(A01) Recent status of SK/SK-Gd

新学術領域「ニュートリノで拓く素粒子と宇宙」
Exploration of Particle Physics and Cosmology with Neutrino
March 7th, 2022

Kamioka observatory, Institute for Cosmic Ray Research (ICRR), the University of Tokyo.
Yuuki Nakano (中野 佑樹)
E-mail: ynakano@km.icrr.u-tokyo.ac.jp

科研費 KAKENHI
自然ニュートリノ観測と陽子崩壊探索を通して探る新たな素粒子物理
18H05536

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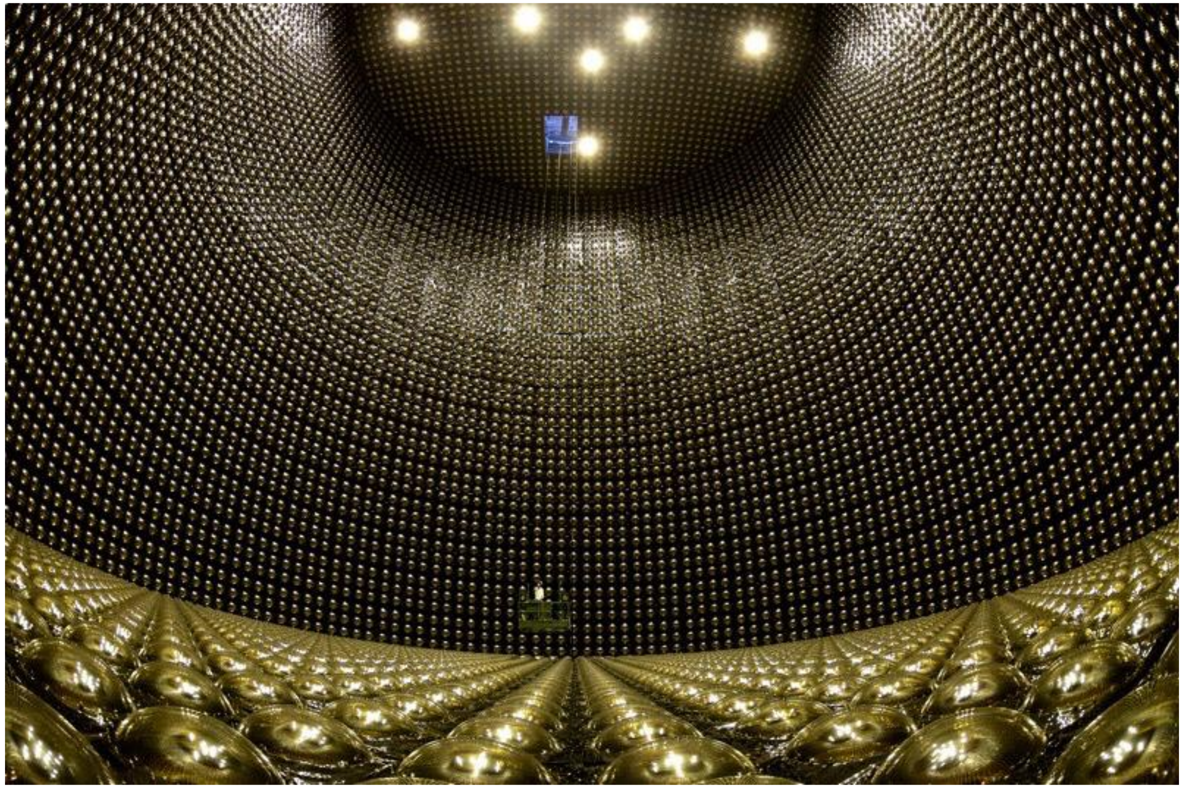
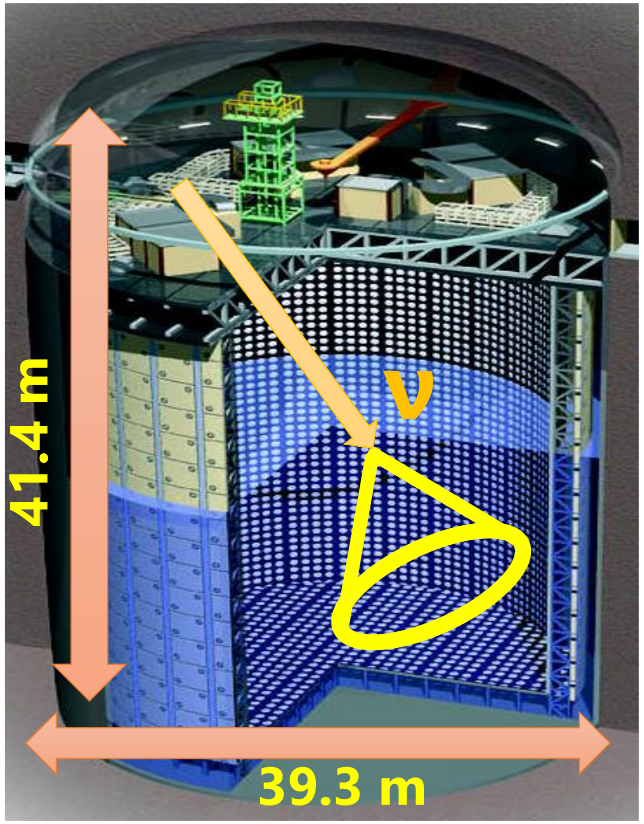


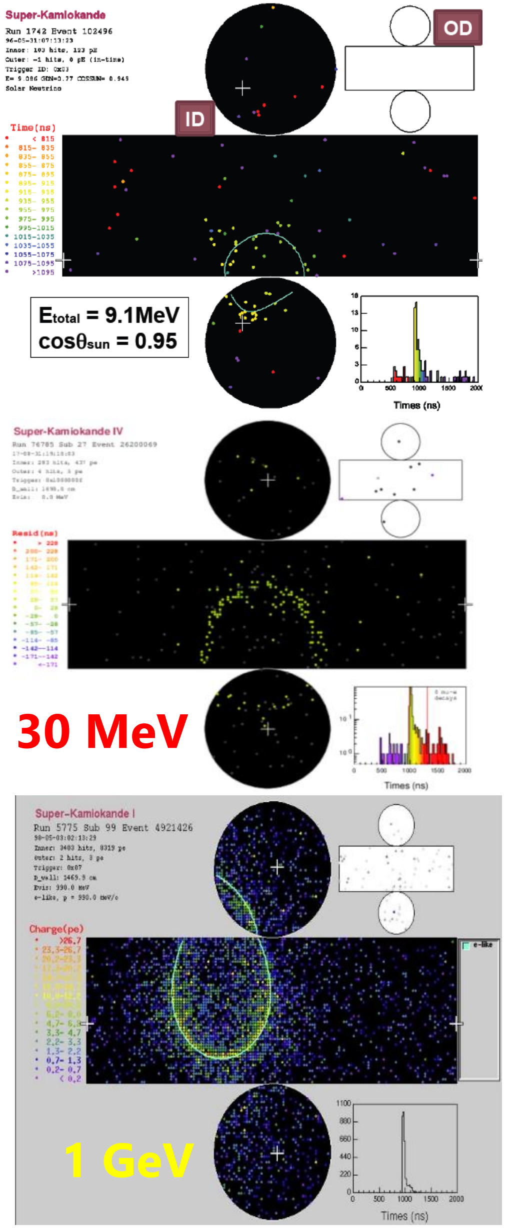
Super-Kamiokande (SK)

■ Detector

- Located at Kamioka Japan.
- 50 kton of ultra pure water tank.
  - 20-inch PMTs, 11,129 for ID.
  - 22.5 kton for analysis fiducial volume.
- Water Cherenkov light technique.

→ Energy, direction, particle identification.





■ Physics target

- Atmospheric neutrino
- Astrophysical neutrino (solar, supernova)
- Proton decay
- Long base line neutrino (T2K) ....

Solar ν
3.5-20 MeV

Supernova ν
20-100 MeV

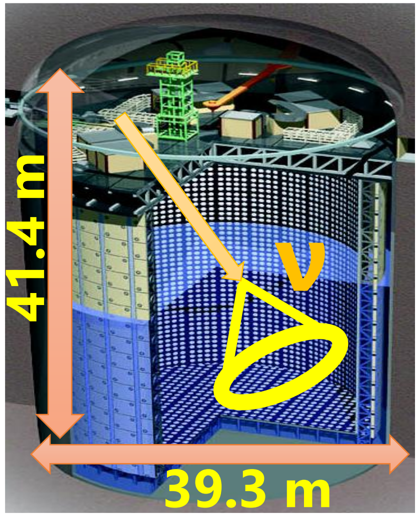
Atmospheric ν Proton decay Galactic ν Accelerator
~100 MeV GeV TeV PeV

History of the SK experiment

■ Operation of the detector

- More than 25 years of operation since 1996.
- Refurbishment work toward SK-Gd in 2018.
- SK-V started on 2019, and **SK-Gd has started since 2020.**

  → **This talk**.

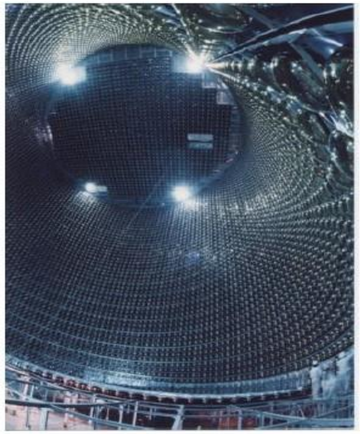


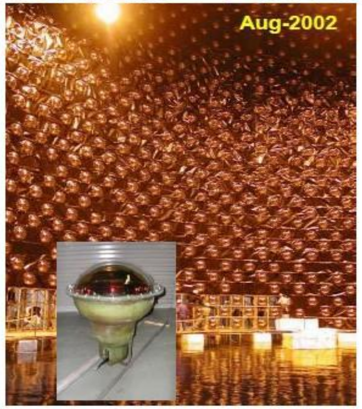
1996 | 2002 | 2006 | 2008 | 2018 | 2019

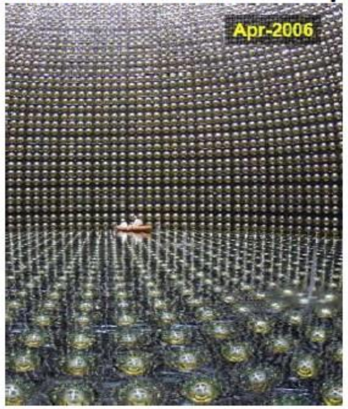
SK-I | SK-II | SK-III | SK-IV | SK-V | SK-Gd

Photo coverage 40% | 20% | 40% | 40% | 40%

Accident | Full reconstruction | Replace electronics & DAQ system | Tank refurbishment

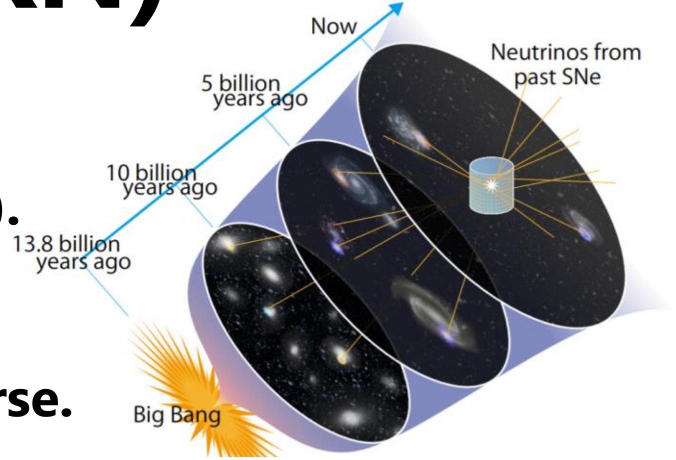






Supernova relic neutrino
and
Results from SK (pure water)

Supernova relic neutrinos (SRN)



■ Supernova (SN) burst neutrinos and relic neutrinos

- Neutrino emissions before the SN explosion (no detection since 1987A).
- A few SN explosions happen every second, so far ***O*(10^{18}) of SN bursts in the universe**.

→ Neutrinos produced **from all past SN bursts** and diffused in the universe.

■ What we can learn

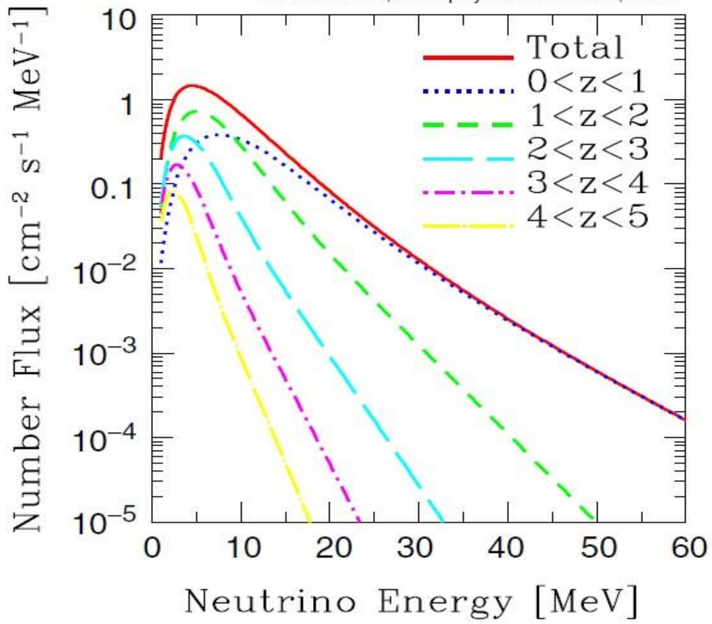
- Galaxy evolution

  → Neutrino energy spectrum contains information about star/black hole formation rate, initial mass function, metallicity.

$$\frac{dF_\nu}{dE_\nu} = c\int_0^{z\mathrm{max}} R_{\mathrm{SN}}(z)\frac{dN_\nu(E'_\nu)}{dE'_\nu}(1+z)\frac{dt}{dz}dz$$

- Mechanism of supernova burst.
- Neutrino oscillation with matter effect in dense medium.

S.Ando et al., Astrophys.J.607:20-31,2004



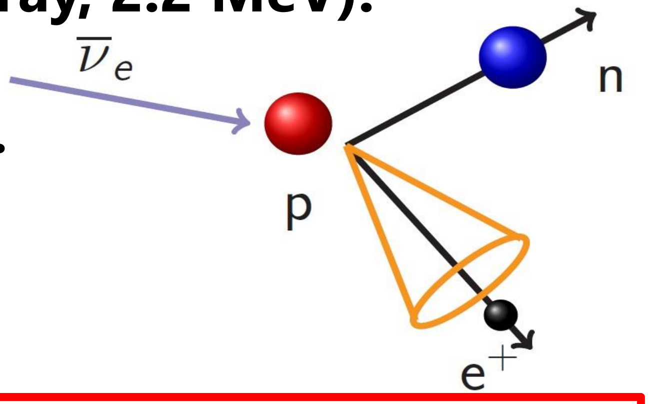
Spectrum shape depends on red shift *z*

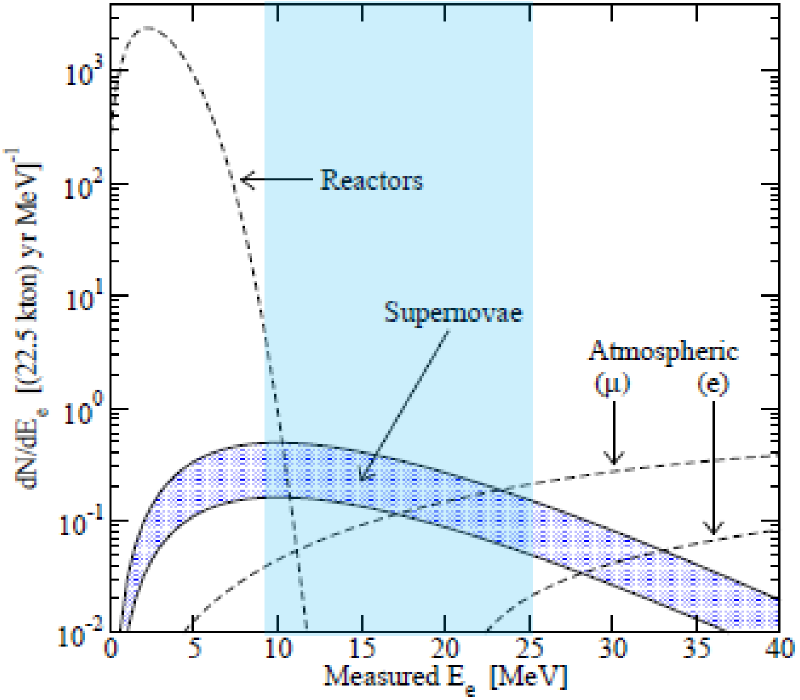
Signal of SRN in the SK detector

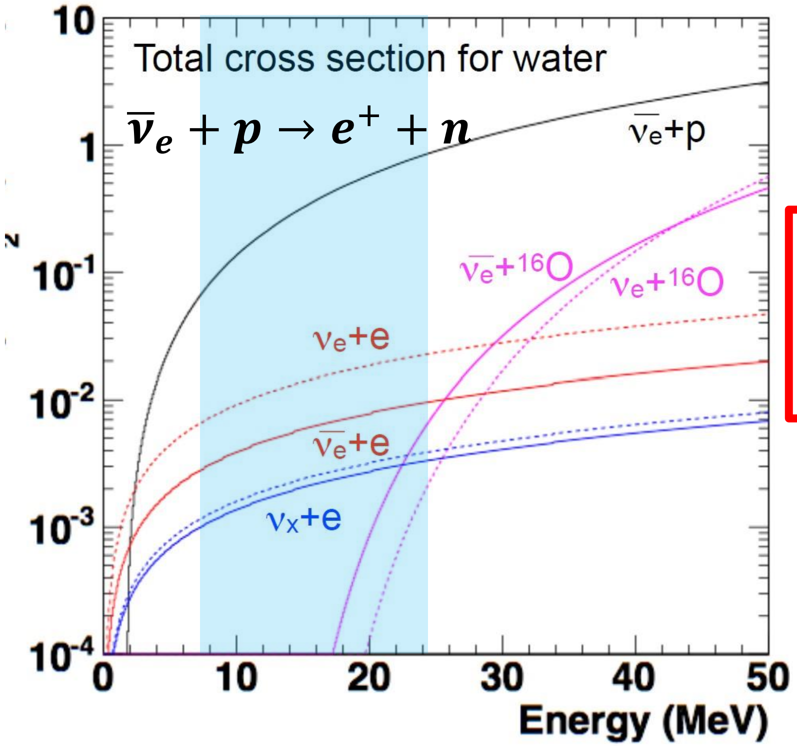
■ Detection possibility

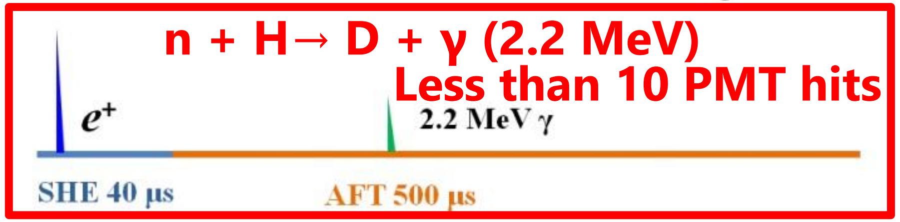
- Signal window between reactor neutrinos and atmospheric neutrinos.
- Large cross section of inverse double beta decay ($\overline{\nu}_e + p \rightarrow e^+ + n$)
  → **Primary signal of positron** and **delayed signal of neutron** (γ-ray, 2.2 MeV).

- Special trigger to record all hits in 500 μs after a primary signal.



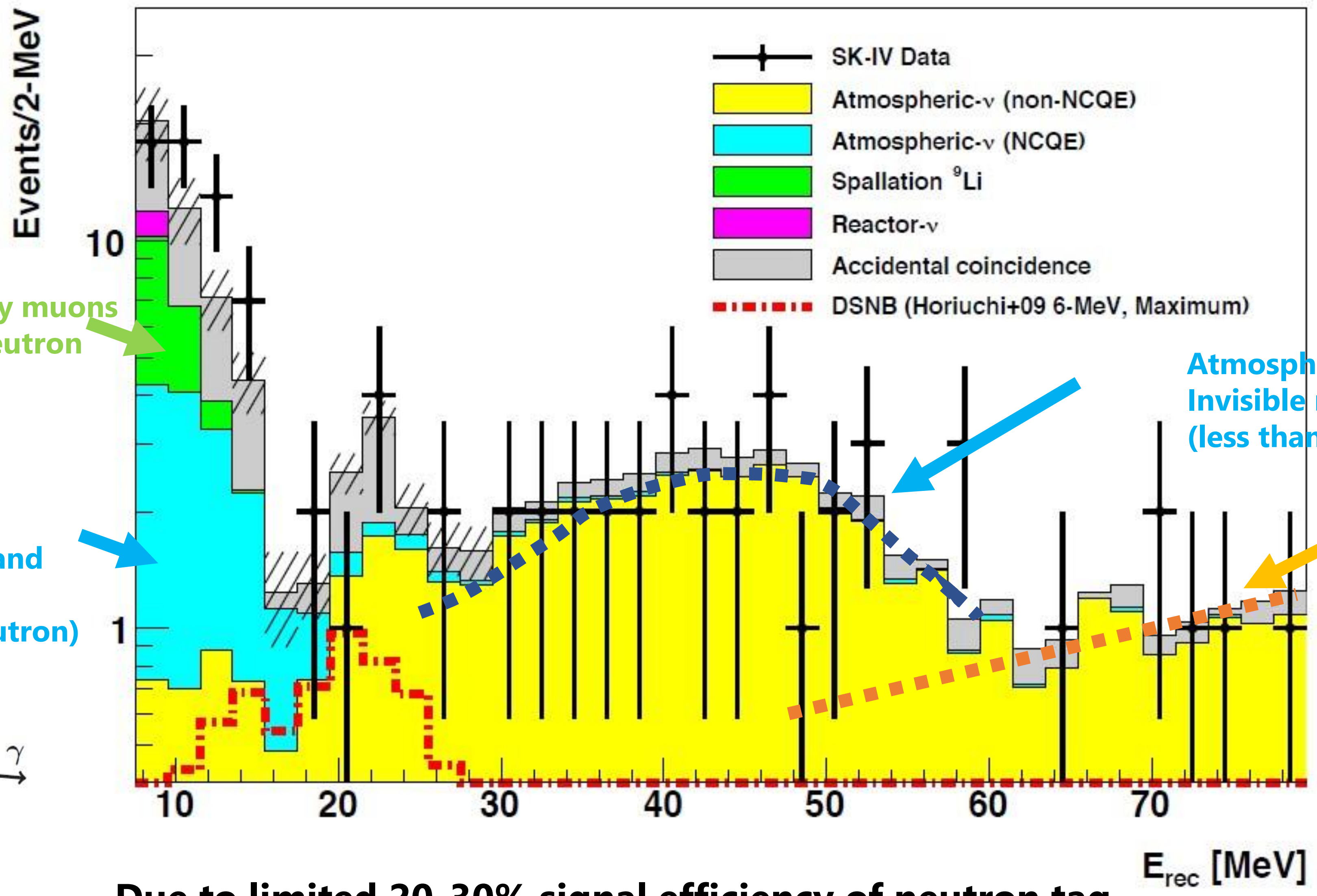






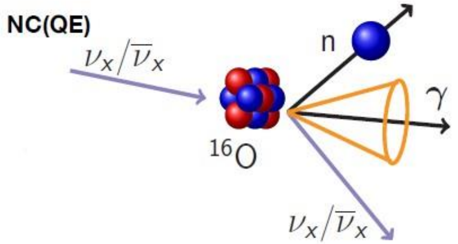
20-30% detection efficiency, in pure water.

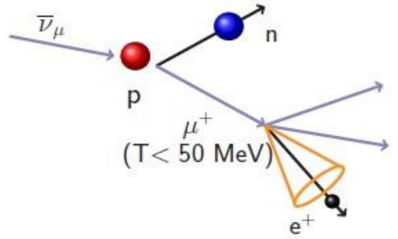
Latest results from SK-IV 2970 days (Pure water)



^{9}Li induced by cosmic ray muons
Produce positron and neutron

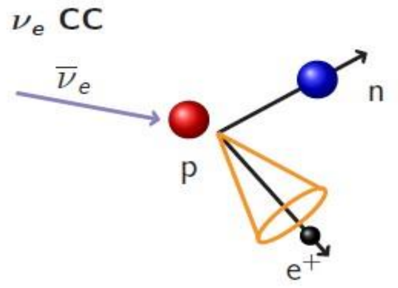
Interaction between atmospheric neutrino and Oxygen nuclei (produce γ-ray and neutron)





Atmospheric muon anti-neutrino
Invisible muon
(less than Cherenkov threshold)

Atmospheric electron neutrino



Due to limited 20-30% signal efficiency of neutron tag, 0.2-3% of fake-tag rate is estimated.

Model independent limit

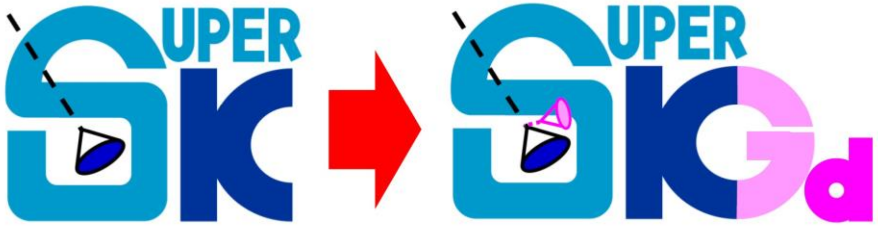
■ Flux limit

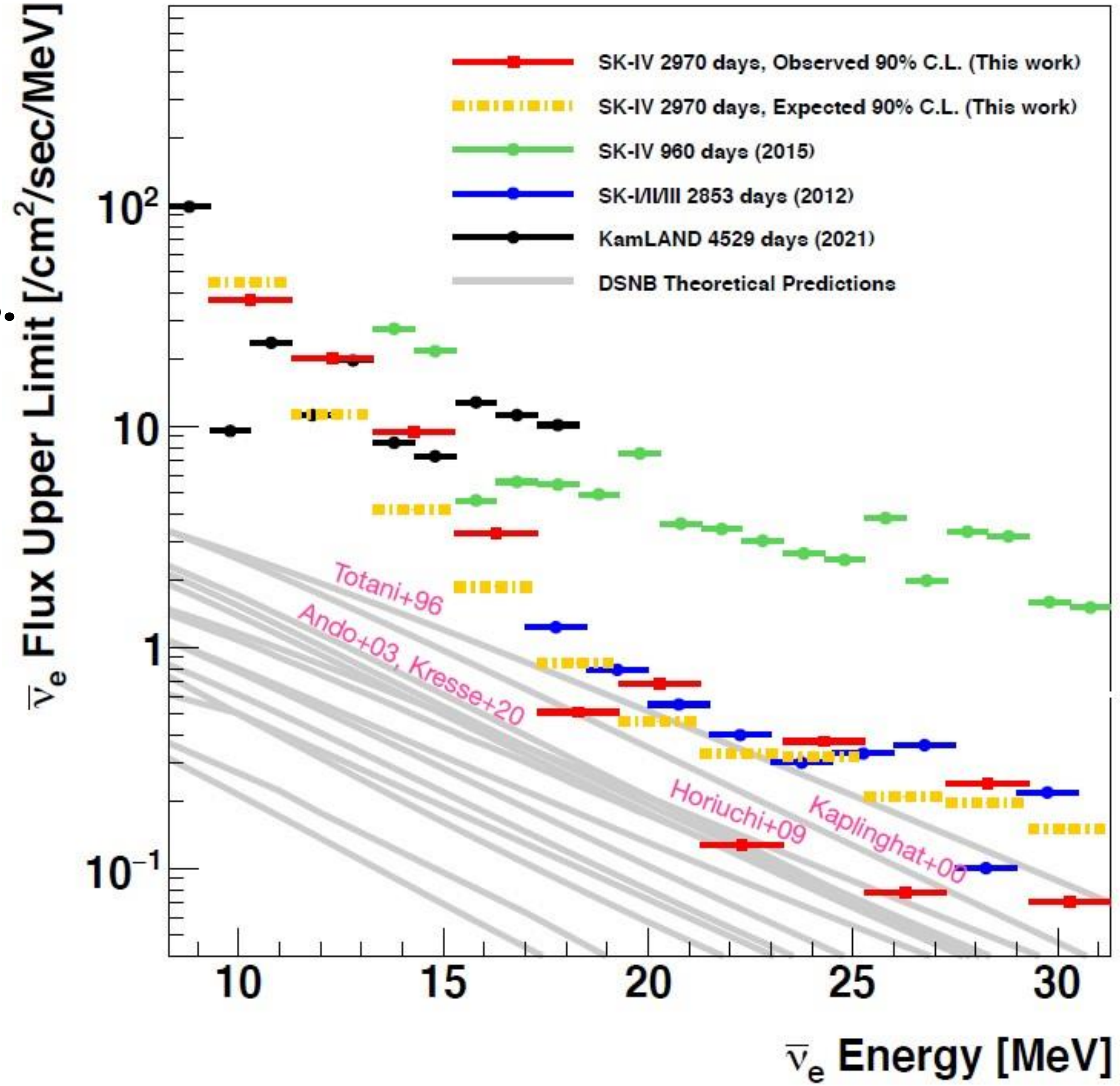
- Upper limit : 4.2 $\bar{\nu}_e$ cm^{-2} s^{-1} (90% C.L.), >15 MeV.
- SK's experimental data reached some of the optimistic model predictions.

- More details can be found in Phys. Rev. D 104, 122002 (2021)

■ Toward observation

- Add Gadolinium to significantly improve the detection efficiency of neutron.





Why Gadolinium

■ Merit

(1) Large cross section to neutron.

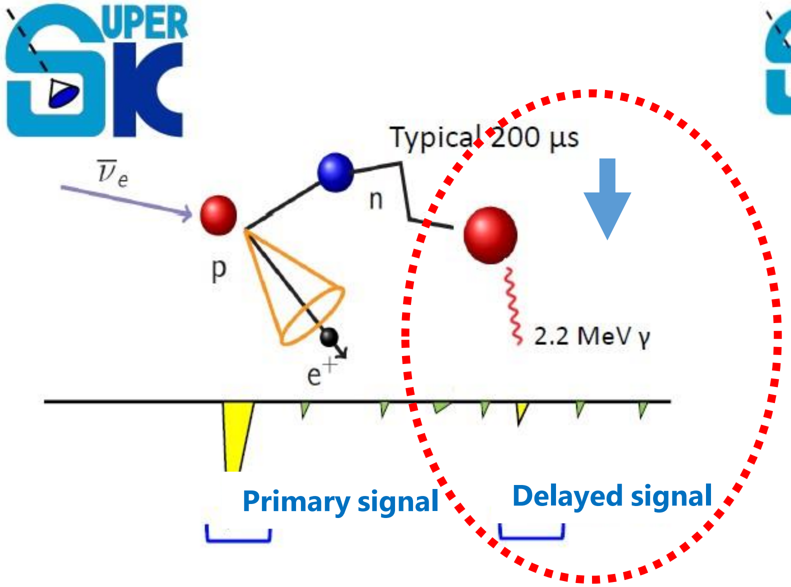
→ 90% (50%) of Gd-n capture efficiency

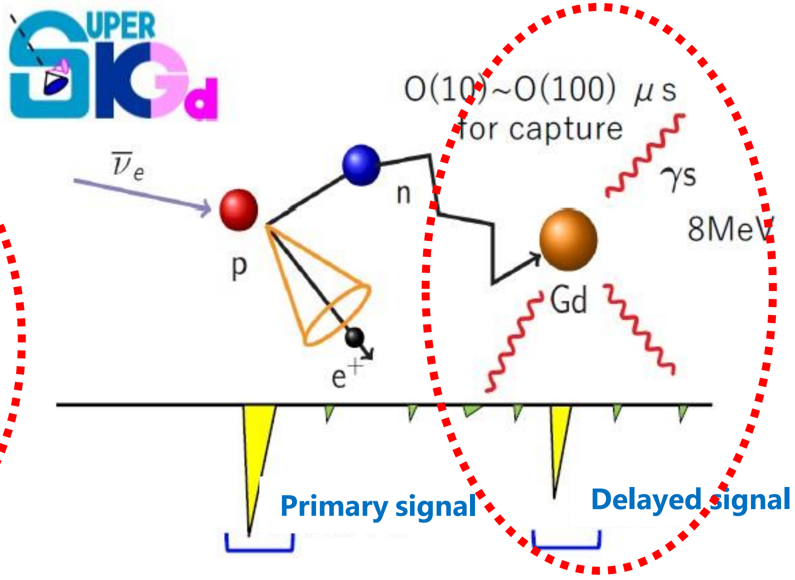
when 0.1% (0.01%) of Gd concentration.

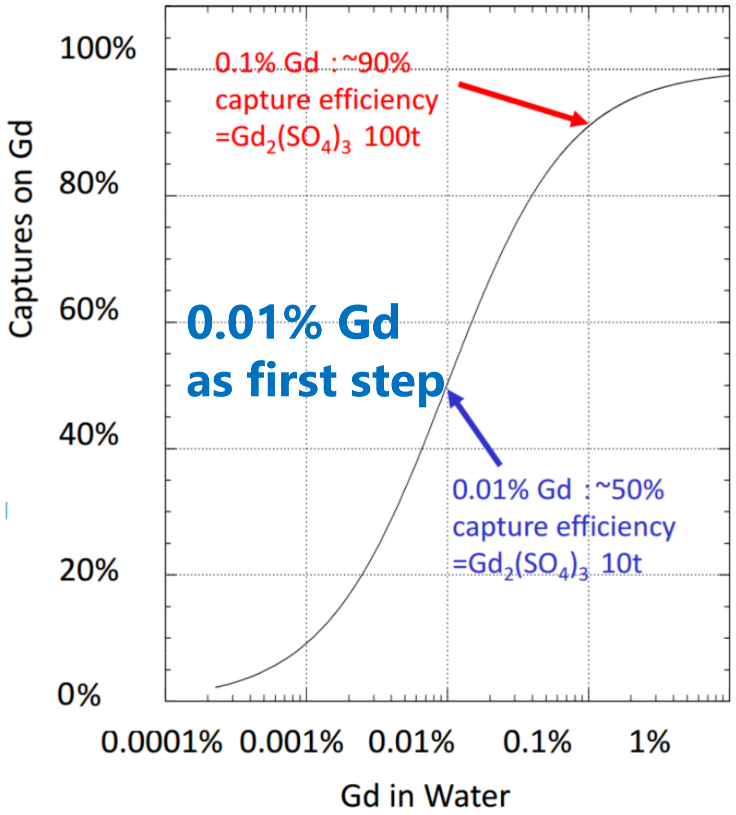
(2) Emission of 8 MeV γ-rays instead of 2.2 MeV γ-ray.

~100 hits ~10 hits

- Enhance detection capability of neutrons from IBD.





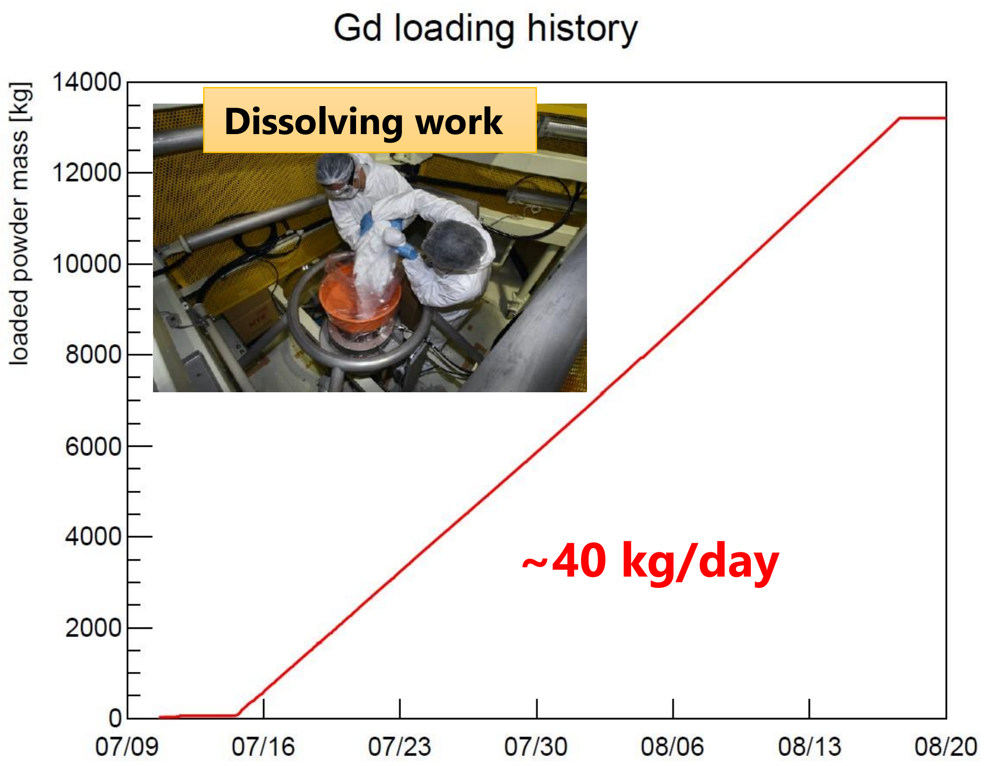


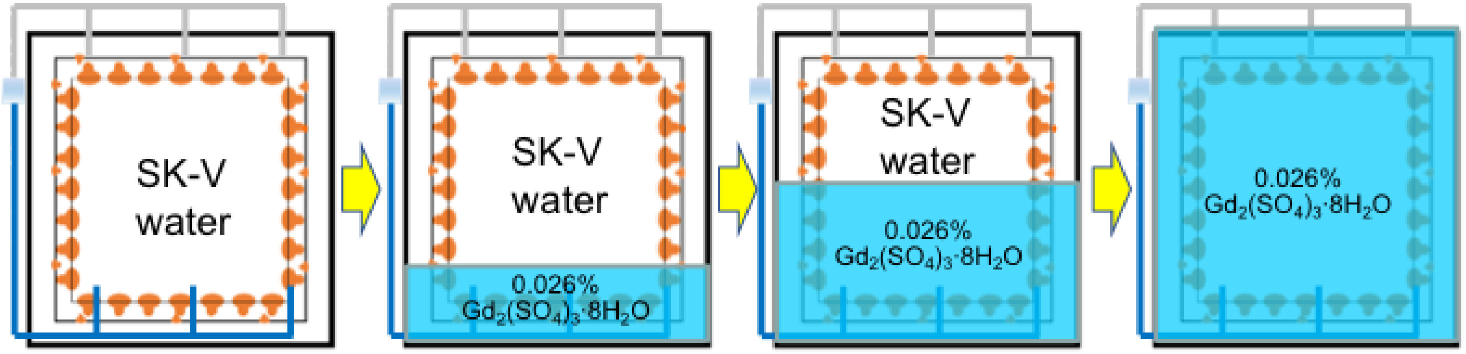
First Gd-loading in 2020

■ Replacement of water

- 13.2 tons of $Gd_2(SO_4)_3 \cdot 8H_2O$ (5 tons of Gd).
  → Screened its radioactive impurities before loading.

- Suck pure water from top.
- Supply cold Gd water from the bottom.
  → from July 14th to august 17th 2020.





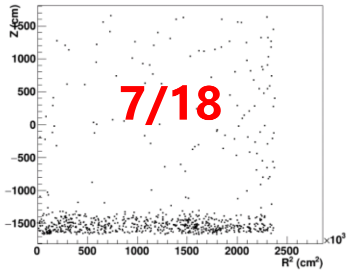
Neutron induced by cosmic ray muons

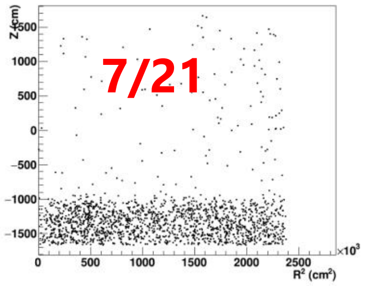
■ Neutrons after muons

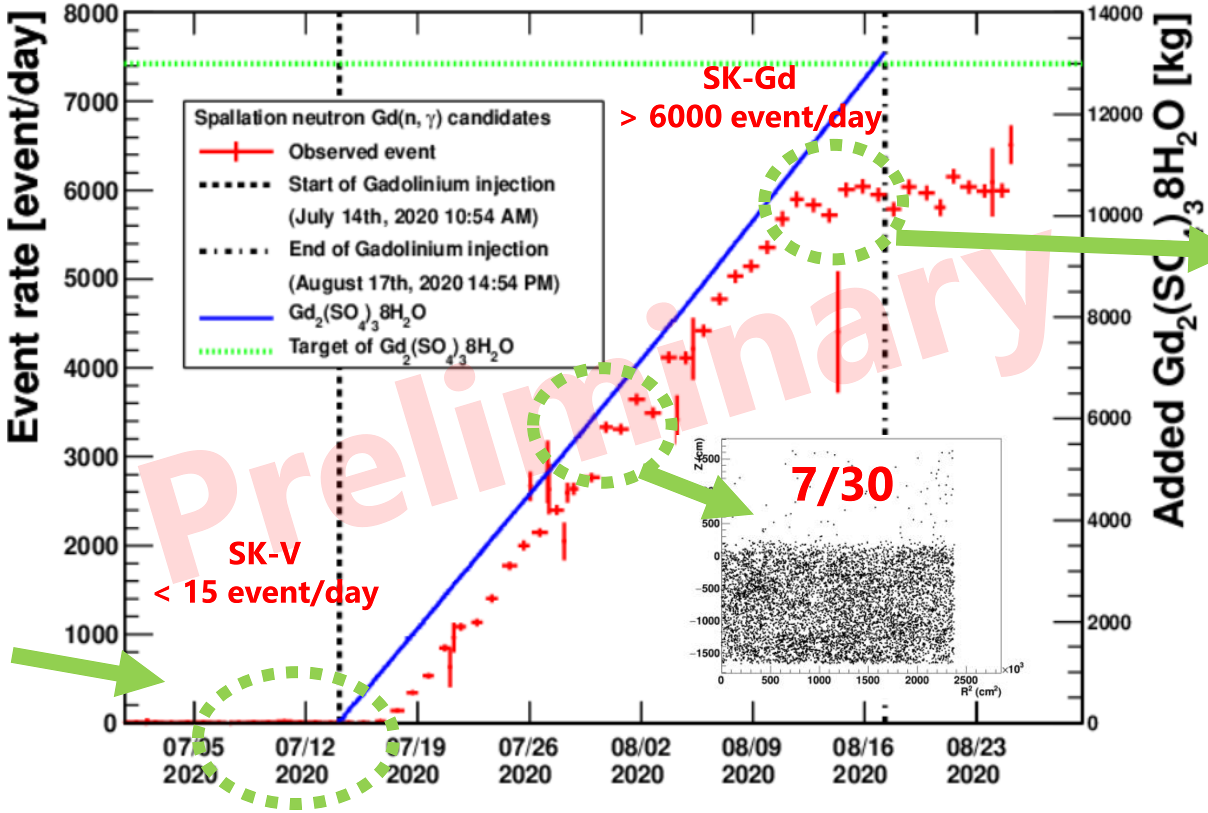
- Tagging rate 15 event/day, when pure water.
- After loading Gd → 6000 event/day.
- Gd-n capture signals were clearly observed.

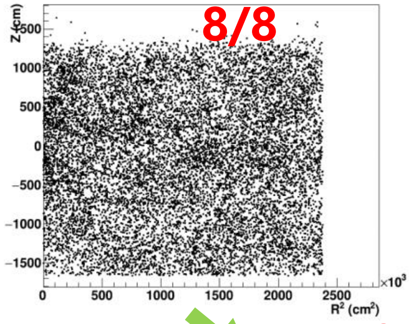
Cosmic ray muons often break Oxygen nuclei.
→ Produce neutrons (spallation products)

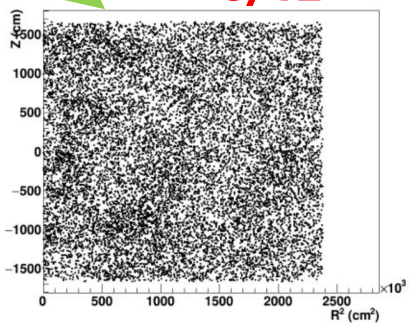
Selection for neutron tag
[+35, +535] μsec
200 cm from the SK wall
N_{50} > 30
200 cm from muon











Muons 2 Hz (160000 event/day)

Uniformity of Gd concentration

100 ppm = 0.01%

■ Monitoring the Gd concentration

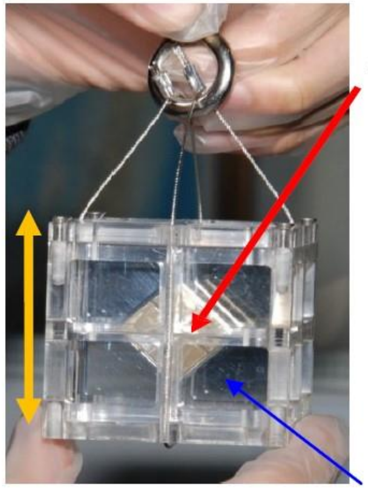
(1) **Atomic Absorption Spectrometer** by directly sampling Gd-loaded water.

→ 114 ± 2 ppm.

(2) **Am/Be+BGO calibration** data in various height in the water tank.

→ Capture time of $115 \pm 1\ \mu s$ corresponding to 111 ± 2 ppm.

- Consistent with the expectation throughout the detector volume.



Am/Be source

100~200 neutrons/s

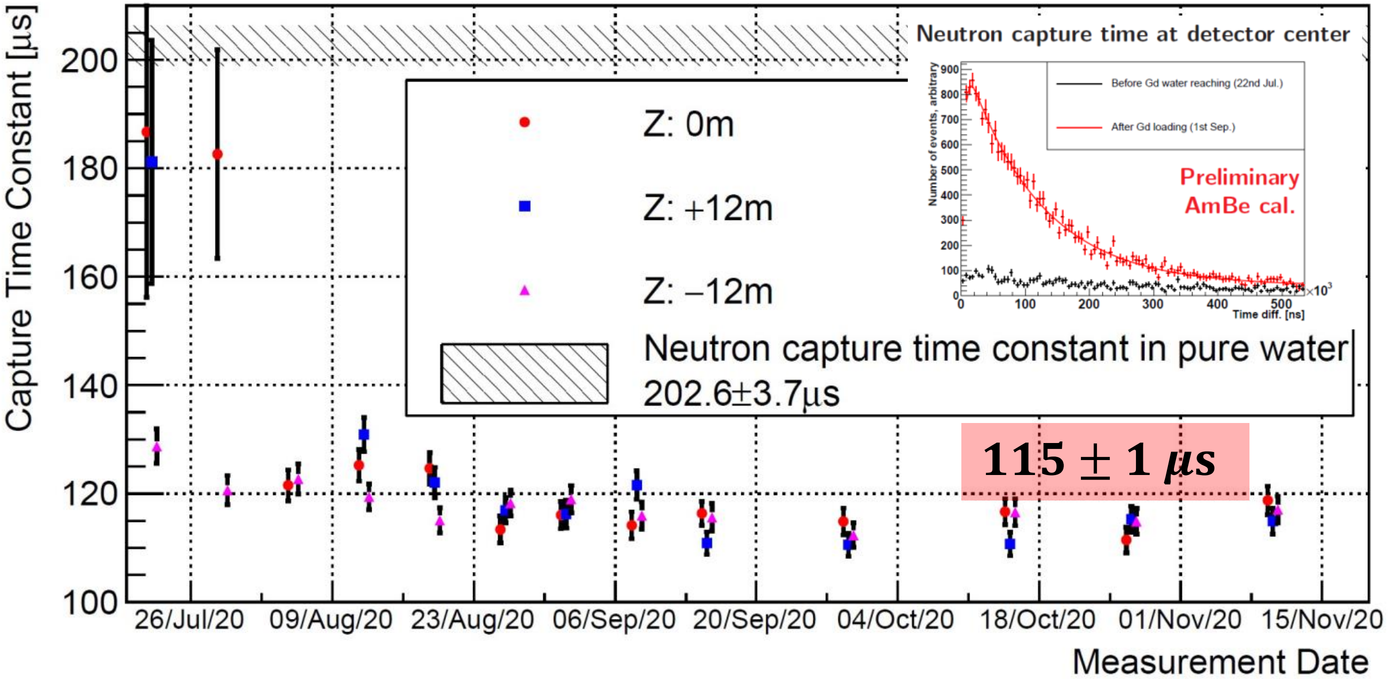
$^{241}Am \rightarrow {}^{237}Np + \alpha$

$^{9}Be + \alpha \rightarrow {}^{13}C^{*} + n$ (2-6 MeV)

$^{13}C^{*} \rightarrow {}^{12}C + \gamma$ (4.43 MeV)

8 BGO Crystals

Scintillation light as primary signal
Neutron as delayed signal



Status after Gd-loading

■ Achievements and recent progress

- Developed the screening method of Gd sulfate powder.
- Established the Gd loading method.
- Clear signals of Gd-n capture.
- Demonstrate the uniformity of the Gd concentration in the tank.

More details
Nucl. Inst. Meth. A 1027, 166248 (2022)

- Evaluate the detector response and performance with calibration devices.
- Analyze the real data including Gd-n capture signals.

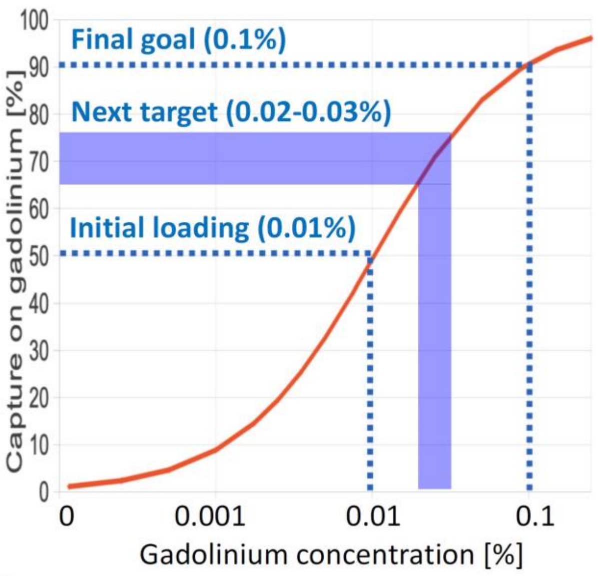
S. Miki, Neutrino event reconstruction with neutron detection in SK-Gd
Y. Maekawa, 光電子増倍管ノイズ解析によるSK-Gdの中性子識別効率向上

Short talks by students

■ Next step

- More Gd as the second Gd-loading in 2022.

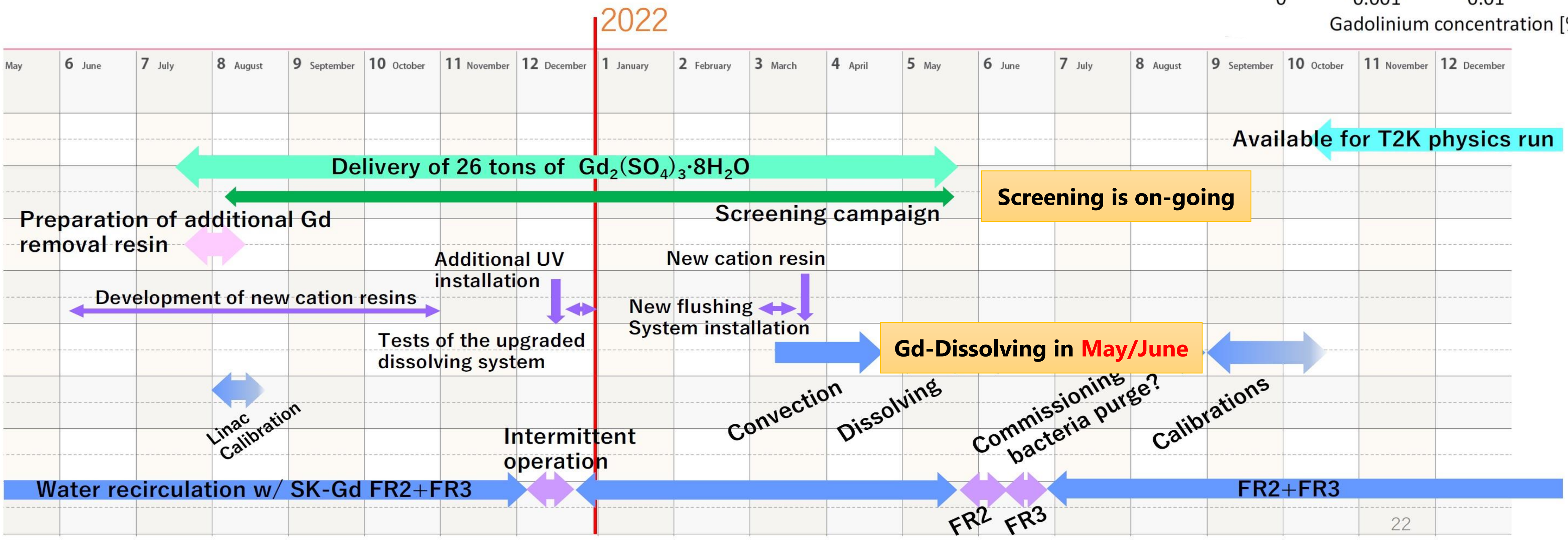
Second Gd loading in 2022



■ Additional Gd-loading

- Dissolving additional 26 tons of $Gd_2(SO_4)_3 \cdot 8H_2O$ in May/June 2022.

	Gd concentration	Gd-n capture efficiency [%]
First Gd-loading in 2020	0.011%	50%
Second Gd-loading in 2022	0.030%	75%



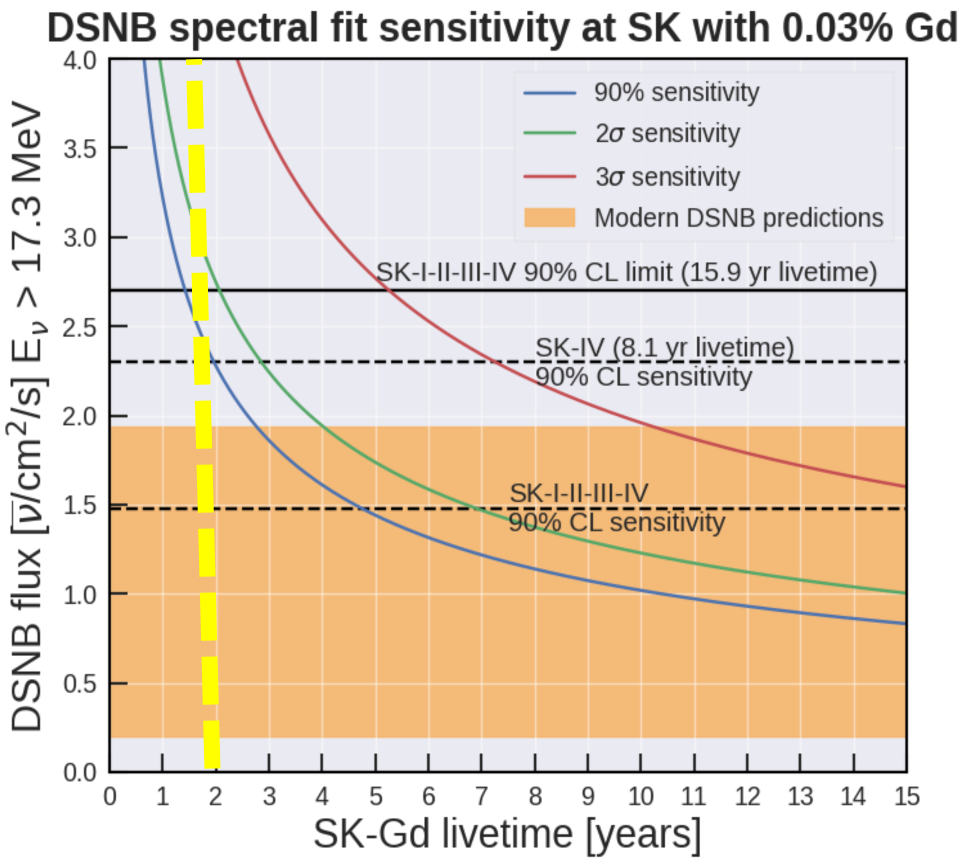
Future prospect when 0.03% of Gd

■ Expected sensitivity

- Two years of operation with 0.03% Gd concentration.
  → 8 years with pure water (~same as SK-IV).

- Background due to atmospheric neutrinos should be reduced for further sensitivity.

- Some of the models can be tested in near future.



Supernova alert on GCN

■ Automatic alert

- SK's automatic alert is sent to GCN.

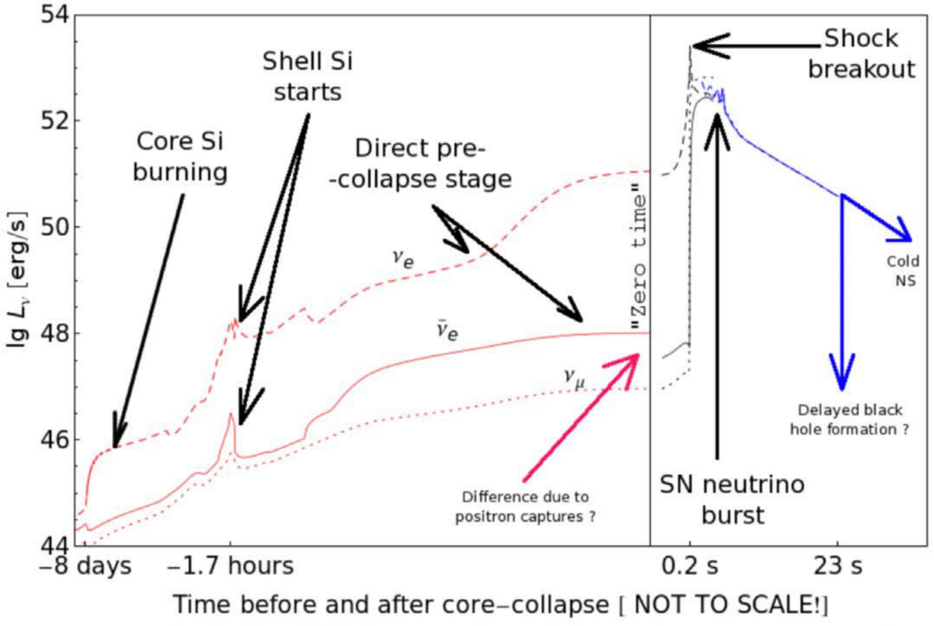
  (The Gamma-ray Coordinates Network).

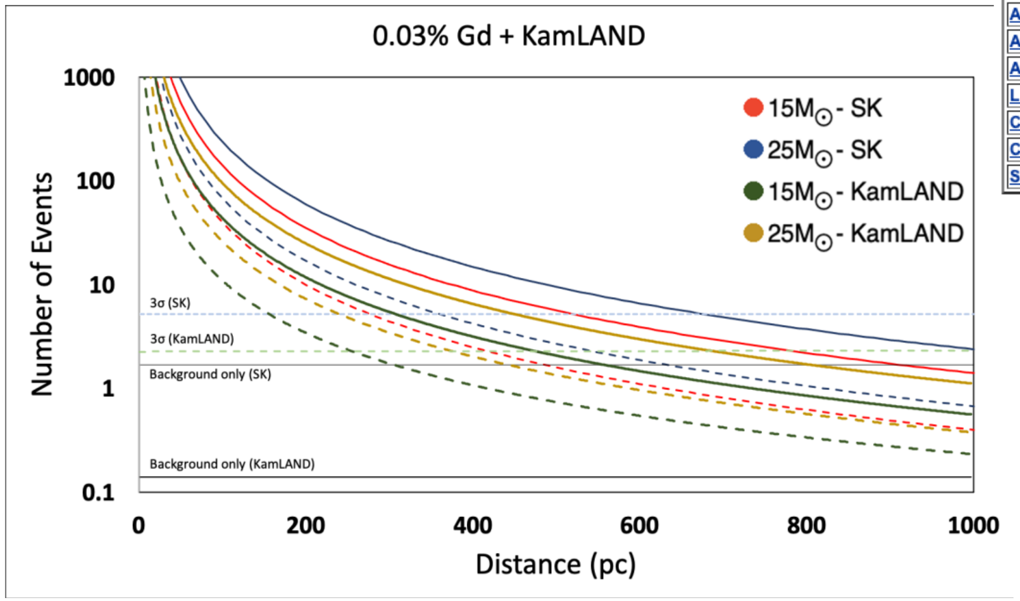
  → Within some minutes after detection of a neutrino burst.

- Pre-Sn signals from Si-burning are also feasible (<200 pc).

  → low energy, low intensity, long-emission before its explosion.

ACTIVE		OLD INACTIVE	
Description	Notice Archive	Description	Notice Archive
IPN		CGRO	n/a
KONUS	table	BeppoSAX	table
INTEGRAL	GRBs table	NEAR	table
INTEGRAL	SPI-ACS table	ALEXIS	table
Swift	GRBs table	HETE	table
Swift	GND_ANALYSIS table	MILAGRO	table
Swift	BAT SubSubThresh table	XTE-PCA, -ASM	table
Swift	BAT Monitor table	Suzaku	table
AGILE	GRBs table		
AGILE	MCAL table		
Fermi	GRBs table		
Fermi	GBM Subthresh table		
Fermi	LAT Monitor&Trans table		
MAXI	table		
MOA	table		
SNEWS	table		
SK_SN	table		
CALET	table		
AMON	Gold&Bronze table	AMON	EHE table
AMON	HAWC table	AMON	HESE table
AMON	NU_EM table		
AMON	CASCADE table		
LIGO/Virgo	table		
Counterpart	table		
Coincidence	table		
SIMBAD-NED	n/a		





Related study by SK
Astrophys . J. 885, 2 (2019)

Summary

- Super-Kamiokande has collected rich data for more than 25 years.
  → Using data with pure water, its sensitivity to supernova relic neutrinos (SRN) reaches most optimistic models.

- SK-Gd project started in 2020 to aim for the first observation of SRN.
- First Gd loading was conducted in July-August 2020.
  → 0.011% of Gd concentration and 50% of Gd-n capture efficiency.

- More Gd will be added in this year.
  → 0.03% of Gd concentration and 75% of Gd-n capture efficiency

- Automatic alert is ready for a SN burst and pre-SN signals.

Back up