Grand Unified Neutrino Spectrum @ Earth

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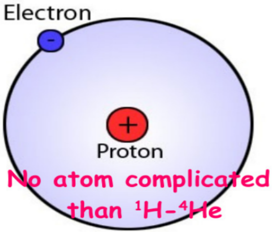
Neutrinos : The Elusive Ghost Particles

- Most abundant massive particles
  - $\sim$ 100 billion neutrinos from sun through thumbnail every second
  - Human body = 20 mg of K-40 emits 340 million neutrinos per day!
- Spin 1/2, neutral, weakly interacting
  - Your body will stop 1 neutrino which passes through it in a lifetime!
- 3 mass eigenstates (ν_1, ν_2, ν_3) & 3 flavor states $(\nu_e, \nu_\mu, \nu_\tau)$
- Neutrinos oscillate among flavors
- Can be Dirac or Majorana

Why Are Neutrinos Necessary? Because, Without Them



No Carbon

No Oxygen

No Water

No Earth

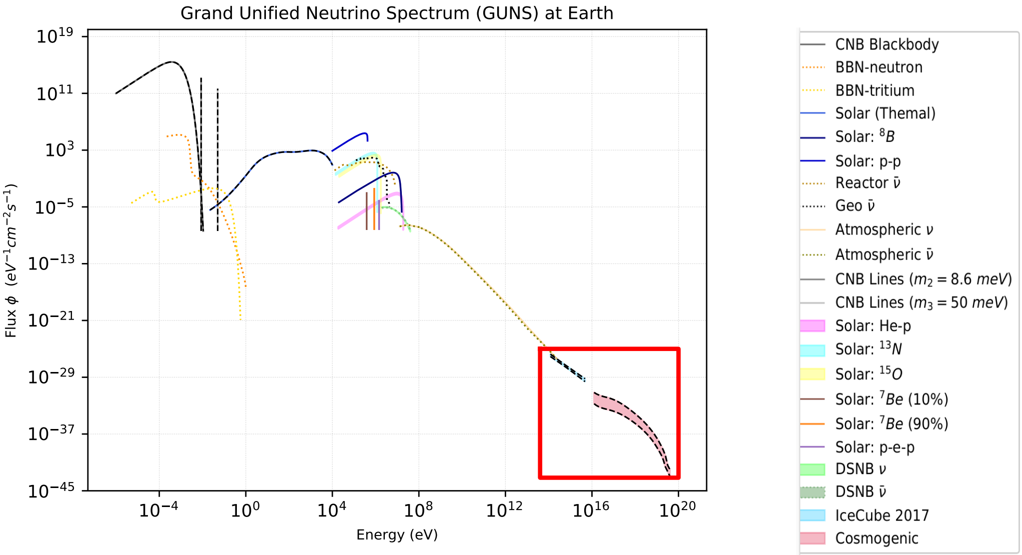
No Moon

No Lives

Also, They Help Us Understand Fundamental Physics

Grand Unified Neutrino Spectrum (GUNS) @Earth

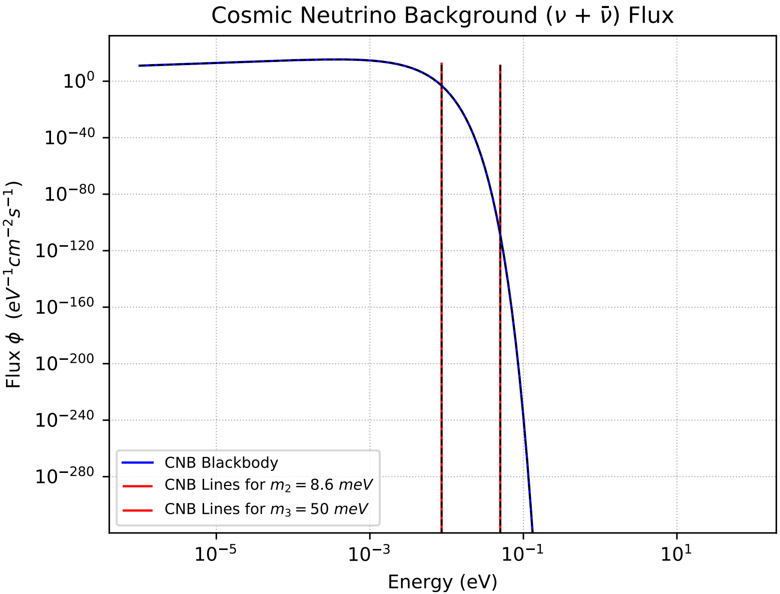
Spanning a range of $10^{18} eV$ from meV to PeV



Cosmic Neutrino Background (CNB)

- Relic neutrinos from about 1 s old Universe
- About 336 neutrinos and antineutrinos per cm^3
- Largest neutrino density at Earth, yet never been detected
- In adiabatic limit, $T_\nu = (4/11)^{1/3} T_\gamma$ implies $T_\nu = 1.954\ K$, $T_{CMB} = 2.725\ K$
- $m_1 = 0$, $m_2 = 8.6\ meV$, $m_3 = 50\ meV$
- $\dfrac{d\Phi_\nu}{dp} = \dfrac{p}{E}\dfrac{dn_\nu}{dp} = \dfrac{1}{2\pi^2}\dfrac{p^3}{\sqrt{p^2 + m_i^2}}\dfrac{1}{e^{p/T_\nu} + 1}$
- $\dfrac{d\Phi_\nu}{dE} = \dfrac{p}{E}\dfrac{dn_\nu}{dE} = \dfrac{1}{2\pi^2}\dfrac{E^2 - m_i^2}{e^{\sqrt{E^2 - m_i^2}/T_\nu} + 1}$

★ **Not detected yet!**

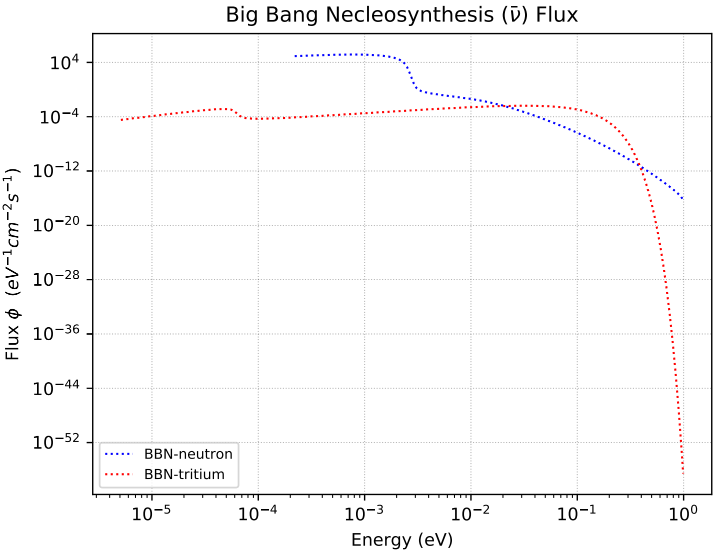


Cosmic Neutrino Background ($\nu + \bar{\nu}$) Flux
Flux ϕ ($eV^{-1}cm^{-2}s^{-1}$)
10^{0}
10^{-40}
10^{-80}
10^{-120}
10^{-160}
10^{-200}
10^{-240}
10^{-280}
10^{-5}
10^{-3}
10^{-1}
10^{1}
Energy (eV)
CNB Blackbody
CNB Lines for $m_2 = 8.6\ meV$
CNB Lines for $m_3 = 50\ meV$

Neutrinos from Big Bang Nucleosynthesis

- Neutron decay: $n \longrightarrow p + e^- + \bar{\nu}_e$ ($\sim 880\ s$)
- Tritium Decay: $^3H \longrightarrow\ ^3He + e^- + \bar{\nu}_e$ ($\sim 17.8\ yr$)
- BBN produced mostly $\bar{\nu}$ but a small fraction of ν too
- $^7Be + e^- \longrightarrow\ ^7Li + \nu_e$, 861.8 keV (89.6%) or 384.2 keV (10.4%)
- The spectra (originally in keV) are downshifted (to meV) by redshift by a factor $1/(z+1)$

★ **Not detected yet!**

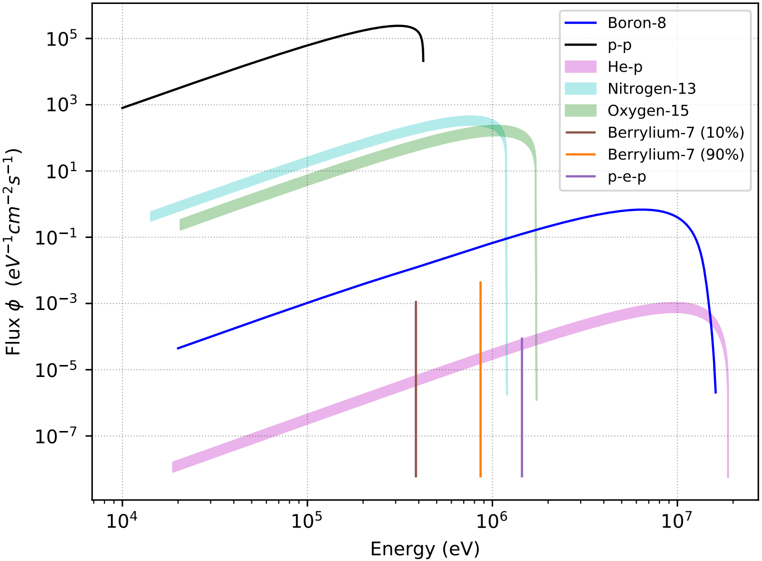

Big Bang Necleosynthesis ($\bar{\nu}$) Flux
10^{4}
10^{-4}
10^{-12}
10^{-20}
10^{-28}
10^{-36}
10^{-44}
10^{-52}
Flux ϕ ($eV^{-1}cm^{-2}s^{-1}$)
BBN-neutron
BBN-tritium
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
Energy (eV)

Solar Neutrinos from Nuclear Reactions

- Sun emits 2.3% of its nuclear energy of MeV-range as ν_e
- Effective fusion reaction: $4p + 2e^- \longrightarrow {}^4He + 2\nu_e + 26.73\ MeV$

Channel	Flux	Reaction	$E_{\rm max}$ (MeV)	$E_{\rm max}$ (MeV)
pp chains (β^+)	Φ_{pp}	$p + p \rightarrow d + e^+ + \nu_e$	0.267	0.423
	$\Phi_{\rm B}$	${}^8{\rm B} \rightarrow {}^8{\rm Be}^* + e^+ + \nu_e$	6.735 ± 0.036	~15
	$\Phi_{\rm hep}$	${}^3{\rm He} + p \rightarrow {}^4{\rm He} + e^+ + \nu_e$	9.628	18.778
pp chains (EC)	$\Phi_{\rm Be}$	$e^- + {}^7{\rm Be} \rightarrow {}^7{\rm Li} + \nu_e$	0.863 (89.7%)	
		$e^- + {}^7{\rm Be} \rightarrow {}^7{\rm Li}^* + \nu_e$	0.386 (10.3%)	
	$\Phi_{\rm pep}$	$p + e^- + p \rightarrow d + \nu_e$	1.445	
CNO cycle (β^+)	$\Phi_{\rm N}$	${}^{13}{\rm N} \rightarrow {}^{13}{\rm C} + e^+ + \nu_e$	0.706	1.198
	$\Phi_{\rm O}$	${}^{15}{\rm O} \rightarrow {}^{15}{\rm N} + e^+ + \nu_e$	0.996	1.732
	$\Phi_{\rm F}$	${}^{17}{\rm F} \rightarrow {}^{17}{\rm O} + e^+ + \nu_e$	0.998	1.736
CNO Cycle (EC)	$\Phi_{\rm eN}$	${}^{13}{\rm N} + e^- \rightarrow {}^{13}{\rm C} + \nu_e$	2.220	
	$\Phi_{\rm eO}$	${}^{15}{\rm O} + e^- \rightarrow {}^{15}{\rm N} + \nu_e$	2.754	
	$\Phi_{\rm eF}$	${}^{17}{\rm F} + e^- \rightarrow {}^{17}{\rm O} + \nu_e$	2.758	

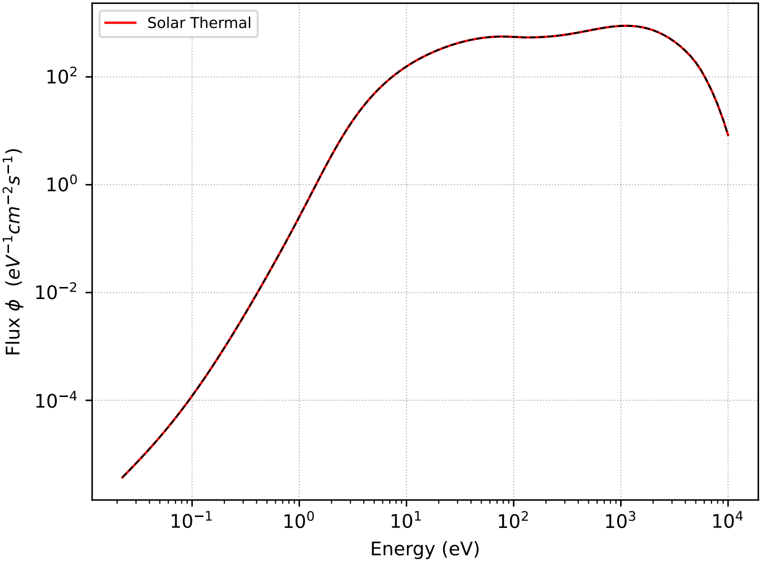
- $\langle E_{\nu_e} \rangle = 0.312\ MeV$
- The solar luminosity is $L_{\odot} = 3.828 \times 10^{33}\ erg/s = 2.39 \times 10^{39}\ MeV/s$
- $\Rightarrow \mathrm{L}_{\nu_e} = 2 \times \frac{L_{\odot}}{26.73\ MeV - 2\langle E_{\nu_e} \rangle} = 1.83 \times 10^{38}\ /s$
- $1\ AU = 1.496 \times 10^{13}\ cm$
- $\Rightarrow\ \Phi_{\nu} = L_{\nu_e}/[4\pi \times (1AU)^2] = 6.51 \times 10^{10}\ cm^{-2}s^{-1}$



Boron-8
p-p
He-p
Nitrogen-13
Oxygen-15
Berrylium-7 (10%)
Berrylium-7 (90%)
p-e-p
Flux ϕ $(eV^{-1}cm^{-2}s^{-1})$
Energy (eV)
10^5
10^3
10^1
10^{-1}
10^{-3}
10^{-5}
10^{-7}
10^4
10^5
10^6
10^7

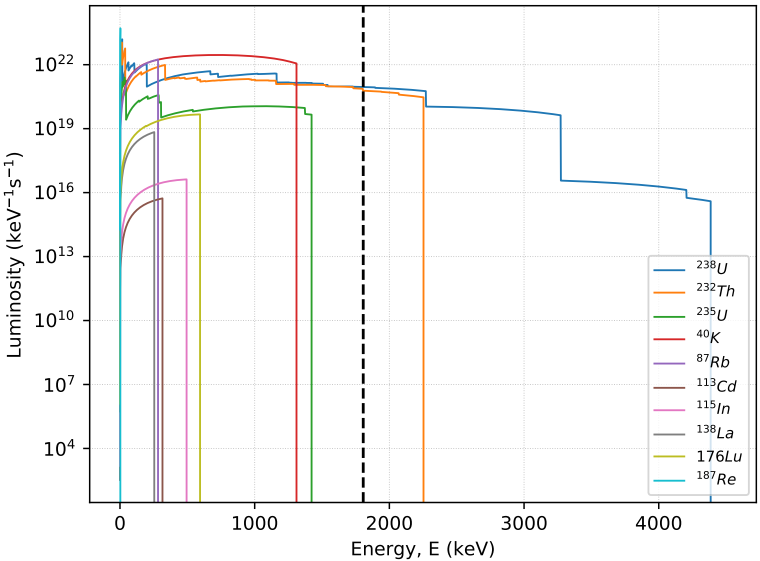
Thermal Neutrinos from Sun

- In the keV range, the Sun produces neutrino pairs of all flavors by thermal processes, notably plasmon decay, the Compton process, and electron bremsstrahlung
- Plasmon Decay: $\gamma \longrightarrow \nu + \bar{\nu}$
- Compton Process: $\gamma + e^- \longrightarrow e^- + \nu + \bar{\nu}$
- Bremsstrahlung: $e^- + Ze^- \longrightarrow Ze^- + e^- + \nu + \bar{\nu}$
- The nonelectron flavors are produced primarily by bremsstrahlung
- Compton process dominates at the highest energies
- For $\nu_e \bar{\nu}_e$, plasmon decay dominates, especially at lower energies
- A numerical integration over the Sun provides the low-energy flux at Earth from bremsstrahlung for either ν or $\bar{\nu}$ as:
$$\frac{d\Phi_\nu}{dE} = \frac{d\Phi_{\bar{\nu}}}{dE} = \frac{7.4 \times 10^6}{keV\ \ s\ \ cm^2} \left(\frac{E}{keV} \left(\frac{\sqrt{E^2 - m_\nu^2}}{keV} \right) \right)$$

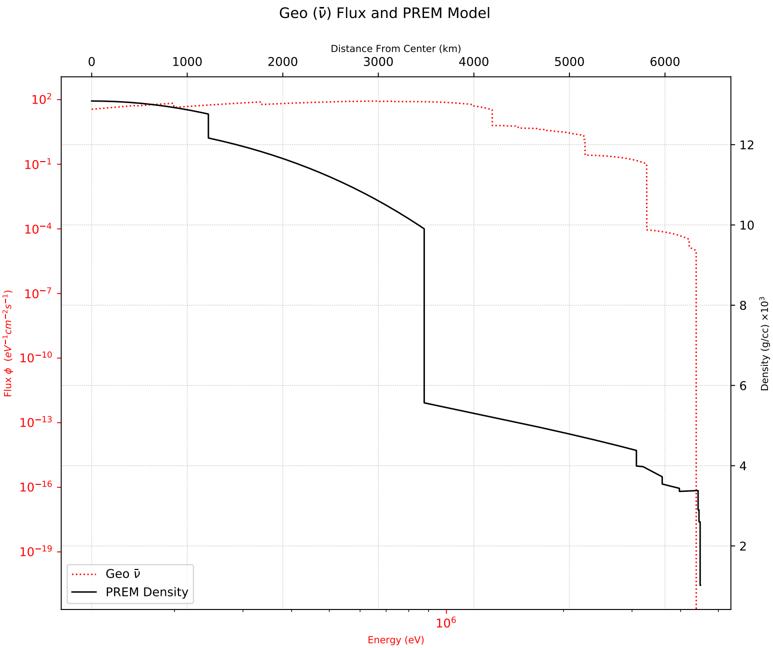

Solar Thermal
10^2
10^0
10^{-2}
10^{-4}
Flux ϕ $(eV^{-1}cm^{-2}s^{-1})$
10^{-1}
10^0
10^1
10^2
10^3
10^4
Energy (eV)

Geo – Neutrinos

- The decay of long-lived natural radioactive isotopes in Earth, notably ^{238}U, ^{232}Th, and ^{40}K, produce an MeV-range $\bar{\nu}_e$ flux exceeding $10^{25}/s$
- $^{238}U \longrightarrow\ ^{206}Pb + 8\alpha + 6e^- + 6\bar{\nu}_e +$ 51.7 MeV
- $^{232}Th \longrightarrow\ ^{208}Pb + 6\alpha + 4e^- + 4\bar{\nu}_e +$ 42.7 MeV
- $^{40}K \longrightarrow\ ^{40}Ca + e^- + \bar{\nu}_e +$ 1.31 MeV (89.3%)
  $e^- +\ ^{40}K \longrightarrow\ ^{40}Ar^* + \bar{\nu}_e +$ 44 keV (10.7%) $\longrightarrow\ ^{40}Ar + \bar{\nu}_e +$ 1441 keV
- The main detection channel is inverse beta decay $\bar{\nu}_e + p \longrightarrow n + e^-$ with a kinematical threshold of 1.806 MeV



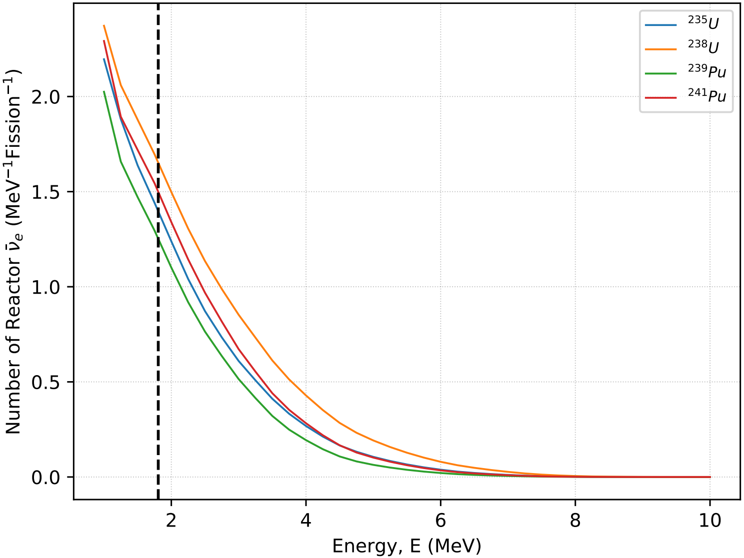
10^{22}
10^{19}
10^{16}
10^{13}
10^{10}
10^{7}
10^{4}
Luminosity (keV^{-1}s^{-1})
0
1000
2000
3000
4000
Energy, E (keV)
^{238}U
^{232}Th
^{235}U
^{40}K
^{87}Rb
^{113}Cd
^{115}In
^{138}La
$176Lu$
^{187}Re



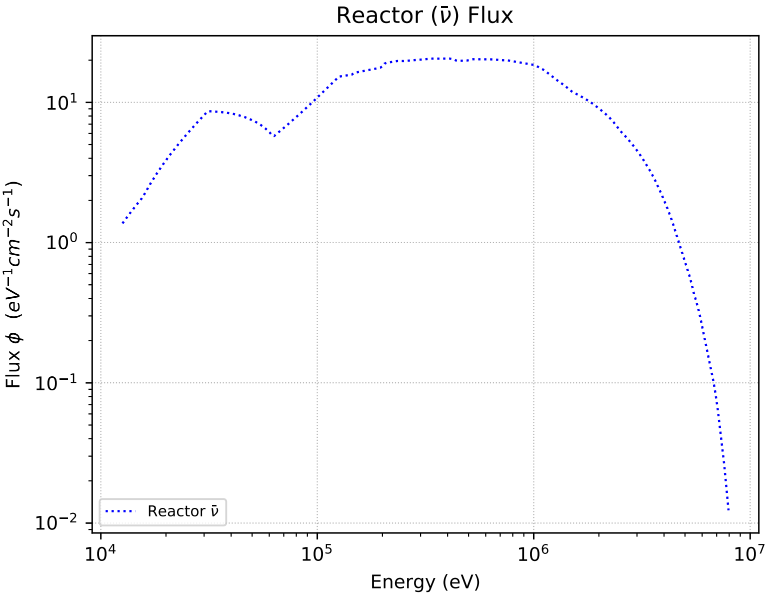
Geo ($\bar{\nu}$) Flux and PREM Model
Distance From Center (km)
0
1000
2000
3000
4000
5000
6000
10^{2}
10^{-1}
10^{-4}
10^{-7}
10^{-10}
10^{-13}
10^{-16}
10^{-19}
Flux ϕ $(eV^{-1}cm^{-2}s^{-1})$
12
10
8
6
4
2
Density (g/cc) $\times 10^{3}$
Geo $\bar{\nu}$
PREM Density
10^{6}
Energy (eV)

Reactor Neutrinos

- Nuclear power plants release a few percent of their energy production in the form of MeV-range $\bar{\nu}_e$ arising from the decay of fission products.
- β decay of U-235 (56%), Pu-239 (30%), U-238 (8%), Pu-241 (6%)
- Also, neutron capture on U-238 produces $\bar{\nu}_e$ below detection threshold of inverse beta decay i.e. 1.806 MeV



Number of Reactor $\bar{\nu}_e$ (MeV^{-1}Fission^{-1})
Energy, E (MeV)
^{235}U
^{238}U
^{239}Pu
^{241}Pu
0.0
0.5
1.0
1.5
2.0
2
4
6
8
10



Reactor ($\bar{\nu}$) Flux
Flux ϕ $(eV^{-1}cm^{-2}s^{-1})$
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{4}
10^{5}
10^{6}
10^{7}
Energy (eV)
Reactor $\bar{\nu}$

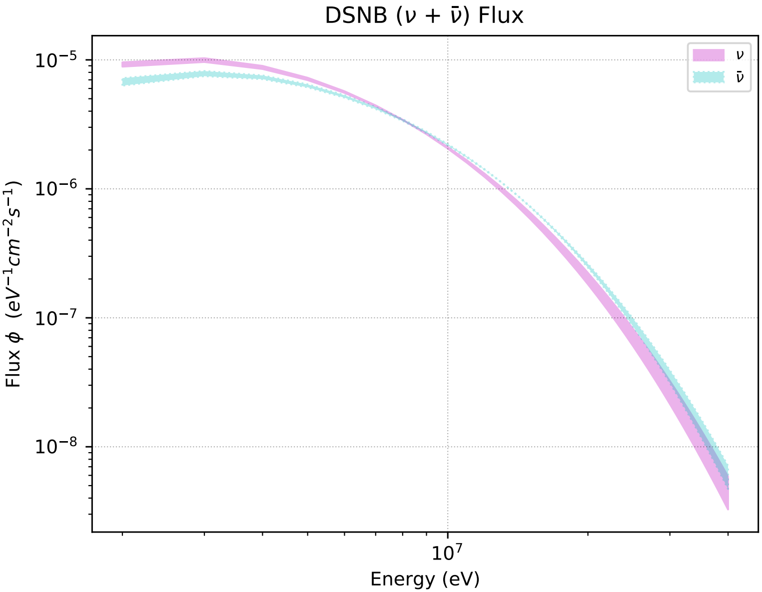
Diffuse Supernova Neutrinos

- All collapsing stars in the visible Universe, a few per second, provide the DSNB. It dominates at Earth for 10–25 MeV
- Neutrino burst from SN 1987A in the Large Magellanic Cloud detected around 20 neutrinos
- For a given species ν, the DSNB flux with $n_{cc} \sim 10^7 \ Mpc^{-3}$ is

$$\frac{d\Phi_\nu}{dE} = \frac{10.3}{MeV \ cm^2 \ s} \frac{n_{cc}}{10^7 \ Mpc^{-3}} \frac{N_\nu}{10^{57}} g_\nu(E)$$

where

$$g_\nu(E) = \frac{a}{T} \arctan \left[b \left(\frac{E}{T} \right)^q \right] \exp - \left(\frac{E}{T} \right)^p$$


DSNB ($\nu + \bar{\nu}$) Flux
ν
$\bar{\nu}$
10^{-5}
10^{-6}
10^{-7}
10^{-8}
Flux ϕ ($eV^{-1}cm^{-2}s^{-1}$)
10^{7}
Energy (eV)

Atmospheric, Astrophysical & Cosmogenic Neutrinos

Cosmogenic νtrinos

$$p + \gamma_{CMB} \xrightarrow{\Delta^+} \begin{cases} p + \pi^0 \longrightarrow p + \gamma + \gamma \\ n + \pi^+ \longrightarrow n + e^+ + \nu_\mu + \nu_e + \bar{\nu}_\mu \end{cases}$$

Astrophysical/Atmospheric νtrinos (Credit [7])

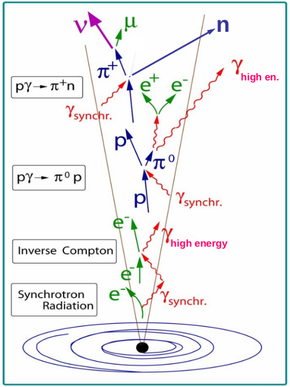
$$p + \gamma \longrightarrow \pi^0 + p$$

$$p + N \longrightarrow \pi + X \qquad (\pi = \pi^0, \pi^+, \pi^-)$$

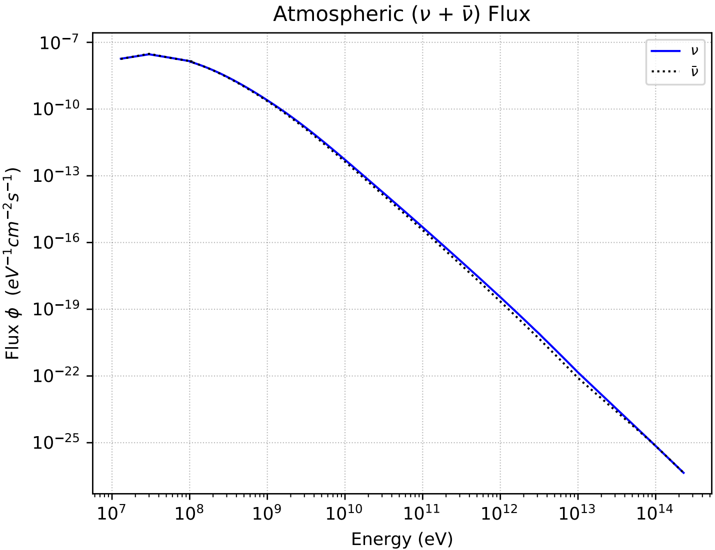
$$\pi^0 \longrightarrow \gamma + \gamma$$

$$\pi^+(\pi^-) \longrightarrow \mu^+(\mu^-) + \nu_\mu(\bar{\nu}_\mu)$$

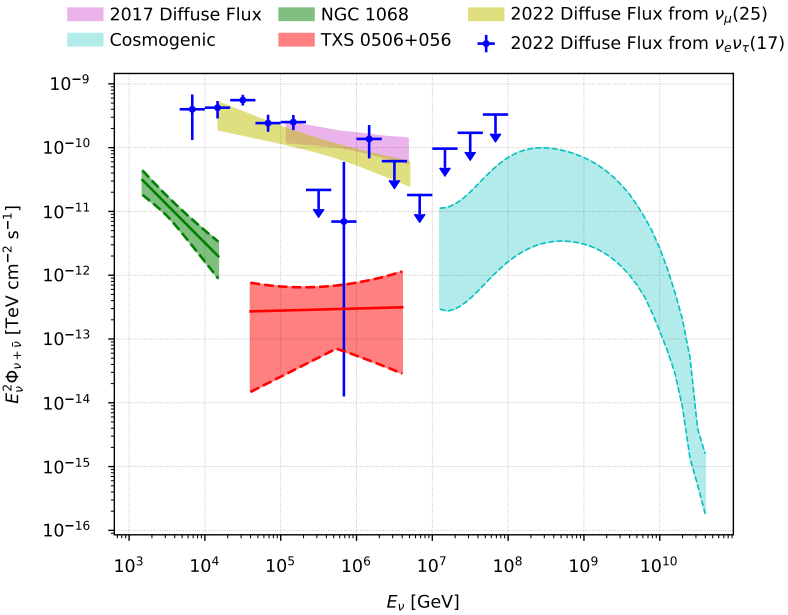
$$\mu^+(\mu^-) \longrightarrow e^+(e^-) + \nu_e(\bar{\nu}_e) + \bar{\nu}_\mu(\nu_\mu)$$



- Huge number of detection every now and then, mostly in Japan



★ No Cosmogenic ν detected yet! (Adapted From: [5], [6])



References

- Solar Data & Plots
- Big Bang Nucleosynthesis
- Geoneutrino Spectrum and Luminosity
- The reactor antineutrino spectrum calculation, S. V. Silaeva and V. V. Sinev
- IceCube Data Releases 2022
- E. Vitagliano, I. Tamborra, and G. Raffelt - "Grand unified neutrino spectrum at Earth: Sources and spectral components", Rev. Mod. Phys. 92, 045006 (2020)
- U.F. Katza, Ch. Spiering - "High-Energy Neutrino Astrophysics: Status and Perspectives", arXiv:1111.0507v1 [astro-ph.HE] 2 Nov 2011




Thank You!




Backup Slides

Abstract

Neutrinos are the fundamental particles which has promising potent to unveil the mysteries of our universe. Besides their importance in understanding fundamental Physics, a new era of multi-messenger astronomy with neutrinos is outspreading which is evident from the large scale neutrino detectors around the world sensitive from meV to PeV energy scales. In this presentation, we discuss the grand unified neutrino spectrum (GUNS) at Earth from various sources. The original work is done by Vitagliano, Tamborra, and Raffelt in their review paper, DOI: 10.1103/RevModPhys.92.045006 [6].

Important Points

- If neutrino masses are of Majorana type and thus violate lepton number, any primordial asymmetry remains conserved, i.e., helicity plays the role of lepton number and allows for a chemical potential. In the Dirac case, the same reasoning implies that the sterile partners will not be thermally excited. Therefore, the standard CNB will be the same for both types of neutrino masses.
- For neutrinos with mass, not the energy but the momentum is redshifted by cosmic expansion, so the phase-space occupation at redshift z for free streaming neutrinos is

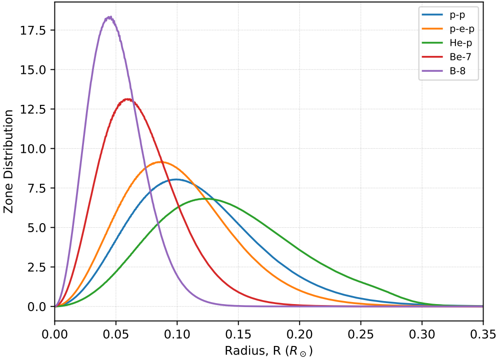
$$f_\nu(p) = \frac{1}{e^{p/T_z} + 1}$$

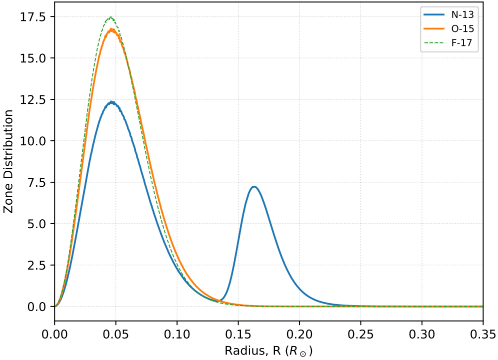
  where

$$T_z = (1+z)T_\nu$$

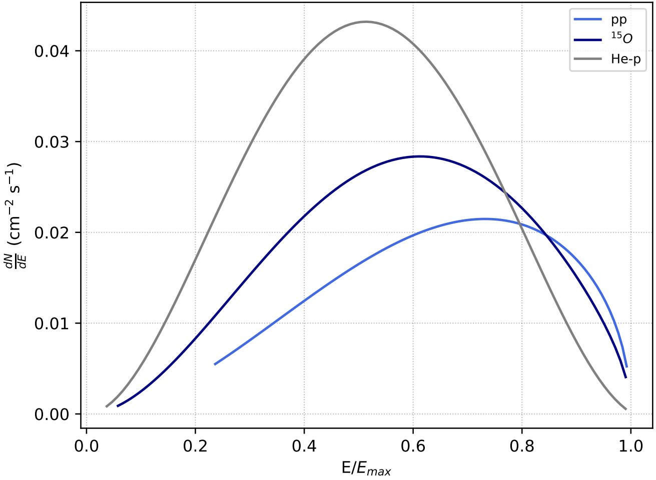
- Early Universe, p and n in β equilibrium: $n/p = e^{-\Delta m/T}$, $\Delta m = 1.293\ MeV$

SSM Prediction



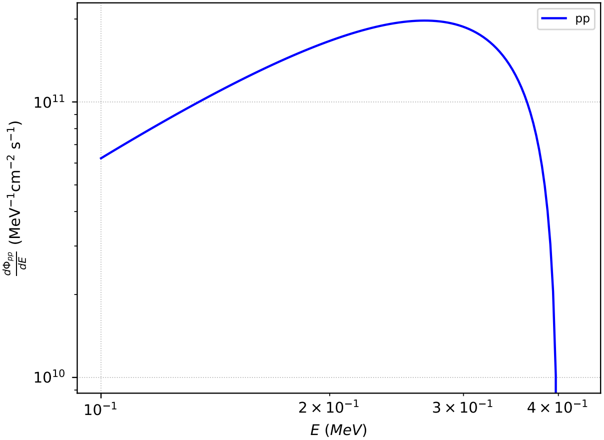


- Except for ^{8}B, the continuum spectra follow $\frac{dN}{dE} \propto E^2(Q-E)\sqrt{(Q-E)^2 - m_e^2}$, $Q = E_{max} + m_e$



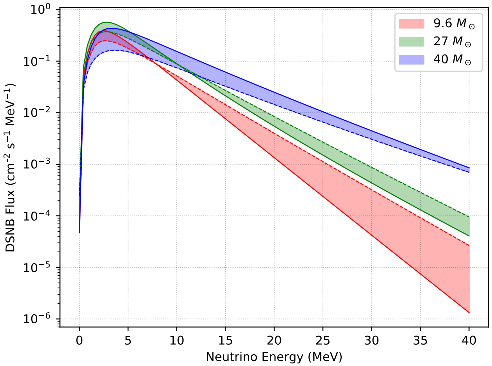
pp Flux Neutrino @Earth

- Total pp flux approximation for the flux at Earth is
$$\frac{d\Phi_{pp}}{dE} = \frac{832.7 \times 10^{10}}{MeV\ \ s\ cm^2}\left(\frac{E}{MeV}\right)^2\left(1 - 2.5\frac{E}{MeV}\right)$$

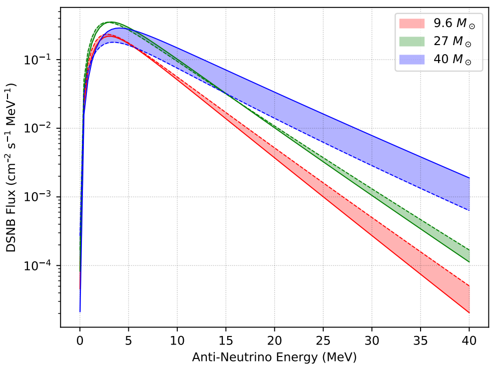


DSNB

		N_ν 10^{57}	$E_\nu^{\rm tot}$ 10^{52} erg	$E_{\rm av}$ (MeV)	α	$E_{\rm av}^{\rm DSNB}$ (MeV)	a	b	q	p	T (MeV)
9.6 $M_\odot$ (SN)	ν_e	2.01	3.17	9.8	2.81	4.59	1.347	1.837	1.837	0.990	2.793
	$\bar{\nu}_e$	1.47	2.93	12.4	2.51	5.83	1.313	1.770	1.703	0.969	3.483
	ν_x	1.61	3.09	12.0	2.10	5.62	1.173	2.350	1.672	0.953	3.432
	$\bar{\nu}_x$	1.61	3.27	12.7	1.96	5.95	1.145	2.401	1.620	0.944	3.617
27 $M_\odot$ (SN)	ν_e	3.33	5.87	11.0	2.17	5.16	1.575	0.489	1.775	0.794	1.824
	$\bar{\nu}_e$	2.61	5.72	13.7	2.25	6.41	1.260	1.791	1.667	0.942	3.700
	ν_x	2.56	5.21	12.7	1.88	5.95	1.153	2.106	1.615	0.916	3.400
	$\bar{\nu}_x$	2.56	5.53	13.5	1.76	6.32	1.111	2.337	1.569	0.916	3.690
40 $M_\odot$ (BH)	ν_e	3.62	9.25	16.0	1.66	7.47	1.065	2.340	1.809	0.866	3.904
	$\bar{\nu}_e$	2.88	8.61	18.7	1.99	8.75	1.089	3.199	1.801	0.951	5.486
	ν_x, $\bar{\nu}_x$	1.72	4.83	17.5	1.46	8.21	1.227	1.090	1.314	0.822	3.707
Mix 1	$\langle\nu\rangle$	2.14	4.14	12.1	1.74	5.66	1.471	0.356	1.755	0.724	1.592
(59,32,9)	$\langle\bar{\nu}\rangle$	1.94	4.20	13.5	1.80	6.34	1.308	0.940	1.614	0.822	2.687
Mix 2	$\langle\nu\rangle$	2.09	4.25	12.7	1.52	5.95	1.362	0.318	1.768	0.690	1.486
(59,20,21)	$\langle\bar{\nu}\rangle$	1.88	4.26	14.2	1.64	6.63	1.301	0.734	1.617	0.777	2.439

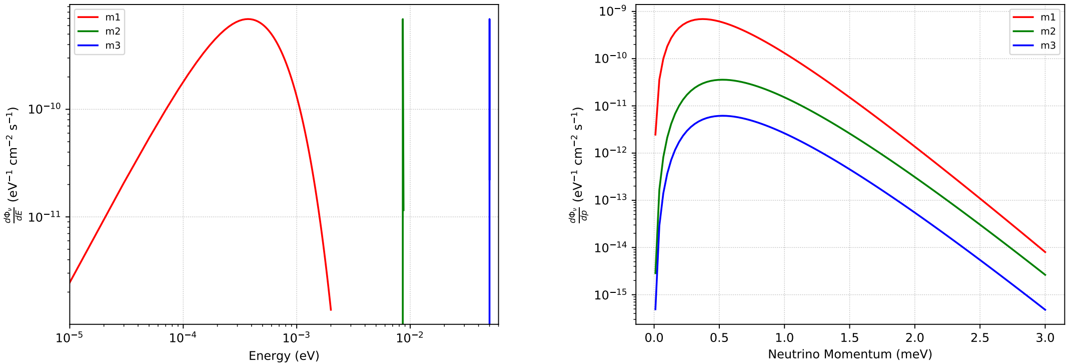


DSNB Flux (cm^{-2} s^{-1} MeV^{-1})
Neutrino Energy (MeV)
9.6 $M_\odot$
27 $M_\odot$
40 $M_\odot$

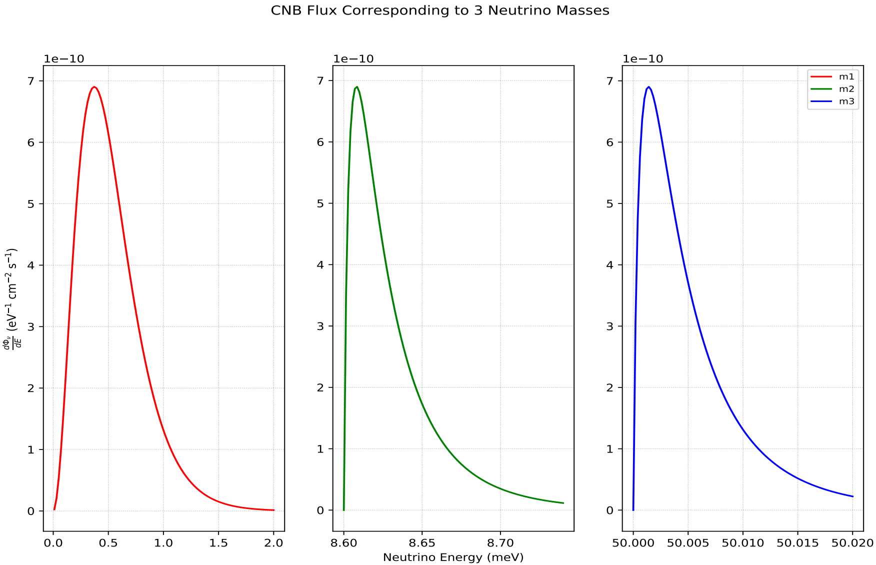


DSNB Flux (cm^{-2} s^{-1} MeV^{-1})
Anti-Neutrino Energy (MeV)
9.6 $M_\odot$
27 $M_\odot$
40 $M_\odot$

CNB


m1
m2
m3
10^{-10}
10^{-11}
$\frac{d\Phi_\nu}{dE}$ (eV^{-1} cm^{-2} s^{-1})
10^{-5}
10^{-4}
10^{-3}
10^{-2}
Energy (eV)
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
$\frac{d\Phi_\nu}{dp}$ (eV^{-1} cm^{-2} s^{-1})
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Neutrino Momentum (meV)

- Maximum flux does not depend on mass
- For larger masses it is tightly concentrated at $E \geq m_i$, $i = 2, 3$



Other Solar Neutrinos

- Sun also produces $\bar{\nu}_e$ from ${}^{40}K$ decay but flux at Earth is of around 100 $cm^{-2}s^{-1}$. With a geo-$\bar{\nu}_e$ luminosity of around $2^{25}/s$ from potassium decay, the average geoneutrino flux is $5 \times 10^6 cm^{-2}s^{-1}$ at Earth's surface.
- An additional flux of higher-energy solar $\bar{\nu}_e$ comes from photofission of heavy elements such as uranium by the 5.5 MeV photon from the solar fusion reaction $p + d \longrightarrow {}^3He + \bar{\nu}_e$. However, this small flux of around $10^3 cm^{-2}s^{-1}$ is vastly overshadowed by reactor neutrinos.