Title: The neutrino matrix & beyond

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Abstract: Since the seminal discovery of the neutrino by Cowan and Reines in the late 1950's, intense experimental and theoretical effort has focused on the elucidation of neutrino properties and the role they play in elementary particle physics, astrophysics, and cosmology. Neutrinos are born in the fusion reactions powering our Sun and are thought to be the driving mechanism for supernova explosions. Neutrinos exist in copious amounts as the primordial afterglow of the Big Bang and, if massive, would play a role in the evolution and ultimate fate of the Universe. Central to many of the key issues in neutrino physics is the question of whether neutrinos possess non-zero rest mass. If neutrinos are massive, then one expects flavor mixing to occur in the neutrino sector which could lead to the phenomena of neutrino oscillations and the possibility of CP violation in the neutrino sector. A detailed understanding of the microscopic properties of neutrinos can serve to pave the way to a unified description of the fundamental forces of Nature.

The Neutrino Matrix & Beyond

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Perimeter Institute of Theoretical Physics
March 23, 2005

History & The Standard Model

Discovery of Neutrino Oscillations

The New Standard Model

Open Questions

Connections to Grand Unification

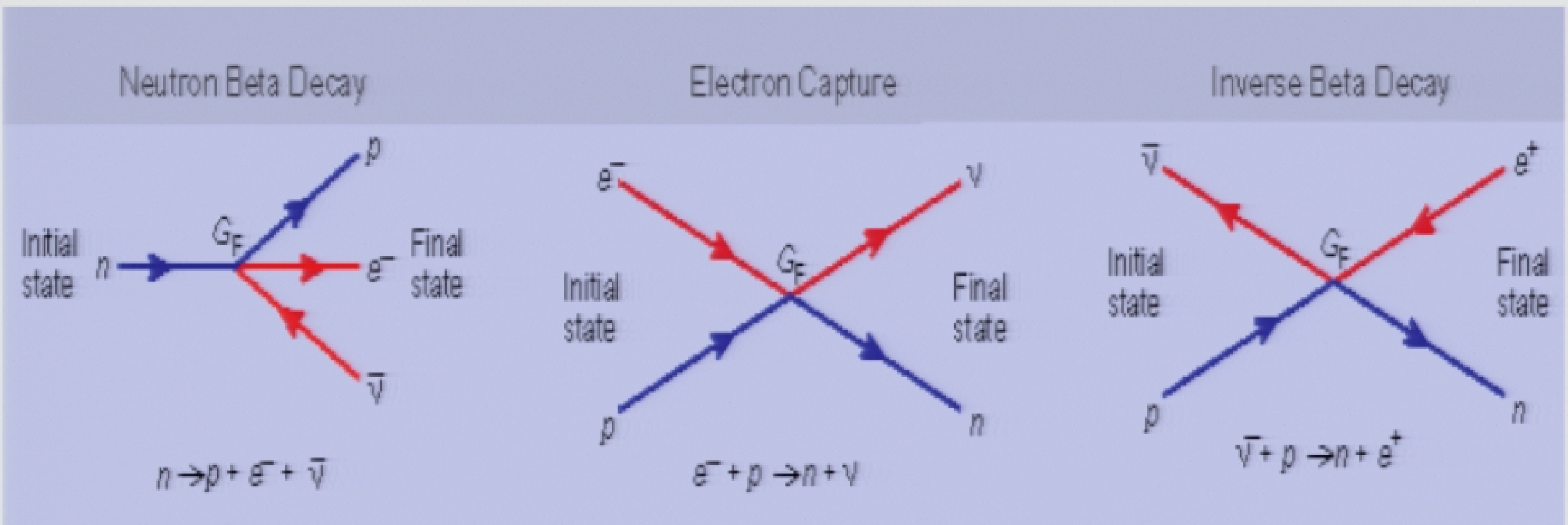
Connections to Cosmology

New Frontiers in Underground Science

Summary

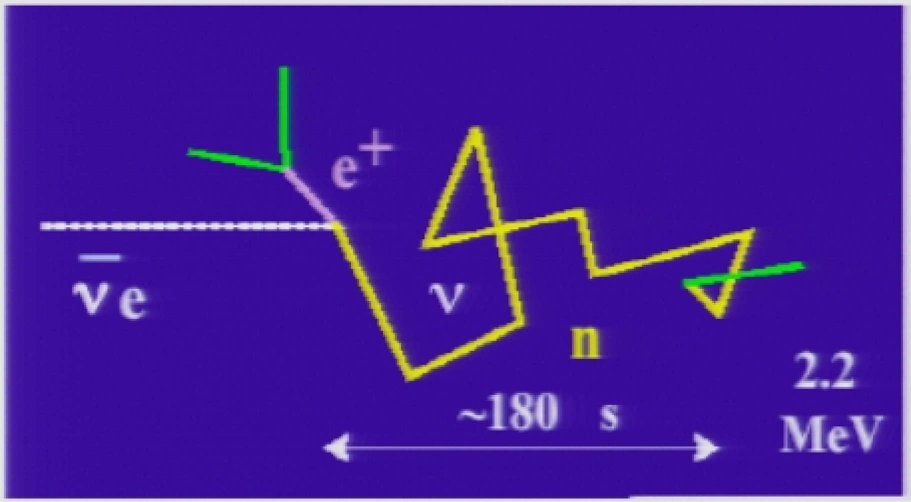
Inventor

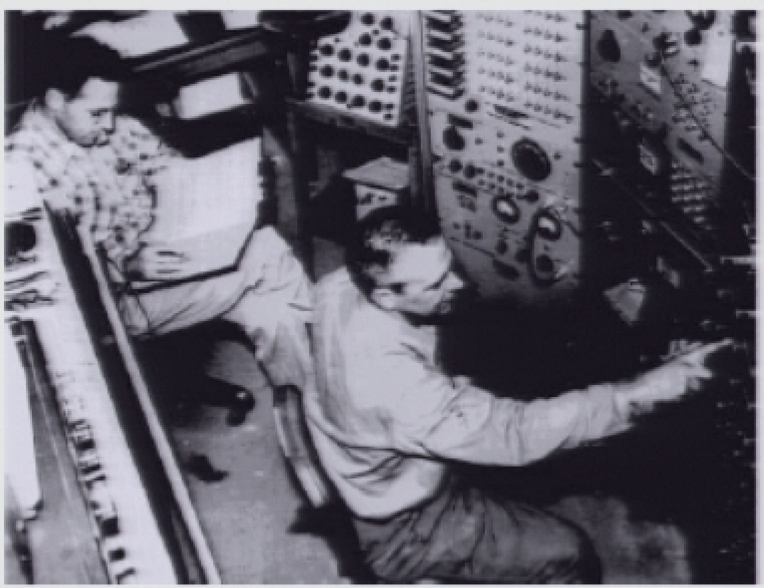
Developer

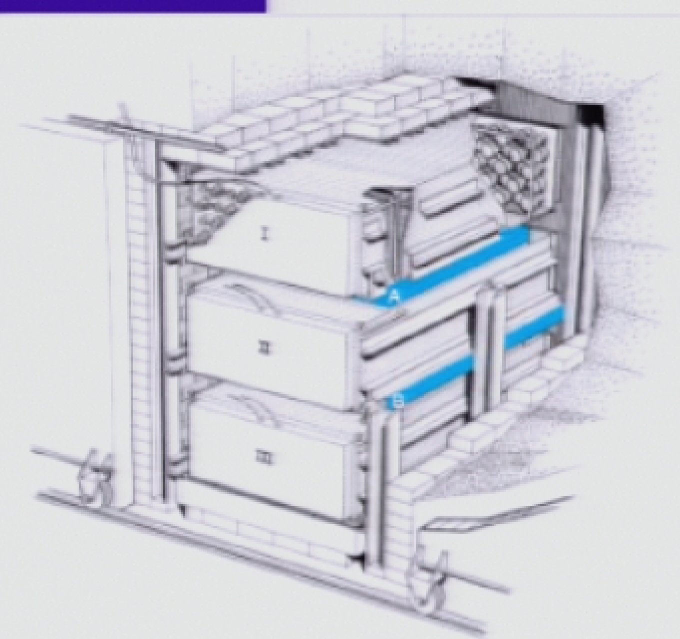


First Direct Detection of the Neutrino

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







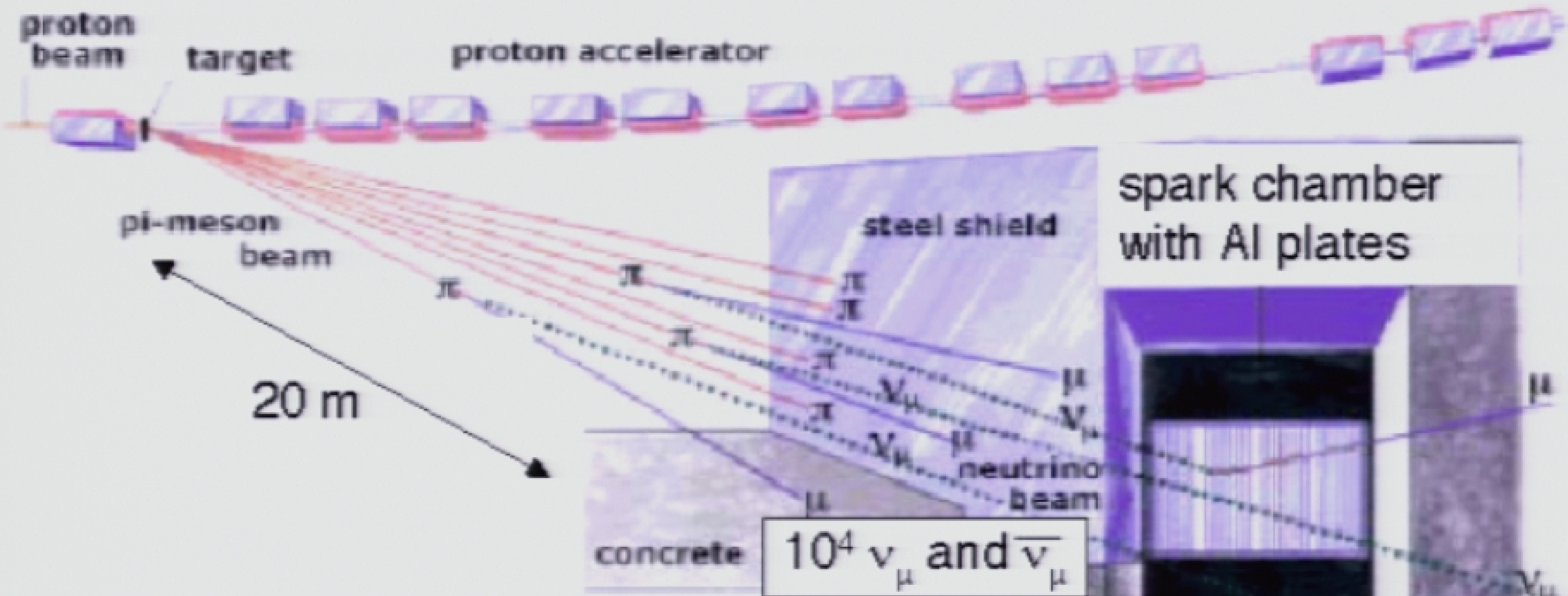
Reines and Cowan 1955

Discovery of Muon Neutrino

1962

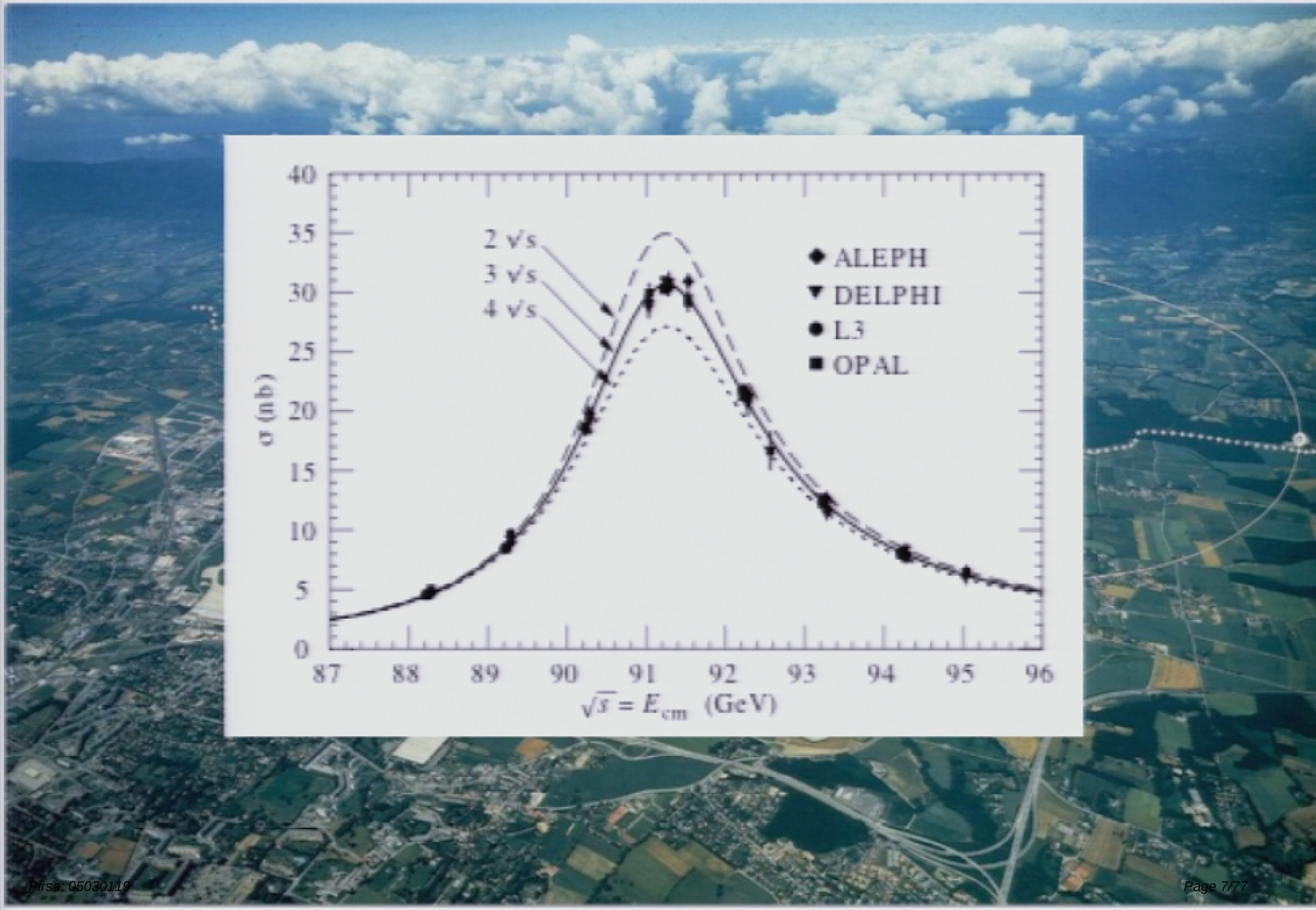
$$\bar{\nu}_\mu + p \rightarrow n + \mu^+$$
$$\nu_\mu + n \rightarrow p + \mu^-$$

Lederman, Schwarts, Steinberger

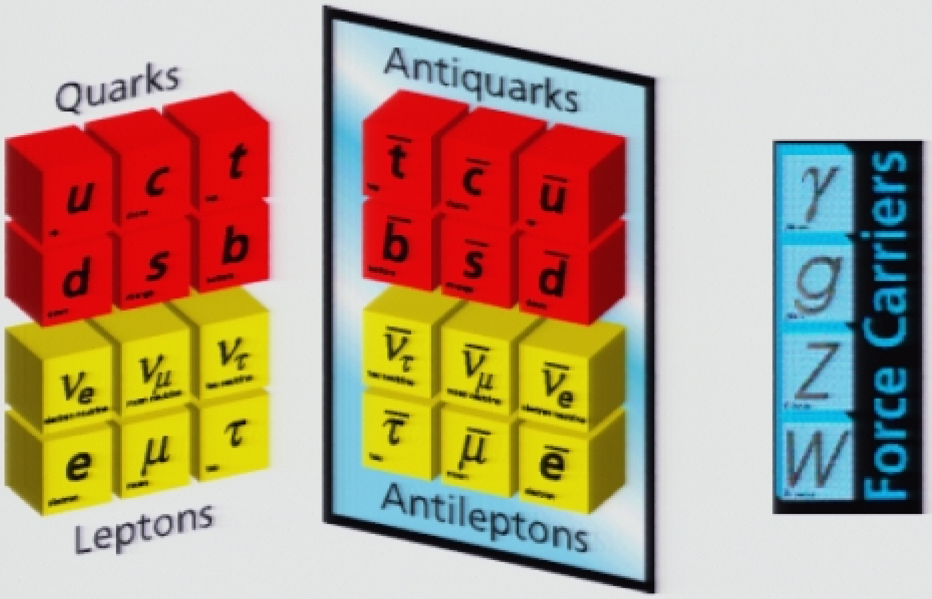


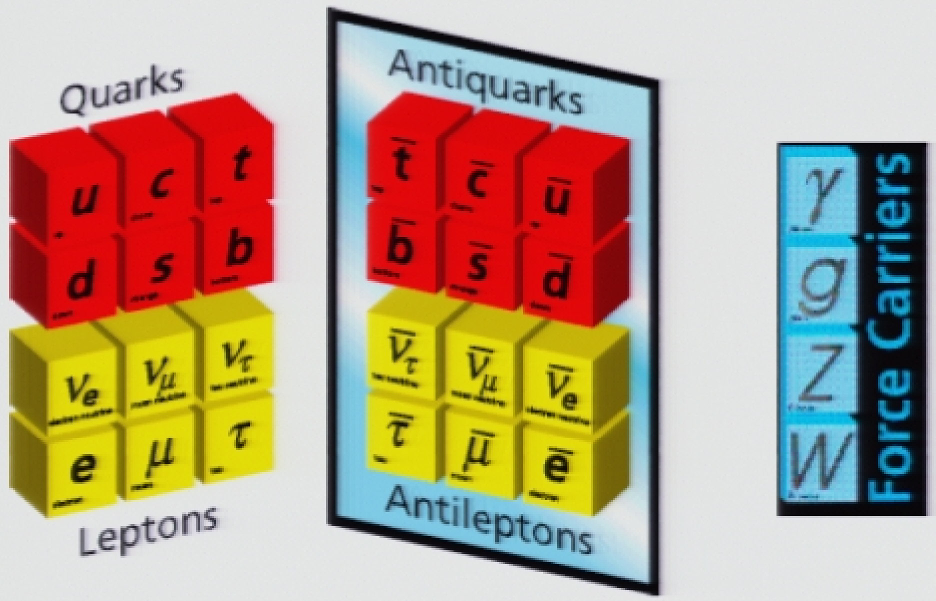
μ produce nice tracks as they go through the chamber (29 events)

e produce showers as they cross Al (0 events)



40
35
30
25
20
15
10
5
0
σ (nb)
87 88 89 90 91 92 93 94 95 96
√s = E_cm (GeV)
2 √s
3 √s
4 √s
ALEPH
DELPHI
L3
OPAL


Quarks
u c t
d s b
ν_e ν_μ ν_τ
e μ τ
Leptons
Antiquarks
$\bar{t}$ $\bar{c}$ $\bar{u}$
$\bar{b}$ $\bar{s}$ $\bar{d}$
$\bar{\nu}_\tau$ $\bar{\nu}_\mu$ $\bar{\nu}_e$
$\bar{\tau}$ $\bar{\mu}$ $\bar{e}$
Antileptons
γ
g
Z
W
Force Carriers



ν-Mass, Mixing, & The Standard Model.

$SU_L(2) \otimes U(1)$

$$\begin{bmatrix} u \\ d \end{bmatrix}_L \begin{bmatrix} c \\ s \end{bmatrix}_L \begin{bmatrix} t \\ b \end{bmatrix}_L , \quad q_R \cdots$$

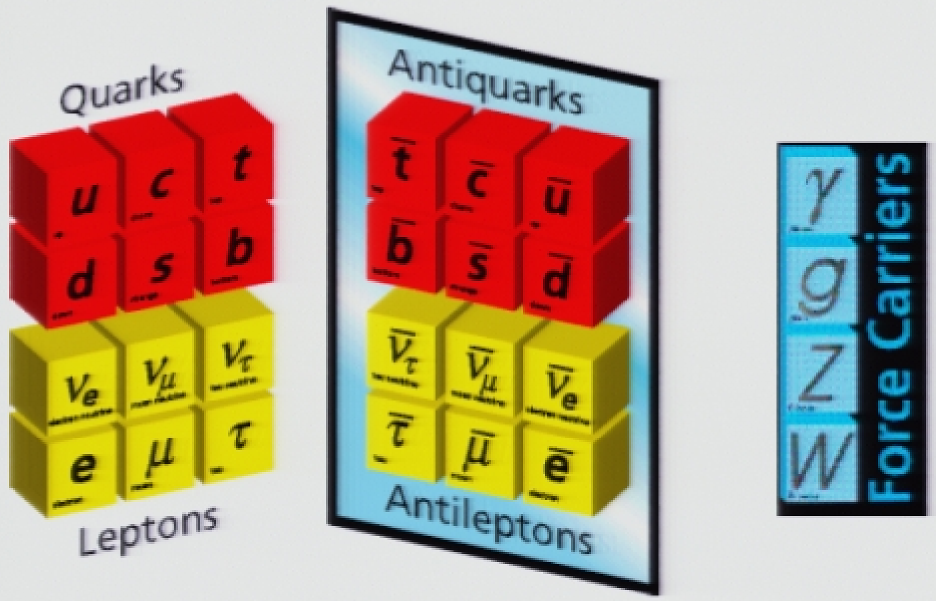
$$\begin{bmatrix} \nu_e \\ e \end{bmatrix}_L \begin{bmatrix} \nu_\mu \\ \mu \end{bmatrix}_L \begin{bmatrix} \nu_\tau \\ \tau \end{bmatrix}_L , \quad e_R , \mu_R , \tau_R$$

Standard (Dirac) Mass Term in Field Theory:

$$\mathcal{L}_M = M \cdot \psi \bar{\psi}$$

$$= M \cdot \left(\bar{\psi}_R \psi_L + \bar{\psi}_L \psi_R \right)$$

∴ Without Right-Handed states in the ν-Sector, ν's are Strictly Massless.



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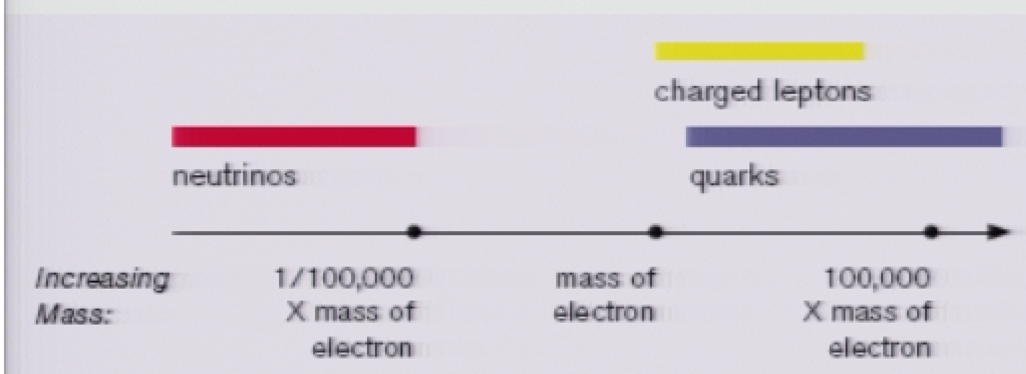

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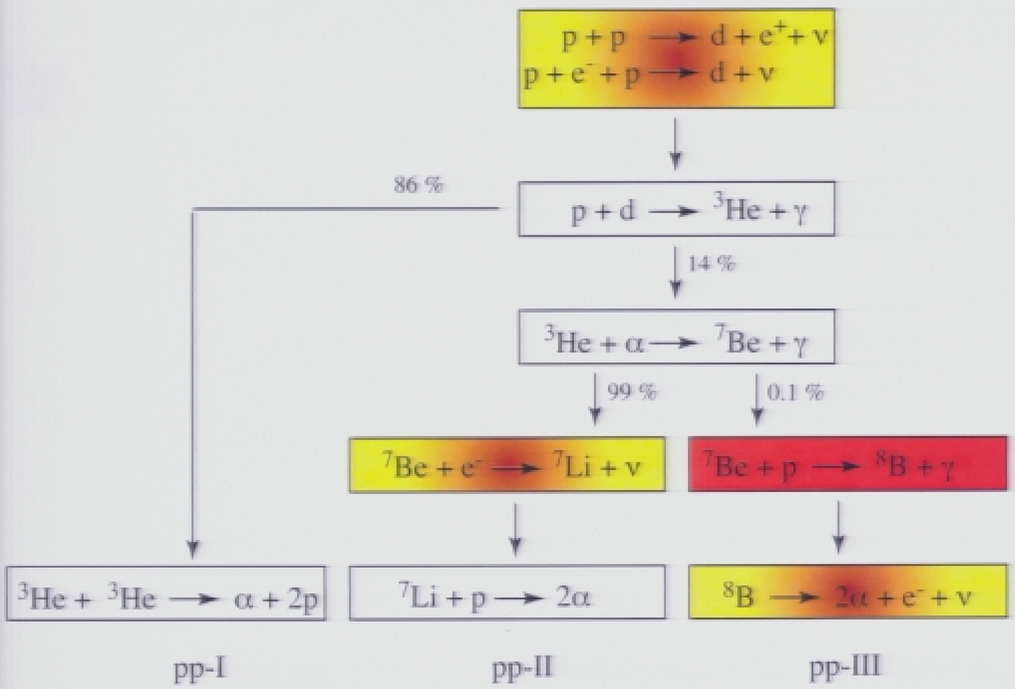
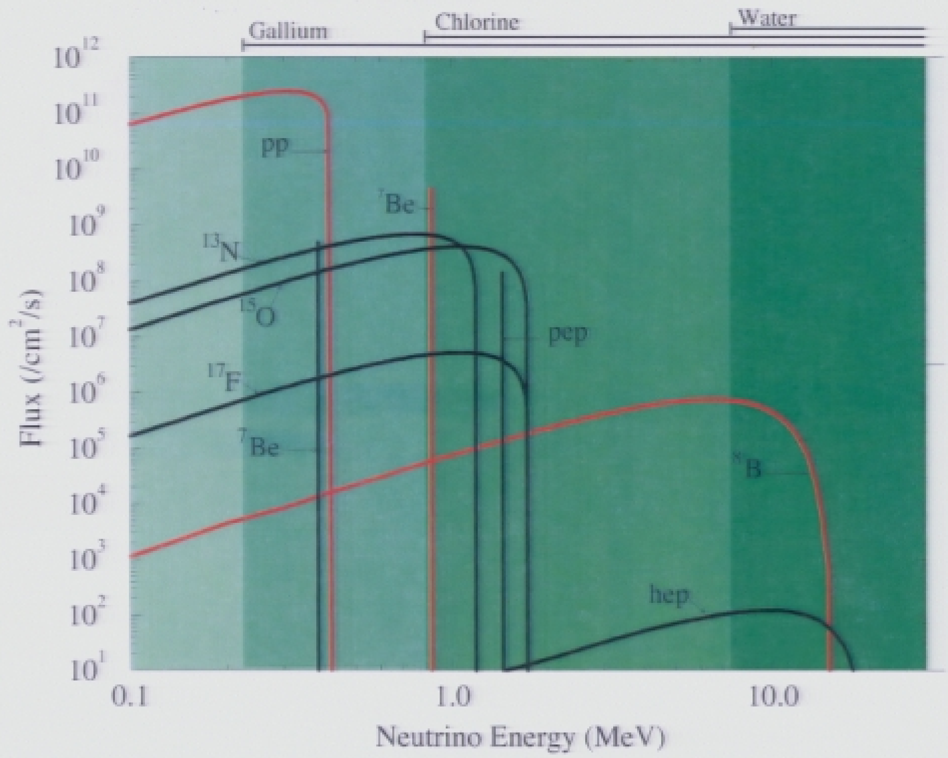
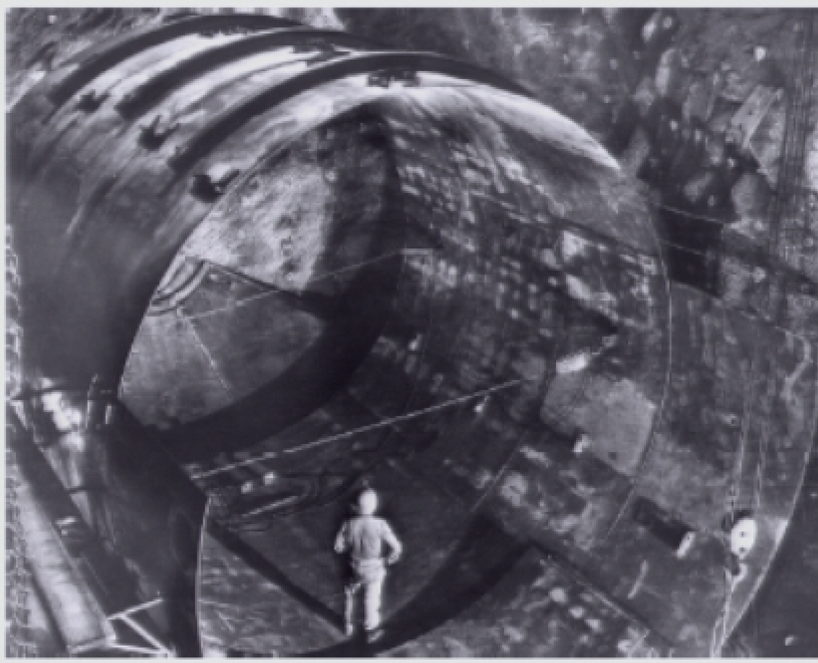
ν-Mass, Mixing, & The Standard Model.

The Standard Solar Neutrino Spectrum





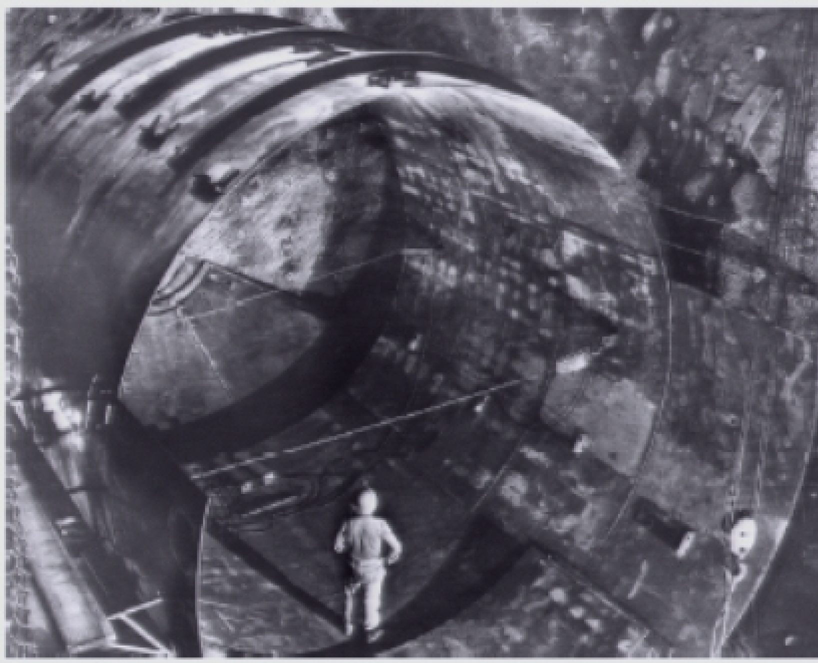
Pioneer of Solar Neutrino Science



$^{37}Cl + \nu_e \rightarrow {}^{37}Ar + e^-$

1968 First Solar Neutrino Experiment

Pioneer of Solar Neutrino Science



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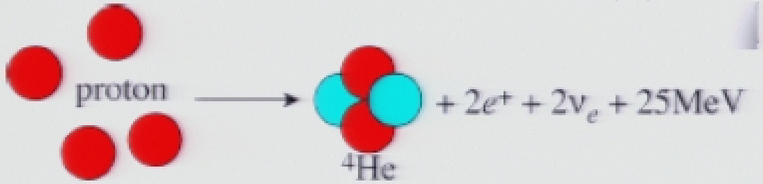


Solar ν Flux

$4p + 2e \rightarrow {}^4He + 2\nu_e + 26.731 \text{ MeV}$

$L_\odot \sim 3.9 \times 10^{6} \text{ W}$

$D \sim 1.496 \times 10^{13} \text{ cm}$

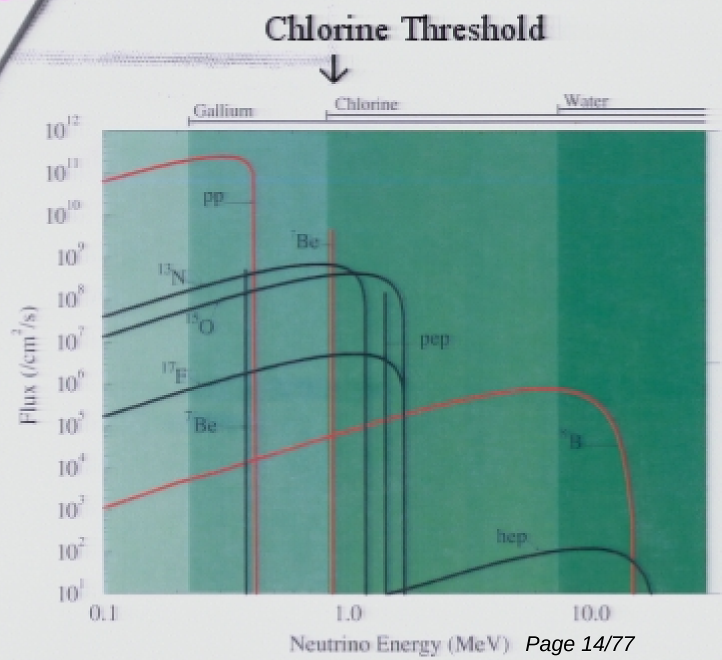
$$\varphi_\nu \sim \frac{2L_\odot}{4\pi D^2 \times 26.7 \text{ MeV}}$$

$\sim 6.48 \times 10^{10} \ \nu/cm^2/s.$

Capture Rate on Cl-Nuclei

$P_\nu \sim 7 \times 10^{-36}$ Captures/Atom/Day

$\sim$ 2 Captures/Day in 1000 tonnes



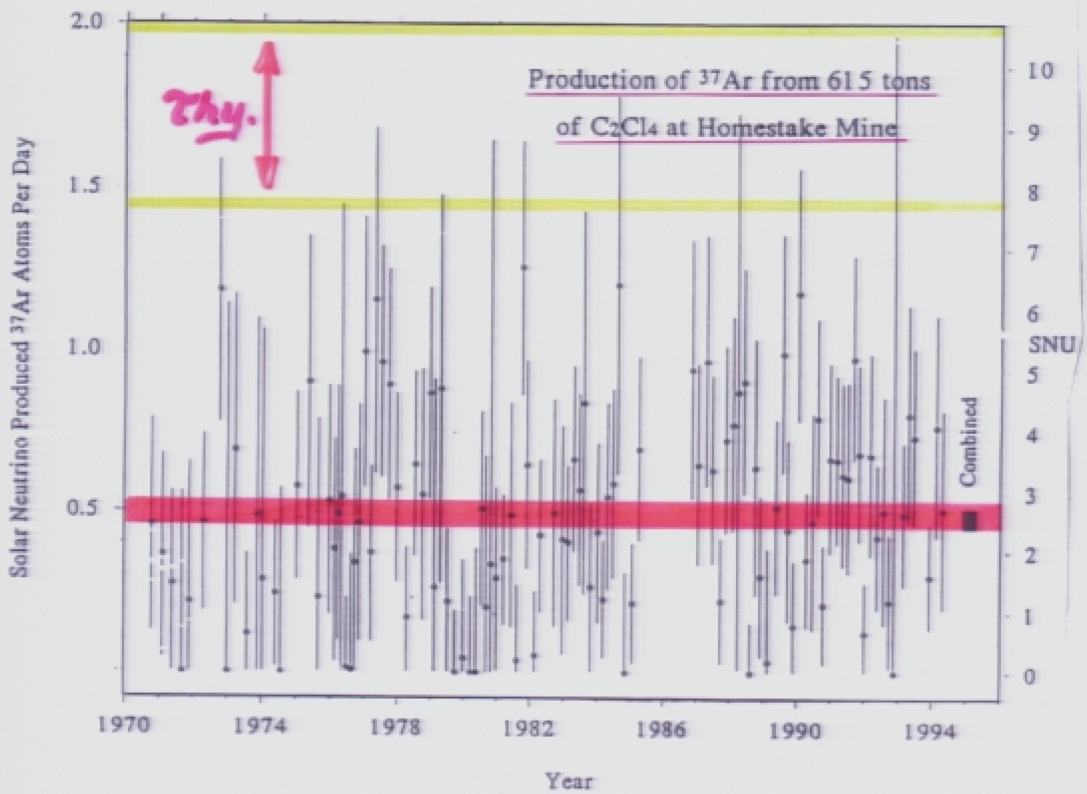
Pontecorvo (1946)
Alvarez (1949)

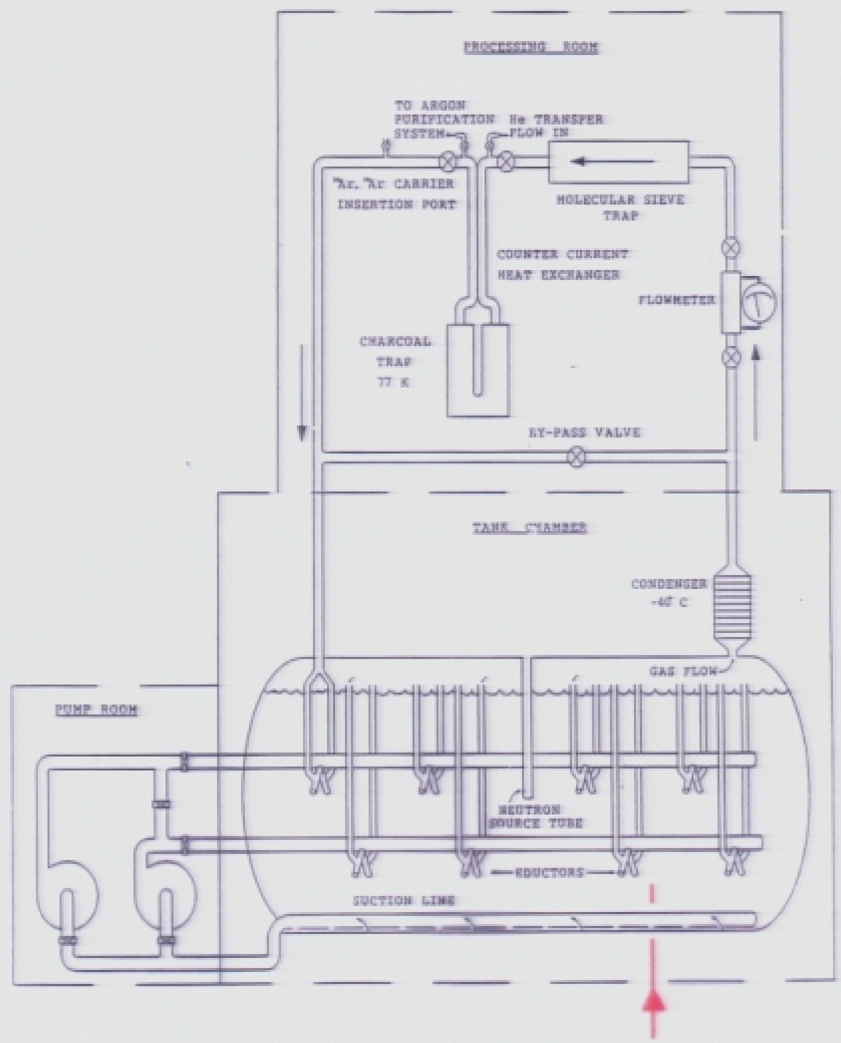
$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$

Ray Davis Chlorine Experiment

Homestake Gold Mine, SD

0.5 Ar atoms produced per day in 10^{30} target atoms !!!





$\phi_{Exp't} = \phi_{Theory} / 3$!!!

615 tons C_2Cl_4

Pontecorvo (1946)
Alvarez (1949)

$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$

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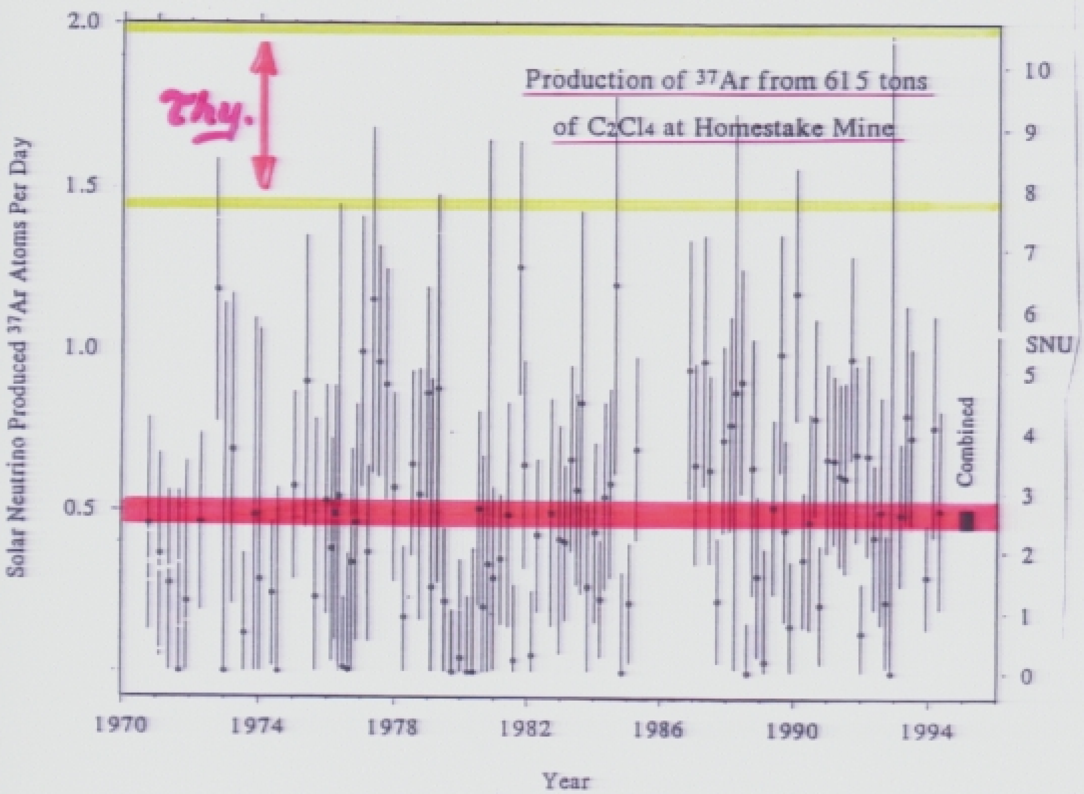
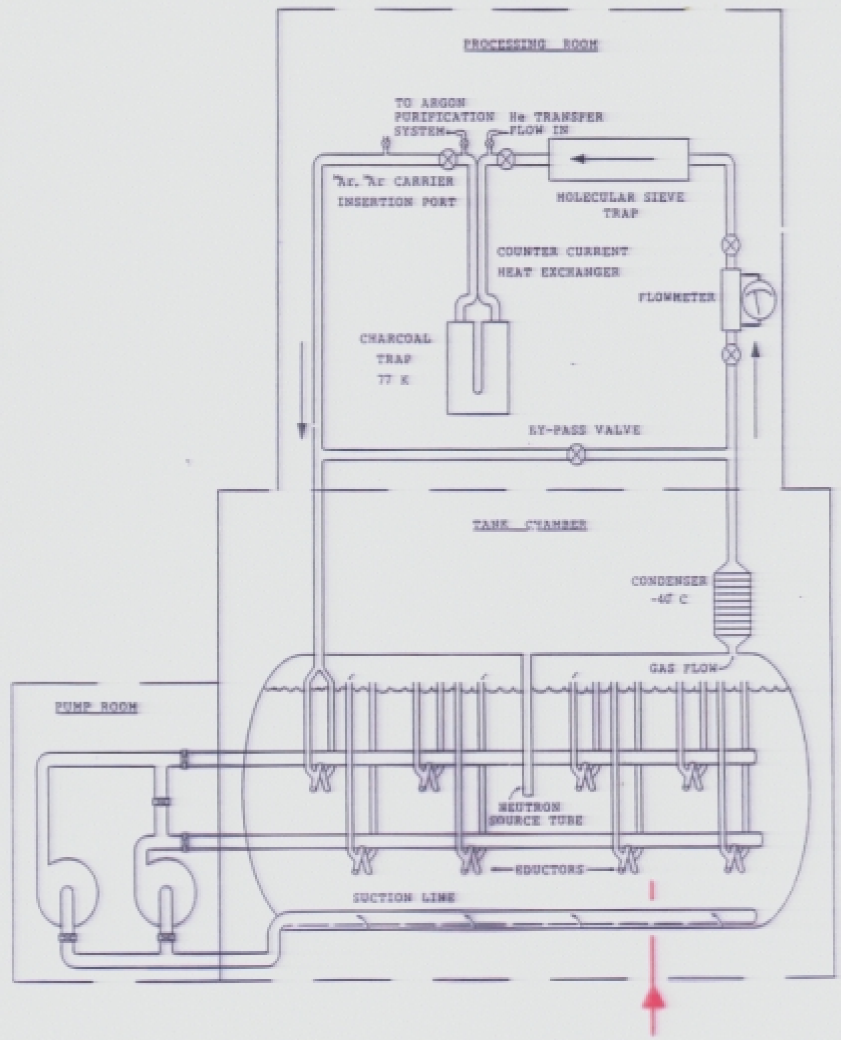




$\phi_{Exp't} = \phi_{Theory} / 3$!!!

615 tons C_2Cl_4

ОБЪЕДИНЕННЫЙ ИНСТИТУТ ЯДЕРНЫХ ИССЛЕДОВАНИЙ

JOINT INSTITUTE FOR NUCLEAR RESEARCH

Москва, Главный почтамт п/я 79. Head Post Office, P.O. Box 79, Moscow, USSR

74/51

April 6/10 1972

Prof. J.N.Bahcall
The Institute for Advanced Study
School of Natural Science
Princeton, New Jersey 08540, USA

Dear Prof. Bahcall,

Thank you very much for your letter and the abstract of the new Davis investigation the numerical results of which I did not know. It starts to be really interesting! It would be nice if all this will end with something unexpected from the point of view of particle physics. Unfortunately, it will not be easy to demonstrate this, even if nature works that way.

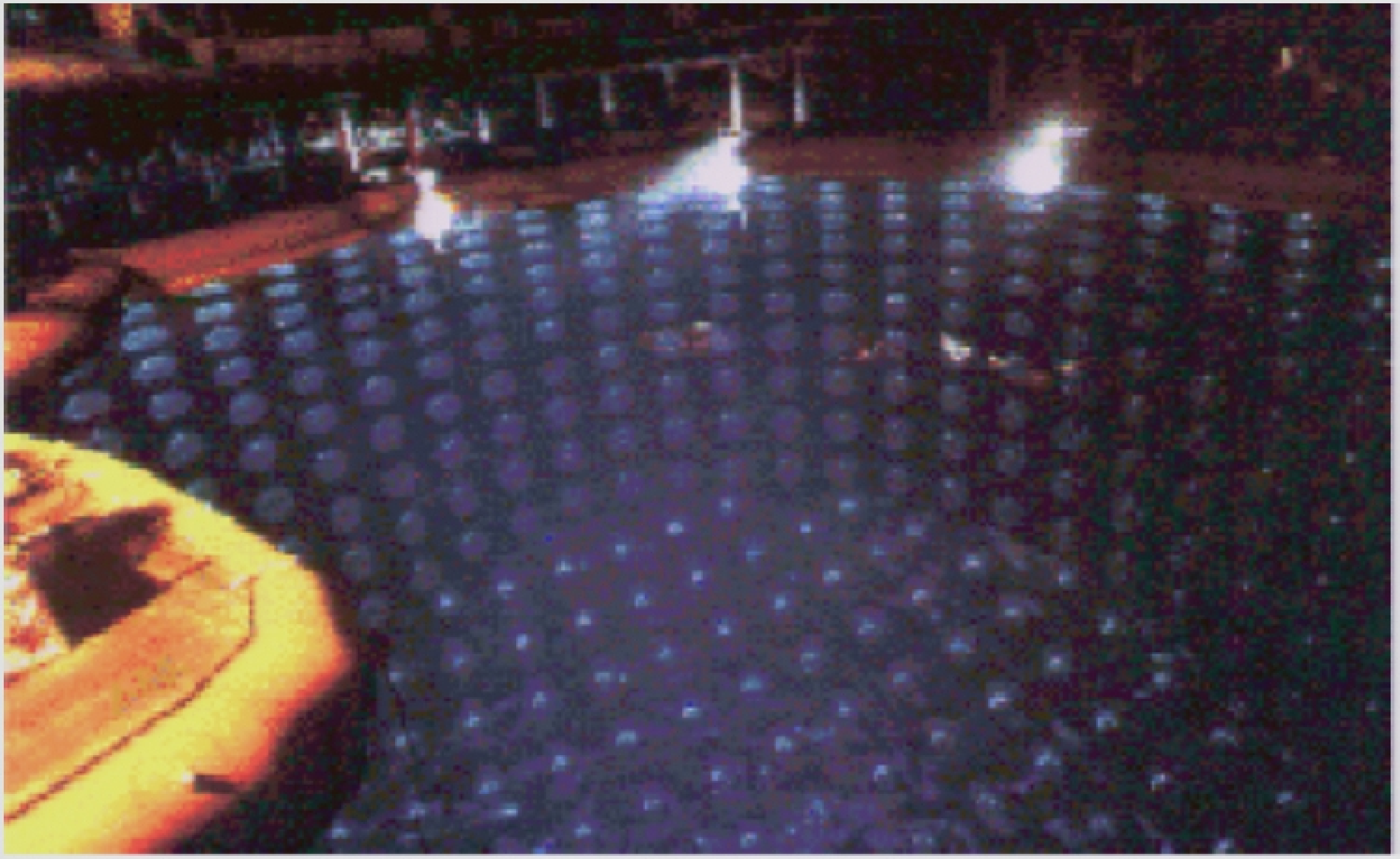
I will attend the Balaton meeting on neutrinos and looking forward to see you there.

Yours sincerely,

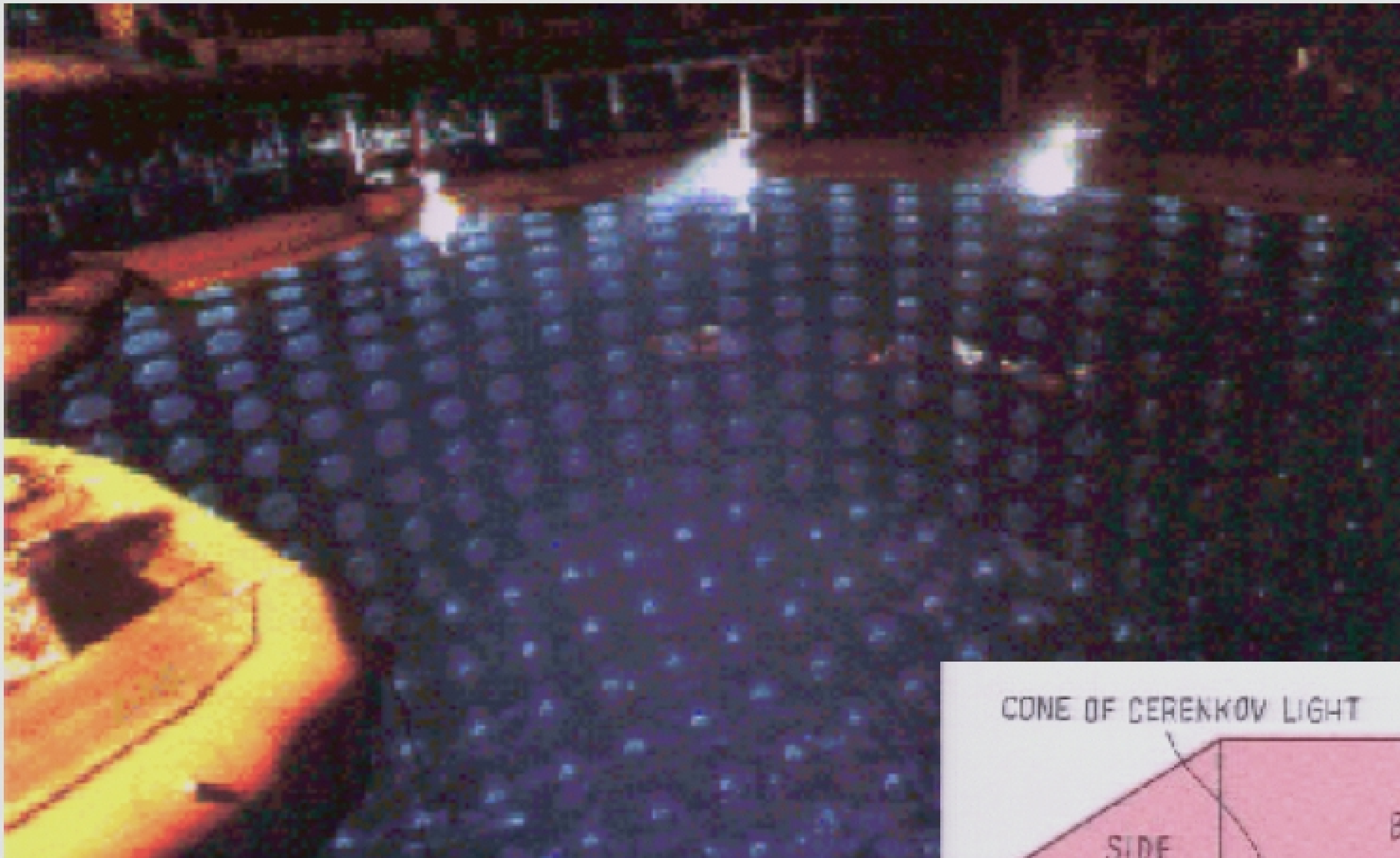
B Pontecorvo

B.Pontecorvo

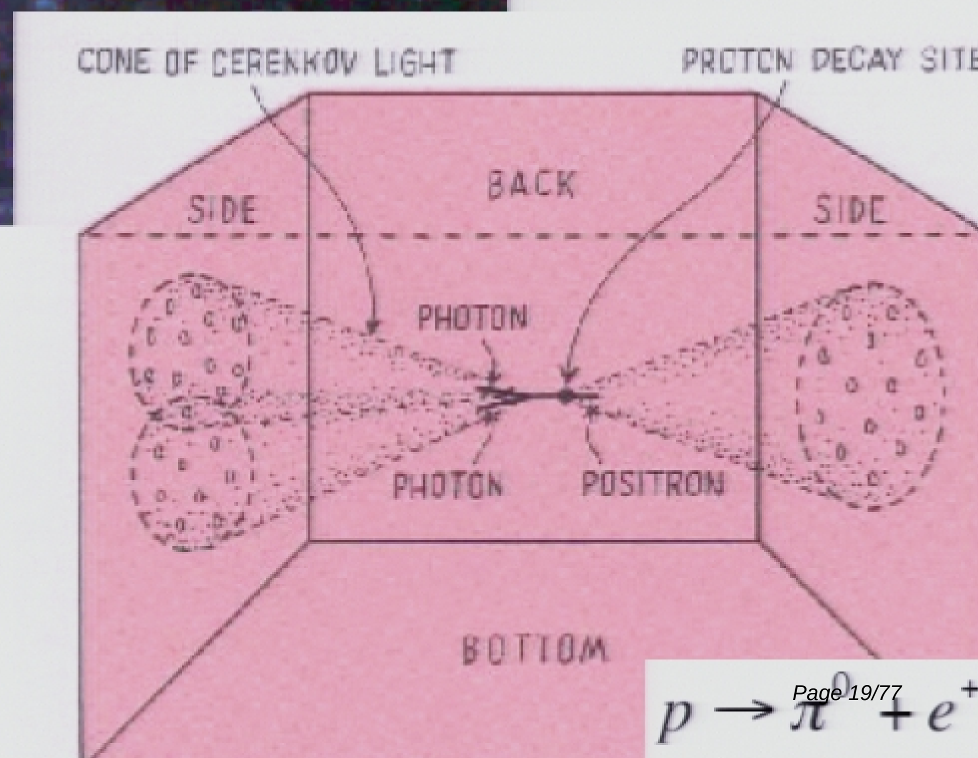
BMP/nn



Kamiokande



Kamiokande

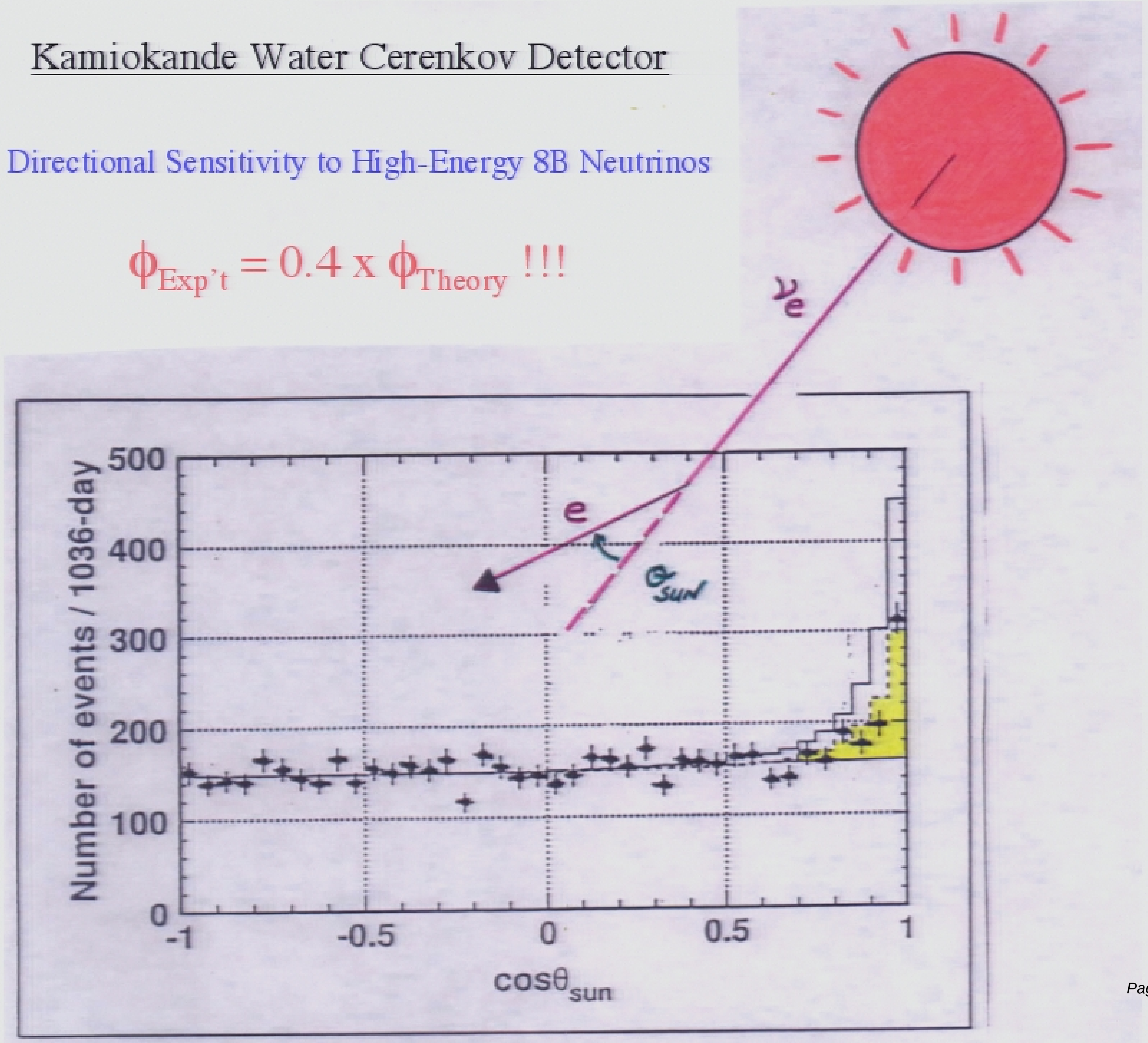


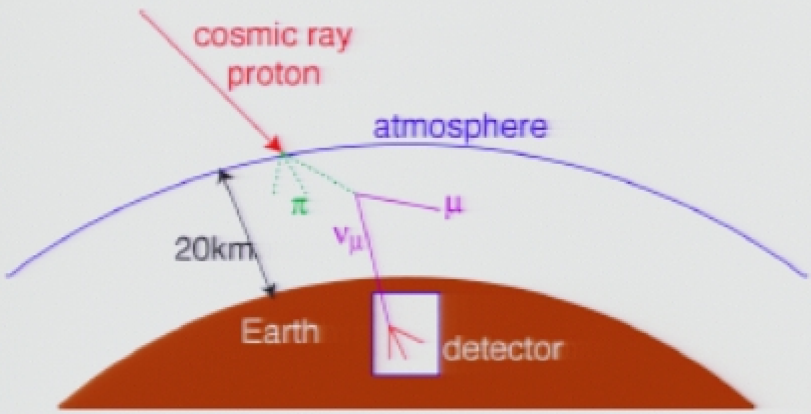
$$p \rightarrow \pi^0 + e^+$$

Kamiokande Water Cerenkov Detector

Directional Sensitivity to High-Energy 8B Neutrinos

$\phi_{Exp't} = 0.4 \times \phi_{Theory}$!!!

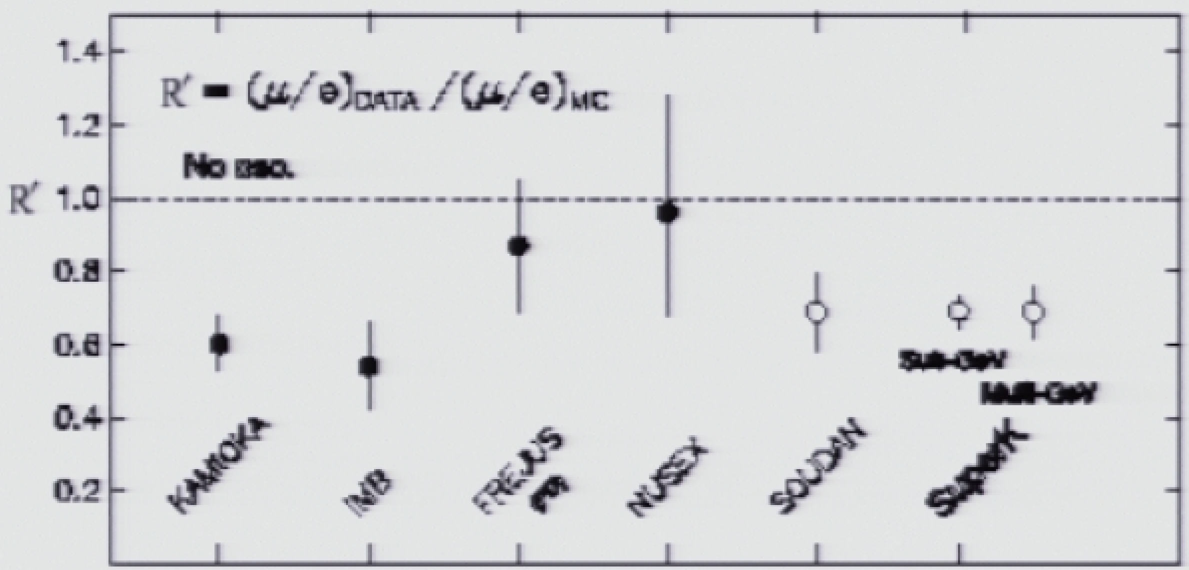




$$\pi \to \mu + \nu_\mu$$

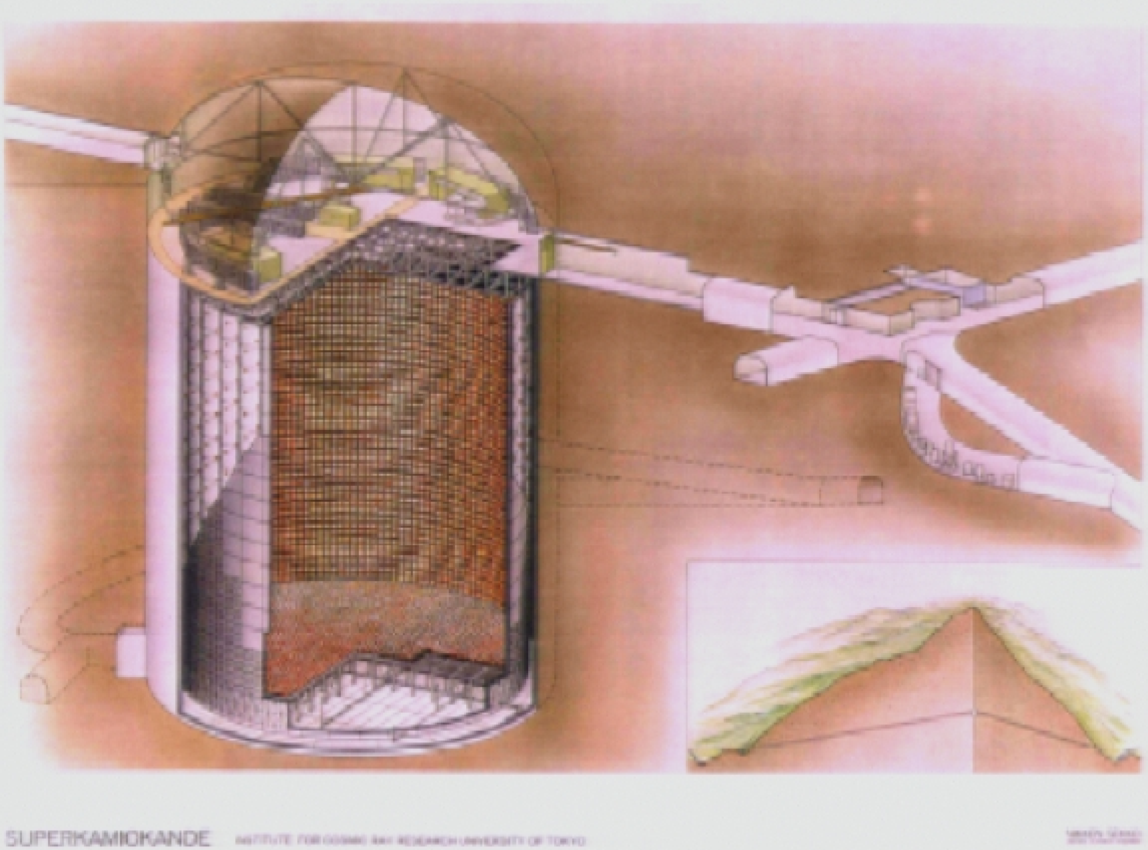
$$\mu \to e + \nu_e + \nu_\mu$$

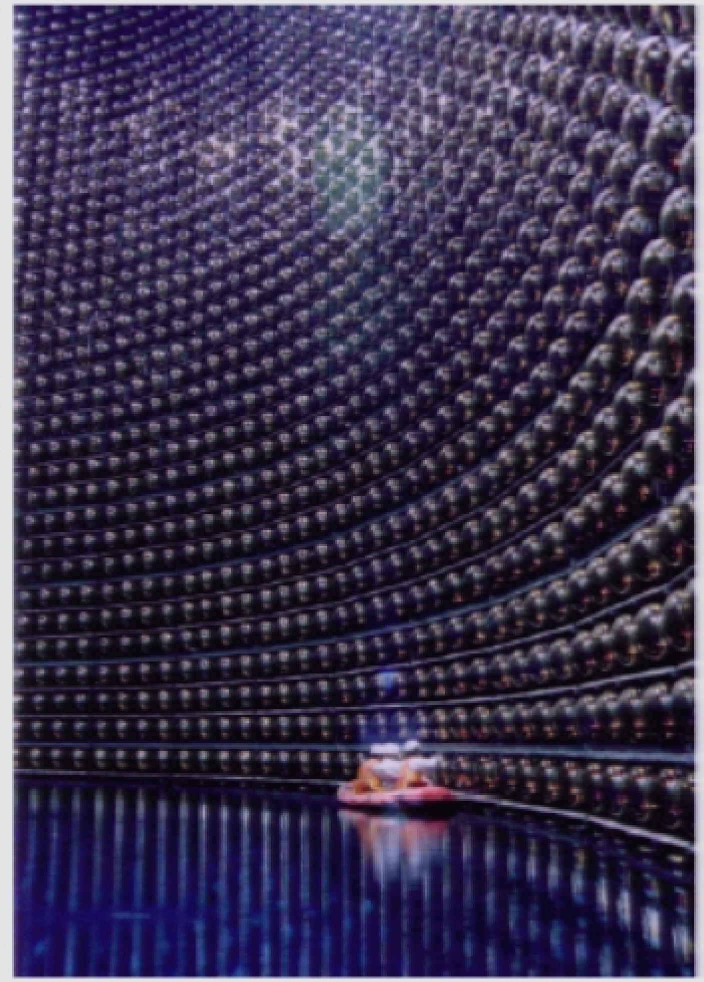
$$\longrightarrow \quad N\nu_\mu = 2N\nu_e$$



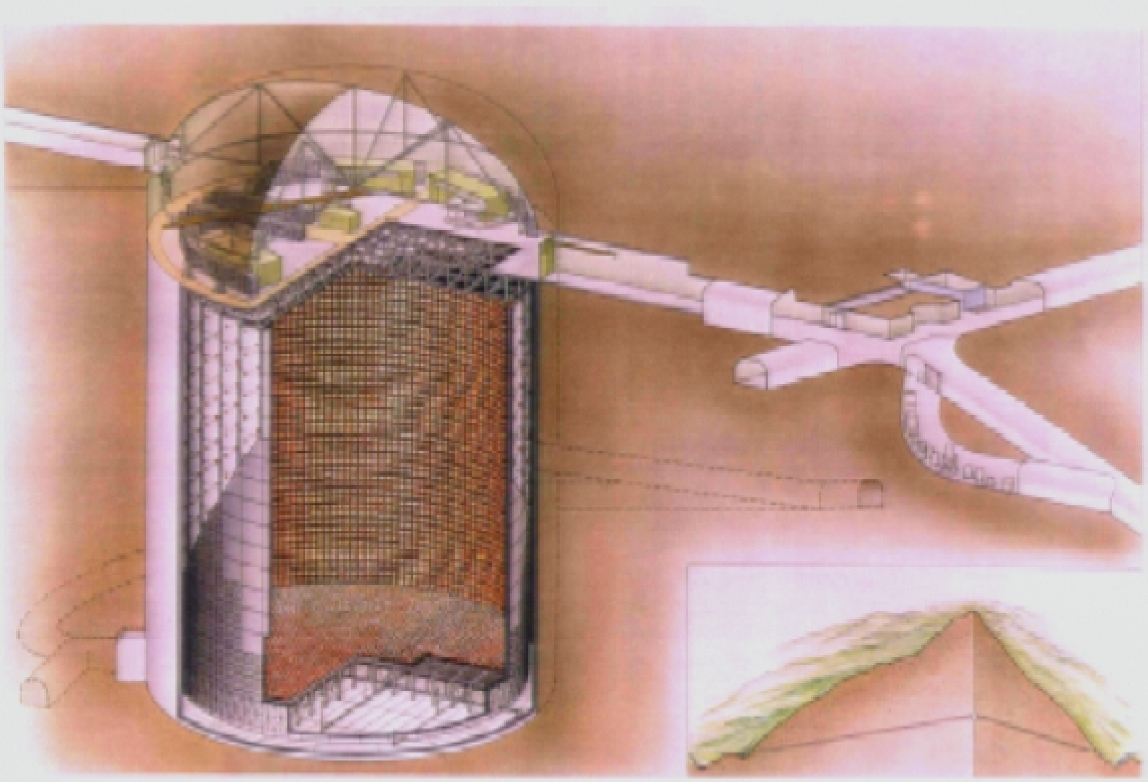
Too few ν_μ

Super - Kamiokande

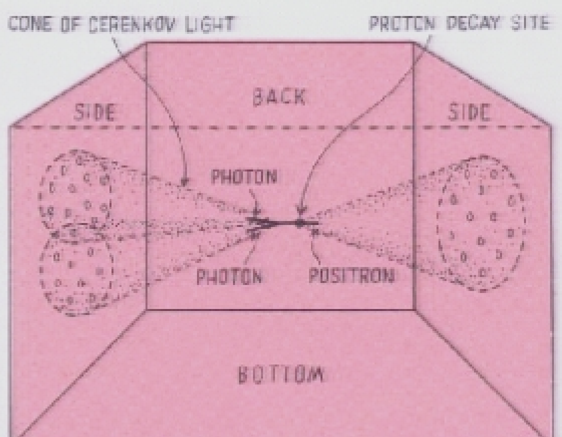


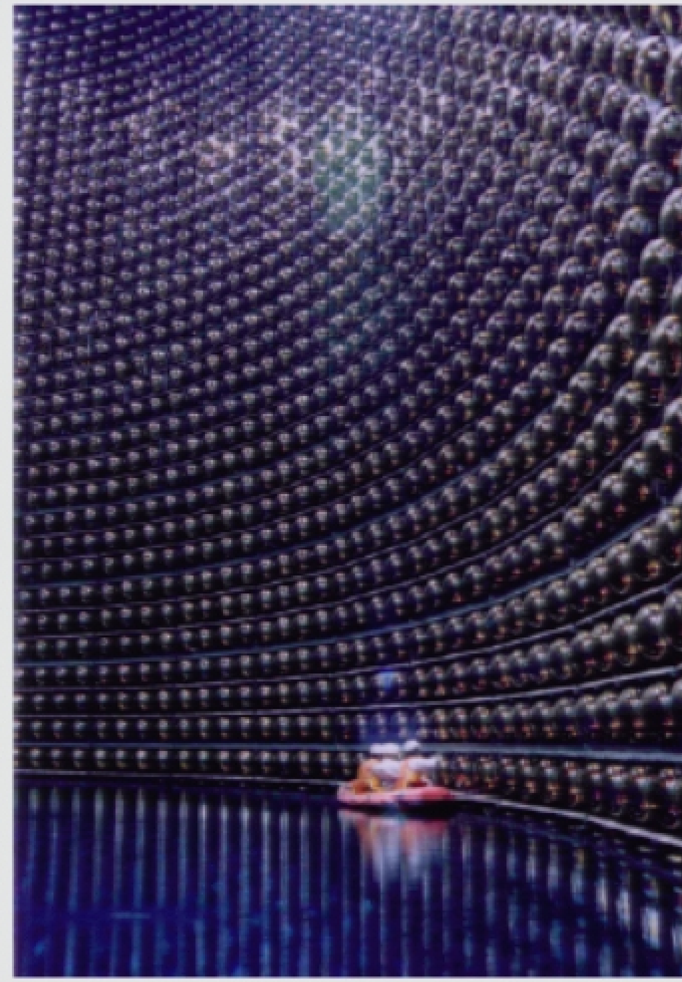


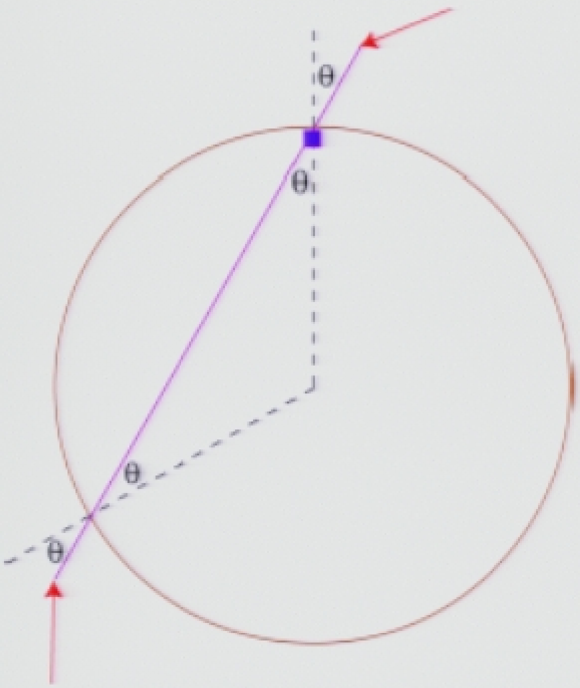
Super - Kamiokande

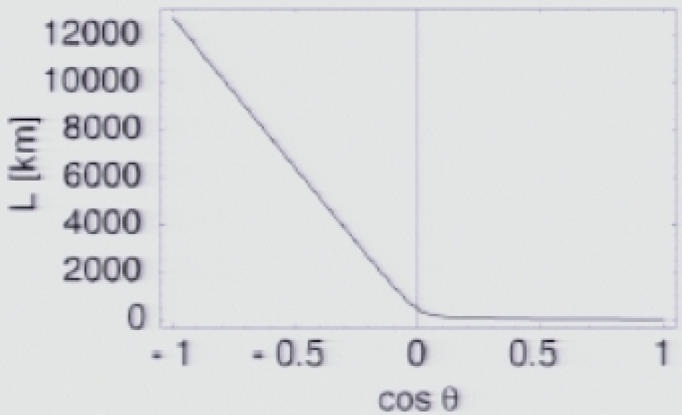


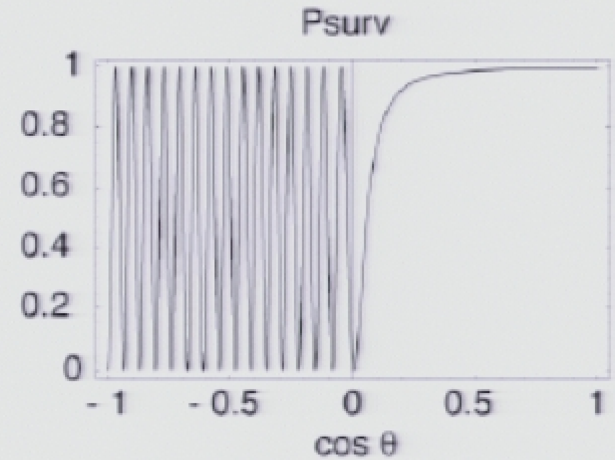
SUPERKAMIOKANDE

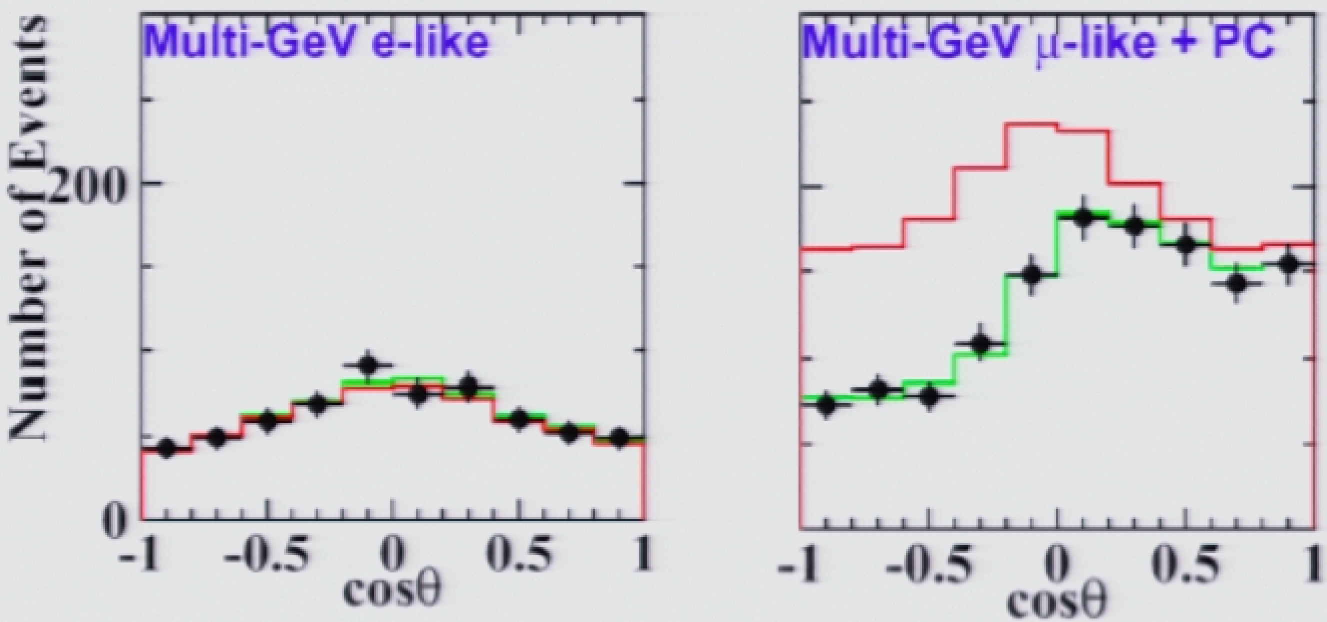




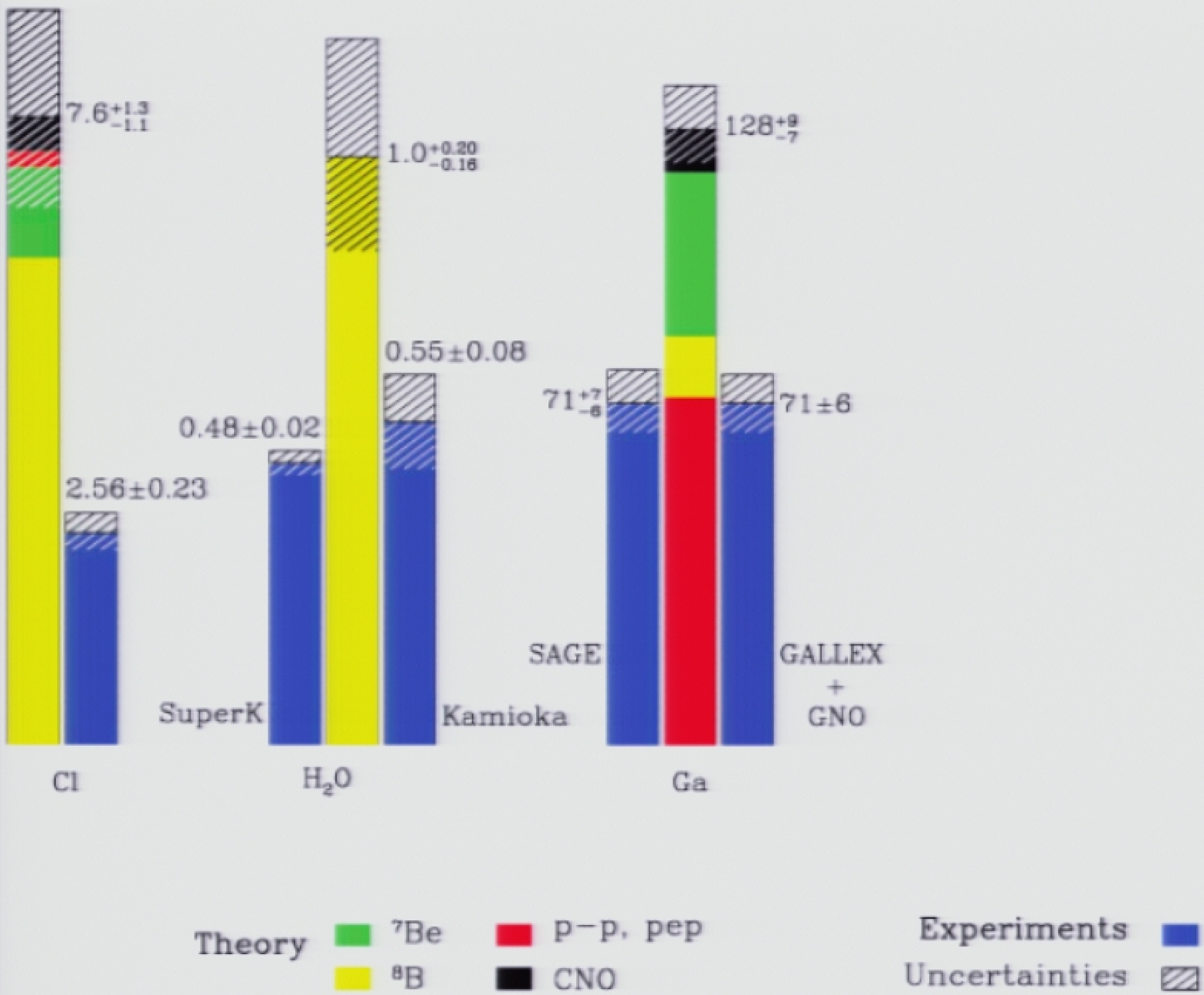


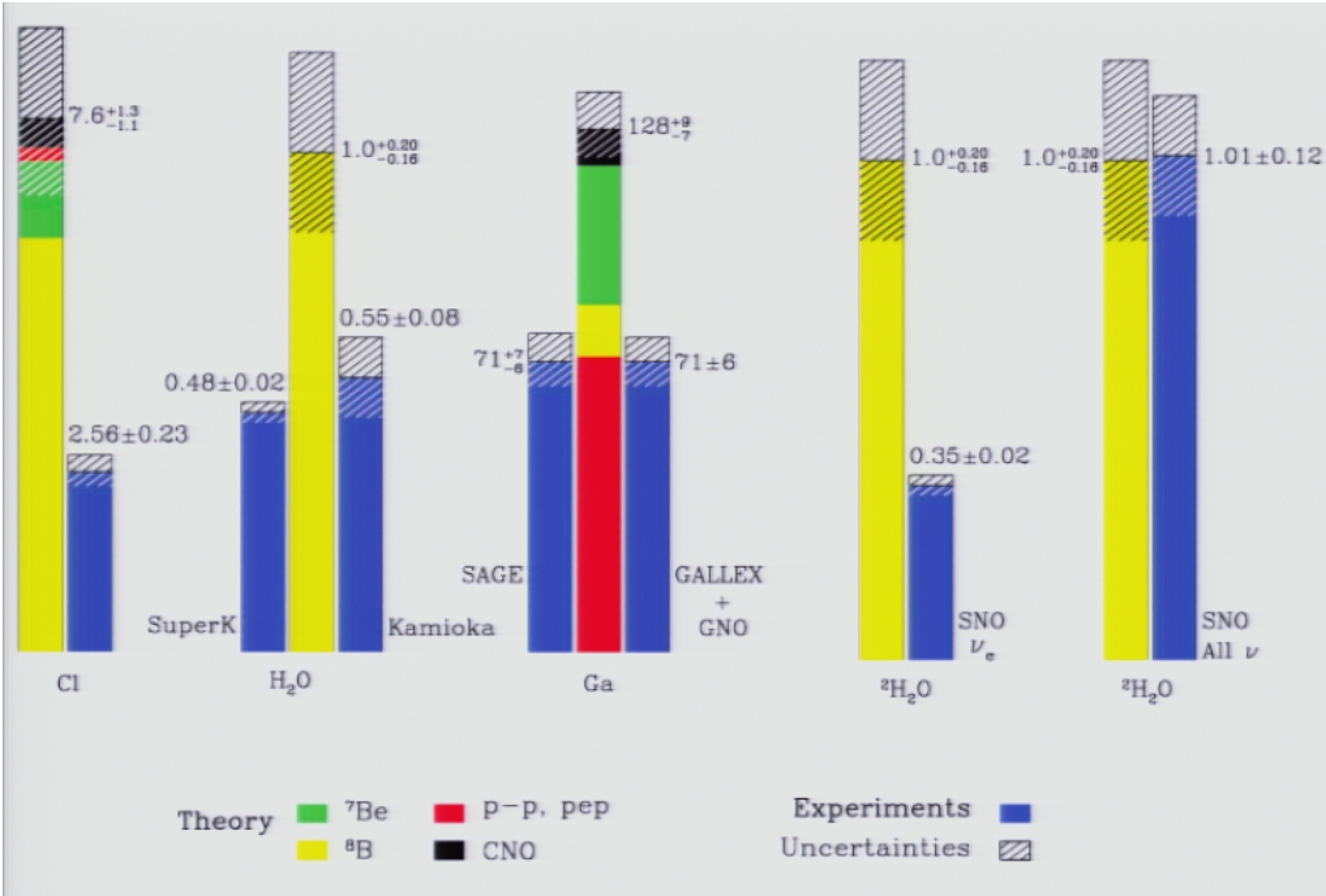




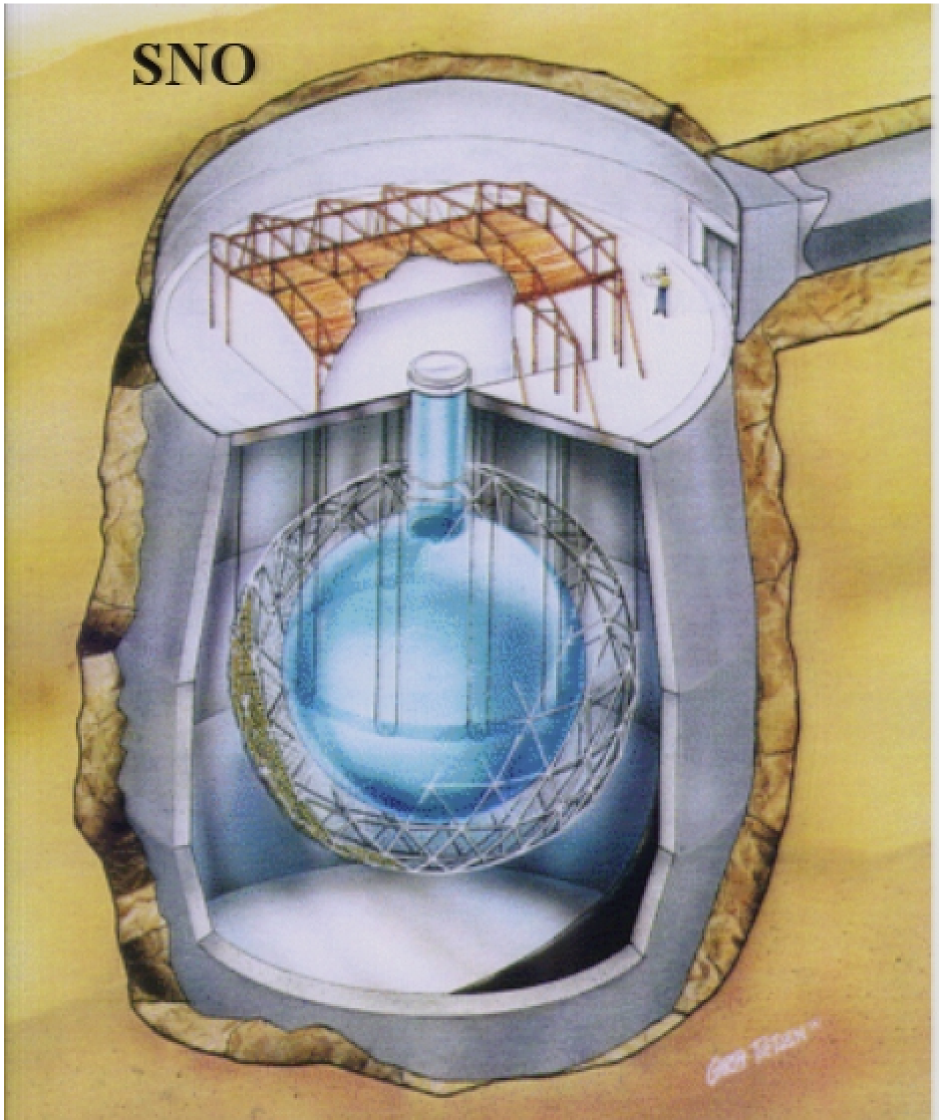


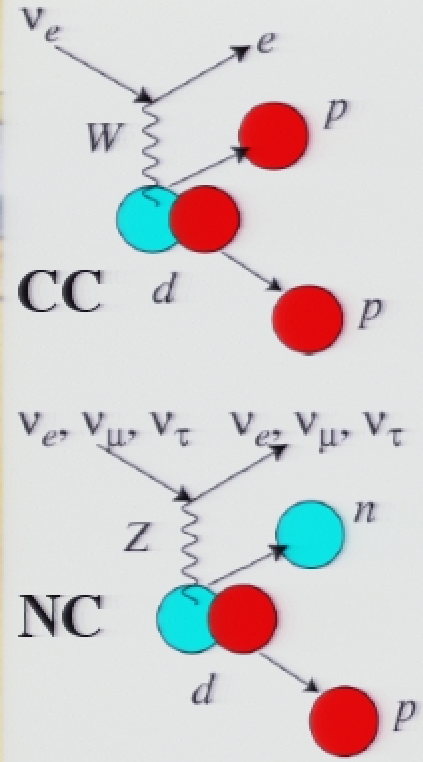
Evidence for neutrino oscillations from SuperK

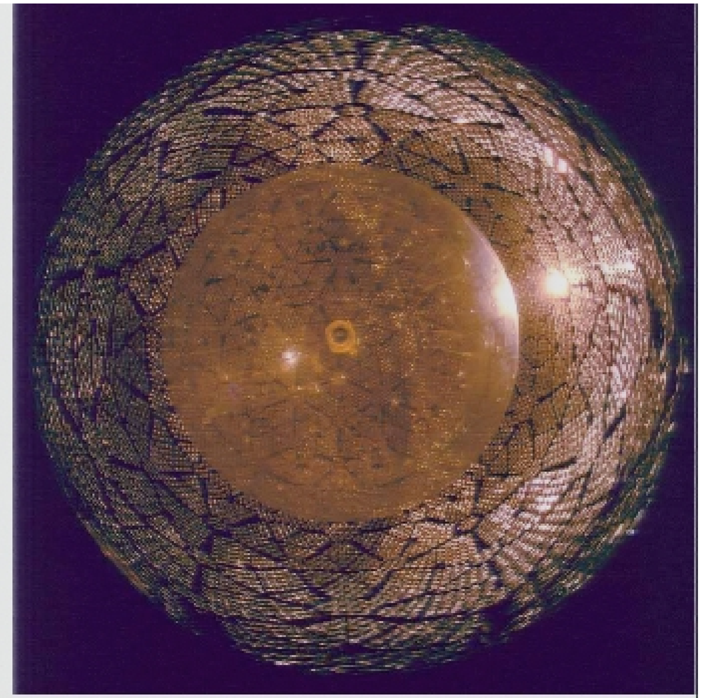

7.6+1.3 −1.1
1.0+0.20 −0.16
128+9 −7
0.55±0.08
71+7 −6
71±6
0.48±0.02
2.56±0.23
SAGE
GALLEX + GNO
SuperK
Kamioka
Cl
H2O
Ga
Theory
7Be
8B
p−p, pep
CNO
Experiments
Uncertainties

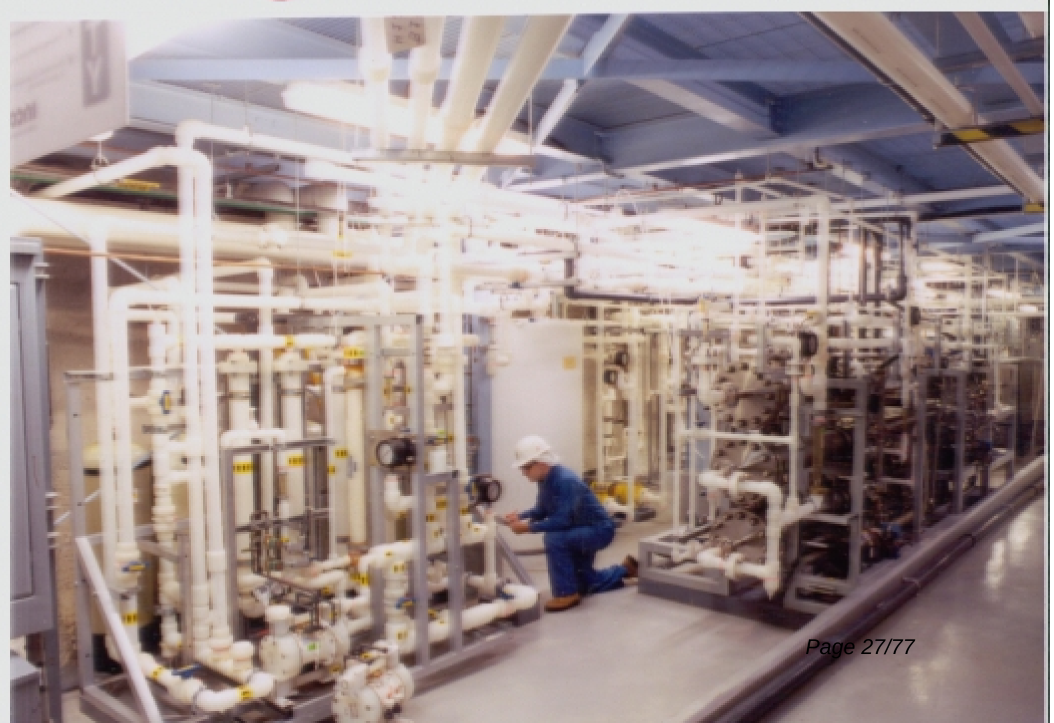


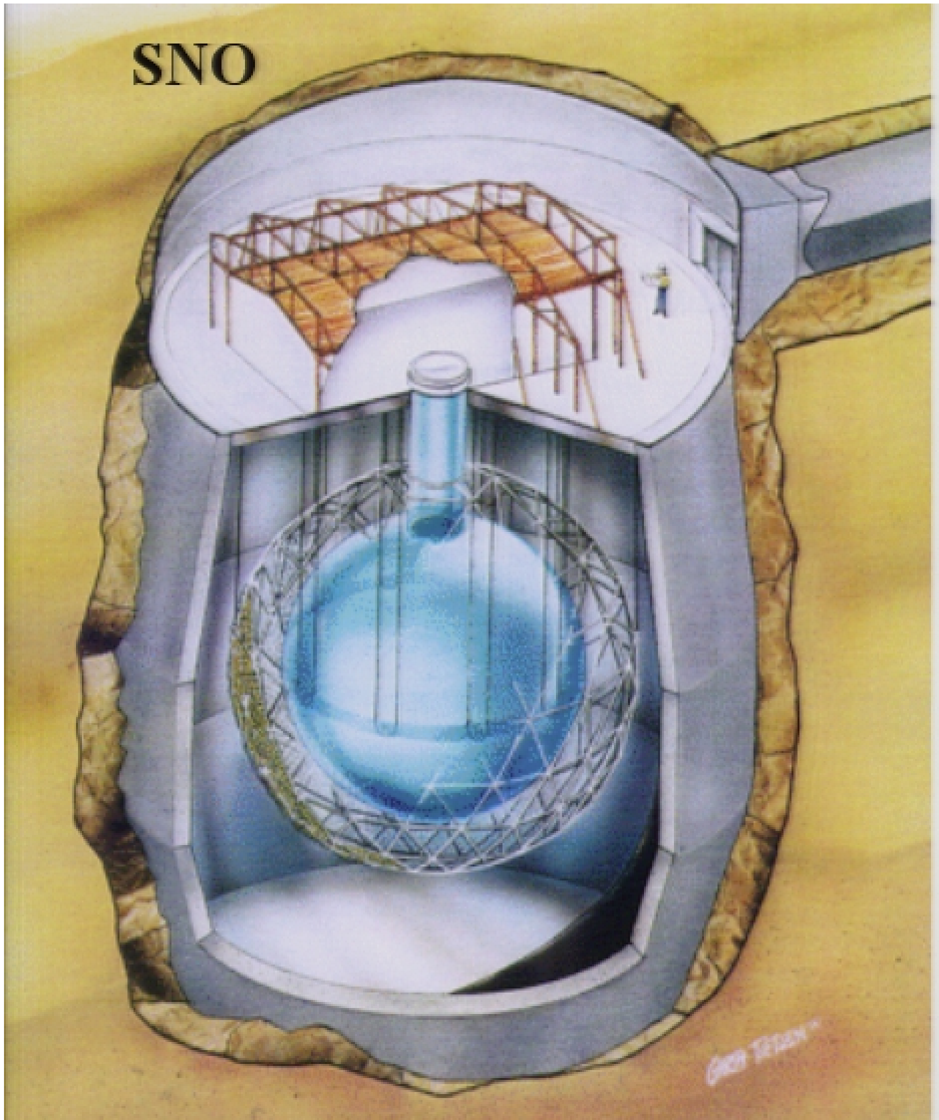
7.6 +1.3 −1.1
2.56±0.23
Cl
1.0 +0.20 −0.16
0.48±0.02
0.55±0.08
SuperK
Kamioka
H2O
128 +9 −7
71 +7 −6
71±6
SAGE
GALLEX + GNO
Ga
1.0 +0.20 −0.16
0.35±0.02
SNO νe
2H2O
1.0 +0.20 −0.16
1.01±0.12
SNO All ν
2H2O
Theory
7Be
8B
p−p, pep
CNO
Experiments
Uncertainties

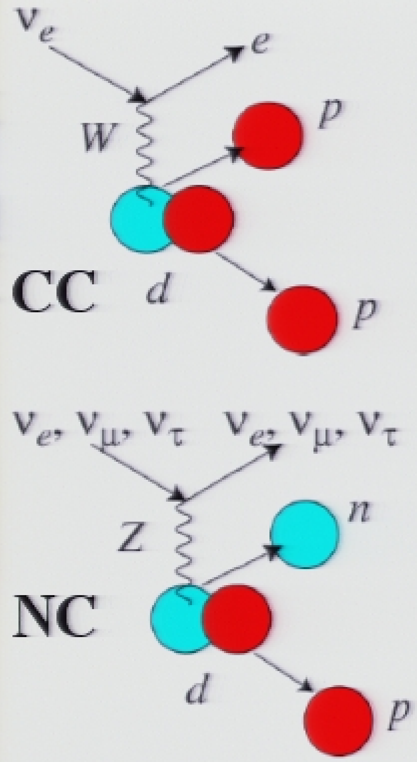

SNO

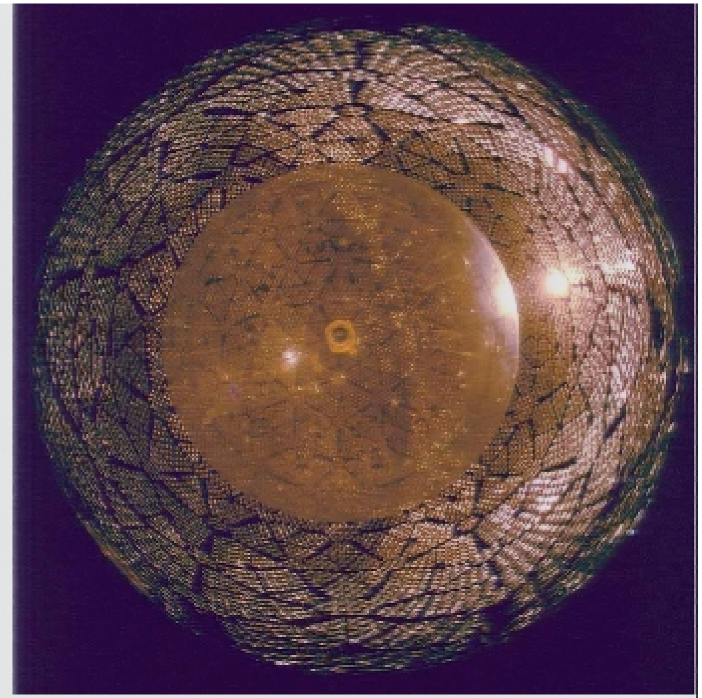

νe
e
W
p
CC
d
p
νe, νμ, ντ
νe, νμ, ντ
Z
n
NC
d
p

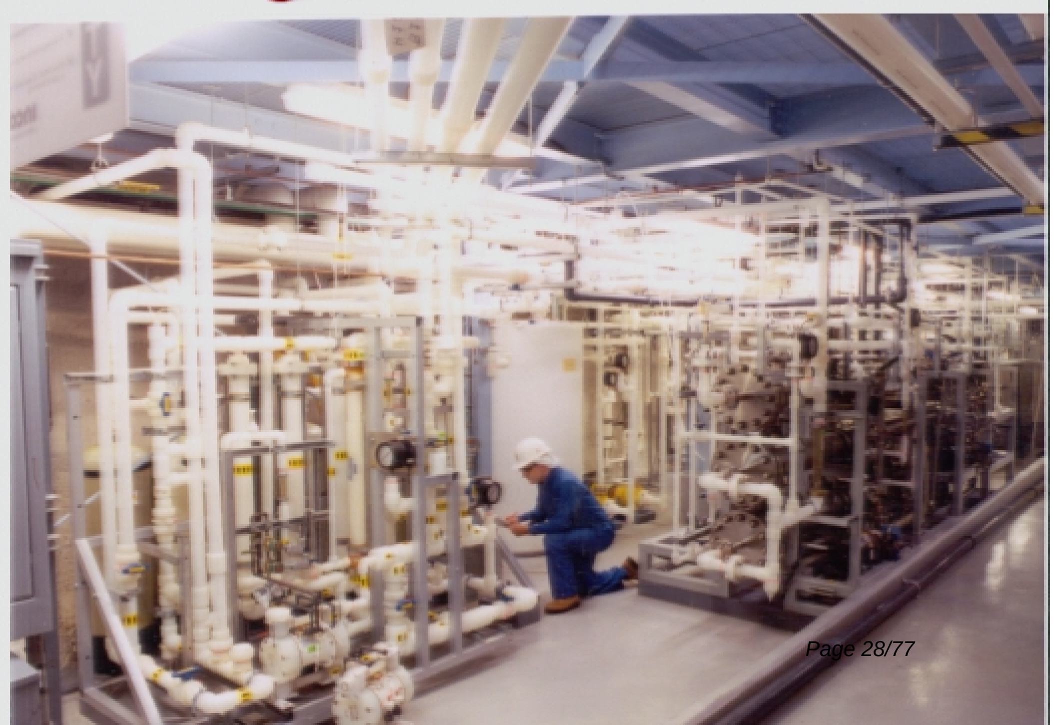








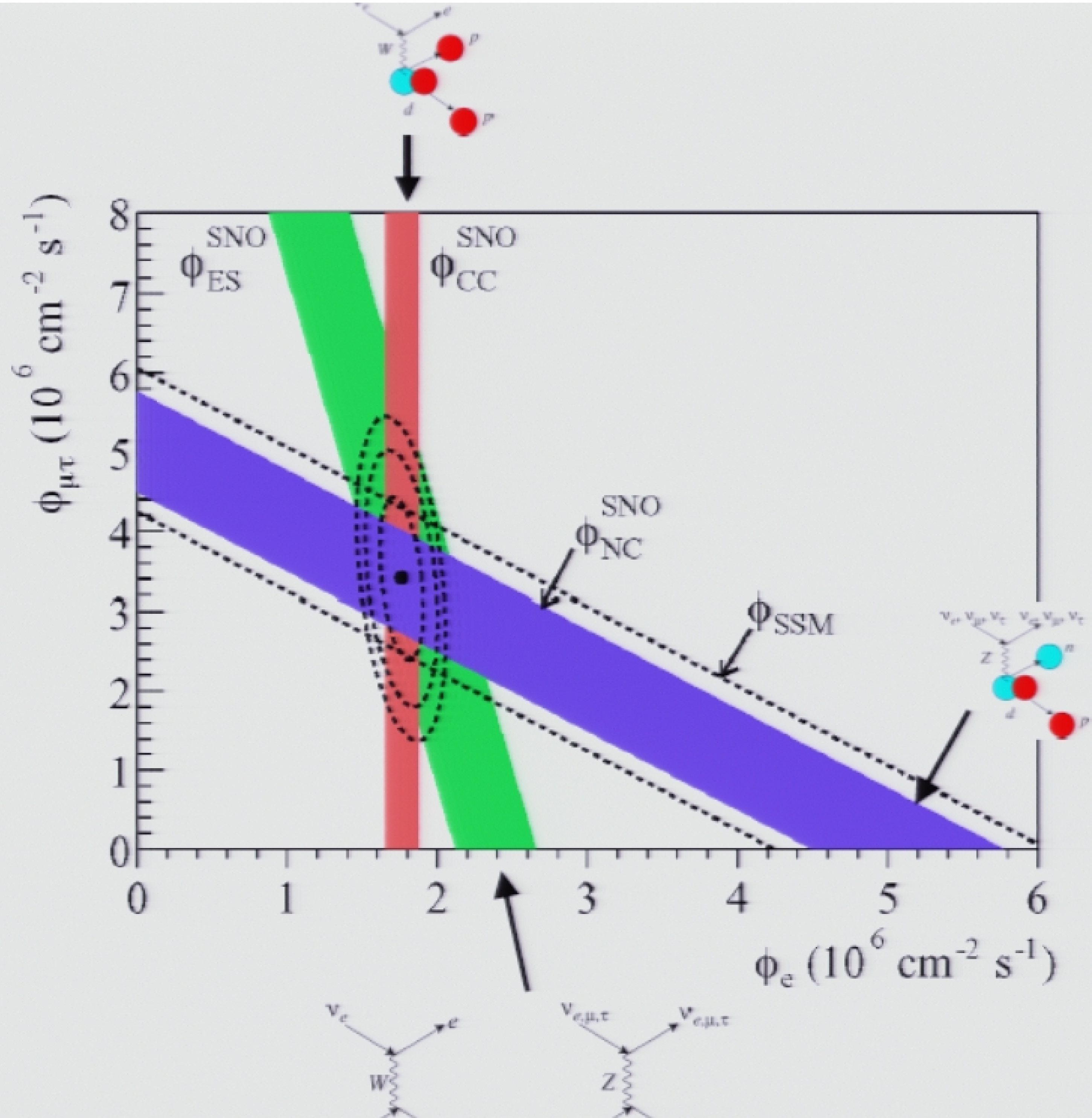




High-purity water & detector construction materials … NC background equivalent to

< 1 neutron / 1 kt / day

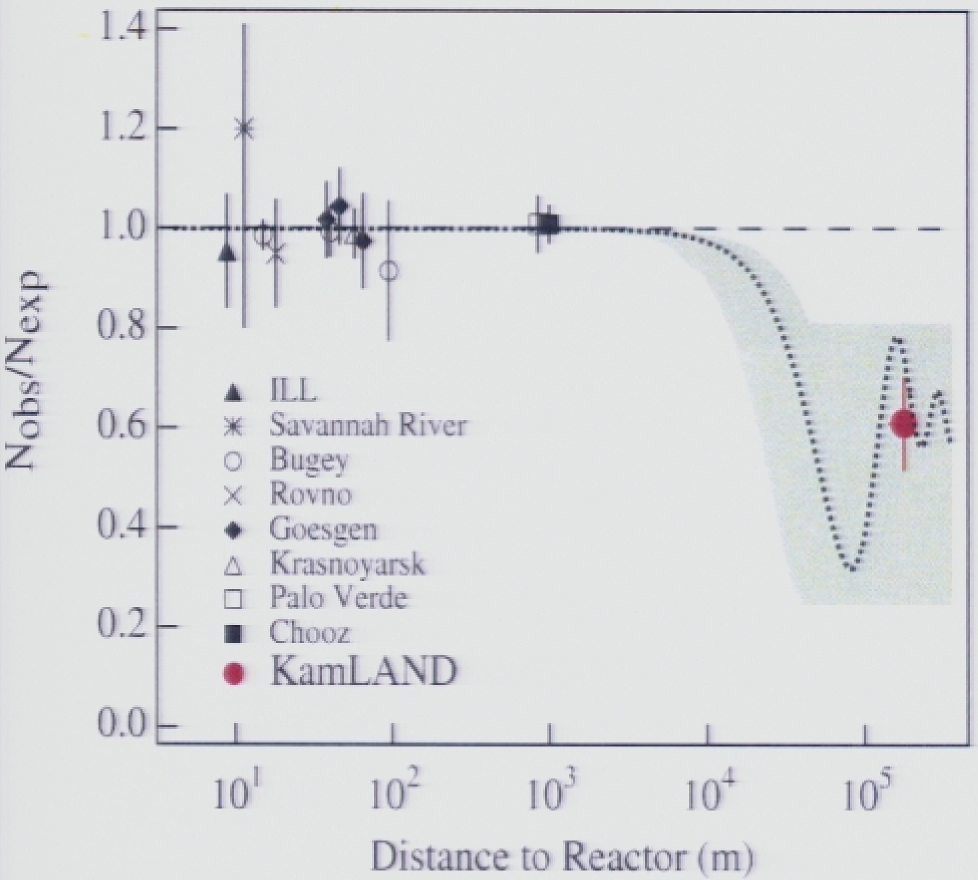
~0.4 neutrons / tonne / year!

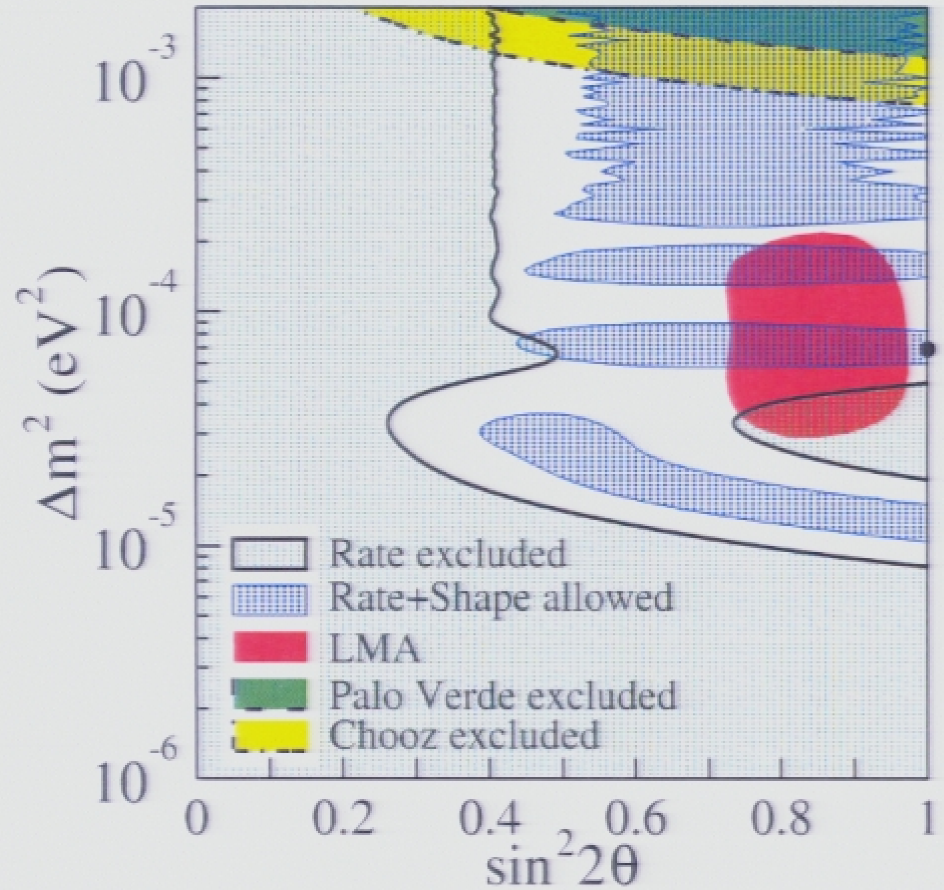


SNO
ϕ_{ES}
SNO
ϕ_{CC}
SNO
ϕ_{NC}
ϕ_{SSM}
$\phi_{\mu\tau}$ (10^6 cm^{-2} s^{-1})
ϕ_e (10^6 cm^{-2} s^{-1})
0
1
2
3
4
5
6
7
8
W
Z
ν_e
e
$\nu_{e,\mu,\tau}$

First Results from KamLAND

hep-ex/0212021





U_{MNSP} Matrix

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

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

$\theta_{23} \sim 45^\circ$ $\tan^2\theta_{13} < 0.03$ at 90% CL $\theta_{12} \sim 32^\circ$

U_{MNSP} Matrix

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

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

$\theta_{23} \sim 45°$ $\tan^2\theta_{13} < 0.03$ at 90% CL $\theta_{12} \sim 32°$

U_{MNSP} Matrix

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

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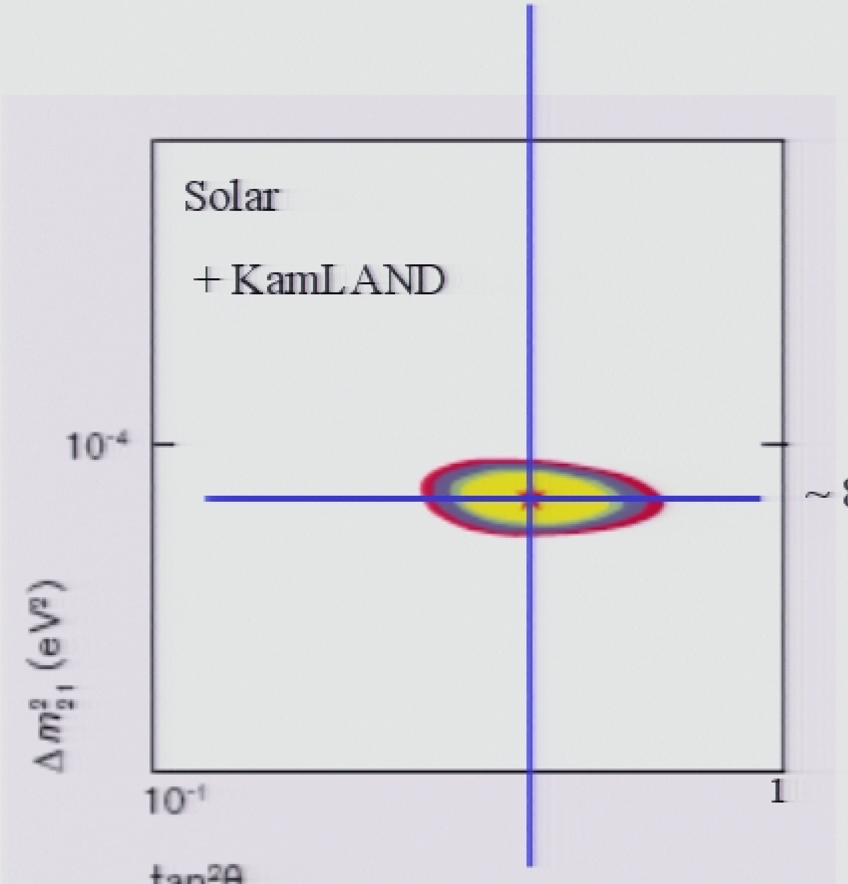
$\theta_{23} \sim 45^\circ$ $\tan^2\theta_{13} < 0.03$ at 90% CL $\theta_{12} \sim 32^\circ$



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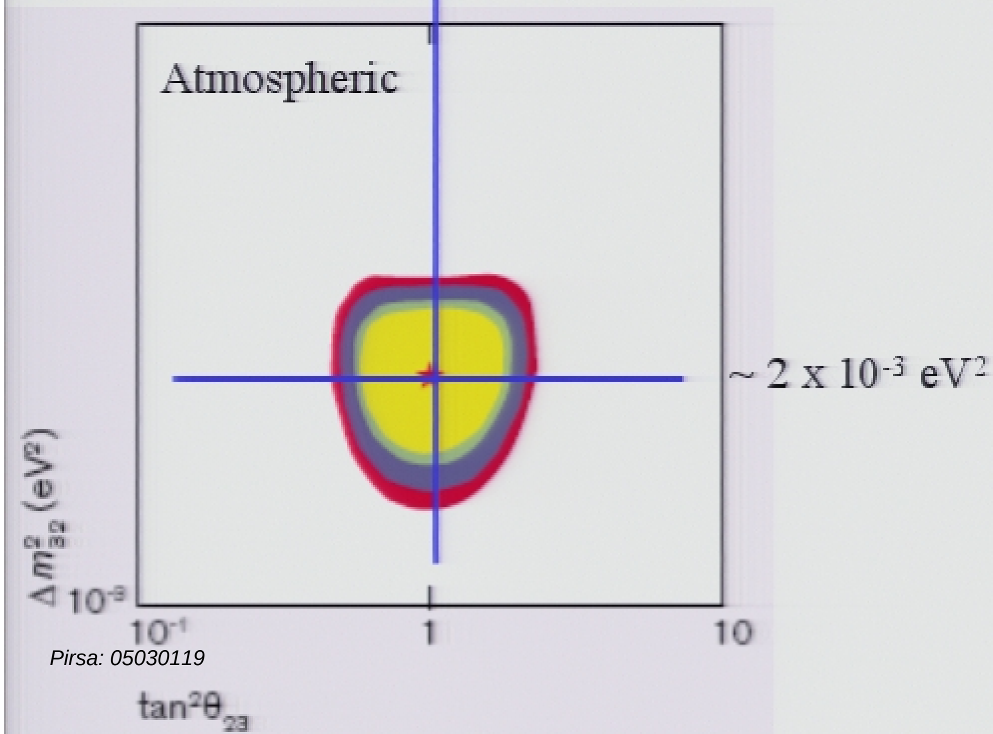

U_{MNSP} Matrix

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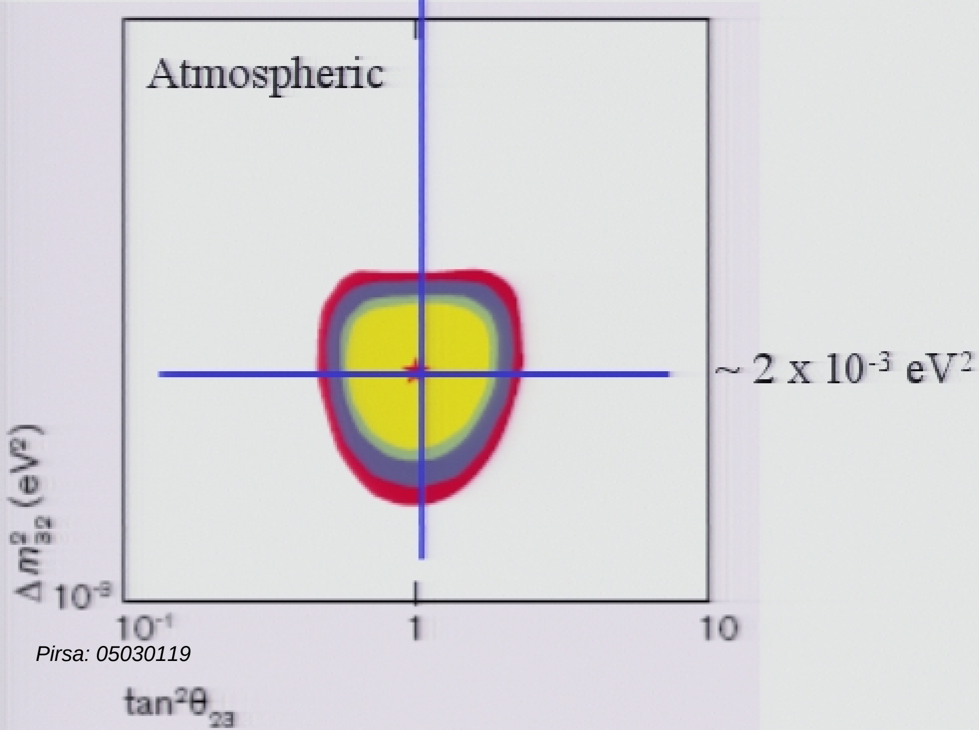

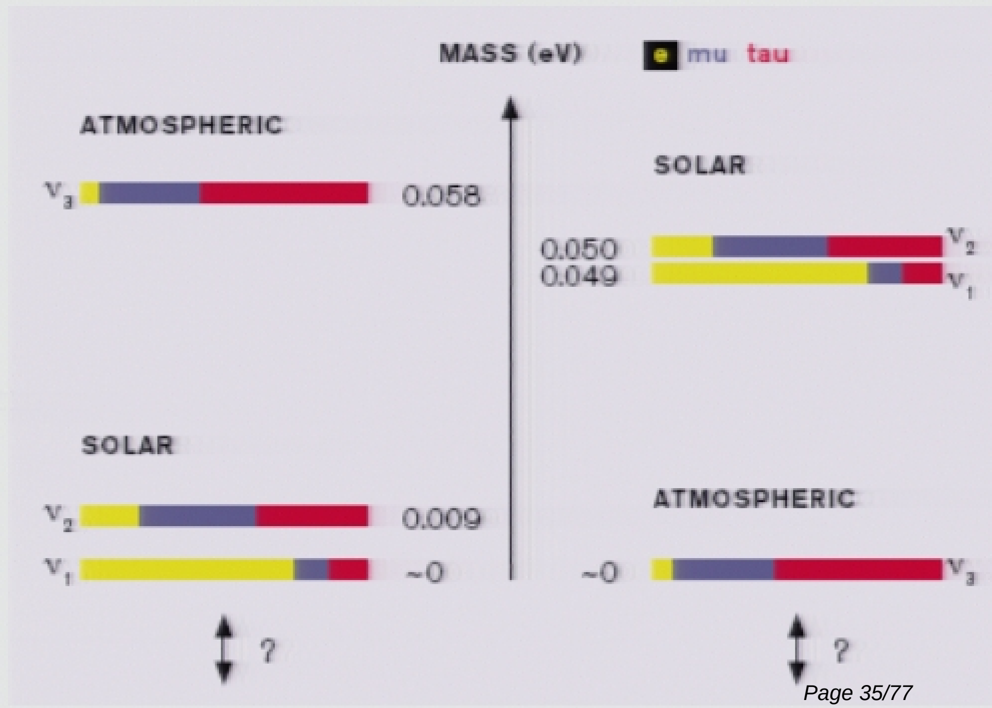

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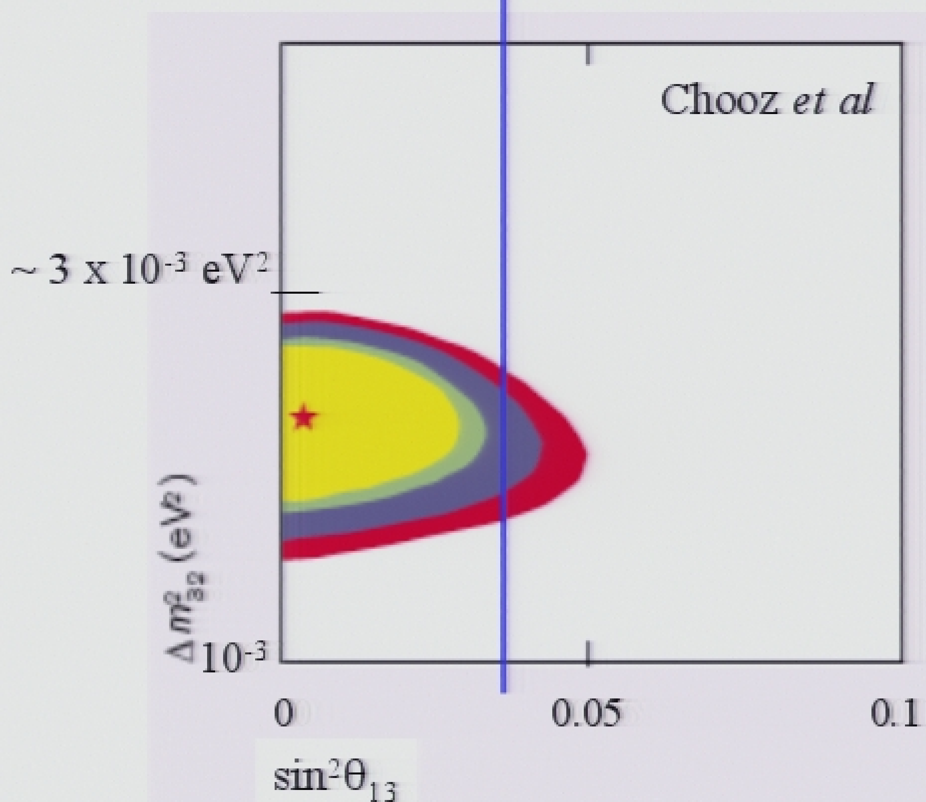

U_{MNSP} Matrix

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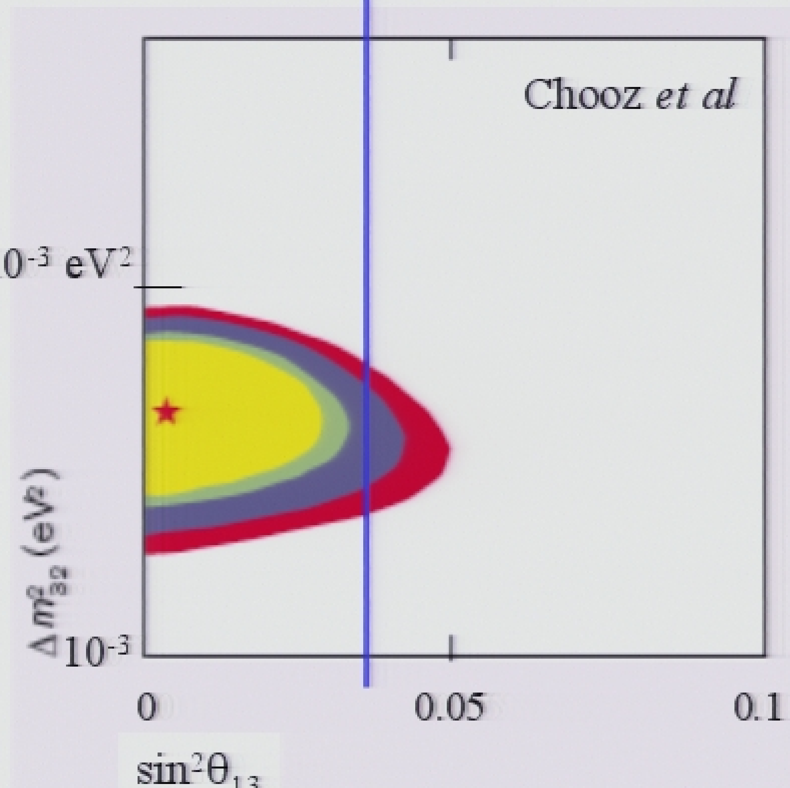
Additional CP Phases for Majorana Neutrinos ↓

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

$\theta_{23} \sim 45°$ $\tan^2\theta_{13} < 0.03$ at 90% CL $\theta_{12} \sim 32°$

$\sim 3 \times 10^{-3}\ eV^2$



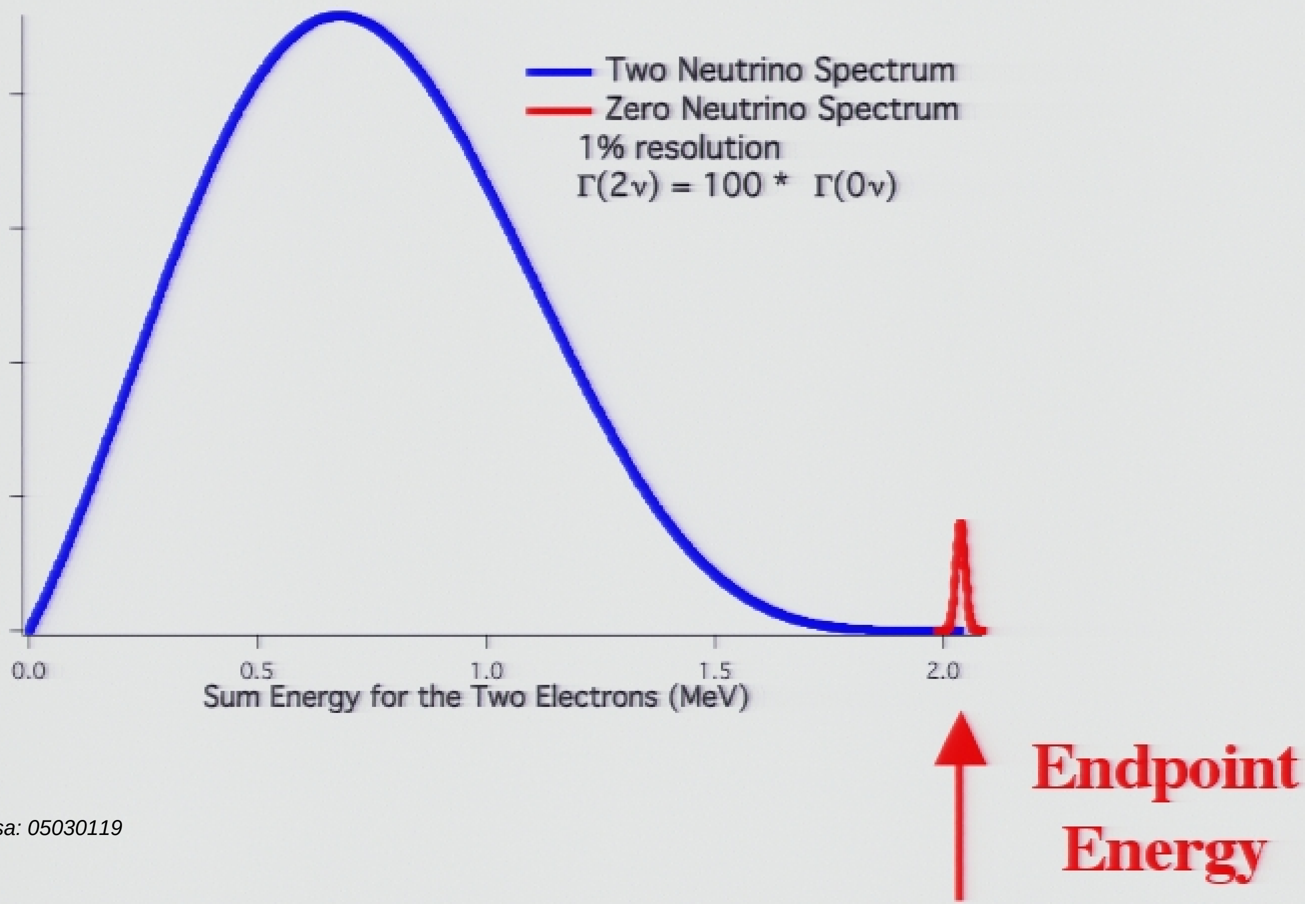
Values of θ_{13} & δ_{CP}?

CP Violation in Neutrino Sector?

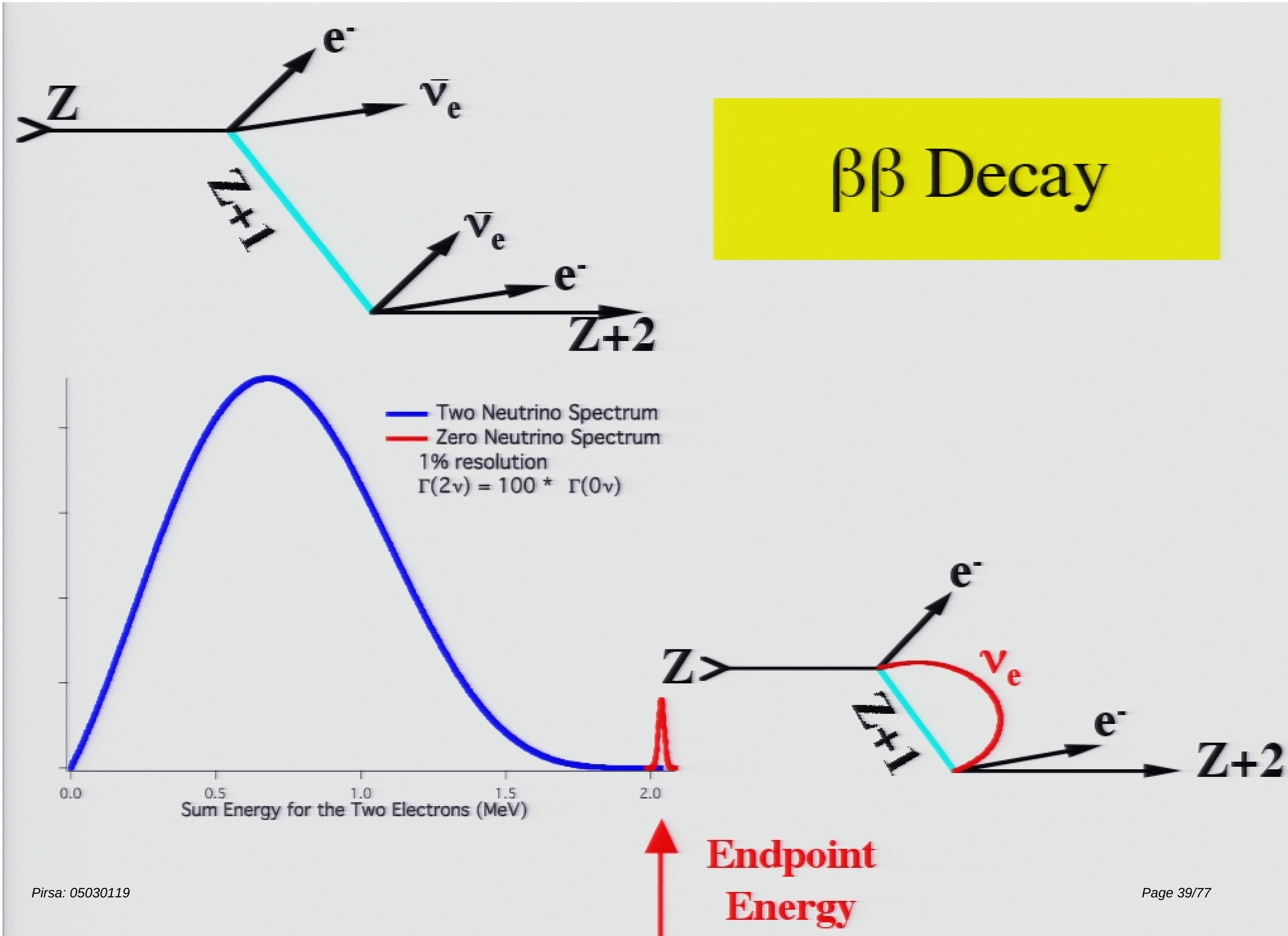
Leptogenesis & Matter-Antimatter Asymmetry in the Universe?

Are Neutrinos their own Antiparticles?

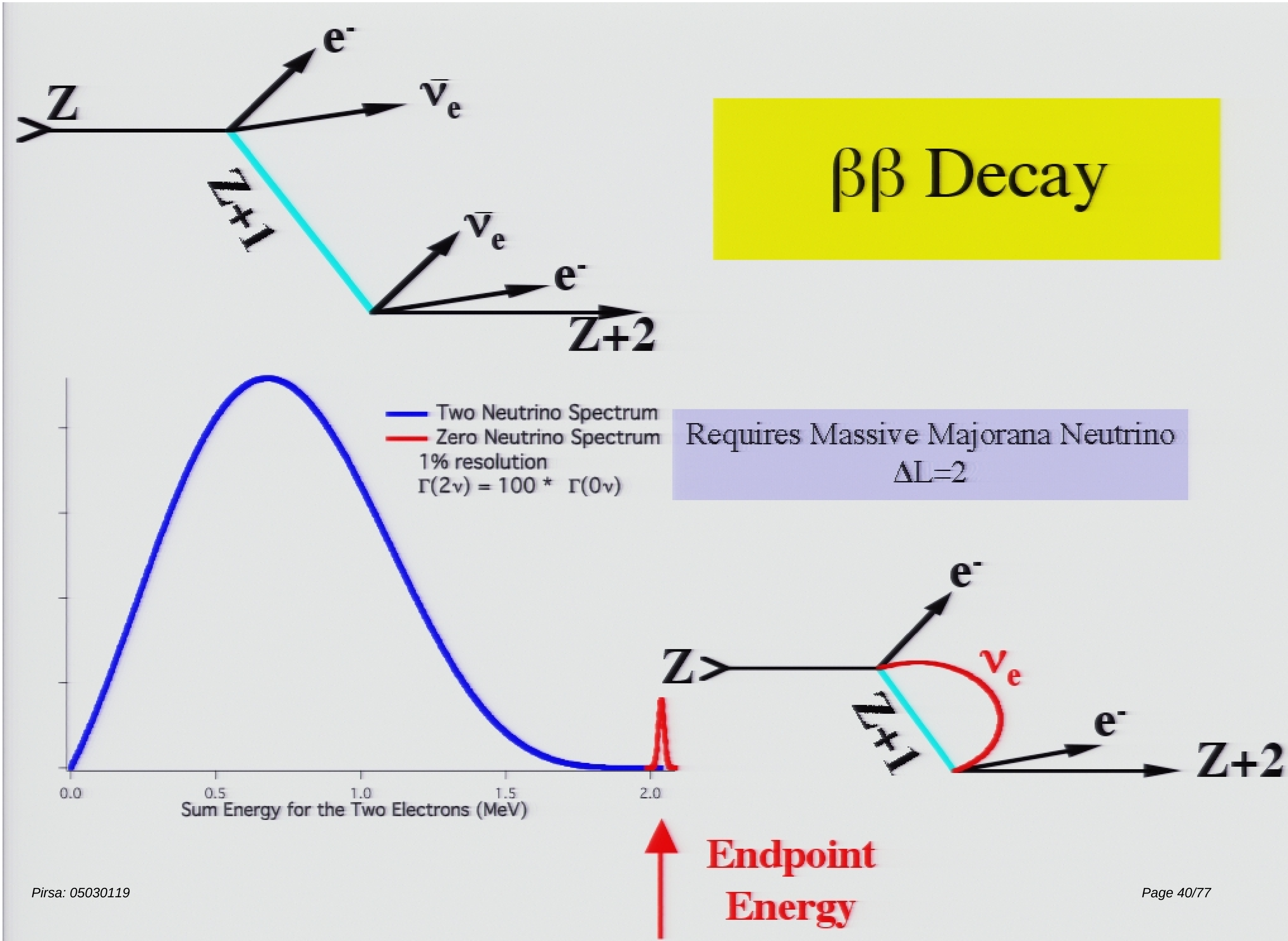
ββ Decay



Two Neutrino Spectrum
Zero Neutrino Spectrum
1% resolution
Γ(2ν) = 100 * Γ(0ν)
0.0
0.5
1.0
1.5
2.0
Sum Energy for the Two Electrons (MeV)
Endpoint
Energy

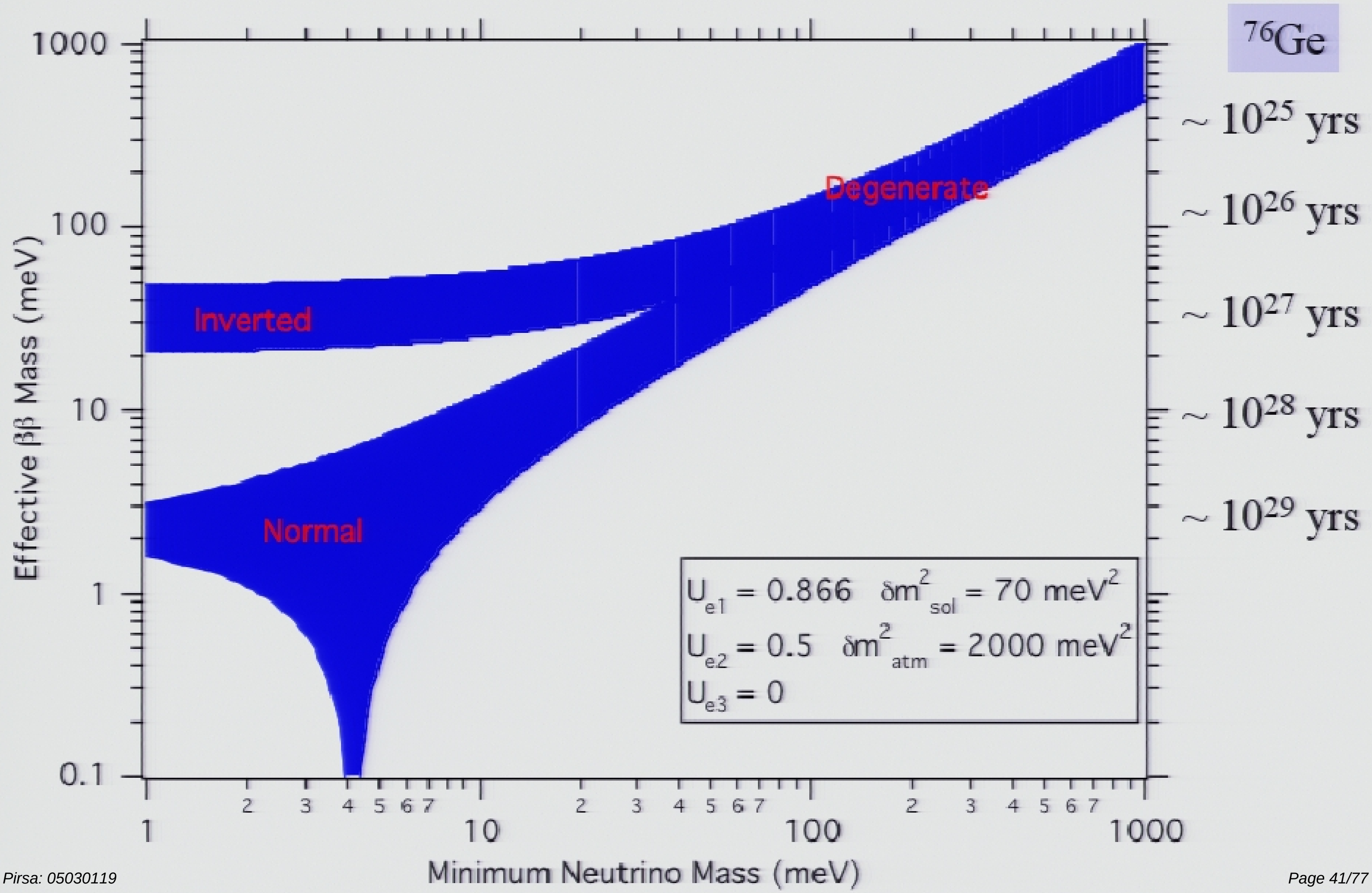


βββ Decay
Z
e-
$\bar{\nu}_e$
Z+1
$\bar{\nu}_e$
e-
Z+2
Two Neutrino Spectrum
Zero Neutrino Spectrum
1% resolution
Γ(2ν) = 100 * Γ(0ν)
0.0
0.5
1.0
1.5
2.0
Sum Energy for the Two Electrons (MeV)
Z
e-
ν_e
Z+1
e-
Z+2
Endpoint Energy



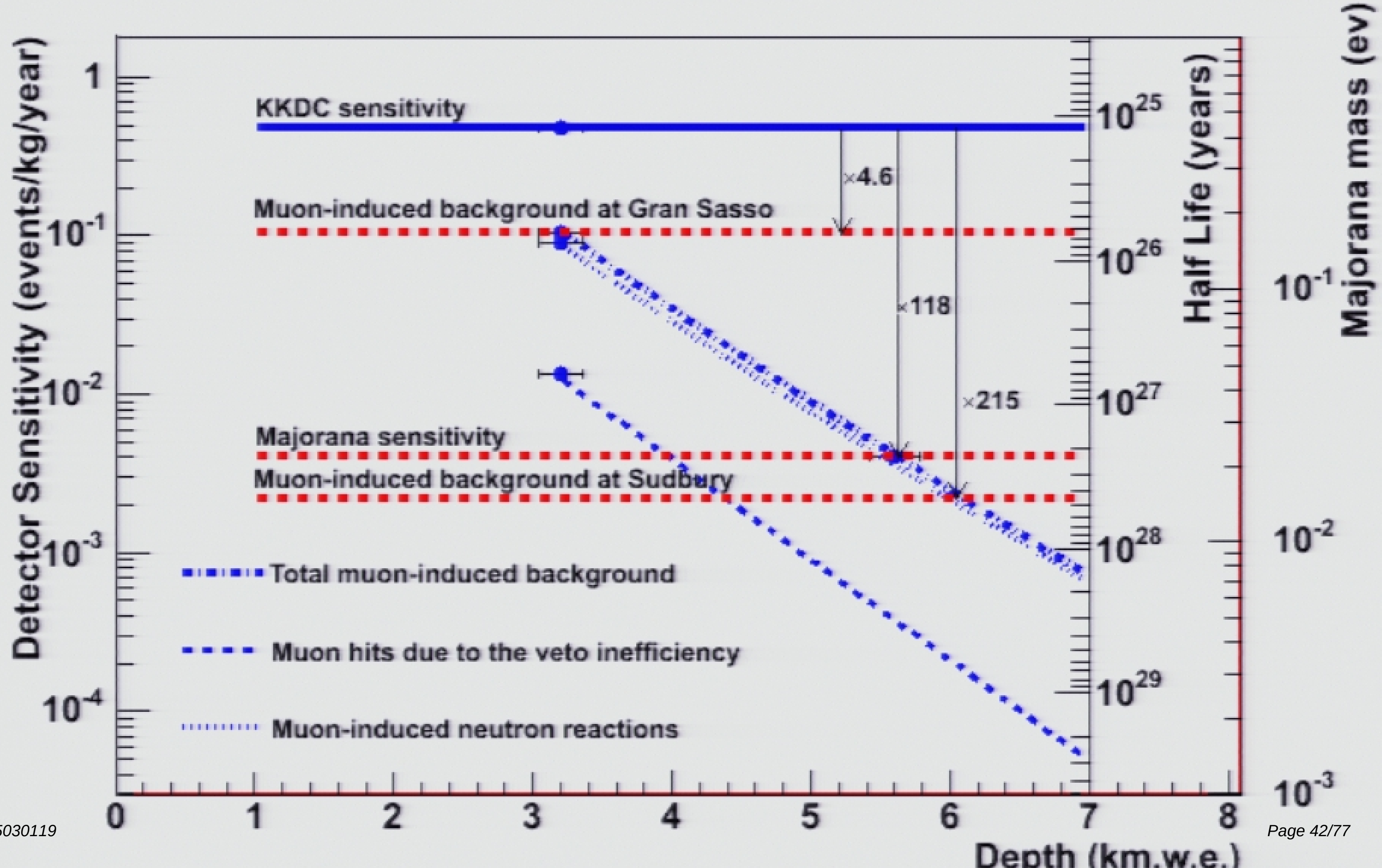
ββ Decay
Z
e-
ν̄e
Z+1
ν̄e
e-
Z+2
Two Neutrino Spectrum
Zero Neutrino Spectrum
1% resolution
Γ(2ν) = 100 * Γ(0ν)
0.0
0.5
1.0
1.5
2.0
Sum Energy for the Two Electrons (MeV)
Requires Massive Majorana Neutrino
ΔL=2
Z
e-
νe
Z+1
e-
Z+2
Endpoint
Energy

Allowed Phase Space for a Majorana Neutrino Mass



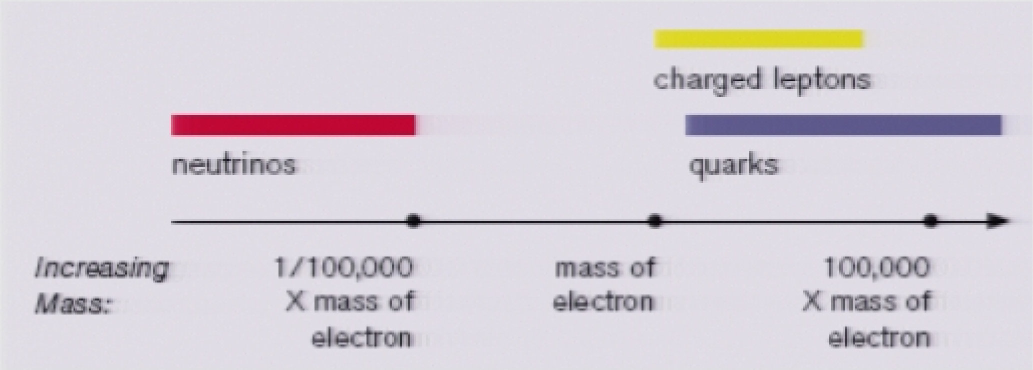
Double Beta Decay *versus* Depth

Dongming Mei & AH, *preliminary*



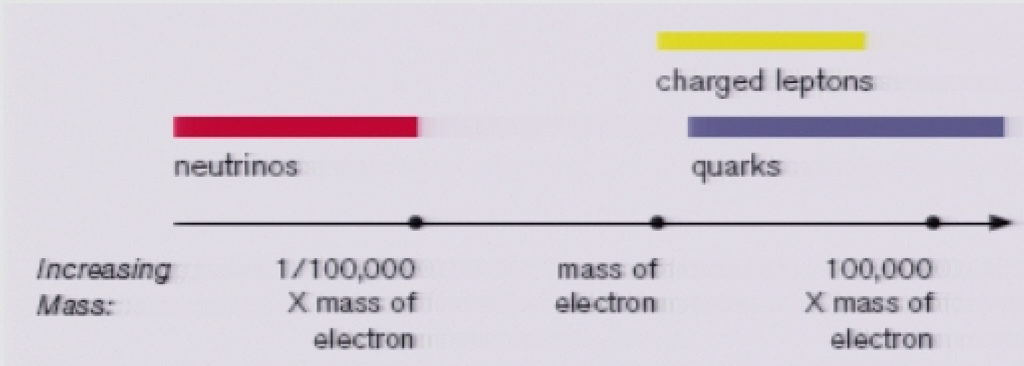
Majorana Neutrino Mass & GUT Scale

Majorana Neutrino Mass & GUT Scale



$$m_\nu \ll m_\ell, m_q$$

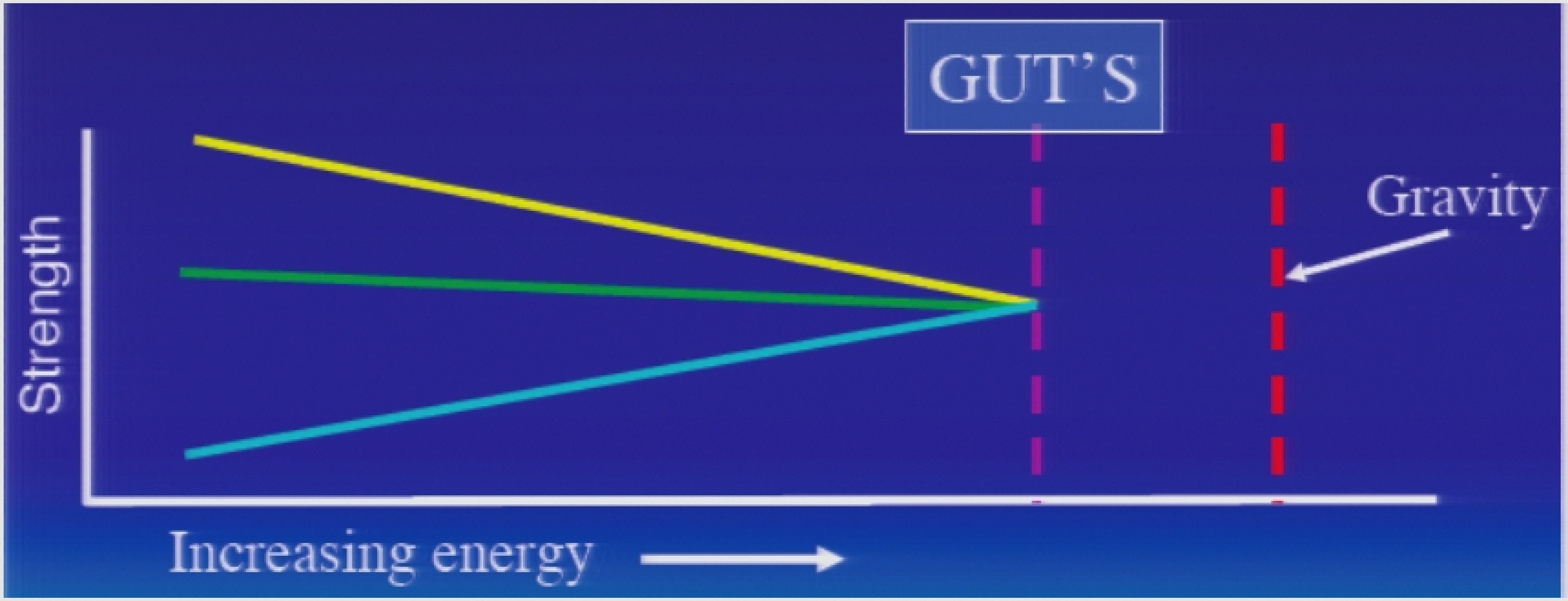
Majorana Neutrino Mass & GUT Scale

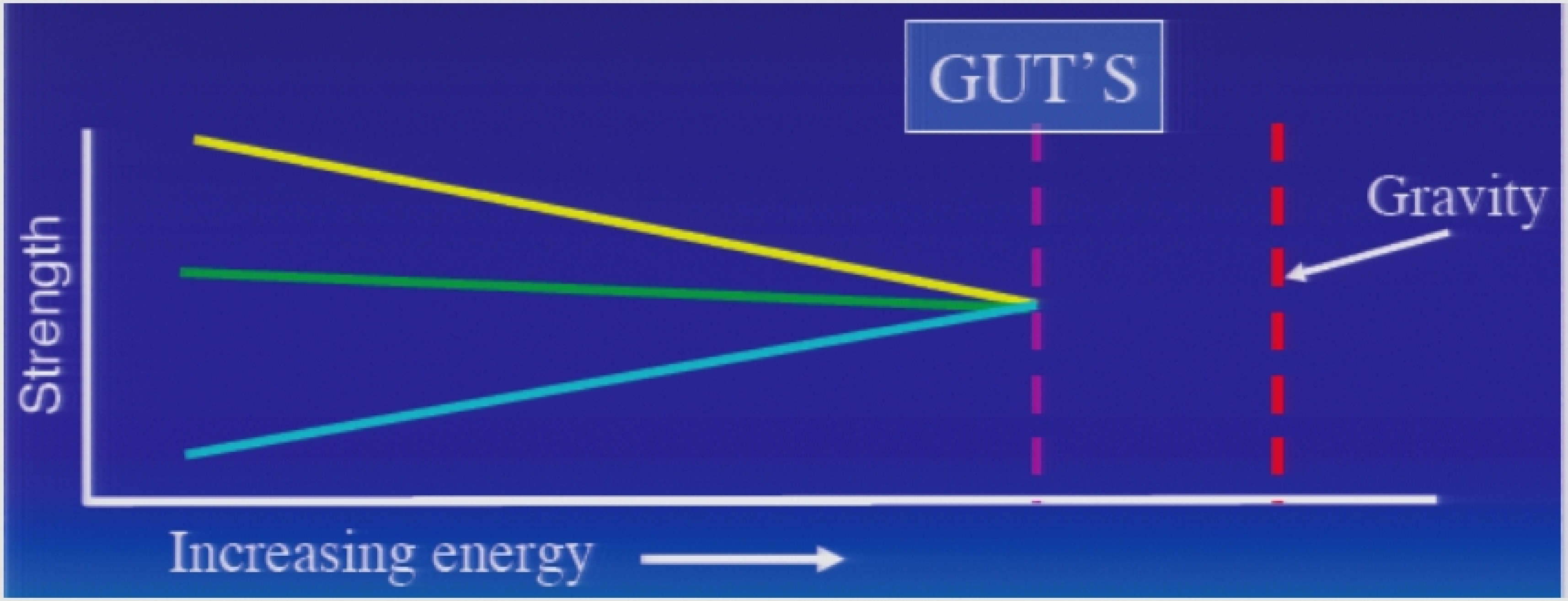


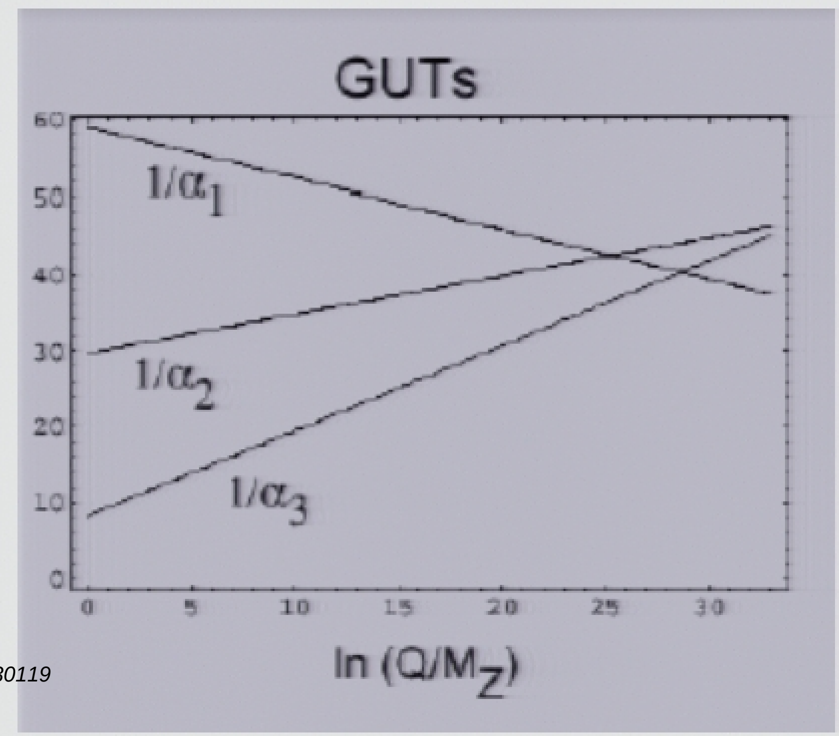
$$m_\nu \ll m_\ell, m_q$$

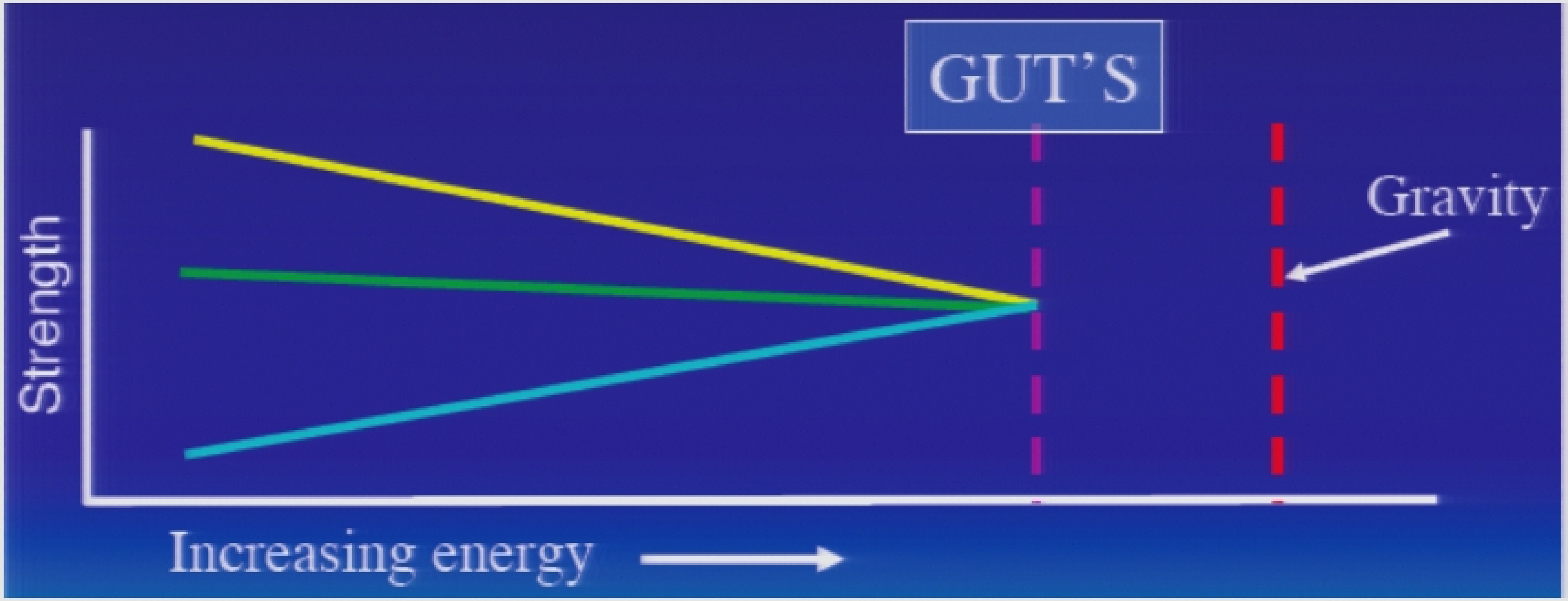
$$m_\nu \propto \frac{m_D^2}{M_R}$$

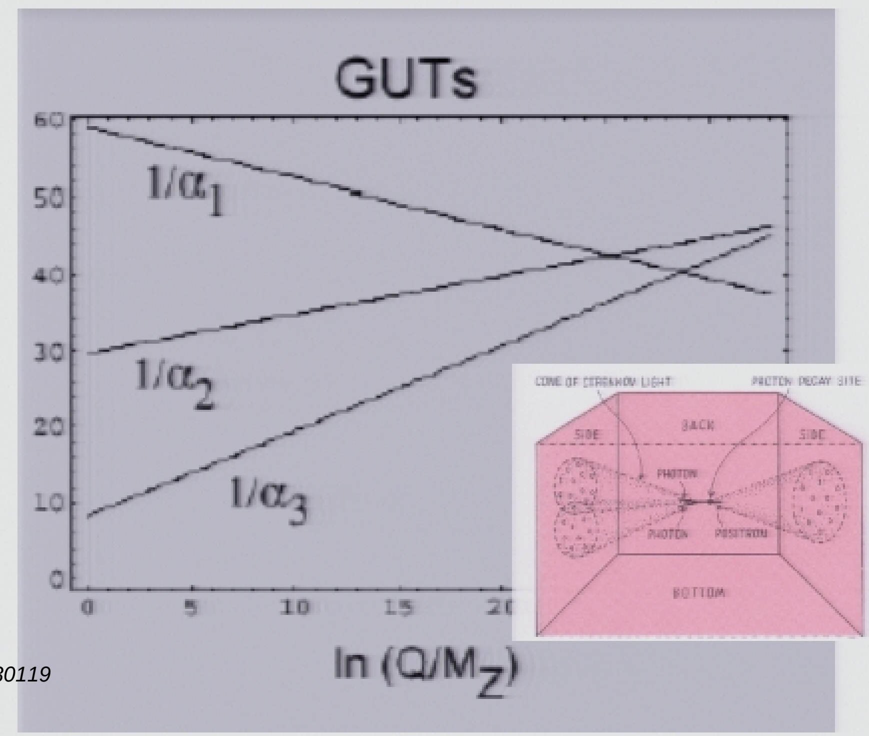
Seesaw Mechanism

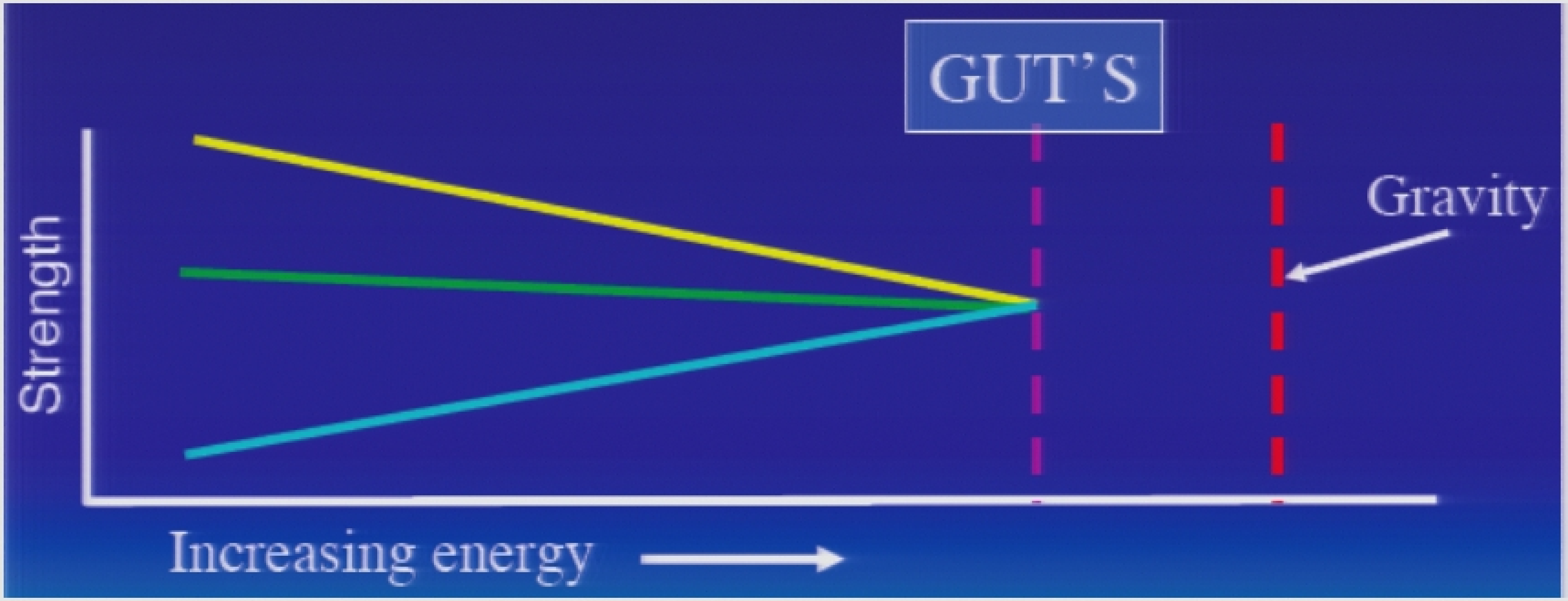

GUT'S
Gravity
Strength
Increasing energy

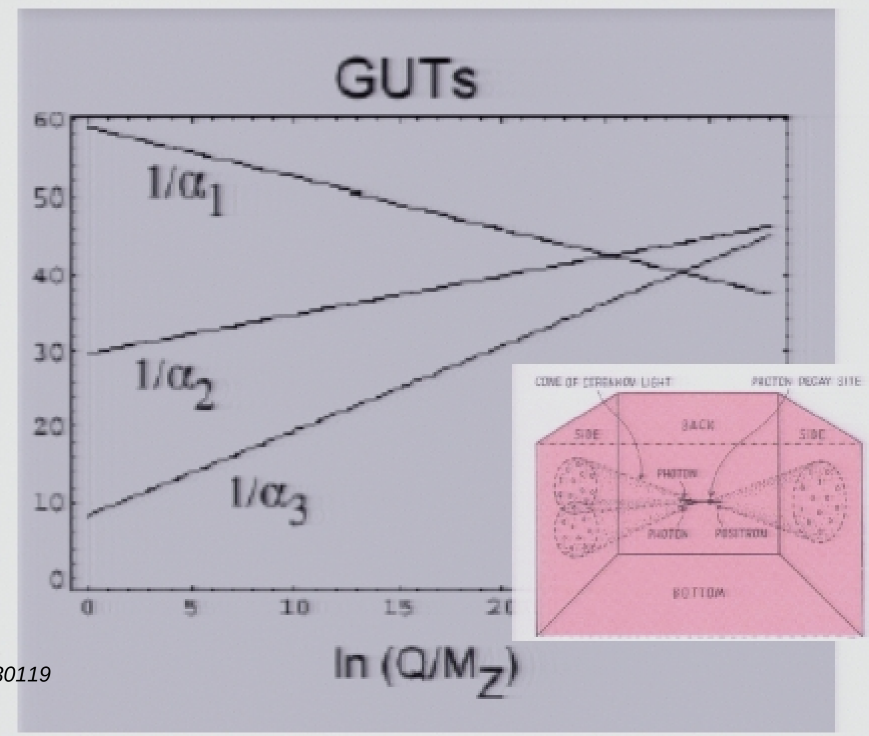

GUT'S
Gravity
Strength
Increasing energy

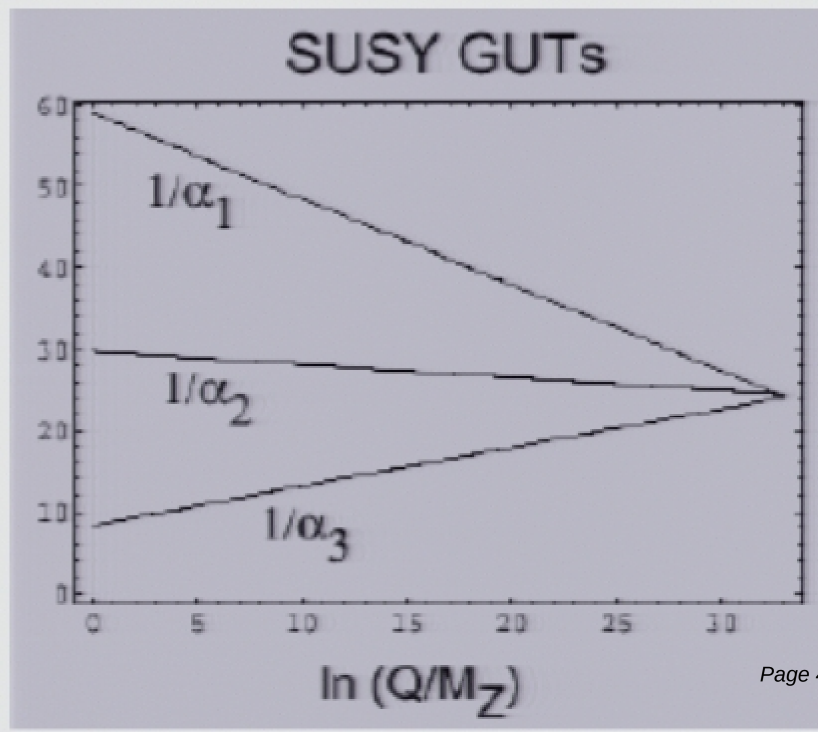

GUTs
60
50
40
30
20
10
0
$1/\alpha_1$
$1/\alpha_2$
$1/\alpha_3$
0
5
10
15
20
25
30
ln (Q/M$_Z$)

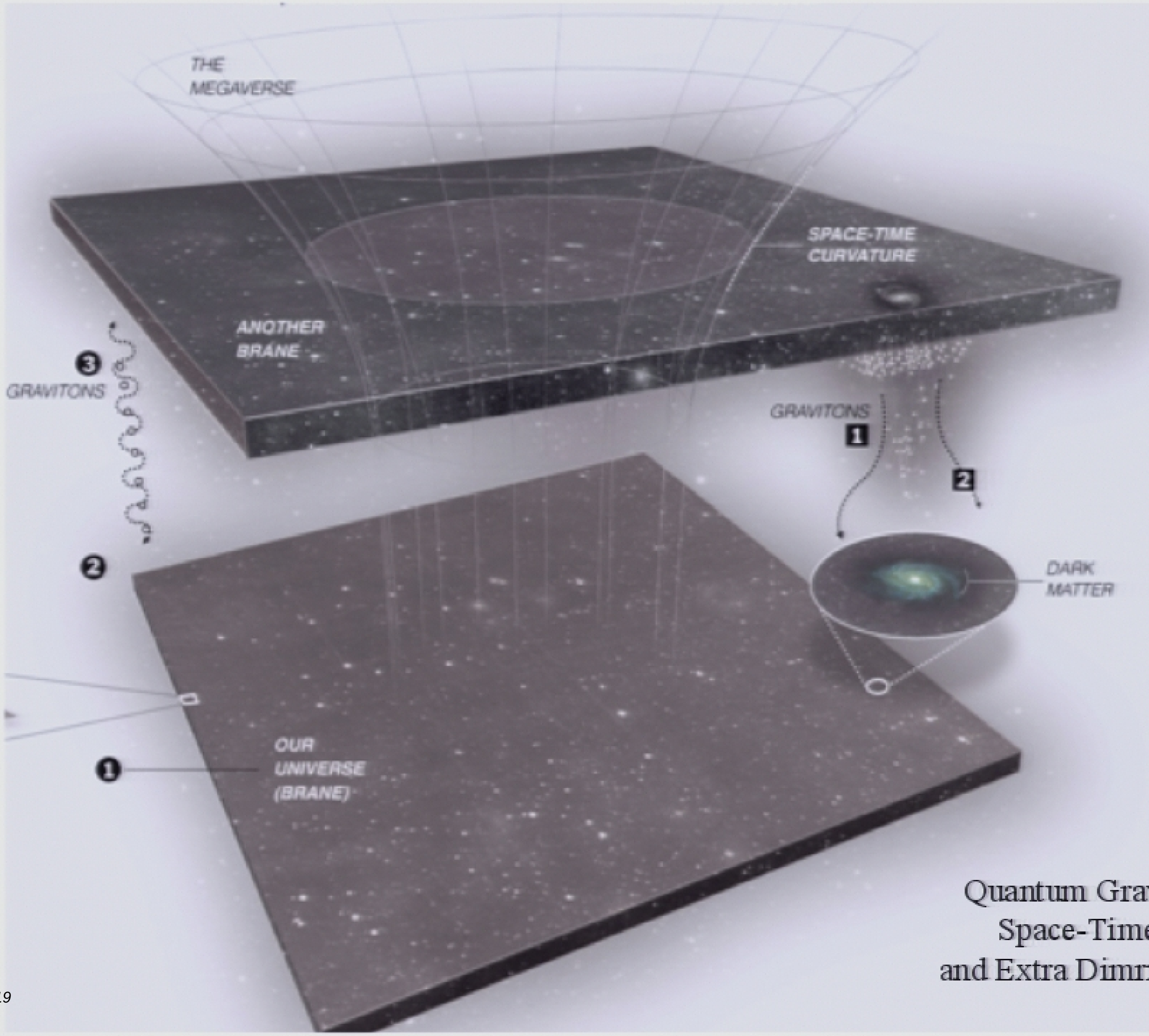

GUT'S
Gravity
Strength
Increasing energy


GUTs
$1/\alpha_1$
$1/\alpha_2$
$1/\alpha_3$
60
50
40
30
20
10
0
0
5
10
15
20
ln (Q/M$_Z$)
CONE OF CERENKOV LIGHT
PROTON DECAY SITE
BACK
SIDE
SIDE
PHOTON
PHOTON
POSITRON
BOTTOM


GUT'S
Gravity
Strength
Increasing energy

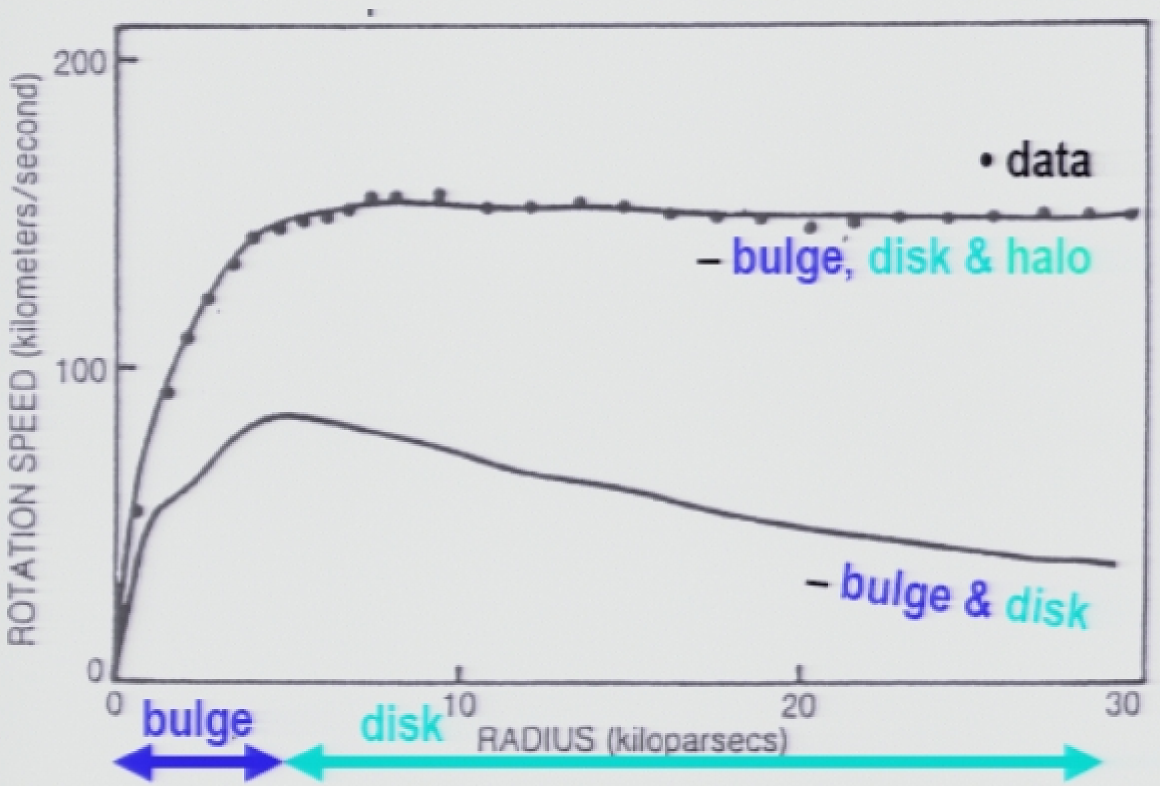

GUTs
60
50
40
30
20
10
0
$1/\alpha_1$
$1/\alpha_2$
$1/\alpha_3$
0
5
10
15
20
ln (Q/M$_Z$)
CONE OF CERENKOV LIGHT
PROTON DECAY SITE
SIDE
BACK
SIDE
PHOTON
PHOTON
POSITRON
BOTTOM

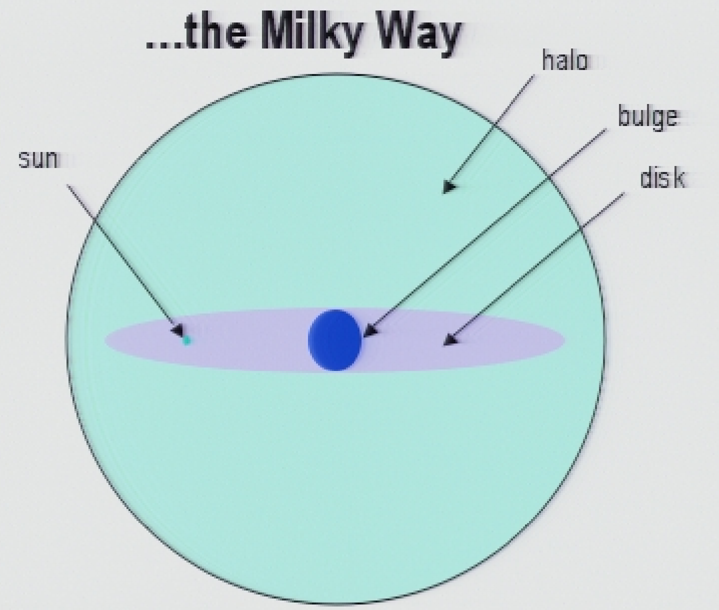

SUSY GUTs
60
50
40
30
20
10
0
$1/\alpha_1$
$1/\alpha_2$
$1/\alpha_3$
0
5
10
15
20
25
30
ln (Q/M$_Z$)

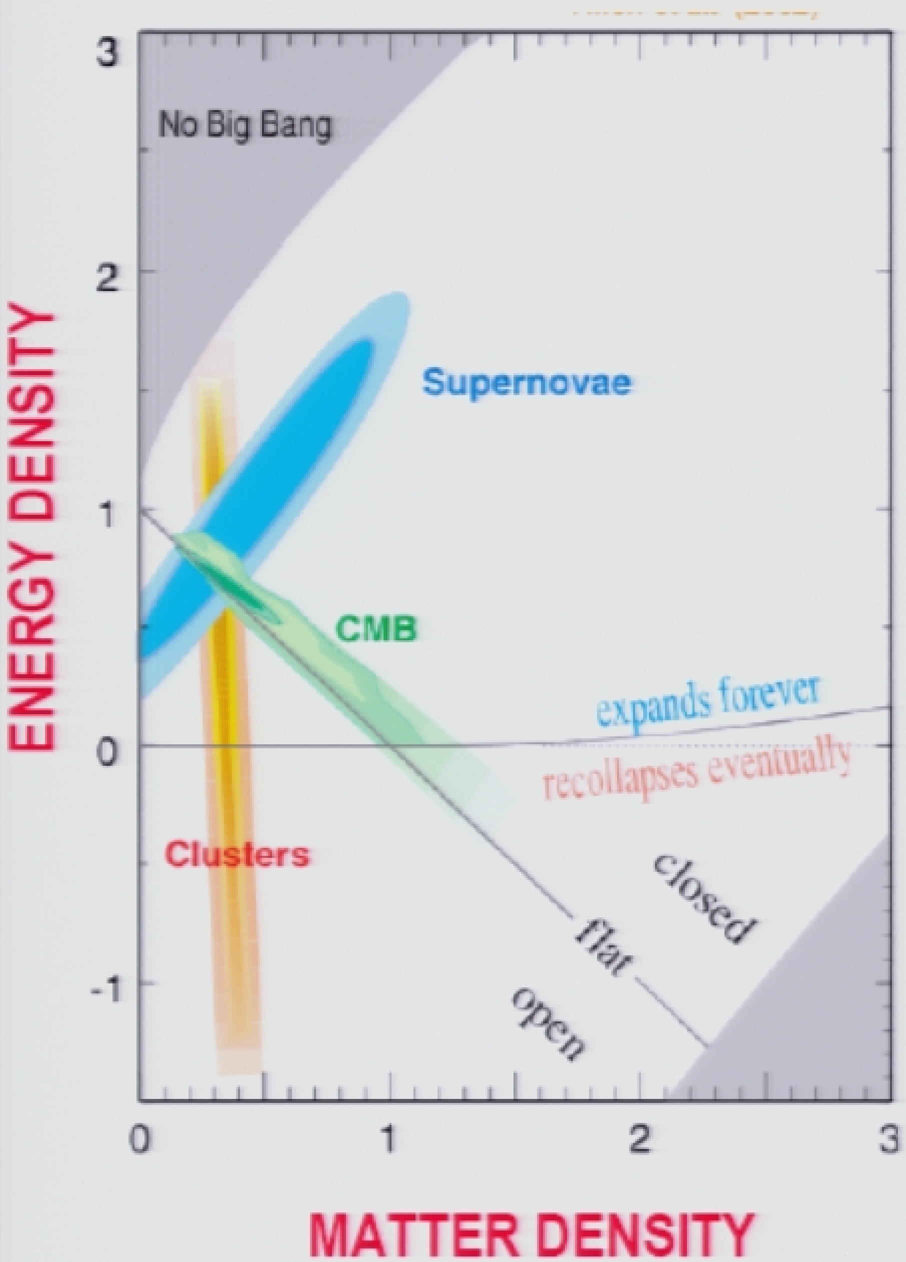


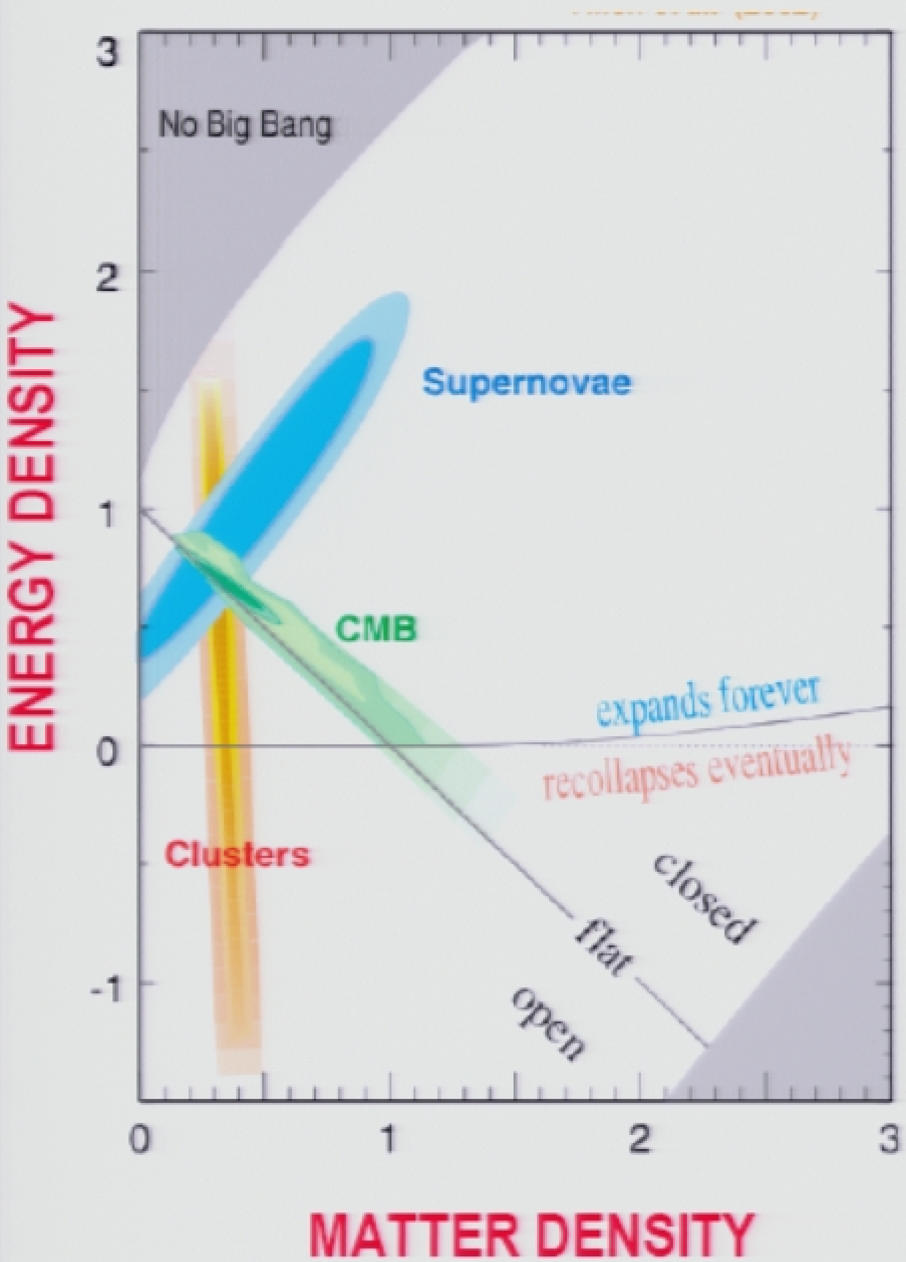
Quantum Gravity,
Space-Time,
and Extra Dimrnsions

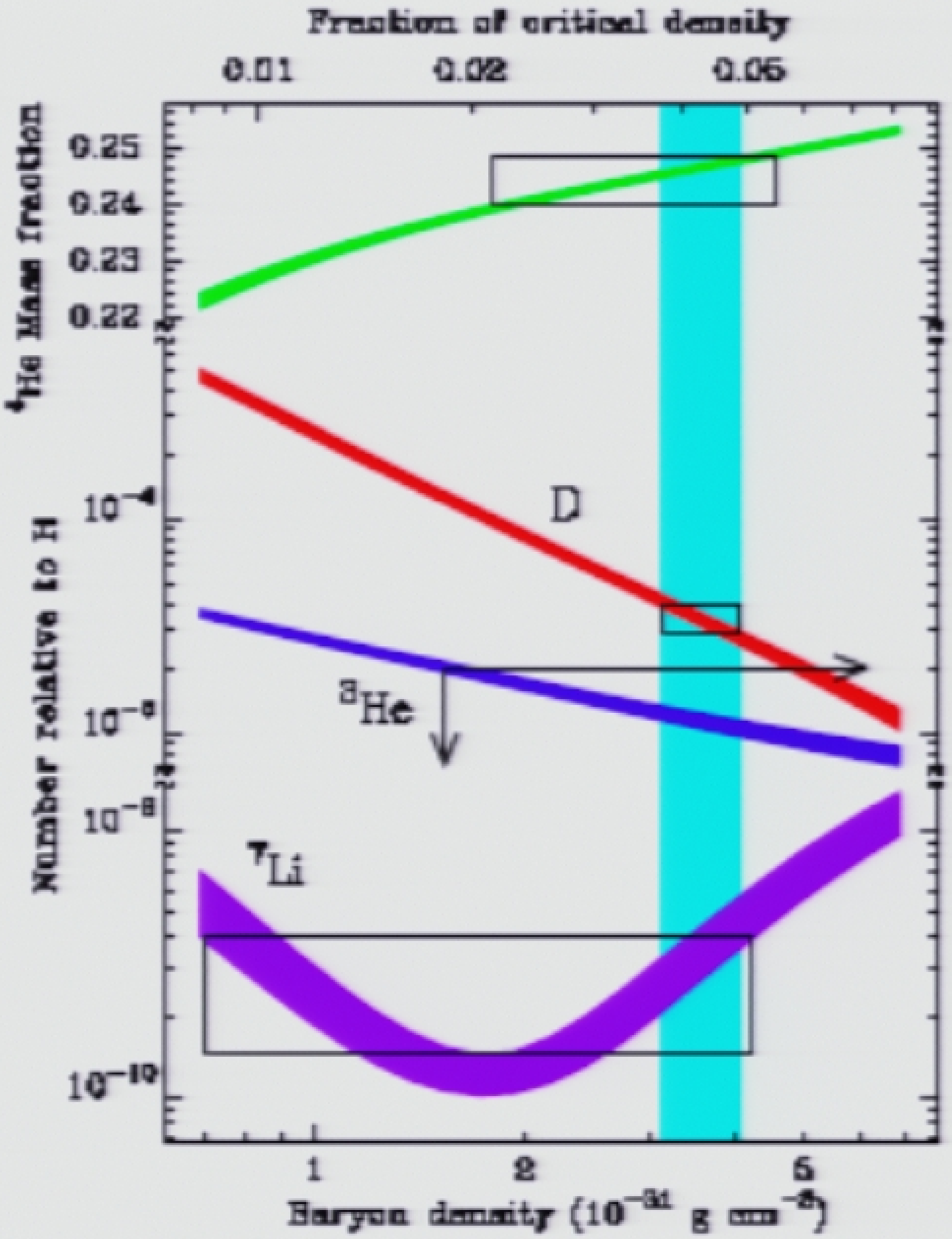
We live in a dark universe …






No Big Bang
Supernovae
CMB
Clusters
expands forever
recollapses eventually
closed
flat
open
ENERGY DENSITY
MATTER DENSITY
3
2
1
0
-1
0
1
2
3





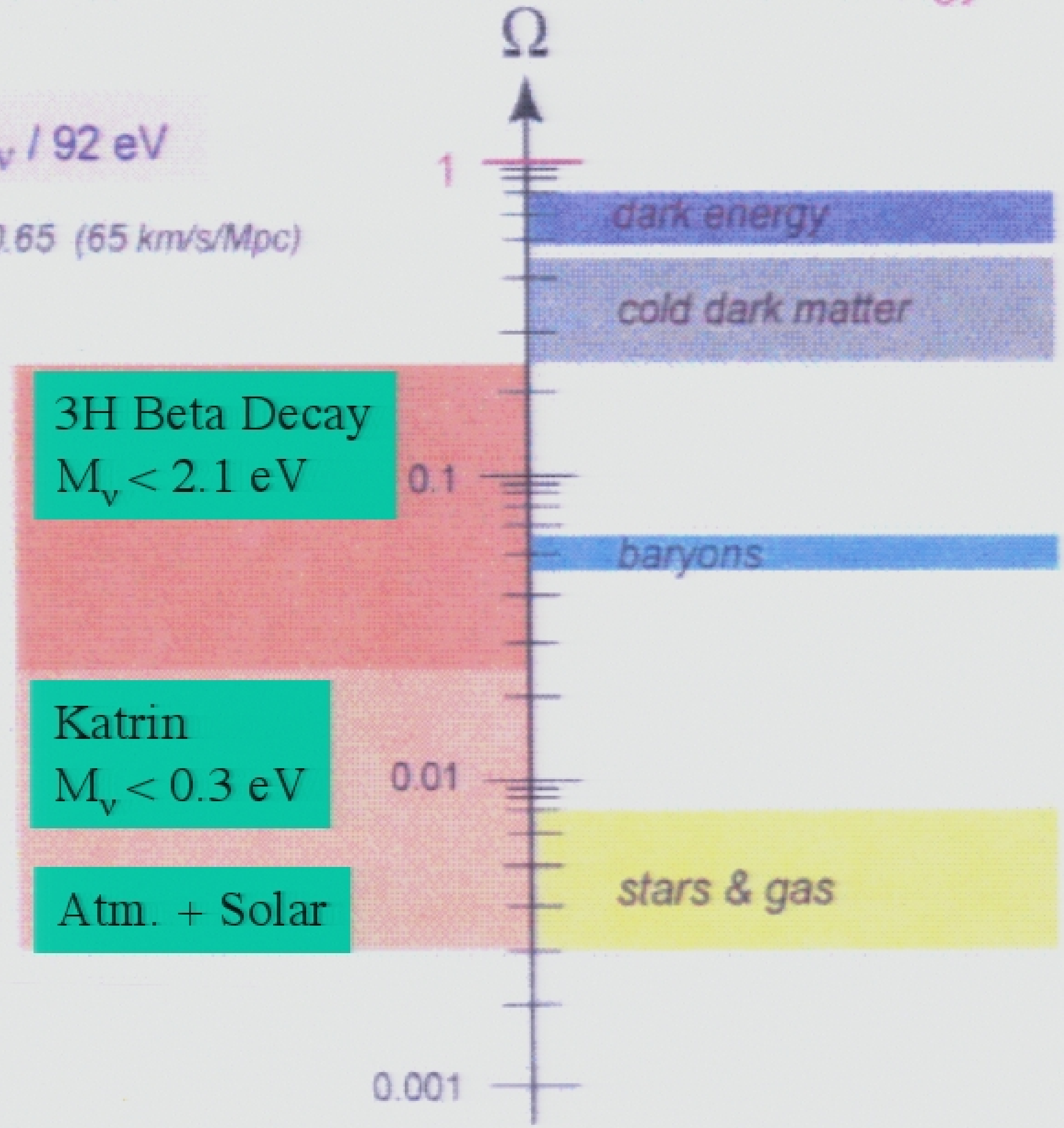
D. Tytler et al /astro-ph/0001318

neutrino HDM

matter & energy

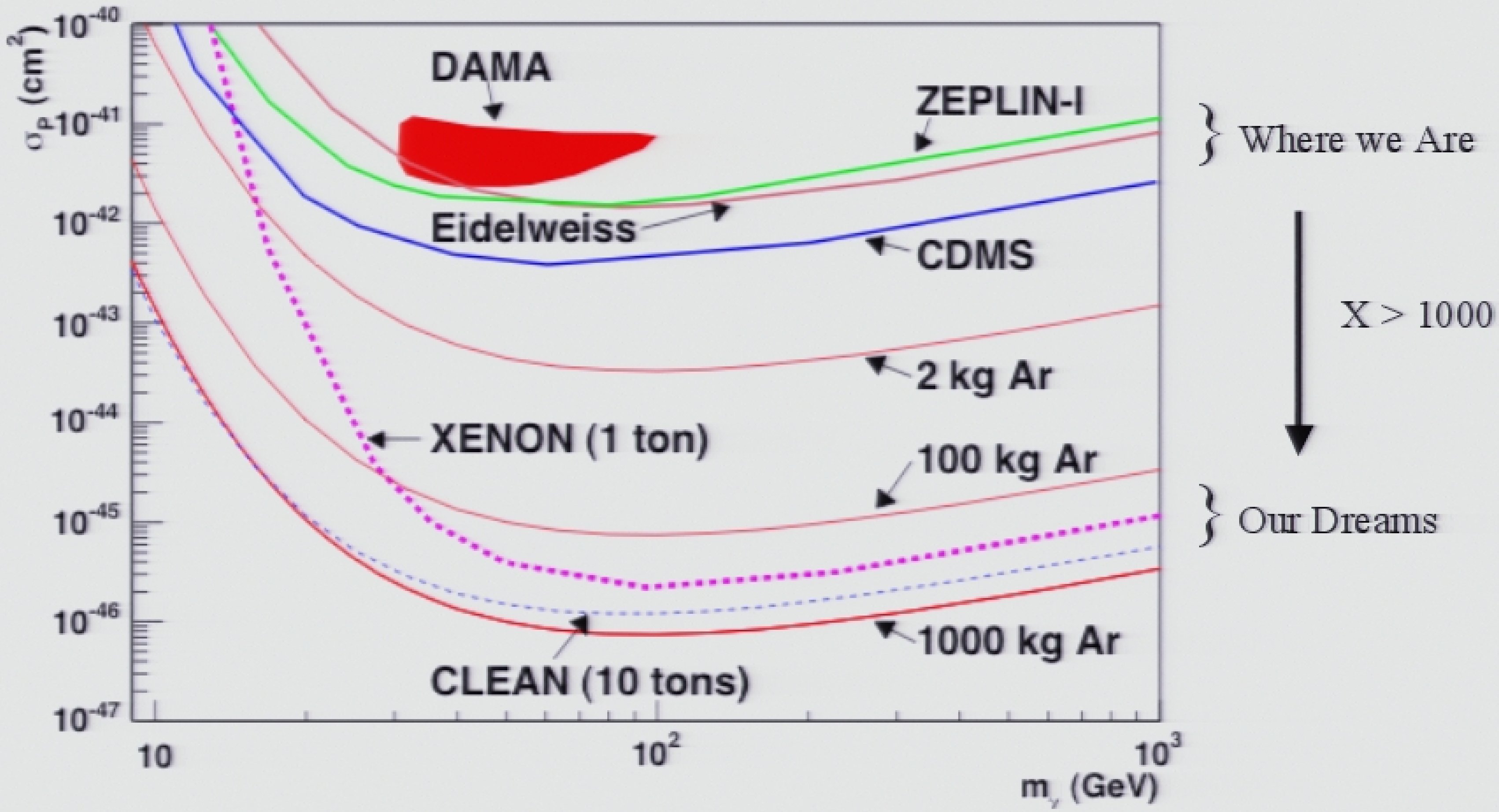
$\Omega_\nu h^{\leq} = \sum m_\nu / 92$ eV

Hubble Parameter h = 0.65 (65 km/s/Mpc)



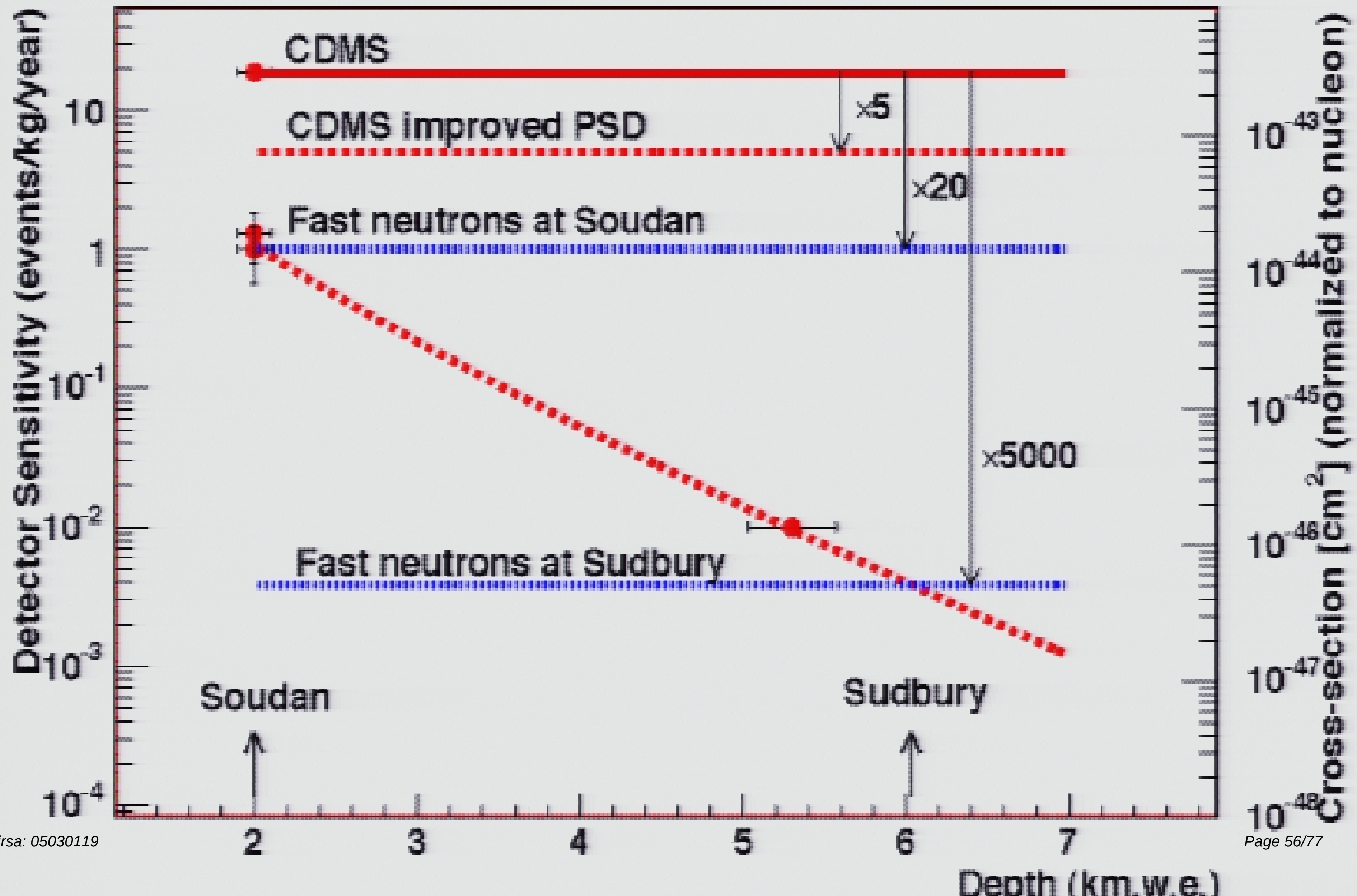
Dark Matter Results & Dreams

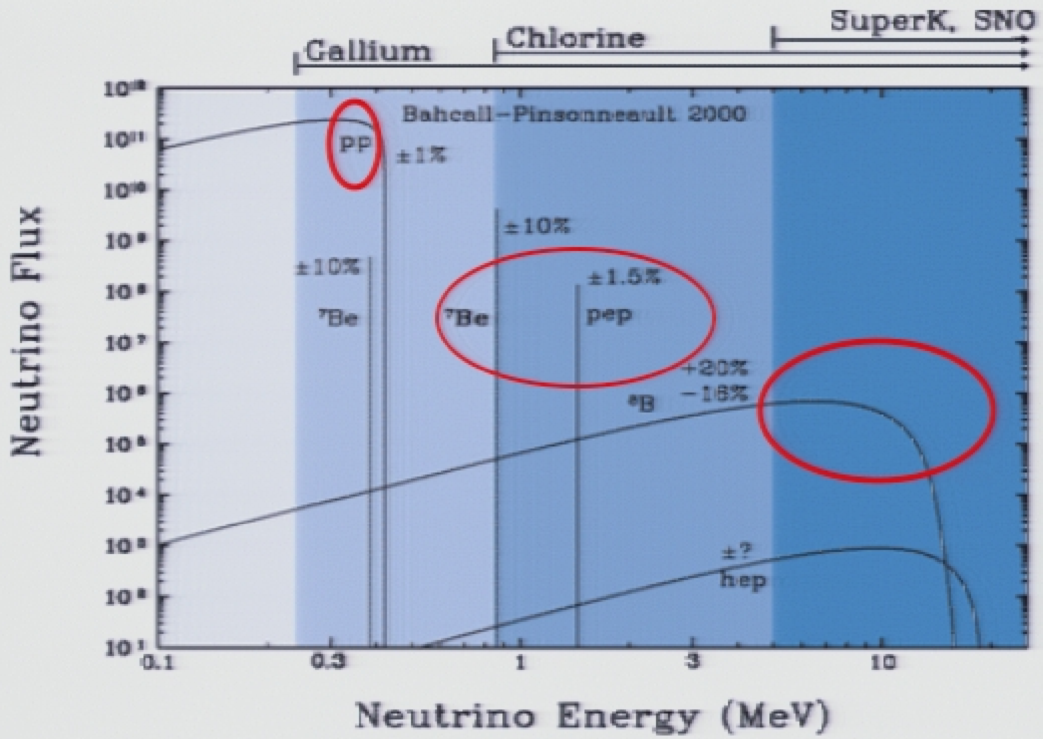
M.G. Boulay & AH, astro-ph/04113588



Dark Matter Sensitivity *versus* Depth

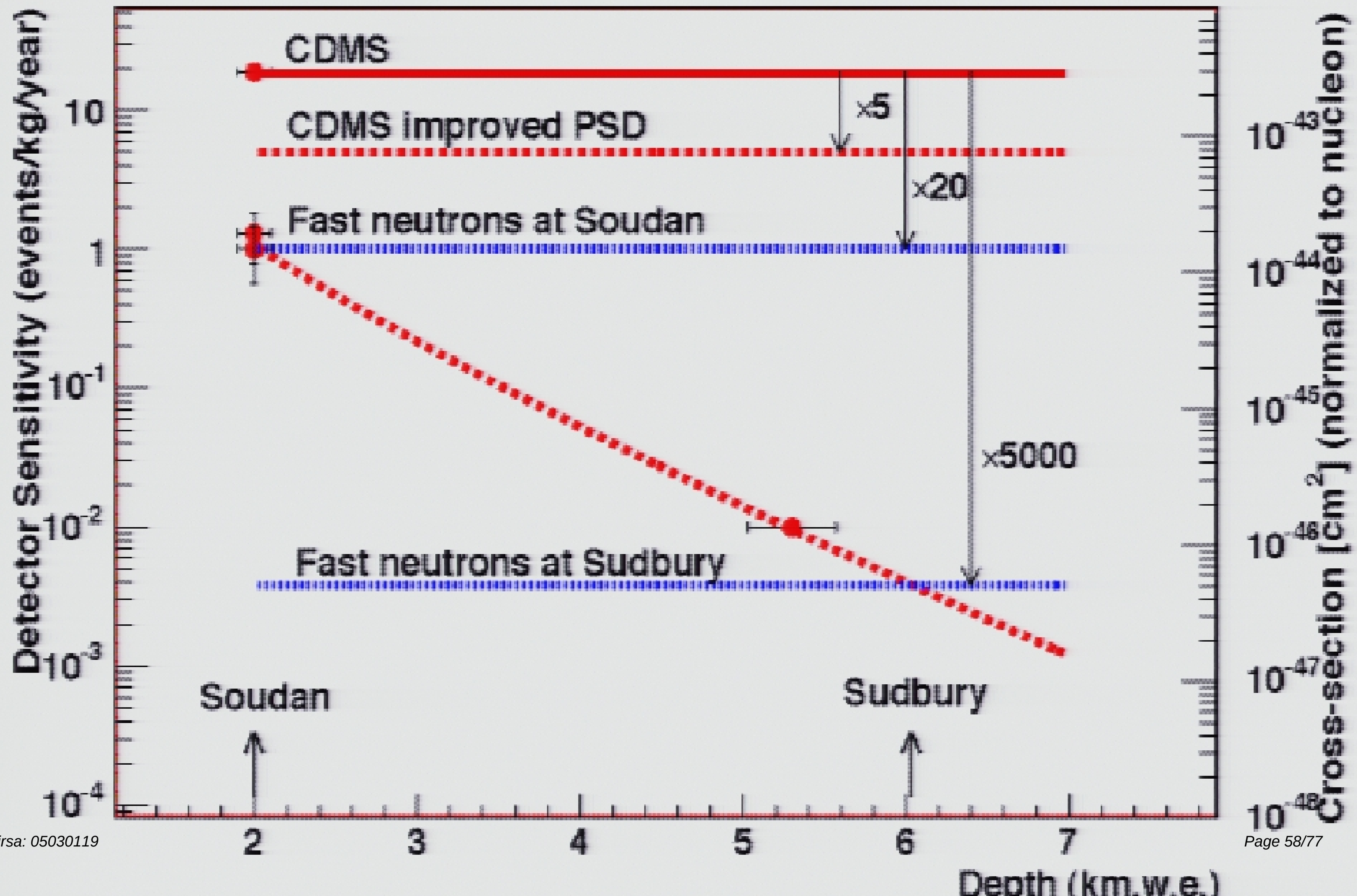
Dongming Mei & AH, *preliminary*




Gallium
Chlorine
SuperK, SNO
Bahcall–Pinsonneault 2000
PP
±1%
±10%
±10%
±1.5%
7Be
7Be
pep
+20%
−16%
8B
±?
hep
Neutrino Flux
Neutrino Energy (MeV)
0.1
0.3
1
3
10

Dark Matter Sensitivity *versus* Depth

Dongming Mei & AH, *preliminary*



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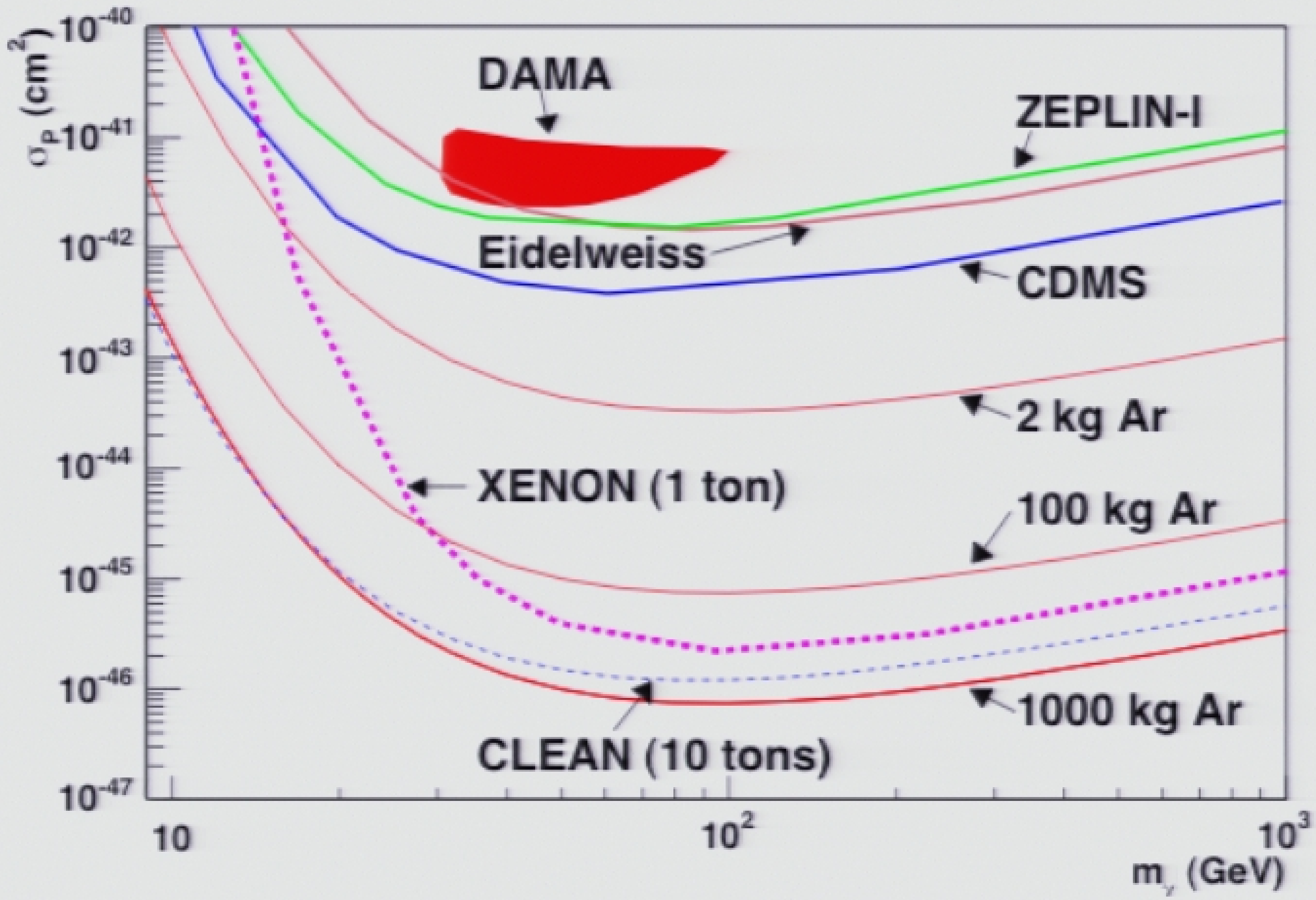
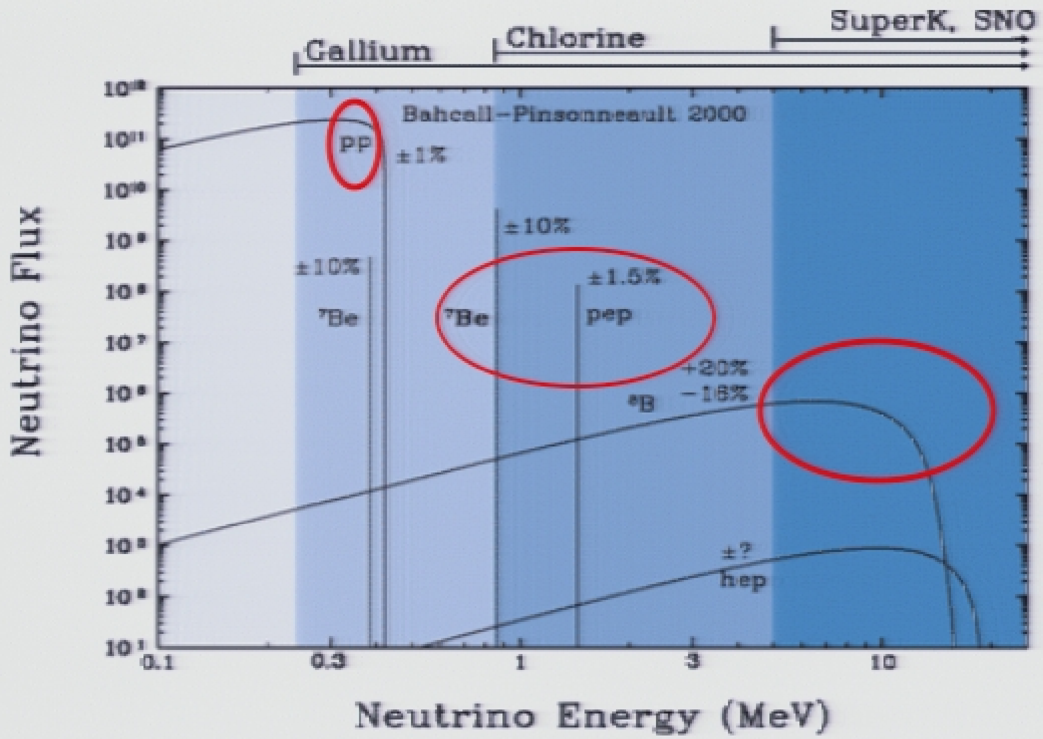


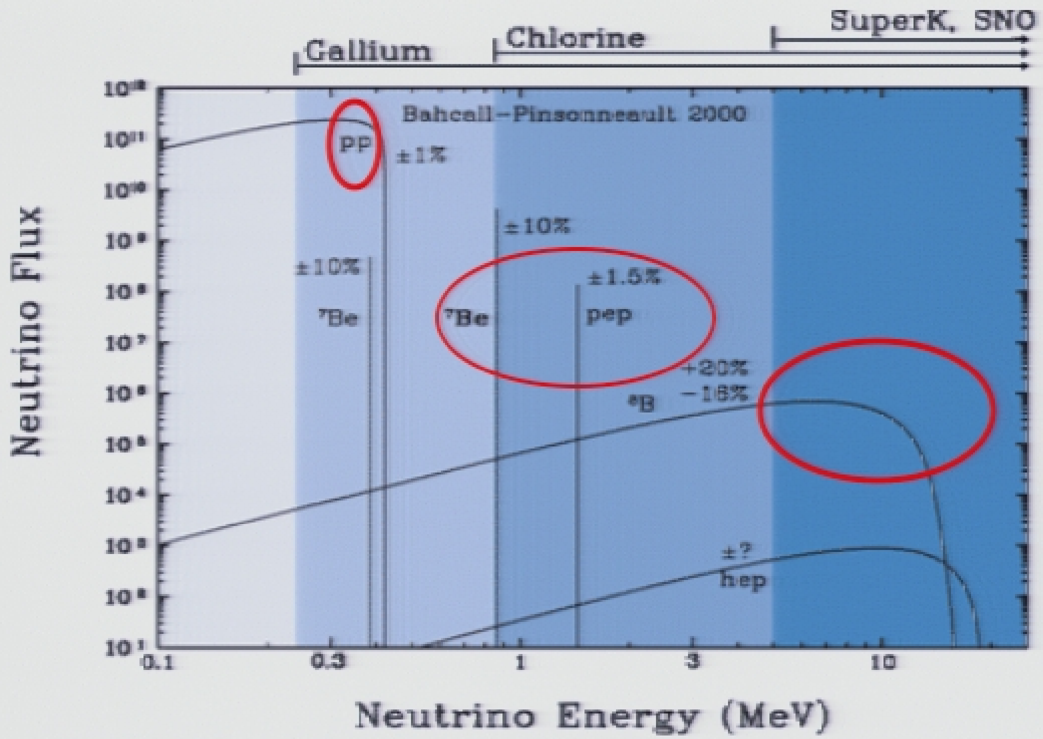
} Where we Are

X > 1000

} Our Dreams



Gallium
Chlorine
SuperK, SNO
Bahcall−Pinsonneault 2000
pp
±1%
±10%
±10%
⁷Be
⁷Be
±1.5%
pep
+20%
−16%
⁸B
±?
hep
Neutrino Flux
Neutrino Energy (MeV)
0.1
0.3
1
3
10

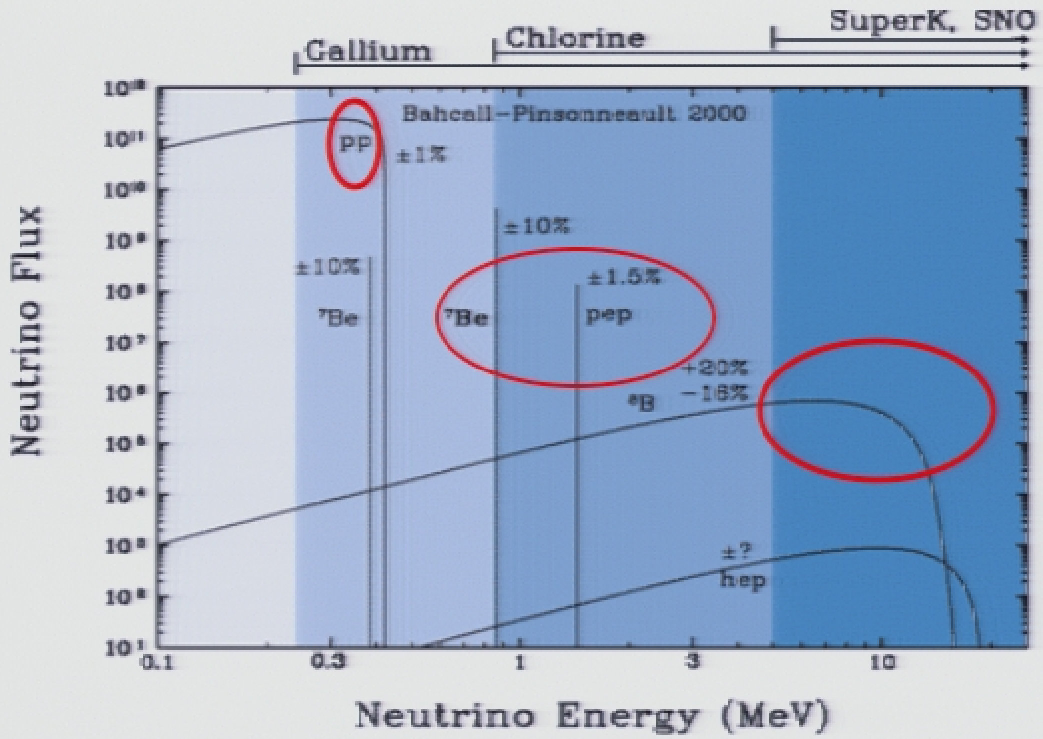


Stellar Evolution

… Solar Neutrino Flux Predictions

v.s. Expt'l Constraints

… Neutrino v.s. Photon Luminosity



Stellar Evolution

… Solar Neutrino Flux Predictions

v.s. Expt'l Constraints

… Neutrino v.s. Photon Luminosity

Fundamental Neutrino Properties

… Precision in θ_{12}

… 3-Flavor Mixing & θ_{13}

CP Violation, Leptogenesis …

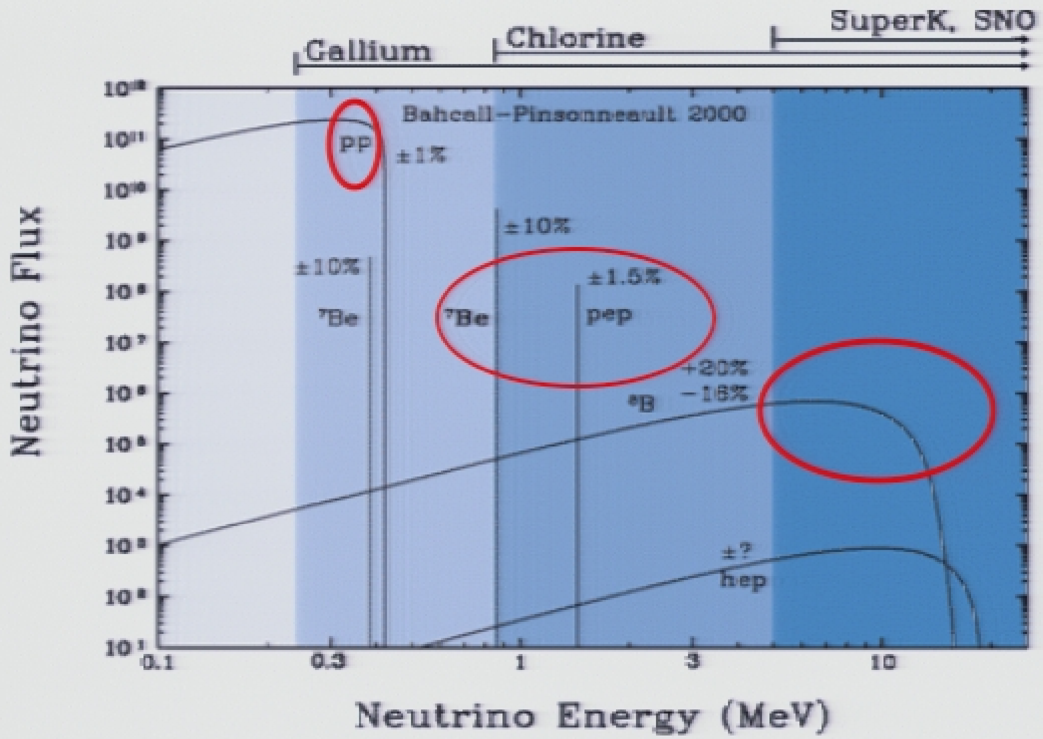
… Exotic Physics

Sterile Neutrinos

CPT Violation

New Interactions

Mass Varying Neutrinos …



Stellar Evolution

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Fundamental Neutrino Properties

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CP Violation, Leptogenesis …

… Exotic Physics

Sterile Neutrinos

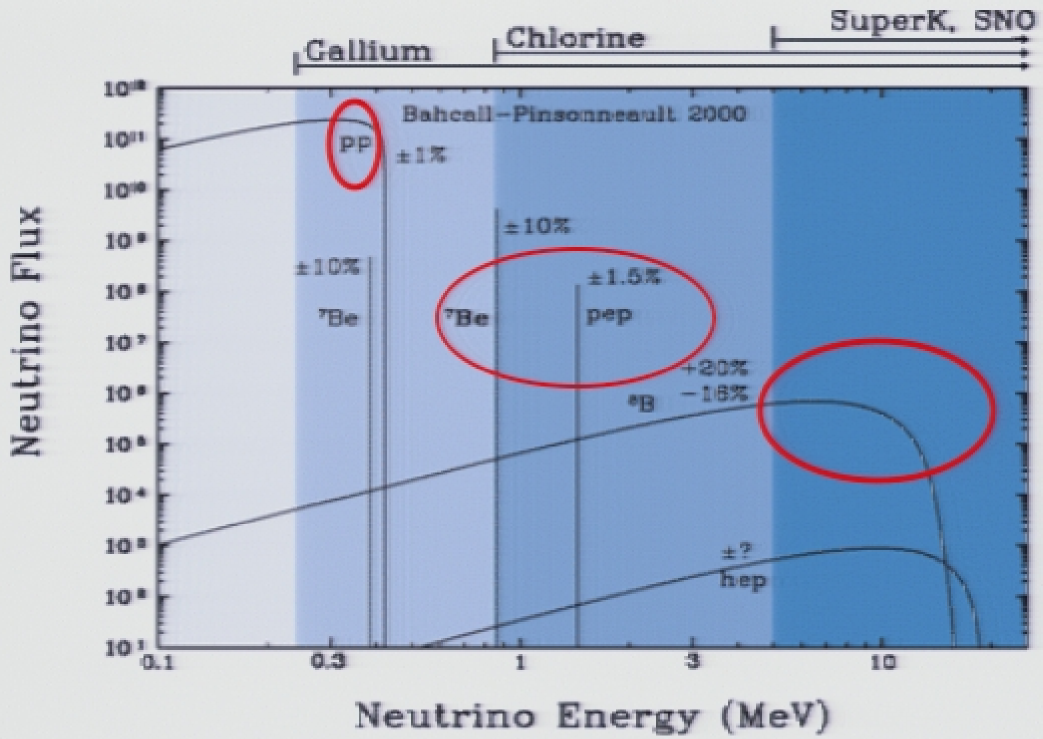
CPT Violation

New Interactions

Mass Varying Neutrinos …

… Does the "new standard model" hang together ?

… Are more surprises lurking?



Stellar Evolution

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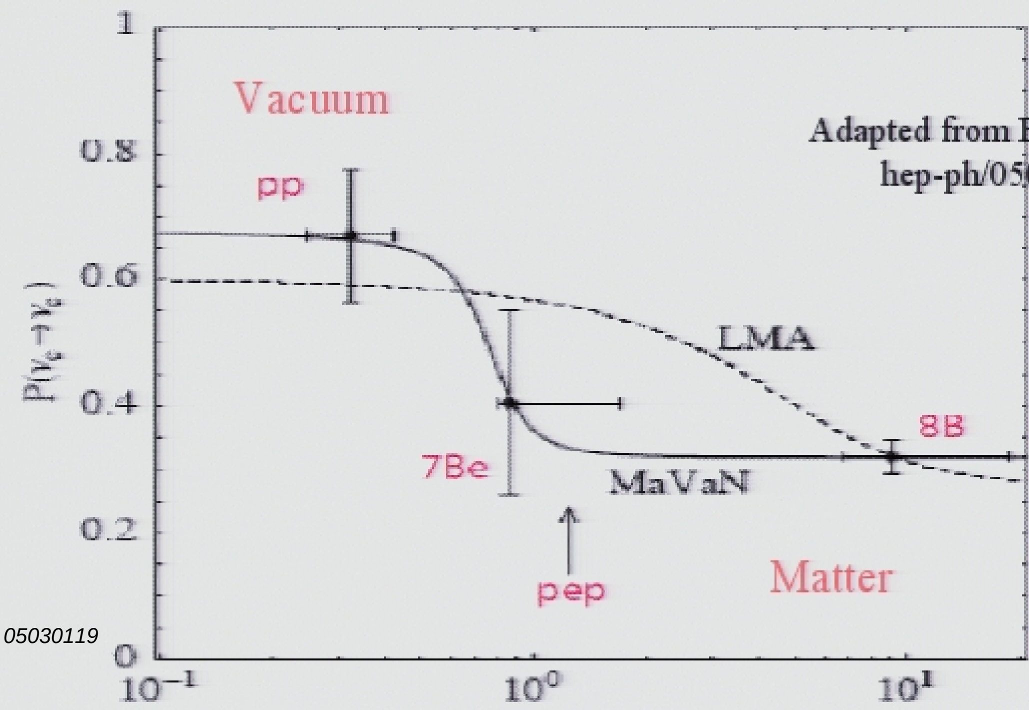
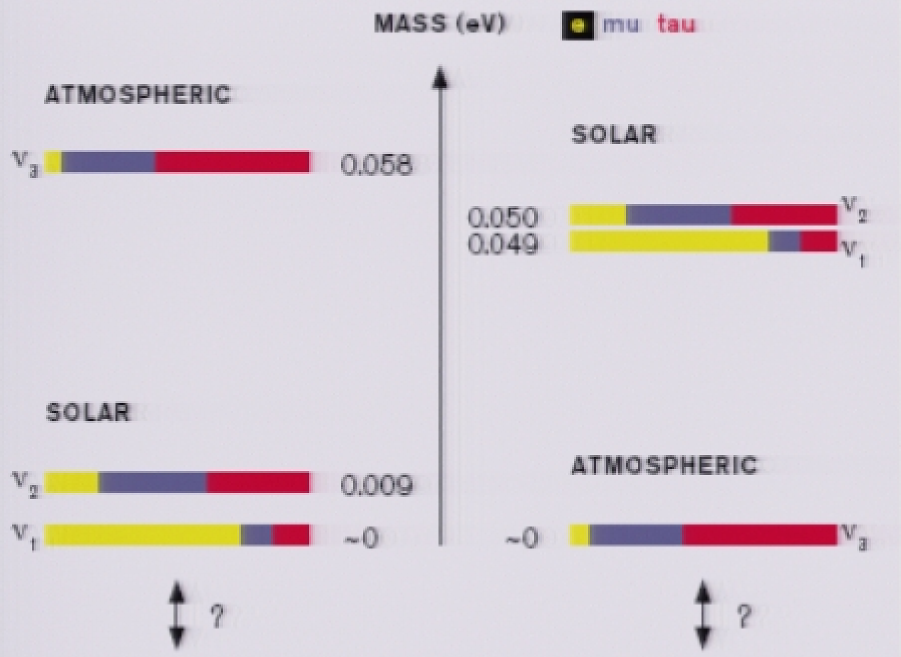
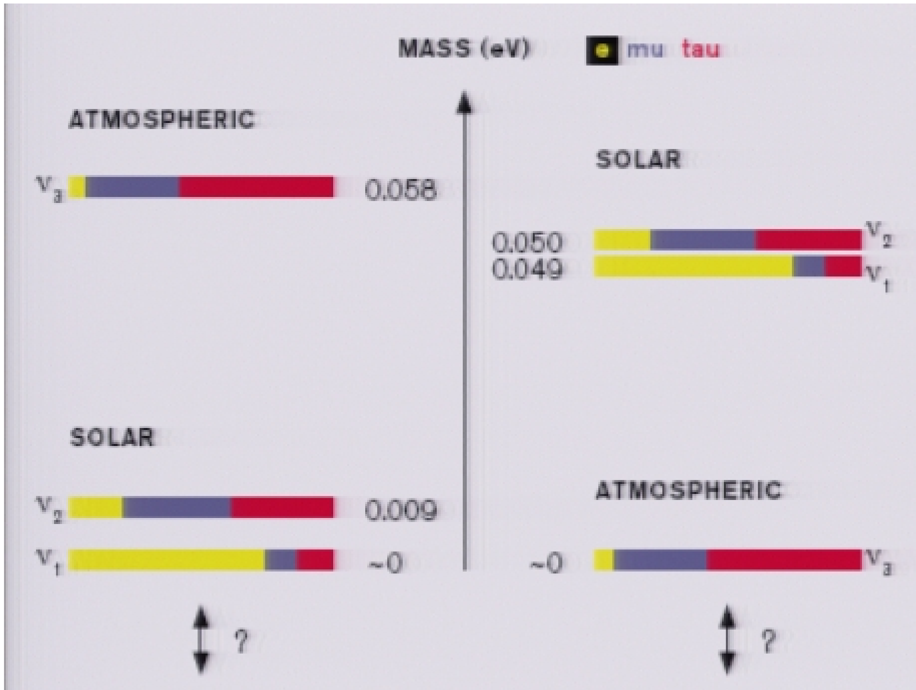


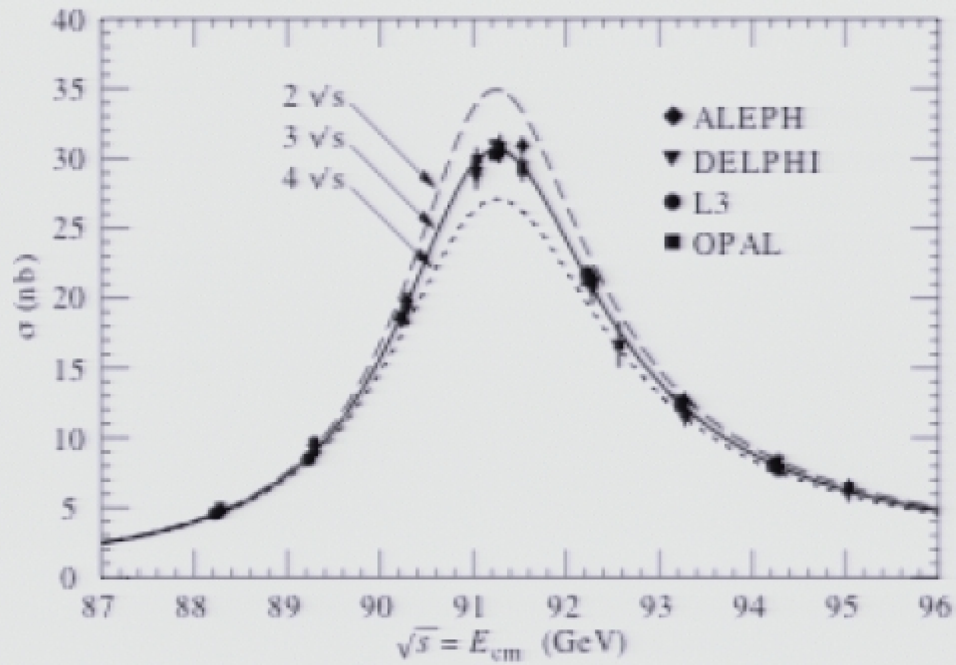
Adapted from Barger *et al*
hep-ph/0502196

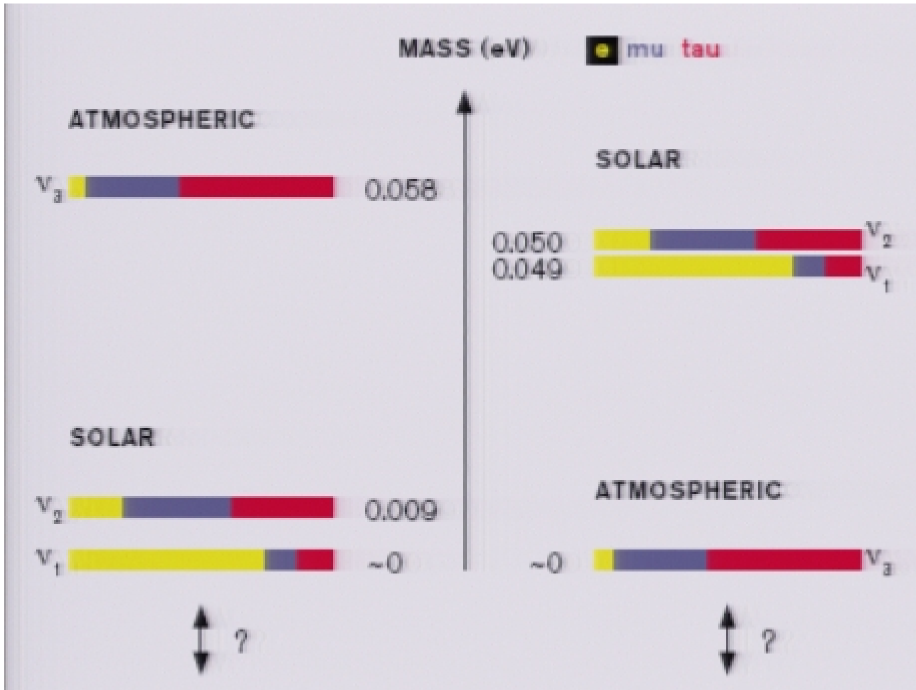
… Does the "new standard model" hang together ?

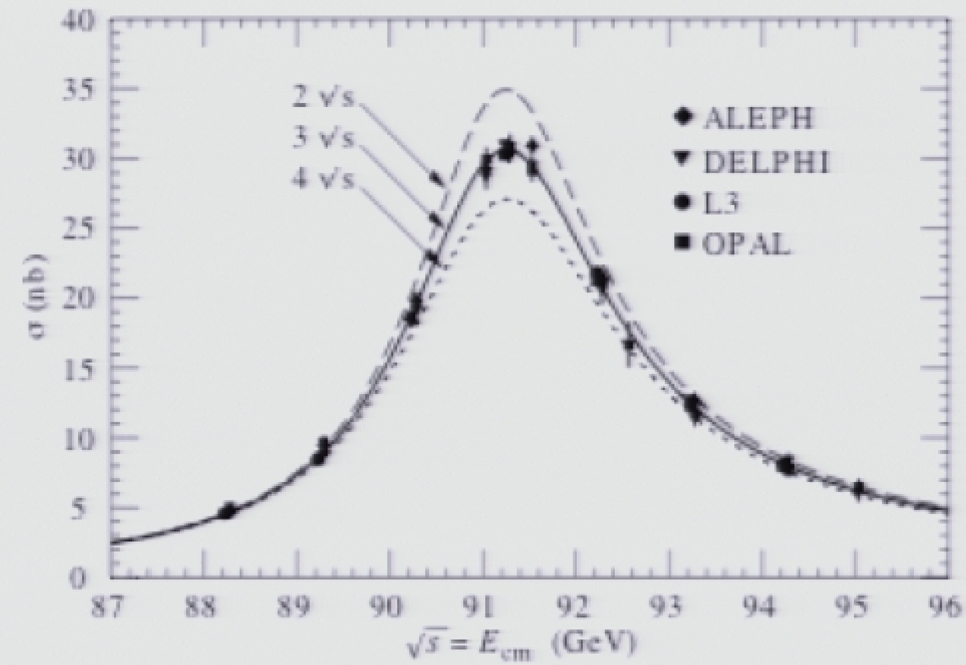
… Are more surprises lurking?

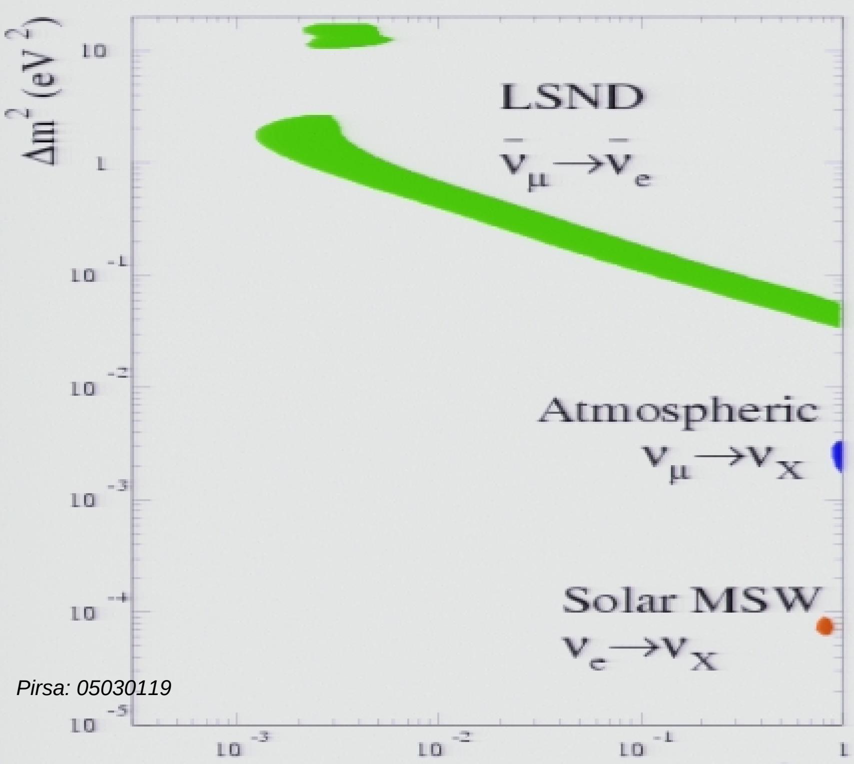

MASS (eV)
e mu tau
ATMOSPHERIC
ν_3
0.058
SOLAR
ν_2
0.009
ν_1
~0
?
SOLAR
0.050
0.049
ν_2
ν_1
ATMOSPHERIC
~0
ν_3
?

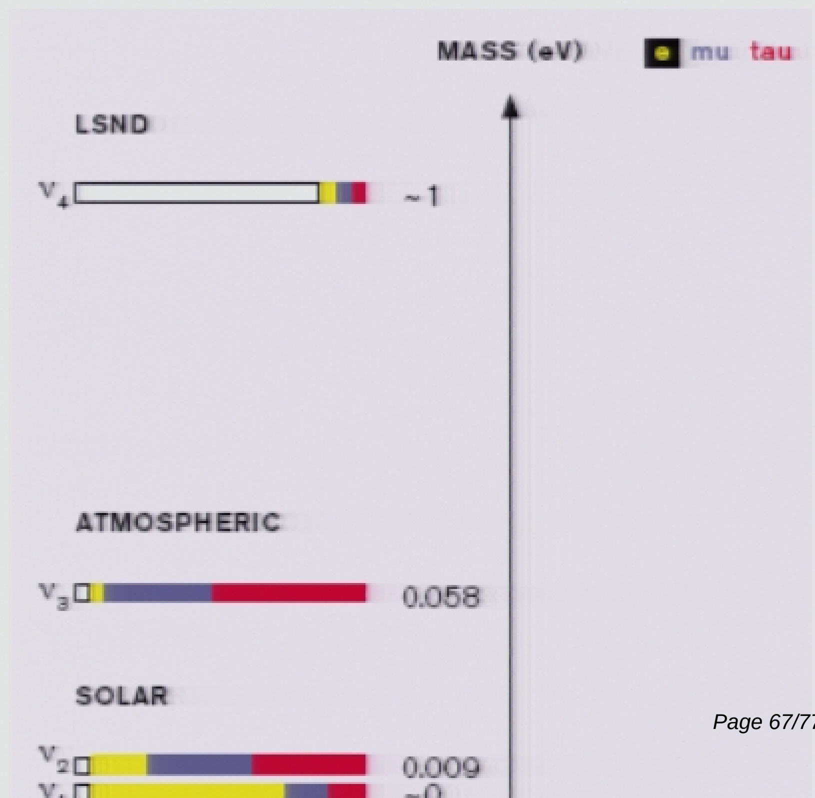

MASS (eV)
e mu tau
ATMOSPHERIC
ν3 0.058
SOLAR
0.050 ν2
0.049 ν1
SOLAR
ν2 0.009
ν1 ~0
ATMOSPHERIC
~0 ν3
?
?


2 ν's
3 ν's
4 ν's
ALEPH
DELPHI
L3
OPAL
σ (nb)
0 5 10 15 20 25 30 35 40
87 88 89 90 91 92 93 94 95 96
√s = E_cm (GeV)

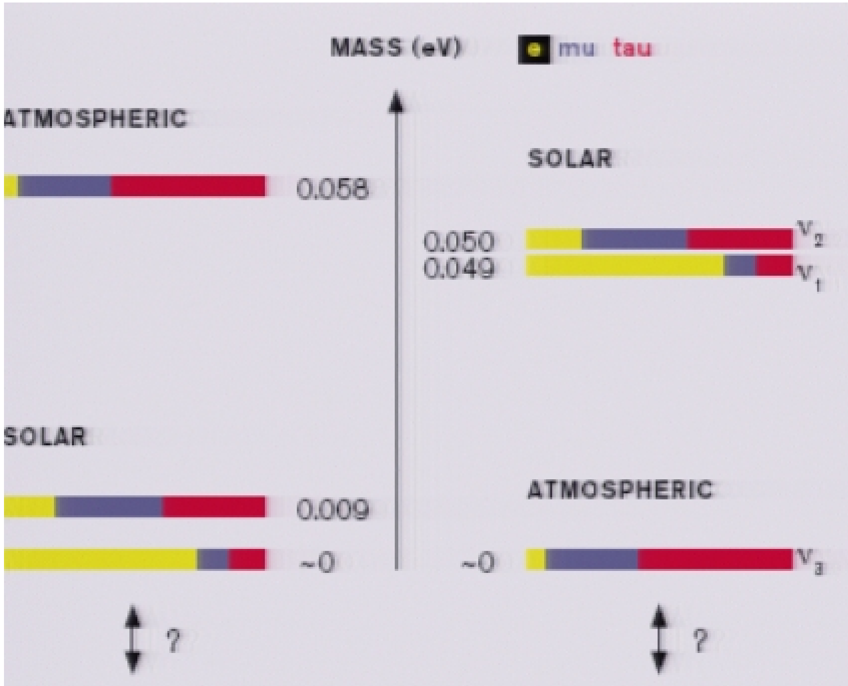

MASS (eV)
e mu tau
ATMOSPHERIC
ν_3 0.058
SOLAR
0.050 ν_2
0.049 ν_1
SOLAR
ν_2 0.009
ν_1 ~0
ATMOSPHERIC
~0 ν_3
?
?

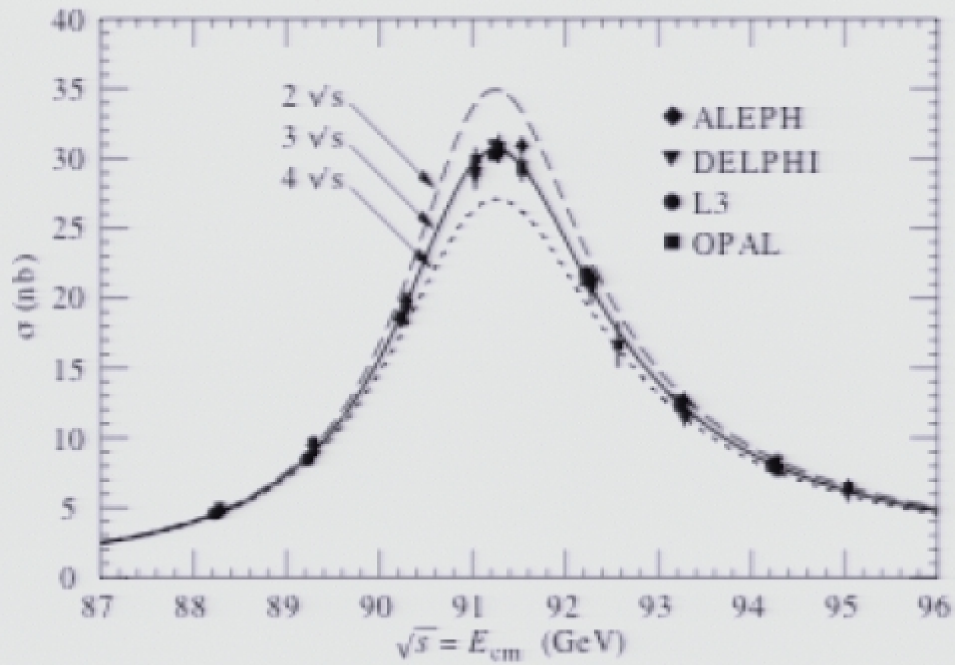

2 ν's
3 ν's
4 ν's
ALEPH
DELPHI
L3
OPAL
σ (nb)
$\sqrt{s} = E_{cm}$ (GeV)

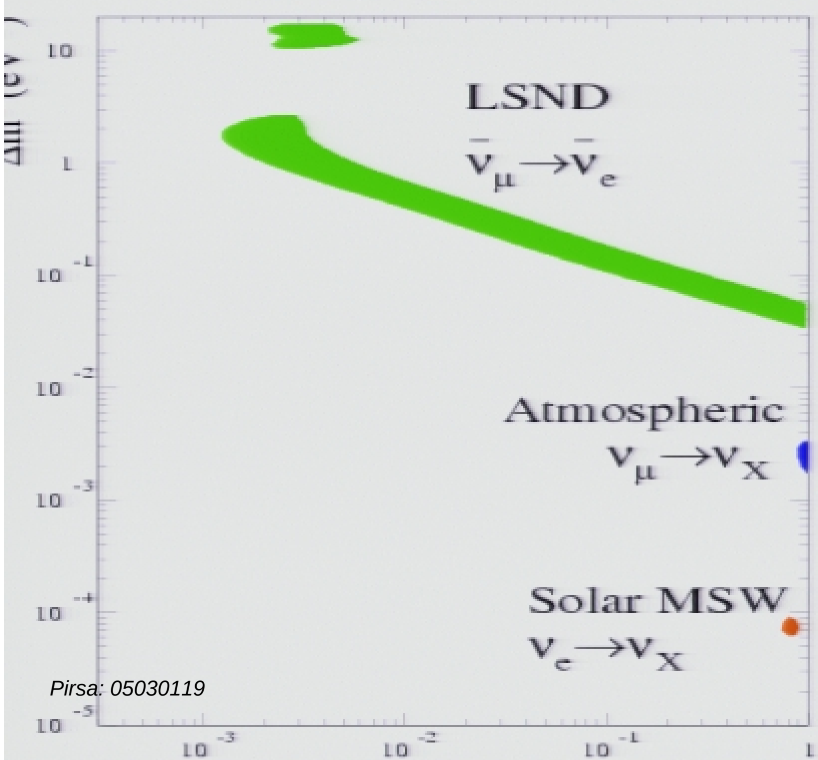

Δm^2 (eV^2)
LSND
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
Atmospheric
$\nu_\mu \rightarrow \nu_X$
Solar MSW
$\nu_e \rightarrow \nu_X$

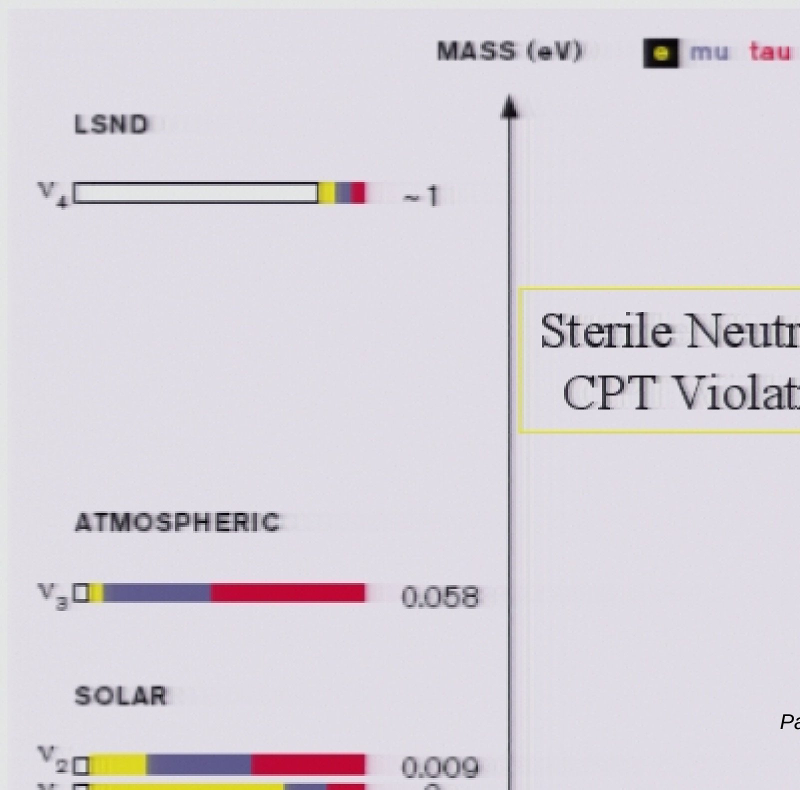

MASS (eV)
e mu tau
LSND
ν_4 ~1
ATMOSPHERIC
ν_3 0.058
SOLAR
ν_2 0.009

[redacted]

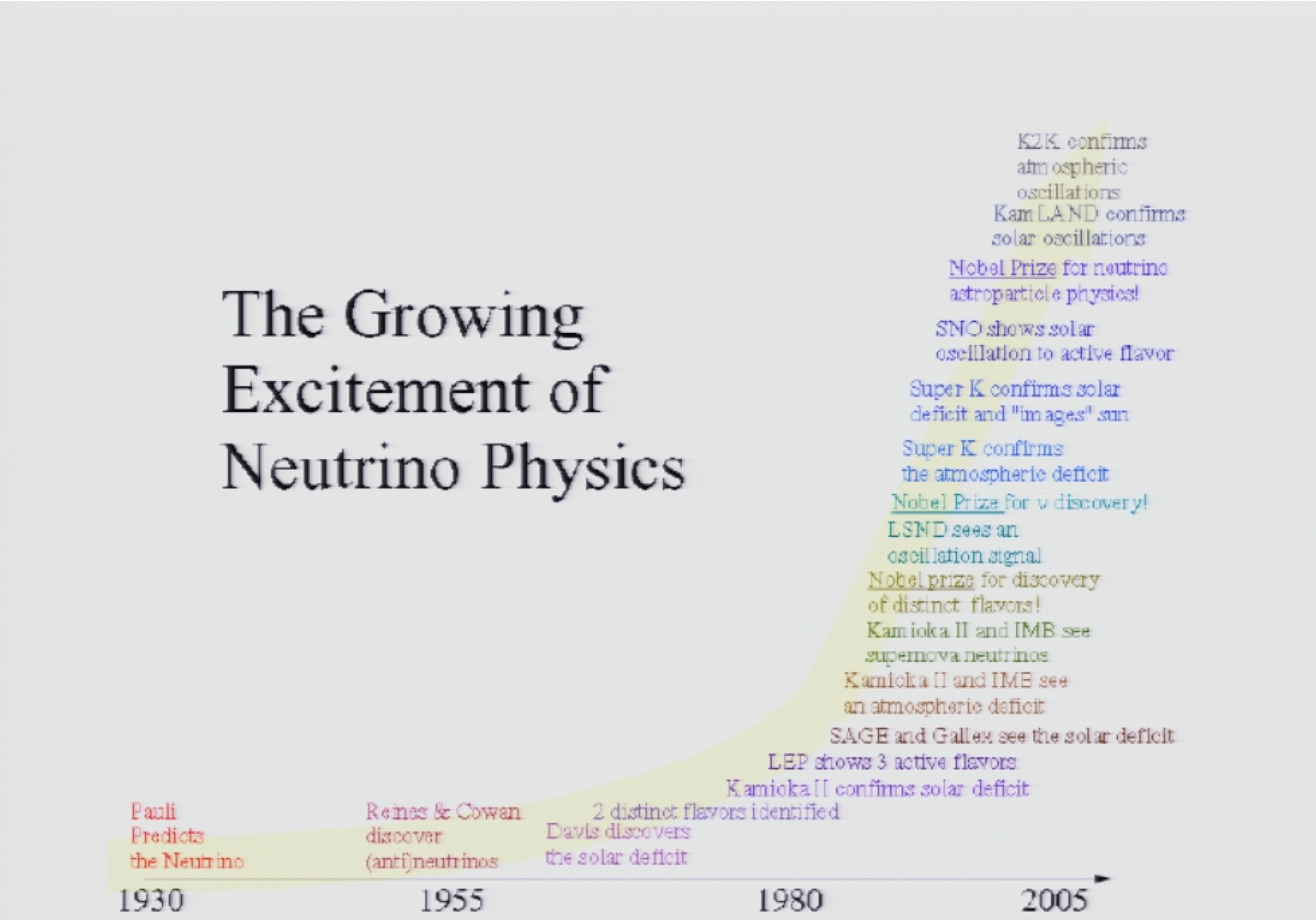




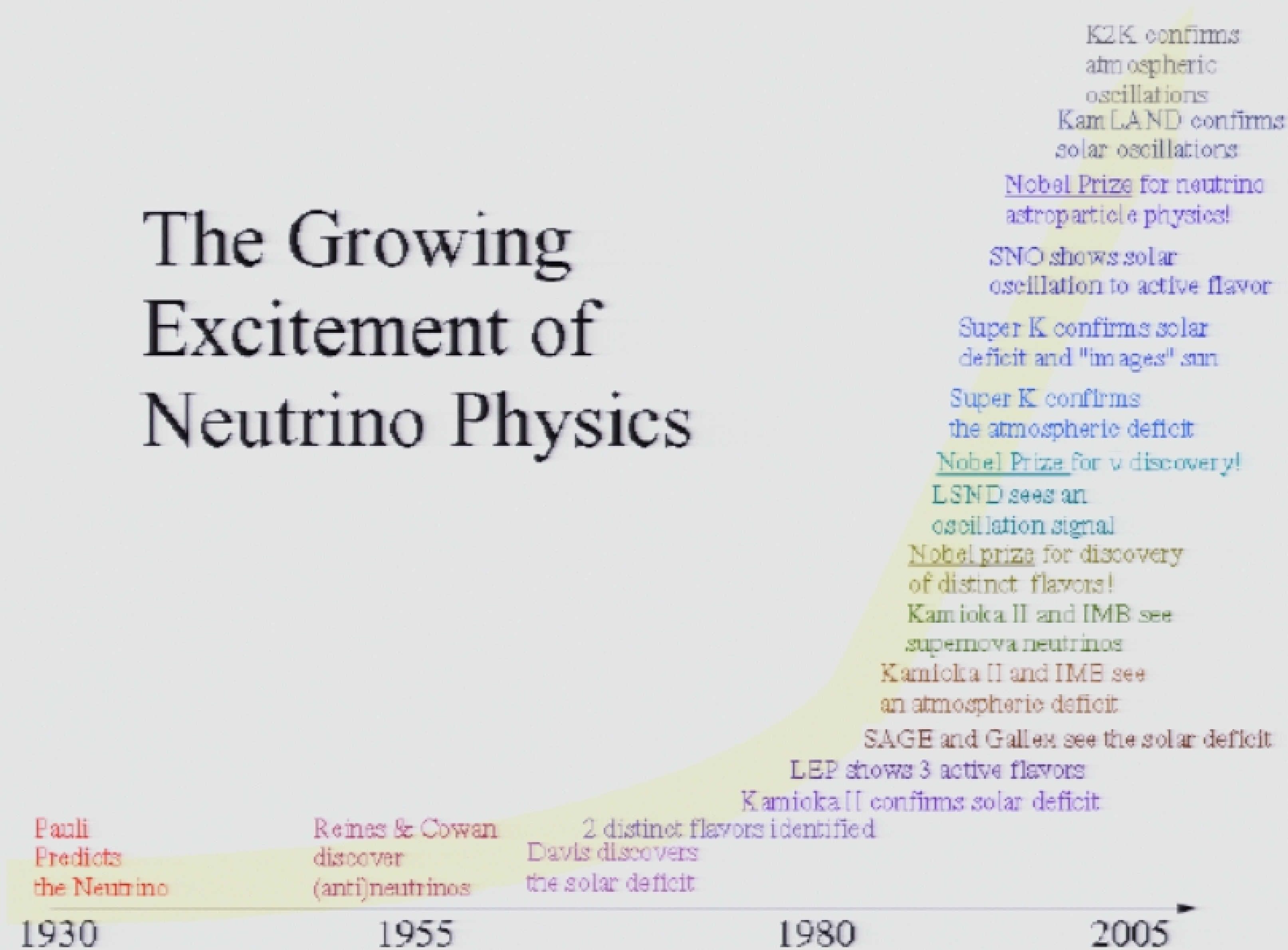




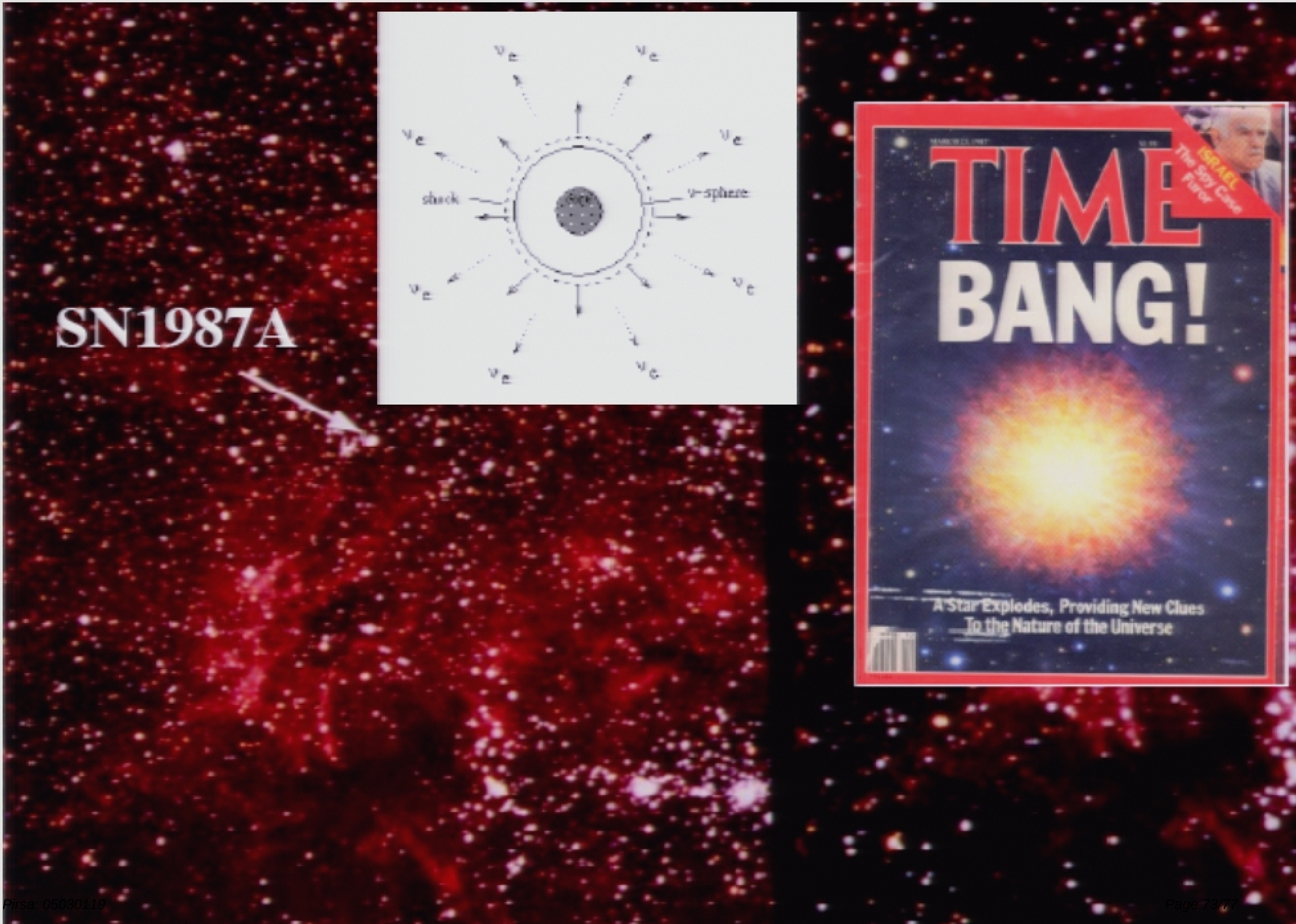
Sterile Neutrinos?
CPT Violation?

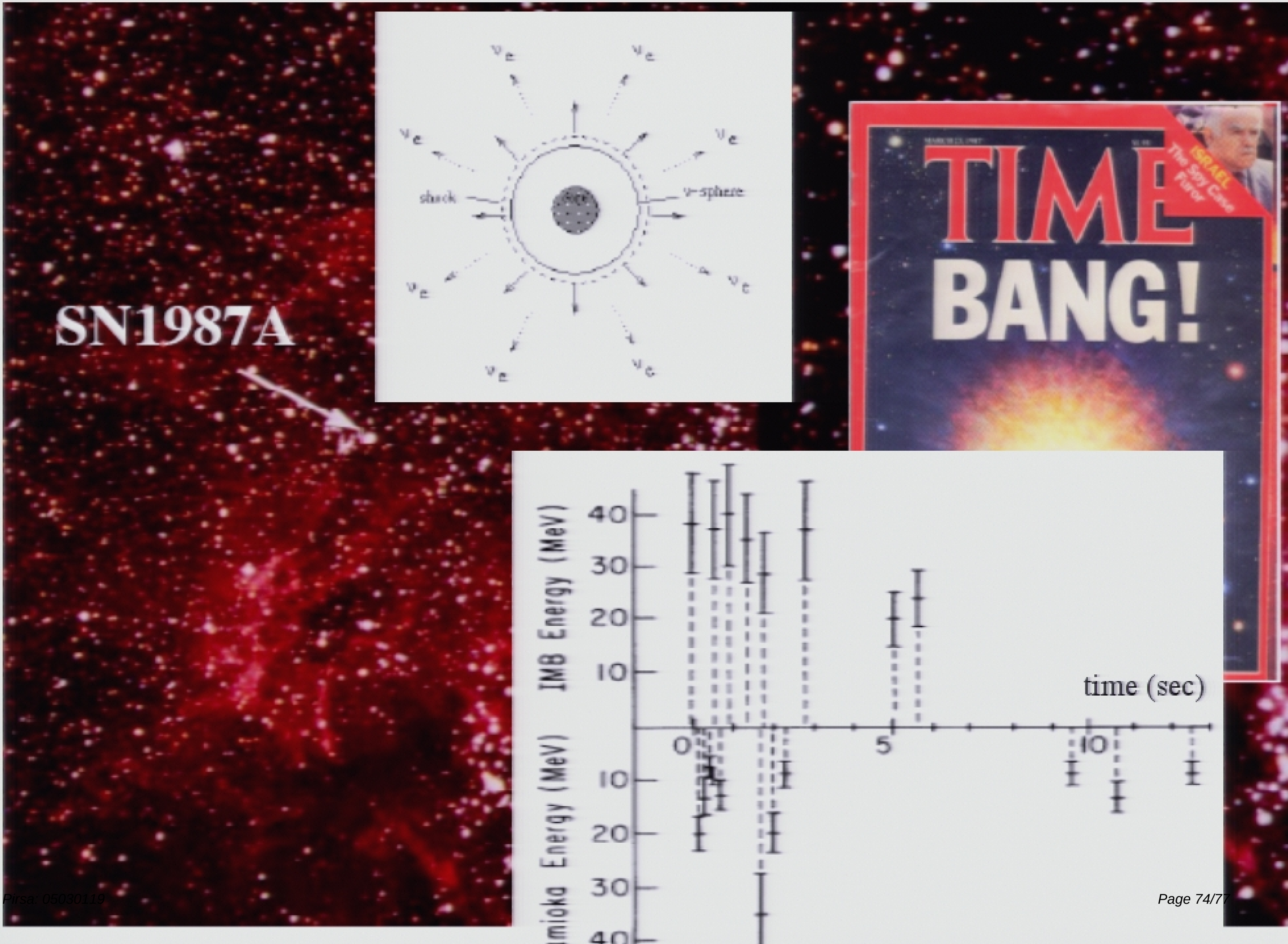

The Growing Excitement of Neutrino Physics
K2K confirms atmospheric oscillations
KamLAND confirms solar oscillations
Nobel Prize for neutrino astroparticle physics!
SNO shows solar oscillation to active flavor
Super K confirms solar deficit and "images" sun
Super K confirms the atmospheric deficit
Nobel Prize for ν discovery!
LSND sees an oscillation signal
Nobel prize for discovery of distinct flavors!
Kamioka II and IMB see supernova neutrinos
Kamioka II and IMB see an atmospheric deficit
SAGE and Gallex see the solar deficit
LEP shows 3 active flavors
Kamioka II confirms solar deficit
2 distinct flavors identified
Davis discovers the solar deficit
Reines & Cowan discover (anti)neutrinos
Pauli Predicts the Neutrino
1930
1955
1980
2005

The Growing Excitement of Neutrino Physics

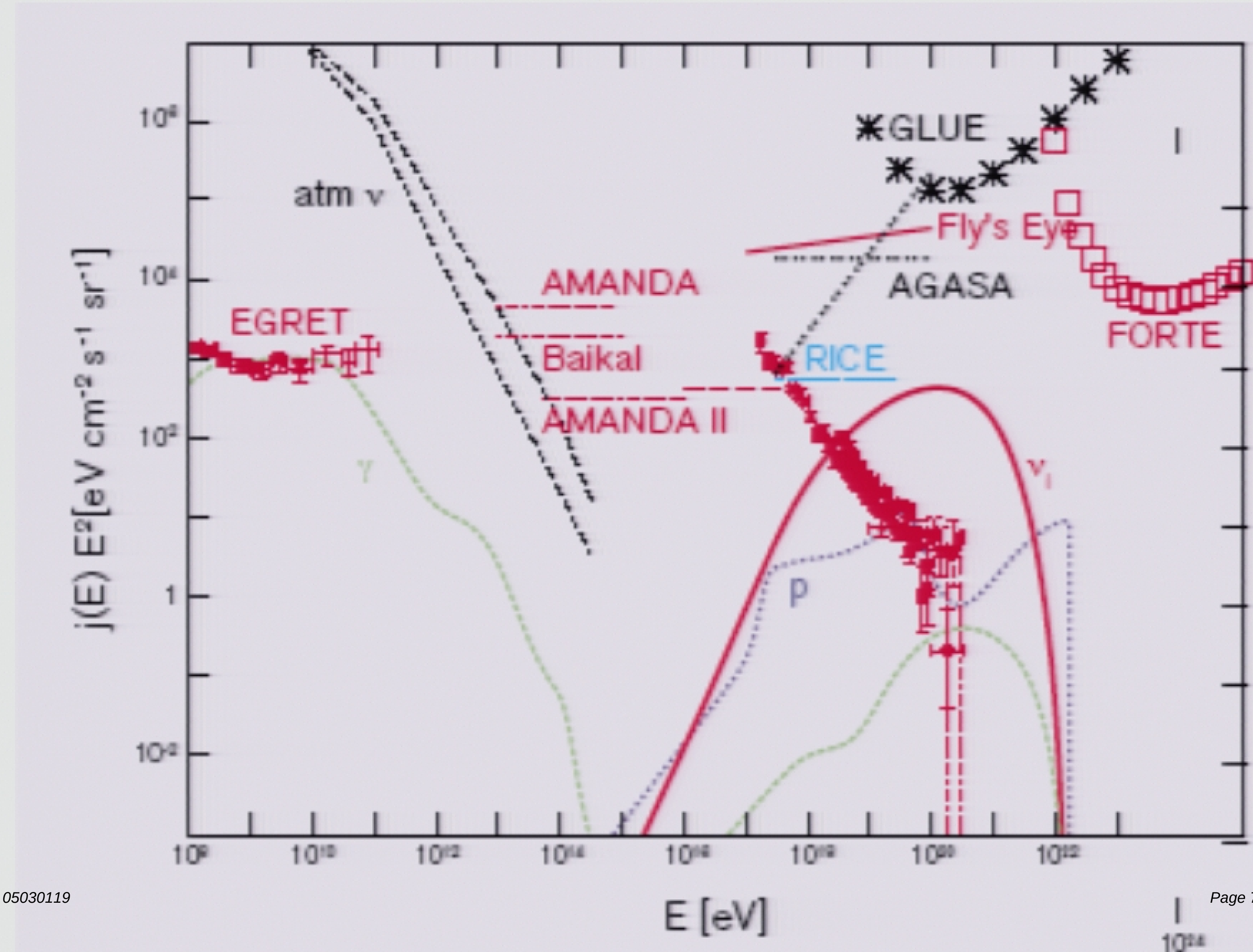



SN1987A
TIME
ISRAEL
The Spy Case
Furor
BANG!
A Star Explodes, Providing New Clues
To the Nature of the Universe


SN1987A
νe
shock
ν-sphere
TIME
ISRAEL
The Spy Case
Furor
BANG!
A Star Explodes, Providing New Clues
To the Nature of the Universe


SN1987A
νe
shock
ν-sphere
TIME
ISRAEL
The Spy Case
Furor
BANG!
IMB Energy (MeV)
amioka Energy (MeV)
time (sec)
40
30
20
10
0
5
10
10
20
30
40

Origins of Ultra-High Energy Cosmic Rays & Neutrinos?



The DNP/DPF/DAP/DPB

Joint Study on the Future of Neutrino Physics

The Neutrino Matrix

Summary … 10 Big Questions for Neutrino Physics

1. What are the masses of the neutrinos?
2. What is the pattern of mixing among the different types of neutrinos?
3. Are neutrinos their own antiparticles?
4. Do neutrinos violate the symmetry CP?
5. Are there sterile neutrinos?
6. Do neutrinos have exotic properties?
7. What do neutrinos tell us about the intriguing proposals for new models of fundamental physics?
8. What is the role of neutrinos in shaping the universe?
9. Are neutrinos the key to the understanding of the matter-antimatter asymmetry in the universe?
10. What can neutrinos disclose about the deep interior of astrophysical objects, and about the mysterious sources of very high energy cosmic rays?