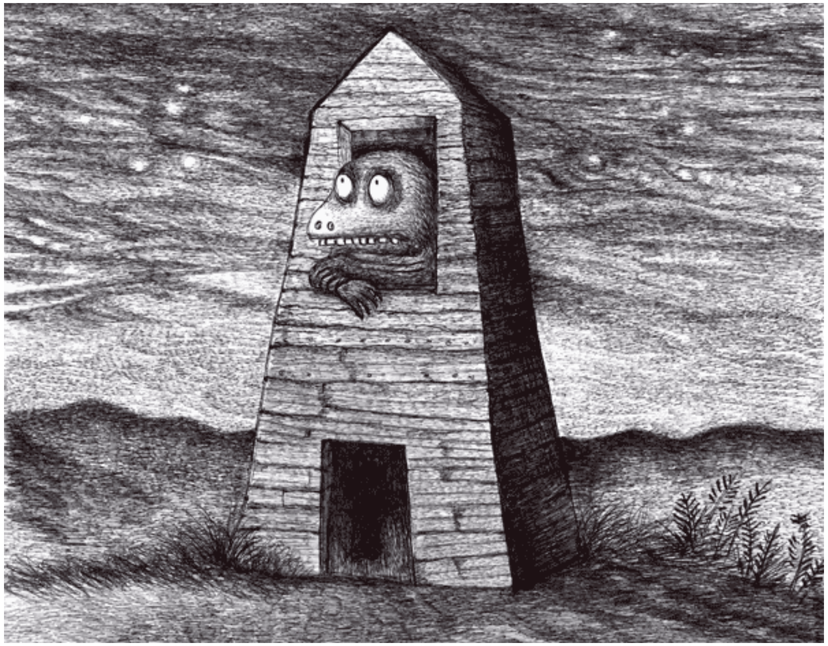
Supernova Neutrinos

MeV Messengers of the Extreme



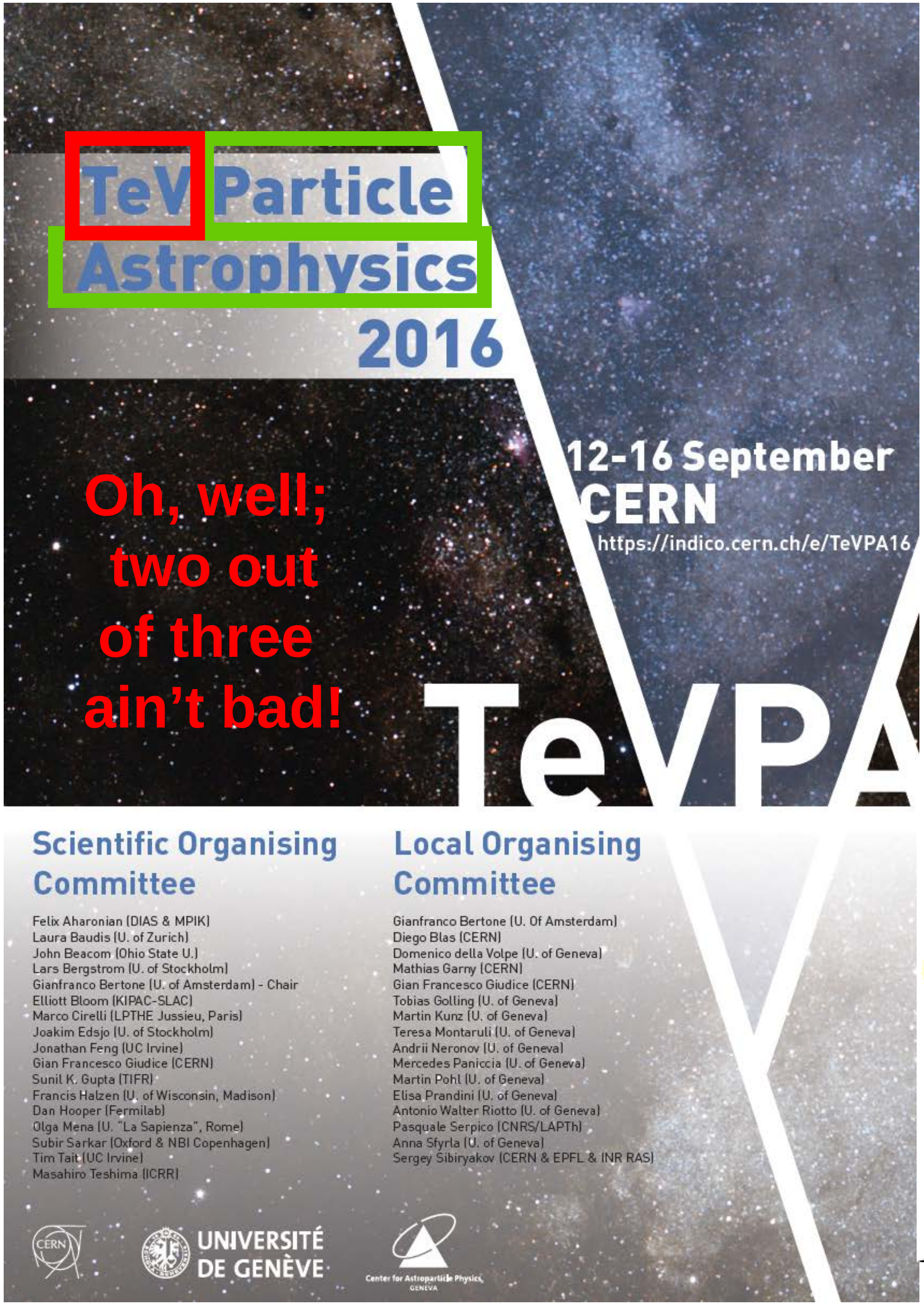
Mark Vagins

Kavli IPMU, University of Tokyo

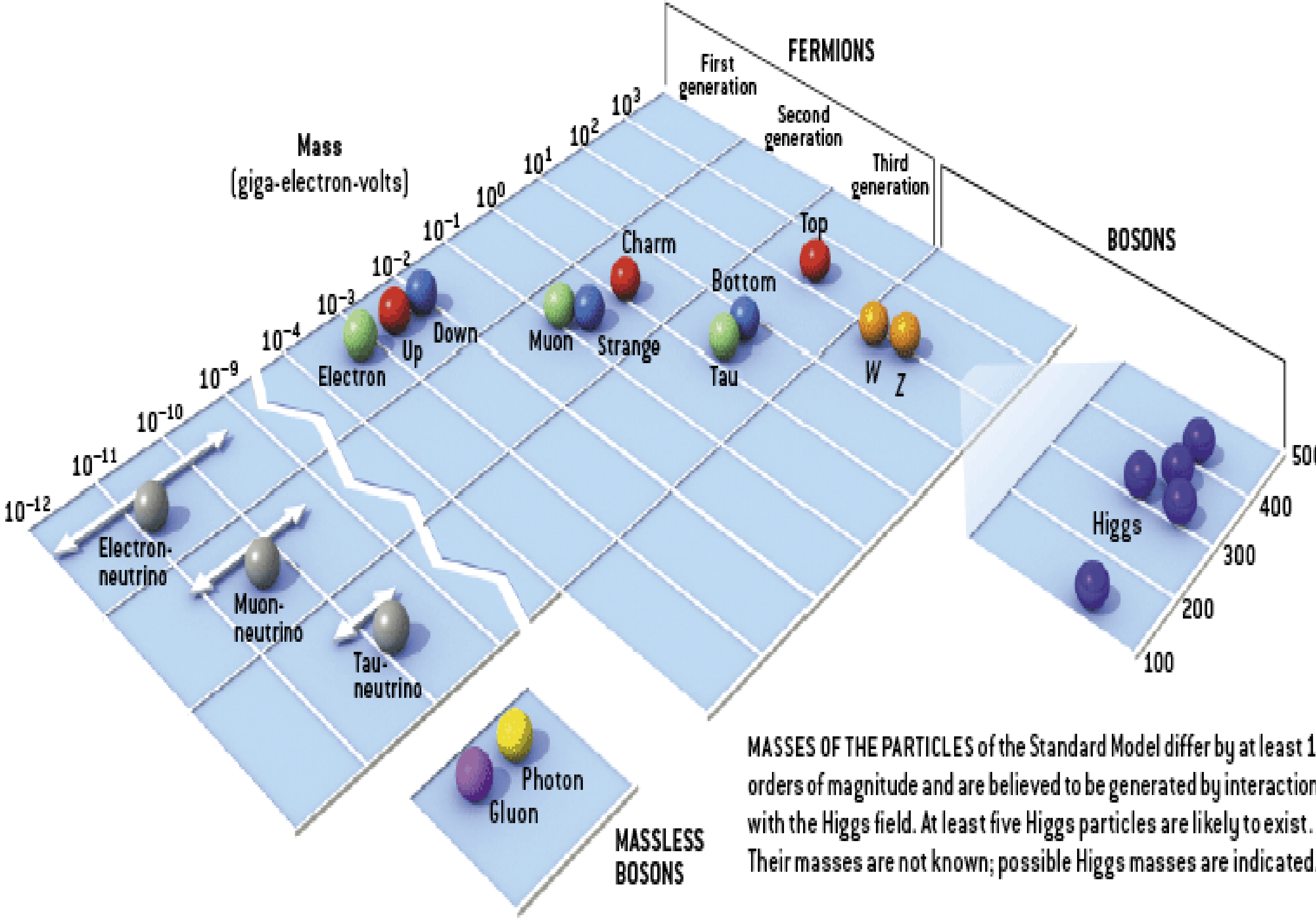
TeV Particle Astrophysics 2016, CERN

September 13, 2016

Now, to tell you the truth, I was honored but a bit surprised when I was invited to give this talk…



…since supernova neutrinos have about 100,000 times less energy than this.

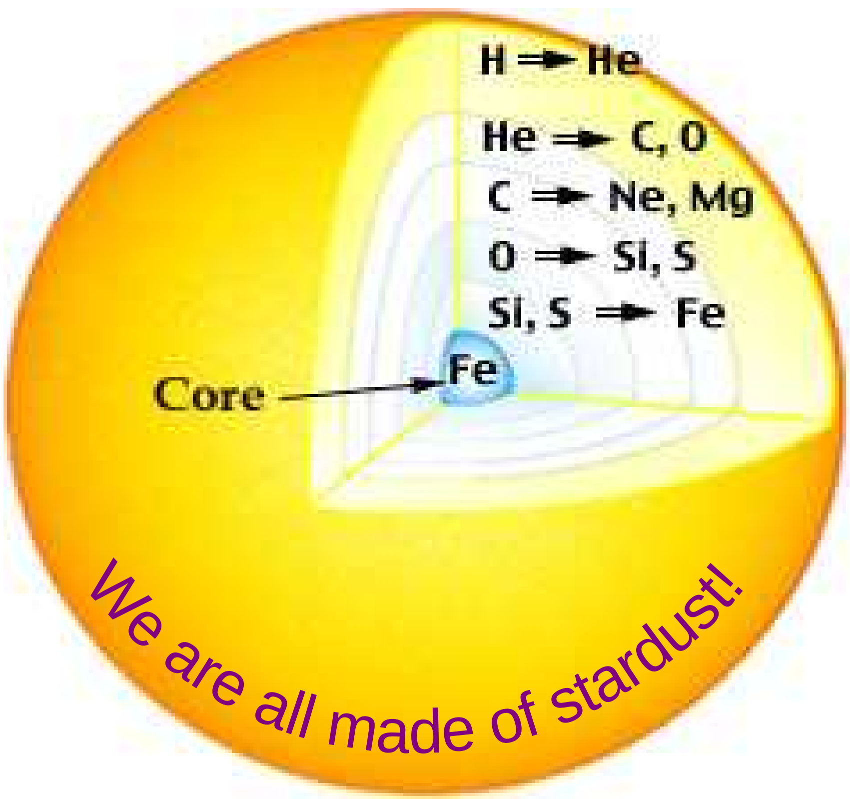


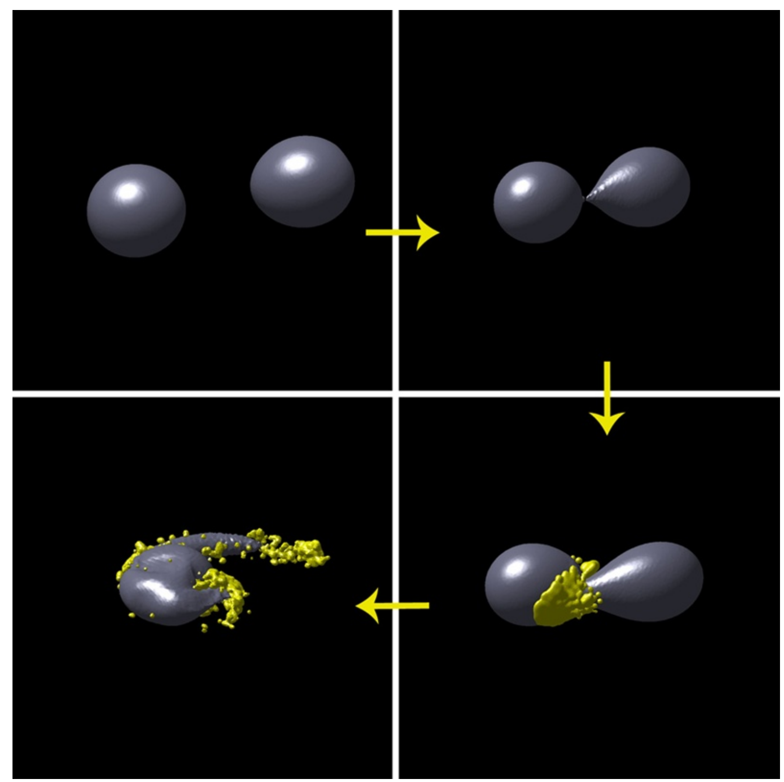
MASSES OF THE PARTICLES of the Standard Model differ by at least 11 orders of magnitude and are believed to be generated by interactions with the Higgs field. At least five Higgs particles are likely to exist. Their masses are not known; possible Higgs masses are indicated.

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

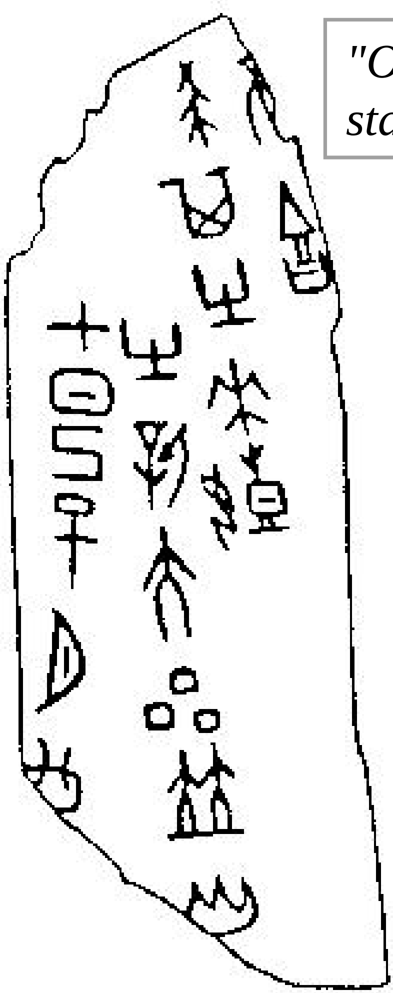
To understand this, we <u>must</u> understand supernovas.

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.



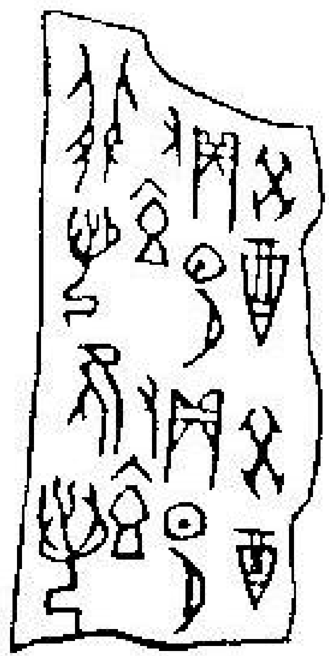


The appearance of new, temporary stars has long captured the attention of people around the world:



"On the Jisi day, the 7th day of the month, a big new star appeared in the company of the Ho star."

The Ho star is Antares.

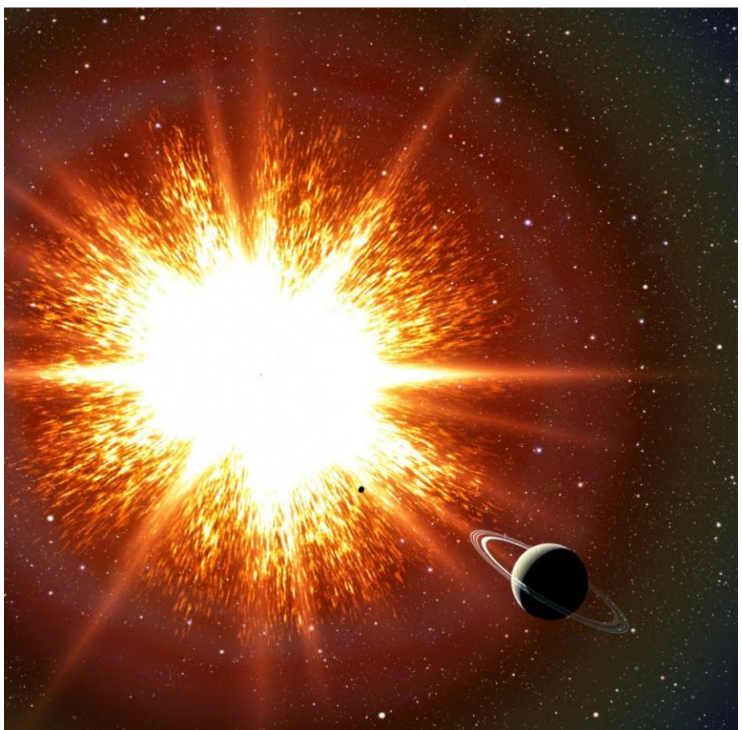


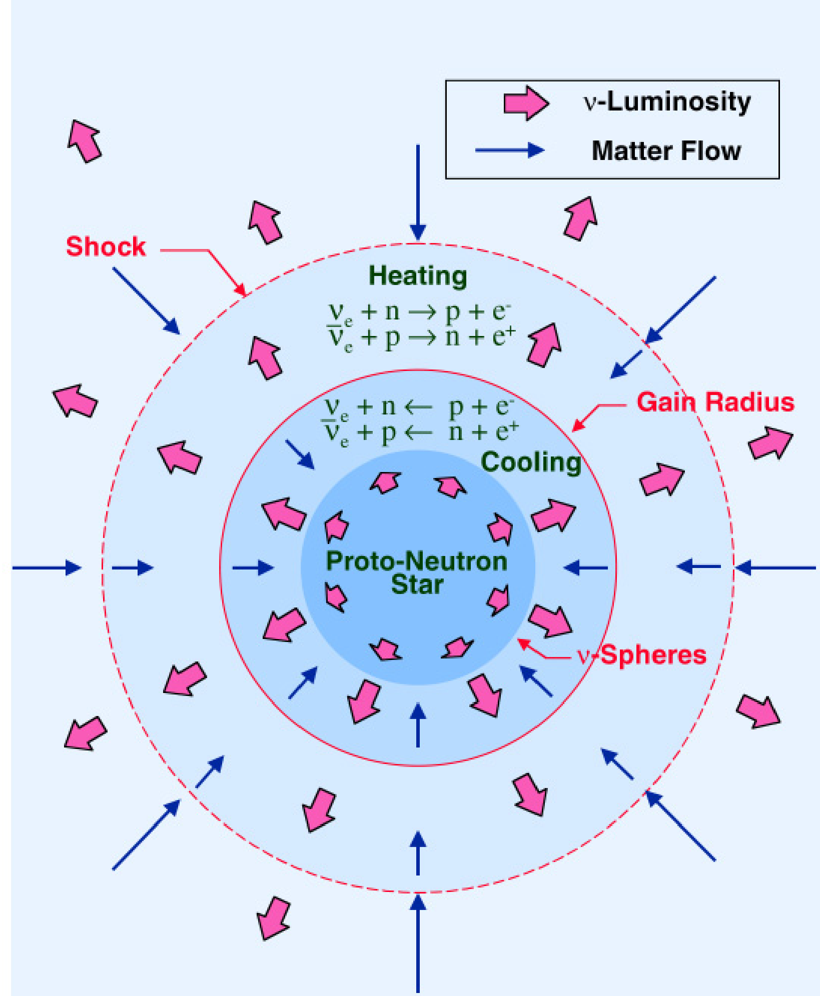
→ This is a 3,500 year-old record of a supernova explosion!

"On the Xinwei day the new star dwindled."

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.

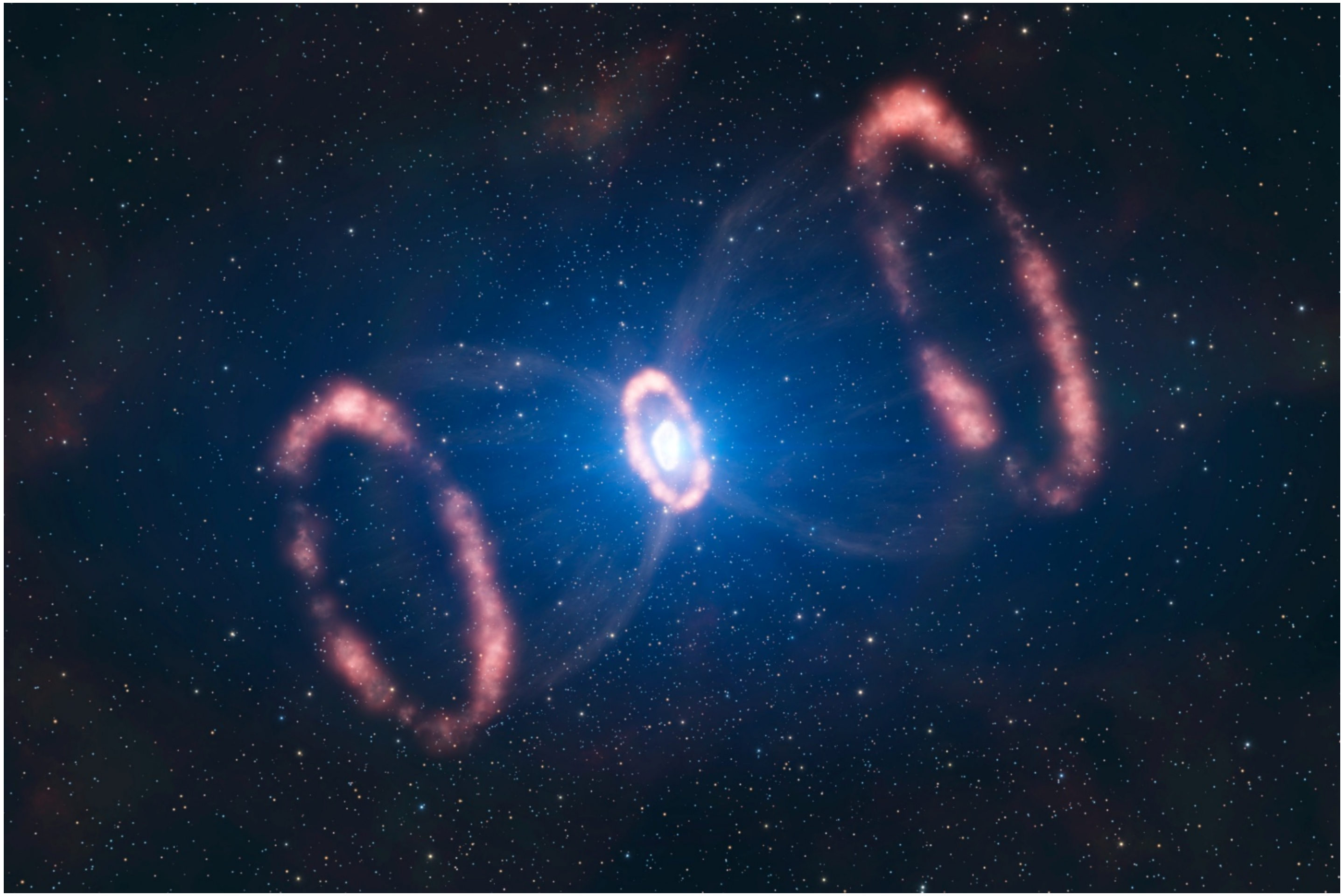




Neutrinos, along with gravitational waves, provide the only possible windows into core collapses’ inner dynamics.

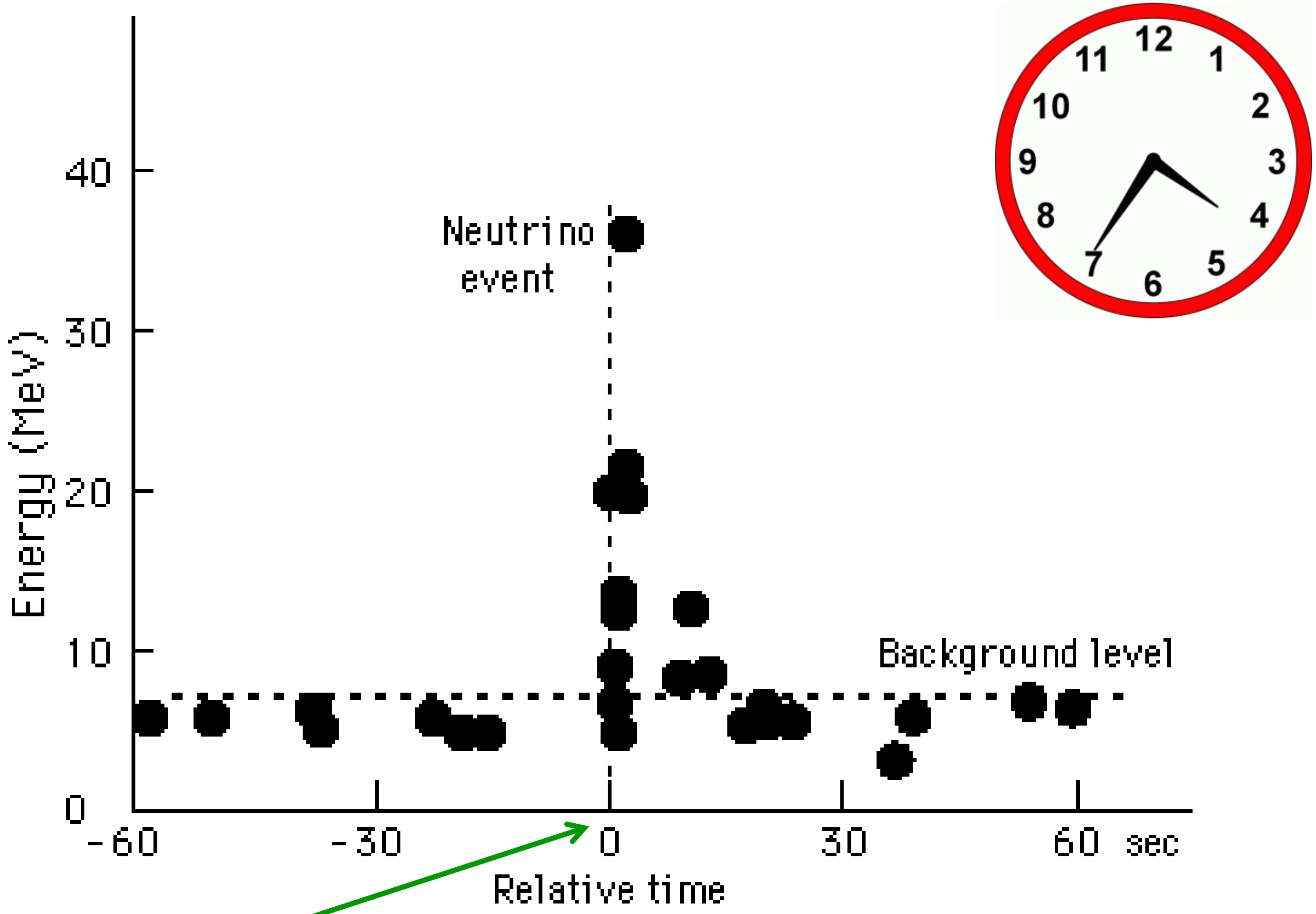
A long time ago, in a (neighbor) galaxy far, far away…

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

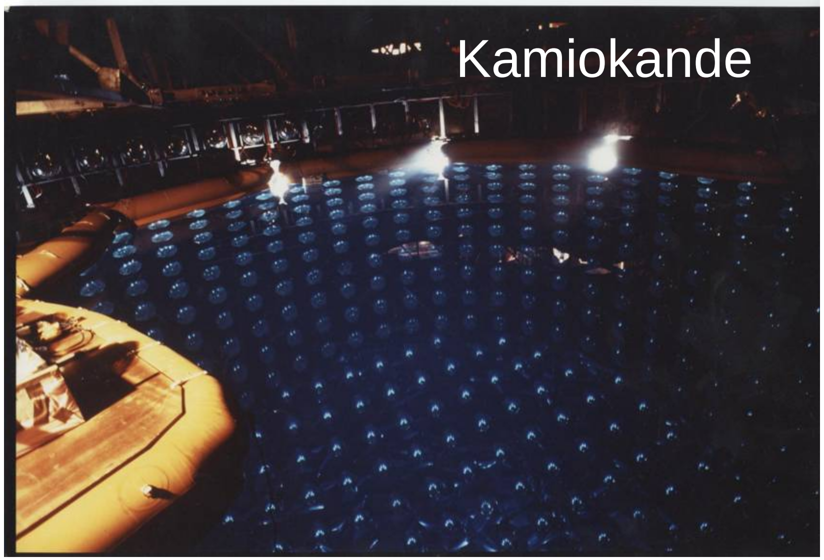


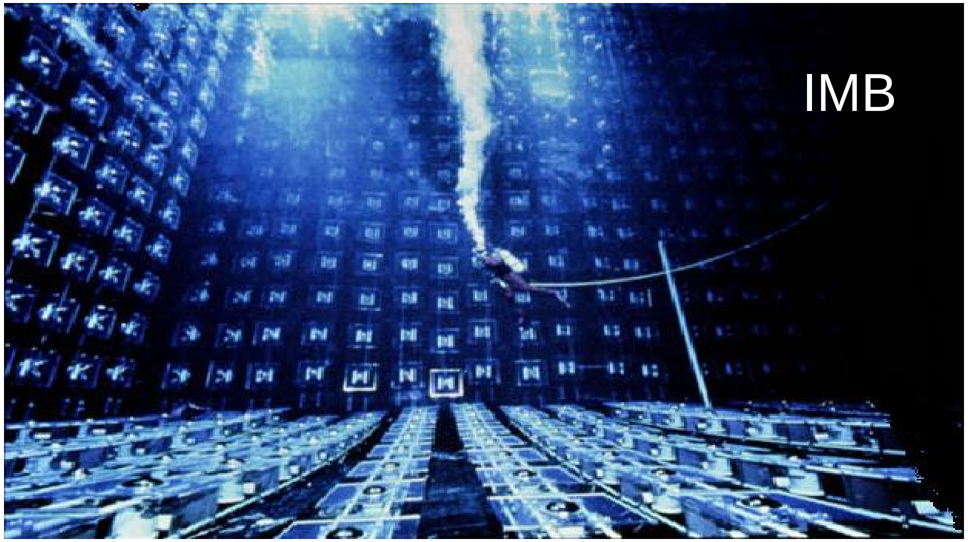
The explosion happened 170,000 years ago,
but we finally got the news on February 24th, 1987.

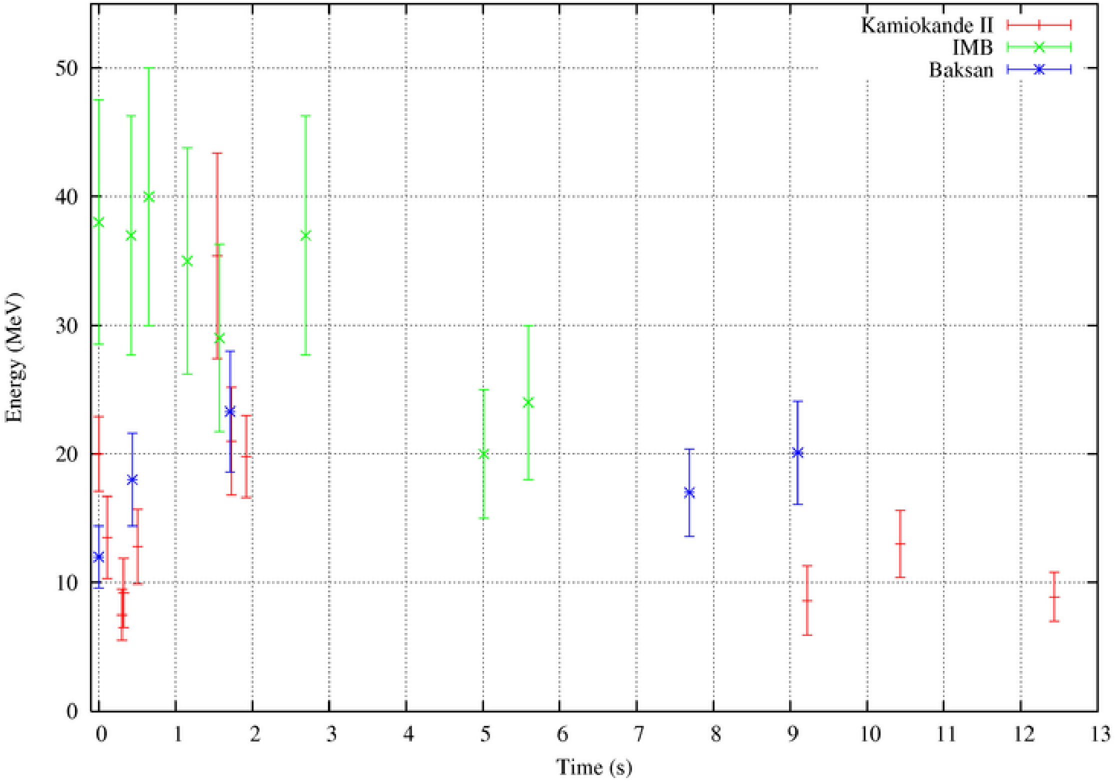
Kamiokande's Burst Time Structure



16:35:41 JST on February 24th, 1987

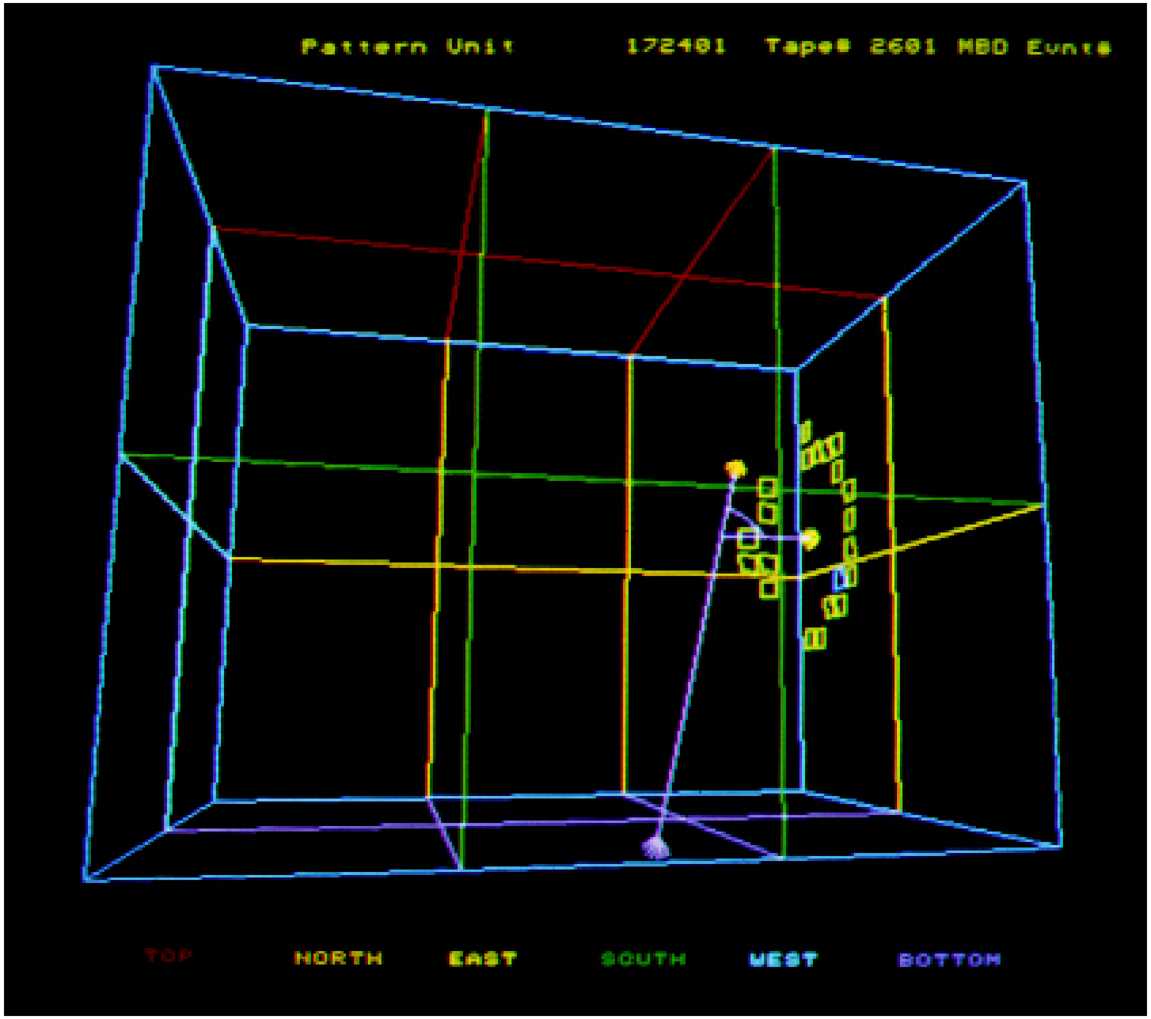






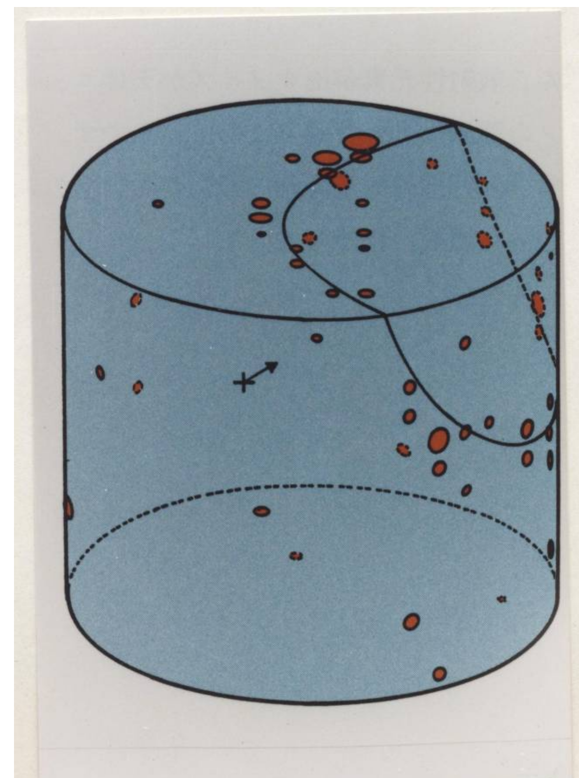
One paper published every ten days…

for the last 29 years!



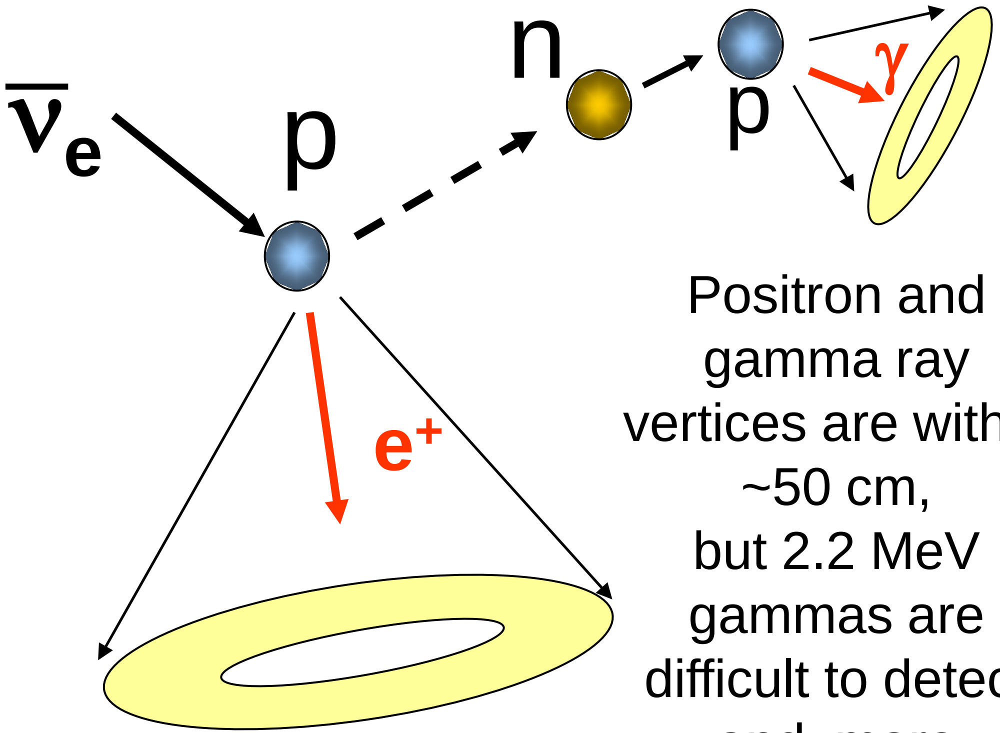
IMB
(in USA)

Kamiokande
(in Japan)



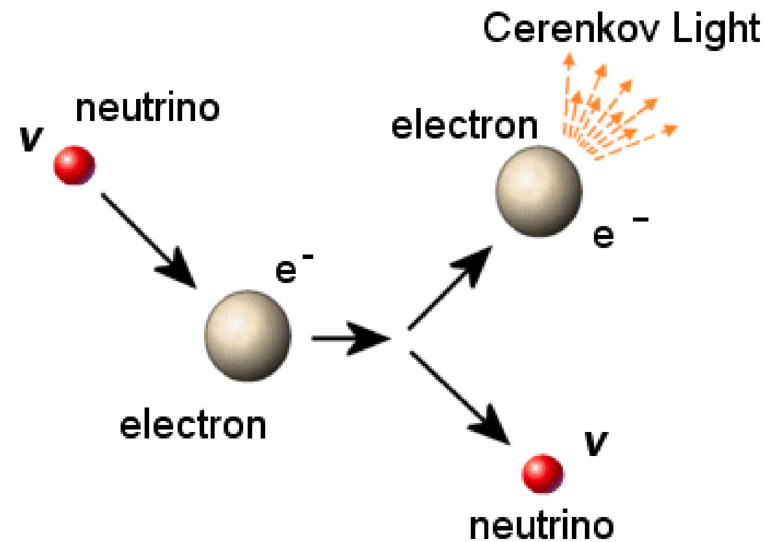
Event Displays of Actual Neutrinos from SN1987A

Inverse Beta Decay
(~80% of events → dominant)



Positron and gamma ray vertices are within ~50 cm, but 2.2 MeV gammas are difficult to detect and, more importantly, difficult to distinguish from backgrounds.

Elastic Scattering
(~3% → directional)



Masatoshi Koshiba ultimately received the Nobel Prize in physics for observing the neutrinos from SN1987A.

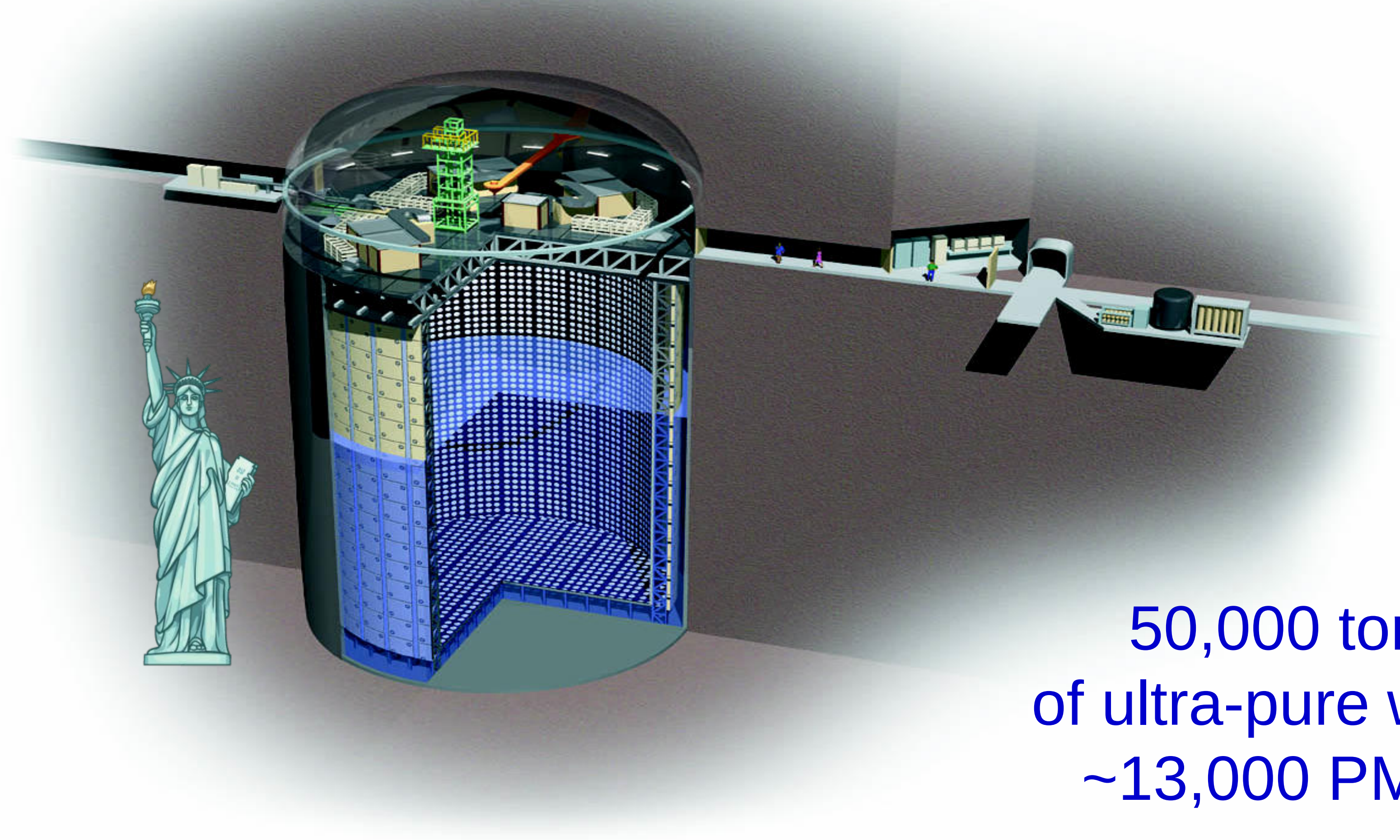
December 10, 2002

My beloved Super-Kamiokande

– already the best supernova ν detector in the world –

has been taking data, with an occasional interruption,

for over twenty years now… but no SN neutrinos so far!



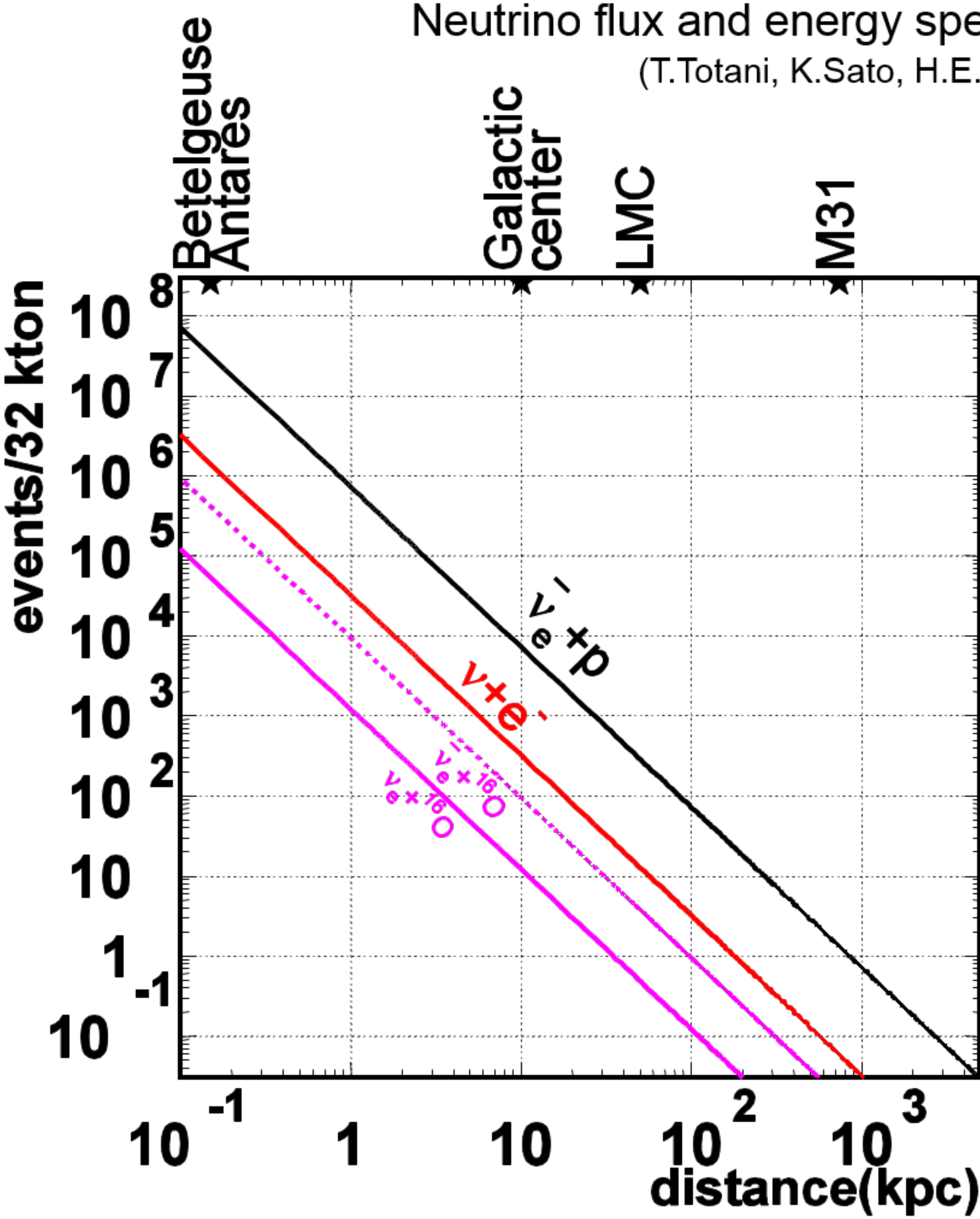
50,000 tons

of ultra-pure water,

~13,000 PMT's

Expected number of events from a supernova at SK

Neutrino flux and energy spectrum from Livermore simulation
(T.Totani, K.Sato, H.E.Dalhed and J.R.Wilson, ApJ.496,216(1998))



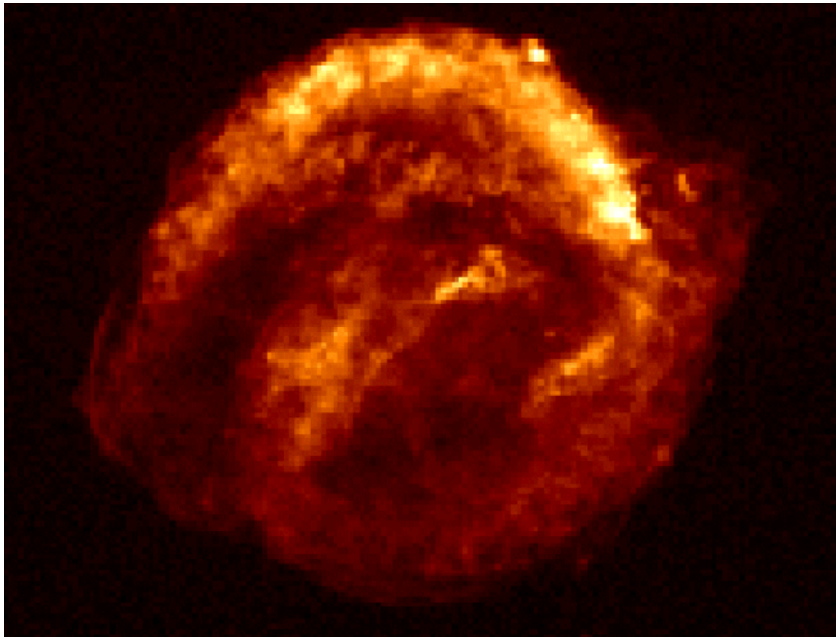
5 MeV threshold

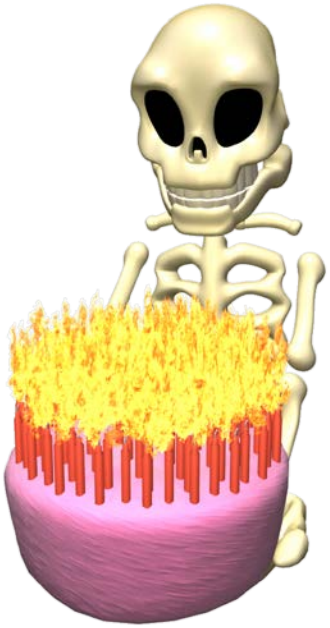
~7,300 $\bar{\nu}_e$+p events
~300 ν+e events
~100 $\overset{(-)}{\nu}_e$+^{16}O events

for 10 kpc supernova

Super-Kamiokande is ready 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.** ←



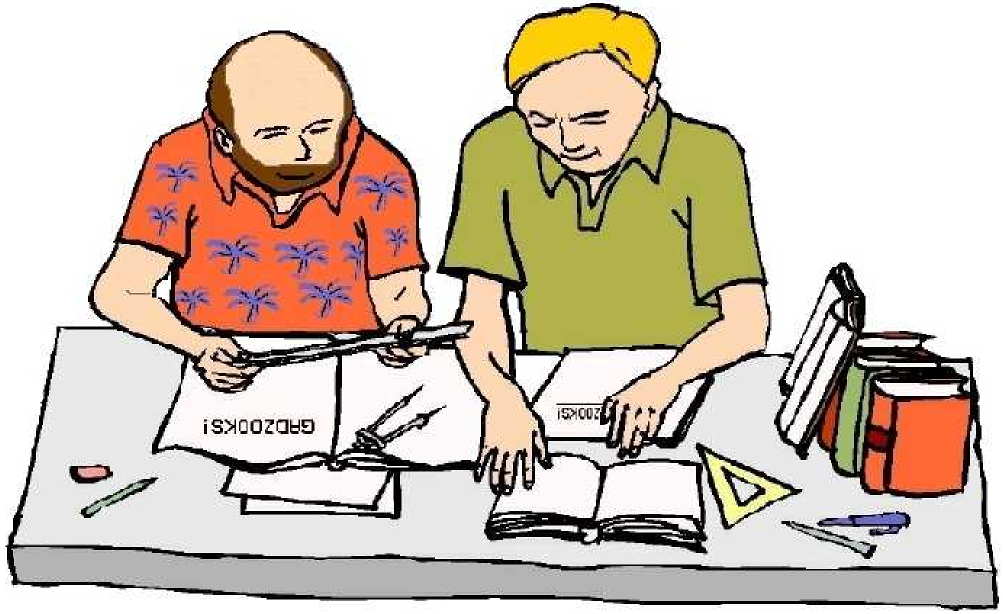


Unfortunately, it has been nearly three decades since SN1987A, and <u>411 years and 339 days</u> since a supernova was last definitely observed within our own galaxy!

Of course, no neutrinos were recorded that mid-October day in 1604…

but it was probably a type Ia, anyway!

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

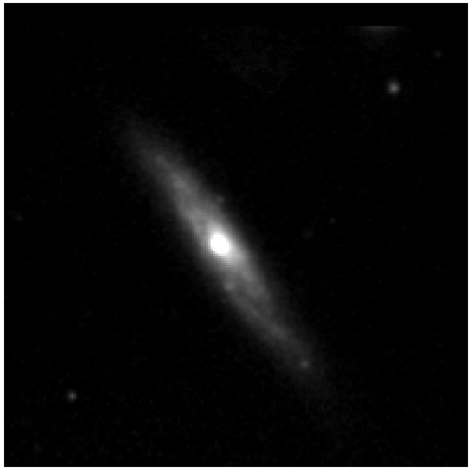
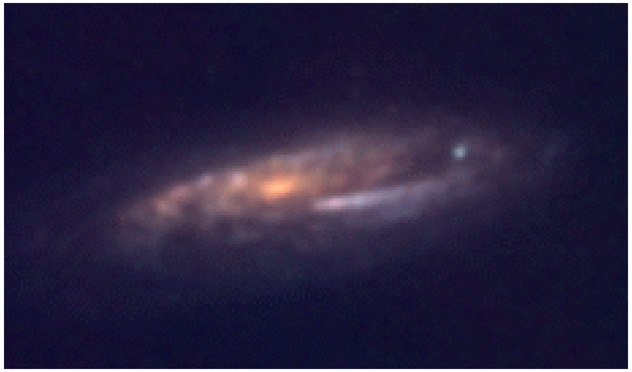
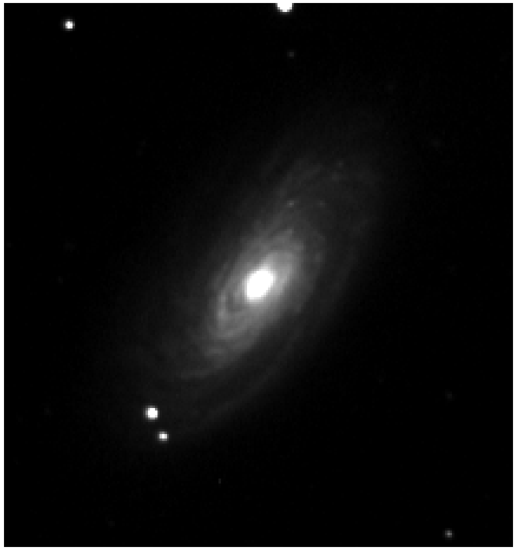


A while ago theorist John Beacom and I wrote the original GADZOOKS!

(Gadolinium Antineutrino Detector Zealously Outperforming Old Kamiokande, Super!) paper.

It proposed loading big WC detectors, specifically Super-K, with water soluble gadolinium, and evaluated the physics potential and backgrounds of a giant antineutrino detector.

[Beacom and Vagins, *Phys. Rev. Lett.*, **93**:171101, 2004]
(270 citations $\rightarrow$ one every 16 days for twelve years)

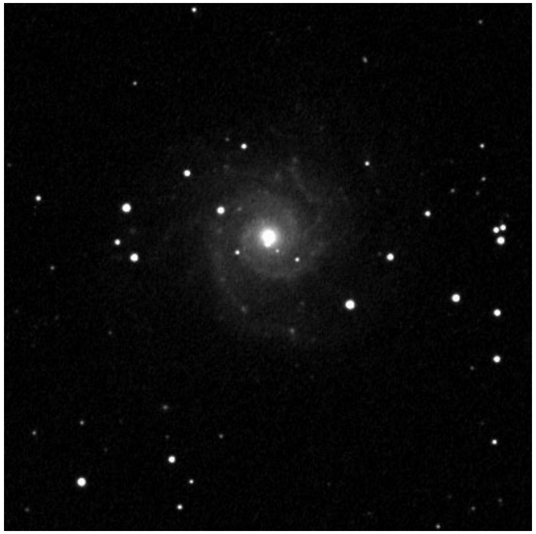




(videos are looped)

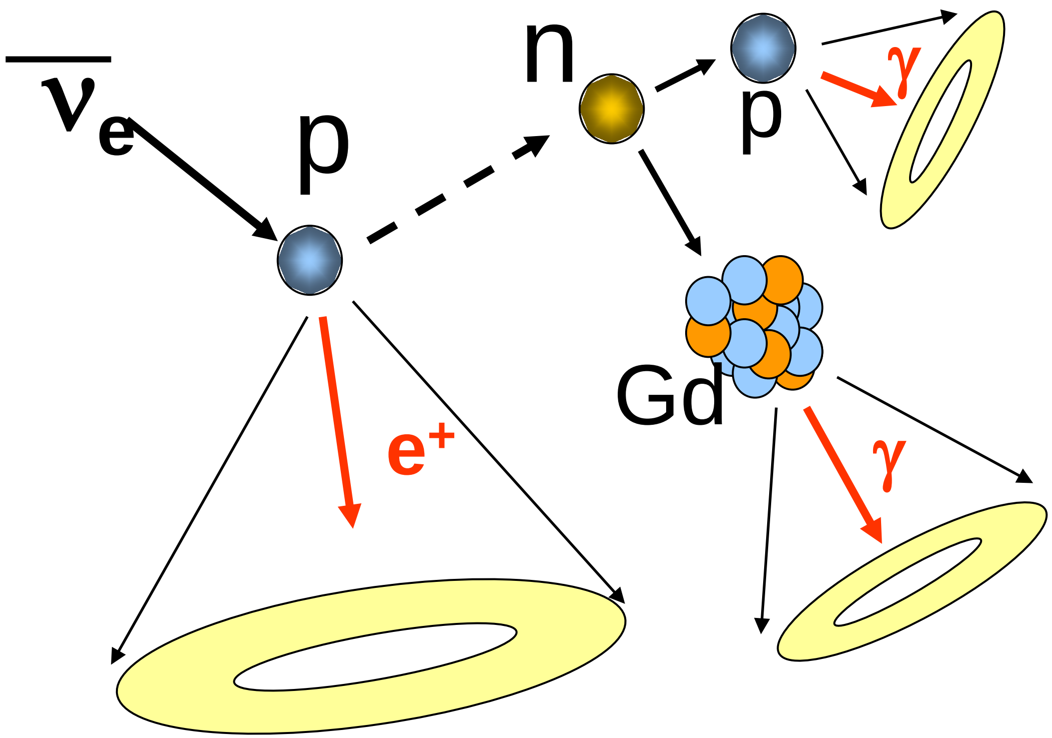
On average, there is <u>one supernova explosion each second</u> in the universe. It will be the Milky Way's turn again someday.

When it happens, Super-Kamiokande will be running and ready!

Until then, let's look for neutrinos from these distant explosions…

Adding 0.2% of a water soluble gadolinium compound to Super-K will amplify the supernova signal!



Possibility 1: 10% or less

$n+p \rightarrow d + \gamma$

2.2 MeV γ-ray

Possibility 2: 90% or more

$n+Gd \rightarrow \sim 8MeV\ \gamma$

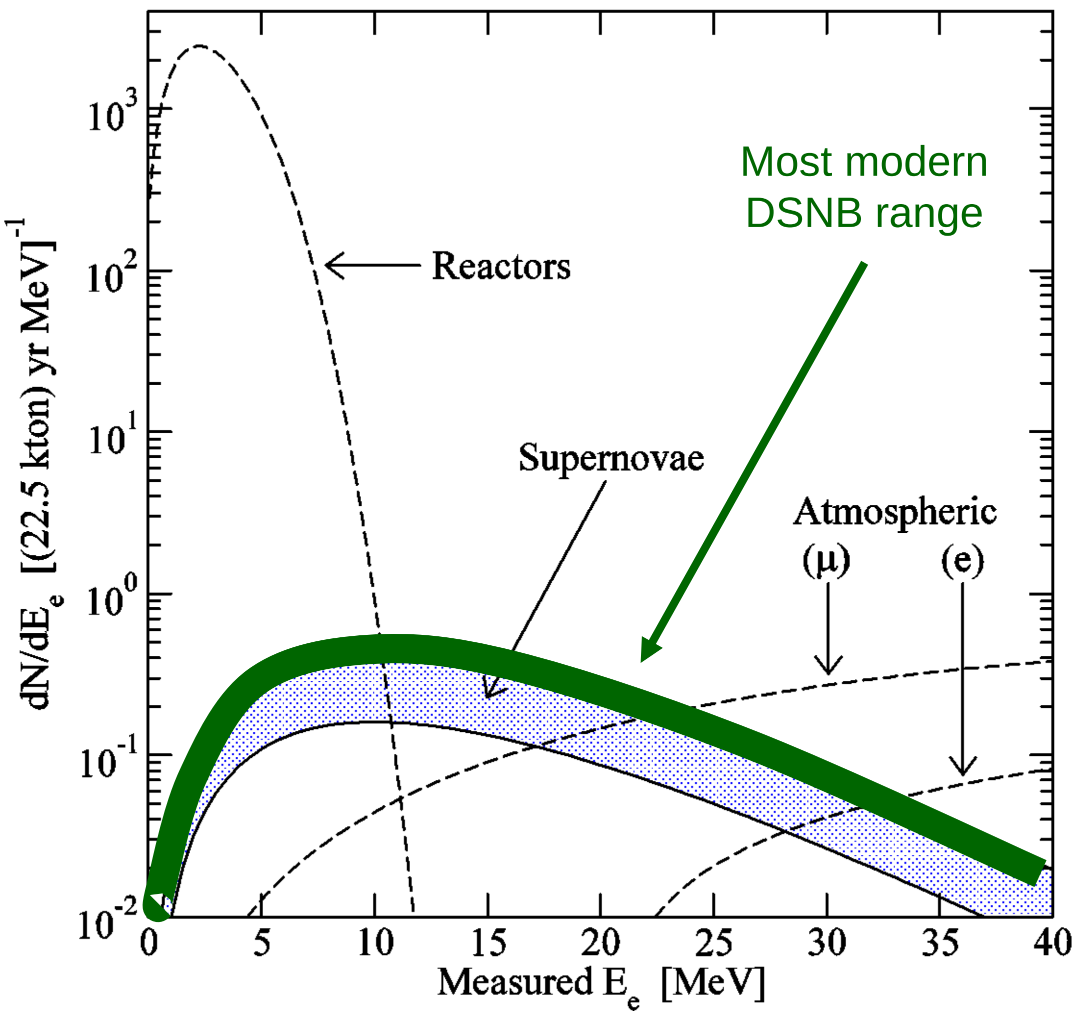
$\Delta T = \sim 30\ \mu sec$

Positron and gamma ray vertices are within ~50cm.

$\overline{\nu}_e$ can be identified by delayed coincidence.

[Beacom and Vagins, *Phys. Rev. Lett.*, **93**:171101, 2004]

Here's what the coincident signals in Super-K with $Gd_2(SO_4)_3$ will look like (energy resolution is applied):



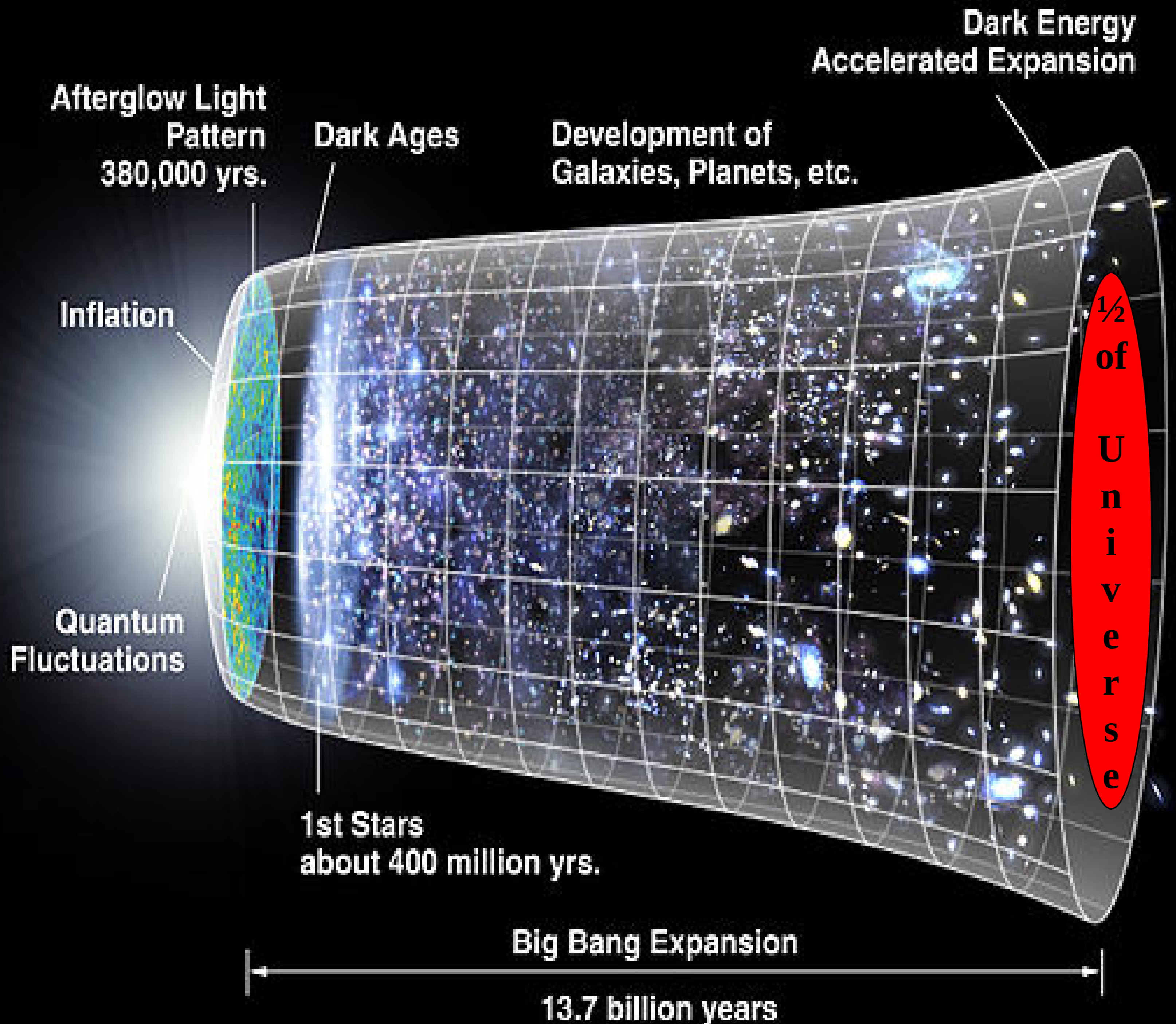
$\bar{\nu}_e + p \rightarrow e^+ + n$

spatial and temporal separation between prompt e^+ Cherenkov light and delayed Gd neutron capture gamma cascade:

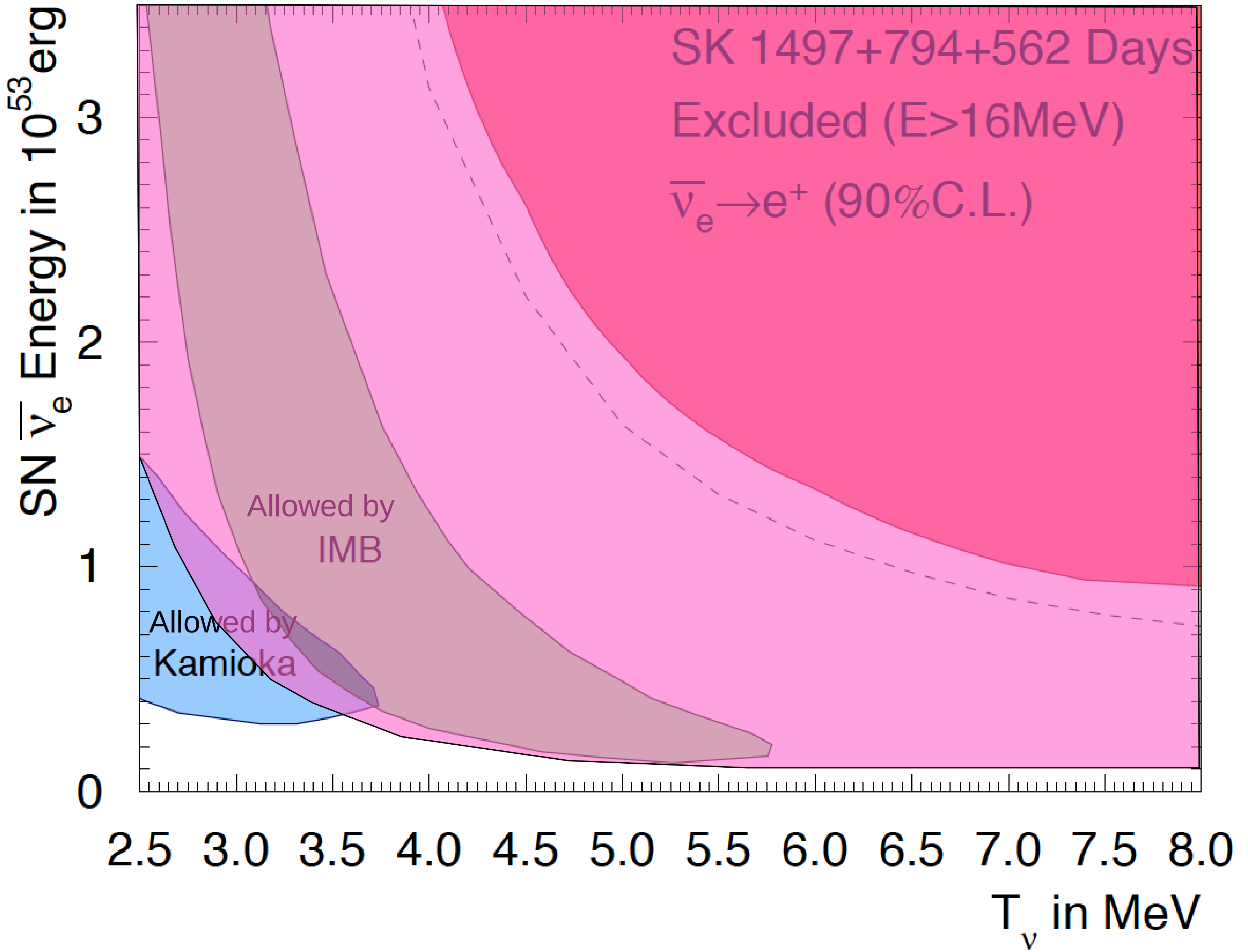
λ=~4cm, τ=~30μs

→ A few clean events/yr in Super-K with Gd

Adding Gd will expand Super-K's supernova sensitivity!



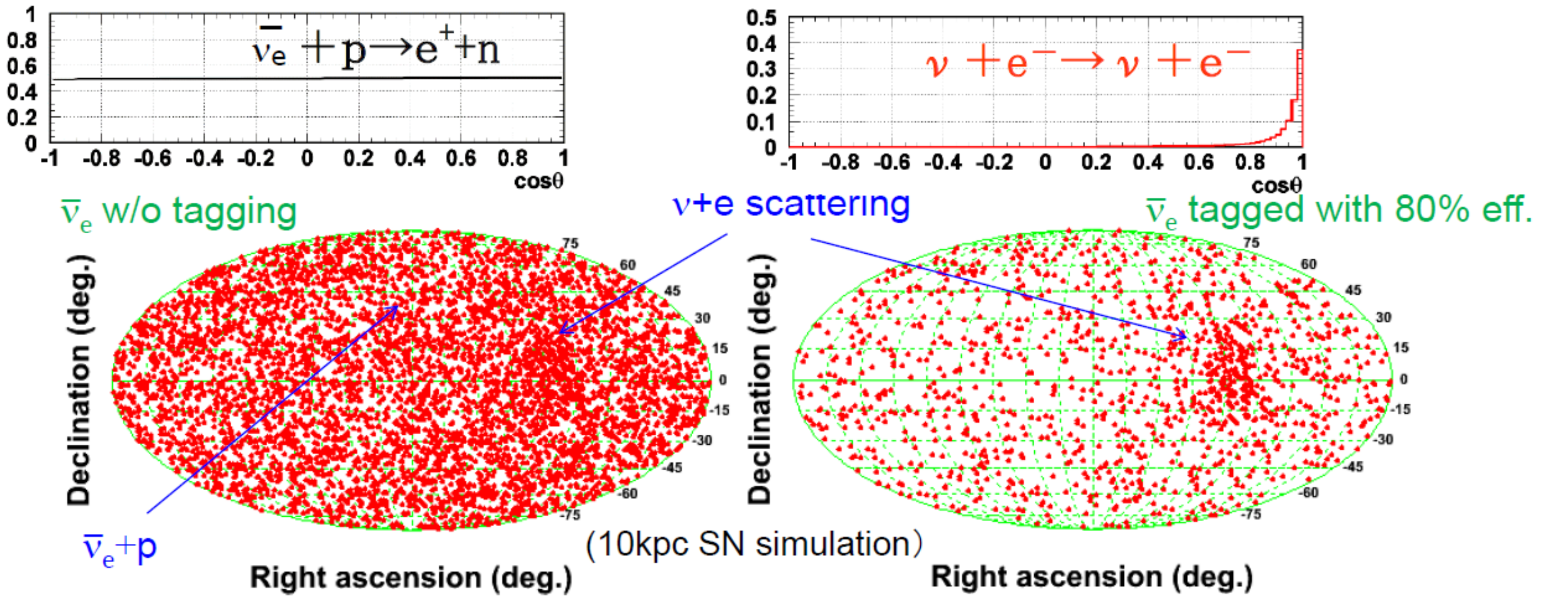
DSNB Discovery Region After Six Years With Gd In SK



Supernovas and Gd loading:

Not only for DSNB

- If $\bar{\nu}_e$ can be tagged, directional events (ν+e scattering events) are enhanced.
  Pointing accuracy should be improved. For 10kpc SN ~5° → ~3° (@90%C.L.)



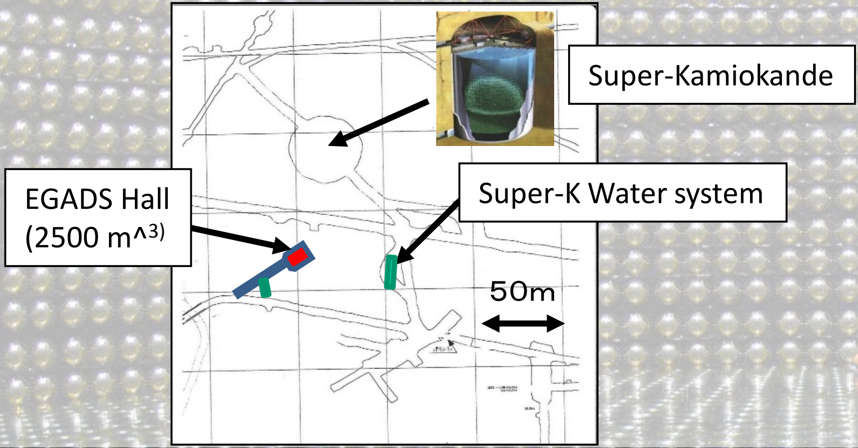
- Sensitive to $\bar{\nu}_e$ of Si burning phase. 800~2000 events/day for pre-supernova at 200pc

In the case of a galactic supernova, having $Gd_2(SO_4)_3$ in Super-K will provide many important benefits:

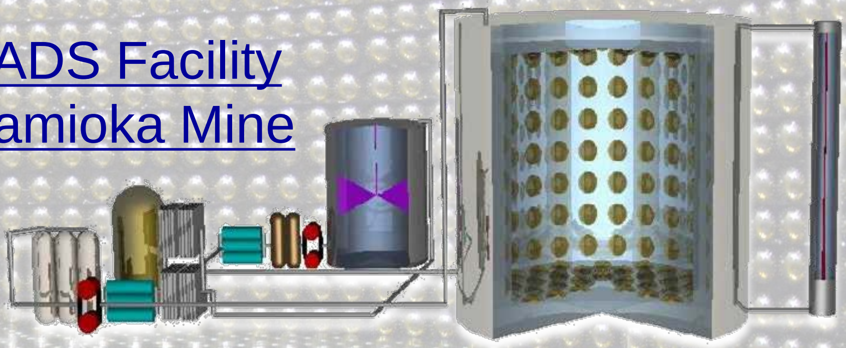
- Allows the exact $\bar{\nu}_e$ flux, energy spectrum, and time profile to be determined via the extraction of a tagged, pure sample of inverse beta events.
- Instantly identifies a burst as genuine via “Gd heartbeat”.
- Doubles the ES pointing accuracy. Error circle cut by 75%.
- Helps to identify the other neutrino signals, especially the weak neutronization burst of ν_e.
- Enables a search for very late time black hole formation.
- Provides for very early warning of the most spectacular, nearby explosions so we can be sure not to miss them.

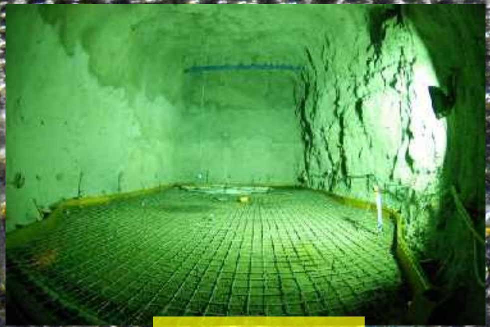
EGADS → Gd-loaded Super-K

EGADS (Evaluating Gadolinium's Action on Detector Systems) is a dedicated gadolinium demonstrator which includes a working 200 ton scale model of SK.

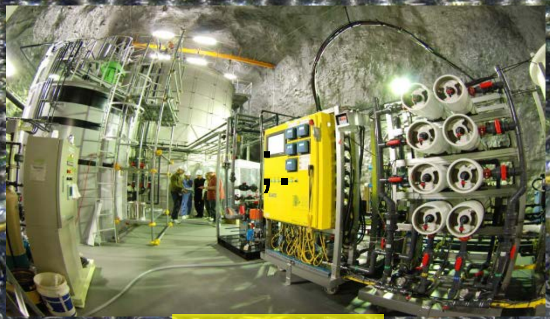


EGADS Facility in Kamioka Mine



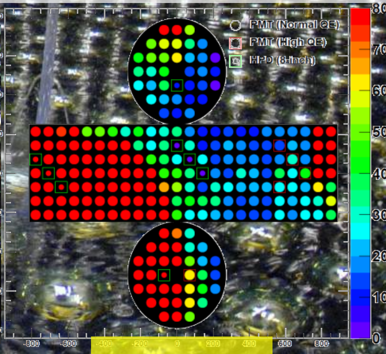


12/2009



11/2011

8/2013



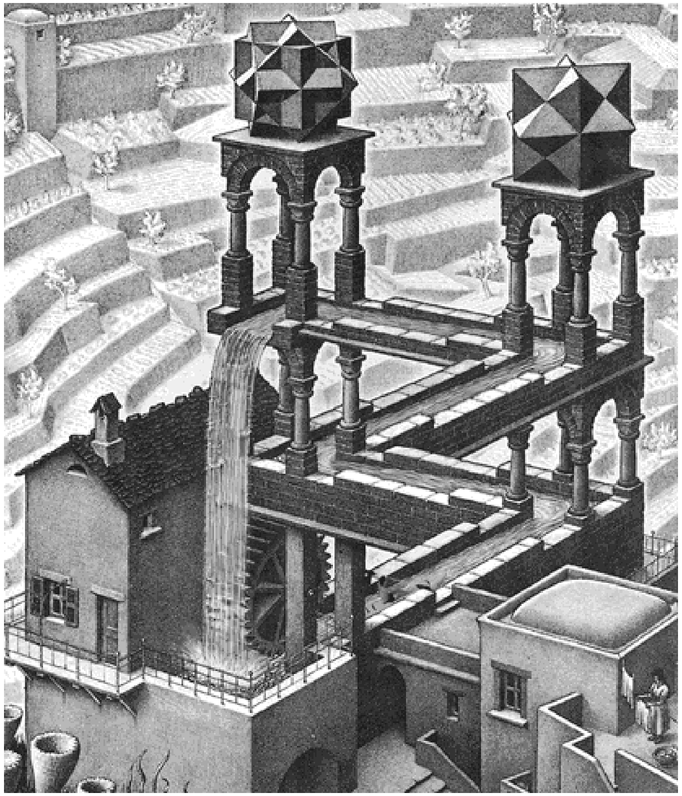
6/2015

Since April 2015, the EGADS detector has been fully loaded (0.2%) with gadolinium sulfate, and is functioning perfectly.

<u>The Essential Magic Trick</u>

→ We must keep the water in any Gd-loaded detector perfectly clean… *without removing the dissolved Gd.*

→ I've developed a new technology:
"Molecular Band-Pass Filtration"
Staged nanofiltration <u>selectively</u> retains Gd while removing impurities.



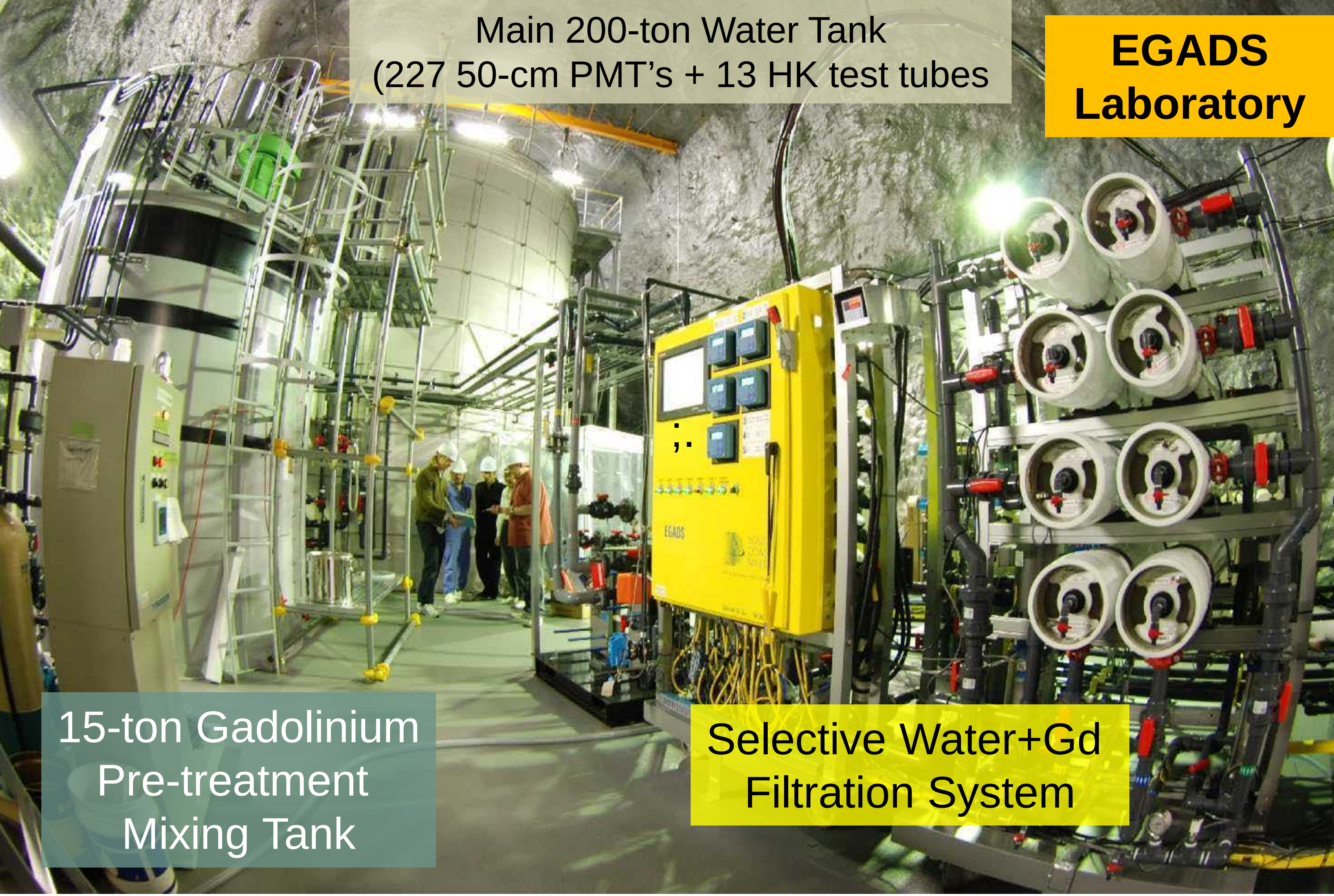
Amazingly, the darn thing works!

This technology will support a variety of applications, such as:

→ Supernova neutrino and proton decay searches

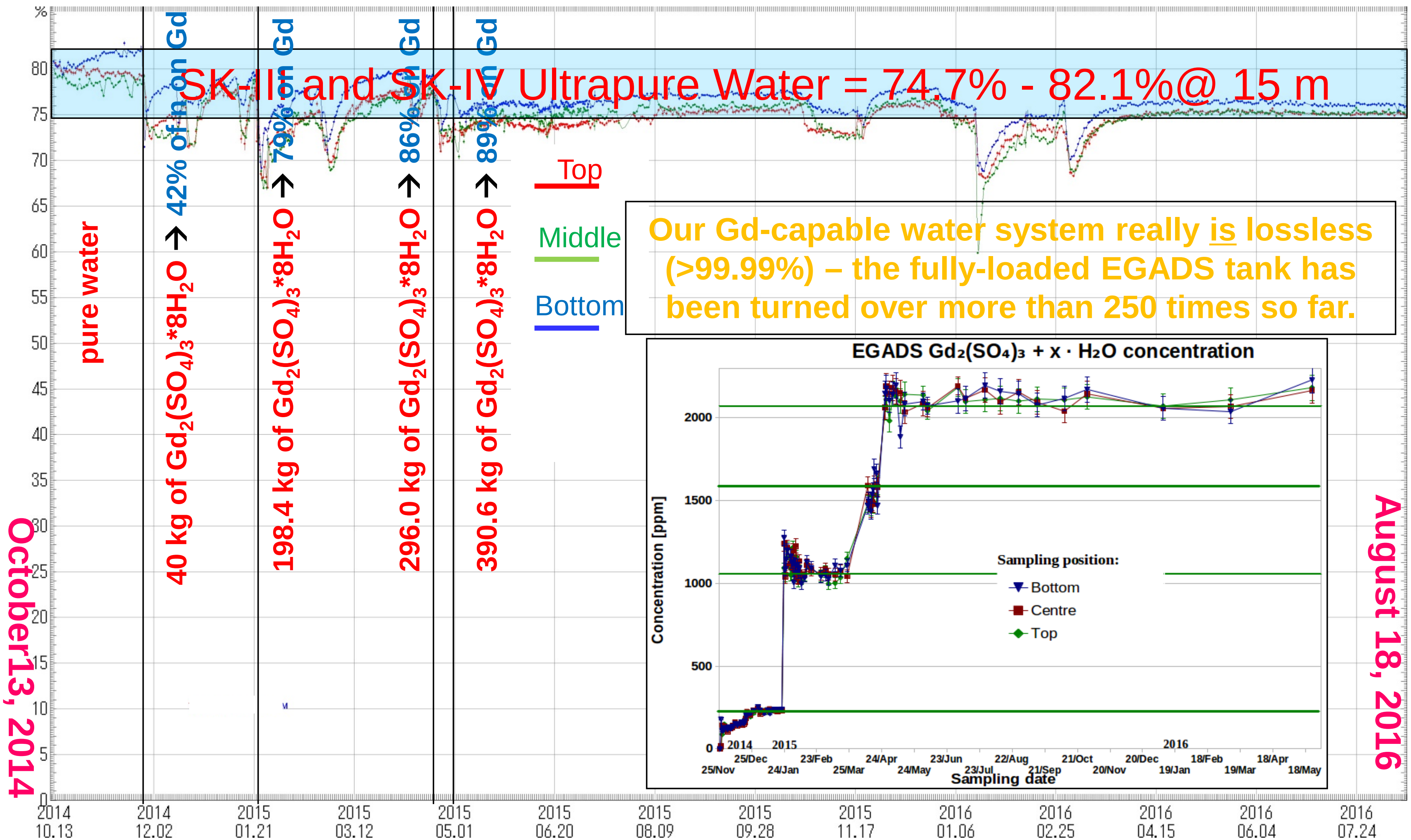
→ Remote detection of clandestine fissile material production

→ Efficient generation of clean drinking water without electricity



After a decade of extremely promising studies on three continents, EGADS has provided the conclusive final test of Gd loading this year.

Light @ 15 meters in the 200-ton EGADS tank

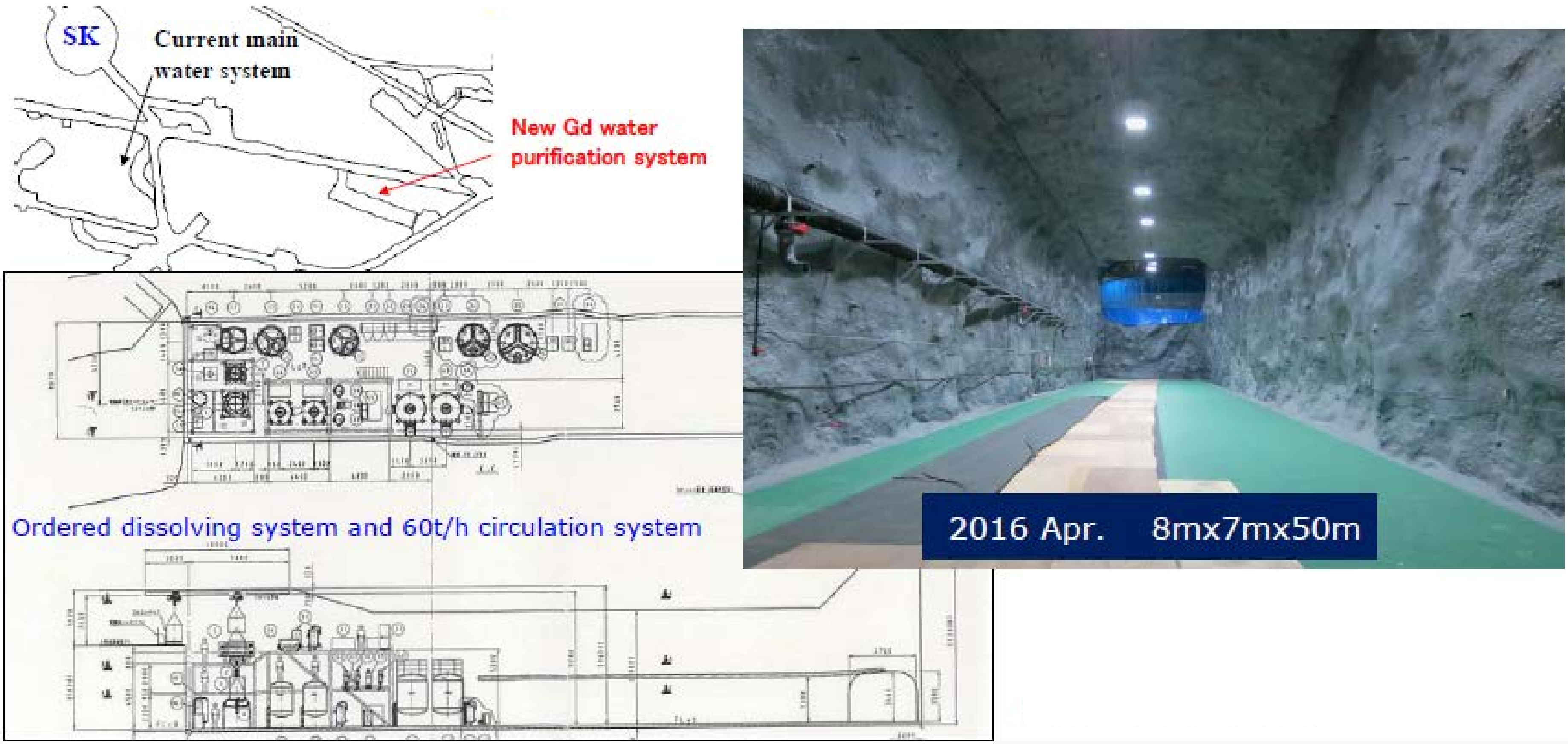


Gadolinium Loading | Steady-state Operations | Water System Tuning Studies | Steady-state Operations

As was discussed in the original 2004 Beacom/Vagins paper, as well as in the 270 papers to date which have cited it, the physics benefits provided to water Cherenkov detectors by dissolved gadolinium are numerous and compelling.

After years of testing and study – culminating in these powerful EGADS results – both the Super-Kamiokande and T2K Collaborations have formally approved the plan to load SK with Gd, with a nominal project start in 2018.

Preparations for the coming Gd era in Kamioka are already well underway…



It’s been a very good year for neutrinos.

Takaaki Kajita and Art MacDonald at the 2015 Nobel Prize ceremony, accepting the physics prize for Super-Kamiokande’s and SNO’s neutrino studies.

It's been a very good year for neutrinos.

2015 Nobel banquet

It's been a very good year for neutrinos.

2016 Breakthrough Prize; wins for SK, SNO, Daya Bay, K2K/T2K, and KamLAND for their neutrino oscillation studies

→ Thanks to the results from EGADS, <u>we are going to put Gd into SK, and keep the good times for neutrinos coming!</u>←

While Super-Kamiokande is waiting for the next galactic supernova explosion, adding gadolinium will allow us to continuously collect supernova neutrinos from explosions halfway across the universe!

We are planning to begin the in-tank work in 2018.