Solar neutrino physics in the standard model and beyond

Xun-Jie Xu / 许勋杰

Institute of High Energy Physics (IHEP)

Chinese Academy of Sciences (CAS)

https://xunjiexu.github.io/

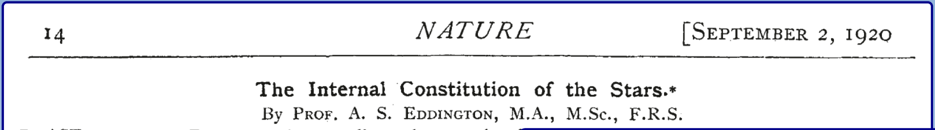
2024/01/20, 广州中山大学, 2024 年太阳中微子研讨会, https://indico.ihep.ac.cn/event/21371/

Talk based on 2209.14832/PPNP'23, in collaboration with Zhe Wang and Shaomin Chen

How does the Sun shine?

gravitational contraction → solar energy?

— the contraction hypothesis, prevailing before 1920


14 NATURE [SEPTEMBER 2, 1920

The Internal Constitution of the Stars.*

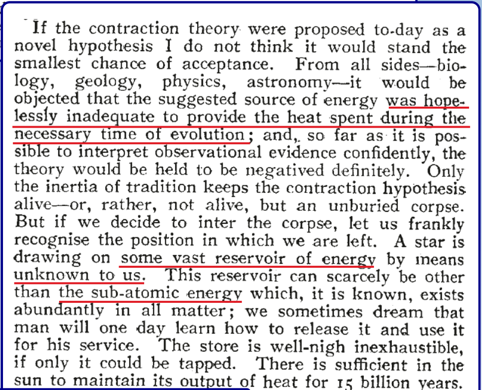
By PROF. A. S. EDDINGTON, M.A., M.Sc., F.R.S.

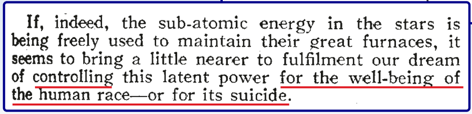
LAST year at Bournemouth we listened to a proposal from the President of the Association to bore a hole in the crust of the

the
there
throu

1920, Eddington:

- “hopelessly inadequate to provide the heat”
- “some unknown, vast reservoir of energy”
- “sub-atomic energy”
- [human] “controlling this power ”
  - “well-being ... or ... suicide”?

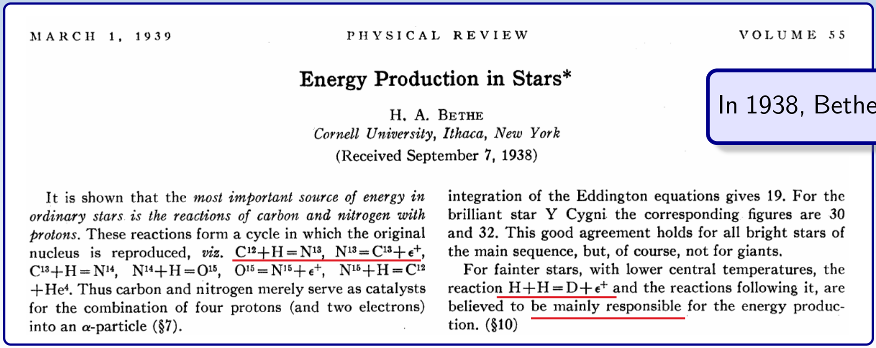

If the contraction theory were proposed to-day as a novel hypothesis I do not think it would stand the smallest chance of acceptance. From all sides—biology, geology, physics, astronomy—it would be objected that the suggested source of energy was hopelessly inadequate to provide the heat spent during the necessary time of evolution; and, so far as it is possible to interpret observational evidence confidently, the theory would be held to be negatived definitely. Only the inertia of tradition keeps the contraction hypothesis alive—or, rather, not alive, but an unburied corpse. But if we decide to inter the corpse, let us frankly recognise the position in which we are left. A star is drawing on some vast reservoir of energy by means unknown to us. This reservoir can scarcely be other than the sub-atomic energy which, it is known, exists abundantly in all matter; we sometimes dream that man will one day learn how to release it and use it for his service. The store is well-nigh inexhaustible, if only it could be tapped. There is sufficient in the sun to maintain its output of heat for 15 billion years.


If, indeed, the sub-atomic energy in the stars is being freely used to maintain their great furnaces, it seems to bring a little nearer to fulfilment our dream of controlling this latent power for the well-being of the human race—or for its suicide.

... powered by fusion

- 1896, radioactivity discovered;
- 1911, Rutherford model (atmoic, not nuclear);
- 1915, $^{14}\text{N} + \alpha \to {}^{17}\text{O} + p$ by Rutherford;
- 1932, nuclear fusion achieved in lab;
- 1938, nuclear fission discovered;
- 1940s, Manhattan Project ...

How much did Eddington know about "sub-atomic energy" in 1920?



MARCH 1, 1939 PHYSICAL REVIEW VOLUME 55

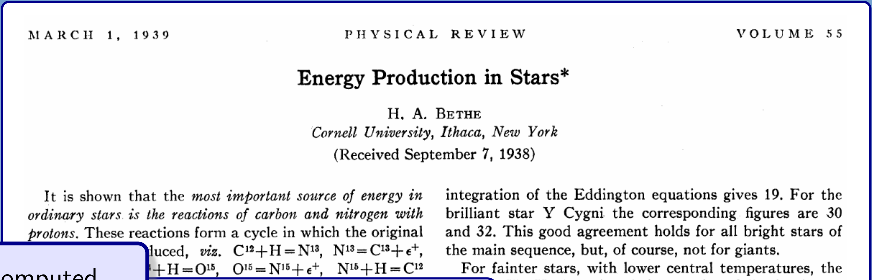
Energy Production in Stars*

H. A. BETHE
Cornell University, Ithaca, New York
(Received September 7, 1938)

It is shown that the *most important source of energy in ordinary stars is the reactions of carbon and nitrogen with protons.* These reactions form a cycle in which the original nucleus is reproduced, *viz.* $C^{12}+H=N^{13}$, $N^{13}=C^{13}+\epsilon^+$, $C^{13}+H=N^{14}$, $N^{14}+H=O^{15}$, $O^{15}=N^{15}+\epsilon^+$, $N^{15}+H=C^{12}+He^4$. Thus carbon and nitrogen merely serve as catalysts for the combination of four protons (and two electrons) into an α-particle (§7). integration of the Eddington equations gives 19. For the brilliant star Y Cygni the corresponding figures are 30 and 32. This good agreement holds for all bright stars of the main sequence, but, of course, not for giants.

For fainter stars, with lower central temperatures, the reaction $H+H=D+\epsilon^+$ and the reactions following it, are believed to be mainly responsible for the energy production. (§10)

In 1938, Bethe computed ...



MARCH 1, 1939 PHYSICAL REVIEW VOLUME 55

Energy Production in Stars*

H. A. Bethe
Cornell University, Ithaca, New York
(Received September 7, 1938)

It is shown that the *most important source of energy in ordinary stars is the reactions of carbon and nitrogen with protons*. These reactions form a cycle in which the original

luced, *viz.* $C^{12}+H=N^{13}$, $N^{13}=C^{13}+\epsilon^+$,

$+H=O^{15}$, $O^{15}=N^{15}+\epsilon^+$, $N^{15}+H=C^{12}$

integration of the Eddington equations gives 19. For the brilliant star Y Cygni the corresponding figures are 30 and 32. This good agreement holds for all bright stars of the main sequence, but, of course, not for giants.

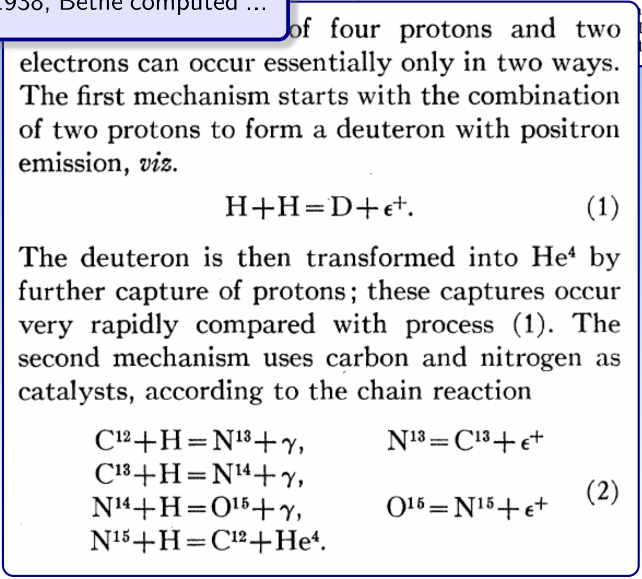
For fainter stars, with lower central temperatures, the

$H+H=D+\epsilon^+$ and the reactions following it, are

to be mainly responsible for the energy produc-

10)

In 1938, Bethe computed …



of four protons and two electrons can occur essentially only in two ways. The first mechanism starts with the combination of two protons to form a deuteron with positron emission, *viz.*

$$H+H=D+\epsilon^+. \qquad (1)$$

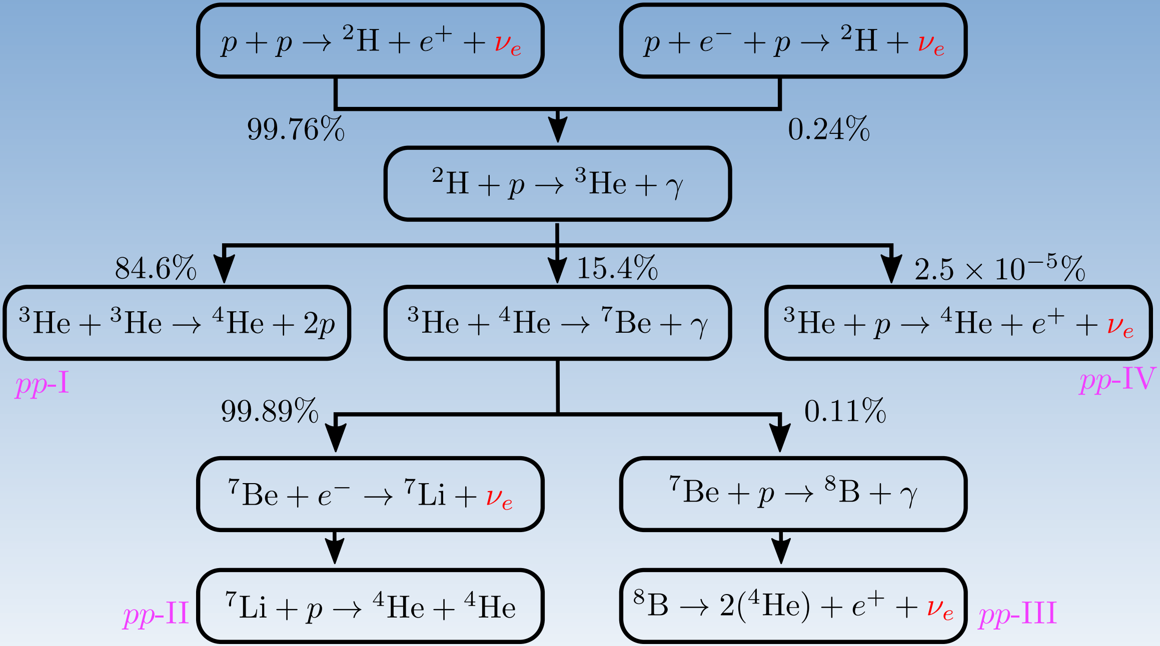
The deuteron is then transformed into He^4 by further capture of protons; these captures occur very rapidly compared with process (1). The second mechanism uses carbon and nitrogen as catalysts, according to the chain reaction

$$\begin{array}{ll} C^{12}+H=N^{13}+\gamma, & N^{13}=C^{13}+\epsilon^+ \\ C^{13}+H=N^{14}+\gamma, & \\ N^{14}+H=O^{15}+\gamma, & O^{15}=N^{15}+\epsilon^+ \\ N^{15}+H=C^{12}+He^4. & \end{array} \qquad (2)$$

No neutrinos?

proposed in 1930
detected in 1956

see also:
neutrinos.fnal.gov/history/



$p + p \rightarrow {}^2\mathrm{H} + e^+ + \nu_e$

$p + e^- + p \rightarrow {}^2\mathrm{H} + \nu_e$

99.76%

0.24%

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

84.6%

15.4%

$2.5 \times 10^{-5}\%$

${}^3\mathrm{He} + {}^3\mathrm{He} \rightarrow {}^4\mathrm{He} + 2p$

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

${}^3\mathrm{He} + p \rightarrow {}^4\mathrm{He} + e^+ + \nu_e$

pp-I

pp-IV

99.89%

0.11%

${}^7\mathrm{Be} + e^- \rightarrow {}^7\mathrm{Li} + \nu_e$

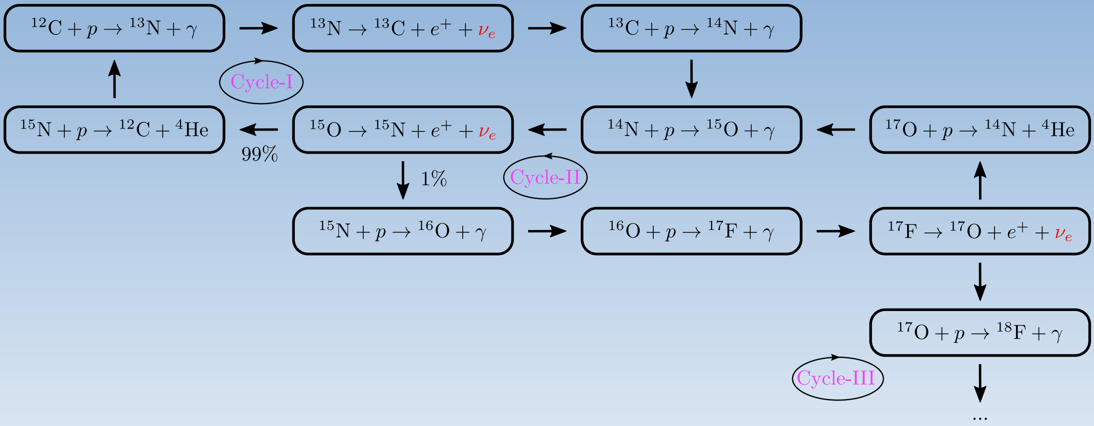
${}^7\mathrm{Be} + p \rightarrow {}^8\mathrm{B} + \gamma$

pp-II

${}^7\mathrm{Li} + p \rightarrow {}^4\mathrm{He} + {}^4\mathrm{He}$

${}^8\mathrm{B} \rightarrow 2({}^4\mathrm{He}) + e^+ + \nu_e$

pp-III



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

$^{13}\mathrm{N} \to {}^{13}\mathrm{C} + e^{+} + \nu_e$

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

Cycle-I

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

99%

$^{15}\mathrm{O} \to {}^{15}\mathrm{N} + e^{+} + \nu_e$

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

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

1%

Cycle-II

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

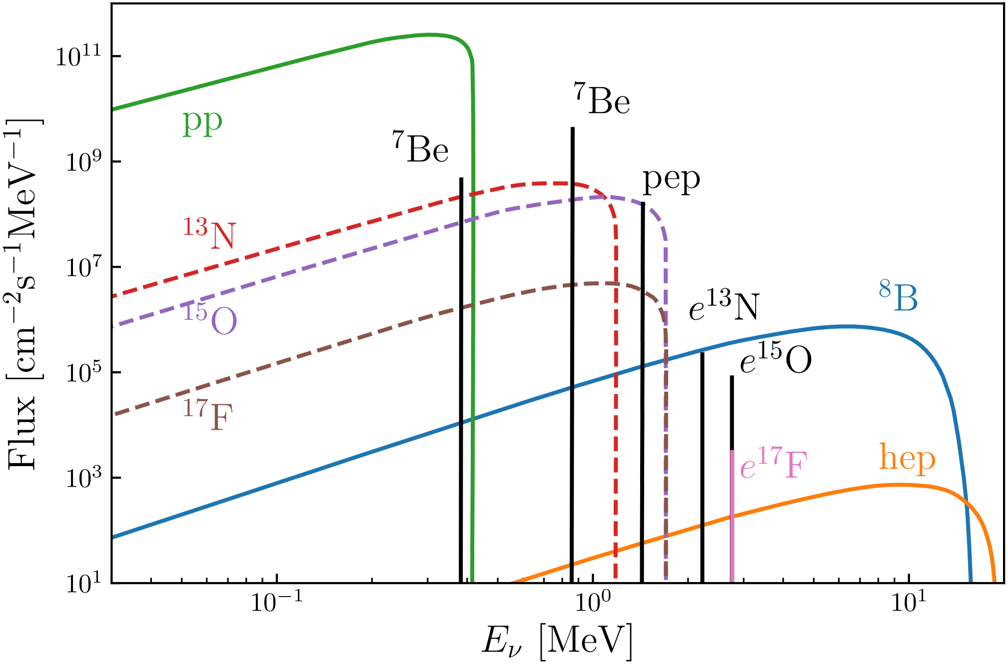
$^{16}\mathrm{O} + p \to {}^{17}\mathrm{F} + \gamma$

$^{17}\mathrm{F} \to {}^{17}\mathrm{O} + e^{+} + \nu_e$

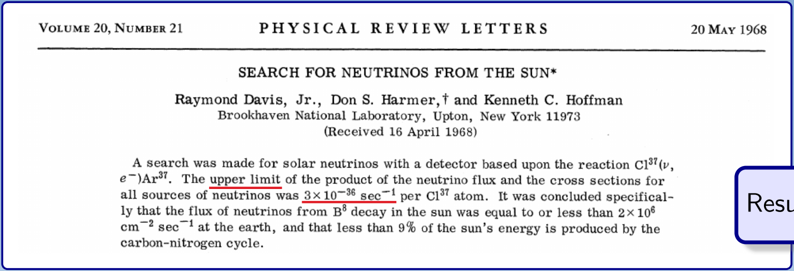
$^{17}\mathrm{O} + p \to {}^{18}\mathrm{F} + \gamma$

Cycle-III

…


pp
^{7}Be
^{7}Be
pep
^{13}N
^{15}O
^{17}F
e^{13}N
e^{15}O
e^{17}F
^{8}B
hep
10^{11}
10^9
10^7
10^5
10^3
10^1
10^{-1}
10^0
10^1
Flux [cm^{-2}s^{-1}MeV^{-1}]
E_ν [MeV]

Solar neutrinos: the pioneering effort



VOLUME 20, NUMBER 21 PHYSICAL REVIEW LETTERS 20 MAY 1968

SEARCH FOR NEUTRINOS FROM THE SUN*

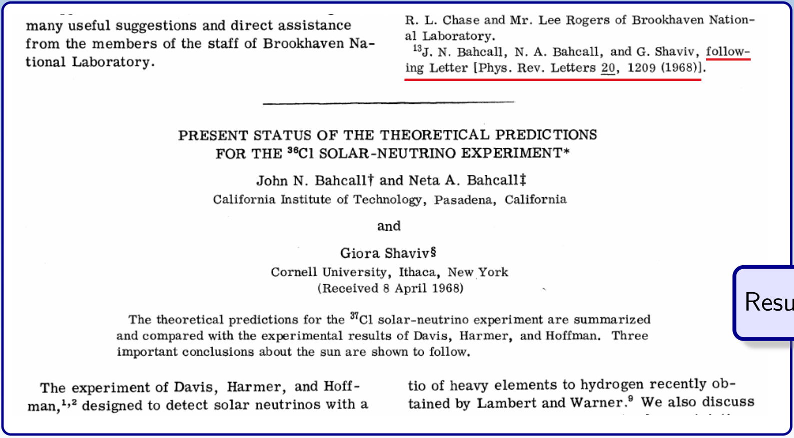
Raymond Davis, Jr., Don S. Harmer,† and Kenneth C. Hoffman
Brookhaven National Laboratory, Upton, New York 11973
(Received 16 April 1968)

A search was made for solar neutrinos with a detector based upon the reaction $Cl^{37}(\nu, e^-)Ar^{37}$. The upper limit of the product of the neutrino flux and the cross sections for all sources of neutrinos was 3×10^{-36} sec^{-1} per Cl^{37} atom. It was concluded specifically that the flux of neutrinos from B^8 decay in the sun was equal to or less than 2×10^6 cm^{-2} sec^{-1} at the earth, and that less than 9% of the sun's energy is produced by the carbon-nitrogen cycle.

Two papers, same volume:

Exp: PRL 20, 1205 (1968)
Th: PRL 20, 1209 (1968)

Result: $\Phi_\nu \lesssim 3$ SNU



many useful suggestions and direct assistance from the members of the staff of Brookhaven National Laboratory.

R. L. Chase and Mr. Lee Rogers of Brookhaven National Laboratory.

[13] J. N. Bahcall, N. A. Bahcall, and G. Shaviv, following Letter [Phys. Rev. Letters 20, 1209 (1968)].

PRESENT STATUS OF THE THEORETICAL PREDICTIONS FOR THE ^{36}Cl SOLAR-NEUTRINO EXPERIMENT*

John N. Bahcall† and Neta A. Bahcall‡
California Institute of Technology, Pasadena, California

and

Giora Shaviv§
Cornell University, Ithaca, New York
(Received 8 April 1968)

The theoretical predictions for the ^{37}Cl solar-neutrino experiment are summarized and compared with the experimental results of Davis, Harmer, and Hoffman. Three important conclusions about the sun are shown to follow.

The experiment of Davis, Harmer, and Hoffman,[1,2] designed to detect solar neutrinos with a

tio of heavy elements to hydrogen recently obtained by Lambert and Warner.[9] We also discuss

cited each other

Result: $\Phi_\nu \approx 11$ SNU

in fact, 5 models, $\Phi_\nu =$ 21, 11, 7.7, 4.4, 11 SNU

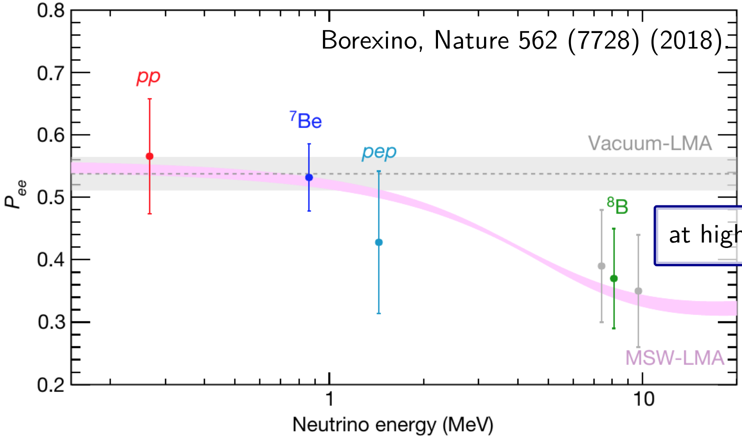
After decades of exp+th effort, ...

$$\Rightarrow \text{exp} \approx \frac{\text{th}}{3}$$

... the so-called “solar neutrino problem”

Various explanations: oscillation, decay, spin-flavor precession ...

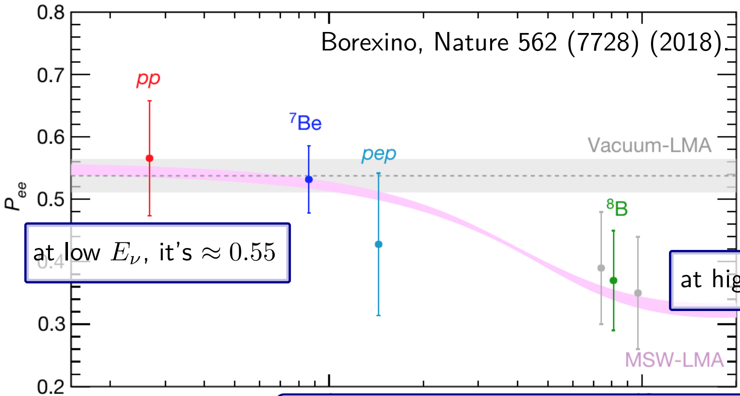
Today, we know it’s osc.



Borexino, Nature 562 (7728) (2018)

at high E_ν, indeed it’s $\sim 1/3$

Today, we know it's osc.



Borexino, Nature 562 (7728) (2018)

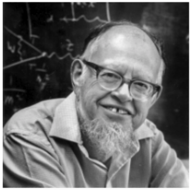
at low E_ν, it's ≈ 0.55

at high E_ν, it's ≈ 0.3

... not just osc, also MSW.

S. Mikheyev
(1940-2011)

A. Smirnov
(1951-)



L. Wolfenstein
(1923-2015)

The MSW effect

An estimate

ν can fly through the Sun/Earth so easily

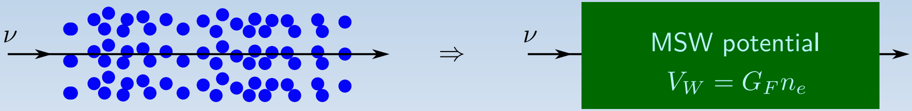
$$\sigma n L = 10^{-41}\text{cm}^2 \times 5\text{g}/\text{cm}^3/m_n \times 6400\text{km}$$
$$= 10^{-11}$$

only $1/10^{11}$ neutrinos are stopped by scattering

→

Question

Only 10^{-11}! Why matter matters?
Answer: coherency



MSW potential
$V_W = G_F n_e$

The concept of "coherent forward scattering"

$\neq$ scattering with individual particles
$\equiv$ scattering with all particles simultaneously

All particles, together, form an effective potential

How do neutrinos oscillate?

The Schrödinger equation:

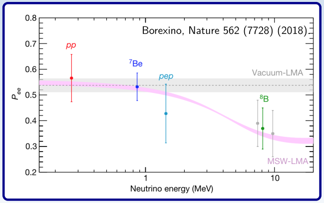
$$i\frac{d}{dL}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = H\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}, \tag{1}$$

$$H = \frac{1}{2E_\nu}U_{\rm PMNS}\begin{pmatrix}m_1^2 & & \\ & m_2^2 & \\ & & m_3^2\end{pmatrix}U^\dagger_{\rm PMNS} + \begin{pmatrix}V_e & & \\ & 0 & \\ & & 0\end{pmatrix}, \tag{2}$$

$$\hookrightarrow \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{\rm CP}} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta_{\rm CP}} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta_{\rm CP}} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta_{\rm CP}} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta_{\rm CP}} & c_{13}c_{23} \end{pmatrix}$$

where $V_e \equiv \sqrt{2}G_F n_e$ is the MSW effective potential.

Solve Eq. (1) $\Longrightarrow$


Borexino, Nature 562 (7728) (2018)

How do neutrinos oscillate?

$$i\frac{d}{dL}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = H\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}, \tag{1}$$

$$H = \frac{1}{2E_\nu}U_{\mathrm{PMNS}}\begin{pmatrix}m_1^2 & & \\ & m_2^2 & \\ & & m_3^2\end{pmatrix}U_{\mathrm{PMNS}}^\dagger + \begin{pmatrix}V_e & & \\ & 0 & \\ & & 0\end{pmatrix}, \tag{2}$$

Let's solve it ...

An outline of next few slides:

- Simple analytic formula for students
- Adiabatic approximation
- Earth matter effect (D/N asymmetry)

If you solve Eq. (1) by brute force, then you can ignore them all!

... which I strongly discourage

Simple analytic formula for students

Maltoni and Smirnov [1507.05287]

$$P_{ee} = (c_{13} c_{13}^m)^2 \left(\frac{1}{2} + \frac{1}{2} \cos 2\theta_{12}^m \cos 2\theta_{12} \right) + (s_{13} s_{13}^m)^2 \,,$$

$$\left.\begin{aligned} \cos 2\theta_{12}^m &\approx \frac{\cos 2\theta_{12} - \beta_{12}}{\sqrt{(\cos 2\theta_{12} - \beta_{12})^2 + \sin^2 2\theta_{12}}} \,, \\ (s_{13}^m)^2 &\approx s_{13}^2 \, (1 + 2\beta_{13}) \,, \end{aligned}\right\} \quad \text{effective mixing angles}$$

$$\beta_{12} \equiv \frac{2 c_{13}^2 V_e^0 E_\nu}{\Delta m_{21}^2} \,,$$

$$\beta_{13} \equiv \frac{2 V_e^0 E_\nu}{\Delta m_{31}^2} \,.$$

If matter density $\to 0$ ($\beta_{12,13} \to 0$),
$\cos 2\theta_{12}^m \to \cos 2\theta_{12}$; $s_{13}^m \to s_{13}$

- simple and fast, of practical use
  - especially for those students addicted to coding:-)
- sufficient accuracy
  - for current precision of measurement
- straightforward to see how P_{ee} varies with θ_{12}, θ_{13}, ...

Simple analytic formula for students

If $\theta_{13} \to 0$, more simplified:

$$P_{ee}^{\odot} = \frac{1}{2} + \frac{1}{2}\cos 2\theta_{12}^m \cos 2\theta_{12}$$

$$\cos 2\theta_{12}^m \approx \frac{\cos 2\theta_{12} - \beta_{12}}{\sqrt{(\cos 2\theta_{12} - \beta_{12})^2 + \sin^2 2\theta_{12}}}\,, \qquad \theta_{12}^m \to \begin{cases} \theta_{12} & (\beta_{12} \to 0) \\ -1 & (\beta_{12} \to \infty) \end{cases}$$

$$\beta_{12} \equiv \frac{2V_e^0 E_\nu}{\Delta m_{21}^2}\,,$$

vacuum limit ($\beta_{12} \to 0$):

$$P_{ee} \approx c_{12}^4 + s_{12}^4 \approx 5/9$$

strong matter effect limit ($\beta_{12} \to \infty$):

$$P_{ee} \approx s_{12}^2 \approx \frac{1}{3}$$

vacuum limit ($\beta_{12} \to 0$):

$$P_{ee} \approx c_{12}^4 + s_{12}^4 \approx 5/9$$

strong matter effect limit ($\beta_{12} \to \infty$):

$$P_{ee} \approx s_{12}^2 \approx \frac{1}{3}$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{\rm CP}} \\ \cdots & \cdots & c_{13}s_{23} \\ \cdots & \cdots & c_{13}c_{23} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$\langle \nu_e | \nu_1 \rangle = c_{12}c_{13} \approx c_{12}$$

$$\langle \nu_e | \nu_2 \rangle = s_{12}c_{13} \approx s_{12}$$

The result is easy to understand:

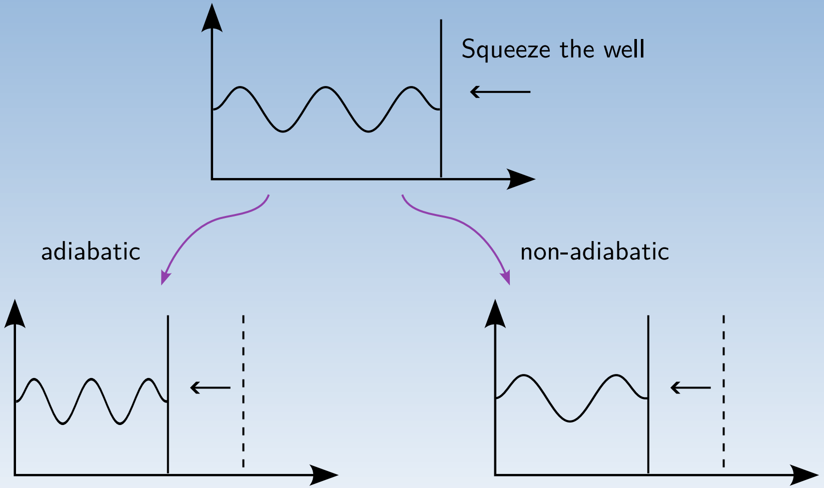
- When ν_e is produced, it consists of $c_{12}\nu_1 + s_{12}\nu_2$. Each mass eigenstate propagates to the Earth independently. Due to the long distance they lose coherence. At production, the probability of ν_e being ν_1 (ν_2) is c_{12}^2 (s_{12}^2); at detection, the probability of ν_1 (ν_2) being detected as ν_e is also c_{12}^2 (s_{12}^2). Hence the survival probability of ν_e at detection is given by $(c_{12}^2)^2 + (s_{12}^2)^2$.

- When ν_e is produced at the center with a high electron number density, it is almost pure ν_2^m due to the strong matter effect ($\theta_{12}^m \approx 90^\circ$). As the density slowly decreases to zero, the evolution of all mass eigenstates is adiabatic, which means ν_2^m will eventually come out to the surface as ν_2. Since the probability of ν_2 being detected as ν_e is s_{12}^2, the survival probability in the high-E_ν limit is simply s_{12}^2.

The adiabatic approximation

What does “adiabatic” mean?

Quantum mechanics:
Consider a wave function in a well ...



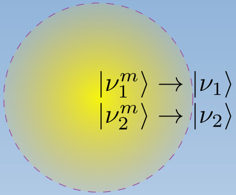
Squeeze the well

adiabatic

non-adiabatic

The adiabatic approximation

What does "adiabatic" mean for solar neutrinos?



$|\nu_1^m\rangle \to |\nu_1\rangle$

$|\nu_2^m\rangle \to |\nu_2\rangle$

$$\boxed{P_{ee} = \sum_i |U_{ei}^m|^2 |U_{ei}|^2}$$

obtained by re-diagonalizing H:

$$H = \frac{1}{2E_\nu} U^m \mathrm{diag}\left(\tilde{m}_1^2,\ \tilde{m}_2^2,\ \tilde{m}_3^2\right) U^{m\dagger}$$

How good is it?

$$\boxed{\delta P \sim \frac{\gamma^2}{4} \lesssim 10^{-7}}$$

More generally,

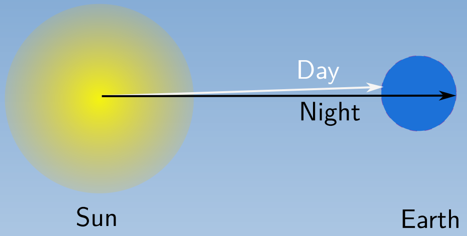
smirnov *et al* [hep-ph/0404042]

$$\gamma \equiv \frac{4\Delta m_{21}^2 E_\nu^2 \sin 2\theta_{12}}{\left(\Delta m_{21}^4 \sin^2 2\theta_{12} + (\Delta m_{21}^2 \cos 2\theta_{12} - 2E_\nu V_e)^2\right)^{3/2}} \frac{dV_e}{dr} \ll 1$$

most fragile at resonance: $\gamma_{\mathrm{resonance}} = \frac{4E_\nu^2}{\Delta m_{21}^4 \sin^2 2\theta_{12}} \frac{dV_e}{dr}$

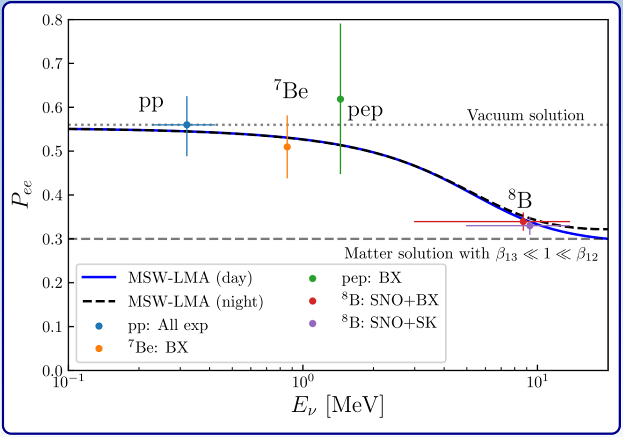
still good enough: 1 GeV → $\gamma \approx 0.1$

The Earth matter effect (aka Day-Night asymmetry)



$$\Delta P \equiv P_{ee}^{(\mathrm{day})} - P_{ee}^{(\mathrm{night})}$$
$$\approx \frac{1}{2} c_{13}^6 \frac{\cos 2\theta_{12}^m \sin^2 2\theta_{12} K V_\oplus}{K^2 - 2c_{13}^2 \cos 2\theta_{12} V_\oplus K + V_\oplus^2}$$

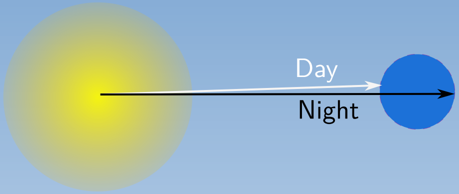
where $K = \Delta m_{21}^2/(2E_\nu)$,
$V_\oplus$ = MSW potential at Earth.



Neutrino 2022:
SK reported $3\ \sigma$ significance:

$$A_{DN} \equiv 2\frac{R_D - R_N}{R_D + R_N} = (-2.9 \pm 0.9)\%$$

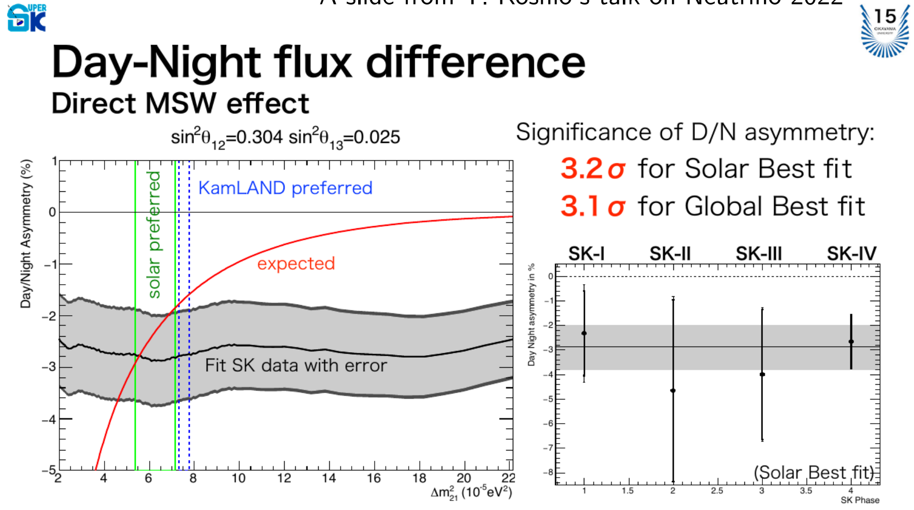
The Earth matter effect (aka Day-Night asymmetry)



Neutrino 2022:
SK reported $3\ \sigma$ significance:

$$A_{DN} \equiv 2\frac{R_D - R_N}{R_D + R_N} = (-2.9 \pm 0.9)\%$$

A slide from Y. Koshio's talk on Neutrino 2022



Day-Night flux difference

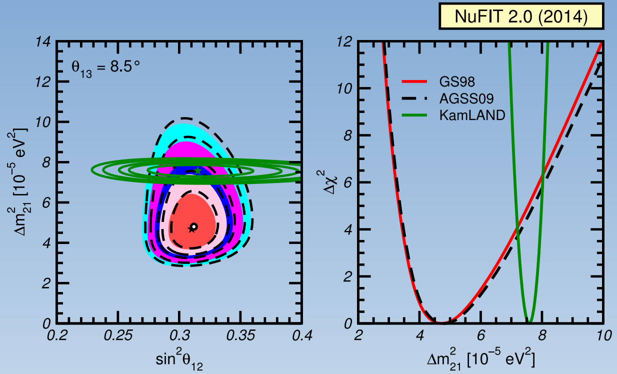
Direct MSW effect

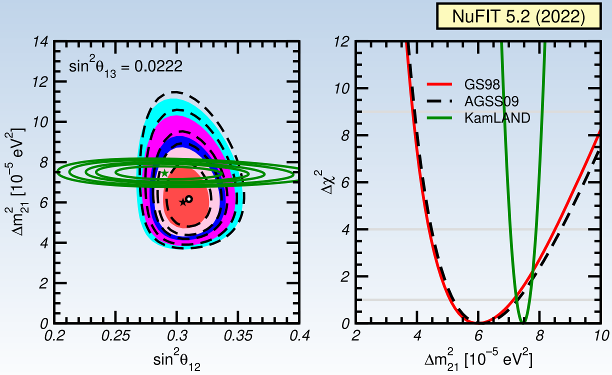
Significance of D/N asymmetry:

3.2 σ for Solar Best fit

3.1 σ for Global Best fit

The fate of the long-standing 2σ tension



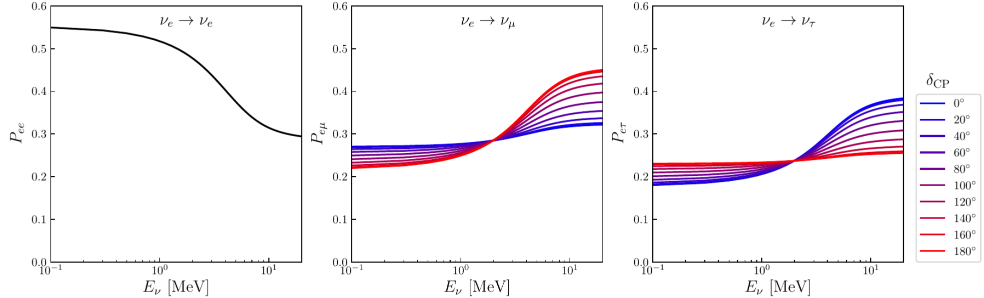


θ_{12}, θ_{13} θ_{23}, δ_{CP}, Δm^2_{21}, Δm^2_{31}, ...

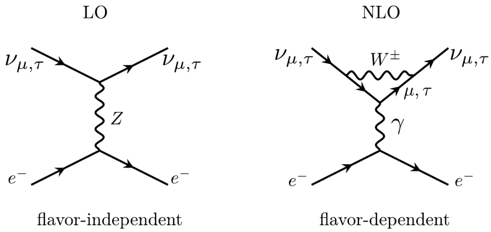
Which can be measured by solar neutrino exps?

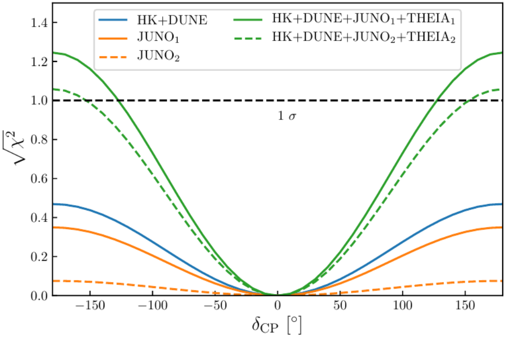
Can we measure more?

太阳中微子测量 CP 破坏的可能性: Brdar, Xu, PLB'23



太阳中微子的 $\nu_e \to \nu_\mu$, $\nu_e \to \nu_\tau$ 有显著的 CP 依赖性, 可以用来测中微子的 CP 相角吗?





Solar neutrino physics in the standard model and beyond

Solar neutrino missing problem → discovery of ν osc.

Can solar neutrinos surprise us again?

Maybe ..., a variety of new physics, hard to be comprehensive...

We put forth our best effort [2209.14832]:

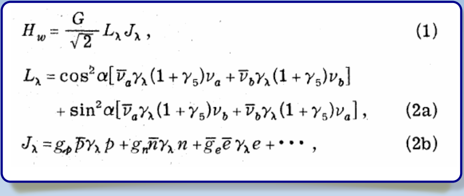
NSI

NSI (Non-Standard Interaction)

$$\mathcal{L} \supset \frac{G_F}{\sqrt{2}} \sum_{f=e,u,d} \overline{\nu}_\alpha \gamma^\mu (1-\gamma^5) \nu_\beta \left[\overline{f} \gamma^\mu (\varepsilon^V_{\alpha\beta} + \varepsilon^A_{\alpha\beta} \gamma^5) f \right],$$

- Lepton Flavor Violation (LFV)
- first proposed by Wolfenstein
- interesting osc pheno
    - e.g., ν osc without mass

Wolfenstein, PRD 17 (1978) 2369



$$H_w = \frac{G}{\sqrt{2}} L_\lambda J_\lambda\,, \tag{1}$$

$$L_\lambda = \cos^2\alpha[\overline{\nu}_a \gamma_\lambda (1+\gamma_5)\nu_a + \overline{\nu}_b \gamma_\lambda (1+\gamma_5)\nu_b] + \sin^2\alpha[\overline{\nu}_a \gamma_\lambda (1+\gamma_5)\nu_b + \overline{\nu}_b \gamma_\lambda (1+\gamma_5)\nu_a]\,, \tag{2a}$$

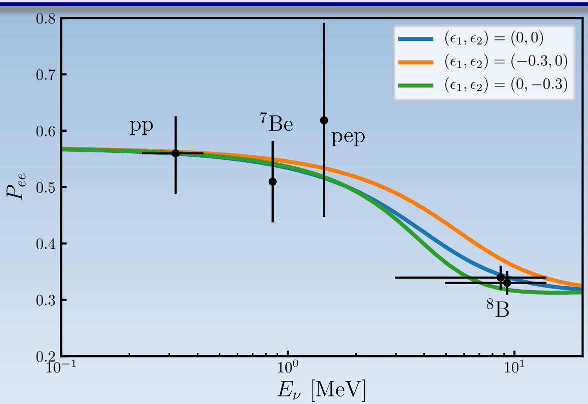
$$J_\lambda = g_p \overline{p} \gamma_\lambda p + g_n \overline{n} \gamma_\lambda n + \overline{g}_e \overline{e} \gamma_\lambda e + \cdots\,, \tag{2b}$$

$$H = \frac{1}{2E_\nu} U_{\mathrm{PMNS}} \begin{pmatrix} m_1^2 & & \\ & m_2^2 & \\ & & m_3^2 \end{pmatrix} U^\dagger_{\mathrm{PMNS}} + V_e \begin{pmatrix} 1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon^*_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon^*_{e\tau} & \varepsilon^*_{\mu\tau} & \varepsilon_{\tau\tau} \end{pmatrix}$$

NSI

NSI (Non-Standard Interaction)

$$\mathcal{L} \supset \frac{G_F}{\sqrt{2}} \sum_{f=e,u,d} \overline{\nu}_\alpha \gamma^\mu (1-\gamma^5) \nu_\beta \left[\overline{f} \gamma^\mu (\varepsilon^V_{\alpha\beta} + \varepsilon^A_{\alpha\beta} \gamma^5) f \right],$$

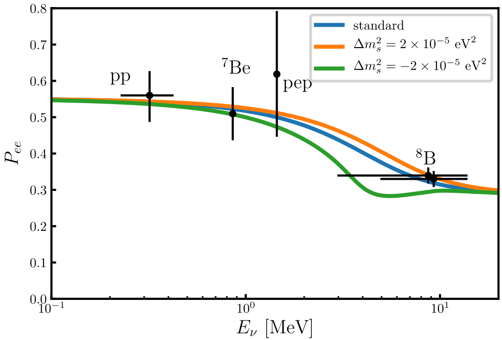


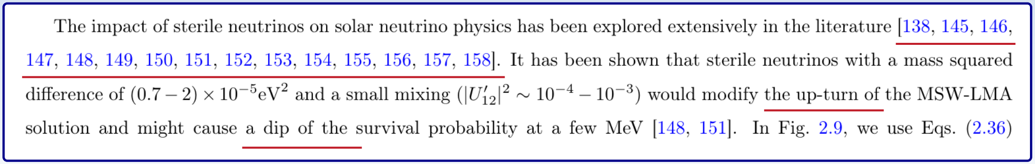
A note on the LMA-D solution (θ_{12} in the other octant, compensated by large NSI).

- If $\theta_{12} \to \pi/2 - \theta_{12}$, $\Delta m^2_{31} \to -\Delta m^2_{31}$, and $\delta_{\text{CP}} \to \pi/2 - \delta_{\text{CP}}$, then $H \to -H^*$.
- Many papers: ... + Chaves, Schwetz [2102.11981]
- currently disfavored by $\nu + e$ scattering data at 2σ CL.

Sterile neutrino

$$\begin{pmatrix} \nu_s \\ \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_s' \\ \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \qquad H = \frac{1}{2E_\nu} U \begin{pmatrix} m_s^2 & & & \\ & m_1^2 & & \\ & & m_2^2 & \\ & & & m_3^2 \end{pmatrix} U^\dagger + V_e \begin{pmatrix} \frac{n_n}{2n_e} & & & \\ & 1 & & \\ & & 0 & \\ & & & 0 \end{pmatrix},$$




The impact of sterile neutrinos on solar neutrino physics has been explored extensively in the literature [138, 145, 146, 147, 148, 149, 150, 151, 152, 153, 154, 155, 156, 157, 158]. It has been shown that sterile neutrinos with a mass squared difference of $(0.7-2)\times 10^{-5}\text{eV}^2$ and a small mixing ($|U_{12}'|^2 \sim 10^{-4}-10^{-3}$) would modify the up-turn of the MSW-LMA solution and might cause a dip of the survival probability at a few MeV [148, 151]. In Fig. 2.9, we use Eqs. (2.36)

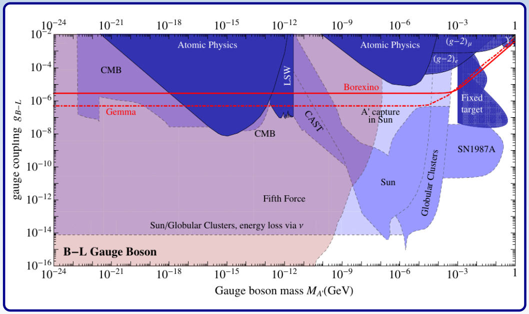
Emitting light new particles

- Neutrinos are light, penetrating, ...
  - $\Rightarrow$ abundant production from the Sun.
- What if there are other particles also ...
  - E.g., axions, dark photons, ...
  - Indeed, CERN even built an experiment

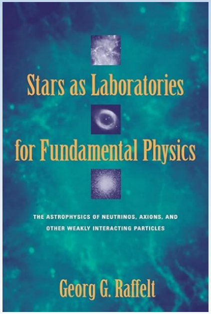
- Detection varies for different particles.
- But a rather robust bound comes from ...

Stellar cooling!

i.e. Extra energy loss of the Sun/Red giants/...

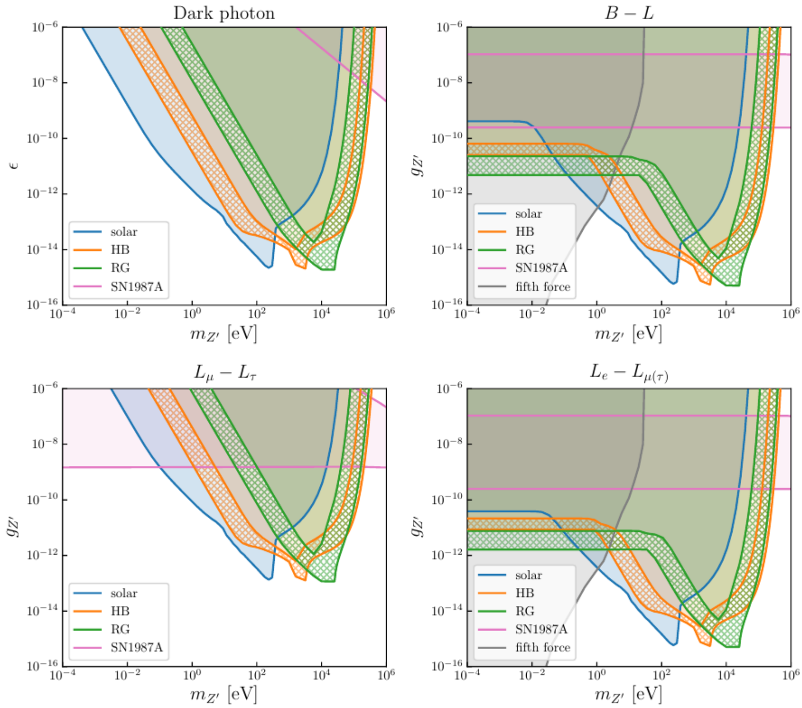


Harnik, Kopp, Machado, 1202.6073

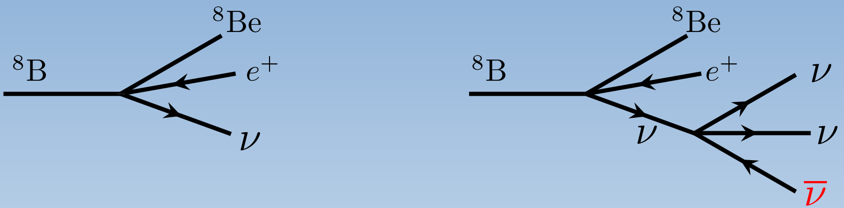


...long been used to set more restrictive bounds on light particles.
— see many of G. Raffelt's papers and his book

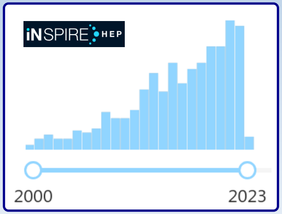
Stellar cooling bounds on various dark Z' [Li, Xu, JCAP'23]



Neutrino self-interactions and solar antineutrino searches (Q. Wu, XJX, 2308.15849)



- increasing interest in ν-self int.
  - especially since 2019, due to H_0 tension



- Any 4-ν operator → solar production of $\overline{\nu}$
- IBD-based detectors would be very happy

$$\mathcal{L}_S = \frac{1}{\Lambda_S^2}(\nu\nu)(\nu\nu) + \text{h.c.}\,,$$

$$\mathcal{L}_{S'} = \frac{1}{\Lambda_{S'}^2}(\nu\nu)(\nu^\dagger\nu^\dagger)\,,$$

$$\mathcal{L}_V = \frac{1}{\Lambda_V^2}(\nu^\dagger\overline{\sigma}^\mu\nu)(\nu^\dagger\overline{\sigma}_\mu\nu)\,,$$

$$\mathcal{L}_{V'} = \frac{1}{\Lambda_{V'}^2}(\nu^\dagger\overline{\sigma}^\mu\nu)(\nu\sigma_\mu\nu^\dagger)\,,$$

$$\mathcal{L}_T = \frac{1}{\Lambda_T^2}(\nu\sigma^{\mu\nu}\nu)(\nu\sigma_{\mu\nu}\nu) + \text{h.c.}$$

Neutrino self-interactions and solar antineutrino searches (Q. Wu, XJX, 2308.15849)

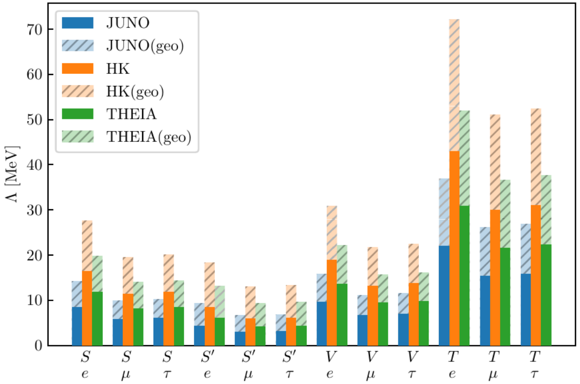
$$\mathcal{L}_S = \frac{1}{\Lambda_S^2}(\nu\nu)(\nu\nu) + \text{h.c.}\,,$$

$$\mathcal{L}_{S'} = \frac{1}{\Lambda_{S'}^2}(\nu\nu)(\nu^\dagger\nu^\dagger)\,,$$

$$\mathcal{L}_V = \frac{1}{\Lambda_V^2}(\nu^\dagger\overline{\sigma}^\mu\nu)(\nu^\dagger\overline{\sigma}_\mu\nu)\,,$$

$$\mathcal{L}_{V'} = \frac{1}{\Lambda_{V'}^2}(\nu^\dagger\overline{\sigma}^\mu\nu)(\nu\sigma_\mu\nu^\dagger)\,,$$

$$\mathcal{L}_T = \frac{1}{\Lambda_T^2}(\nu\sigma^{\mu\nu}\nu)(\nu\sigma_{\mu\nu}\nu) + \text{h.c.}$$

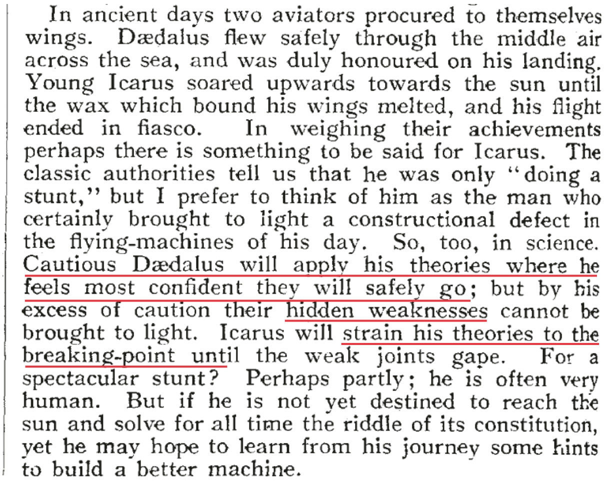


... to be compared with cosmologically favored value

$$\Lambda_{H_0\ \text{tension}} = \begin{cases} 4.6 \pm 0.5\ \text{MeV} & \text{(SI)} \\ 90^{+170}_{-60}\ \text{MeV} & \text{(MI)} \end{cases},$$

Strain the theory to the breaking point

The last paragraph of Eddington's paper



In ancient days two aviators procured to themselves wings. Dædalus flew safely through the middle air across the sea, and was duly honoured on his landing. Young Icarus soared upwards towards the sun until the wax which bound his wings melted, and his flight ended in fiasco. In weighing their achievements perhaps there is something to be said for Icarus. The classic authorities tell us that he was only "doing a stunt," but I prefer to think of him as the man who certainly brought to light a constructional defect in the flying-machines of his day. So, too, in science. Cautious Dædalus will apply his theories where he feels most confident they will safely go; but by his excess of caution their hidden weaknesses cannot be brought to light. Icarus will strain his theories to the breaking-point until the weak joints gape. For a spectacular stunt? Perhaps partly; he is often very human. But if he is not yet destined to reach the sun and solve for all time the riddle of its constitution, yet he may hope to learn from his journey some hints to build a better machine.

"fly too close to the sun" 的希腊神话起源

D= 代达罗斯 I= 伊卡洛斯
D 安全飞回, 获得荣耀
I 越飞越高 → 粘羽毛的蜡融化 → 坠亡

Solar neutrino physics: the beginning of end or the end of beginning?
Shall we be Daedalus or Icarus?

Thank you!