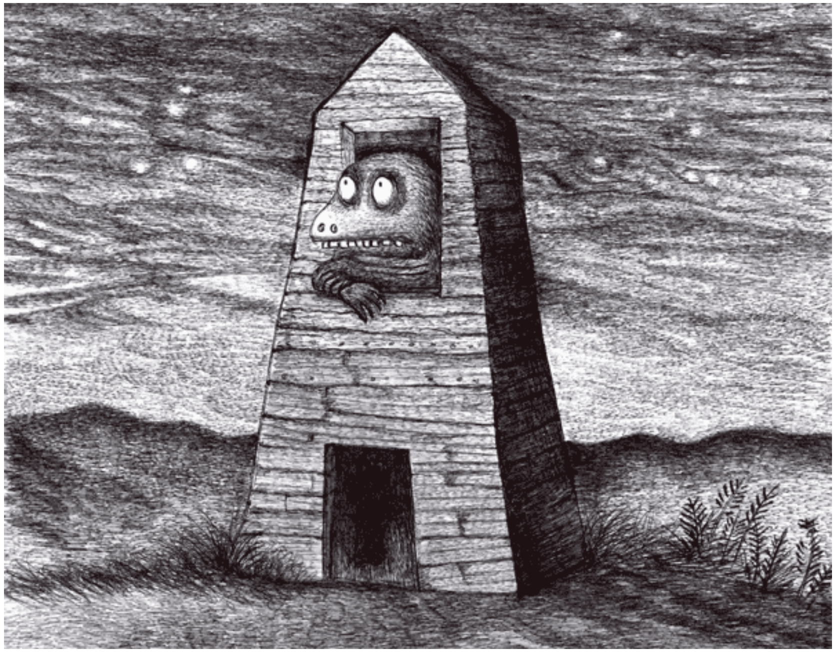
# Supernova Physics with Neutrinos in Very Large Detectors



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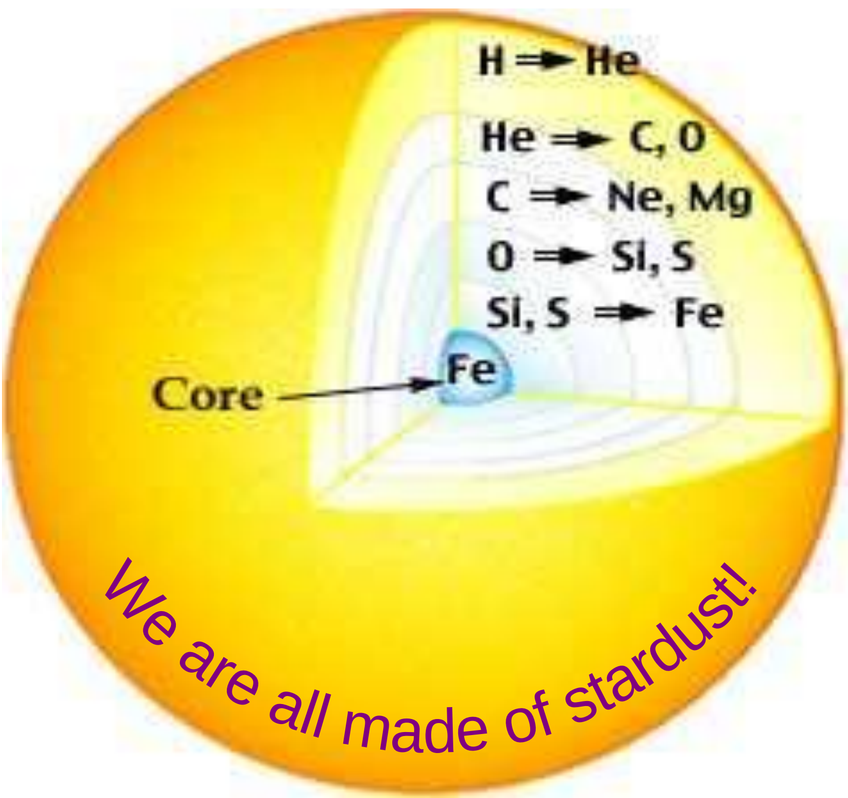
2nd EU Workshop on Water Cherenkov Experiments for Precision Physics (WCD-2025)

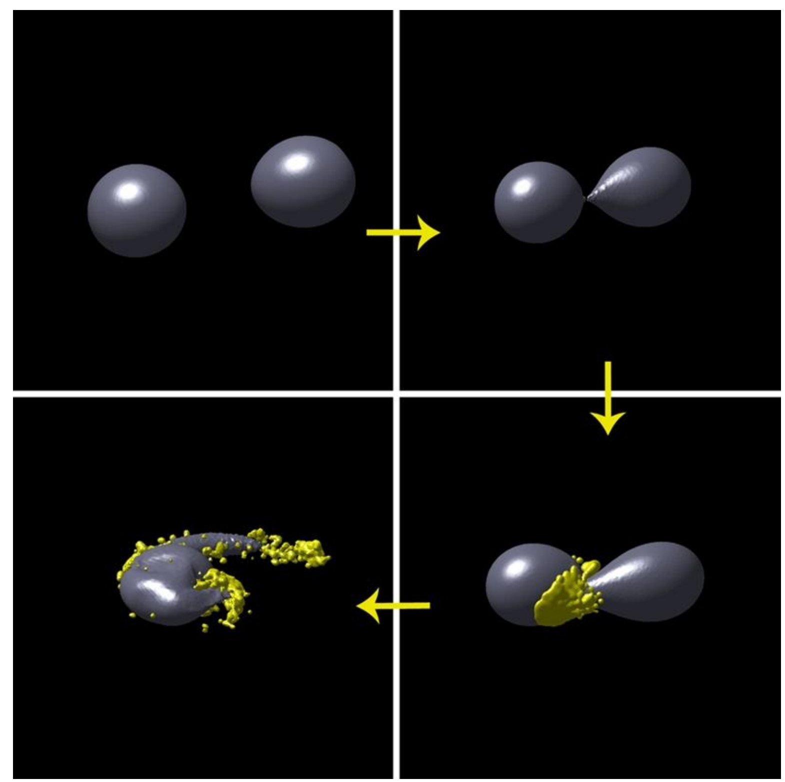
Kraków, Poland September 19, 2025

One of humanity's core questions is:
***Why do we exist at all?***

To understand this, we <u>must</u> understand supernovas.

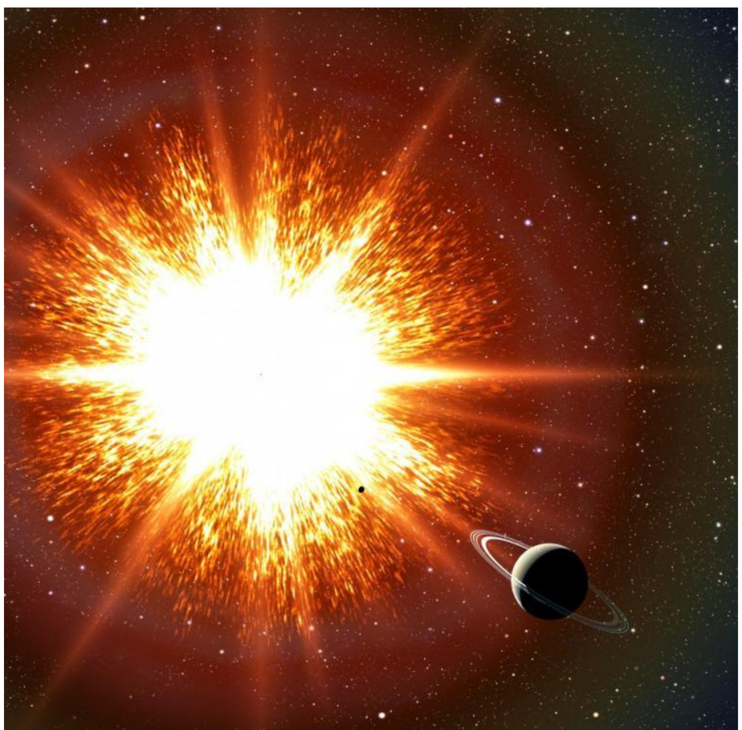
Except for hydrogen and helium (and a bit of lithium), all of the elements of nature – and life – are the products of burning (up through iron) and exploding (> iron) stars.

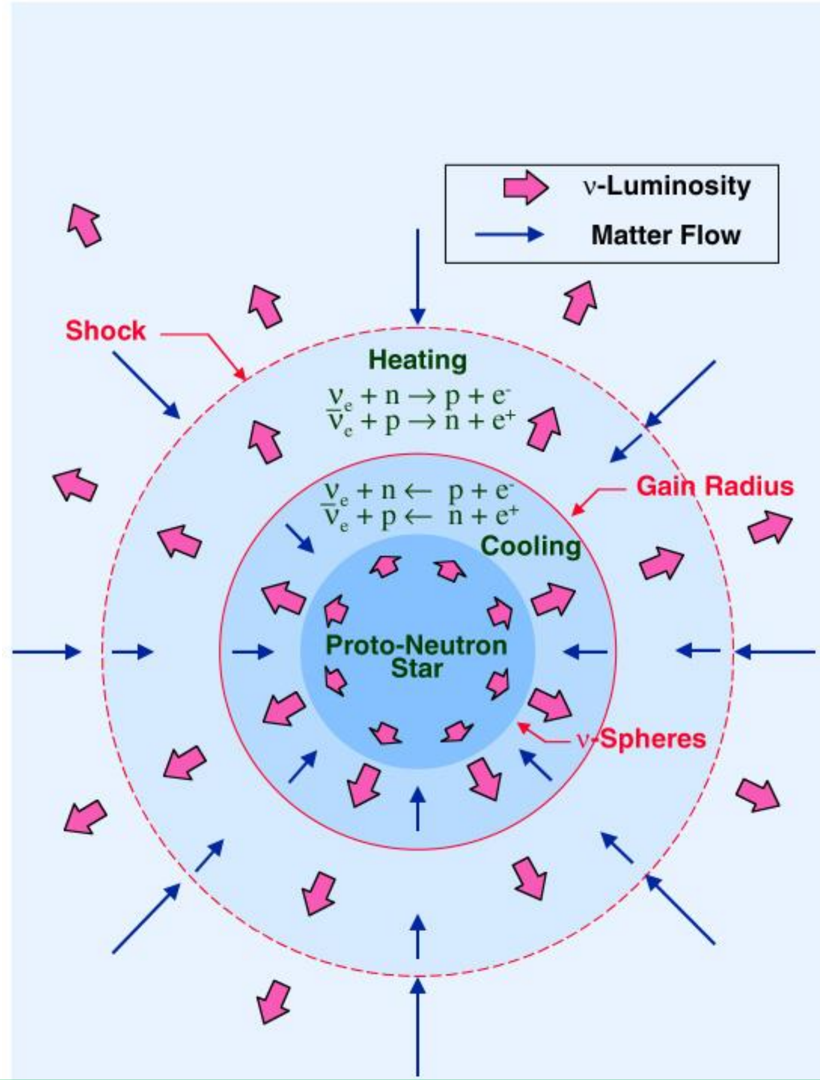


A core-collapse supernova is a nearly perfect "neutrino bomb".

Within ten seconds of collapse it releases >98% of its huge energy (equal to **$10^{12}$** hydrogen bombs exploding per second since the beginning of the universe!) as neutrinos.






Neutrinos, and possibly gravitational waves, provide the only windows into core collapses' inner dynamics.

# A long time ago, in a (neighbor) galaxy far, far away…

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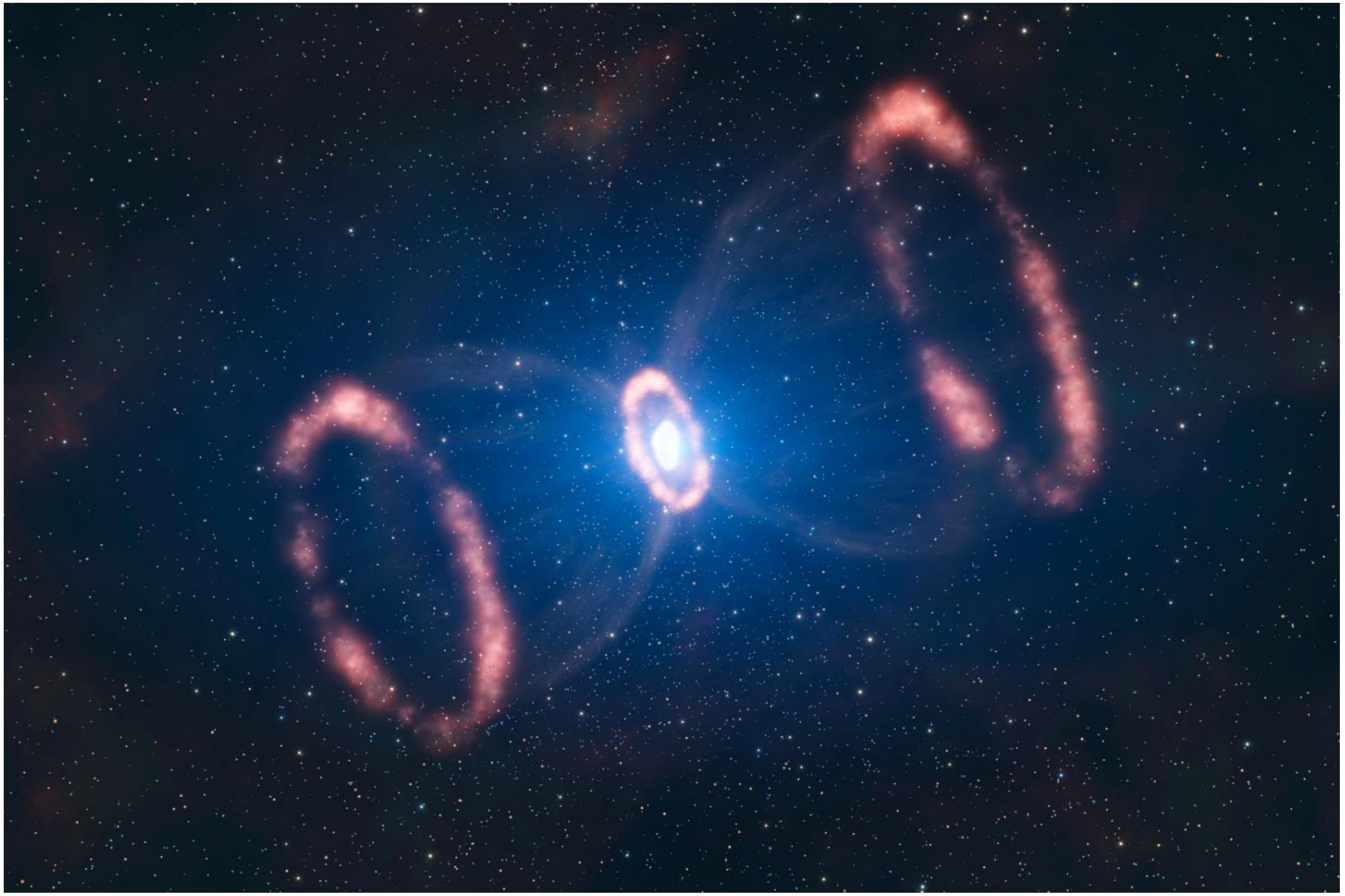
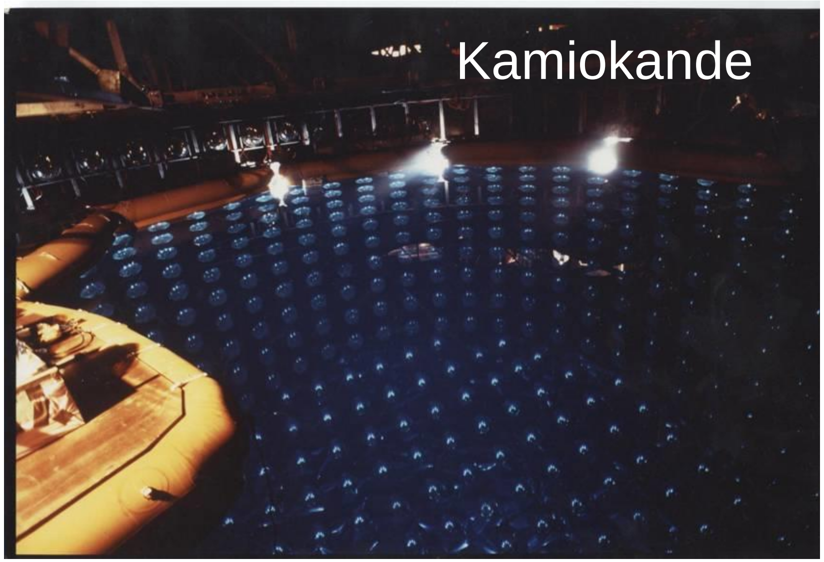
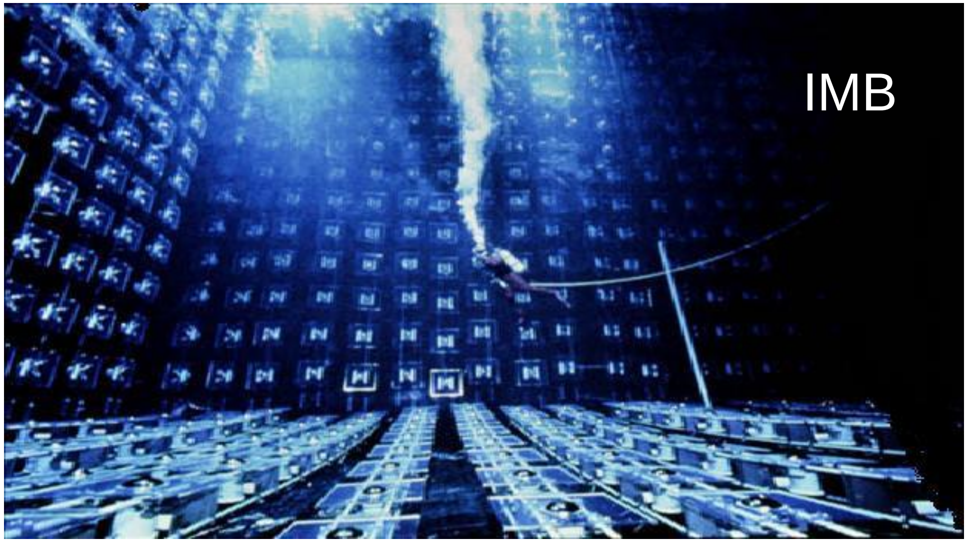
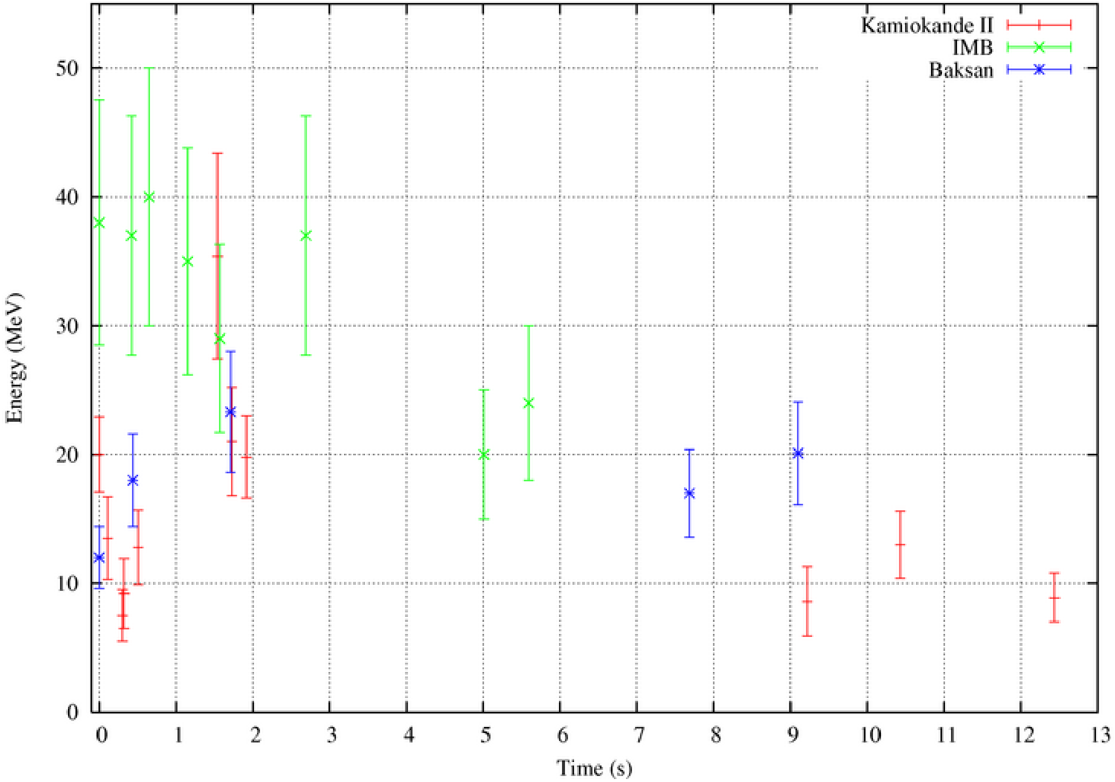
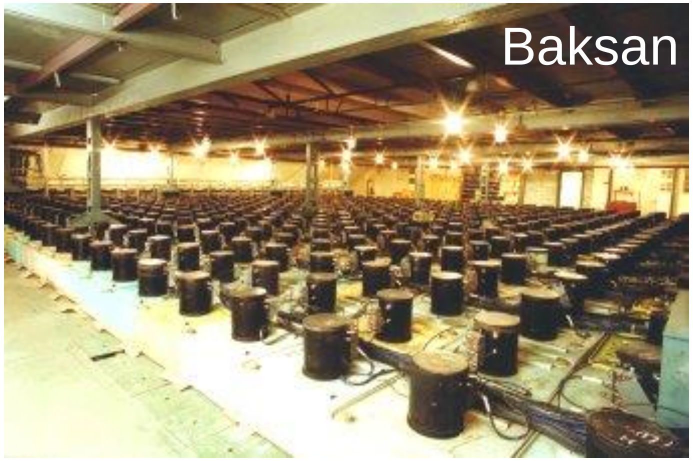


The explosion happened 170,000 years ago in the Large Magellanic Cloud, but we finally got the news (and $\nu$'s) on February 23$^{rd}$, 1987.
This became known as SN1987A.



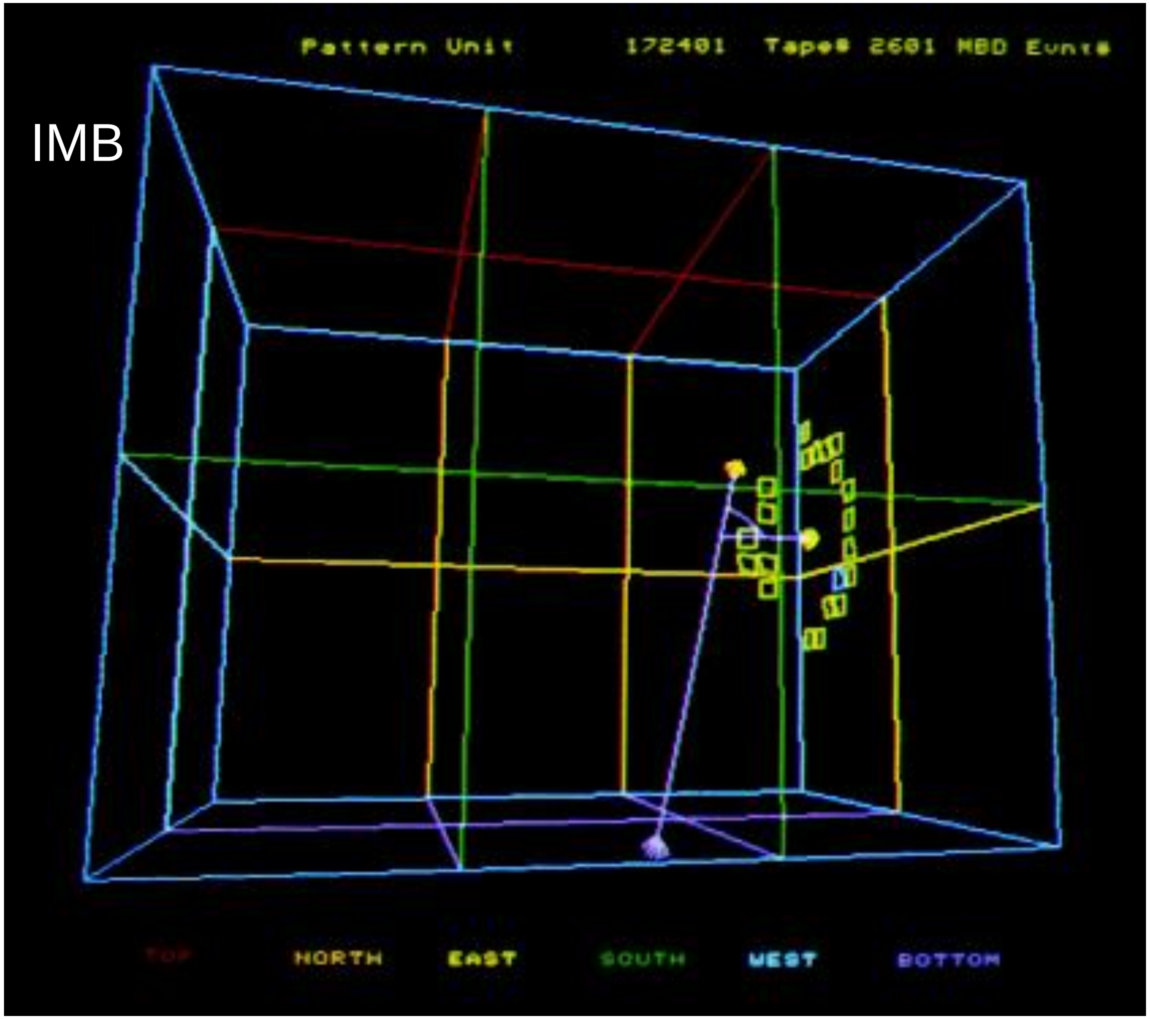



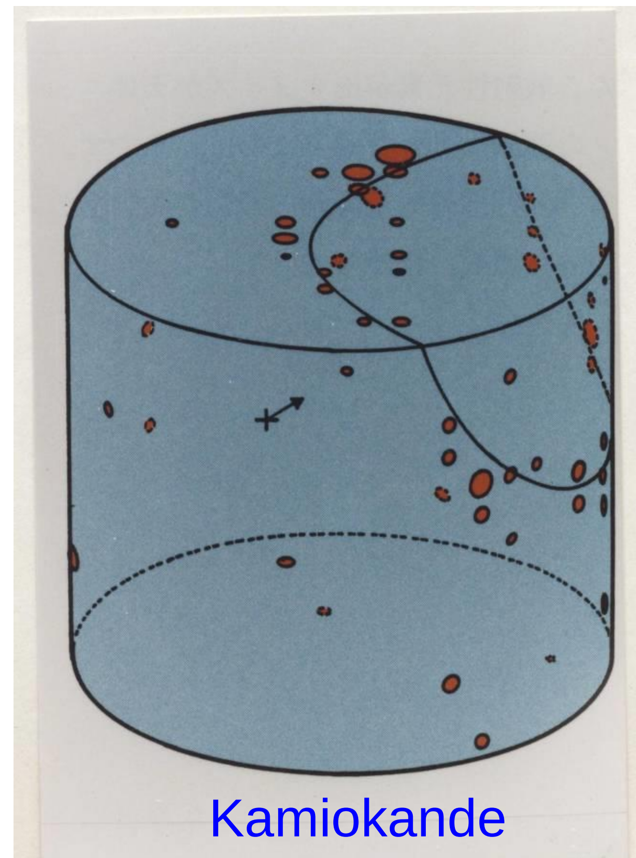



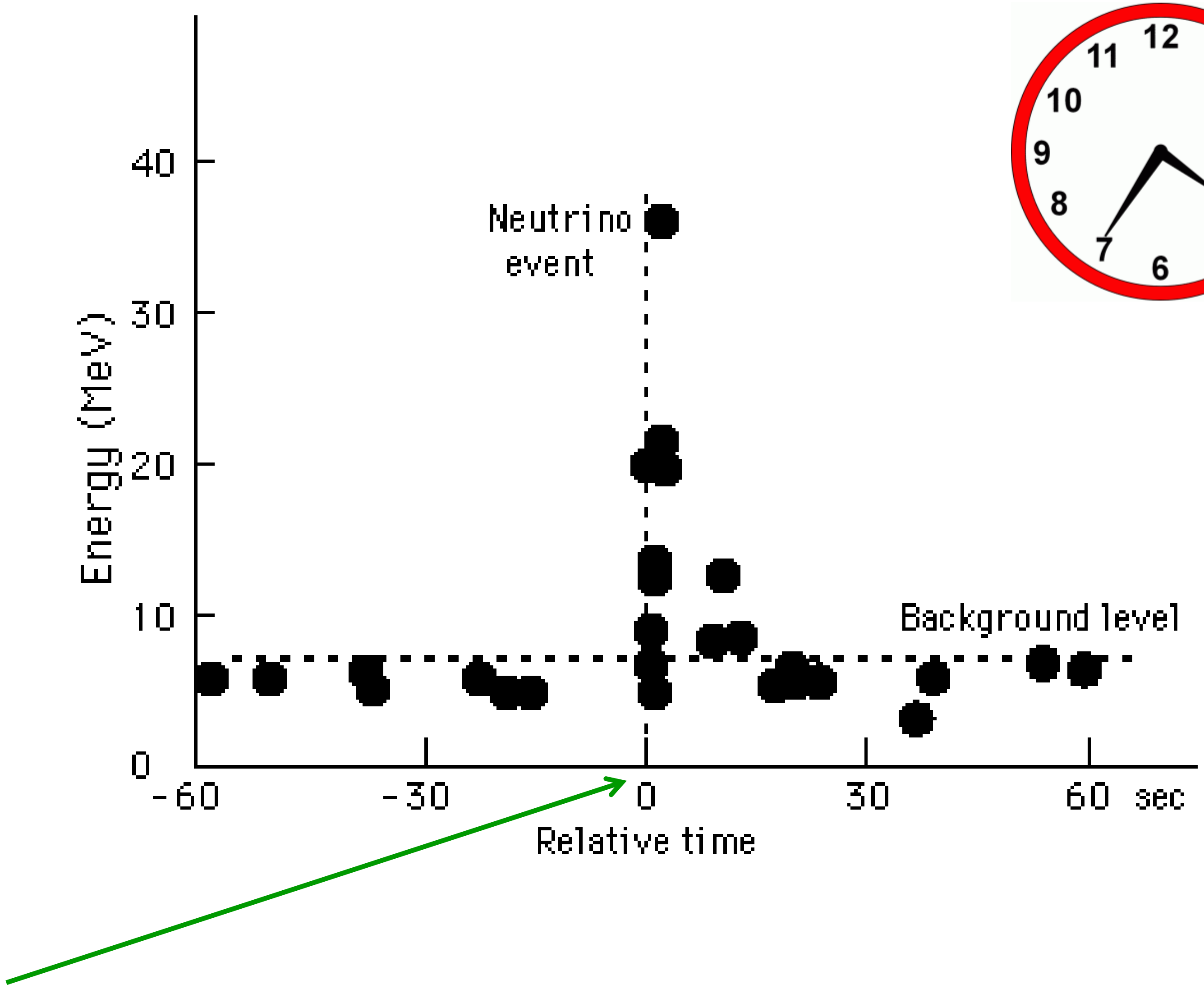

*These 24 events from SN1987A remain the entire set of detected supernova neutrinos.*

Event displays of actual SN1987A neutrino events!

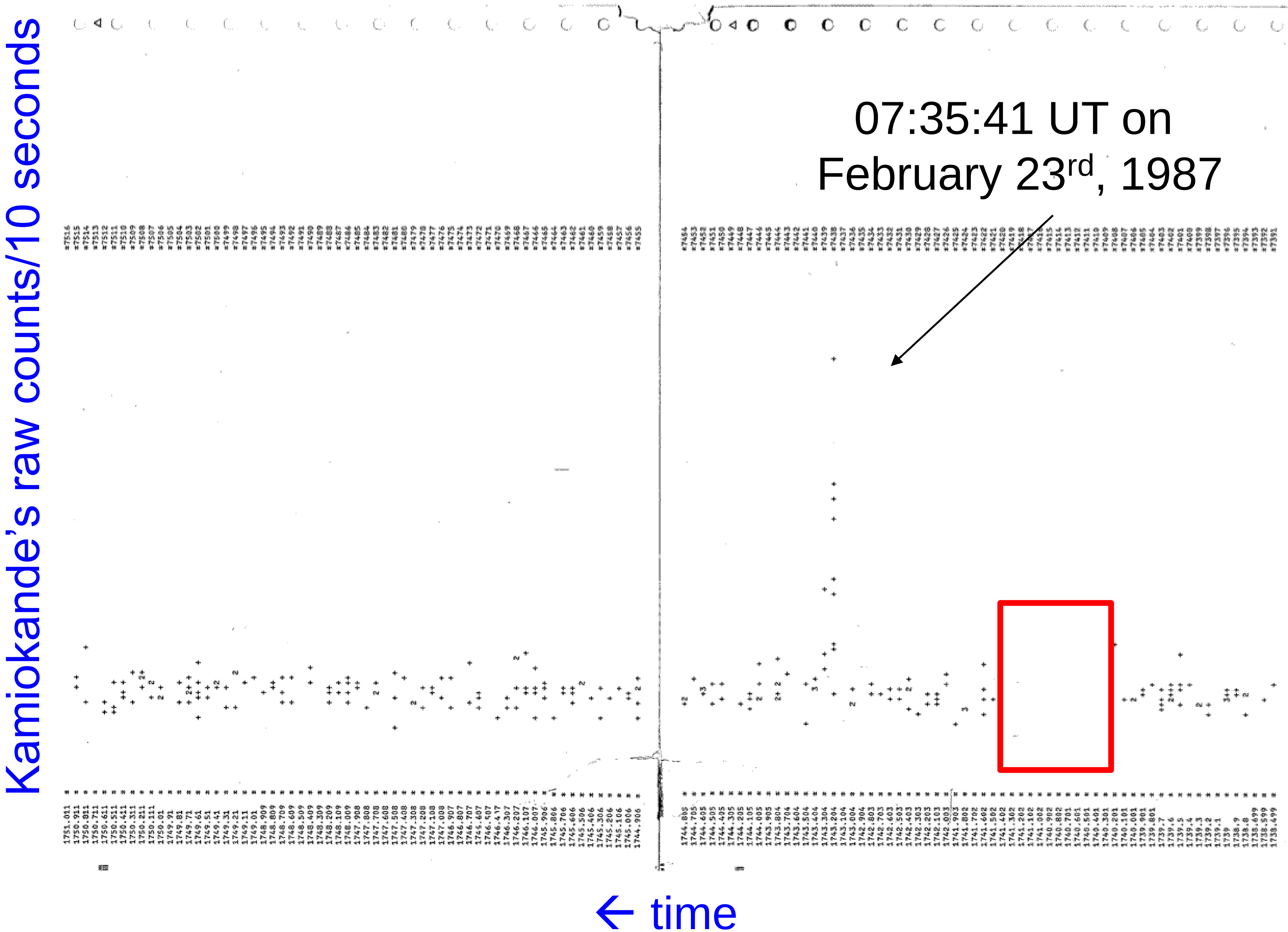


# Kamiokande's Burst Time Structure




16:35:41 JST on February 23rd, 1987


Kamiokande's raw counts/10 seconds
07:35:41 UT on February 23rd, 1987
← time

Currently, Super-Kamiokande is ready (~99% SN uptime) and waiting to detect supernova neutrinos from an explosion anywhere in our galaxy.

→ **We will let the world know the light is on its way.** ←

In order to do physics with SN neutrinos, a detector needs to be both big, and sensitive.


Super-K/Hyper-K (individual event reconstruction)

neutrino burst time structure, energy spectrum, neutrino direction, primarily sensitive to $\overline{\nu}_e$

JUNO (individual event reconstruction)

neutrino burst time structure, energy spectrum, primarily sensitive to $\overline{\nu}_e$

DUNE (individual event reconstruction(?))

neutrino burst time structure, energy spectrum, neutrino direction, primarily sensitive to $\nu_e$

$[\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*]$

IceCube/KM3NeT/P-ONE/TRIDENT/BAIKAL-GVD (non-statistical fluctuation of PMT dark rate)

neutrino burst time structure, average energy

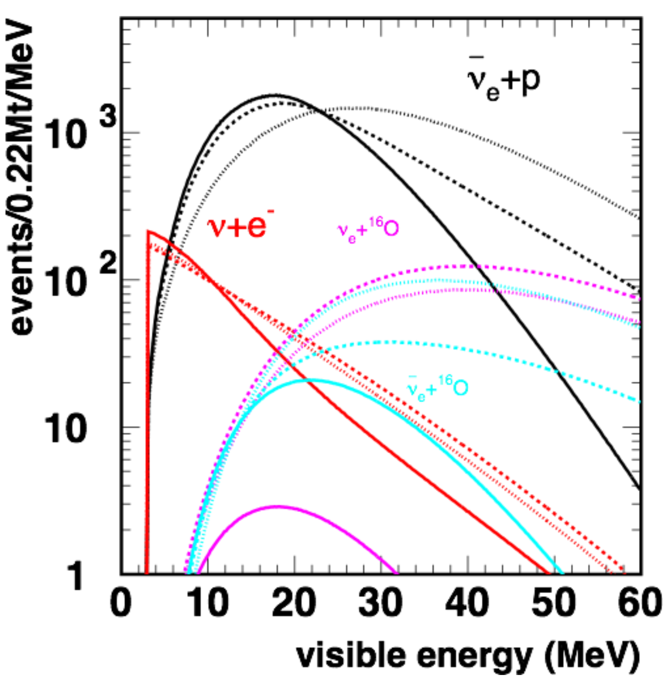
***Hyper-K will become the world's dominant galactic supernova neutrino detector once it turns on!***

# Supernova ν's in Hyper-K

## Main detection channels

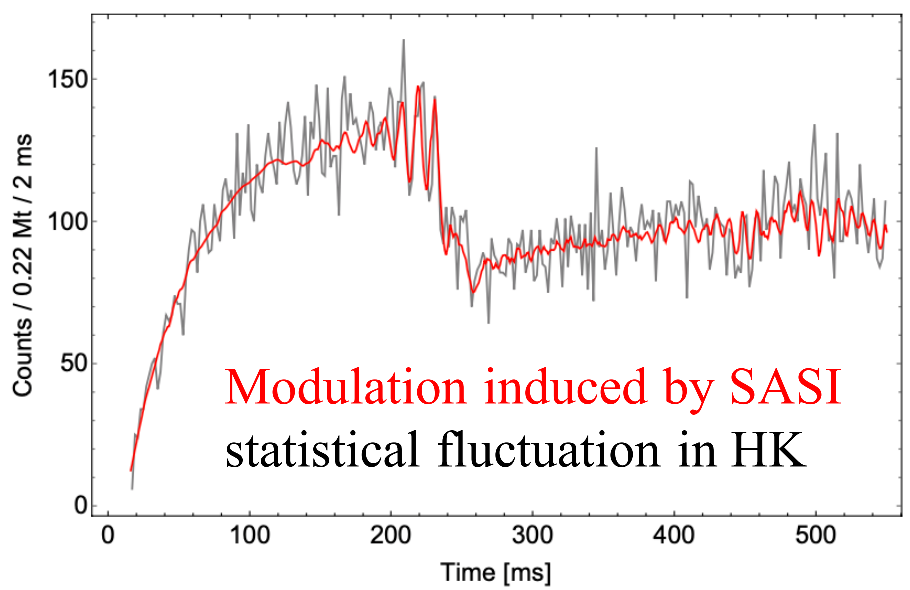
| | | |
|---|---|---|
| Inverse beta decay | $\bar{\nu}_e + p \rightarrow e^+ + n$ | E > 1.8 MeV |
| ν-e scattering | $\nu + e^- \rightarrow \nu + e^-$ | |
| $\nu_e$ $^{16}$O CC | $\nu_e + {}^{16}\mathrm{O} \rightarrow e^- + {}^{16}\mathrm{F}^{(*)}$ | E > 15 MeV |
| $\bar{\nu}_e$ $^{16}$O CC | $\bar{\nu}_e + {}^{16}\mathrm{O} \rightarrow e^+ + {}^{16}\mathrm{N}^{(*)}$ | E > 11 MeV |

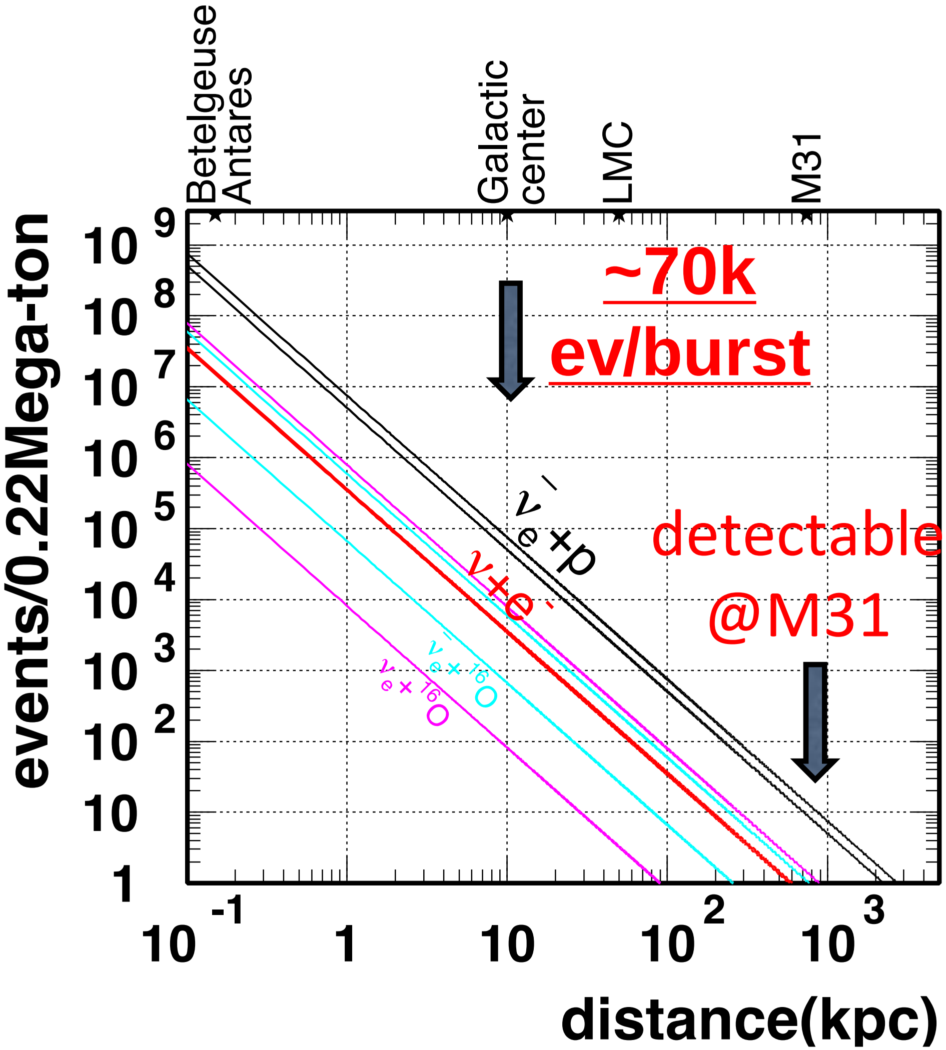
Total energy spectrum

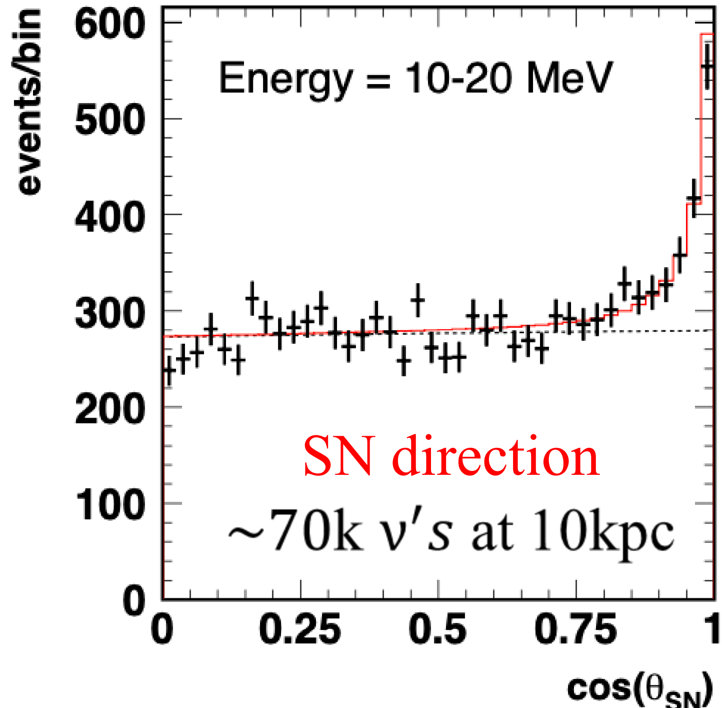


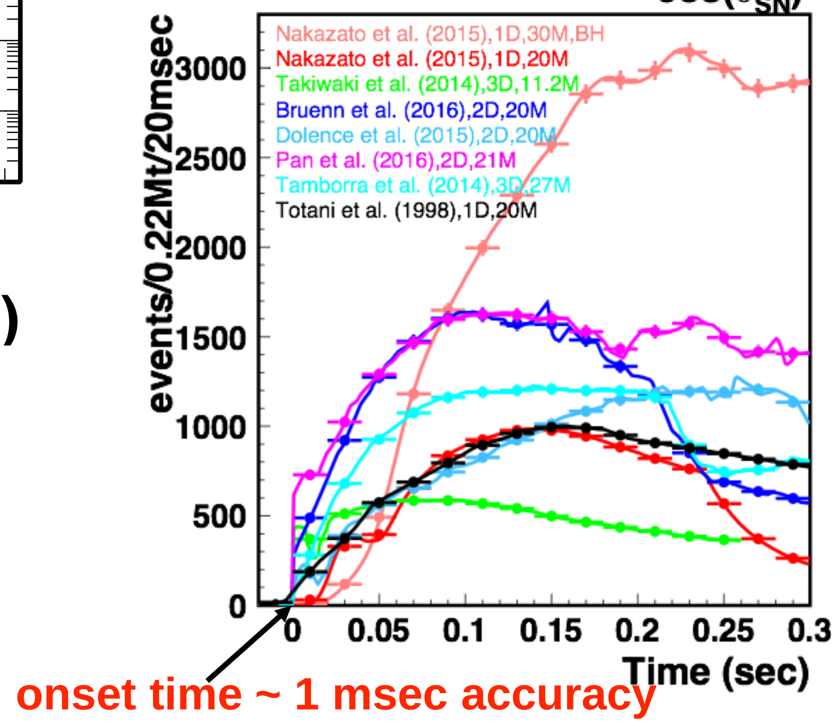

Time modulation of event rate

galactic supernova at 10 kpc (our $r_{gal}$= 8 kpc)





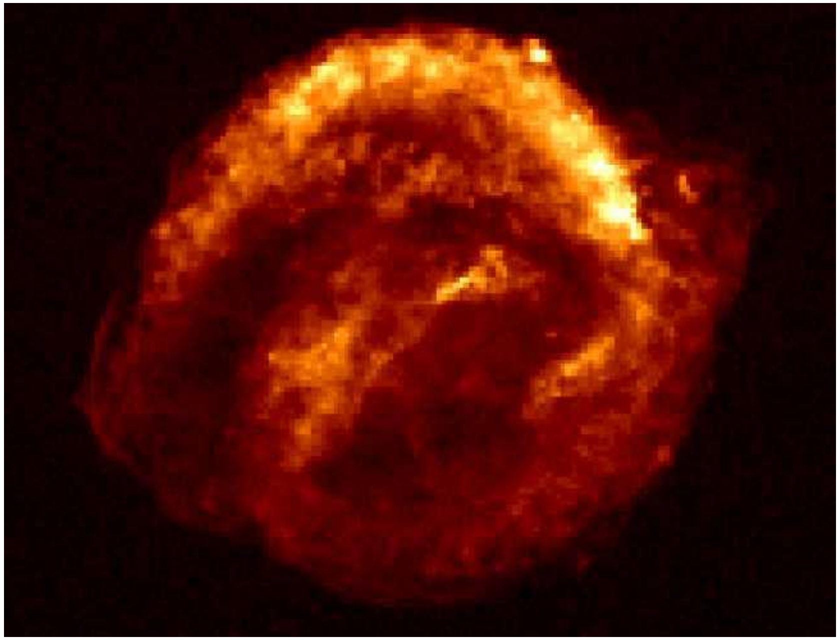



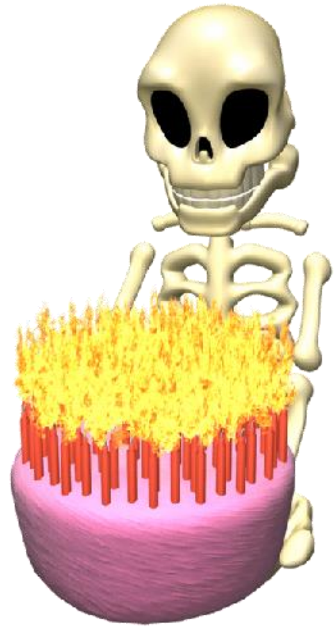




## ~70k events/burst in HK

- explosion mechanism
- BH/NS formation
- alert with ~1° pointing

# We would very much like to collect some more supernova neutrinos!





But it has already been over a third of a century since SN1987A, and exactly <u>420 years, 11 months, and 10 days</u> since a supernova was last definitely observed within our own galaxy.

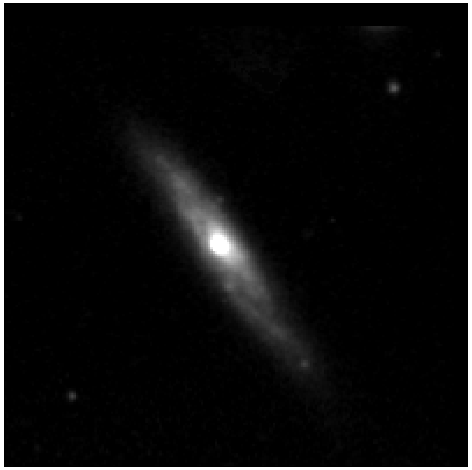
"Observing the Next Galactic Supernova", S. M. Adams, C. S. Kochanek, J. F. Beacom, M. R. Vagins, and K. Z. Stanek, *Astrophys.J.* **778**, 164 (2013)

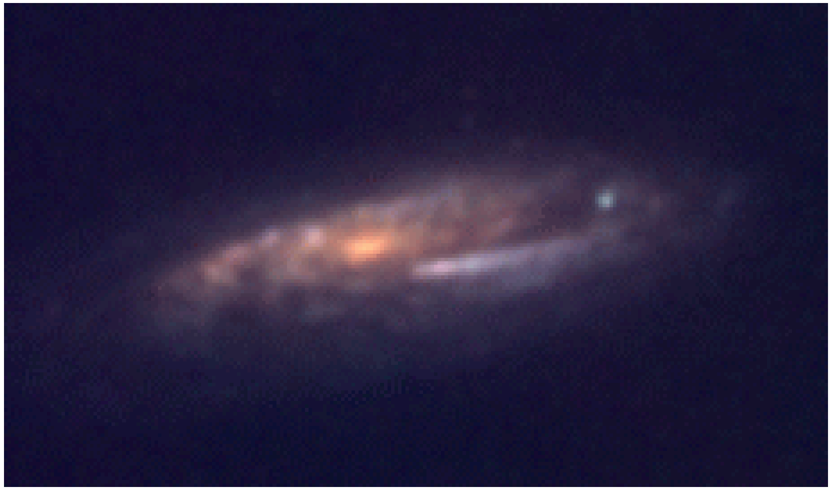
**Yes, it's been a long, cold winter for SN neutrinos…**
**but there is hope!**


So, how can we be certain to see more supernova neutrinos without having to wait too long?

# This is not the typical view of a supernova! Which, of course… is good.

Yes, nearby supernova explosions may be rare, but supernova explosions are extremely common.





Here's how most supernovas look to us on Earth (video is looped).

There is about *one SN explosion per second* in the universe as a whole.

These produce the as-yet unobserved diffuse supernova neutrino background [DSNB].

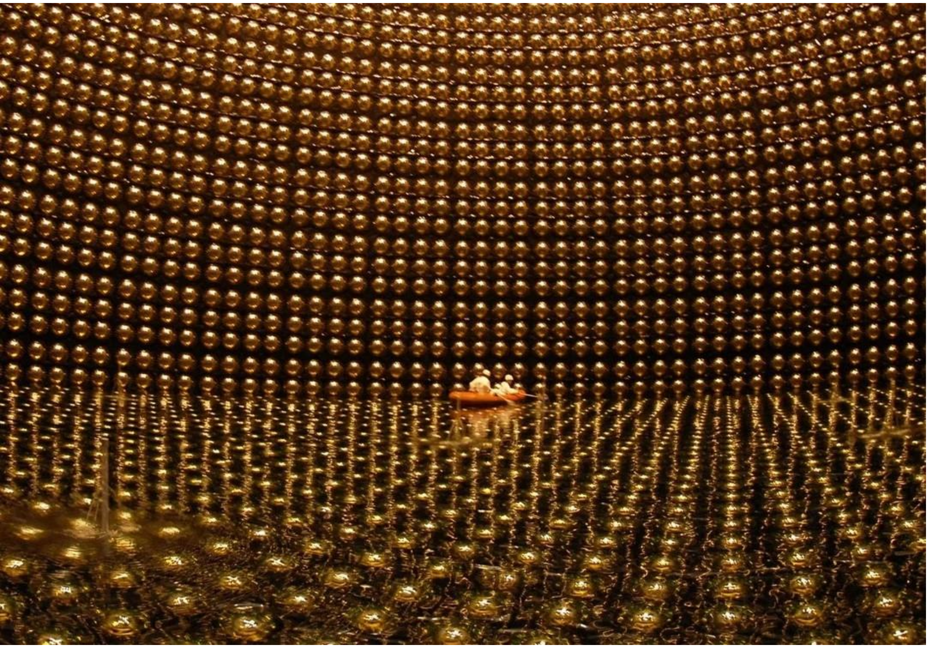
Adding gadolinium to SK should make the DSNB visible, *up to several neutrino events per year!*

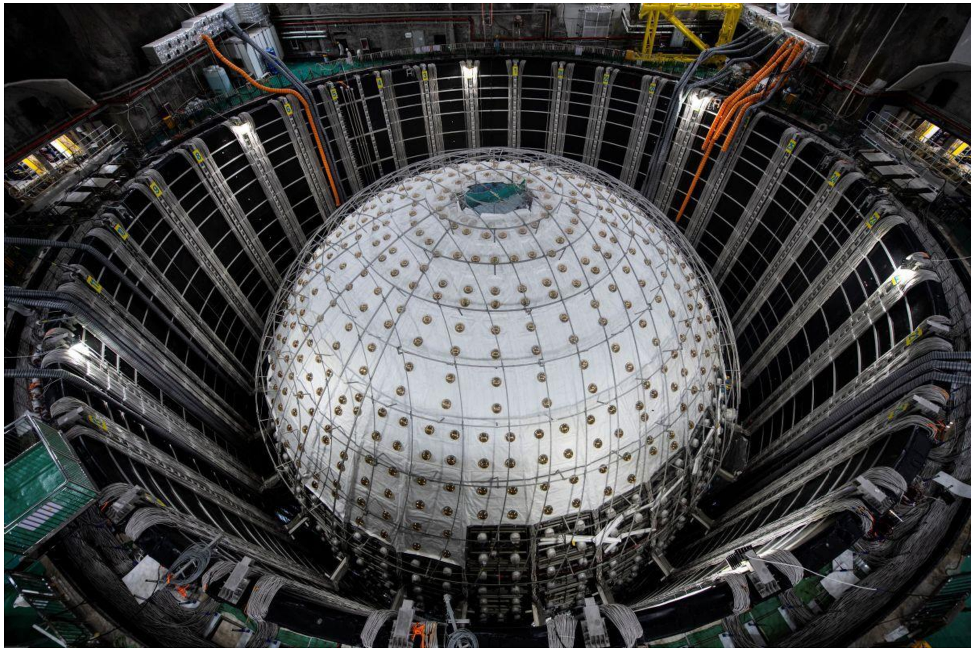
[see my previous talk at this meeting (on Wednesday) and Rudolph Rogly's talk (next)]

In early 2022, a German phenomenologist, Michael Wurm, a Chinese JUNO collaborator, Yu-Feng Li, and I published a paper in *Universe* evaluating the prospects of DSNB discovery in the coming decade:

> "Prospects for the Detection of the Diffuse Supernova Neutrino Background with the Experiments SK-Gd and JUNO", Yu-Feng Li, Mark Vagins, and Michael Wurm, Universe **8.3** (2022), p. 181

Until gadolinium goes into Hyper-K, we quickly realized that the only relevant experiments on this near-future time scale are going to be SK-Gd and JUNO.





[Our published figure and DSNB reference model from 2022] (note JUNO start date)

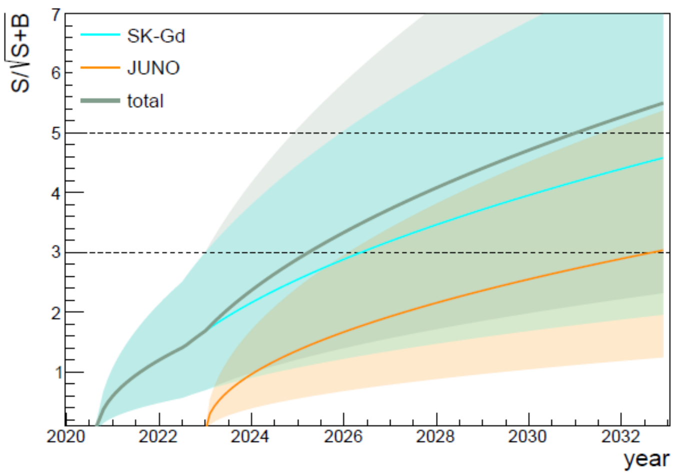
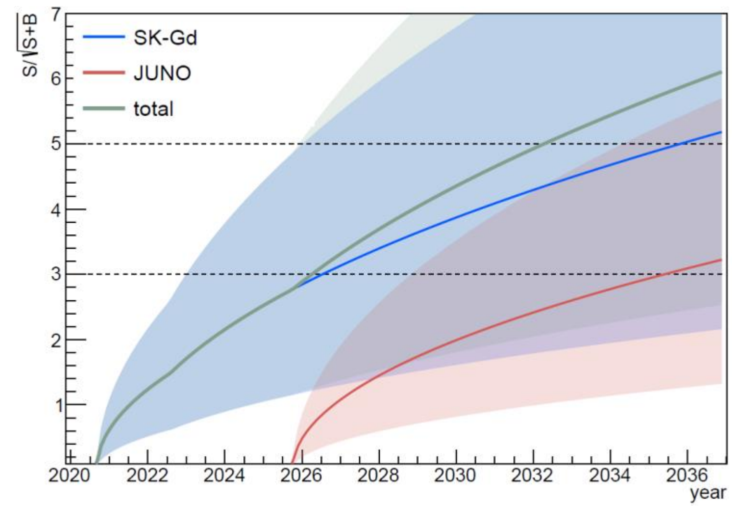



FIG. 6: Statistical significance of a DSNB signal rate $S$ excess over background rate $B$ based on the figure of merit $S/\sqrt{S+B}$. Individually, both experiments can reach a $3\sigma$ significance level over about 10 years of measuring. The combined sensitivity reaches $5\sigma$ in the early 2030s.




[Updated figure from May 2025]

TABLE I: Parameters of the DSNB *reference model* based on current most-likely predictions [8]. The parameter ranges adopted to reflect the uncertainties of these predictions are indicated in brackets.

| Parameter | Successful SNe | | Failed SNe | |
|---|---|---|---|---|
| Total energy $E_{\text{total}}$ [erg] | $5.0 \times 10^{52}$ | | $8.6 \times 10^{52}$ | |
| Mean energy $\langle E_\nu \rangle$ [MeV] | 15 | (12 .. 18) | 18.72 | |
| Relative fraction $f_{\text{BH}}$ | 0.73 | $(1 - f_{\text{BH}})$ | 0.27 | (0 .. 0.4) |
| Present SN rate $R_{\text{SN}}(0)$ | $1.0 \times 10^{-4}$ | $(0.5 .. 2.0) \times 10^{-4}$ | | $\text{yr}^{-1}\,\text{Mpc}^{-3}$ |

→ **A 5-sigma discovery of the DSNB is within reach with continued running of SK-Gd at its current loading!**

Since 1987 we have been dreaming of seeing more supernova neutrinos. All we have to do now is **keep running SK-Gd for several more years beyond the start of Hyper-Kamiokande, and we should have convincingly discovered the DSNB flux!**

But of course, nothing is truly guaranteed in life or in physics, so what if we do not see convincing evidence for the DSNB flux?


This is a very rare case in science: if we see the DSNB flux, then great, we have found a "new" source of neutrinos to study. Please note that the study of all previous neutrino sources, be they nuclear reactor, particle accelerator, supernova burst, the Sun, the atmosphere, cosmic neutrinos, or geoneutrinos, have resulted in a Nobel Prize, a Breakthrough Prize, or at least the cover of *Nature* or *Science*. Every source was important and taught us new things about the universe.

But if we see *nothing*, then we have a new mystery...

✓ We already know from SN1987A that core collapse supernova explosions make about the expected number of neutrinos.

✓ We also know the approximate rate of SN explosions in the universe, based on increasingly more accurate astronomical surveys.

Therefore, if there is no detectable DSNB signal in SK-Gd, we have found a smoking gun for new physics! *What is happening to these ancient neutrinos on their way to Earth?*

→ This could be called the *"Supernova Neutrino Problem".* ←

**So, there is really no way to lose here, *except* by turning off SK-Gd before Hyper-K has gadolinium in it!**