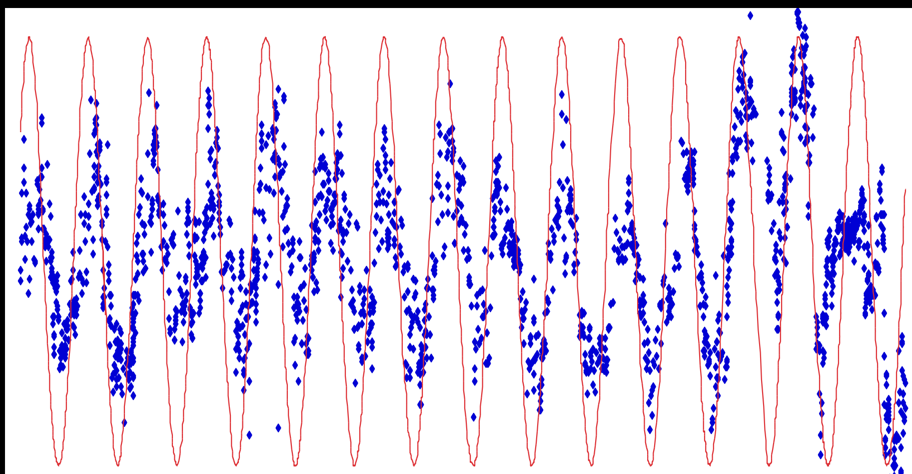
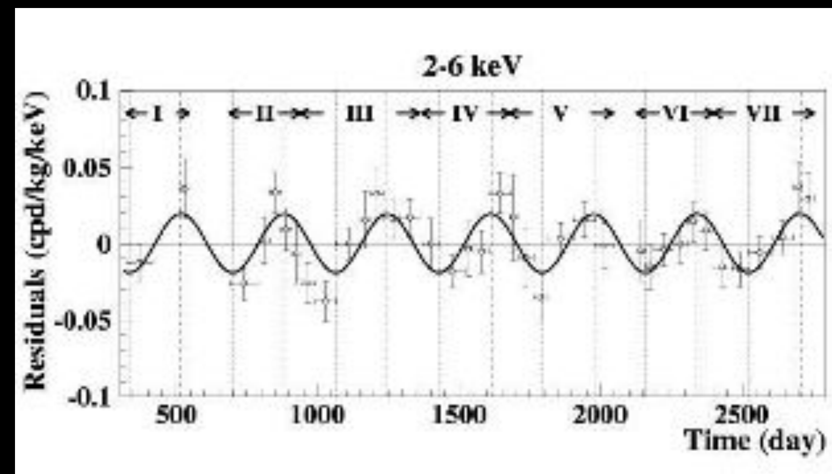
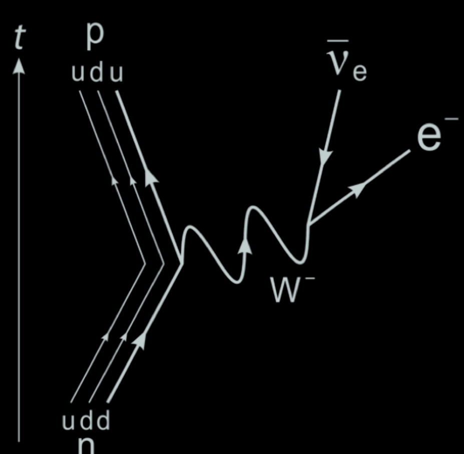
What's Causing Annual Periodicities in Beta Decay Data?





Dennis E. Krause



Purdue Colleagues

Ephraim Fischbach

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Outline

I. Radioactive Decay
   A. Unstable Particles
   B. Exponential Decay Law
   C. Sinusoidal Variation of Decay Rates
II. Explanation for Decay Anomalies?
   A. How to Modify Decay Rates
   B. Neutrinos
   C. Neutrino Refractive Index and Decay Rates
III. Discussion

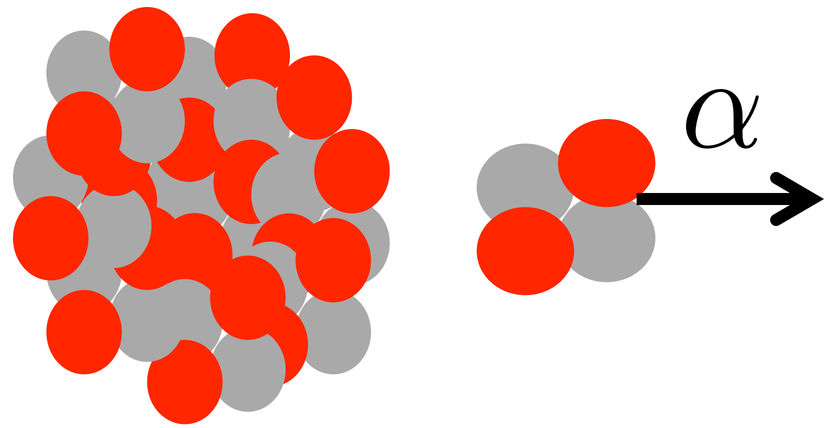
Unstable Particles
&
Radioactive Decay

Examples of Unstable Particles

Radioactive Nuclei

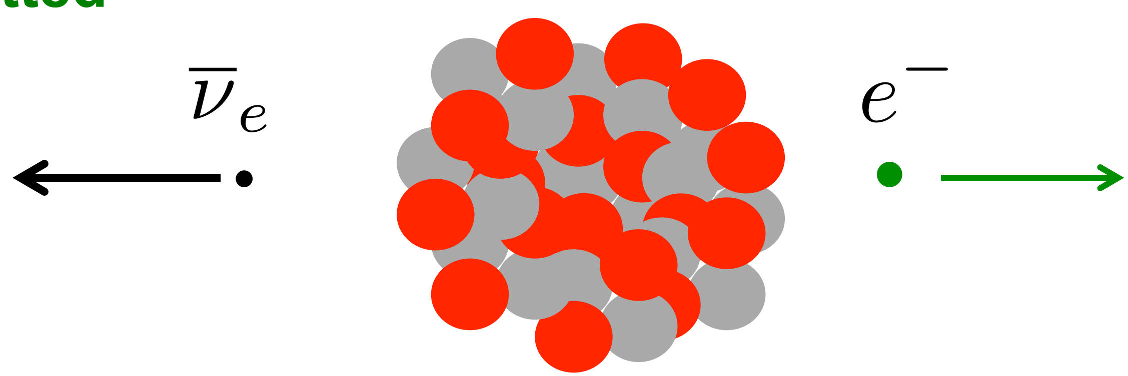
Alpha Decay: **Strong & EM process where ^4He tunnels out of nucleus**

$$ {}^{238}_{92}\mathrm{U} \rightarrow {}^{234}_{90}\mathrm{Th} + {}^{4}_{2}\mathrm{He} $$



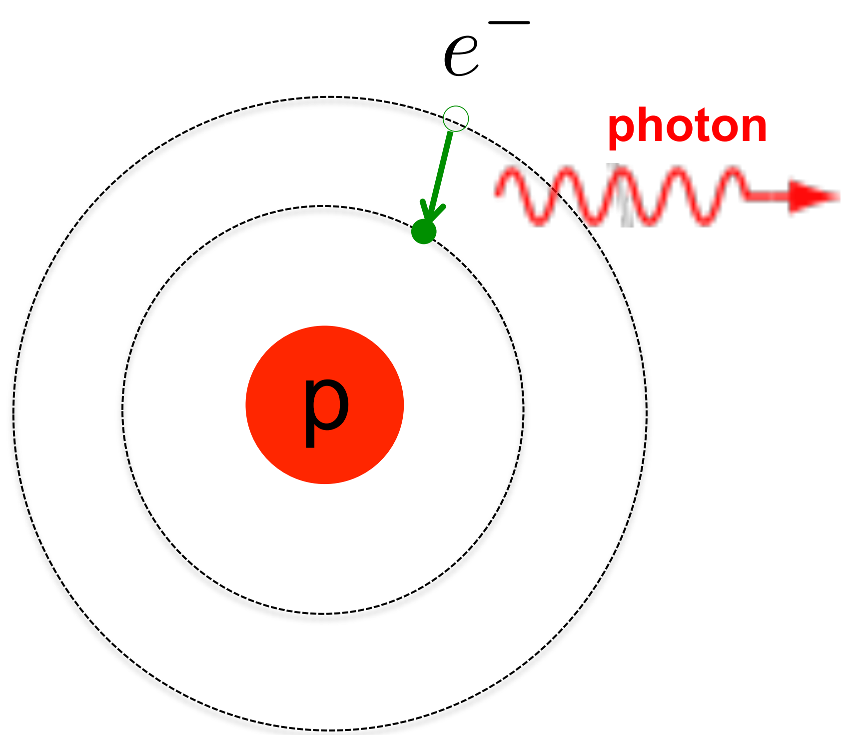
Beta Decay: **Weak interaction process where electron + electron anti-neutrino (or positron and electron neutrino) are emitted**

$$ {}^{137}_{55}\mathrm{Cs} \rightarrow {}^{137}_{56}\mathrm{Ba} + e^- + \overline{\upsilon}_e $$



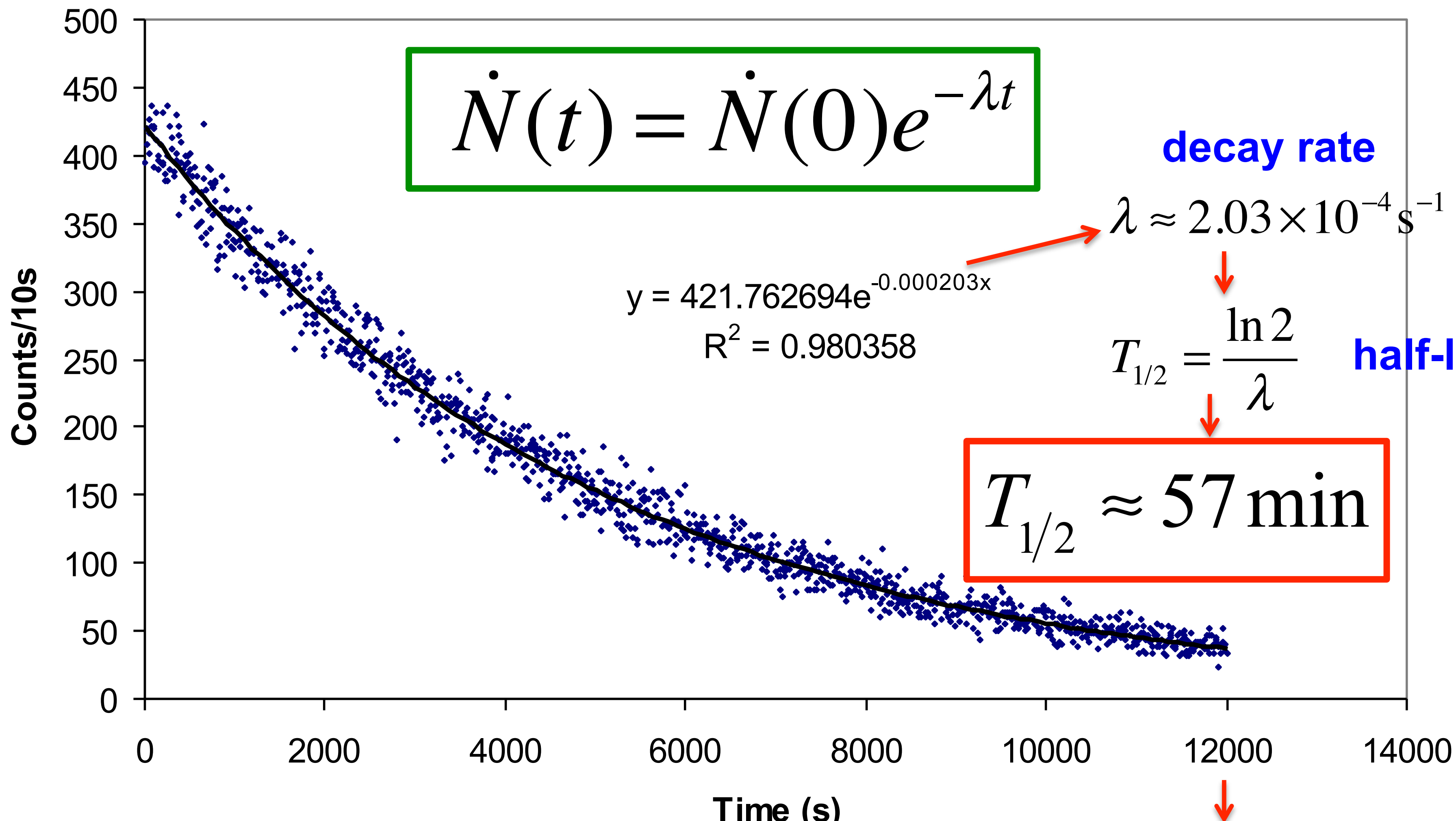
Examples of Unstable Particles

Photon Emission: Electromagnetic transition from an excited state of an atom (~eV) or nucleus (~MeV gamma ray)



Exponential Decay Law: ^{116m}In

$\dot{N}(t)$



$$\dot{N}(t) = \dot{N}(0)e^{-\lambda t}$$

decay rate

$$\lambda \approx 2.03\times10^{-4}\,\mathrm{s}^{-1}$$

$$T_{1/2} = \frac{\ln 2}{\lambda}$$

half-life

$$T_{1/2} \approx 57\,\mathrm{min}$$

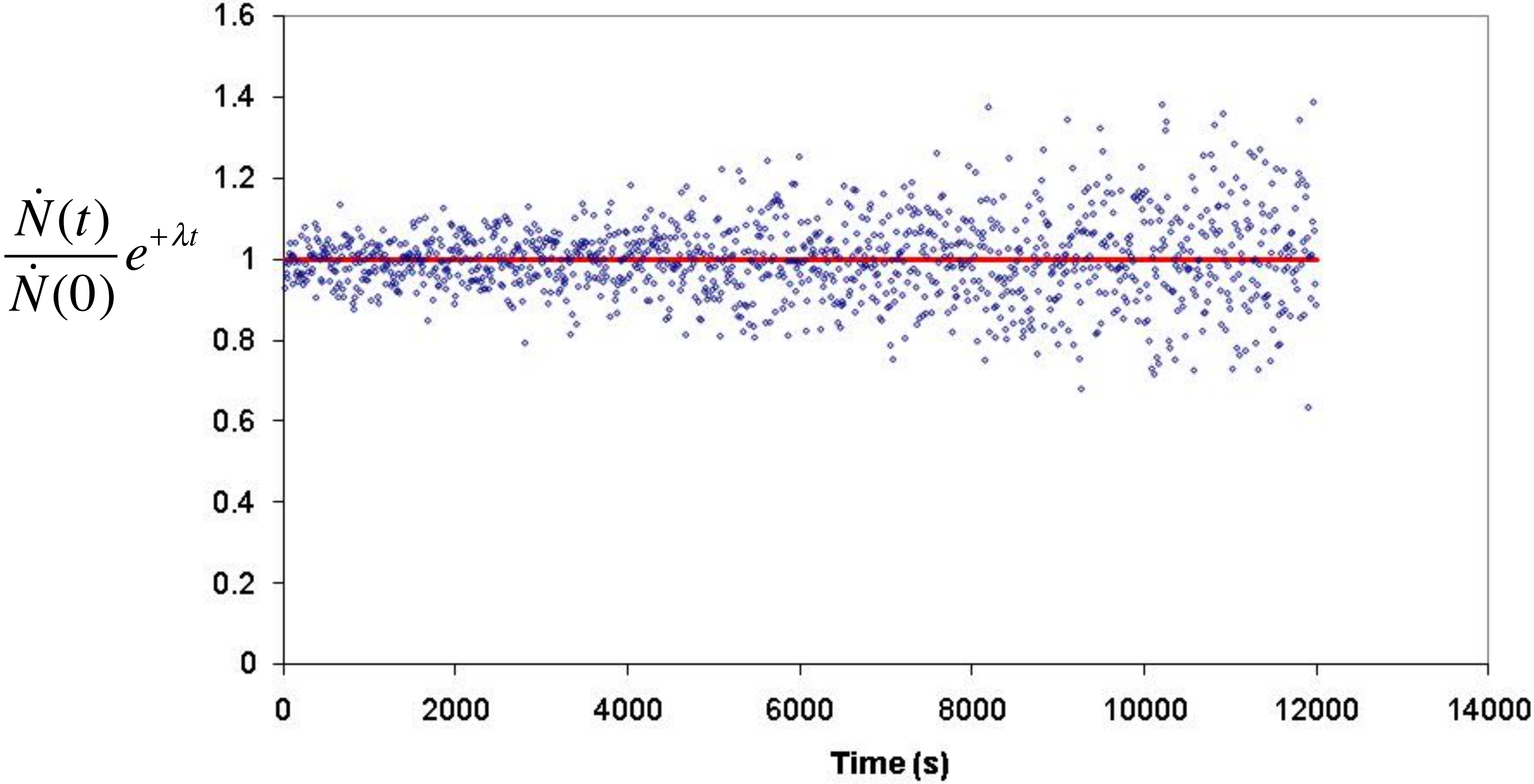
3.3 hrs

$$\dot{N}(t) \equiv \frac{dN}{dt} = \text{ activity}$$

Data taken by Jere Jenkins (Purdue)

^{116m}In Decay: Normalized Data

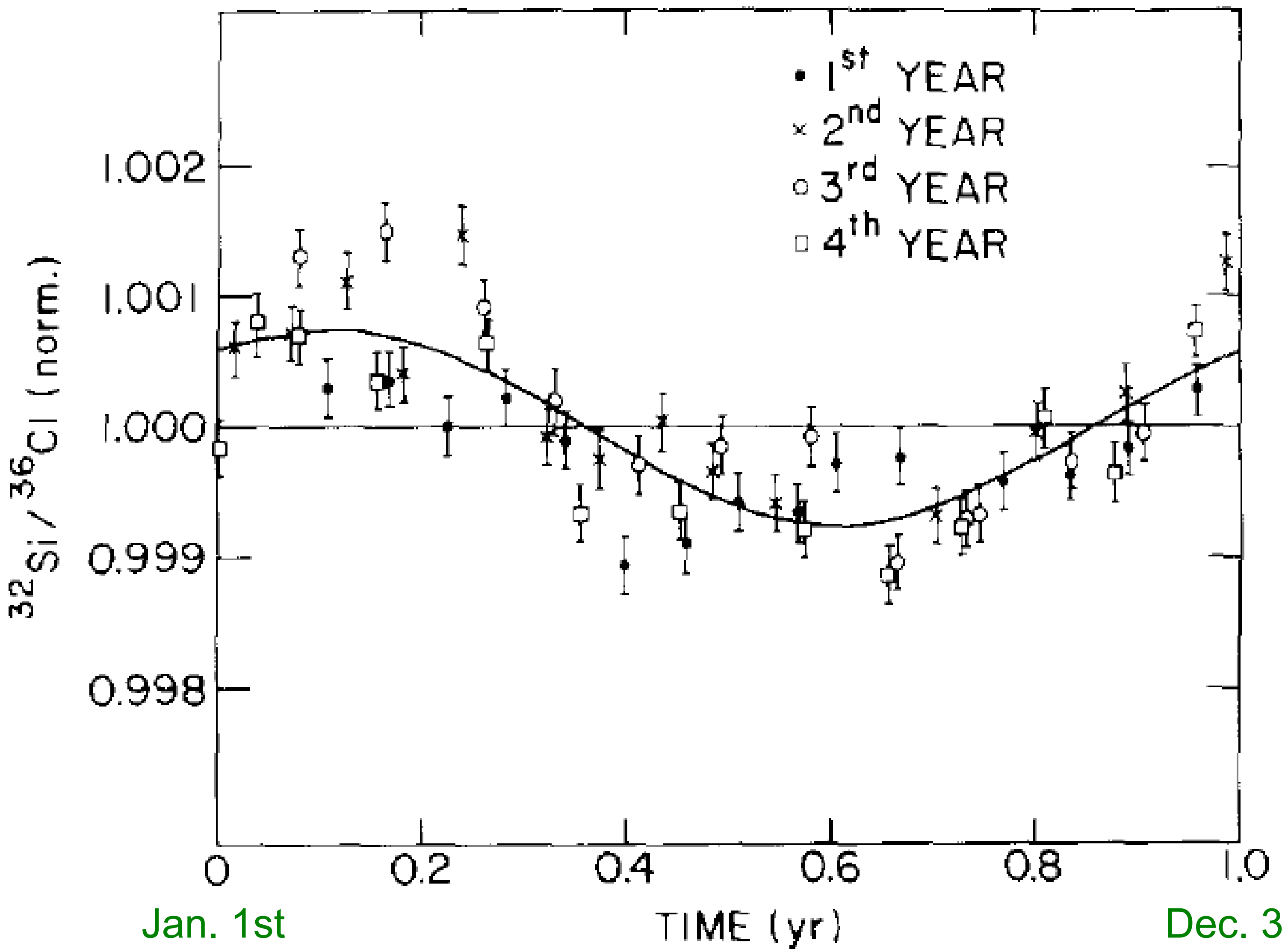
$$\dot{N}(t) = \dot{N}(0)e^{-\lambda t}$$



Data taken by Jere Jenkins (Purdue)

Decay Anomalies

^{32}Si Half-Life
Brookhaven National Lab (BNL) 1982-1986



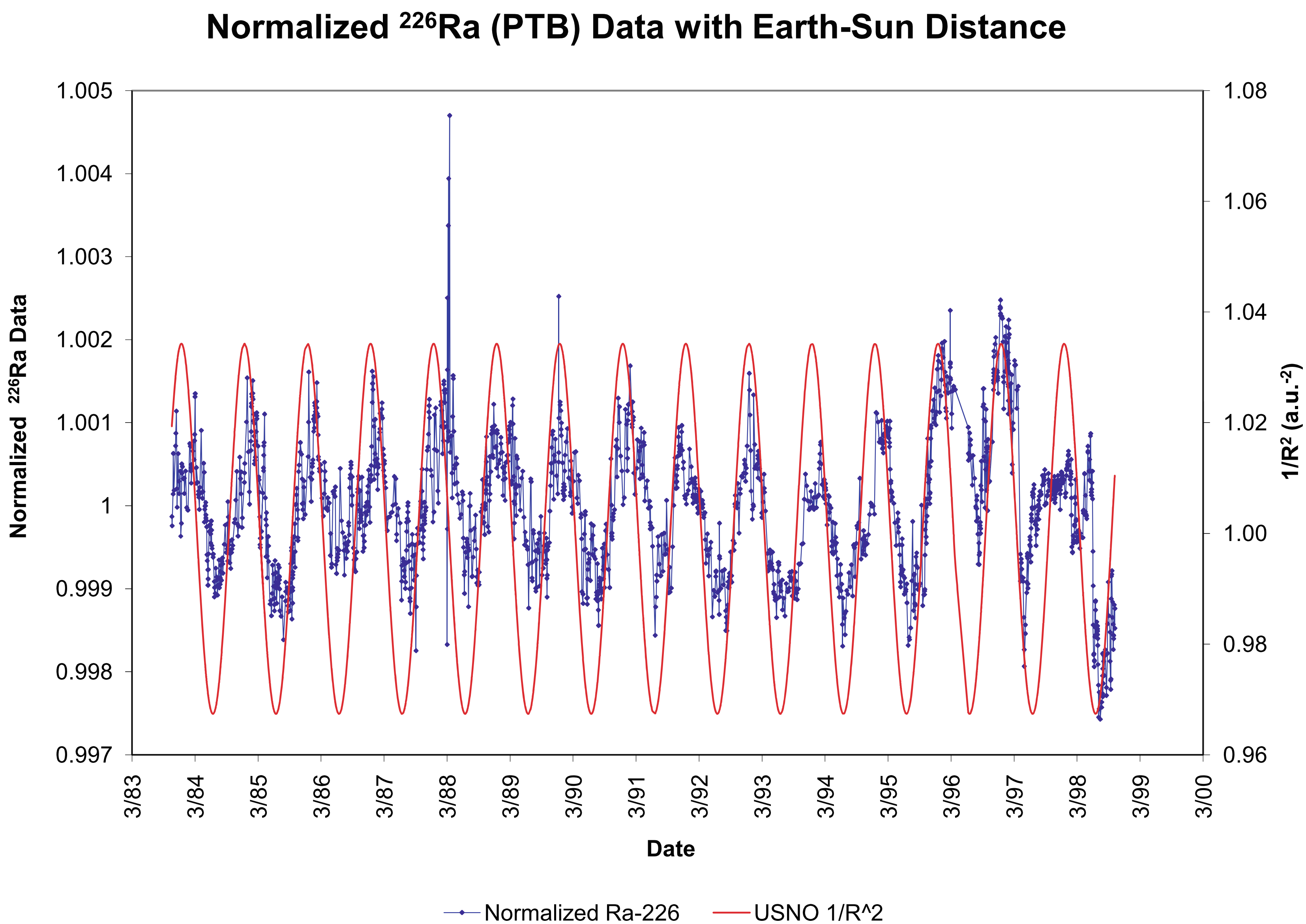
Jan. 1st

Dec. 31st

Reference: D.E. Alburger, G. Harbottle, E.F. Norton, Earth and Planetary Science Letters **78** (1986) 168.

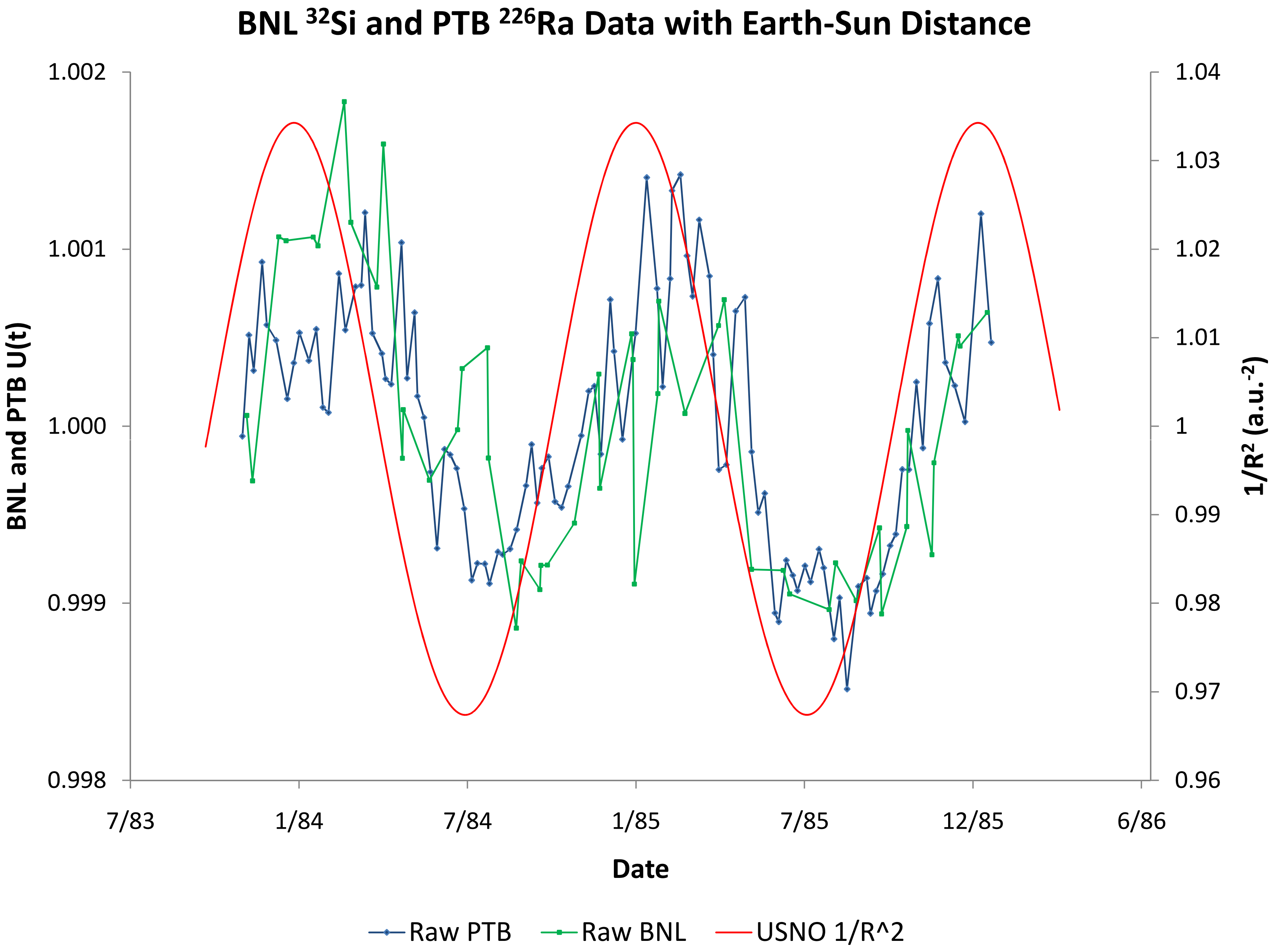
^{226}Ra

Physikalisch-Technische Bundesanstalt (PTB)



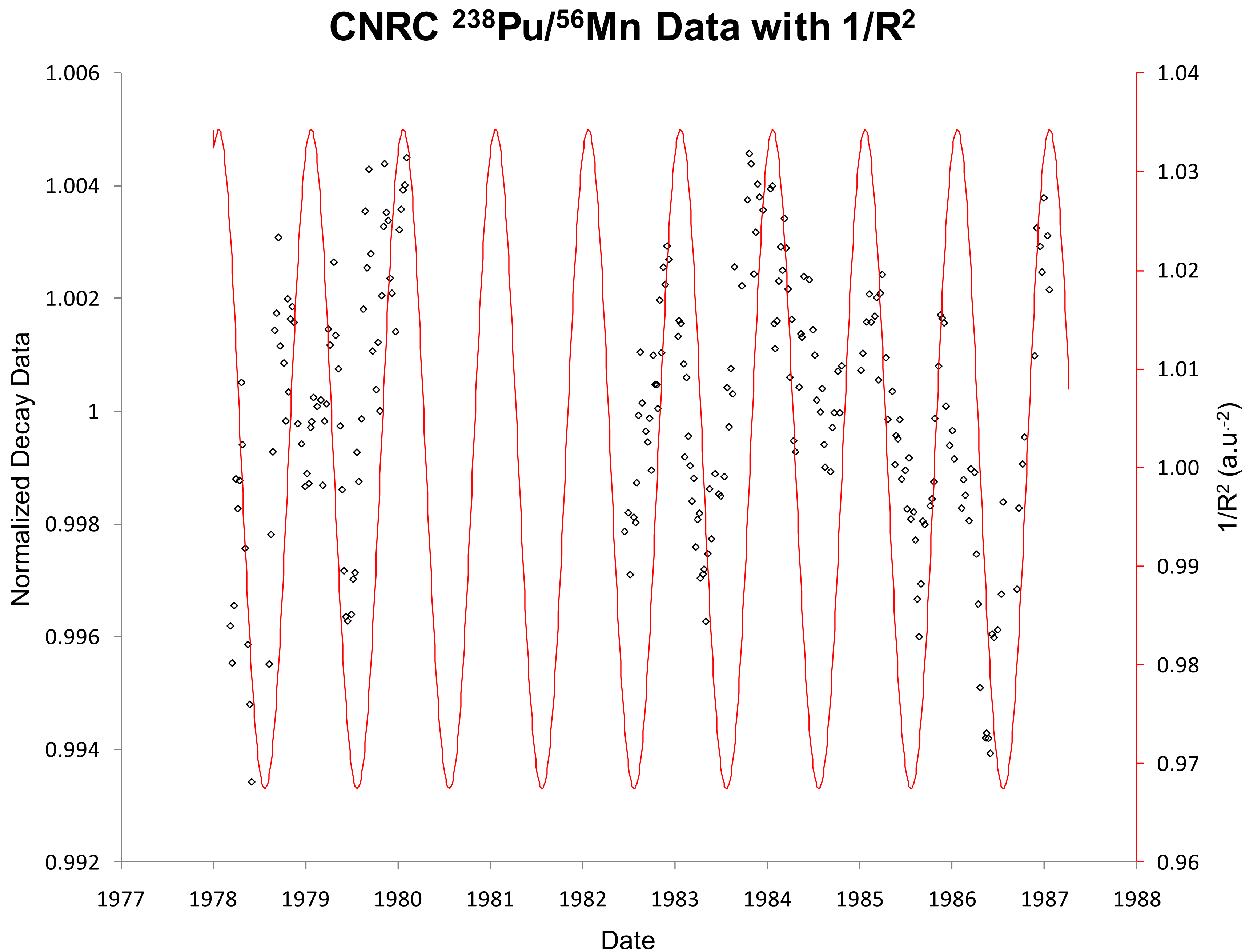
Reference: E. Fischbach, et al., Space Sci. Rev. **145**, 285 (2009)

Correlations between BNL and PTB Data



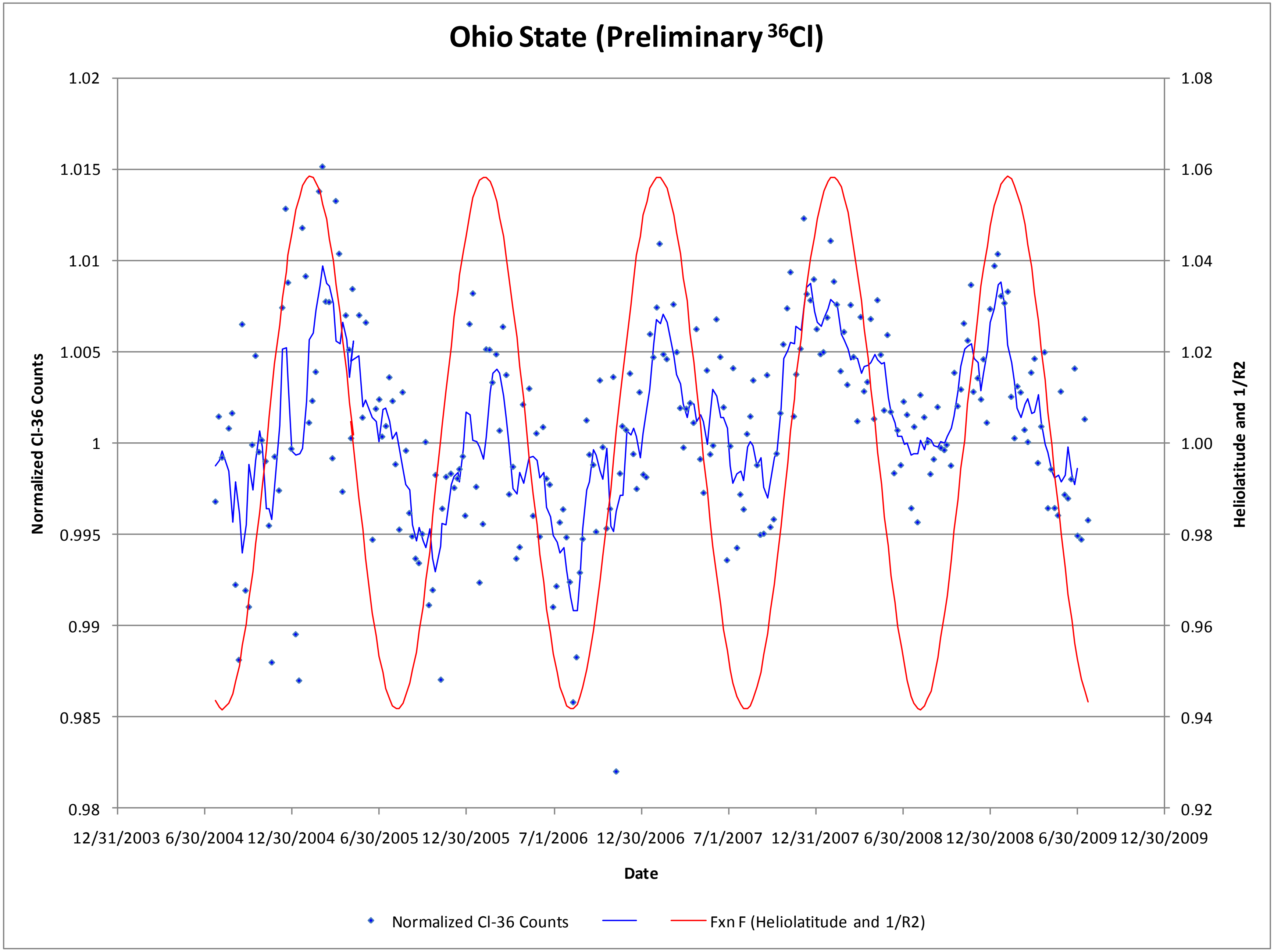
Reference: E. Fischbach, et al., Space Sci. Rev. **145**, 285 (2009)

^{56}Mn (Baylor University)



Reference: K. Ellis, Phys. Med. Biol., **35**, 1079-1088 (1990)

^{36}Cl (OSU Research Reactor)



Experiments Showing Beta Decay Rates with Annual Periods

Experiment	Source	Mode	Duration	$\tau_{1/2}$ (d)	Q (keV)	$10^3\xi$
Ellis[7,8]	^{56}Mn	β^-	1978-87	1.1×10^{-1}	3695.5	3
Purdue[9]	^{54}Mn	EC	2008-13	3.1×10^{2}	1377.1	1
Parkhomov[8]	^{60}Co	β^-	1999-03	1.9×10^{3}	2823.9	2
Norman[3,10]	^{22}Na/^{44}Ti	β^+,EC	1994-96	–	–	0.34
	^{22}Na	β^+		9.5×10^{2}	2842.2	–
	^{44}Ti	EC		2.2×10^{3}	267.5	–
Schrader[11]	^{154}Eu	β^-	1990-96	3.1×10^{3}	1968.4	1
Schrader[11]	^{85}Kr	β^-	1990-96	3.6×10^{3}	687.1	1
Falkenberg[12]	^{3}H	β^-	1980-82	4.5×10^{3}	18.59	3.7
Schrader[11]	^{152}Eu	β, EC	1990-96	4.9×10^{3}	1874.3	1
Parkhomov[8]	^{90}Sr	β^-	2000-10	1.1×10^{4}	546.0	1.3
BNL[13]	^{32}Si	β^-	1982-86	5.5×10^{4}	224.5	1.5
Schrader[11]	^{108m}Ag	β^+	1990-96	1.5×10^{5}	1918	1
PTB[14]	^{226}Ra	various	1981-96	5.8×10^{5}	various	1.5
Mathews[15]	^{14}C	β^-	2016	2.2×10^{6}	156.4	2–4
BNL[13]	^{36}Cl	β^-	1982-86	1.1×10^{8}	708.6	1.5
Ohio Sate[16]	^{36}Cl	β^-	2005–2011	1.1×10^{8}	708.6	5.8

$$\frac{\Delta\lambda}{\lambda} \simeq \xi \cos\left(\frac{2\pi t}{T} + \phi\right)$$

$T \sim \mathbf{1\ year}$

Q = Energy released by decay

What's Causing the Annual Periodicities of Beta Decay Rates?

- An unknown instrumental effect caused by the environment
  - Temperature
  - Atmospheric pressure
  - Humidity
  - Radon
  - Muons
- Interesting New Physics?

What can affect nuclear decay rates?

Ingredients of the Decay Rate

$$\lambda \propto (\text{interaction})(\text{phase space})$$

Interaction causing transition
(electromagnetic, strong, weak forces)

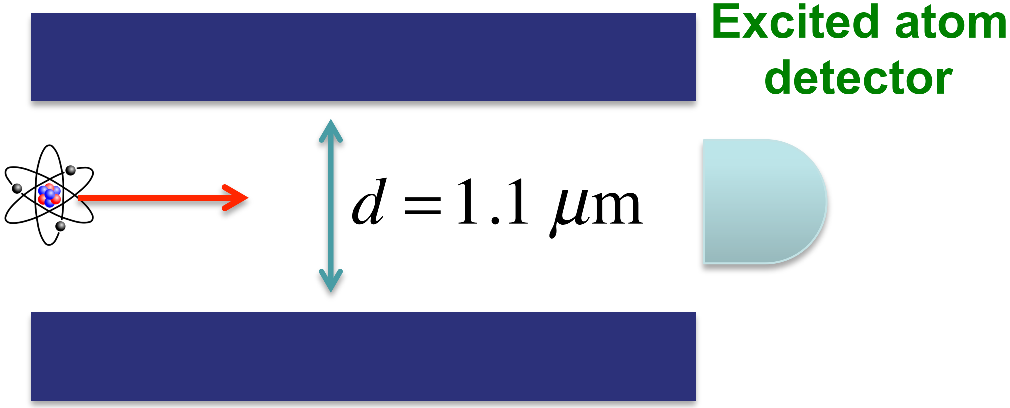
Stronger interaction → faster decay

Available
energy/momentum "space"
for decay products
(conservation laws)

More phase space → faster decay

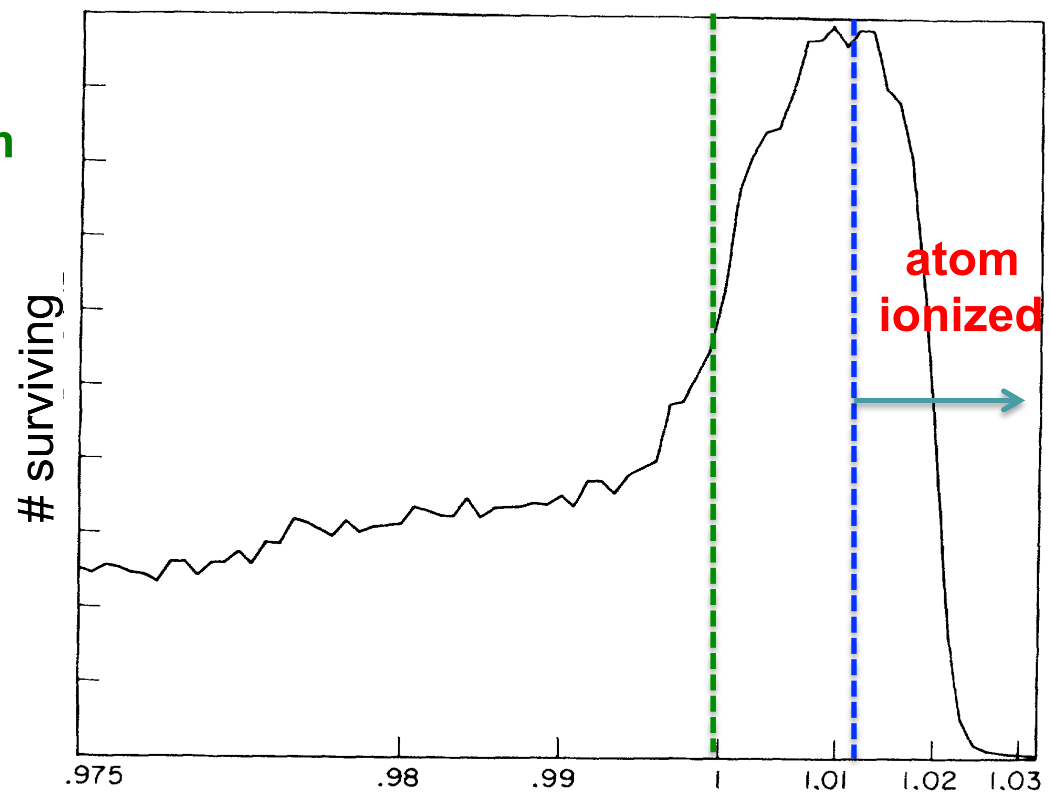
Inhibiting Decay: Cavity QED

Atoms in excited state directed through a cavity:



In order for the light to fit in the cavity,

$$\frac{\text{light wavelength}}{2d} \leq 1$$



$$\frac{\text{light wavelength}}{2d}$$

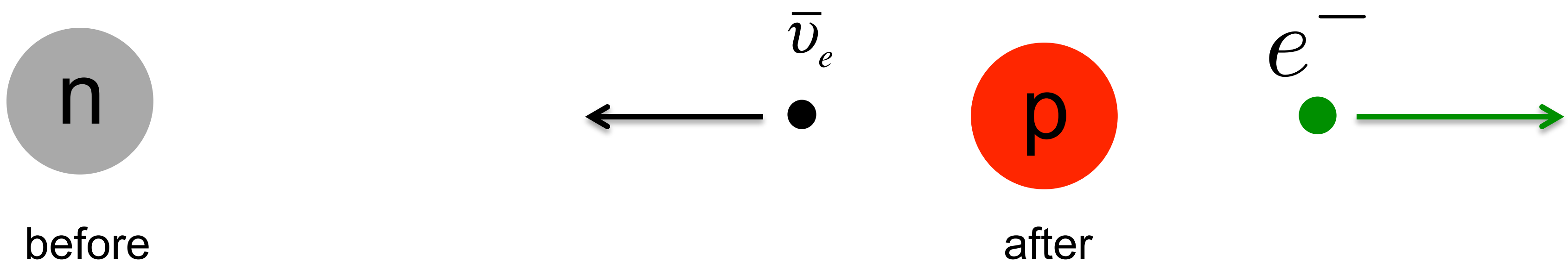
Observed lifetime increased >20 times from free space value!

Reference: R. G. Hulet, et al. Phys. Rev. Lett. **55**, 2137 (1985)

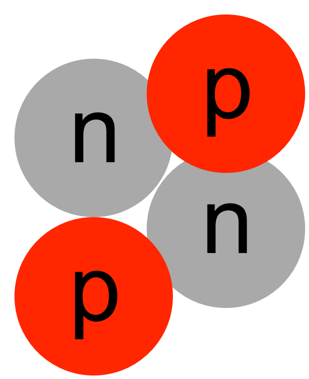
Inhibiting Decay: Neutron in Nucleus

A free neutron is unstable: **half-life ≈ 10 minutes**

$$n \to p + e^{-} + \bar{\upsilon}_e$$



But stable in many nuclei:



Moral

The decay rate λ of an unstable particle is not an intrinsic property of the particle (like mass), but depends on the particle's environment.

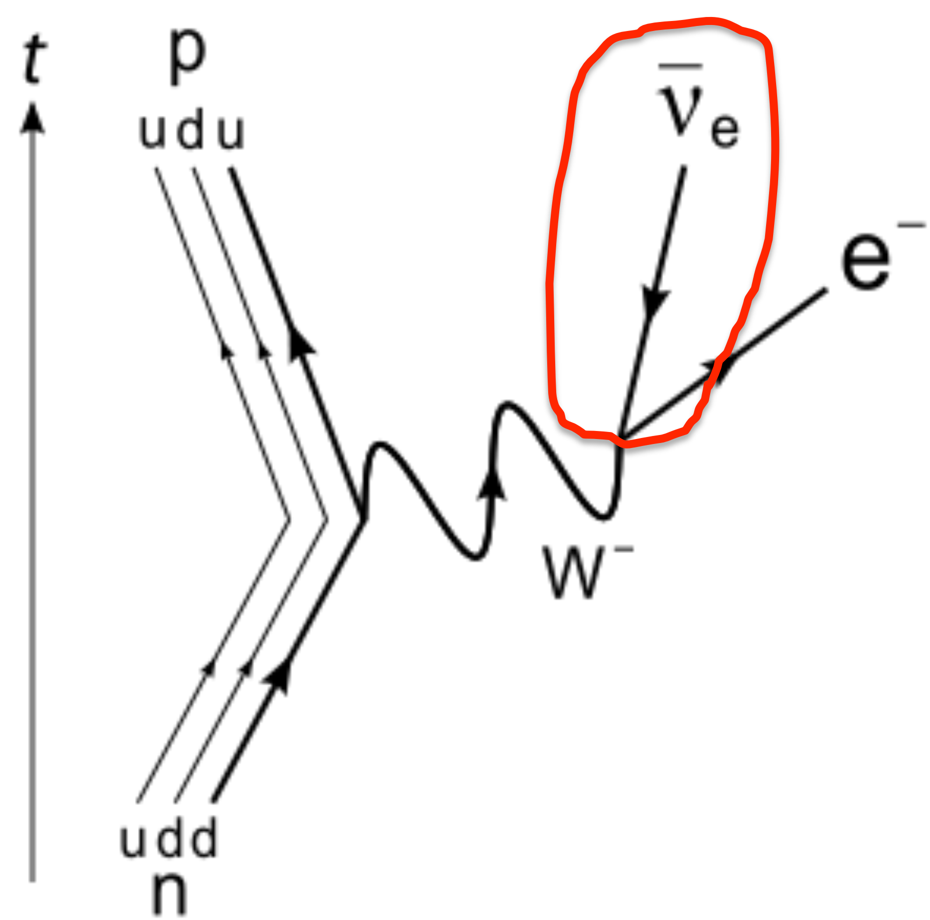
It is conceivable that the decay rate could be affected by external influences.

A Closer Look at Beta Decay

A free neutron decay $n \rightarrow p + e^- + \overline{\upsilon}_e$

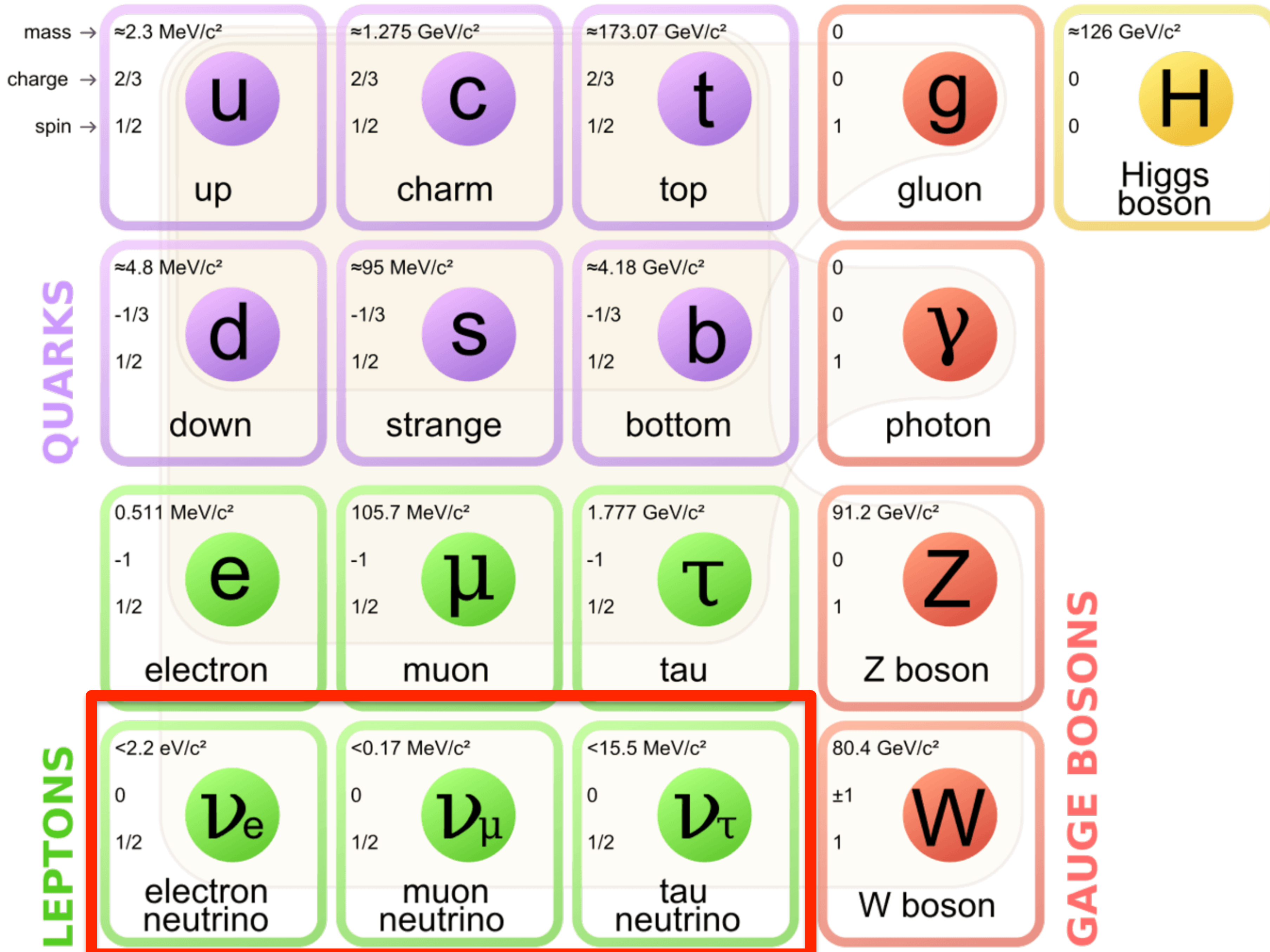
Feynman Diagram

Electron anti-neutrino



https://en.wikipedia.org/wiki/Beta_decay

Standard Model Particles



http://www.iflscience.com/physics/how-neutrinos-which-barely-exist-just-ran-another-nobel-prize/

Neutrinos: Properties

- Only interact with other particles through the weak interaction and gravity
- 50% of the neutrinos in a beam will make it through a light-year of lead
- Created by beta decay, nuclear reactions (Sun, supernovae, reactors, Big Bang)
- Solar Neutrino flux at Earth: ~65 billion /cm^2/s

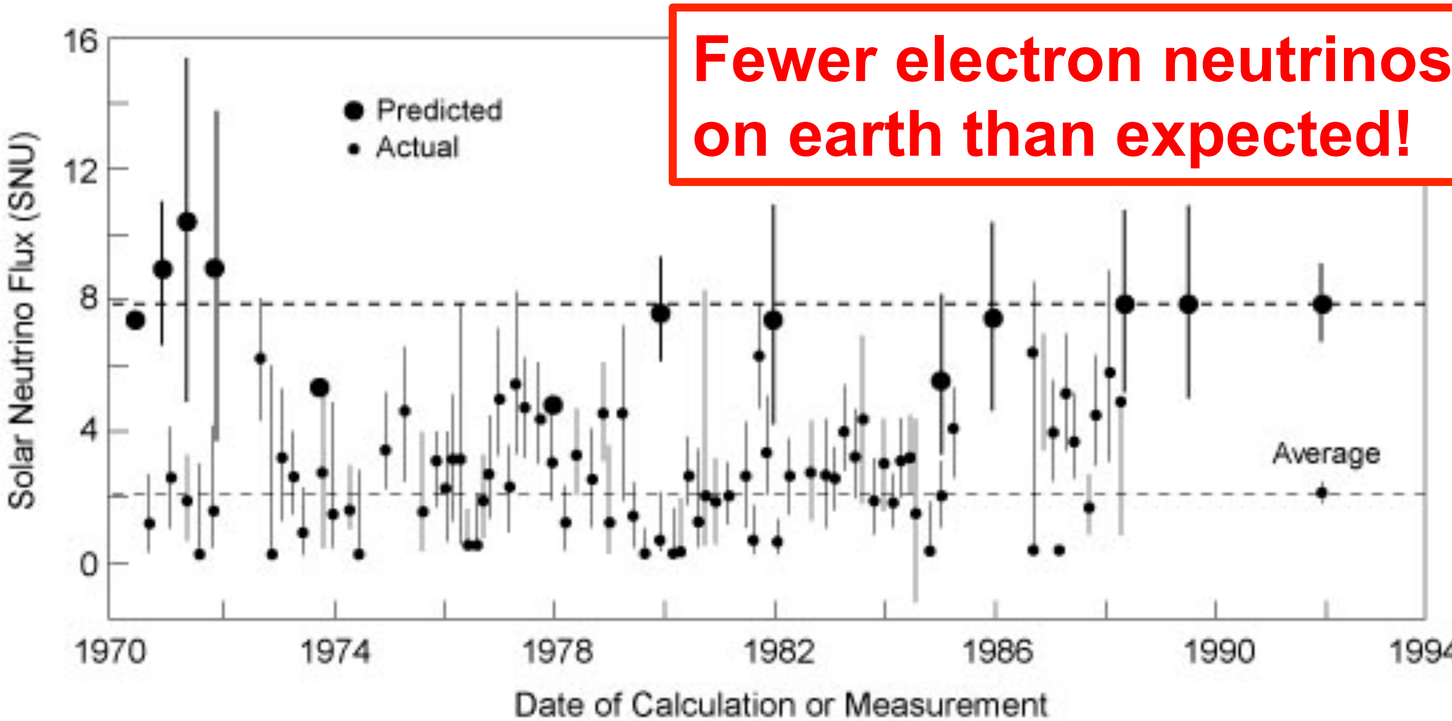
http://www.iflscience.com/physics/how-neutrinos-which-barely-exist-just-ran-another-nobel-prize/

Neutrino Mass

Neutrinos were thought to be massless

$$E^2 = m^2c^4 + p^2c^2 \Rightarrow \boxed{E_\nu = p_\nu c}$$

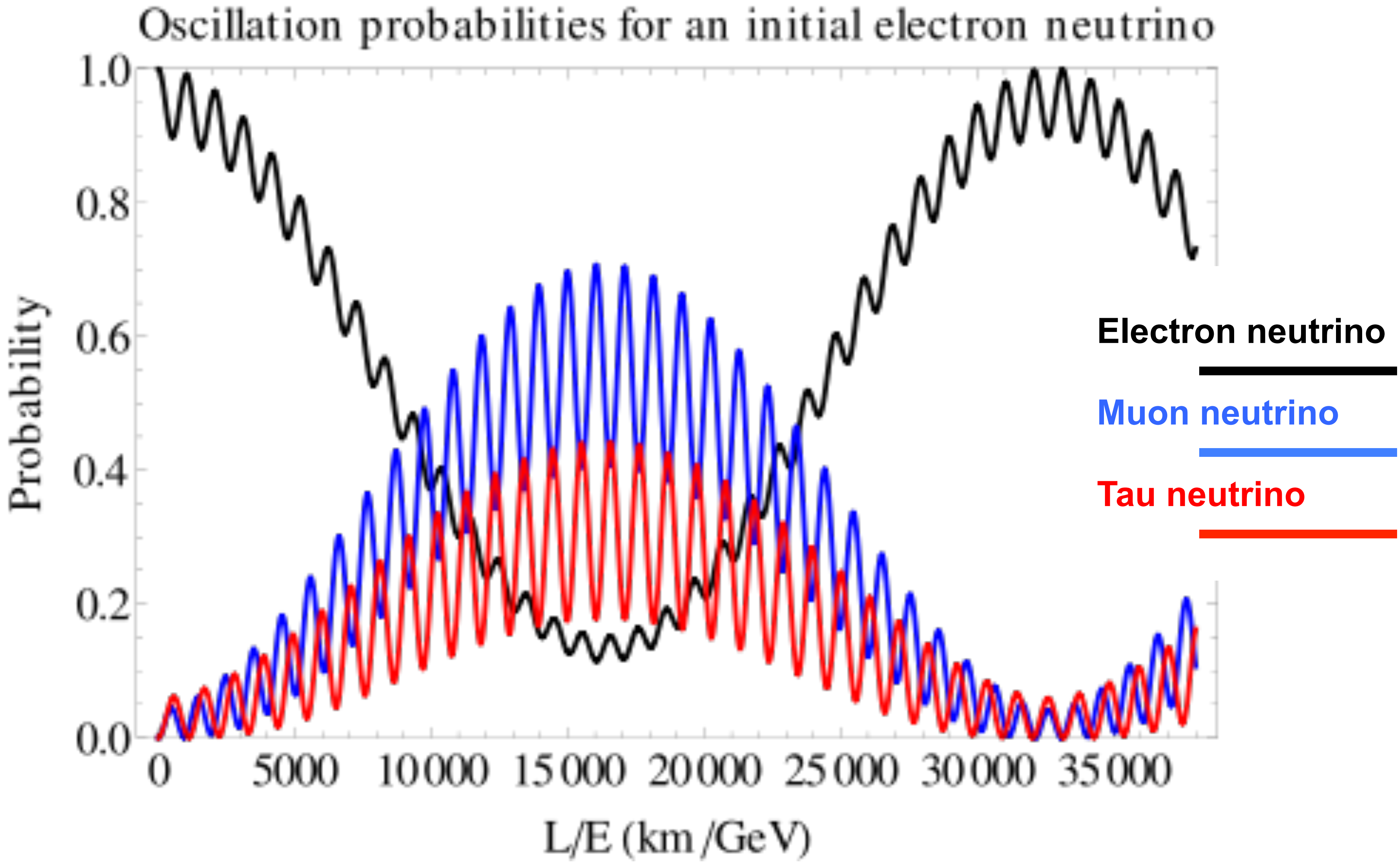
Solar Neutrino Problem:



Fewer electron neutrinos detected on earth than expected!

https://ase.tufts.edu/cosmos/print_images.asp?id=37

Neutrino Oscillations in Vacuum: Massive Neutrinos
2015 Physics Nobel Prize



https://en.wikipedia.org/wiki/Neutrino_oscillation

Neutrino Refractive Index of Matter

Solar Neutrinos Propagating Through the Sun

$$n_{\nu,\bar{\nu}} - 1 = \frac{2\pi}{p^2} \sum_a N_a f^a_{\nu,\bar{\nu}}(0)$$

MSW Effect:

PHYSICAL REVIEW D VOLUME 17, NUMBER 9 1 MAY 1978

Neutrino oscillations in matter

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(Received 6 October 1977; revised manuscript received 5 December 1977)

The effect of coherent forward scattering must be taken into account when considering the oscillations of neutrinos traveling through matter. In particular, for the case of massless neutrinos for which vacuum oscillations cannot occur, oscillations can occur in matter if the neutral current has an off-diagonal piece connecting different neutrino types. Applications discussed are solar neutrinos and a proposed experiment involving transmission of neutrinos through 1000 km of rock.

- Interactions with matter are different for the different flavors of neutrinos.
- Each flavor experiences a different refractive index.
- Neutrino flavor changes and neutrinos travel through matter.

Neutrino Refractive Index of Cosmic Neutrino Background

PHYSICAL REVIEW D **93,** 053004 (2016)

Neutrino refraction by the cosmic neutrino background

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Institute for Theoretical Physics, Karlsruhe Institute of Technology (KIT), 76128 Karlsruhe, Germany
(Received 7 December 2015; published 4 March 2016)

We have determined the dispersion relation of a neutrino test particle propagating in the cosmic neutrino background. Describing the relic neutrinos and antineutrinos from the hot big bang as a dense medium, a matter potential or refractive index is obtained. The vacuum neutrino mixing angles are unchanged, but the energy of each mass state is modified. Using a matrix in the space of neutrino species, the induced potential is decomposed into a part which produces signatures in beta-decay experiments and another part which modifies neutrino oscillations. The low temperature of the relic neutrinos makes a direct detection extremely challenging. From a different point of view, the identified refractive effects of the cosmic neutrino background constitute an ultralow background for future experimental studies of nonvanishing Lorentz violation in the neutrino sector.

DOI: 10.1103/PhysRevD.93.053004

Neutrino Refractive Index and Beta Decay

Neutrinos in a Medium

Index of Refraction: $n = \frac{c}{v}$

For plane wave: $\cos(kx - \omega t)$

$$\omega = \frac{kc}{n} = k_0 c \Rightarrow k = nk_0$$

$$k_0 = \frac{2\pi}{\lambda_{\text{vacuum}}}$$

For a neutrino, $E_\nu = \hbar\omega \quad p_\upsilon = \hbar k$

$$E_\nu \approx \frac{pc}{n}$$

assuming $m_\nu \approx 0$

Now let $n = 1 + \epsilon$ **where** $\epsilon \ll 1$

$$E_\nu \simeq \frac{pc}{1+\epsilon} \simeq (1-\epsilon) p_\nu c$$

Beta Decay in a Medium

Decay Rate

$$\lambda = (\text{matrix elements})(\text{phase space})$$

$$\Downarrow$$

$$\text{phase space} \propto d^3k = n^3 d^3k_0 \quad \text{where} \quad n = 1 + \epsilon$$

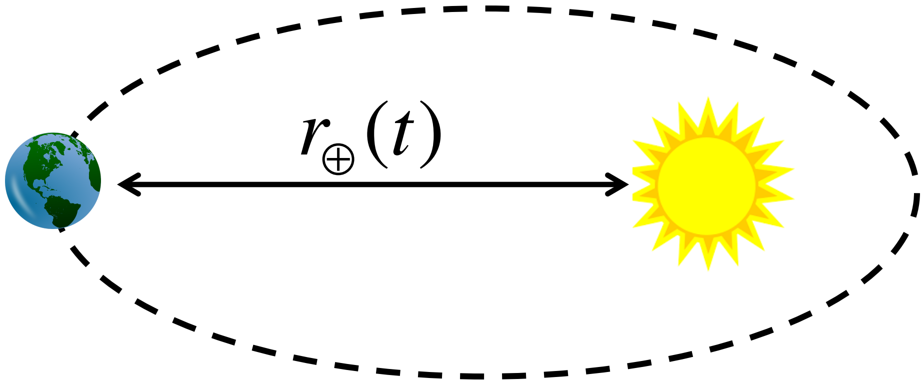
$$\Downarrow$$

$$\lambda \propto n^3 \lambda_0 = (1+\epsilon)^3 \lambda_0 \simeq (1 + 3\epsilon)\lambda_0$$

$$\Downarrow$$

$$\boxed{\frac{\Delta\lambda}{\lambda_0} \simeq 3\epsilon}$$

Annual Modulation of Decay Rates: General Idea



$$r_\oplus(t) \simeq \bar{r}_\oplus \left[1 + \varepsilon_\oplus \cos\left(\frac{2\pi t}{T_\oplus} + \phi_\oplus\right)\right]$$

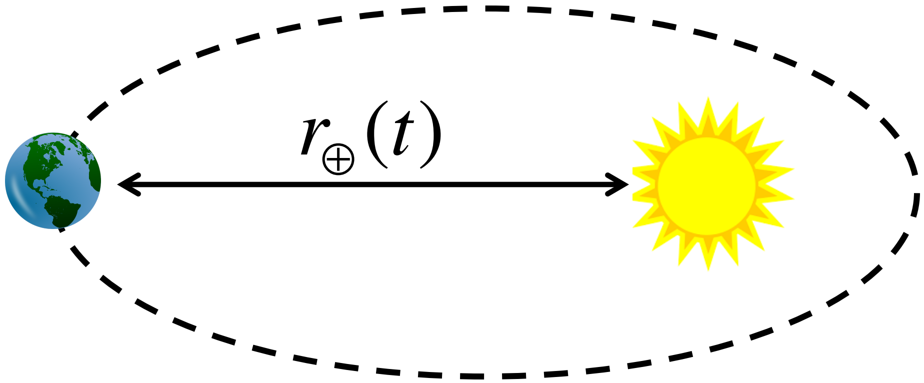
Orbital eccentricity

$$\varepsilon_\oplus \simeq 0.0167$$

An annual sinusoidal variation in beta decay rate can arise if $n_\nu = 1 + \epsilon$ is a function of the Earth-Sun separation $r_\oplus(t)$. This can arise if $\epsilon = \epsilon(r_\oplus)$ is due to

- Solar neutrino flux
- Dark matter
- Relic neutrinos
- Intrinsic violation of Lorentz non-invariance

Annual Modulation of Decay Rates: Example



$$r_\oplus(t) \simeq \bar{r}_\oplus \left[1 + \varepsilon_\oplus \cos\left(\frac{2\pi t}{T_\oplus} + \phi_\oplus\right)\right]$$

Orbital eccentricity

$$\varepsilon_\oplus \simeq 0.0167$$

Assume $n = 1 + \epsilon(r)$ **where** $\epsilon(r) = \zeta \left(\frac{1\ \mathrm{au}}{r}\right)^2$

$$\frac{\Delta\lambda(t)}{\lambda_\oplus} \simeq 6\varepsilon_\oplus \zeta \cos\left(\frac{2\pi t}{T_\oplus} - \phi_\oplus + \pi\right)$$

To produce observed variations: $\xi \simeq 6\varepsilon_\oplus \zeta \sim 10^{-3}$

Other Consequences of Neutrino Refractive Index

1. **Would affect neutrino's speed:** $v = \frac{c}{n}$

   - **Current neutrino speed measurements apply to higher energy neutrinos**

2. **Would affect neutrino mass experiments:**

$$m_{\text{eff}}^2 \simeq m_\nu^2 - 2\epsilon c^2 p_\nu^2$$

   - **A number of neutrino mass experiments find results consistent with** $m_{\text{eff}}^2 < 0$

Current Particle Data Group value for electron neutrino:

$$m_{\text{eff}}^2 = -0.6 \pm 1.9 \text{ eV}$$

What's Causing Annual Periodicities in Beta Decay Data?

1. Most likely explanation is instrumental/environmental effects of unknown origin.
2. Sameness of the amplitude of the variations $\Delta\lambda/\lambda$ for beta decay of many different nuclei can be understood as a consequence of neutrinos propagating through a medium of undetermined nature.
3. There is no shortage of possible sources for such a "medium" (relic neutrinos, dark matter, dark energy…)
4. Such a refractive index would also affect the speed of neutrinos, observed mass of neutrinos, and …
5. This is a fun project, touching upon many very interesting areas of physics, which still might be able to tell us something fundamental about our universe.

Thank you!