

SK-Gd: New era in Super-Kamiokande detector



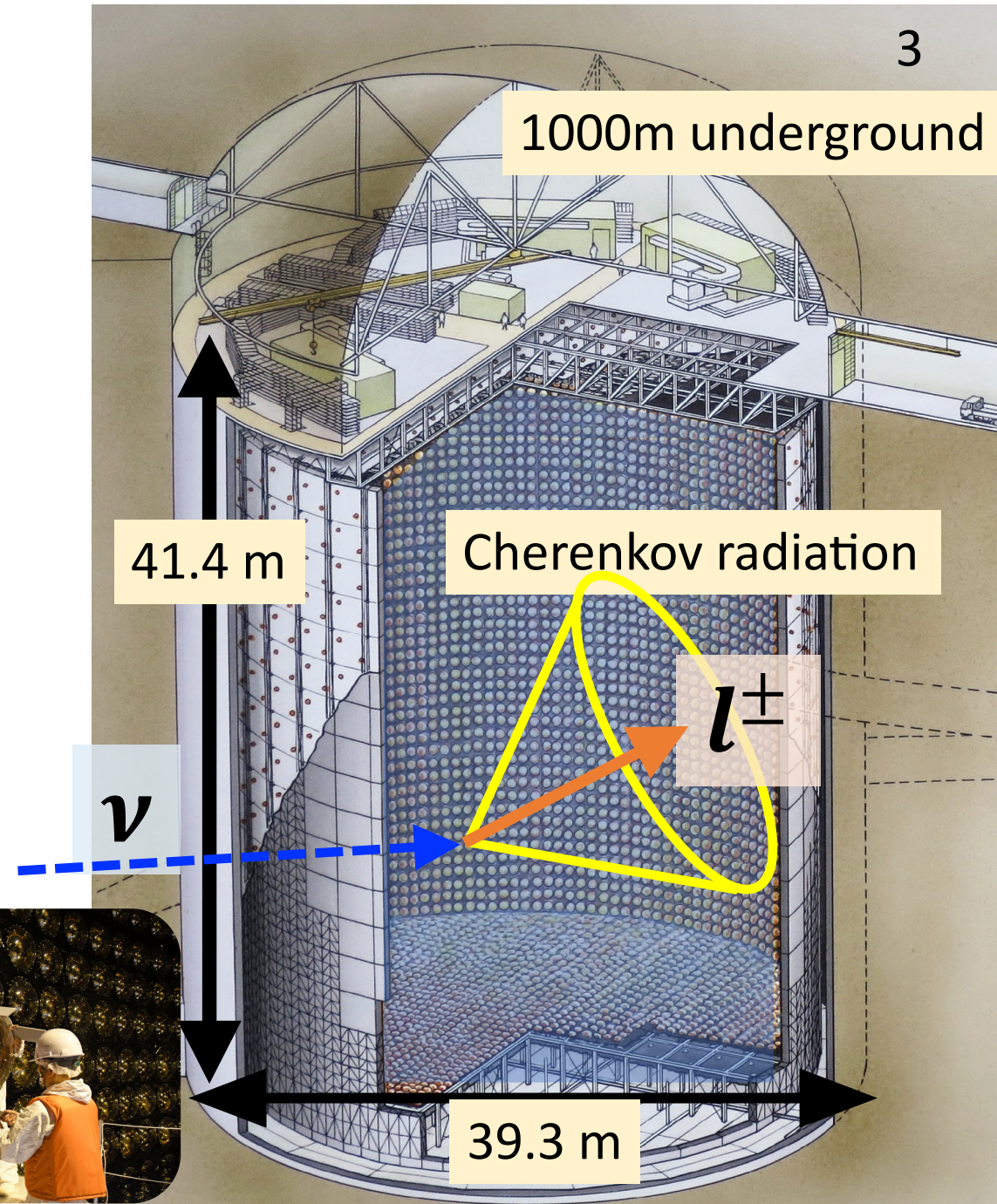
- Aug. 3, 2023
SLAC FPD seminar
- Shintaro MiKi (ICRR, Univ. of Tokyo)
smiki@km.icrr.u-tokyo.ac.jp

Outline

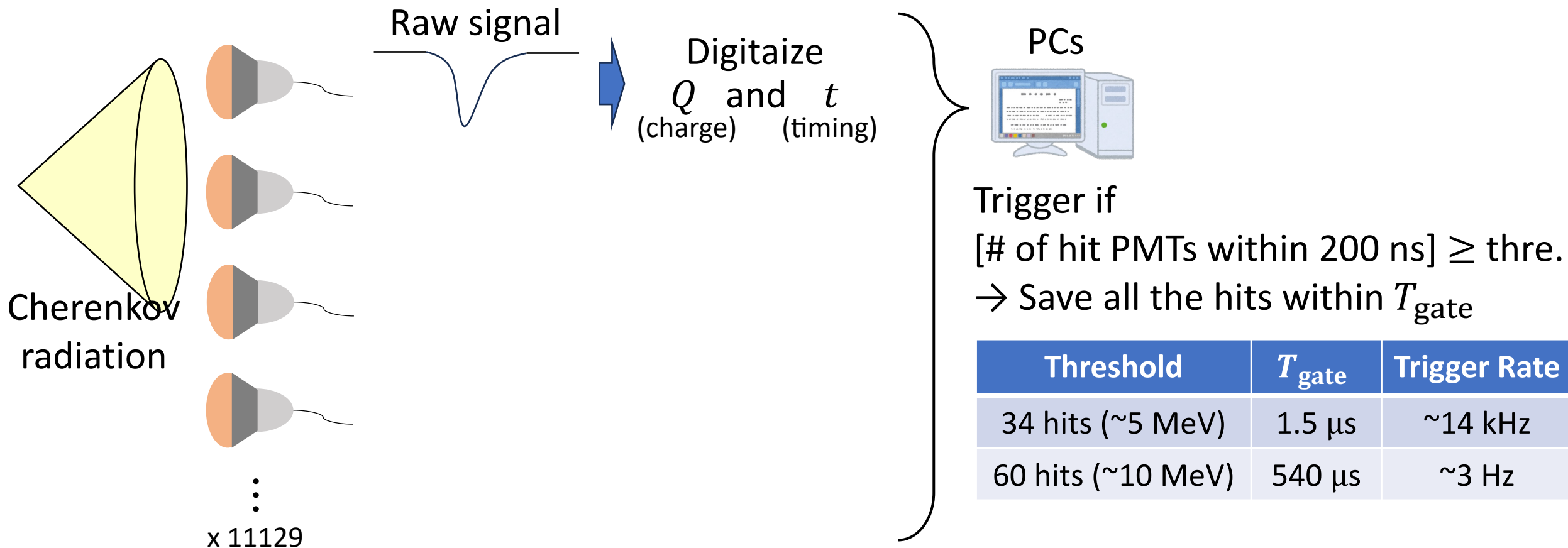
- Super-Kamiokande detector
- SK-Gd and neutron detection strategy
- Benefits of neutron detection to physics capabilities

Super-Kamiokande (SK)

- Water-Cherenkov detector @Kamioka mine, Japan.
- 50 kton pure water as target and detector.
 - Circulated for purification in ~ 1 month.
- 11,129 50cm PMTs.
 - Photo coverage $\sim 40\%$
- Optically divided outer region ($\sim 2\text{m}$ thick) works as veto and shield for incoming particles. (cosmic rays, neutrons)
- Started in 1996, running for 27 years.



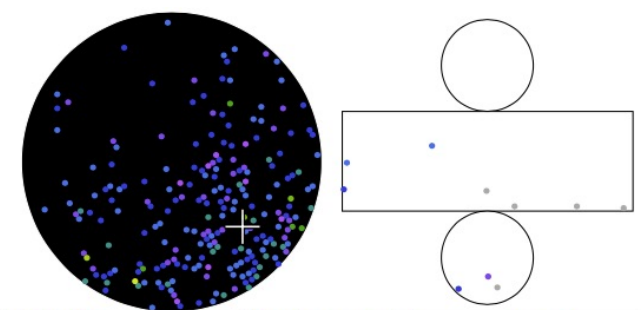
Data flow in SK



Events in SK

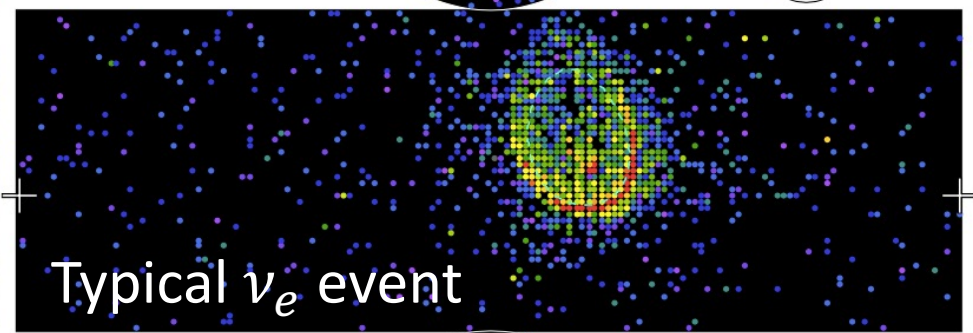
- Cherenkov light is observed as a ring.
- Michel electrons are observed separated in time.

Super-Kamiokande VI
 Run 85038 Sub 243 Event 212714364
 20-07-20:22:53:10
 Inner: 1520 hits, 5406 pe
 Outer: 5 hits, 5 pe
 Trigger: 0x10000007
 D_wall: 615.6 cm
 Evis: 570.9 MeV
 e-like, p = 570.9 MeV/c



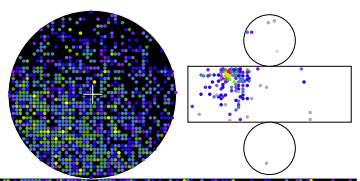
Charge (pe)

- >26.7
- 23.3-26.7
- 20.2-23.3
- 17.3-20.2
- 14.7-17.3
- 12.2-14.7
- 10.0-12.2
- 8.0-10.0
- 6.2- 8.0
- 4.7- 6.2
- 3.3- 4.7
- 2.2- 3.3
- 1.3- 2.2
- 0.7- 1.3
- 0.2- 0.7
- < 0.2



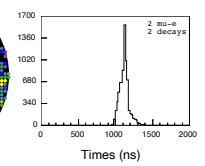
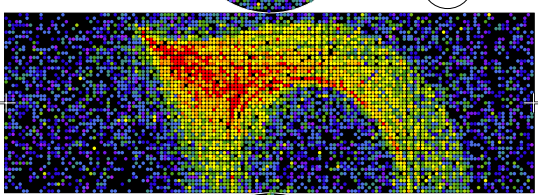
Typical ν_e event

Super-Kamiokande VI
 Run 85015 Sub 2 Ev 1113326
 20-07-19:17:02:26
 Inner: 7707 hits, 46228 pe
 Outer: 104 hits, 362 pe
 Trigger: 0x1000000F
 D_wall: 1690.0 cm
 Evis: 0.0 MeV



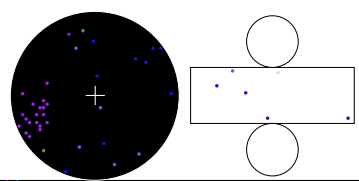
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- < 0.2



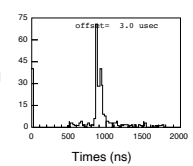
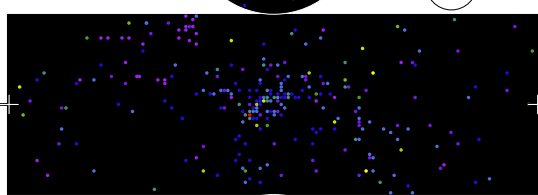
Cosmic muon

Super-Kamiokande VI
 Run 85015 Sub 2 Ev 1113326
 20-07-19:17:02:26
 Inner: 7707 hits, 46228 pe
 Outer: 104 hits, 362 pe
 Trigger: 0x1000000F
 D_wall: 1690.0 cm
 Evis: 0.0 MeV



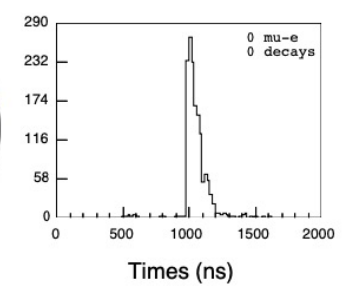
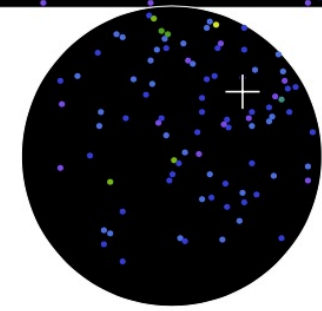
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Michel e

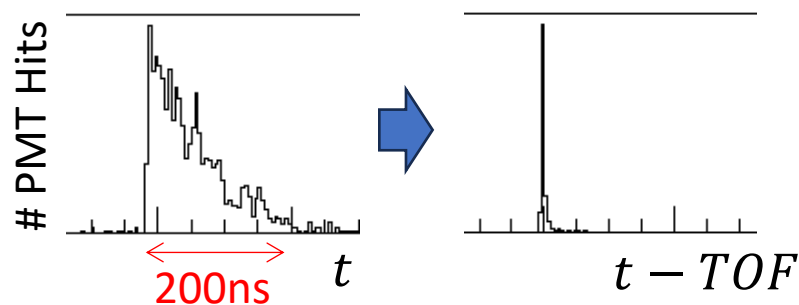
→
 $O(2\mu s)$



Event reconstruction

Interaction vertex

- Find vertex to minimize spread of $t - TOF$.



- Resolution: ~ 30 cm for GeV event

Direction

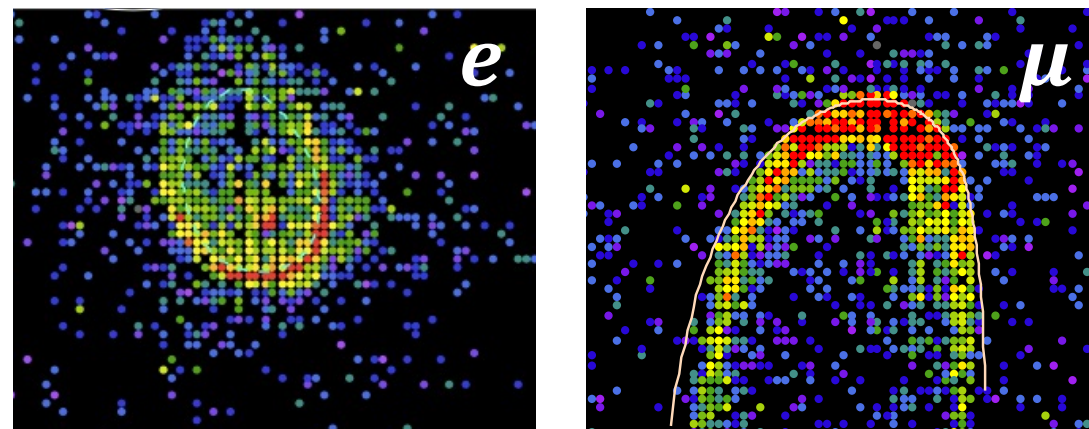
- Reconstruct from event geometry.
- Resolution: several degrees for GeV event

Momentum

- (Roughly) Proportional to total charge.
- Resolution: several % for GeV event

Particle ID (e -like or μ -like)

- Ring edge is obscure $\rightarrow e$ -like, clear $\rightarrow \mu$ -like



- Insensitive to sign of charge

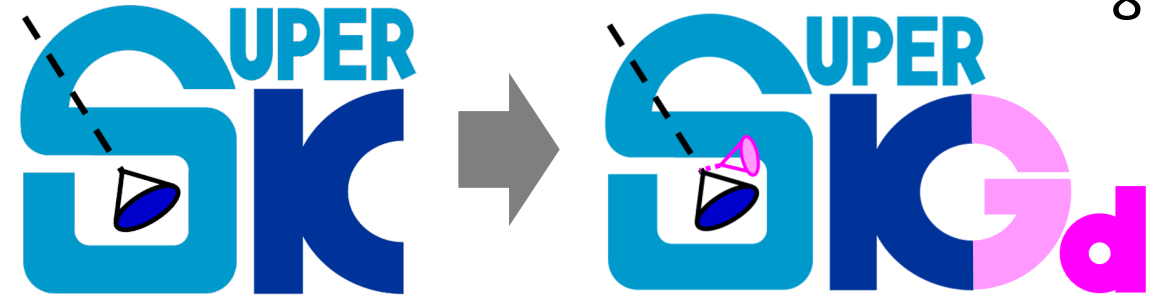
Physics in SK

- Neutrino oscillation measurement
 - Atmospheric ν : \sim GeV
 - Accelerator ν (T2K experiment) : \sim GeV
 - Solar ν : several – 10 MeV
- Search for nucleon decay
- Astrophysical neutrino observation
 - Supernova ν
 - Diffuse supernova neutrino background (DSNB)
 - other sources (such as GRB)

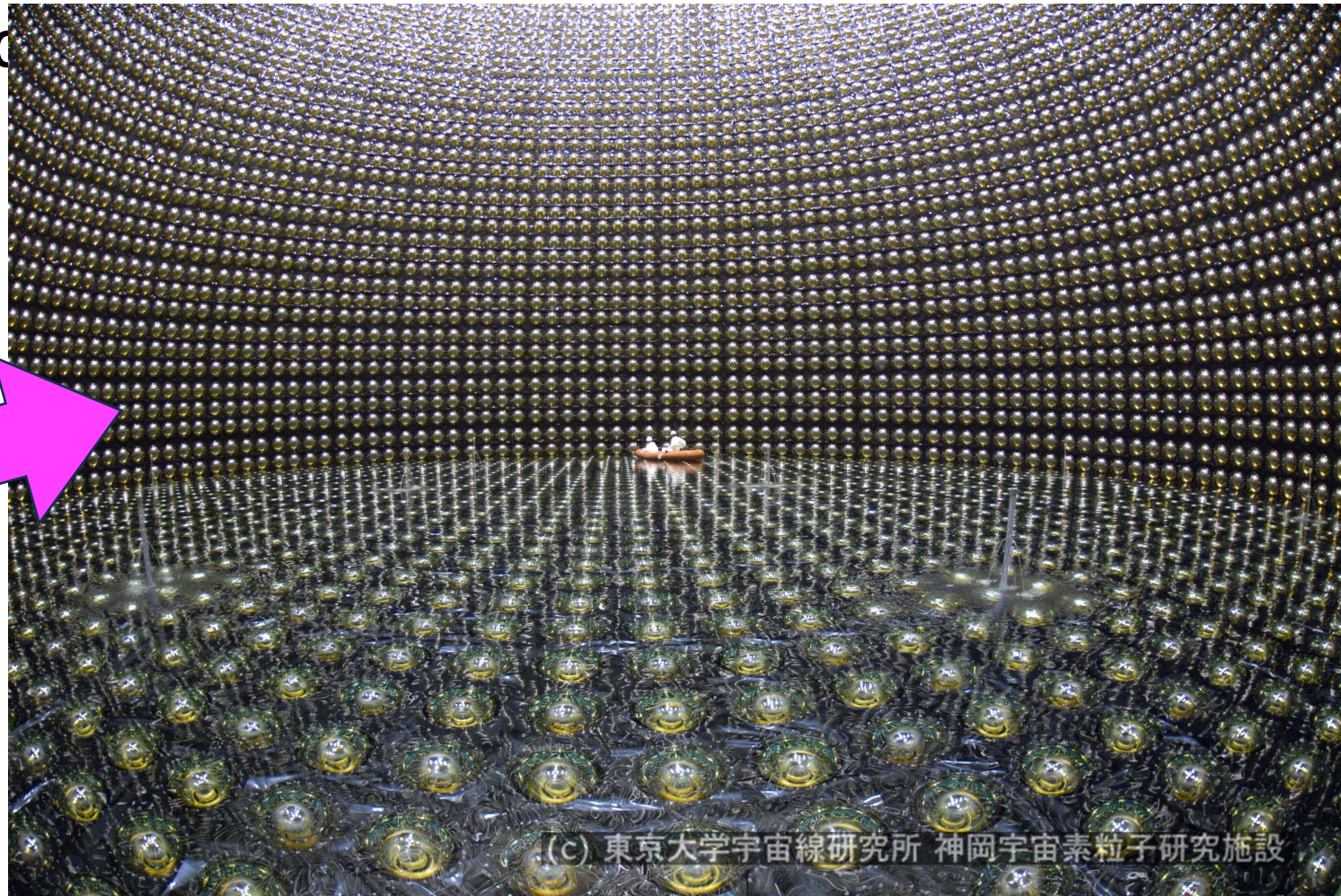
Details later

SK-Gd

- Super-Kamiokande has become completely different with Gd since 2020.

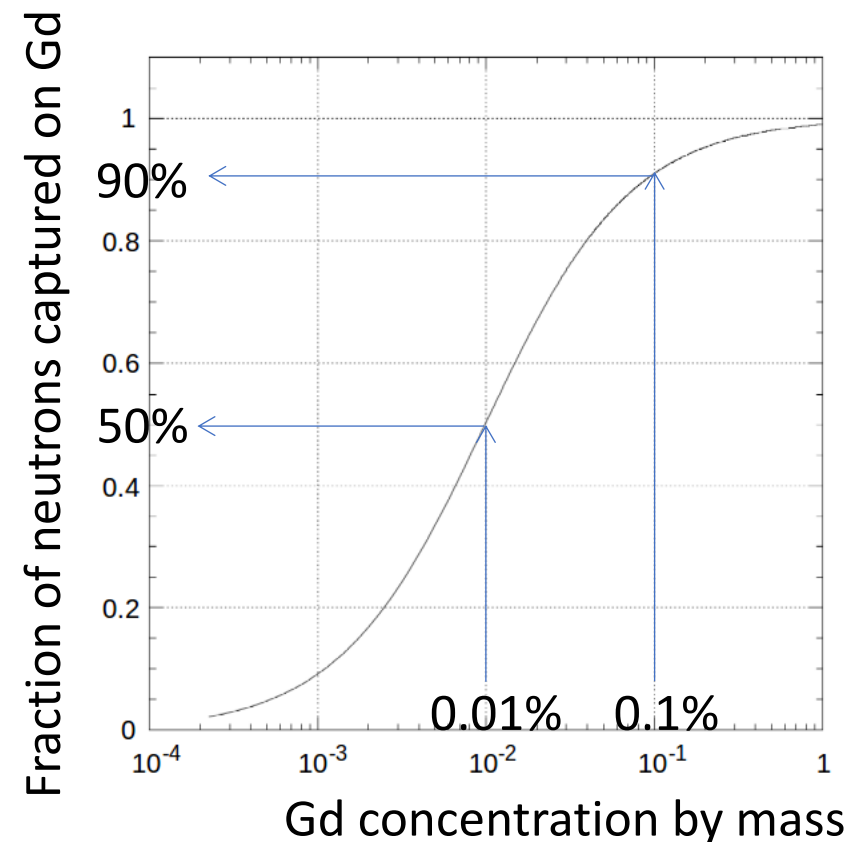
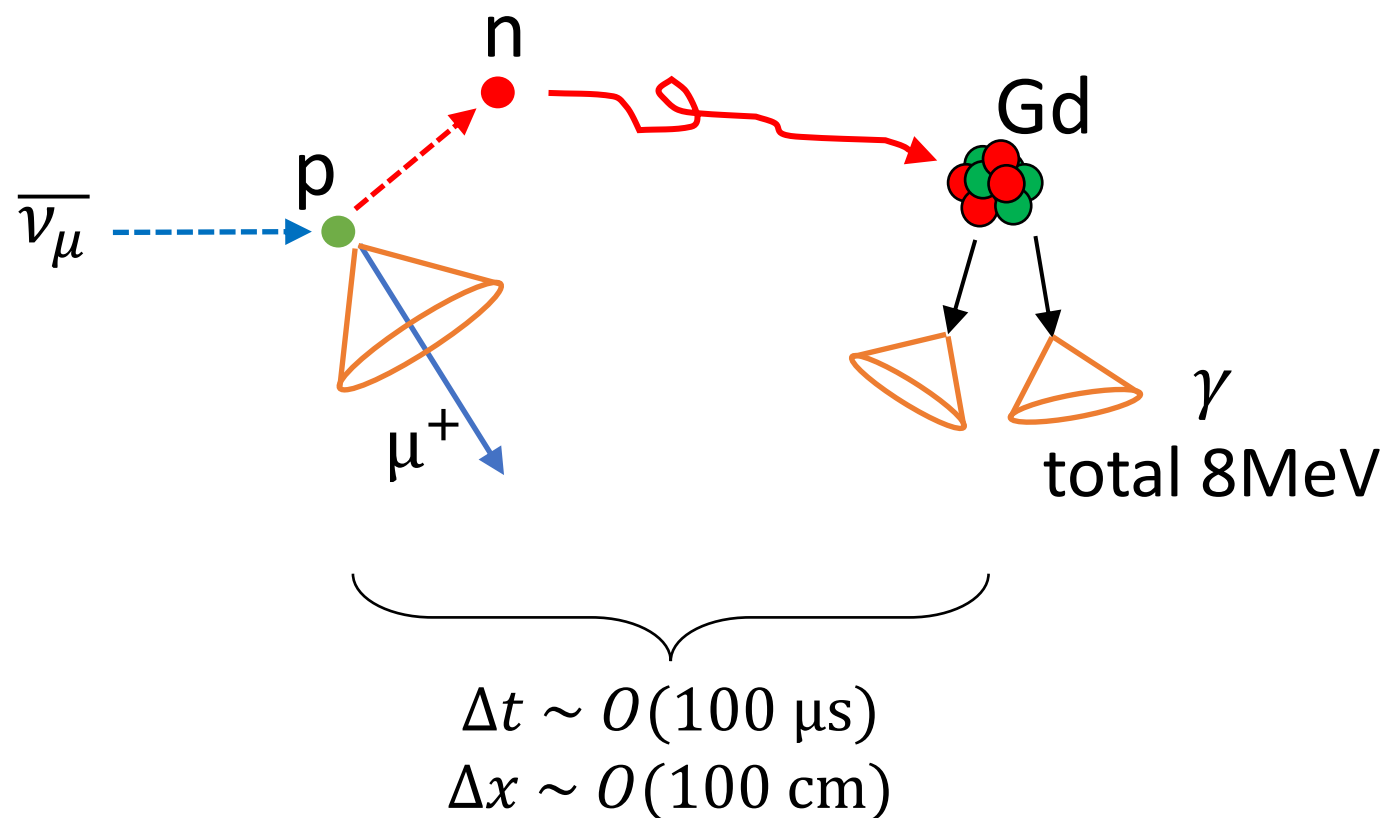


13 tons of $Gd_2(SO_4)_3 \cdot 8H_2O$



Why gadolinium?

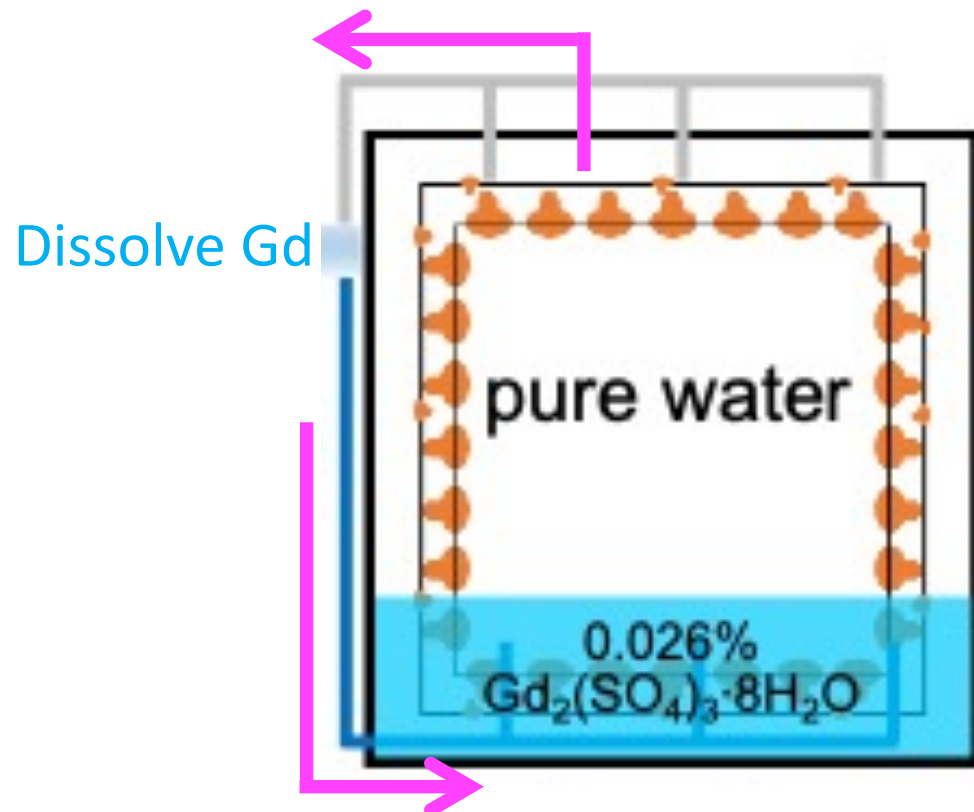
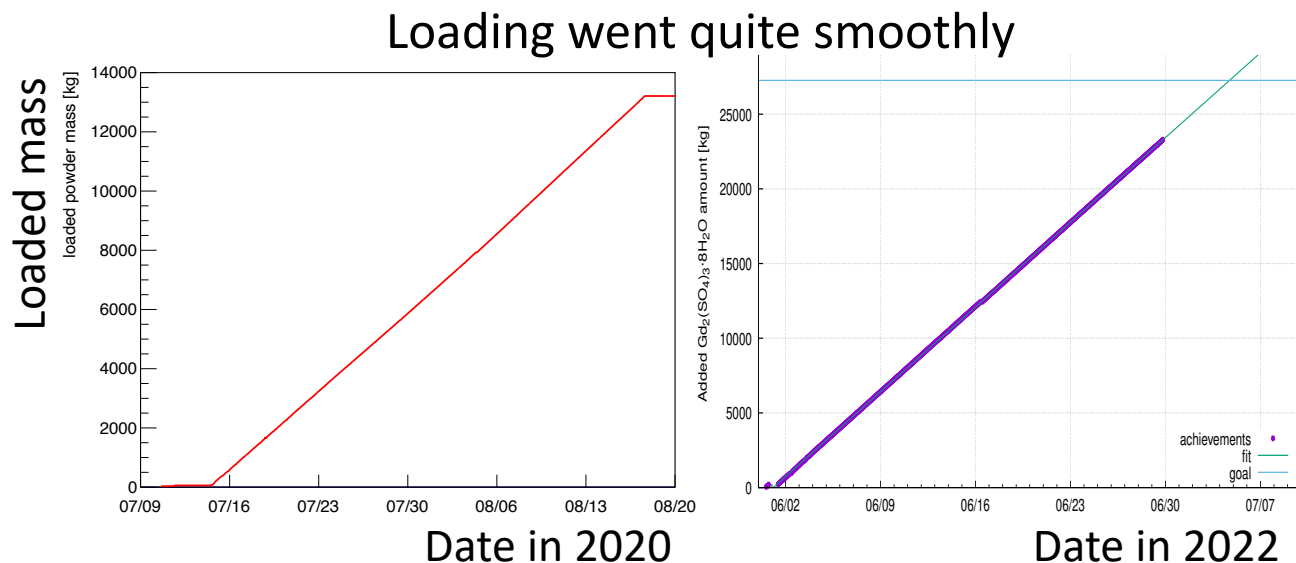
- Gd was added to improve **neutron detection efficiency**.
 - Gd has large cross section for neutron capture (254,000 barn for ^{157}Gd) and emits multiple γ 's.



Gd loading

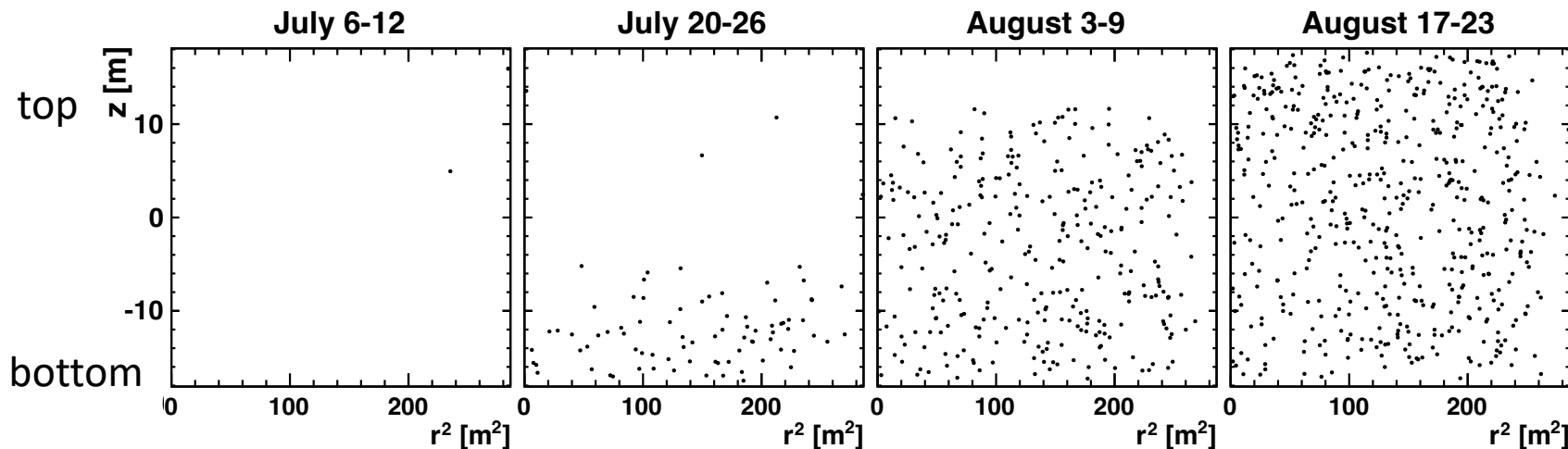
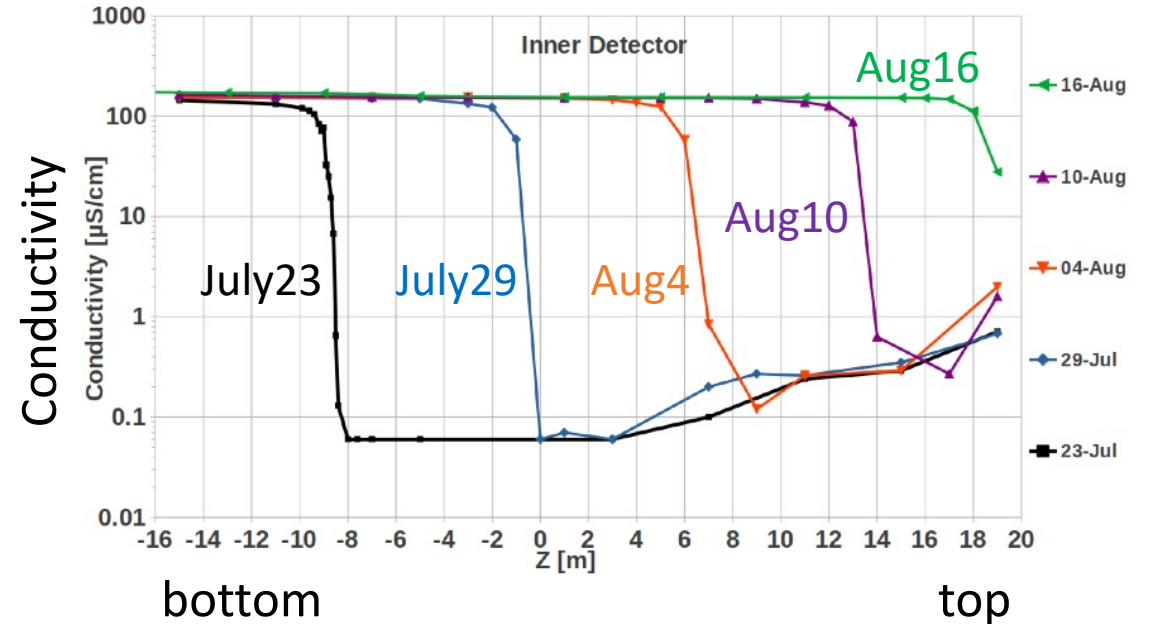
- Done in two steps so far.
- Through water circulation system. Sent Gd-loaded water from tank bottom.
- Took ~1 month to complete each loading.

	Amount of $\text{Gd}_2(\text{SO}_4)_3 \cdot 8\text{H}_2\text{O}$	Gd concentration	Fraction of n captured on Gd
July 2020	13 tons	0.01%	50%
June 2022	+26 tons	0.03%	75%



Gd loading monitoring

- Loading was monitored by various ways:
 - Contactivity
 - Atomic absorption spectrometer
 - Neutrons from RI source
 - Neutrons from cosmic muons
- Figures in first loading in 2020.



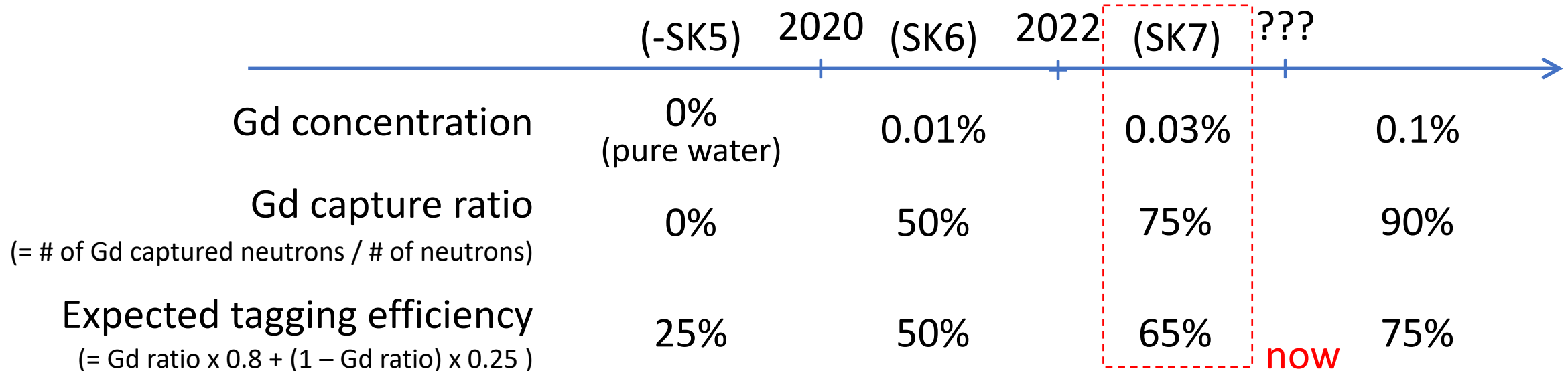
← Vertex of detected neutrons produced from $^{16}\text{O}(\mu^-, \nu_\mu)$ by cosmic muons

My work!

Neutron detection via proton

- Actually, neutrons can be detected even before Gd loading via $p(n, \gamma)$.
- γ energy is only 2.2 MeV \rightarrow Detection efficiency $\sim 25\%$

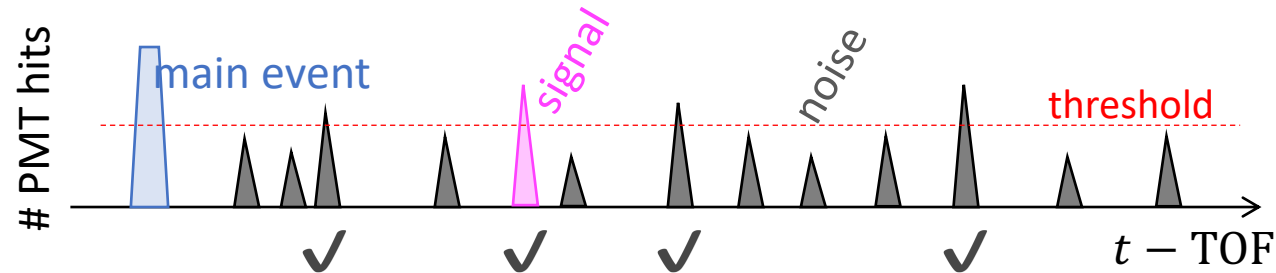
	# γ	γ energy	Efficiency in SK
$p(n, \gamma)$	1	2.2 MeV	$\sim 25\%$
Gd(n, γ)	multiple	~ 8 MeV in total	$\sim 80\%$



Neutron detection algorithm

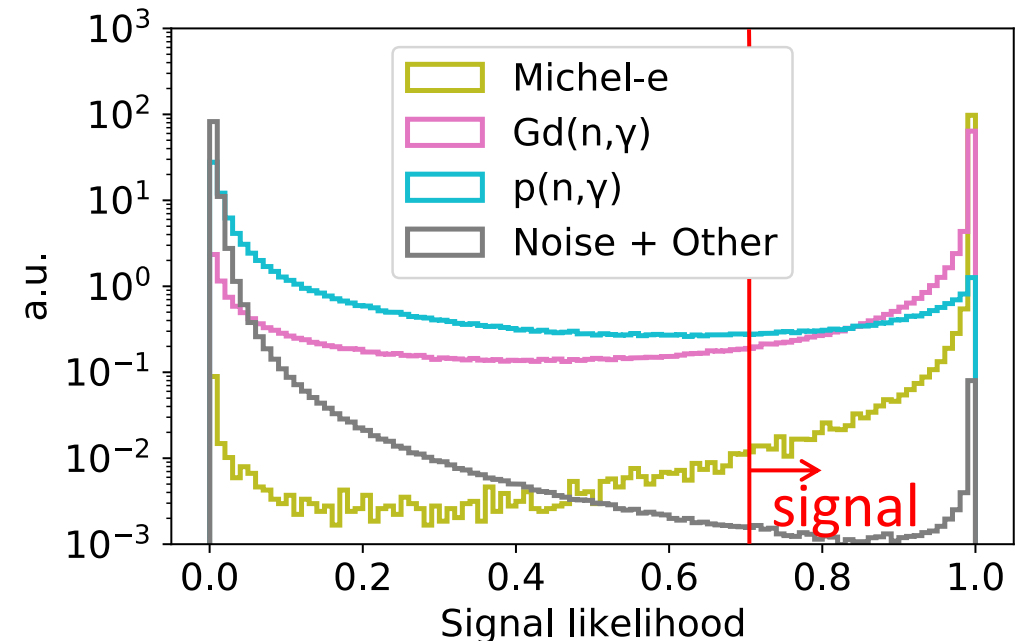
- Neutrons are detected as signals following high energy event in offline analyses.

- 1st step: Candidate search



- 2nd step: Classification by neural network

- ~15 feature variables, trained with simulation
 - Num of PMT hits
 - Hit time spread
 - Hit direction spread
 - Correlation to dark hits

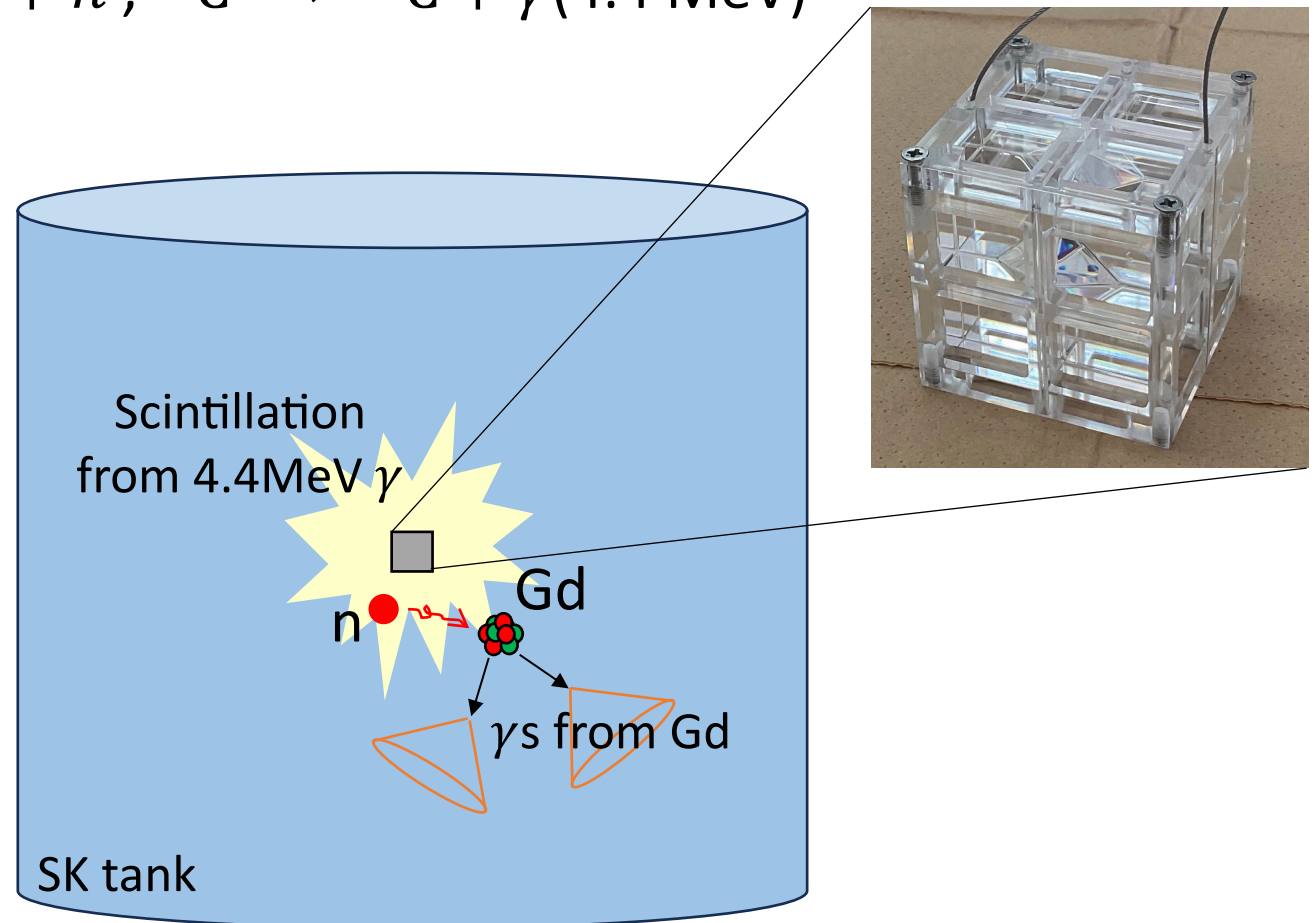


Efficiency calibration with Am/Be source

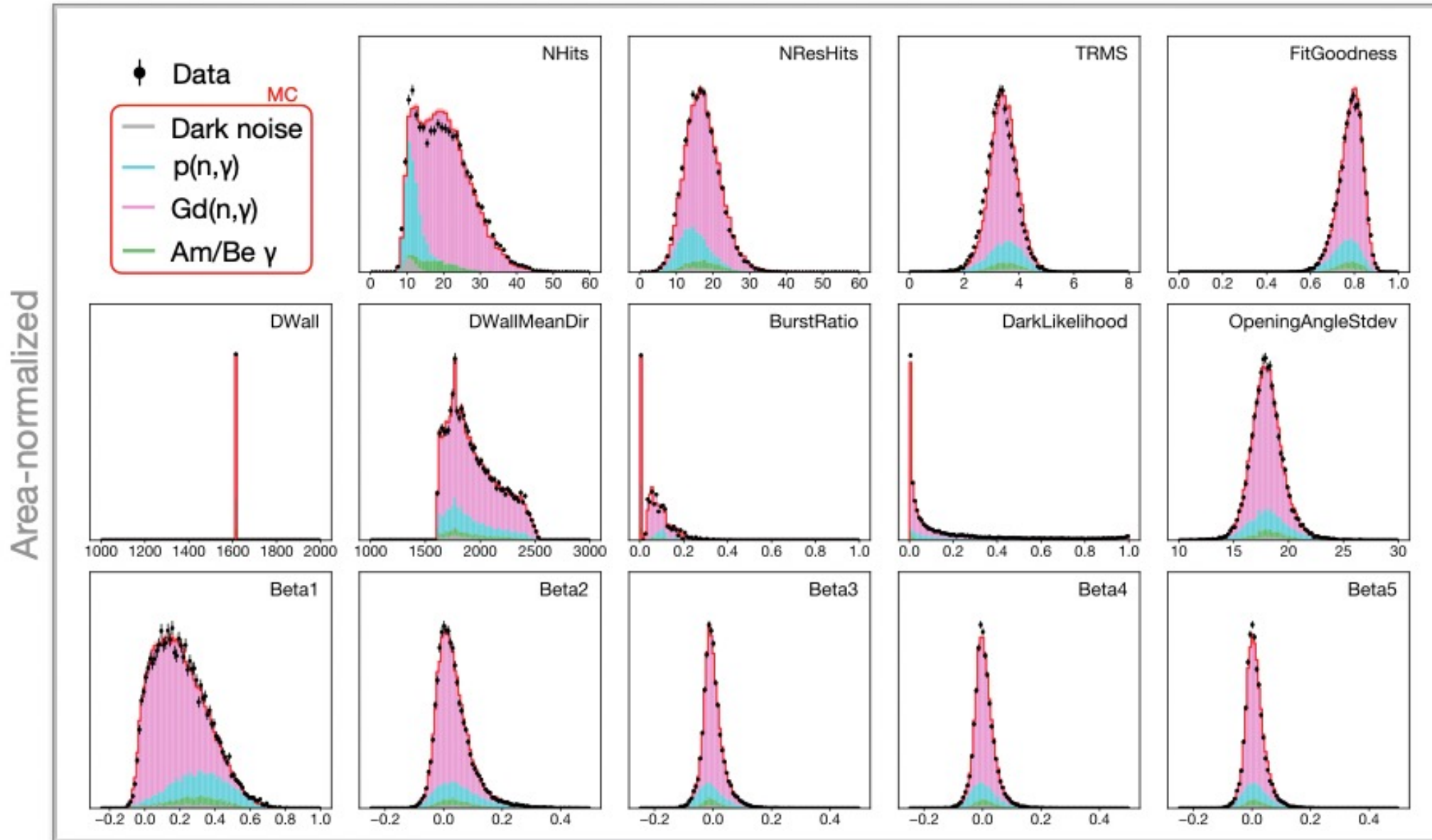
- Am/Be neutron source constantly emits n with γ :
 - $^{241}\text{Am} \rightarrow ^{237}\text{Np} + \alpha$, $^9\text{Be} + \alpha \rightarrow ^{12}\text{C}^* + n$, $^{12}\text{C}^* \rightarrow ^{12}\text{C} + \gamma(4.4 \text{ MeV})$
- Put source + scintillator in the tank.

- Neutron detection efficiency

$$= \frac{\text{Detected neutrons}}{\gamma \text{ scintillation events}}$$



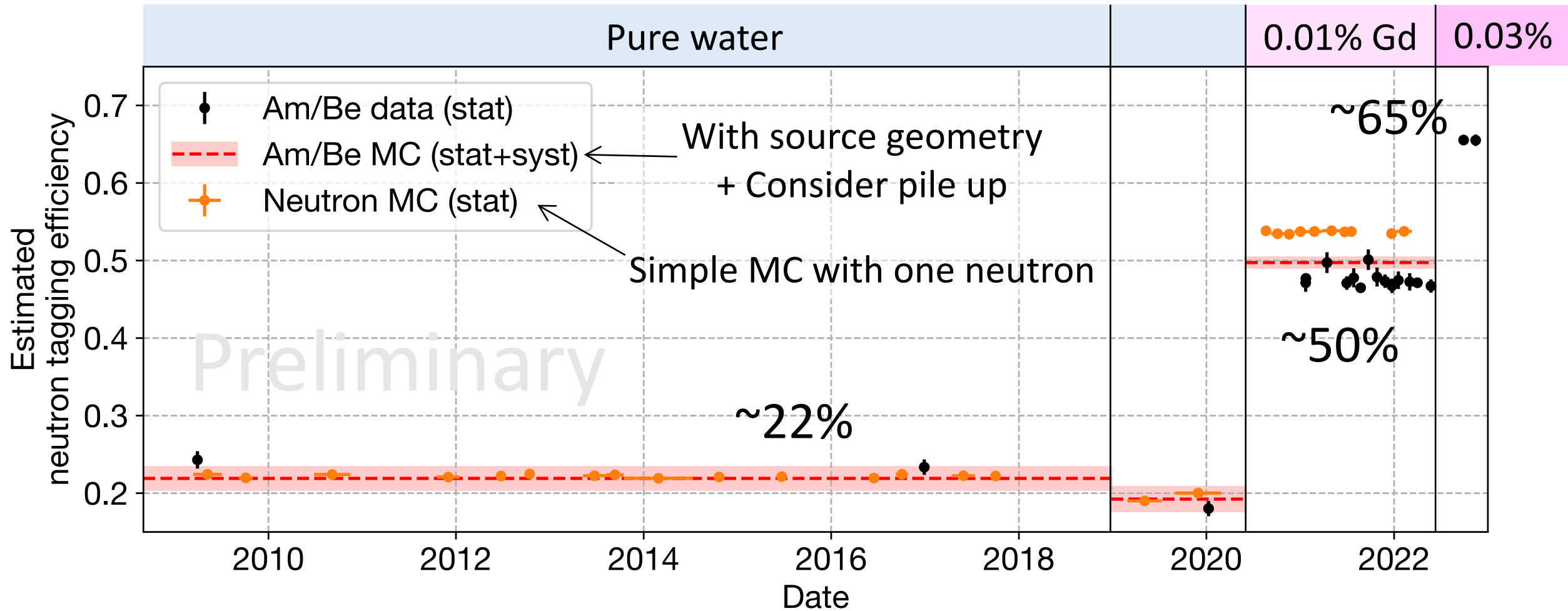
Neutron feature variables



Good agreement
with MC

by S. Han (ICRR)

Evolution of neutron efficiency



SK in winter

17



- So, the two Gd loading's were performed in early summer.

Benefits of SK-Gd to physics

- Neutrino oscillation measurement
 - Atmospheric ν : \sim GeV
 - Accelerator ν (T2K experiment) : \sim GeV
 - Solar ν : several - 10MeV
- Search for nucleon decay
- Astrophysical neutrino observation
 - Supernova ν
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Neutrino oscillation

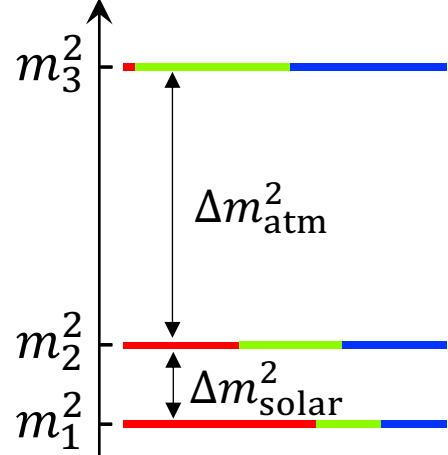
- Oscillation takes place because of flavor-mass mixing:

$$U_{\text{PMNS}} = \underbrace{\begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix}}_{\substack{\text{Atmospheric + Accelerator} \\ \theta_{23} \sim 45^\circ}} \underbrace{\begin{pmatrix} c_{13} & & s_{13}e^{-i\delta_{CP}} \\ & 1 & \\ -s_{13}e^{i\delta_{CP}} & & c_{13} \end{pmatrix}}_{\substack{\text{Reactor} \\ \theta_{13} \sim 8^\circ}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix}}_{\substack{\text{Solar} \\ \theta_{12} \sim 34^\circ}}$$

- Open questions:

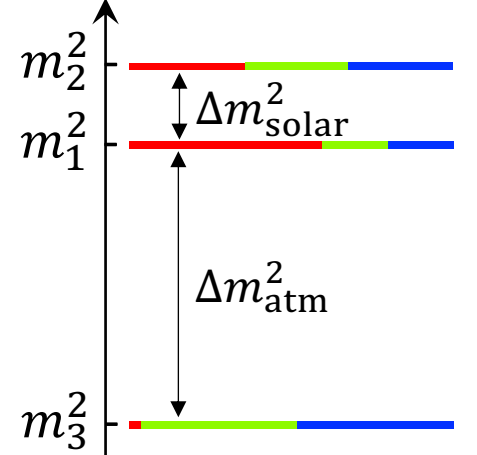
- Mass ordering : Sign of $\Delta m_{32}^2 \equiv m_3^2 - m_2^2$
 - Oscillation prob. depends on $|\Delta m_{23}^2|$
 - Need to see matter effect
- CP violating phase : δ_{CP}
 - Possible source of baryon asymmetry

Normal ordering



$$m_1 < m_2 \ll m_3$$

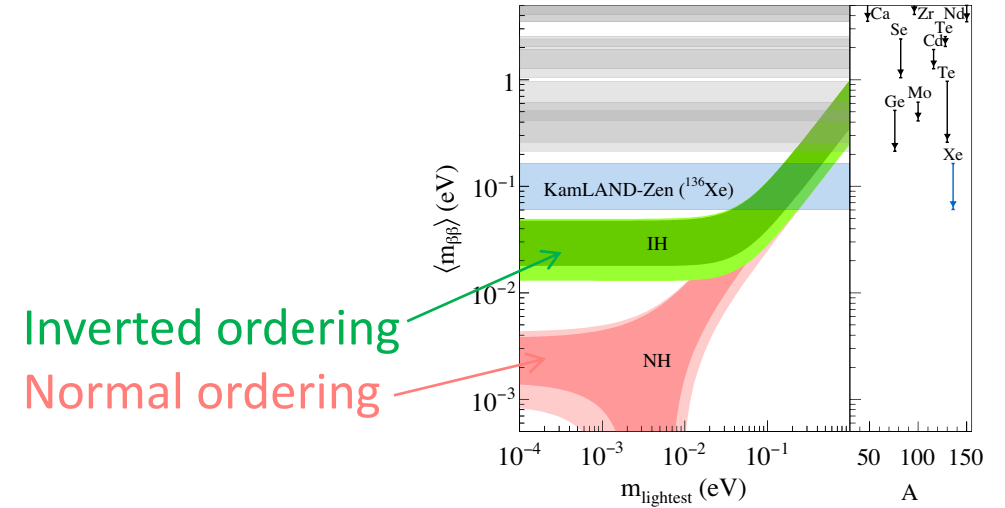
Inverted ordering



$$m_3 \ll m_1 < m_2$$

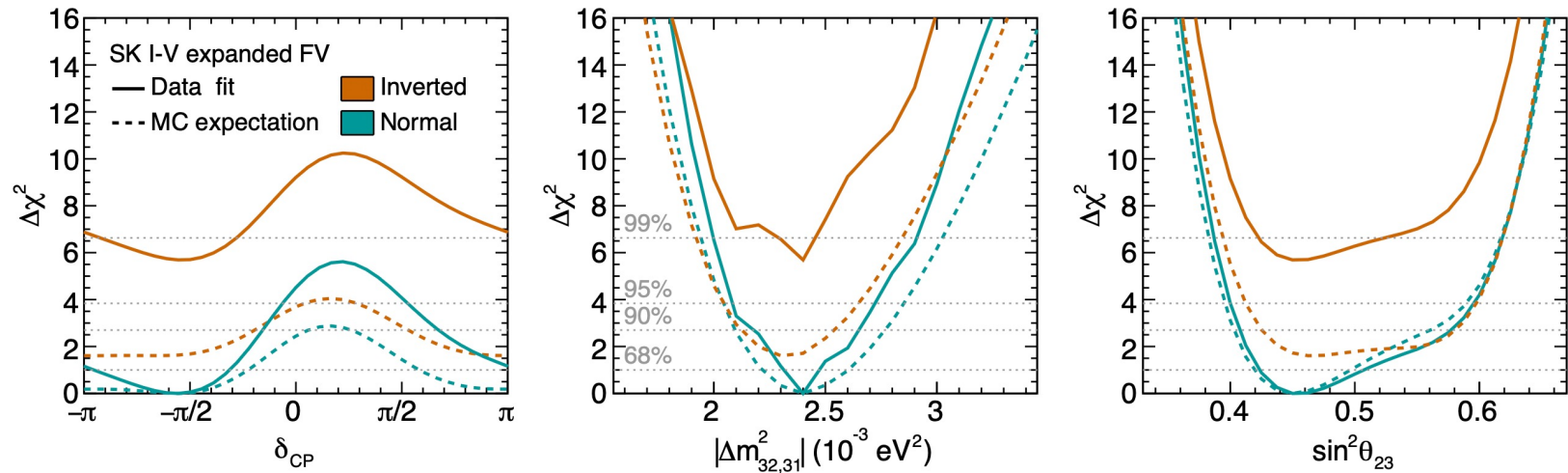
Mass ordering

- Why important?
 - Determine structure of mass matrix.
 - Structure of flavor mixing
 - Related to other ν measurements.
- Latest result from SK (to be published soon)
 - All data from pure-water phase (6511 live-days)
 - Favor normal ordering at the 92.3% level.



Inverted ordering
Normal ordering

Neutrinoless double beta decay ($0\nu\beta\beta$) search result and expectation (KamLAND-Zen collaboration)



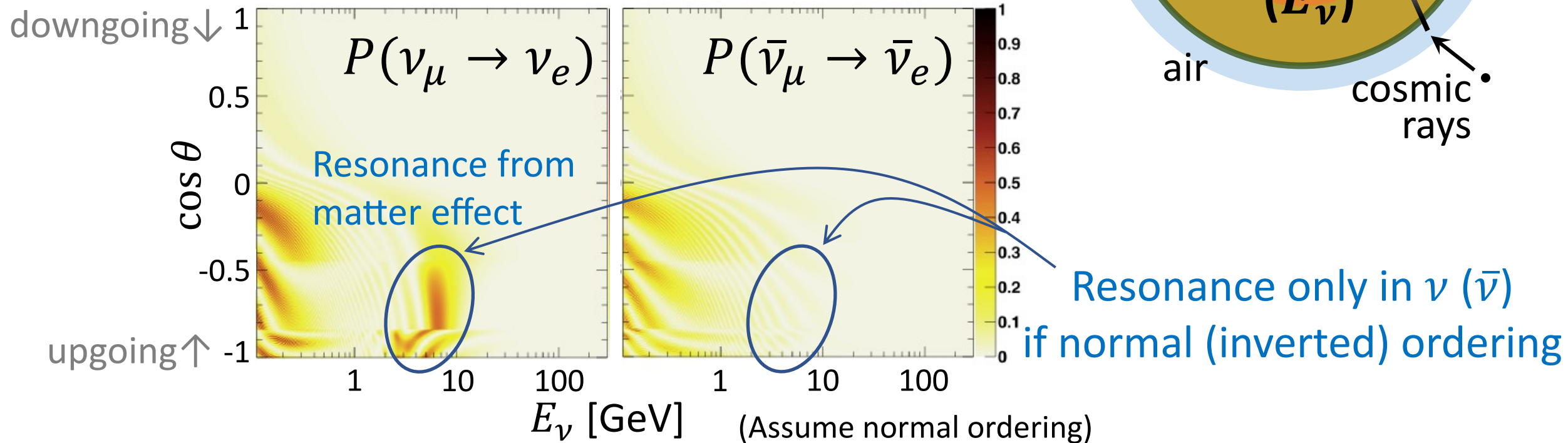
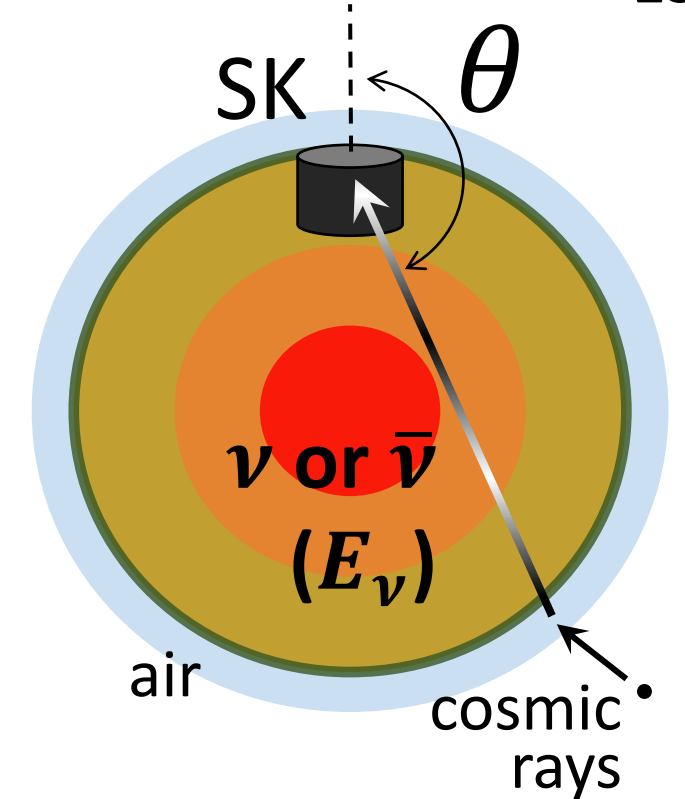
Matter effect in neutrino oscillation

- Neutrinos can interact coherently with particles in dense matter.
- Only ν_e (not ν_μ, ν_τ) feel potential due to coherent charged current (CC) interaction.

→ Effective potential $\begin{pmatrix} \pm\sqrt{2}G_F n_e & & \\ & 0 & \\ & & 0 \end{pmatrix}$ changes oscillation probabilities.
+(-) for (anti-)neutrinos

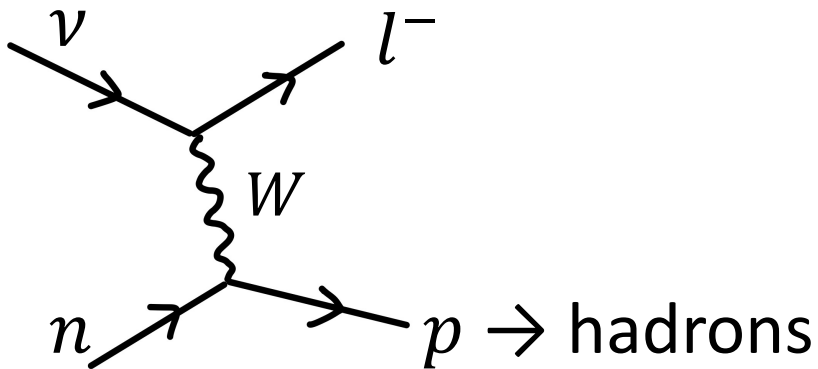
Atmospheric neutrino

- Generated by cosmic rays interacting with earth atmosphere.
- ~ 100 MeV to $> \text{TeV}$, ~ 10 events/day in SK
- Most powerful probe for mass ordering.



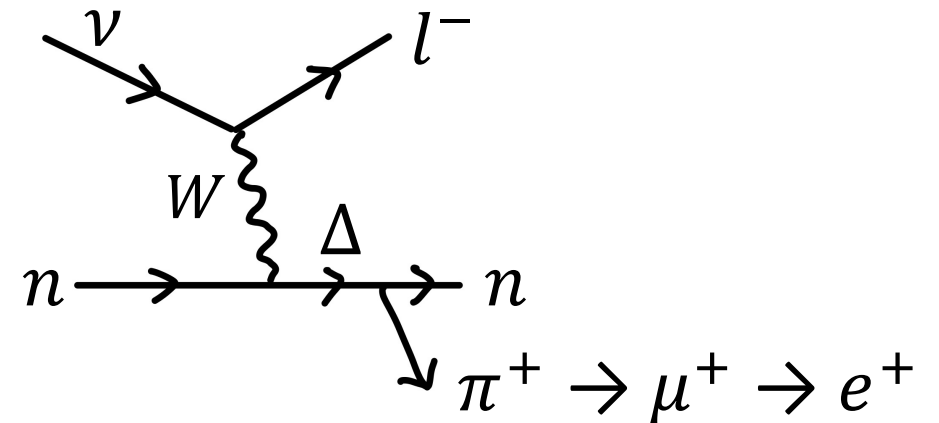
$\nu / \bar{\nu}$ discrimination

- $\nu / \bar{\nu}$ discrimination is crucial to determine mass ordering.
 - but SK is insensitive to sign of charge.
- Classify events based on momentum ratio among cherenkov rings and number of Michel-e's.



Larger momentum transfer than $\bar{\nu}$
(due to V-A structure)

→ Momentum fraction of lepton is smaller in ν



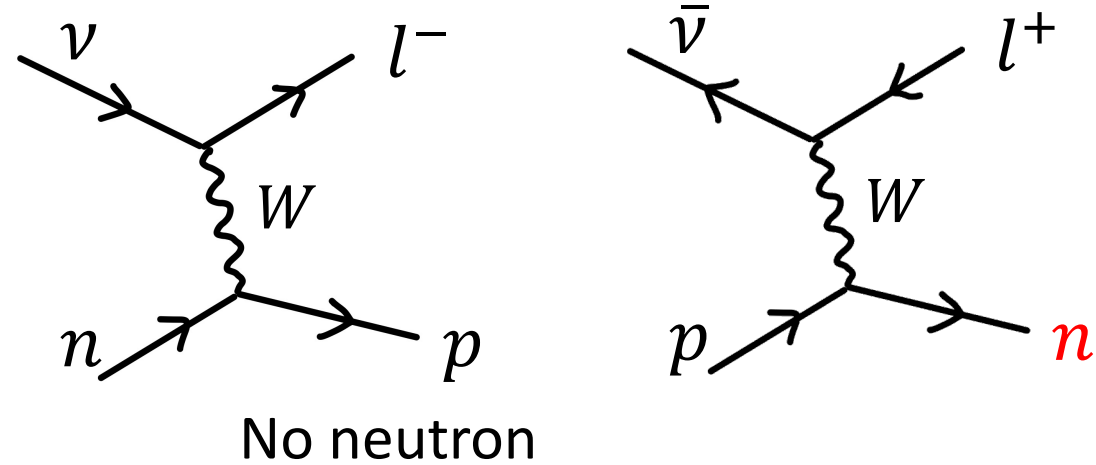
$\bar{\nu}$ generates π^- , which is captured on ^{16}O without Michel-e

→ More Michel-e's in ν

Discrimination with neutrons



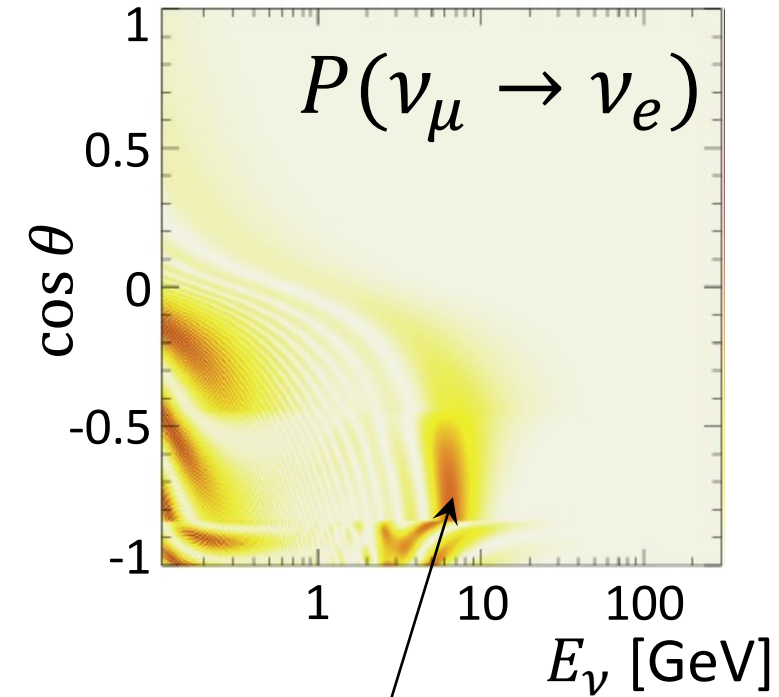
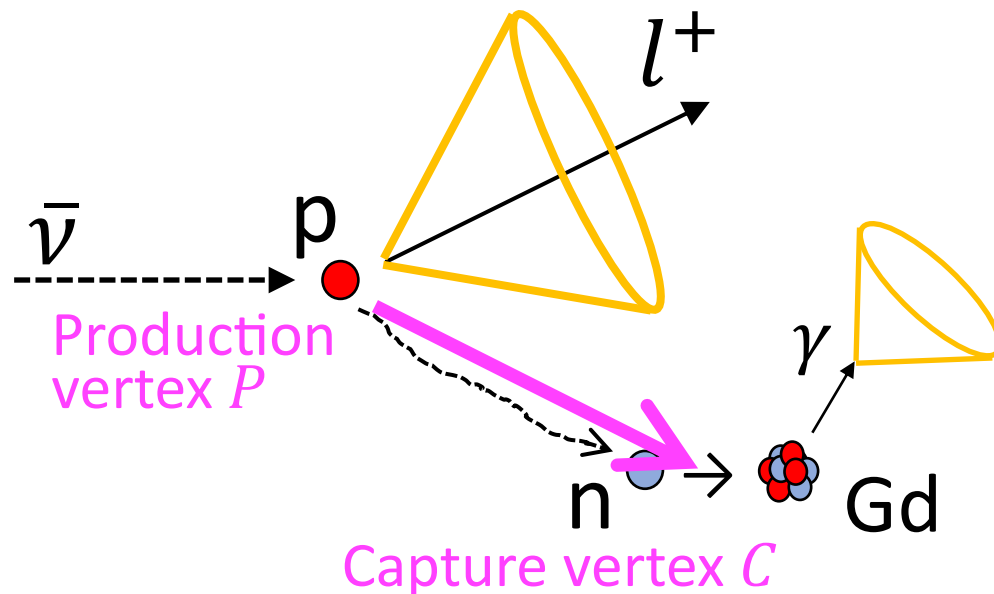
- Now, we can see neutrons!
- $\bar{\nu}$ is more likely to produce neutrons.



- In single-ring multi-GeV sample (sensitive to mass ordering), purity of $\bar{\nu}_e$ sample is improved 36% \rightarrow 48% with 0.01%Gd.
- Sensitivity to mass ordering will be improved by $\sim 30\%$ in $\Delta\chi^2$. Work in progress.

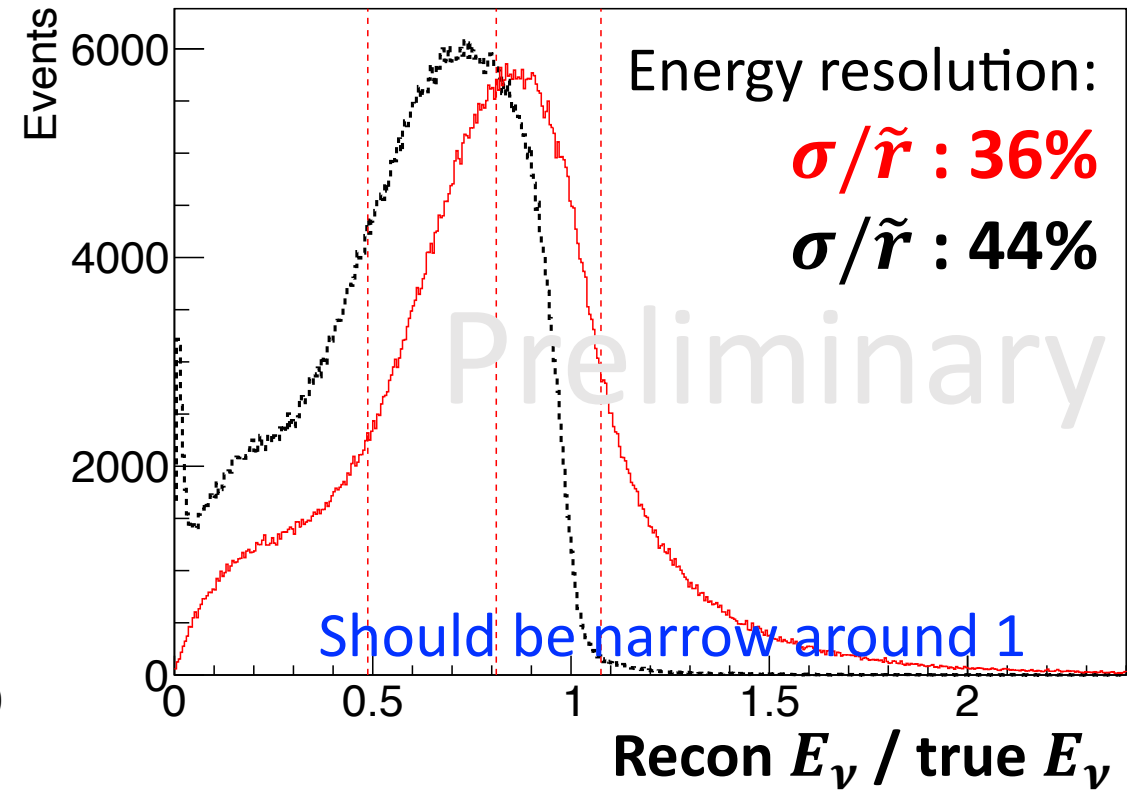
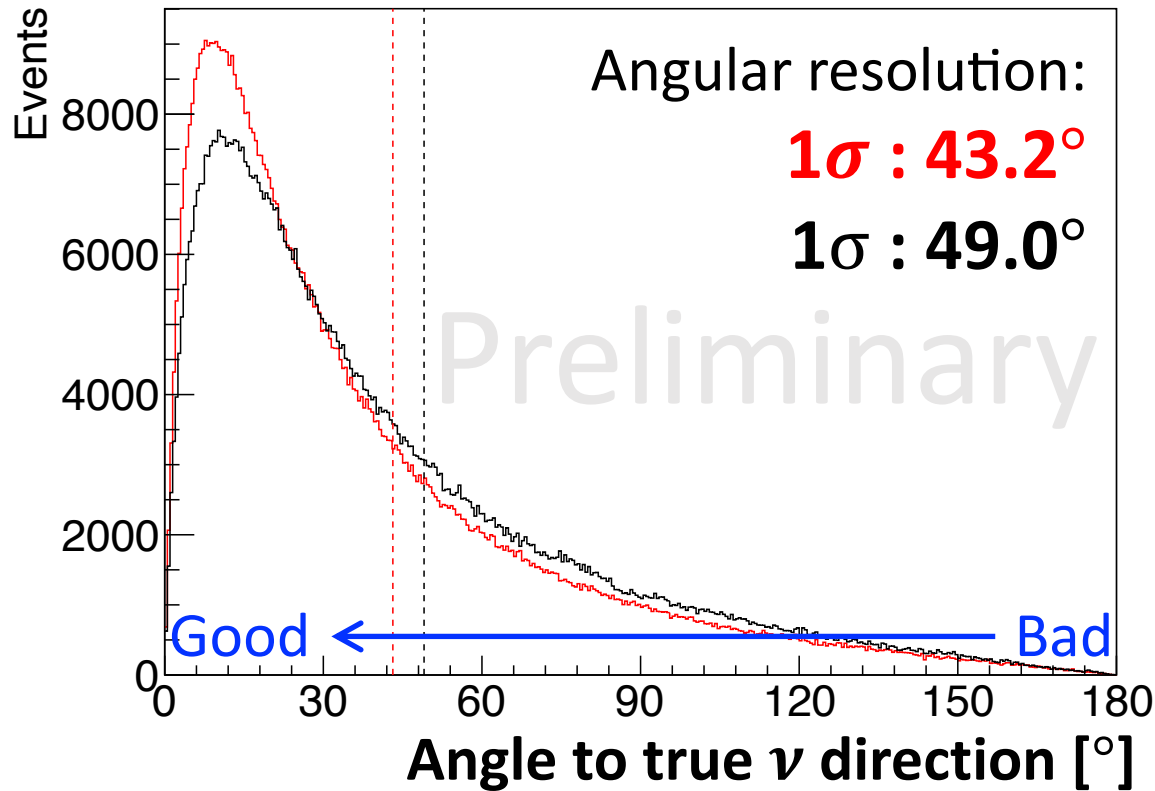
Reconstructing neutrinos

- Previous atmospheric neutrino analysis in SK compares **charged particle information** between data and MC.
→ Energy and direction are different from that of neutrinos.
- Try to reconstruct neutrino information by **correcting neutron momentum**, from its displacement.



E_ν and \vec{d}_ν resolution is important to observe clear resonance

Resolution for neutrinos



Resolution for neutrinos with tagged n

- Correct neutron momentum
- Assume ring direction & energy

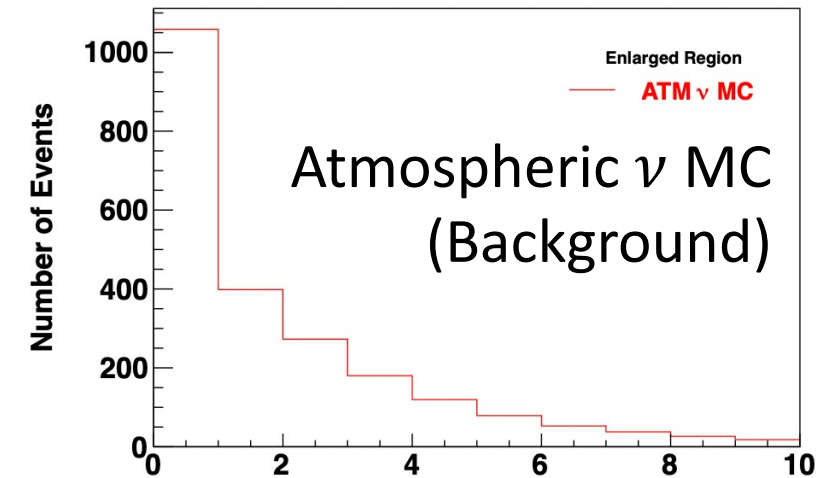
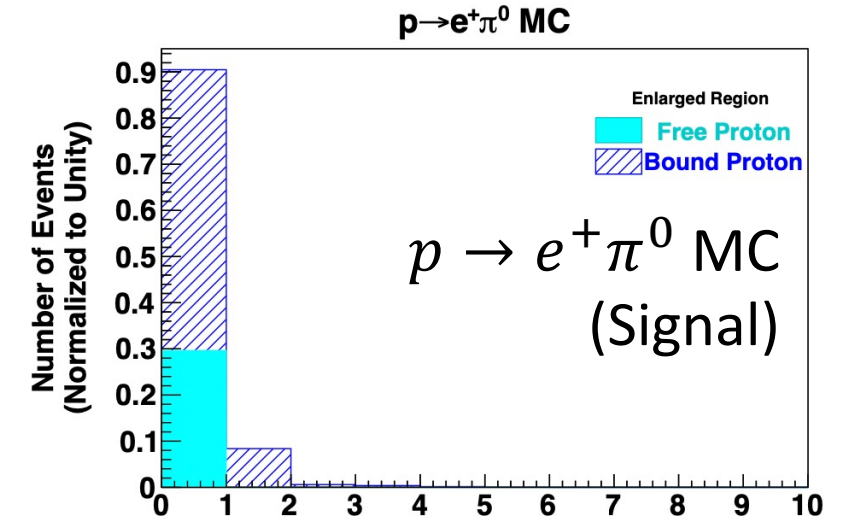
- Method tested in MC with 0.01%Gd.
- The improvements will benefit the sensitivity to mass ordering by $\sim 5\%$ in $\Delta\chi^2$.

Benefits of SK-Gd to physics

- Neutrino oscillation measurement
 - Atmospheric ν : $\sim\text{GeV}$ $\rightarrow \nu/\bar{\nu}$ discrimination, improve reconstruction
 - Accelerator ν (T2K experiment) : $\sim\text{GeV}$
 - Solar ν : several - 10MeV
- **Search for nucleon decay**
- Astrophysical neutrino observation
 - Supernova ν
 - Diffuse supernova neutrino background (DSNB)
 - other sources (such as GRB)

Neutrons in nucleon decay search

- Direct evidence of [Grand Unification Theory \(GUT\)](#).
- Examples:
 - $p \rightarrow e^+ \pi^0$: Current limit $\tau > 2.4 \times 10^{34}$ years
 - $p \rightarrow \bar{\nu} K^+$: Current limit $\tau > 0.8 \times 10^{34}$ years
- Atmospheric neutrino is dominant background.
 - Neutrino events \rightarrow Likely to have neutrons
 - Nucleon decay events \rightarrow Only $\lesssim 10\%$ have neutrons
- Neutron detection provides [efficient background rejection](#).



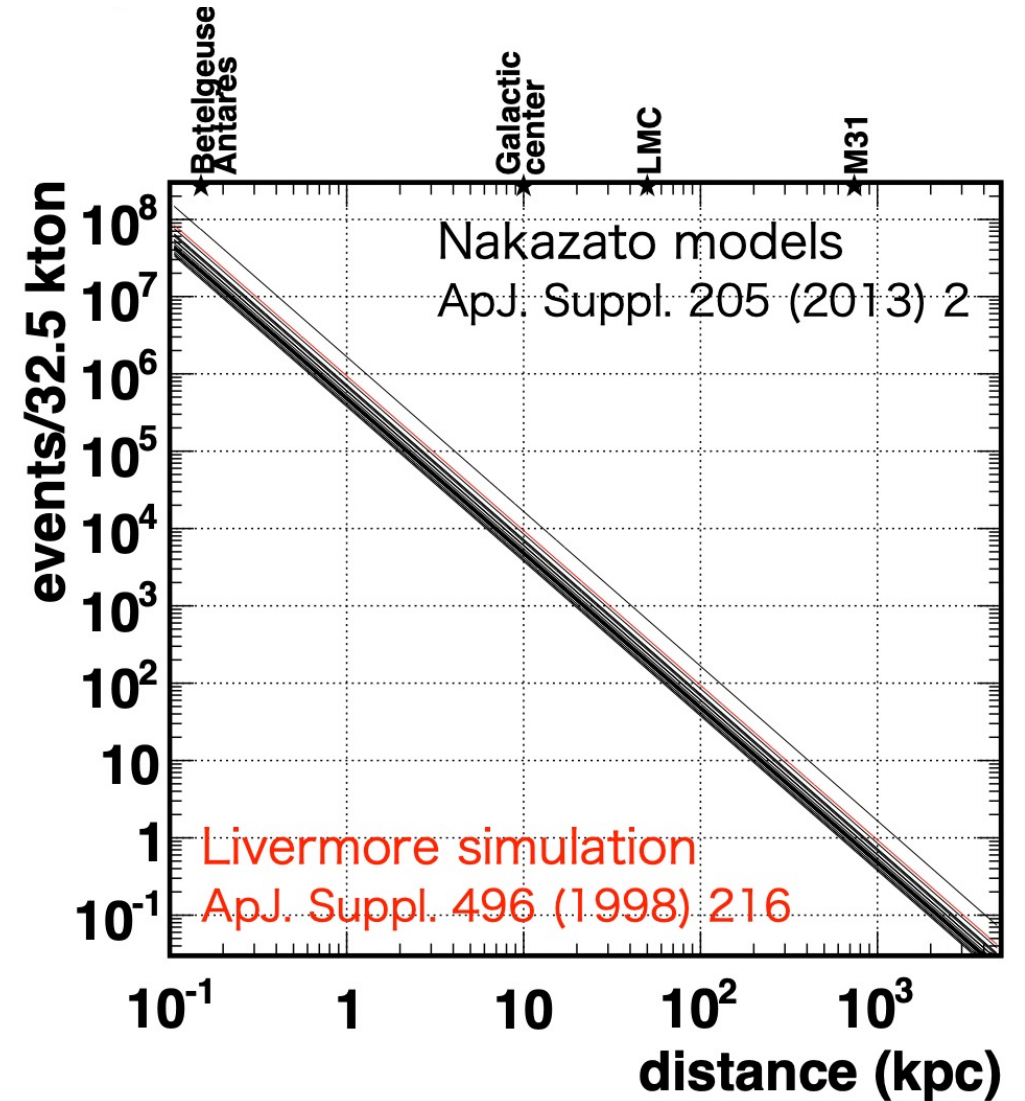
Number of produced neutrons
after basic cuts for proton decay search

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- Search for nucleon decay \rightarrow Background rejection
- Astrophysical neutrino observation
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Supernova burst neutrino

- Supernova burst ν have been observed only once in 1987, by Kamiokande, IMB, and Baksan.
 - Neutrinos bring information **inside the supernova**, come $O(10)$ hours **earlier than light**.
 - Realtime direction information provided by ν can **guide optical observations** to the supernova.
- ν play an **important role in multi-messenger astronomy**.

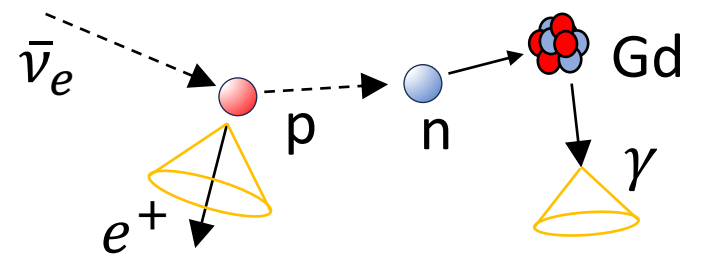


Expected number of ν events in SK by supernova.

Pointing accuracy with neutron detection

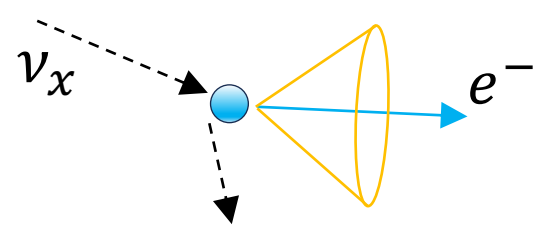
- Two interactions:

Inverse beta decay (IBD)



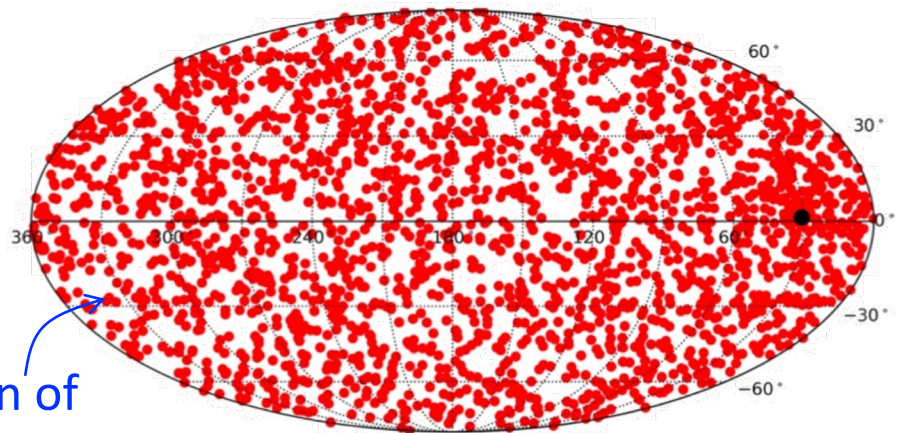
- Isotropic
- Neutron produced
- Dominant

Elastic scattering (ES)



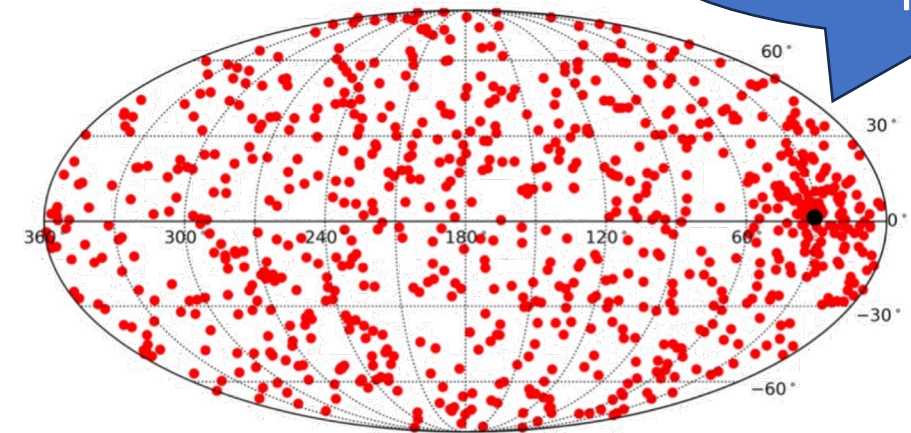
- Directional to ν
- No neutron

- Simulation for supernova at 10kpc (~Galactic center):



Direction of each event

Without neutron detection



Neutron efficiency 72% (expexed with 0.1%Gd) → Removed

Pointing accuracy improved

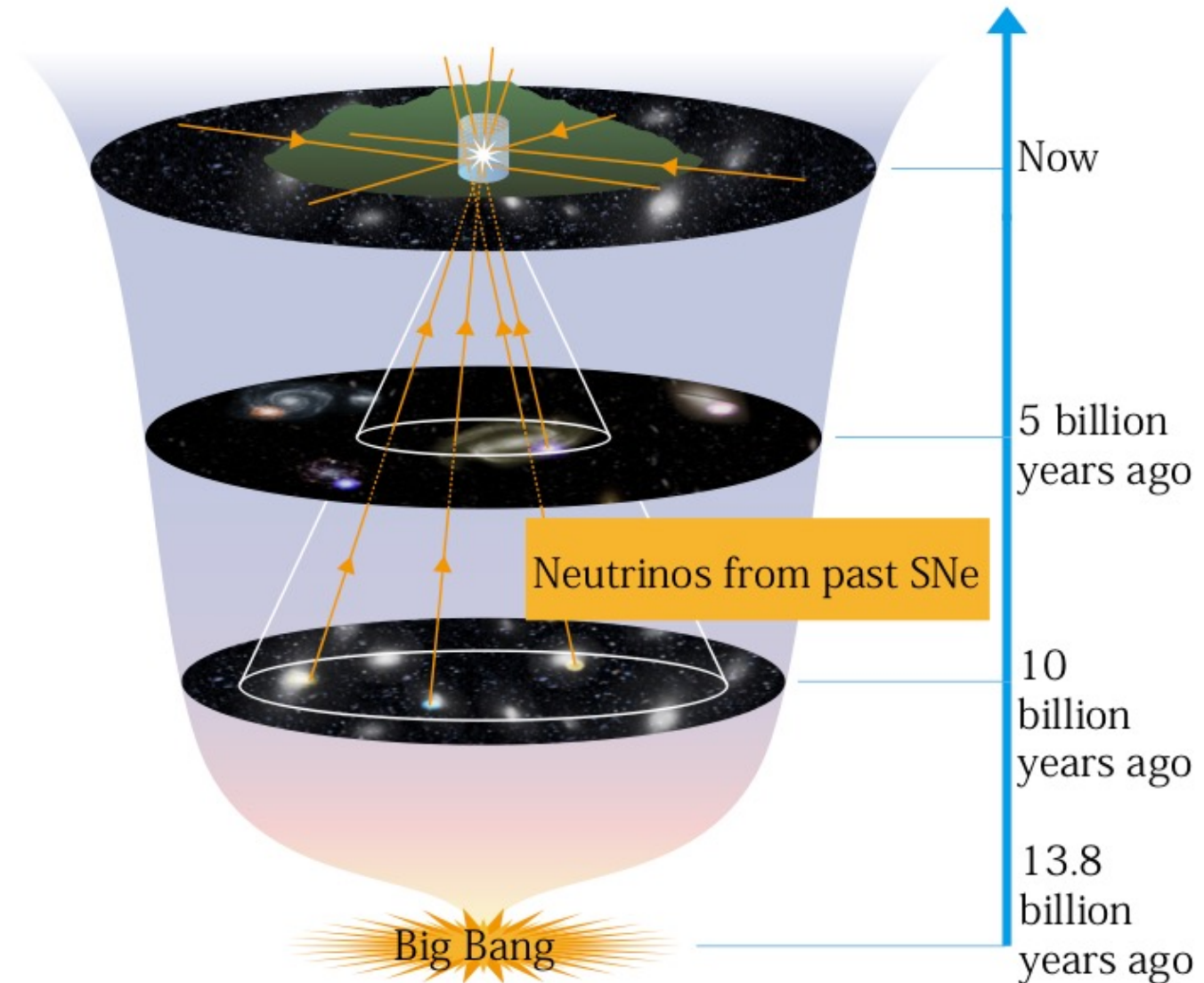
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- Search for nucleon decay → Background rejection
- Astrophysical neutrino observation
 - Supernova ν → Pointing accuracy due to IBD rejection
 - **Diffuse supernova neutrino background (DSNB)**
 - other sources (such as GRB)

Diffuse supernova neutrino background (DSNB)

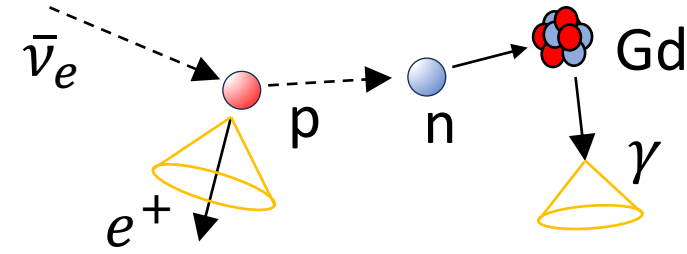
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- We expect only a few supernovae /century in our galaxy.
- The universe is full of **accumulated flux of neutrinos from past supernovae** (DSNB).
- DSNB flux depends on various parameters:
 - Star formation rate
 - States of remnant neutron stars
 - Galaxy metallicity
 - Neutrino mass ordering
- Not observed yet.

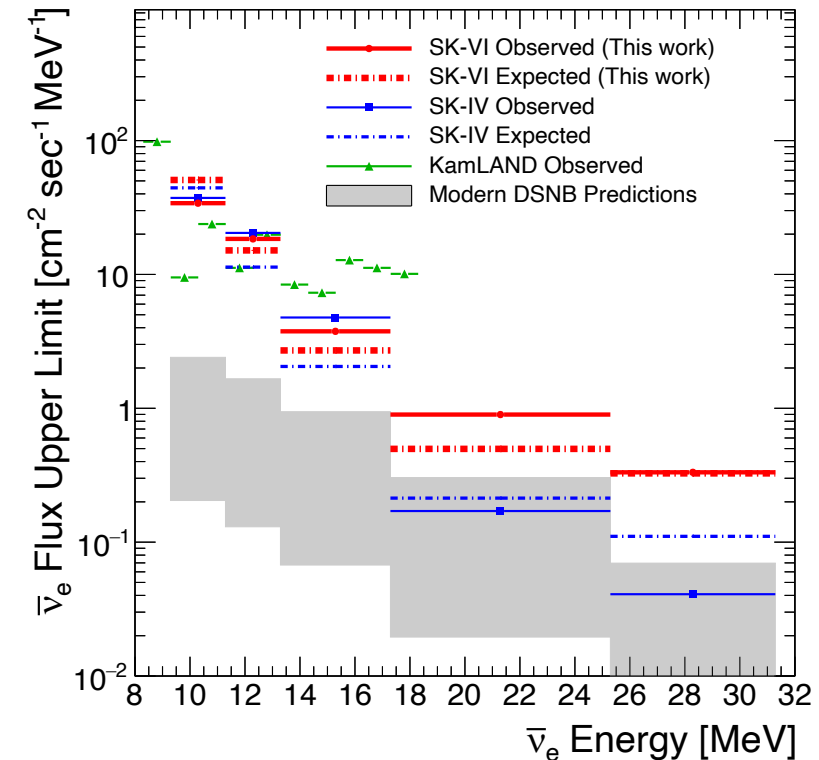
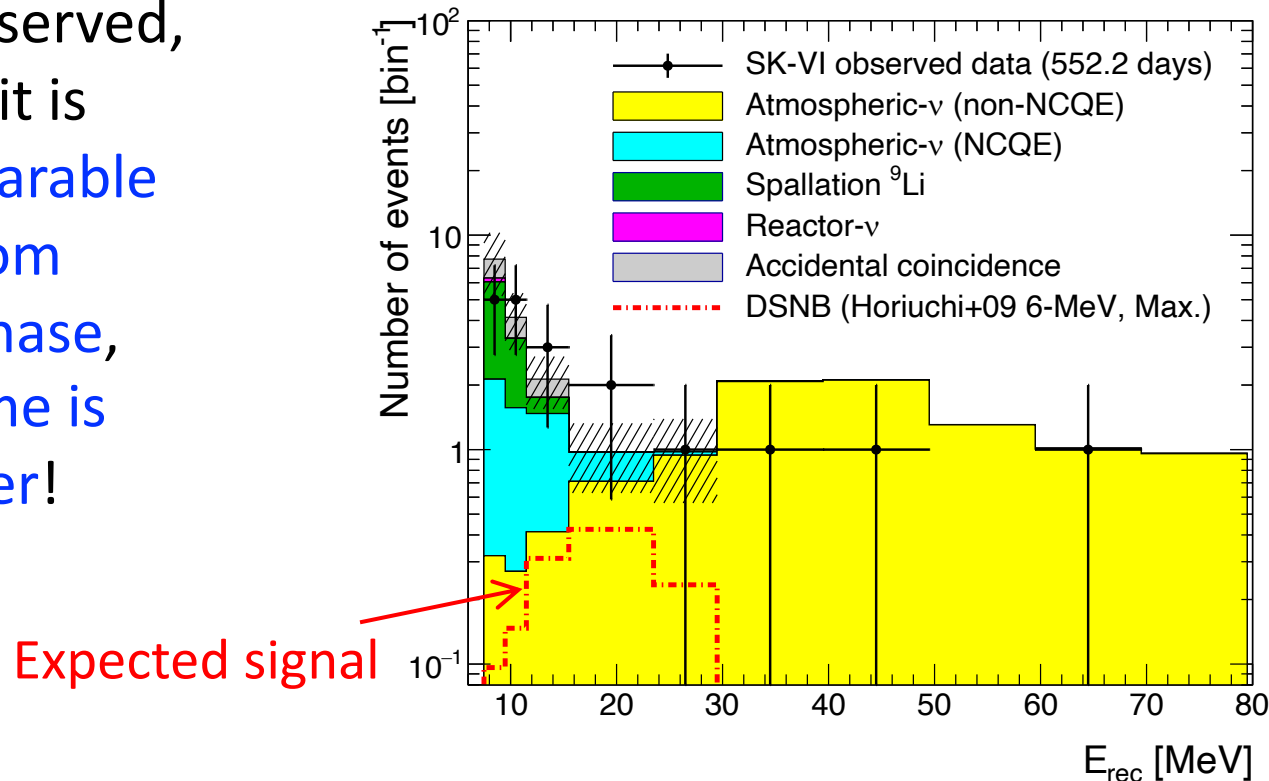


DSNB search

- Signal is inverse beta decay (IBD).
→ Background rejection by neutron detection
- First published physics result from SK-Gd.
- Excess not observed, but upper limit is already **comparable with result from pure-water phase, though livetime is 5 times smaller!**



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



Summary

- Super-Kamiokande started its completely new phase SK-Gd in 2020.
- Neutrons can be detected with **efficiency ~50% (~65%) with 0.01% (0.03%) Gd**.
- **Neutron detection** capability has been **confirmed with various neutron sources**: Am/Be, cosmic muons, atmospheric neutrinos.

Physics

- In atmospheric neutrino oscillation analysis aiming for mass ordering determination, **$\nu/\bar{\nu}$ discrimination** is improved and **neutrino reconstruction** is possible.
- **Efficient background rejection** is possible in searches for nucleon decay and DSNB.
- **Pointing accuracy** is improved for supernova by IBD rejection.