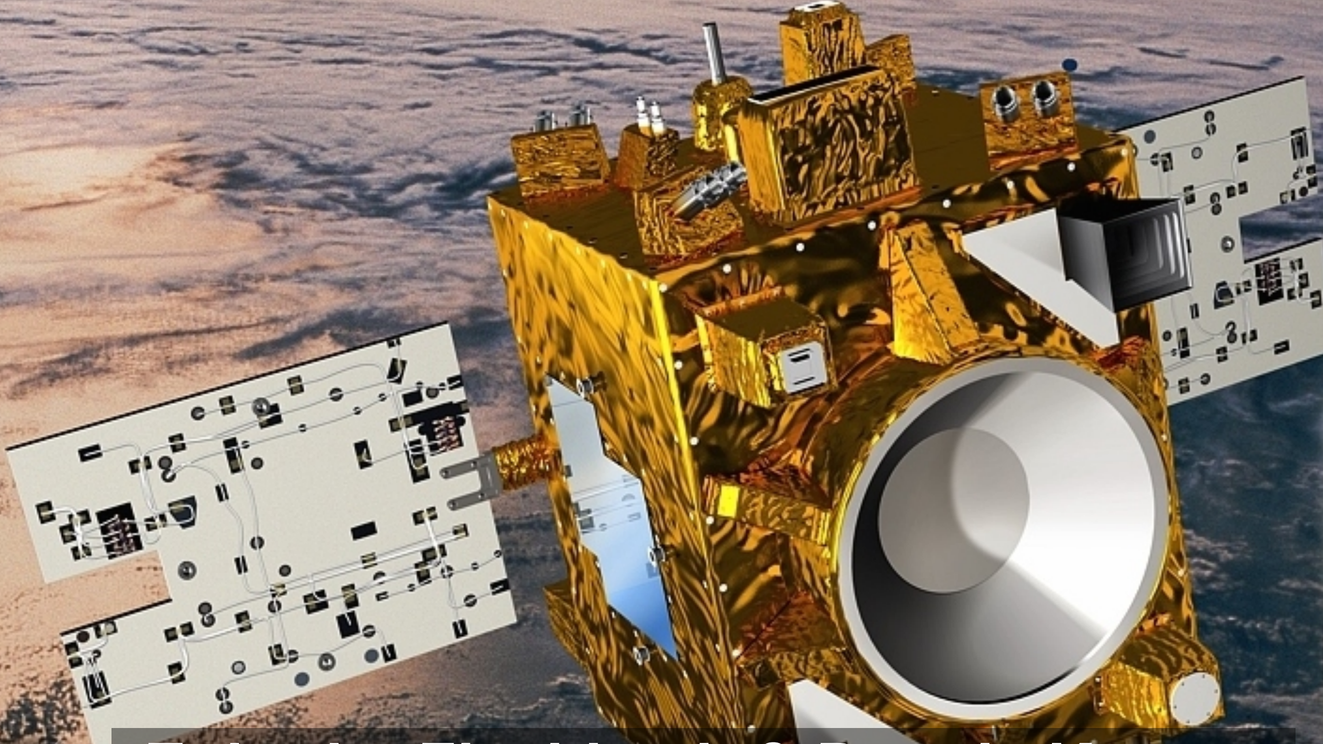
MICROSCOPE as a Test of Lorentz Invariance and Neutrino Physics



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Motivation

- We live an ambiance of neutrinos from both relic neutrinos and the sun which, in some sense, defines a preferred frame.
- Anomalies in radioactive decays suggest that solar neutrinos and, perhaps, relic neutrinos may be interacting with matter in novel ways.
- If this preferred frame interacts with MICROSCOPE test masses, then the connection between violation of Lorentz invariance and violation of WEP might suggest that MICROSCOPE could detect could detect the violation of WEP.
- If periodic signals are observed in MICROSCOPE, they may be different from those expected if the source of the anomalies was the Earth.

Outline

Lorentz Non-Invariance and Eötvös-type Experiments:

- Nielsen-Picek Model of LNI
- LNI contributions to inertial mass and WEP violation
- Limits from Eötvös-type Experiments
- SME Model of WEP Violation

Lorentz Non-Invariance in the Neutrino sector:

- 2-Neutrino exchange interaction
- Neutrino Contribution to rest energy

Implications for Neutrino Masses

Lorentz Non-Invariance and Eötvös-type Experiments

LNI Model of Nielsen and Picek

Low-energy Z^0 or W-boson propagator: $\boxed{D_{\mu\nu}(x-y) = \frac{-ig_{\mu\nu}}{m_{W,Z}^2}\delta(x-y)}$

$$x^\mu = (\vec{x}, x_4 \equiv icx^0) \qquad g_{\mu\nu} = \delta_{\mu\nu}$$

$$g_{\mu\nu} \to g_{\mu\nu} + \chi_{\mu\nu} \qquad\qquad \chi_{\mu\nu} = \alpha\begin{pmatrix} \frac{1}{3} & & & \\ & \frac{1}{3} & & \\ & & \frac{1}{3} & \\ & & & -1 \end{pmatrix}$$

where the form of $\chi_{\mu\nu}$ is determined by Hermiticity, tracelessness, and rotational invariance

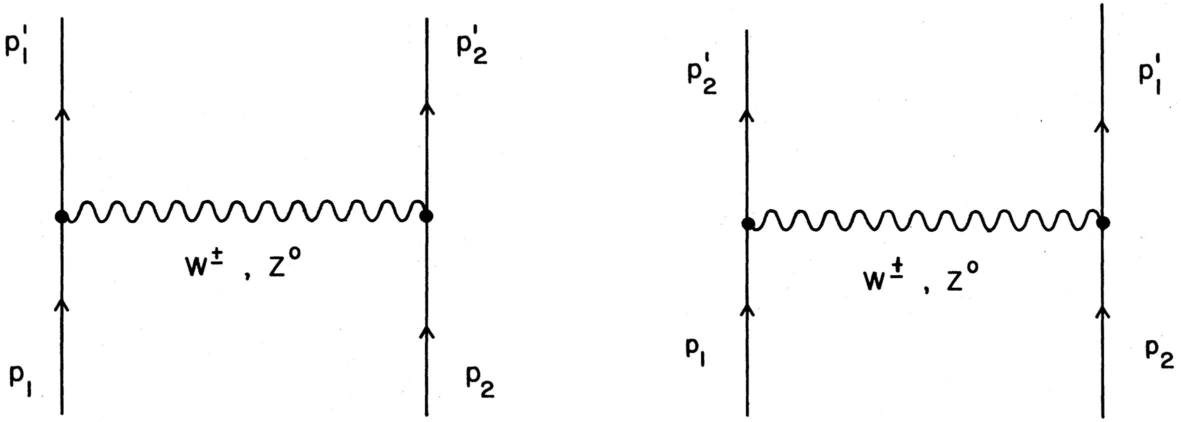
Relative to the preferred frame (CBR):

$$-g_{\mu\nu}p^\mu p^\nu = m^2 \to m^2 - \chi_{\mu\nu}p^\mu p^\nu = m^2 - \alpha\left(\tfrac{1}{3}\vec{p}^{\,2} + p_0^2\right)$$

H. B. Nielsen and I. Picek, Phys. Lett. **114B**, 141 (1982); Nucl. Phys. **B211**, 269 (1983)

LNI Model of Nielsen and Picek

Contributions to parity-conserving amplitude for nucleon-nucleon scattering



$$\mathcal{H}_{\text{eff}}(x) = \frac{G_F}{\sqrt{2}} J_\mu^\dagger(x)(\delta_{\mu\nu} + \chi_{\mu\nu})J_\nu(x) + \text{H.c.}$$

$$J_\mu(x) = i\overline{p}(x)\gamma_\mu(1+\gamma_5)n(x)$$

Using these expressions, the weak-interaction contribution to a test body's inertial mass can be calculated

LNI Model and WEP

Total inertial mass:

$$M(Z,N) = \bar{M}_0 + M_w = \bar{M}_0 + A_w + \alpha B_w\left(1 + \tfrac{4}{3}\vec{v}^{\,2}\right)$$

A_w = LI weak-contribution to inertial mass

B_w = LNI weak-contribution to inertial mass

Total conserved energy of a test mass in a gravitational field:

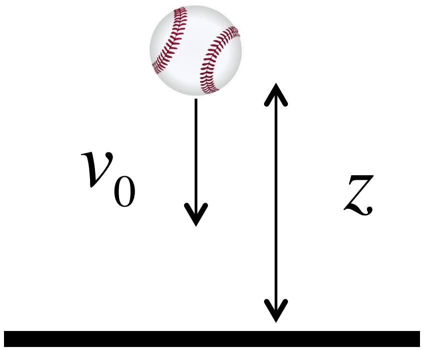
$$E = M + \tfrac{1}{2}M\vec{v}^{\,2} + M'gz$$

$$\cong M_0 + \tfrac{1}{2}M_0\vec{v}^{\,2} + \alpha B_w\left(1 + \tfrac{11}{6}\vec{v}^{\,2}\right) + M'gz$$

$M_0 = \bar{M}_0 + A_w$ = Lorentz invariant inertial mass

M' = Passive gravitational mass

LNI Model of WEP Violation



Energy conservation and

$$\vec{v}=\vec{v}_0+\vec{a}t$$

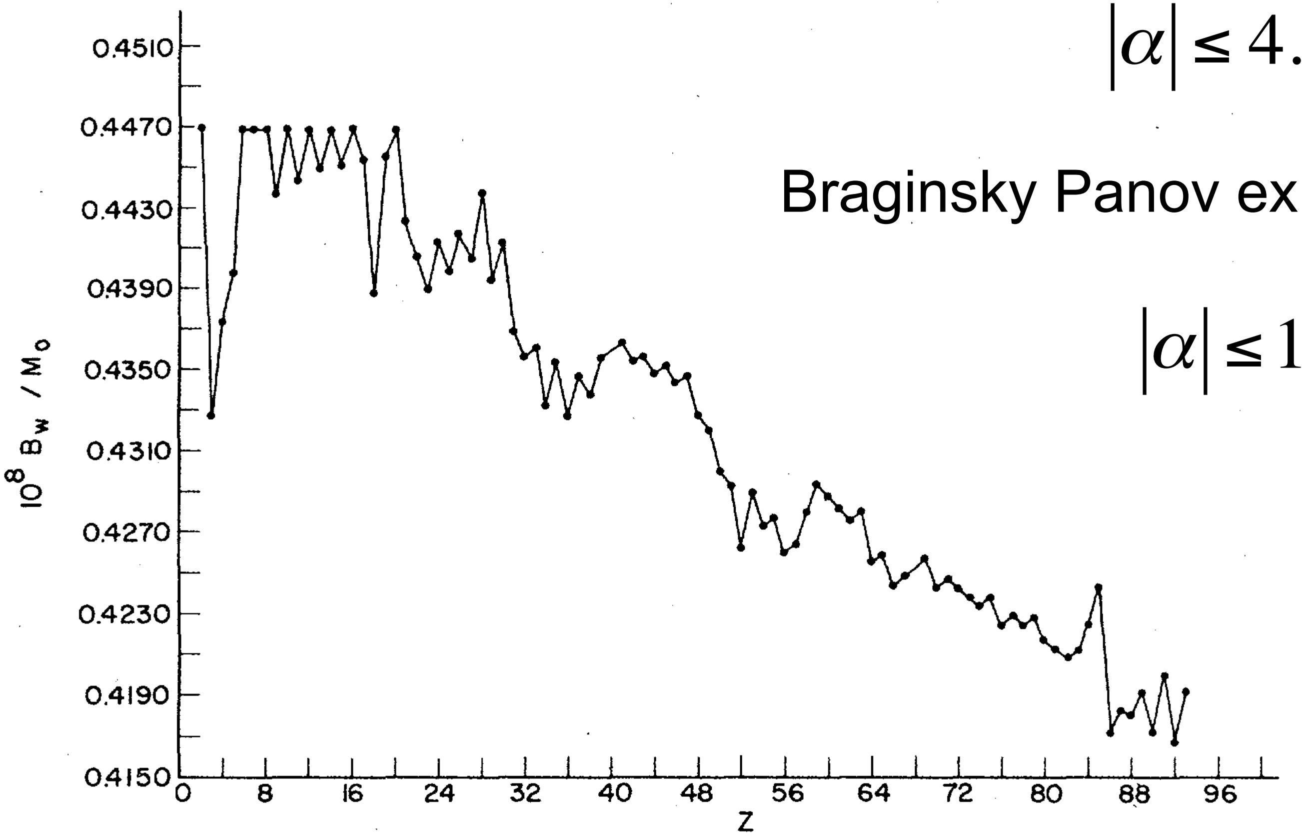
$$\vec{r}=\vec{v}_0t+\frac{1}{2}\vec{a}t^2$$

$$a\left[1+\frac{11}{3}\frac{\alpha B_w}{M_0}\right]=\frac{M'}{M_0}g$$

$$\frac{\boxed{\Delta a}}{g}=\frac{a_1-a_2}{g}\approx-\boxed{\alpha}\frac{11}{3}\left[\frac{B_{w1}}{M_{01}}-\frac{B_{w2}}{M_{02}}\right]$$

E. Fischbach, M.P. Haugan, D. Tadić, and H.-Y. Cheng, Phys. Rev. D **32**, 154 (1985)

Variation of B_w/M_0 as a Function of Z and Limits from Tests of WEP



RKD experiment:

$$|\alpha| \le 4.1 \times 10^{-2} \ \text{(Al-Au)}$$

Braginsky Panov experiment:

$$|\alpha| \le 1.5 \times 10^{-3} \ \text{(Al-Pt)}$$

WEP Violation in Standard Model Extension (SME)

General Dispersion Relation:

$$E^2 = m^2 + p^2 + \frac{p^4}{\mu^2} \Rightarrow E = m + \frac{p^2}{2m} + \frac{p^4}{2m\mu^2} + V(z)$$

$$\mu = \text{ model-dependent constant}$$

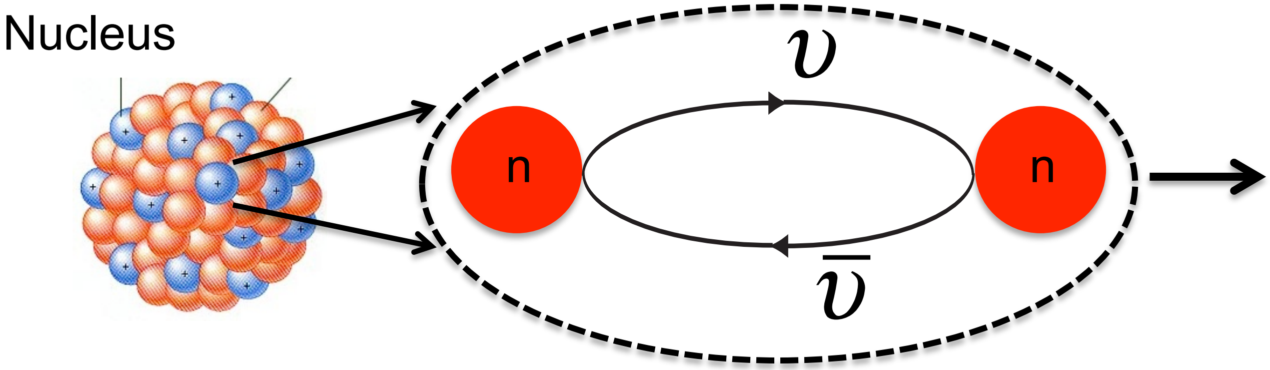
Acceleration of freely falling particle: $a = g\left(1 + \frac{6m^2v^2}{\mu^2}\right)$

$$\boxed{\frac{\Delta a}{g} = \frac{a_1 - a_2}{g} \approx 6v^2\left[\frac{m_1^2}{\mu_1^2} - \frac{m_2^2}{\mu_2^2}\right]}$$

Search for Lorentz Non-Invariance in the Neutrino Sector

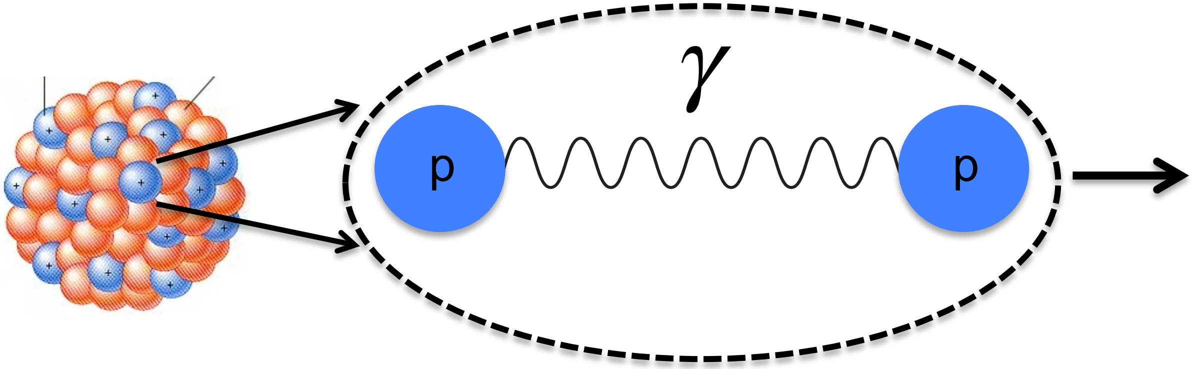
Neutrino Contribution to Rest Mass

Aim: Search for violations of Lorentz invariance of the neutrino contribution via test of the WEP



$$\boxed{V_{\upsilon\bar{\upsilon}}(r) = \frac{\kappa}{r_{12}^{5}}}$$

This interaction contributes to the mass-energy of a nucleus in analogy to the electromagnetic interaction.



$$\boxed{V_{\gamma}(r) = \frac{e^{2}}{r_{12}}}$$

Electromagnetic Energy

In each case we need $\langle V_{\upsilon\bar{\upsilon}} \rangle \equiv U_{\upsilon\bar{\upsilon}}$ or $\langle V_\gamma \rangle \equiv U_\gamma$, where $\langle \cdots \rangle$

is the average energy/pair over the nucleus. For V_γ we find

$$U_\gamma = e^2 \rho^2 \int_0^R dr_2\ r_2^2 \int_0^R dr_1\ r_1^2 \int d\Omega_1 \int d\Omega_2 \frac{1}{|\vec{r}_1 - \vec{r}_2|} = \frac{6}{5}\frac{e^2}{R}$$

The final result for *Z* protons in a nucleus of radius *R* is:

$$\boxed{W_\gamma \equiv \frac{1}{2} Z(Z-1) U_\gamma = \frac{3}{5} Z(Z-1) \frac{e^2}{R}}$$

This gives the well-known contribution to the semi-empirical mass formula for nuclei.

Neutrino Exchange Energy

However, for $U_{\upsilon\bar{\upsilon}}$ there is a problem: The analog of U_{γ} is is divergent due to $1/|\vec{r}_1 - \vec{r}_2|^5$.

Solution: Incorporate the nucleon-nucleon hard core

$$|\vec{r}_1 - \vec{r}_2| \geq r_c \cong 0.5 \text{ fm}$$

Then

$$U_{\upsilon\bar{\upsilon}} = \kappa\rho^2 \underset{\boxed{|\vec{r}_1 - \vec{r}_2| \geq r_c}}{\int^{R} dr_2\; r_2^2 \int^{R}} dr_1\; r_1^2 \int d\Omega_1 \int d\Omega_2 \frac{1}{|\vec{r}_1 - \vec{r}_2|^5}$$

(For the electromagnetic case, we can set $r_c = 0$.)

New Problem: The integral for $U_{\upsilon\bar{\upsilon}}$ is hard to do due to the presence of r_c.

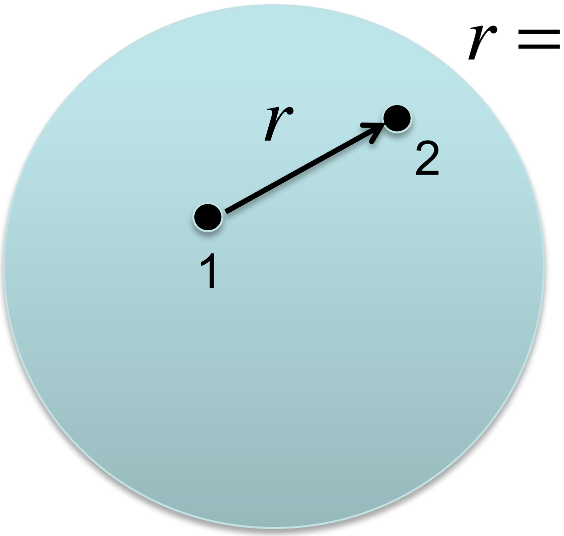
Geometric Probability

Utilizing ideas from geometric probability. Rewrite $U_{\nu\bar{\nu}}$ as

$$U_{\nu\bar{\nu}} = \langle V_{\nu\bar{\nu}} \rangle = \int_{r_c}^{2R} dr\; P(r) V_{\nu\bar{\nu}}(r)$$

where the probability of two points inside a sphere of radius *R* are separated by a distance *r* is

$$P(r) = \frac{3r^2}{R^3} - \frac{9}{4}\frac{r^3}{R^4} + \frac{3}{16}\frac{r^5}{R^6}$$



$$r = \left| \vec{r}_1 - \vec{r}_2 \right|$$

For the electromagnetic case

$$U_\gamma = \langle V_\gamma \rangle = e^2 \int_0^{2R} dr \left(\qquad\qquad \right) \frac{1}{r} = \frac{6}{5}\frac{e^2}{R}$$

Neutrino-Exchange Energy

For the neutrino interaction,

$$U_{\upsilon\bar{\upsilon}} = \langle V_{\upsilon\bar{\upsilon}} \rangle = \int_{r_c}^{2R} dr\; P(r) V_{\upsilon\bar{\upsilon}}(r)$$

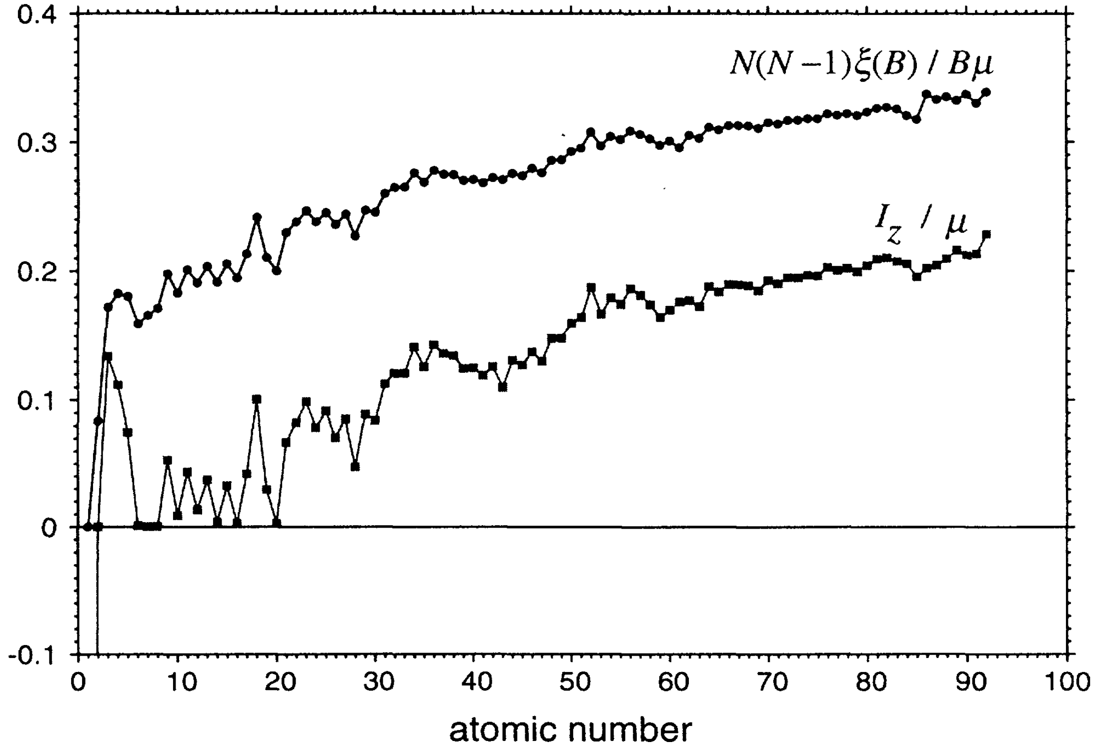
$$= \kappa \left[\frac{3}{2R^3 r_c^2}\left(1 - \frac{r_c^2}{4R^2}\right) - \frac{9}{4R^4 r_c}\left(1 - \frac{r_c}{2R}\right) + \frac{3}{16R^6}(2R - r_c) \right]$$

$$\simeq \boxed{\frac{3\kappa}{2}\frac{1}{R^3 r_c^2}.}$$

An anomalous gravitational interaction of neutrinos could show up at a non-trivial level in the current version of the MICROSCOPE satellite experiment which aims to measure gravitational acceleration differences to ~10^{-17}-10^{-18}. Our work is now one of the motivations for such an experiment

E. Fischbach, D.E. Krause, and D. Tadić, Phys. Rev. D **52**, 5417(1995)

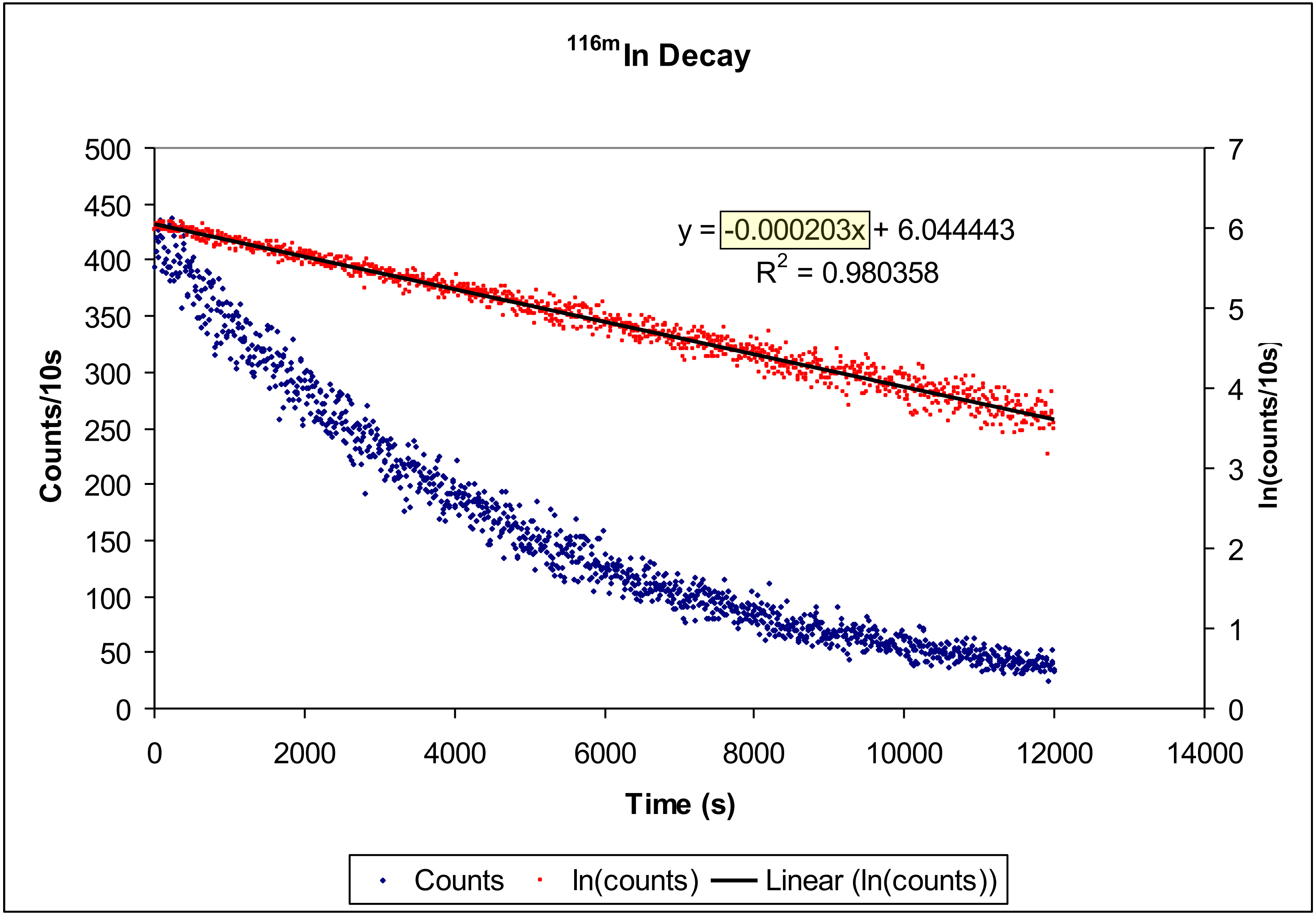
$$\frac{\Delta a}{g} \equiv \frac{a_1 - a_2}{g} = \eta_{\nu\bar{\nu}}\,(1.4 \times 10^{-16}) \left[\frac{N_1(N_1-1)}{B_1\mu_1}\,\xi(B_1) - \frac{N_2(N_2-1)}{B_2\mu_2}\,\xi(B_2) \right] . \qquad (3.18)$$

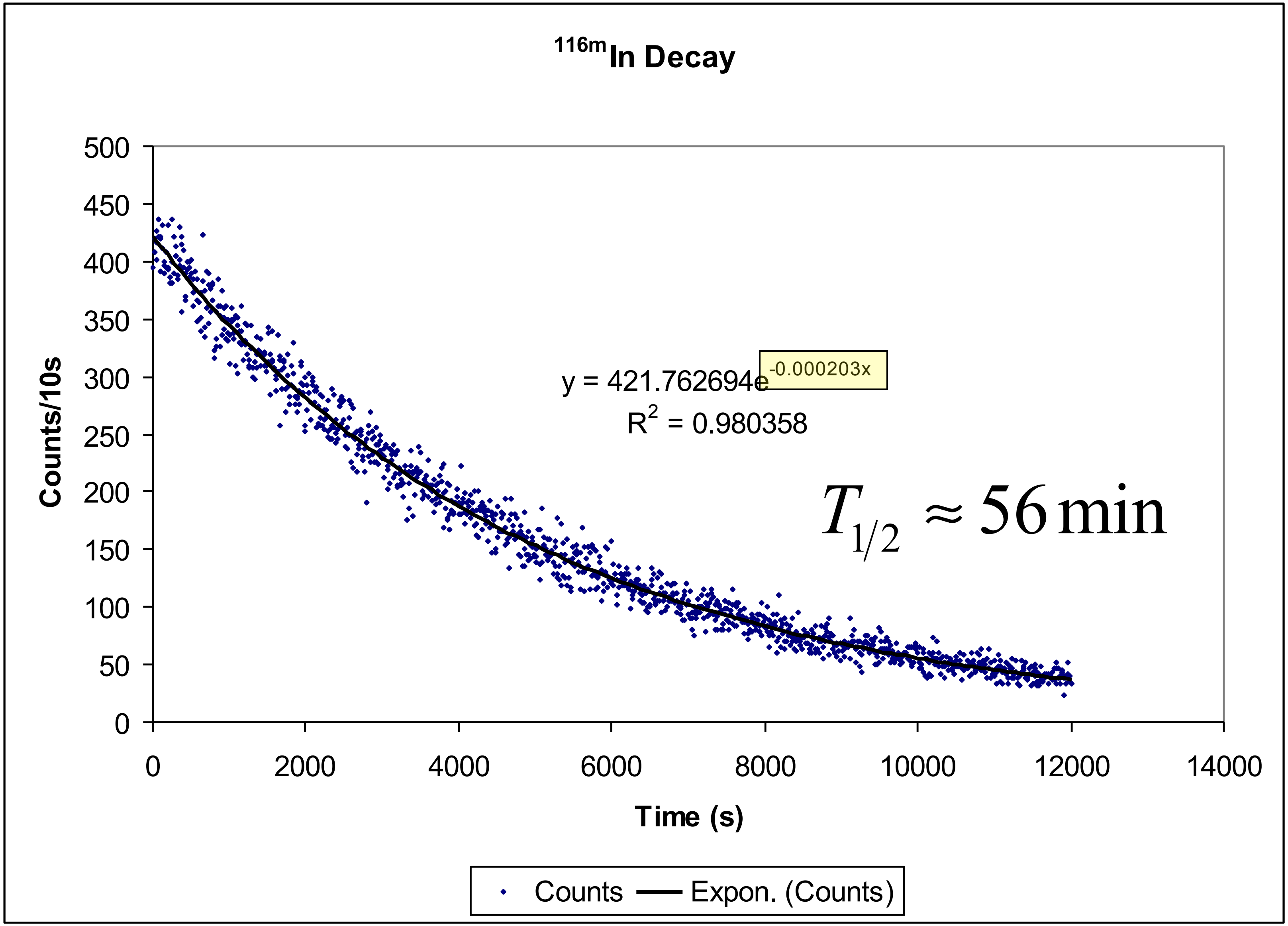


To complete this calculation, all we need is a specific model describing LNI coupling to neutrinos analogous to Nielsen-Picek

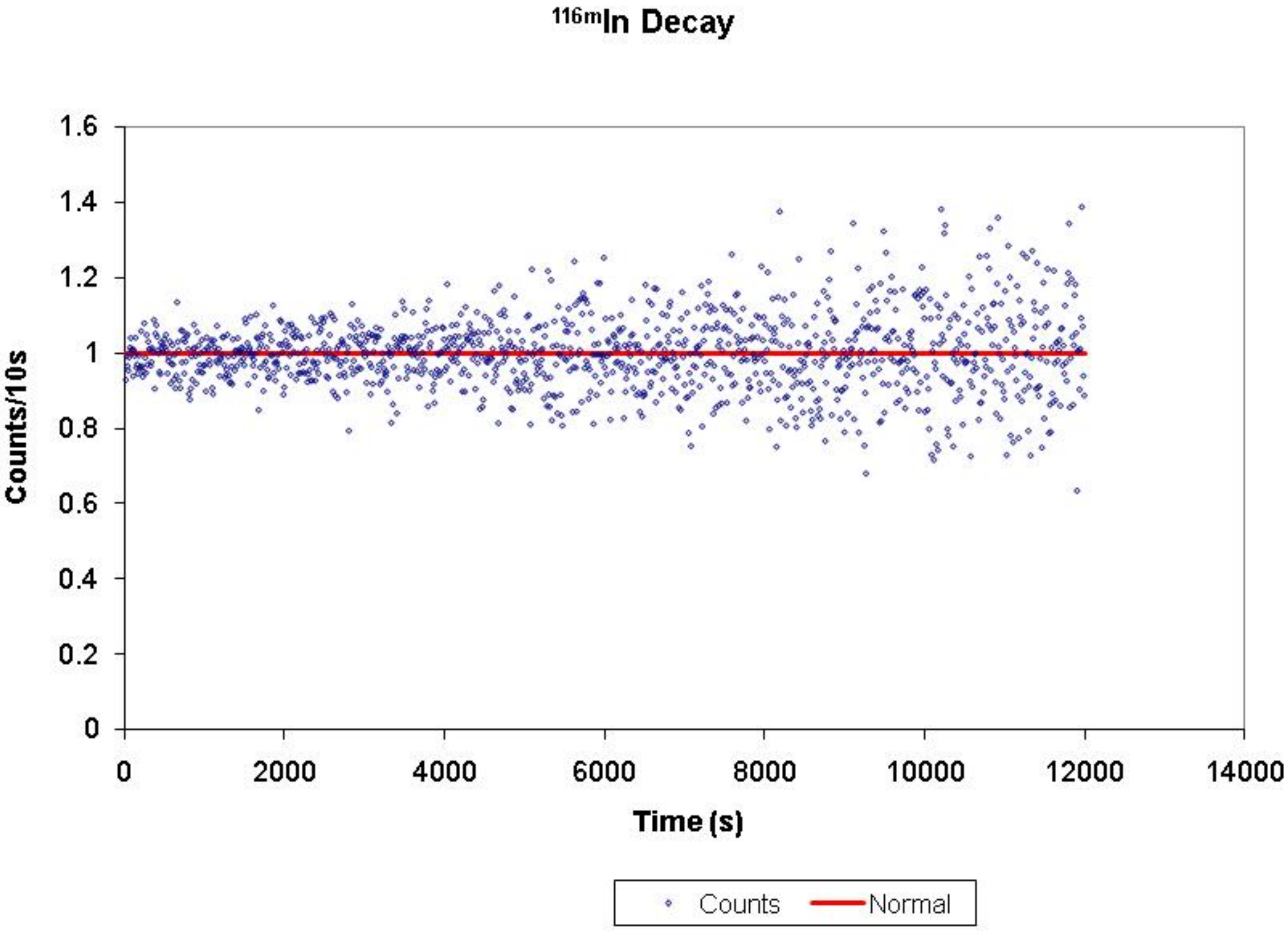
New Results

Decay Data over Short Time Intervals

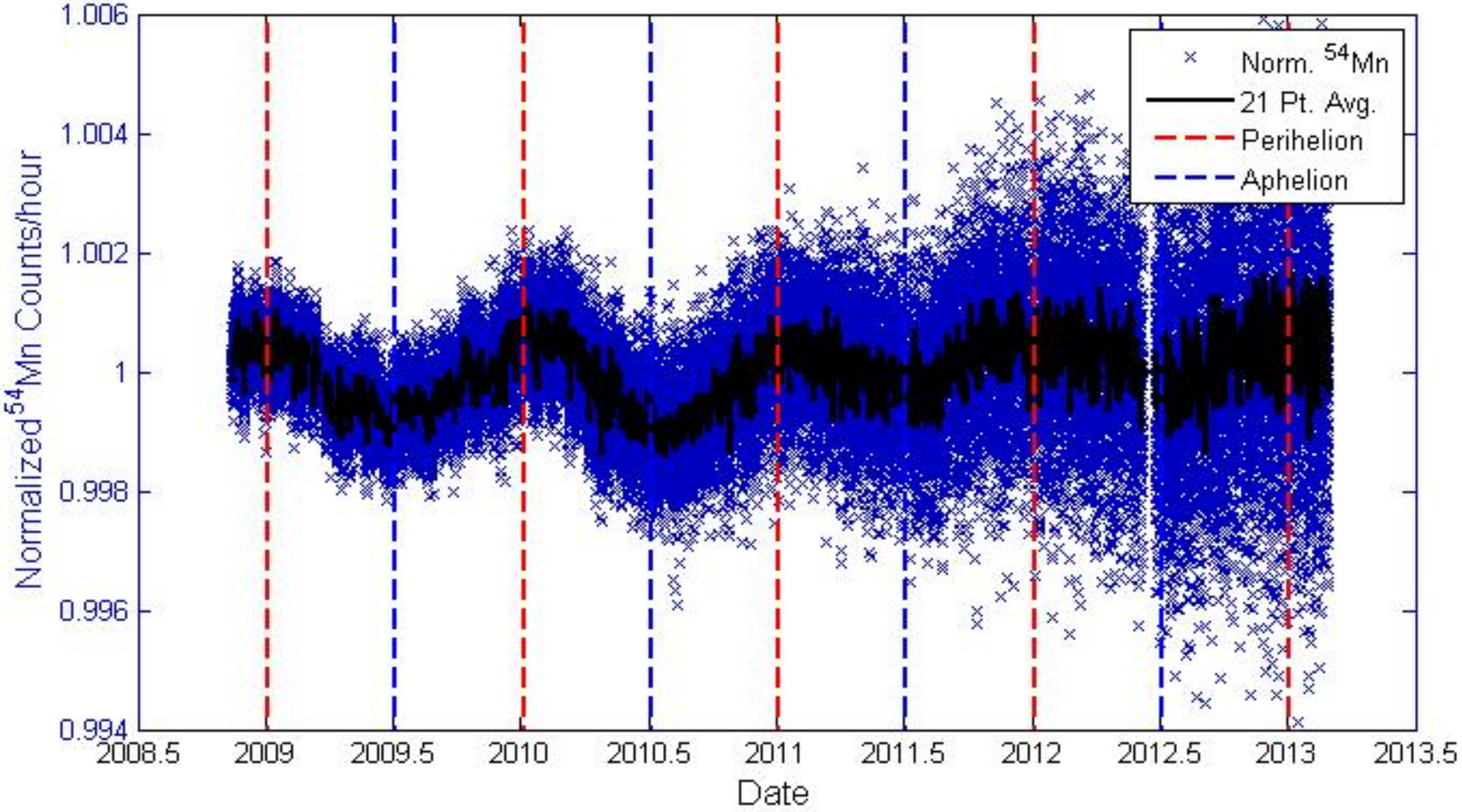




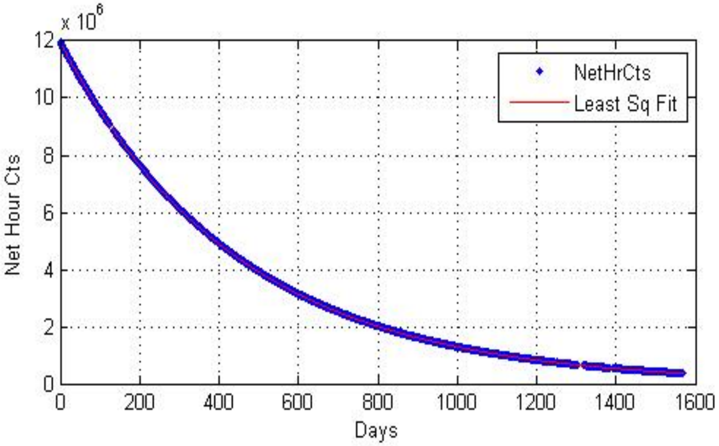
$$T_{1/2} \approx 56\,\text{min}$$

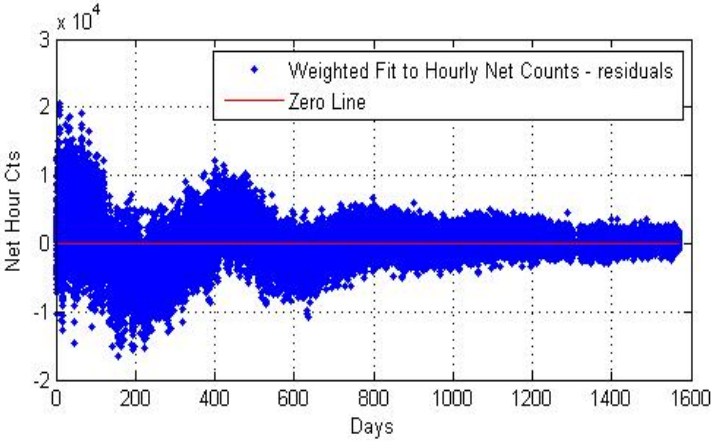

^{116m}In Decay
Counts/10s
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
2000
4000
6000
8000
10000
12000
14000
Time (s)
Counts
Normal

^{54}Mn Decays 2008-2013



^{54}Mn Half-life (2008-2013)





- Literature value (NNDC, 2013): **$T_{1/2}$ = 312.12(6) days**
- Detail (Net counts):
  - **34,442** 1-hour counts
  - **1568.8** days (5.03 half-lives),
  - **1.11x10^{11}** events detected in full energy peak.
- **Weighted linear fit: $T_{1/2}$ = 311.662(1) days**, χ^2/d.o.f. = 1.66
- **Weighted exponential fit:** General model

  Exp1: f(x) = a*exp(b*x)
  - Coefficients (with 95% confidence bounds):
    - a = 1.196e+07 (1.196e+07, 1.196e+07)
    - **b = -0.002224 (-0.002224, -0.002224)**

      $T_{1/2}$ =311.667(1) days
    - Goodness of fit:
      - SSE: 1.707e+008
      - R-square: 1.00000
      - Adjusted R-square: 1.00000
      - RMSE: 70.4

Experiments Exhibiting Time-Dependent Decay Parameters

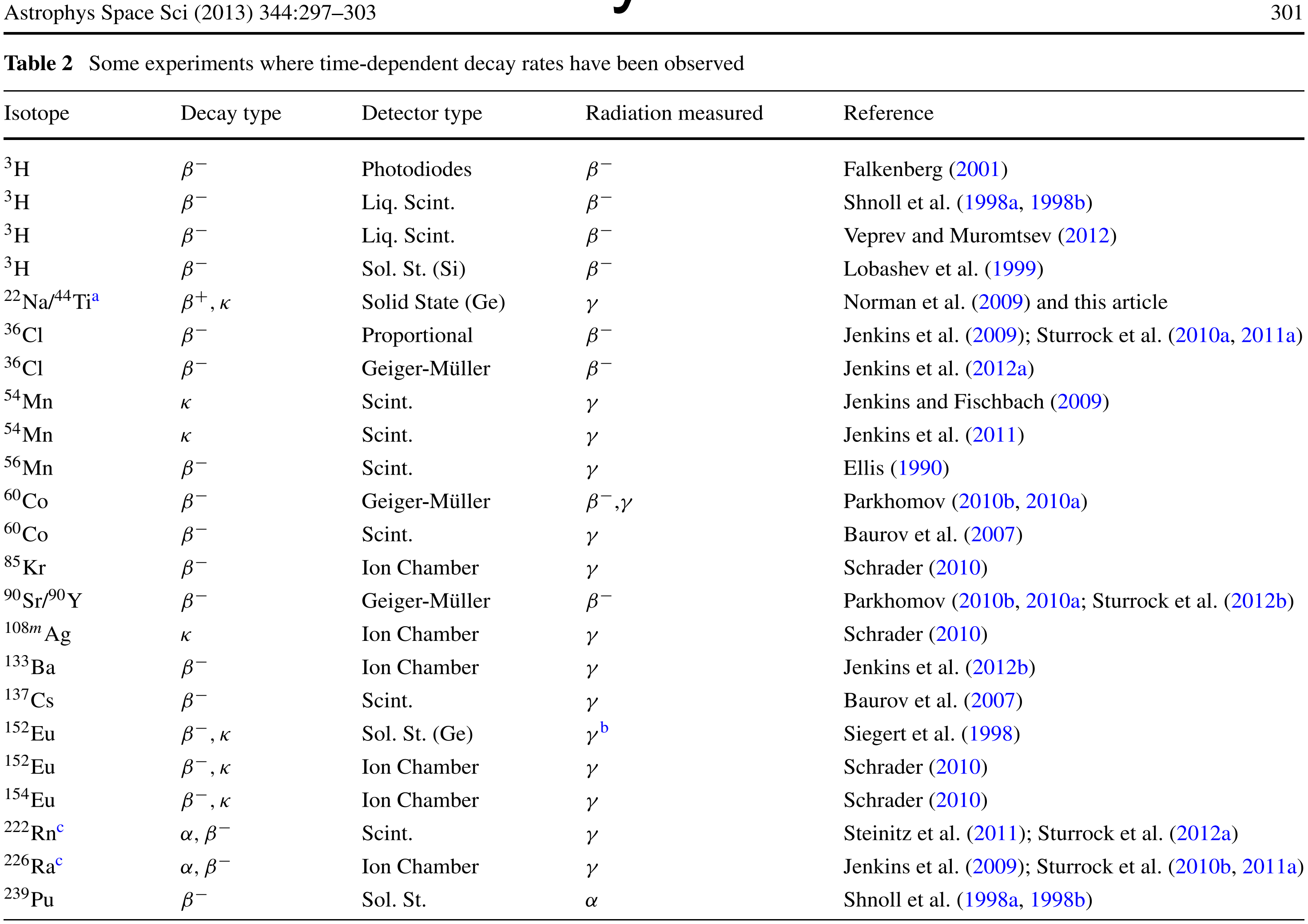


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Table 2 Some experiments where time-dependent decay rates have been observed

Isotope	Decay type	Detector type	Radiation measured	Reference
^{3}H	β^-	Photodiodes	β^-	Falkenberg (2001)
^{3}H	β^-	Liq. Scint.	β^-	Shnoll et al. (1998a, 1998b)
^{3}H	β^-	Liq. Scint.	β^-	Veprev and Muromtsev (2012)
^{3}H	β^-	Sol. St. (Si)	β^-	Lobashev et al. (1999)
^{22}Na/^{44}Ti[a]	β^+, κ	Solid State (Ge)	γ	Norman et al. (2009) and this article
^{36}Cl	β^-	Proportional	β^-	Jenkins et al. (2009); Sturrock et al. (2010a, 2011a)
^{36}Cl	β^-	Geiger-Müller	β^-	Jenkins et al. (2012a)
^{54}Mn	κ	Scint.	γ	Jenkins and Fischbach (2009)
^{54}Mn	κ	Scint.	γ	Jenkins et al. (2011)
^{56}Mn	β^-	Scint.	γ	Ellis (1990)
^{60}Co	β^-	Geiger-Müller	β^-,γ	Parkhomov (2010b, 2010a)
^{60}Co	β^-	Scint.	γ	Baurov et al. (2007)
^{85}Kr	β^-	Ion Chamber	γ	Schrader (2010)
^{90}Sr/^{90}Y	β^-	Geiger-Müller	β^-	Parkhomov (2010b, 2010a; Sturrock et al. (2012b)
^{108m}Ag	κ	Ion Chamber	γ	Schrader (2010)
^{133}Ba	β^-	Ion Chamber	γ	Jenkins et al. (2012b)
^{137}Cs	β^-	Scint.	γ	Baurov et al. (2007)
^{152}Eu	β^-, κ	Sol. St. (Ge)	γ[b]	Siegert et al. (1998)
^{152}Eu	β^-, κ	Ion Chamber	γ	Schrader (2010)
^{154}Eu	β^-, κ	Ion Chamber	γ	Schrader (2010)
^{222}Rn[c]	α, β^-	Scint.	γ	Steinitz et al. (2011); Sturrock et al. (2012a)
^{226}Ra[c]	α, β^-	Ion Chamber	γ	Jenkins et al. (2009); Sturrock et al. (2010b, 2011a)
^{239}Pu	β^-	Sol. St.	α	Shnoll et al. (1998a, 1998b)

Experiments Exhibiting Discrepant Decay Parameters

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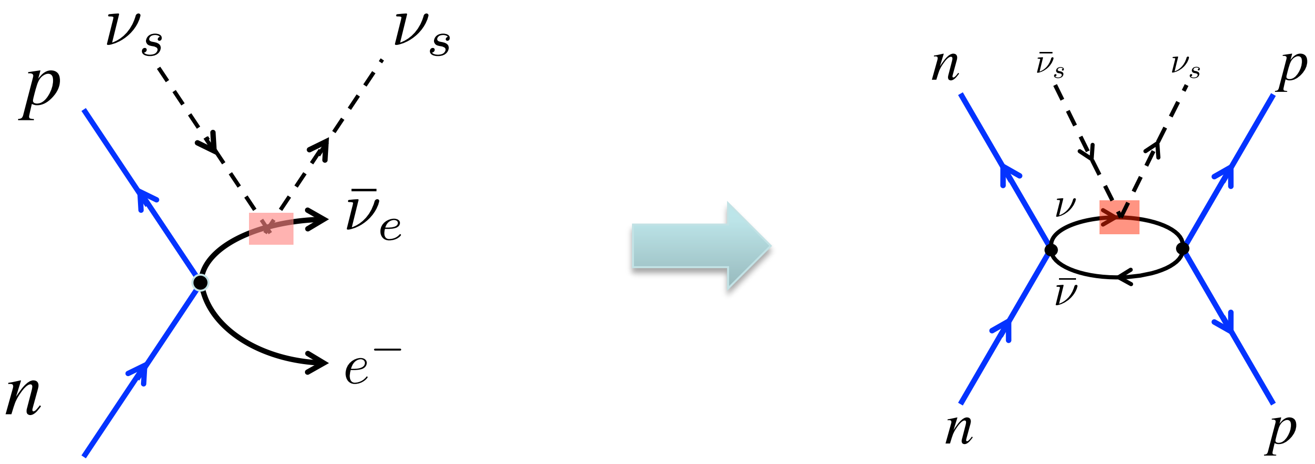
Is there a connection between decay anomalies and violations of the WEP?

Anomalous Beta Decay

WEP Violation



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

Anomalous Neutrino Interaction in Tritium Neutrino Mass Experiments

$$(E_0 - E)^2 \rightarrow (E_0 - E)\sqrt{(E_0 - E)^2 - m_\nu^2}$$

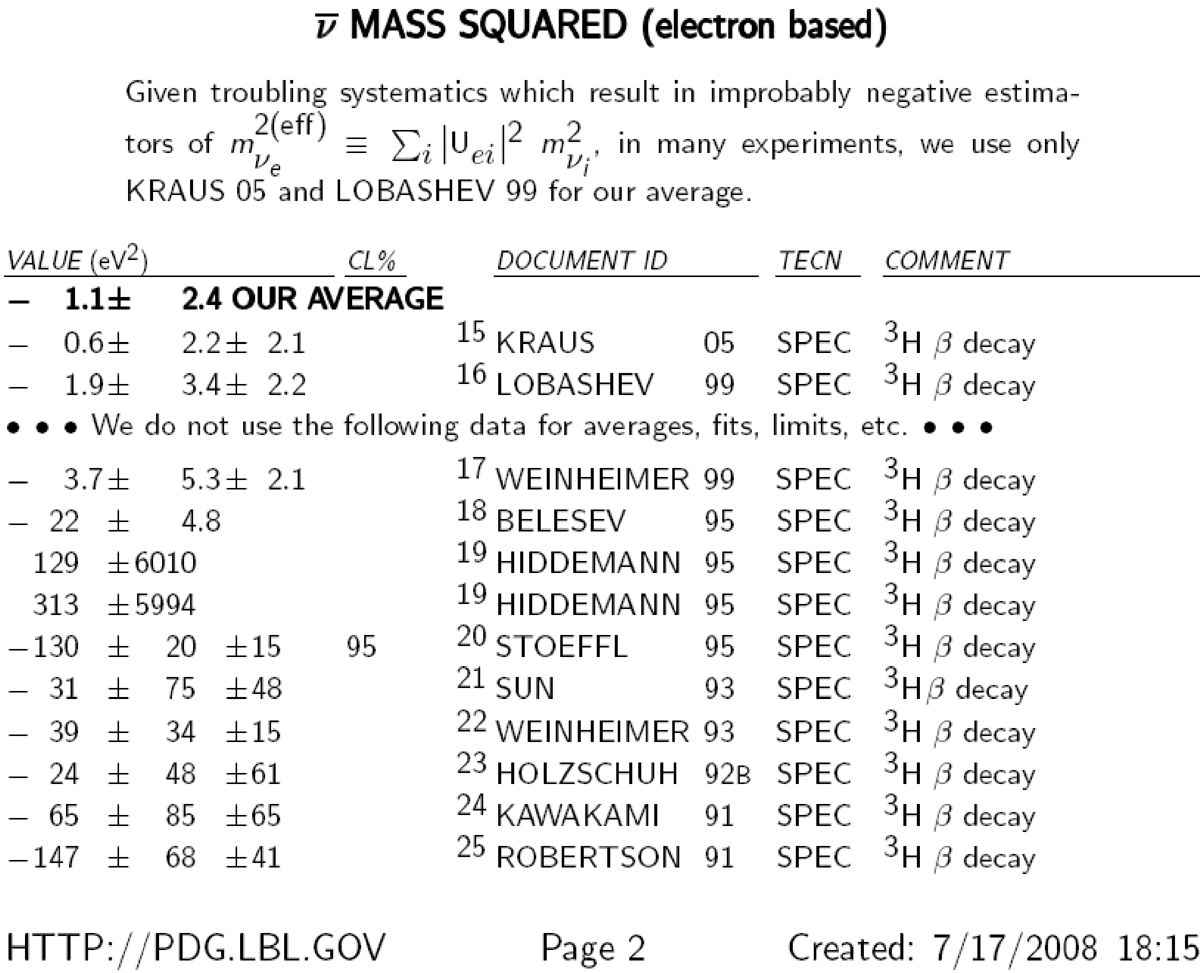
$$For\ (E_0 - E)^2 \gg m_\nu^2, \Delta^2 \Rightarrow \boxed{\Delta^2 \approx -\frac{1}{2} m_\nu^2}$$

$$m_\nu^2 = -100\text{ eV}^2 \text{ to } -10\text{ eV}^2.$$

$$\Rightarrow \boxed{\Delta^2 = 50\text{ eV}^2 \text{ to } 5\text{ eV}^2}$$

This *may* be compatible with current limits on neutrino magnetic dipole moments.

Implications for Neutrino Mass Experiments

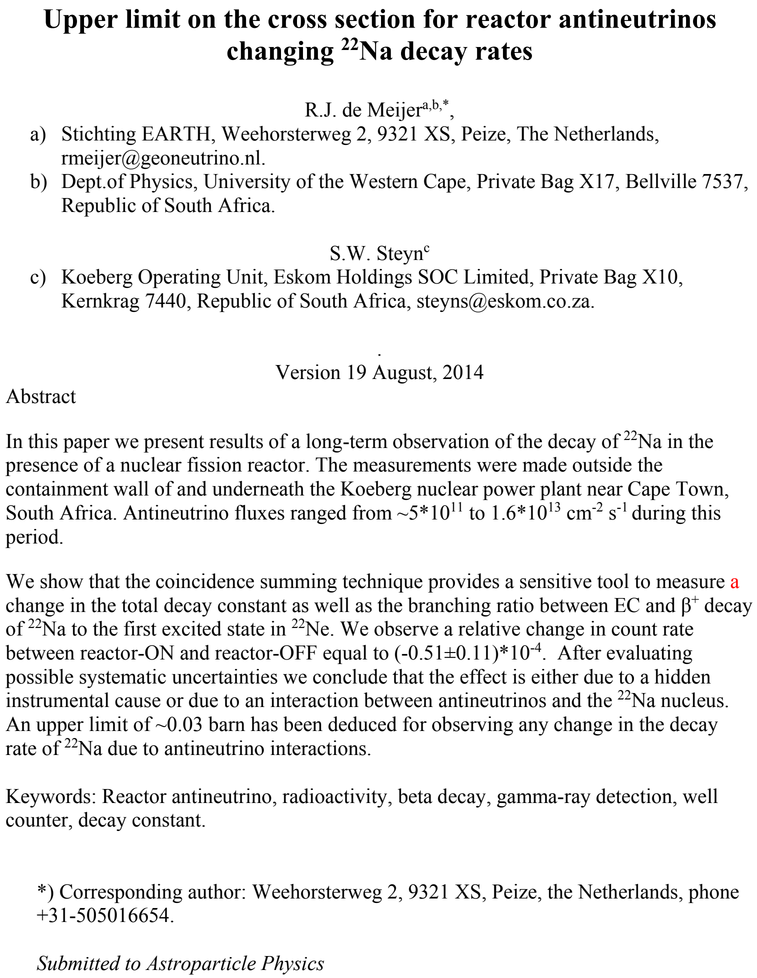


$\overline{\nu}$ MASS SQUARED (electron based)

Given troubling systematics which result in improbably negative estimators of $m^{2(\mathrm{eff})}_{\nu_e} \equiv \sum_i |U_{ei}|^2 \, m^2_{\nu_i}$, in many experiments, we use only KRAUS 05 and LOBASHEV 99 for our average.

VALUE (eV^2)	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
− 1.1± 2.4 OUR AVERAGE				
− 0.6± 2.2± 2.1		[15] KRAUS 05	SPEC	^{3}H β decay
− 1.9± 3.4± 2.2		[16] LOBASHEV 99	SPEC	^{3}H β decay
• • • We do not use the following data for averages, fits, limits, etc. • • •				
− 3.7± 5.3± 2.1		[17] WEINHEIMER 99	SPEC	^{3}H β decay
− 22 ± 4.8		[18] BELESEV 95	SPEC	^{3}H β decay
129 ±6010		[19] HIDDEMANN 95	SPEC	^{3}H β decay
313 ±5994		[19] HIDDEMANN 95	SPEC	^{3}H β decay
−130 ± 20 ±15	95	[20] STOEFFL 95	SPEC	^{3}H β decay
− 31 ± 75 ±48		[21] SUN 93	SPEC	^{3}Hβ decay
− 39 ± 34 ±15		[22] WEINHEIMER 93	SPEC	^{3}H β decay
− 24 ± 48 ±61		[23] HOLZSCHUH 92B	SPEC	^{3}H β decay
− 65 ± 85 ±65		[24] KAWAKAMI 91	SPEC	^{3}H β decay
−147 ± 68 ±41		[25] ROBERTSON 91	SPEC	^{3}H β decay

Reactor Experiments



Upper limit on the cross section for reactor antineutrinos changing ^{22}Na decay rates

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Abstract

In this paper we present results of a long-term observation of the decay of ^{22}Na in the presence of a nuclear fission reactor. The measurements were made outside the containment wall of and underneath the Koeberg nuclear power plant near Cape Town, South Africa. Antineutrino fluxes ranged from ~$5*10^{11}$ to $1.6*10^{13}$ cm^{-2} s^{-1} during this period.

We show that the coincidence summing technique provides a sensitive tool to measure a change in the total decay constant as well as the branching ratio between EC and β^{+} decay of ^{22}Na to the first excited state in ^{22}Ne. We observe a relative change in count rate between reactor-ON and reactor-OFF equal to $(-0.51\pm0.11)*10^{-4}$. After evaluating possible systematic uncertainties we conclude that the effect is either due to a hidden instrumental cause or due to an interaction between antineutrinos and the ^{22}Na nucleus. An upper limit of ~0.03 barn has been deduced for observing any change in the decay rate of ^{22}Na due to antineutrino interactions.

Keywords: Reactor antineutrino, radioactivity, beta decay, gamma-ray detection, well counter, decay constant.

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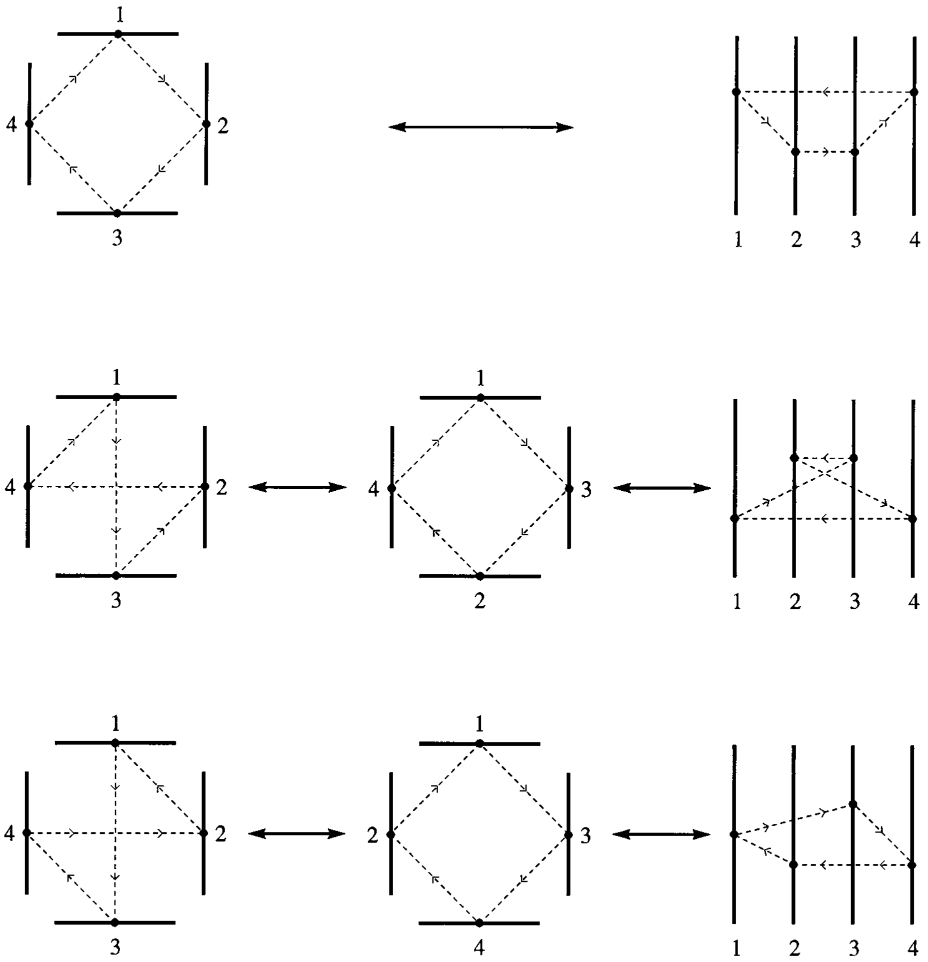
Implications for Neutrino Mass

k-body Neutrino Exchange Energy



$$W^{(k)} \sim \frac{1}{k!}\frac{1}{R}\left(\frac{G_F N}{R^2}\right)^k$$

N = total # of nucleons
R = Radius

For typical neutron stars,

$$\boxed{\frac{G_F N}{R^2} \sim 10^{13}}$$

Lower Limit on Neutrino Mass

For typical neutron stars, this leads to an unphysically-large energy density unless neutrinos have a minimum non-zero mass given by:

$$\boxed{mc^2 \gtrsim \frac{\sqrt{2}\, G_F\, |a_n|\, \rho}{3e^3} = 0.4\ \mathrm{eV}}$$

a_n = neutrino-nucleon coupling constant
ρ = neutron star density
e = 2.71828…

E. Fischbach, Ann. Phys. (NY) **247**, 213 (1996)

Constraints on Neutrino Masses