Credits: SN 1987A ESO (eso0708a), ESA/Euclid/Euclid Consortium/NASA

A review of neutrino fluxes at Earth
or:
The Grand Unified Neutrino Spectrum

NuPhys 2023
PROSPECTS IN NEUTRINO PHYSICS
King's College (London), UK
Dec 18, 2023

Edoardo Vitagliano
edoardo.vitagliano@mail.huji.ac.il
Hebrew University of Jerusalem

האוניברסיטה העברית בירושלים
THE HEBREW UNIVERSITY OF JERUSALEM

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Three questions about neutrinos

- Where do they come from?

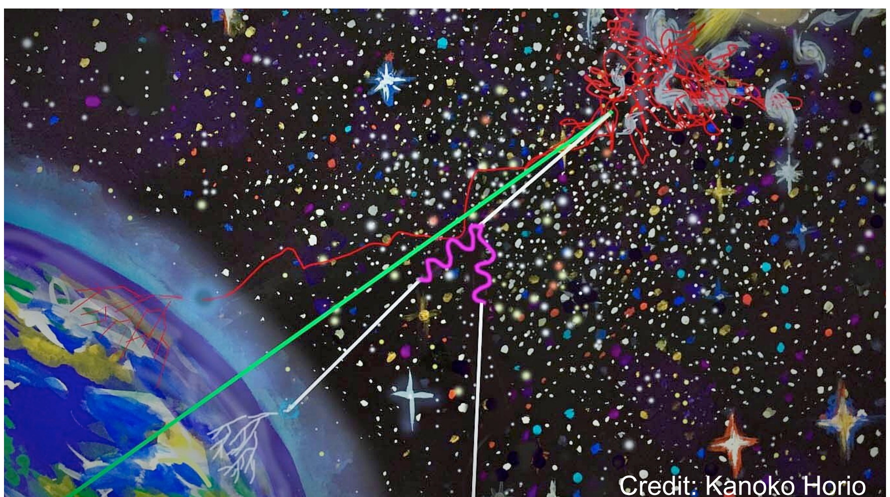
Three questions about neutrinos

- Where do they come from?
- How do we detect them?

Three questions about neutrinos

- Where do they come from?
- How do we detect them?
- What can we learn?

Astrophysics



Credit: Kanoko Horio

Particle physics

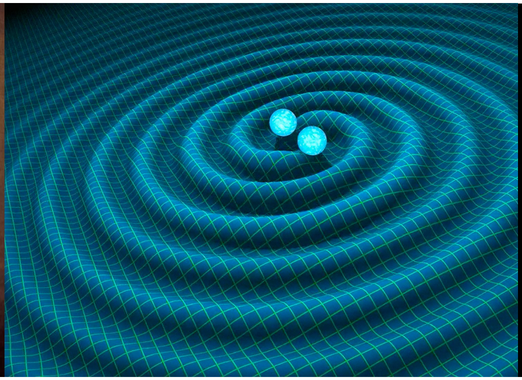
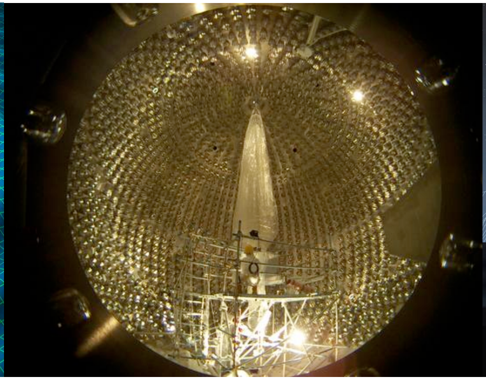
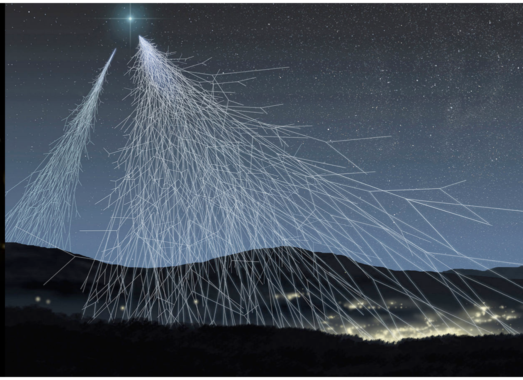
Credit: Sandbox Studio, Chicago with Ana Kova

Dawn of multi-messenger astronomy

From Wikipedia…

Multi-messenger astronomy is astronomy based on the coordinated observation and interpretation of disparate "messenger" signals. The four extrasolar messengers are ***electromagnetic radiation****,* ***gravitational waves****,* ***neutrinos****, and* ***cosmic rays****. They are created by different astrophysical processes, and thus reveal different information about their sources.*

https://en.wikipedia.org/wiki/Multi-messenger_astronomy

Images credits: Rex, R. Hurt/Caltech-JPL/EPA, Virginia Tech Physics, ASPERA/Novapix/L. Bret

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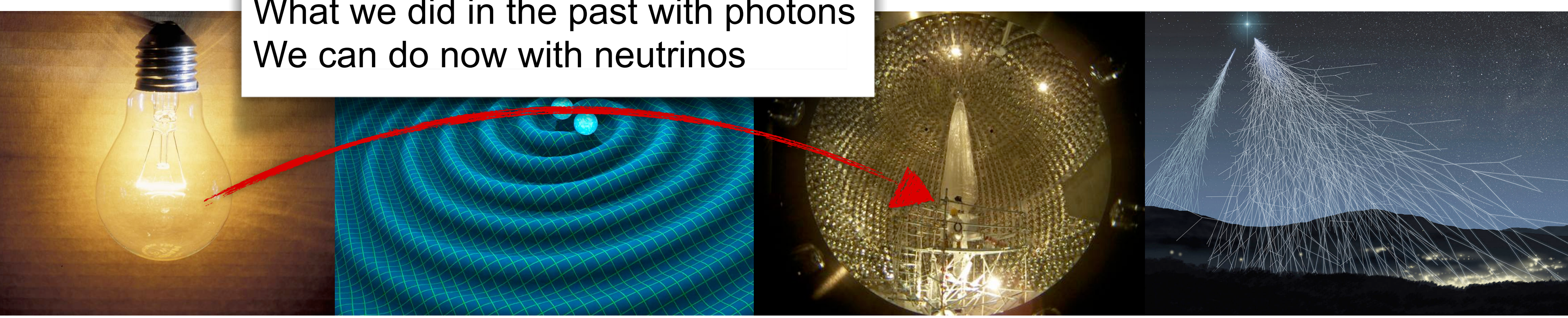
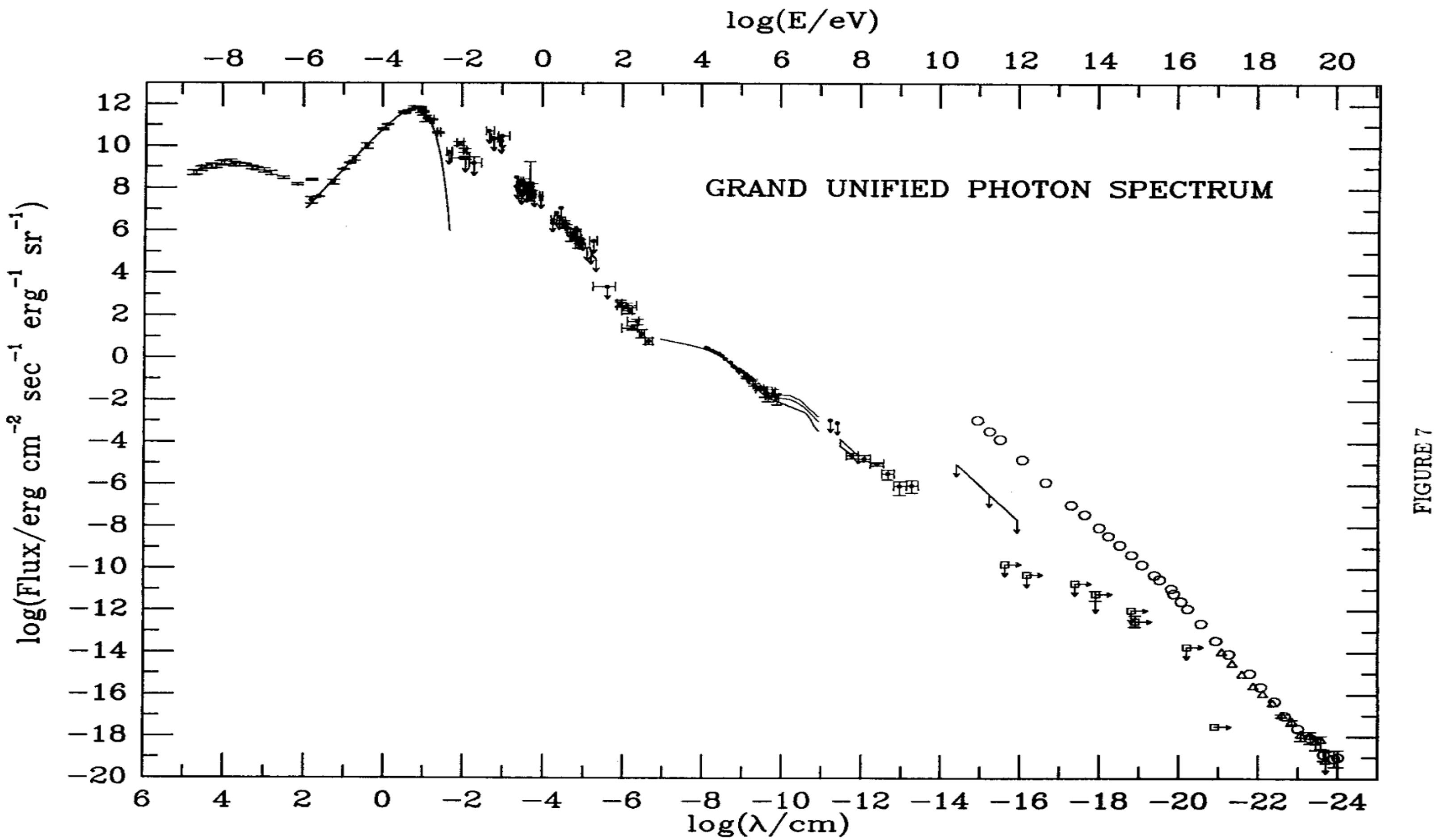
What we did in the past with photons
We can do now with neutrinos



Images credits: Rex, R. Hurt/Caltech-JPL/EPA, Virginia Tech Physics, ASPERA/Novapix/L. Bret

Grand Unified Photon Spectrum

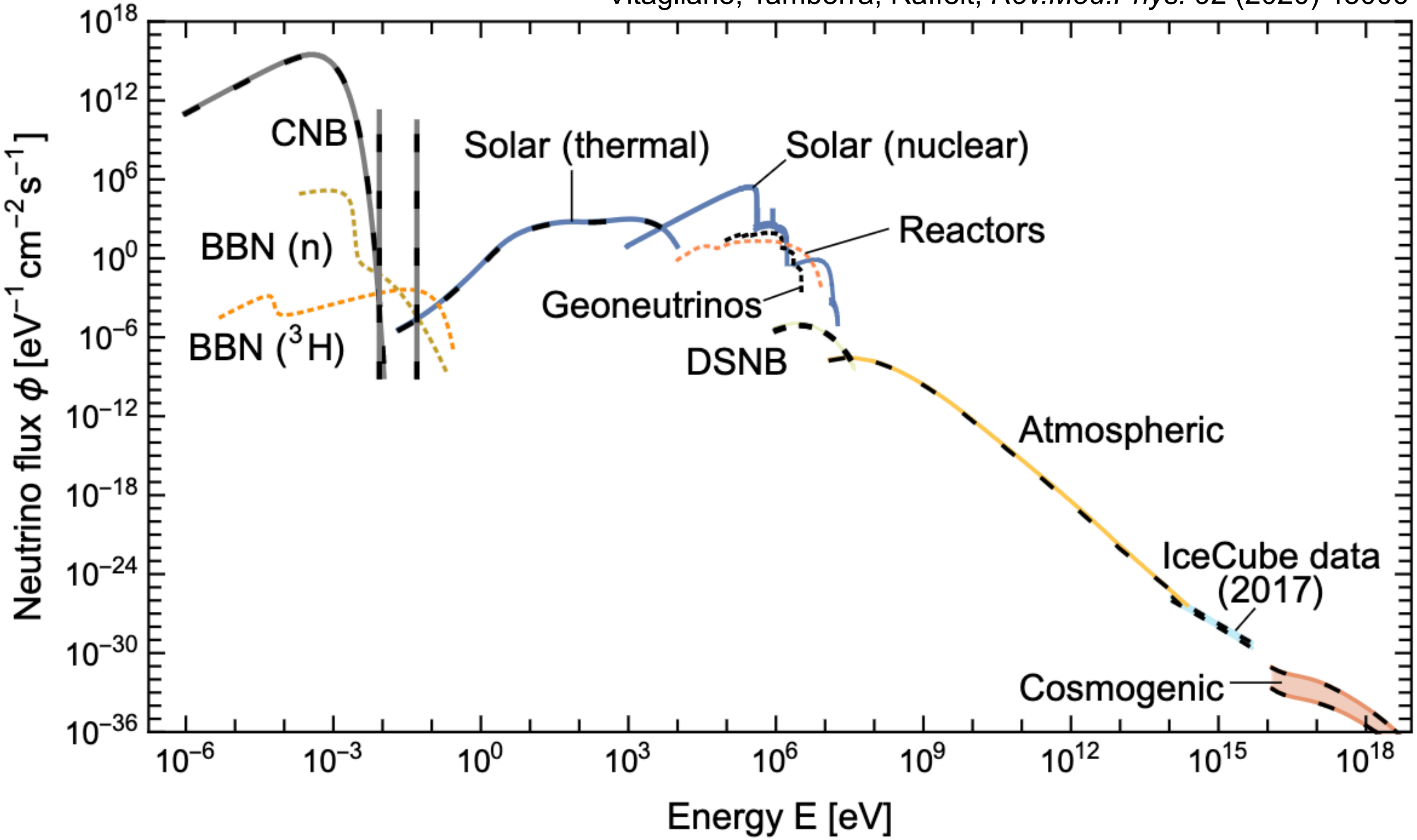


Ressell and Turner, Comments Astrophys. 14 (1990) 323

(The spectrum at Earth of photons from any possible source)

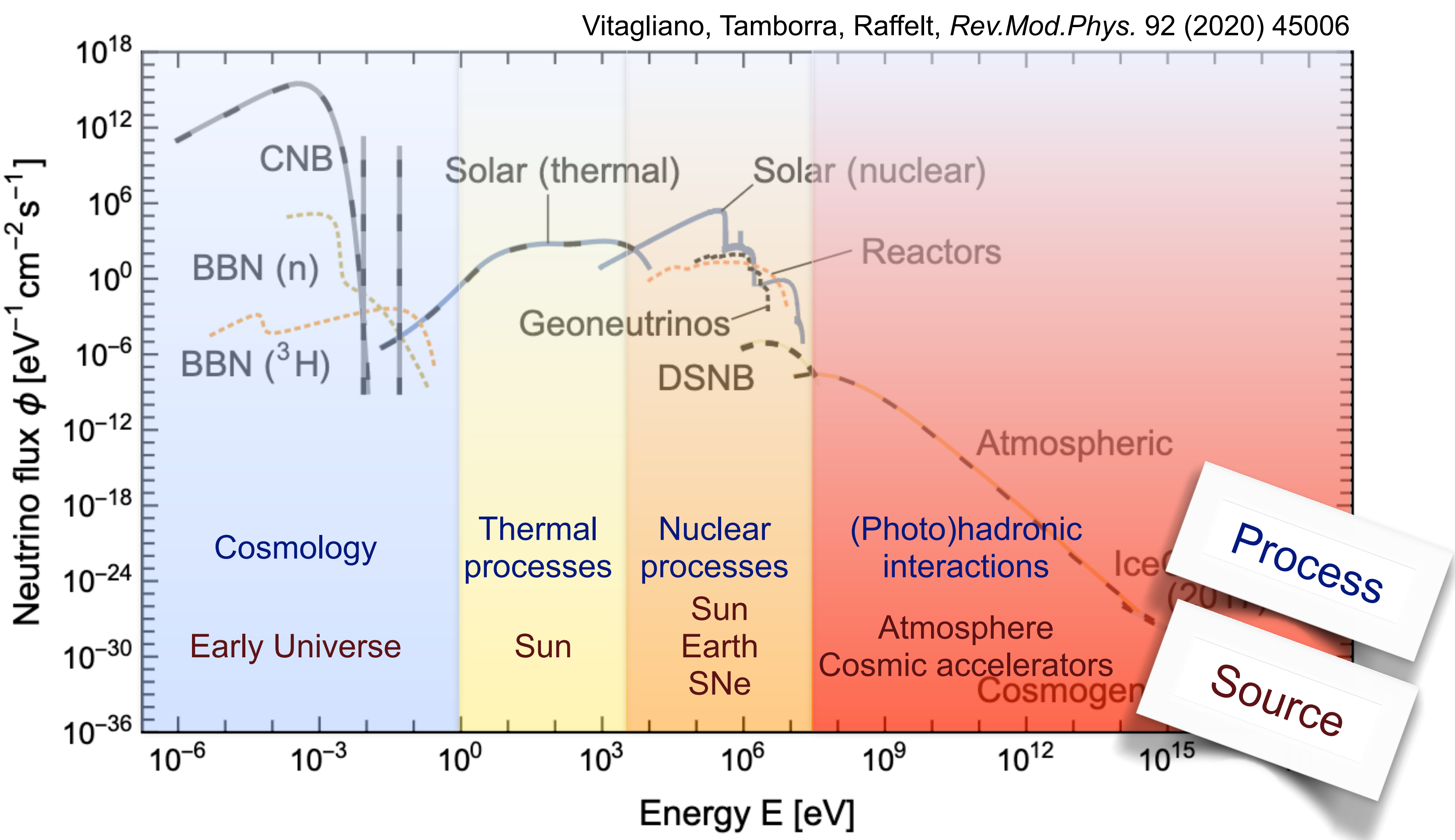
Grand Unified Neutrino Spectrum

Vitagliano, Tamborra, Raffelt, *Rev.Mod.Phys.* 92 (2020) 45006



(The spectrum at Earth of neutrinos from any possible source)

Grand Unified Neutrino Spectrum



(The spectrum at Earth of neutrinos from any possible source)

Cosmic neutrinos

Cosmic neutrino background

- In the hot big bang phase, the universe expands

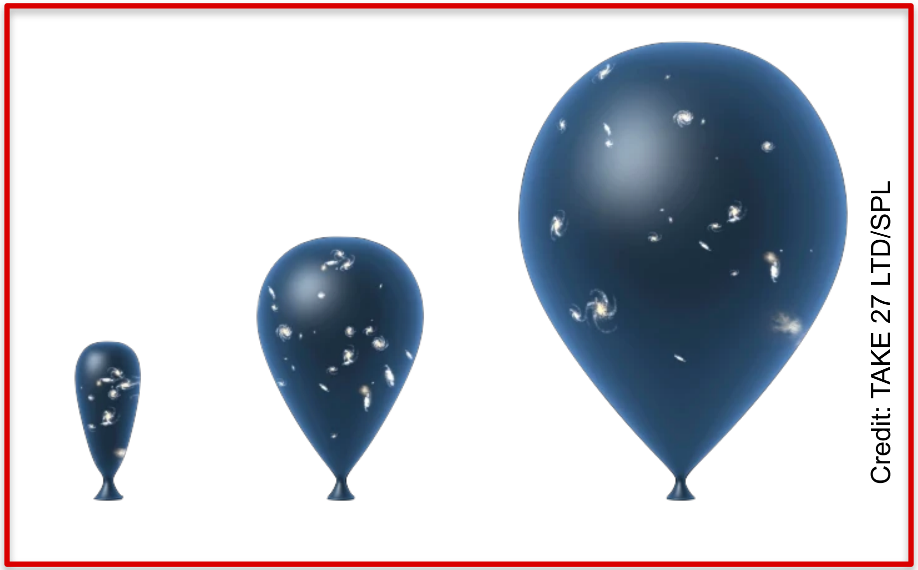
- The density and cross section of neutrinos becomes smaller and smaller

- When the interaction rate is $\Gamma \simeq H$, neutrinos decouple:

$$n\sigma \simeq T^3 G_F^2 T^2 \simeq \frac{T^2}{m_P}$$

- At around $1\,\mathrm{MeV}$, the neutrino distribution is frozen, and after $e^\pm$ annihilation the temperature is

$$T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma$$



Massive neutrinos (assuming one to be massless):
$m_1 = 0, m_2 = 8.6\,\mathrm{meV}, m_3 = 50\,\mathrm{meV}$
Today, $T_\nu = 1.945\,\mathrm{K}\,(= 0.168\,\mathrm{meV})$

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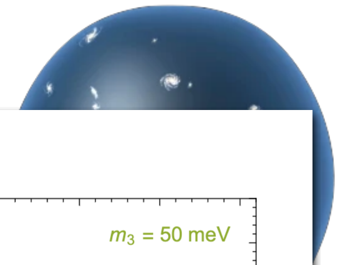
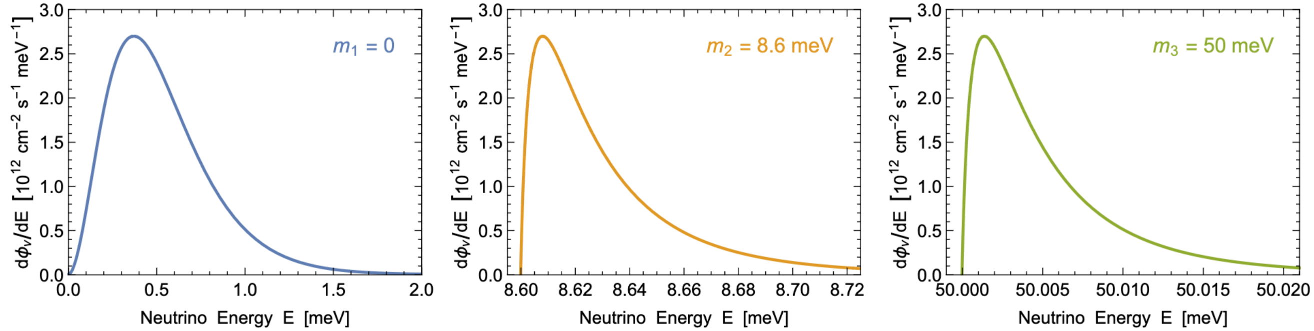


Credit: TAKE 27 LTD/SPL



CνB is dark matter!

massless):

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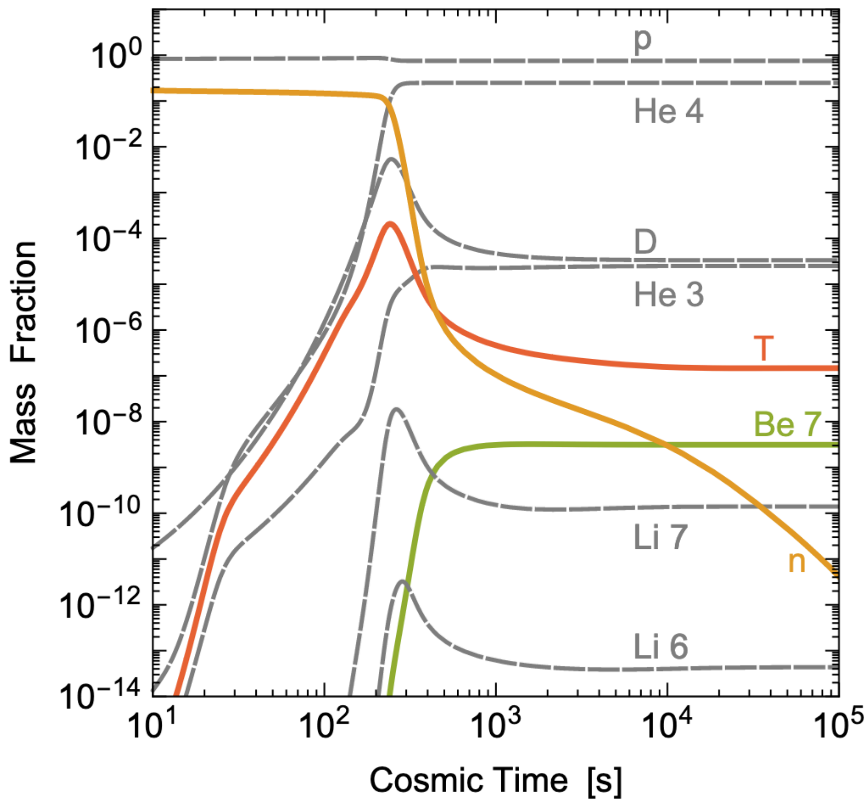
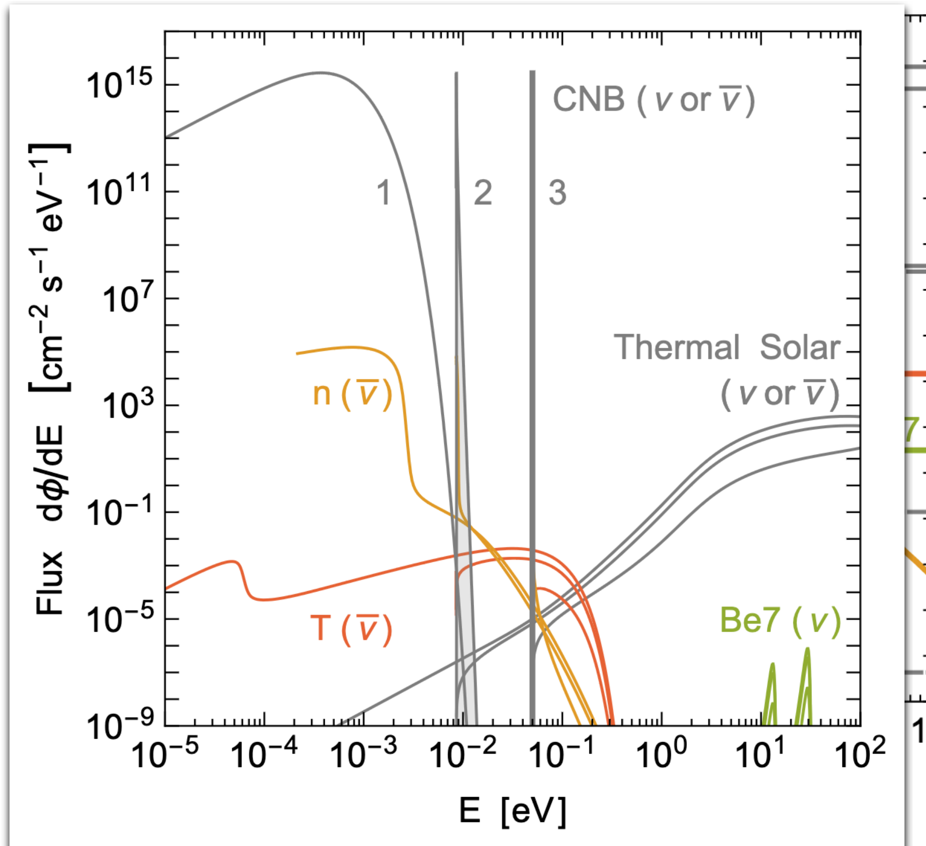
BBN neutrinos

- Solve a nuclear reaction network in the expanding universe



BBN neutrinos

- Solve a nuclear reaction network in the expanding universe
- Be7 electron capture to Li7 (similar process in stars for solar neutrino aficionados)
- Tritium decay with lifetime 17.8 years
  $^3\mathrm{H} \rightarrow {}^3\mathrm{He} + e + \bar{\nu}_e$
- Neutron decay with lifetime of 880 s
  $n \rightarrow p + e + \bar{\nu}_e$

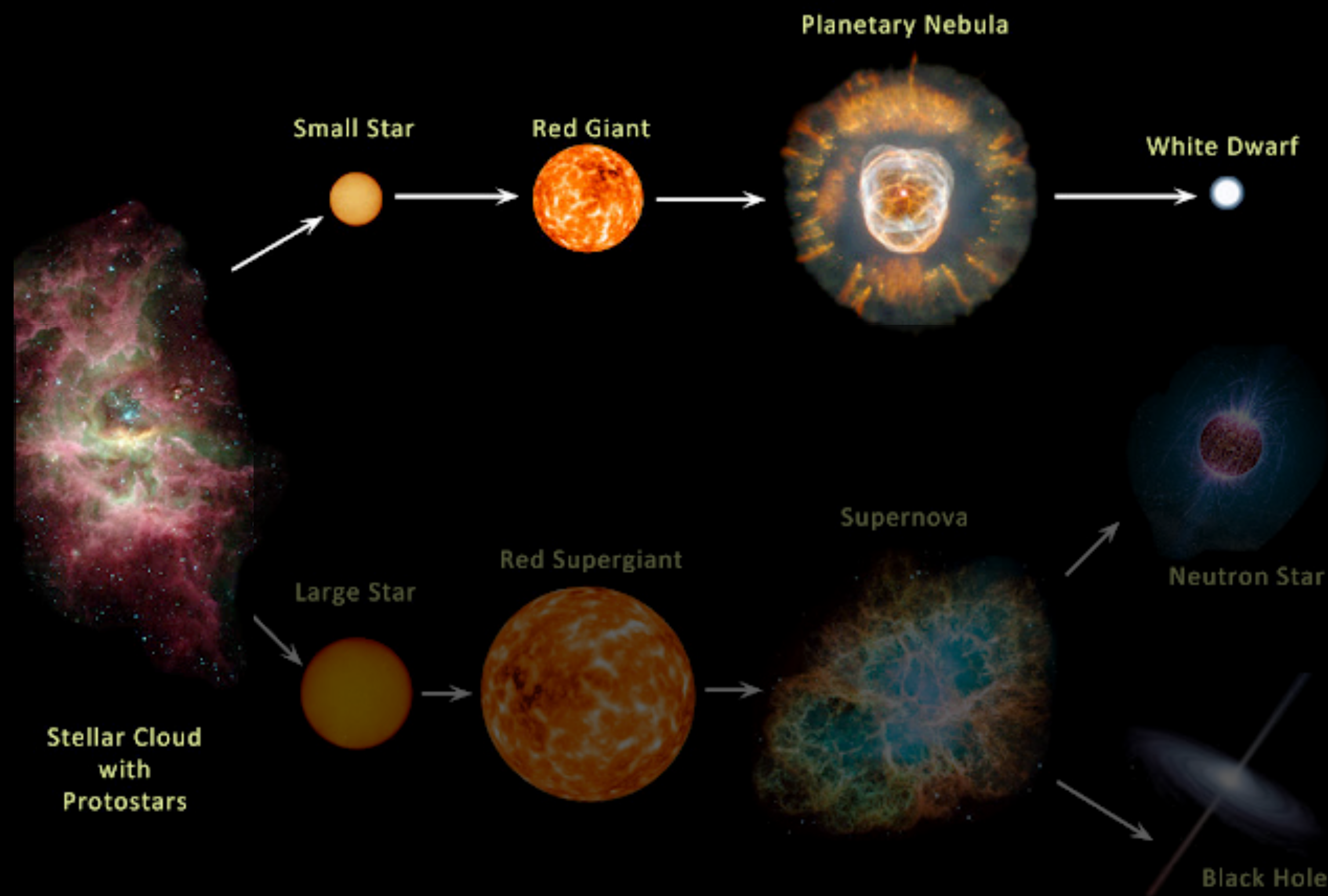


Detection prospects: PTOLEMY, several proposals based on asymmetry close to Earth

Neutrinos from the Sun

A brief history of stars

(Inspired by G. Raffelt)

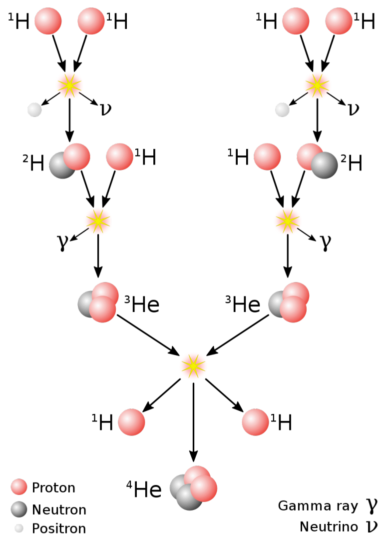


Credit: http://earthspacecircle.blogspot.com/2013/07/stellar-evolution.html

Neutrino production in stars

Two mechanisms of production: nuclear reactions and thermal productions

Nuclear processes: MeV neutrinos (also CNO)



$$L_{\nu_e} = 2 \times \frac{L_\odot}{26.73\ \mathrm{MeV} - 2\,\langle \mathrm{E}_{\nu_e} \rangle} = 1.83 \times 10^{38}\ \mathrm{s}^{-1}$$

$$\Phi_\nu = 6.51 \times 10^{10}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$$

Thermal processes: Depends on T and ρ

Vitagliano, Redondo, Raffelt, *JCAP* 12 (2017) 010

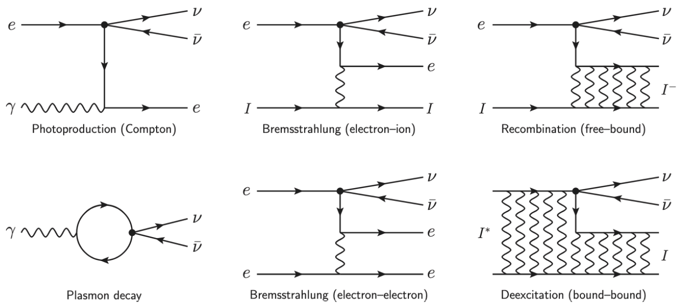


Figure 1. Processes for thermal neutrino pair production in the Sun.

$$\Phi_\nu \simeq 5 \times 10^5\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$$

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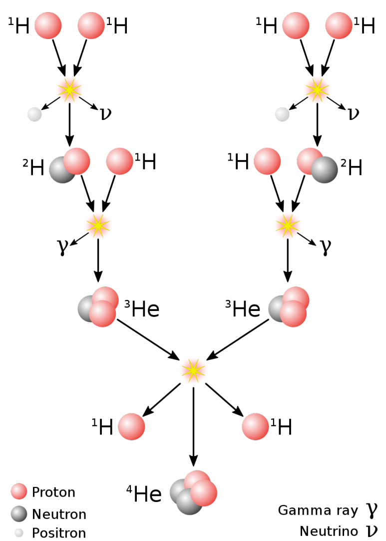

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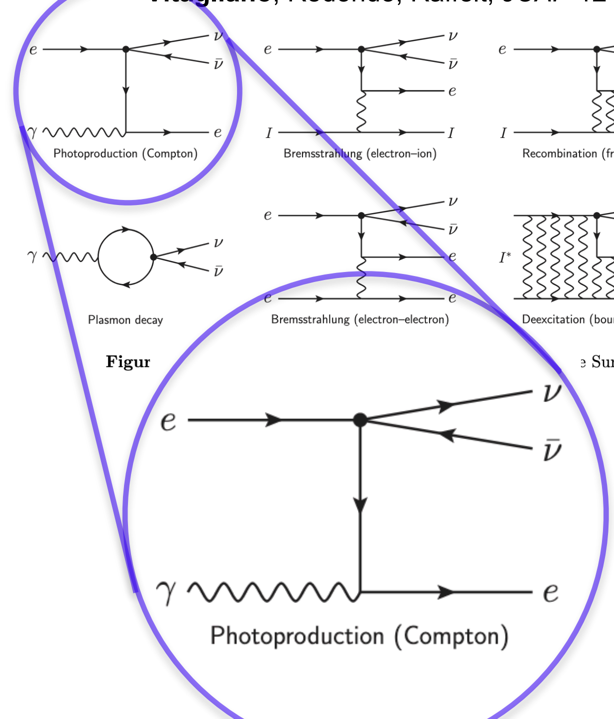

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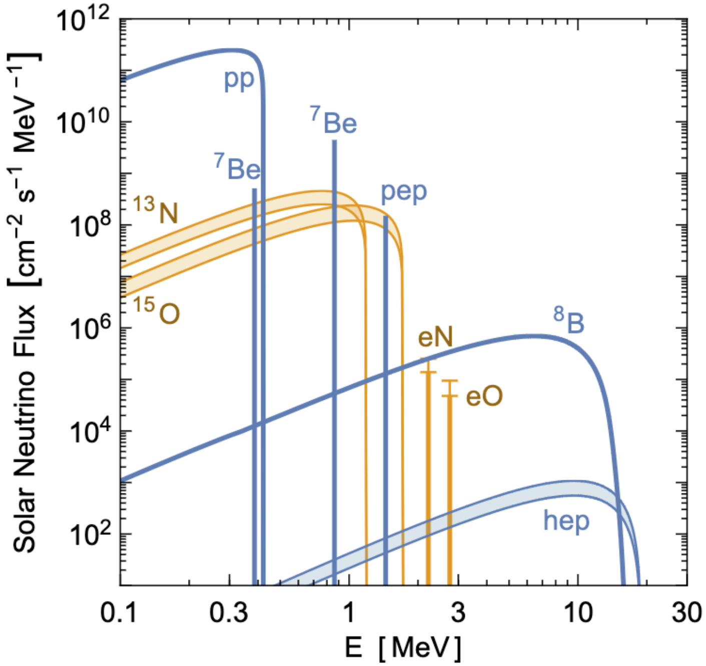
Neutrino fluxes from the Sun

Two mechanisms of production: nuclear reactions and thermal productions

Nuclear processes: MeV neutrinos (also CNO)

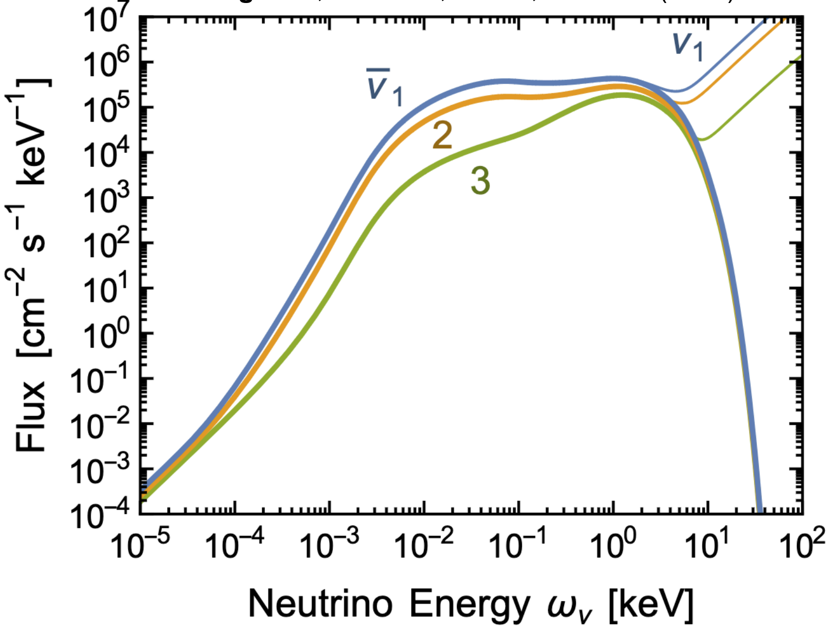


Only neutrinos*, matter oscillation at larger energies

*your mileage may vary

Thermal processes: Depends on T and ρ

Vitagliano, Redondo, Raffelt, *JCAP* 12 (2017) 010

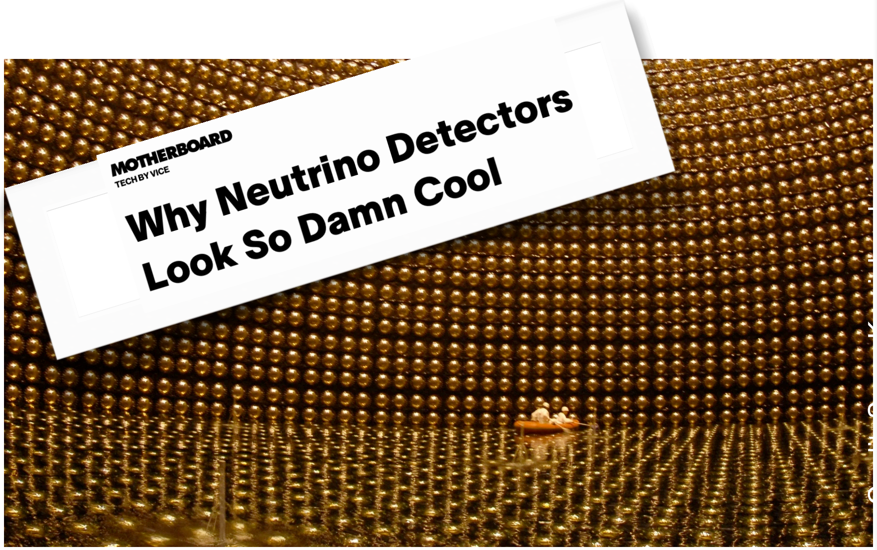


Neutrino-antineutrino pairs, vacuum oscillations

Detection

Two mechanisms of production: nuclear reactions and thermal productions

Nuclear processes:
MeV neutrinos (also CNO)



Chlorine, Gallium, water, mineral oil…

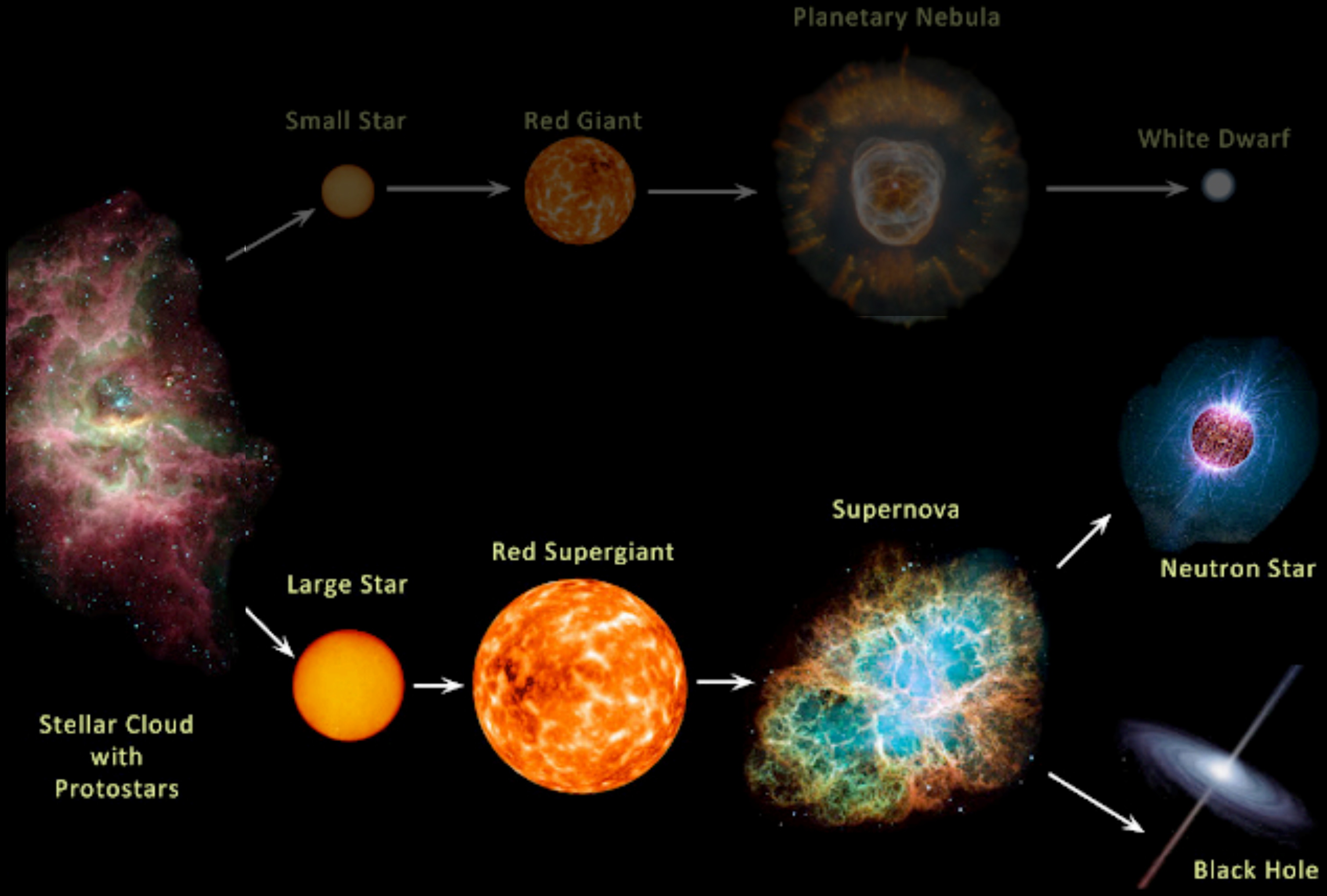
Thermal processes:
Depends on T and ρ

Any idea is welcome

Supernova neutrinos

A brief history of stars

(Inspired by G. Raffelt)



Credit: http://earthspacecircle.blogspot.com/2013/07/stellar-evolution.html

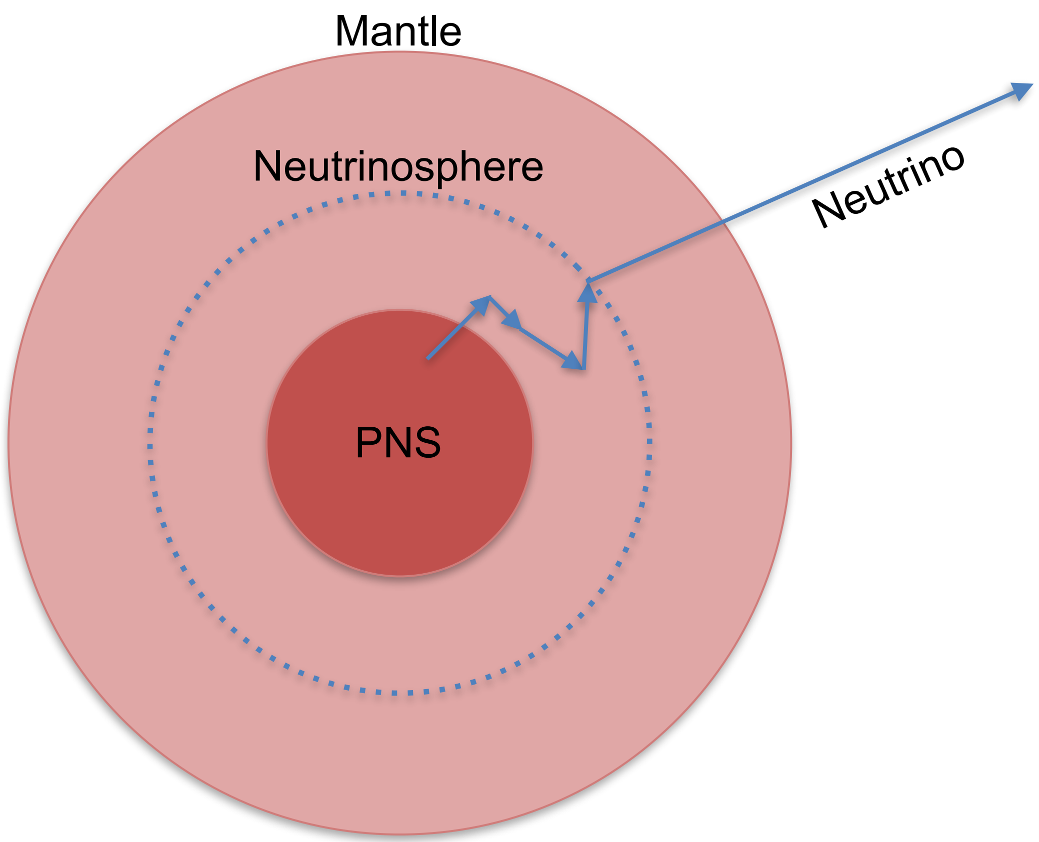
Stellar collapse

Protoneutron star, it has

- $T = \mathcal{O}(10\,\mathrm{MeV})$
- $\rho = 3 \times 10^{14} \mathrm{g/cm^3}$
- $R_{\mathrm{PNS}} = 20\,\mathrm{km}$

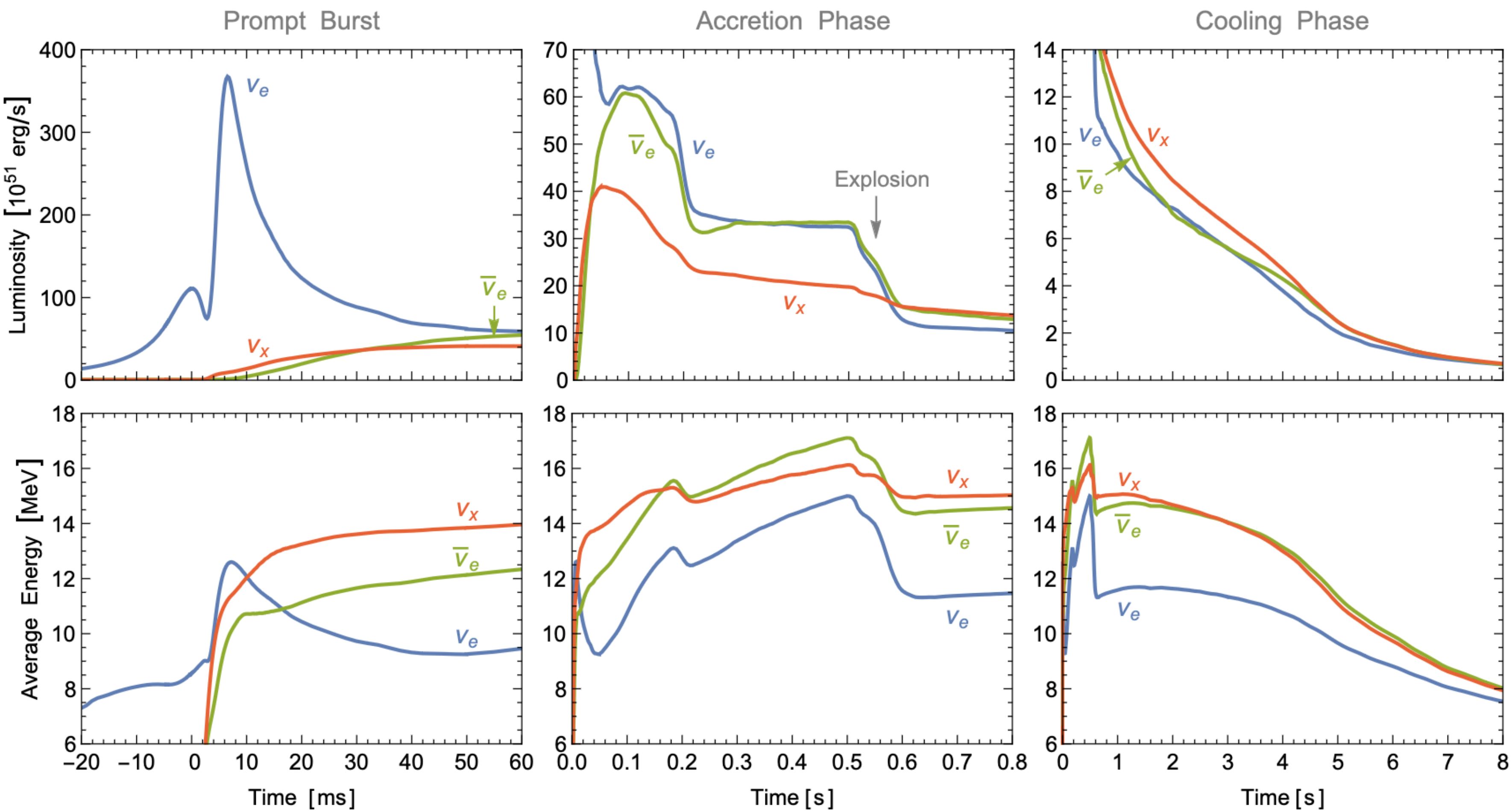
And produce many neutrinos,

- $L_\nu = 3 \times 10^{53} \mathrm{erg/3s}$
- Energy deposited: 1%



(Analogous to photons in the Sun)

Stellar collapse



Neutronization

Explosion comes to a halt

As seen in 1987

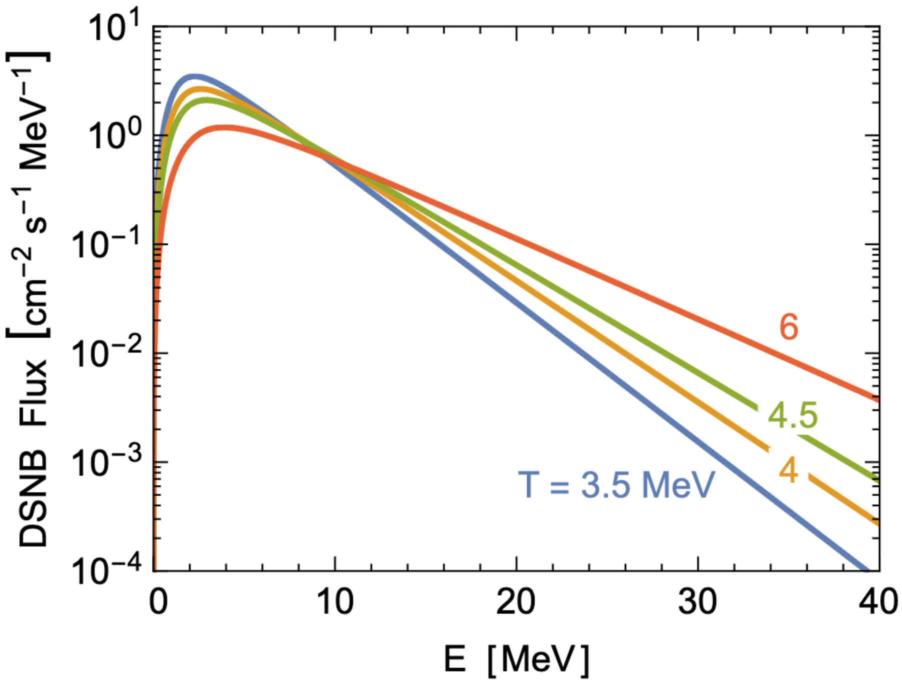
Diffuse SN neutrino background

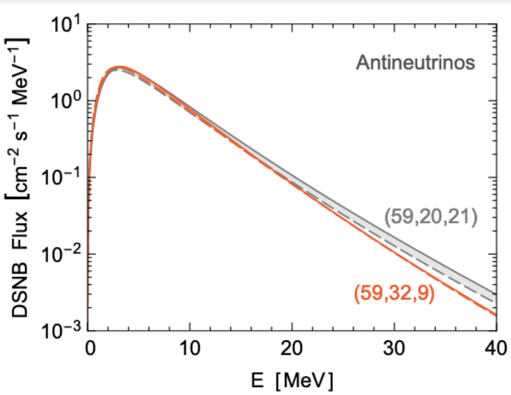
Neutrino number density

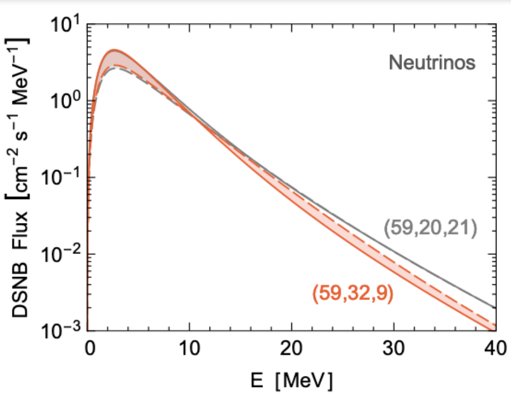
$$\frac{dn_\nu}{dE} = \int_0^\infty dz\,(z+1)\,\underbrace{F_\nu(E_z)}_{\text{Single SN}}\,\underbrace{n'_{\rm cc}(z)}_{\text{Redshift distribution}}$$

Assuming Maxwell-Boltzmann distribution

$$\frac{d\Phi_\nu}{dE} = 4.45\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{MeV}^{-1}\ \frac{n_{\rm cc}}{10^7\ \mathrm{Mpc}^{-3}} \times \frac{6\,E_\nu^{\rm tot}}{2\times10^{53}\ \mathrm{erg}}\left(\frac{4\ \mathrm{MeV}}{T}\right)^2 \underbrace{g_\nu(E/T)}_{=\,1.15\,\arctan\left[3\,(E/T)^{3/2}\right]\,e^{-1.03\,E/T}}$$







(More realistic: take suites of SN simulations)

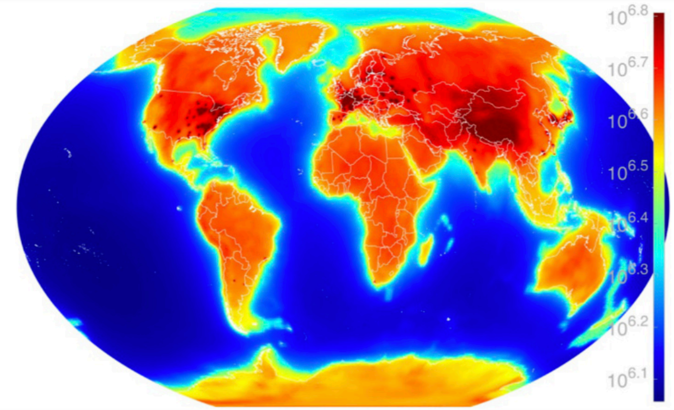
Antineutrino fluxes

Geoneutrinos

Earth has abundant Heat Producing Elements in the mantle and the crust:

$$
\begin{aligned}
{}^{238}\mathrm{U} &\to {}^{206}\mathrm{Pb} + 8\alpha + 8e + 6\overline{\nu}_e + 51.7\ \mathrm{MeV},\\
{}^{232}\mathrm{Th} &\to {}^{208}\mathrm{Pb} + 6\alpha + 4e + 4\overline{\nu}_e + 42.7\ \mathrm{MeV},\\
{}^{40}\mathrm{K} &\to {}^{40}\mathrm{Ca} + e + \overline{\nu}_e + 1.31\ \mathrm{MeV}\ (89.3\%),\\
e + {}^{40}\mathrm{K} &\to {}^{40}\mathrm{Ar}^* + \nu_e + 0.044\ \mathrm{MeV}\ (10.7\%).
\end{aligned}
$$

Mostly antineutrinos



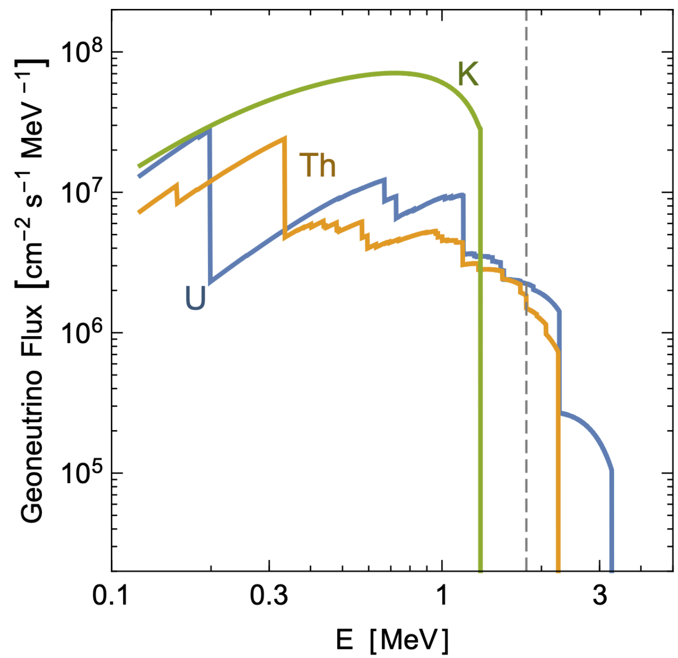
The spectrum is

$$
\Phi_{\overline{\nu}_e}(E,\vec{r}) = \sum_i \underbrace{A_i}_{\text{Decay per unit mass}} \underbrace{\frac{dn_i}{dE}}_{\text{Spectrum}} \int_{\oplus} d^3\vec{r}\,' \frac{\overbrace{a_i(\vec{r}\,')}^{\text{Isotope abundance}}\overbrace{\rho(\vec{r}\,')}^{\text{Density}}\overbrace{P_{ee}(E,|\vec{r}-\vec{r}\,'|)}^{\text{Survival probability}}}{4\pi|\vec{r}-\vec{r}\,'|^2}
$$

Isotope abundance: Bulk Silicate Earth

Density and Survival probability: Preliminary Reference Earth Model

Decay per unit mass and Spectrum: Nuclear physics input



Around 40 TW of radiogenic heat

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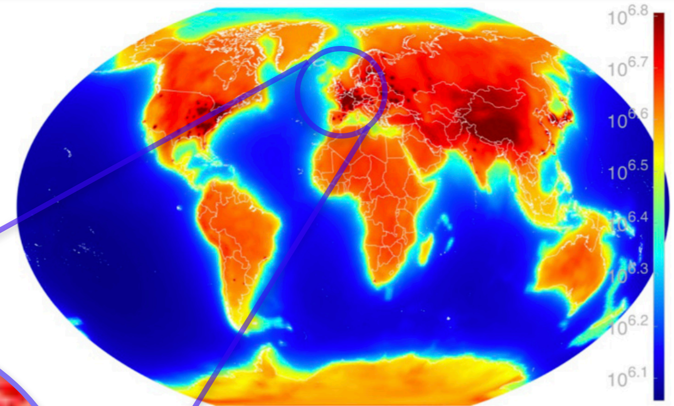
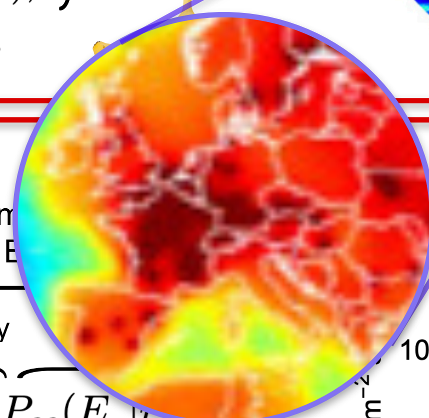
Mostly antineutrinos (first three reactions)





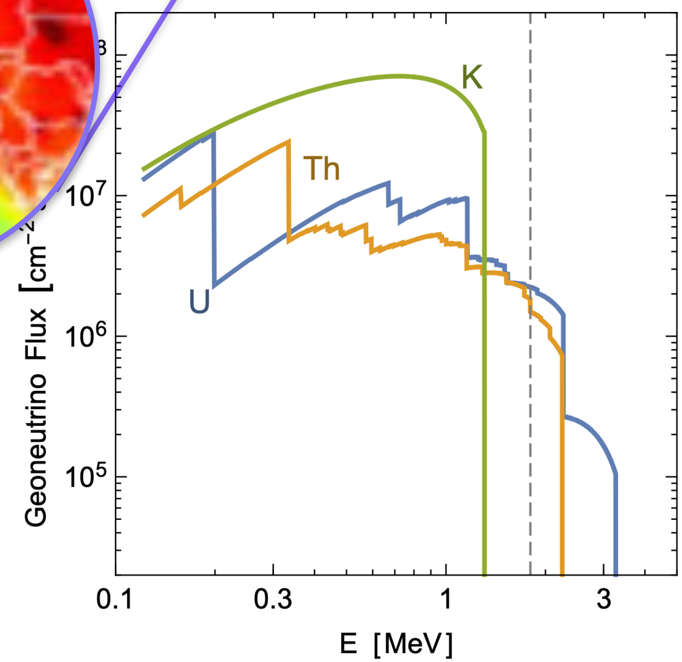
The spectrum is

Bulk Silicate Earth (over Isotope abundance) · Prelim... E... (over Density)

$$\Phi_{\overline{\nu}_e}(E,\vec{r}) = \sum_i A_i \frac{dn_i}{dE} \int_{\oplus} d^3\vec{r}' \frac{a_i(\vec{r}')\rho(\vec{r}')P_{ee}(E,|\vec{r}-\vec{r}'|)}{4\pi|\vec{r}-\vec{r}'|^2}$$

A_i: Decay per unit mass; $\frac{dn_i}{dE}$: Spectrum — together: Nuclear physics input

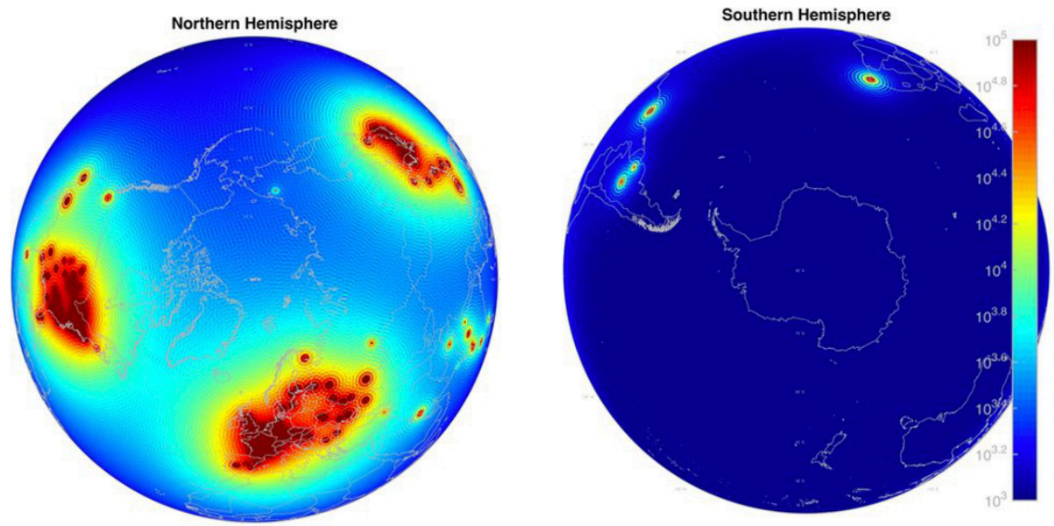
$a_i(\vec{r}')$: Isotope abundance; $\rho(\vec{r}')$: Density

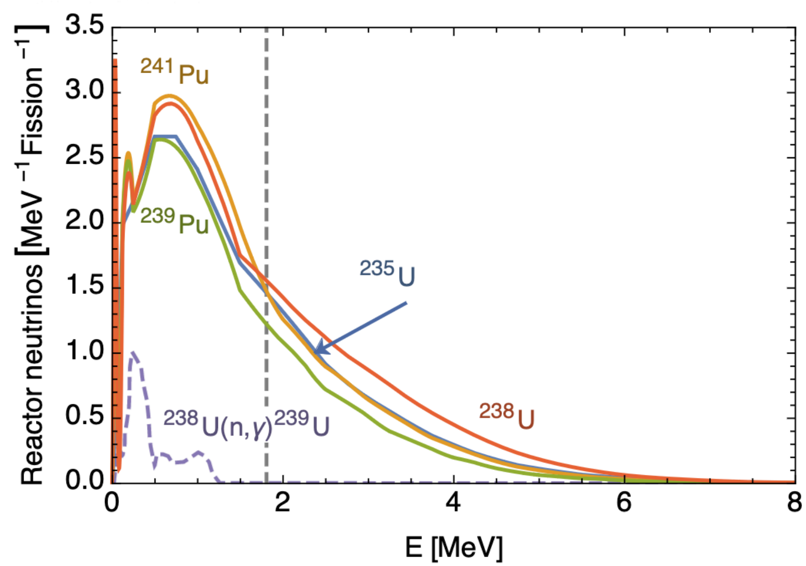


Around 40 TW of radiogenic heat

Reactor neutrinos

- A fission event releases about 6 neutrinos and a total energy of about 200 MeV
- A nuclear power plant producing 1 GW of thermal power will then produce a flux of $2 \times 10^{20}\,\mathrm{s}^{-1}$
- The globally installed nuclear power corresponds to around 0.4 TW electric or, with a typical efficiency of 33%, to 1.2 TW thermal





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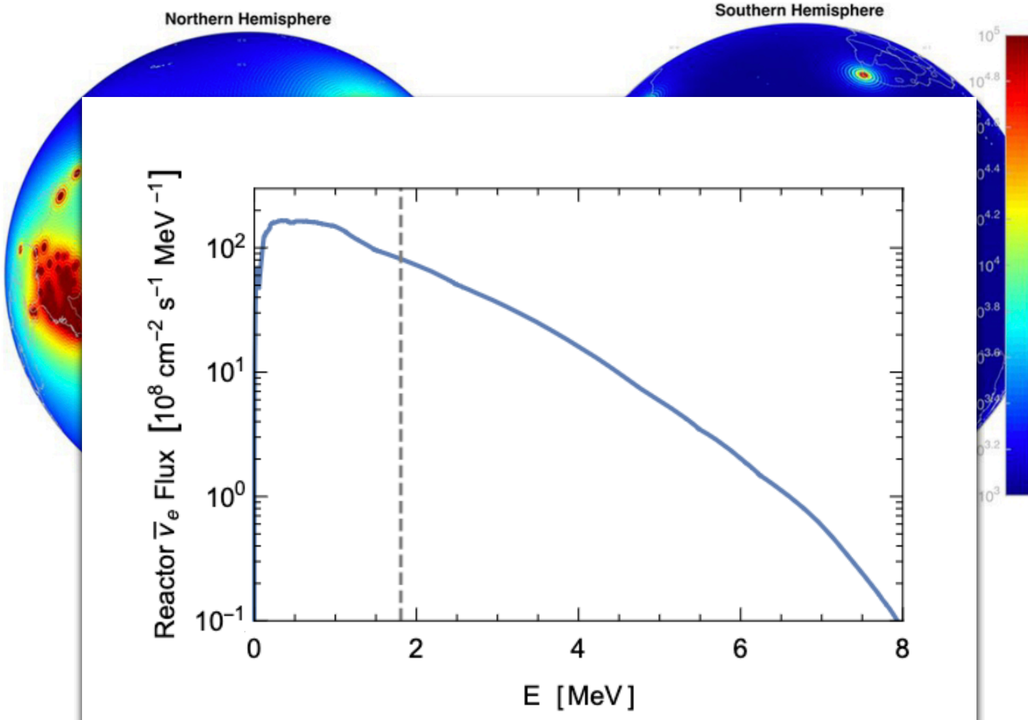
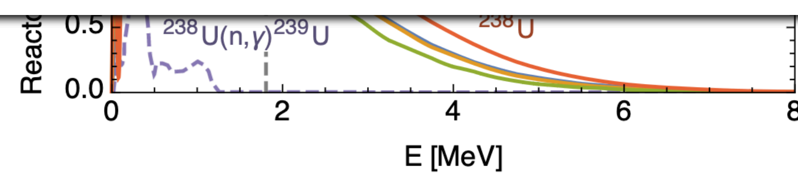


Typical reactor neutrino spectrum, here from the Japanese experimental fast reactor JOYO at a distance of 24.3 m



Neutrinos from
hadronic interactions

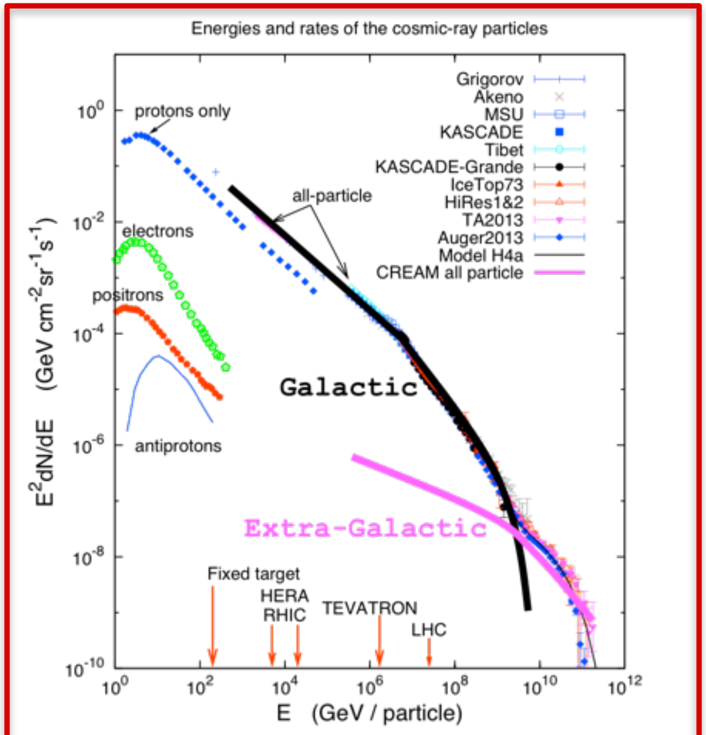
Atmospheric neutrinos

- Electrons, protons and heavier nuclei are accelerated within cosmic reservoirs or on their way to Earth in the presence of astrophysical shocks and magnetic turbulence

- They scatter in the atmosphere, and the products decay to neutrinos

- 3 ingredients: spectrum and composition of CR, cross sections, and lifetime of the products

$$\frac{dN_N}{dE} = \overbrace{\frac{1.8 \times 10^4}{(\mathrm{GeV/nucleon})\ \mathrm{m}^2\ \mathrm{s\ sr}}}^{\text{Normalization}} \underbrace{\left(\frac{E}{\mathrm{GeV/nucleon}}\right)^{-(\gamma+1)}}_{\gamma\,=\,1.7 \text{ up to } 3\times10^6\,\mathrm{GeV}}$$



$$\pi^\pm \to \mu^\pm + \nu_\mu(\overline{\nu}_\mu)$$
$$\downarrow$$
$$e^\pm + \nu_e(\overline{\nu}_e) + \overline{\nu}_\mu(\nu_\mu)$$

Example of a decay

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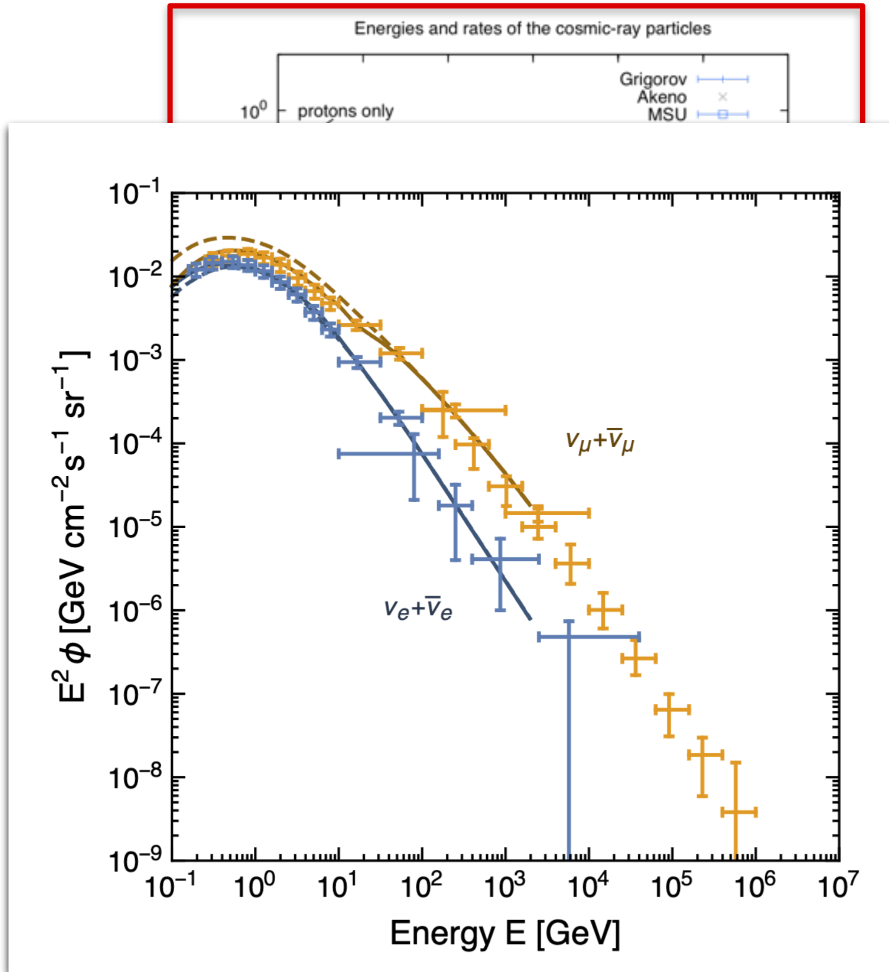

$$e^{\pm} + \nu_e(\bar{\nu}_e) + \bar{\nu}_\mu(\nu_\mu)$$

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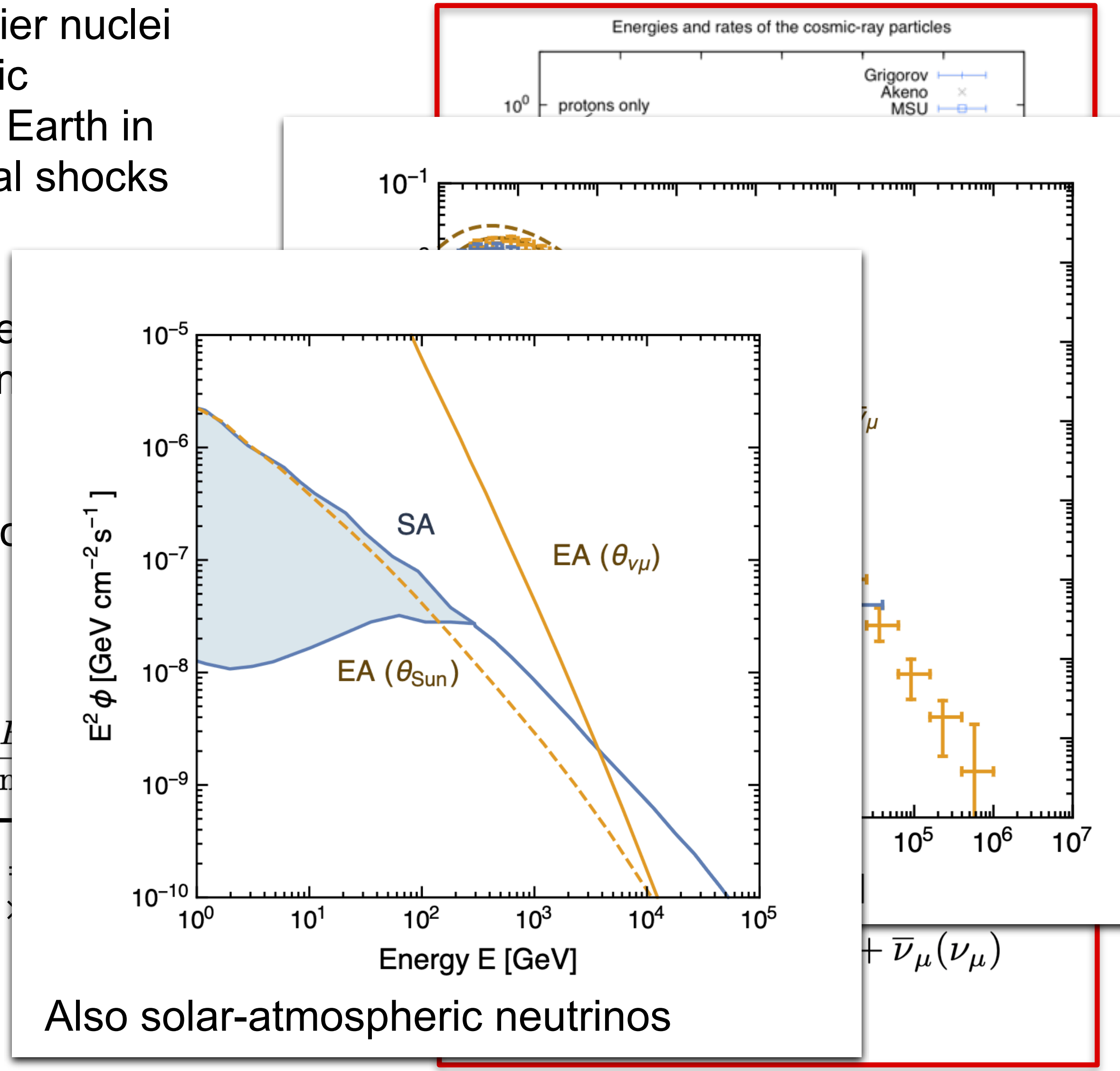
γ = … 3 × …



Also solar-atmospheric neutrinos

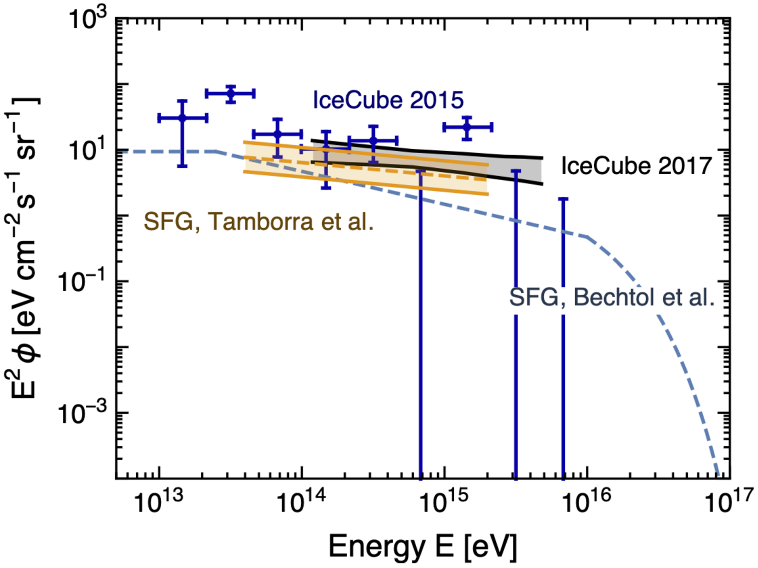
Astrophysical neutrinos

The same processes can happen in CR reservoirs

Redshift and luminosity distribution

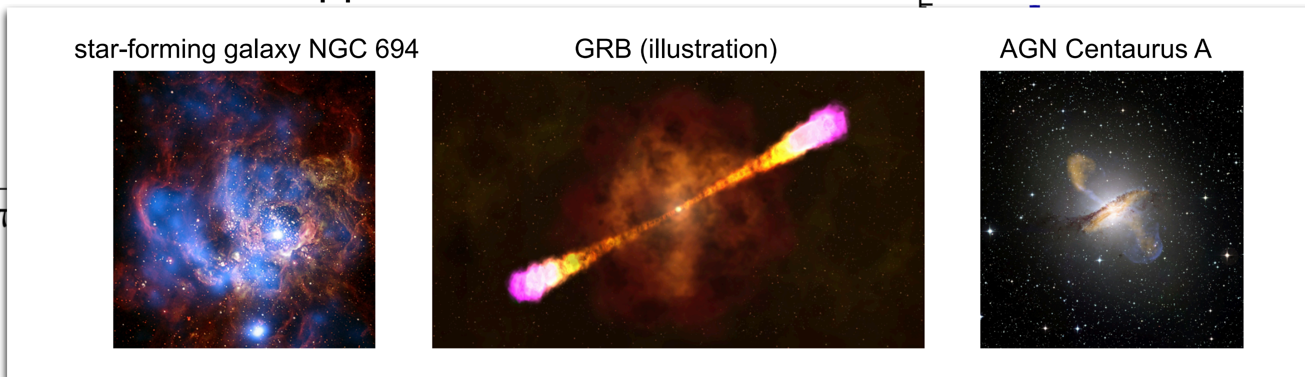
$$\phi(E_\nu) = \frac{1}{4\pi}\int_0^\infty dz \int_{L_{\min}}^{L_{\max}} dL_\nu \overbrace{\frac{1}{H(z)}\rho(z, L_\nu)}^{} \times \underbrace{\sum_\alpha F_{\nu_\alpha}\left[(1+z)E_\nu\right]}_{}$$

Spectrum from a single source

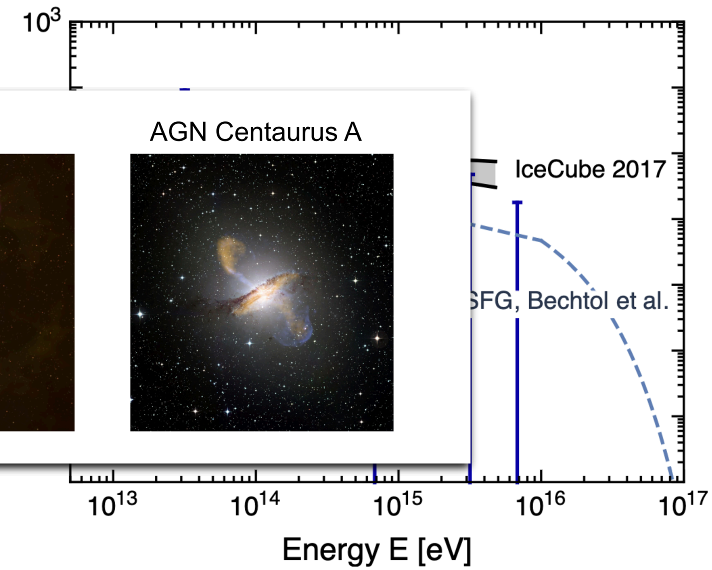


Astrophysical neutrinos

The same processes can happen in CR reservoirs



$$\phi(E_\nu) = \frac{1}{4\pi \cdots}$$

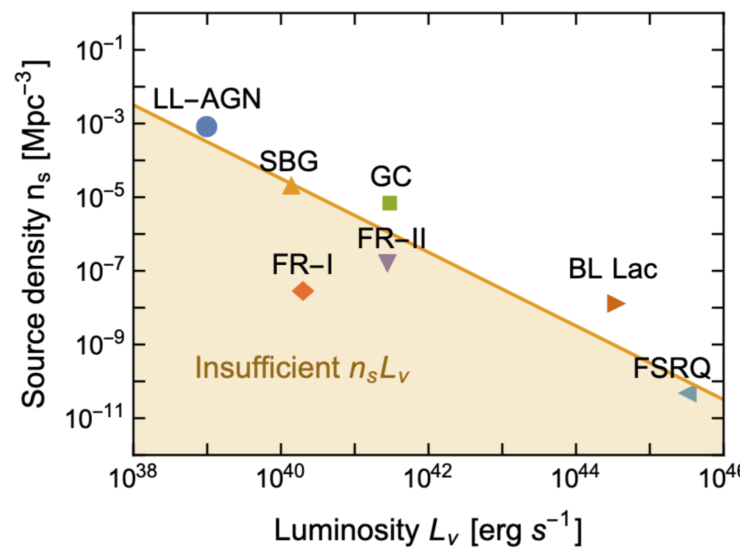


Spectrum from a single source

A simple approximation (Waxman-Bahcall) gives

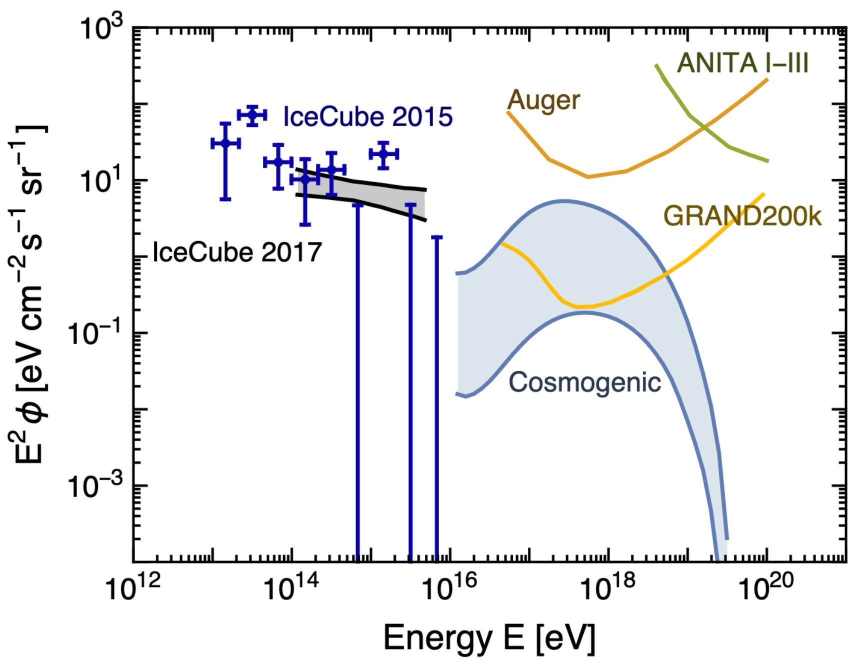
$$\phi_\nu = \xi \frac{L_\nu n_\mathrm{s} R_H}{4\pi} \simeq \underbrace{2.8 \times 10^{-8}\ \mathrm{GeV/cm^2\ s\ sr}}_{\text{IceCube flux at around 100 TeV}}$$

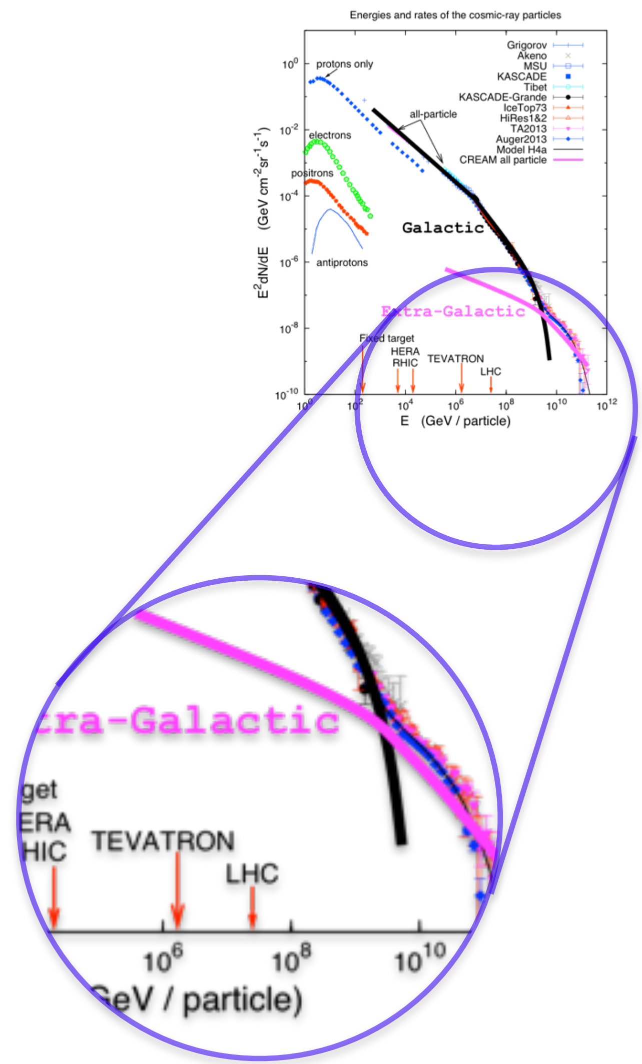
$$n_\mathrm{s} L_\nu = \frac{4 \times 10^{43}}{\xi} \frac{\mathrm{erg}}{\mathrm{Mpc^3\ yr}} \sim 10^{43} \frac{\mathrm{erg}}{\mathrm{Mpc^3\ yr}}$$



Cosmogenic neutrinos

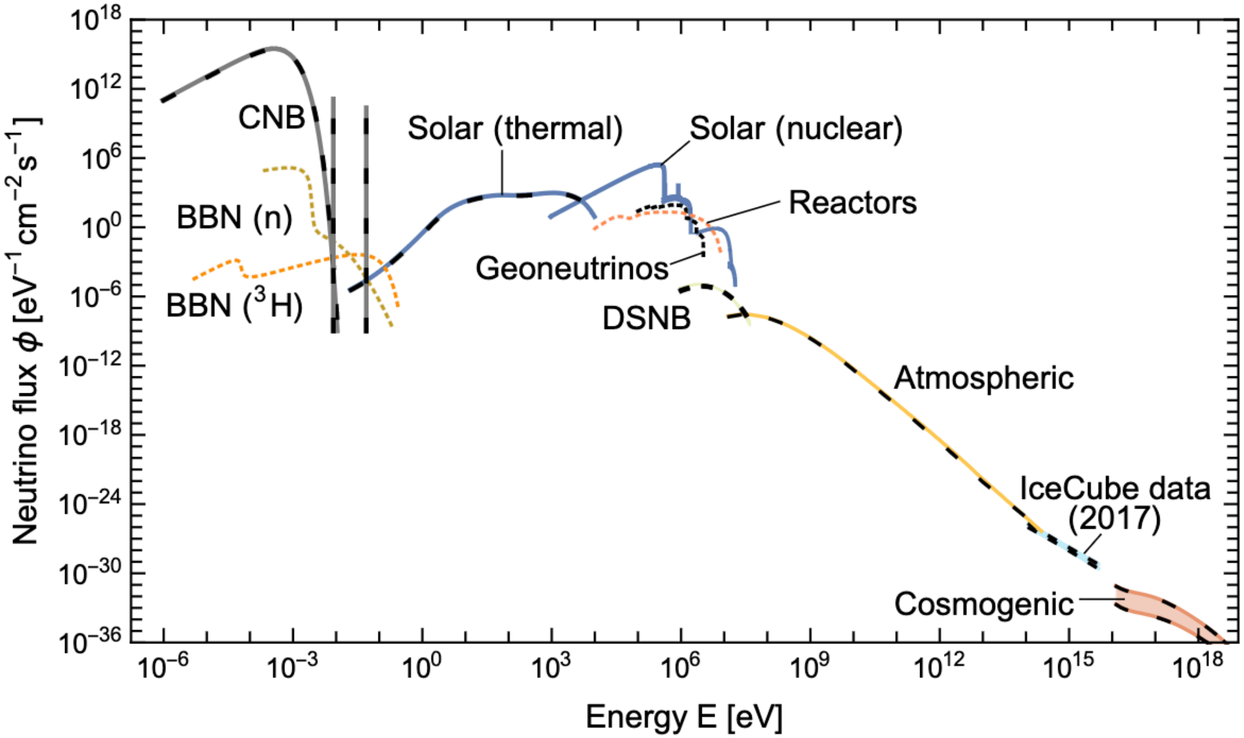
- Scattering of CR on the CMB and the EBL can produce particles that decay to neutrinos
- They can probe high redshift
- To be detected in future Radio facilities





Conclusions

Conclusions



- Many sources, diverse physics, huge energy range
- Still many experimental frontiers (cosmic neutrinos, DSNB, cosmogenic neutrinos)
- Neutrino astrophysics has just started
- What if we find an unexpected flux?

Thank you

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