The Niels Bohr International Academy

VILLUM FONDEN

Supernova Explosions and Neutrinos

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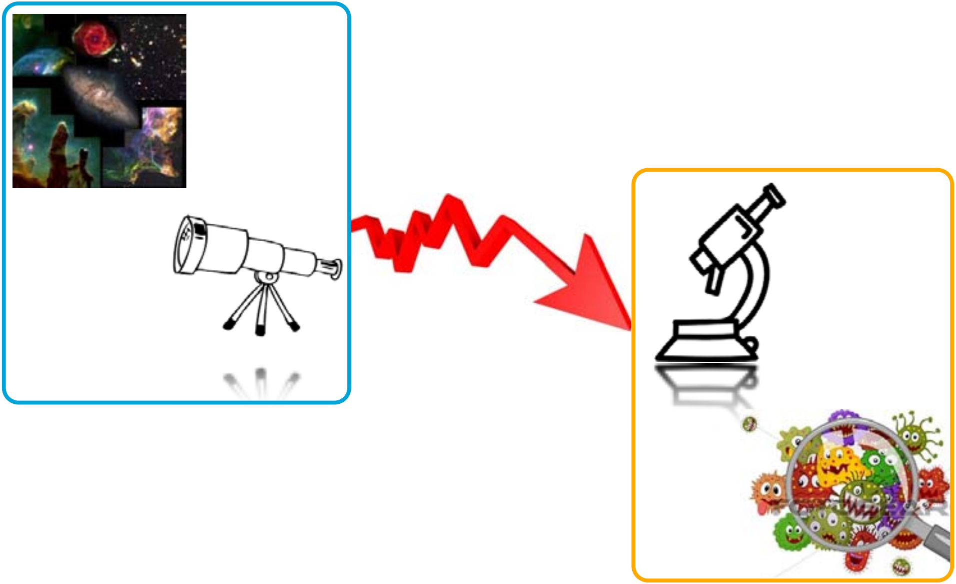
The nitrogen in our DNA, the calcium in our teeth, the iron in our blood, the carbon in our apple pies were made in the interiors of collapsing stars.
We are made of starstuff.

Carl Sagan, Cosmos

Stellar Explosions:
From Macroscopic to Microscopic



What Is a Neutrino?

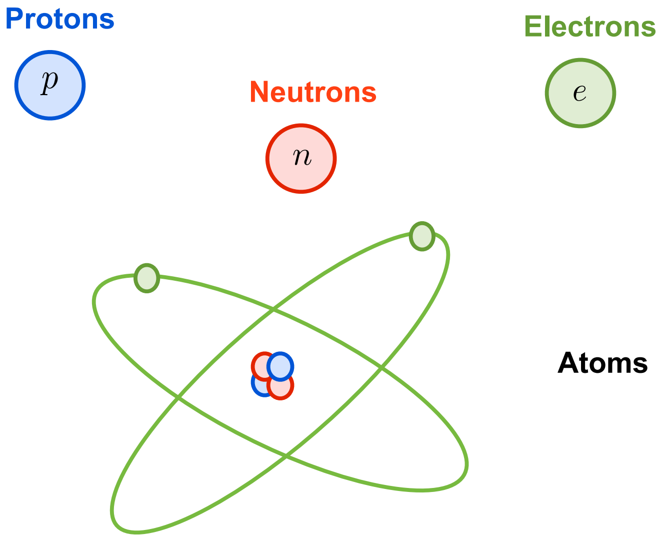
Living Creatures

Objects

Our Planet

Building Blocks of Matter

Matter is made of three kinds of elementary particles bundled together to make atoms.



Building Blocks of Matter

Is our Universe made only of protons, neutrons and electrons? **NO!**

Protons

p

Neutrons

n

Electrons

e

For every protons, neutron and electron, the Universe contains **a billion of neutrinos**!

Neutrinos

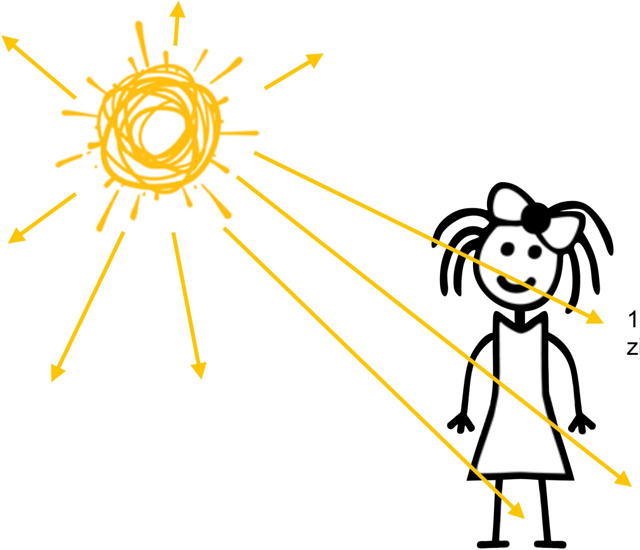
ν

One neutrino is 1/1,000 the size of an atomic nucleus.

In order to understand the Universe, we must understand neutrinos!

Neutrinos

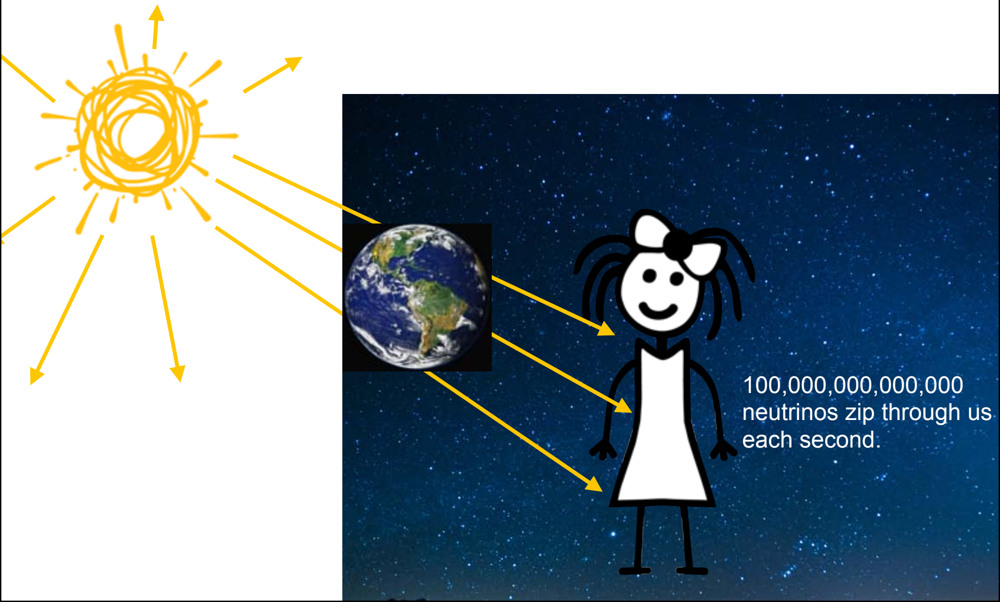
Our Sun is an intense source of neutrinos that zip through us undisturbed.



100,000,000,000,000 neutrinos zip through us each second.

Neutrinos

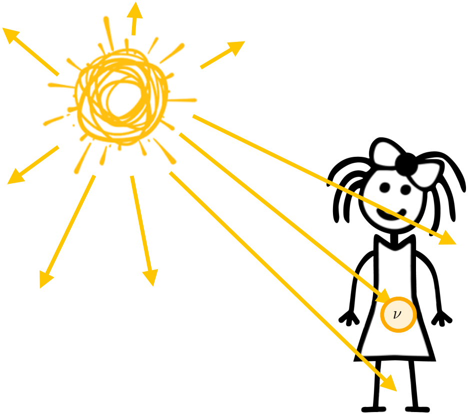
Our Sun is an intense source of neutrinos that zip through us undisturbed **even at night!**



Neutrinos

Should we worry about all those neutrinos?

No! Neutrinos interact **very weakly**. On average, one neutrino from the Sun stops in our body in a lifetime (producing one harmless electron).



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

Neutrinos Are ...

Ghostly

Abundant

Elusive

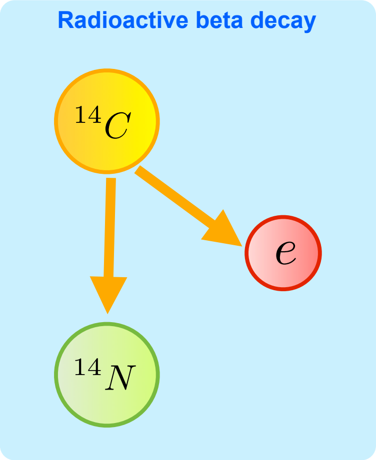
Weakness of interactions makes neutrino hard to detect and to study.

Are Neutrinos Important to Us?

- Our Sun would not shine without neutrinos.
- Supernovae would not explode without neutrinos.
- No atoms more complex than Hydrogen and elements crucial to our life.
- No Us!

We could not exist without neutrinos!

How did We Discover Neutrinos?

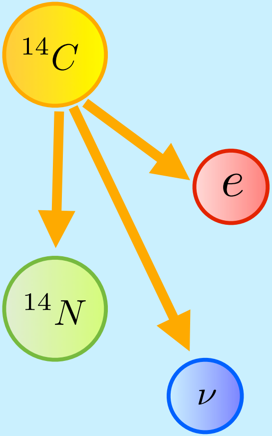


Niels Bohr

"... we have no argument, either empirical or theoretical, for upholding the energy principle."

How did We Discover Neutrinos?

Radioactive beta decay



"Neutron" (1930)

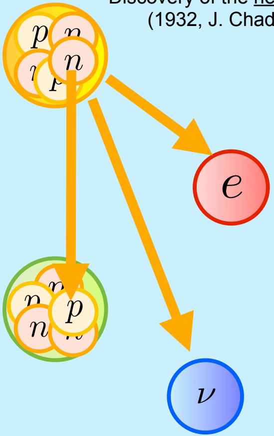
Wolfgang Pauli

"I have done something very bad today by proposing a particle that cannot be detected; it is something no theorist should ever do."

How did We Discover Neutrinos?

Radioactive beta decay

Discovery of the <u>neutron</u>
(1932, J. Chadwick)

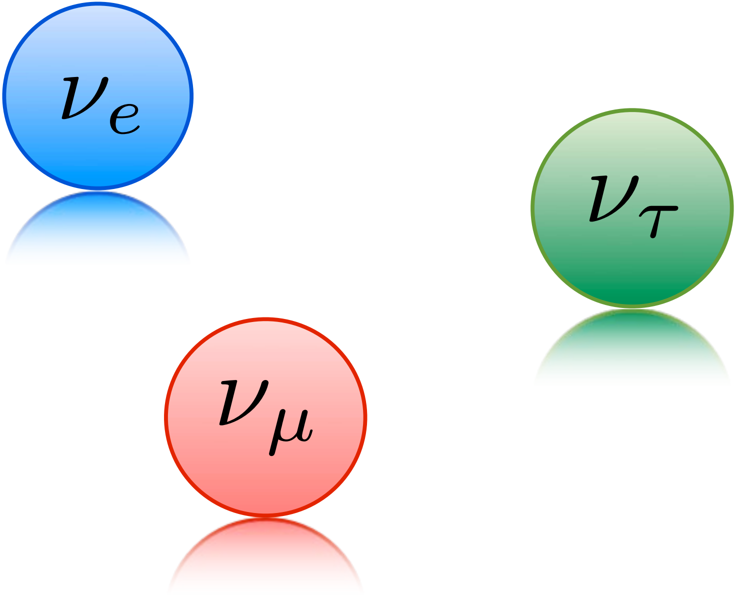


“Neutrino” (E. Amaldi)

Wolfgang Pauli

How Many Types of Neutrinos?

Neutrinos come in three different flavors.



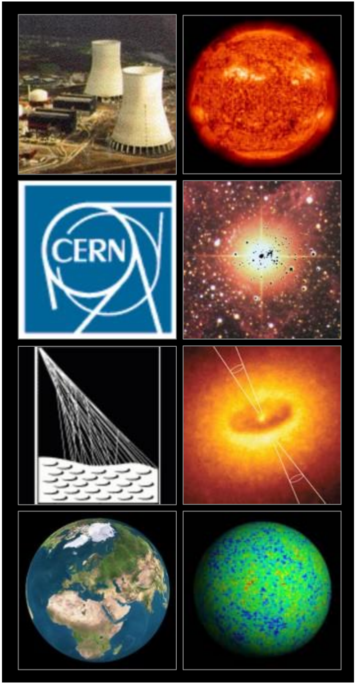
Where Are Neutrinos Produced?

Nuclear reactors

Particle accelerators

Atmosphere

Earth



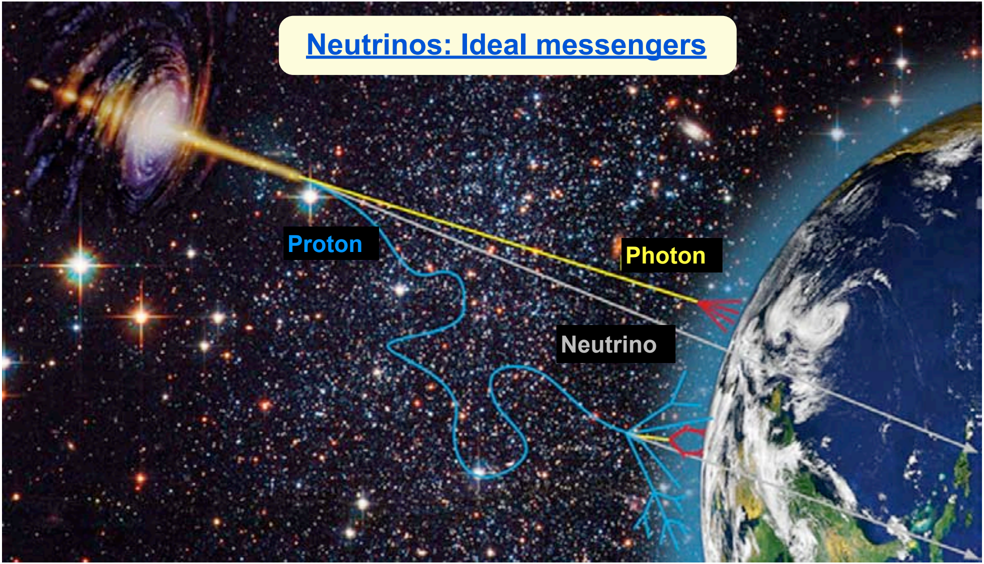
Sun

Supernovae

Gamma-ray bursts and other cosmic accelerators

Big Bang

Neutrinos: New Frontier in Astronomy



The Dream of Neutrino Astronomy

If [there are no new forces] -- one can conclude that there is no practically possible way of observing the neutrino.

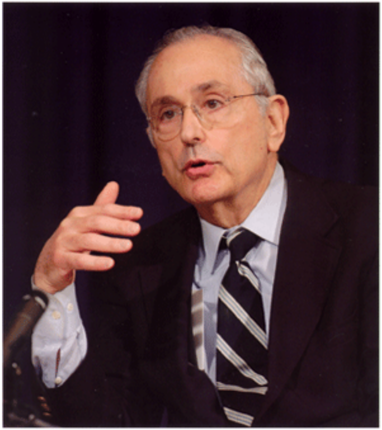
Bethe and Peierls (1934)

Only neutrinos, with their extremely small cross sections, can enable us to see into the interior of a star ...

Bahcall (1964)

The title is more of an expression of hope than a description of the book's contents ...
the observational horizon of neutrino astrophysics may grow ... perhaps in a time as short as one or two decades.

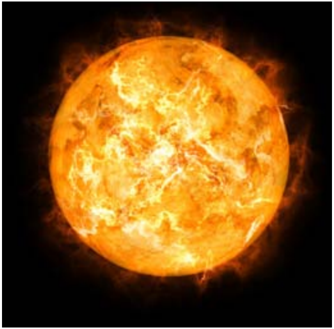
Bahcall, Neutrino Astrophysics (1989)

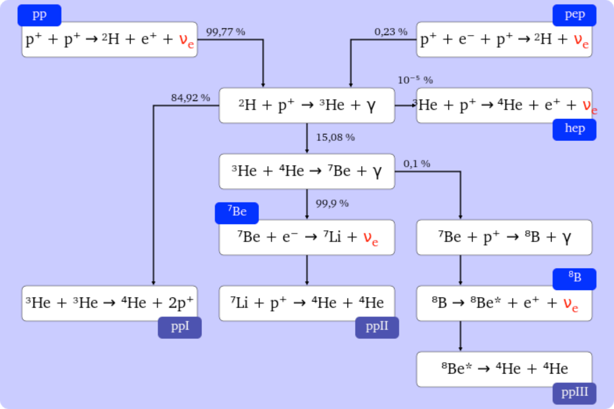


John Bahcall

How did We Learn About our Sun? Neutrinos!

Solar Neutrinos

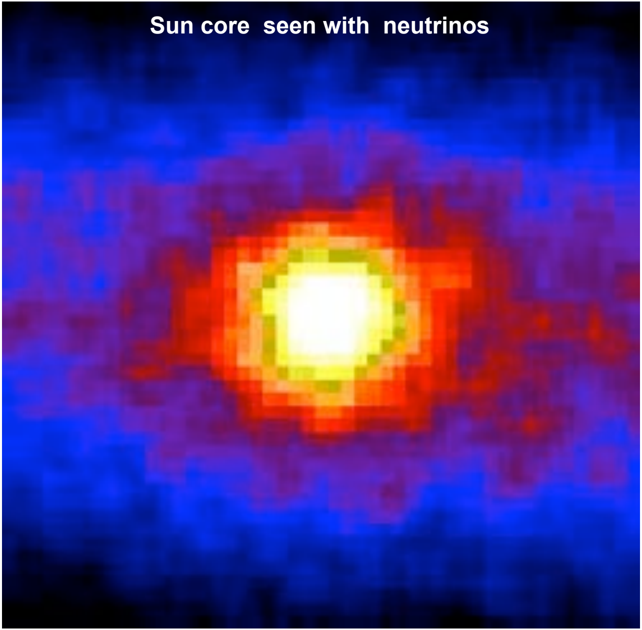




The Sun is powered by nuclear reactions. Neutrinos are emitted in huge quantities.

- Radiation from the Sun (98 % Light, 2% Neutrinos).
- 66 milliards/cm^2/s of neutrinos here at Earth.
- Photons take 200,000 years to escape from the Sun, neutrinos 2 seconds!

How Did We Learn About the Sun? Neutrinos!



Hunting Neutrinos from the Sun

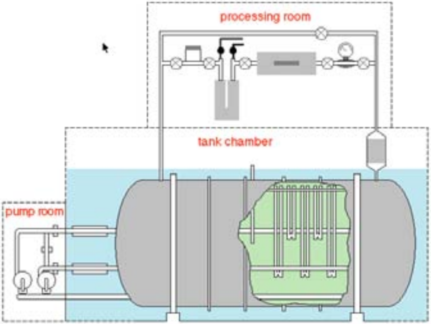
In 1960's Ray Davis and John Bahcall begun to hunt neutrinos from the Sun.

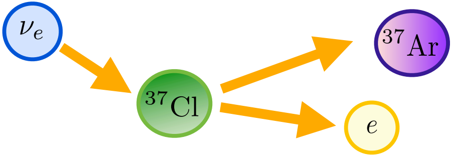
Raymond Davis

John Bahcall

Homestake Experiment

615 tons of cleaning fluid (C_2Cl_4)

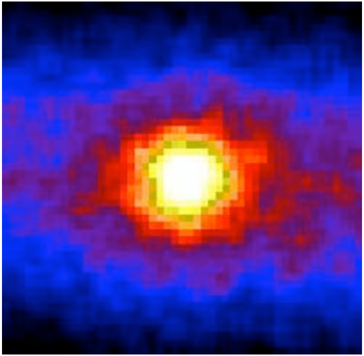




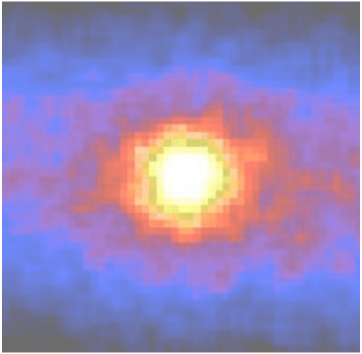
Davis measured only 1/3 of the flux predicted by Bahcall!

The Solar Neutrino Problem

Theoretical prediction



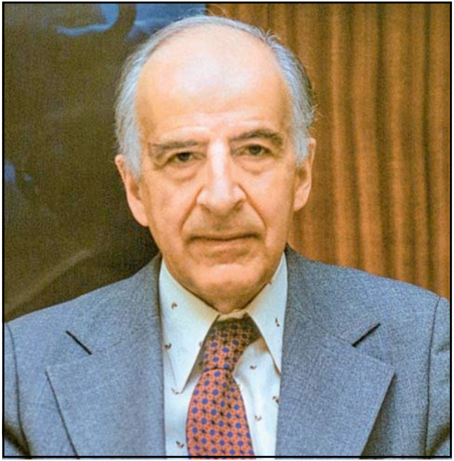
Experimental result



Where did the missing neutrinos go?

Neutrinos Can Oscillate

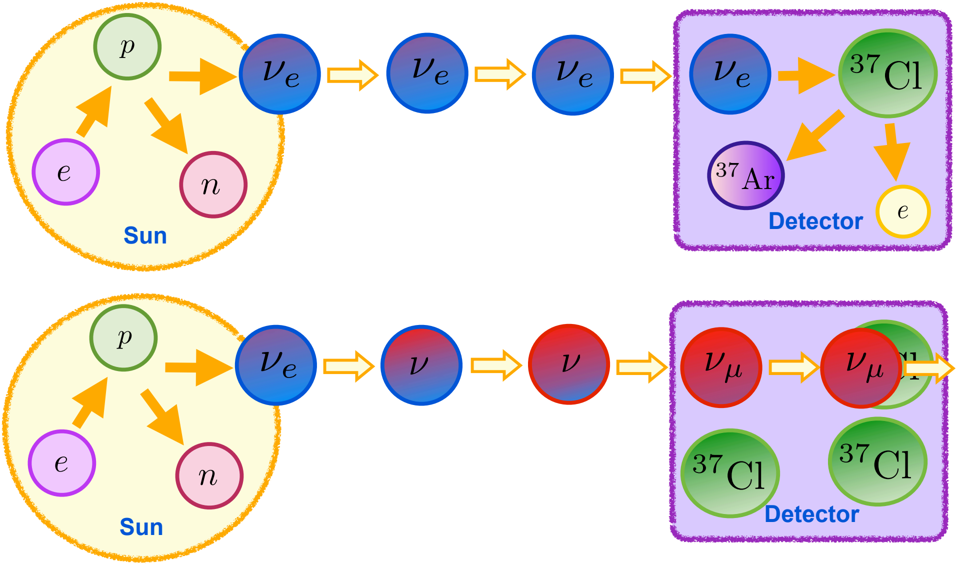
In 1957, Pontecorvo suggested that neutrinos can oscillate.



Bruno Pontecorvo

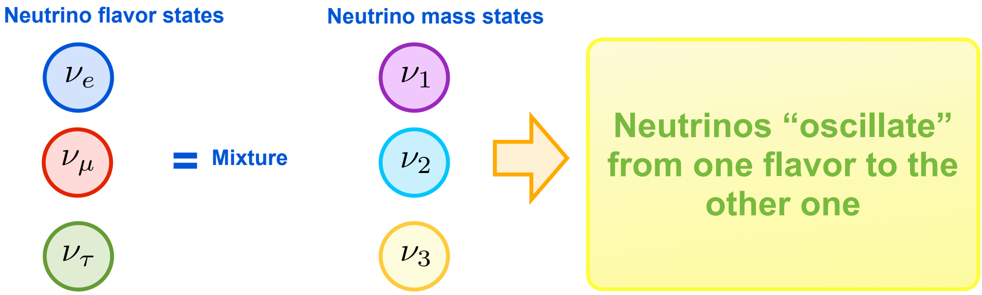
In 1969, Gribov and Pontecorvo published a paper titled “Neutrino astronomy and lepton charge” following the solar neutrino deficit observation.

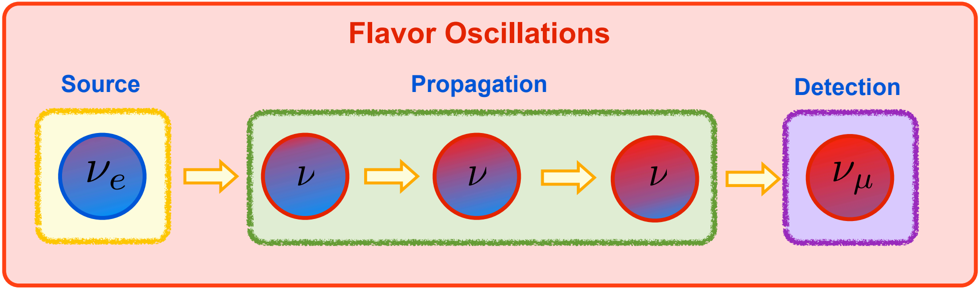
Neutrinos Can Oscillate



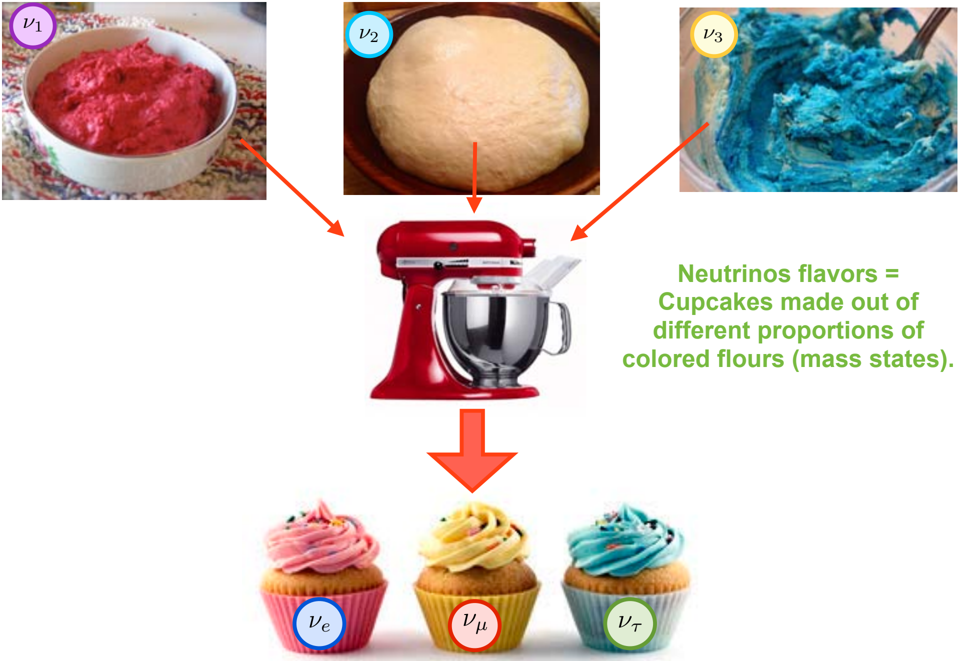
Davis measured 1/3 of the flux predicted by Bahcall because neutrinos oscillate!

Truly Novel Property of Neutrinos



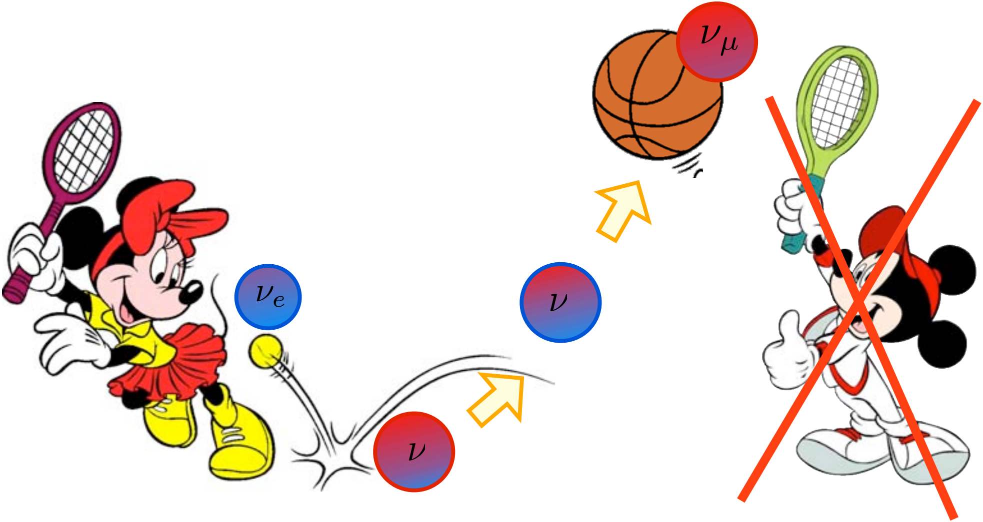


Truly Novel Property of Neutrinos



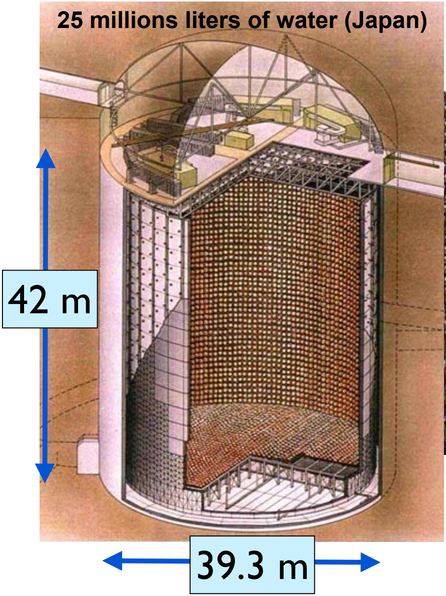
Neutrinos flavors = Cupcakes made out of different proportions of colored flours (mass states).

Truly Novel Property of Neutrinos

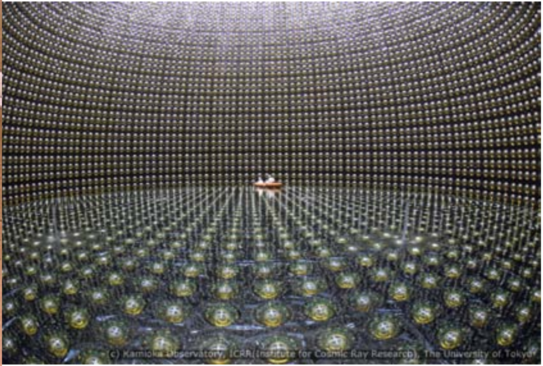


Davis measured 1/3 of the flux predicted by Bahcall because neutrinos oscillate!

(Super-)Kamiokande Neutrino Detector

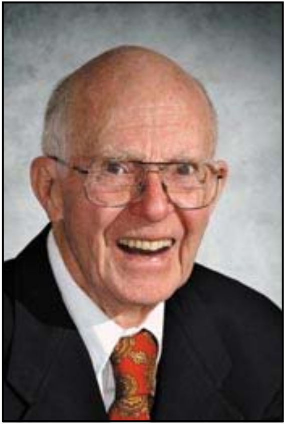


11,000 “electronic eyes”



1 solar neutrino per day is caught with one million liters of water.

Nobel Prize for Neutrino Astronomy



Raymond Davis Jr.

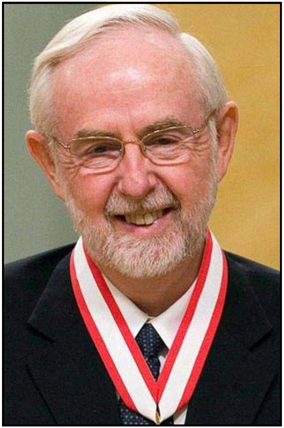
Masatoshi Koshiba

2002

“For pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos.”

Nobel Prize for Neutrino Oscillations

Takaaki Kajita

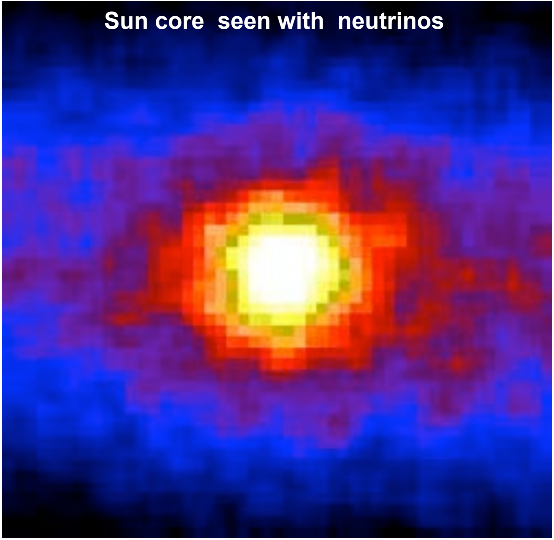


Arthur B. McDonald

2015

"For the discovery of neutrino oscillations, which shows that neutrinos have mass."

How Did We Learn About the Sun? Neutrinos!

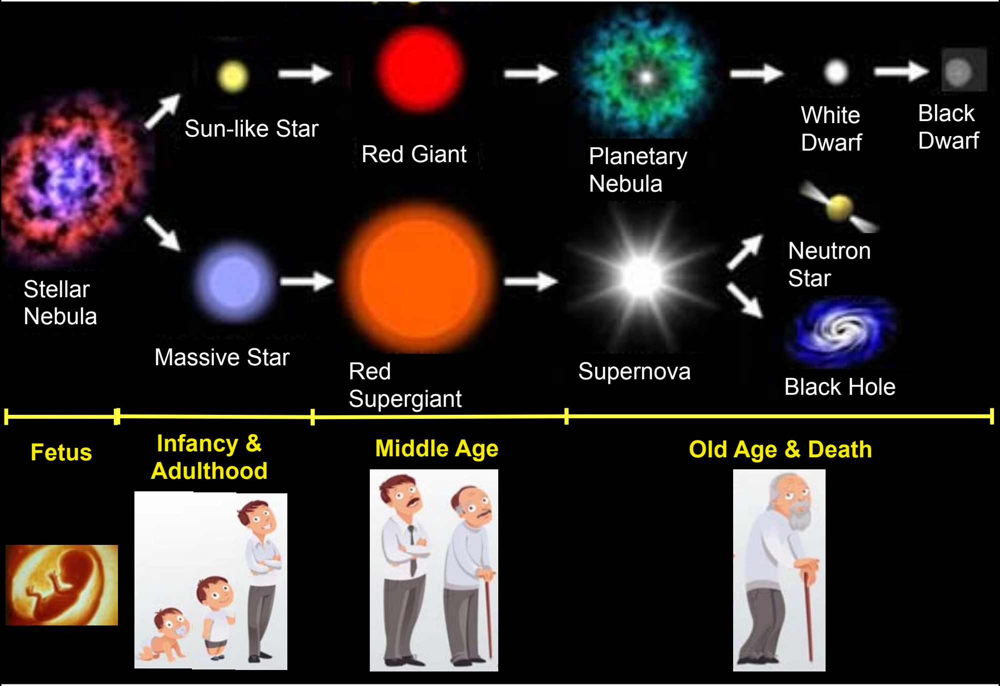


- Deficit of measured solar neutrino flux. ⇨ **Discovery of neutrino oscillations**.
- Neutrino flux strongly dependent from Sun core structure. ⇨ **Standard Solar Model Test**.

Neutrino from Supernovae

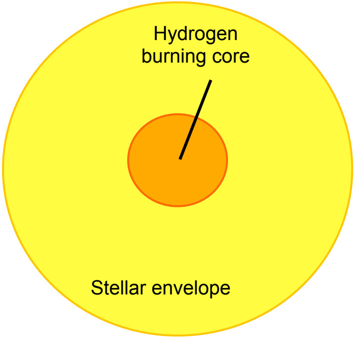
What Is a Supernova?

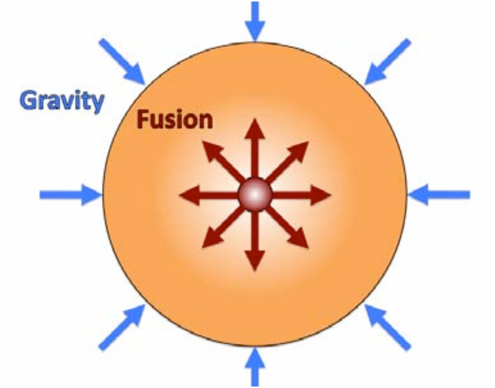
Lifecycle of a Star



Stellar Adulthood

A young star fuses hydrogen into helium (keeps burning until it runs out of hydrogen).





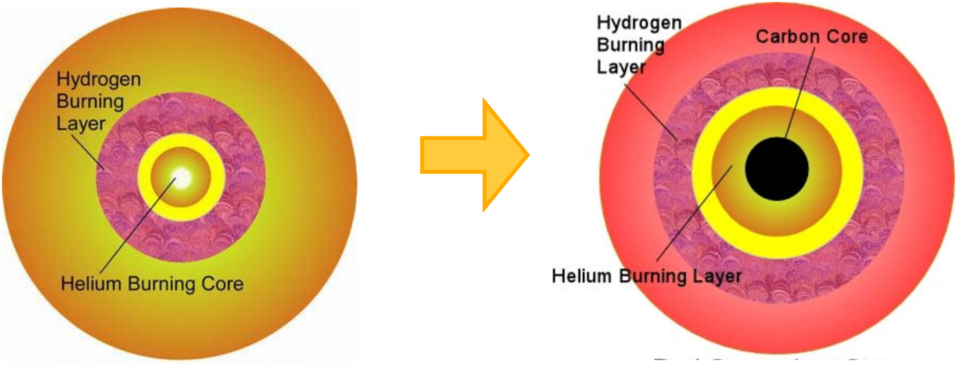
Pressure = Gravity

↓

Equilibrium

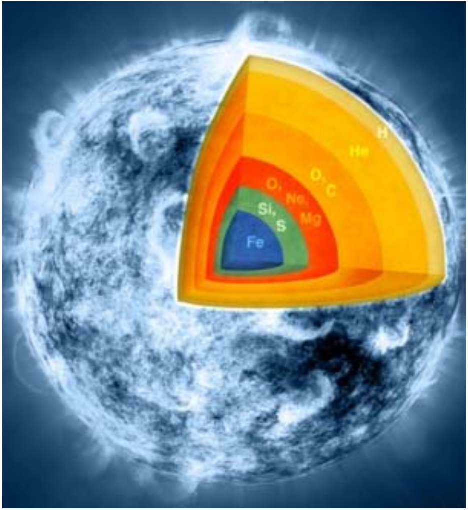
Stellar Middle Age

When star exhausts its fuel (Hydrogen), the core drops its pressure. Gravity compresses the core and the latter heats up. Helium burning starts. It continues for all elements up to Iron.



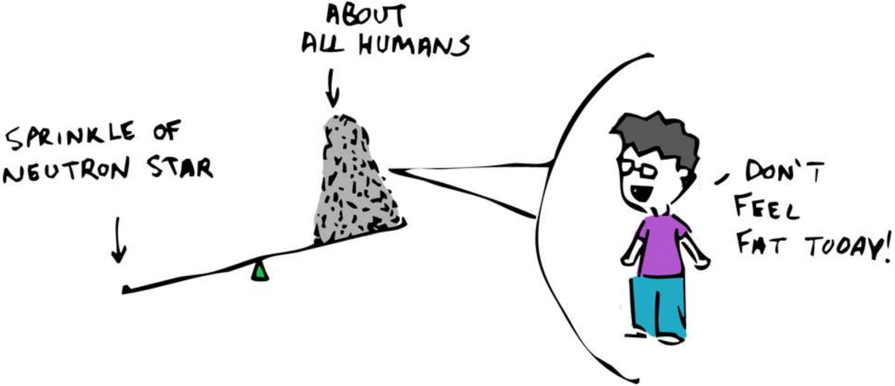
Stellar Old Age

When iron is formed, no more temperature raising occurs, no more counter pressure. Core collapses by gravitation and explosion. **Core-collapse supernova**.



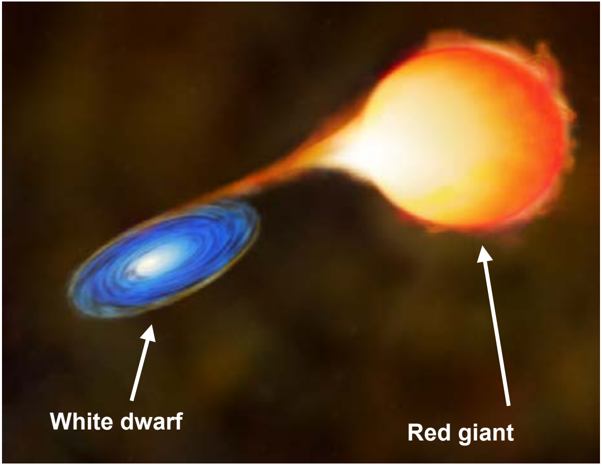
Stellar Final Stage

- The star blows away its outer layers during the supernova explosion.
- The central core will collapse in a compact object of a few solar masses (**neutron star**).
- Pressure is so high that electrons and protons combine to form stable neutrons.



But… there is an alternative path to supernova explosions …

Stellar "Cannibalism"

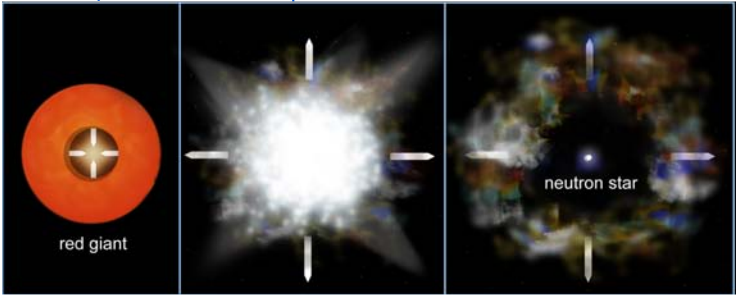


- Many stars live in binary systems.
- A white dwarf may accumulate material from a companion star (often a red giant).
- **Thermo-nuclear supernova explosion**.

SupernovaTypes

<u>Core-collapse or type II supernova</u>

Core implosion | Explosion | Remnant with neutron star



<u>Thermonuclear or type I supernova</u>

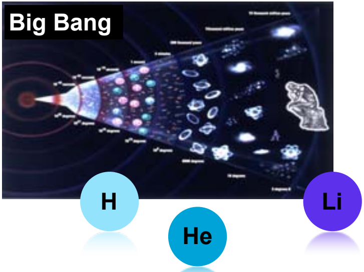
Accretion onto a white dwarf | Explosion | Remnant without neutron star

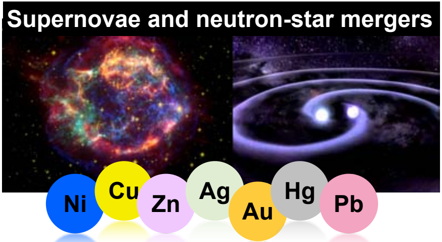
Supernova Classification

Spectral Type	Type I	Core Collapse
Physical Mechanism	Nuclear explosion of low-mass star	Core collapse of massive star
Compact remnant	None	Neutron star (black hole)
Rate	~ 0.36	~ 0.8
Neutrinos	Almost none	**A LOT**

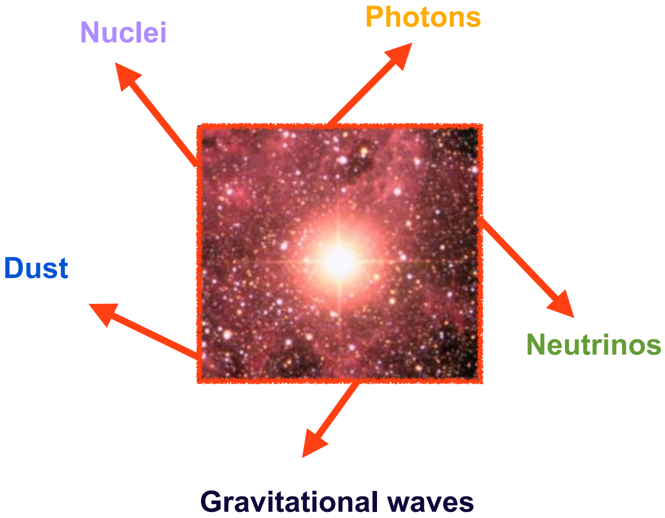
The Birth of Elements

Nucleosynthesis occurs in the new-born Universe, in star interiors, supernovae, and neutron-star mergers.



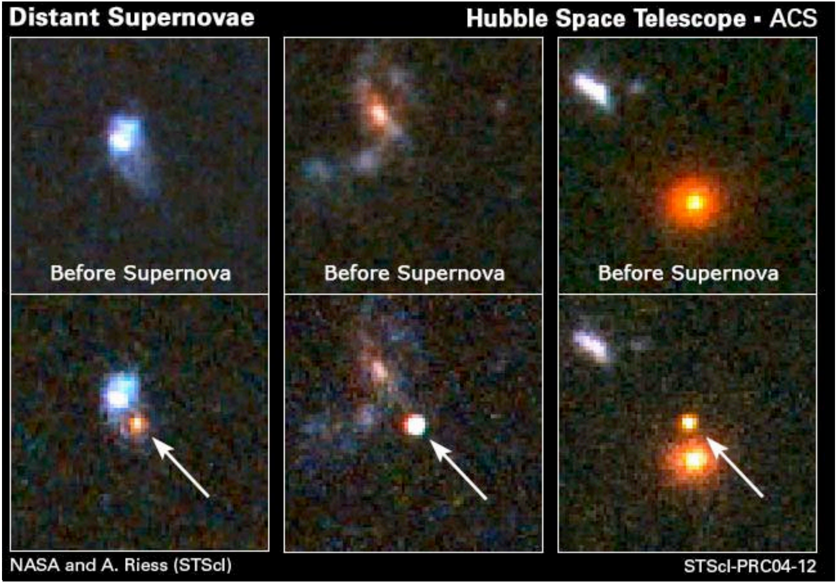


Supernova Products & Messengers



Shining Supernovae

Supernovae are optically bright objects.



The Birth of Supernova Astronomy

In 185 AD, Chinese astronomers noticed a mysterious body twinkling in the sky.

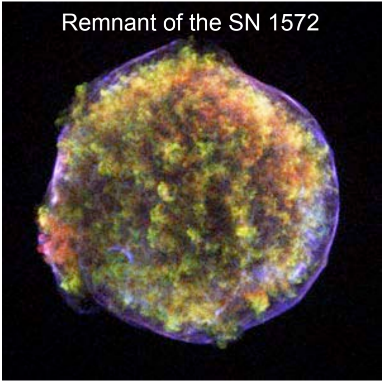
First documented **supernova** observation. We observe its remnant RCW 86.

Tycho’s Supernova

In 1572, Tycho Brahe saw a “new star” in Cassiopeia.

Tycho noted that the object remained stationary from night to night, never changing its parallax, so it had to lie far away against common believe of the time.

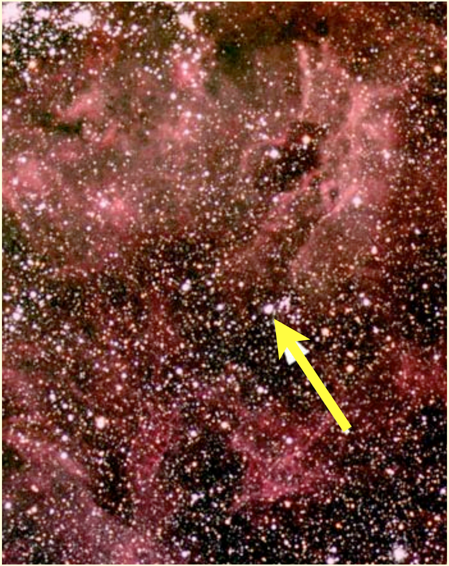
Star map of Cassiopeia



Last Nearby Supernova: SN 1987A

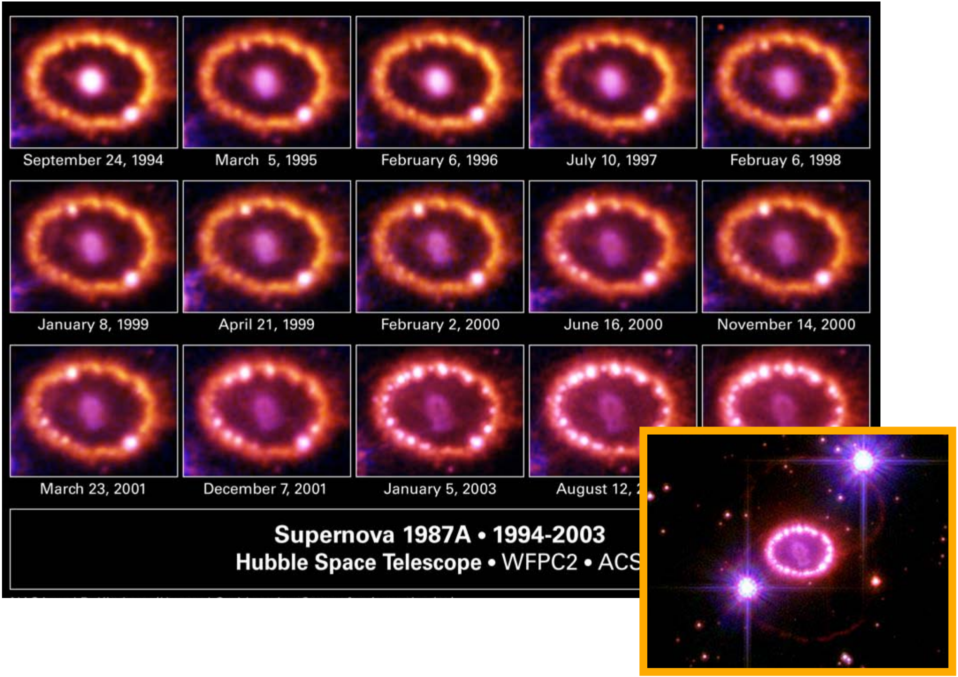
SN 1987A occurred in 1987 in the Large Magellanic Cloud (50 kpc, 163,000 light-years).

Sanduleak -69° 202



SN 1987A (Feb. 23, 1987)

Remnant SN 1987A

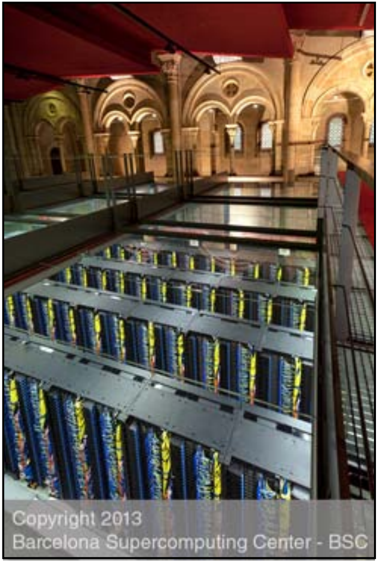


How Does the Supernova Engine Work?

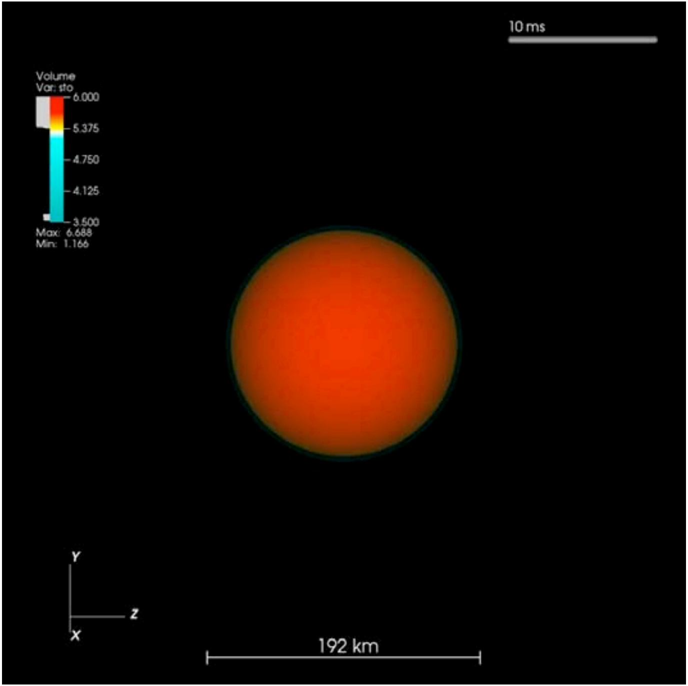
Man-Made Supernovae

To understand the supernova engine, supernova explosions are simulated on super-computers. Simulations are performed on ~15,000 CPU’s. It could take 1/2 year of computational time.

SuperMuc supercomputer of the Leibniz Computing Center, Garching.



20 M_{sun} Supernova Simulation (Garching group, 2015)



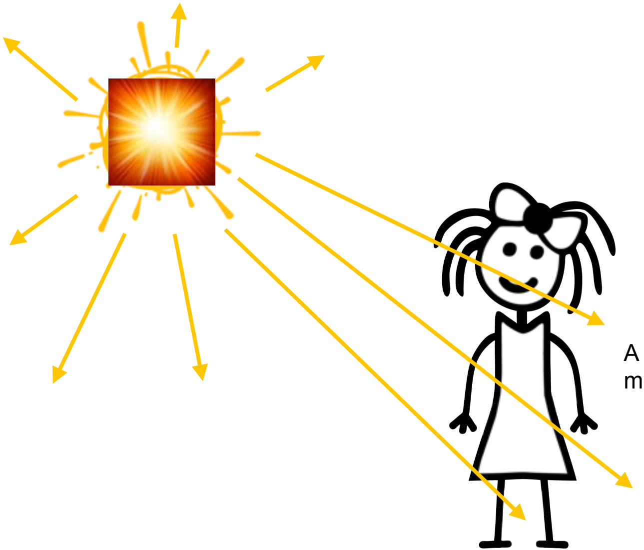
A core-collapse supernova explodes because of

NEUTRINOS!

10^{58} neutrinos are emitted!

Supernova Neutrinos

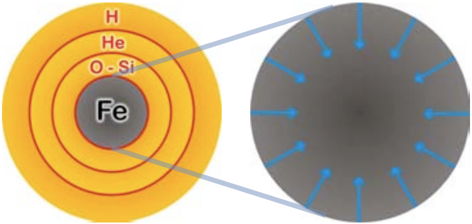
If the Sun were a supernova, aliens on Mars would be incinerated by neutrino radiation!



A supernova shines 10^{20} times more than the Sun in neutrinos!

Core-Collapse Supernova Explosion

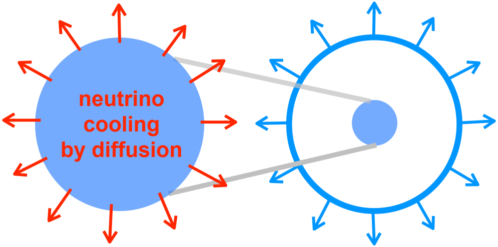
Implosion (Collapse)



Neutrinos carry 99% of the released energy (~ 10^{53} erg).

Gravitational binding energy:
~ 3 x 10^{53} erg ~ 17% $M_{sun}c^2$.
Neutrino luminosity:
~ 3 x 10^{19} L_{sun}.

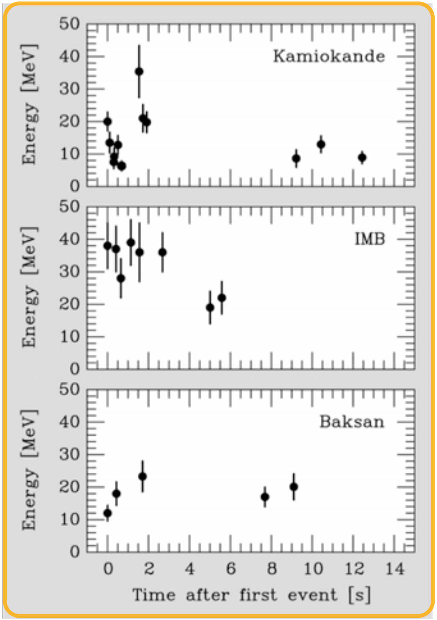
Explosion



Neutrino emission time: ~ 10 s.

Supernova 1987A

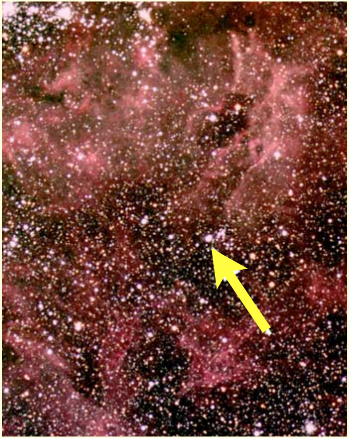
Few detectors were able to detect SN 1987A neutrinos.



Supernova 1987A

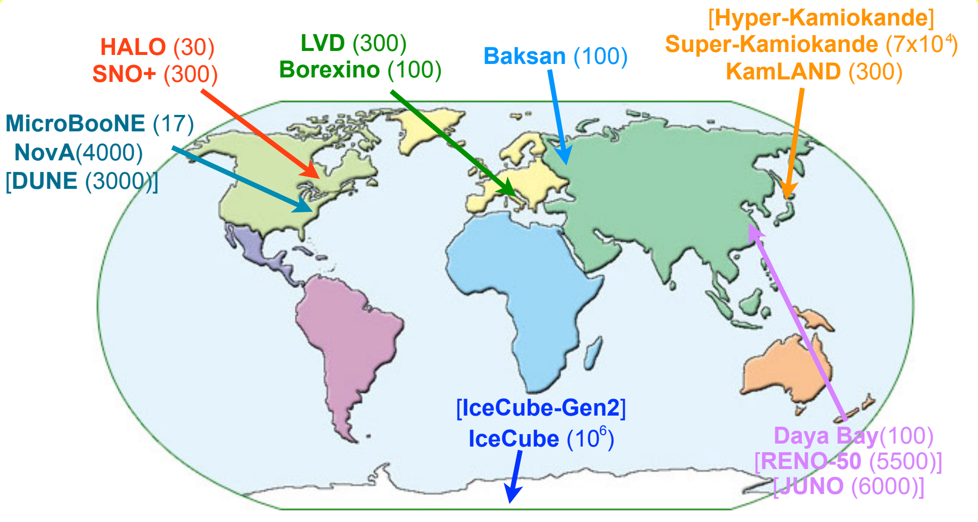
First and only supernova observed in neutrinos.
First verification of stellar evolution mechanism.

Sanduleak -69° 202



SN 1987A (Feb. 23, 1987)

Are We Ready for the Next Supernova?



Expected number of events for a SN at 10 kpc in parenthesis.

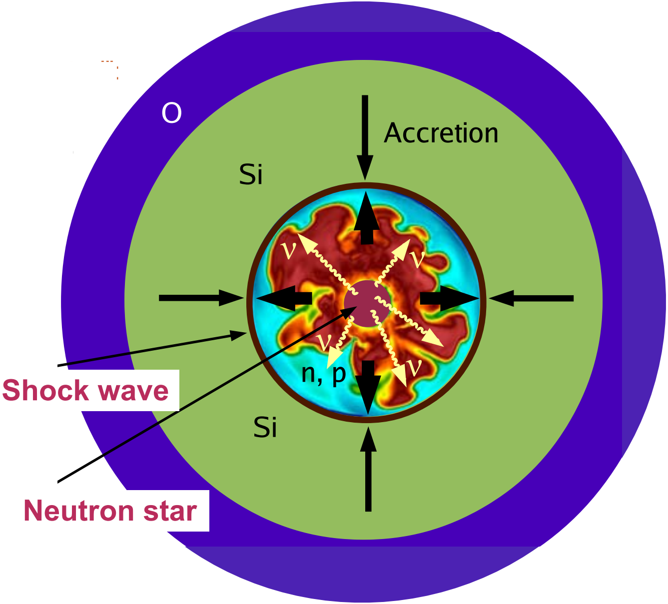
The next supernova explosion: A lifetime opportunity!

Why Do We Care About Neutrinos from Core-Collapse Supernovae?

- Neutrino luminosity of a supernova is 100 times its optical luminosity.
- Neutrino signal emerges from the core promptly.
  Photons may take hours to days to emerge from the stellar envelope.
- Supernovae would not explode without neutrinos.
  Elements could not be formed.
- Neutrinos provide information inaccessible from other kinds of astronomy.
- An optical supernova display may never be seen for a given core collapse.

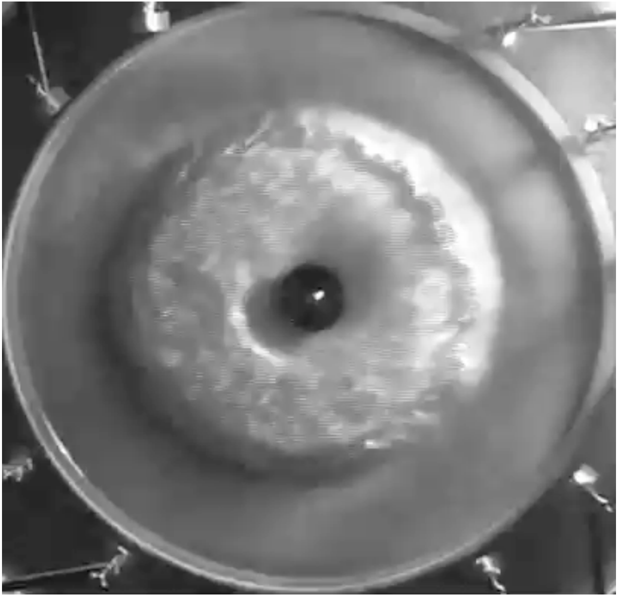
Delayed Neutrino-Driven Explosion

Shock wave forms within the iron core. It dissipates energy dissociating iron layer. **Neutrinos** provide energy to stalled shock wave to start re-expansion.



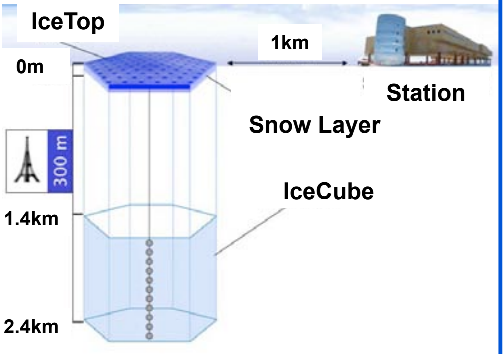
Standing Accretion Shock Instability

SWASI Experiment (Foglizzo et al., 2012)



The IceCube Neutrino Telescope

IceCube Telescope (South Pole)

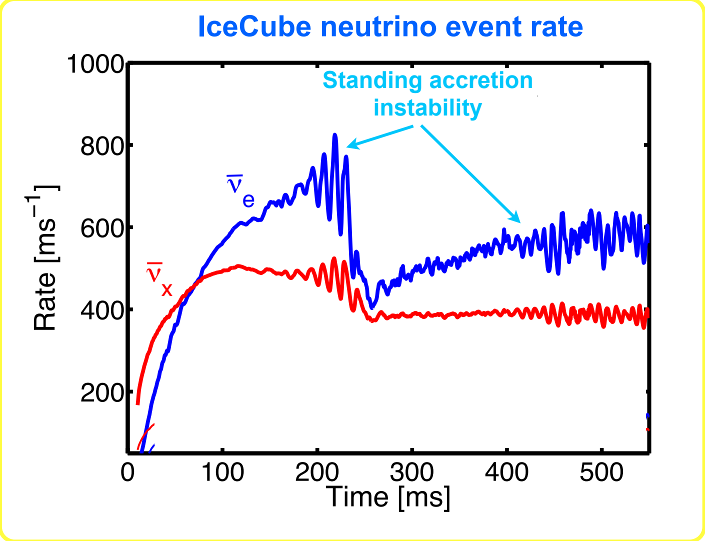


5,600 “electronic eyes”

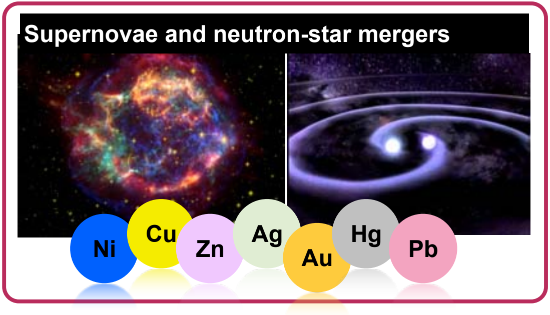
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

Standing Accretion Shock Instability

Neutrinos (and gravitational waves) can probe the explosion mechanism.



Supernova Nucleosynthesis



Synthesis of new elements in supernovae could not happen without neutrinos.

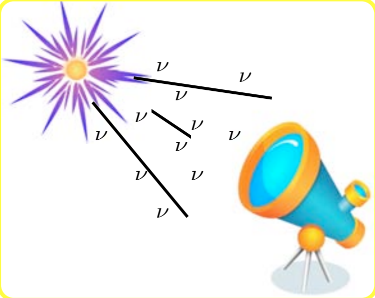
$$n + \nu_e \rightarrow e^- + p$$

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

Neutrino Alert

SuperNova Early Warning System (SNEWS).

Network to alert astronomers of a burst (neutrinos reach us earlier than photons).



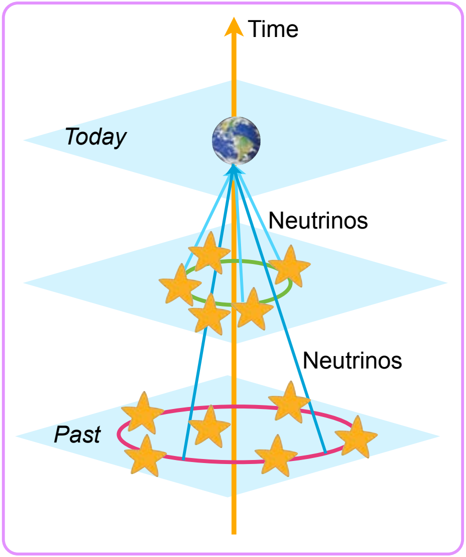
Determination of **supernova direction** with neutrinos.

Crucial for vanishing or weak supernova.

Diffuse Supernova Neutrino Background

Diffuse Supernova Neutrino Background

On average 1 SN/s somewhere in the universe → Diffuse neutrino background (**DSNB**).

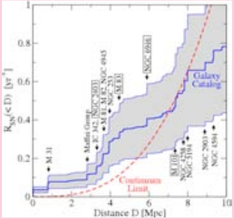


- Detectable flux at the Earth.
- Constraints on the stellar population.
- New frontiers for neutrino astronomy.

Supernova Neutrino Detection Frontiers

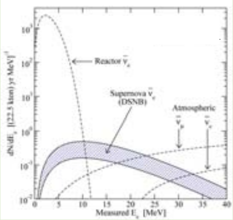
Supernova in our Galaxy (one burst per 40 years).

Excellent sensitivity to details.



Supernova in nearby Galaxies (one burst per year).

Sensitivity to general properties.



Diffuse Supernova Neutrino Background
(one supernova per second).

Average supernova emission. Signal is always there.

Summary

- ★ Neutrinos are abundant ghostly particles.
- ★ Neutrinos are thrilling particles. They change flavors.
- ★ Supernovae work because of neutrinos.
- ★ We would not be here without neutrinos.

We are stardurst because of neutrinos!

Thank you for your attention!