CNO cycle

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

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

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

$$p + {}^{14}\mathrm{N} \rightarrow {}^{15}\mathrm{O} + \gamma$$ ← slowest (why?)

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

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

Z_C=6, Z_N=7, Z_O=8

Higher $E_G = (\pi \alpha Z_A Z_B)^2 2\mu c^2$

→ requires higher T_c than p-p

→ dominates for M>1.2 $M_\odot$

→ $\varepsilon \sim T^{18}$ (cf. $\sim T^4$ for p-p)

→ in Sun, 98.4% of energy from p-p, 1.6% from CNO

Net similar to p-p:

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

$$4p \rightarrow {}^{4}\mathrm{He} + Q_{eff}$$

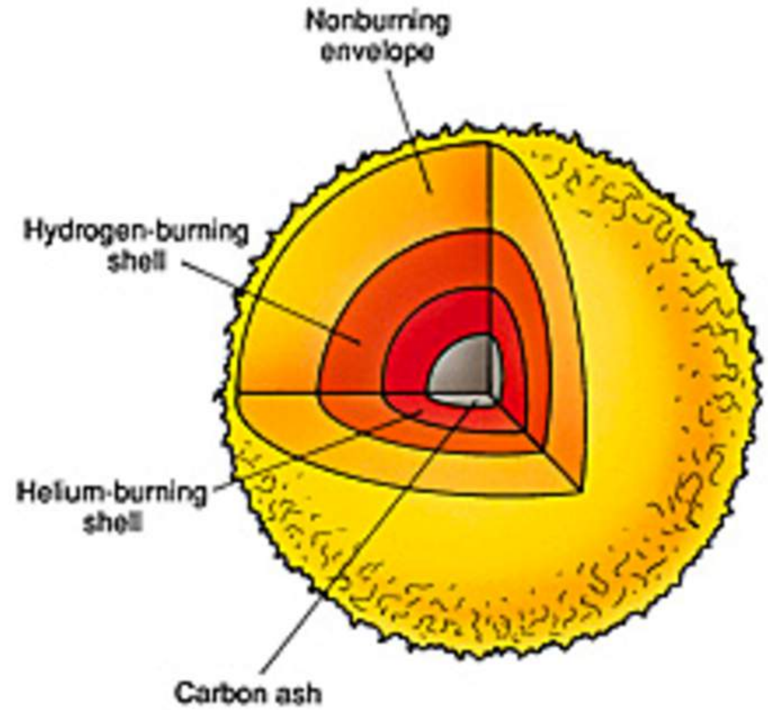
Q_{eff}=23.8 MeV in K.E., annihilation of e^{+}'s, γ's, but not ν_e's (escape)

Nucleosynthesis in CNO cycle

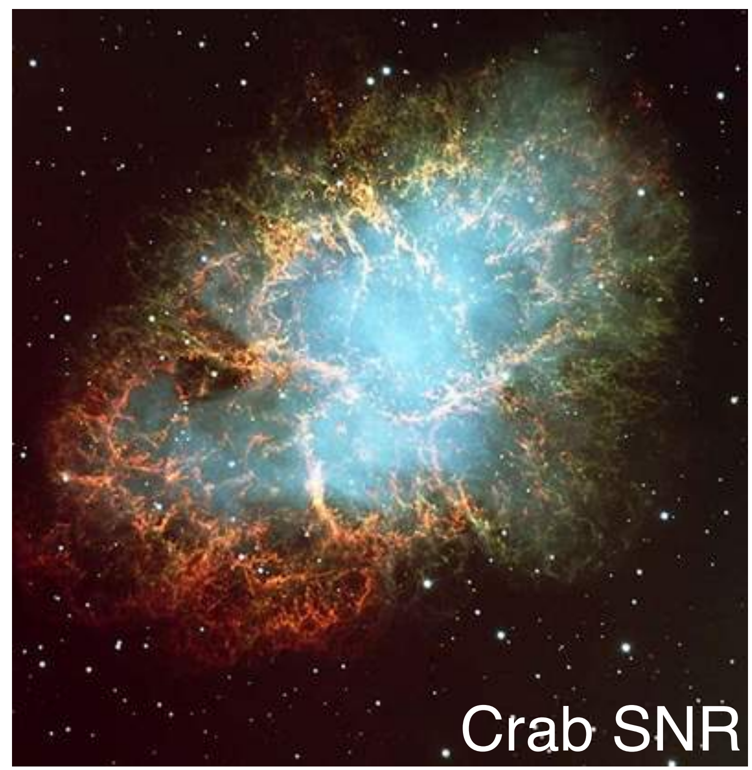
→ C, N, O are catalysts

→ need ^{12}C to start

→ produced by He burning in earlier stars



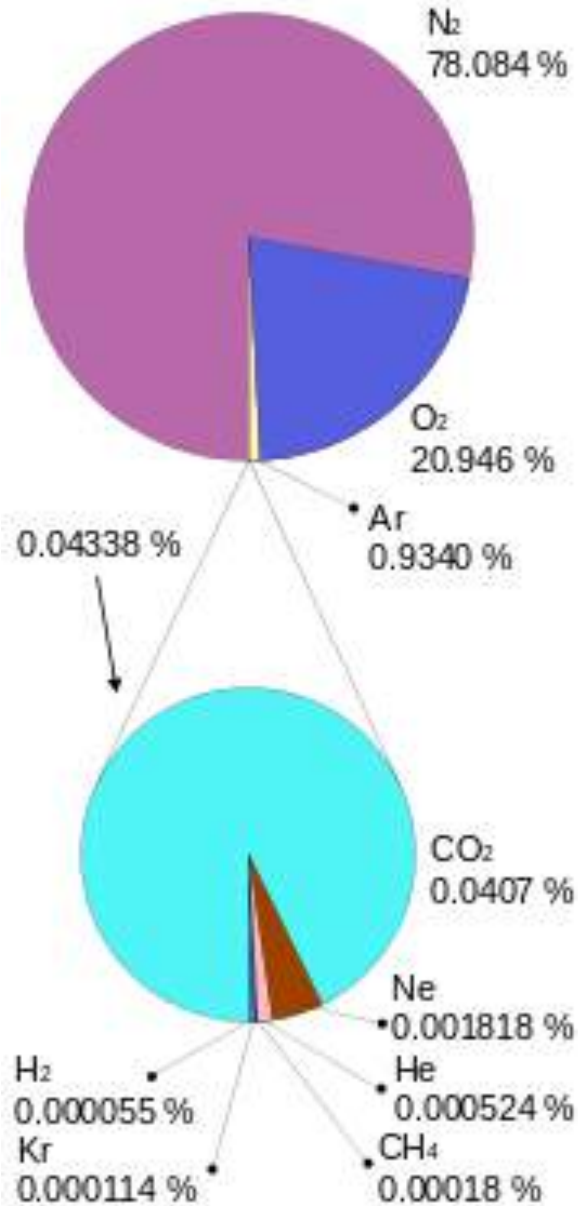
Although isotopes of C, N, O are not on the net produced *during a single CNO cycle*, at any given time they are present in equilibrium abundances



→ when a star dies, C, N, O isotopes can be returned to ISM!

→ main known source of cosmic N (other reactions can produce C and O)

Nitrogen



Earth's atmosphere

- 78% by volume in Earth's atmosphere
- 3% by mass in human body

Two stable isotopes ^{14}N, ^{15}N are produced in CNO cycle but ^{14}N is much more abundant (99.6% of all N atoms) because it partakes in the slowest leg of the CNO cycle (think about this argument)

Neutrinos

Extremely weakly interacting, neutral particles produced in weak force-mediated reactions, e.g. nuclear β decay and its inverse:

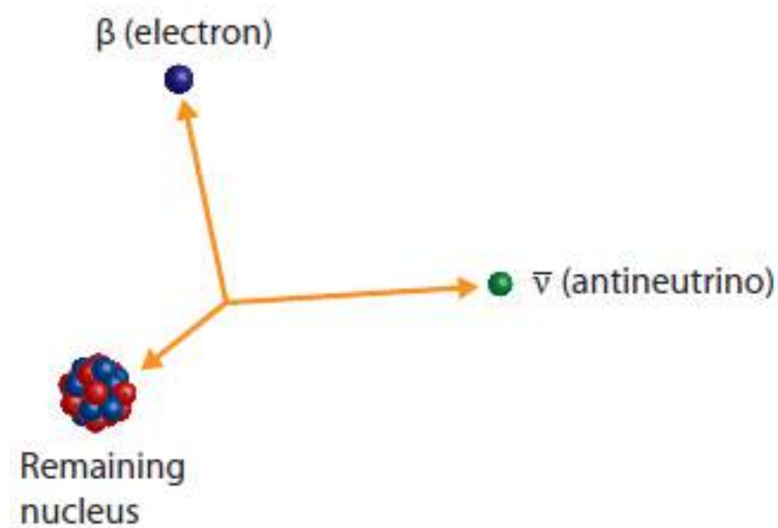
$$\mathrm{n} \rightarrow \mathrm{p} + \mathrm{e}^- + \bar{\nu}_\mathrm{e}$$

$$\mathrm{p} \rightarrow \mathrm{n} + \mathrm{e}^+ + \nu_\mathrm{e}$$

Three flavors: electron ν_e
muon ν_μ
tau ν_τ

each paired with a lepton

Proposed by Pauli (1930) to “rescue" energy & momentum conservation in β decay (an “invisible" particle to carry away the missing energy and momentum)



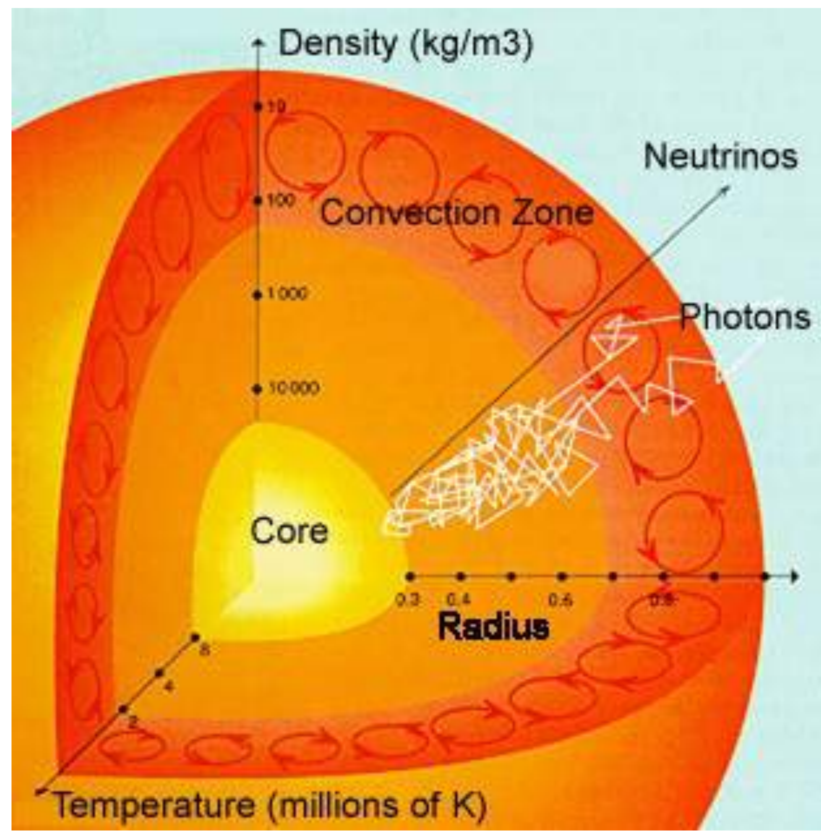
Solar neutrinos

p-p chain produces two ν_e for each 26.3 MeV of energy going into solar radiation

→ expect electron neutrino flux on Earth

$$f_{\nu_e} = \frac{2 f_\odot}{26.2 \text{ MeV}} = 6.7 \times 10^{10} \text{ s}^{-1} \text{ cm}^{-2}$$

huge number, but hard to detect due to small cross section ~10^{-44} cm^{-2}



→ if can detect, probe deep solar interior!

Detecting solar neutrinos

Solar neutrinos first detected by R. Davis in 1968 in a pioneering experiment in the Homestake Gold Mine, South Dakota (mine shields from cosmic rays and other possible contaminants)

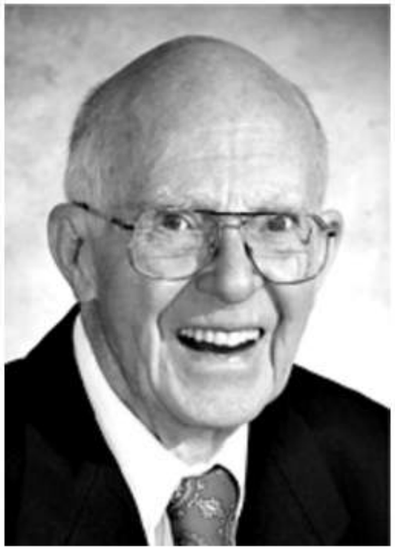
610-ton tank of dry-cleaning fluid (C_2Cl_4)

Look for argon-producing

$$\nu_e + ^{37}\mathrm{Cl} \rightarrow ^{37}\mathrm{Ar} + e^{+}$$

^{37}Ar is radioactive so small number of atoms can be counted

The Nobel Prize in Physics 2002



Raymond Davis Jr.
Prize share: 1/4

Masatoshi Koshiba
Prize share: 1/4

Riccardo Giacconi
Prize share: 1/2

The Nobel Prize in Physics 2002 was divided, one half jointly to Raymond Davis Jr. and Masatoshi Koshiba *"for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"* and the other half to Riccardo Giacconi *"for pioneering contributions to astrophysics, which have led to the discovery of cosmic X-ray sources"*.

Solar neutrino problem (1960s-early 2000s)

Davis ran the Homestake experiment for over 30 years

Worked closely with theoretical astrophysicist J. Bahcall, creator of the ‘Standard Solar Model’

The Homestake experiment consistently detected only about 1/3 of the predicted electron neutrinos!

Problem with the experiment? Problem with our understanding of the Sun?

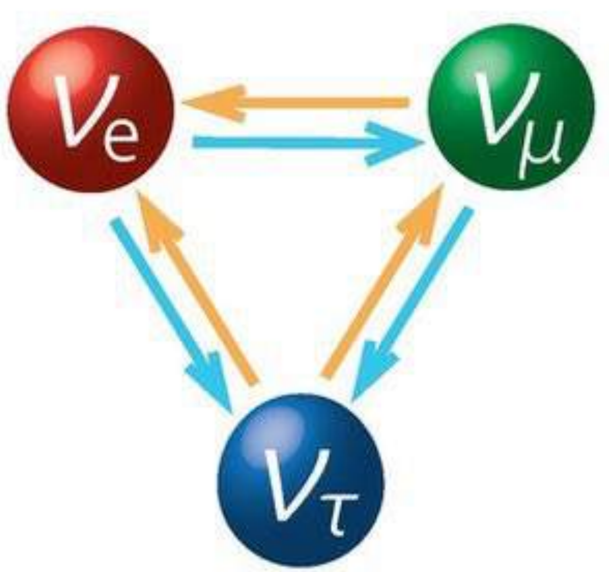
Davis (left) and Bahcall (right), Homestake 1967

Neutrino oscillations: neutrinos change flavor!

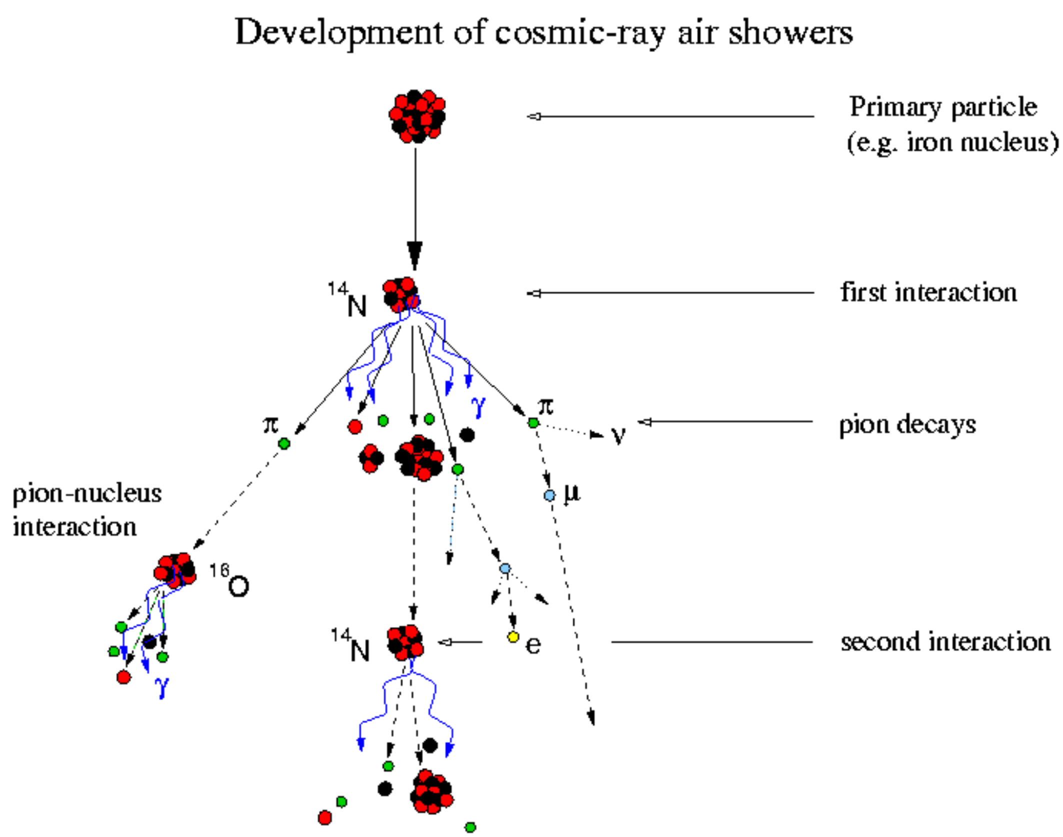
Mikheyev–Smirnov–Wolfenstein (MSW) effect: neutrinos change flavor as they propagate through matter

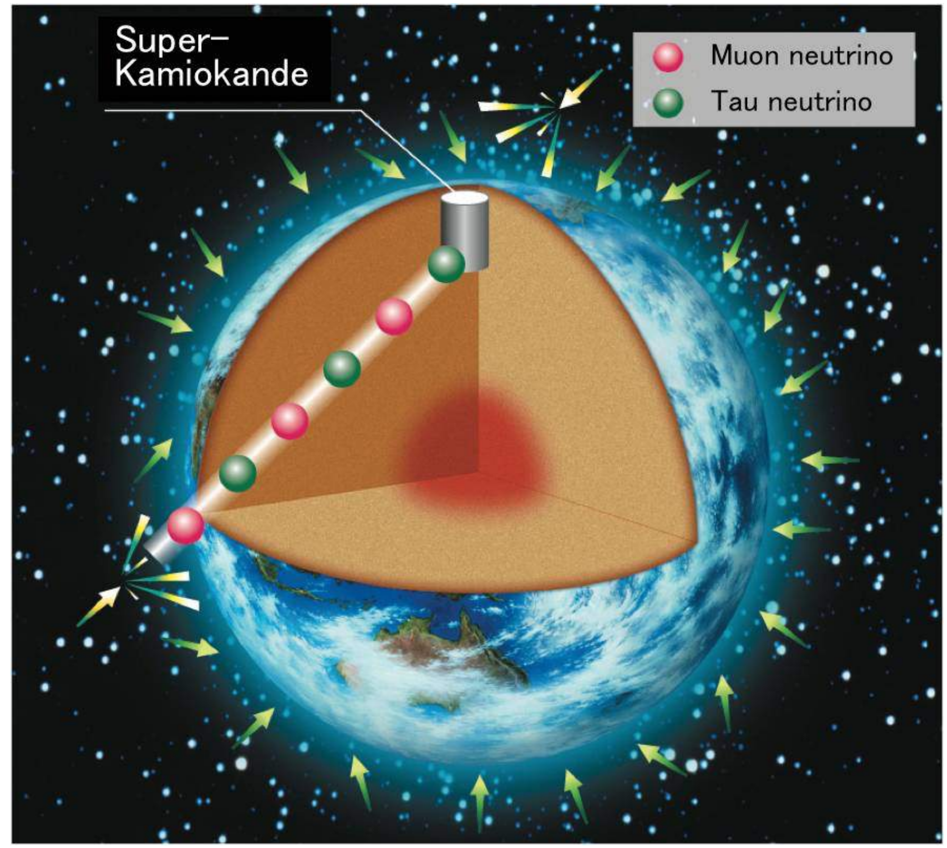
In particle physics models, this requires that neutrinos have mass (previously, they were assumed massless)

Furthermore, the flavor eigenstates differ from the mass eigenstates



Atmospheric neutrinos





electron, muon neutrinos are created in CR showers (when CRs interact with the Earth's atmosphere), but very few tau neutrinos are

MSW → muon neutrinos oscillate into tau neutrinos while propagating through Earth

Super-Kamiokande discovers atmospheric neutrino oscillations (1998)

1,000 m underground, Mozumi Mine, Japan

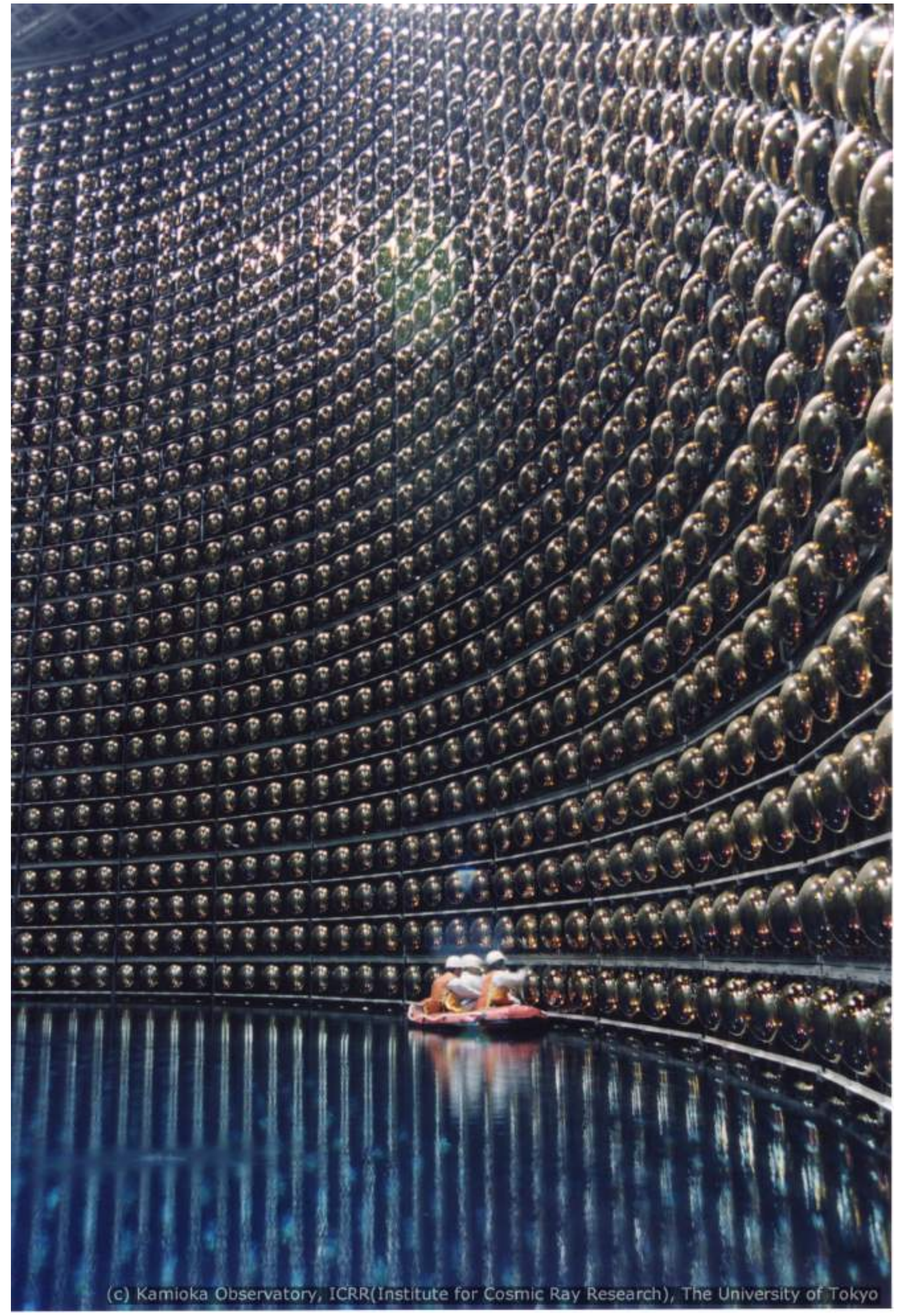
50,000 tons of ultra pure water

Neutrino-electron scattering

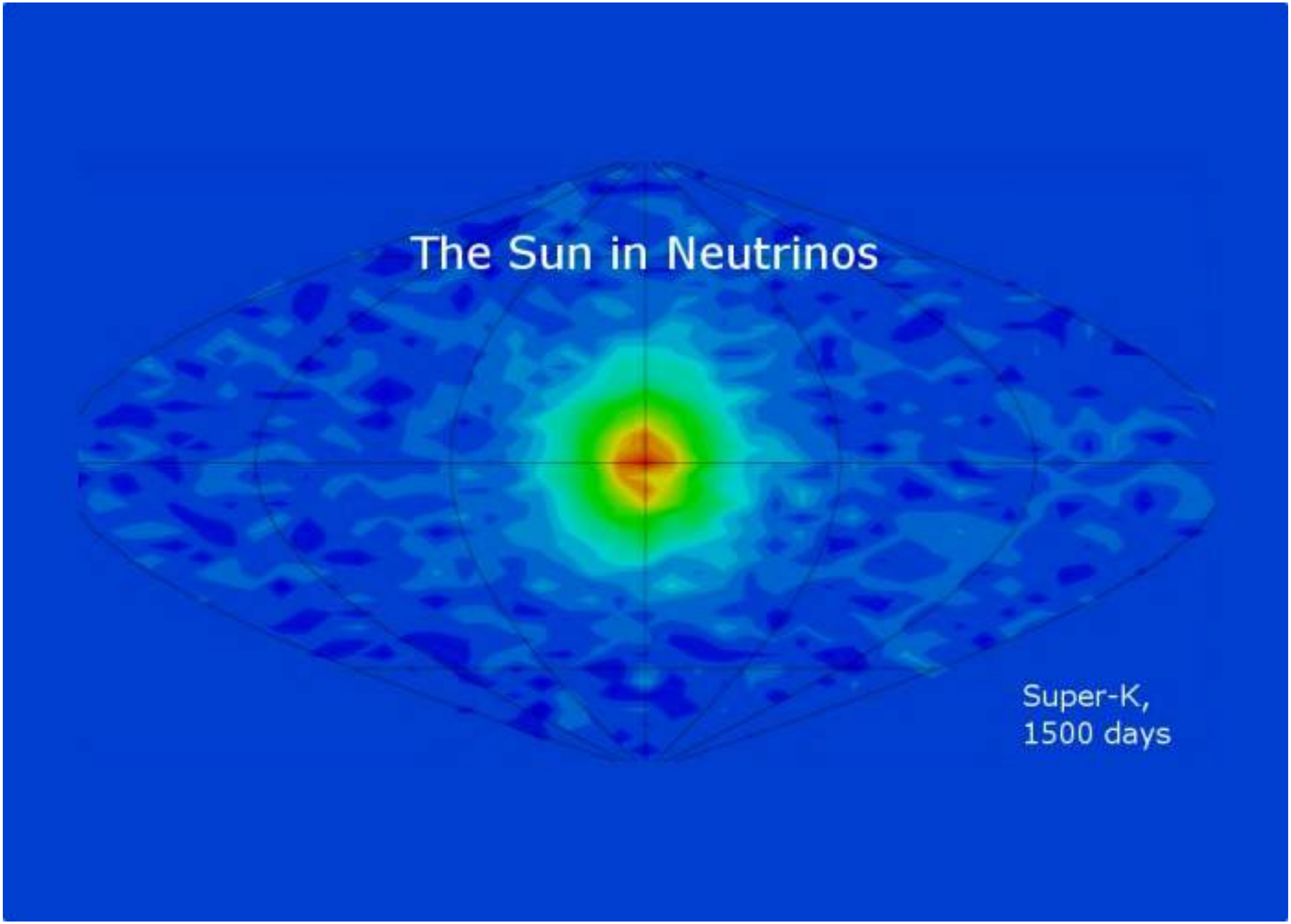
$$\nu_{\mathrm{x}} + e^{-} \rightarrow \nu_{\mathrm{x}} + e^{-}$$

produces Cherenkov radiation detected by photomultipliers

ν_e/ν_μ ratio depends on whether looking through Earth or not



Super-Kamiokande's ν_e view of the Sun



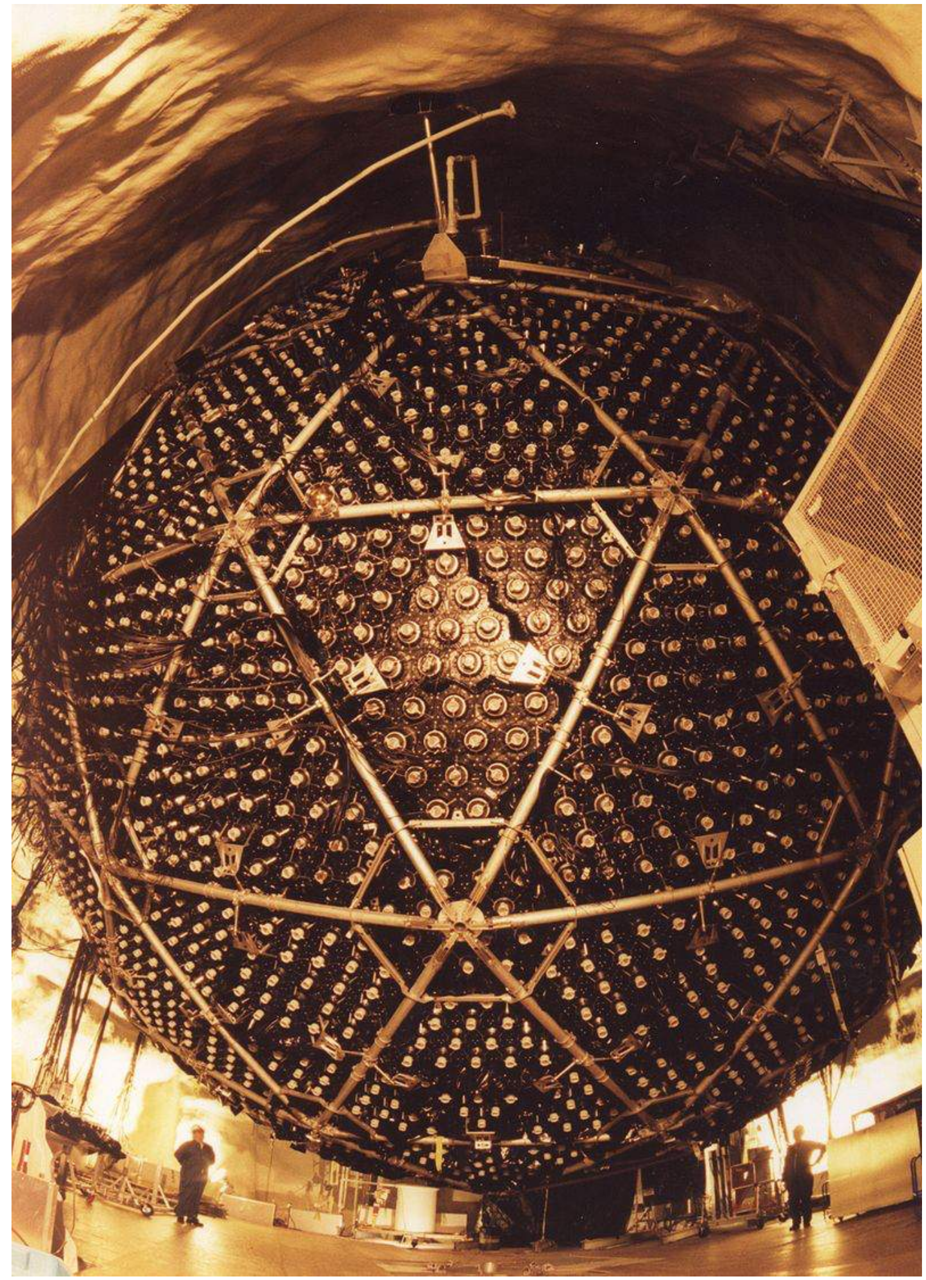
Sudbury Neutrino Observatory (SNO) directly detects solar neutrino oscillations (2001)

2,100 m underground, Creighton Mine, Canada

1,000 tons of heavy water (^2H_2O)

Neutrino-electron scattering but also other interactions with $^2H_2$ atoms produce Cherenkov radiation → better ability to distinguish between different neutrino flavors

first detected muon, tau neutrinos from the Sun — confirming reason for missing electron neutrinos is oscillations



The Nobel Prize in Physics 2015

Photo: A. Mahmoud

Takaaki Kajita

Prize share: 1/2

Photo: A. Mahmoud

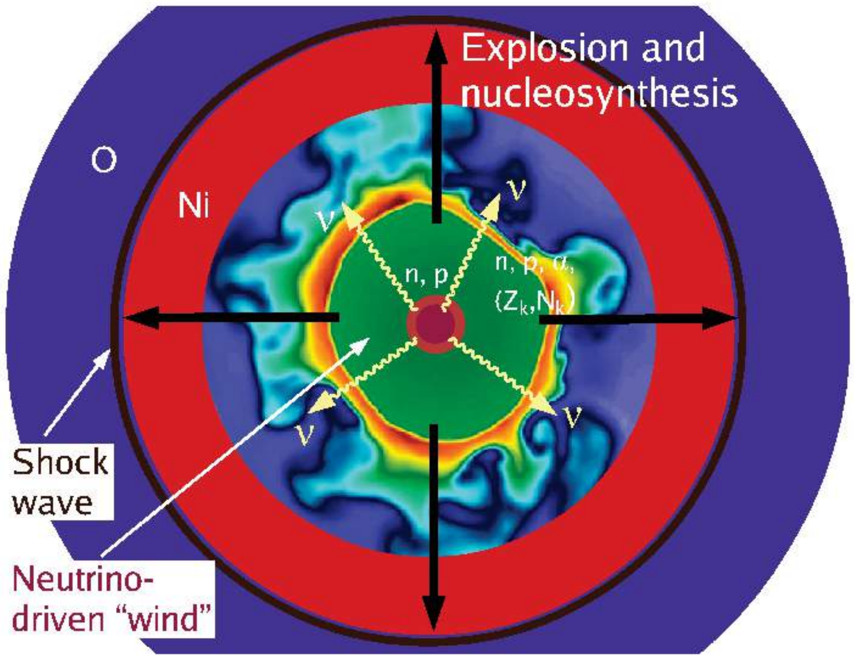
Arthur B. McDonald

Prize share: 1/2

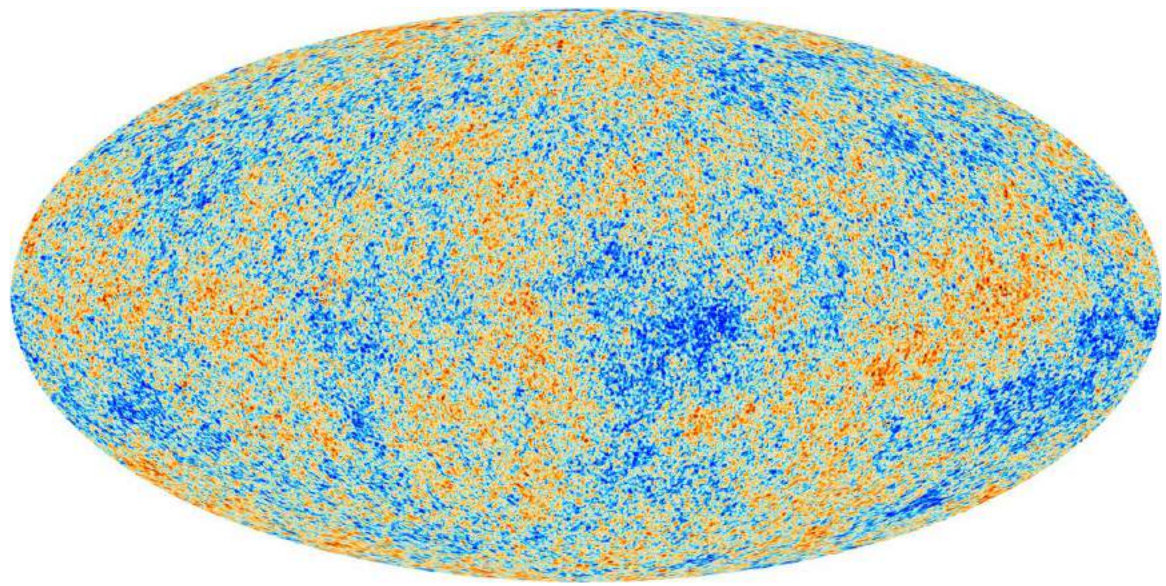
The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*

Other sources of neutrinos

Core collapse supernovae
(during NS formation)



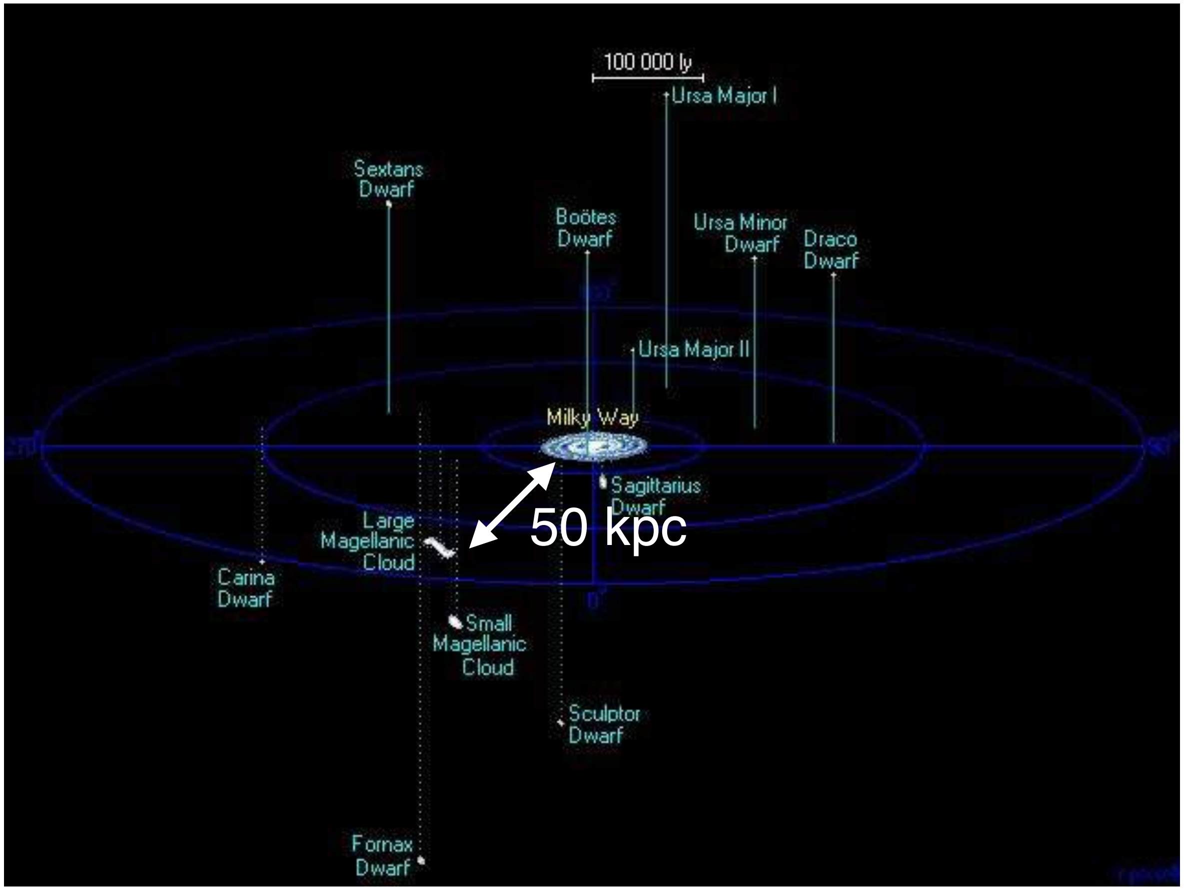
Cosmic neutrino background
(analog of microwave background left over from the Big Bang, shown here)

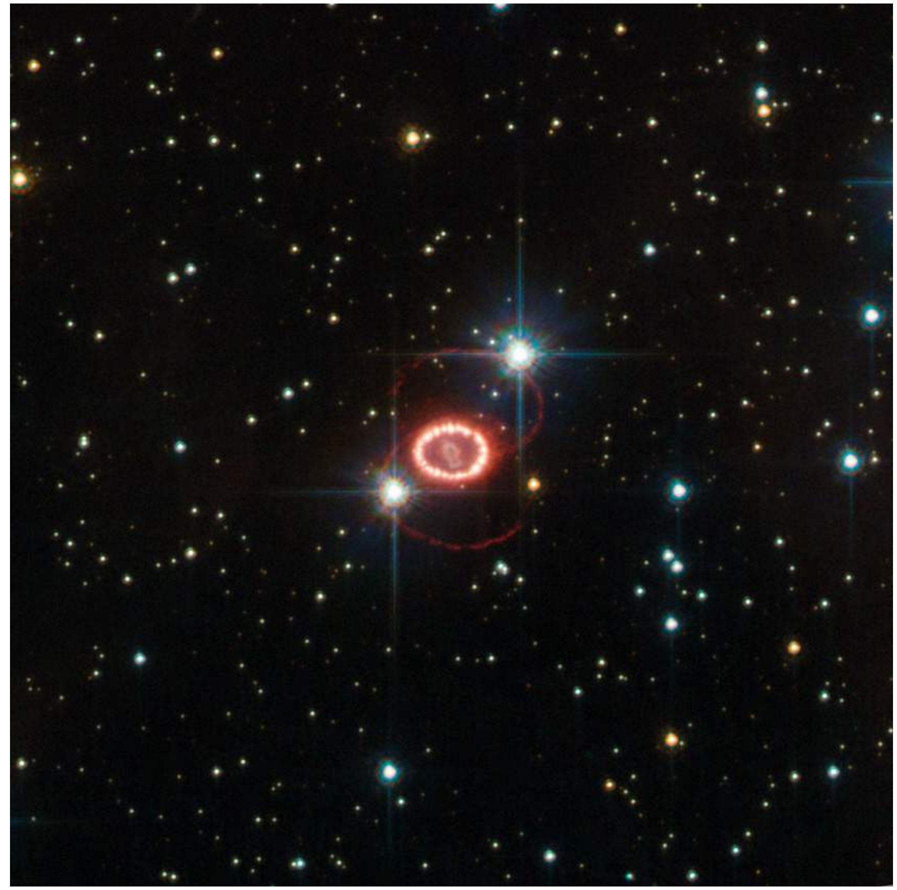


+ other energetic phenomena, e.g. gamma-ray bursts, and yet-to-be-discovered sources

SN 1987A

First supernova discovered in 1987, originates from the Large Magellanic Cloud, a nearby satellite of the Milky Way galaxy





Rule of thumb: ~1 SN per 100 M_{sun} of new stars formed

Milky Way has SFR ~2 M_{sun}/yr, so expect one Galactic SN every ~50 yrs

Observation of a Neutrino Burst from the Supernova SN1987A

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E. W. Beier, L. R. Feldscher, S. B. Kim, A. K. Mann, F. M. Newcomer, R. Van Berg, and W. Zhang
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and

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California Institute of Technology, Pasadena, California 91125
(Received 10 March 1987)

A neutrino burst was observed in the Kamiokande II detector on 23 February 1987, 7:35:35 UT (±1 min) during a time interval of 13 sec. The signal consisted of eleven electron events of energy 7.5 to 36 MeV, of which the first two point back to the Large Magellanic Cloud with angles 18° ± 18° and 15° ± 27°.

PACS numbers: 97.60.Bw, 14.60.Gh, 95.85.Sz, 97.60.Jd

Fig. 6.3 Energy and time of arrival of neutrinos from the supernova SN1987A as registered by the Kamiokande I I and 1MB detectors. In all, 20 neutrinos were detected and the duration of the neutrino pulse was about 10 seconds

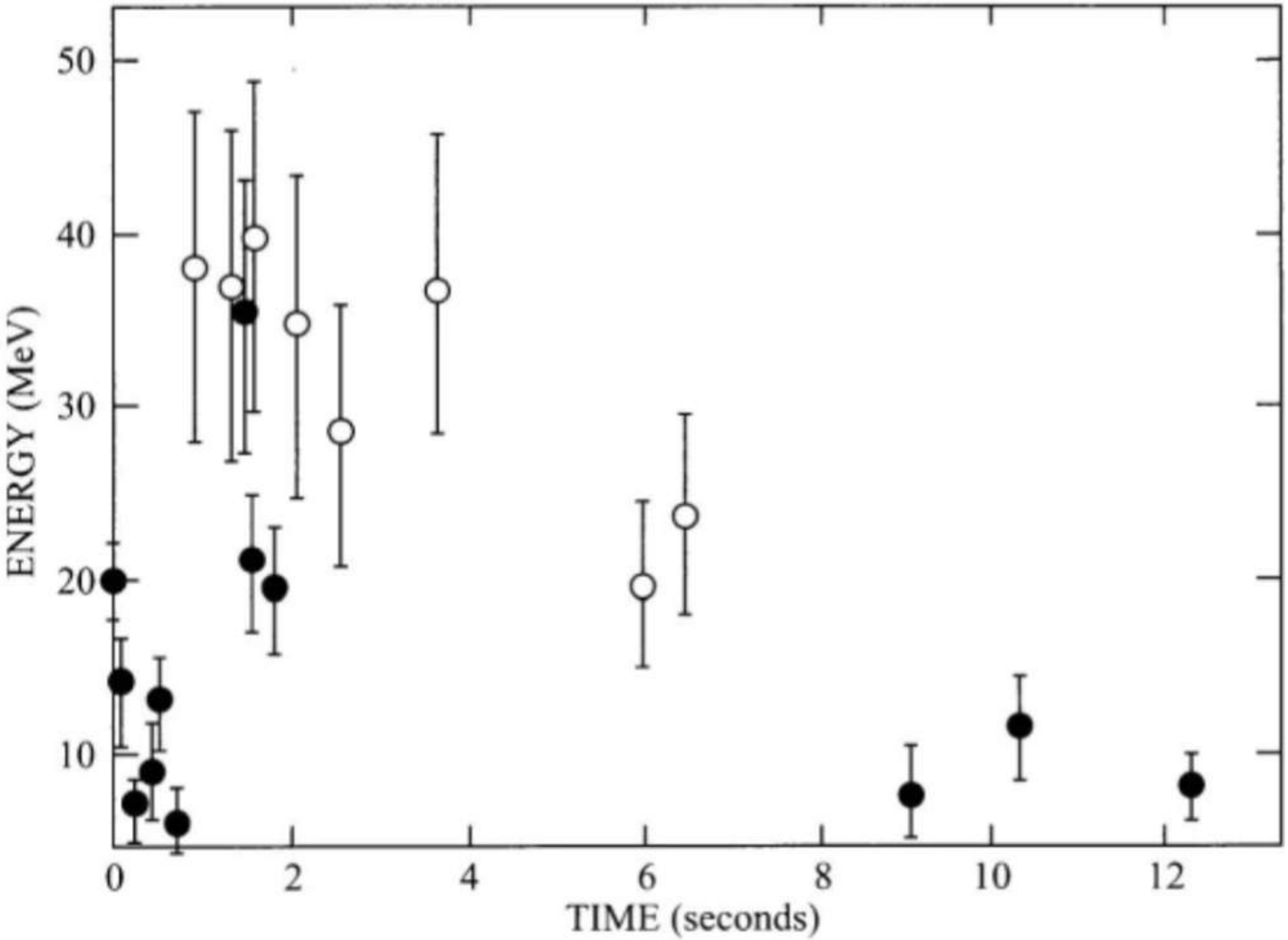


Figure from Phillips

Bound on neutrino mass from dispersion in times of arrival (Phillips problem 6.5)

Special relativity:

$$E^2 = (pc)^2 + (mc^2)^2$$

$$E = \gamma mc^2$$

$$p = \gamma mv$$

$$\gamma = \frac{1}{\sqrt{1 - v^2/c^2}}$$

• massless (*m=0*) ⇒ *v=c*

⇒ all neutrinos emitted in a burst arrive at the same time at distance *d*

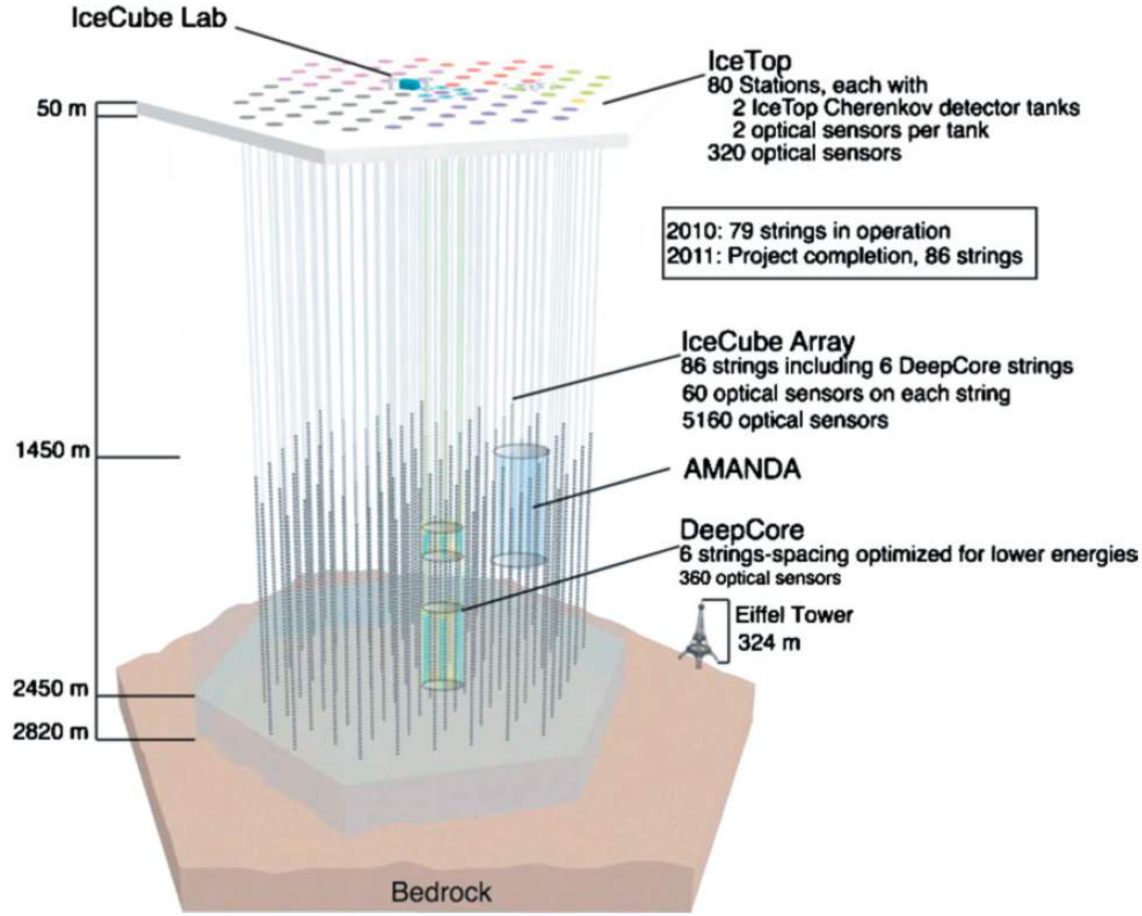
• for *m>0*, given *E* implies a certain *v<c*
⇒ because of different travel speeds, neutrinos of different energies arrive at different times

Note: If neutrinos arrive at different times, it could be because they are emitted at different times/places. But we can use maximum difference in times of arrival can be used to put upper limit on neutrino mass, under the assumption that all observed neutrinos were emitted at the same place and time.

IceCube Neutrino Observatory

Thousands of photo-sensors in cubic km under Antarctic ice

Designed to look for neutrinos in TeV energy range to explore to explore highest energy astrophysical processes



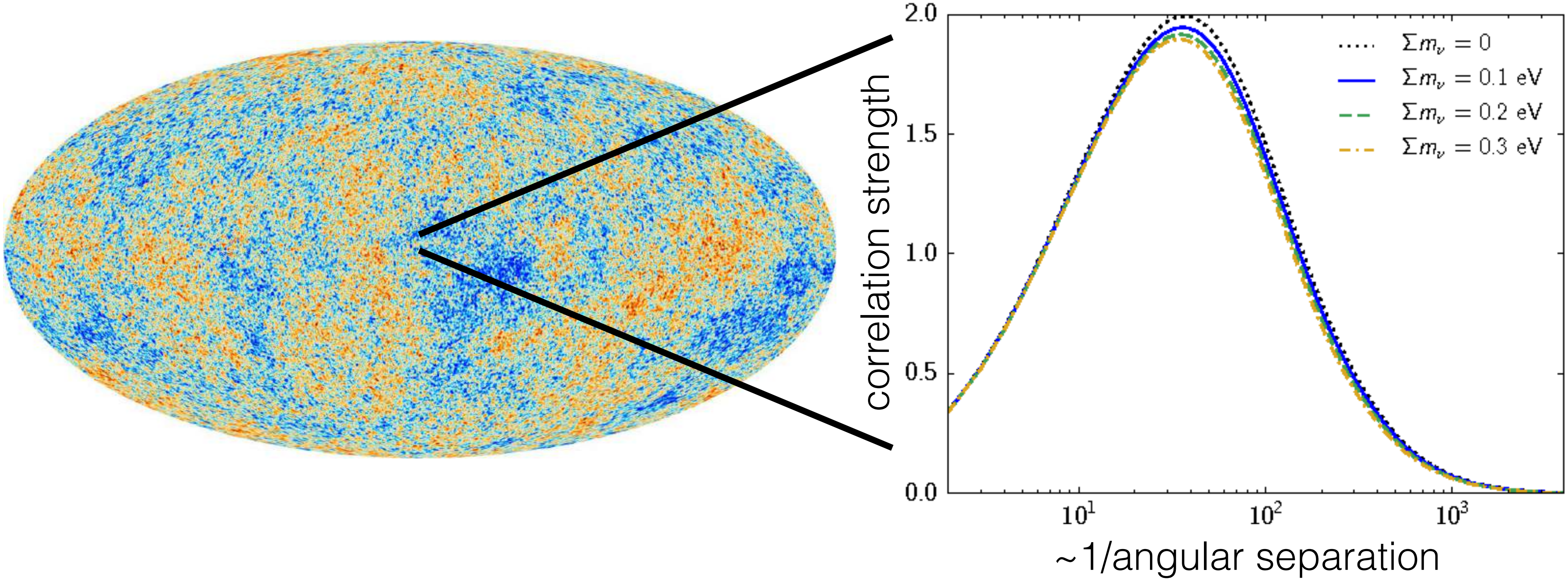
Current bounds on neutrino masses

$$0.05\ \text{eV} < \Sigma m_\nu < 0.23\ \text{eV}$$

oscillation experiments

CMB measurements (Planck 2013)

Microwave background correlation statistics sensitive to neutrino mass



Massive neutrinos slightly affect development of cosmic structure via the gravitational forces they exert. Effect should be detectable in next ~5 years.