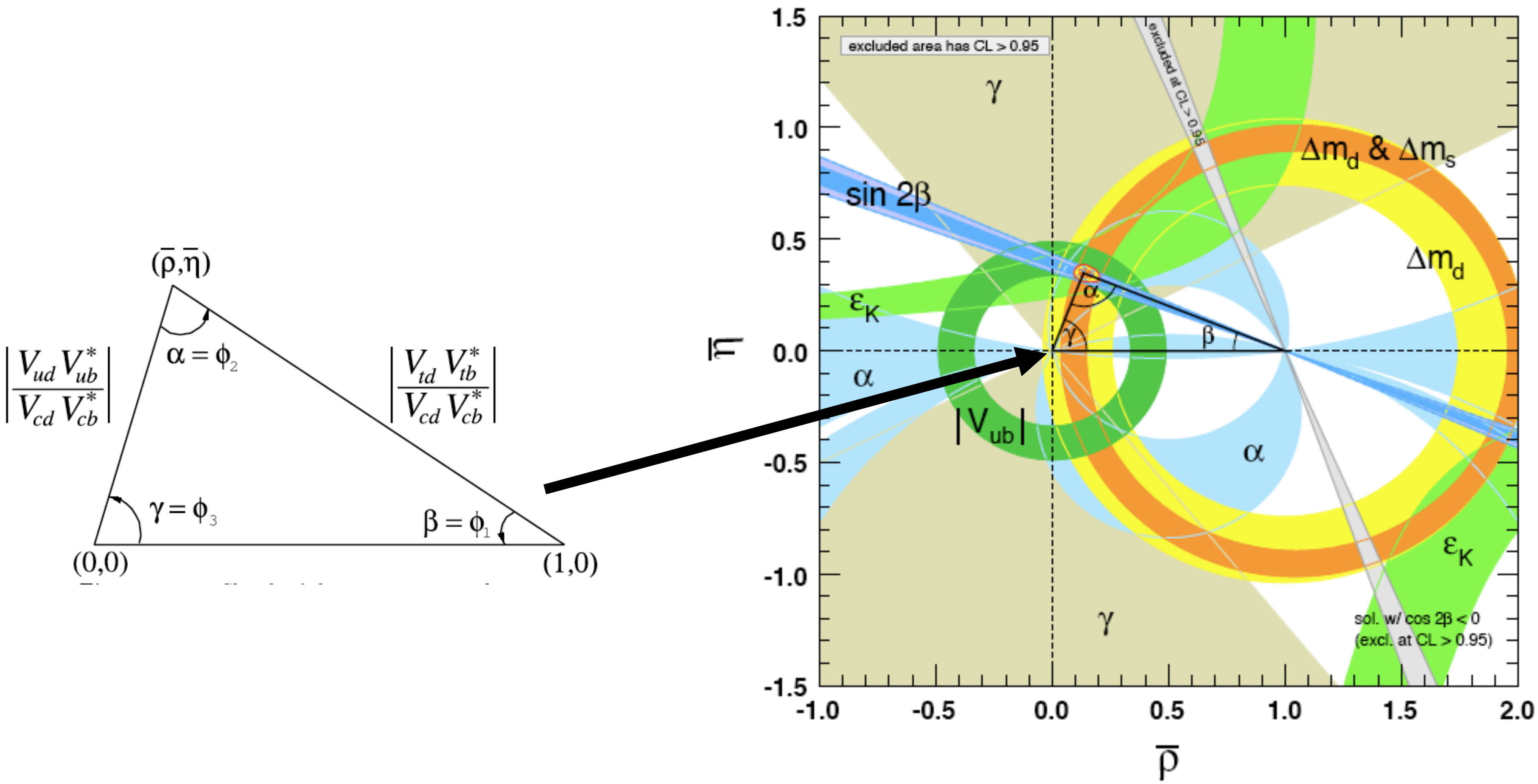
BABAR™

BABAR TM & L de Brunhoff

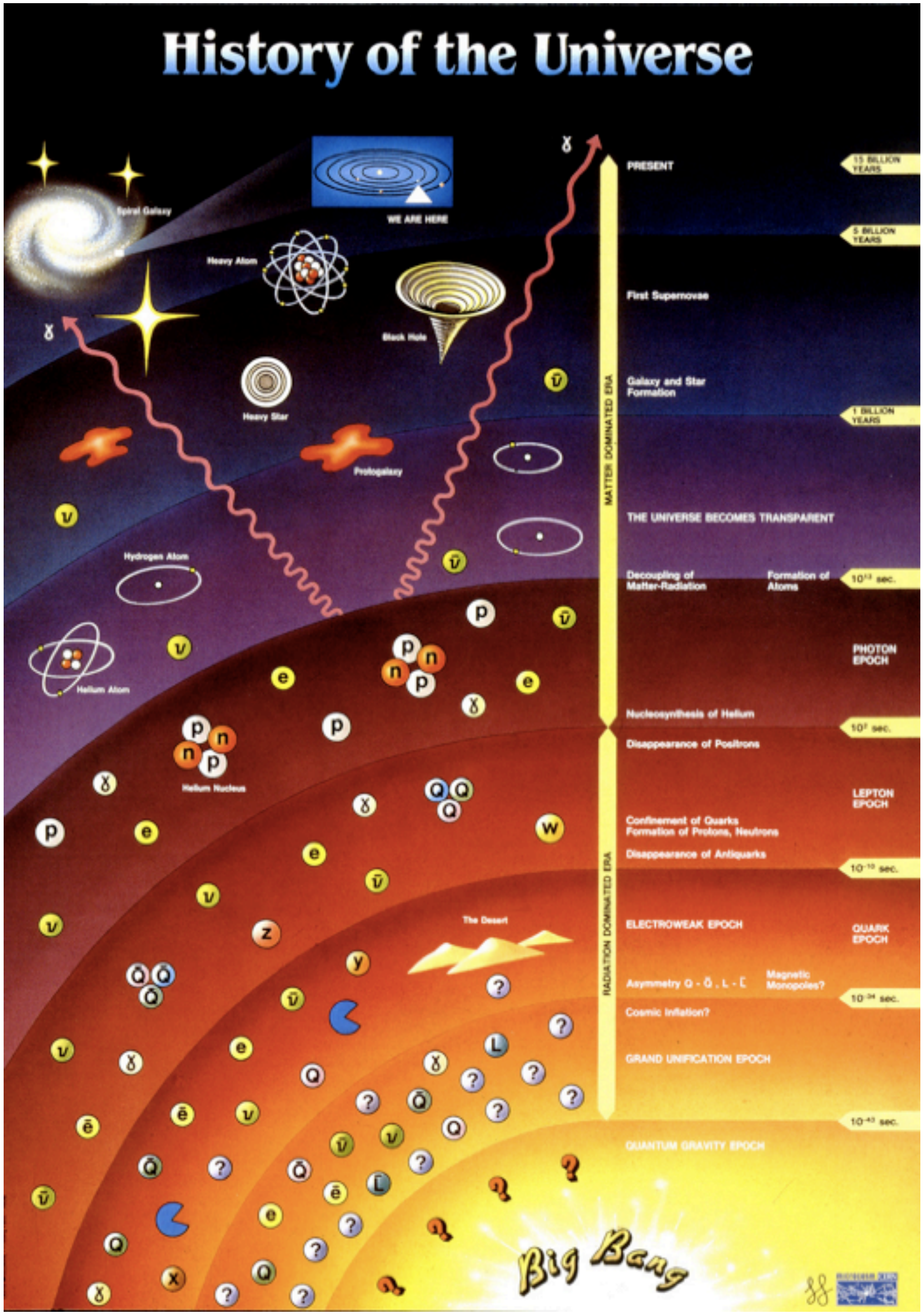




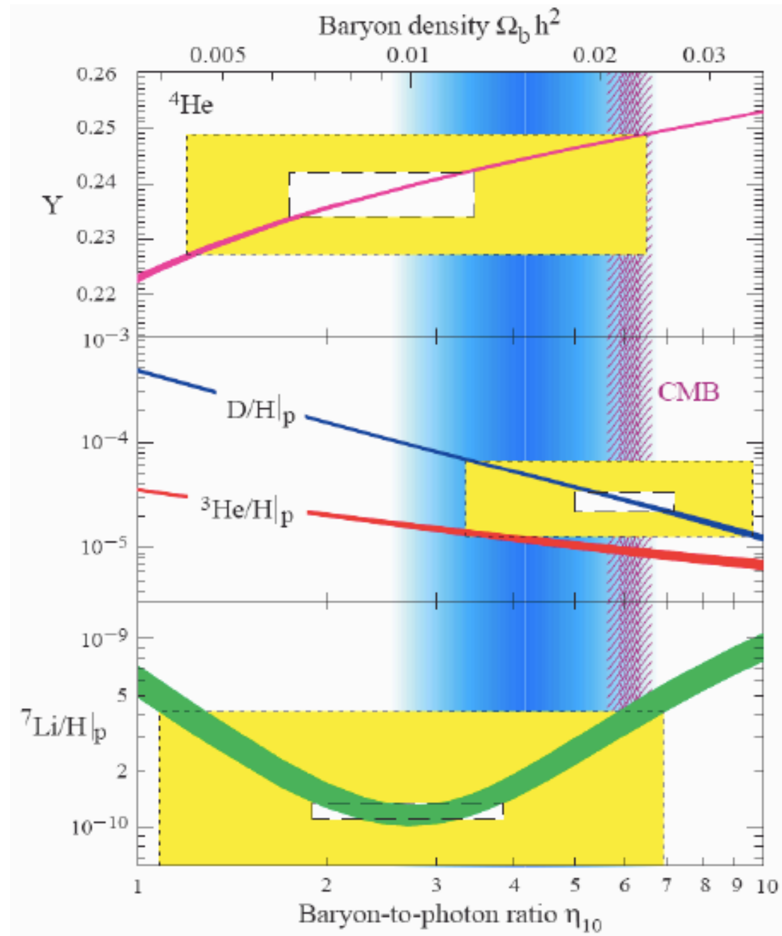
CKM Phenomenology



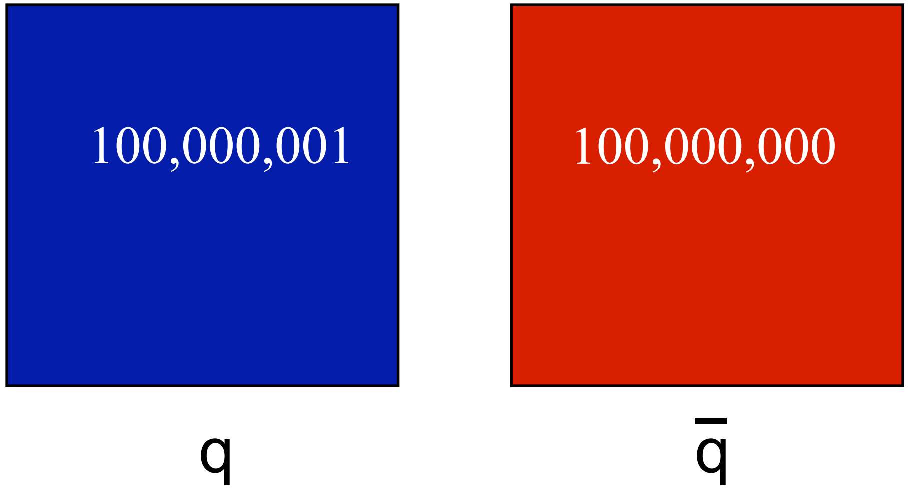
$$V_{\rm CKM} = \begin{pmatrix} 0.97419 \pm 0.00022 & 0.2257 \pm 0.0010 & 0.00359 \pm 0.00016 \\ 0.2256 \pm 0.0010 & 0.97334 \pm 0.00023 & 0.0415^{+0.0010}_{-0.0011} \\ 0.00874^{+0.00026}_{-0.00037} & 0.0407 \pm 0.0010 & 0.999133^{+0.000044}_{-0.000043} \end{pmatrix},$$



Nucleosynthesis



There should be as much antimatter as matter!



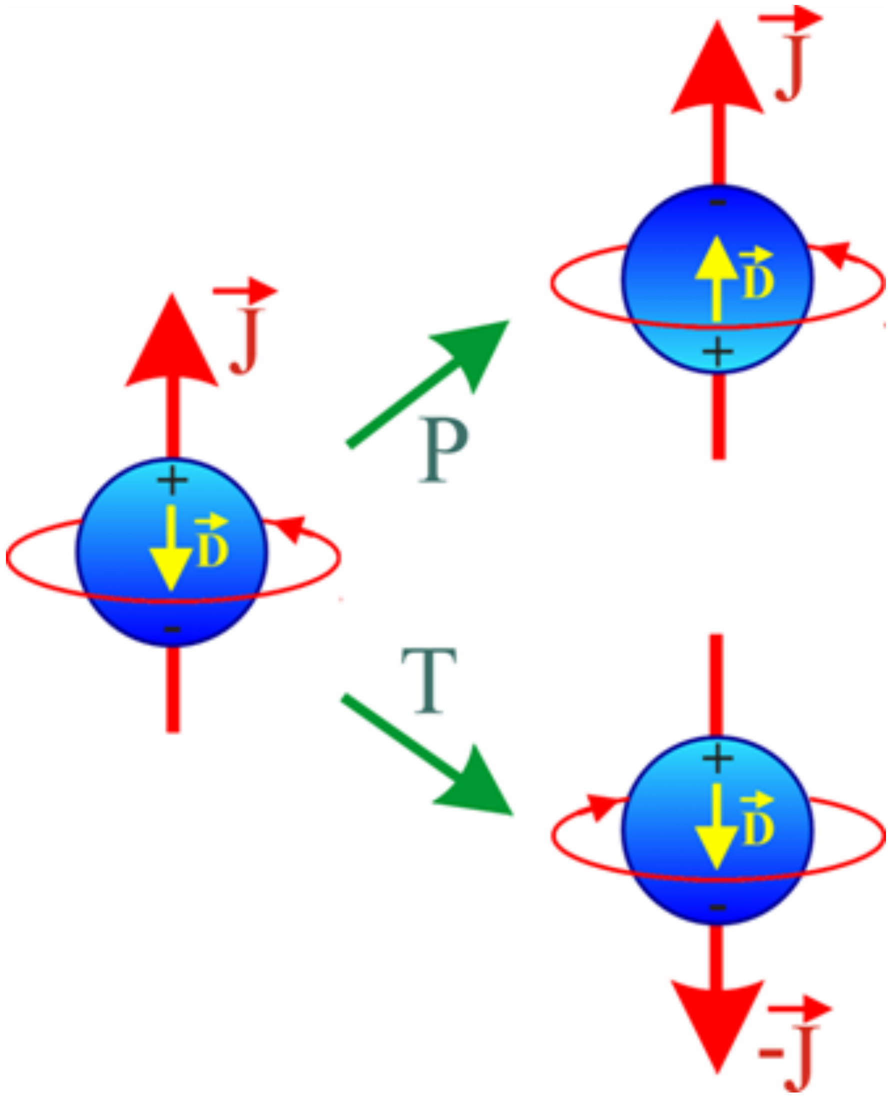
Matter – Antimatter Asymmetry

Sakharov Criteria:

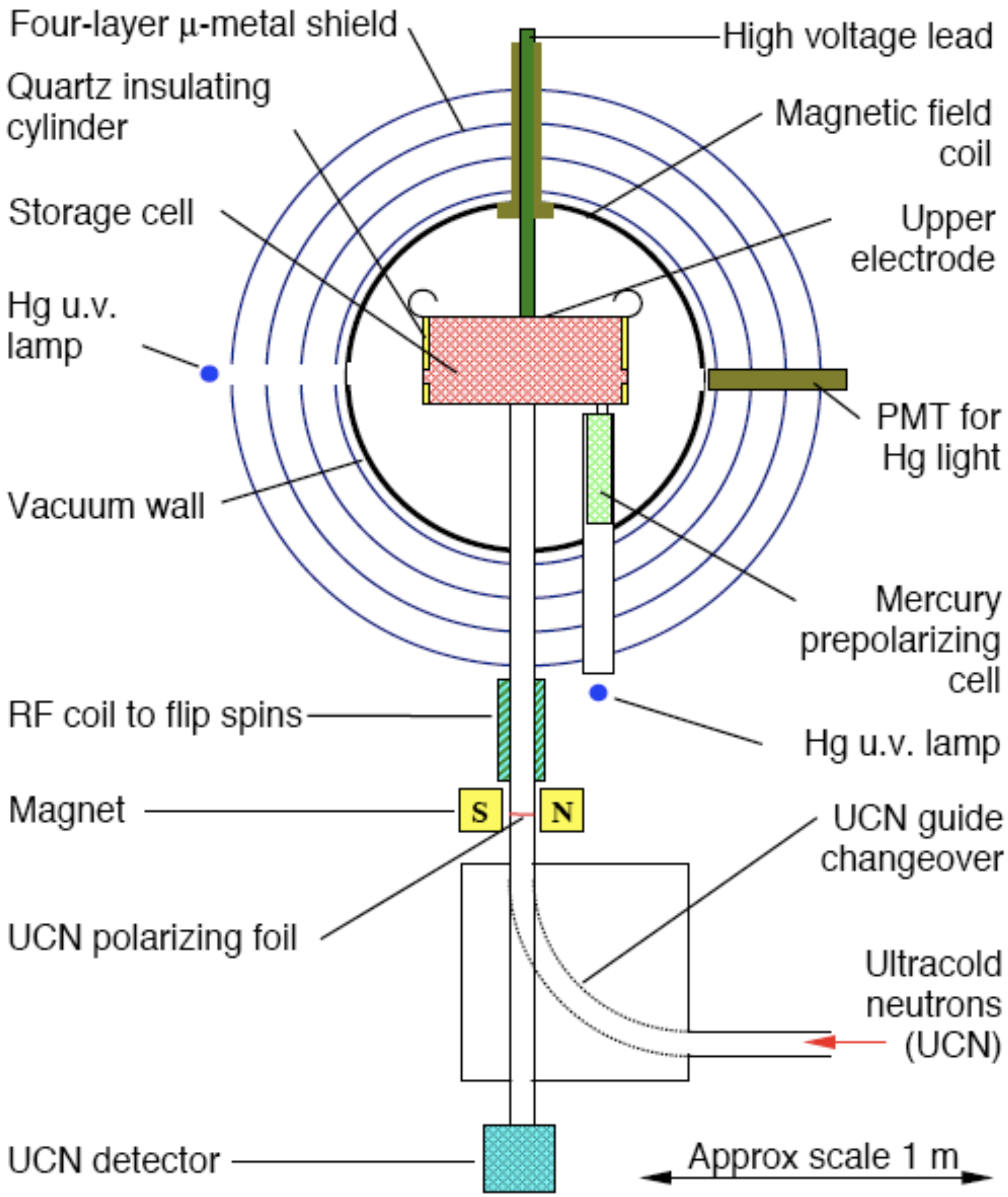
- Baryon number violation (or L→B)(not observed)
- T violation (larger than observed so far)
- Non-equilibrium evolution of the universe

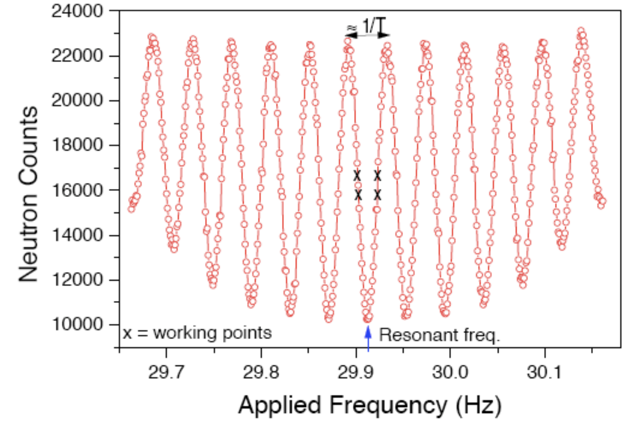
The search for large Time reversal symmetry violation and lepton-baryon number violation goes on!

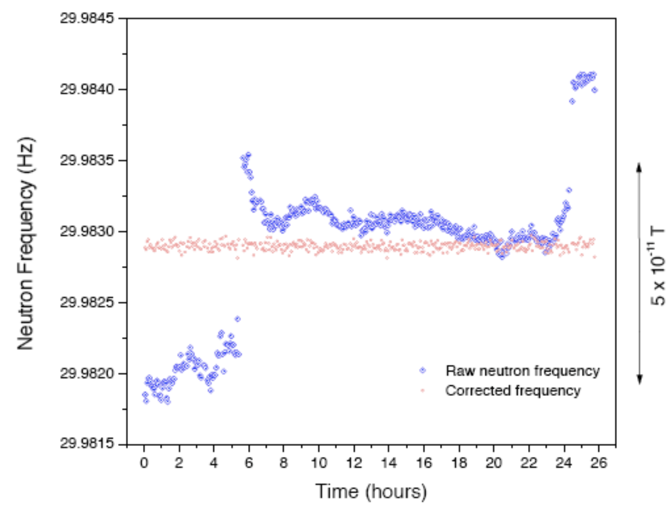
Electric Dipole Moment

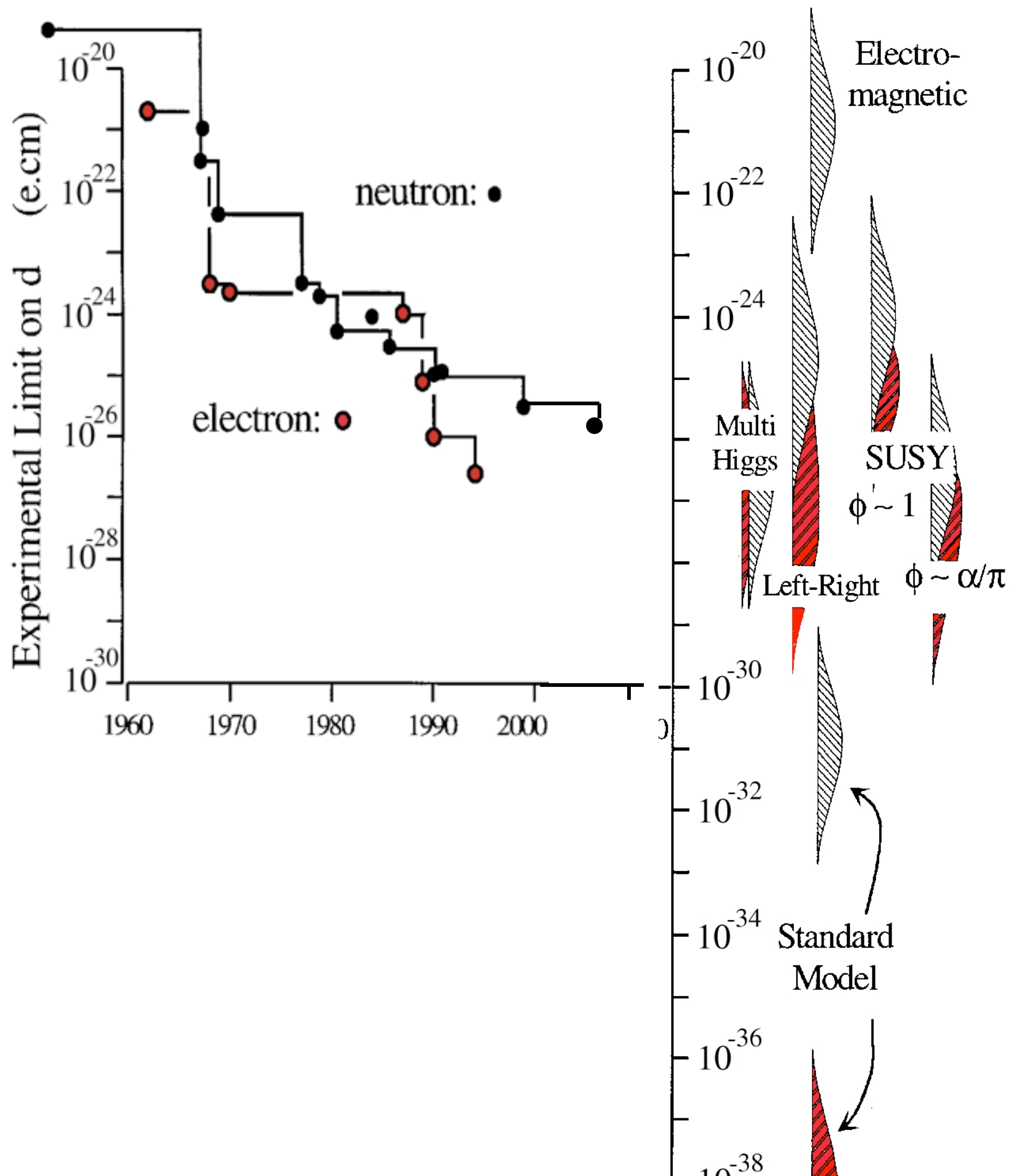


ILL Neutron EDM Experiment









Experimental Limit on d (e.cm)
neutron: ●
electron: ●
1960
1970
1980
1990
2000
10^{-20}
10^{-22}
10^{-24}
10^{-26}
10^{-28}
10^{-30}
10^{-32}
10^{-34}
10^{-36}
10^{-38}
Electro-
magnetic
Multi
Higgs
Left-Right
SUSY
$\phi \sim 1$
$\phi \sim \alpha/\pi$
Standard
Model

The Mysterious Neutrino

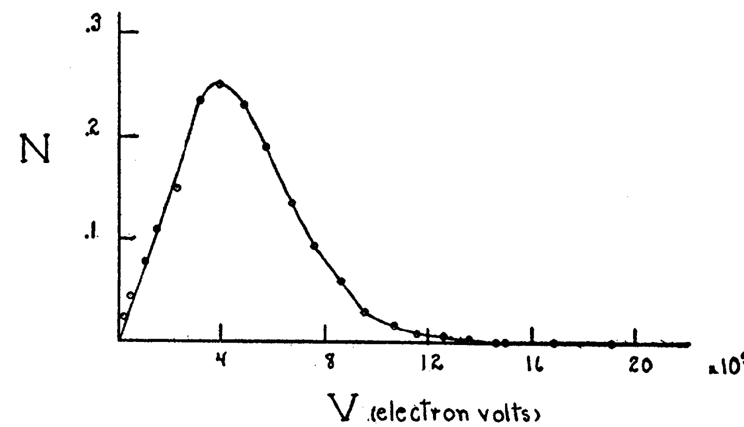


FIG. 5. Energy distribution curve of the beta-rays.

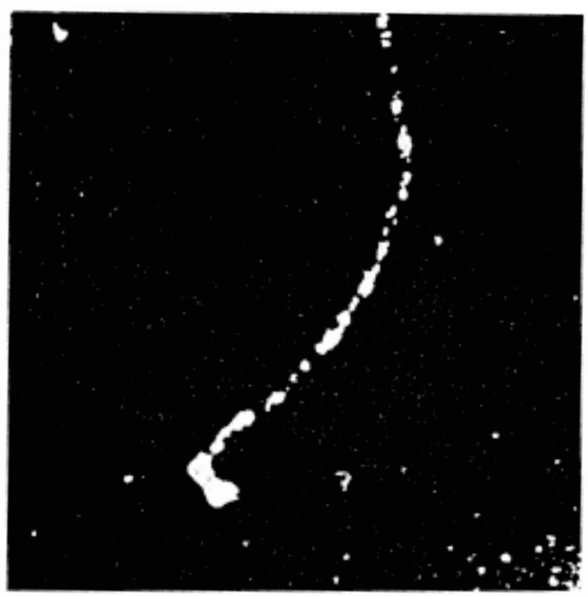
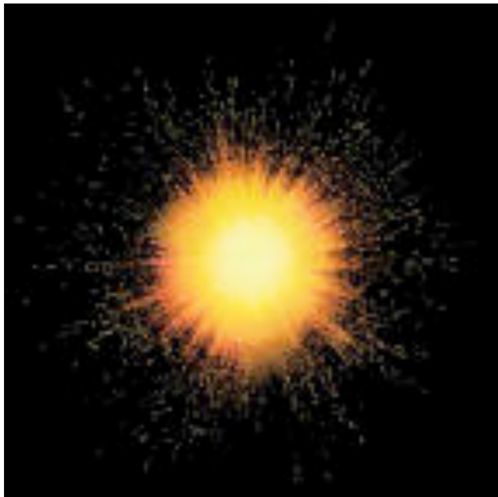


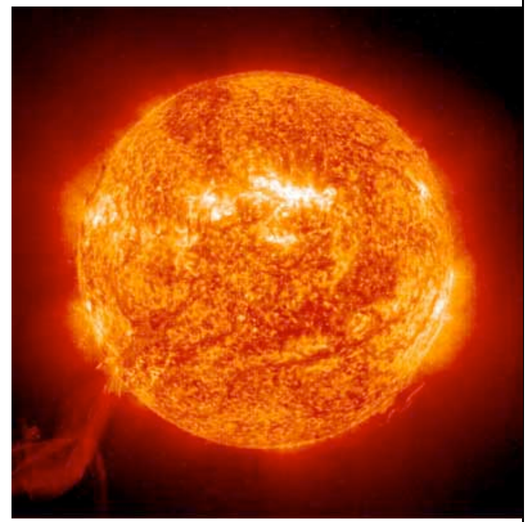
Fig. 1.2. Cloud chamber picture of the decay of He⁶ (Csikai et al. [1958]).

$^{6}He \rightarrow {}^{6}Li + e^{-} + \bar{\nu}$



Neutrinos are all around

Big-Bang neutrinos ~ 0.0004 eV



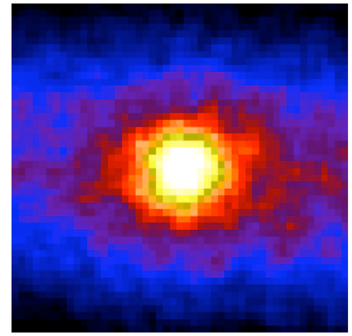
Neutrinos from the Sun < 20 MeV
depending of their origin.

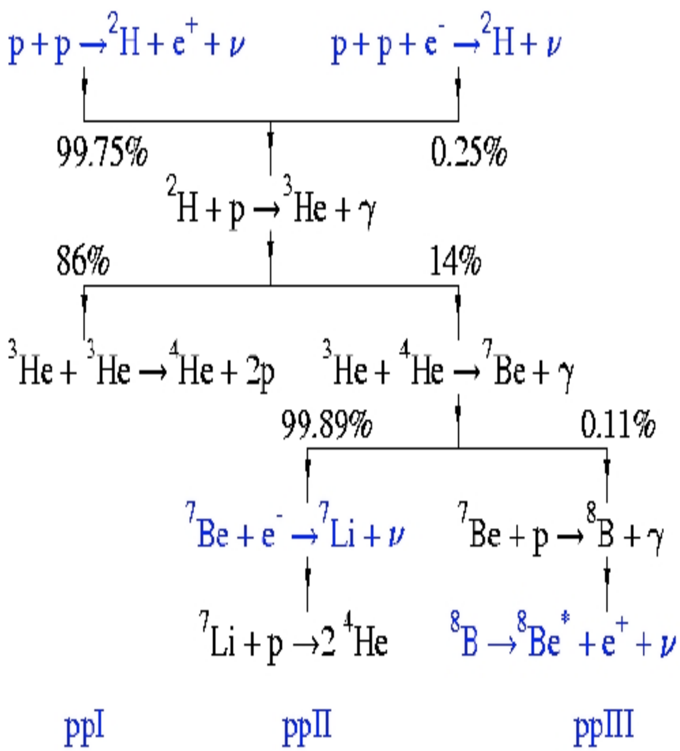
Atmospheric neutrinos ~ GeV

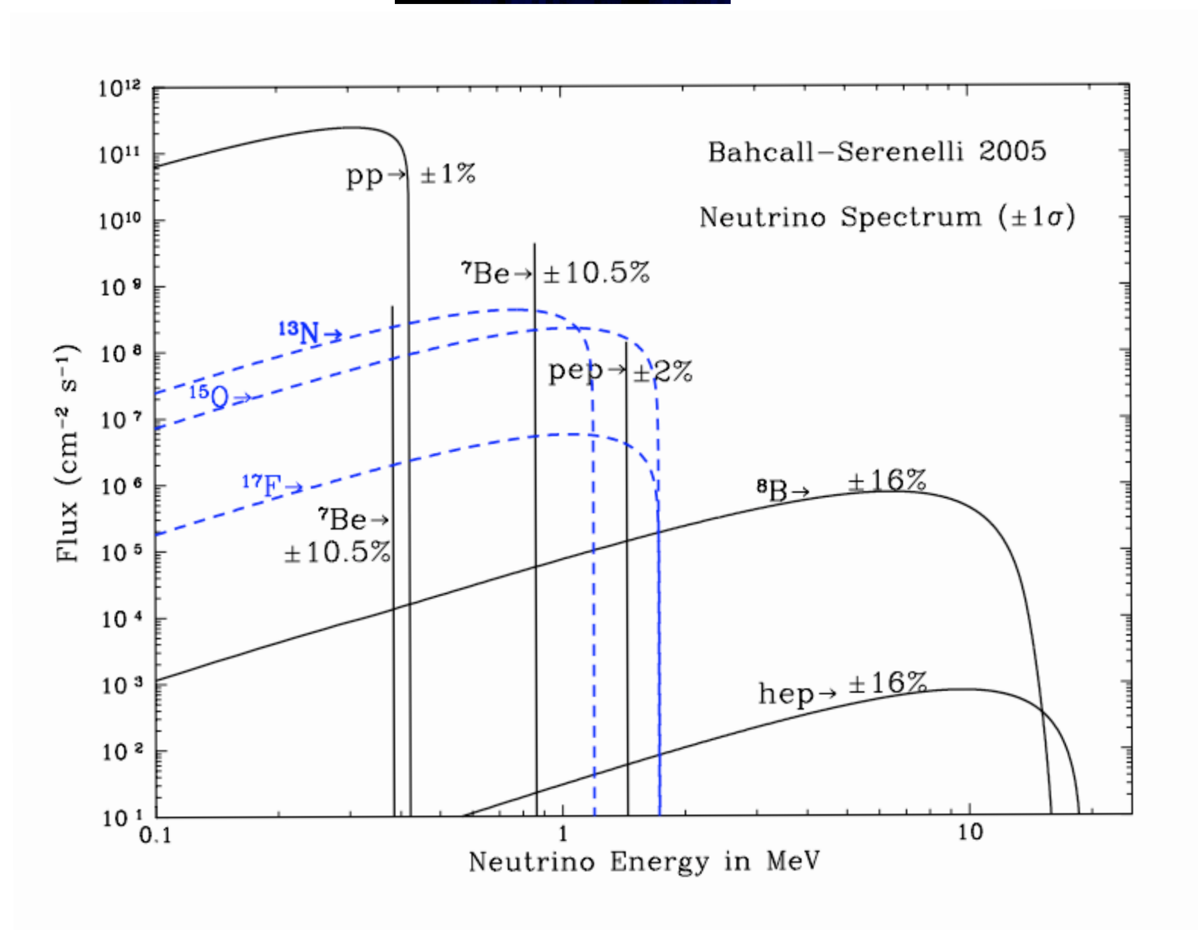
Antineutrinos from nuclear reactors < 10.0 MeV

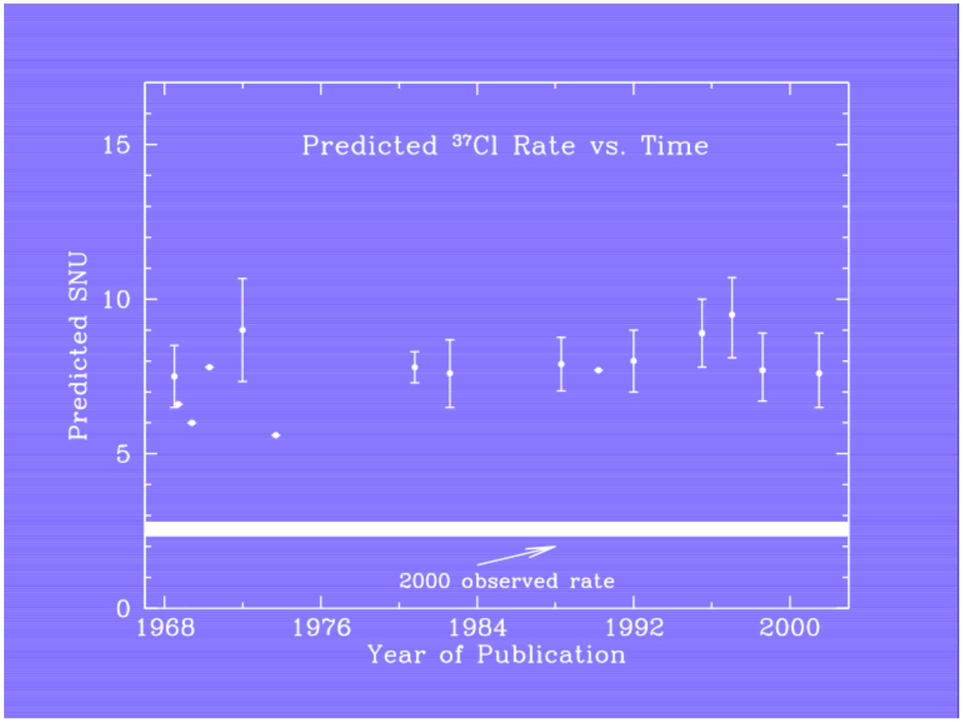
Neutrinos from accelerators up to GeV (10^9 eV)

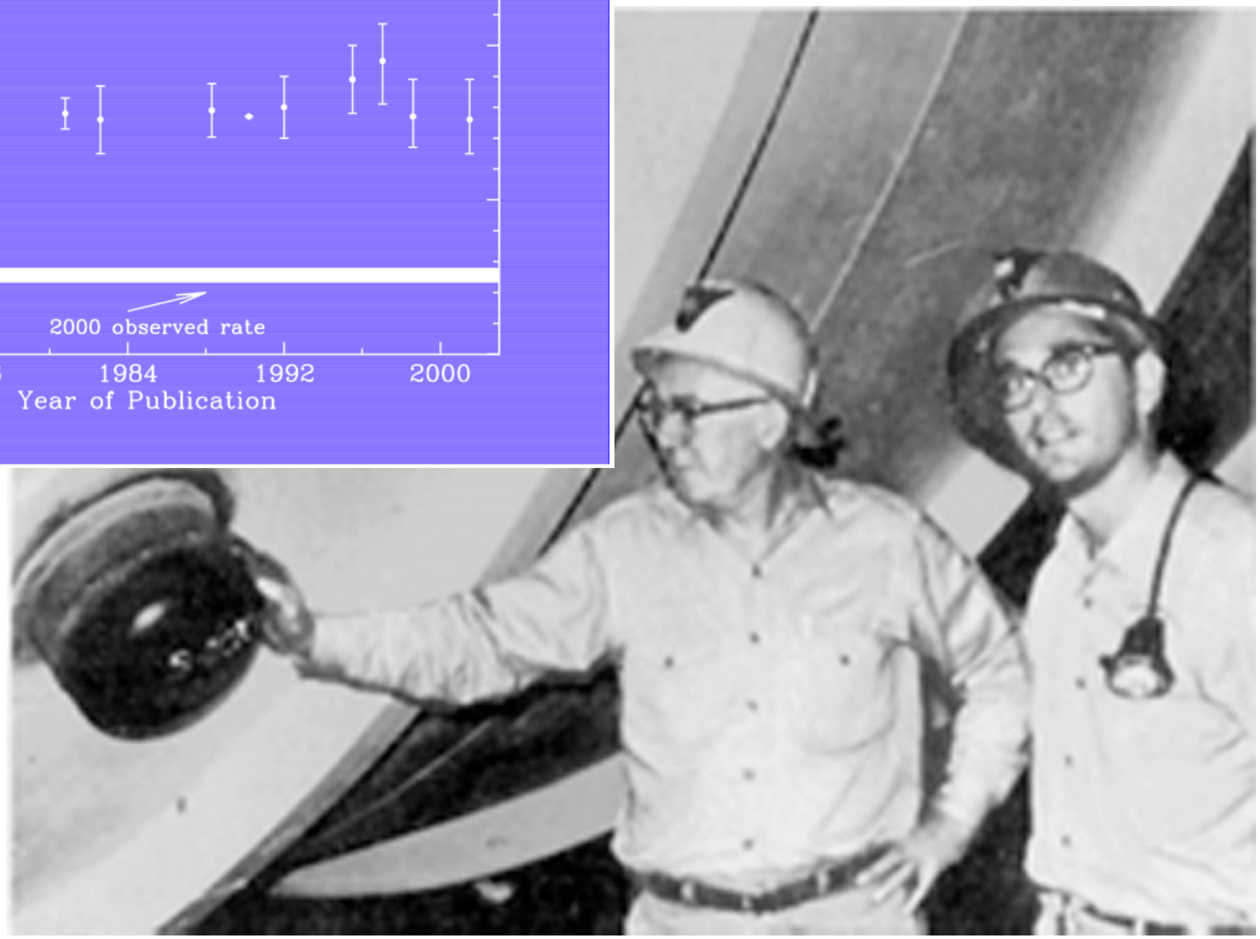
Solar Nucleosynthesis









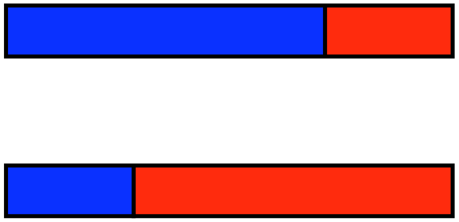


Ray Davis and John Bahcall

Essentials of Neutrino Oscillations

m_2c^2

m_1c^2



$$|\nu_e> = |\psi_{\nu_e}(0)> = \cos\theta\,|\nu_1> + \sin\theta\,|\nu_2>$$

$$|\psi_{\nu_e}(t)> = \cos\theta e^{-\frac{im_1c^2t}{\hbar}}\,|\nu_1> + \sin\theta e^{-\frac{im_2c^2t}{\hbar}}\,|\nu_2>$$

$$P_{ee}(t) = \left|<\psi_{\nu_e}(0)\,|\psi_{\nu_e}(t)>\right|^2 = \left|\cos^2\theta e^{-\frac{im_1c^2t}{\hbar}} + \sin^2\theta e^{-\frac{im_2c^2t}{\hbar}}\right|^2$$

$$P_{ee}(t) = 1 - \sin^2 2\theta \sin^2\left(\frac{(m_2-m_1)c^2}{2\hbar}t\right)$$

$$t = \frac{t_{lab}}{\gamma} \approx \frac{L}{\gamma c} \qquad \gamma = \frac{E}{mc^2} \qquad m = \frac{m_1+m_2}{2}$$

$$P_{ee}(L) = 1 - \sin^2 2\theta \sin^2\left(\frac{(m_2^2-m_1^2)c^4}{4\hbar c}\frac{L}{E}\right)$$

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

Leptons

$$\begin{pmatrix} e_L \\ \nu_{eL} \end{pmatrix} \qquad \begin{pmatrix} \mu_L \\ \nu_{\mu L} \end{pmatrix} \qquad \begin{pmatrix} \tau_L \\ \nu_{\tau L} \end{pmatrix}$$

$$|\nu_{eL}> = U_{e1}|\nu_{1L}> + U_{e2}|\nu_{2L}> + U_{e3}|\nu_{3L}>$$

Maki-Nakagawa-Sakata Matrix

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}$$

Discoveries in Neutrino Physics

Natural Sources

The Sun

^{37}Cl	Kamiokande
GALLEX	SuperKamiokande
SAGE	SNO

Atmospheric Neutinos

IMB	Kamiokande
Soudan	SuperKamiokande
MACRO	...

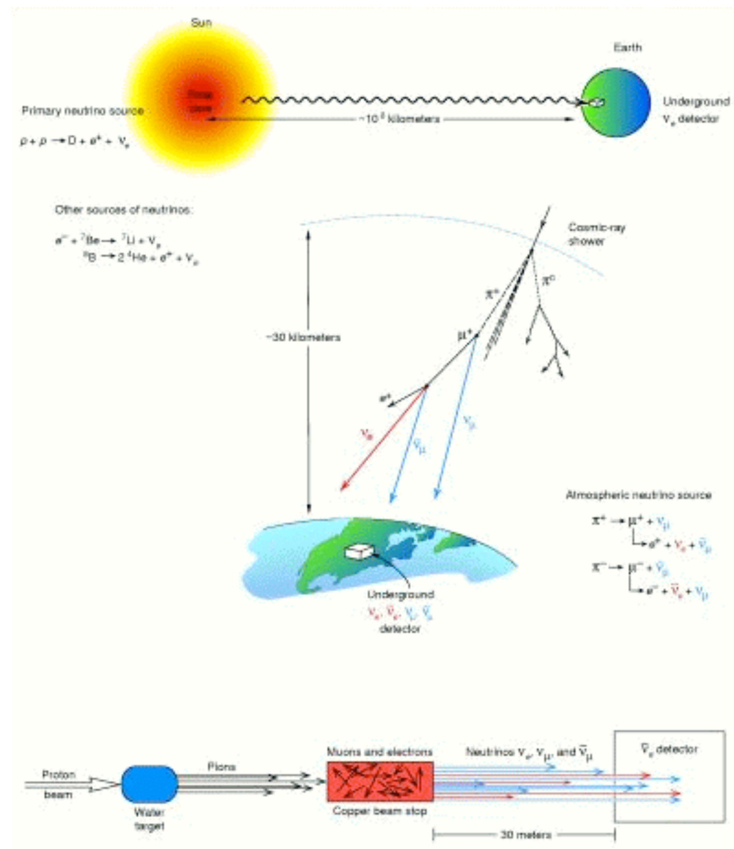
Man-Made Sources

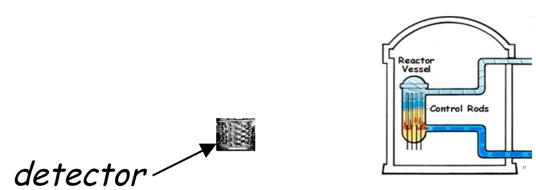
Accelerators

K2K	Chorus
Opera	LSND Miniboone
MINOS	...

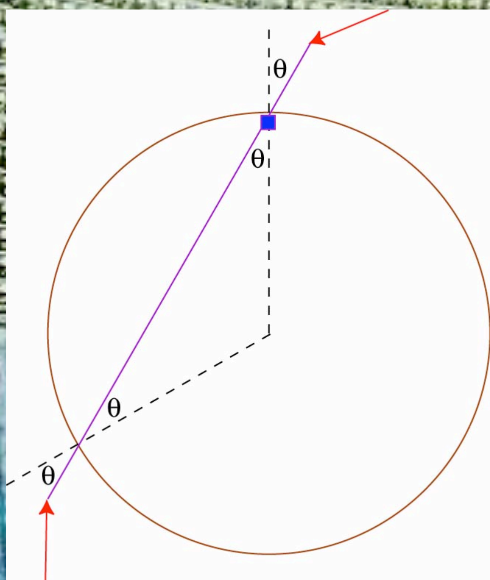
Nuclear Reactors

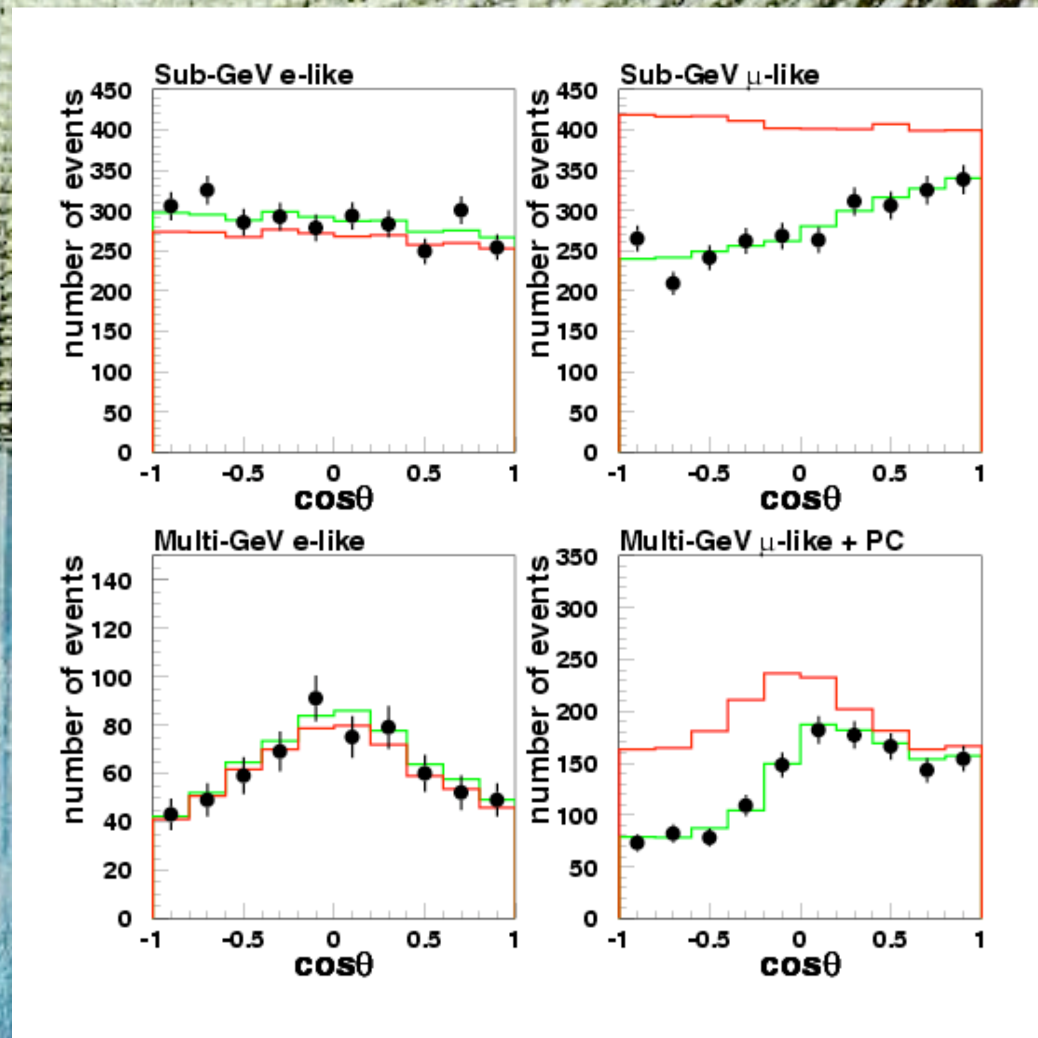
Bugey	Goesgen
ILL	Chooz
Palo Verde	KamLAND



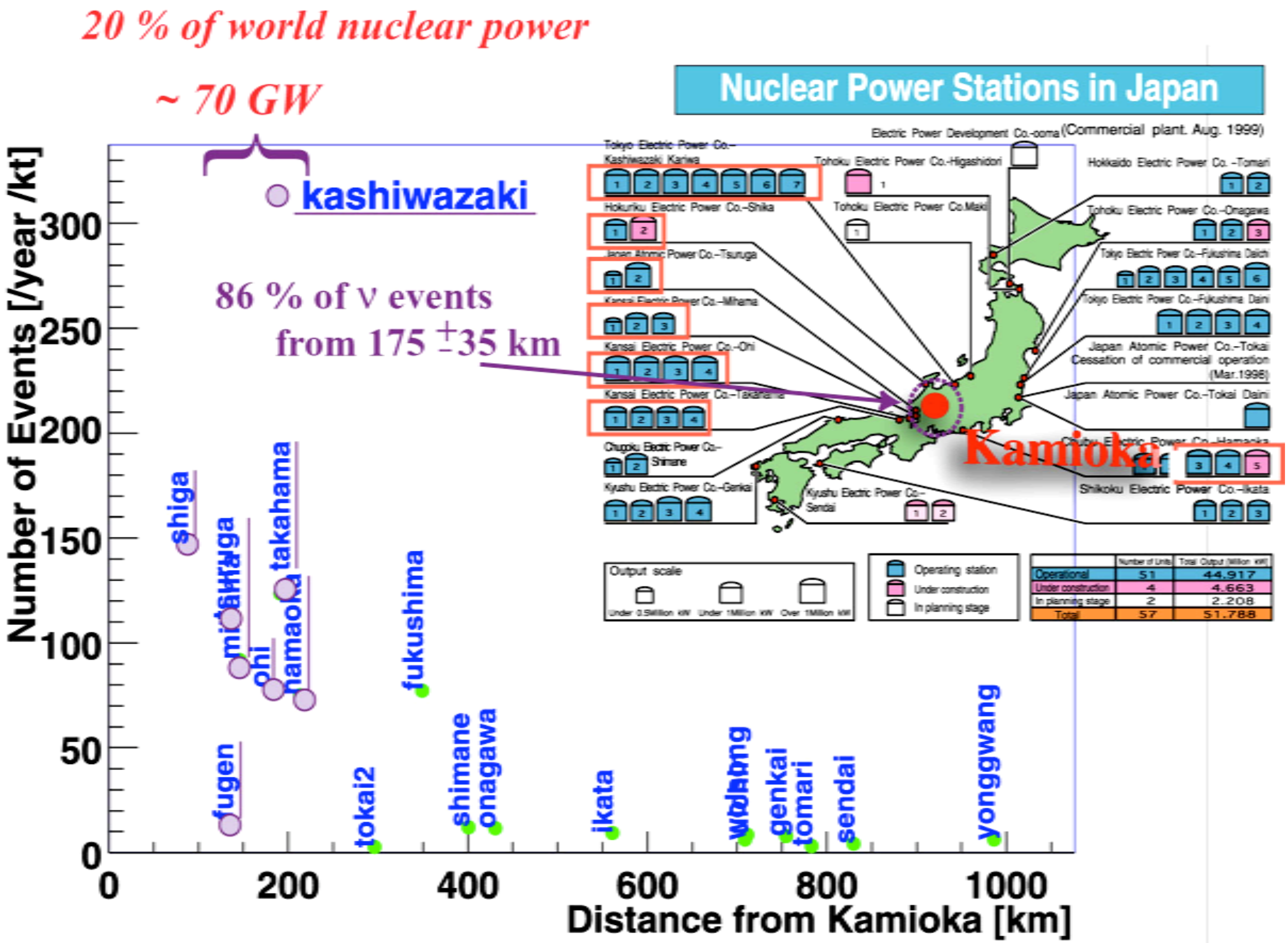


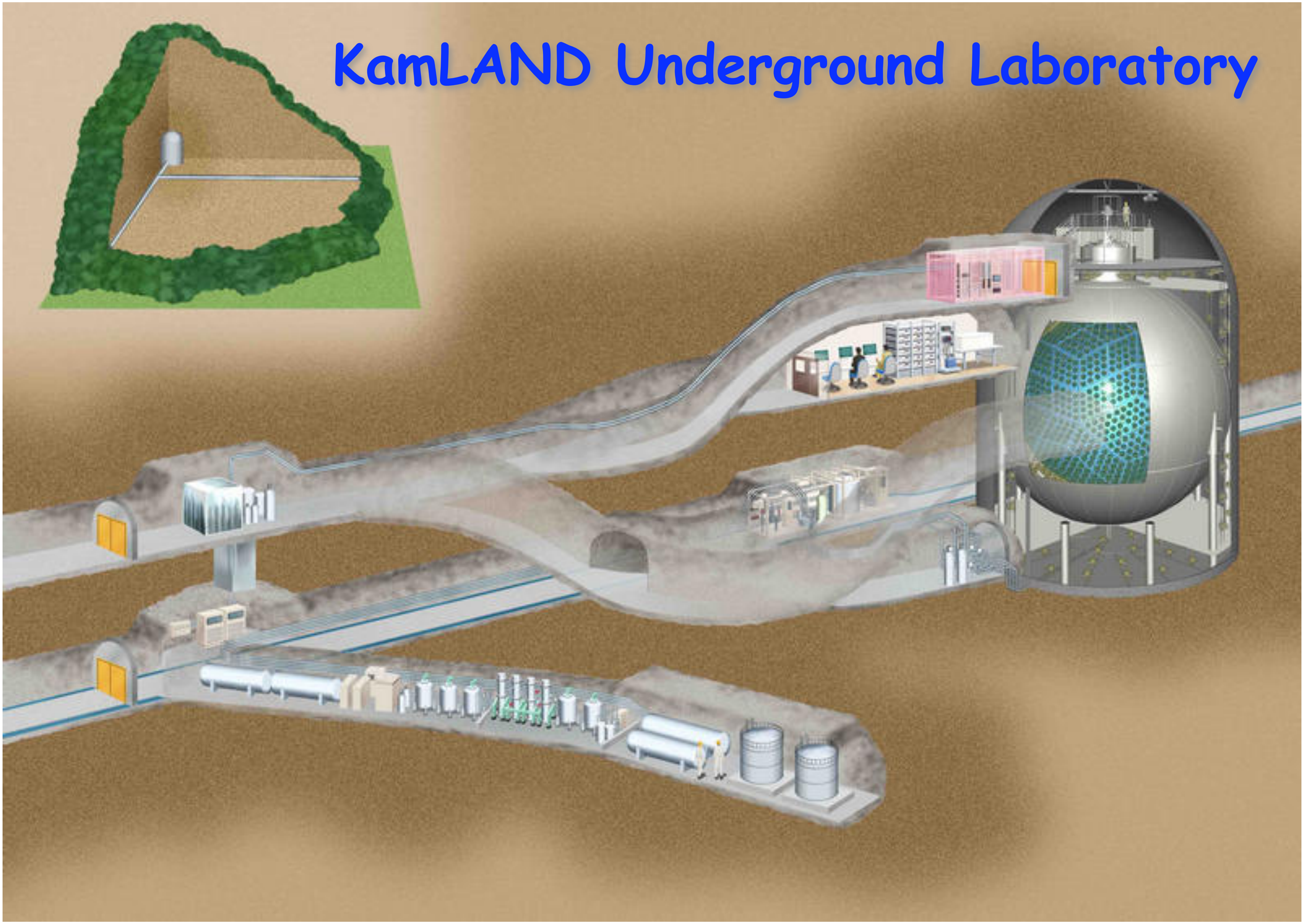
The SuperKamiokaNDE Light-Water Cherenkov Detector

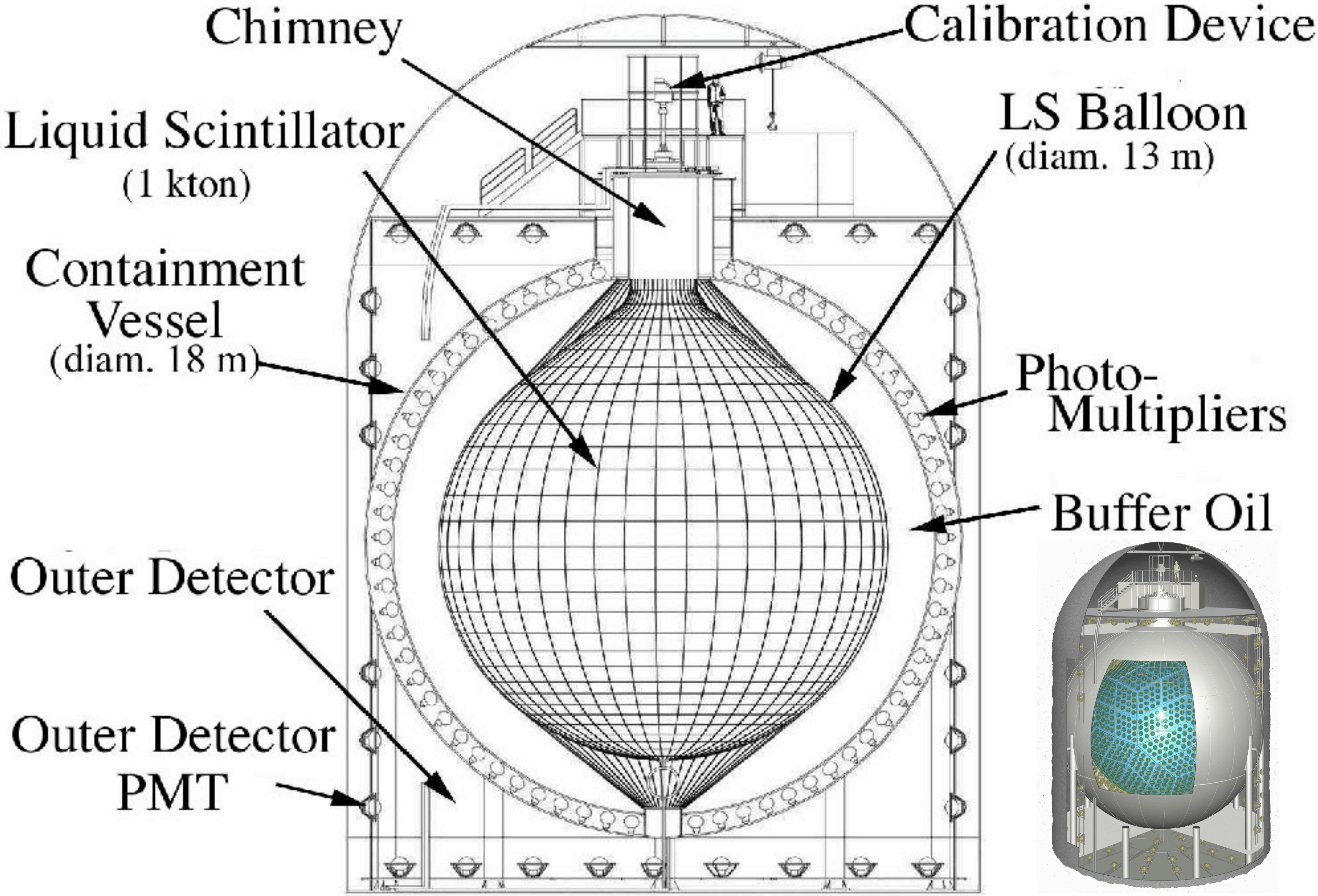




KamLAND Long Baseline Reactor Experiment

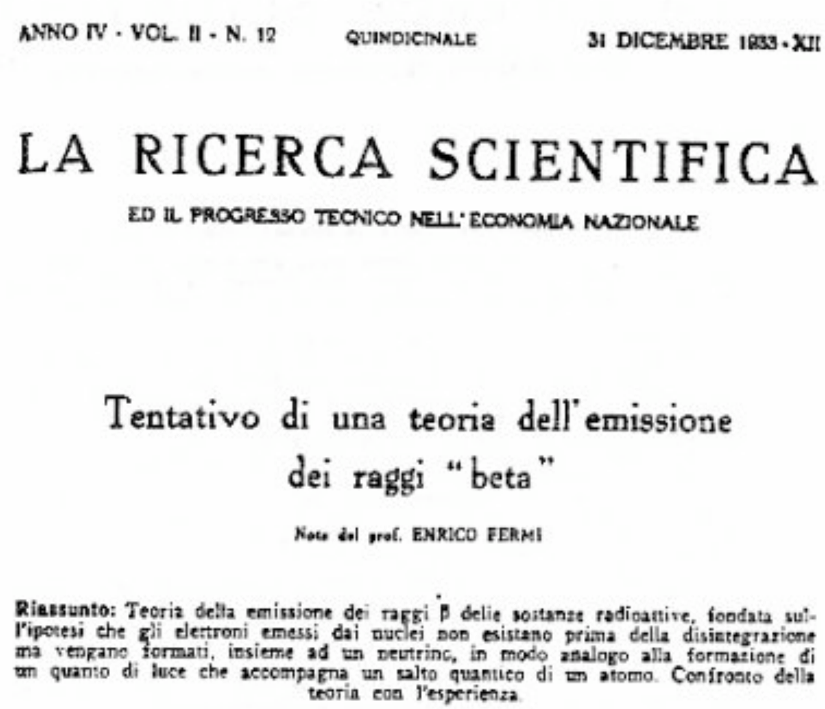



KamLAND Underground Laboratory



3.2 ton water veto

Fermi's Theory of the Weak Interaction


ANNO IV - VOL. II - N. 12 QUINDICINALE 31 DICEMBRE 1933 - XII

LA RICERCA SCIENTIFICA

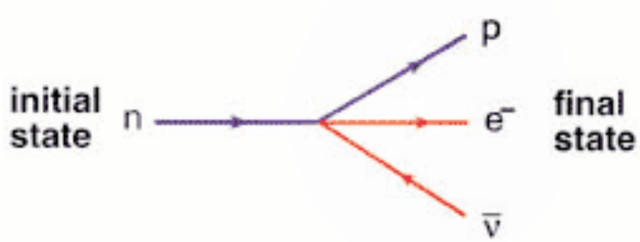
ED IL PROGRESSO TECNICO NELL'ECONOMIA NAZIONALE

Tentativo di una teoria dell'emissione dei raggi "beta"

Nota del prof. ENRICO FERMI

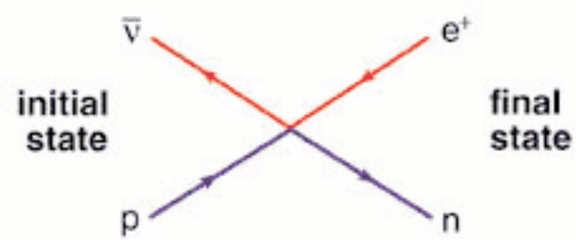
Riassunto: Teoria della emissione dei raggi β delle sostanze radioattive, fondata sull'ipotesi che gli elettroni emessi dai nuclei non esistono prima della disintegrazione ma vengano formati, insieme ad un neutrino, in modo analogo alla formazione di un quanto di luce che accompagna un salto quantico di un atomo. Confronto della teoria con l'esperienza.

Neutron Beta Decay



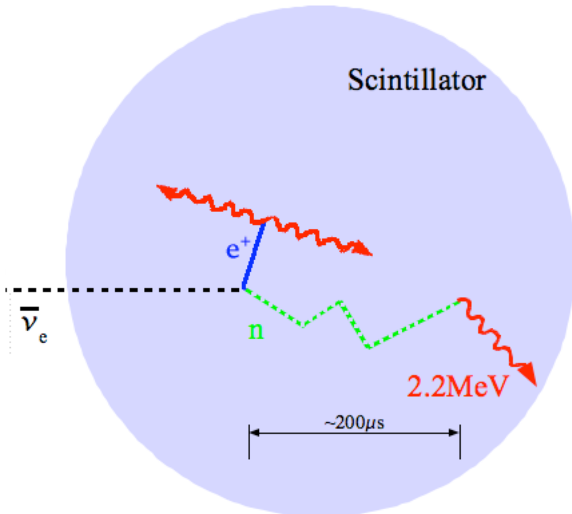
$$n \rightarrow p + e^{-} + \overline{\nu}$$

Inverse Beta Decay



$$\overline{\nu} + p \rightarrow n + e^{+}$$

First Direct Detection of the Neutrino

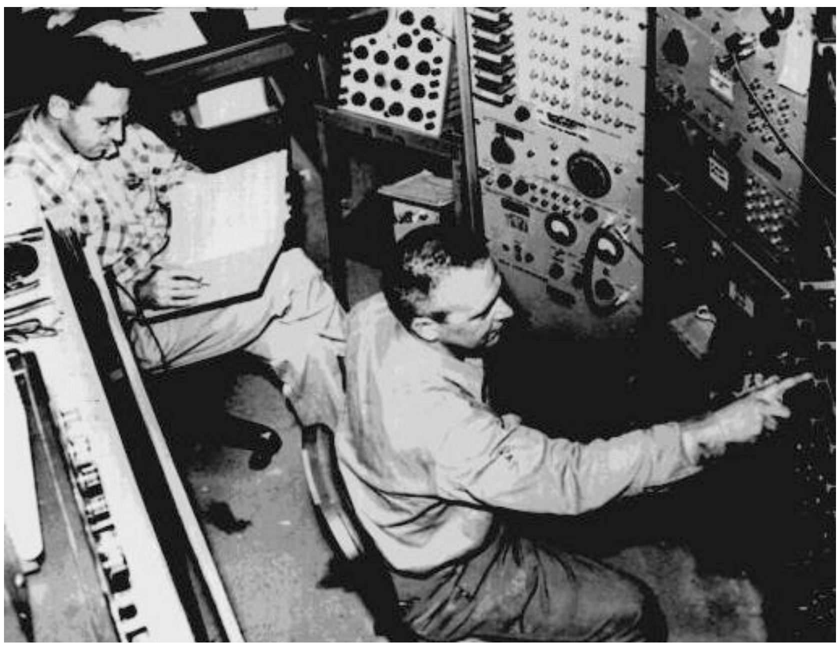


$$\bar{\nu}_e + p \rightarrow e^+ + n$$

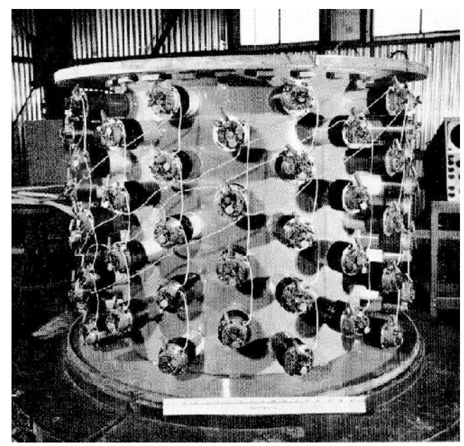
$$\tau \approx 200\ \mu s$$

$$n + p \rightarrow d + \gamma\,(2.2\ MeV)$$

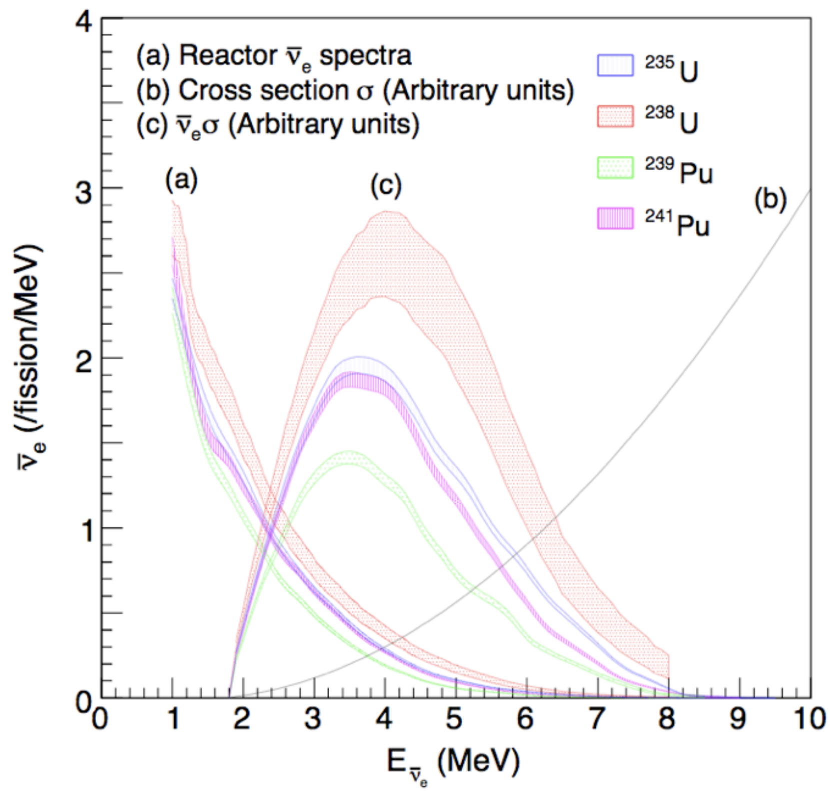
$$E_{prompt} \cong E_\nu - \overline{E_n} - 0.8\ MeV$$



Reines and Cowan 1956

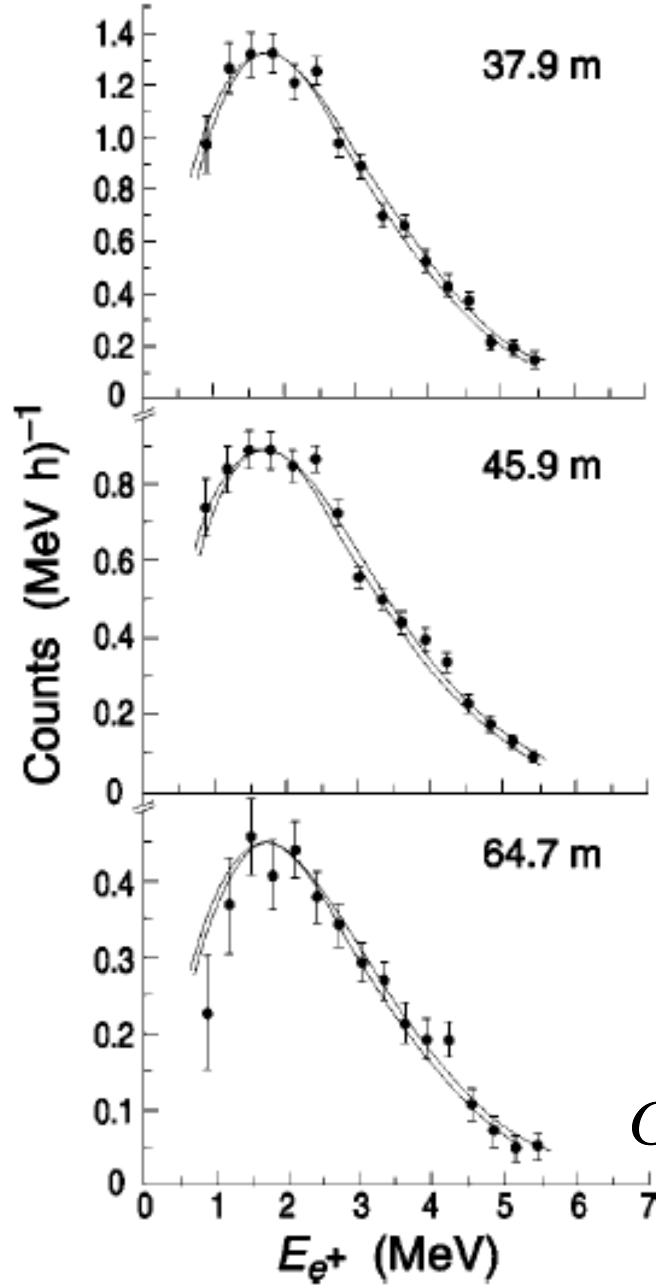


Neutrino Spectrum

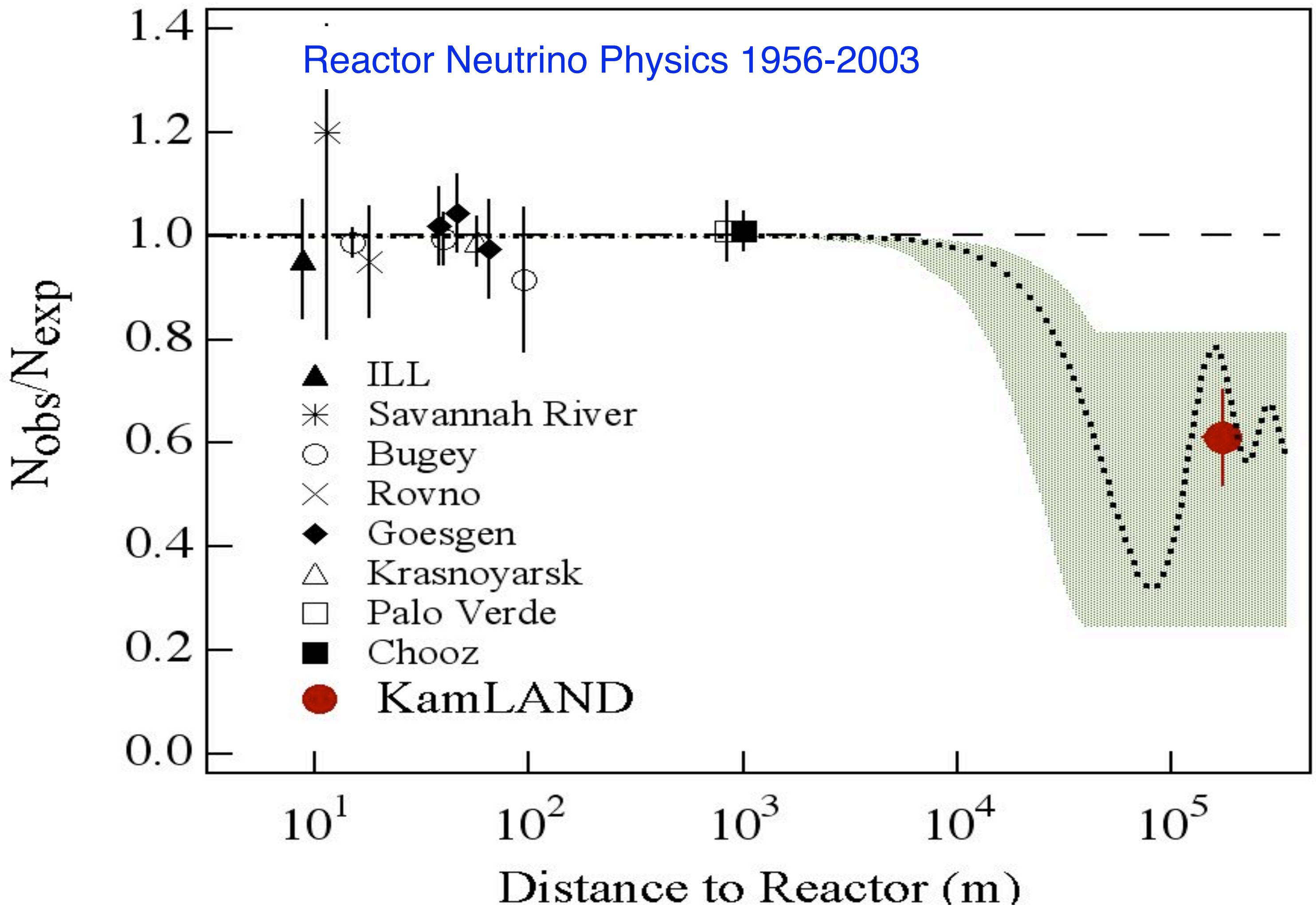


Nakajima NIMA 569, 837-844 (2006)

Positron Spectrum

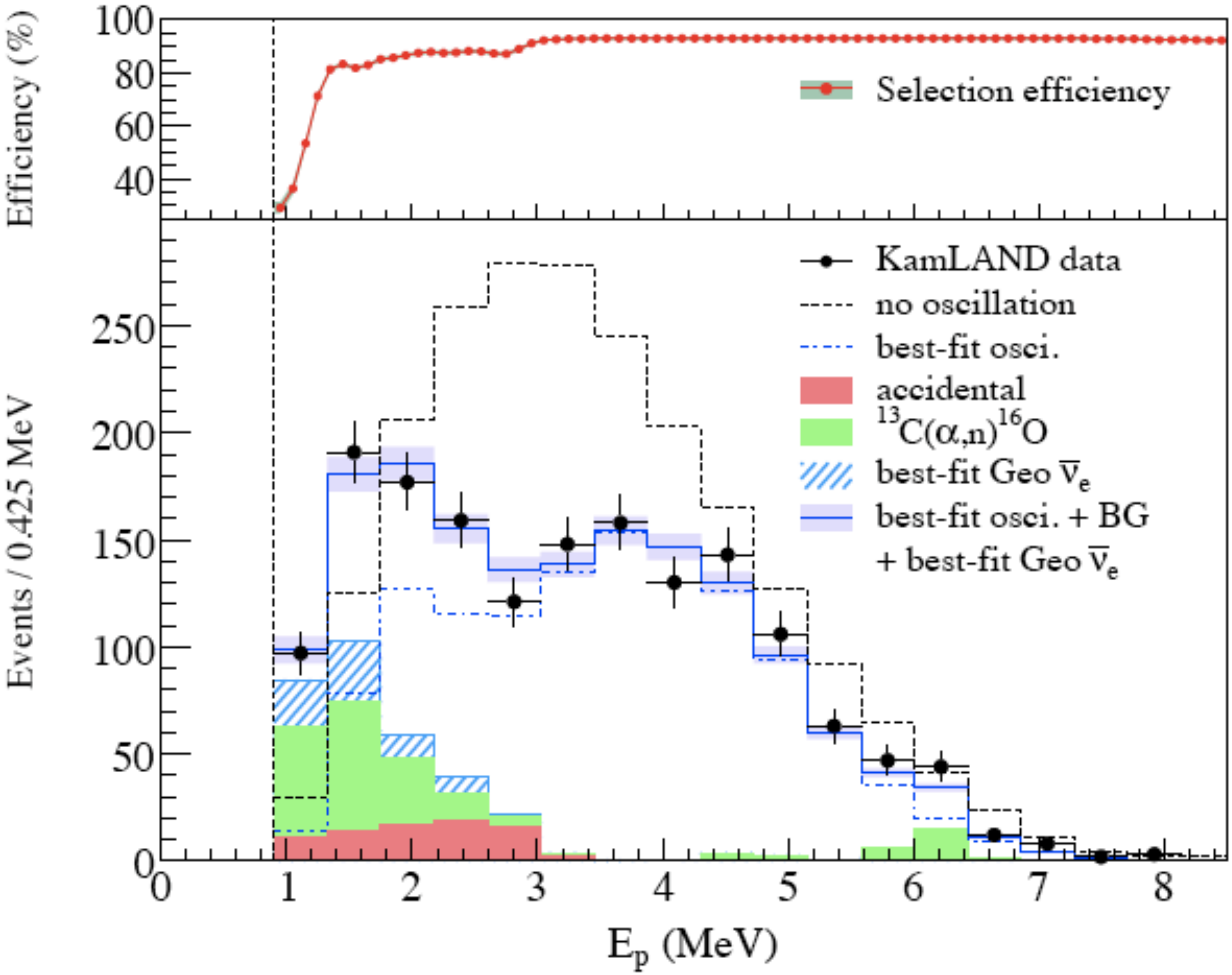


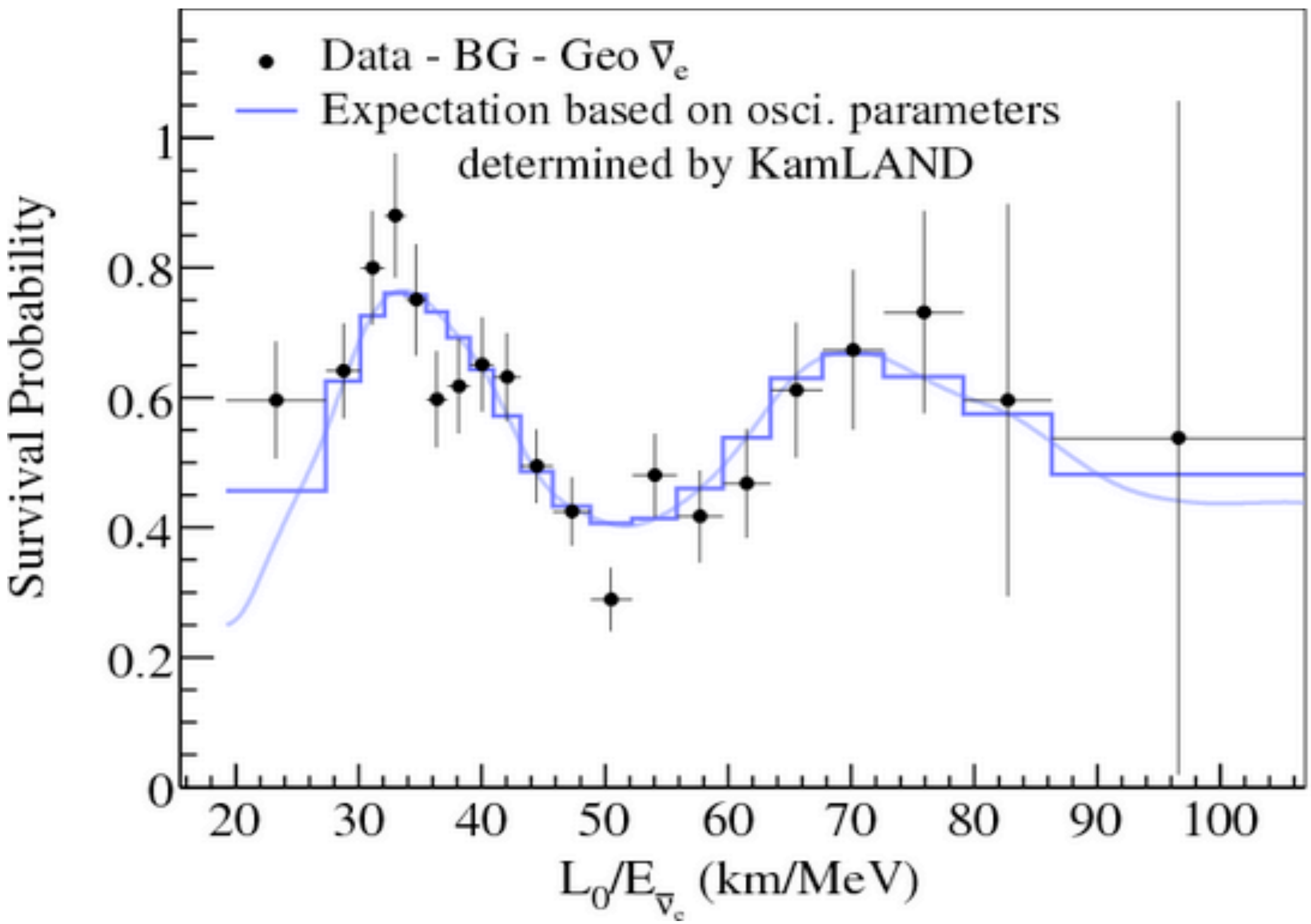
Goesgen



Reactor Neutrino Physics 1956-2003
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
N_{obs}/N_{exp}
ILL
Savannah River
Bugey
Rovno
Goesgen
Krasnoyarsk
Palo Verde
Chooz
KamLAND
10^1
10^2
10^3
10^4
10^5
Distance to Reactor (m)

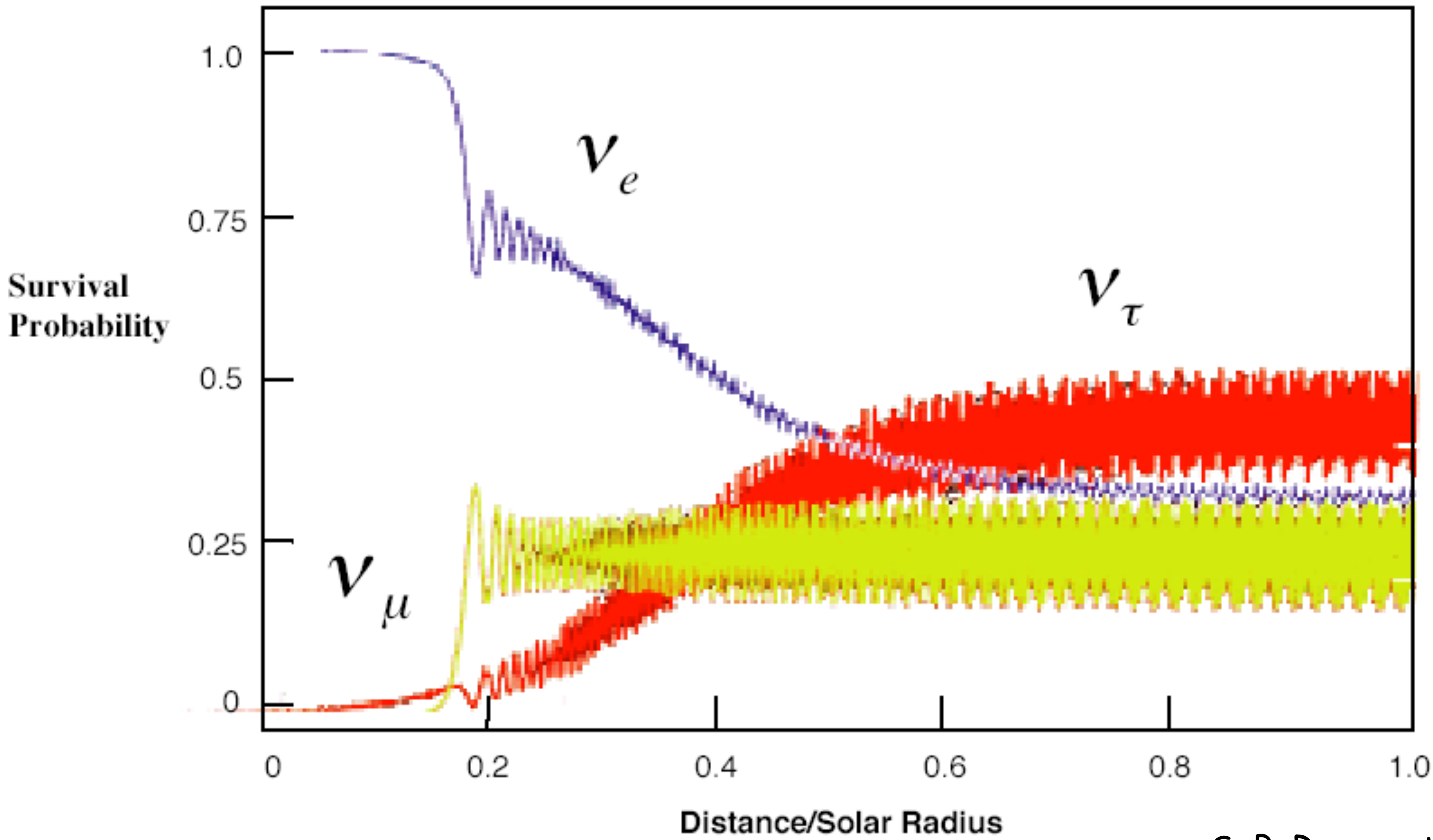
2008 Data Set



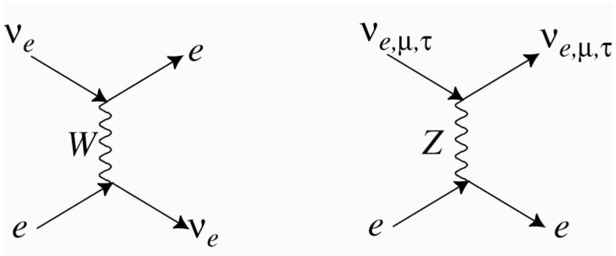


Data - BG - Geo $\bar{\nu}_e$
Expectation based on osci. parameters
determined by KamLAND
Survival Probability
0
0.2
0.4
0.6
0.8
1
20
30
40
50
60
70
80
90
100
$L_0/E_{\bar{\nu}_e}$ (km/MeV)

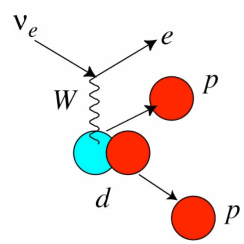
MSW Effect



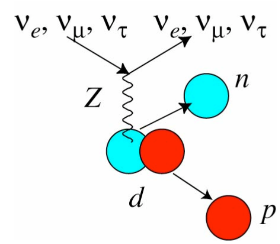
S. P. Rosen et al



$$\nu_x + e^- \rightarrow \nu_x + e^- \quad \text{ES}$$



$$\nu_e + d \rightarrow p + p + e^- \quad \text{CC}$$



$$\nu_x + d \rightarrow p + n + \nu_x \quad \text{NC}$$

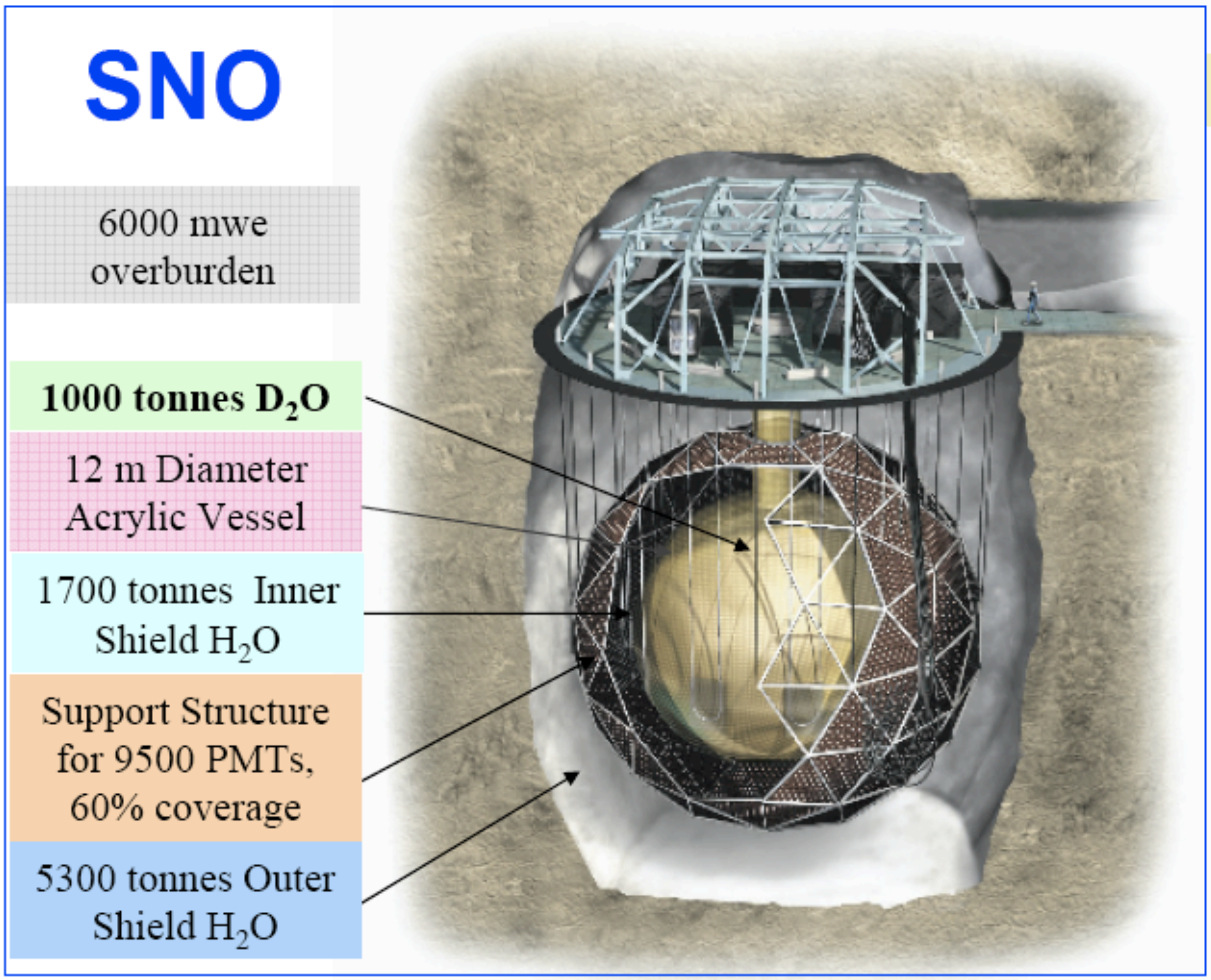


Image courtesy National Geographic

3 Reactions:

$$\nu_x + e^- \rightarrow \nu_x + e^- \quad \text{ES}$$

$$\nu_e + d \rightarrow p + p + e^- \quad \text{CC}$$

$$\nu_x + d \rightarrow p + n + \nu_x \quad \text{NC}$$

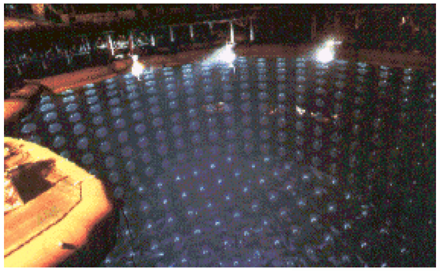
3 neutron detection methods:

$$n + d \rightarrow t + \gamma + 6.25 \text{ MeV}$$

$$n + {}^{35}Cl \rightarrow {}^{36}Cl + \gamma + 8.6 \text{ MeV}$$

$$n + {}^{3}He \rightarrow p + t + 0.76 \text{ MeV}$$

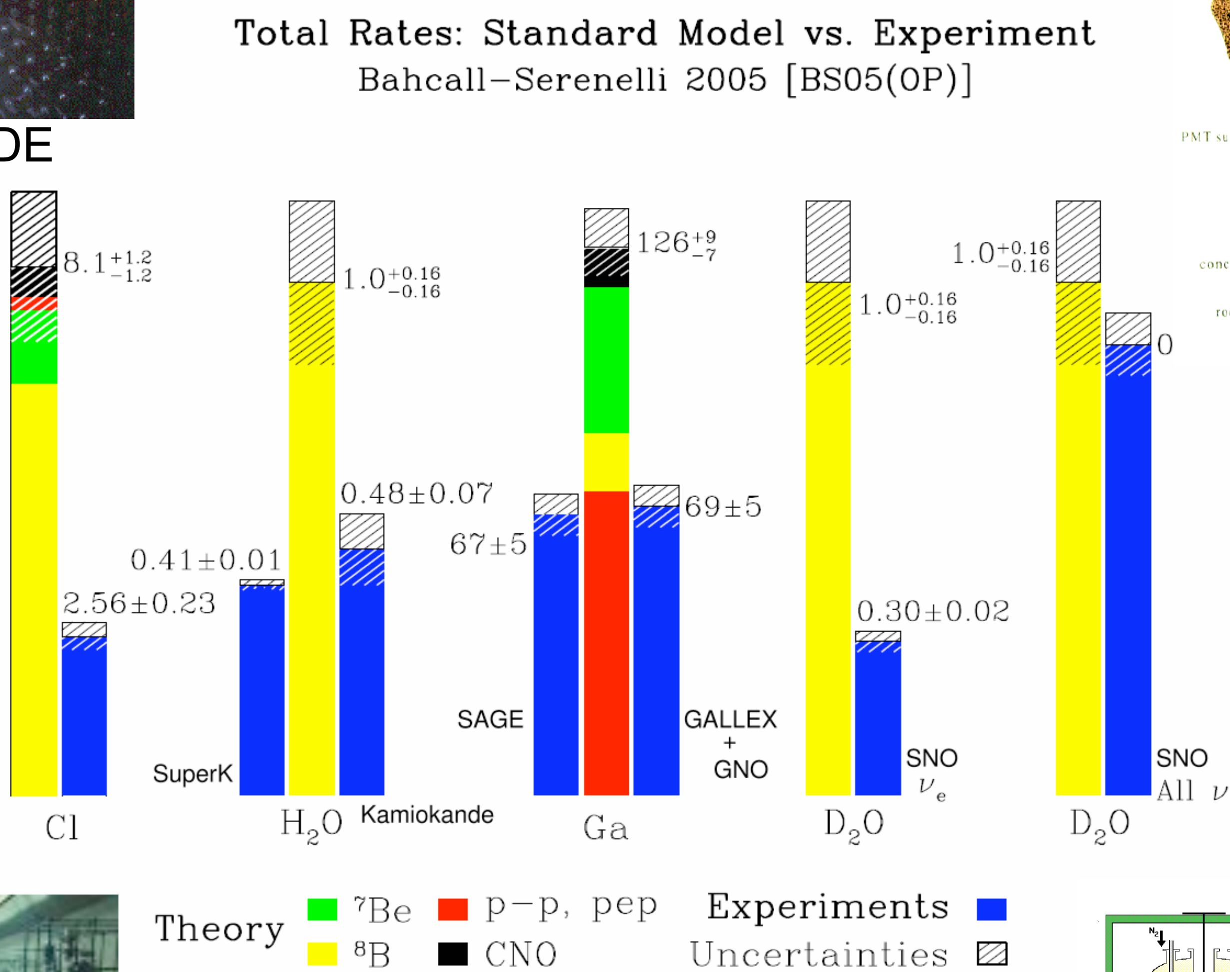
Present Accounting

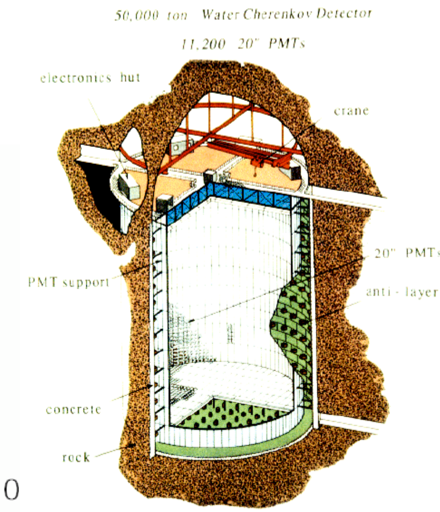


KamiokaNDE

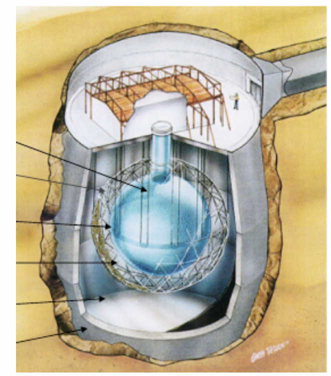
Chlorine

SAGE

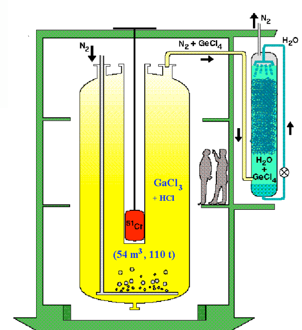




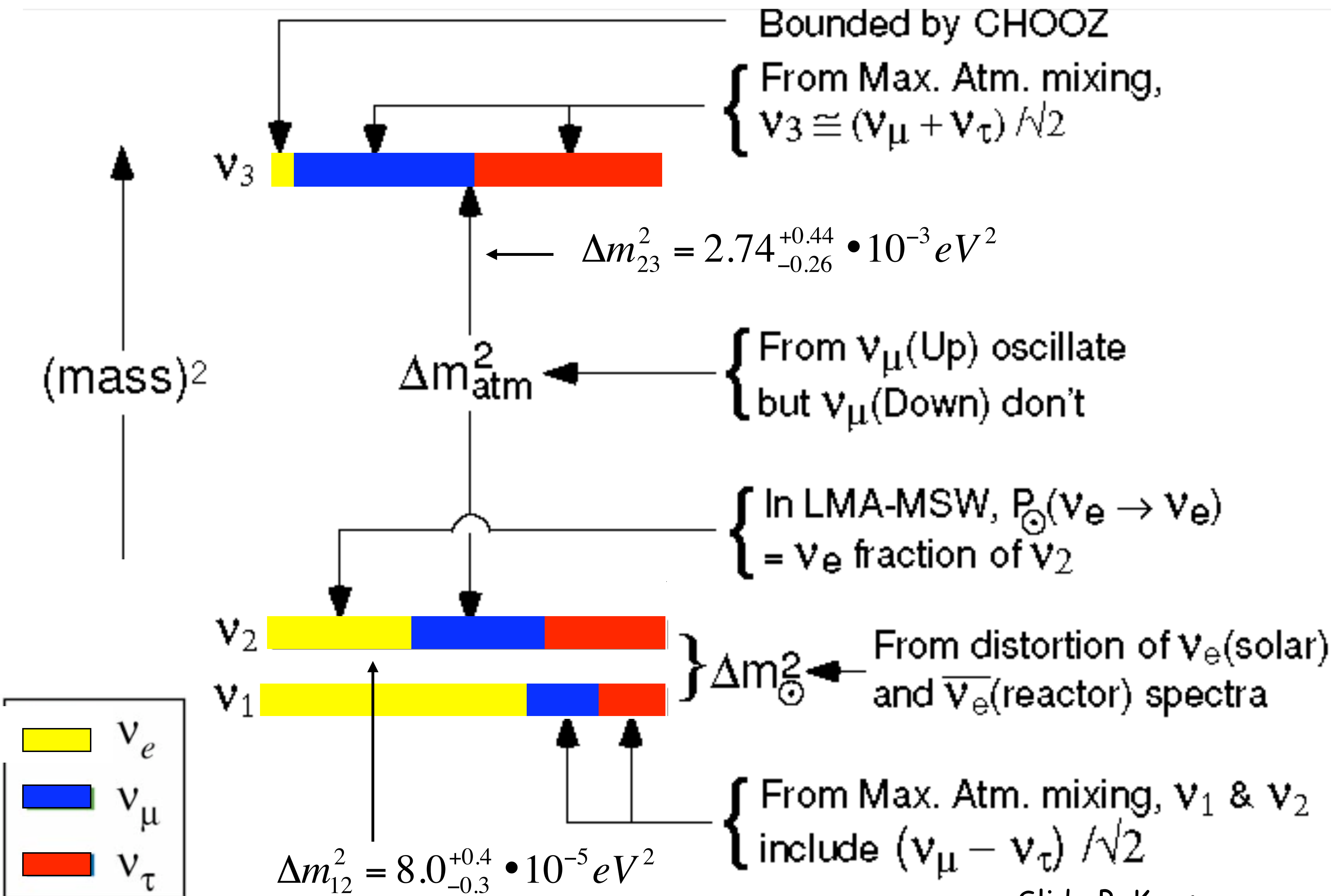
SuperK



SNO

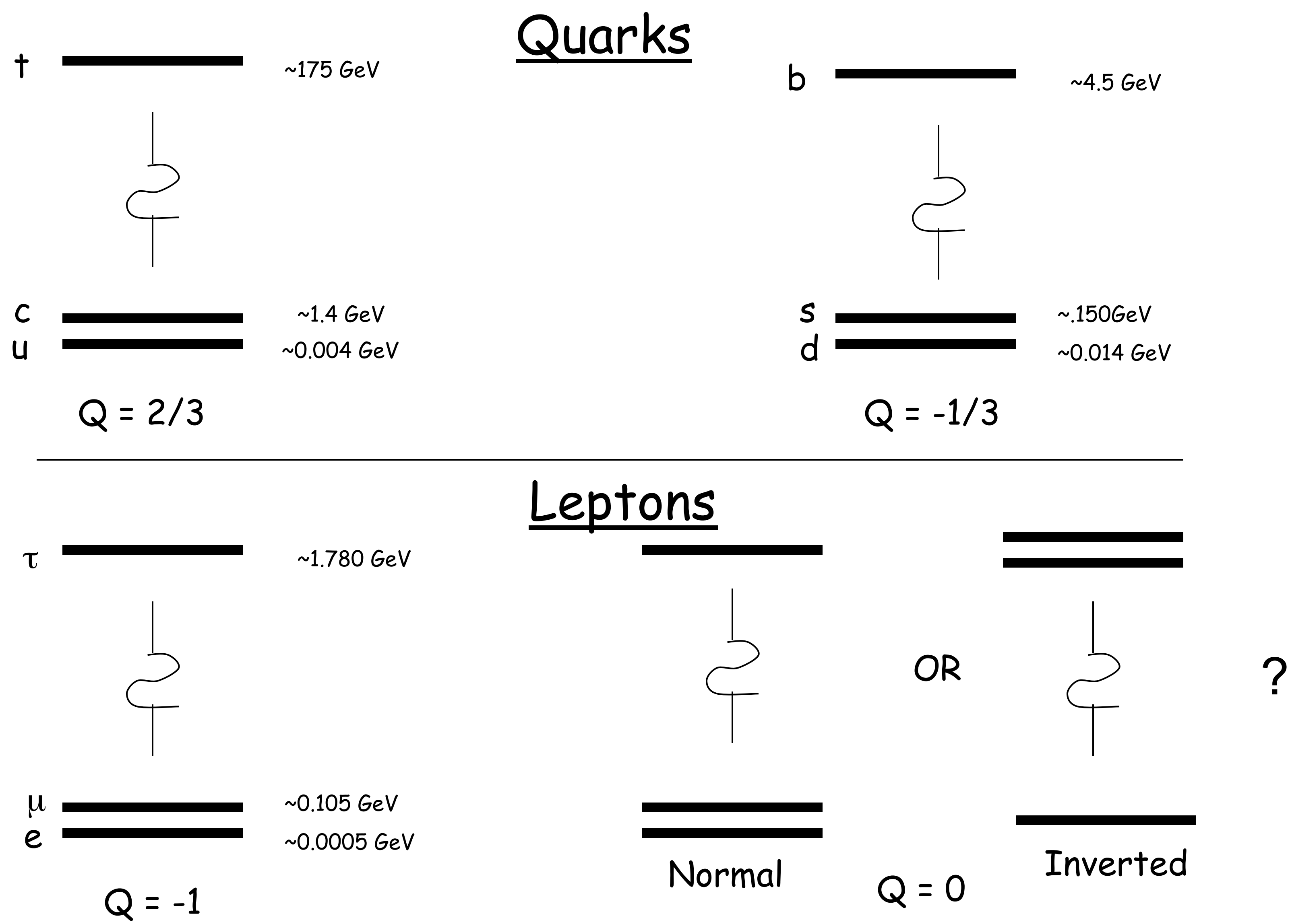


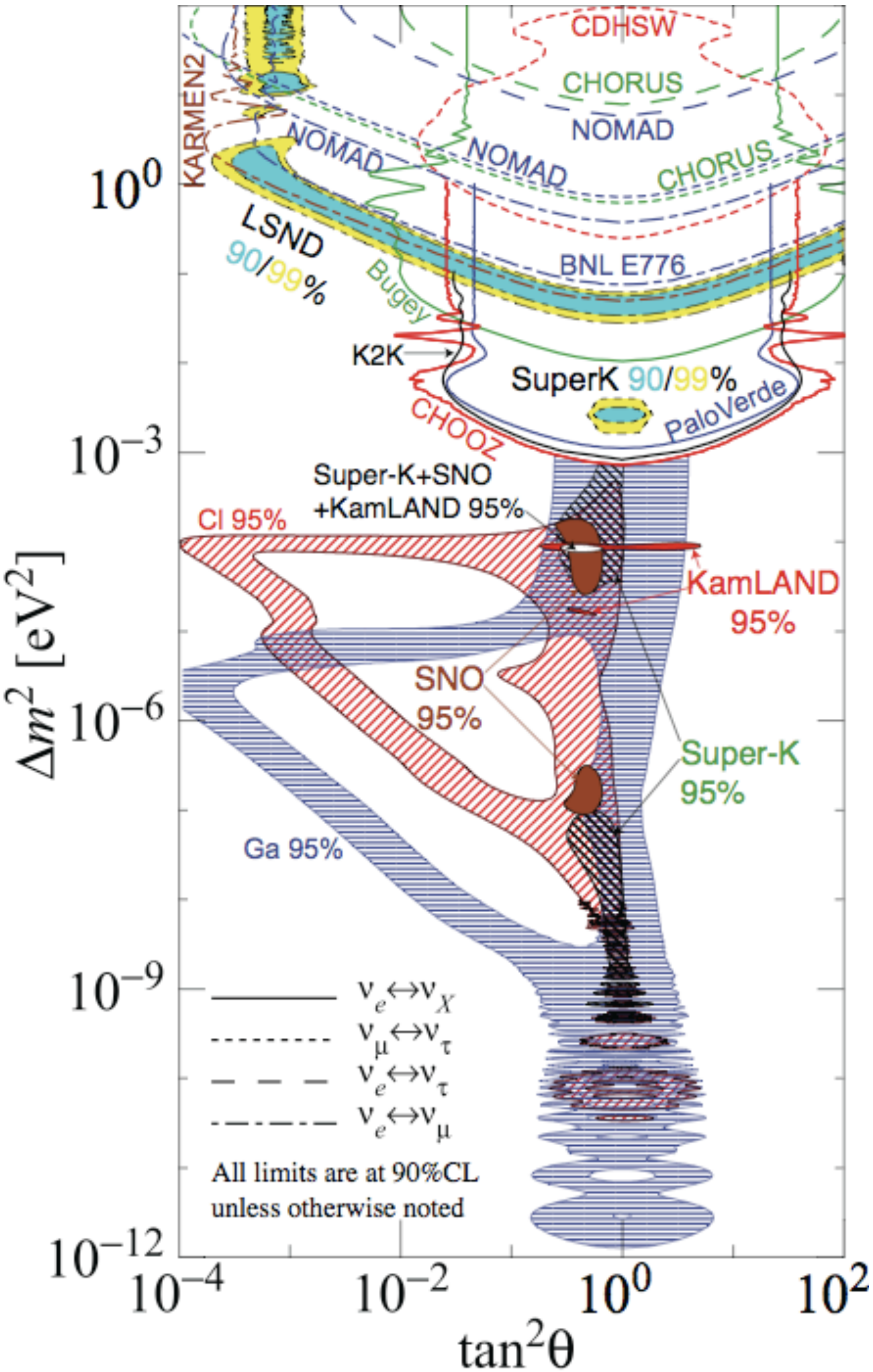
GALLEX



Slide B. Kayser

Mass Hierarchy





CDHSW
CHORUS
NOMAD
KARMEN2
NOMAD
NOMAD
CHORUS
LSND
90/99%
Bugey
BNL E776
K2K
SuperK 90/99%
PaloVerde
CHOOZ
Super-K+SNO
+KamLAND 95%
Cl 95%
KamLAND
95%
SNO
95%
Super-K
95%
Ga 95%
$\nu_e \leftrightarrow \nu_X$
$\nu_\mu \leftrightarrow \nu_\tau$
$\nu_e \leftrightarrow \nu_\tau$
$\nu_e \leftrightarrow \nu_\mu$
All limits are at 90%CL
unless otherwise noted
Δm^2 [eV^2]
10^0
10^{-3}
10^{-6}
10^{-9}
10^{-12}
10^{-4}
10^{-2}
10^0
10^2
$\tan^2\theta$

Open Questions

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}} \sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}} \sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}$$

$\theta_{23} = (45 \pm 7)^\circ$

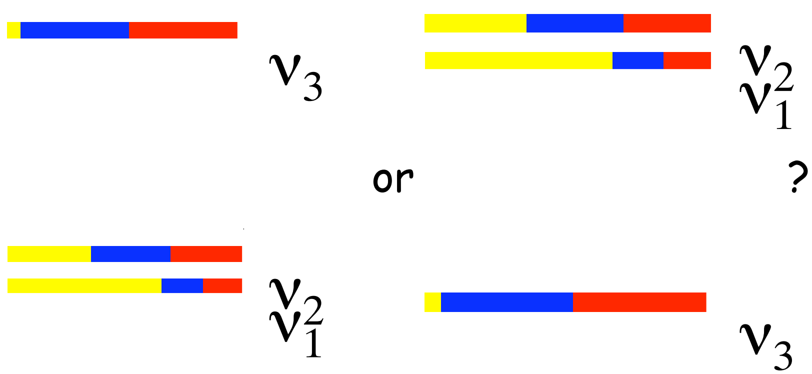
$\theta_{13} < 13^\circ$

$\delta = ?$

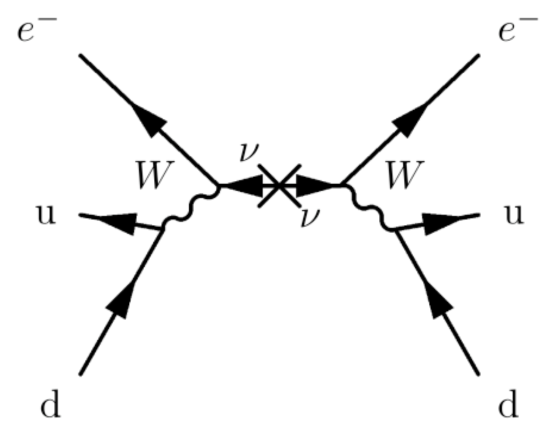
$\theta_{12} = (33.9^{+2.4}_{-2.2})^\circ$

$\alpha = ?$

$\beta = ?$



Normal or Inverted?

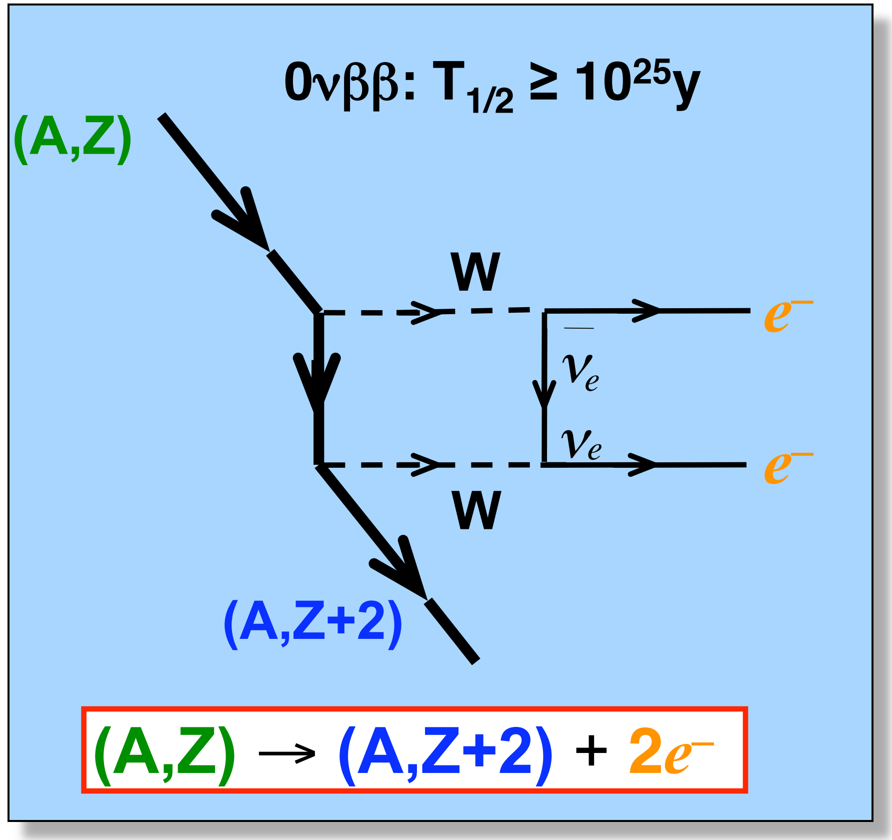


Majorana or Dirac?

Neutrino-less Double Beta Decay

0νββ *First suggested by Furry*

1937

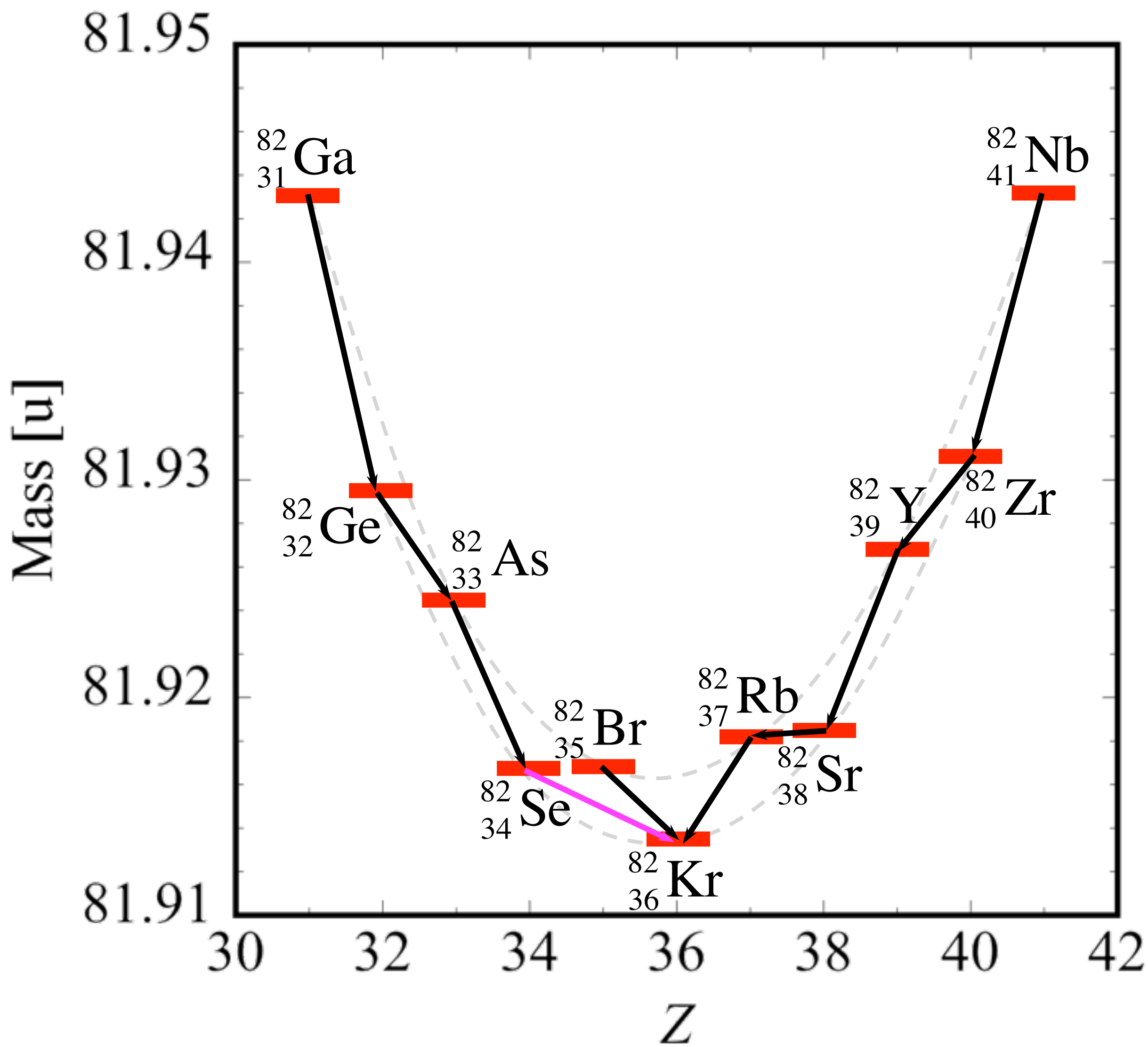


Bethe-Von Weizsacker semi-empirical mass relation

$$M(A,Z) = Zm_p + (A-Z)m_n - a_v A + a_s A^{2/3} + a_c Z^2 A^{-1/3} + a_a (A-2Z)^2 A^{-1} + \delta$$

$\delta = -a_p A^{-3/4}$ (even,even) or $+a_p A^{-3/4}$ (odd,odd) or 0 (even,odd)

a_p -> 33.5 MeV



Claimed Observation of 0νββ in ^{76}Ge

5 detectors of overall 10.96 kg enriched to 86%.
Most sensitive to date.

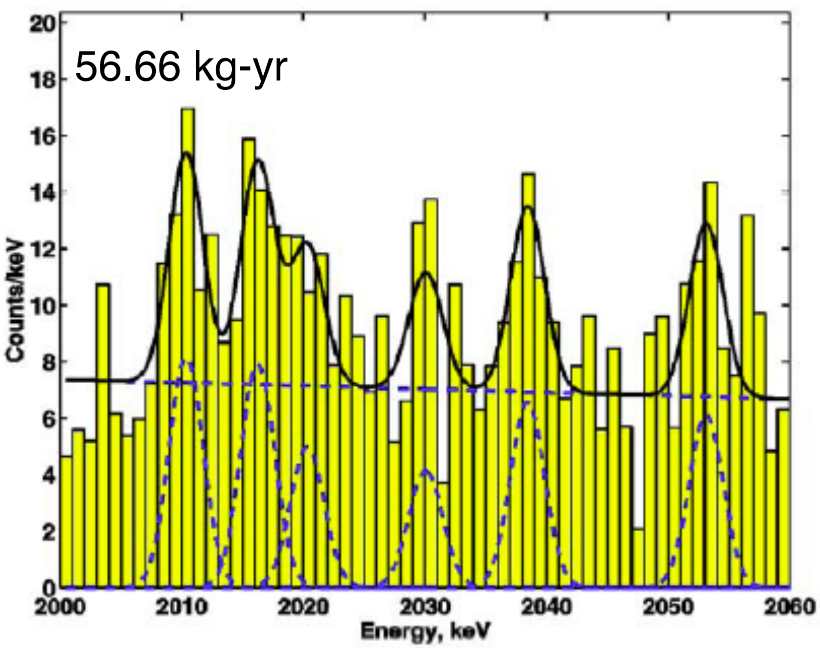
$T_{1/2}$ = (0.67 - 4.45) x 10^{25} *years* (99.73% *C.L.)*

Majorana ν Mass

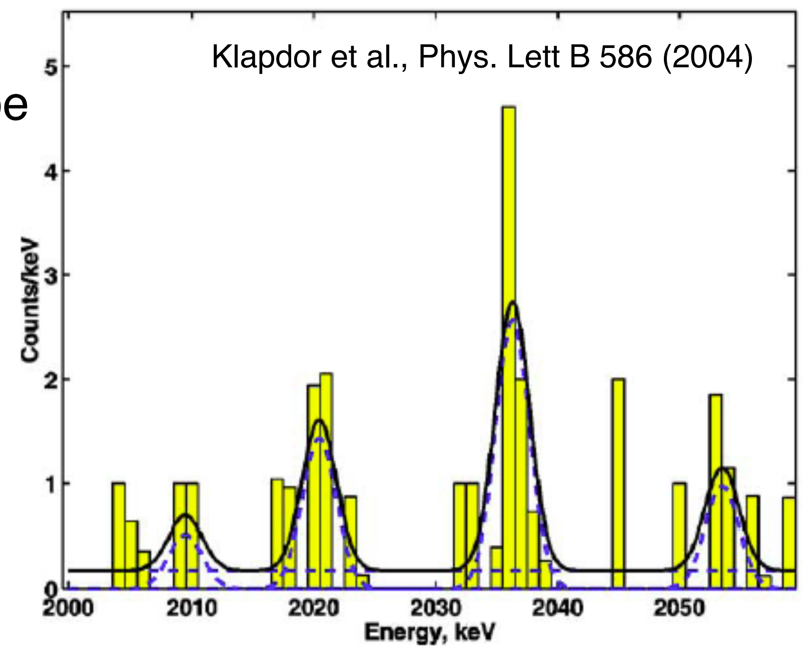
$<m_{\beta\beta}>$ = (0.1 - 0.9) eV (99.73% *C.L.*)

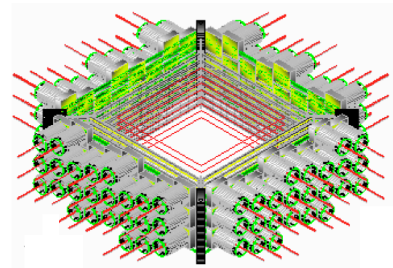
$<m_{\beta\beta}>_{best}$ = 0.45 *eV*

Backgrounds from ^{214}Bi

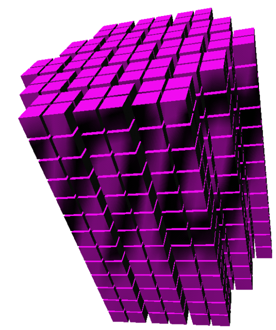


Pulse-shape selection





MOON



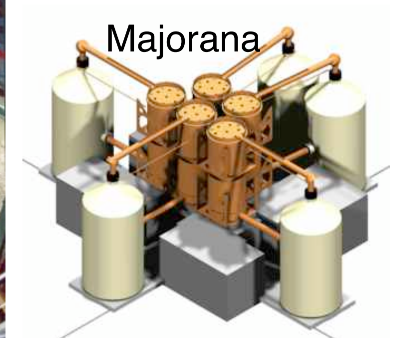
CUORE

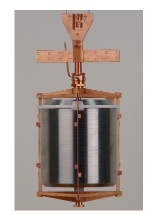
Candidate Experiments

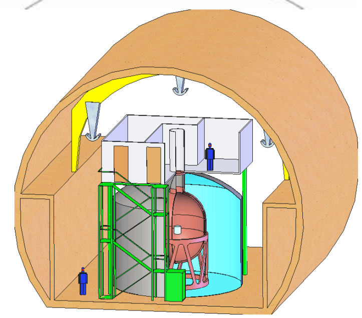
$\sin^2 2\theta_{13}$

Experiment	Nucleus	Detector
NEMO III	^{100}Mo et al	10 kg of enrich. Isotopes -tracking
Cuoricino	^{130}Te + etc.	40 kg of TeO_2 bolometers (nat)
CUORE	^{130}Te + etc.	750 kg of TeO_2 bolometers (nat)
EXO	^{136}Xe	200kg - 1 t Xe TPC
GERDA	^{76}Ge	30 – 40 kg – 1t Ge diodes in LN
Majorana	^{76}Ge	180 kg - 1t Ge diodes
MOON	^{100}Mo	nat.Mo sheets in plastic sc.
DCBA	^{150}Nd	20 kg Nd-tracking
CAMEO	^{116}Cd	1 t $CdWO_4$ in liquid scintillator
COBRA	^{116}Cd , ^{130}Te	10 kg of CdTe semiconductors
Candles	^{48}Ca	Tons of CaF_2 in liquid scintillators
GSO	^{116}Cd	2 t Gd_2SiO_5:Ce scintill.in liquid sc.
Xe	^{136}Xe	1.56 Xenon in liquid scintillator.
Xmass	^{136}Xe	1 t of liquid Xe

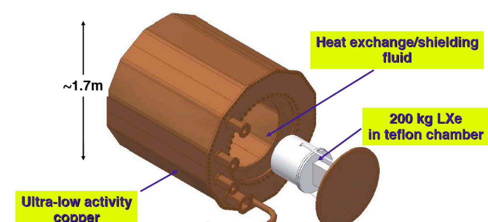
NEMO







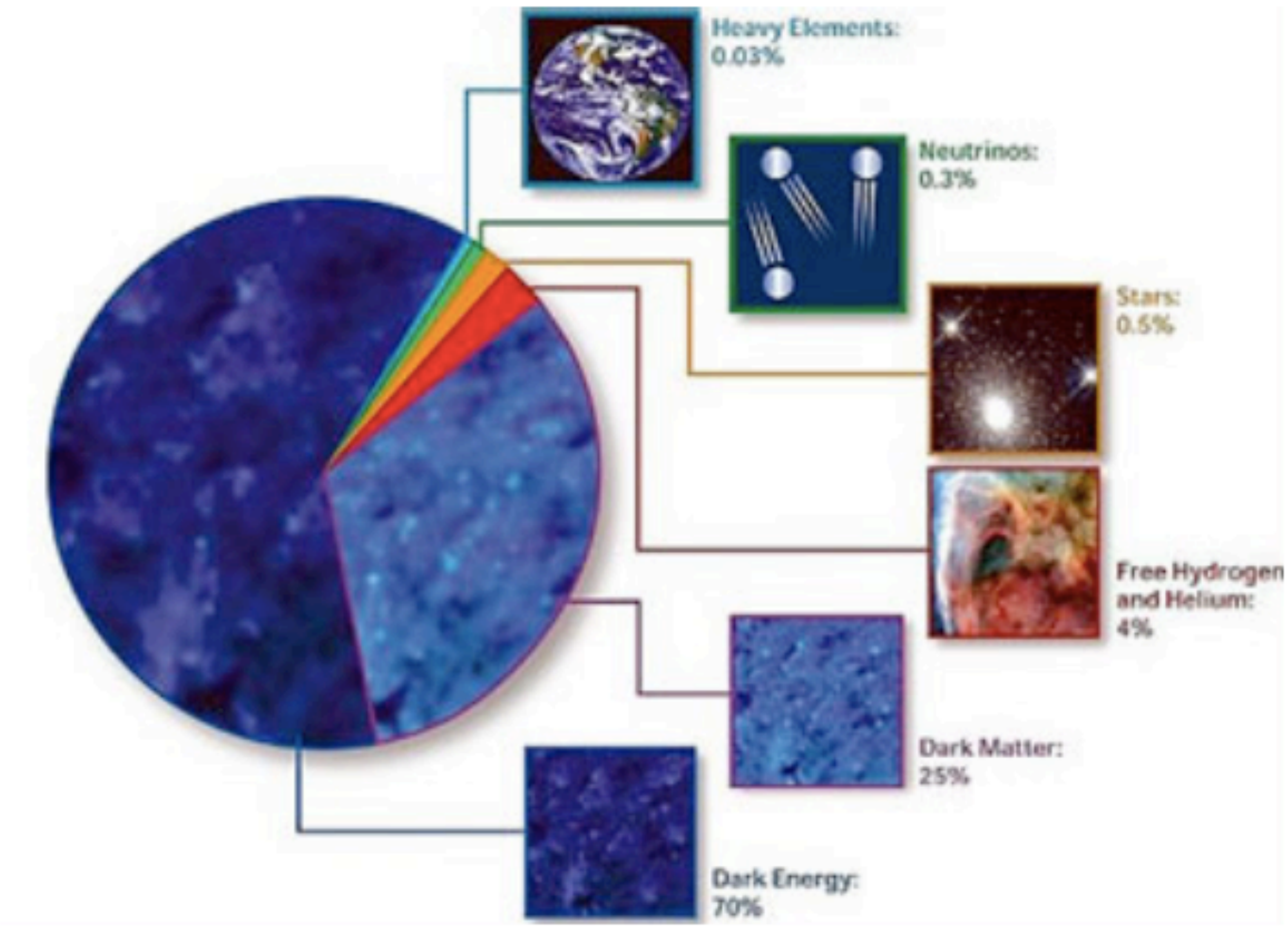
GERDA



EXO


Nearly all the mass shown in this photograph is invisible and not explained by the Standard Model

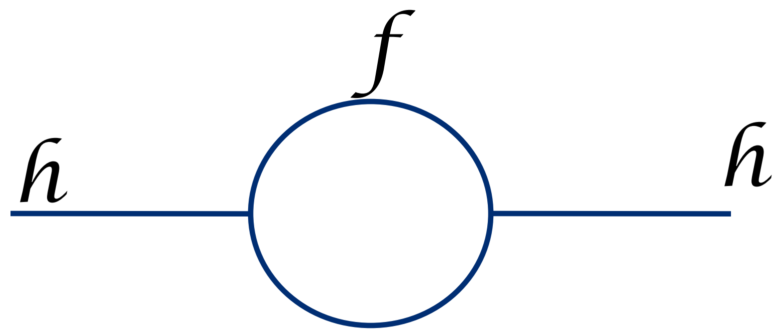
Accounting for the mass of the Universe



What is the Dark Energy and Dark Matter?

Why are there so few antiparticles?

TeV Scale Particles needed to Stabilize the Higgs

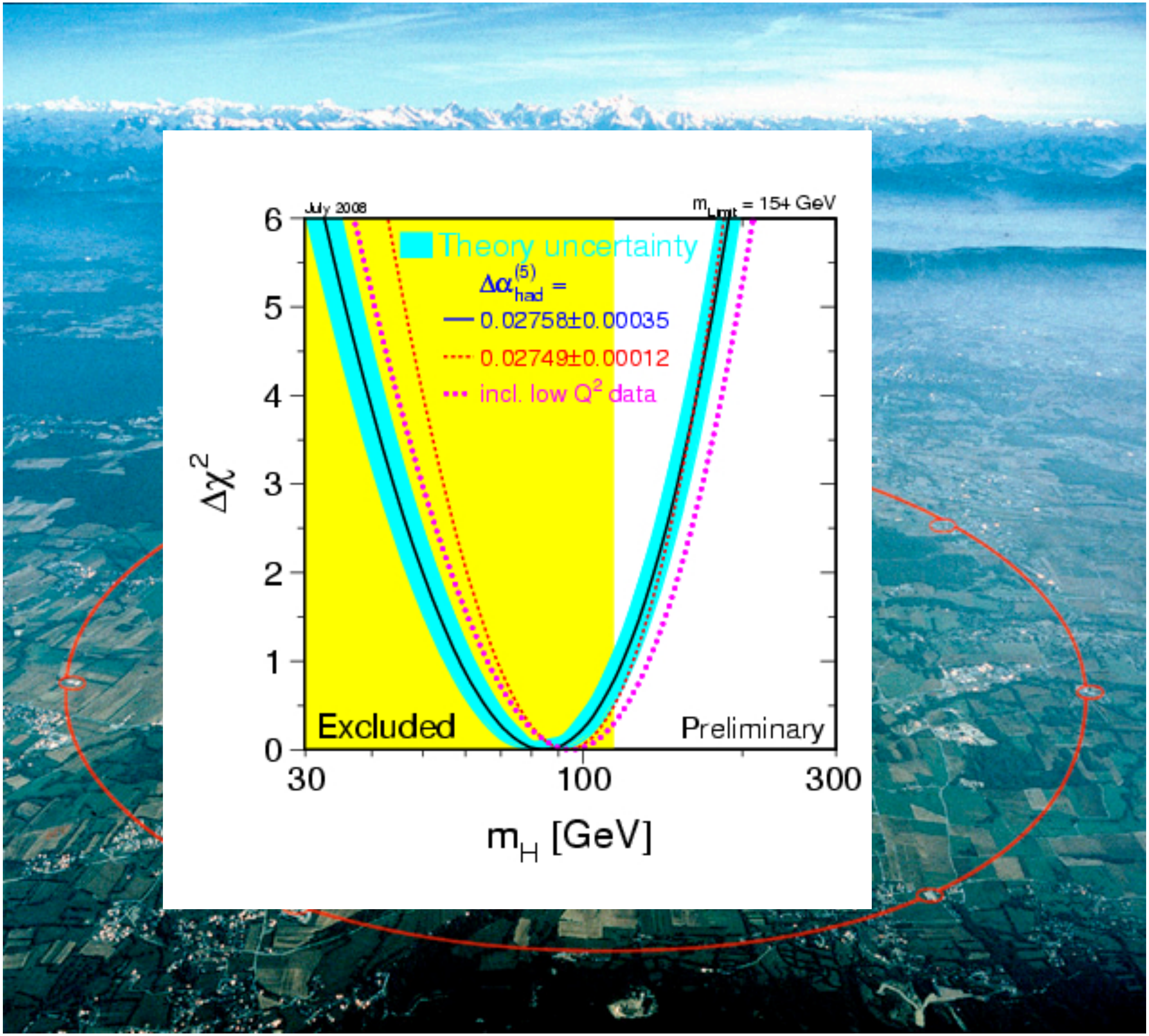


(f = t,b,τ,μ, …)

$$M_h^2 = (M_h^2)_0 + kg^2\Lambda^2/(16\pi^2)$$

$$M_h \rightarrow M_{GUT} \rightarrow M_{Planck}$$

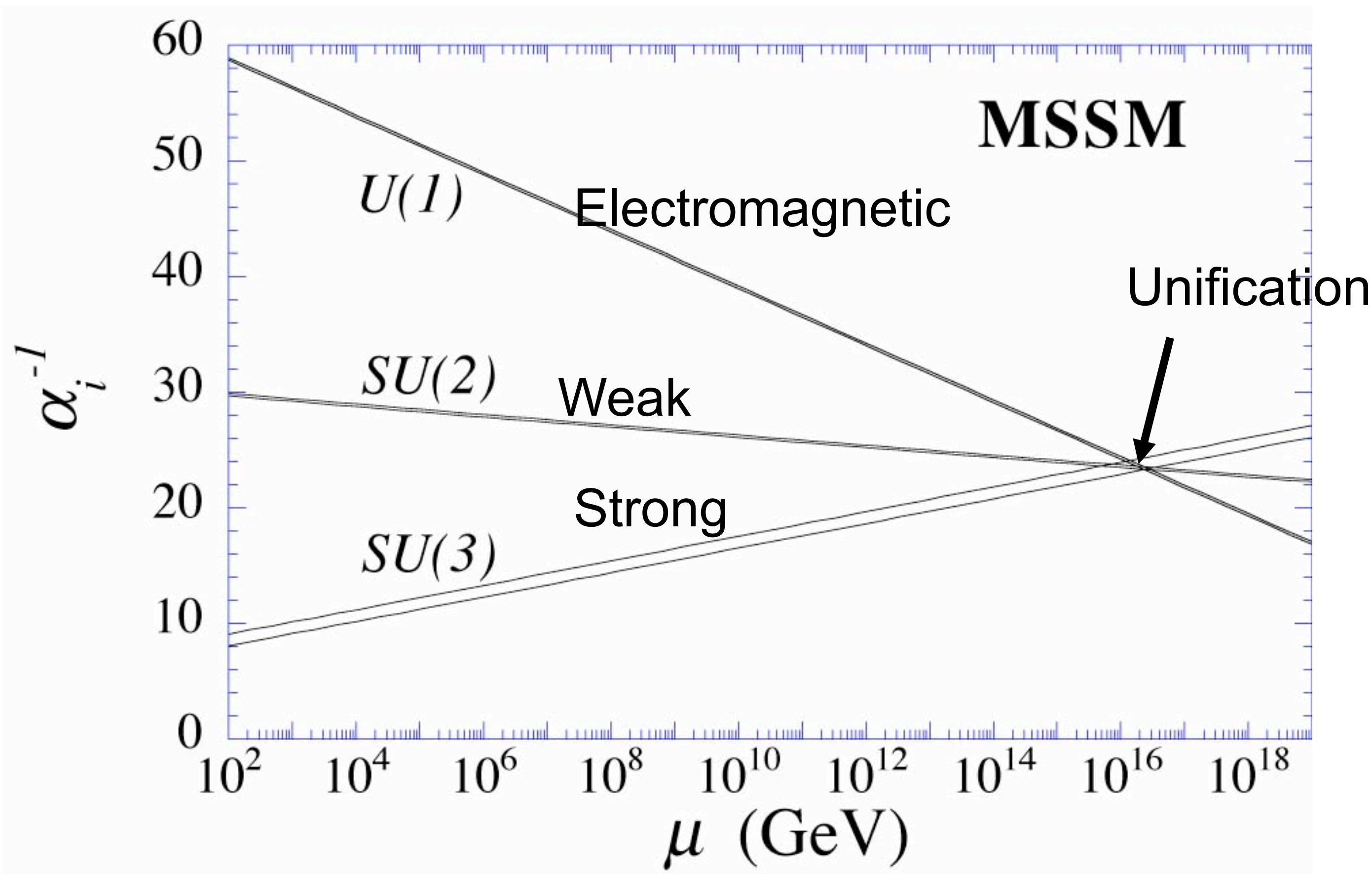
- New Physics at TeV scale?


July 2008
m_{Limit} = 154 GeV
Theory uncertainty
$\Delta\alpha_{had}^{(5)}$ =
0.02758±0.00035
0.02749±0.00012
incl. low Q^2 data
Excluded
Preliminary
$\Delta\chi^2$
m_H [GeV]
0
1
2
3
4
5
6
30
100
300

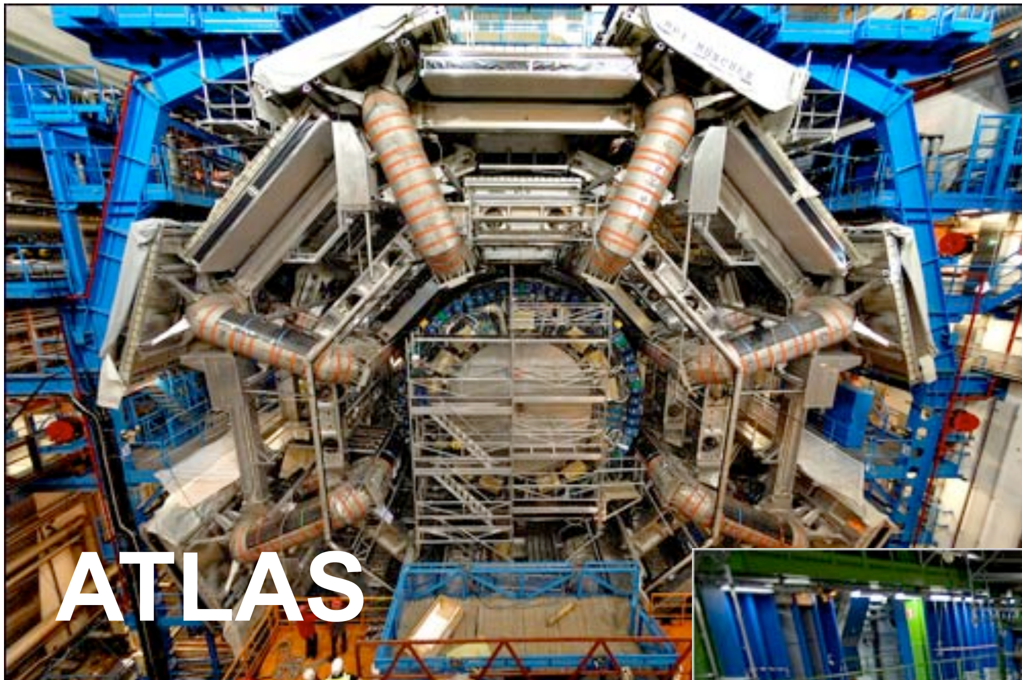
Supersymmetry suggests many new particles

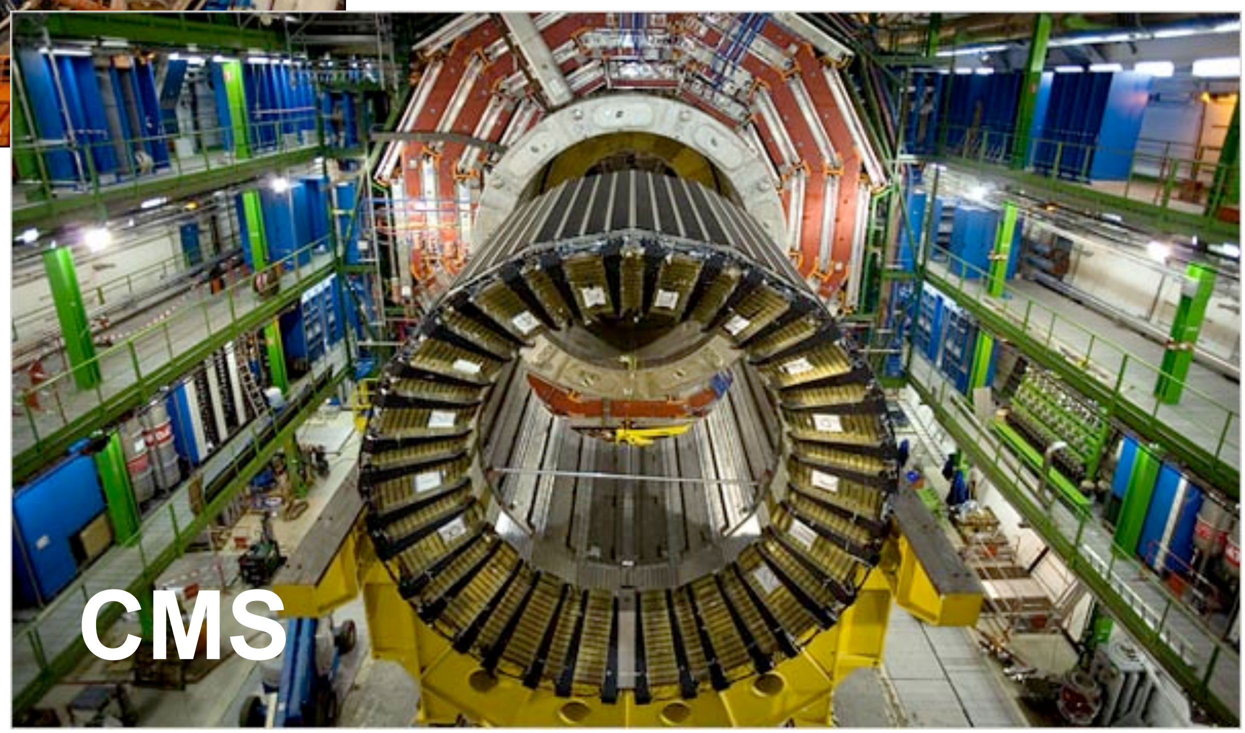
SM (R_p+)		Superparticle (R_p–)	
Quarks	u_i	Squarks	$\tilde{u}_i$
	d_i		$\tilde{d}_i$
Leptons	ν_i	Sleptons	$\tilde{\nu}_i$
	e_i		$\tilde{e}_i$
Gauges	g	Gauginos	$\tilde{g}$
	W		$\tilde{W}$
	B		$\tilde{B}$
Higgses	$h_{u,d}$	Higgsinos	$\tilde{h}_{u,d}$
Graviton	G	Gravitino	$\tilde{G}$

Supersymmetry Models helps resolve the “fine tuning problem” and has other successes -- but unfortunately there is absolutely no experimental evidence supporting it.



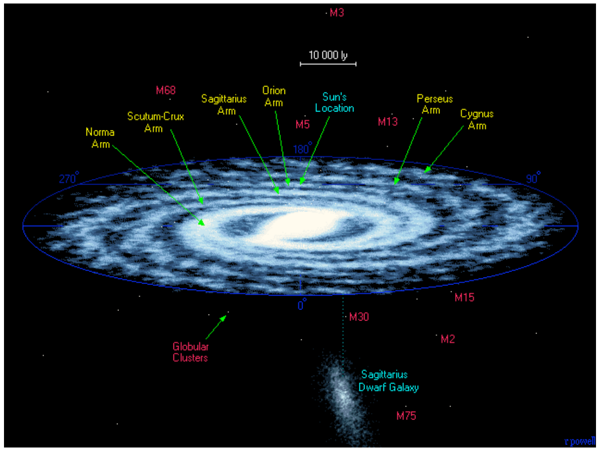
LHC Detectors are Poised to find the Higgs Boson and Supersymmetric Particles

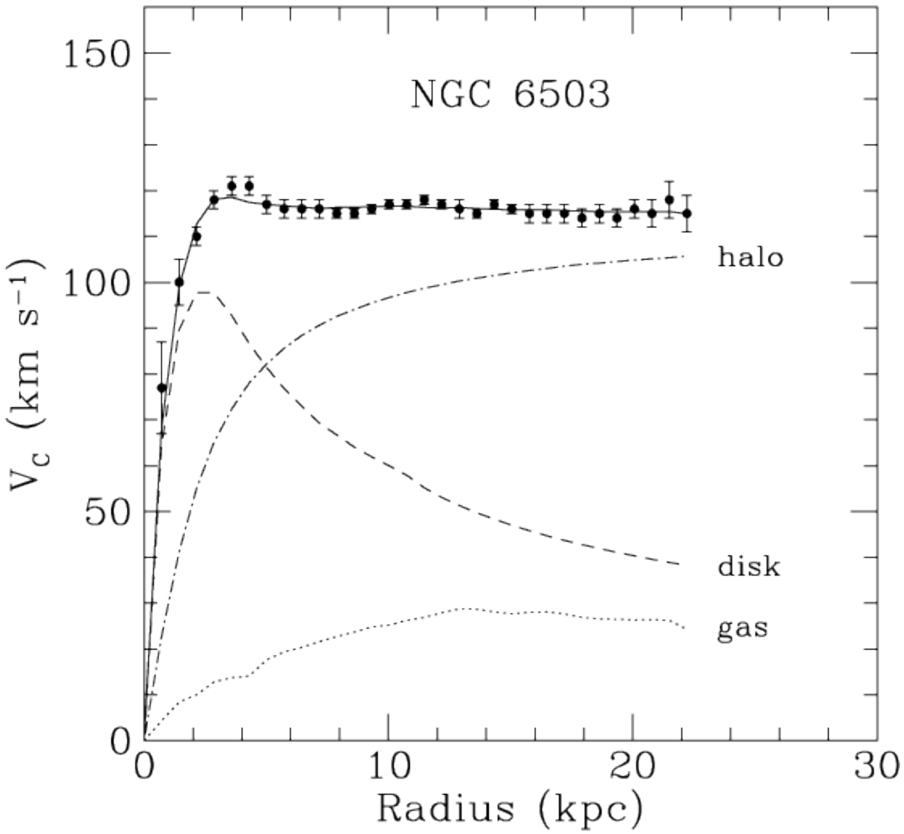


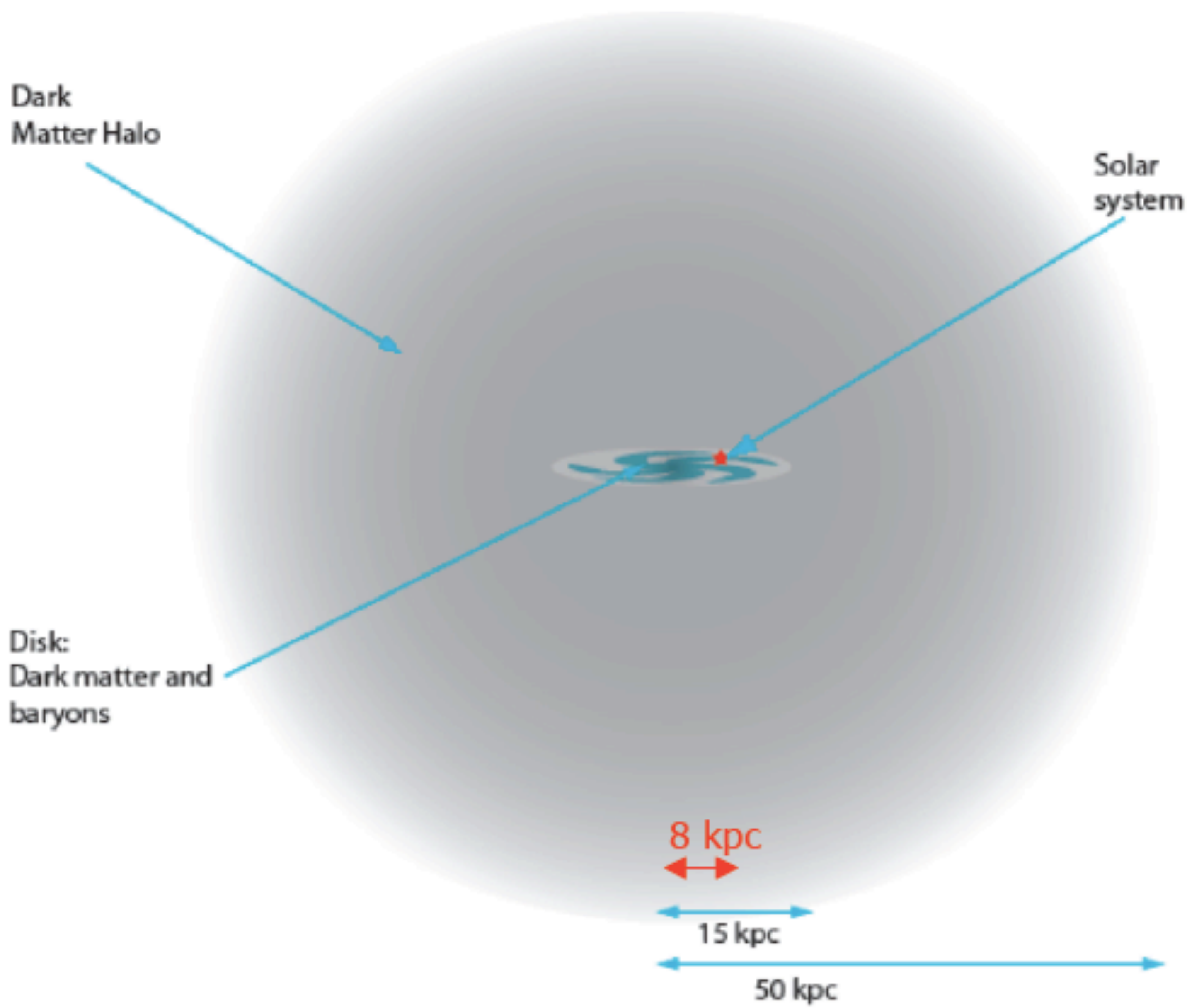


Evidence For Dark Matter

$$V(r) = \left(\frac{GM(r)}{r} \right)^{1/2}$$

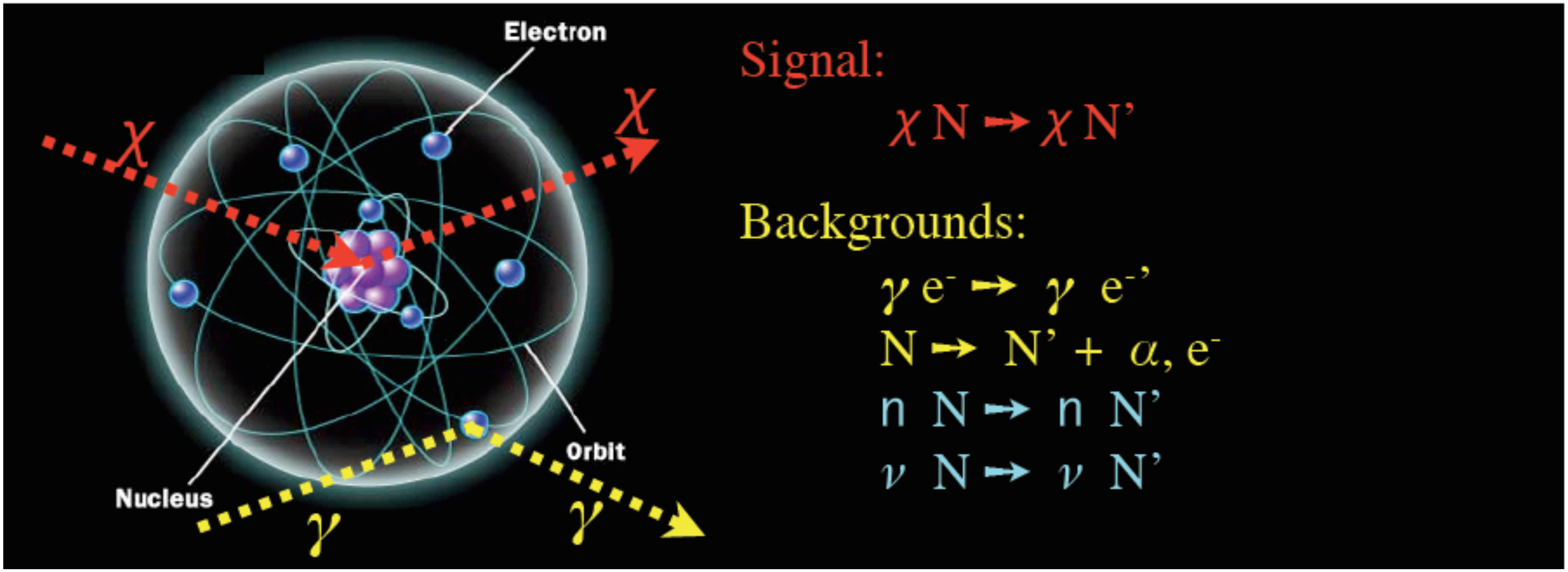




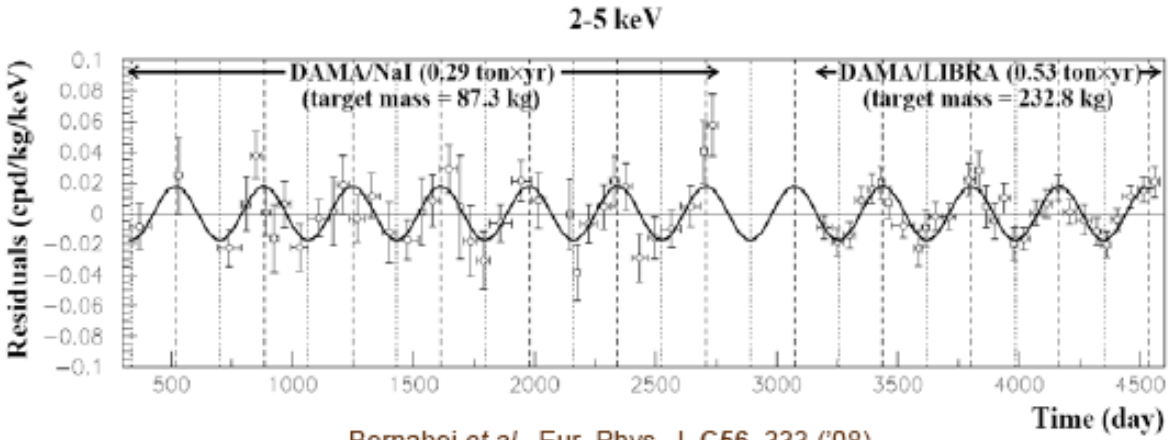

Dark
Matter Halo
Solar
system
Disk:
Dark matter and
baryons
8 kpc
15 kpc
50 kpc

Dark Matter

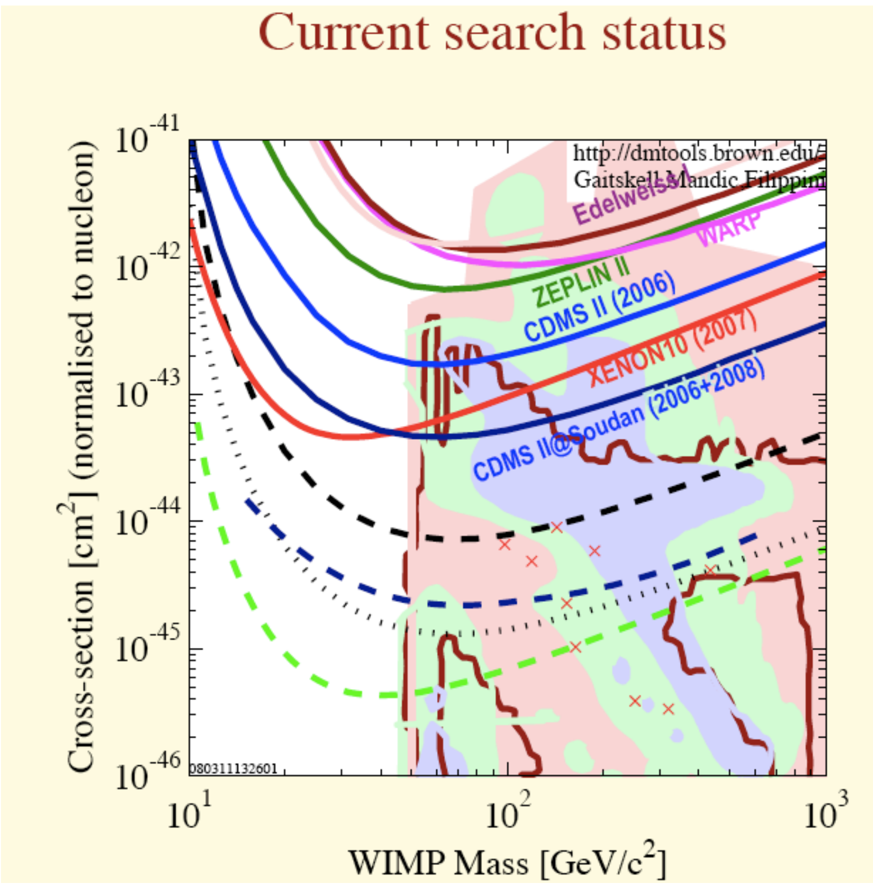
Detectors are designed to observe the nuclear recoil induced by a incident ~200 Km/sec Dark-Matter particle



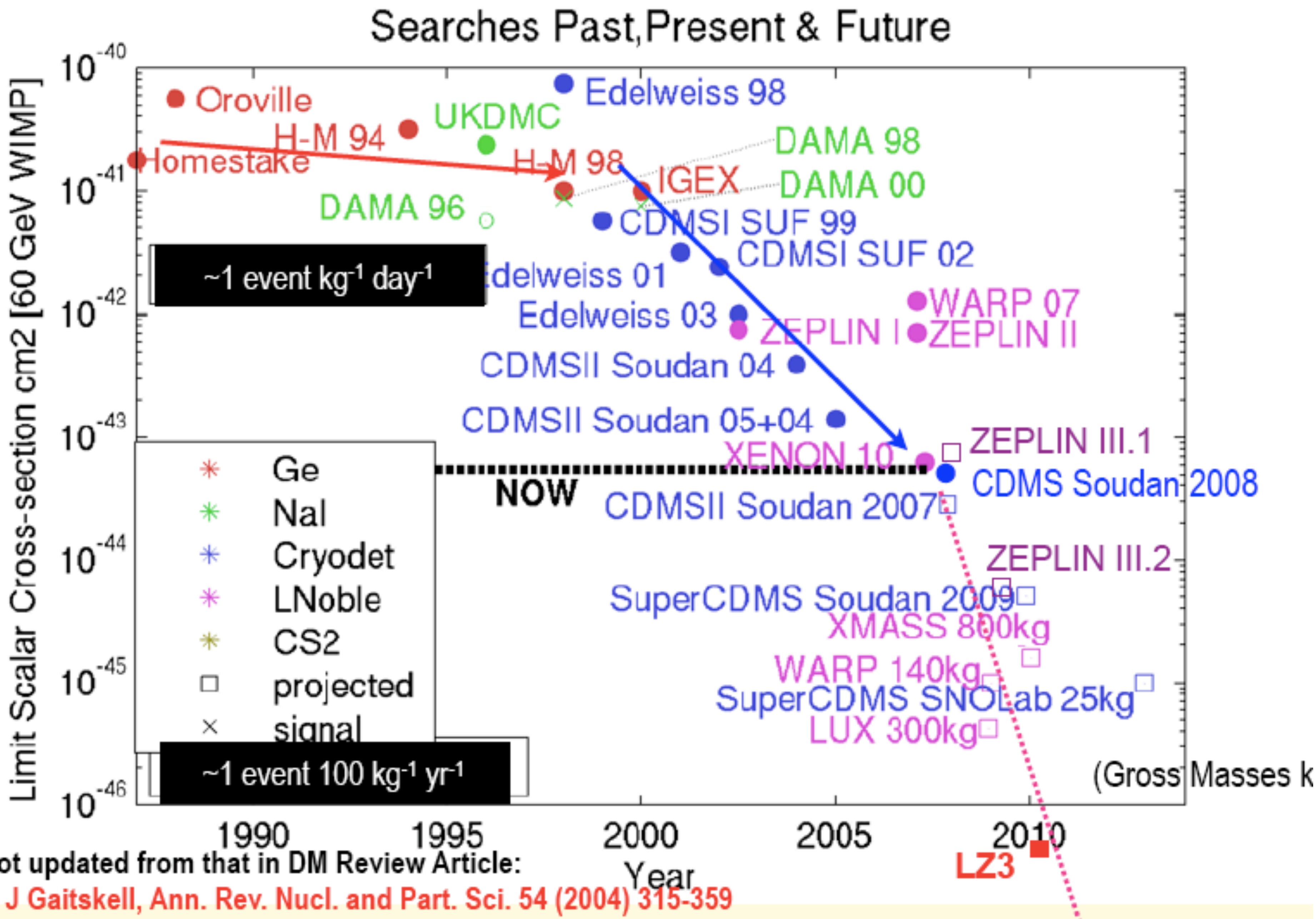
DAMA annual modulation



Bernabei *et al.*, Eur. Phys. J. C56, 333 ('08)



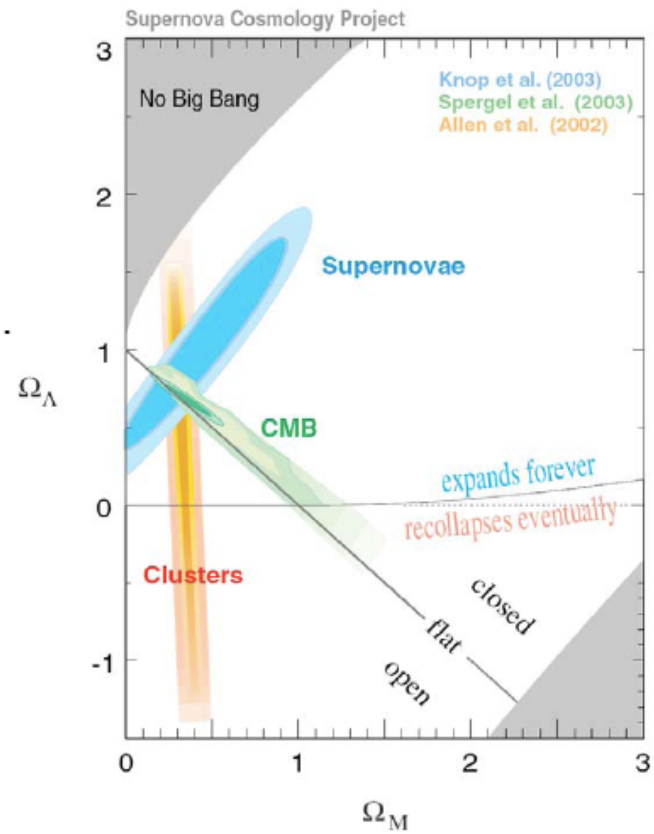
Inconsistent with other experiments?

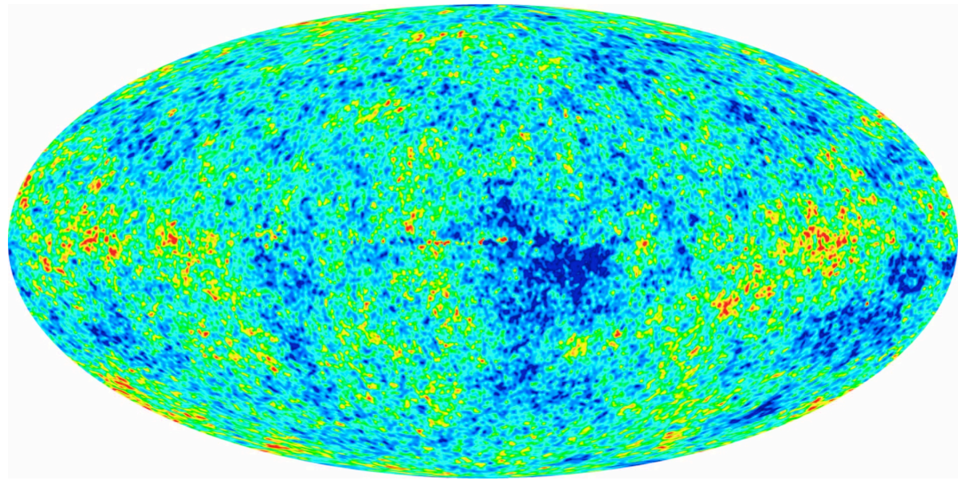


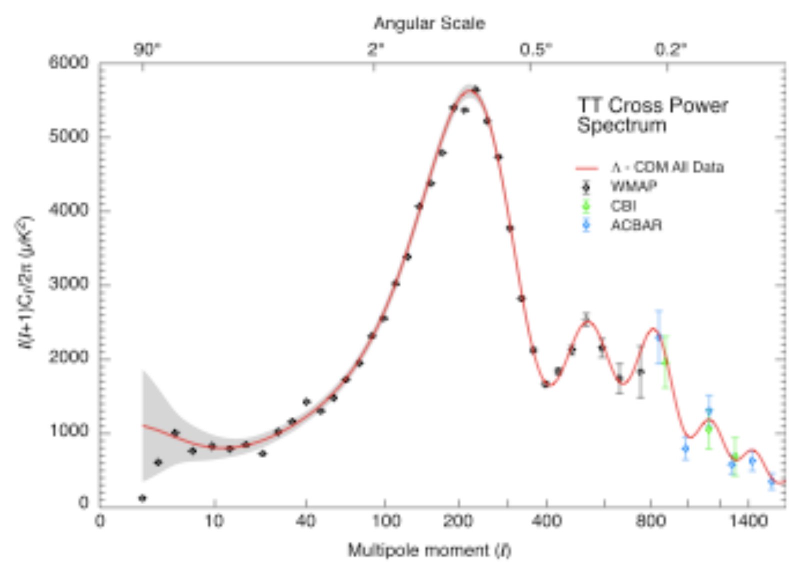
Plot updated from that in DM Review Article:

R J Gaitskell, Ann. Rev. Nucl. and Part. Sci. 54 (2004) 315-359

Dark Energy an Experimental Fact?







Big Questions in Particle Physics:

- Does mass really come from the Higgs mechanism?
- "Why" is the Universe nearly all matter?
- Is there another source time-reversal-symmetry breaking?
- Are neutrinos their own antiparticles? Do they violate CP?
- What is the dark matter?
- What is the dark energy?
- Can the known forces be unified with gravity? Quantum Gravity.
- What will be discovered in the newest experiments?

A final remark:

I haven’t said anything about String Theory.

A comment: …………..

Thank you for your attention