Cours/Lecture Series

1992 – 1993 ACADEMIC TRAINING PROGRAMME

SPEAKER	:	H. HARARI / Weizmann Institute & CERN–TH
TITLE	:	Particle Physics, Cosmology andAstrophysics constraints on neutrino masses, oscillations and decays.
TIME	:	14, 15 & 16 April, from 11.00 to 12.00 hrs
PLACE	:	Auditorium

ABSTRACT

We review the properties of neutrinos, especially their masses decays and mixing angles, from the points of view of particle physics, astrophysics and cosmology. Constraints imposed by the standard model of cosmology and the standard model of particle physics, as well as experimental constraints from solar neutrino experiments, neutrino oscillations and other particle physics experiments are analyzed. We consider several possible scenarios for the values of neutrino masses. A favorite solution raises the possibility that the tau-neutrino is the main component of the dark matter of the universe and that MSW oscillations between the mu-neutrino and the electron neutrino are responsible for the small solar neutrino signal observed. We discuss experimental ways of testing this hypothesis.

DIRAC MASS

$$g_\ell \overset{(2)}{\varphi} \overset{(2)}{\nu_L} \overset{(1)}{\bar{\nu}_L}$$

$$m_D(\nu_\ell) = g_\ell \langle\varphi\rangle$$

$$m_D(\nu_\ell) \sim m_D(\ell^-)$$

[SAY, WITHIN FACTOR 10 OR SO]

↙

m_ℓ

$\overset{\circ}{\nu}_L$	$\bar{\nu}_L$
MAJORANA MASS (L)	**DIRAC MASS**
$\overset{(3)}{g'\Delta_L}\,\overset{(2)}{\nu_L}\,\overset{(2)}{\nu_L}$	$g_\ell\,\overset{(2)}{\varphi}\,\overset{(2)}{\nu_L}\,\overset{(1)}{\bar{\nu}_L}$
$m_L(\nu_\ell) = g'\langle\Delta_L\rangle$	$m_D(\nu_\ell) = g_\ell\langle\varphi\rangle$
$\langle\Delta_L\rangle \ll \langle\varphi\rangle$ (FOR $\frac{M_W}{M_Z} = \sin\theta_W$)	$m_D(\nu_\ell) \sim m_D(\ell^-)$
[$\langle\Delta_L\rangle = 0$ OR $\langle\Delta_L\rangle$ TINY]	[SAY, WITHIN FACTOR 10 OR SO]
→ 0	→ m_ℓ

$\bar{\nu}_L$

(ν_L)

MAJORANA MASS (L)

$$\overset{(3)}{g'}\,\overset{(2)}{\Delta_L}\,\overset{(2)}{\nu_L}\,\nu_L$$

$$m_L(\nu_\ell) = g'\langle\Delta_L\rangle$$

$\langle\Delta_L\rangle \ll \langle\varphi\rangle$ (FOR $\frac{M_W}{M_Z} = \sin\theta_W$)

[$\langle\Delta_L\rangle = 0$ OR $\langle\Delta_L\rangle$ TINY]

→ 0

$(\bar{\nu}_L)$

DIRAC MASS

$$\overset{(2)}{g_\ell}\,\overset{(2)}{\varphi}\,\overset{(1)}{\nu_L}\,\bar{\nu}_L$$

$$m_D(\nu_\ell) = g_\ell\langle\varphi\rangle$$

$$m_D(\nu_\ell) \sim m_D(\ell^-)$$

[SAY, WITHIN FACTOR 10 OR SO]

→ m_ℓ

M

↑

$M \sim g'\Lambda$ (LARGE)

$\langle\Delta_R\rangle \sim O(\Lambda)$ [NEW PHYSICS "BEYOND STANDARD"

$$m_R(\nu) = g'\langle\Delta_R\rangle$$

$$\overset{(1)}{g'}\,\overset{(1)}{\Delta_R}\,\overset{(1)}{\nu_R}\,\nu_R \text{ OR } \overset{(1)}{g'}\,\overset{(1)}{\bar{\Delta}_R}\,\overset{(1)}{\bar{\nu}_L}\,\bar{\nu}_L$$

MAJORANA MASS (R)

(ν_L)

MAJORANA MASS (L)

[illegible]

[illegible] (FOR $\frac{M_W}{M_Z} = \sin\theta_W$)

[illegible] $\langle\Delta_L\rangle$ TINY]

($\bar{\nu}_L$)

DIRAC MASS

$$\overset{(2)}{g_\ell}\,\overset{(2)}{\varphi\nu_L}\,\overset{(1)}{\bar{\nu}_L}$$

$$m_D(\nu_\ell) = g_\ell\langle\varphi\rangle$$

$$m_D(\nu_\ell) \sim m_D(\ell^-)$$

[SAY, WITHIN FACTOR 10 OR SO]

$$\begin{pmatrix} 0 & m_\ell \\ m_\ell & M \end{pmatrix}$$

$$m_D(\nu)$$

$$\overset{(2)}{g_\ell\varphi}\,\overset{(1)}{\bar{\nu}_L}\,\overset{(2)}{\nu_L}$$

DIRAC MASS

$M \sim g'\Lambda$ (LARGE)

$\langle\Delta_R\rangle \sim O(\Lambda)$ [NEW PHYSICS "BEYOND S.ANDA[RD]

$$m_R(\nu) = g'\langle\Delta_R\rangle$$

$$\overset{(1)}{g'\Delta_R}\,\overset{(1)}{\nu_R}\,\overset{(1)}{\nu_R} \text{ OR } \overset{(1)}{g'\bar{\Delta}_R}\,\overset{(1)}{\bar{\nu}_L}\,\overset{(1)}{\bar{\nu}_L}$$

MAJORANA MASS (R)

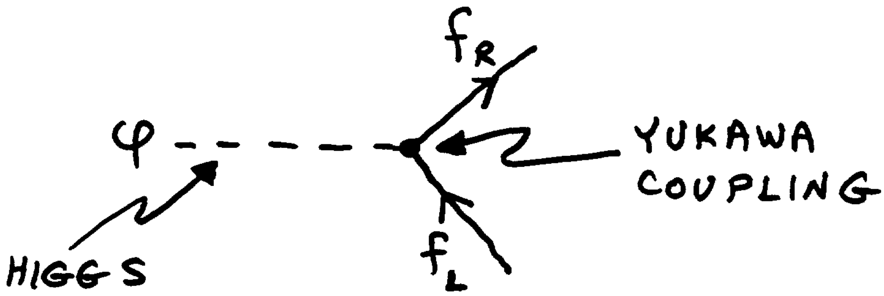
FERMION MASSES IN THE STANDARD MODEL

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \quad \begin{pmatrix} c \\ s \end{pmatrix}_L \quad \begin{pmatrix} t \\ b \end{pmatrix}_L$$

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$$

$SU(2) \times U(1)$

- L : DOUBLETS
- R : SINGLETS



$$\lambda \varphi \bar{f}_L f_L$$

f_L, $\bar{f}_R$: DOUBLET

f_R, $\bar{f}_L$: SINGLET

φ : DOUBLET

V.E.V. $\langle \varphi \rangle$

$$\underbrace{\lambda \langle \varphi \rangle}_{\Downarrow} \bar{f}_L f_L$$

$$m_f$$

(DIRAC MASS)

(HIGGS TRIPLET?
NO. $\left[\frac{M_W}{M_Z} = \sin\theta_W\right]$
HIGGS SINGLET?
NO MASS CONTRIBUTION)

IS ν MASSLESS OR LIGHT

IF MASSLESS, WHY?

NO DECENT EXPLANATION!

IF LIGHT, WHY?

ONE DECENT EXPLANATION!

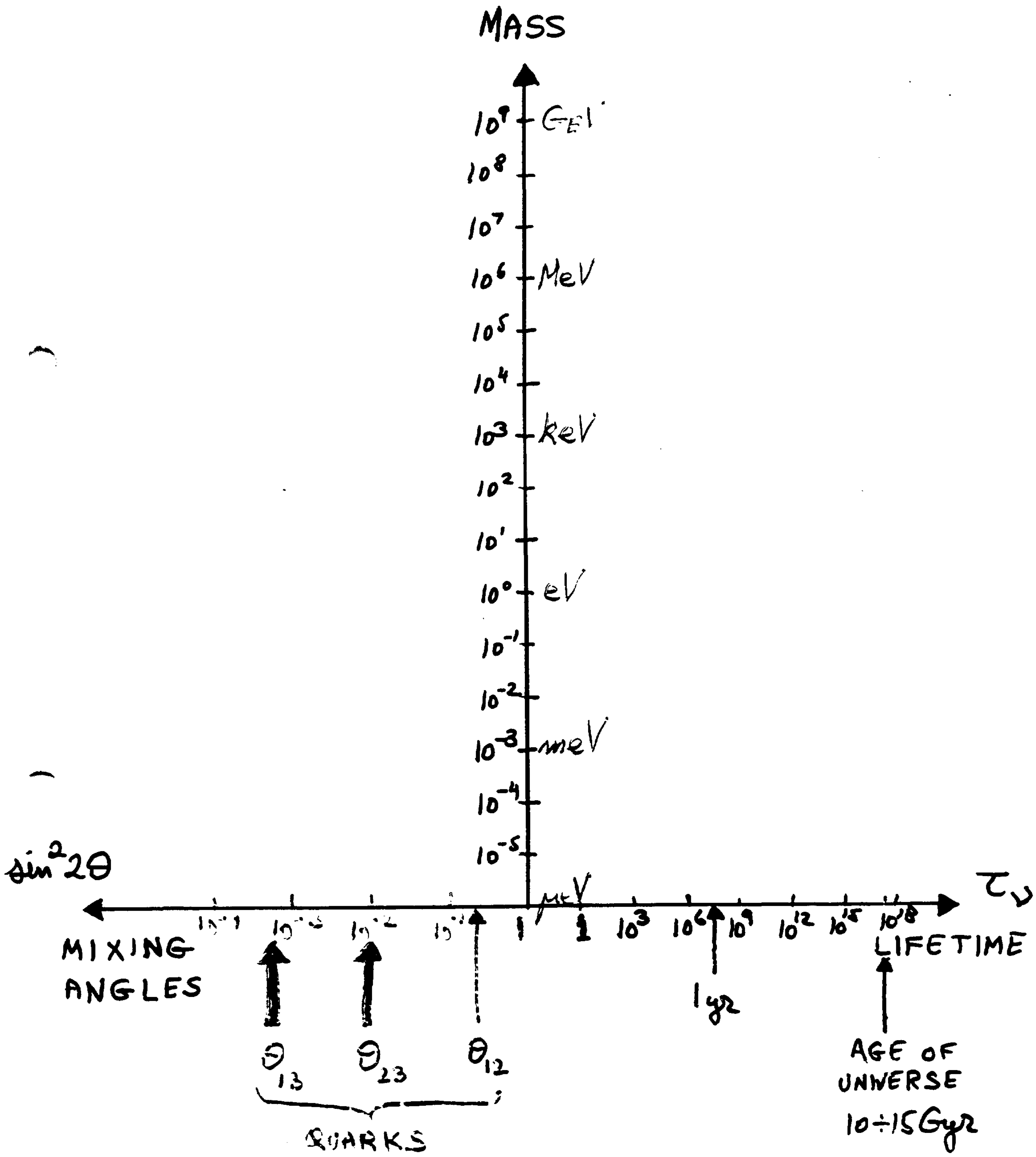
"SEE-SAW"

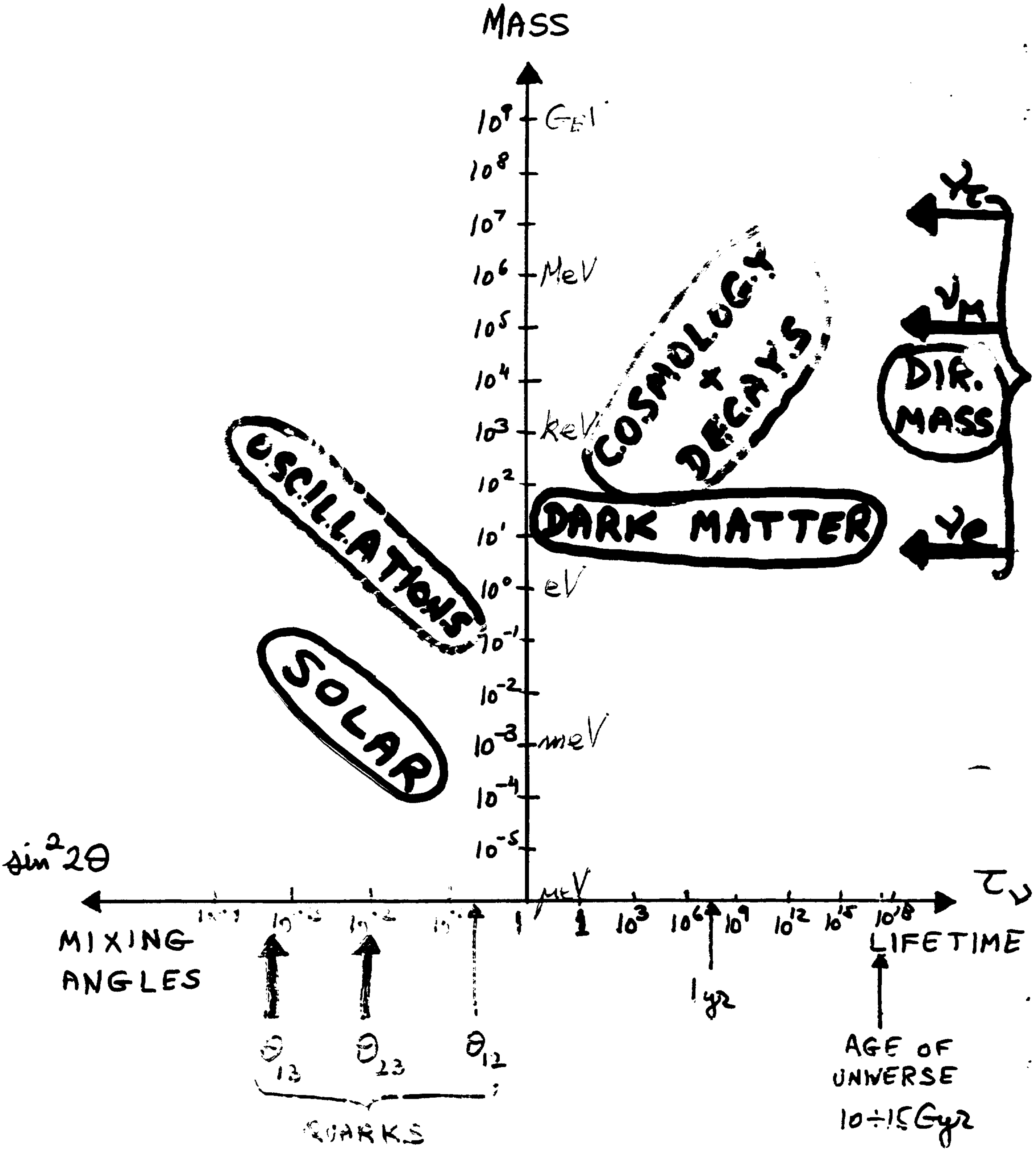
$$\left\{\begin{array}{l}\text{PARTICLE PHYSICS}\\ \text{COSMOLOGY}\\ \text{ASTROPHYSICS}\end{array}\right\}\ \text{CONSTRAINTS ON}\ \nu \left\{\begin{array}{l}\text{MASSES}\\ \text{MIXING}\\ \text{DECAYS}\end{array}\right\}$$

HAIM HARARI
WEIZMANN INSTITUTE

CERN ACADEMIC TRAINING LECTURE SERIES
APRIL 14, 15, 16 1993

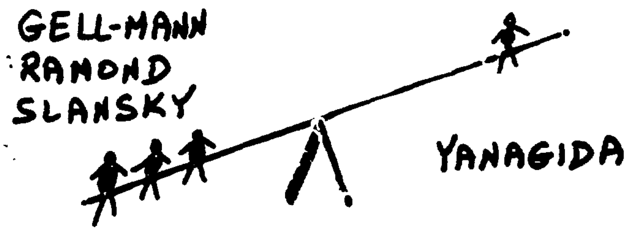
- ν-MASSES : DIRAC & MAJORANA
- "SEE - SAW" MECHANISM
- ν-MASS RATIOS
- DIRECT MEASUREMENTS
- COSMOLOGICAL BOUNDS : STABLE ν
- COSMOLOGICAL BOUNDS : UNSTABLE ν
- ν-DECAYS : BOUNDS ON ν MASSES & LIFETIMES
- DARK MATTER
- ν-MIXING ANGLES
- ν-OSCILLATIONS : REACTOR, ACCELERATOR, DECAYS
- ν-OSCILLATIONS IN MATTER : MSW
- SOLAR - ν
- SCENARIOS FOR ν-MASSES
- A FAVORITE SCENARIO
- OPEN THEORETICAL PROBLEMS
- FUTURE EXPERIMENTS.


MASS
10^9 GeV
10^8
10^7
10^6 MeV
10^5
10^4
10^3 keV
10^2
10^1
10^0 eV
10^{-1}
10^{-2}
10^{-3} meV
10^{-4}
10^{-5}
μeV
$\sin^2 2\theta$
MIXING ANGLES
θ_{13}
θ_{23}
θ_{12}
QUARKS
τ_ν
1
10^3
10^6
10^9
10^{12}
10^{15}
10^{18}
LIFETIME
1 yr
AGE OF UNIVERSE
10÷15 Gyr



MASS
10^9 GeV
10^8
10^7
10^6 MeV
10^5
10^4
10^3 keV
10^2
10^1
10^0 eV
10^-1
10^-2
10^-3 meV
10^-4
10^-5
μeV
COSMOLOGY + DECAYS
OSCILLATIONS
SOLAR
DARK MATTER
DIR. MASS
ν_τ
ν_μ
ν_e
sin²2θ
MIXING ANGLES
τ_ν
1
1
10^3
10^6
10^9
10^12
10^15
10^18
LIFETIME
1 yr
AGE OF UNIVERSE
10÷15 Gyr
θ_13
θ_23
θ_12
QUARKS

"SEE-SAW" MECHANISM



$$\begin{pmatrix} \sim 0 & m \\ m & M \sim \Lambda \end{pmatrix}$$

$$\nu_1 \sim \nu_L + \varepsilon \bar{\nu}_L$$

$$\bar{\nu}_2 \sim \bar{\nu}_L - \varepsilon \nu_L$$

$$m(\nu_1) \sim \frac{m^2}{M} \ll m(\ell^-)$$

$$m(\nu_2) \sim M \sim O(\Lambda)$$

FOR $m \sim MeV$, $M \sim TeV$ ➡ $m(\nu_1) \sim eV$

N-GENERATIONS: m, M ARE $N \times N$ MATRICES

"BLOCK" DIAGONALIZATION: $\begin{pmatrix} m M^{-1} m & 0 \\ 0 & M \end{pmatrix}$

"COMPLETE" DIAGONALIZATION: $\begin{cases} N & \text{LIGHT } \nu\text{'s.} \\ N & \text{HEAVY } \nu\text{'s.} \end{cases}$

NOTE:
BECAUSE OF LIGHT-HEAVY MIXING (SMALL), MIXING MATRIX IN LIGHT SECTOR IS ONLY APPROXIMATELY UNITARY.

3-GENERATION SEE-SAW

$$\left(\begin{array}{c|c} 0 & m \\ \hline m & M \end{array}\right)$$

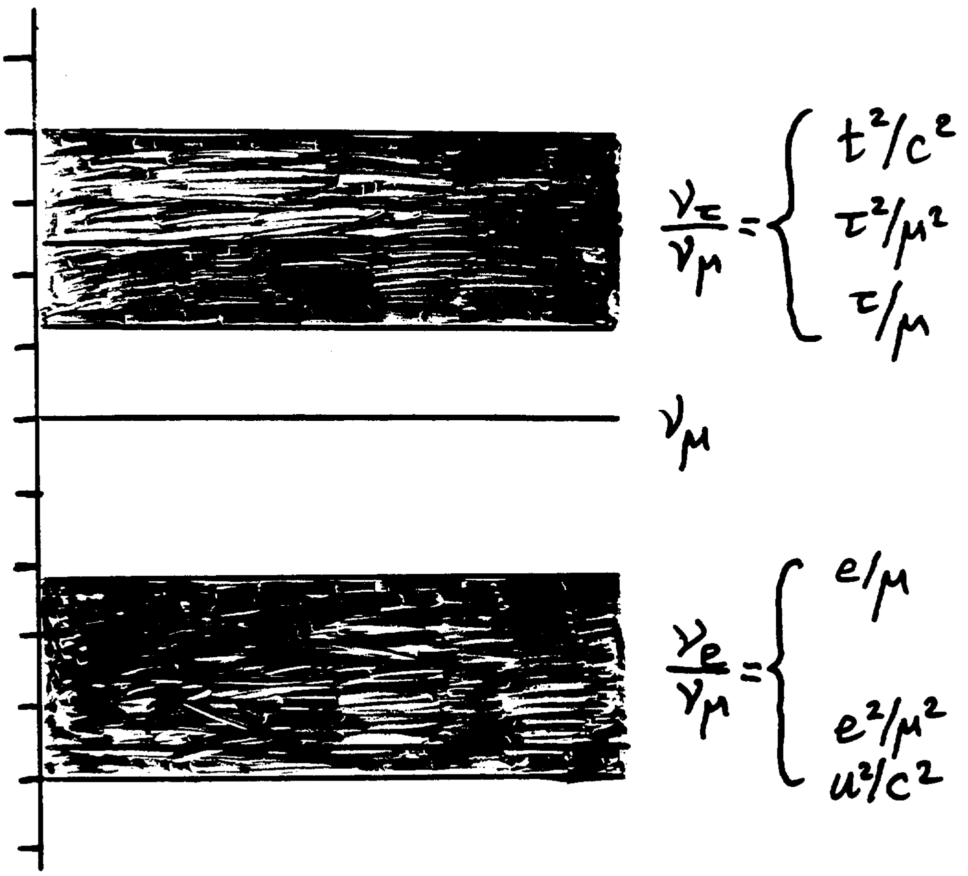
$$m \sim \begin{pmatrix} m_e & \times & \times \\ \times & m_\mu & \times \\ \times & \times & m_\tau \end{pmatrix} ?$$

$$m \sim \begin{pmatrix} m_u & \times & \times \\ \times & m_c & \times \\ \times & \times & m_t \end{pmatrix} ?$$

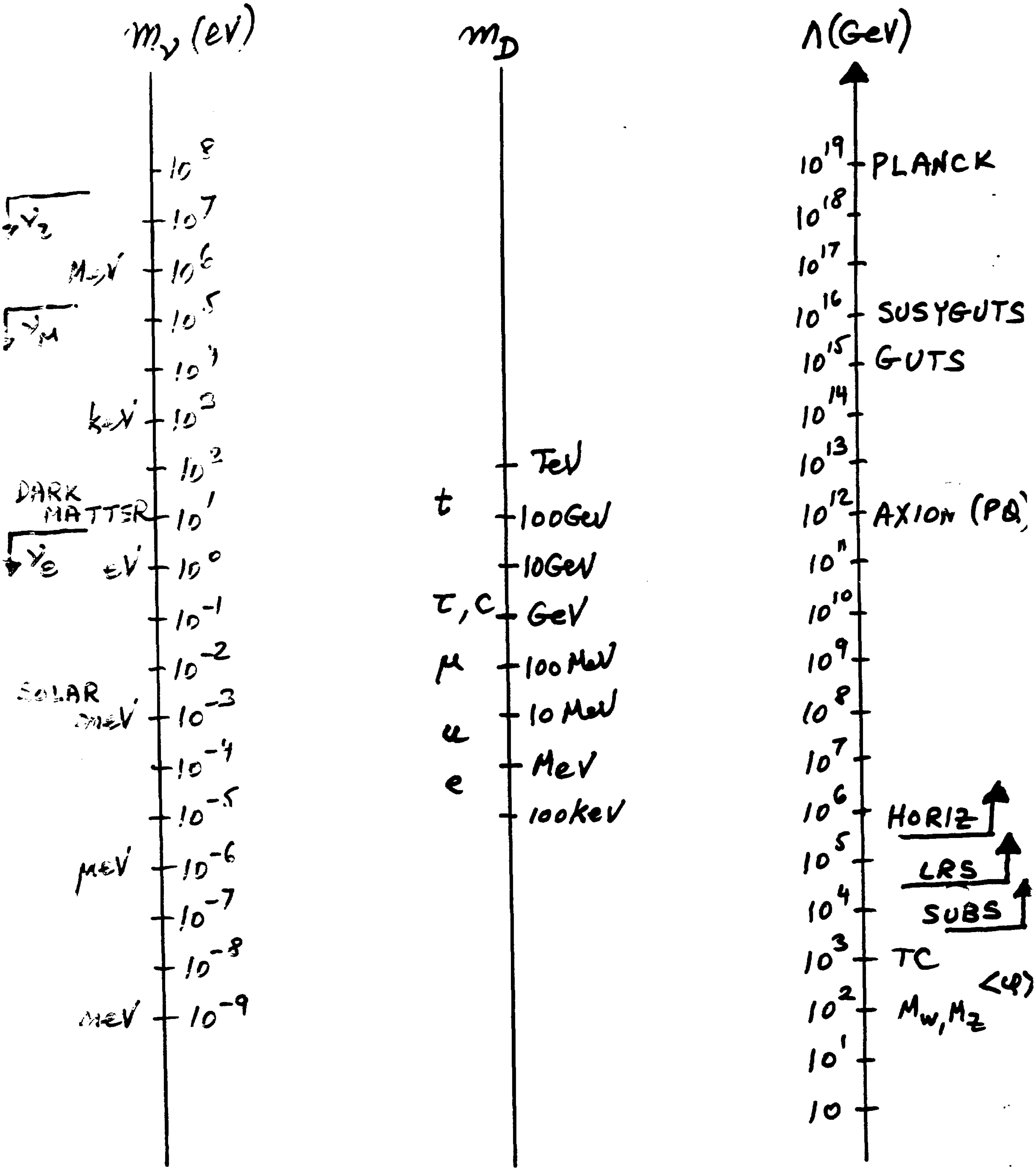
$$M \sim \begin{pmatrix} \Lambda & \times & \times \\ \times & \Lambda & \times \\ \times & \times & \Lambda \end{pmatrix} \sim \begin{pmatrix} f_1\Lambda & \times & \times \\ \times & f_2\Lambda & \times \\ \times & \times & f_3\Lambda \end{pmatrix} ?$$

$$m(\nu_e) : m(\nu_\mu) : m(\nu_\tau) \sim \begin{Bmatrix} m_e^2 : m_\mu^2 : m_\tau^2 & (?) \\ m_u^2 : m_c^2 : m_t^2 & (?) \\ m_e : m_\mu : m_\tau & (?) \end{Bmatrix}$$

$$\frac{m(\nu_\tau)}{m(\nu_\mu)} \sim \begin{Bmatrix} 300 \\ 10{,}000 \\ 20 \end{Bmatrix} (?)$$



$\nu_\tau / \nu_\mu = $
t^2/c^2
τ^2/μ^2
τ/μ
ν_μ
$\nu_e / \nu_\mu = $
e/μ
e^2/μ^2
u^2/c^2



m_ν (eV)
m_D
Λ(GeV)
10^8
ν_τ
10^7
MeV
10^6
ν_μ
10^5
10^4
keV
10^3
10^2
DARK MATTER
10^1
ν_e
eV
10^0
10^{-1}
10^{-2}
SOLAR
meV
10^{-3}
10^{-4}
10^{-5}
μeV
10^{-6}
10^{-7}
10^{-8}
neV
10^{-9}
TeV
t
100GeV
10GeV
τ, c
GeV
μ
100 MeV
10 MeV
u
MeV
e
100keV
10^{19} PLANCK
10^{18}
10^{17}
10^{16} SUSYGUTS
10^{15} GUTS
10^{14}
10^{13}
10^{12} AXION (PQ)
10^{11}
10^{10}
10^9
10^8
10^7
10^6 HORIZ
10^5 LRS
10^4 SUBS
10^3 TC
$\langle\varphi\rangle$
10^2 M_W, M_Z
10^1
10

ν - [redacted]

DIRECT & "ALMOST DIRECT"

- DIRECT "END-POINT" MEASUREMENTS:
  - $m(\nu_\tau) < 31$ MeV
  - $m(\nu_\mu) < 270$ keV
  - $m(\nu_e) < 7$ eV

- SN 87A

  $m(\nu_e) \lesssim 10$ eV

  [ALSO INFORMATION ON $m(\nu_\tau)$]

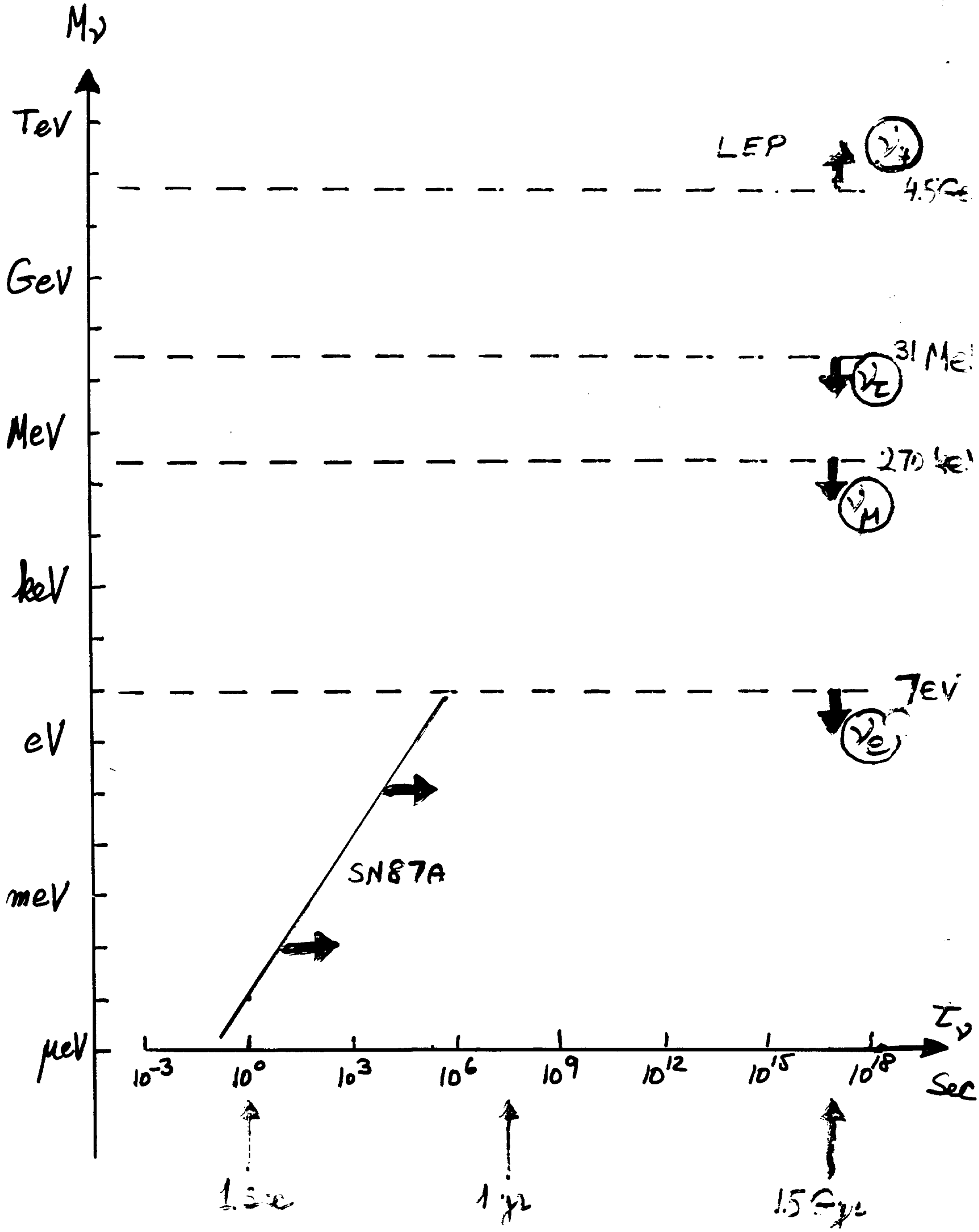
- LEP

  $m(\nu_4) > 45$ GeV

- NUCLEOSYNTHESIS

  3 <u>LIGHT</u> NEUTRINOS.

  ($m <$ MeV)



M_ν
TeV
GeV
MeV
keV
eV
meV
μeV
LEP
31 MeV
7 eV
ν_τ
ν_μ
ν_e
SN87A
τ_ν
10^{-3}
10^{0}
10^{3}
10^{6}
10^{9}
10^{12}
10^{15}
10^{18}
Sec
1 yr

COSMOLOGY AND NEUTRINO MASSES

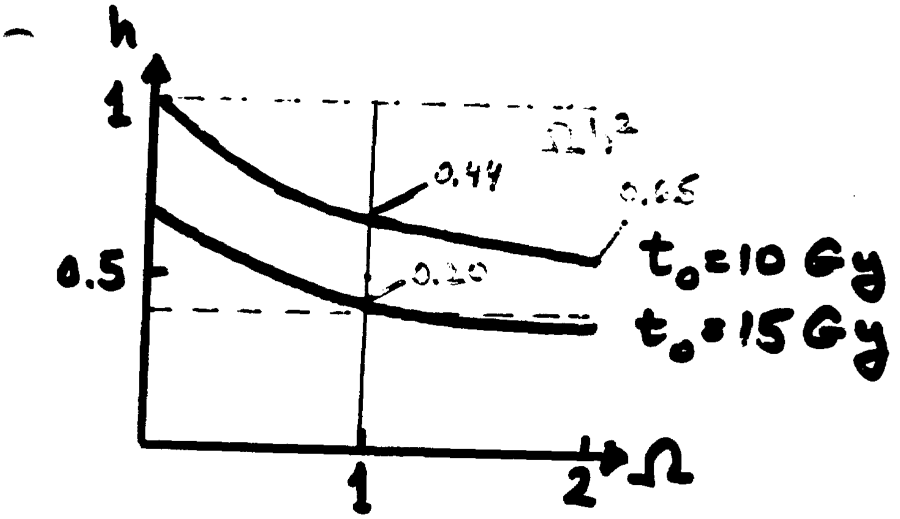
DENSITY OF THE UNIVERSE —

$$\rho_0 \equiv \Omega\,\rho_c = \Omega \cdot \frac{3H_0^2}{8\pi G} = \left\lfloor \Omega h^2 \right\rfloor \cdot 11\,\frac{\text{keV}}{\text{cm}^3}$$

ρ_0 → NOW

Ω → $\left(\Omega \begin{array}{ll} >1 & \text{CLOSED} \\ =1 & \text{FLAT} \\ <1 & \text{OPEN} \end{array}\right)$

$H_0 = h \cdot 100\,\frac{\text{km/sec}}{\text{Mpc}}$



≤ 2 BOUND
$= 1$ THEORY
$>$ ... "...ARY"

$0.4 \le h \le 1$

"BEST": $\rho_0 \sim 2\,\frac{\text{keV}}{\text{cm}^3}$;

"CONSERVATIVE": $\rho_0 \le 7\,\frac{\text{keV}}{\text{cm}^3}$

COULD BE MUCH SMALLER!

THE SUM OF ALL NEUTRINO MASSES PER cm^3 <u>MUST</u> BE LESS THAN ρ_0, HENCE $\le 7\,\frac{\text{keV}}{\text{cm}^3}$.

HOW MANY NEUTRINOS PER cm^3?

IN THE EARLY UNIVERSE, NEUTRINOS DECOUPLED AT TEMPERATURE AROUND FEW MeV. SINCE THAT TIME THEY ARE ESSENTIALLY A NON-INTERACTING GAS.

CASE I LIGHT STABLE ν

(m_ν < MeV)

AT DECOUPLING $n_\nu = \frac{3}{11} n_\gamma$.

SINCE THEN $\frac{n_\nu}{n_\gamma}$ FIXED.

NOW $n_\gamma \sim 400\ cm^{-3}$, HENCE $n_\nu \sim 110\ cm^{-3}$

$$m_\nu < \Omega h^2 \cdot 100\ eV$$

① $m_\nu < 65\ eV$

② IF ν IS $\Omega = 1$ DARK MATTER, $m_\nu \sim 20$–45 eV

③ IF ν IS LIGHTER, DARK MATTER IS NOT LIGHT NEUTRINOS.

GERSTEIN–ZELDOVICH

COWSIK–MCCLELLAND

CASE II — HEAVY STABLE ν

$(m_\nu > 10 \text{ MeV})$

AT EQUILIBRIUM (BEFORE DECOUPLING) $N_\nu \propto e^{-\frac{m_\nu}{kT}}$

WHEN THE DUST SETTLES, (DIFFERENTIAL Eq., NUMERICAL SOLUTION)

$$N_\nu \propto \frac{1}{m_\nu^3} \text{ (APPROXIMATELY).}$$

CONTRIBUTION TO ρ: $\propto \frac{1}{m_\nu^2}$

LARGER m_ν CONTRIBUTES <u>LESS</u> TO ρ !!

$$m_\nu > \left(\frac{1}{\sqrt{\Omega h^2}}\right) 3.4 \text{ GeV}$$

1. FOR $\Omega h^2 < 0.65$, $m_\nu > 4.2 \text{ GeV}$. (ν_e) (ν_μ)
2. IF ν IS $\Omega = 1$ DARK MATTER, $m_\nu \sim 5 - 7.5$ GeV
3. IF ν IS HEAVIER, DARK MATTER IS NOT HEAVY NEUTRINOS.

HUT
LEE-WEINBERG
DICUS-KOLB-TEPLITZ

CASE III UNSTABLE ν

IF τ_ν IS VERY SHORT, THE NEUTRINO MASS IMMEDIATELY CONVERTS TO KINETIC ENERGY OF "MASSLESS" DECAY PRODUCTS (γ, LIGHTER ν, GOLDSTONE)

A "RADIATION DOMINATED" UNIVERSE FOLLOWS $\rho \sim R^{-4}$, NOT $\rho \sim R^{-3}$, AND IS THEREFORE ALLOWED TO START AT A HIGHER DENSITY AT DECAY TIME.

THE SHORTER THE LIFETIME, THE STRONGER THE EFF

$$m_\nu^2 \tau_\nu < 2 \cdot 10^{20}\ eV^2 \cdot sec \qquad \text{FOR } m_\nu < MeV$$

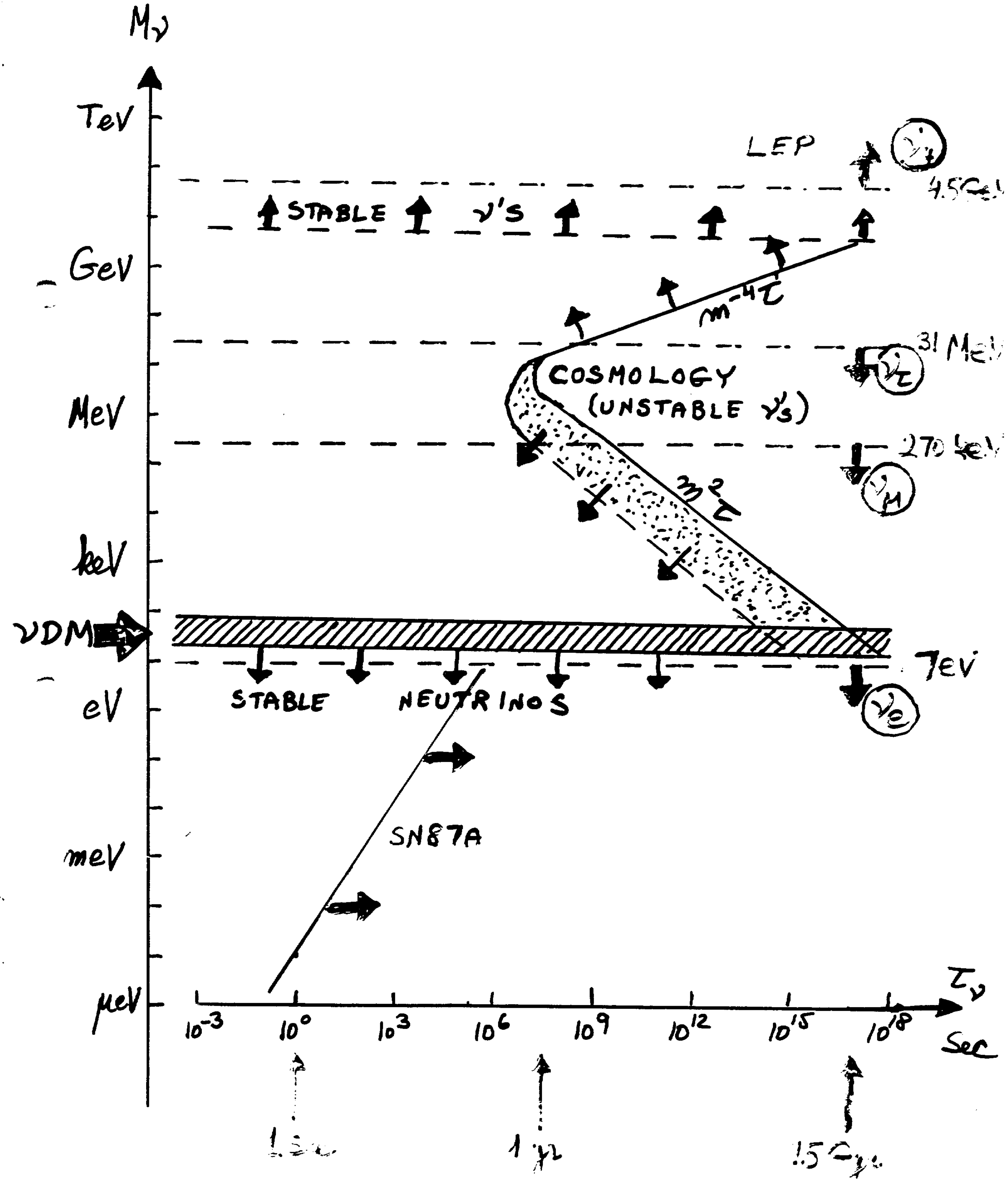
$$m_\nu^{-4} \tau_\nu < 1.5 \times 10^{-22}\ eV^{-4} \cdot sec \qquad \text{FOR } m_\nu > MeV$$

(THIS HOLDS FOR $t_0 > 10\,Gy$. FOR $t_0 \sim 15\,Gy$, BOUNDS MUCH STRONG

HOWEVER -

STEIGMAN-TURNER

LARGE SCALE STRUCTUR
DICTATES STRONGER
BOUNDS!


M_ν
TeV
GeV
MeV
keV
νDM
eV
meV
μeV
LEP
4.5 GeV
STABLE ν's
$m^{-4}\tau$
31 MeV
COSMOLOGY
(UNSTABLE ν's)
270 keV
$m^2\tau$
7 eV
STABLE NEUTRINOS
SN87A
ν_τ
ν_μ
ν_e
τ_ν
Sec
10^{-3}
10^0
10^3
10^6
10^9
10^{12}
10^{15}
10^{18}
1 yr

COSMOLOGICAL DARK MATTER

(ALSO DARK MATTER IN GALAXIES, CLUSTERS etc.)

CANDIDATES:

1. LIGHT ν ($m_\nu \sim 20$ eV)
2. WIMP's (SUSY? $M \sim$ few GeV?)
3. AXION ("INVISIBLE", $\frac{m_f}{\Lambda} \chi \bar{f} f$, $\Lambda \sim 10^{12}$ GeV)
4. OTHERS (?)

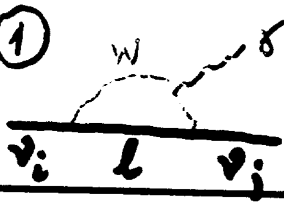
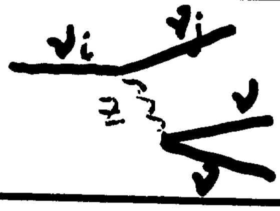
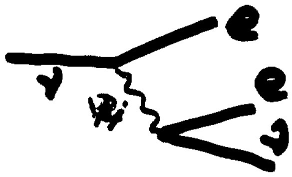
QUESTIONS:

- DO THEY EXIST?
- CAN THEY "CLUMP"?
- IS THERE ONLY ONE KIND?

NEUTRINO DECAYS

$\nu_i \rightarrow \nu_j + \gamma$	
$\nu_i \rightarrow \nu_j + \gamma + \gamma$	
$\nu_i \rightarrow \nu_j + \nu_k + \nu_l$	
$\nu_i \rightarrow \nu_j + e^+ + e^-$	ONLY FOR $m > 2m($
$\nu_i \rightarrow \nu_j + \text{majoron}$	ALSO OTHER GOLDSTO

NEUTRINO DECAYS

<table>
<tr><th></th><th>STANDARD MODEL</th><th></th></tr>
<tr><td>$\nu_i \rightarrow \nu_j + \gamma$</td><td>(1)

</td><td></td></tr>
<tr><td>$\nu_i \rightarrow \nu_j + \gamma + \gamma$</td><td>
</td><td></td></tr>
<tr><td>$\nu_i \rightarrow \nu_j + \nu_k + \nu_l$</td><td>
</td><td></td></tr>
<tr><td>$\nu_i \rightarrow \nu_j + e^+ + e^-$</td><td>
</td><td>ONLY ν_τ FOR $m > 2m(e)$</td></tr>
<tr><td>$\nu_i \rightarrow \nu_j + \text{majoron}$</td><td>—</td><td>ALSO OTHER GOLDSTONE</td></tr>
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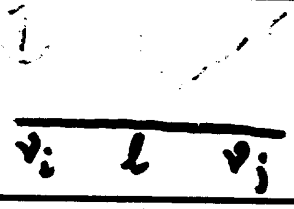
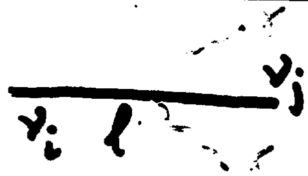
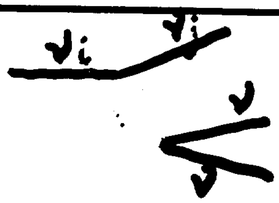
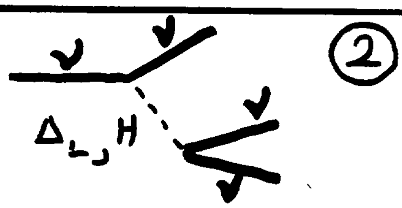
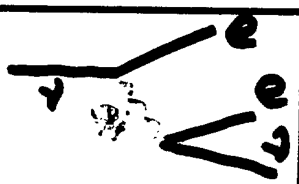
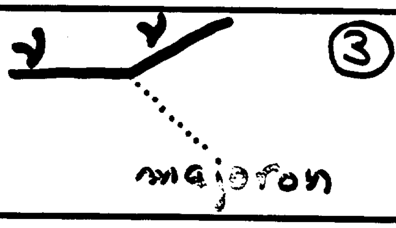
HH + NIR

NEUTRINO DECAYS

	STANDARD MODEL	BEYOND STANDARD	
[illegible]		SIMILAR. MORE SUPPRESSION.	
[illegible]		"	
[illegible]			
[illegible]		SIMILAR TO ②.	ONLY FOR $m > 2m($
[illegible]	———		ALSO OTHER GOLDSTO

FOR $\Lambda \sim M_{PLANCK}$, M_{GUT}, 10^{11} GeV : (i) $m_\nu \sim \frac{m^2}{\Lambda}$ IS TINY.

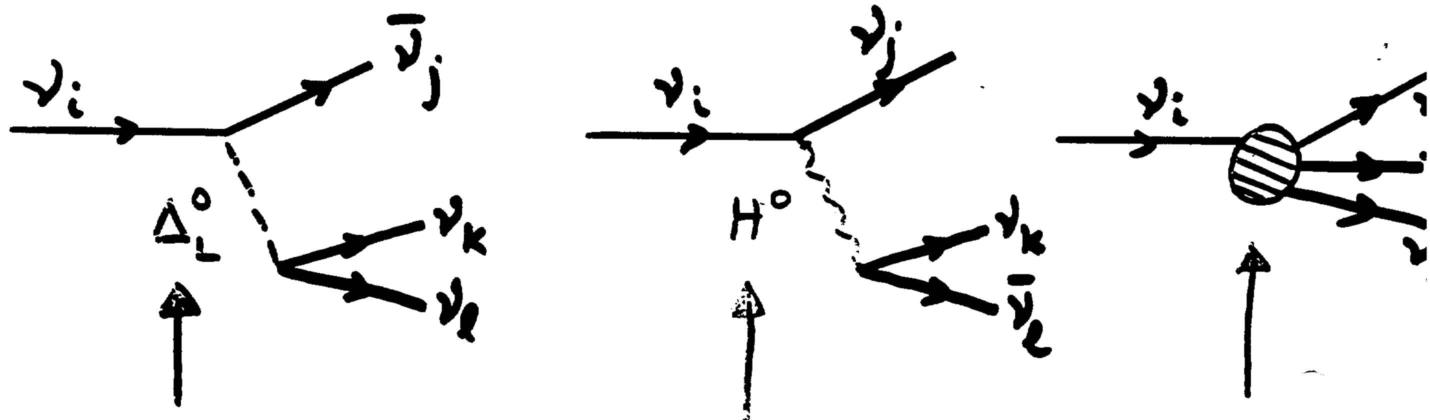
(ii) ALL EXCHANGES : Λ^{-}

"DANGEROUS" MODELS ARE THOSE WITH: TeV < Λ < PeV

LRS , HORIZONTAL, SUBSTRUCTURE

(2)

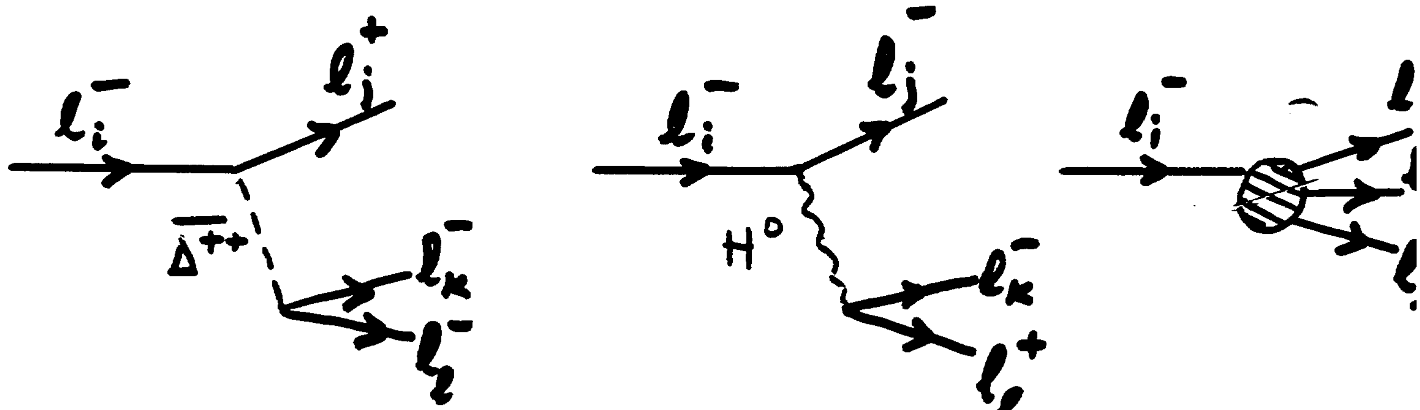
$$\nu_i \longrightarrow \nu_j + \nu_k + \nu_l$$



HIGGS TRIPLET
$(\Delta_L^{++}, \Delta_L^{+}, \Delta_L^{0})$
(SAME MASSES).

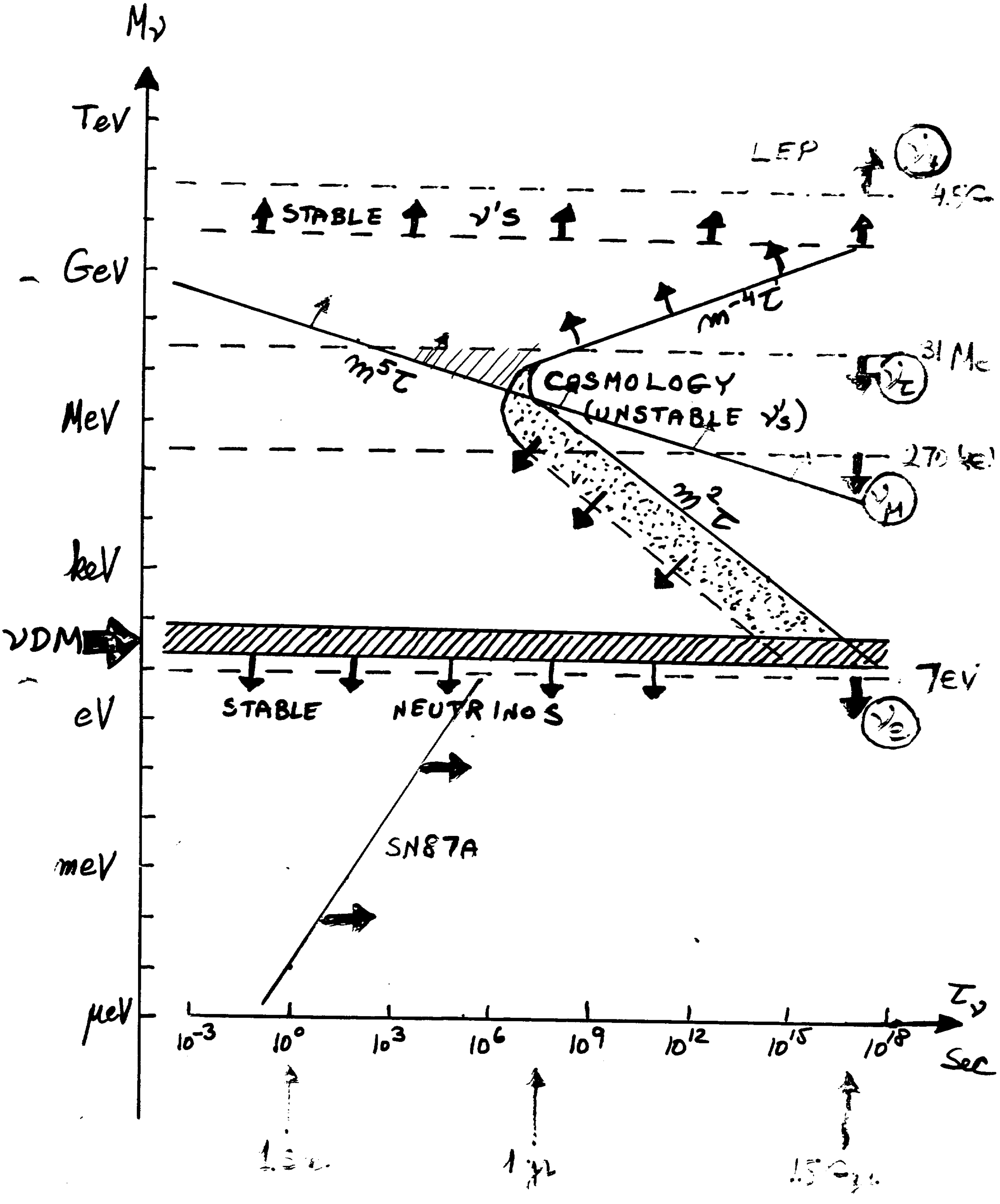
HORIZONTAL GAUGE BOSON

SUBSTRUCTURE SCALE



$\mu \to 3e$
$\tau \to 3e$
$\tau \to 3\mu$
$\tau \to ee\mu$
$\tau \to e\mu\mu$

$$\frac{\Gamma(\nu_i \to \nu_j \nu_k \nu_l)}{\Gamma(l_i \to l_j l_k l_l)} = \left[\frac{m(\nu_i)}{m(l_i)}\right]^5$$



M_ν
TeV
GeV
MeV
keV
νDM
eV
meV
μeV
LEP
STABLE ν'S
$m^{-4}\tau$
$m^5\tau$
COSMOLOGY
(UNSTABLE ν's)
$m^2\tau$
31 Mev
270 keV
7eV
STABLE NEUTRINOS
SN87A
τ_ν
10^{-3}
10^0
10^3
10^6
10^9
10^{12}
10^{15}
10^{18}
Sec
1 yr

BUT A ν_τ WITH $O(\text{MeV})$ "COUNTS" AS MORE THAN ONE LIGHT NEUTRINO IN THE ANALYSIS OF PRIMORDIAL NUCLEOSYNTHESIS.

FOR $\tau(\nu_\tau) > 1$ sec:

$0.5 \text{ MeV} < m_{\nu_\tau} < 25 \text{ MeV}$ IS FORBIDDEN

FOR $\tau(\nu_\tau) > 10^3$ sec:

$0.5 \text{ MeV} < m_{\nu_\tau} < 32 \text{ MeV}$ IS FORBIDDEN

KOLB et al, PRL '91

$$\nu_i \rightarrow \bar{\nu}_j + J \text{ (MAJORON)}$$

"NORMAL"

$$m_{\nu_i}^4 \tau_{\nu_i} = 5 \times 10^{34} \text{ eV}^4 \text{sec} \times$$

$$\times \left[\frac{0.1}{g'}\right]^2 \left[\frac{65 \text{eV}}{m(\nu_j)}\right] \left[\frac{M}{\text{TeV}}\right]^4$$

GLASHOW: $M \sim 50$ GeV

"PEEPHOLE" $\Rightarrow \nu_\mu \rightarrow \bar{\nu}_e + J$

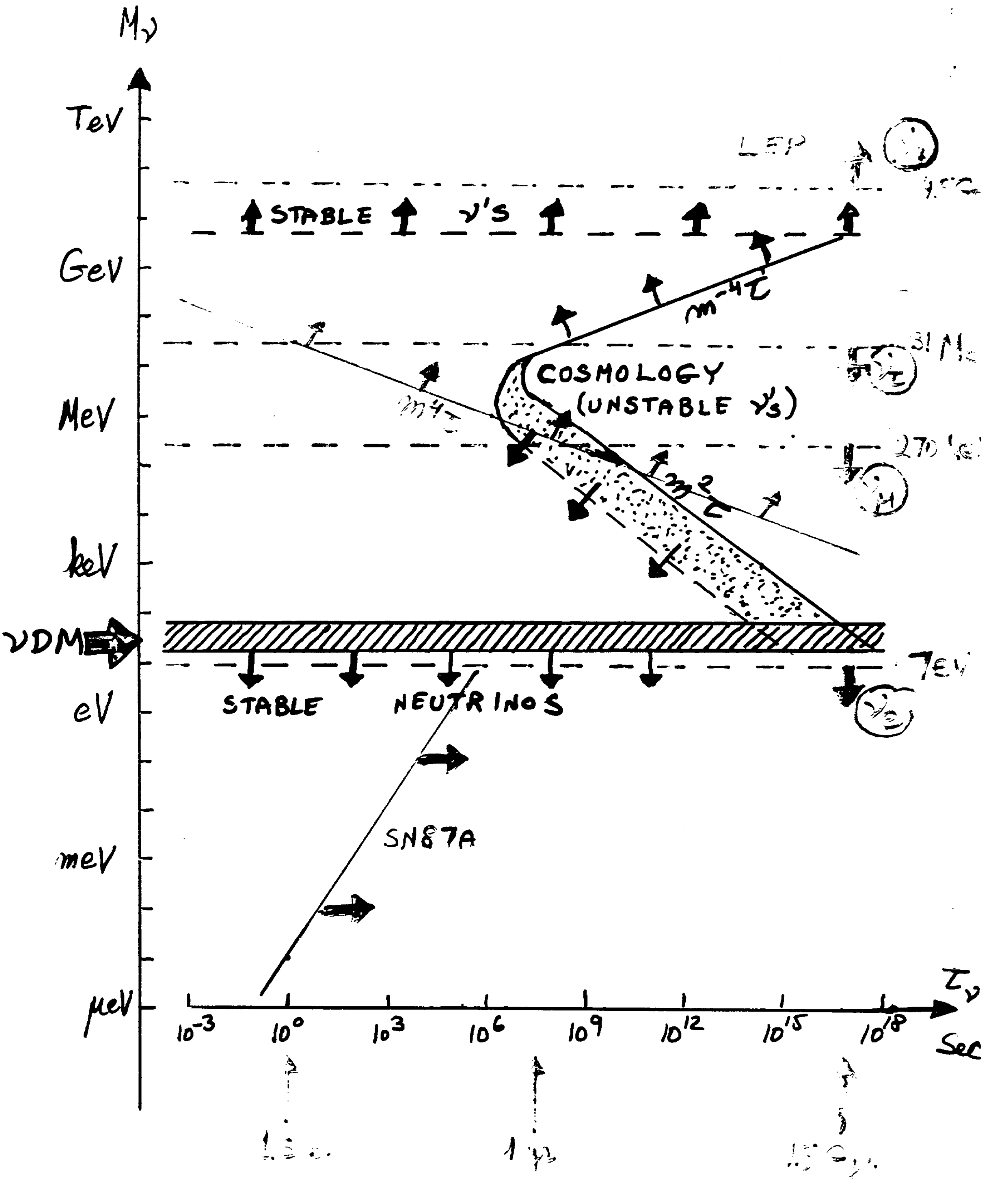
"PSEUDO-DIRAC"

2 HEAVY $O(M)$

2 "NORMAL" $O(m)$

2 LIGHT $O\left(\frac{m^2}{M}\right)$

$$m_{\nu_i}^2 \tau_{\nu_i} \sim \text{"POSSIBLE"}$$



Mν
TeV
GeV
MeV
keV
νDM
eV
meV
μeV
LEP
STABLE ν's
m^-4 τ
COSMOLOGY
(UNSTABLE ν's)
m^2 τ
STABLE NEUTRINOS
SN87A
τν
10^-3
10^0
10^3
10^6
10^9
10^12
10^15
10^18
Sec
1 yr

QUARK MIXING

CHARGED WEAK CURRENT

$$(\bar{u} \quad \bar{c} \quad \bar{t}) \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

(0.22) $V_{us} \sim \sin\theta_{12}$; $\theta_{12} \sim 13^\circ$

(0.05) $V_{cb} \sim \sin\theta_{23}$; $\theta_{23} \sim 2.5^\circ$

(0.004) $V_{ub} \sim \sin\theta_{13}$; $\theta_{13} \sim 0.2^\circ$

MASS-ANGLE RELATIONS?

$\sin\theta_{12} \sim \sqrt{\frac{m_d}{m_s}}$ (??!) WORKS!

GOOD "HAND-WAVING" ARGUMENTS FOR

$\theta_{13} < \theta_{12}, \theta_{23}$; $\theta_{ij} \to 0$ WHEN $\frac{m_i}{m_j} \to 0$;

AN IMPORTANT CHALLENGE!

NEUTRINO MIXING

MASS EIGENSTATES: ν_1, ν_2, ν_3

CHARGED WEAK CURRENT

$$(\bar{\nu}_1 \;\; \bar{\nu}_2 \;\; \bar{\nu}_3) \begin{pmatrix} \text{THIS MATRIX} \\ \text{IS NOT EXACTLY} \\ \text{UNITARY. IT IS} \\ \text{PART OF } 6\times6 \end{pmatrix} \begin{pmatrix} e \\ \mu \\ \tau \end{pmatrix}$$

WE HAVE NO KNOWLEDGE OF $\theta_{12}^{\ell}, \theta_{23}^{\ell}, \theta_{13}^{\ell}$

WILD GUESS:

$$\theta_{12}^{\ell} \sim \sqrt{\frac{m_e}{m_\mu}} \sim 0.07 \quad ??$$

(DON'T BELIEVE IT!)

ν - OSCILLATIONS

CONSIDER 2 GENERATIONS:

$$\nu_e(t) = \cos\vartheta\, \nu_1 e^{-iE_1 t} + \sin\vartheta\, \nu_2 e^{-iE_2 t}$$

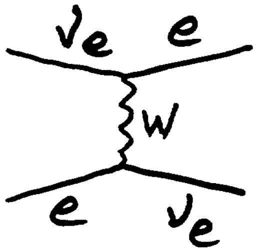
$$\nu_\mu(t) = -\sin\vartheta\, \nu_1 E^{-iE_1 t} + \cos\vartheta\, \nu_2 e^{-iE_2 t}$$

$$-i\frac{d}{dt}\begin{pmatrix}\nu_e(t)\\ \nu_\mu(t)\end{pmatrix} = \begin{pmatrix}-\Delta E\cos 2\vartheta & \Delta E \sin 2\vartheta\\ \Delta E\sin 2\vartheta & \Delta E\cos 2\vartheta\end{pmatrix}\begin{pmatrix}\nu_e(t)\\ \nu_\mu(t)\end{pmatrix}$$

$$\Delta E = \frac{\Delta m^2}{2p}$$

$$\boxed{P(\nu_e \to \nu_\mu) = \sin^2 2\vartheta\, \sin^2\left(1.27\cdot\frac{L}{E}\cdot\Delta m^2\right)}$$

IN MATTER:



[NO SIMILAR PROCESS FOR $\nu_e \leftrightarrow \nu_\mu$, $\nu_\mu \to \nu_\mu$.]

MSW

$$\begin{pmatrix}A-\Delta E\cos 2\vartheta & \Delta E\sin 2\vartheta\\ \Delta E\sin 2\vartheta & \Delta E\cos 2\vartheta\end{pmatrix}$$

$A \propto G_F n_e$

FOR $A = 2\Delta E\cos 2\vartheta$: MAXIMUM MIXING

$$-i\frac{d}{dt}\begin{pmatrix}\nu_e(t)\\ \nu_\mu(t)\end{pmatrix} = \begin{pmatrix}0 & 1\\ 1 & 0\end{pmatrix}\Delta E\sin 2\vartheta\begin{pmatrix}\nu_e(t)\\ \nu_\mu(t)\end{pmatrix}$$

ν – OSCILLATIONS

PROBING MASSES AND MIXING ANGLES

$$P = \sin^2 2\theta \cdot \sin^2\left[\frac{2\pi}{5}\left(\frac{L}{E}\right)\Delta m^2\right]$$

$$\left(\frac{km}{GeV} \quad eV^2\right)$$

- REACTOR

  $\nu_e \, \nu_x$ (DISAPPEARANCE)

- ACCELERATOR

  $\nu_\mu \, \nu_x$ (DISAPPEARANCE)

  $\nu_\mu \, \nu_e$; $\nu_\mu \, \nu_\tau$ (APPEARANCE)

- ATMOSPHERIC

  ν_μ / ν_e RATIO

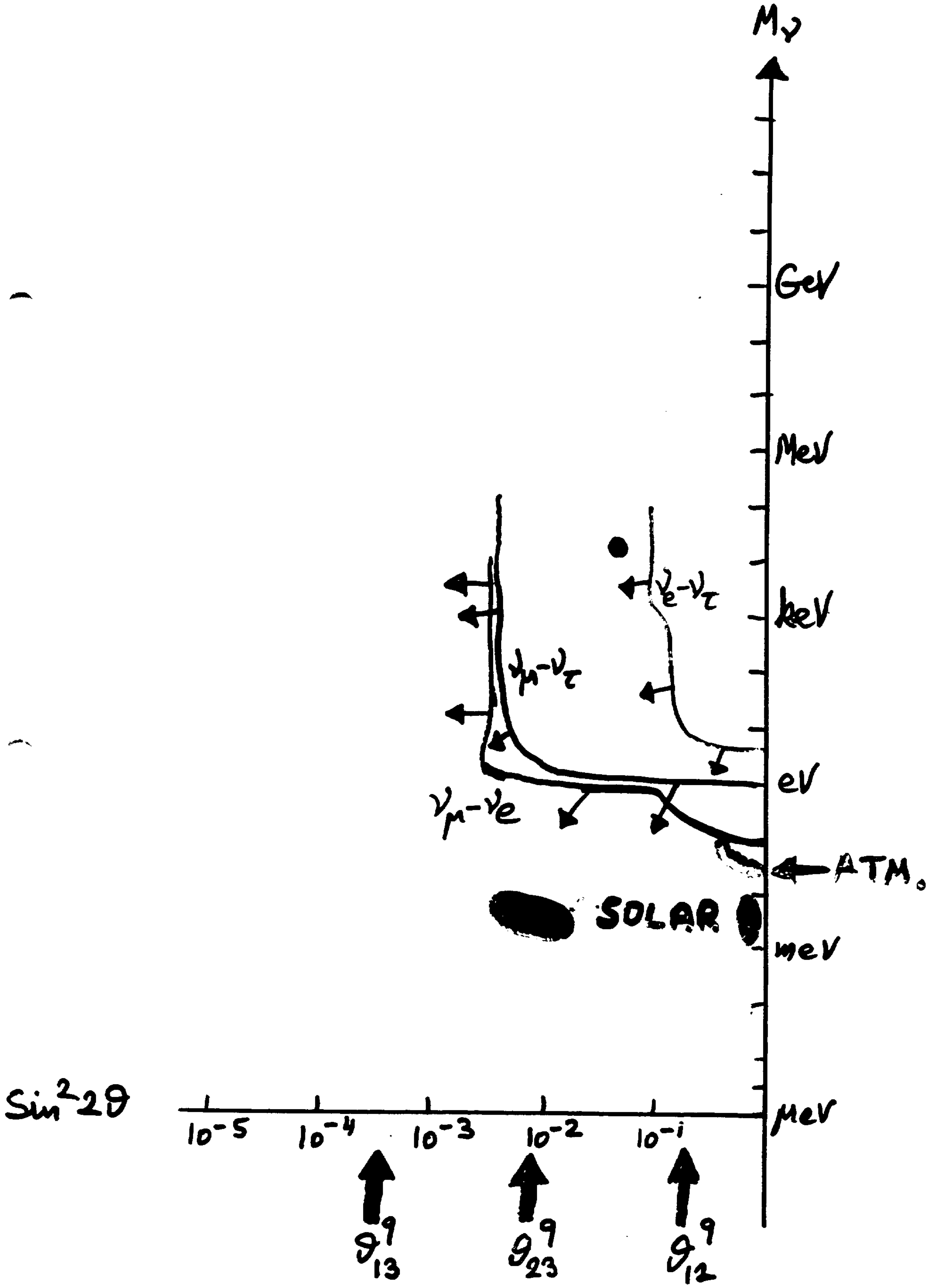
  $\left[\begin{array}{l} \pi \rightarrow \mu + \nu_\mu \\ \mu \rightarrow \nu_\mu + \nu_e + e \end{array}\right] \frac{\nu_\mu}{\nu_e} \sim 2$

- K, π DECAYS

  $K \not\rightarrow \mu \nu_x$; $\pi \not\rightarrow \mu \nu_x$

- SOLAR NEUTRINOS

  MSW (MATTER OSCILLATIONS)



M_ν
GeV
MeV
keV
eV
meV
μeV
$\nu_e-\nu_\tau$
$\nu_\mu-\nu_\tau$
$\nu_\mu-\nu_e$
ATM.
SOLAR
$\sin^2 2\theta$
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
θ_{13}^q
θ_{23}^q
θ_{12}^q

SOLAR NEUTRINOS

① DAVIS $E > 0.81\ \text{MeV}$ $Cl^{37} \to A^{37}$

$$\frac{EXP}{SSM} = \frac{2.1 \pm 0.3}{8 \pm 3}$$

② KAMIOKANDE $E > 7.5\ \text{MeV}$ $\nu e \to \nu e$

$$\frac{EXP}{SSM} = 0.49 \pm 0.05$$

③ SAGE $E > 0.23\ \text{MeV}$ $Ga^{71} \to Ge^{71}$

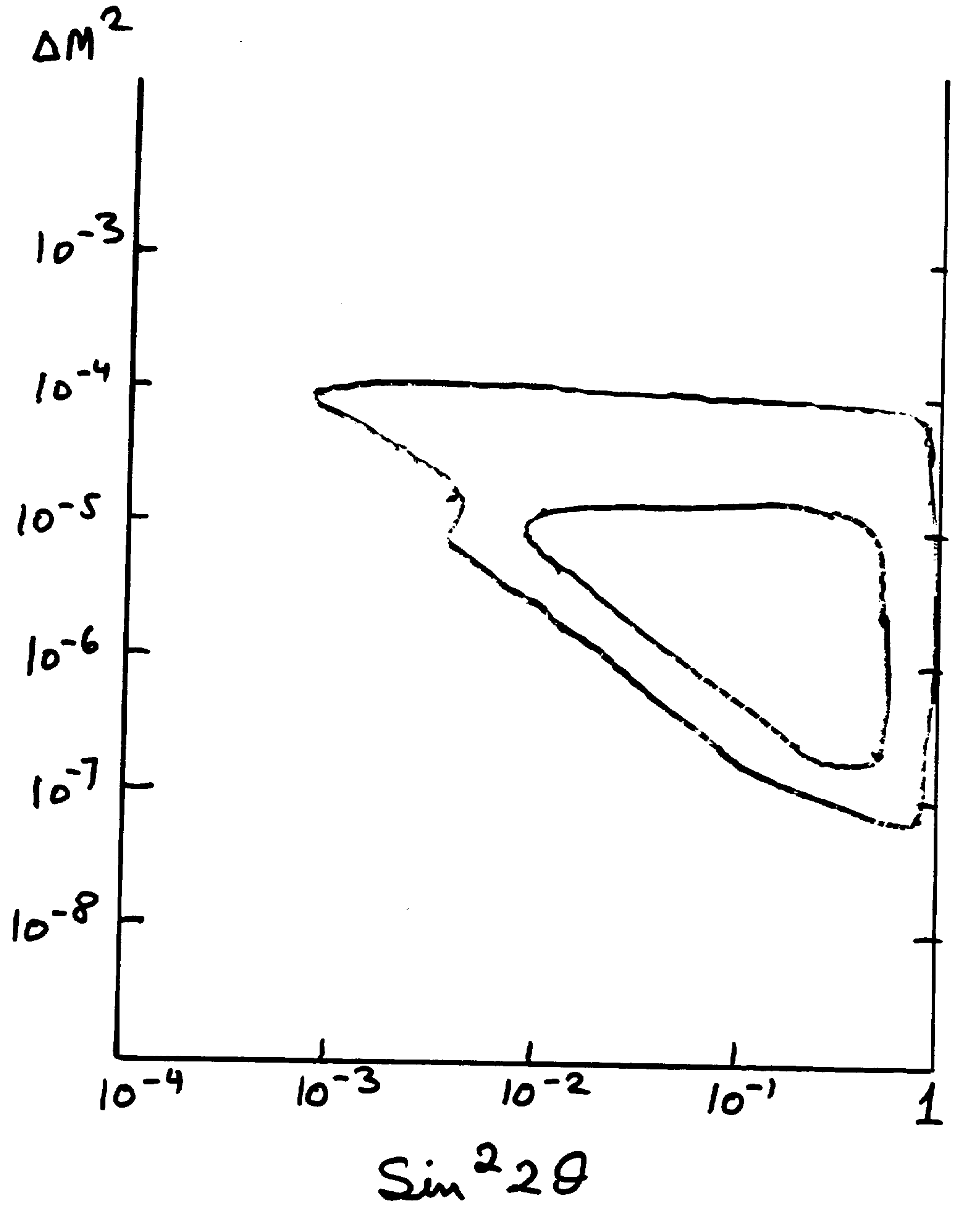
$$\frac{EXP}{SSM} \leq \frac{60 \pm 30}{130 \pm 20}$$ ['90+'91 DATA]

④ GALLEX $E > 0.23\ \text{MeV}$ $Ga^{71} \to Ge^{71}$

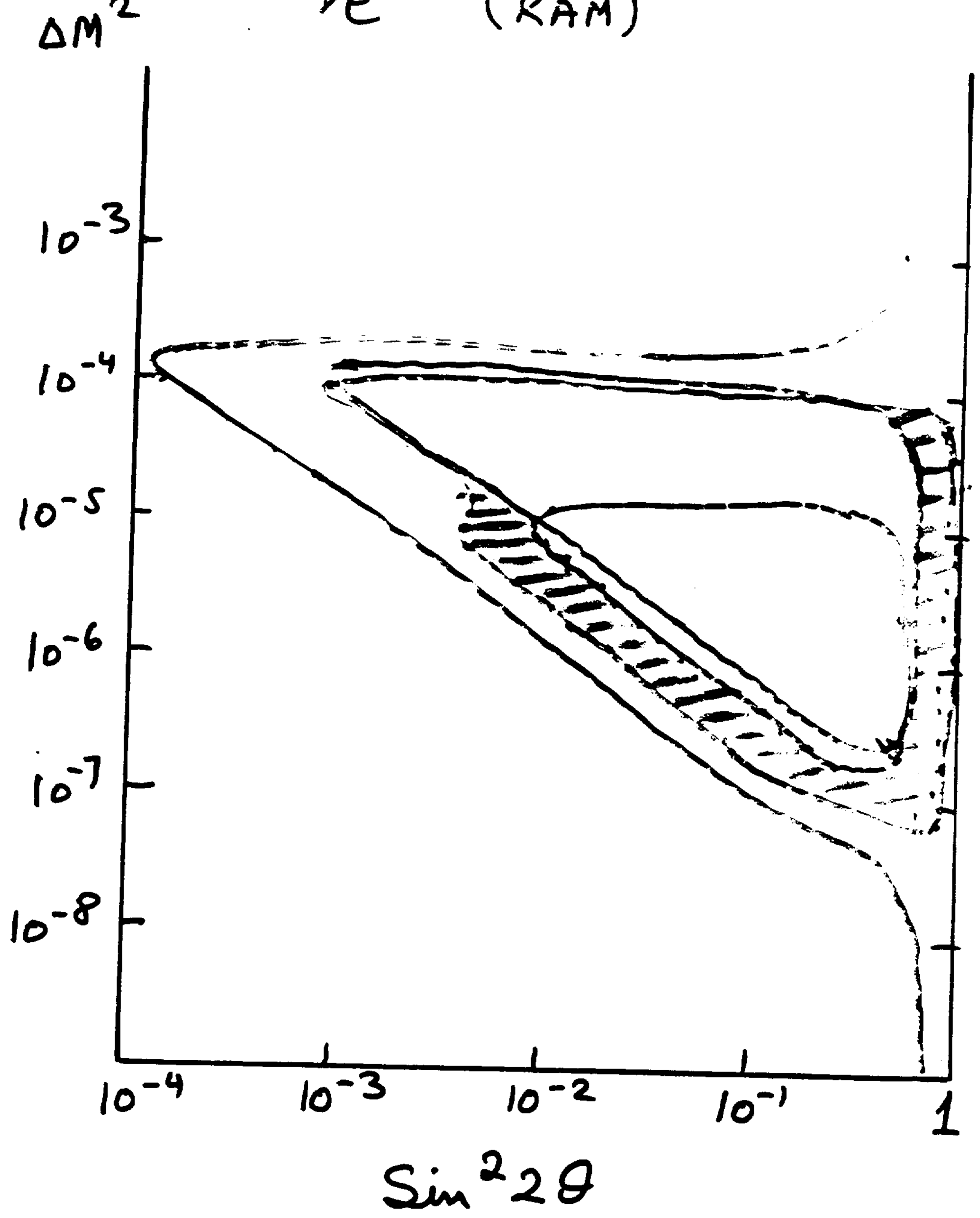
$$\frac{EXP}{SSM} = \frac{83 \pm 19 \pm 8}{130 \pm 20}$$

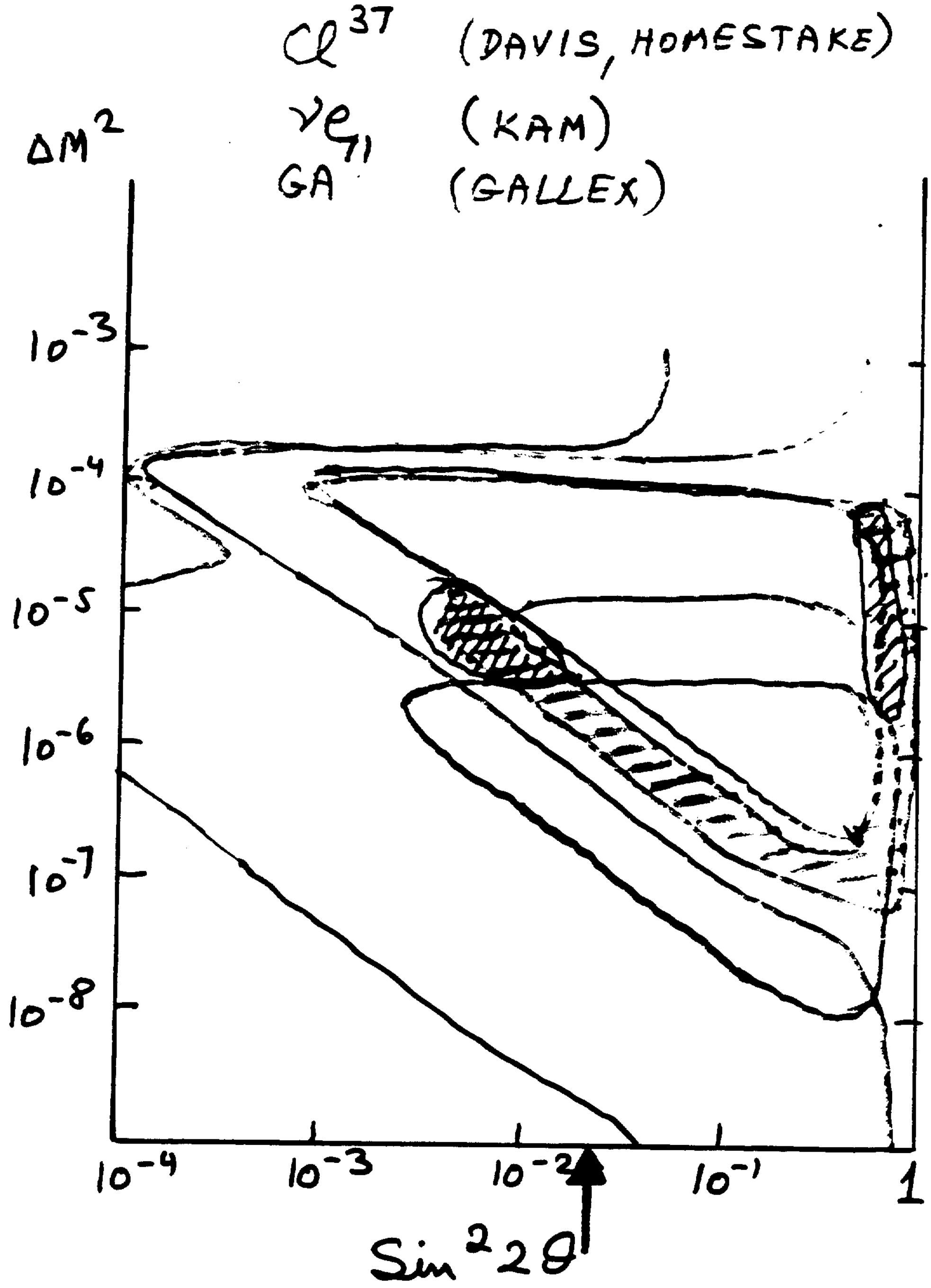
ADDITIONAL EXPERIMENTS.

Cl^{37} (DAVIS, HOMESTAKE)

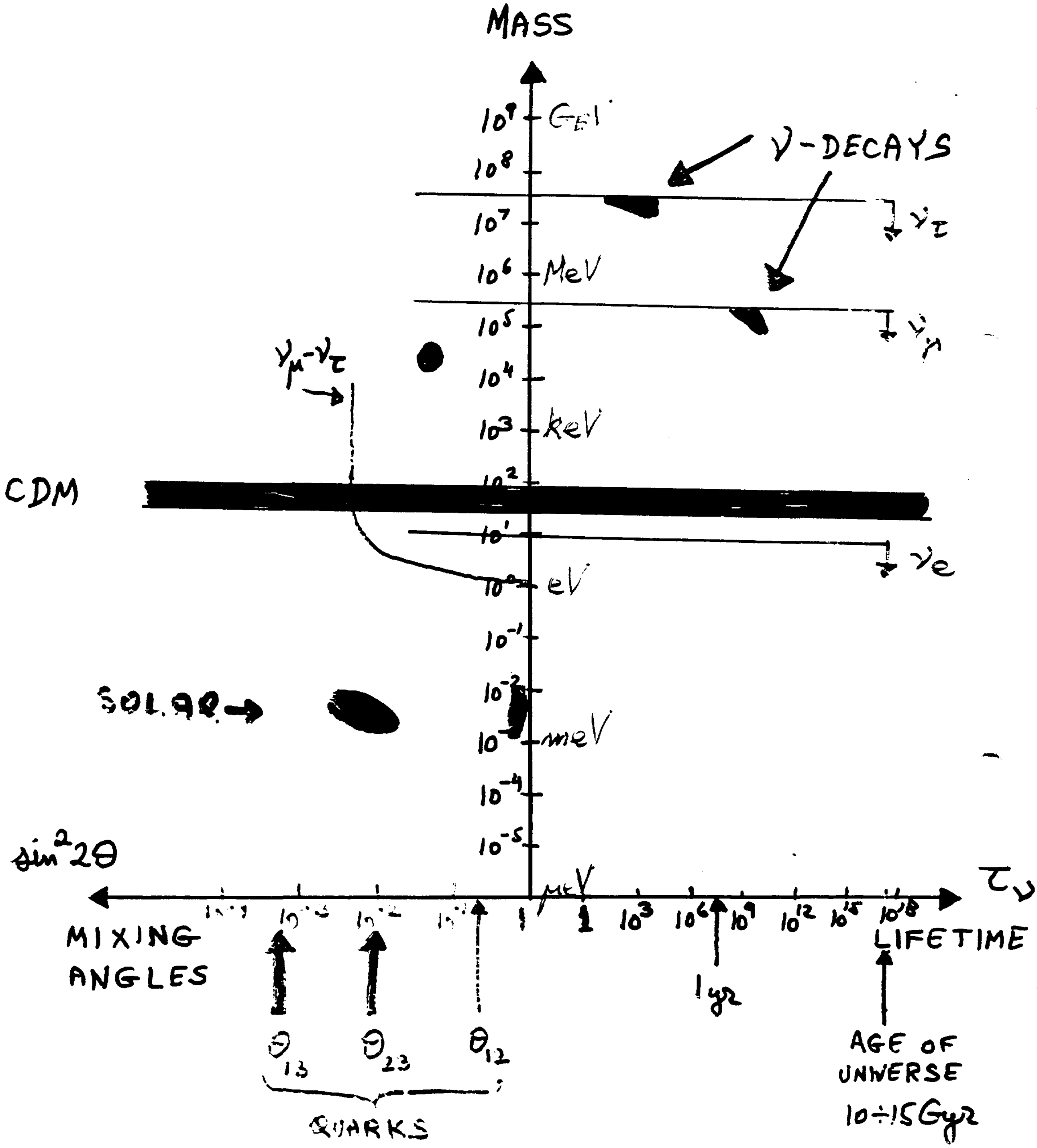


Cl^{37} (DAVIS, HOMESTAKE)
νe (KAM)





Cl^{37} (DAVIS, HOMESTAKE)
νe (KAM)
GA^{71} (GALLEX)
ΔM^2
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
$\sin^2 2\theta$


MASS
GeV
MeV
keV
eV
meV
μeV
ν-DECAYS
ν_τ
ν_μ
ν_e
ν_μ-ν_τ
CDM
SOLAR
$\sin^2 2\theta$
MIXING ANGLES
τ_ν
LIFETIME
θ_{13}
θ_{23}
θ_{12}
QUARKS
1 yr
AGE OF UNIVERSE
10÷15 Gyr

"SCENARIOS" FOR $m(\nu)$

1) $m(\nu_\tau) \sim O(10\ \text{MeV})$ — "NEUTRINOS AT THE LIMIT"

$m(\nu_\mu) \sim O(200\ \text{keV})$

$m(\nu_e) \sim O(\text{eV})$

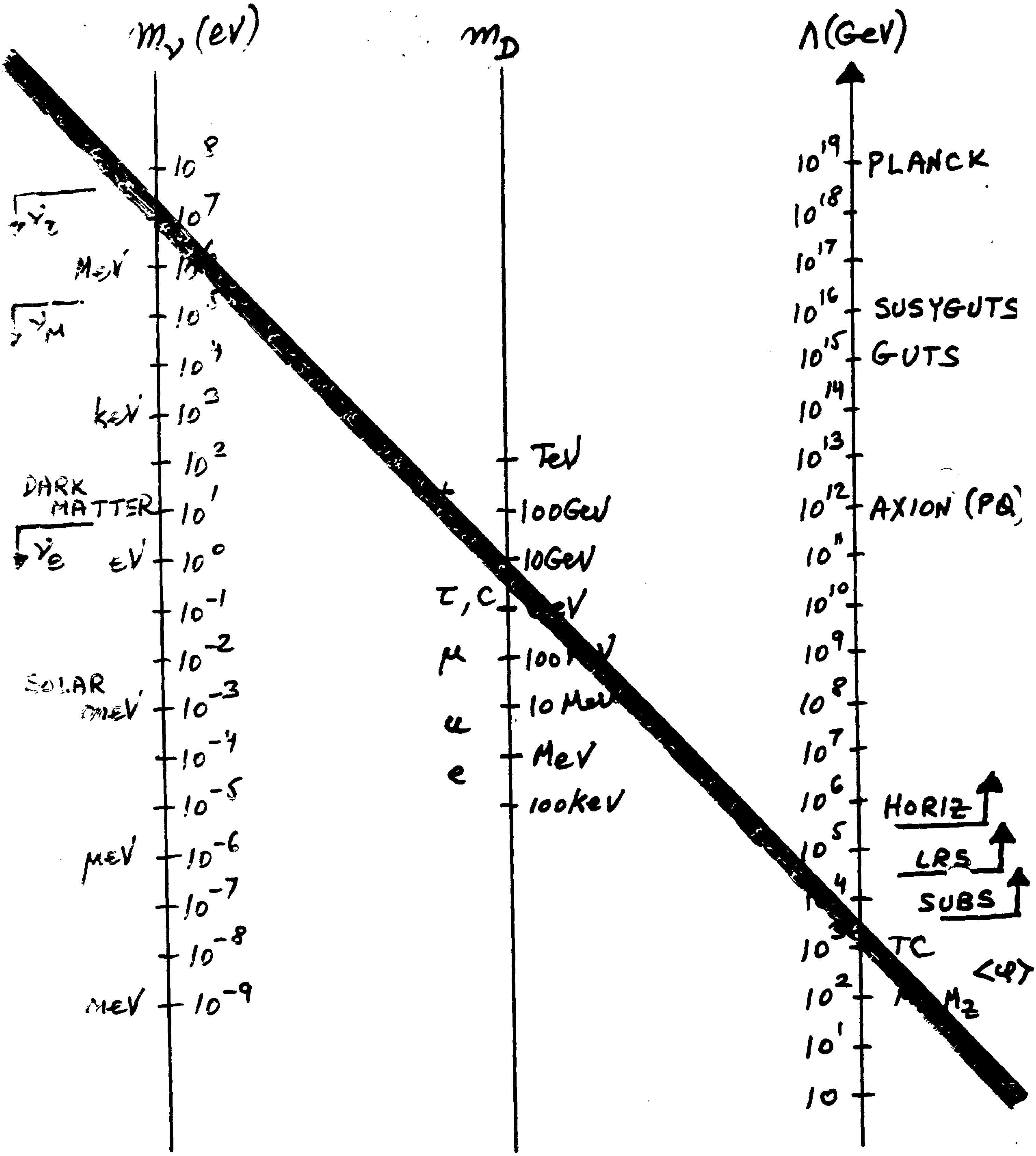
EXTREMELY UNLIKELY:

* IT REQUIRES NEW PHYSICS BELOW 100 GeV [$m(\nu_R) \sim O(50\ \text{GeV})$].
* A MAJORON.
* A "YOUNG" UNIVERSE (10–11 Gyr).
* AVOIDING THE PRIMORDIAL NUCLEOSYNTHESIS ARGUMENT.
* OTHER POTENTIAL DIFFICULTIES IN ASTROPHYSICS
* NO EXPLANATION FOR SOLAR ν

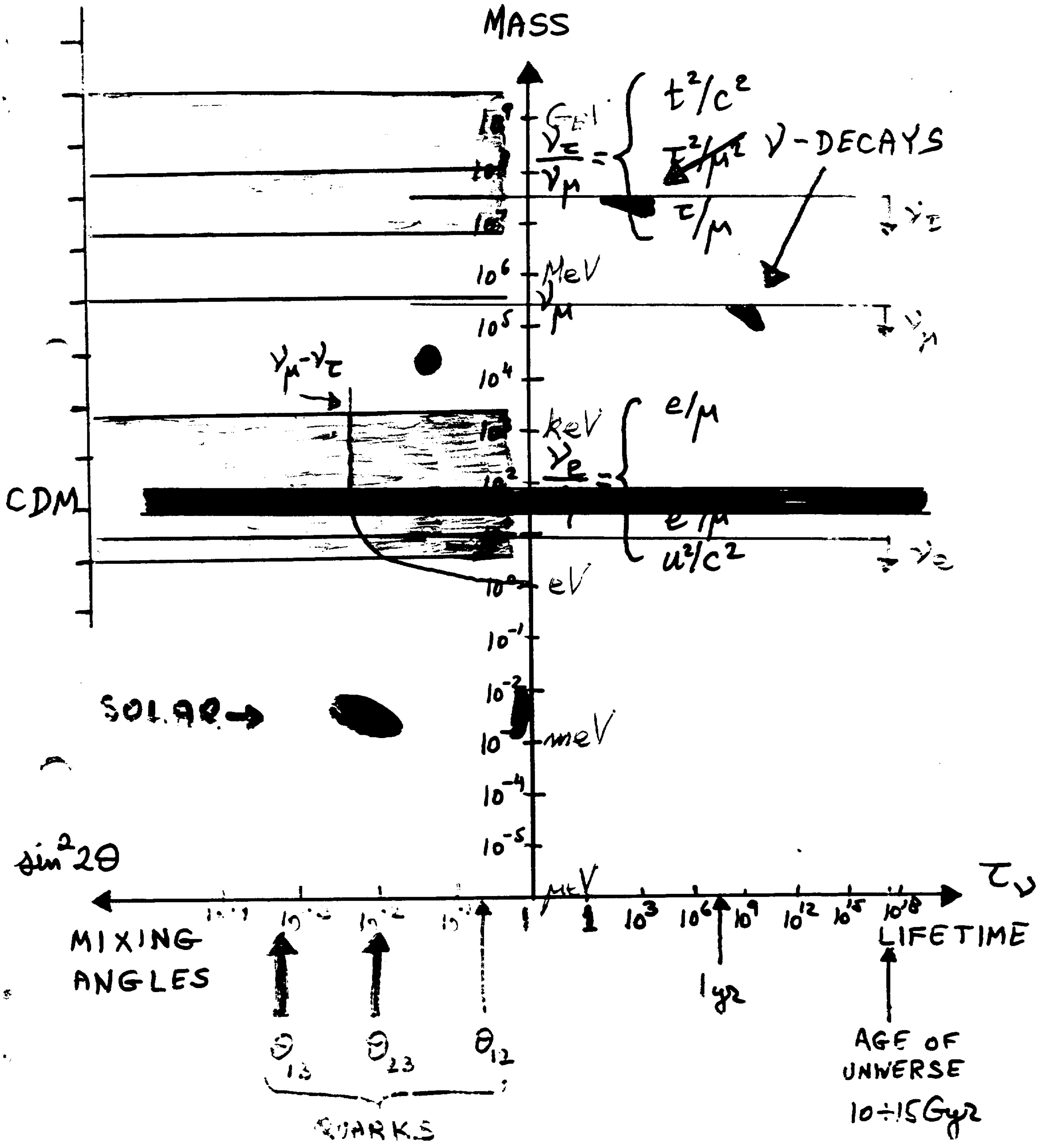
and – NO REDEEMING FEATURES!

BUT:
- DIRECT MEASUREMENTS OF MASS.
- NEUTRINOLESS DOUBLE BETA DECAY

ARE RELEVANT IN THIS CASE.



m_ν (eV)
m_D
Λ(GeV)
10^8
10^7
ν_τ
MeV
10^5
ν_μ
10^4
keV
10^3
10^2
DARK MATTER
10^1
ν_e
eV
10^0
10^{-1}
10^{-2}
SOLAR
meV
10^{-3}
10^{-4}
10^{-5}
μeV
10^{-6}
10^{-7}
10^{-8}
neV
10^{-9}
TeV
t
100GeV
10GeV
τ, c
μ
u
e
10 MeV
MeV
100keV
10^{19}
PLANCK
10^{18}
10^{17}
10^{16}
SUSYGUTS
10^{15}
GUTS
10^{14}
10^{13}
10^{12}
AXION (PQ)
10^{11}
10^{10}
10^9
10^8
10^7
10^6
HORIZ
10^5
LRS
SUBS
TC
$\langle\varphi\rangle$
10^2
M_Z
10^1
10


MASS
GeV
MeV
keV
eV
meV
μeV
t^2/c^2
τ/μ
ν-DECAYS
e/μ
u^2/c^2
CDM
ν_μ-ν_τ
SOLAR
$\sin^2 2\theta$
MIXING ANGLES
θ_{13}
θ_{23}
θ_{12}
QUARKS
τ_ν
LIFETIME
1 yr
AGE OF UNIVERSE
10÷15 Gyr

2) $m(\nu_\tau)$, $m(\nu_\mu)$ IN "NO MAN'S LAND" BETWEEN DIRECT LIMIT & 65 eV

FORBIDDEN BY COMBINATION OF COSMOLOGY & PARTICLE PHYSICS.

THE NOW DEFUNCT 17 keV NEUTRINO IS A GOOD EXAMPLE:

INCREDIBLE CONCOCTIONS, NEW PARTICLES & NEW PHENOMENA NEEDED TO "EXPLAIN IT".

IT WAS A GOOD LESSON!

③ $m(\nu_\tau) \sim O(20\,\text{eV})$

> ν_τ IS THE COSMOLOGICAL DARK MATTER!

	m_τ/m_μ	$(m_\tau/m_\mu)^2$	$(m_t/m_c)^2$
$\dfrac{m(\nu_\tau)}{m(\nu_\mu)} =$	20 ?	300 ?	10,000 ?
$m(\nu_\mu) \sim$	1 eV	10^{-1} eV	2×10^{-3} eV

2×10^{-3} eV ⟷ SOLAR-ν SOLUTION

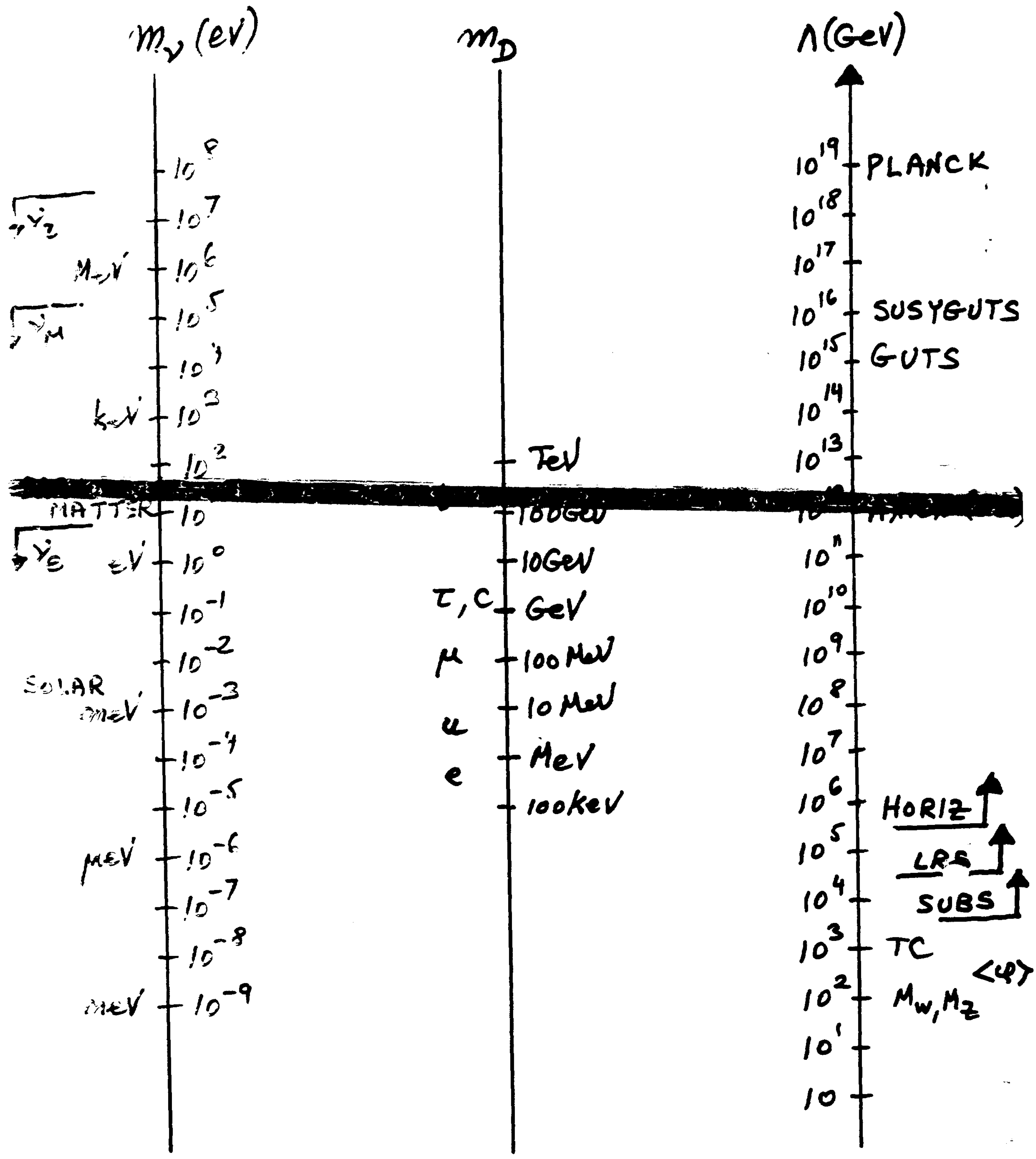
BUT:

* $\Lambda \sim O(10^{12}\,\text{GeV}) \ll \Lambda_{GUT}, \Lambda_{SUSYGUT}$

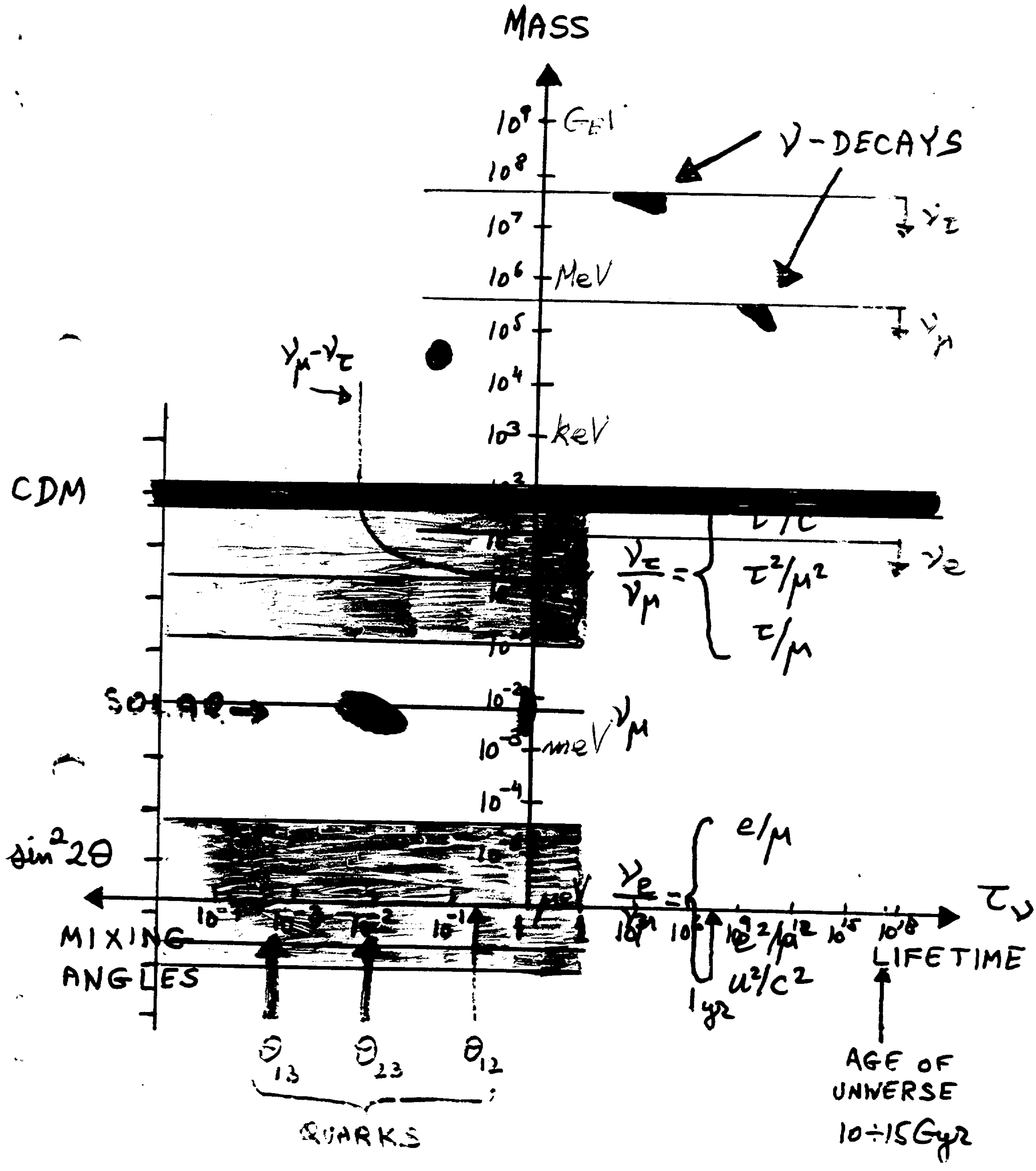
  [PERHAPS, BUT THEN WHY $\dfrac{m(\nu_\tau)}{m(\nu_\mu)} \sim \left(\dfrac{m_t}{m_c}\right)^2$?

* ATMOSPHERIC NEUTRINOS

THE FAVORITE !!!



m_ν (eV)
m_D
Λ(GeV)
10^8
10^7
ν_τ
MeV
10^6
10^5
ν_μ
10^4
keV
10^3
10^2
MATTER
10
ν_e
eV
10^0
10^{-1}
10^{-2}
SOLAR
meV
10^{-3}
10^{-4}
10^{-5}
μeV
10^{-6}
10^{-7}
10^{-8}
meV
10^{-9}
TeV
10GeV
τ, c
GeV
μ
100 MeV
10 MeV
u
MeV
e
100keV
10^{19}
PLANCK
10^{18}
10^{17}
10^{16}
SUSYGUTS
10^{15}
GUTS
10^{14}
10^{13}
10^{11}
10^{10}
10^9
10^8
10^7
10^6
HORIZ
10^5
LRS
10^4
SUBS
10^3
TC
$\langle\varphi\rangle$
10^2
M_W, M_Z
10^1
10


MASS
GeV
MeV
keV
meV
ν-DECAYS
ν_μ-ν_τ
CDM
SOLAR
$\sin^2 2\theta$
MIXING ANGLES
$\frac{\nu_\tau}{\nu_\mu} = \tau/c$, τ^2/μ^2, τ/μ
$\frac{\nu_e}{\nu_\mu} = e/\mu$, u^2/c^2
τ_ν
LIFETIME
1 yr
θ_{13} θ_{23} θ_{12}
QUARKS
AGE OF UNIVERSE 10÷15 Gyr

4. $m(\nu_\mu) \sim O(0.003\ \mathrm{eV})$

ACCOMODATING SOLAR ν.

$$20\, m(\nu_\mu) \sim 0.06\ \mathrm{eV}$$
$$m(\nu_\tau) \sim 350\, m(\nu_\mu) \sim 1\ \mathrm{eV}$$
$$10^4\, m(\nu_\mu) \sim \text{DARK MATTER}$$

5. $m(\nu_\tau) \sim O(0.003\ \mathrm{eV})$

ACCOMODATING SOLAR ν

* BUT THEN $\nu_e - \nu_\tau$ MIXING IS QUITE LARGE.
* ν_μ, ν_e MUCH LIGHTER.
* $\Lambda \sim O(10^{16}\ \mathrm{GeV})$ for $m(\nu_\tau) \sim \frac{m_t^2}{\Lambda}$

6. ALL THREE NEUTRINOS ARE LIGHTER THAN 10^{-3} eV

UNLIKELY, UNNECESSARY, UNWANTED.

THE FAVORITE

$m(\nu_\tau) \sim 20\, eV$ — ✱ COSMOLOGICAL DM ✱ AVAILABLE FOR $\nu_\mu - \nu_\tau$ OSCILLATIONS.

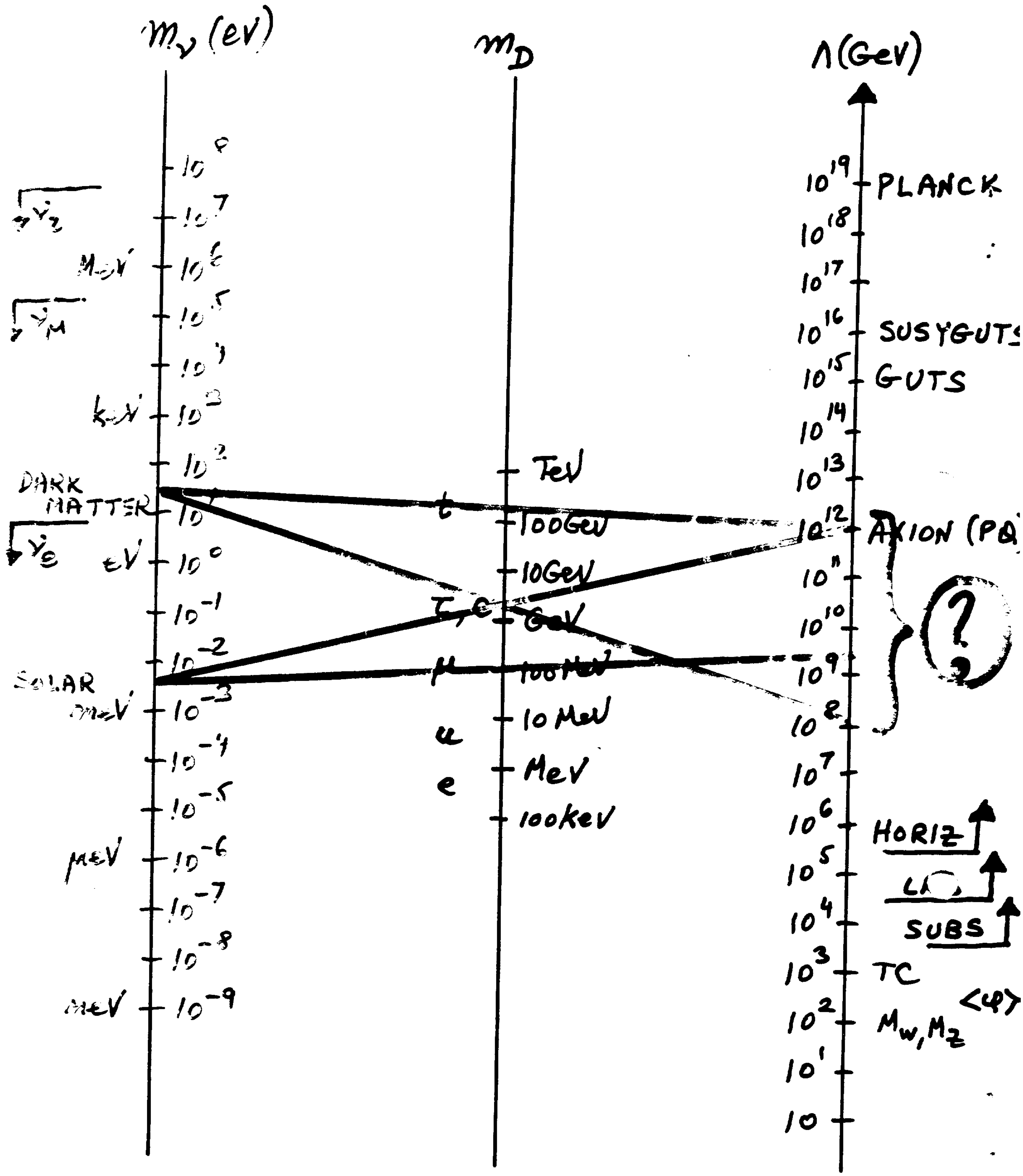
$m(\nu_\mu) \sim$ few meV — ✱ EXPLAINING SOLAR ν

$m(\nu_e) \sim$ perhaps $10^{-8}\, eV$ — ✱ TOO SMALL FOR ANYTHING

$\sin^2 2\theta_{e\mu} \sim 10^{-2}$ — ✱ FROM SOLAR ν; RELATED TO $\sqrt{\frac{m_e}{m_\mu}}$ (!)

$\sin^2 2\theta_{\mu\tau} \sim 10^{-3}$?? — ✱ WISHFUL THINKING ✱ SIMILAR TO θ_{23}? ✱ ACCESSIBLE TO $\nu_\mu - \nu_\tau$ OSCILLATIONS.

[ACCELERATOR → DARK MATTER
SUN → $m(\nu_\mu)$, $\theta_{e\mu}$!]



m_ν (eV)
m_D
Λ (GeV)
10^8
10^7
MeV
10^6
10^5
10^4
keV
10^3
10^2
DARK MATTER
10^1
eV
10^0
10^{-1}
10^{-2}
SOLAR
meV
10^{-3}
10^{-4}
10^{-5}
μeV
10^{-6}
10^{-7}
10^{-8}
neV
10^{-9}
TeV
t
100GeV
10GeV
τ, c
GeV
μ
100MeV
10 MeV
u
e
MeV
100keV
10^{19}
PLANCK
10^{18}
10^{17}
10^{16}
SUSYGUTS
10^{15}
GUTS
10^{14}
10^{13}
10^{12}
AXION (PQ
10^{11}
10^{10}
10^9
10^8
?
10^7
10^6
HORIZ
10^5
10^4
SUBS
10^3
TC
10^2
M_W, M_Z
<φ>
10^1
10

EXPERIMENTS

1 GENERAL

- IMPROVE DIRECT LIMITS ON $m(\nu_i)$
- MEASURE RELATED DECAYS ($\mu \to 3e$ etc).
- IMPROVE KNOWLEDGE OF Ω, h, t_0
- ν-LESS DOUBLE β-DECAY
- MORE ACCURATE $\nu_\mu - \nu_e$ OSCILLATION
- RECHECK ATMOSPHERIC ν EXPERIMENT
- SEARCH FOR OTHER D.M. CANDIDATES

2 SPECIFIC TO "FAVORITE SCENARIO"

- $\nu_\mu - \nu_\tau$ OSCILLATIONS
- MORE SOLAR EXPERIMENTS
- LONG BASELINE OSCILLATIONS

SEARCHING FOR DARK MATTER

- THE <u>ONLY</u> DARK MATTER CANDIDATE WHICH <u>SURELY</u> EXISTS IS ν.

- THE HEAVIEST NEUTRINO IS $\underline{\nu_\tau}$

- IF ν_τ IS C.D.M., $m(\nu_\tau) \sim \underline{20\ \text{eV}}$

- THE ONLY WAY TO PROBE $m(\nu_\tau) \sim 20\,\text{eV}$ IS <u>OSCILLATIONS</u>.

- $\underline{\nu_\mu}$ IS MORE ACCESSIBLE THAN ν_e AND $\underline{\theta_{\tau\mu}}$ IS LIKELY TO BE LARGER THAN $\theta_{\tau e}$

- HENCE: THE <u>BEST</u> WAY TO SEARCH FOR COSMOLOGICAL DARK MATTER IS TO LOOK FOR <u>$\nu_\mu - \nu_\tau$ OSCILLATIONS</u> IN AN <u>ACCELERATOR</u> EXPERIMENT.

- <u>IMPROVE ON $\theta_{\tau\mu}$</u>, NOT ON $m(\nu_\tau)$!

$\nu_\mu - \nu_\tau$ OSCILLATIONS

SIGNAL: $\nu_\mu \xrightarrow[\text{OSC}]{} \nu_\tau \rightarrow \tau \rightarrow \begin{cases} \mu \\ e \\ \text{HAD} \end{cases}$

NOISE: $\nu_\mu \rightarrow \begin{cases} \mu \\ \text{HAD} \end{cases}$

BACKGROUND: τ FROM DIRECT SOURCES (D_s)

NEED $O(10^5)$ ν-EVENTS

WHAT WEIGHS A TON AND HAS A RESOLUTION OF 10 μm ?

(FERMILAB E531)

ONLY GOOD OLD **EMULSION**

HENCE: CHORUS (94-95)

ALSO NOMAD.

THEORETICAL ISSUES

* UNDERSTAND THE SCALE Λ
* STUDY MASS-ANGLE RELATIONS
* UNDERSTAND LARGE SCALE STRUCTURE

EXPERIMENTAL ISSUES

"NEW FRONTIER"

* $\nu_\mu - \nu_\tau$ OSCILLATIONS
* SOLAR
* ATMOSPHERIC
* LONG BASE-LINE

"OLD FRONTIER"

* DIRECT MEASUREMENTS
* ν-LESS 2-β DECAY
* "STANDARD $\nu_\mu - \nu_e$ OSC."

ν-PHYSICS IS POSSIBLY THE BEST PLACE TO OBSERVE "BEYOND STANDARD" PHYSICS AND TO CONNECT $\begin{Bmatrix} \text{PARTICLES} \\ \text{COSMOLOGY} \end{Bmatrix}$