Hunting the tachyon
and finding three unicorns and a herd of elephants

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“Speeds greater than light have no possibility of existence”

1905

But he only ruled out FTL Speeds for particles initially having sub-light speed

1962
Dependence of energy on speed

\[ E = \frac{mc^2}{\sqrt{1-v^2/c^2}} \]

Energy vs speed

- \( E/m \)
- \( m^2 > 0 \)
- \( m^2 < 0 \)
- \( m = 0 \)

Imaginary mass means that they speed up as they lose energy.

Why only neutrons might be tachyons?

No neutrinos ever observed with \( v < c \) or \( m^2 > 0 \).
Conventional view of neutrino mass states

Absolute scale unknown

normal hierarchy (NH)

\[ m^2 \]

\[ \Delta m_{\text{atm}}^2 = 2.32 \times 10^{-3} \text{ eV}^2 \]

\[ \Delta m_{\text{sol}}^2 = 7.59 \times 10^{-5} \text{ eV}^2 \]

3 nearly equal masses & same for inverted hierarchy

What is the basis for this conventional view?
Origin of 3 + 3 Model

based on neutrinos from SN 1987A

First noted in 1987 (Huzita) & 1988 (Cowsik)
Neutrino “burst” from SN 1987A

Of $10^{58}$ neutrinos emitted 25 were detected:

Kamiokande II 12
IMB 8
BAKSAN 5

Also: Mont Blanc detector saw 5 events (*almost 5 hr early*) usually ignored
12 event neutrino burst
in Kamiokande detector on Feb 24, 1987

publication included 7 other such plots from the same day

$E_{\text{vis}} = 8 \text{ MeV}$
Finding the neutrino mass from SN 1987A

Standard approach: Assume nearly equal m’s & get only an upper limit $m < 5.7$ eV.$^1$

My 2012 analysis$^2$: Remain agnostic on whether masses nearly equal and assume emissions are nearly simultaneous.

This assumption allows you to find masses of individual neutrinos based on their arrival times (using $E$ & $t$)

$^1$Loredo and Lamb, Phys. Rev. D65 (2002) 063002

$^2$R. Cowsik, Phys. Rev. D 37, 16851687 (1988);
Finding neutrino mass for simultaneous emissions

\[ \Delta t = t - T \]

- Leads light
- Lags light

\[ \frac{1}{E^2} = \frac{2}{Tm^2} \Delta t \]

Slope

\( T \) is light travel time

\( t \) is neutrino travel time

\( m^2 < 0 \)

\( \frac{1}{E^2} \)
25 Neutrinos from SN 1987A fits 2 m’s
(Ignore 5 from Mont Blanc for now)

\[ \frac{1}{E^2} = \frac{2}{Tm^2} \Delta t \]

- \( m_1 = 4.0 \pm 0.5 \text{ eV} \)
- \( m_2 = 21.4 \pm 1.2 \text{ eV} \)

Conclusions

The 25 neutrinos all cluster about 2 specific masses 4.0 eV & 21.4 eV

Inconsistent with conventional neutrino mass hierarchy

Not the only reason why conventional neutrino model is suspect
3 + 3 Model: 3 active-sterile doublets

$21.4^2 \text{eV}^2$

$m^2 > 0$

$4.0^2 \text{eV}^2$

Identical fractional splitting

$\Delta m^2 / m^2 = 5.0 \times 10^{-6}$

A 3\textsuperscript{rd} doublet having $m^2 < 0$ is needed to keep the effective flavor state masses small

Effective flavor state mass

$$m^2_i = \sum |U_{i,j}|^2 m^2_j$$
Other evidence for 3 + 3 model masses

Sterile neutrinos are a good candidate for dark matter
Why dark matter in galaxy?
Find neutrino mass by fit to DM radial profile

(1) Deduce "observed" dark matter halo profile from rotation curve

(2) Derive Equation of state for slightly degenerate neutrinos

\[ P(r) = n(r)kT_s + \frac{n^2(r)h^3}{16\pi^{3/2}g_s\left(m_\text{s}kT_s\right)^{-3/2}\left(kT_s\right)^{-1/2}}. \]

(3) Set neutrino mass density \( n(r) \) at \( r = 0 \) to "observed" value & integrate outward using Eq. for hydrostatic equilibrium in order to find \( M(r) \):

\[ \frac{dP(r)}{dr} = -\frac{Gm_\text{s}M(r)n(r)}{r^2}, \quad M(r) = M_D(r) + M_B(r) \]

(4) Find \( v(r) = \left(2GM(r)/r\right)^{1/2} \)

Observed and fitted rotation curve for Milky Way with $m = 21.4 \pm 1.2$ eV neutrinos

Clusters of galaxies

Properties:
The largest known gravitationally-bound structures containing 100 to 1,000 galaxies (only 1% of total mass)
- the rest: hot gas (9%) and dark matter (90%)

Dark matter fits:
Can infer DM profile from v of individual galaxies using the Virial Theorem
Only measure v along line of sight
Observed and fitted mass profiles for 4 clusters of galaxies with $m = 4.0 \pm 0.5$ eV neutrinos

**Observed uncertainty** (Error bars) due to limited numbers of galaxies in cluster

**Uncertainty in fitted profiles** (Dotted curves) for +/- 1 sigma in neutrino mass
What about the $m^2 < 0$ mass?

Five early neutrinos seen in the Mont Blanc detector

\[
\frac{1}{E^2} = \frac{2}{Tm^2} \Delta t
\]

Just solve for $m^2$

\[
m^2 \sim -0.36 \text{keV}^2
\]

Within a factor of two of the $3 + 3$ mass value. Also 5 neutrinos consistent with having the same energy.
Suppose the 5 Mont Blanc neutrinos have $m^2 < 0$

Requires an 8 MeV spectral line???

\[ \frac{\Delta E}{E} = 0.02\% \]

\[ \frac{1}{E^2} = \frac{2}{Tm^2}\Delta t \]

The 5 Mont Blanc neutrinos are in fact consistent with having the same energy!
How to get monochromatic 8 MeV SN neutrinos?
Assume DM X-particles in stellar core

X \rightarrow Z' \text{ mediated reaction} \rightarrow \text{ monochromatic } \sim 8 \text{ MeV neutrinos & e}^+ \text{ e}^- \text{ pairs}

X = \text{COLD dark matter particles of mass 8.4 MeV}

Z' = 16.7 \pm 0.6 \text{ MeV boson}
Krasznahorkay (2016)

Test of this model: Wait for next supernova?

Maybe 8.4 MeV dark matter X particles also exists near galactic center

Impact on spectrum of galactic center gamma rays
Gamma ray spectrum from GC

Enhancements above a power law are shown for 3 dark matter masses of 5, 10 & 50 MeV.

Fit yields $M_x = 10^{+5/-2}$ MeV. Validates the Z’ mediated reaction.
Recall the main idea here:

Mont Blanc neutrinos were tachyons → An 8 MeV neutrino line from SN 1987A

Shouldn’t we also see an 8 MeV spectral line for the $m > 0$ neutrinos?

Might an 8 MeV neutrino line be hiding in plain sight in the SN 1987A data?

Recall the 7 extra data plots from Kamiokande (~1000 events over 136 min)
Difficulty of spotting a neutrino line

Not like spotting visible spectral lines. Any neutrino line will be considerably broadened.

Need large enough amplitude or it will fade into the background.

Need a line many times taller than one at 8 MeV to get this.
Spotting the hidden 8 MeV line
In Kamiokande data

But very suspicious that line occurs at the peak of the background!

Kamiokande data on day of SN 1987A – total of 136 min
Bkgd is from a search for solar neutrinos some months later

Solid: assumes same bkgd, dashed: corrected for different triggers

Ehrlich (2018)
The 3 unicorns?

- Mont Blanc neutrinos are tachyons
- 8 MeV mass dark matter particles
- 8 MeV neutrino line

Unicorn definition

1. a mythical animal with a single straight horn.
2. something that is highly desirable but difficult to find.
Usual assumption of only a single effective mass. The value of the neutrino mass affects mainly the very end of the spectrum, where there are only a minute fraction of all decays.

Wouldn’t 3 + 3 masses be seen in Lab experiments?

\[ ^3\text{H} \rightarrow ^3\text{He} + e^- + \bar{\nu}_e \]

half life: \( t_{1/2} = 12.32 \text{ a} \)

\( \beta \) end point energy: \( E_0 = 18.57 \text{ keV} \)

entire spectrum

region close to \( \beta \) end point

rel. rate [a.u.]

only 2 \times 10^{-13} of all decays in last 1 eV

\( m(\nu_e) = 0 \text{ eV} \)

\( m(\nu_e) = 1 \text{ eV} \)
Determination of $m^2$ from spectrum shape

Fit the region of the spectrum near $E_0$, using 4 free parameters:

- Neutrino mass squared
- Endpoint energy
- Signal amplitude
- Background amplitude

John von Neumann famous quote about fitting data using four free parameters:

“With four parameters I can fit an elephant, and with five I can make him wiggle his trunk.”
KATRIN Experiment

Should be a factor of ten improvement on previous results

Started taking data in 2019 & published initial results then
KATRIN 2019 results: Fit to spectrum using 4 free parameters

\[
m^2_\nu = (-1.0^{+0.9}_{-1.1}) \text{ eV}^2
\]

First results from KATRIN in 2019 fit the 3 + 3 model better than a single mass
The “herd of elephants”

KATRIN 2021 results

From their paper:

In addition to the neutrino mass squared, $m_{
u}^2$, the parameters $A_s(r_j)$, $R_{bg}(r_j)$, and the effective endpoint $E_0(r_j)$ are treated as independent parameters for the 12 detector rings, leading to a total number of free parameters of $1 + 3 \times 12 = 37$ in the fit. The introduction of ring-dependent parameters was chosen to allow for possible unaccounted radial effects. In particular, the effective

“Don’t worry guys. With 37 free parameters the hunters will never spot us.”
Questions about KATRIN’s results

Why did KATRIN fit their 2019 initial spectrum using four free parameters, but then resort to 37 free parameters for their 2021 data?

What were those 37 parameters?

Might they have first done a four free parameter fit & found it a very poor one?

Was it a poor fit because of two “bumps” like 3 + 3 model predicts?
FTL particles OK if mass imaginary or $m^2 < 0$: Sudarshan (1962)

Neutrinos are the only candidates among known particles: Chodos (1985)

3+3 model of neutrino masses from SN 1987A: Ehrlich (2013)

Many separate data sets support the 3+3 model: Ehrlich (2018)

1st KATRIN results (2019) -- neutrino $m < 1$ eV (a four free parameter fit); they also fit $3 + 3$ model. Ehrlich (2019]

2021 KATRIN results do their fit with 37 free parameters “the herd of elephants” → $3 + 3$ still lives. Ehrlich(2021)
New book expected in 2022

Hunting the Faster-than-light Tachyon: Finding three unicorns and a herd of elephants

CRC Press, Taylor & Francis Group

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