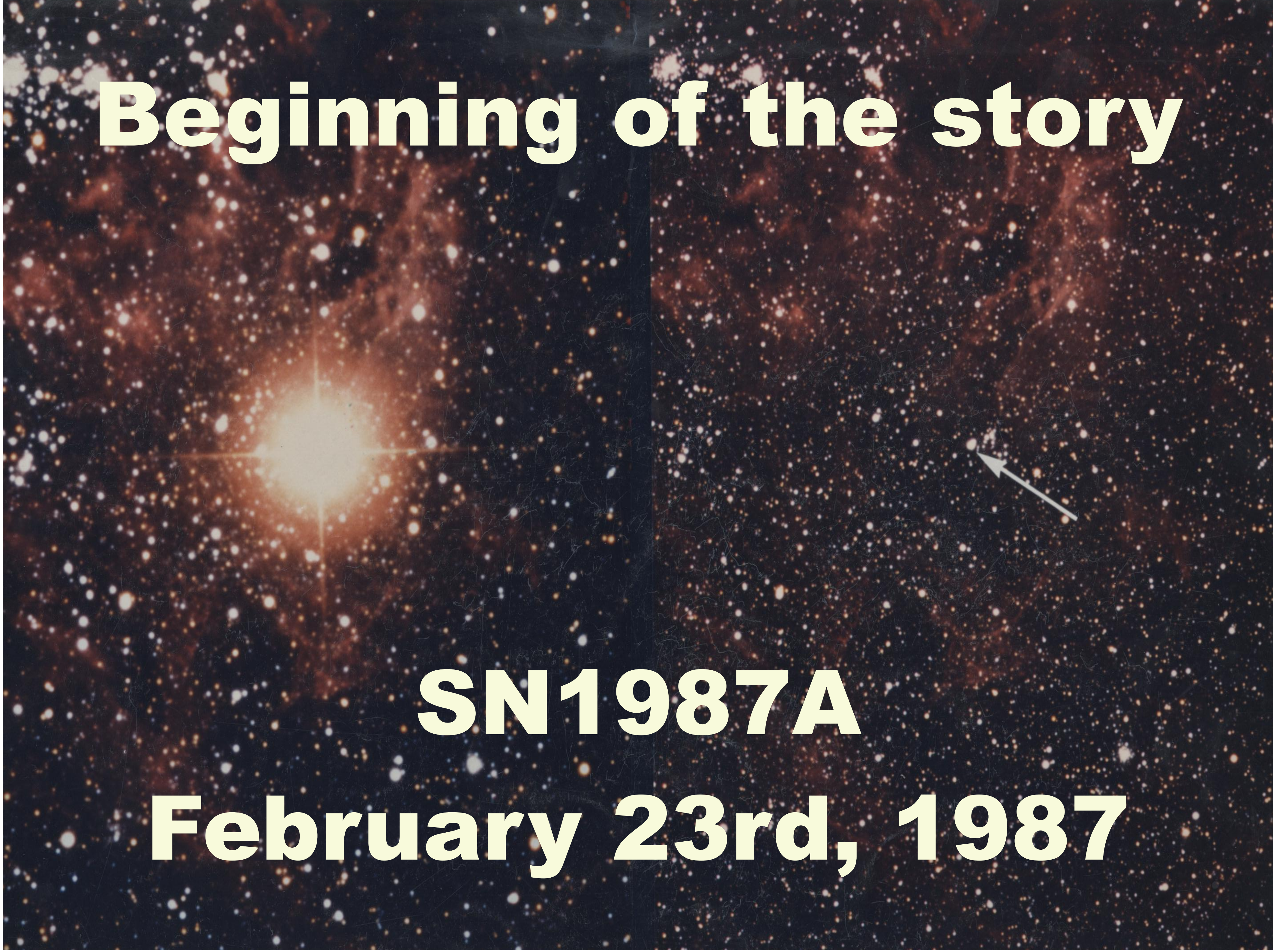
The Supernova neutrino detection in Super- and Hyper-Kamiokande

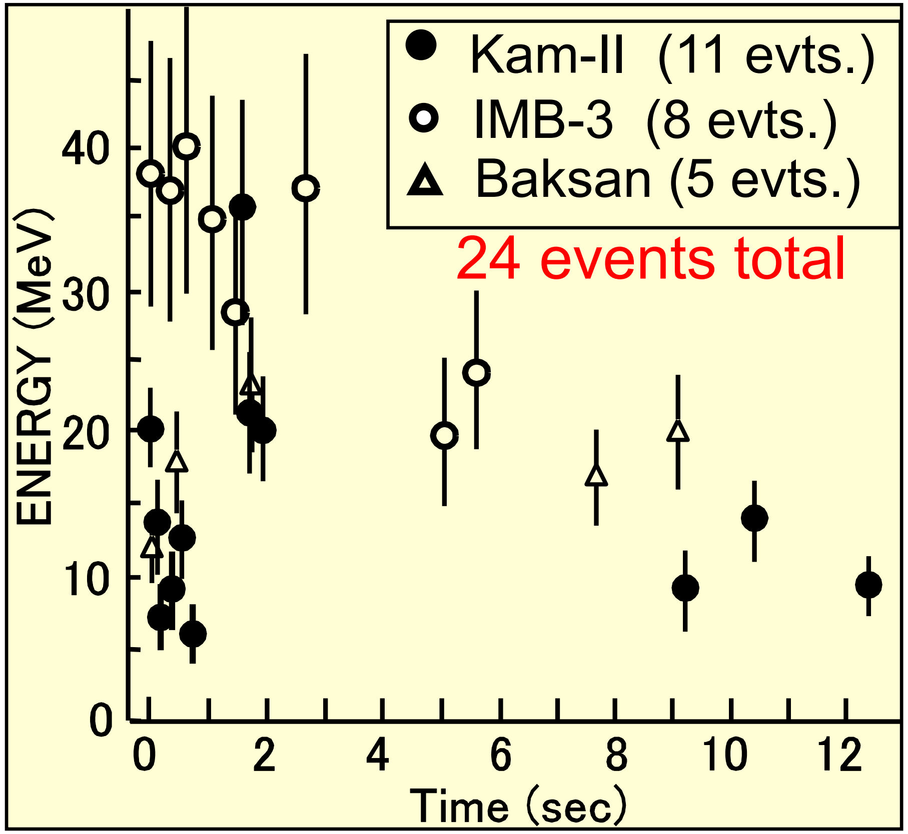
Yusuke Koshio (Okayama University, Japan)

LPNHE, Paris, France, 13th December, 2023


Beginning of the story
SN1987A
February 23rd, 1987

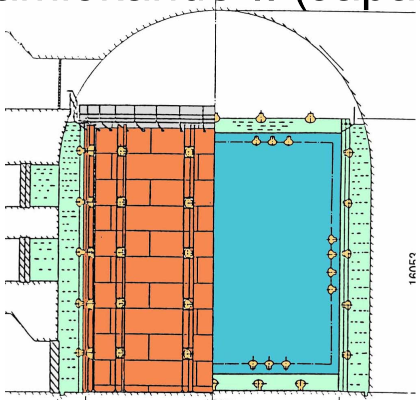
SN1987A Large Magellanic Cloud

~50 kpc, ν's were seen ~2.5 hours before first light

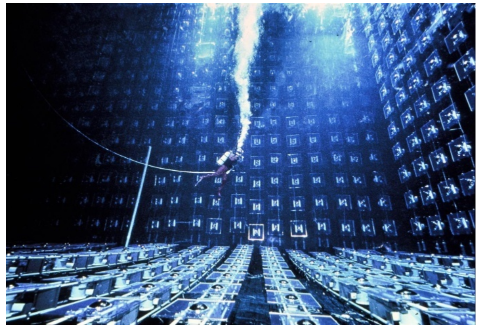


Water Cherenkov

Kamiokande-II (Japan)

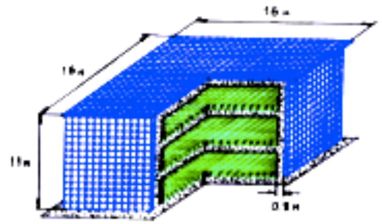


IMB-3 (US)



Liquid Scintillator

Baksan (Russia)

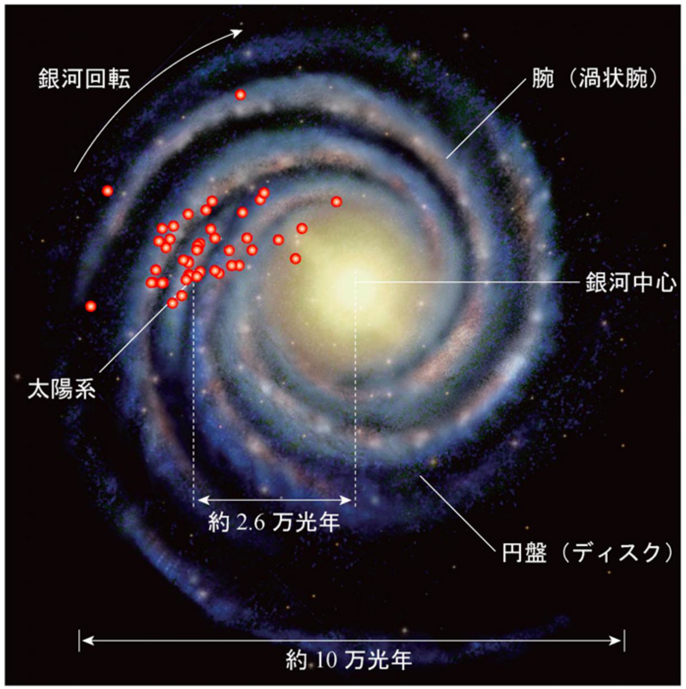


This was the first Supernova observed with the naked eye in 383 years!

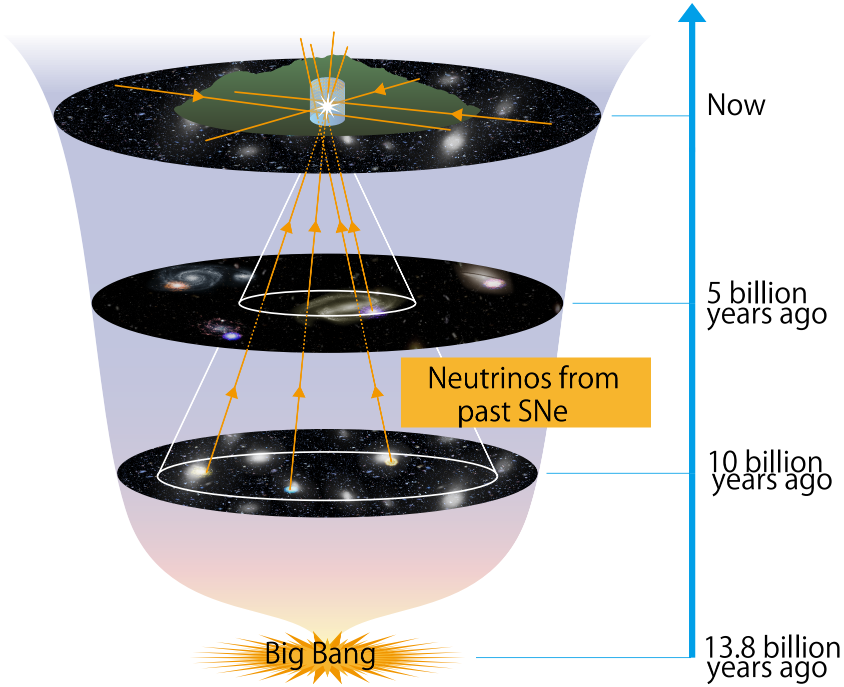
No chance for Supernova neutrino detection for the next hundred's years?

We believe, yes!

Galactic Supernova burst (a few per century)

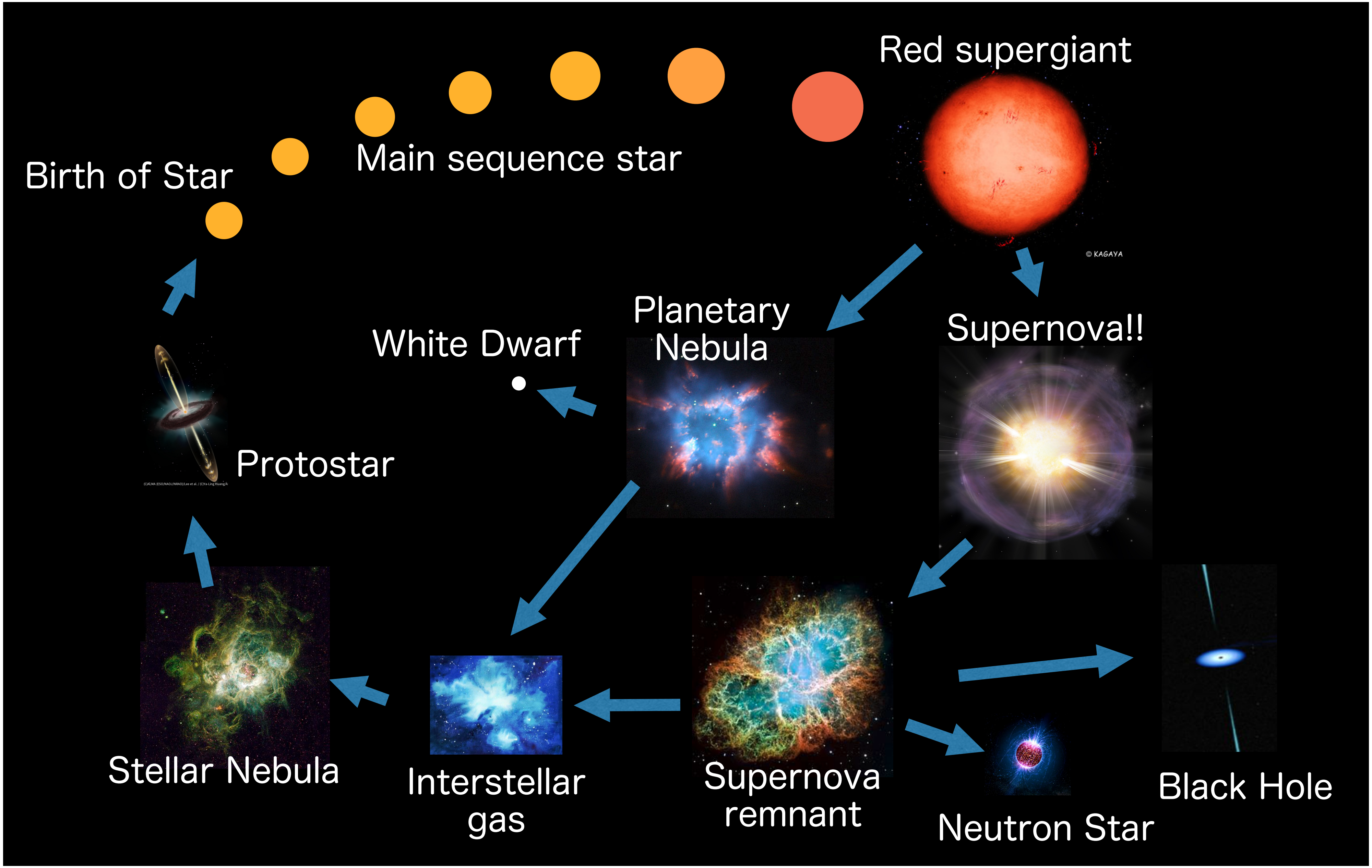


Diffuse Supernova Neutrino Background

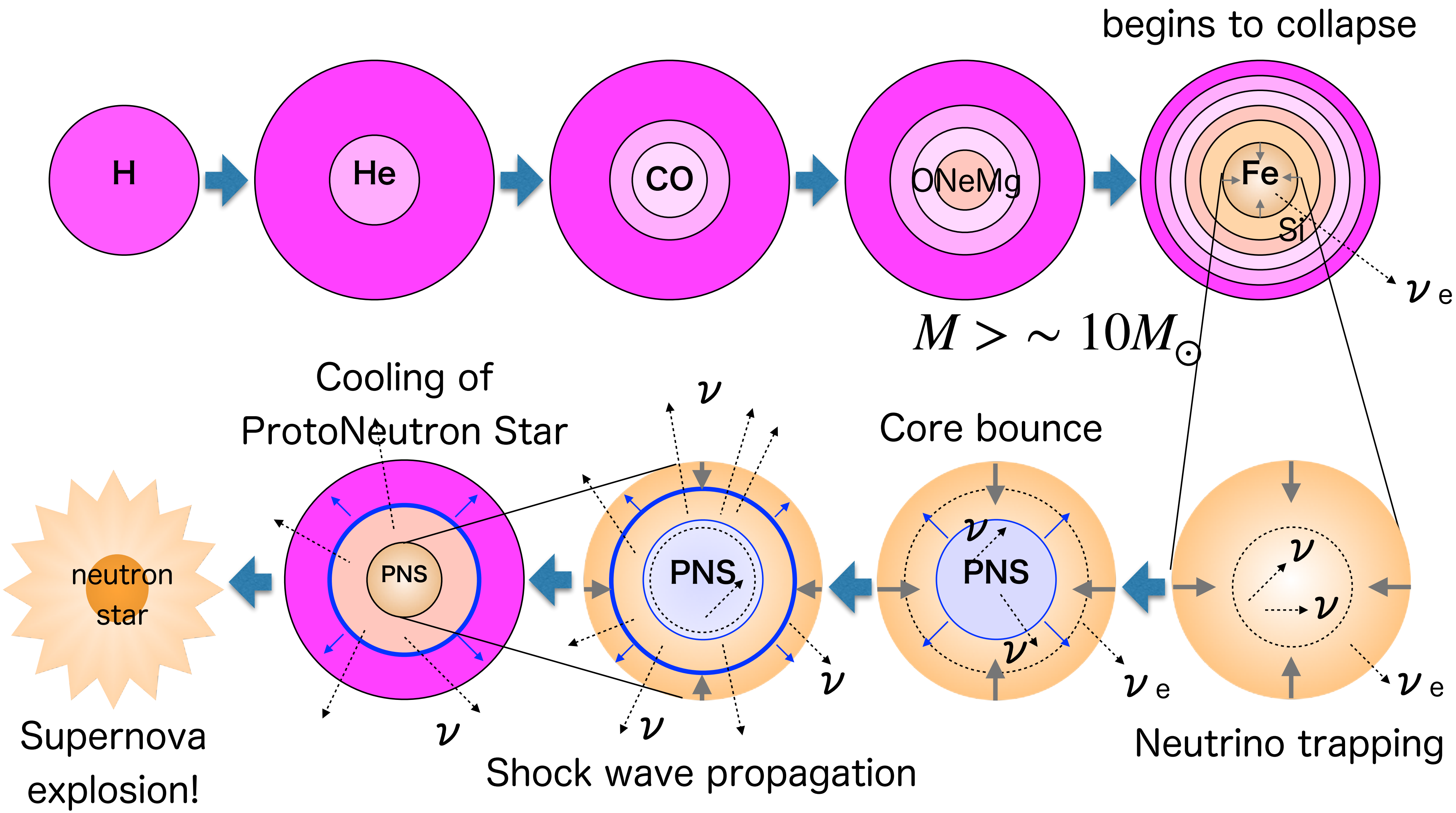



Supernova neutrinos

Life cycle of a star

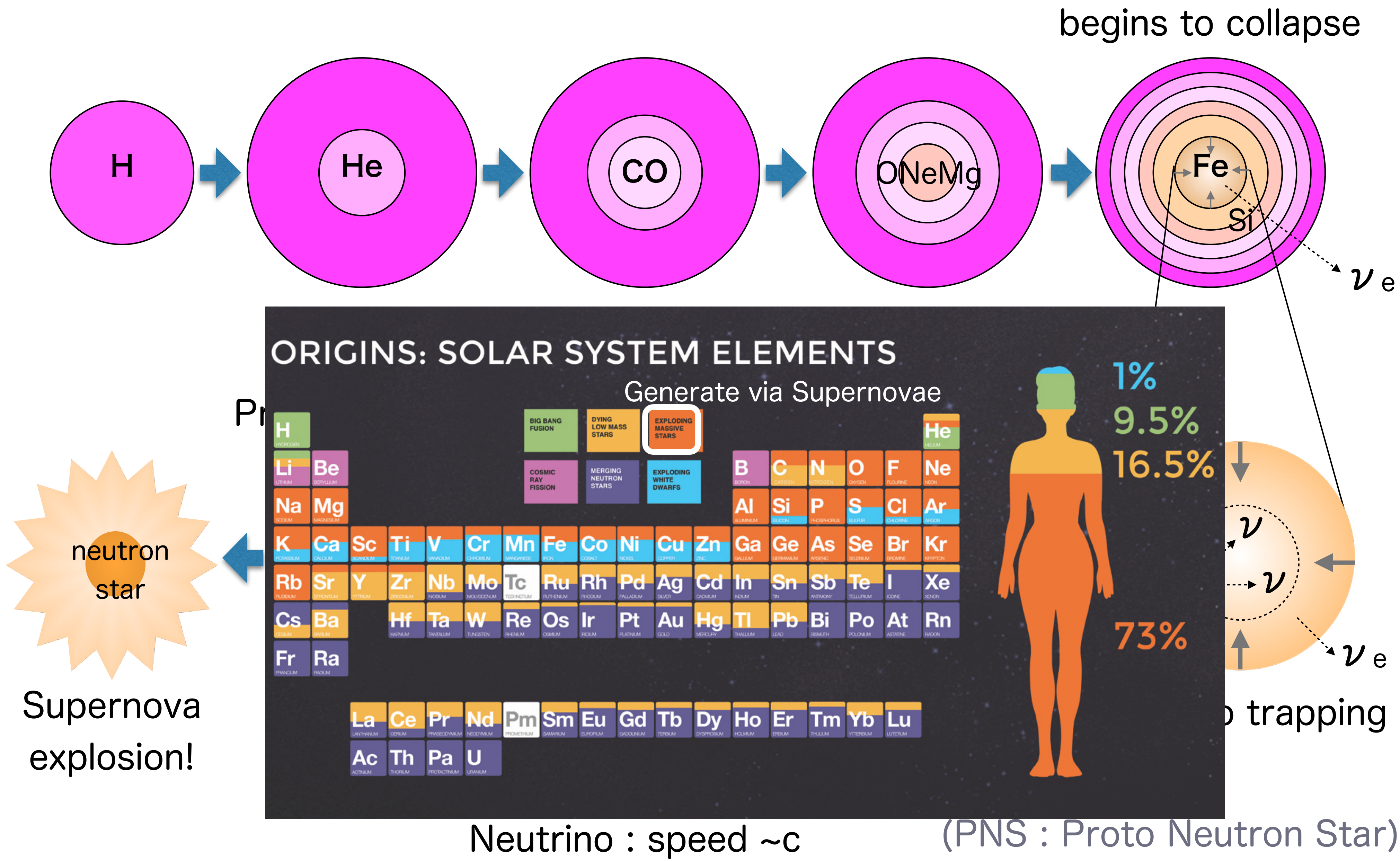


Core-Collapse Supernovae



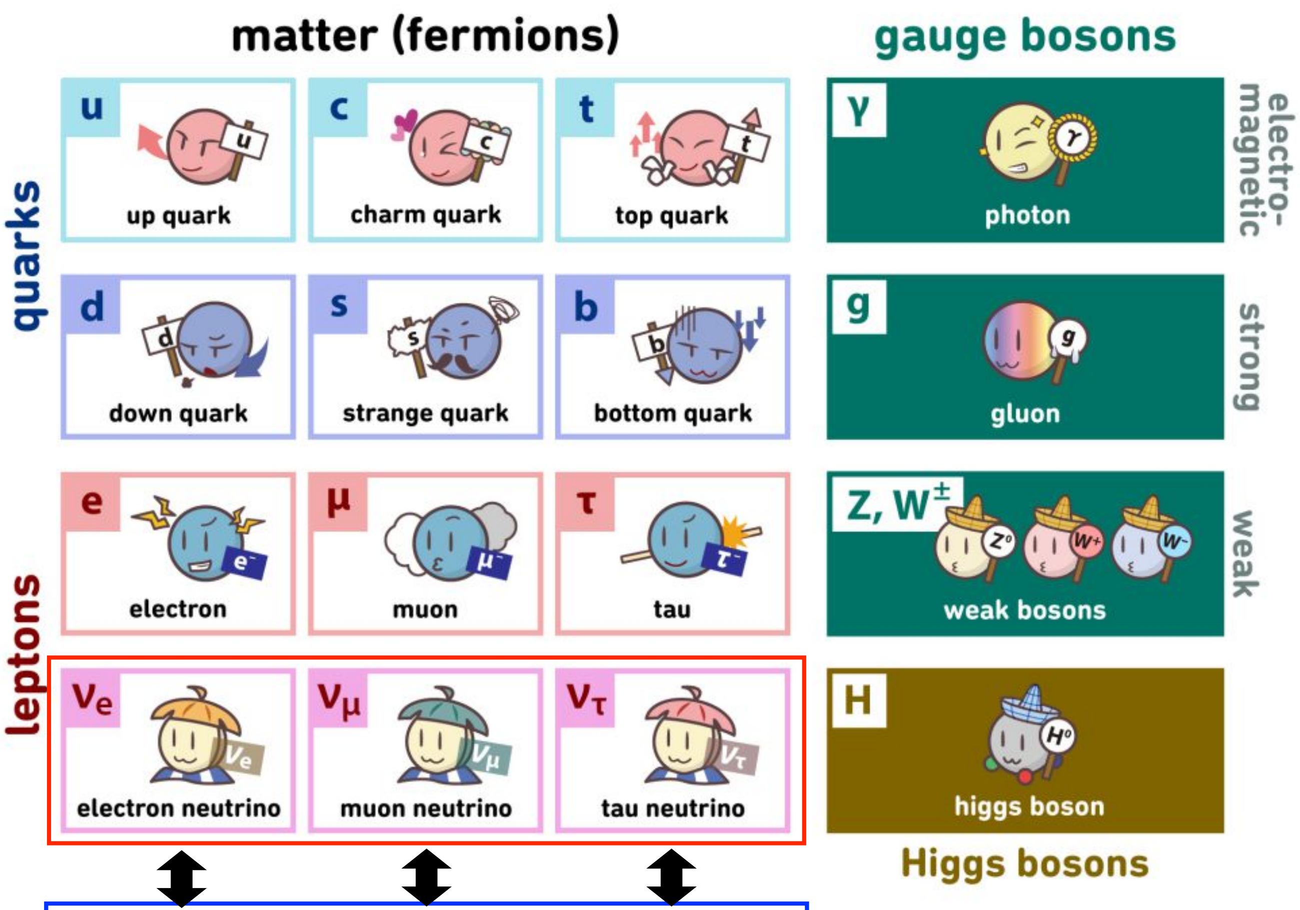
(PNS : Proto Neutron Star)

Core-Collapse Supernovae



What's neutrinos

http://higgstan.com

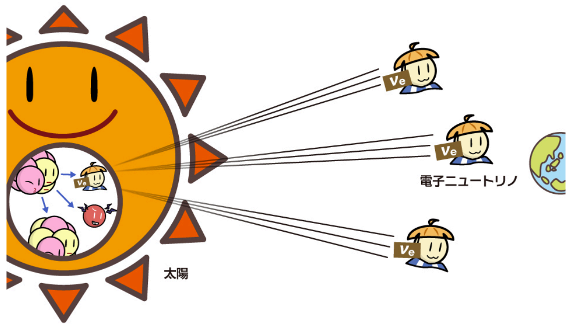


electron antineutrino $(\bar{\nu}_e)$	muon antineutrino $(\bar{\nu}_\mu)$	tau antineutrino $(\bar{\nu}_\tau)$

Properties of neutrinos

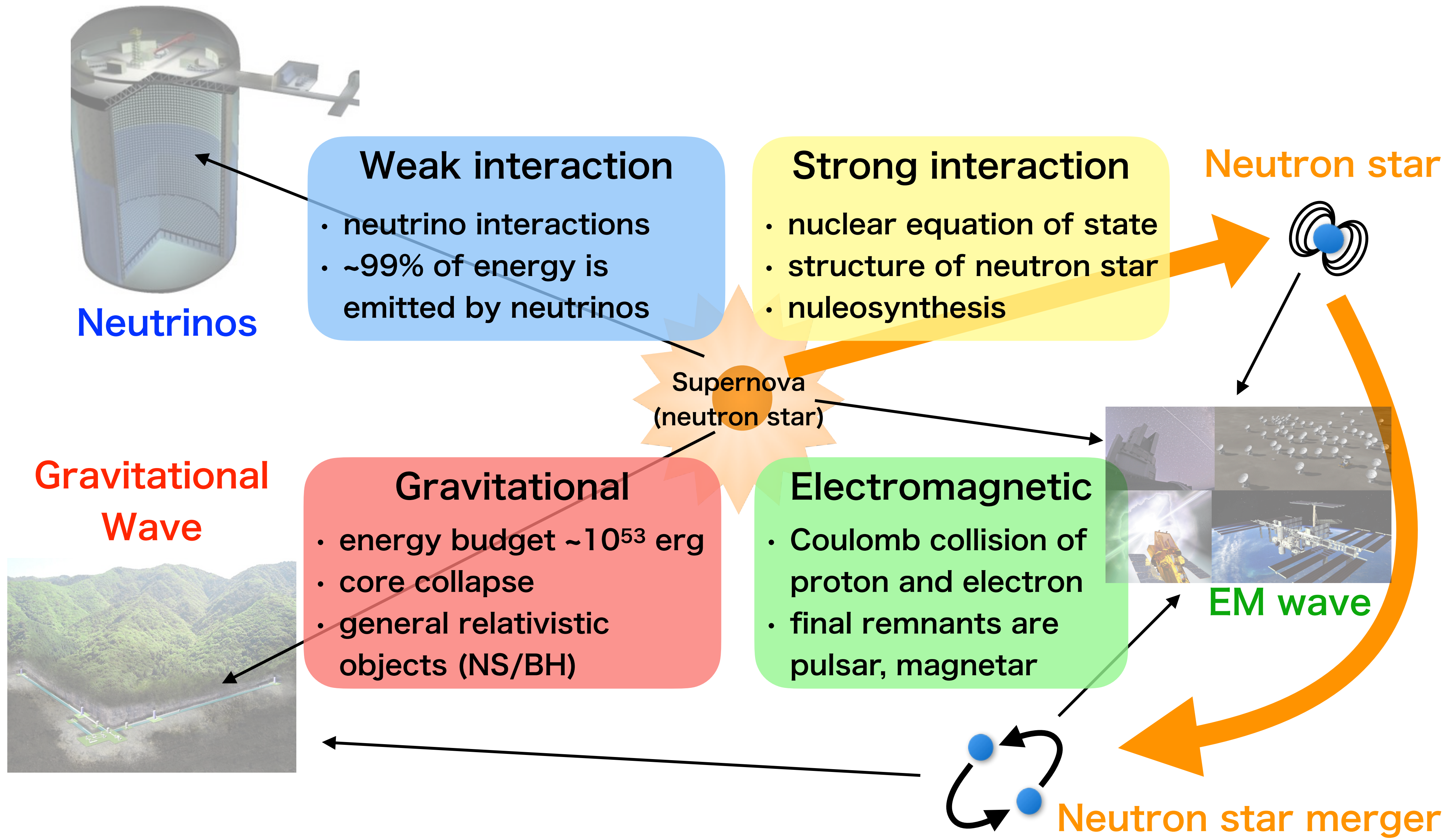
- Three flavors
- No electric charge
- Rarely interact with matter

Large numbers of neutrinos are constantly passing through us



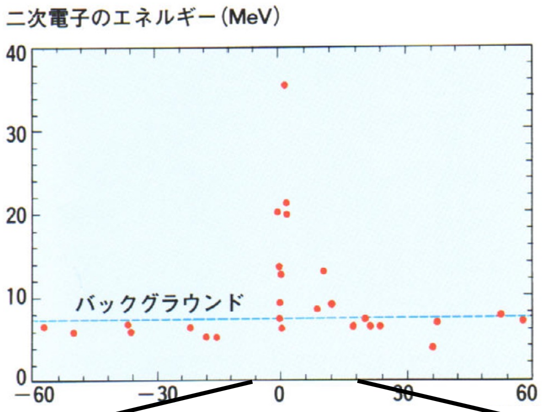
For example, 60,000,000,000 cm^{-2} sec^{-1} neutrinos reach Earth from the Sun

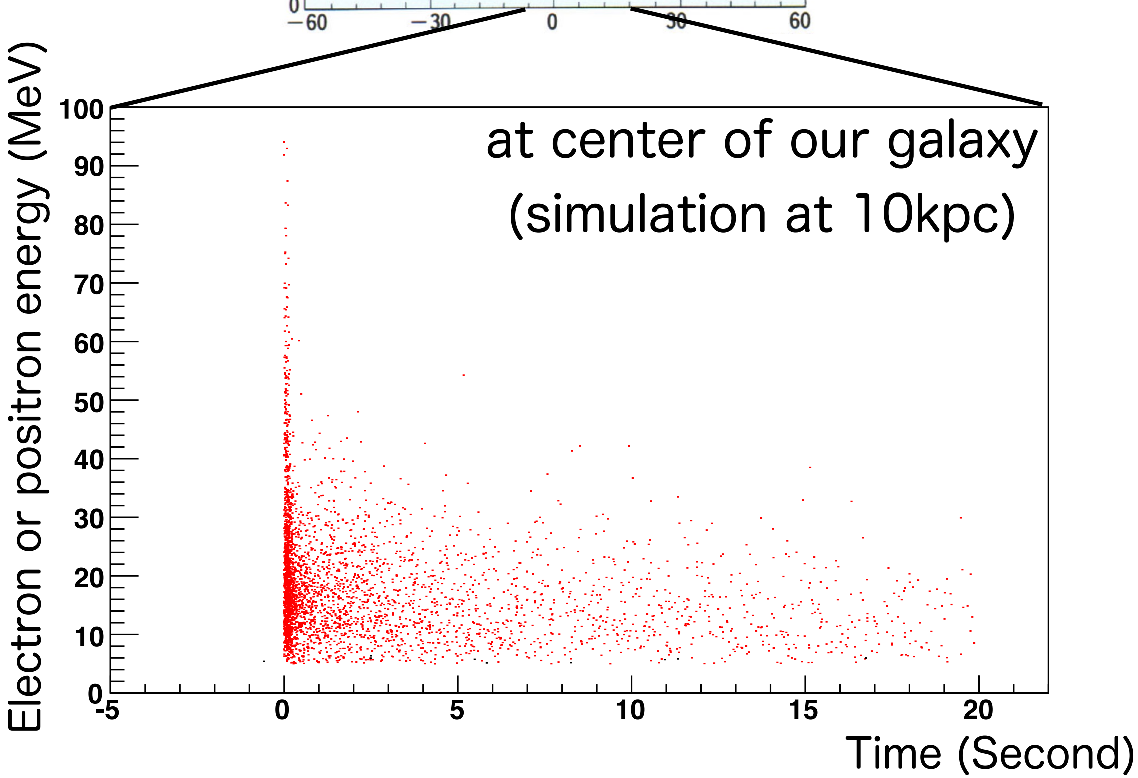
Supernova as 'Multi-physics' object



If a nearby supernova happens now..

11 events in KAMIOKANDE for SN1987A





Order of thousands of neutrino signal is expected in Super-Kamiokande

Simulated Supernova

As Seen in Real-Time by Super-K

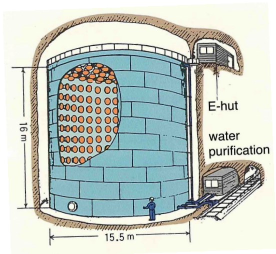
Movie by: Cully Little

Acknowledgments: this movie made use of the tscan event display (primary author Tomasz Barsczak), Super-K collaboration software tools and the previous efforts of Steve Farrell and Ben Reed.

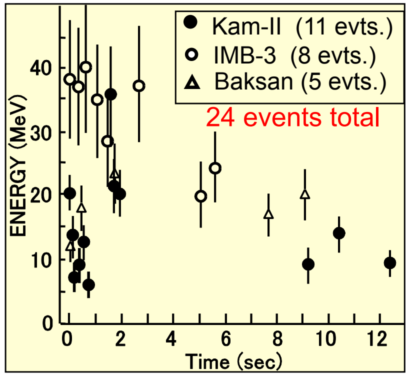

Super-Kamiokande
n, p, e-

Three generations of “Kamiokande”

KAMIOKANDE (1983-1995)

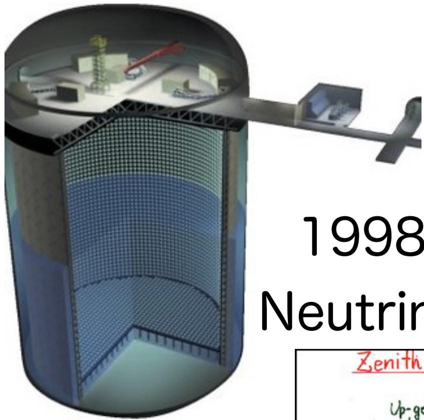


3000 ton



SN1987A

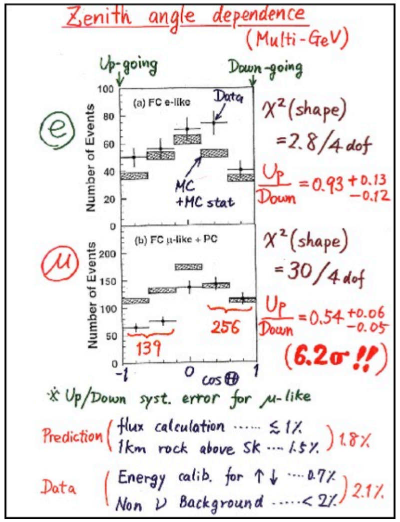
Super-Kamiokande (1996-)



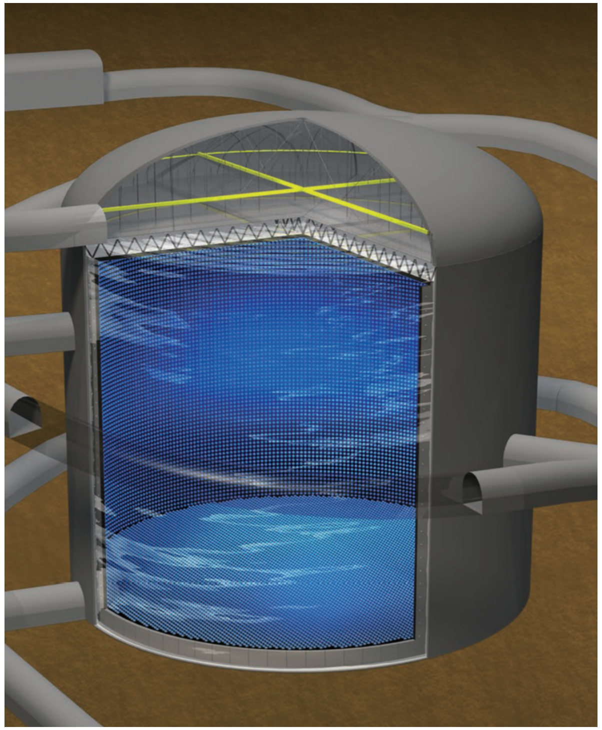
50,000 ton

1998 Takayama

Neutrino oscillation



Hyper-Kamiokande (2027-)

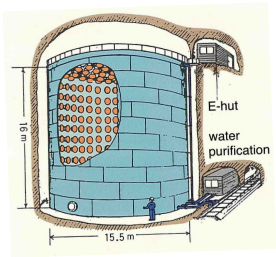


260,000 ton

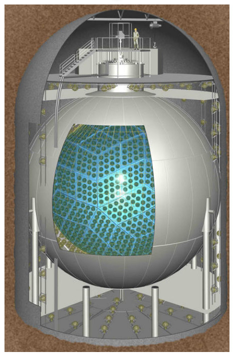
What can we find?

Three generations of "Kamiokande"

KAMIOKANDE (1983-1995)

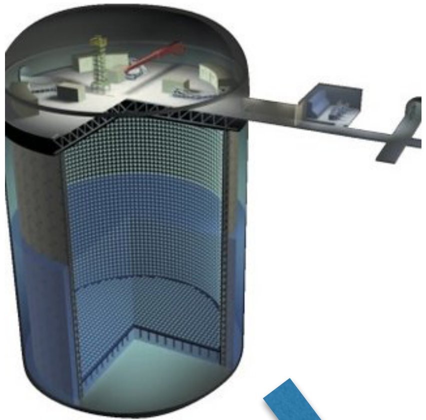


3000 ton



KamLAND (2002-)

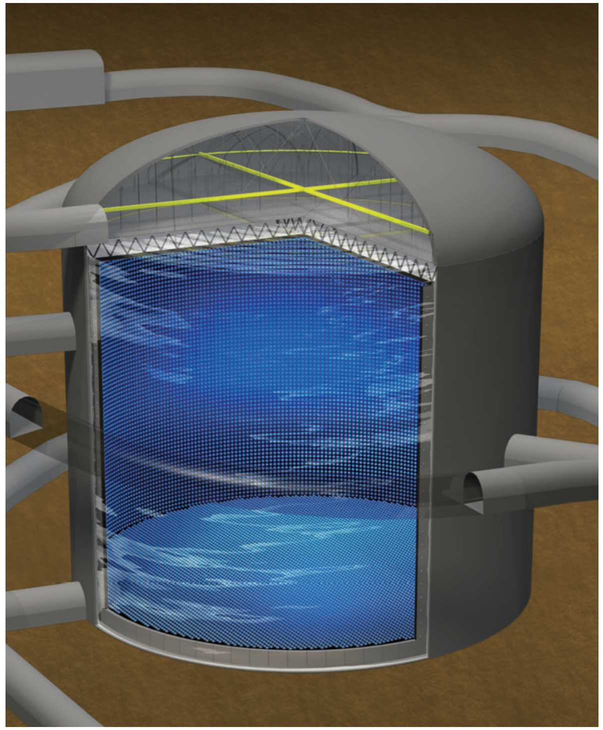
Super-Kamiokande (1996-)



50,000 ton

SK-Gd (2020-)

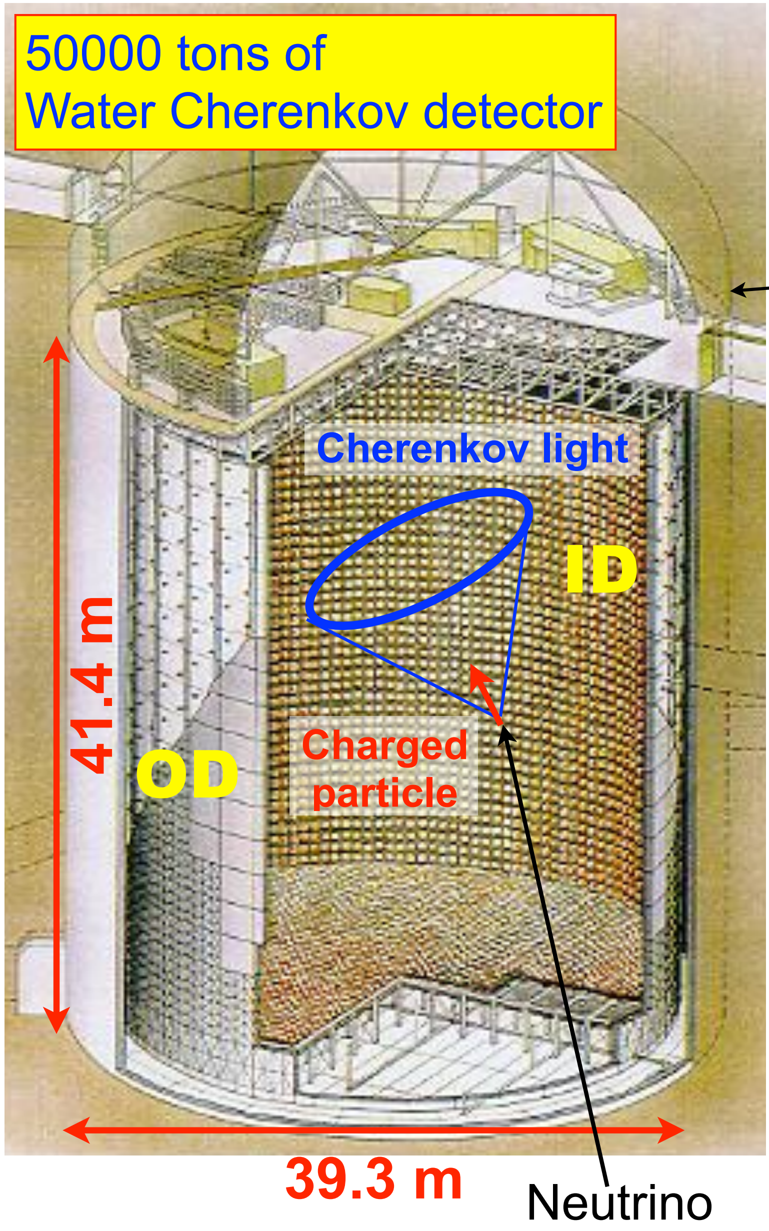
Hyper-Kamiokande (2027-)

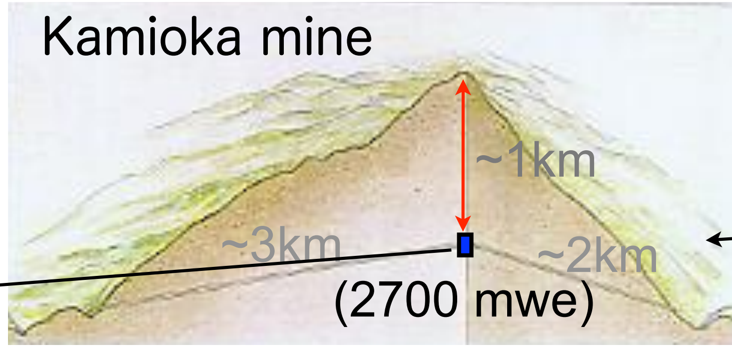


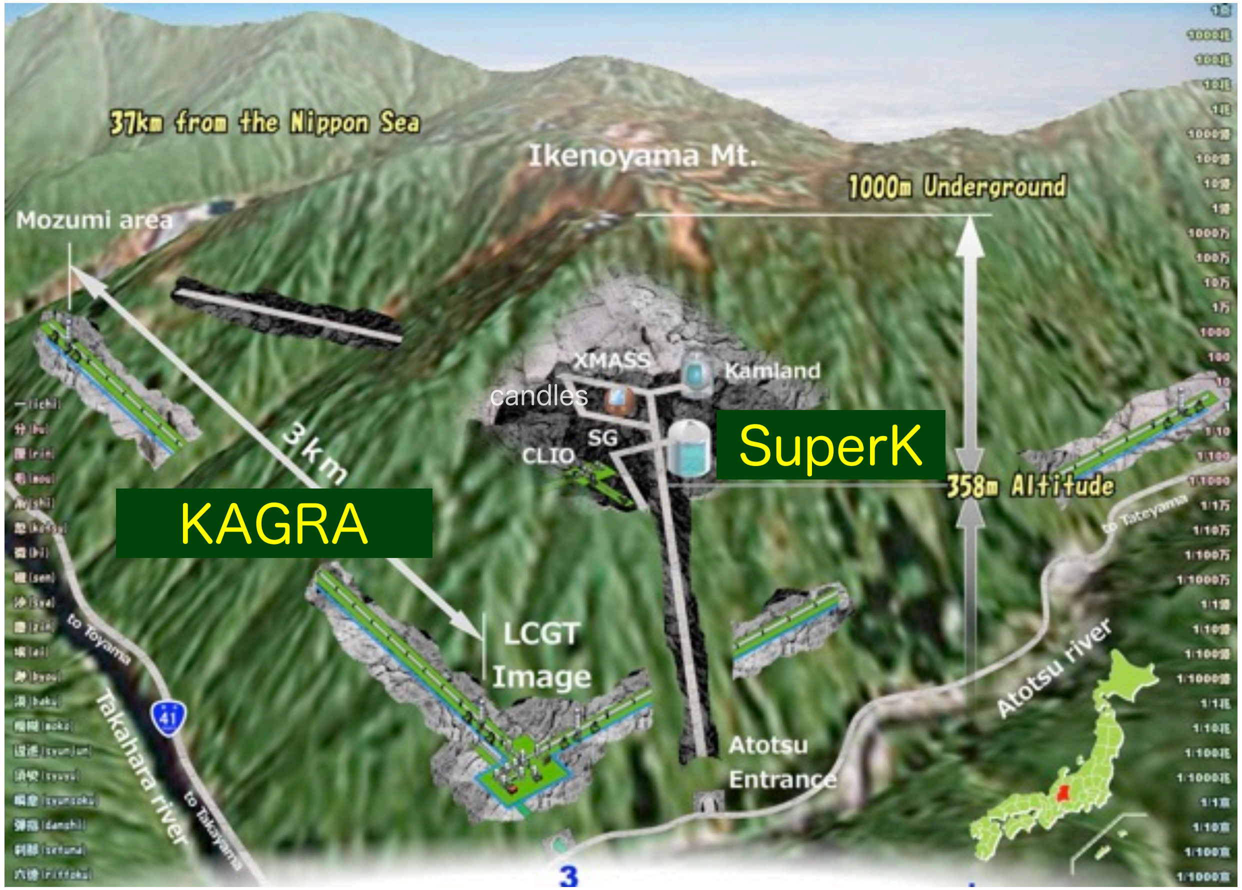
260,000 ton

What can we find?

Super-Kamiokande (SK)





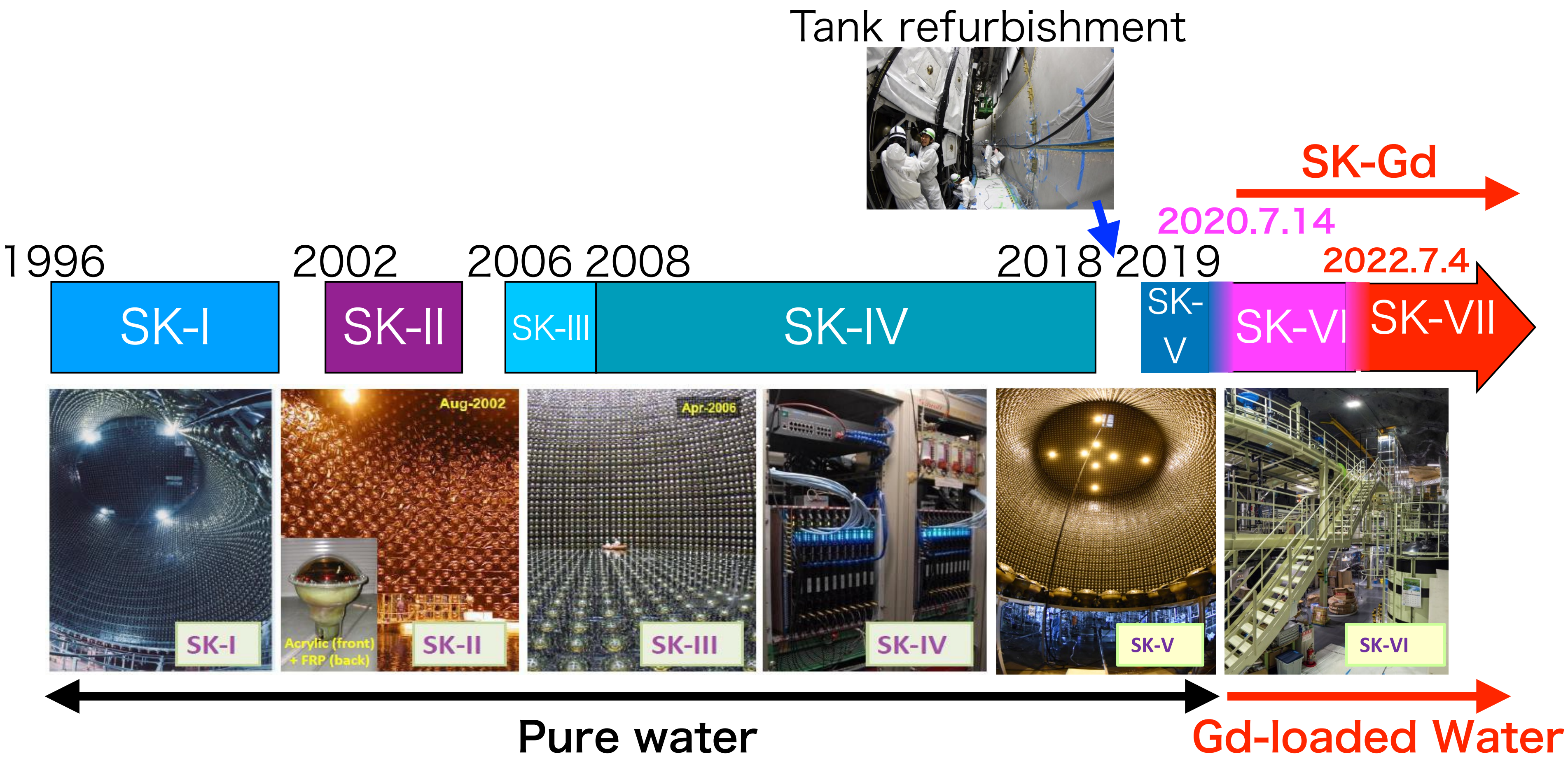


Super-Kamiokande collaboration

Kamioka Observatory, ICRR, Univ. of Tokyo, Japan
RCCN, ICRR, Univ. of Tokyo, Japan
University Autonoma Madrid, Spain
BC Institute of Technology, Canada
Boston University, USA
University of California, Irvine, USA
California State University, USA
Chonnam National University, Korea
Duke University, USA
Fukuoka Institute of Technology, Japan
Gifu University, Japan
GIST, Korea
University of Hawaii, USA
IBS, Korea
IFIRSE, Vietnam
Imperial College London, UK
ILANCE, France
INFN Bari, Italy
INFN Napoli, Italy
INFN Padova, Italy
INFN Roma, Italy
Kavli IPMU, The Univ. of Tokyo, Japan
Keio University, Japan
KEK, Japan
King's College London, UK
Kobe University, Japan
Kyoto University, Japan
University of Liverpool, UK
LLR, Ecole polytechnique, France
Miyagi University of Education, Japan
ISEE, Nagoya University, Japan
NCBJ, Poland
Okayama University, Japan
University of Oxford, UK
Rutherford Appleton Laboratory, UK
Seoul National University, Korea
University of Sheffield, UK
Shizuoka University of Welfare, Japan
Sungkyunkwan University, Korea
Stony Brook University, USA
Tohoku University, Japan
Tokai University, Japan
The University of Tokyo, Japan
Tokyo Institute of Technology, Japan
Tokyo University of Science, japan
TRIUMF, Canada
Tsinghua University, China
University of Warsaw, Poland
Warwick University, UK
The University of Winnipeg, Canada
Yokohama National University, Japan

~230 collaborators from 51 institutes in 11 countries

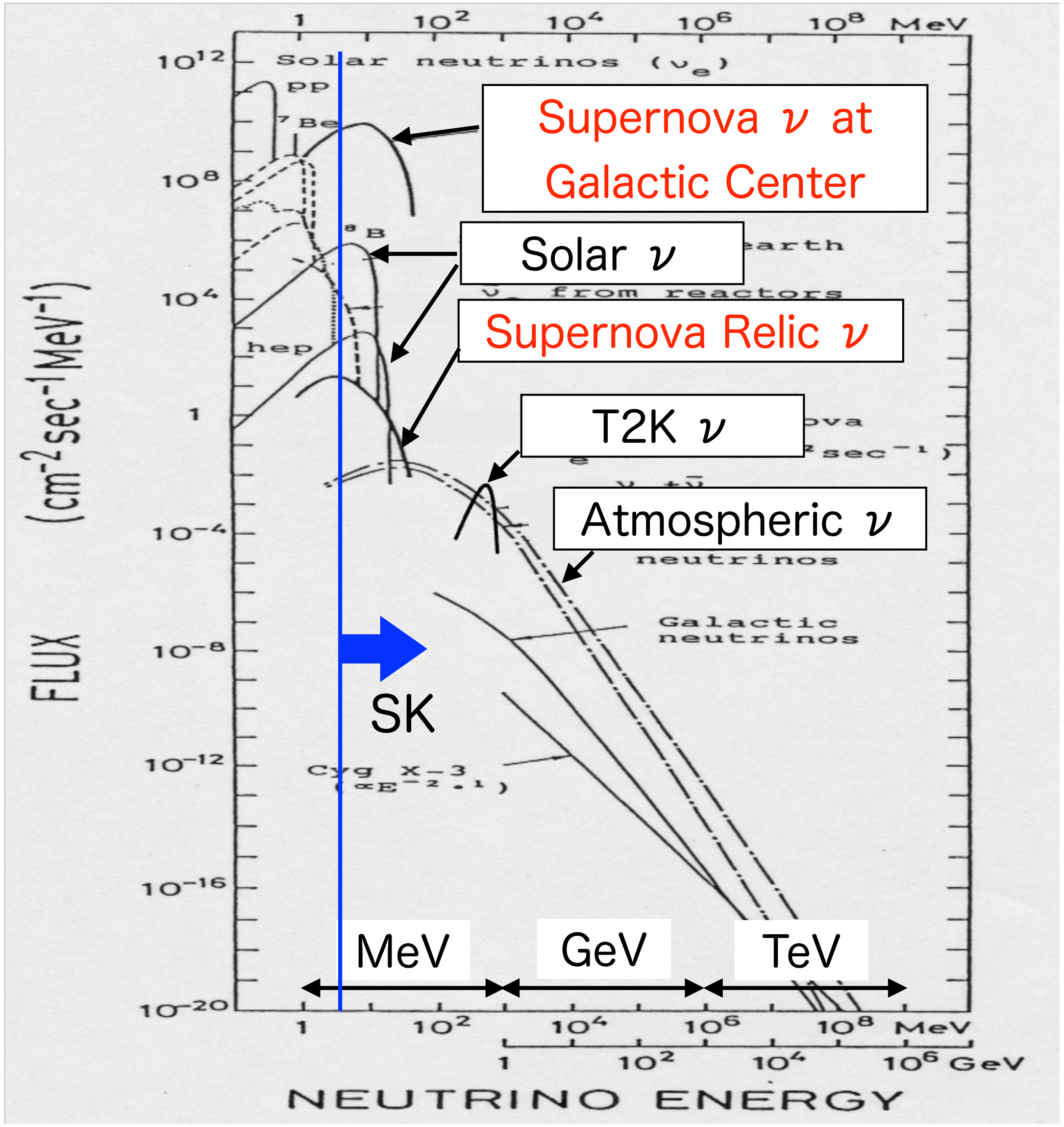
History of the Super-Kamiokande



'SK-Gd' is a broad and general term for the experiment after the start of the Gd-loading

Multi-purpose detector

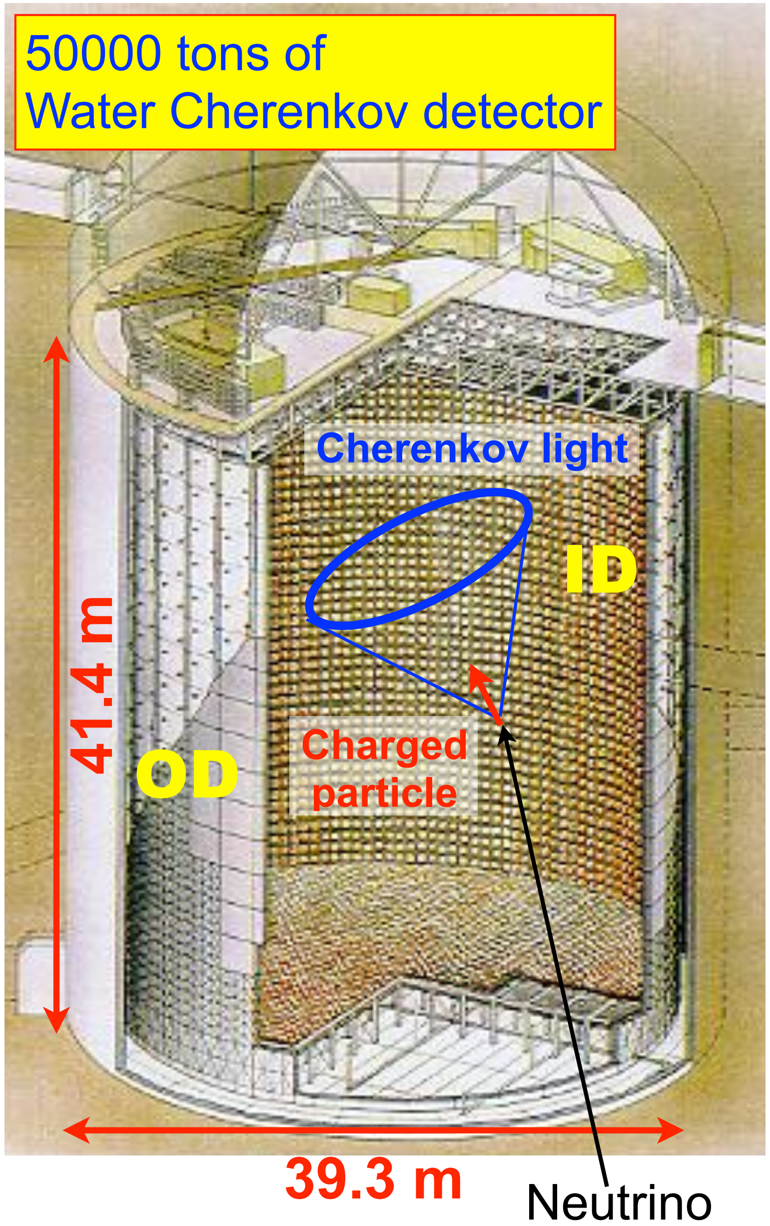
Various neutrino sources



- Neutrino observation with wide energy range (from MeV to TeV)
    - Solar (< 20MeV)
    - Supernova (< 100MeV)
    - Atmospheric (100MeV~TeV)
    - T2K (~600 MeV)
- Proton decay search
- Dark matter search

etc..

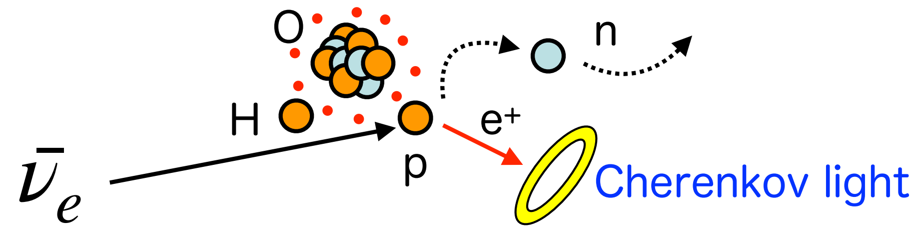
Supernova neutrino detection in SK



Targets of neutrinos are oxygen nuclei, protons and electrons in water

Inverse beta decay

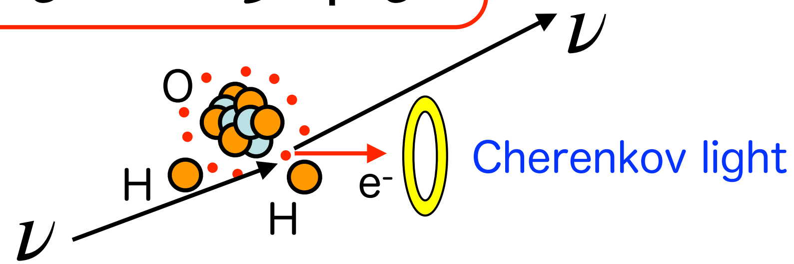
$$\bar{\nu}_e + p \rightarrow e^+ + n$$



more than 100 times larger cross section

Electron elastic scattering

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

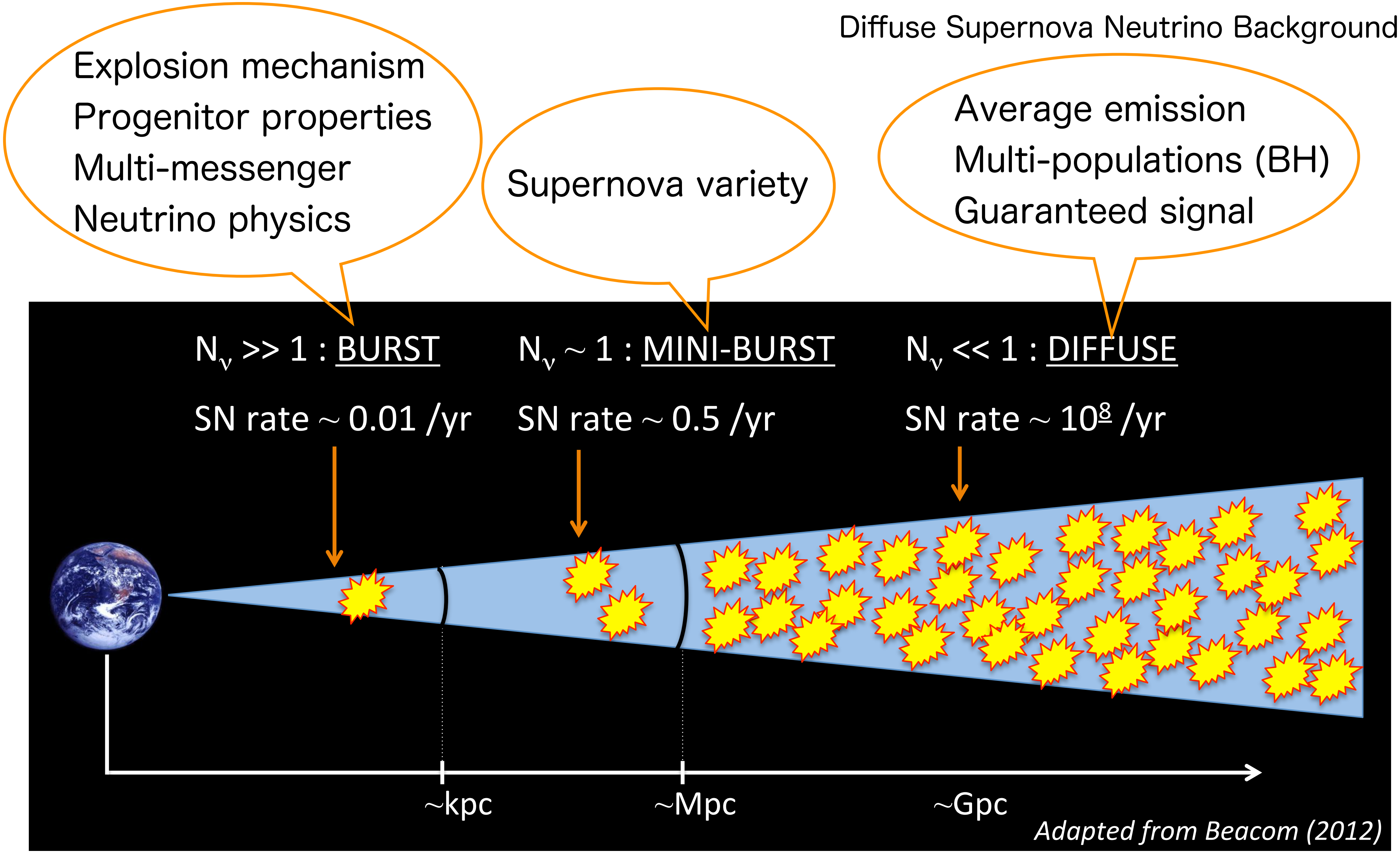


Search for Diffuse Supernova Neutrino Background (DSNB)

$\nu_e, \bar{\nu}_e$

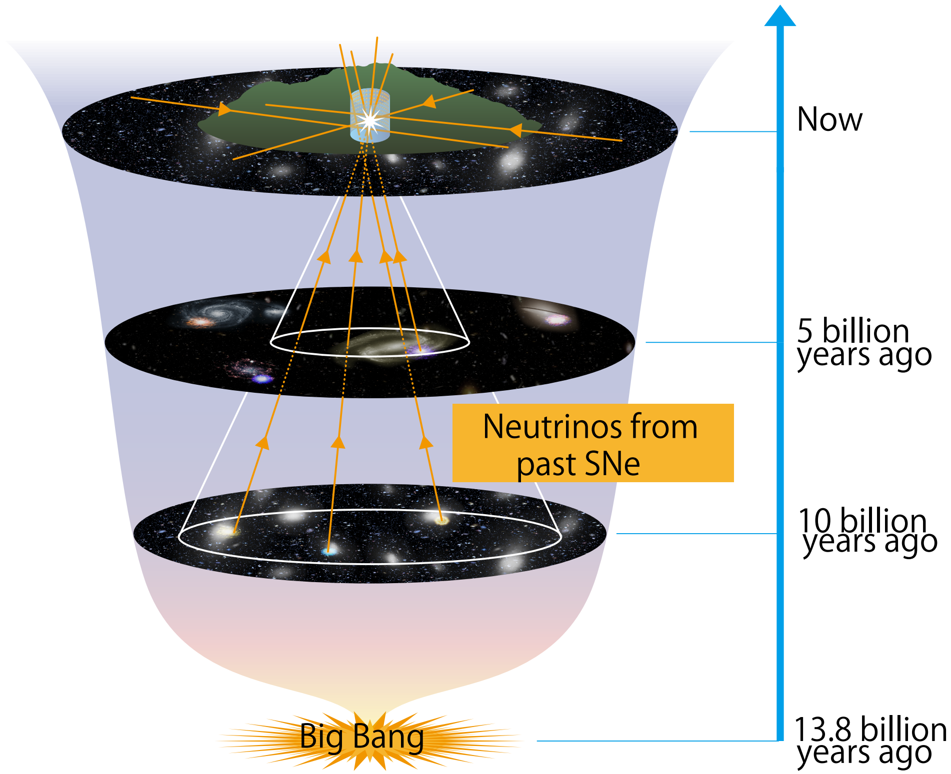
n, p, e^-

Distance scales and physics outcomes of Supernova Neutrinos

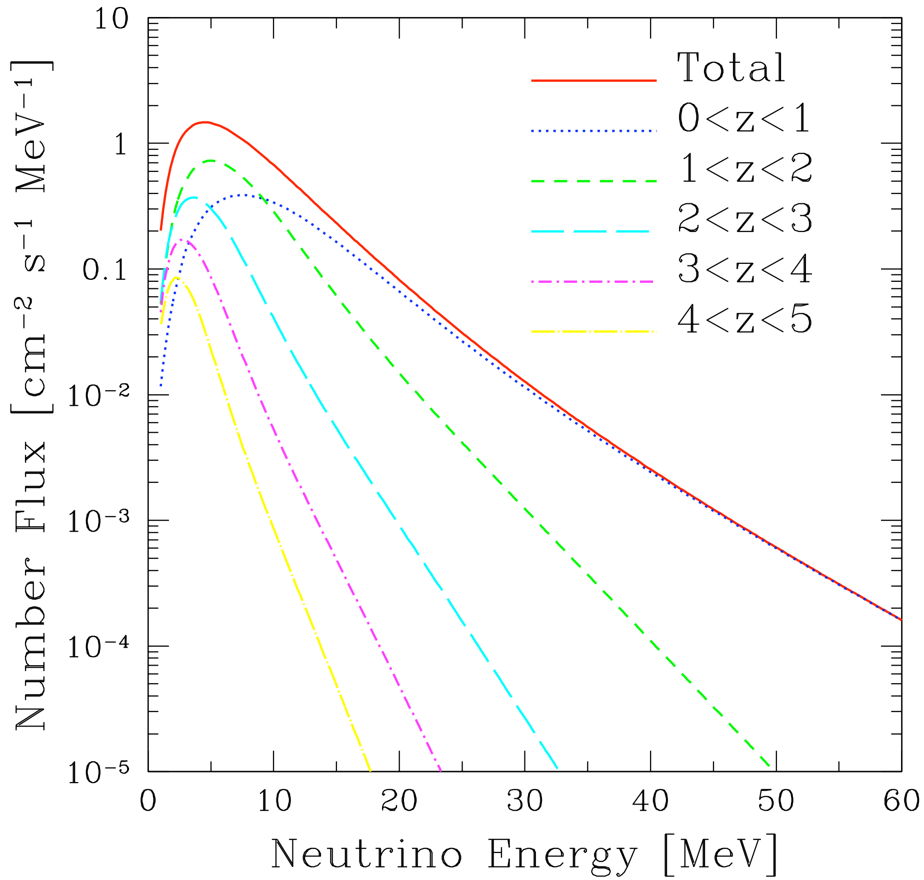


Diffuse Supernova Neutrino Background

(DSNB)



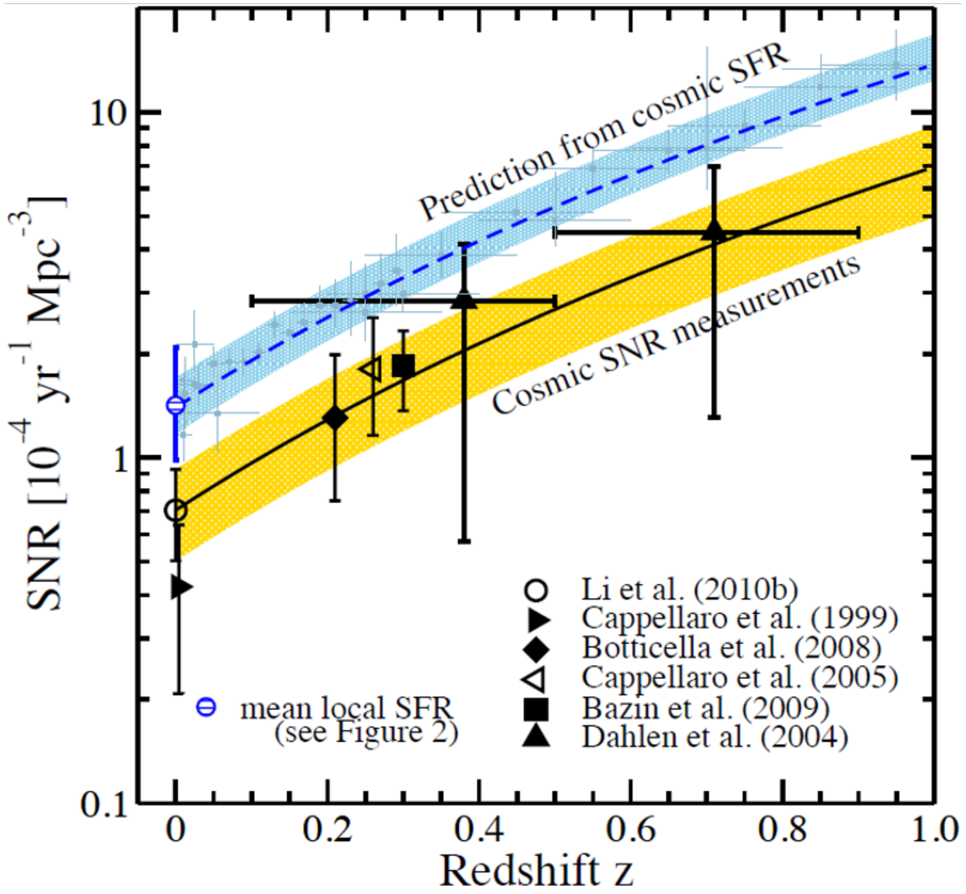
S. Ando, Astrophys. J. 607, 20 (2004)



Neutrinos emitted from past supernovae ~$O(10^{18})$

What do DSNB observation tell us?

Supernova rate problem

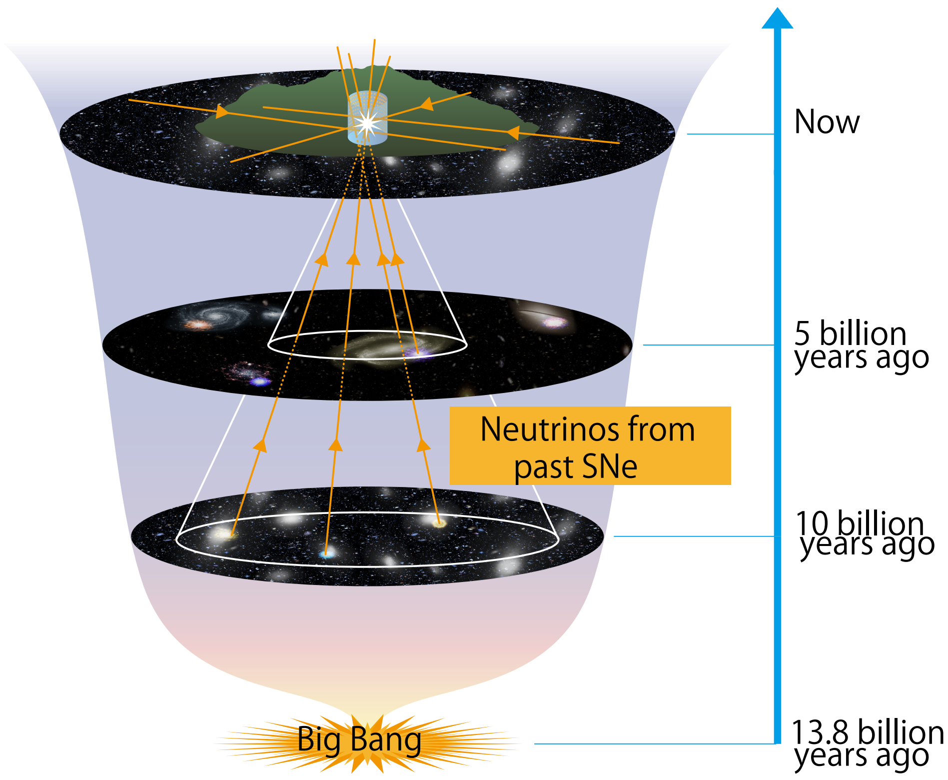


S. Horiuchi et al., Astrophys. J. 738, 154 (2011)

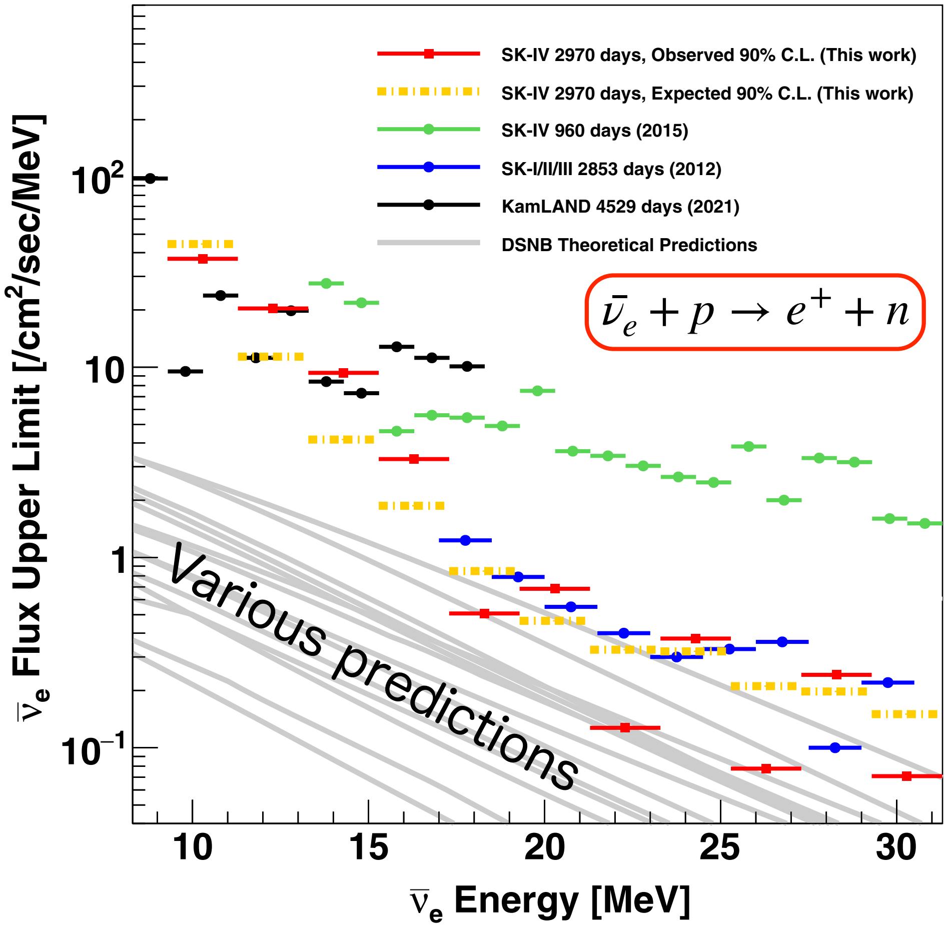
- Observed supernova rate is about half of expectation from star formation rate.
- What is the problem?
  - More supernovae are too dark to be observed?
  - Effect of "something" which interrupts observation?

Observation of DSNB can give critical information on the supernova rate

DSNB search before SK-Gd



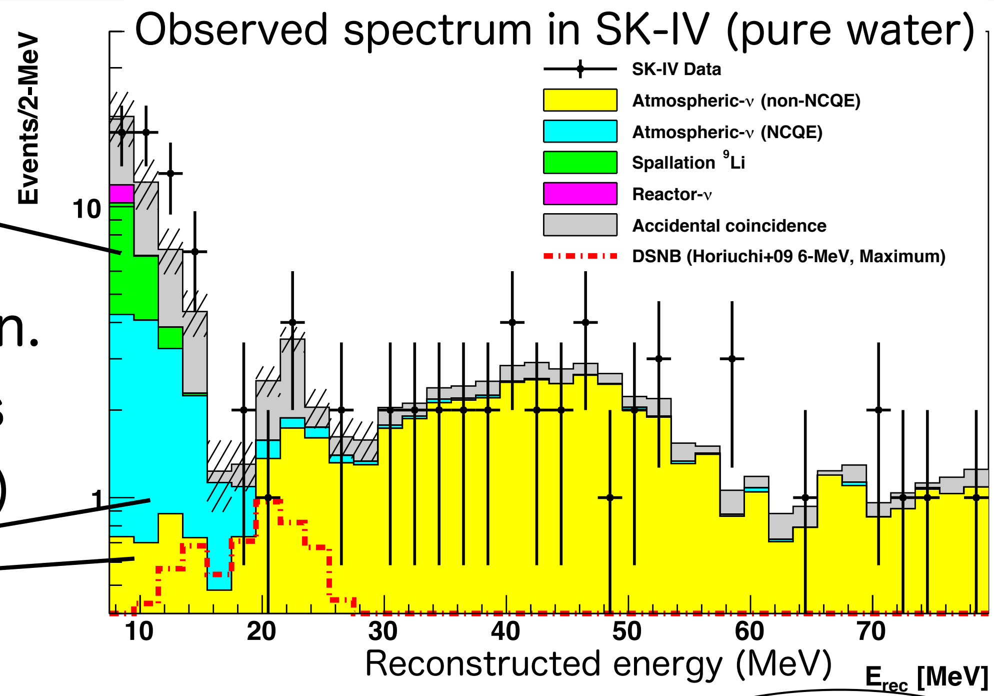
Results in pure water phase (~2018)



Not observed, but the upper limit is approaching the predicted values.

What is the limit?

Background event



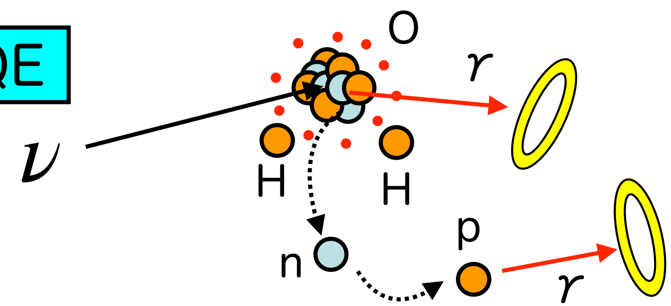
^{9}Li by muon spallation

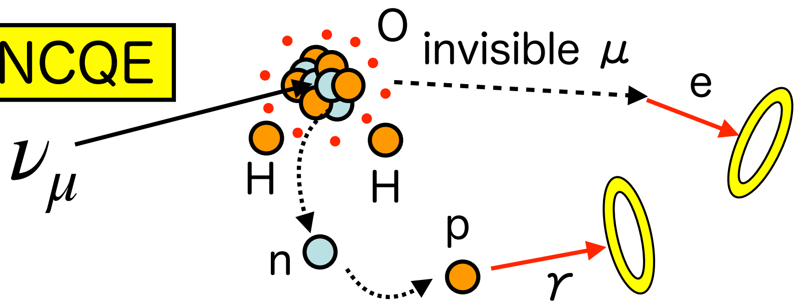
Cosmic muons (~2Hz at SK) make radio isotope after oxygen spallation. Lithium-9 is decay of β+n, which is not identified to DSNB signal (e^{+}+n)

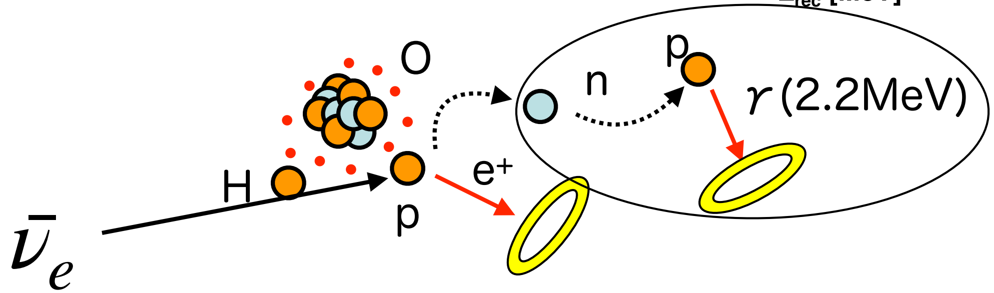
Atmospheric neutrinos

NCQE

non-NCQE







Neutron tagging efficiency was < 20%, not enough for the discovery of DSNB

'SK-Gd' project

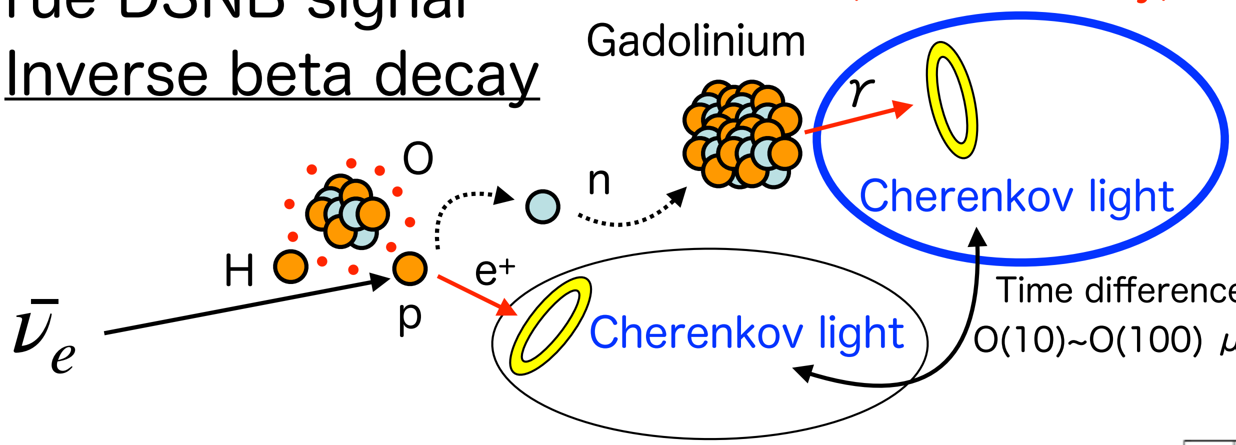
SK-Gd

Original idea (2004)

True DSNB signal

Inverse beta decay

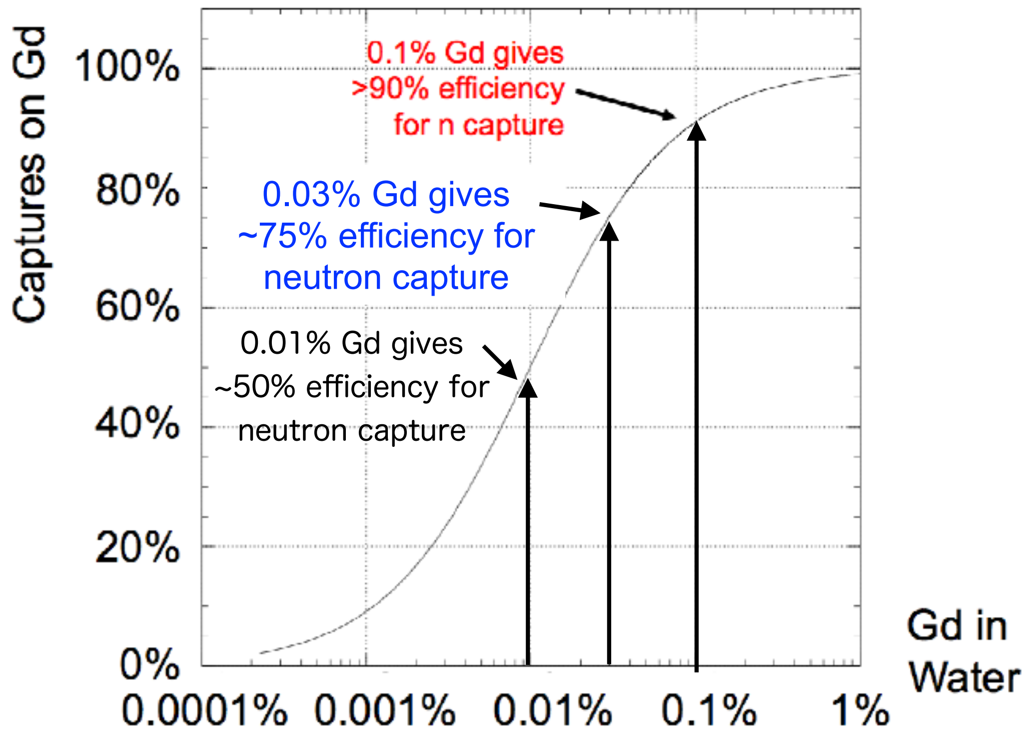
J.Beacom and M.Vagins PRL 93 (2004) 171101



Neutron can be detected with delayed gamma-ray signal from capture on Gd

- Largest neutron capture cross section among all of the elements.
- Emit energetic gamma-rays (~8MeV) after neutron capture.

Neutron tagging efficiency increases even if it is small amount of Gd



Long road to start SK-Gd

How to dissolve Gd into water?

Gd is a metal, not soluble in water → water-soluble compound

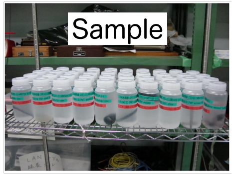
Gadolinium hydrochloride ($GdCl_3$) → Rusts even stainless steel..

Gadolinium nitrate ($Gd(NO_3)_3$) → Bad water transparency..

Gadolinium sulfate ($Gd_2(SO_4)_3$) looks good!

We could not just put them into SK water

A resistance test in which 'ALL' components in SK are immersed into Gd sulfate solution water



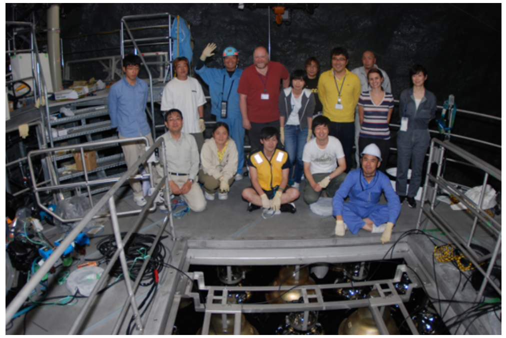
Passed!

EGADS (2009-)

Evaluating Gadolinium's Action on Detector Systems

A mini-tank imitating SK was built underground for verification

Completed in August 2013



SK tank refurbishment (2018)

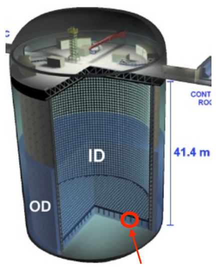
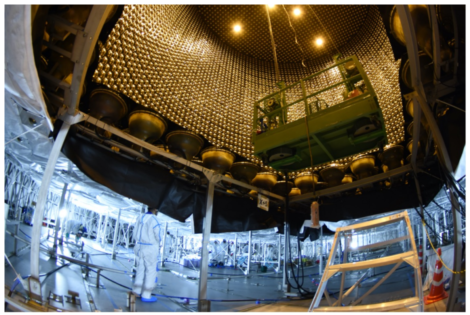


Photo taken from this area looking upward →

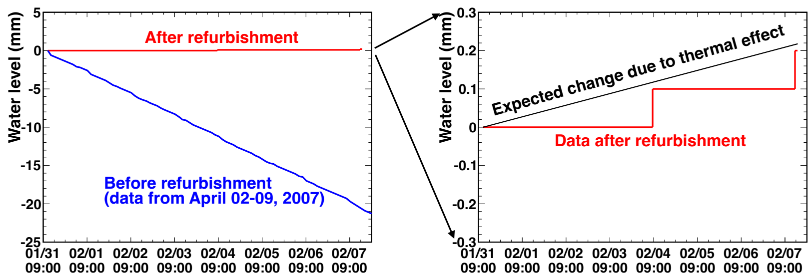
Open the tank for the fist time in 12 years



- Tank leak repair
- Reinforcement of water pipe
  - Doubled the flow rate of water circulation 60m³/h → 120m³/h
- Replacement of 136 broken PMTs
  - Install PMTs which will be used for Hyper-Kamiokande

What about the water leak?

Water leak test : measured the water level



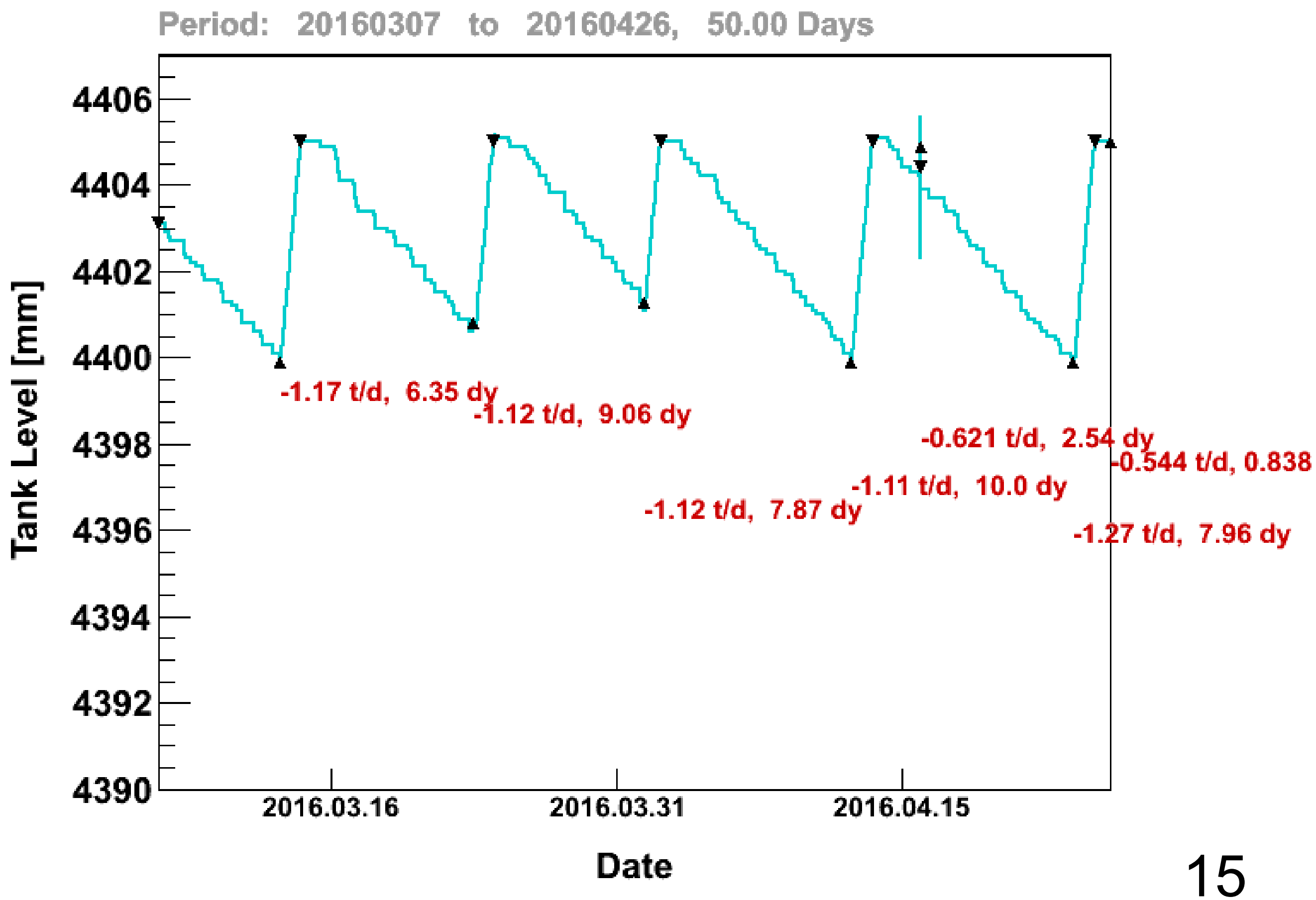
No significant water leak was seen.

Passed the final exam.!

Water leak in SK tank

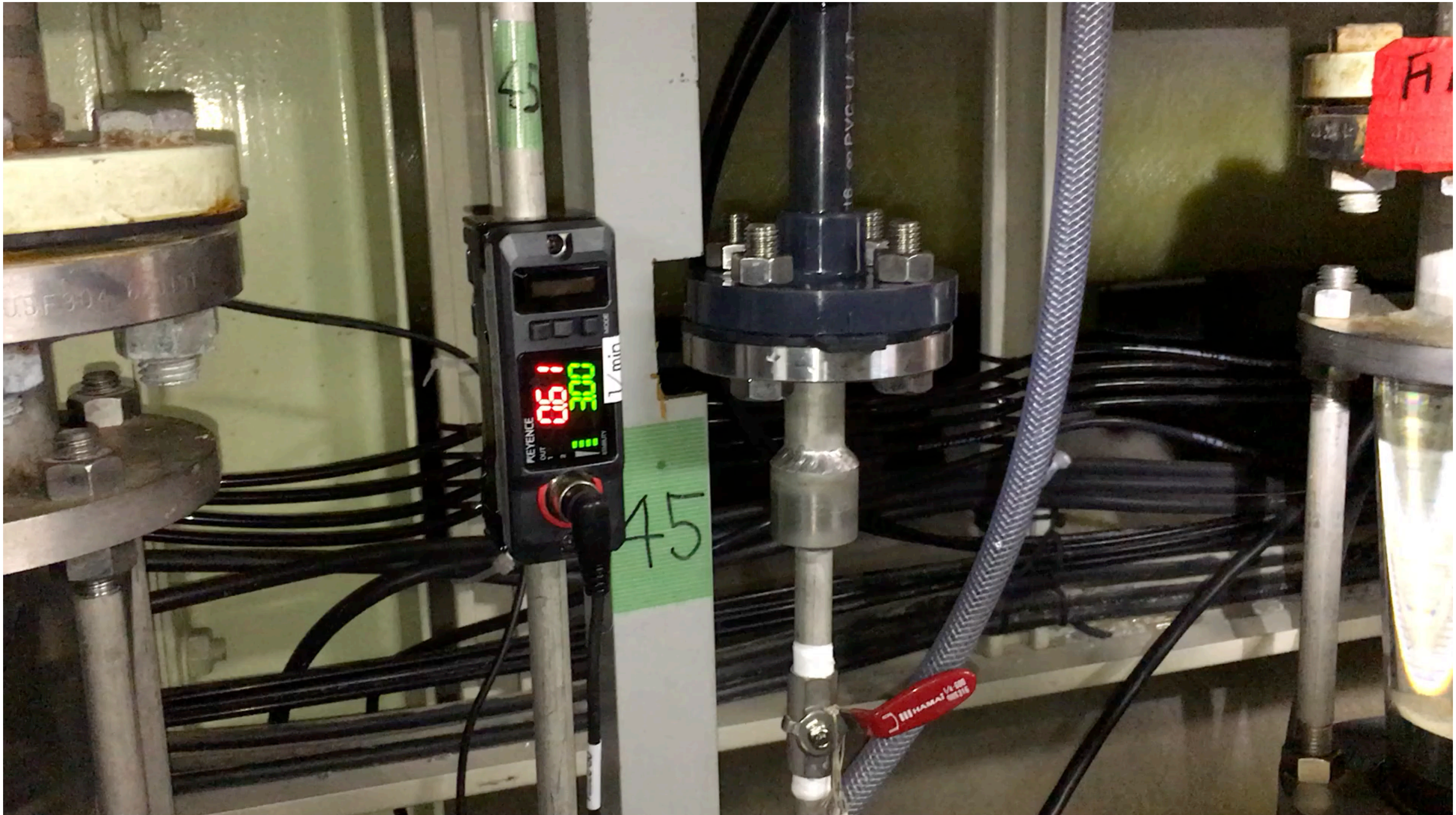
<u>About 1ton water leak per day</u>

Water level at SK

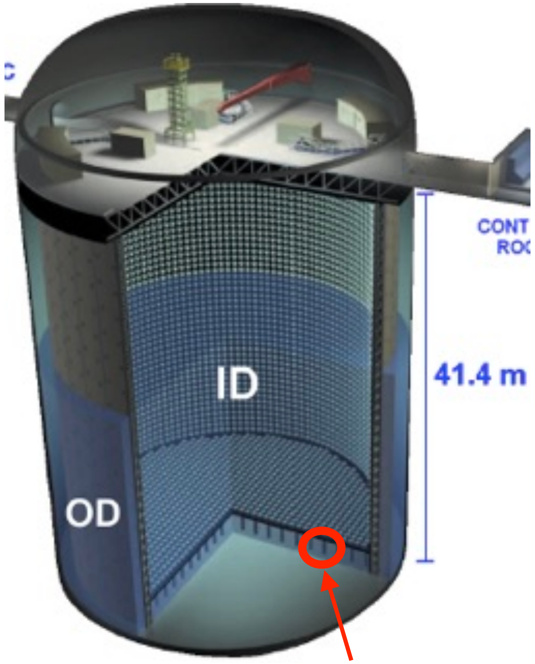


Water leak in SK tank

About 1ton water leak per day



SK tank refurbishment (2018)



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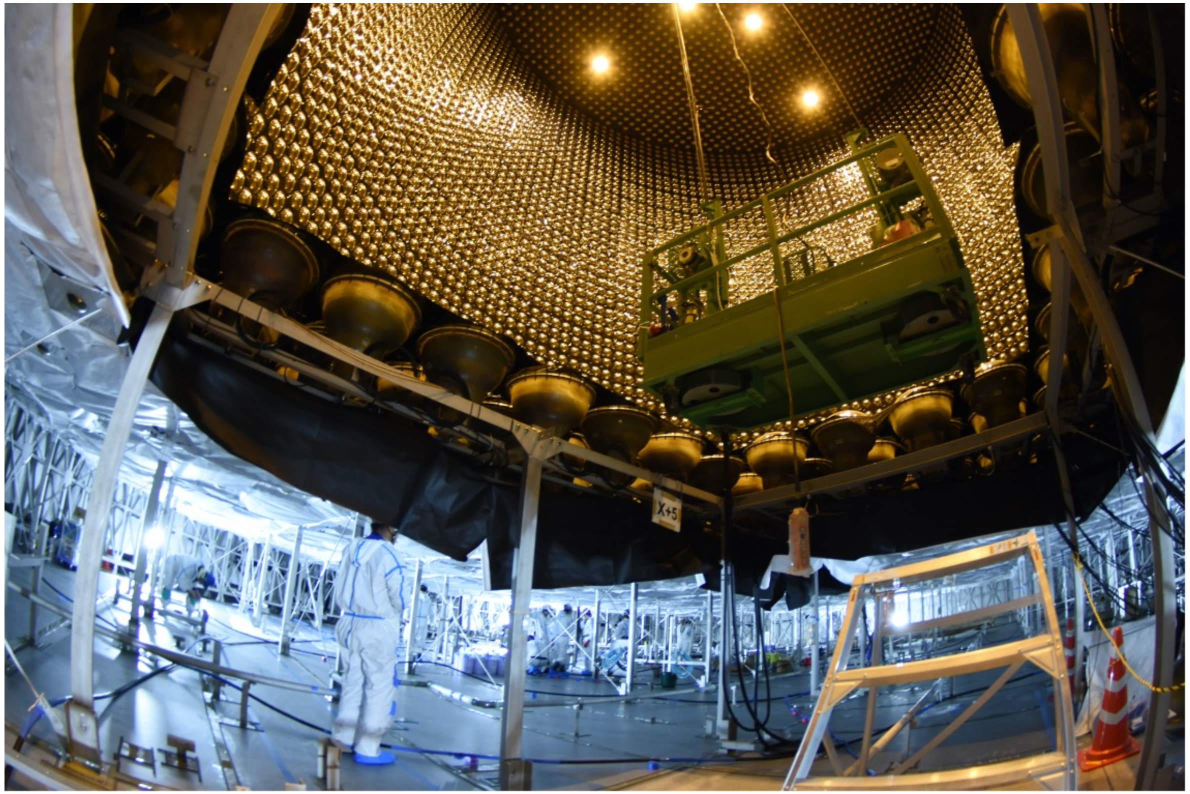

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  - Doubled the flow rate of water circulation $60m^3/h \rightarrow 120m^3/h$
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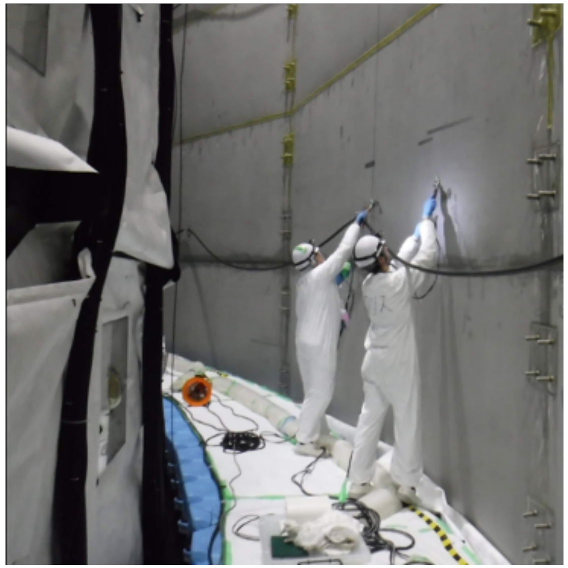
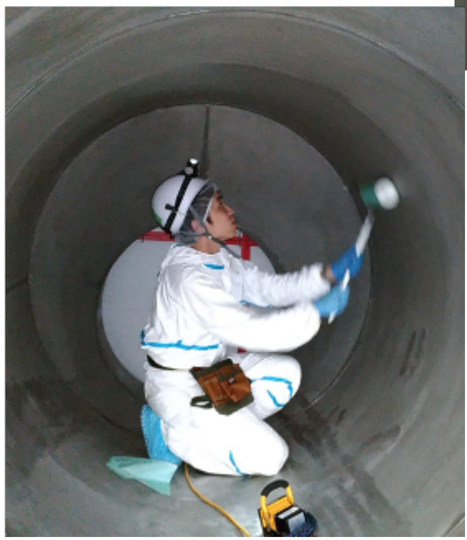
SK tank refurbishment (2018)

Work with collaborators and volunteer students from around the world





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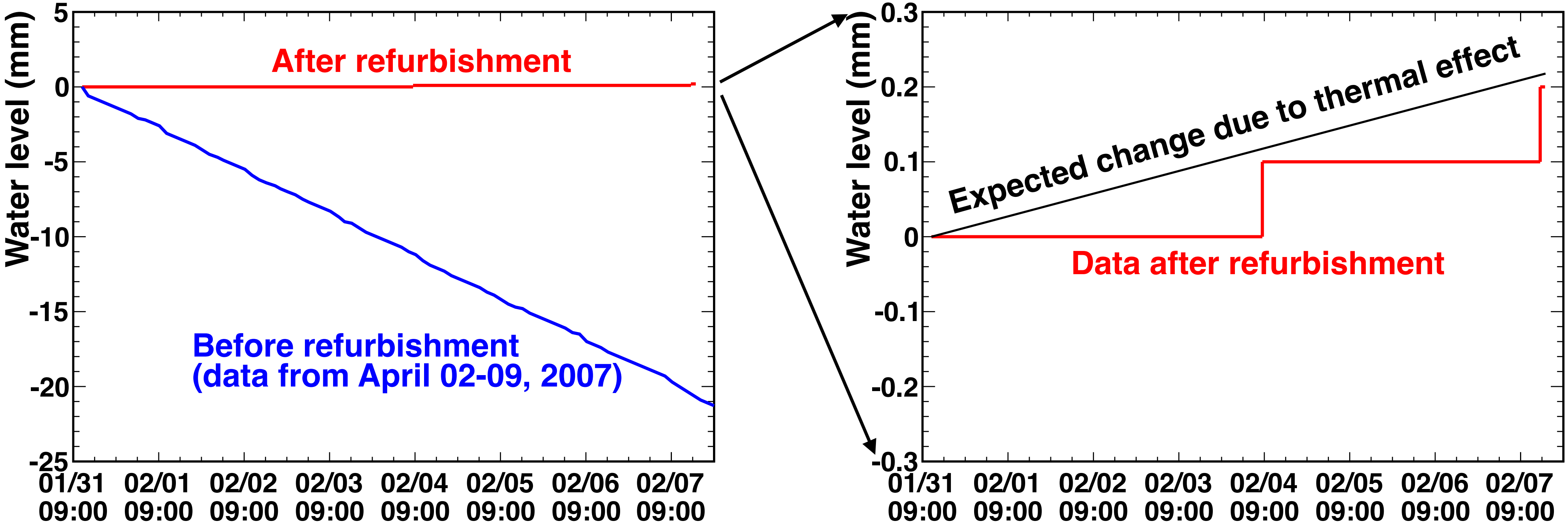
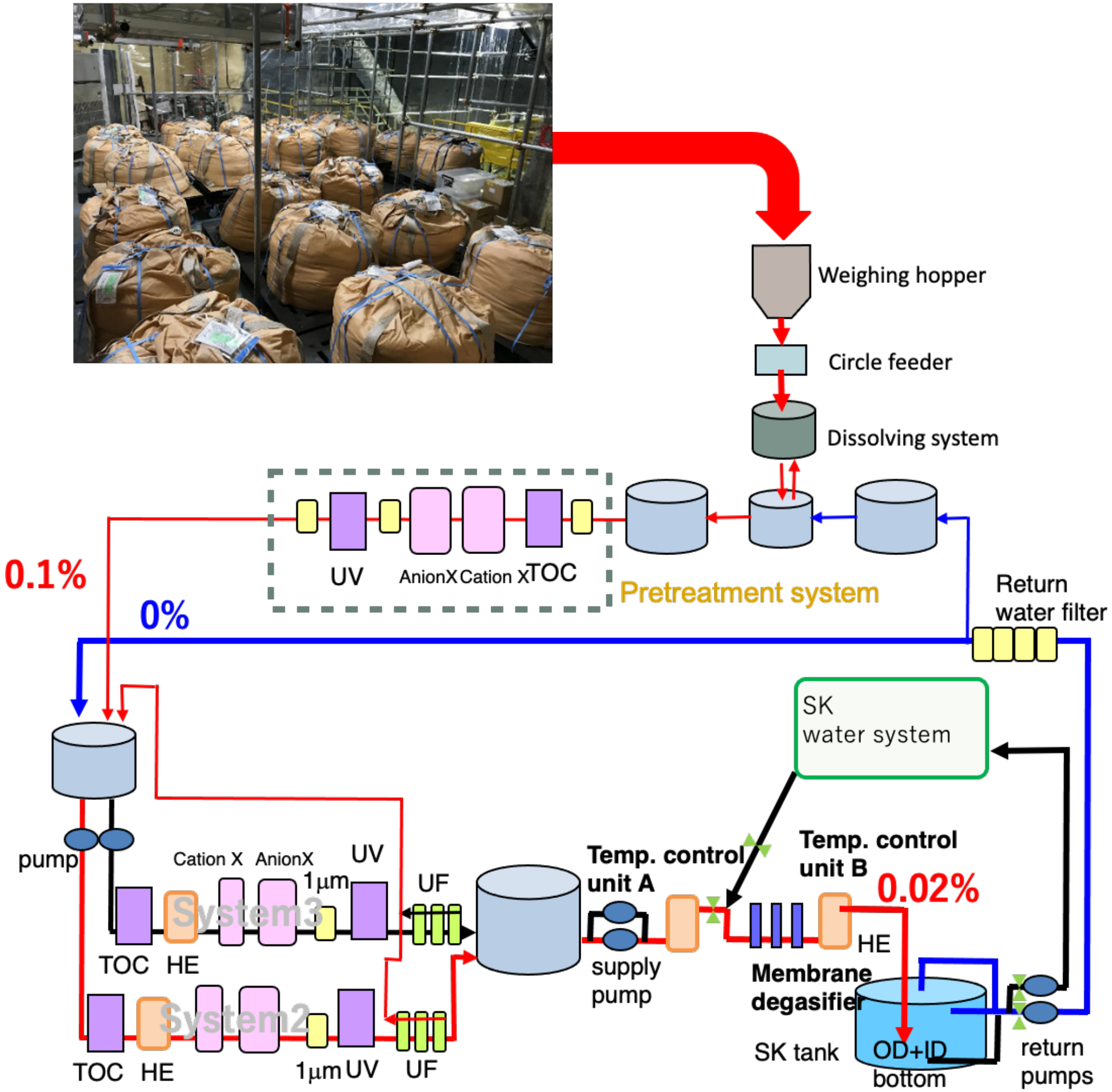


No significant water leak was seen!

Ready to go!

First Gd loading (2020)

<u>At first, dissolve 13 tons of Gd sulfate, which is 0.01% Gd concentration</u>



Newly constructed equipments for dissolving and circulating of Gd sulfate

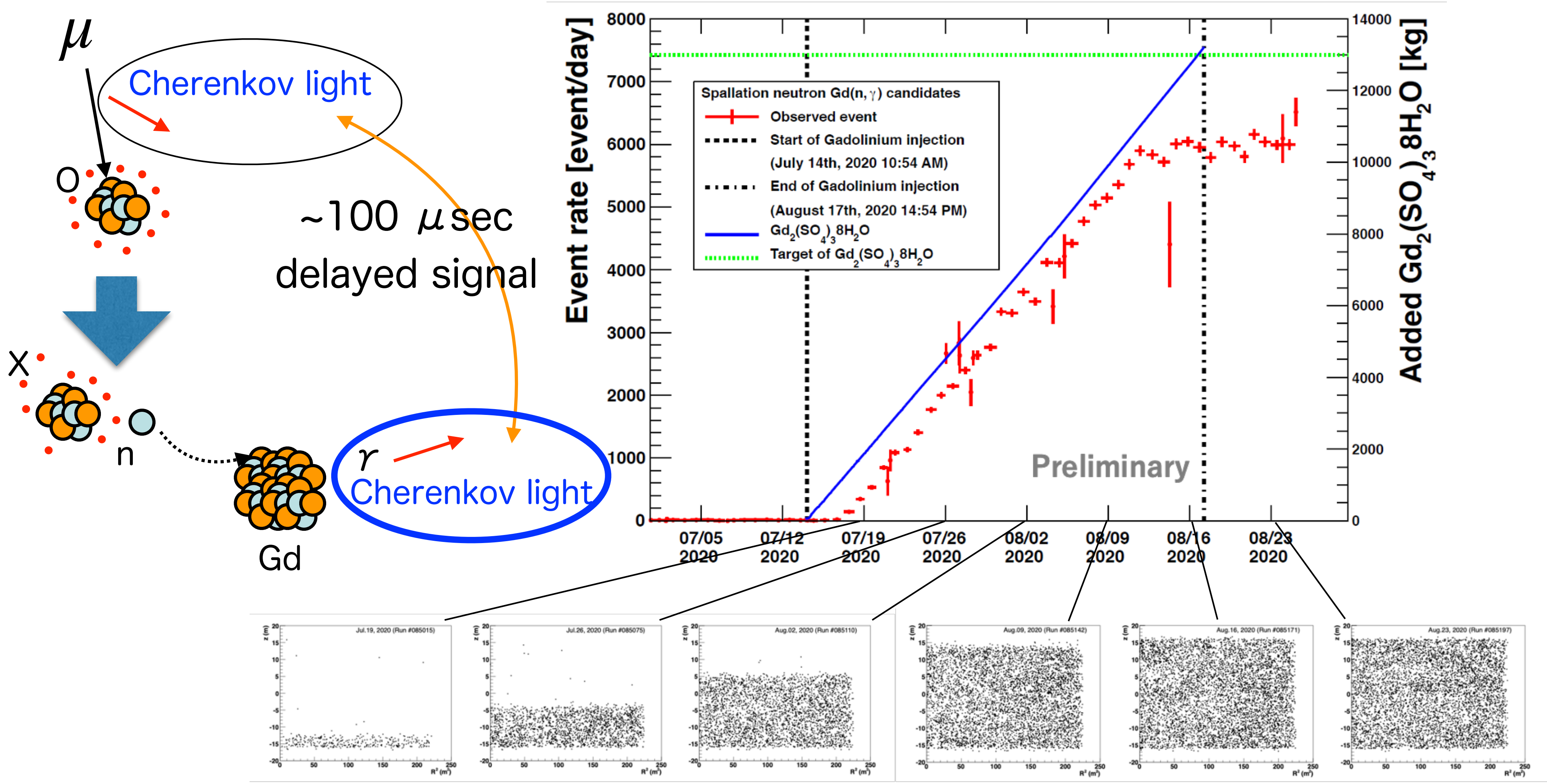
<u>Start loading from July 14, 2020</u>

First Gd loading (2020)

Actual loading work

First Gd loading (2020)

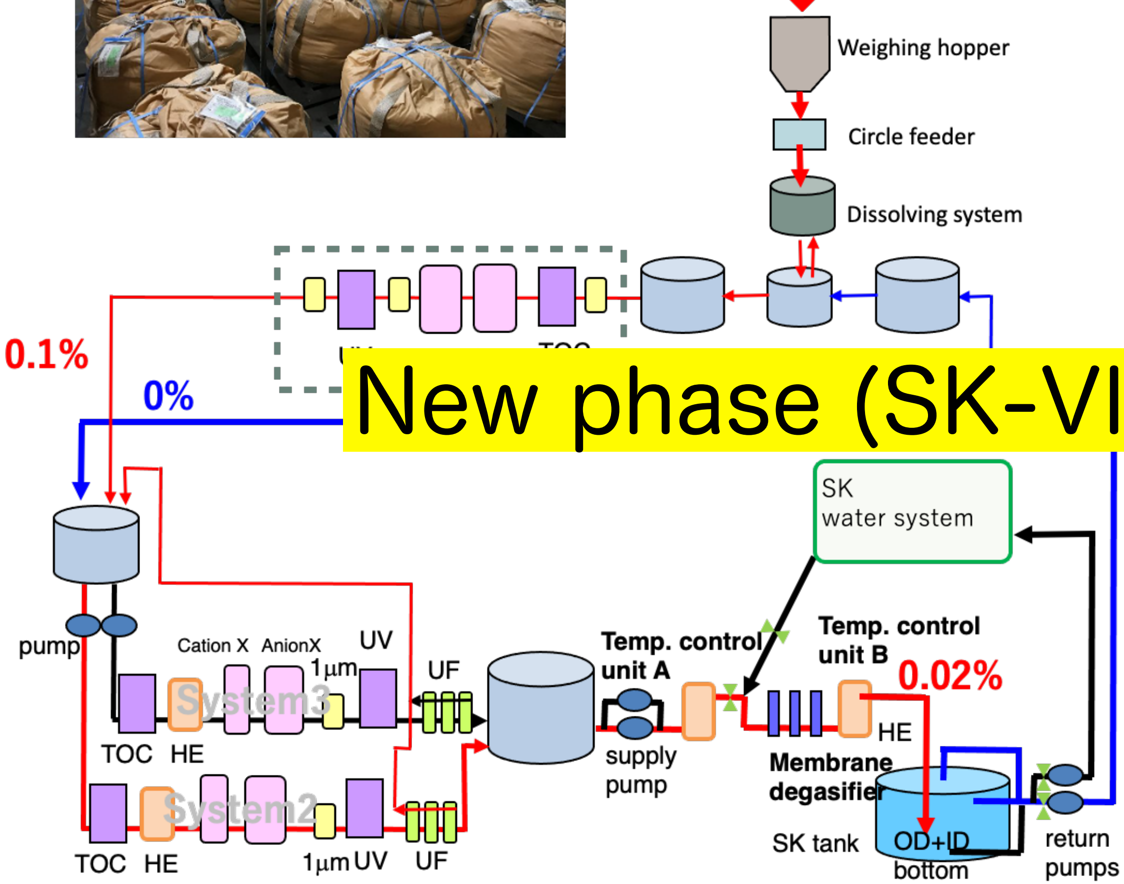
<u>Confirmed that the signal from neutrons increased with the introduction of Gd using cosmic ray muon data!</u>



First Gd loading (2020)

Completed loading on August 17, 2020

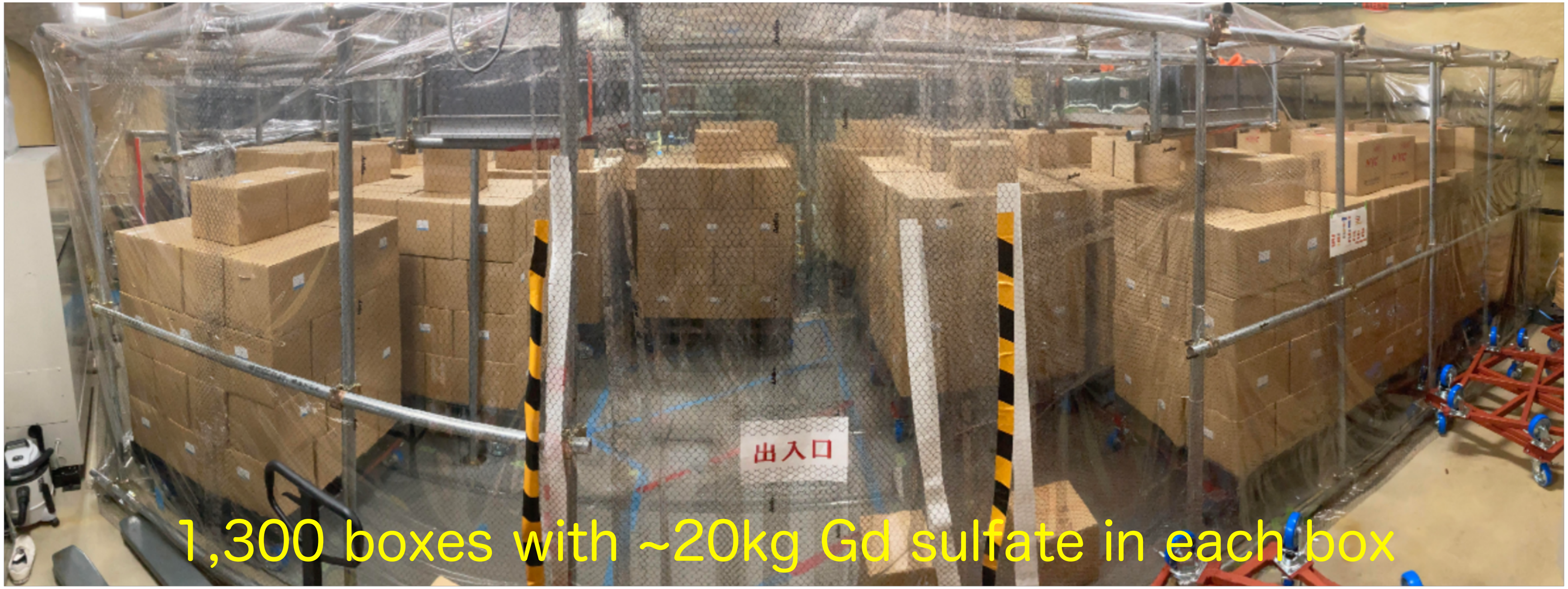
Newly constructed equipments for dissolving and circulating of Gd sulfate



New phase (SK-VI) has started!

Second Gd loading (2022)

<u>Dissolve additional 26 tons of Gd sulfate, which is 0.03% Gd concentration</u>



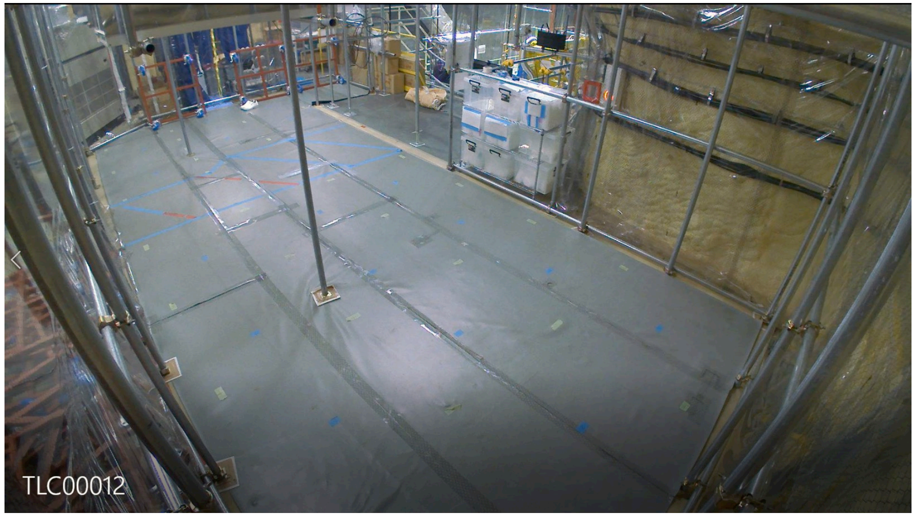
Start loading from 1st June, 2022

Second Gd loading (2022)

Dissolve additional 26 tons of Gd sulfate, which is 0.03% Gd concentration

New phase (SK-VII) has started!

Completed loading on 5th July, 2022



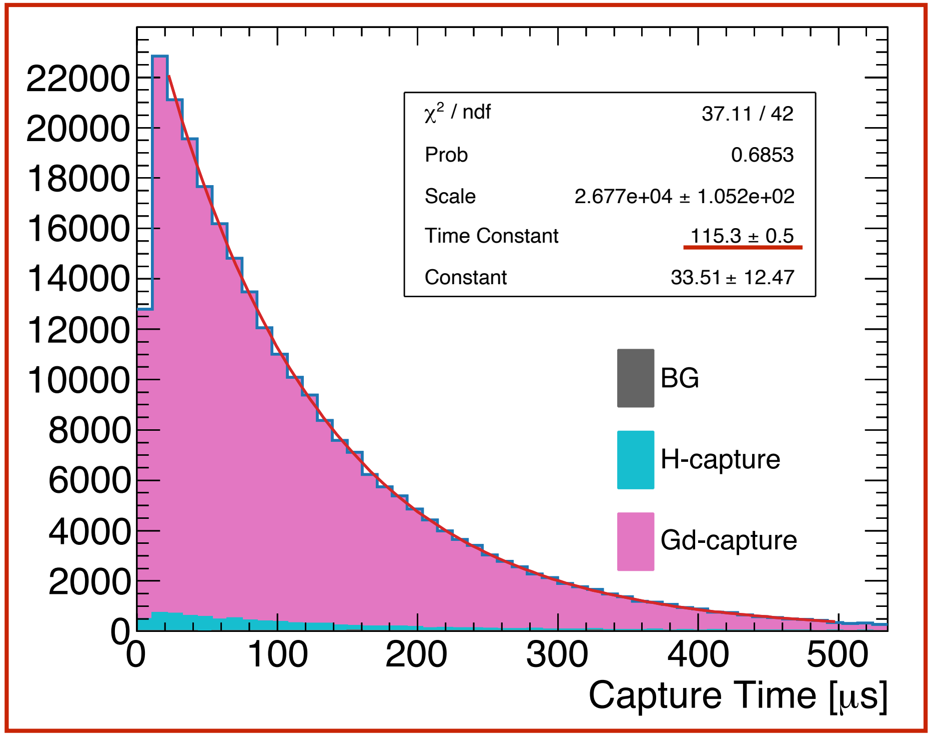
Our lab. members were very active!!

First results of DSNB search in SK-Gd

M. Harada et.al., ApJL. 951:L27 (2023)

Neutron tagging efficiency

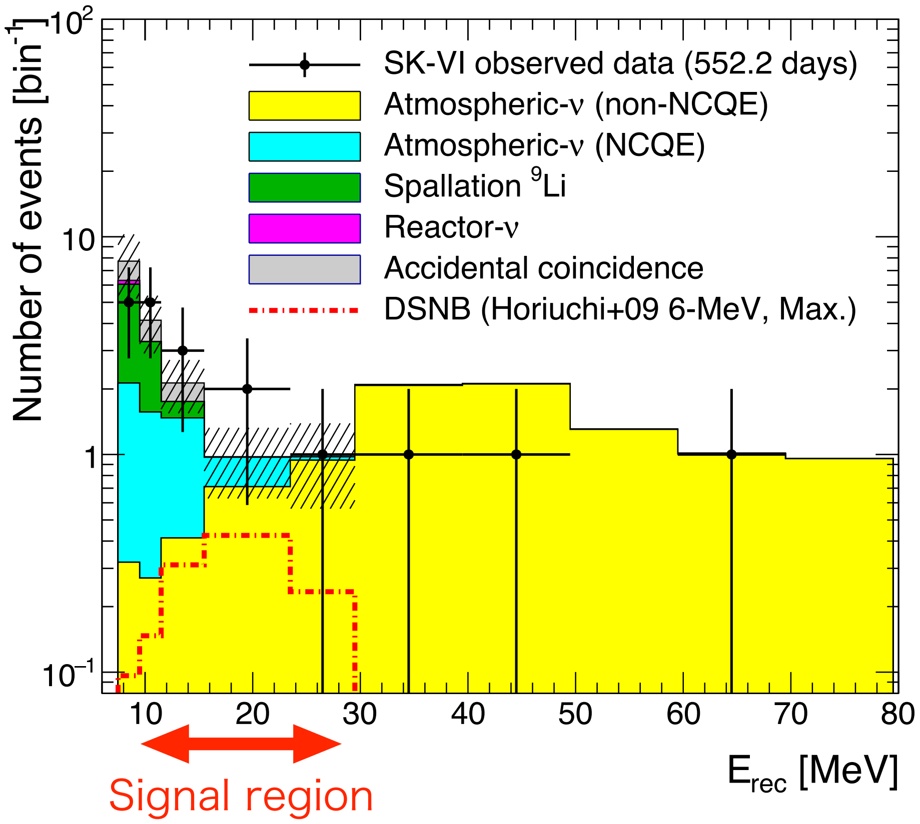
- Pure water phase : ML method to select 2.2MeV gamma-ray (~20%)
- **SK-Gd first result (Gd mass concentration 0.011%)**
  -> Simple rectangular cut to select Gd gamma-rays

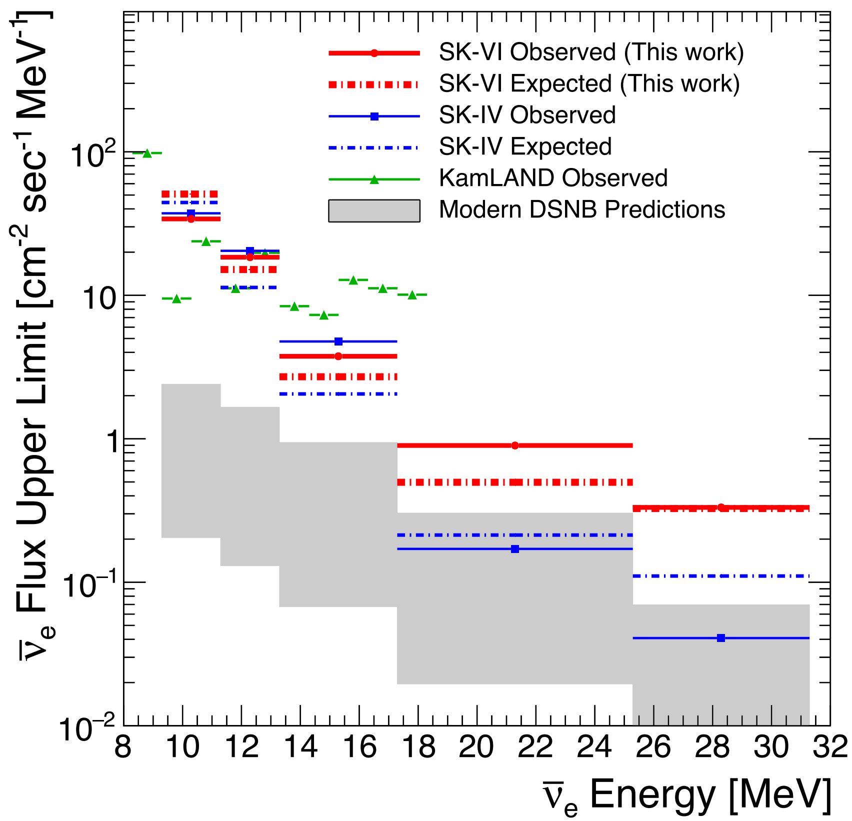


Neutron tagging efficiency ~40%

(Mis-ID rate ~ order of 10^{-4} / event)

Search for DSNB in SK-Gd

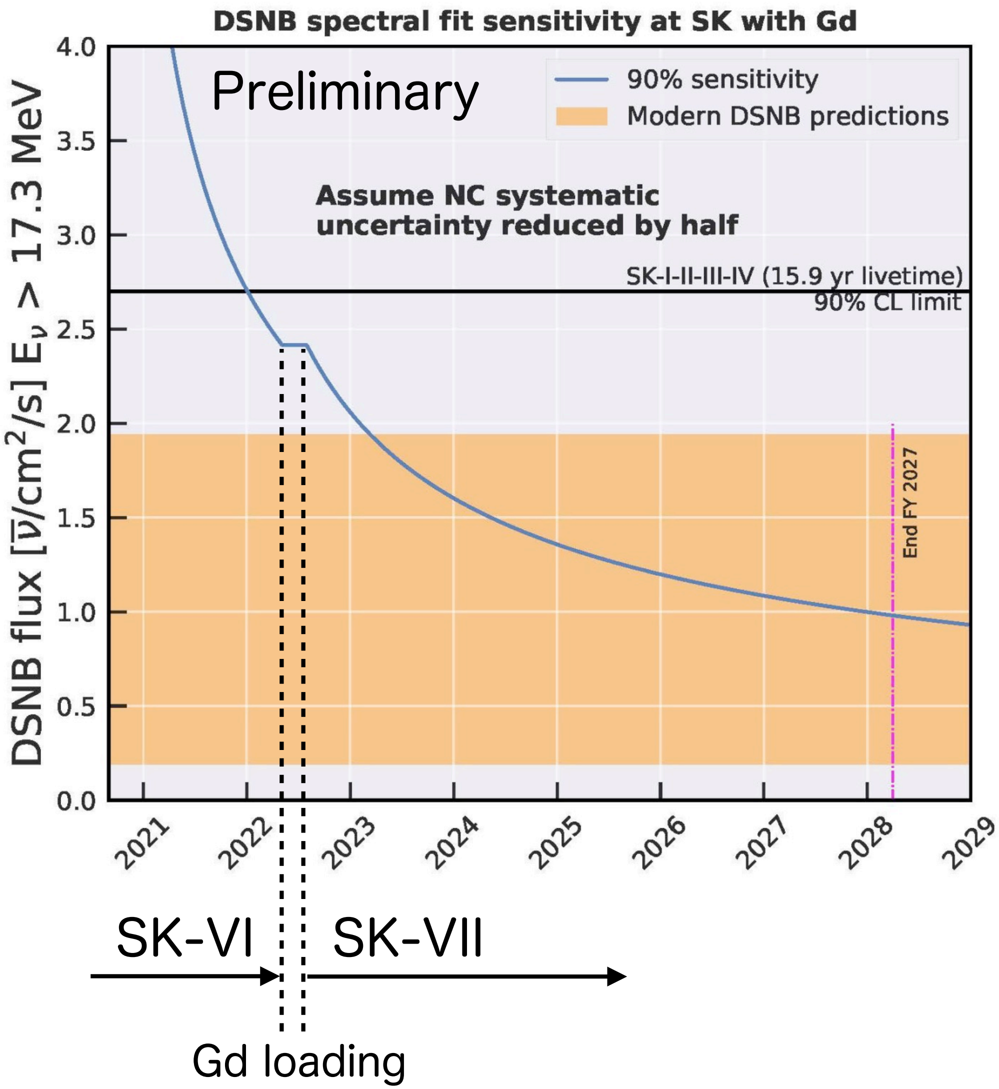




Significant DNSB signal was not observed in SK-Gd 552.2 days of data. Upper limit is comparable with the pure water phase data in SK-IV (2970days) though the live time is 5 times smaller.

Search for DSNB in SK-Gd

Expected sensitivity as a function of FY



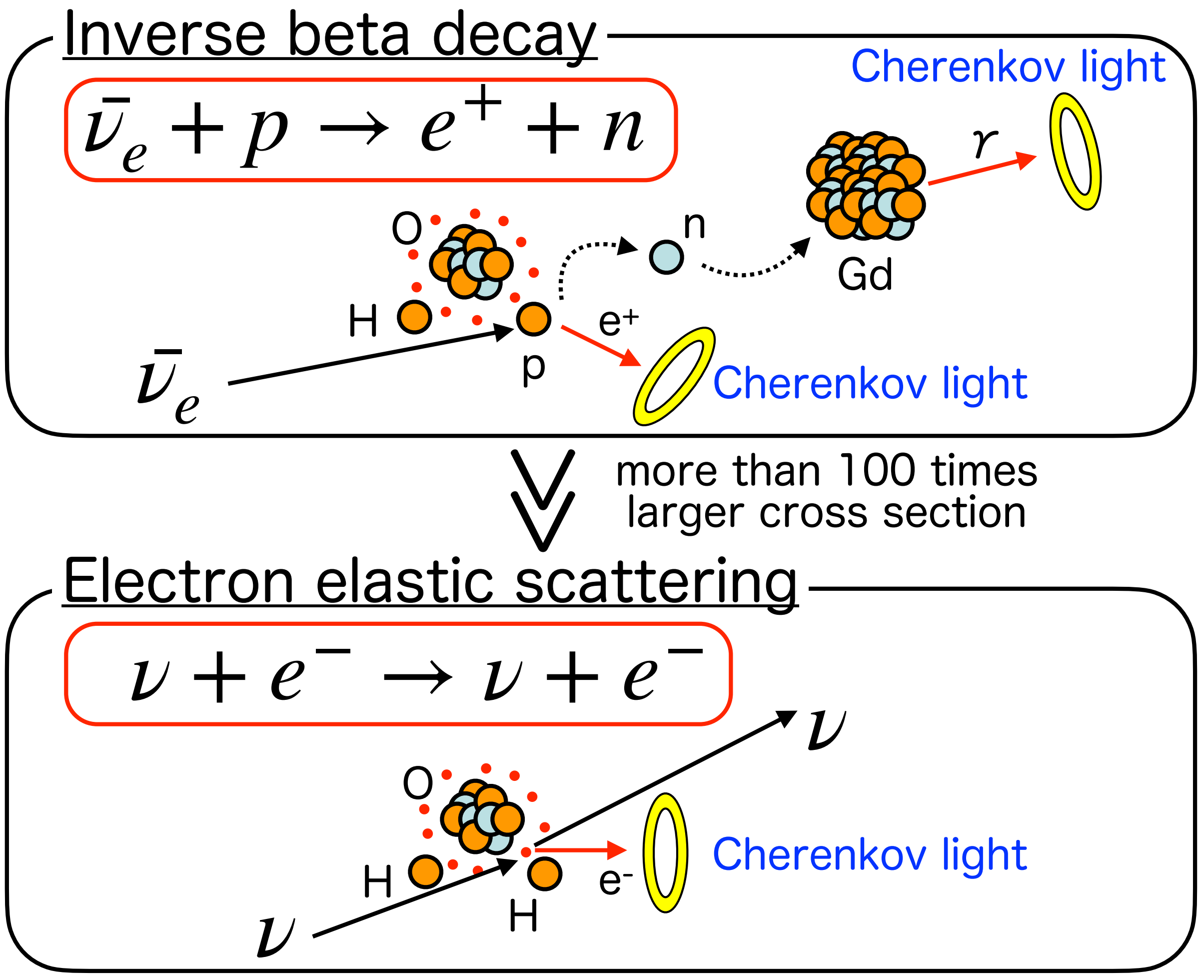
Milestones

- Improved S/N ratio by Gd neutron tagging. (SK-VI : ~50%, SK-VII : ~75%)
- Analyzing SK-VII data is now on going.
- Reduce systematic uncertainties related to atmospheric neutrinos is critical.
  - T2K experiment
  - External nuclear experiments

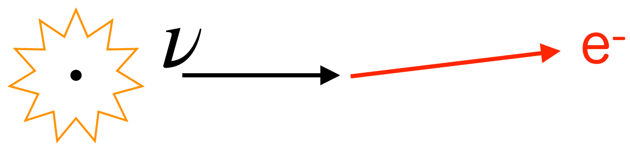
Benefit of neutrino detection from nearby Supernovae in SK-Gd

If a nearby supernova happens..

More accurate in determining the supernova direction by Gd loading



Positron direction does not correlate with the original neutrino direction



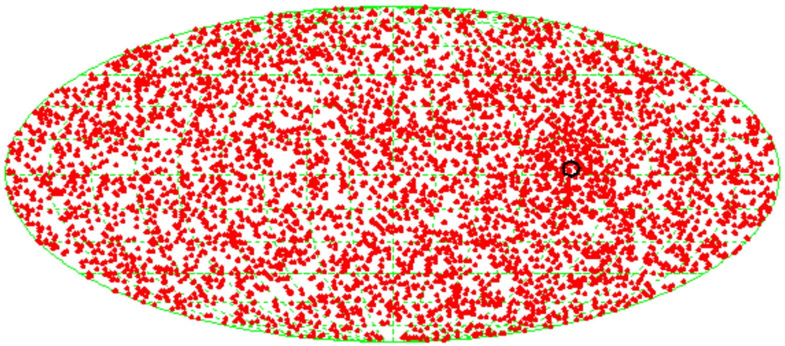
Recoil electron direction strongly correlate with the original neutrino direction

If electron elastic scattering is enhanced by “removing” inverse beta decay using Gd captured signal, the determining Supernova direction will be more precise.

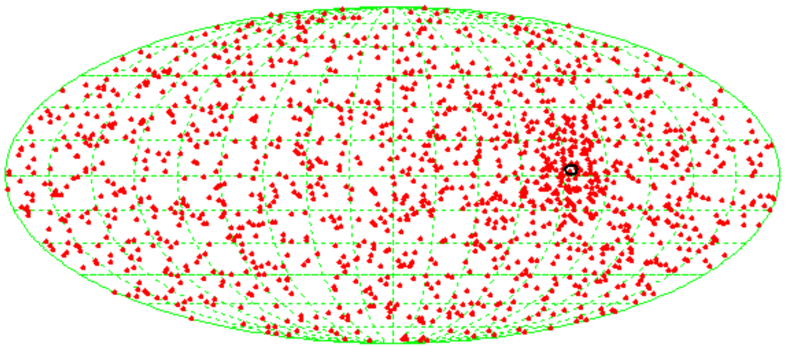
If a nearby supernova happens..

More accurate in determining the Supernova direction by Gd loading

at center of our galaxy
(simulation at 10kpc)

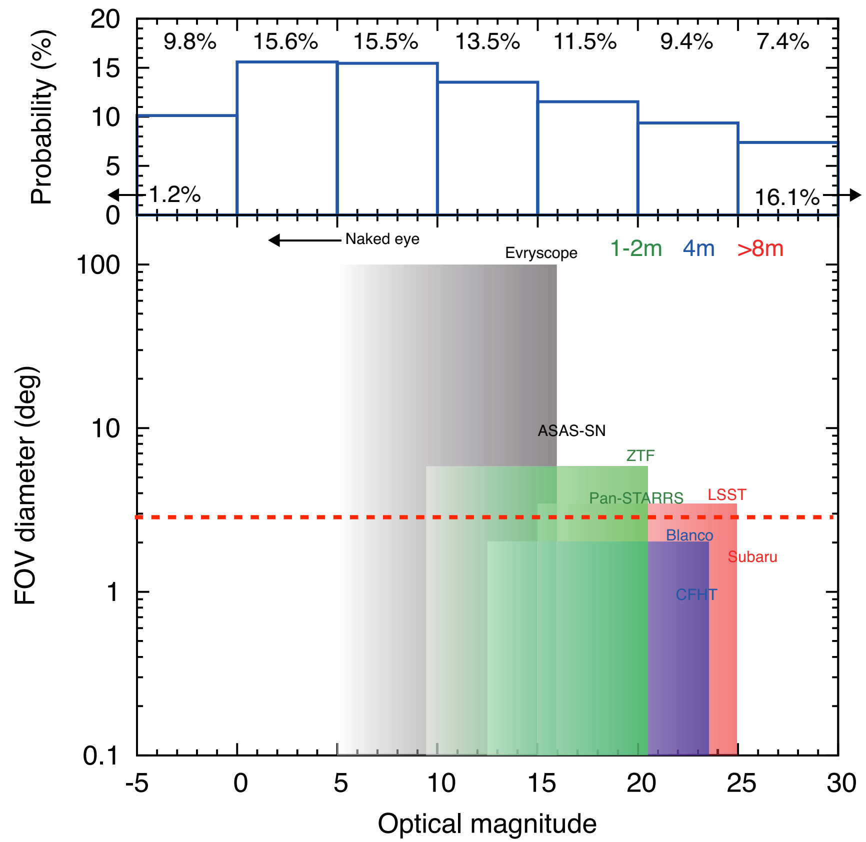


No Gd
4.0 deg



SK-Gd
2.9 deg

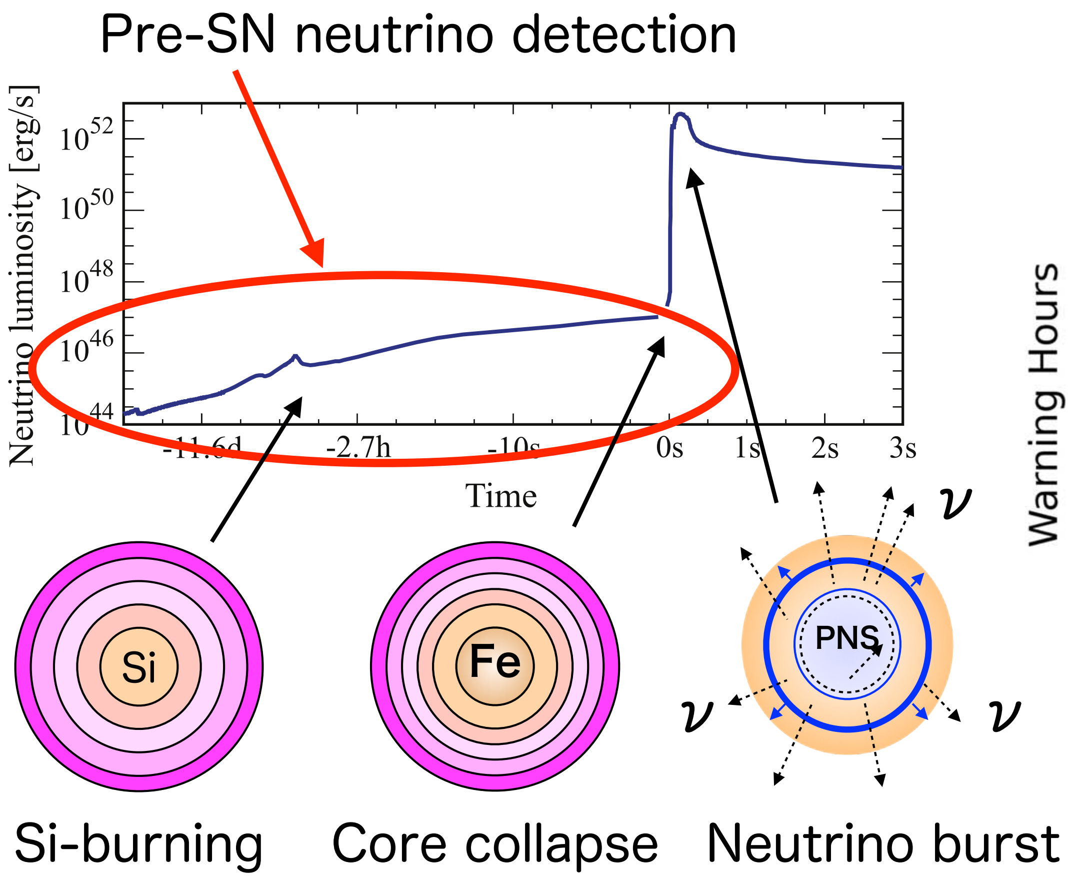
Accuracy of determining
supernova direction



Within the viewing angle of
Subaru Telescope LSST

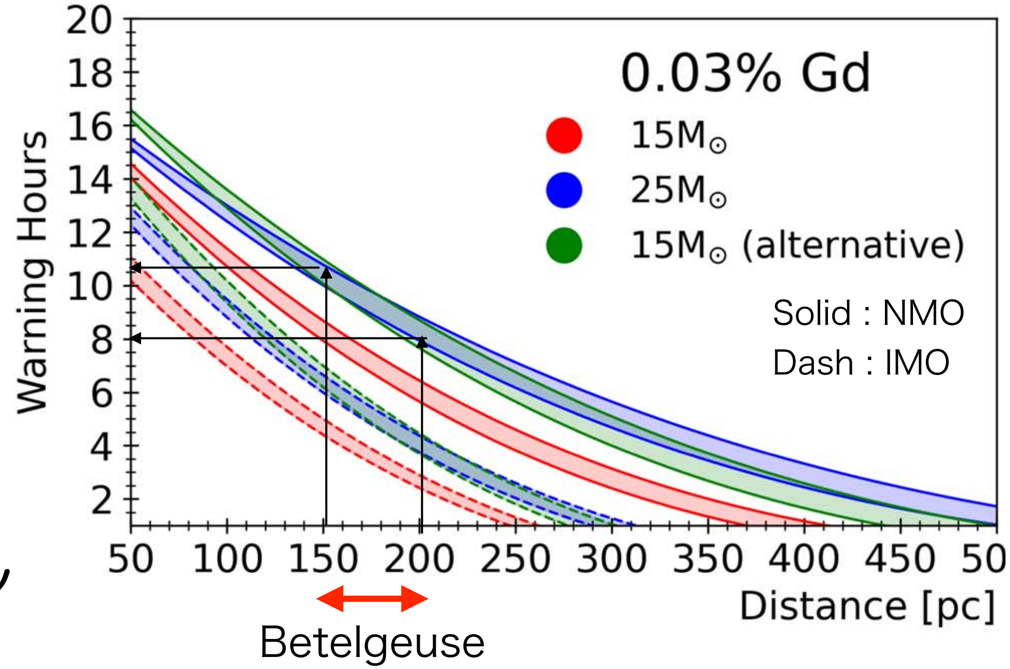
If a (Very) nearby supernova happens..

Prediction of Supernova explosion?



L.Machado et.al., ApJ. 935 40 (2022)

Time 3σ alert to core-collapse

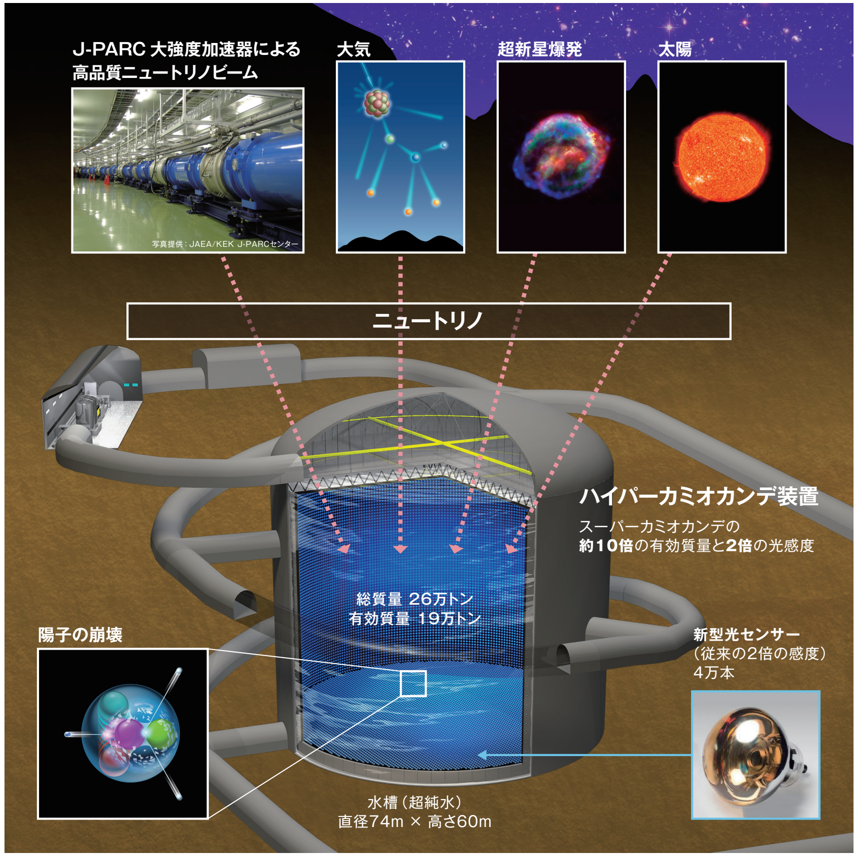


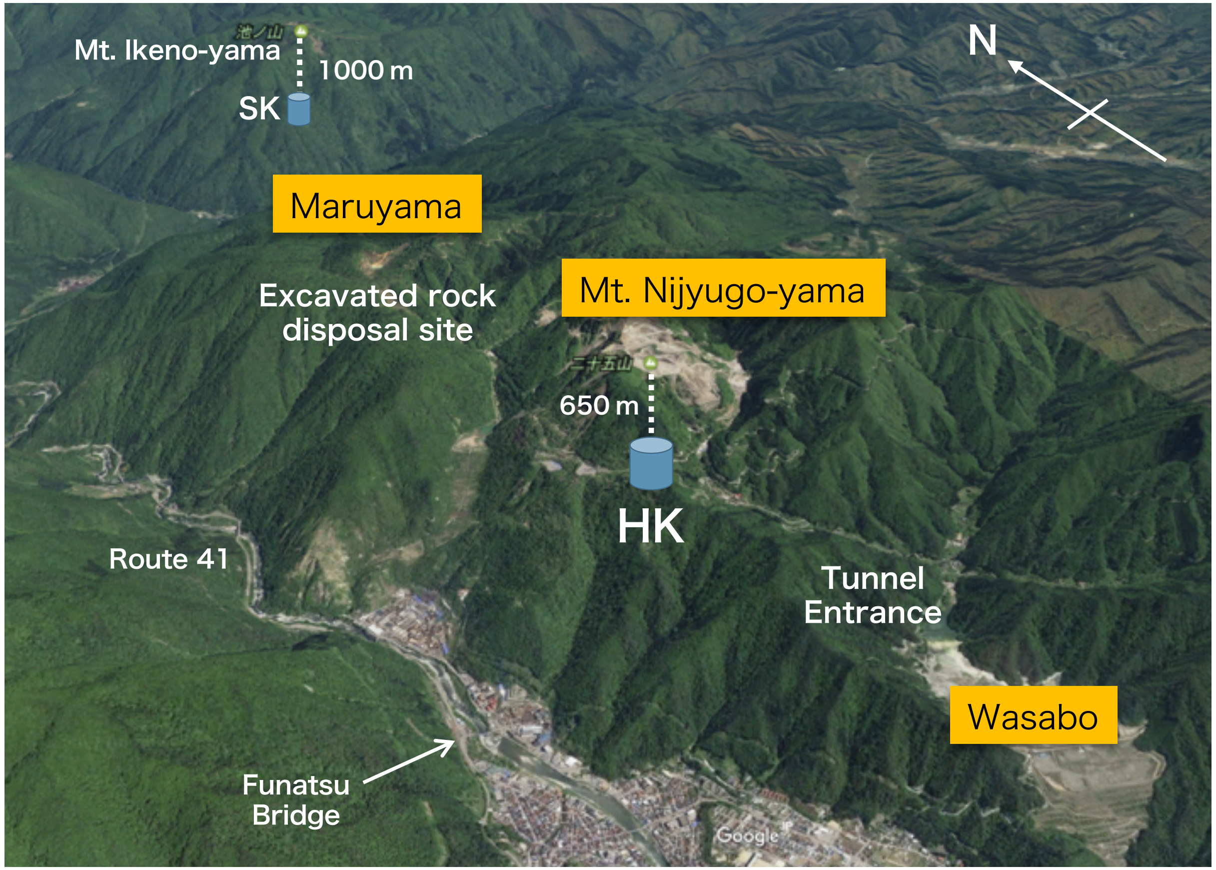
Fore Betelgeuse, we can get 3 sigma alert 8 to 11 hours in advance of its core-collapse


Hyper-Kamiokande
n, p, e-

Hyper-Kamiokande (HK)

Next generation of large neutrino detector



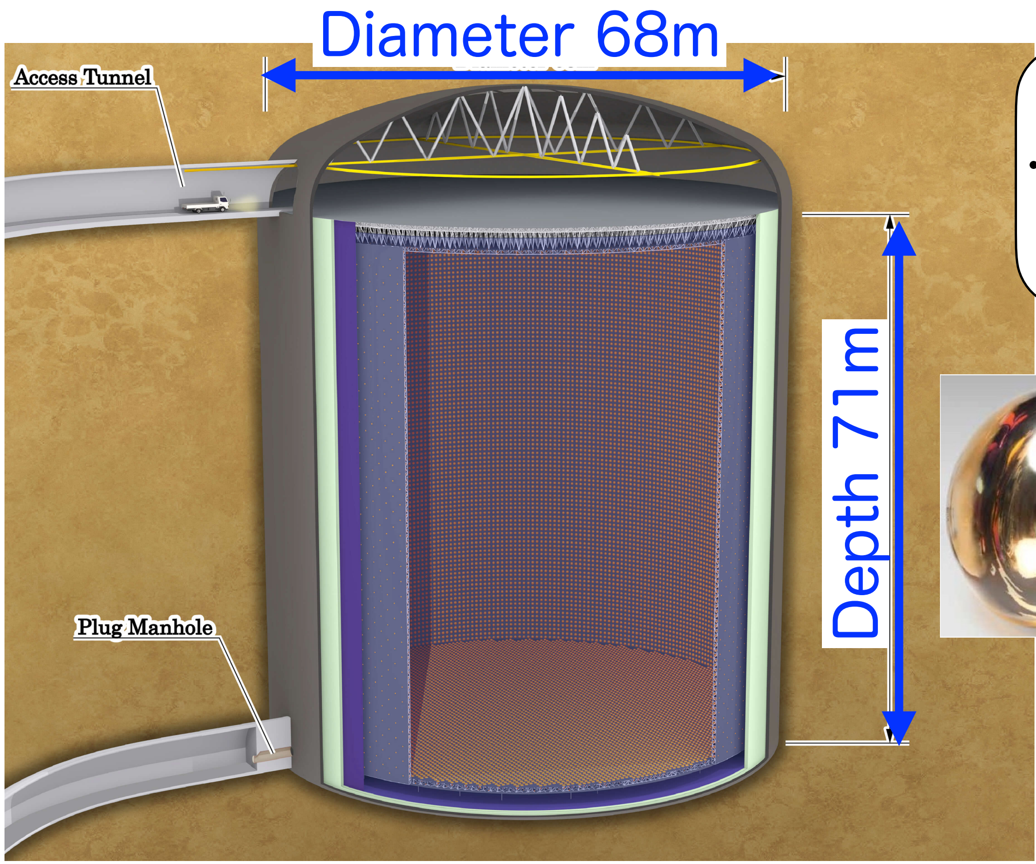


Construction is now on going

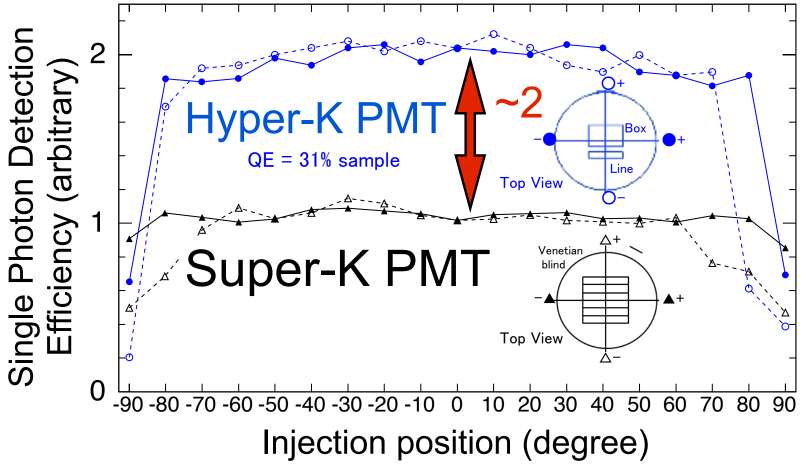
Operation starts 2027

Hyper-Kamiokande (HK)

Next generation of large neutrino detector



- 190 kton Fiducial volume : ~ 8 x SK
- 20,000 improved photomultiplier tubes (PMTs) : twice sensitivity than Super-K

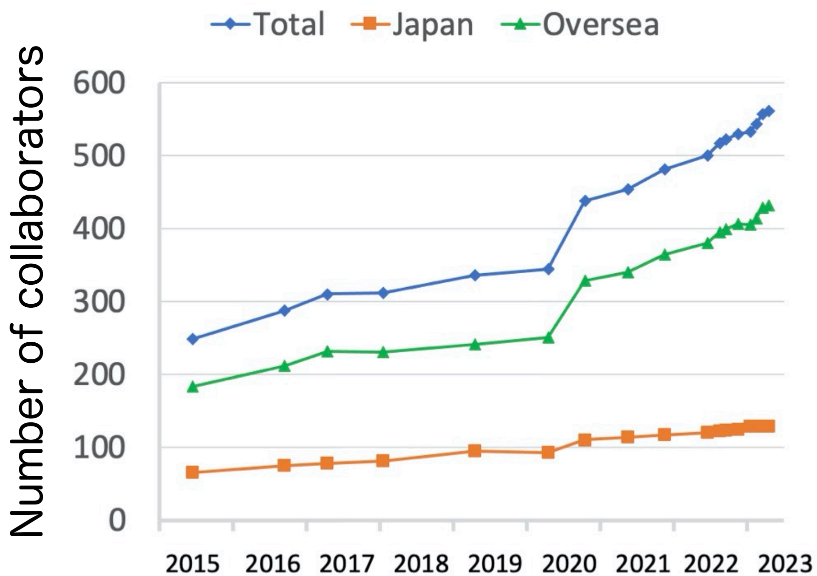


Construction is now on going

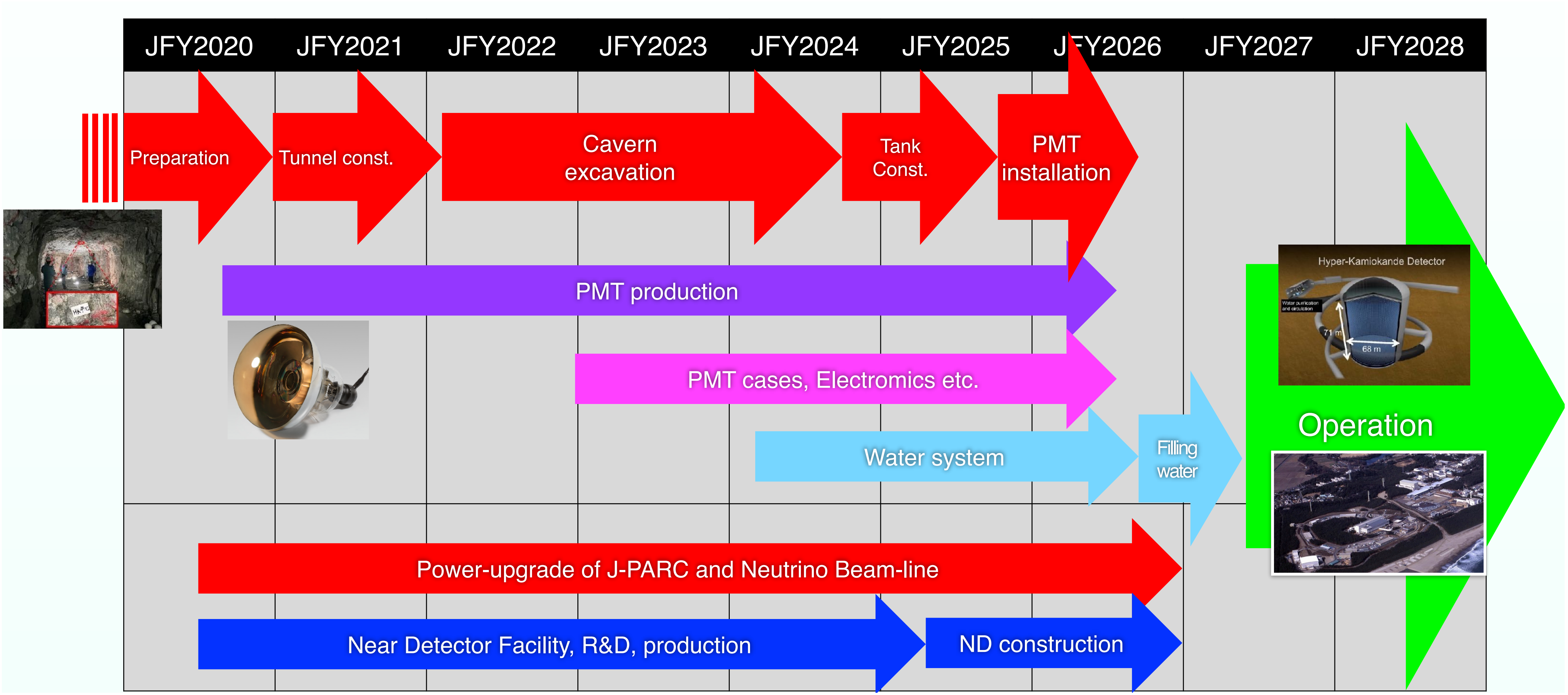
Operation starts 2027

HK Collaboration

~550 members in
102 institutions
from 21 countries



Time line

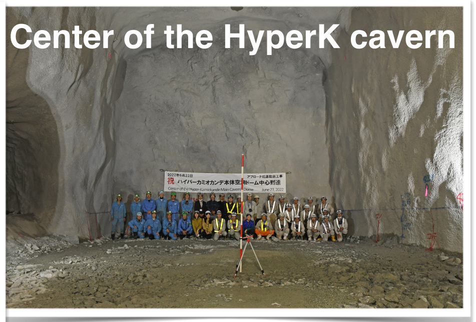


No change of the schedule since 2020 (approval year)

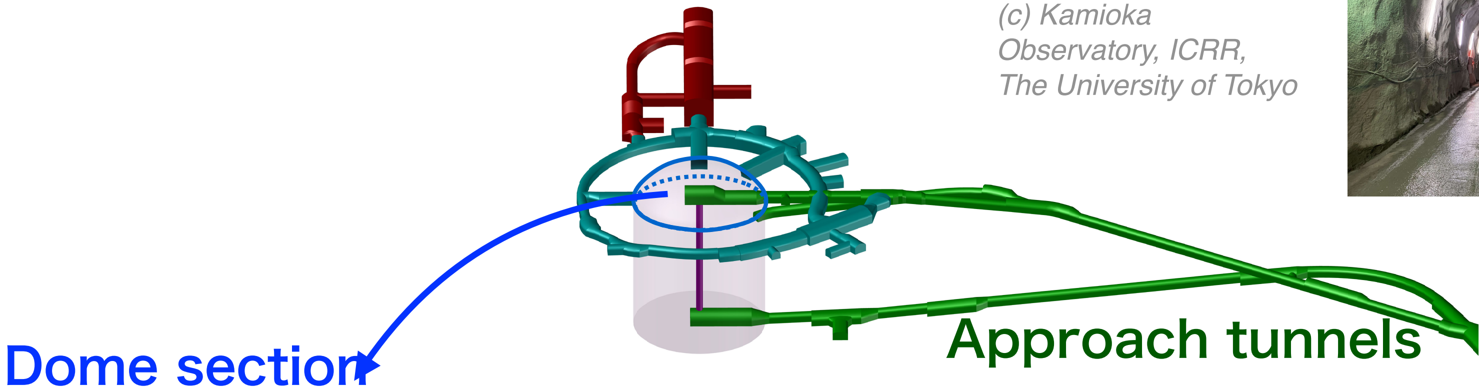
Operation starts 2027

Cavern excavation

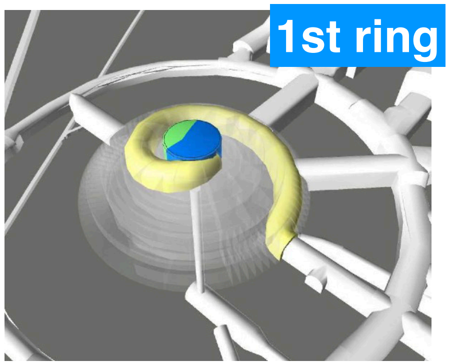
- Approach tunnels: > 2km, Completed in July 2022

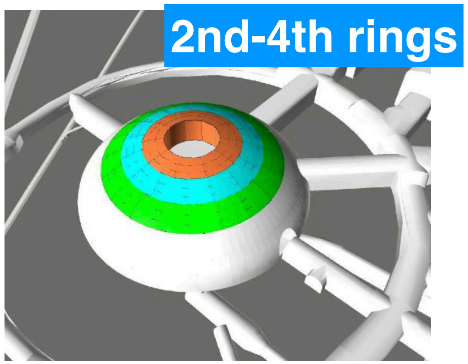


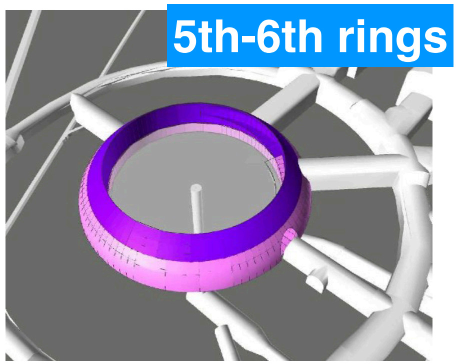
(c) Kamioka Observatory, ICRR, The University of Tokyo



Dome excavation procedure: from the inner rings to the outer ones





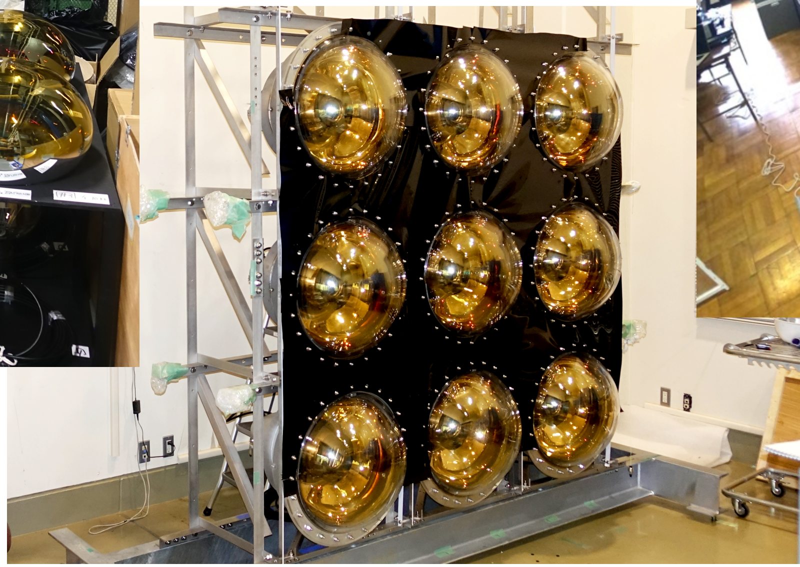


Dome excavation finished!

PMT production and delivery

Delivery to Kamioka

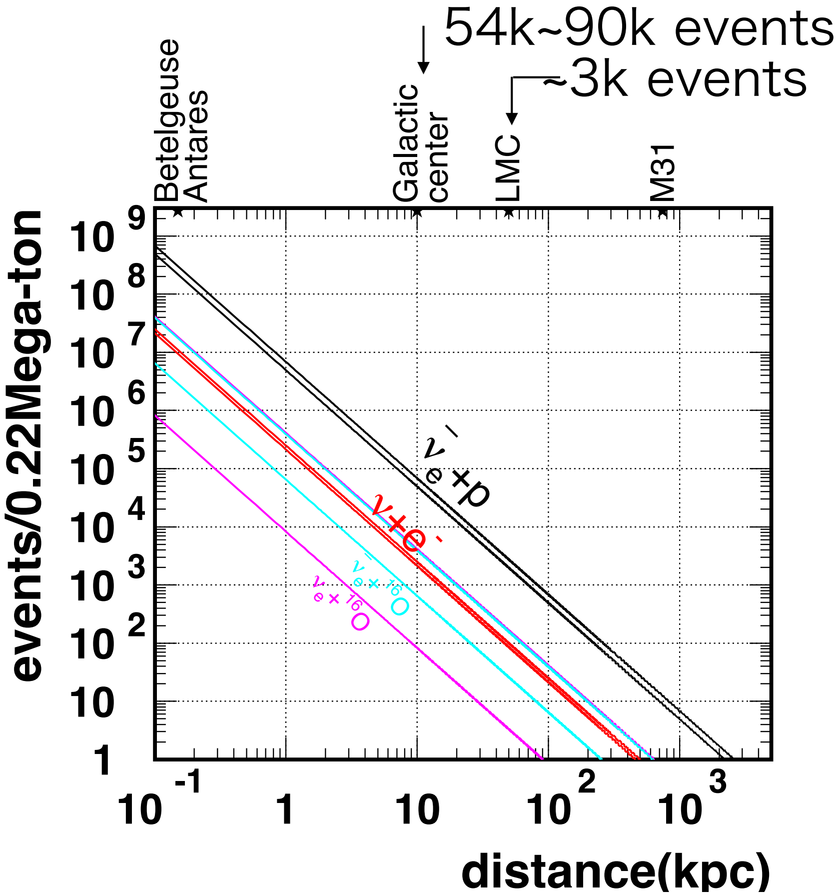
PMT quality inspection



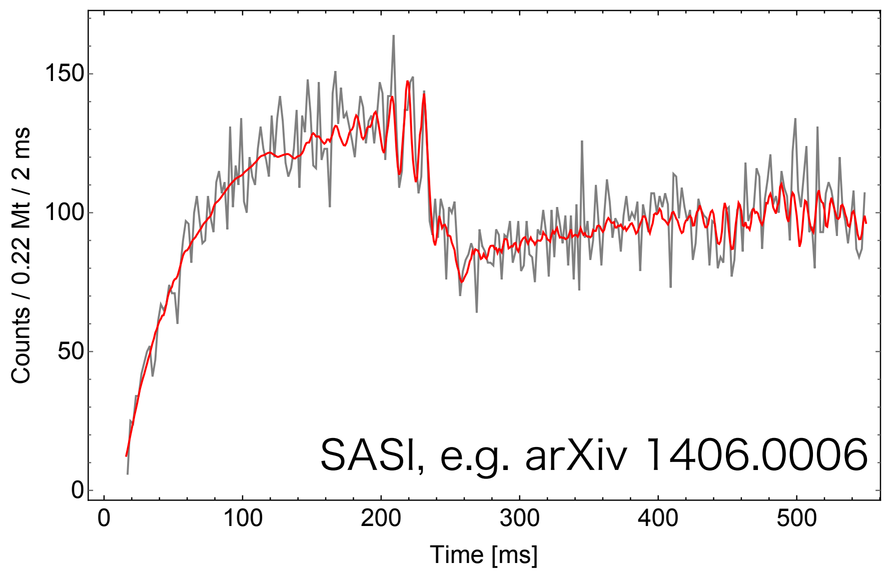
Mock-up test

Nearby Supernova burst

Large statistics and event-by-event time/energy information



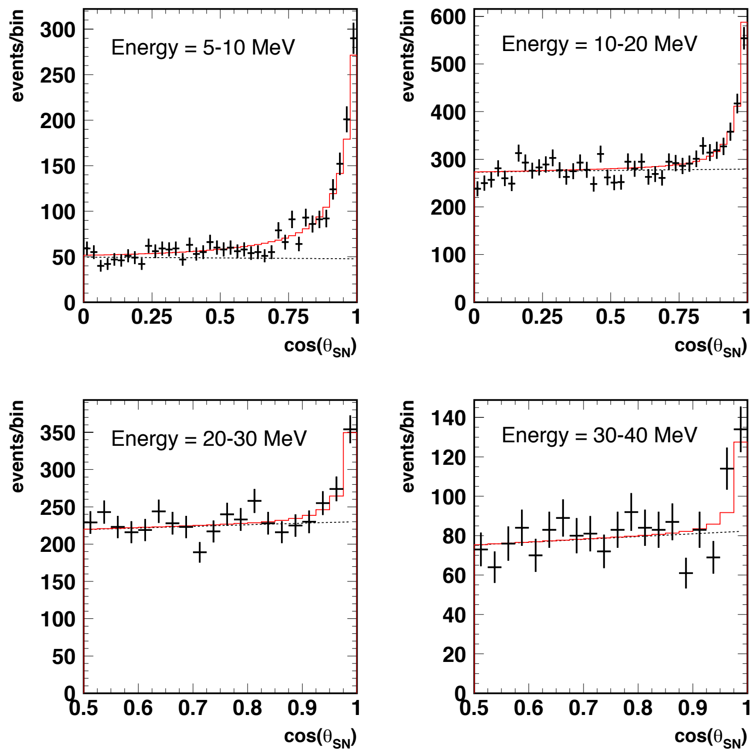
Precise time variation can be observed



Nearby Supernova burst

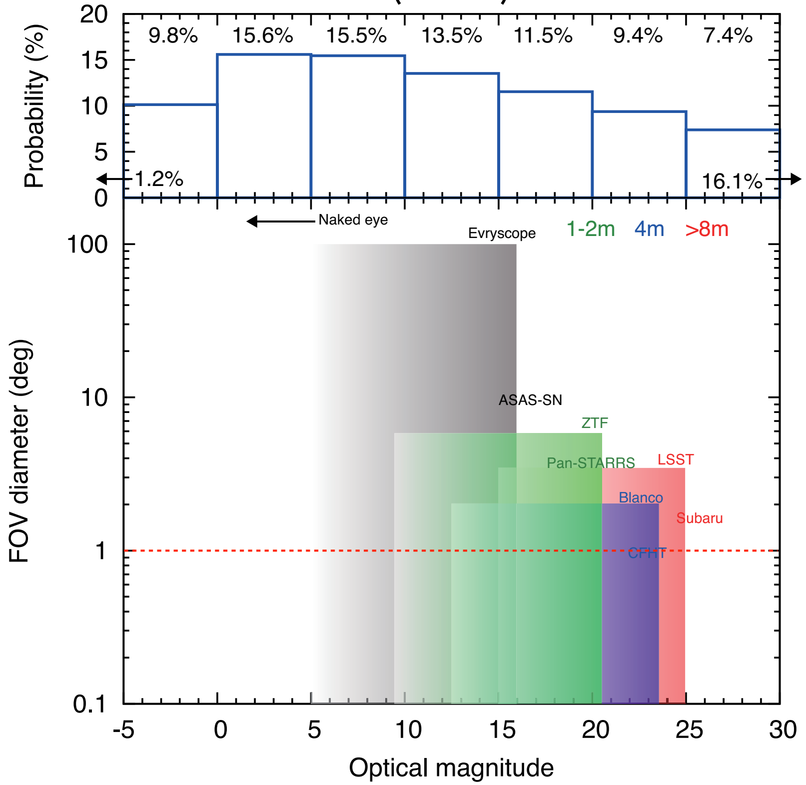
Pointing accuracy

Angular distribution at 10kpc



~1deg.

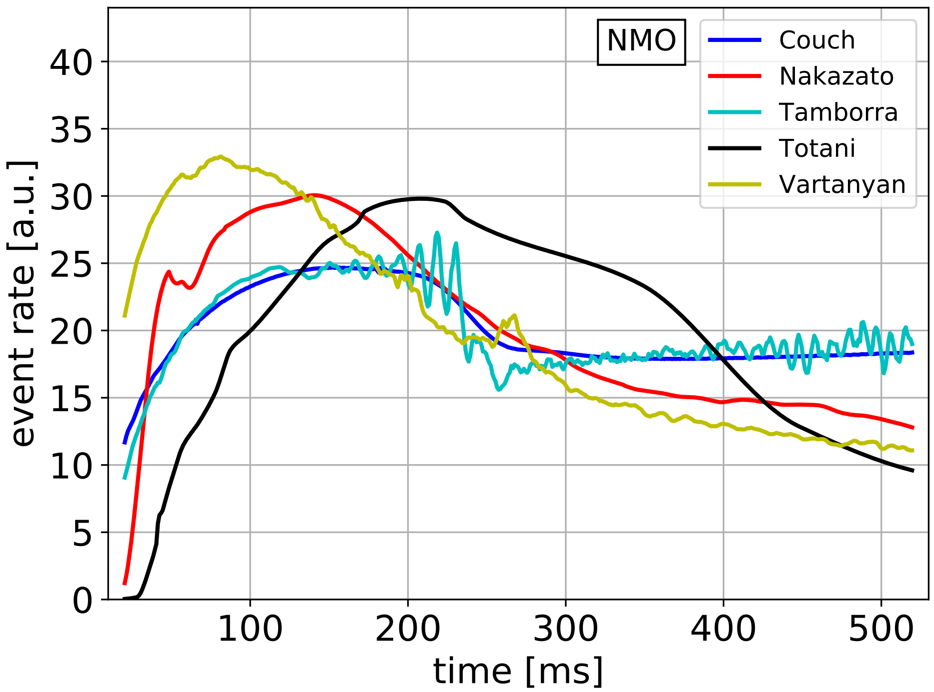
K.Nakamura et. al. MNRAS 461, 3296 (2016)

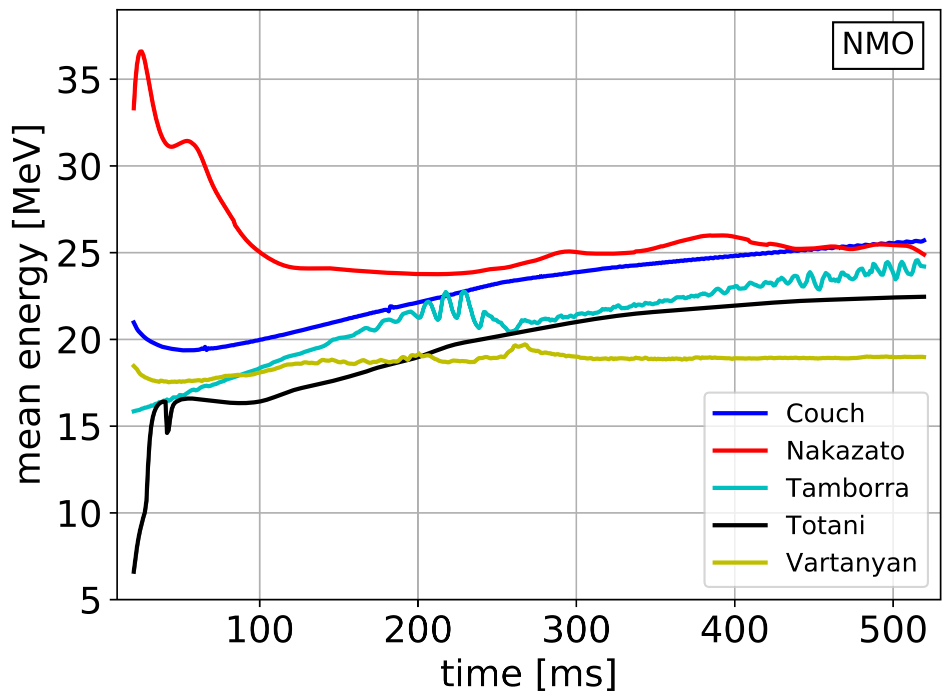


Nearby Supernova burst

Detection at the early stage

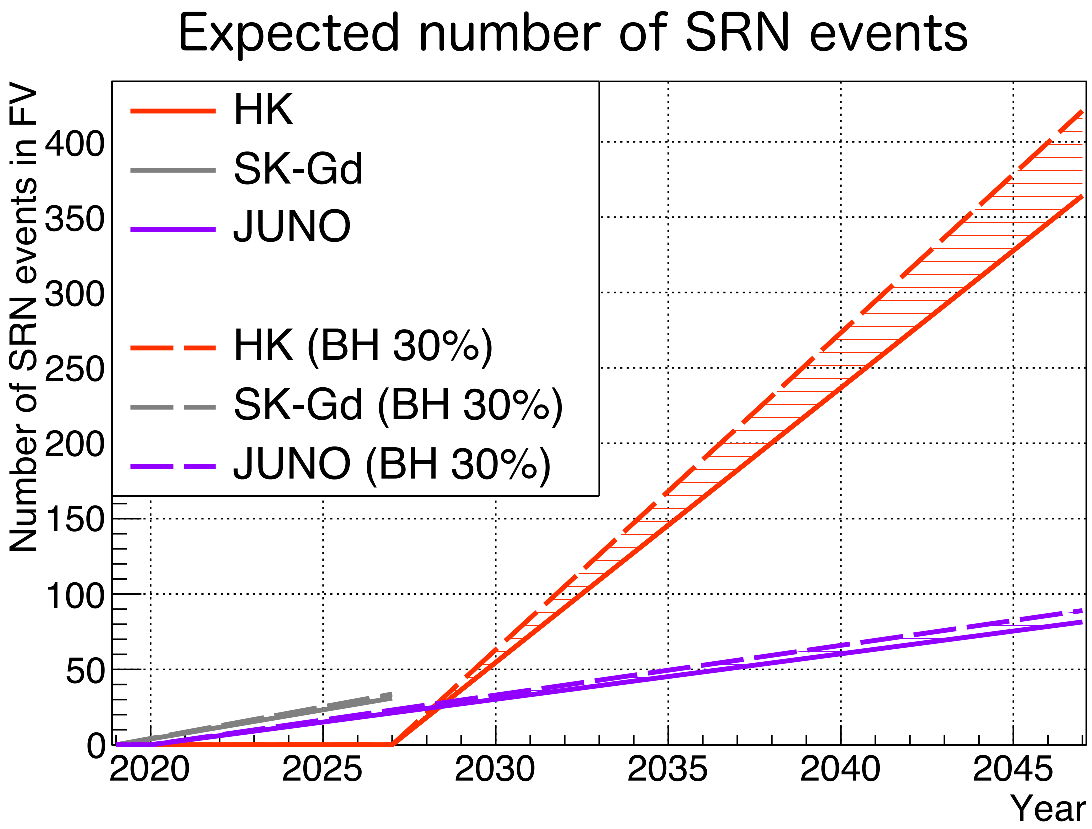
K. Abe et.al., ApJ. 916:15 (2021)

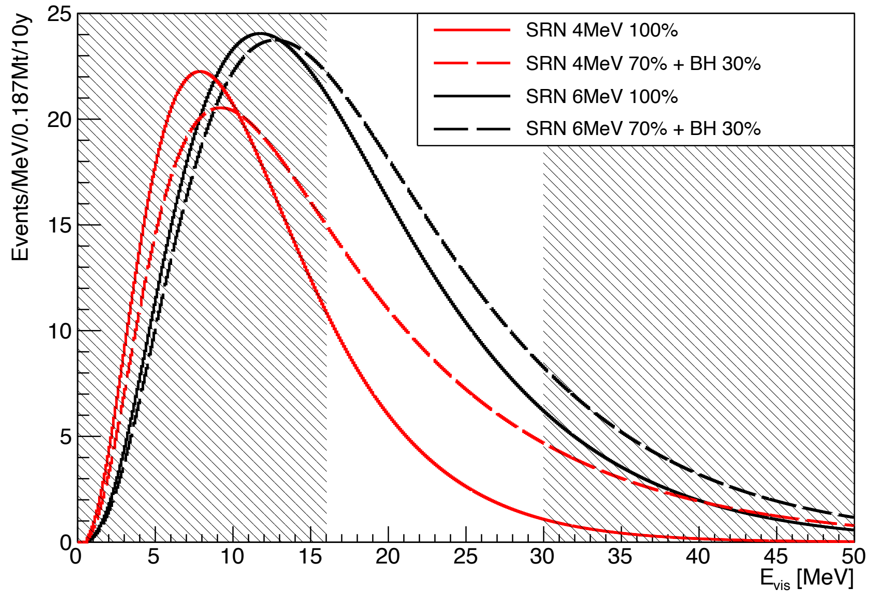




DSNB search

Large statistics make a precise observation possible





First discovery of DSNB in SK-Gd

Precise measurement of DSNB in Hyper-K

Summary

Let’s go supernova!

Thanks