

Catching neutrinos from exploding massive stars

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About 166,000 thousand years ago

- Ice Age on Earth
- in a small galaxy not too far away a large star suddenly exploded

February 23/24,
1987

A few astronomers in Chile
were getting ready to take
routine pictures of the
Large Magellanic Cloud



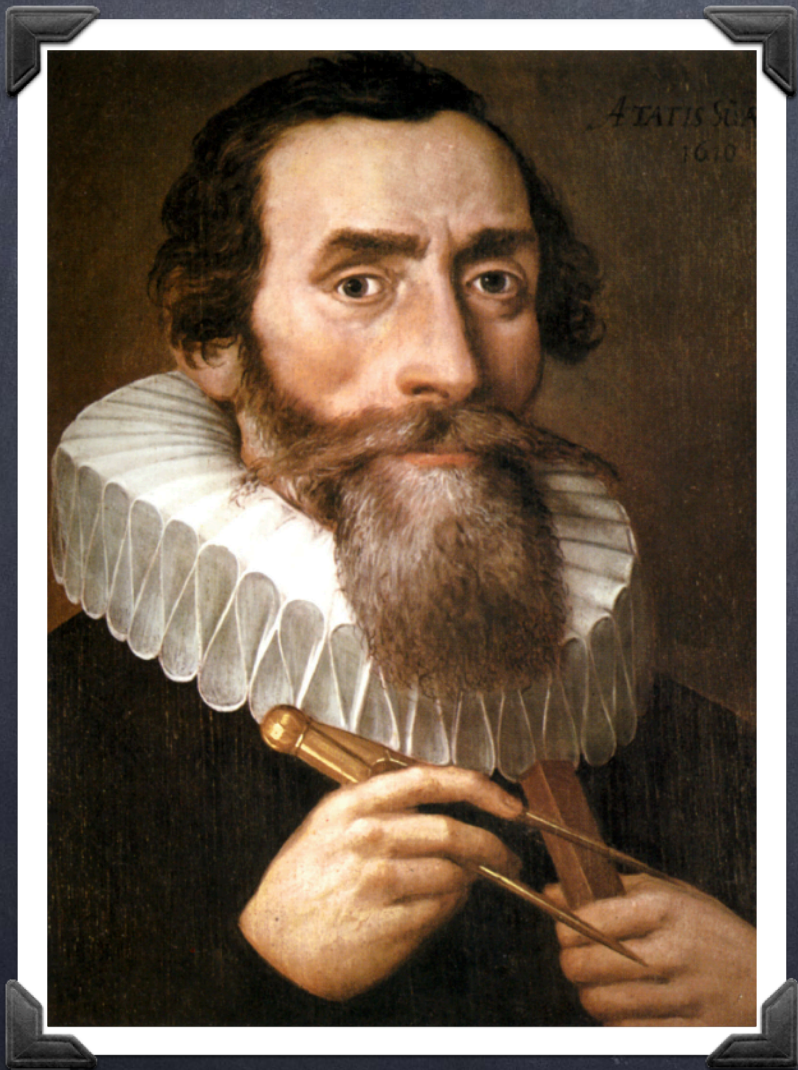
February 23/24,
1987

To their great surprise,
there was an extremely
bright star that should
not have been there



Amazing serendipity!

The last supernova explosion seen
with a naked eye was in 1604



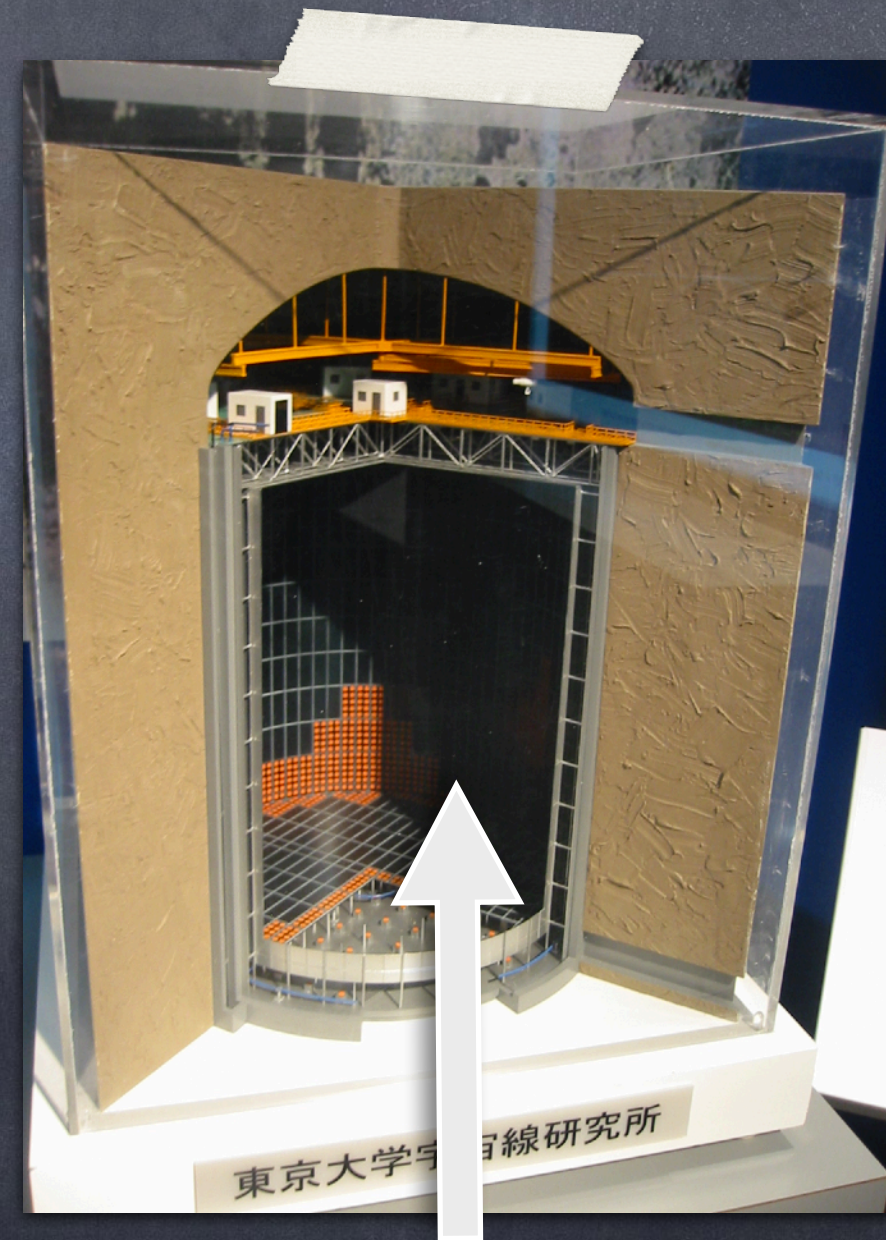
Johannes Kepler



Ian Shelton

Underground detectors

- Japan: KamiokaNDE (Kamioka Neutron Decay Experiment)
- US: IMB (Irvine, Michigan, Brookhaven)
- Large tanks of pure water surrounded by photomultiplier tubes, waiting for tiniest light flashes



3,000 tons of pure water

Why were such detectors built?



- 1970s: attempt to unify different forces of nature
- Matter is not eternal: protons should decay!
- Experimental race to observe this was on!

Unity of All Elementary-Particle Forces

Howard Georgi* and S. L. Glashow

Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138

(Received 10 January 1974)

We present a series of hypotheses and speculations leading inescapably to the conclusion that $SU(5)$ is the gauge group of the world—that all elementary particle forces (strong, weak, and electromagnetic) are different manifestations of the same fundamental interaction involving a single coupling strength, the fine-structure con-

Results

- IMB came online in 1982
- KamiokaNDE in April 1983
- Would detect proton decay for half-life of 10^{31} years
- To their great disappointment, no decays observed!

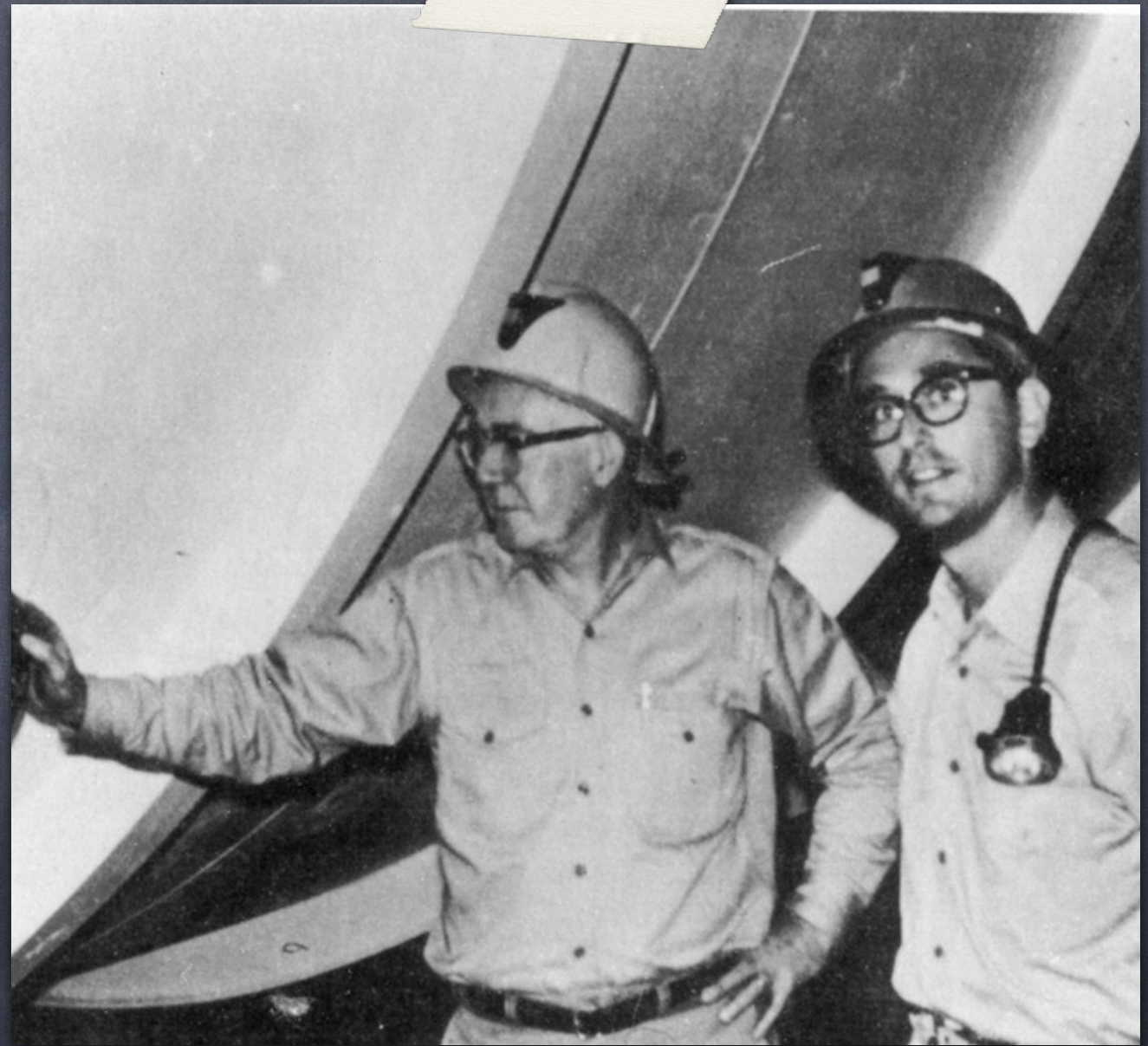


What else could the
Kamiokande detector do?

Look at the "solar neutrino problem"

"The solar neutrino problem", since 1960s

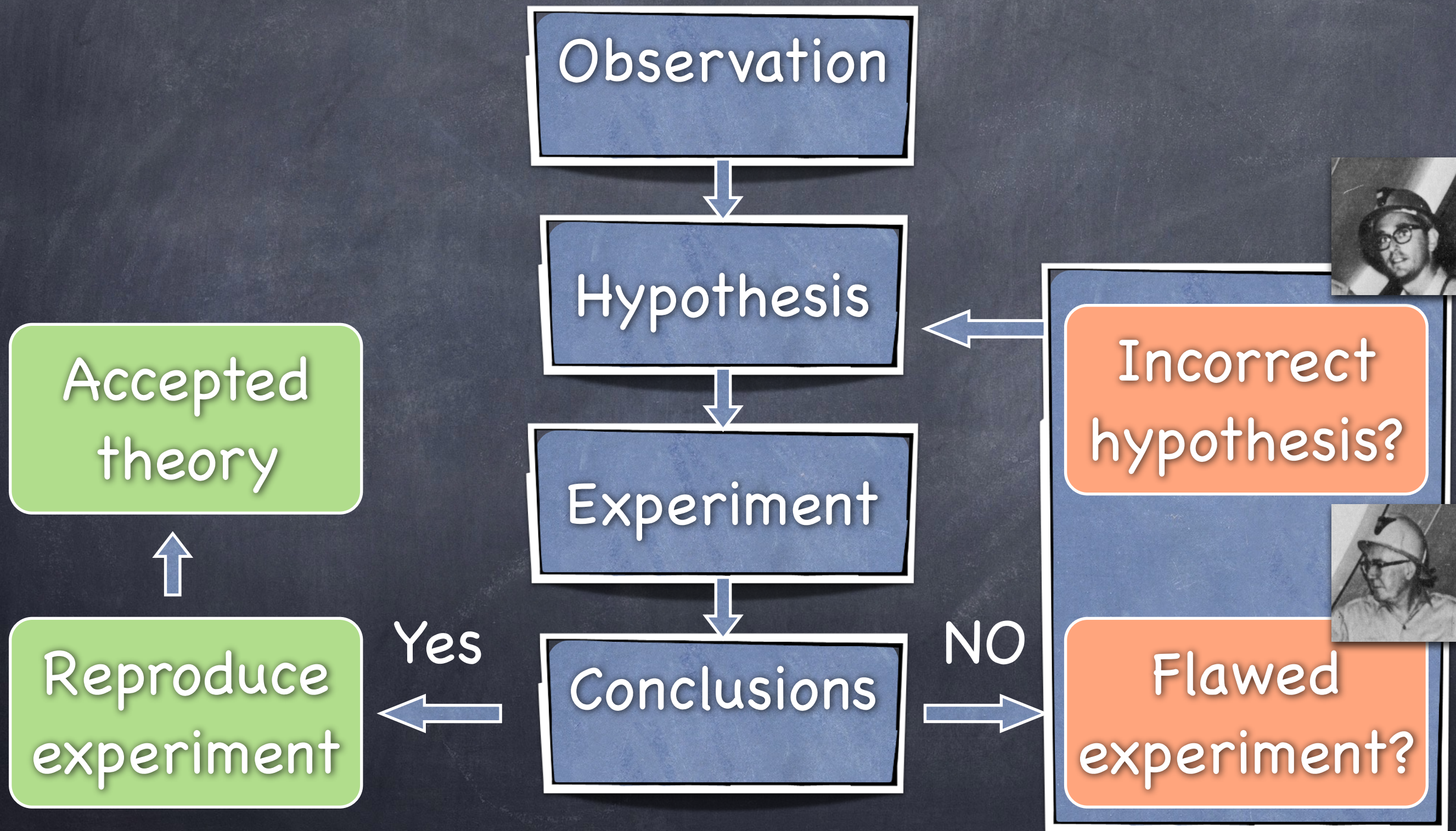
- John Bahcall (theory) and Ray Davis (experiment)
- Apparatus: a tank of 100,000 gallons of dry cleaning fluid (olympic-size pool), deep in a remote gold mine in South Dakota, 4850 feet underground



Missing neutrinos

- Hypothesis: processes generating energy in the core of the Sun release ghostly elementary particles, neutrinos
- These neutrinos would cause a small number of Chlorine atoms in the giant underground tank to convert to Argon
 - Bahcall's calculation: 51 Argon atoms every month
 - Davis's experiment: only about 17 per month
- This profound discrepancy persisted month after month, year after year

Scientific method



Follow-up experiment needed

- Kamiokande already had a detector!
 - Different technology!
- However, a number of significant upgrades were required first: new water purification, new electronics, an additional layer on the outside of the detector
- Upgrade and troubleshooting completed by January 1987

February 23/24, 1987, SN1987A

- The experimental collaborations went back to the data from the underground detectors
- 11 interactions were observed by Kamiokande in a 10 second window, 2 hours before first optical observation
- 8 more interactions were seen in the same time window at IMB
- 5 more at the Baksan Scintillator Telescope

Kamiokande data

- Kamiokande saw 11 SN-induced interactions in a 10 second window
- 2 hours before the first optical observation

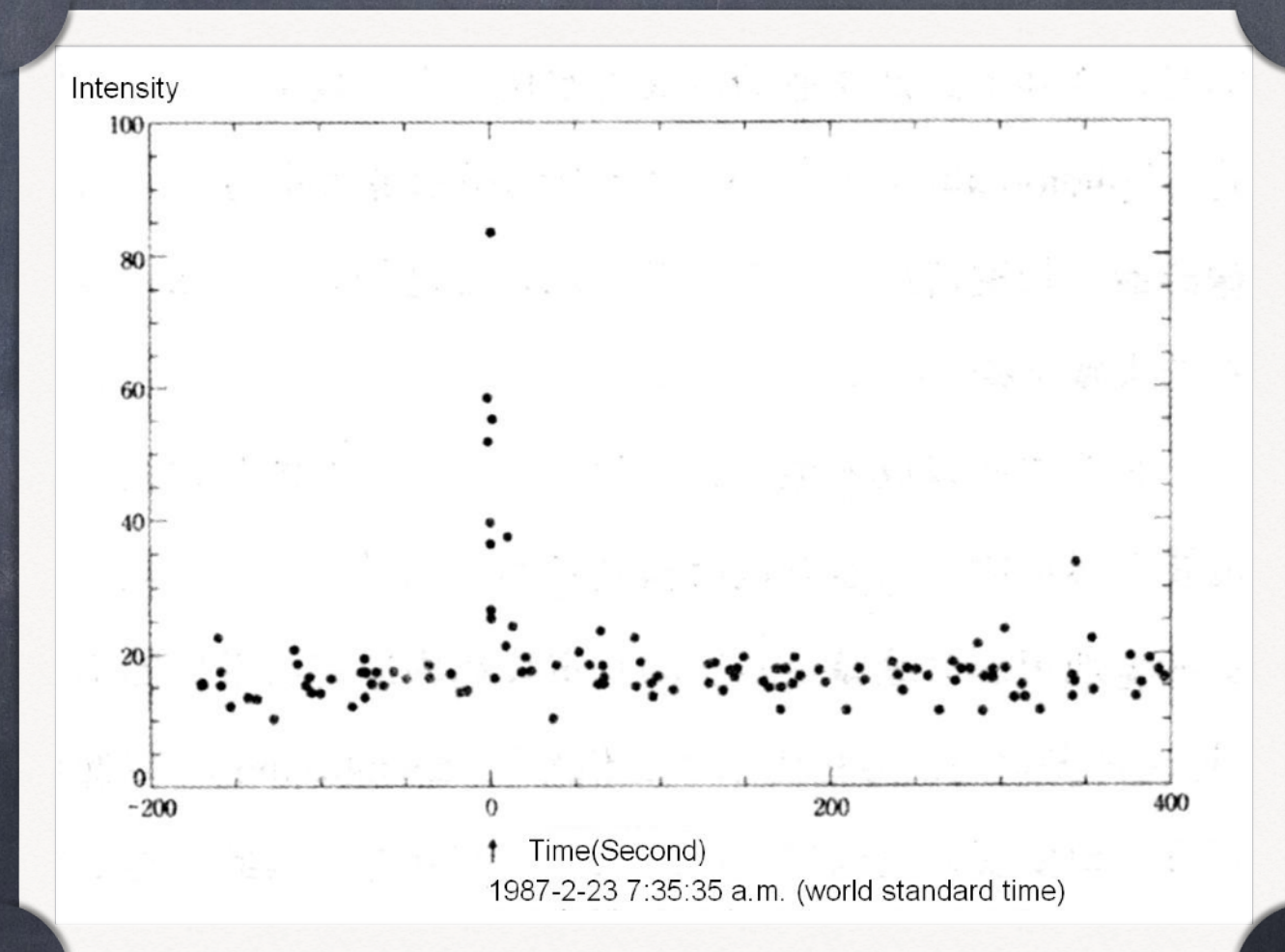
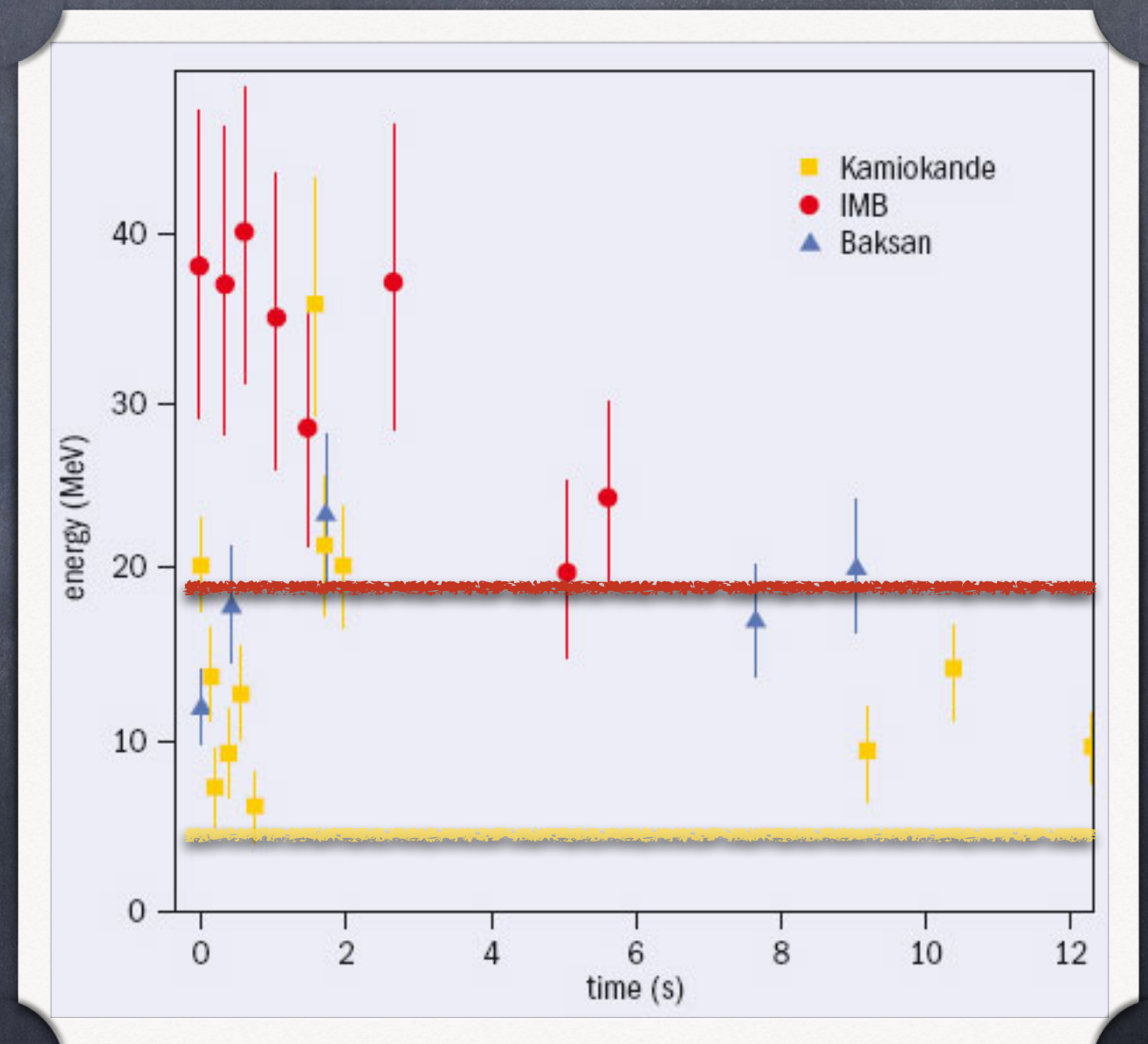


Image credit: K. Hirata et al., PRL 1987

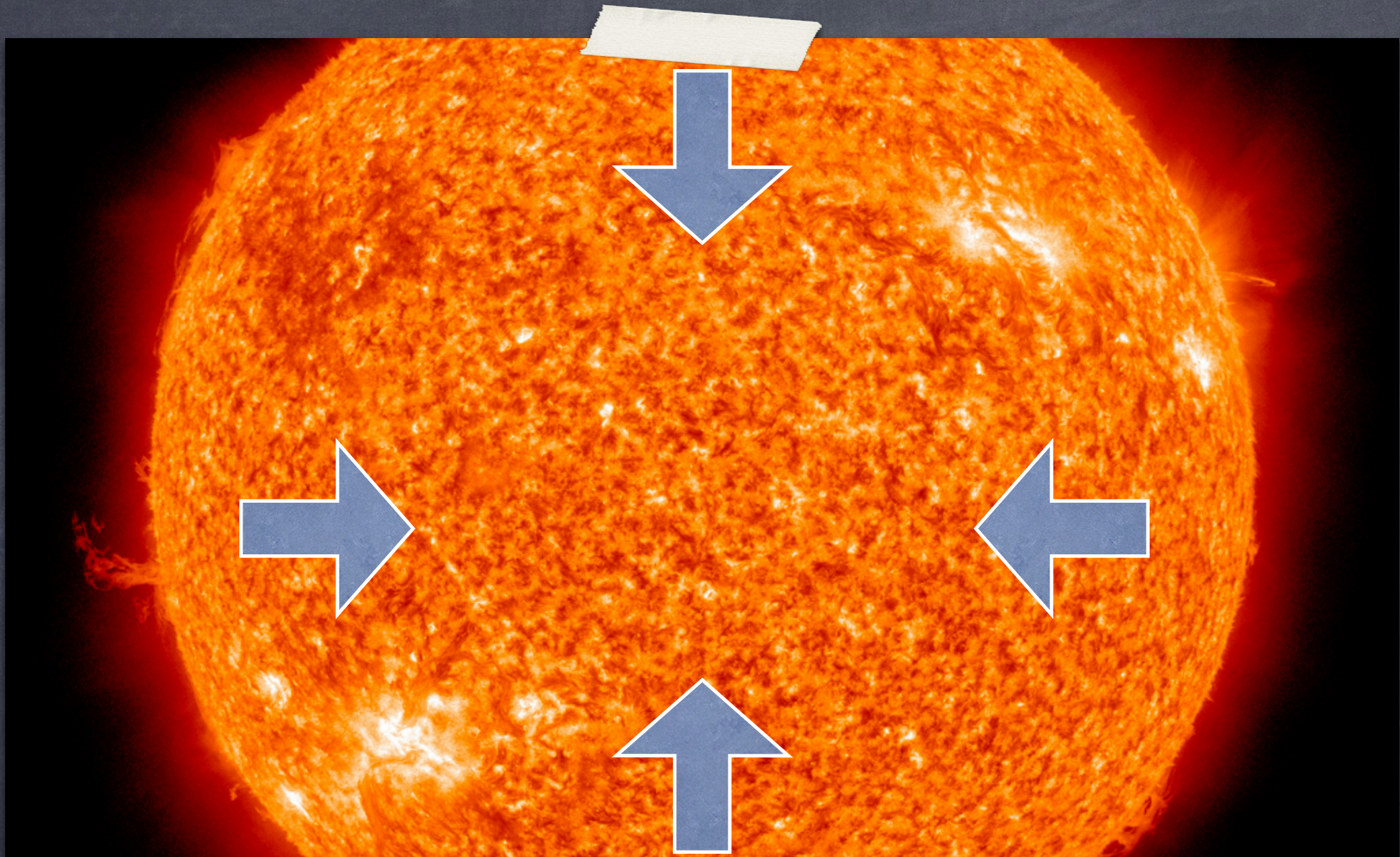
3 detector, 2 dozen events

- 8 more interactions were seen in the same time window at IMB
- 5 more at the Baksan Scintillator Telescope
- These two dozen events confirmed that a gravity-powered neutrino bomb went off inside the star



- These two dozen events, observed deep underground, confirmed that 166,000 years ago, in a neighboring galaxy, a gravity-powered neutrino bomb went off inside a massive star

- What is the role of gravity?
- What are neutrinos and why are they important for the explosion?



Newton's law of universal gravitation

The same force that pushes us to the ground is pushing the star to compress

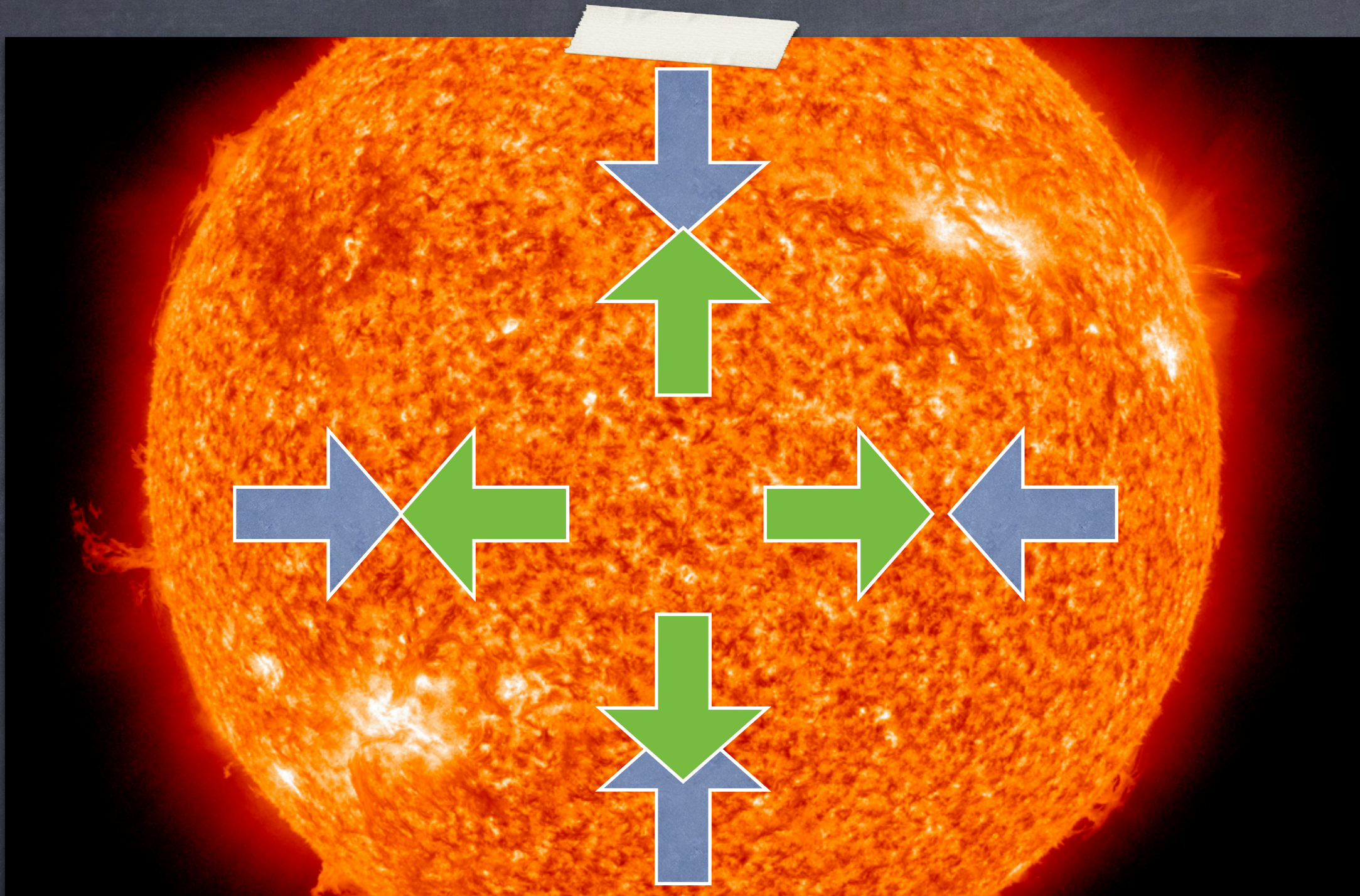
With only gravity, a star would collapse in
free-fall:

✦ For our Sun about 10^3 seconds

$$v^2 \sim GM_*/R_* \rightarrow t \sim R_*/v \sim R_*^{3/2}/\sqrt{GM_*} \sim 1/\sqrt{G\rho_*} \sim 10^3 \text{sec}$$

But we know the Sun does
not collapse

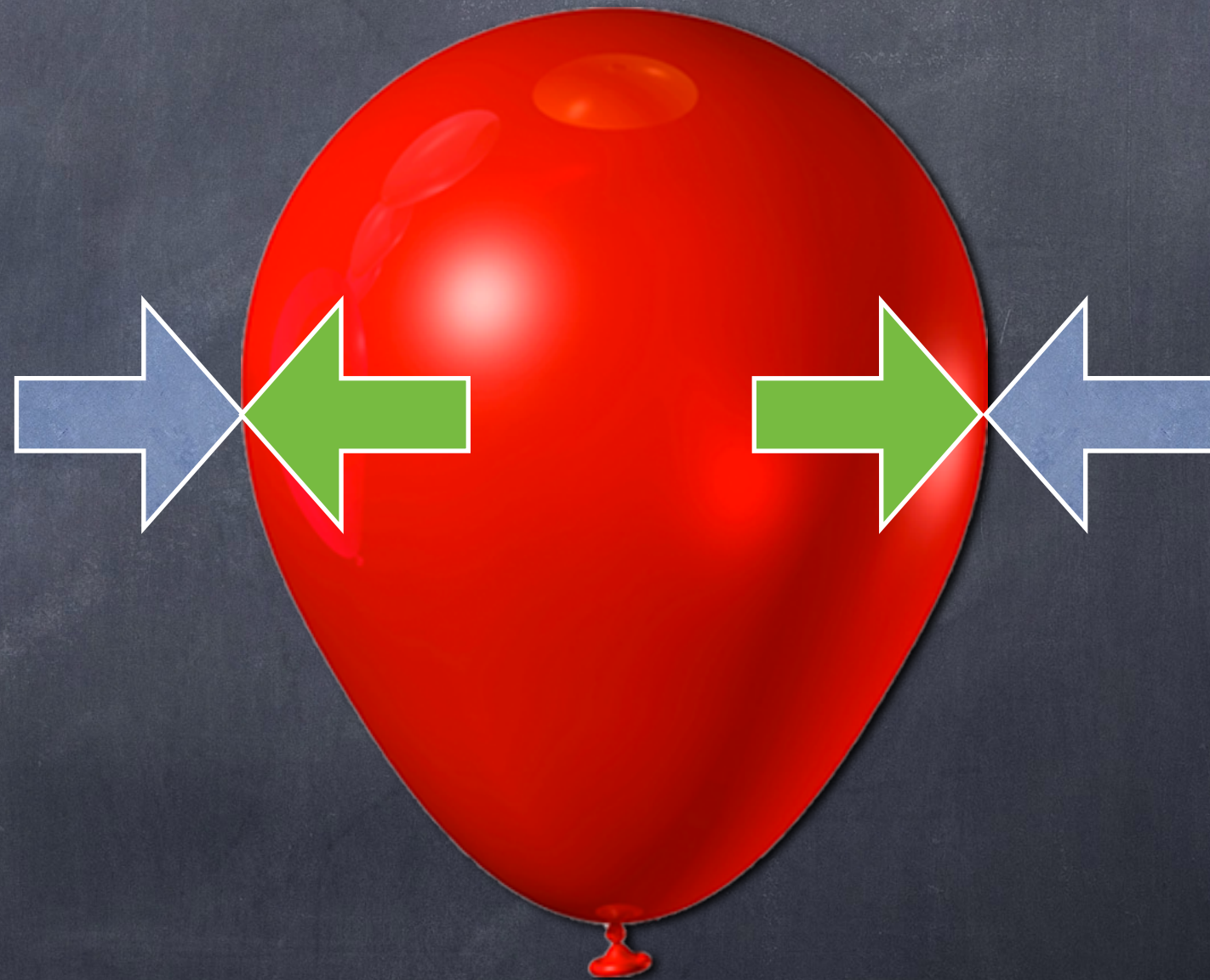
The age of the solar system is 4.7 billion
years



Gravity must be exactly balanced
by internal pressure

The source of this pressure?

- Think of a balloon: kept stable by the pressure of the gas inside
- The hotter the gas, the more pressure it exerts
- The interior of the Sun must be hot!
- Indeed, the Sun is a ball of a very hot plasma, hottest in the center where the pressure is greatest (14,000,000 K)



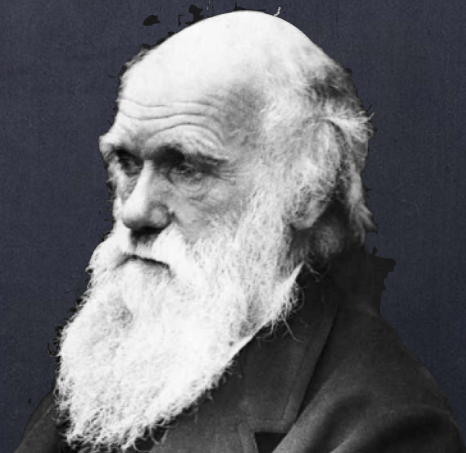
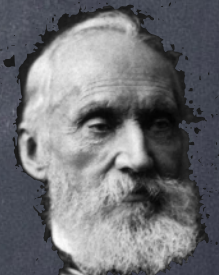
$$\frac{3}{2}kT \sim \frac{1}{2} \frac{GM_* m_p}{R_*} \rightarrow T_{\odot} \sim 10^7 K$$

Leaky balloon!

- Stars leak heat
 - Good thing for us: the Sun shines
- But without sources to replenish the lost heat, the star would have to contract
- Hotter interior → more energy loss → more contraction
- Kelvin, Helmholtz in the 19th century estimated that the lifetime of the Sun would have to be only 30 million years

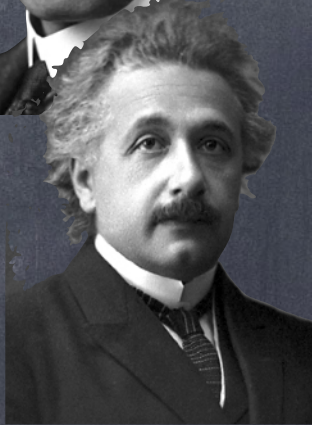
$$U_{\odot} \sim \frac{1}{2} \frac{GM_{\odot}^2}{R_{\odot}} \sim 10^{48} \text{erg} \rightarrow \frac{U_{\odot}}{L_{\odot}} \sim \frac{10^{48} \text{erg}}{10^{33} \text{erg/s}} \sim 10^7 \text{yr}$$

- They gave Charles Darwin a lot of trouble!



From Einstein to Bethe

- Francis Aston, discovered (1920) that four hydrogen nuclei weigh slightly more than a helium nucleus
- Albert Einstein: $E=mc^2$
 - mass could be converted into energy
- Sir Arthur Eddington: the Sun, which was made of hydrogen and helium, could be powered by H to He conversion
- A number of brilliant scientists, including George Gamow and Hans Bethe, developed the theory of solar energy generation in the 1930s



Thermonuclear reactor in the stellar core

- So long as the nuclear reactions replenish the heat, gravitational collapsed is halted
- This process is perfectly self-regulating and the Sun is stable for billions of years, enough for life to evolve into the complex world we see around us

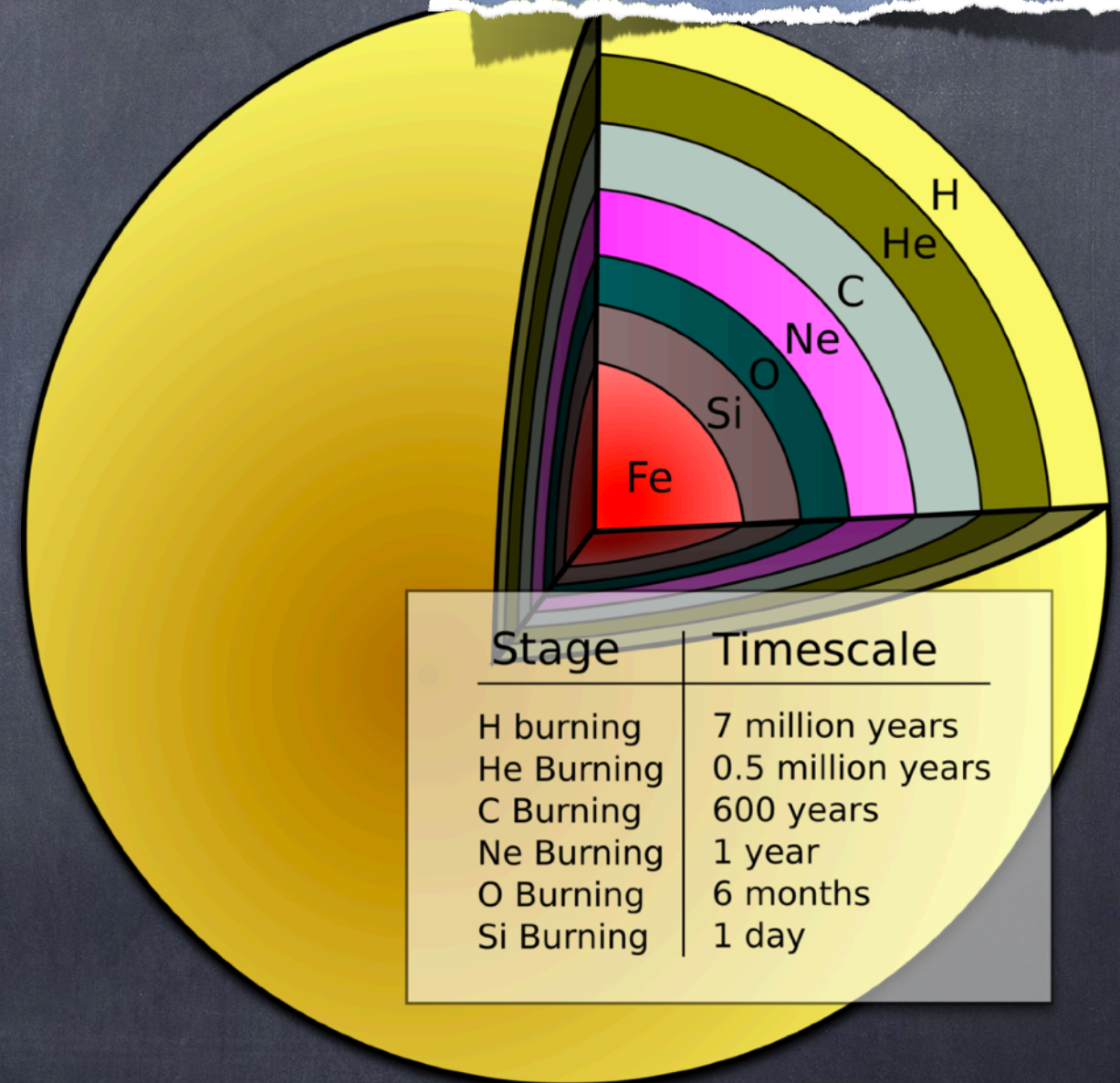
Massive stars

- The interior of massive stars are hotter, they shine much brighter and burn their Hydrogen much faster!
- Gravity is relentless!
- Once all hydrogen is exhausted, the core contracts, until it becomes hot enough to burn Helium into Carbon

The fate of massive stars

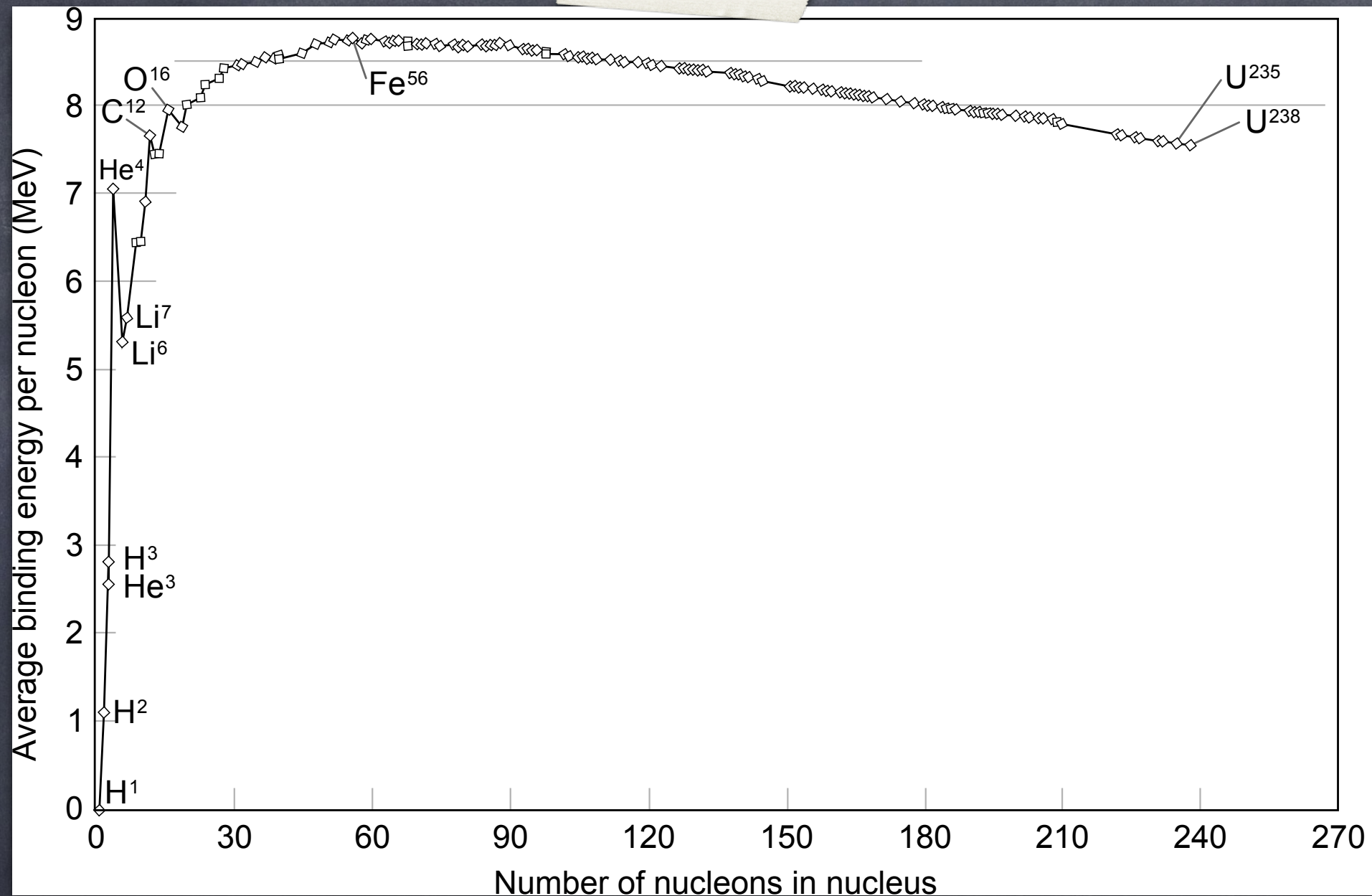
Not to scale!

- As the core keeps contracting, new nuclear reactions ignite in the center
- Eventually, the star develops an onion structure



numbers for 25 solar mass stars

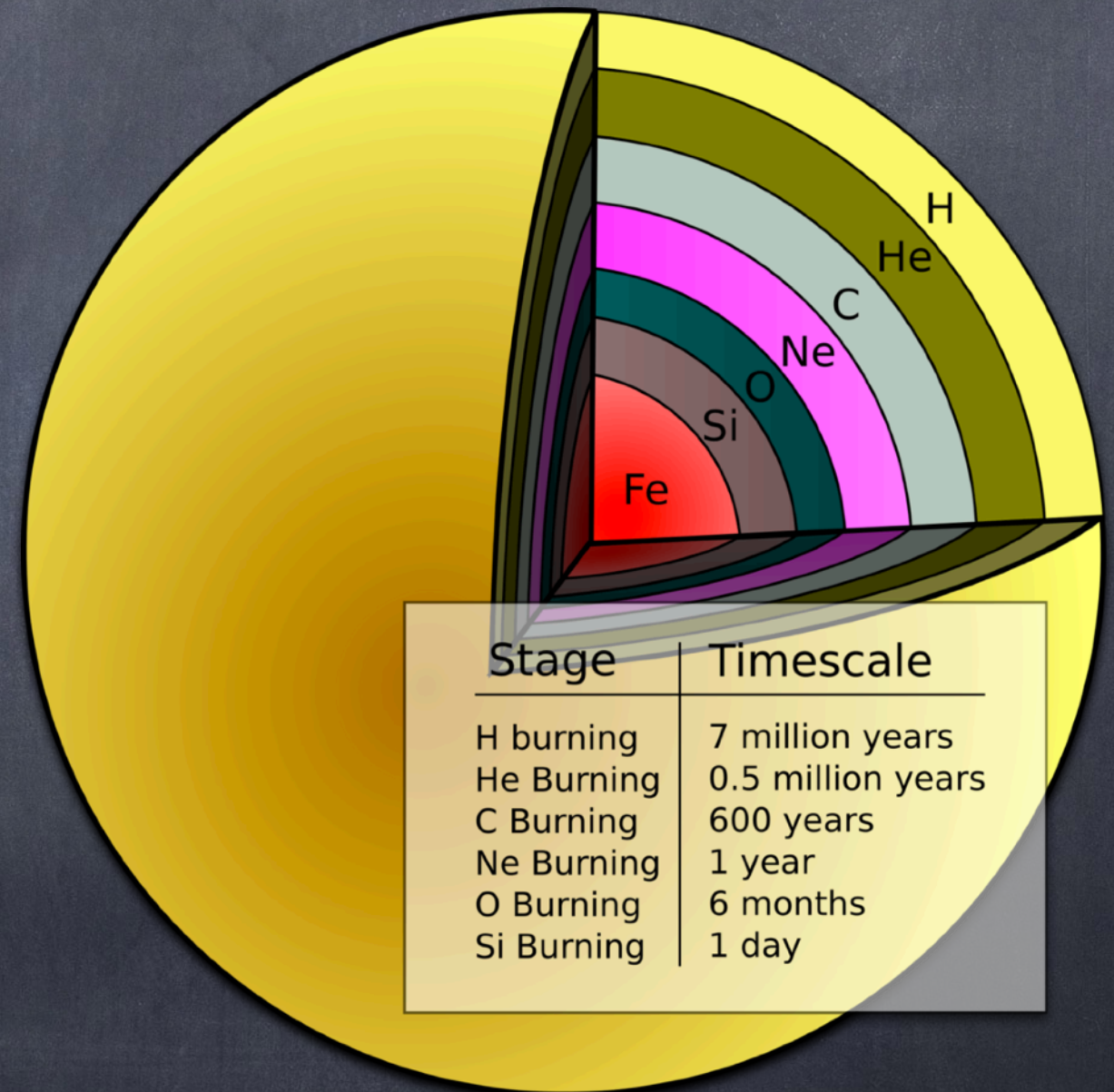
credit: Wikipedia



But Iron is the most stable nucleus!

The fate of massive stars

- Once the Iron core reaches 1.4 solar mass ("Chandrasekhar limit"), it's game over
- Gravity wins
- Free-fall collapse, reaching a quarter of the speed of light in 0.001 second



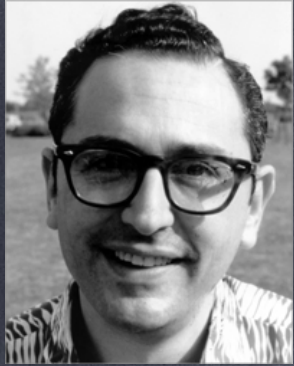
What happens next?

And can we ever be sure?

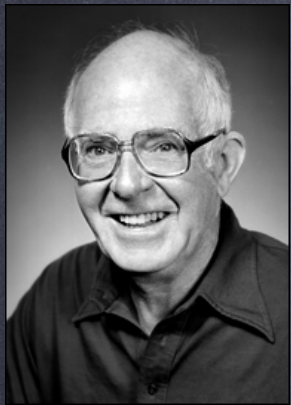
- The core of the star is hidden from us by thick outer layers
- Even the nuclear reactor in the center of the Sun is not directly visible



How big is
his heart?



- Bahcall and Davis: let us look directly in the center of the nearest star, our Sun

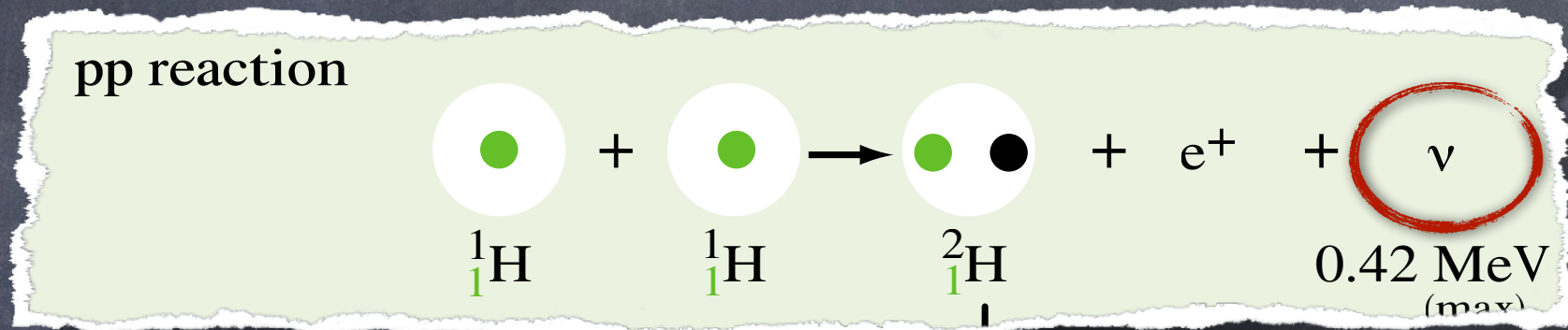


- use ghostly elementary particles called neutrinos as a thermometer for the solar core

- Original ideas by Bruno Pontecorvo (1946 and on)



Key nuclear reactions produce neutrinos

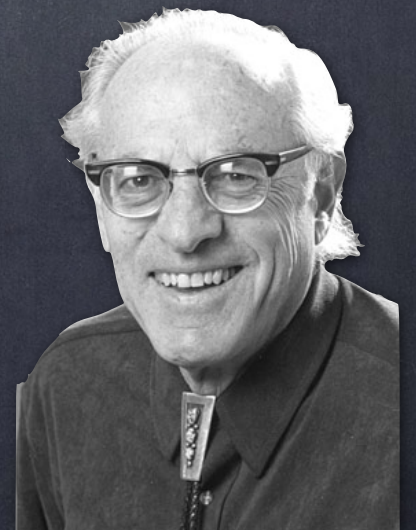


- Wolfgang Pauli in 1930 postulated a new particle with no electric charge
 - "... desperate remedy to save ... the law of conservation of energy" in radioactive decays
- Italian physicist Enrico Fermi called it a "neutrino" (a little neutron) and developed the first theory of weak interaction



Detecting neutrinos

- Extremely weakly interacting. Escape from the center of the Sun without scattering even once
- For a while, it was thought that they could never be seen
 - "There is no practically possible way of observing the neutrino." Hans Bethe (1934)
- Yet, in 1957, Los Alamos scientists Frederick Reines and Clyde Cowan proved Bethe wrong, by placing a large detector next to a nuclear reactor at Savannah River
 - "So why did we want to detect the free neutrino?" Reines later explained, "Because everybody said, you couldn't do it."

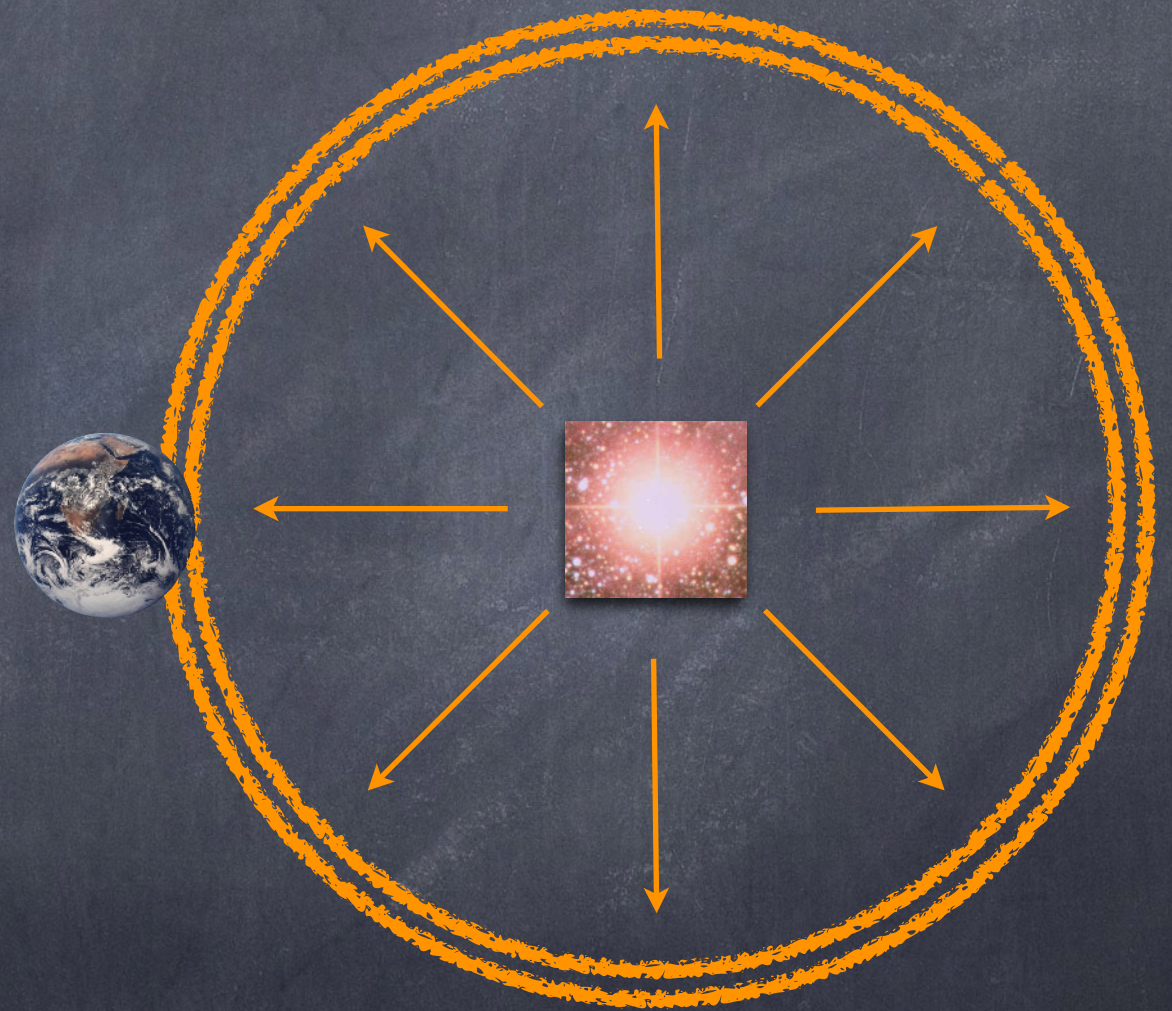


Neutrinos from the 1987 supernova?

- The Homestake experiment detected neutrinos from the core of the Sun, 8 light minutes away
- But from another galaxy, 166,000 light years away??
 - The source would have to be mind-boggling

The Great Neutrino Burst

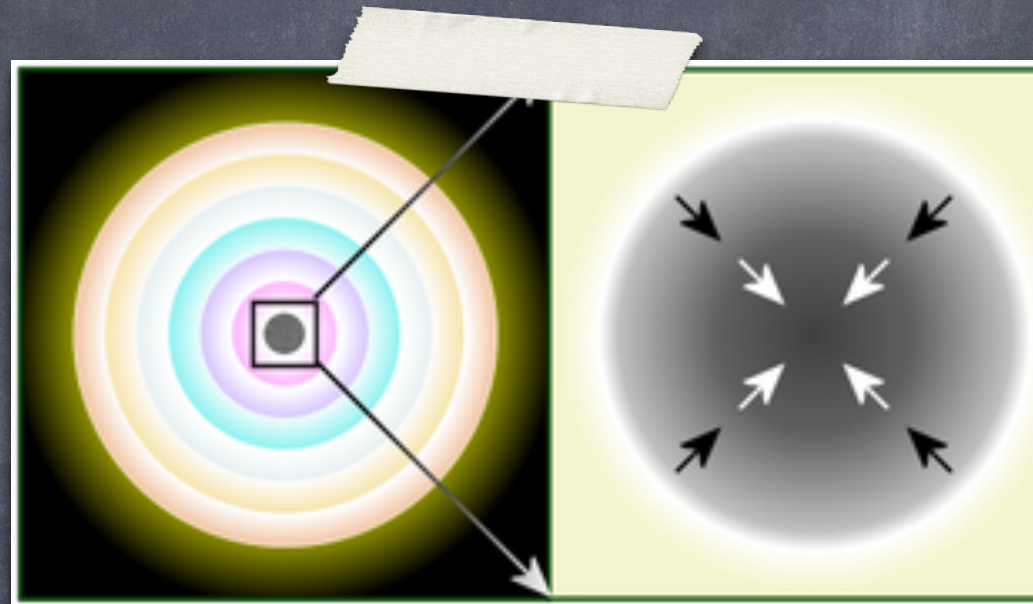
- Neutrinos emitted isotropically
- Among those that do go through the Earth, most go right through
- A typical neutrino can travel through a light-year of water without scattering



Working backwards

- From 24 neutrino events
 - knowing their probability to interact
 - and the distance to the explosion
- Infer the total energy emitted in neutrinos
- The energy of the neutrino burst is 100 times more than the visible explosion!

Core Collapse



- Gravitational binding energy of the core collapsed to nuclear densities is about 10^{27} times greater than the most powerful thermonuclear bombs tested on earth

$$E_{grav} \sim -\frac{G_N M_{\star}^2}{R}$$

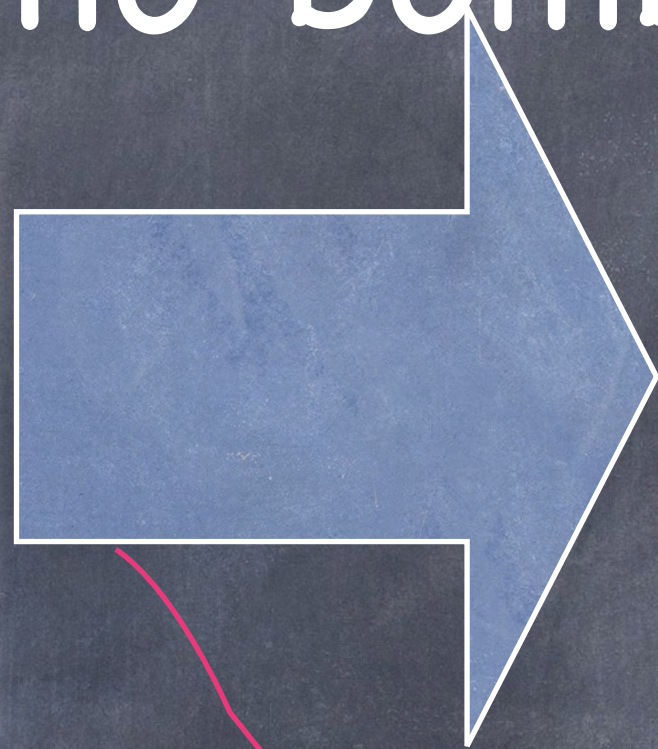
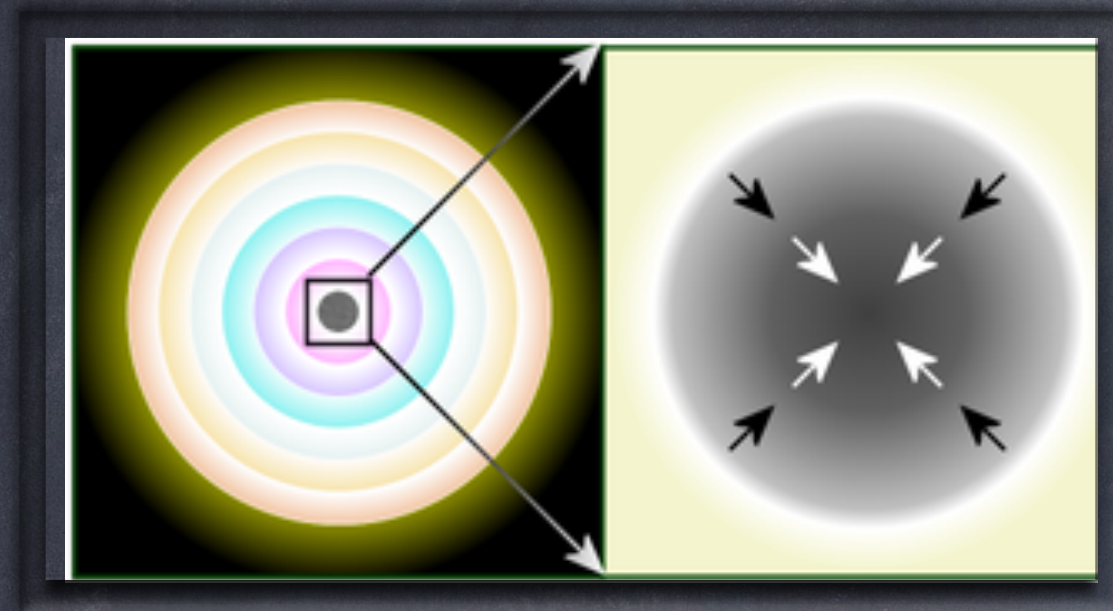
- Using $E=mc^2$ we can say that about a tenth of the mass is converted to energy

Final Neutron Star or Black Hole

How is this energy carried out?

- By the particles that have the easiest time escaping
- With densities of a trillion ounces per cubic inch, photons are hopelessly trapped
- Even neutrinos are trapped, but they diffuse out and escape in only about 10 seconds
- This is the duration of the burst we see

Gravity-powered neutrino bomb



neutrinos

visible
explosion

- The visible explosion is just a tiny perturbation in energy balance
- Yet, it's crucially important
 - makes and spreads heavy elements, including oxygen
 - Seeds formation of a new generation of stars

Thanks to neutrinos, we could peek inside the Sun and supernova 1987A



Raymond Davis
(Homestake)



Masatoshi Koshihara
(Kamiokande)

The 2002 Nobel Prize in Physics "for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"

Can we do more than peek?

- Galactic supernovae are thought to happen every 30–50 years
 - Like major earthquakes in the Bay Area
 - Some will be “Type 1a”, but there is good chance that it will again be “core-collapse”
- Are we prepared?

New gigantic detectors

- An enormous underground detectors are currently being designed for installation in Japan and in the US, in the Homestake mine
- DUNE: 40 thousand tons of pure liquid argon, advanced electronics and software
- International collaboration
- Total cost >\$1 billion

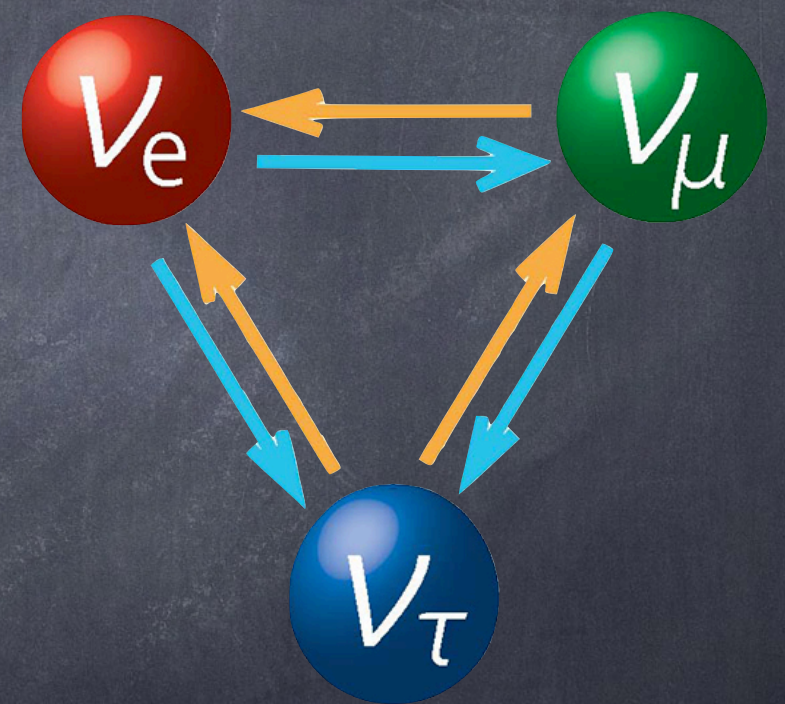
Why is this happening?

Remember about the missing solar neutrinos?

- This was not an experimental fluke
- And the theoretical prediction was exactly correct
- Neutrinos were transforming on their way out of the Sun into another type
- One of the biggest discovery in particle physics in the last three decades

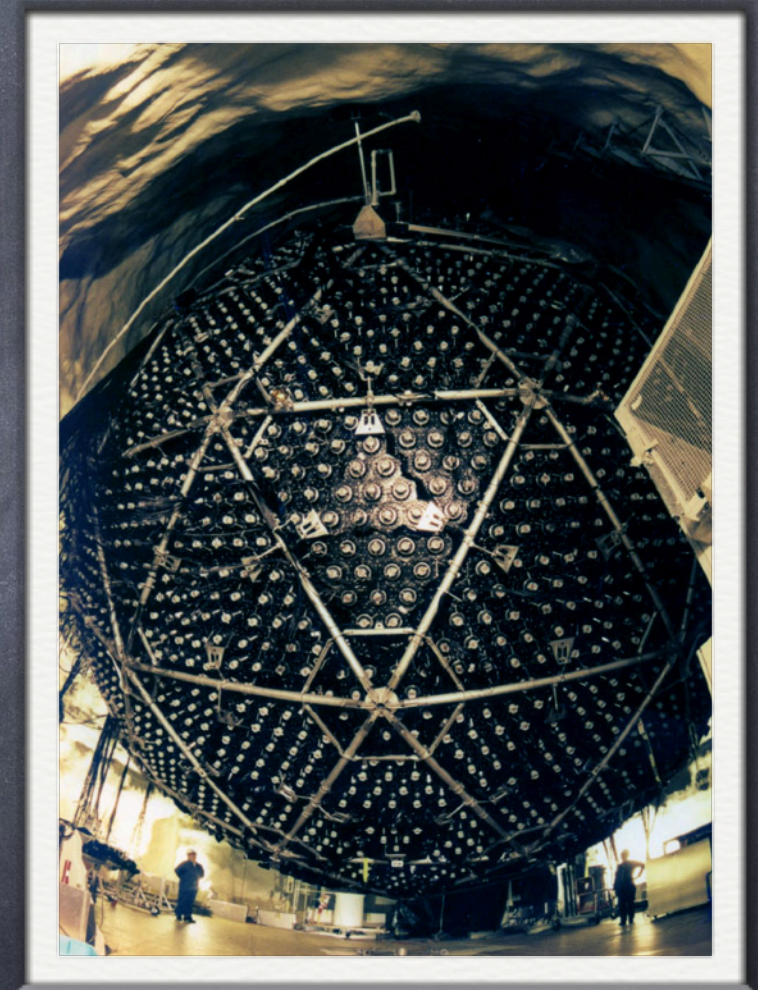
Neutrino oscillations

- Electron has two heavy siblings, Muon and Tau (Tau discovered in CA, at SLAC, Nobel Prize 1995)
- Each of them has its own partner neutrino ("FLAVOR")
- Thanks to quantum mechanics, neutrinos with tiny masses can change flavor in flight



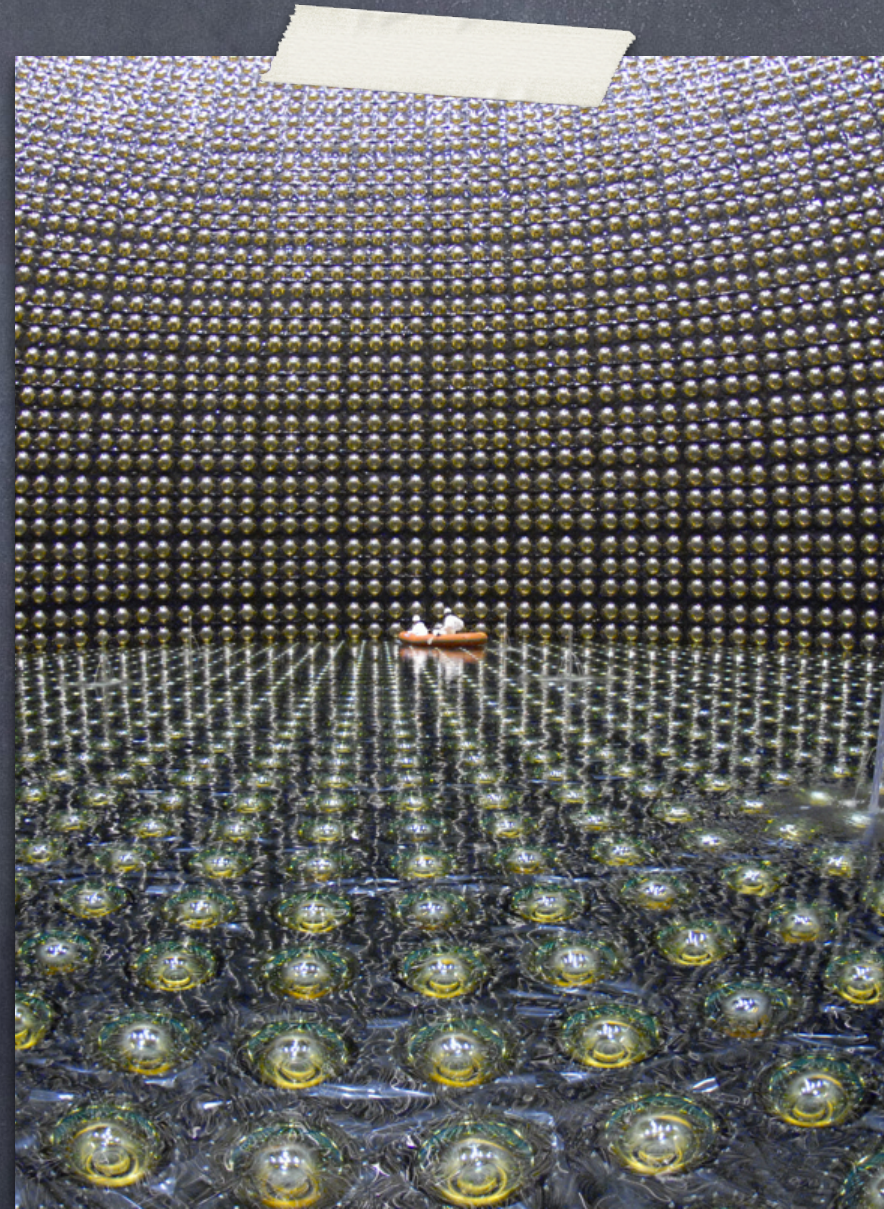
Sudbury Neutrino Experiment

- Came online in 2000
 - Different ways of measuring neutrinos from the Sun, some of which were sensitive to all 3 flavors
- Total flux is as predicted
- Davis was measuring $1/3$ of this flux because only sensitive to electron neutrinos



Oscillations also confirmed in Super-Kamiokande

- A follow-up detector to Kamiokande
- Measured neutrinos produced in the Earth's atmosphere
- Measured flux of muon neutrinos depends on the distance neutrinos traveled
 - Up/down asymmetry!



2015 Nobel Prize in Physics



Art McDonald
(SNO)

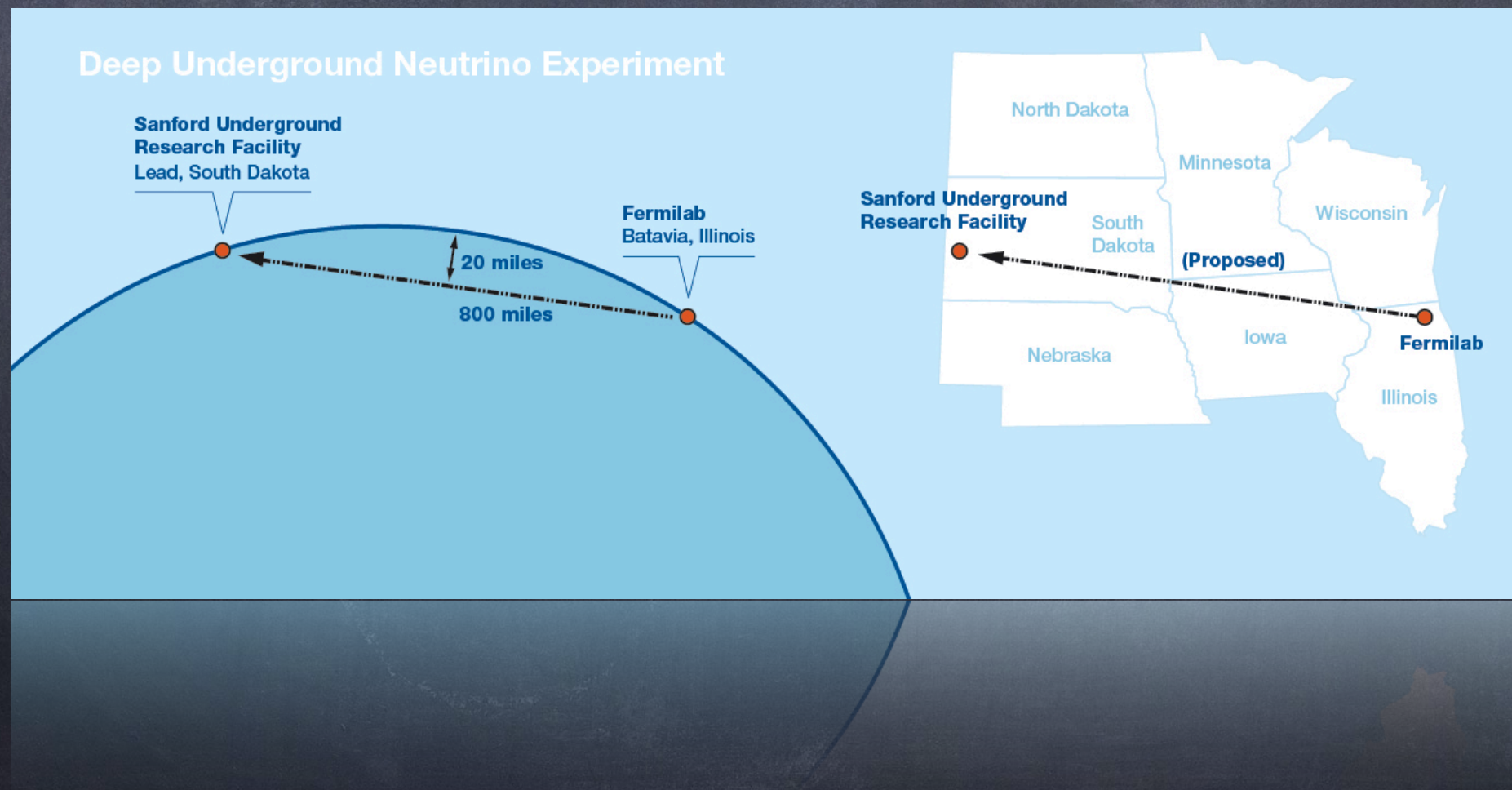


Takaaki Kajita
(Super-Kamiokande)

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

DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

- A powerful beam of neutrinos will be created in Illinois and sent to South Dakota
- Precision oscillation studies + proton decay



Measuring oscillations while waiting for the supernova

- Many thousands of supernova neutrinos will be seen
- What will we learn?
 - How the explosion develops, second by second
 - How matter behaves when compressed to densities unachievable in the lab
 - How neutrinos change flavor in these conditions
 - Whether there are additional particles, with interactions smaller than neutrinos

Science gold mine

- Sometime in the next several decades, for 10 seconds there will be an enormous burst of neutrinos with no warning
- We must figure out now how to be ready for this and build the detectors accordingly
- See the talk by Inés about detection

John Bahcall, 1934–2005

