Neutrinos, and Why I'm Obsessed With Them

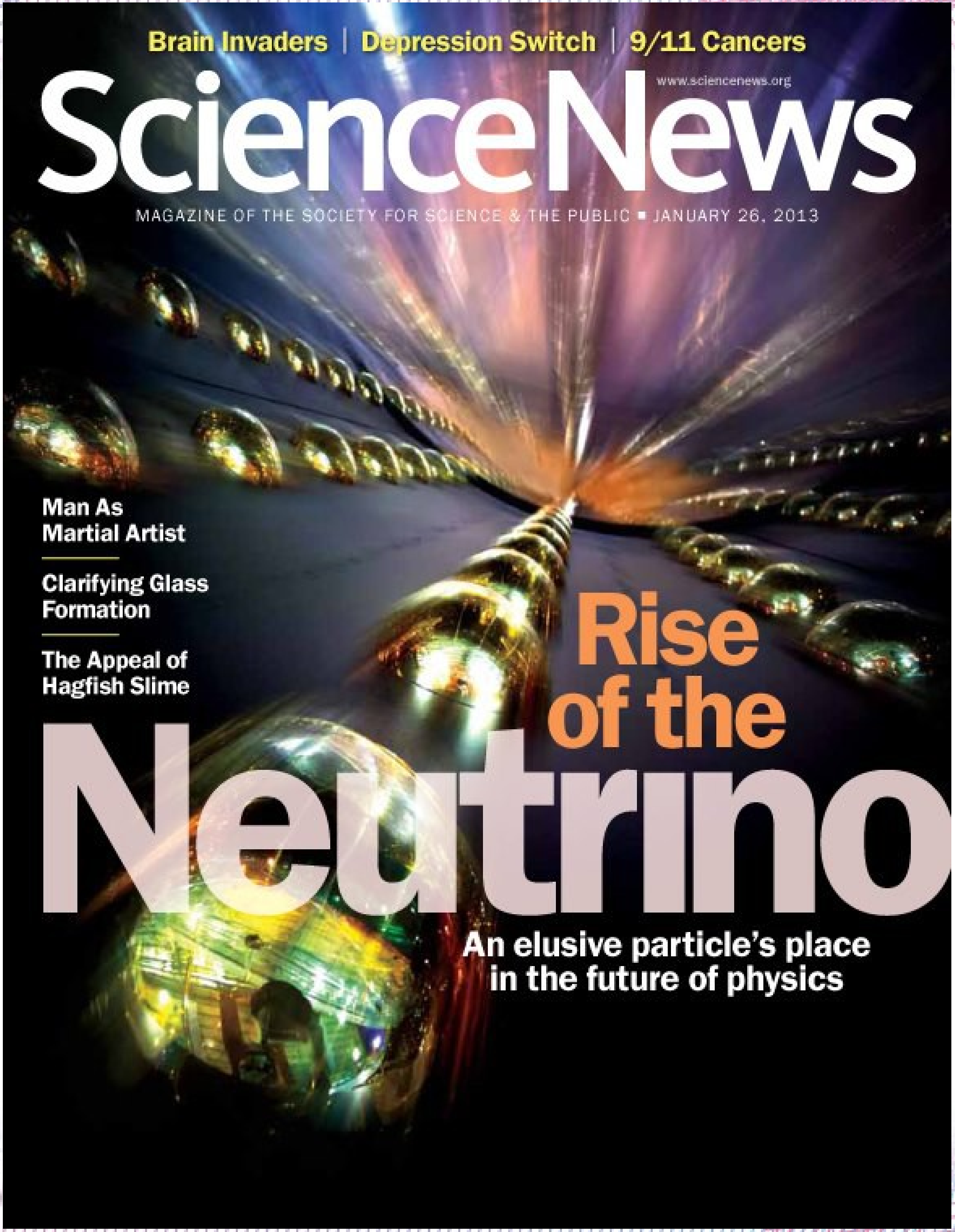
Miriam Diamond
PSIminar, Feb 28 2013

ELECTRON-NEUTRINO
This minuscule bandit is so light, he is practically massless.

MUON-NEUTRINO
Like the other 2 neutrinos, he's got an identity crisis from oscillation.

TAU-NEUTRINO
He's a tau now, but what type of neutrino will he be next?

particlezoo.net



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MAGAZINE OF THE SOCIETY FOR SCIENCE & THE PUBLIC ■ JANUARY 26, 2013

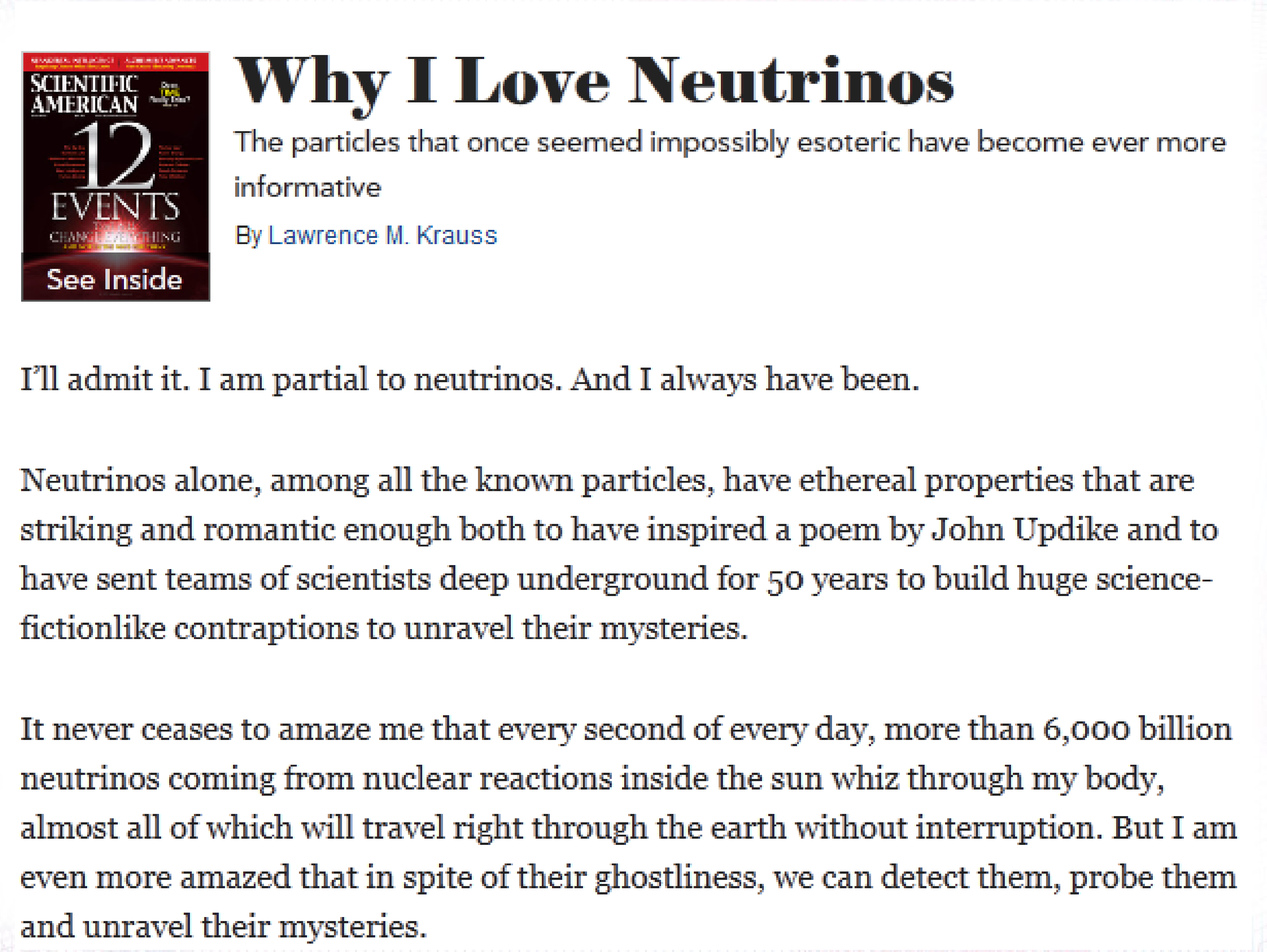
Man As Martial Artist

Clarifying Glass Formation

The Appeal of Hagfish Slime

Rise of the Neutrino

An elusive particle's place in the future of physics



Why I Love Neutrinos

The particles that once seemed impossibly esoteric have become ever more informative

By Lawrence M. Krauss

I'll admit it. I am partial to neutrinos. And I always have been.

Neutrinos alone, among all the known particles, have ethereal properties that are striking and romantic enough both to have inspired a poem by John Updike and to have sent teams of scientists deep underground for 50 years to build huge science-fictionlike contraptions to unravel their mysteries.

It never ceases to amaze me that every second of every day, more than 6,000 billion neutrinos coming from nuclear reactions inside the sun whiz through my body, almost all of which will travel right through the earth without interruption. But I am even more amazed that in spite of their ghostliness, we can detect them, probe them and unravel their mysteries.

NEUTRINOS

- Motivation from Experiment
- Experimental Detection
- The Solar Neutrino Problem
- Neutrino Masses & Oscillations
- Sudbury Neutrino Observatory (SNO)
- Current Frontiers of Neutrino Research
  - Mass Splittings & Oscillation Parameters
  - Right-Handed Neutrinos
  - Neutrino Astrophysics
  - Geoneutrinos
  - Dirac or Majorana?
    - Double Beta Decay
    - Same-Sign Lepton Pairs at LHC
  - Matter-Antimatter Asymmetry
  - Some Examples of Neutrino Models

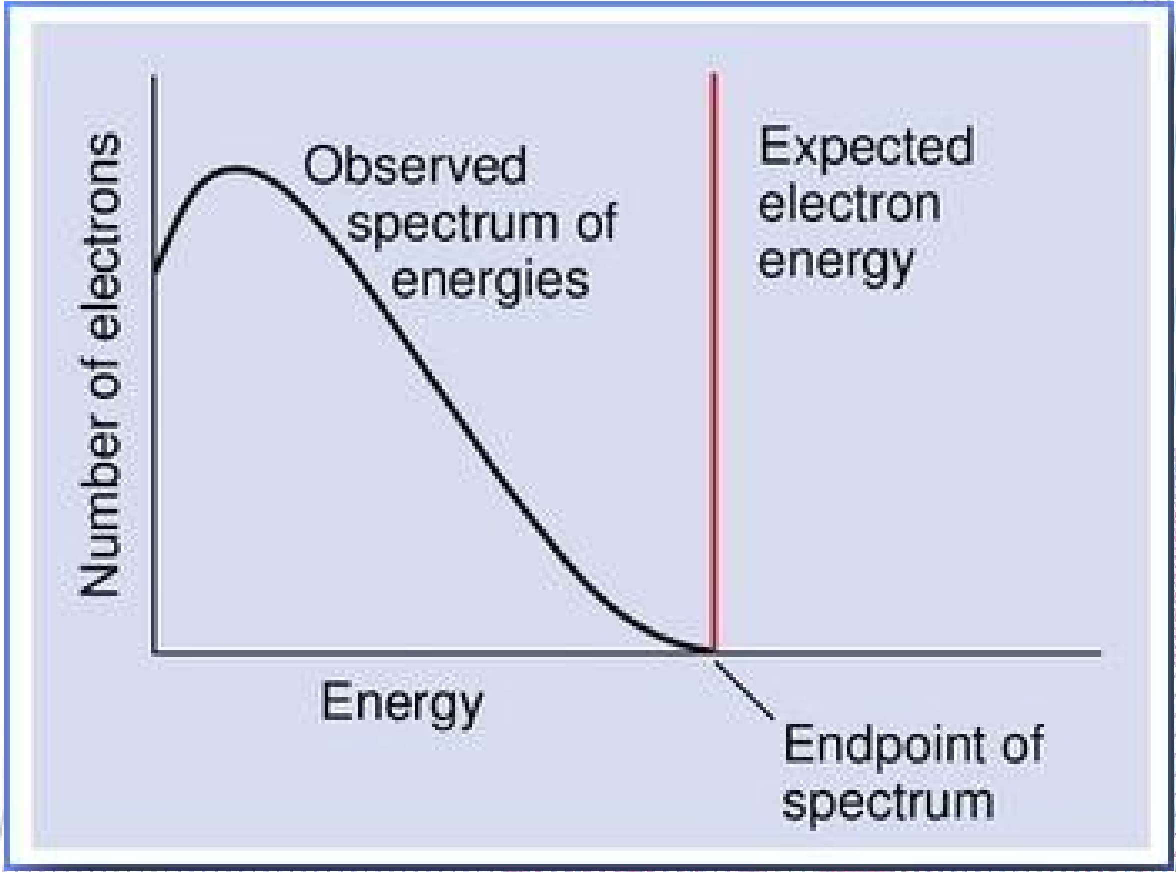
Motivation from Experiment

- Nuclear beta decay: was thought to be 2-body decay, so electron energy should be the same every time

$n \rightarrow p + e^-$???

- Then came...

Experiment!



Motivation from Experiment

- Bohr's suggestion: energy conservation is violated
- Pauli's suggestion (1930 letter to Tübingen conference, 1933 publication at 7th Solvay Conference): 3-body decay, with an invisible neutral particle carrying away some of the energy. But this particle would have to be extremely weakly interacting!

"I have done a terrible thing. I have postulated a particle that cannot be detected."

- Fermi coined the term "neutrino" (little neutral one) in 1934
- Muon-neutrino observed in 1962 (Brookhaven)
- Tau-neutrino observed in 2000 (Fermilab DONUT)

Experimental Detection

- Mean free path of a 1MeV neutrino: ~60 light-years of water!
- Of neutrinos travelling through the Earth, ~1 in 10^{11} interacts
- Main strategies:
  - Neutrino telescopes (Sun produces over 200 trillion trillion trillion neutrinos per second)
  - Take advantage of beams from particle accelerators
  - Set up detectors near nuclear reactors
- Put neutrino experiments underground, to avoid cosmic ray backgrounds

Experimental Detection

- β-decay: electron anti-neutrinos only

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

- CC (charged-current): electron-neutrinos only

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

- NC (neutral-current): involves all neutrino flavours equally

$\nu_x + d \rightarrow p + n + \nu_x$

- ES (elastic-scattering): more likely to involve electron-neutrinos, but can involve muon- or tau- neutrinos

$\nu_x + e^- \rightarrow \nu_x + e^-$

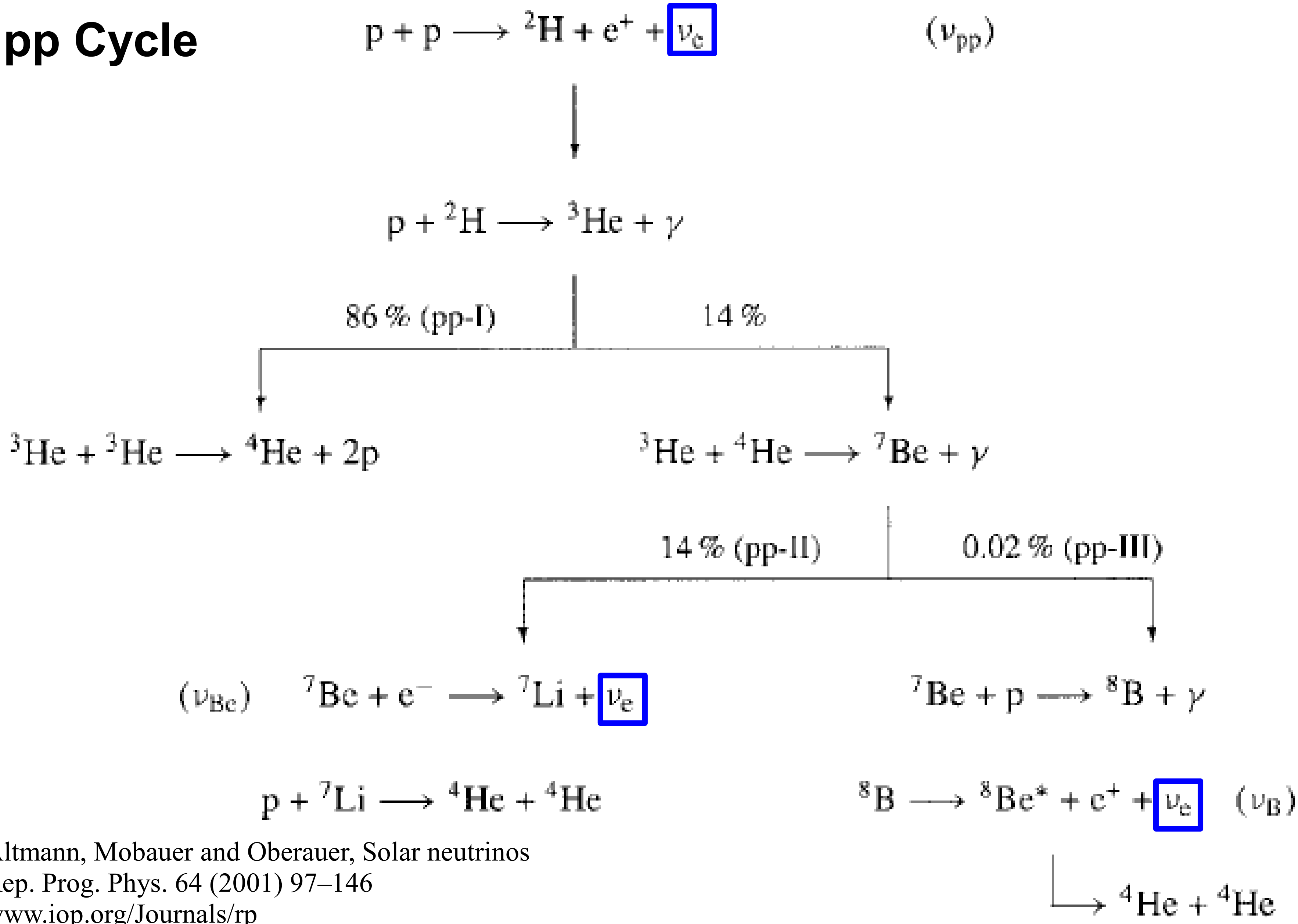
- Missing Transverse Energy (mE_T) in collisions at particle accelerators

Solar Neutrino Problem

- Neutrinos produced in fusion reactions in the core of the Sun escape unhindered
- Based on models of solar dynamics and nuclear processes, we thought we should be able to make good predictions of solar neutrino production rates
- But... more surprises from experiment!
  - Davis (Homestake mine, South Dakota, 1967) radio-chemistry assay with 600 tonne chlorine tank: only one-third the expected number of neutrino events
  - Kamioka (Japan, 1986) light water Cherenkov experiment: only half the expected events
  - SAGE, GALLEX (1990s) gallium detectors: only 60-70% the expected rate
- And, the neutrino deficit appeared to be energy-dependent

Solar Neutrino Problem

pp Cycle



$p + p \longrightarrow {}^{2}H + e^{+} + \boxed{\nu_e}$ (ν_{pp})

$p + {}^{2}H \longrightarrow {}^{3}He + \gamma$

86 % (pp-I) | 14 %

${}^{3}He + {}^{3}He \longrightarrow {}^{4}He + 2p$

${}^{3}He + {}^{4}He \longrightarrow {}^{7}Be + \gamma$

14 % (pp-II) | 0.02 % (pp-III)

(ν_{Be}) ${}^{7}Be + e^{-} \longrightarrow {}^{7}Li + \boxed{\nu_e}$

$p + {}^{7}Li \longrightarrow {}^{4}He + {}^{4}He$

${}^{7}Be + p \longrightarrow {}^{8}B + \gamma$

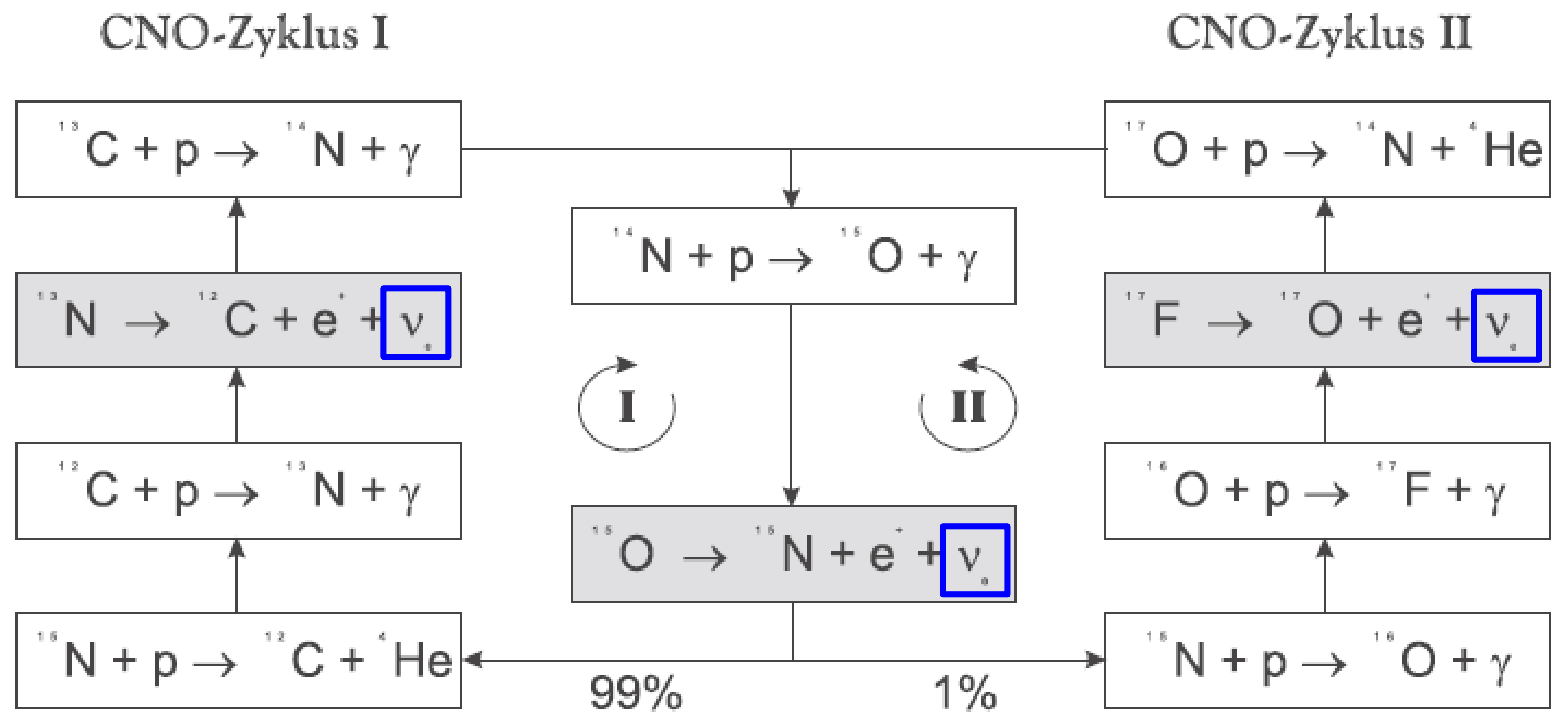
${}^{8}B \longrightarrow {}^{8}Be^{*} + e^{+} + \boxed{\nu_e}$ (ν_{B})

$\longrightarrow {}^{4}He + {}^{4}He$

Altmann, Mobauer and Oberauer, Solar neutrinos
Rep. Prog. Phys. 64 (2001) 97–146
www.iop.org/Journals/rp

Solar Neutrino Problem

CNO Cycle



CNO-Zyklus I

$^{13}C + p \rightarrow {}^{14}N + \gamma$

$^{13}N \rightarrow {}^{12}C + e^{+} + \boxed{\nu_e}$

$^{12}C + p \rightarrow {}^{13}N + \gamma$

$^{15}N + p \rightarrow {}^{12}C + {}^{4}He$

$^{14}N + p \rightarrow {}^{15}O + \gamma$

$^{15}O \rightarrow {}^{15}N + e^{+} + \boxed{\nu_e}$

CNO-Zyklus II

$^{17}O + p \rightarrow {}^{14}N + {}^{4}He$

$^{17}F \rightarrow {}^{17}O + e^{+} + \boxed{\nu_e}$

$^{16}O + p \rightarrow {}^{17}F + \gamma$

$^{15}N + p \rightarrow {}^{16}O + \gamma$

Altmann, Mobauer and Oberauer, Solar neutrinos
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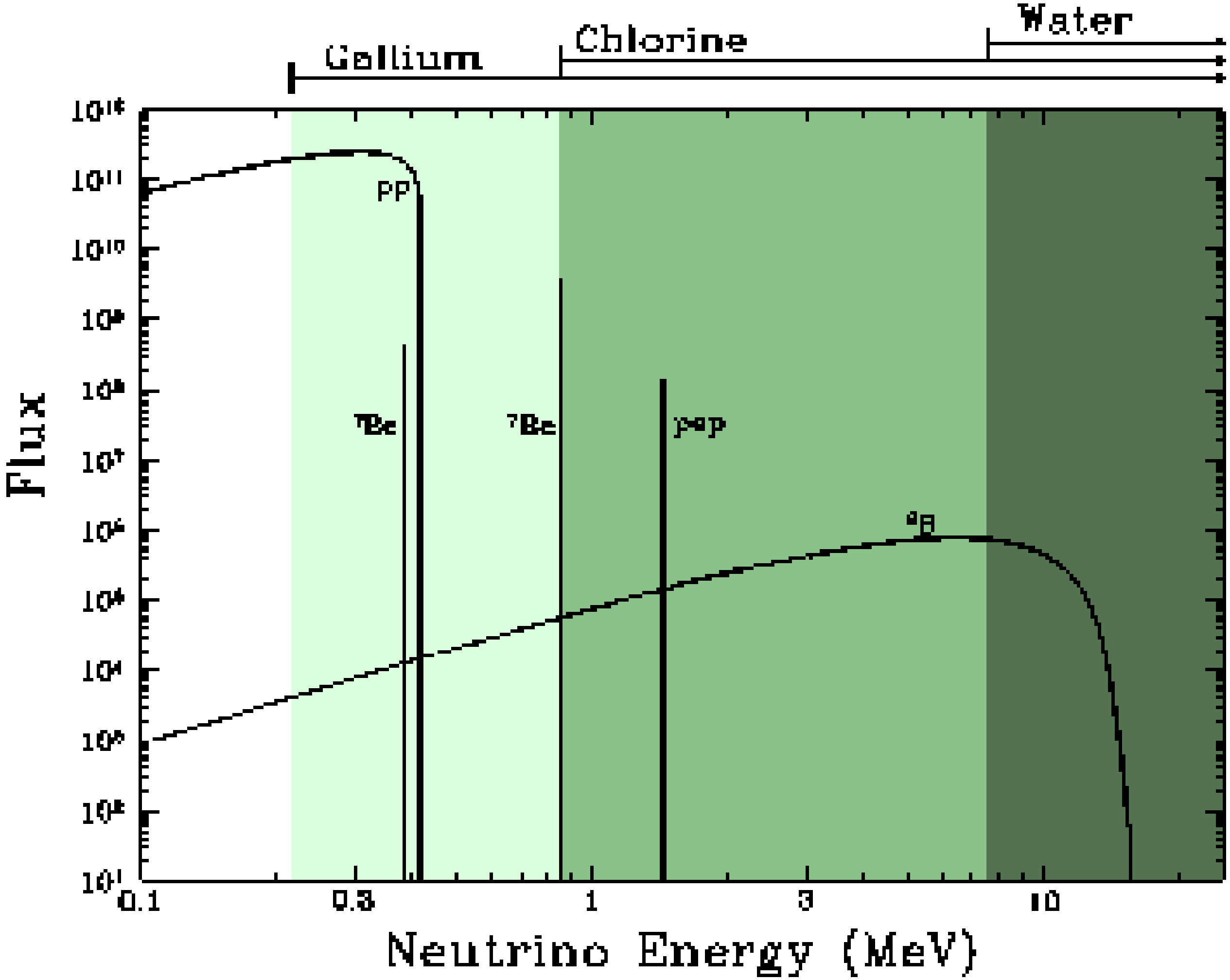
Solar Neutrino Problem

- Solar neutrino spectra:



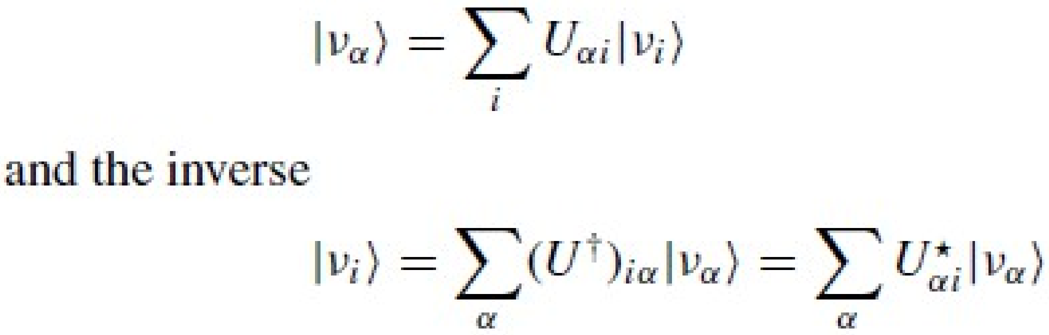
The Neutrino and the SNP
http://www.sno.phy.queensu.ca/sno/neutrino.html

Neutrino Masses & Oscillations

- The solution to SNP!
- Sun only produces electron neutrinos; detectors were only sensitive to electron neutrinos. Neutrinos were undergoing "flavour oscillation" en route to Earth, so their probability of detection was being reduced
- MSW effect: the high mass density in the Sun greatly enhances oscillations compared to vacuum, for neutrinos above a certain energy threshold
- Physicists initially assumed neutrinos were massless. But, due to unitarity considerations, neutrino oscillations can only occur if:
    - Neutrinos have mass
    - At least two of the mass eigenstates are non-degenerate

Neutrino Masses & Oscillations

- Neutrino mass (energy) eigenstates are not the same as the weak-interaction eigenstates (i.e. their relation has non-diagonal matrix elements). Similar to quarks in this regard
  - Weak eigenstate (α): “flavour” in which neutrino is produced / detected
  - Mass eigenstate (i): propagation
- Unitary transformation U: Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix, analogous to CKM:



$$|\nu_\alpha\rangle = \sum_i U_{\alpha i}|\nu_i\rangle$$

and the inverse

$$|\nu_i\rangle = \sum_\alpha (U^\dagger)_{i\alpha}|\nu_\alpha\rangle = \sum_\alpha U^\star_{\alpha i}|\nu_\alpha\rangle$$

Neutrino Masses & Oscillations

- Mass eigenstates are stationary:

$$\nu_i(t) = \exp(-\mathrm{i}E_i t)\nu_i(t = 0)$$

- If we start with a “pure flavour” at time zero, $\nu_\alpha(0)$ evolves as:

$$\nu(t) = \sum_i U_{\alpha i}\exp(-\mathrm{i}E_i t)\nu_i = \sum_{i,\beta} U_{\alpha i}U^\star_{\beta i}\exp(-\mathrm{i}E_i t)\nu_\beta$$

- Probability of finding flavour β at time L ≈ t, for relativistic neutrinos:

$$P(\nu_\alpha \to \nu_\beta) = \left|\sum_i U_{\alpha i}U^\dagger_{i\beta}\exp\left(-\mathrm{i}\frac{m_i^2}{2p_\nu}t\right)\right|^2$$

$$= \sum_i |U_{\alpha i}U^2_{i\beta}|^2 + \mathrm{Re}\sum_i\sum_{j\neq i} U_{\alpha i}U^\dagger_{i\beta}U_{\alpha j}U^\dagger_{j\beta}\exp\left(\mathrm{i}\frac{\Delta m^2_{ij}L}{2E_\nu}\right)$$

Neutrino Masses & Oscillations

- Parameterize in terms of:
  - Δm_{12}, Δm_{23}, Δm_{13}
  - 3 mixing angles (don't worry much about the phase)
    - θ_{12} “solar”
    - θ_{23} “atmospheric”
- Mass eigenstates propagate with different velocities. Interference between them, and therefore oscillations, will only occur if neutrino source remains coherent over a time period comparable to the difference in propagation times
  - This condition is satisfied for solar neutrinos:

$$(V_1 - V_2)\, t \leq c\, \tau_{coh}$$

(t = photon transit time from Sun to Earth,
τ_{coh} = collision time for one proton with another in Sun)

Neutrino Masses & Oscillations

- MSW (Mikheyev, Smirnov, Wolfenstein) Effect: interaction of electron-neutrinos with electrons in matter makes an additional contribution to the Hamiltonian $$H_m = \frac{1}{2p}\begin{pmatrix} m_{2m}^2 & 0 \\ 0 & m_{1m}^2 \end{pmatrix}$$
- Effective masses: $$m_{2m,1m}^2 = \frac{m_1^2 + m_2^2 + A \pm \sqrt{(A - \Delta m^2 \cos(2\theta))^2 + \Delta m^2 \sin^2(2\theta)}}{2}$$ $$A = 2\sqrt{2} G_F N_e p$$
- Effective mass splitting: $m_{2m}^2 - m_{1m}^2 = \Delta m^2 \sqrt{(A/\Delta m^2 - \cos(2\theta))^2 + \sin^2(2\theta)}$
- Effective Hamiltonian in flavour eigenstate basis: $$H_m^\alpha = \frac{1}{4p}\begin{pmatrix} m_1^2 + m_2^2 - \Delta m \cos(2\theta) + 2A & \Delta m^2 \sin(2\theta) \\ \Delta m^2 \sin(2\theta) & m_1^2 + m_2^2 + \Delta m^2 \cos(2\theta) \end{pmatrix}$$
- Effective mixing angle: $$\sin(2\theta_m) = \frac{\sin(2\theta)}{\sqrt{(A/\Delta m^2 - \cos(2\theta))^2 + \sin^2(2\theta)}}$$
- Neutrino resonance in matter: $\frac{A}{\Delta m^2} \approx \cos(2\theta)$

SNO

- Sudbury Neutrino Observatory (SNO): able to detect all 3 flavours of neutrinos
- Observed separately the number of electron neutrinos and the number of all neutrinos
- SNO detector located 6800 feet underground, in INCO's Creighton mine near Sudbury
- 1000 tonnes heavy water, in acrylic vessel 12m in diameter, surrounded by geodesic support structure with 9600 photomultiplier tubes
- Immersed in normal water within 30m barrel-shaped cavity
- Rock overburden as natural shield from cosmic rays; clean lab environment to reduce background signals from radioactive elements present in the mine dust

Measurement of charged current interactions produced by ^{8}B solar neutrinos at the Sudbury Neutrino Observatory

(18 June 2001)

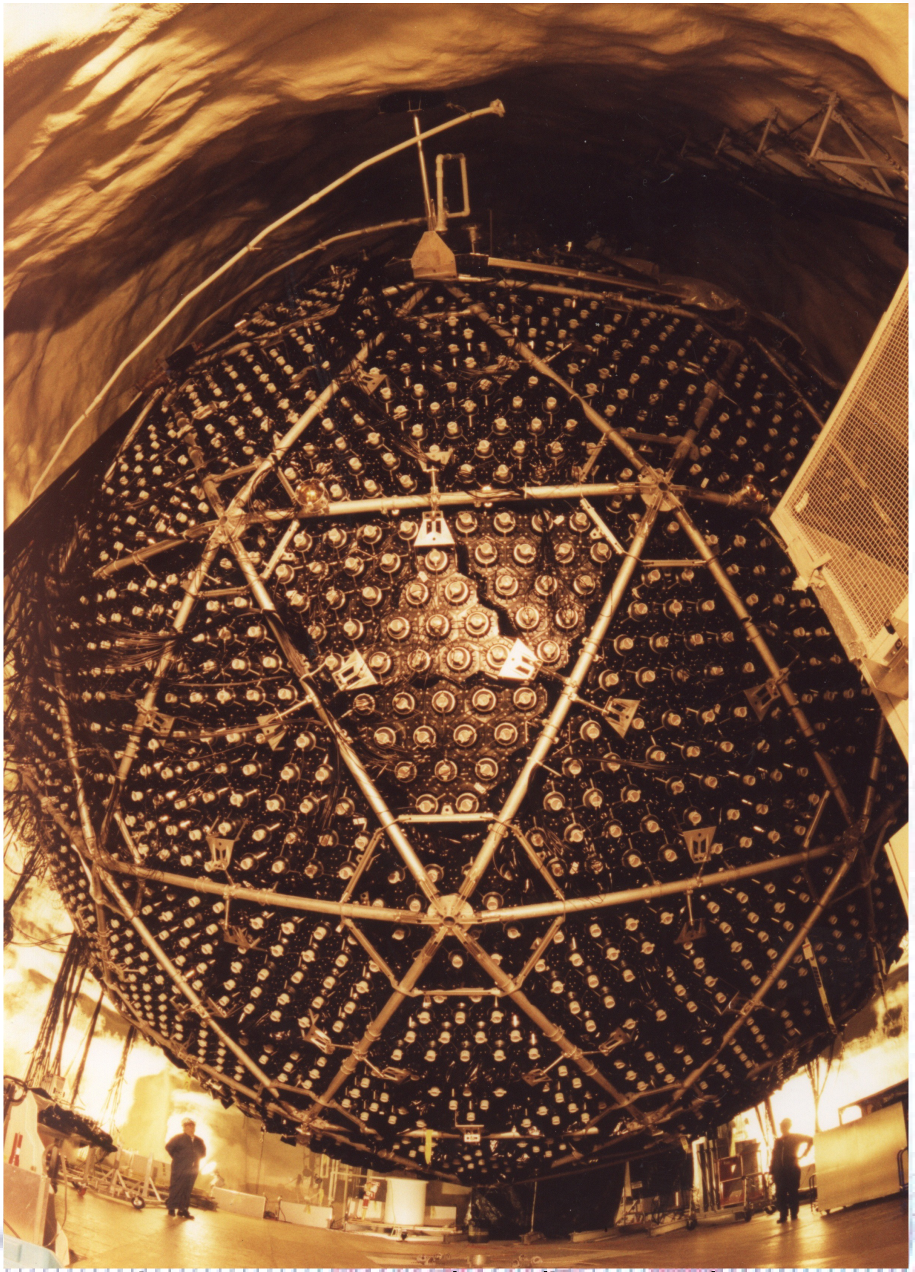
Solar neutrinos from the decay of ^{8}B have been detected at the Sudbury Neutrino Observatory (SNO) via the charged current (CC) reaction on deuterium and by the elastic scattering (ES) of electrons. The CC reaction is sensitive exclusively to ν_e's, while the ES reaction also has a small sensitivity to ν_μ's and ν_τ's. The flux of ν_e's from ^{8}B decay measured by the CC reaction rate is $\phi^{\rm CC}(\nu_e) = 1.75 \pm 0.07\ ({\rm stat.})^{+0.12}_{-0.11}\ ({\rm sys.}) \pm 0.05\ ({\rm theor.}) \times 10^6\ {\rm cm}^{-2}{\rm s}^{-1}$. Assuming no flavor tranformation, the flux inferred from the ES reaction rate is $\phi^{\rm ES}(\nu_x) = 2.39 \pm 0.34\ ({\rm stat.})^{+0.16}_{-0.14}\ ({\rm sys.}) \times 10^6\ {\rm cm}^{-2}{\rm s}^{-1}$. Comparison of $\phi^{\rm CC}(\nu_e)$ to the Super-Kamiokande Collaboration's precision value of $\phi^{\rm ES}(\nu_x)$ yields a 3.3σ difference, providing evidence that there is a non-electron flavor active neutrino component in the solar flux. The total flux of active ^{8}B neutrinos is thus determined to be $5.44 \pm 0.99 \times 10^6\ {\rm cm}^{-2}{\rm s}^{-1}$, in close agreement with the predictions of solar models.

Direct Evidence for Neutrino Flavor Transformation from Neutral-Current Interactions in the Sudbury Neutrino Observatory

(Dated: 19 April 2002)

Observations of neutral-current ν interactions on deuterium in the Sudbury Neutrino Observatory are reported. Using the neutral current, elastic scattering, and charged current reactions and assuming the standard ^{8}B shape, the ν_e component of the ^{8}B solar flux is $\phi_e = 1.76^{+0.05}_{-0.05}({\rm stat.})^{+0.09}_{-0.09}\ ({\rm syst.}) \times 10^6\ {\rm cm}^{-2}{\rm s}^{-1}$ for a kinetic energy threshold of 5 MeV. The non-ν_e component is $\phi_{\mu\tau} = 3.41^{+0.45}_{-0.45}({\rm stat.})^{+0.48}_{-0.45}\ ({\rm syst.}) \times 10^6\ {\rm cm}^{-2}{\rm s}^{-1}$, 5.3σ greater than zero, providing strong evidence for solar ν_e flavor transformation. The total flux measured with the NC reaction is $\phi_{\rm NC} = 5.09^{+0.44}_{-0.43}({\rm stat.})^{+0.46}_{-0.43}\ ({\rm syst.}) \times 10^6\ {\rm cm}^{-2}{\rm s}^{-1}$, consistent with solar models.

SNO



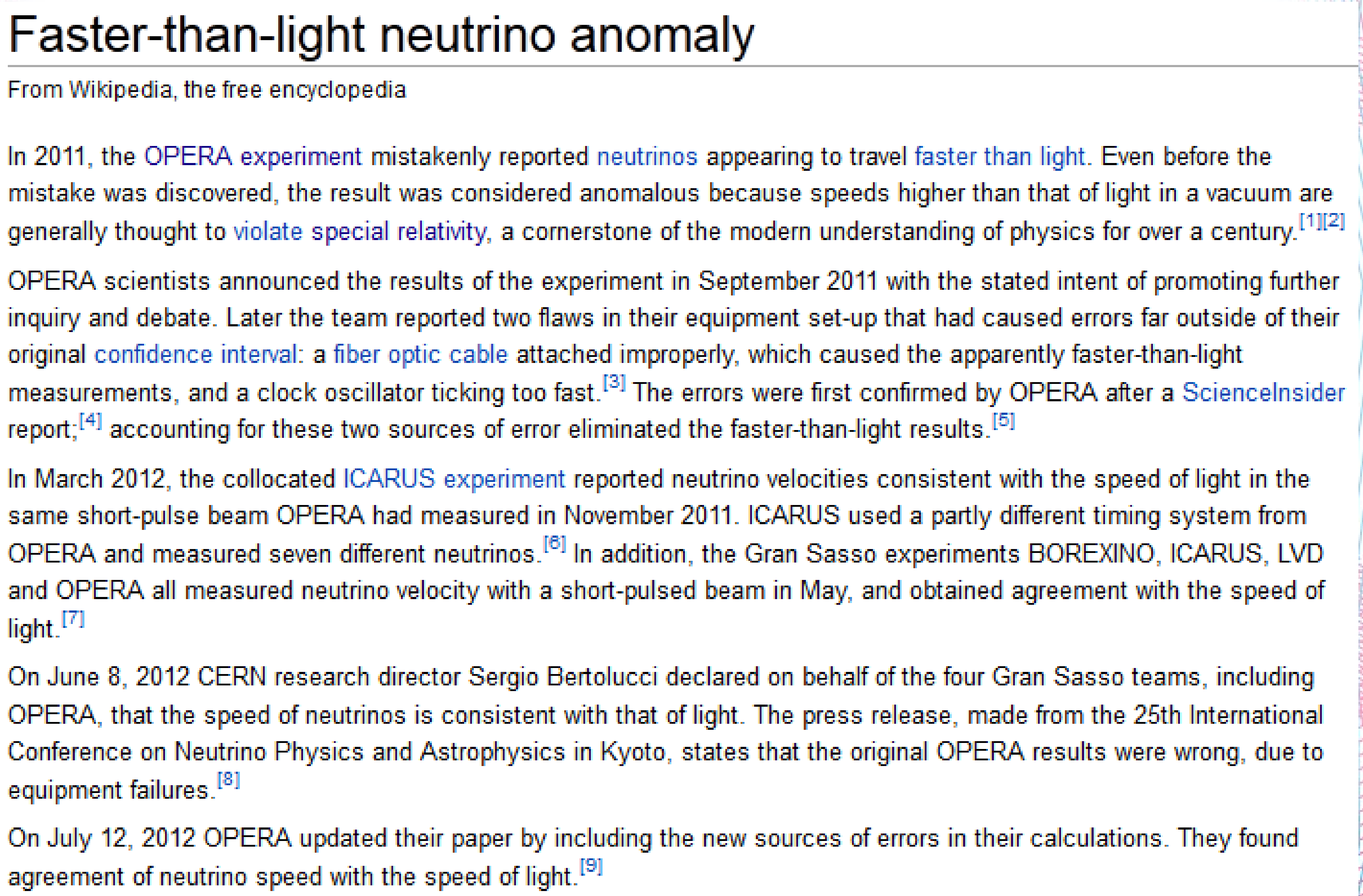
SNO Image Catalogue: http://www.sno.phy.queensu.ca/sno/images/

SNO

SNO Collaboration **Analysis Meeting, Summer 2008**

(can you spot me?)

Current Frontiers of Neutrino Research



Faster-than-light neutrino anomaly

From Wikipedia, the free encyclopedia

In 2011, the OPERA experiment mistakenly reported neutrinos appearing to travel faster than light. Even before the mistake was discovered, the result was considered anomalous because speeds higher than that of light in a vacuum are generally thought to violate special relativity, a cornerstone of the modern understanding of physics for over a century.[1][2]

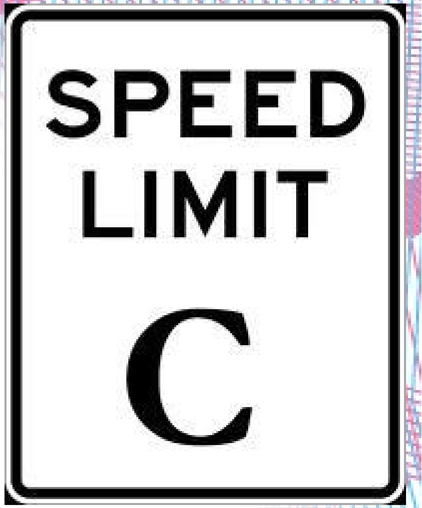
OPERA scientists announced the results of the experiment in September 2011 with the stated intent of promoting further inquiry and debate. Later the team reported two flaws in their equipment set-up that had caused errors far outside of their original confidence interval: a fiber optic cable attached improperly, which caused the apparently faster-than-light measurements, and a clock oscillator ticking too fast.[3] The errors were first confirmed by OPERA after a ScienceInsider report;[4] accounting for these two sources of error eliminated the faster-than-light results.[5]

In March 2012, the collocated ICARUS experiment reported neutrino velocities consistent with the speed of light in the same short-pulse beam OPERA had measured in November 2011. ICARUS used a partly different timing system from OPERA and measured seven different neutrinos.[6] In addition, the Gran Sasso experiments BOREXINO, ICARUS, LVD and OPERA all measured neutrino velocity with a short-pulsed beam in May, and obtained agreement with the speed of light.[7]

On June 8, 2012 CERN research director Sergio Bertolucci declared on behalf of the four Gran Sasso teams, including OPERA, that the speed of neutrinos is consistent with that of light. The press release, made from the 25th International Conference on Neutrino Physics and Astrophysics in Kyoto, states that the original OPERA results were wrong, due to equipment failures.[8]

On July 12, 2012 OPERA updated their paper by including the new sources of errors in their calculations. They found agreement of neutrino speed with the speed of light.[9]

Current Frontiers of Neutrino Research



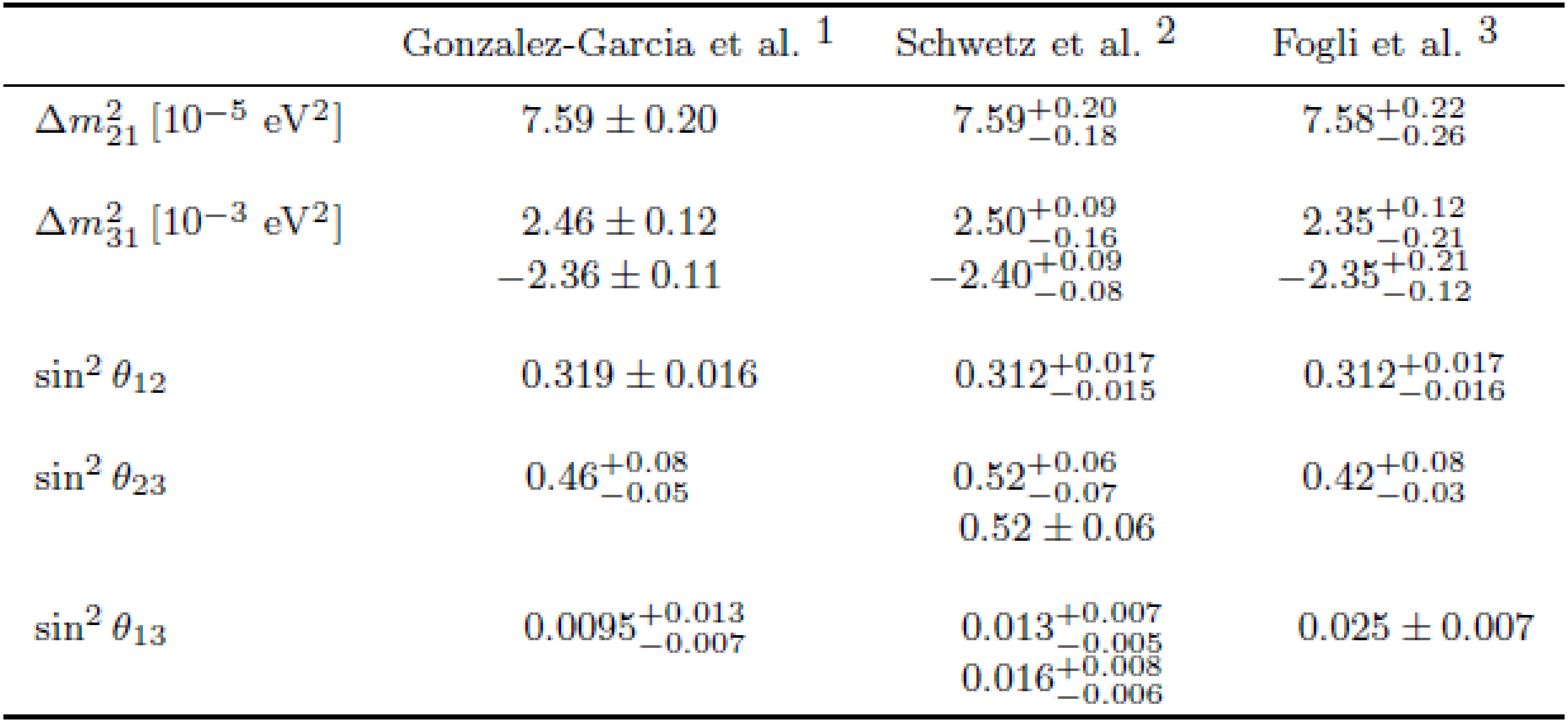
- Bottom line: we have no experimental evidence for superluminal neutrinos!

Helen Grubb's Web-Comic

Mass Splittings & Oscillation Parameters

- Why are neutrino masses so tiny?
    - 6 orders of magnitude lighter than other fermions
- Why is the mass hierarchy so “mild”?
- Inverted or normal mass hierarchy?
    - “Normal”: assume electron-neutrino is mostly made up of the lightest mass eigenstate. “Inverted”: other way around
    - So far, we can experimentally probe the Δm^2 parameters, but not the masses themselves!
- What's with the large mixing angles?
    - Far larger than analogous CKM angles
- Want more accurate measurements of mass splittings and mixing parameters

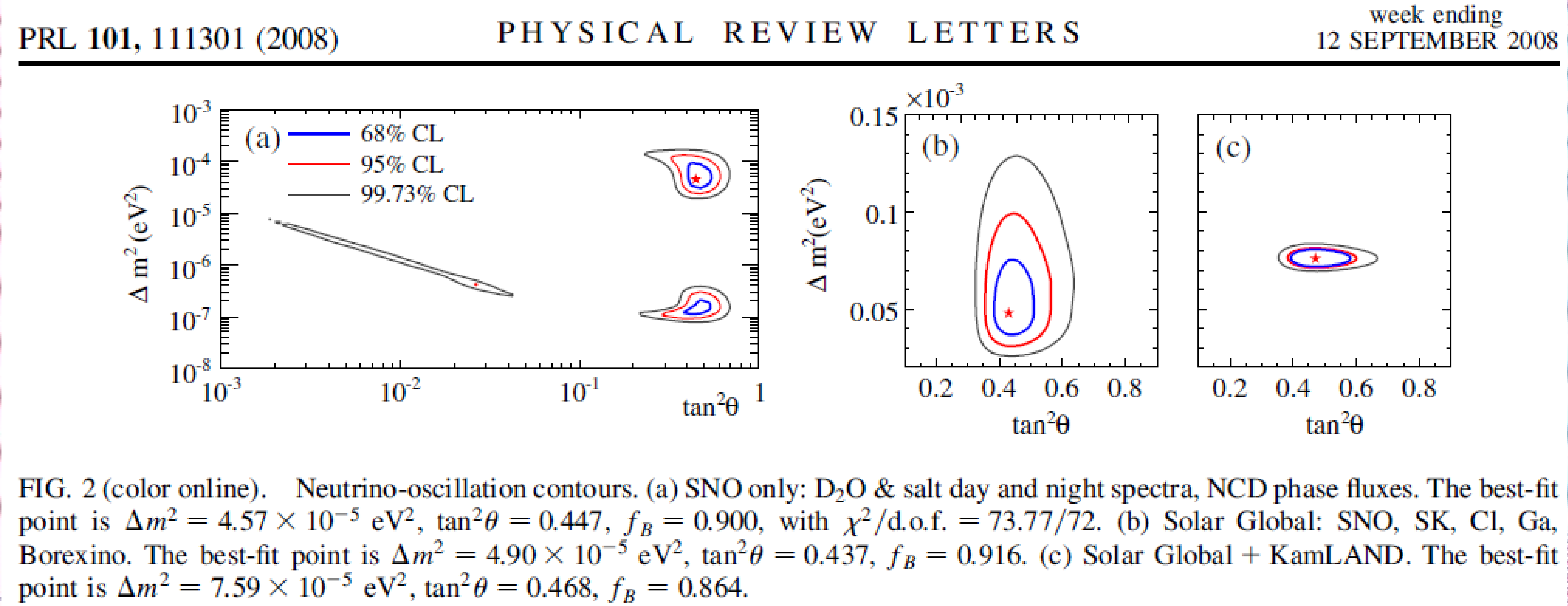
Mass Splittings & Oscillation Parameters



	Gonzalez-Garcia et al.[1]	Schwetz et al.[2]	Fogli et al.[3]
Δm^2_{21} $[10^{-5}\ \mathrm{eV}^2]$	7.59 ± 0.20	$7.59^{+0.20}_{-0.18}$	$7.58^{+0.22}_{-0.26}$
Δm^2_{31} $[10^{-3}\ \mathrm{eV}^2]$	2.46 ± 0.12 -2.36 ± 0.11	$2.50^{+0.09}_{-0.16}$ $-2.40^{+0.09}_{-0.08}$	$2.35^{+0.12}_{-0.21}$ $-2.35^{+0.21}_{-0.12}$
$\sin^2\theta_{12}$	0.319 ± 0.016	$0.312^{+0.017}_{-0.015}$	$0.312^{+0.017}_{-0.016}$
$\sin^2\theta_{23}$	$0.46^{+0.08}_{-0.05}$	$0.52^{+0.06}_{-0.07}$ 0.52 ± 0.06	$0.42^{+0.08}_{-0.03}$
$\sin^2\theta_{13}$	$0.0095^{+0.013}_{-0.007}$	$0.013^{+0.007}_{-0.005}$ $0.016^{+0.008}_{-0.006}$	0.025 ± 0.007

Felipe, Neutrinos and the matter-antimatter asymmetry in the Universe
arXiv:1108.2694v1

Mass Splittings & Oscillation Parameters



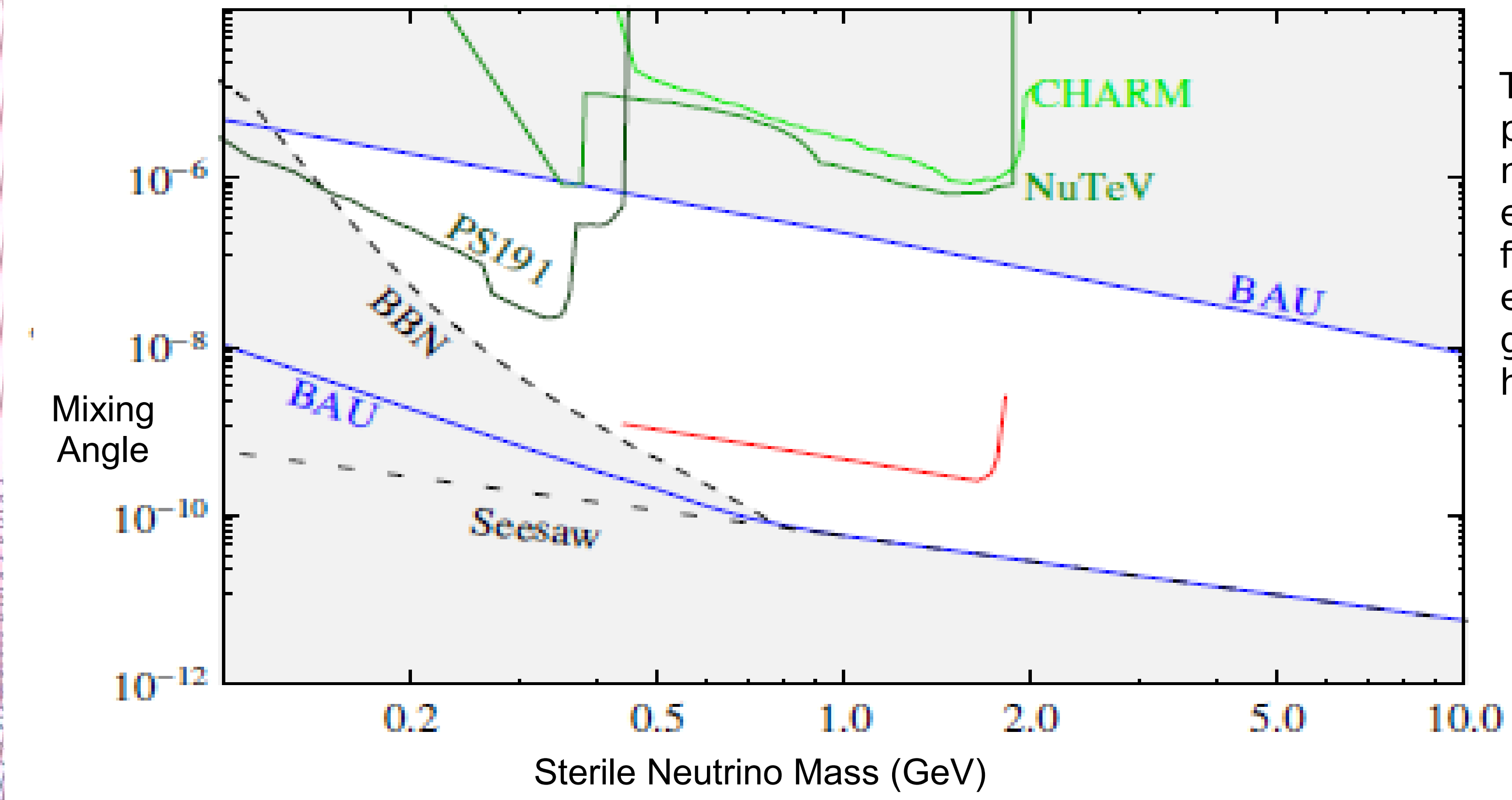
PRL **101,** 111301 (2008) PHYSICAL REVIEW LETTERS week ending 12 SEPTEMBER 2008

FIG. 2 (color online). Neutrino-oscillation contours. (a) SNO only: D_2O & salt day and night spectra, NCD phase fluxes. The best-fit point is $\Delta m^2 = 4.57 \times 10^{-5}$ eV^2, $\tan^2\theta = 0.447$, $f_B = 0.900$, with χ^2/d.o.f. = 73.77/72. (b) Solar Global: SNO, SK, Cl, Ga, Borexino. The best-fit point is $\Delta m^2 = 4.90 \times 10^{-5}$ eV^2, $\tan^2\theta = 0.437$, $f_B = 0.916$. (c) Solar Global + KamLAND. The best-fit point is $\Delta m^2 = 7.59 \times 10^{-5}$ eV^2, $\tan^2\theta = 0.468$, $f_B = 0.864$.

Right-Handed Neutrinos

- Must add right-handed (“sterile”) neutrinos to SM to obtain neutrino masses
- “Sterile” neutrinos would have no interactions except gravitational, Higgs, mixing with active neutrino flavours
- Might have multiple sterile neutrino flavours

- Dark matter candidate?
- Help ensure stability of Higgs mass against quantum corrections?



The allowed region of parameters of sterile neutrinos. Accelerator experiments, searching for heavy neutral leptons exclude regions above green lines. Normal hierarchy.

Gninenko, Gorbunov, and Shaposhnikov,
Search for GeV-scale sterile neutrinos responsible for active neutrino oscillations and baryon asymmetry of the Universe.
arXiv:1301.5516v1

Neutrino Astrophysics

- Type II supernova
  - >99% of gravitational binding energy released as neutrinos
  - Evenly distributed among the 3 flavours, and amongst particles and antiparticles
  - Neutrinos from supernova 1987A (50kpc away, in Large Magellanic Cloud) detected by the Kamiokande II, IMB, and Baksan detectors: 11, 8, and 5 events, respectively, in ~13s. Implications for dark matter, compact dimensions, ...
- “Window to the Sun”: stellar fusion processes, solar flares, solar stability
- Cosmic rays
- Future possibilities: pulsars, gamma-ray bursts, ...

Geoneutrinos

- Anti-neutrinos released in β-decay of radioactive isotopes in Earth's mantle and crust
  - K-40
  - Decay chains of U-238 and Th-232
- Geoneutrino flux serves as indicator of amount of radioactivity present deep inside the Earth
- Radioactivity is thought to be responsible for at least half the heat produced in the Earth
  - Helps tell us how the planet's interior has cooled over time, and how it will behave in the future
- KamLAND (Japan) recent geoneutrino study

Dirac or Majorana?

- Dirac particles: distinct from anti-particles
- Majorana particles: their own anti-particles
- Neutrinos (left- and right-handed) could be either Dirac or Majorana
- Dirac mass term requires very small Yukawa couplings (< 10^{-11})
- See-Saw Mechanism: Majorana mass term interpreted as lowest-order BSM effective operator $y_\nu^2(l\phi)(l\phi)/M$
  - Dimension-5 “Weinberg operator”, where M is mass scale of BSM physics
  - After EWSB, ν's acquire Majorana mass $m_\nu \sim y_\nu^2 v^2/M$
  - Mass easily suppressed if scale M >> electroweak

Double Beta Decay

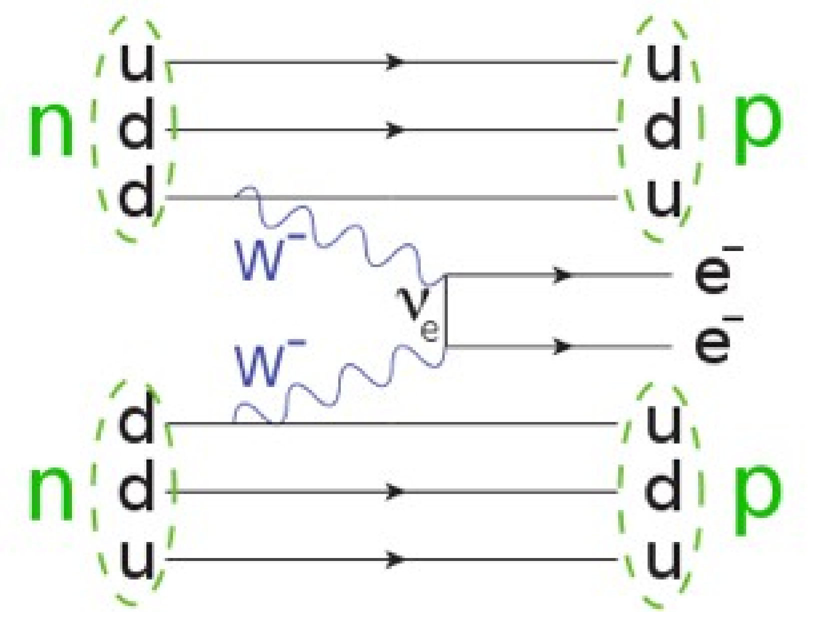
- Double β decay process (when a nucleus is energetically or spin forbidden to decay through single β decay):

  $(A, Z) \rightarrow (A, Z + 2) + 2e^- + 2\bar{\nu}_e$

- **Only if neutrinos are Majorana**: $\bar{\nu}$ emitted by one of the neutrons can be absorbed as ν by the other **(neutrinoless double β decay)**

  $(A, Z) \rightarrow (A, Z + 2) + 2e^-$

  Rate proportional to square of neutrino mass

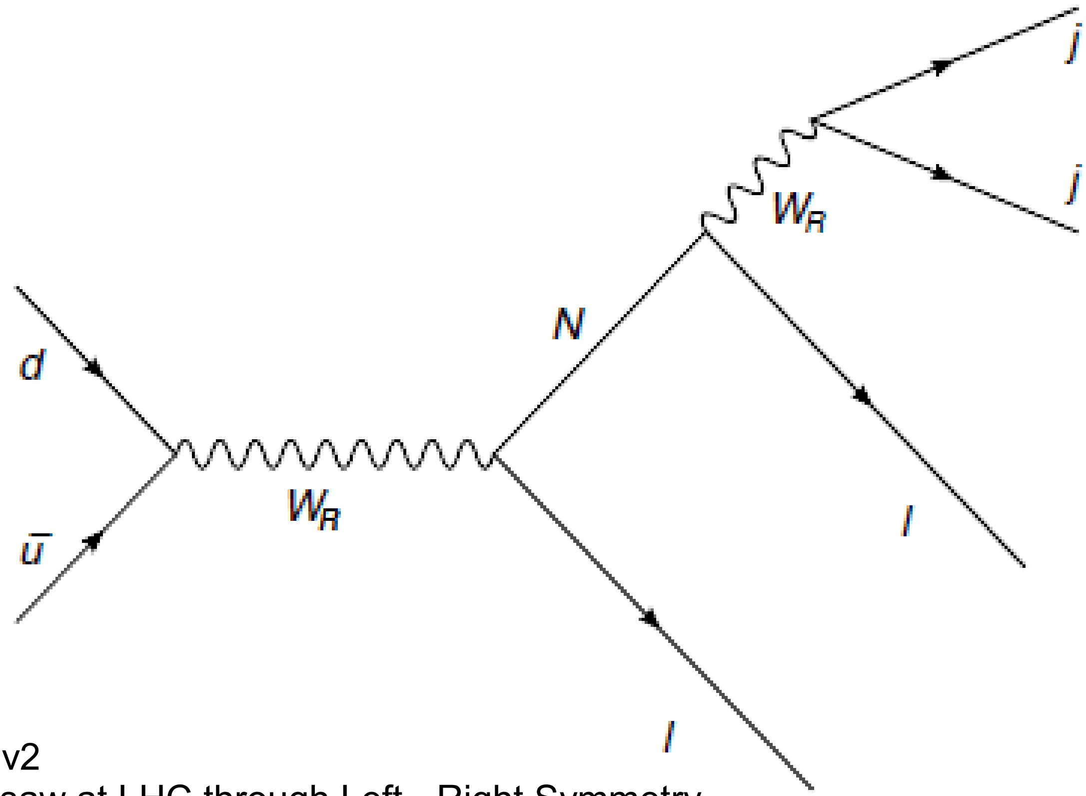


http://snoplus.phy.queensu.ca/Double_Beta.html

Double Beta Decay

- Γ(0νββ) << Γ(ννββ)
- Even ννββ decay is rare: half-life above 10^{20} years (in a sample of 8 billion, 1 would decay in lifetime of universe)
- Experimentally, need:
  - Good energy resolution
  - Large fiducial volume
  - Ability to distinguish the mono-energetic e- pair produced by 0νββdecay from large continuum of e- pairs produced through ννββdecay
- Enriched Xenon Observatory (EXO): uses Xe-136
  - EXO-200 (200kg prototype, currently operating) has set the most stringent limits to date: $T_{1/2} > 1.6 \times 10^{25}$ yr, effective Majorana mass < 140-380 meV
  - nEXO, ("next EXO"): tonne-scale version
- COBRA (Gran Sasso National Laboratory): large array of Cadmium Zinc Telluride semiconductor detectors

Same-Sign Lepton Pairs at LHC



arXiv:1012.4104v2
Senjanovic, Seesaw at LHC through Left - Right Symmetry

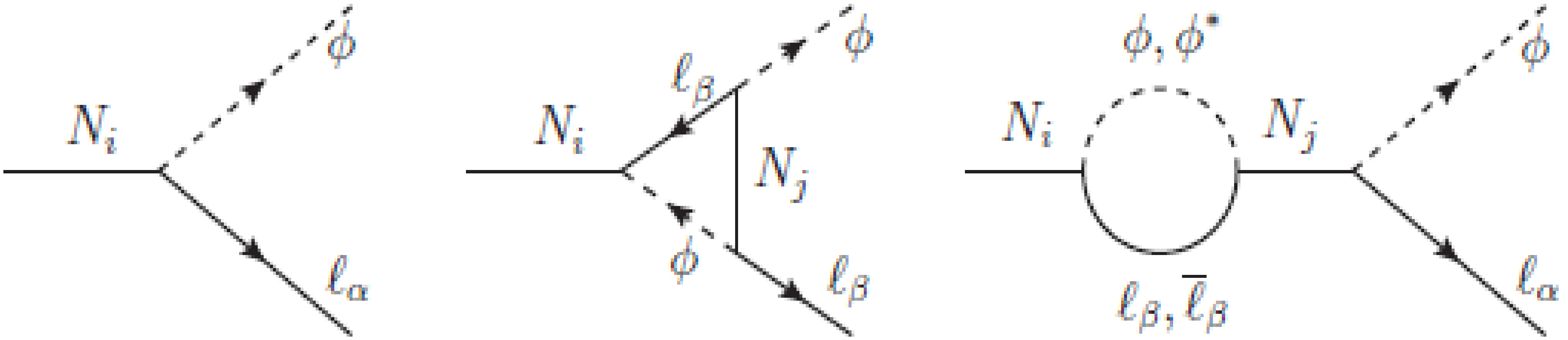
Same-sign lepton pair (l l) + quark and antiquark “jets” (j j) is a very distinctive experimental signature

N = Majorana right-handed neutrino (unstable)
W_R = right-handed gauge boson

Matter-Antimatter Asymmetry

- WMAP, BBN: $\eta_B = \frac{n_B - n_{\overline{B}}}{n_\gamma} = (6.20 \pm 0.15) \times 10^{-10}$
- Sakharov ingredients:
  - Baryon number violation
  - C and CP violation
  - Departure from thermal equilibrium
- All 3 ingredients are present in SM, but not enough – so, need BSM
- One possible solution: “leptogenesis” that generates significant CP asymmetry via right-handed neutrino processes, and also implies seesaw mechanism

Matter-Antimatter Asymmetry



Felipe, Neutrinos and the matter-antimatter asymmetry in the Universe
arXiv:1108.2694v1

Lepton CP asymmetry:

- N_i = right-handed Majorana neutrino flavour *i*
- Φ = heavy BSM particle

$$\epsilon_i^\alpha \equiv \frac{\Gamma(N_i \to \phi\,\ell_\alpha) - \Gamma(N_i \to \phi^\dagger\,\bar{\ell}_\alpha)}{\sum_\beta \left[\Gamma(N_i \to \phi\,\ell_\beta) + \Gamma(N_i \to \phi^\dagger\,\bar{\ell}_\beta)\right]}$$

Examples of Neutrino Models

	N mass	ν masses	BAU	DM	M_H stability	direct search	experi–ment
GUT see–saw	10^{10-16} GeV	YES	YES	NO	NO	NO	–
EWSB	10^{2-3} GeV	YES	YES	NO	YES	YES	LHC
ν MSM	keV – GeV	YES	YES	YES	YES	YES	a'la CHARM
ν scale	eV	YES	NO	NO	YES	YES	a'la LSND

Gninenko, Gorbunov, and Shaposhnikov,
Search for GeV-scale sterile neutrinos responsible for active neutrino oscillations and baryon asymmetry of the Universe. arXiv:1301.5516v1

Cosmic Gall (John Updike)

Neutrinos they are very small.
They have no charge and have no mass
And do not interact at all.
The earth is just a silly ball
To them, through which they simply pass,
Like dustmaids down a drafty hall
Or photons through a sheet of glass.
They snub the most exquisite gas,
Ignore the most substantial wall,
Cold-shoulder steel and sounding brass,
Insult the stallion in his stall,
And, scorning barriers of class,
Infiltrate you and me! Like tall
And painless guillotines, they fall
Down through our heads into the grass.
At night, they enter at Nepal
And pierce the lover and his lass
From underneath the bed – you call
It wonderful; I call it crass.

Neutrino
romance
poetry

But... can you spot the physics errors?