Joint Pre-Supernova Monitor with Super-Kamiokande and KamLAND

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The 9th SN Neutrino Workshop
2023/03/03

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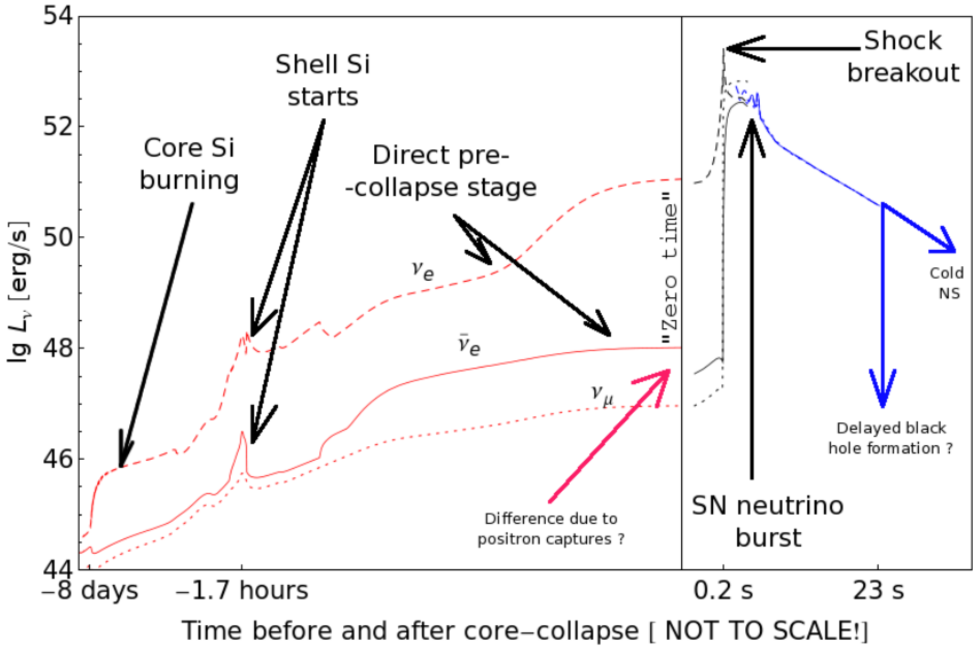
Introduction

Odrzywolek & Heger, *Acta Phys. Pol. B*, 41 (2010)



- Supernovae (SNe) are extremely important astronomical events, thus early warnings are vital.
  - Be ready for SN neutrinos and gravitational wave.

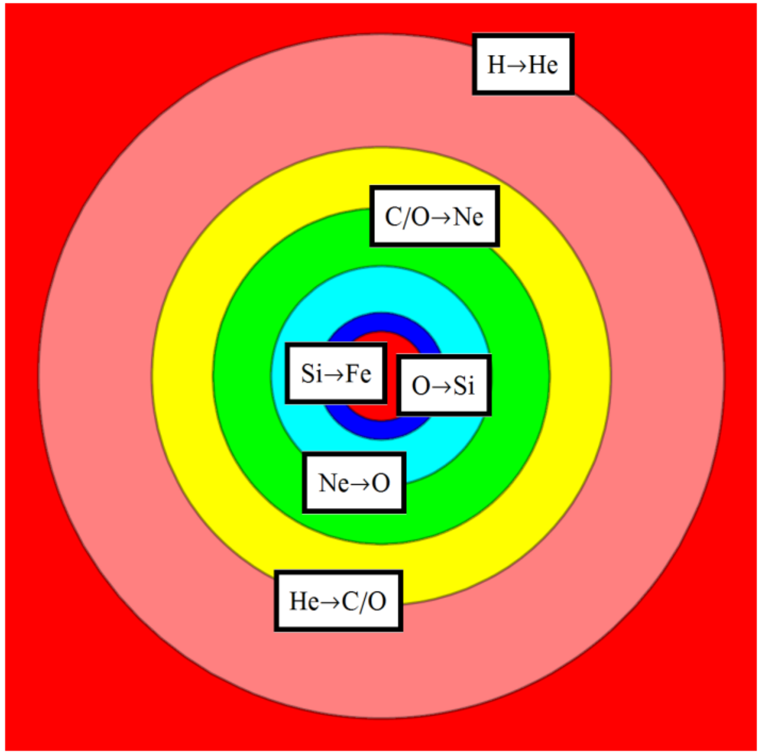
- Ahead of the burst, neutrinos of all flavors are increasingly emitted by the pre-SN star, potentially detectable.

- They are called pre-supernova neutrinos, can be early warnings of a SN.
  - KamLAND pre-SN monitor online in 2015. See 齊藤さん's poster and [K. Asakura et al. *Astrophys. J.* 818 (2016)] for details.
  - Super-K also set a pre-SN monitor in 2021, [L.N. Machado et al. *Astrophys. J.* 935 (2022)].

- A **joint pre-SN monitor** with Super-K and KamLAND is developed.
  - Improve sensitivity to pre-SN neutrino signal

Pre-Supernova Neutrinos

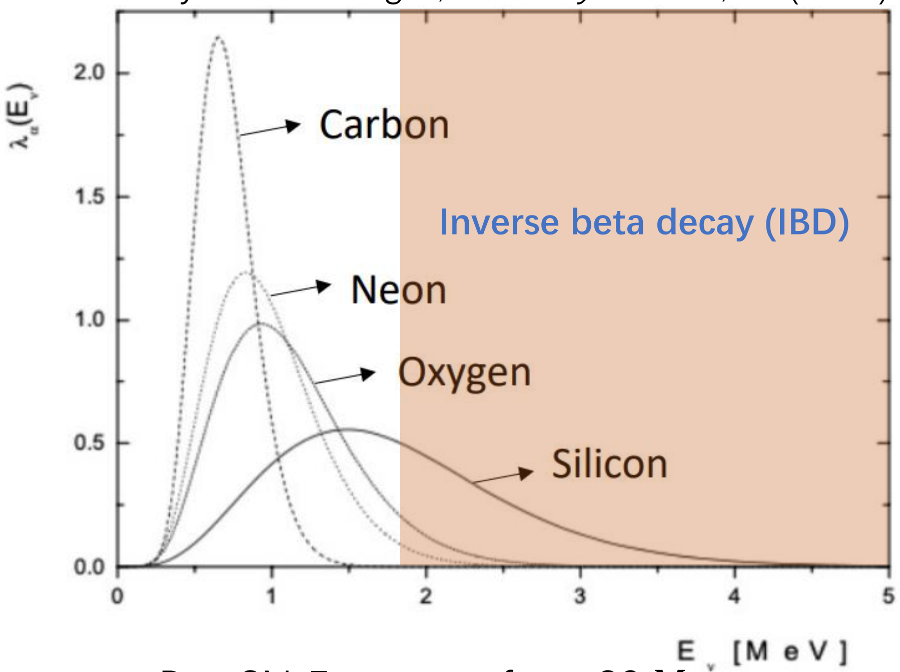
Core-collapse supernova (CCNS)



Scheme of a star before core-collapse (pre-SN star)

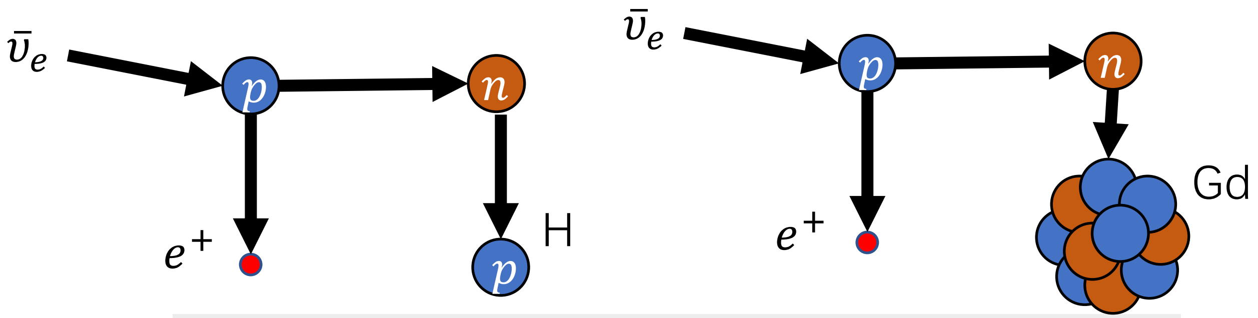
Odrzywolek & Heger, *Acta Phys. Pol. B*, 41 (2010)

Odrzywolek & Heger, *Acta Phys. Pol. B*, 41 (2010)



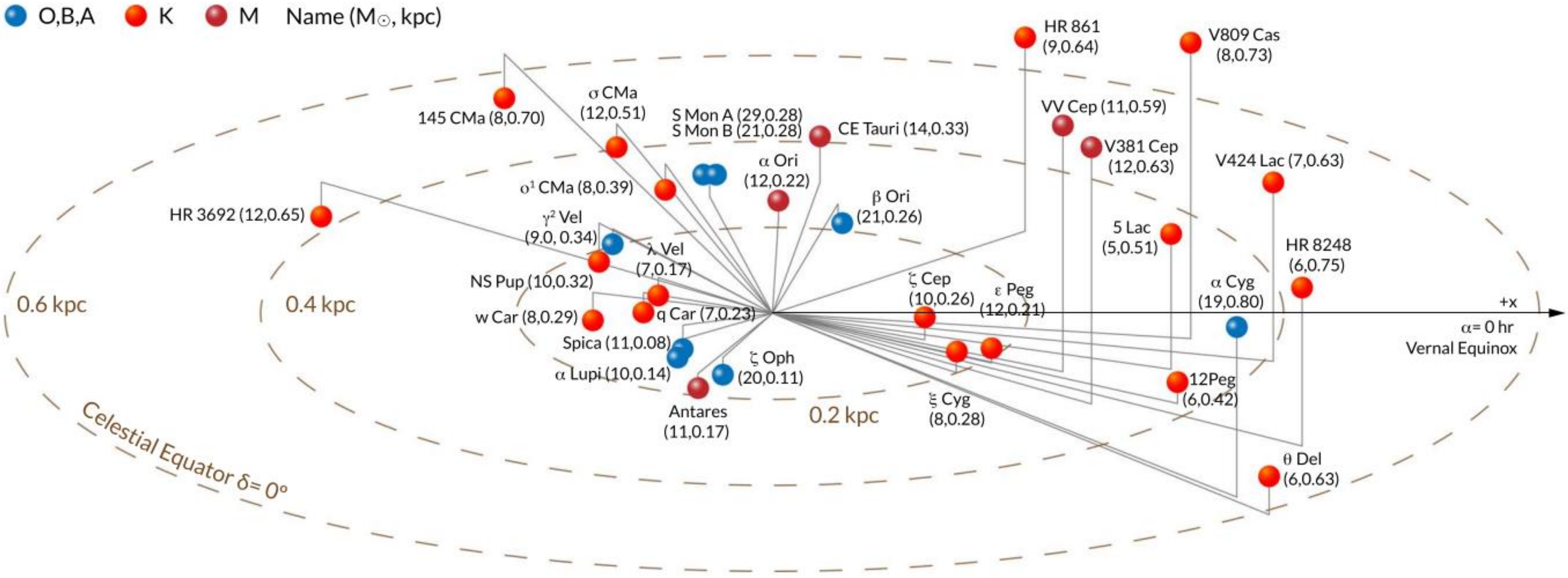
Pre-SN $\bar{\nu}_e$ spectra for a 20 $M_\odot$ star.

A significant fraction of $\bar{\nu}_e$ exceed inverse beta decay (IBD) threshold!



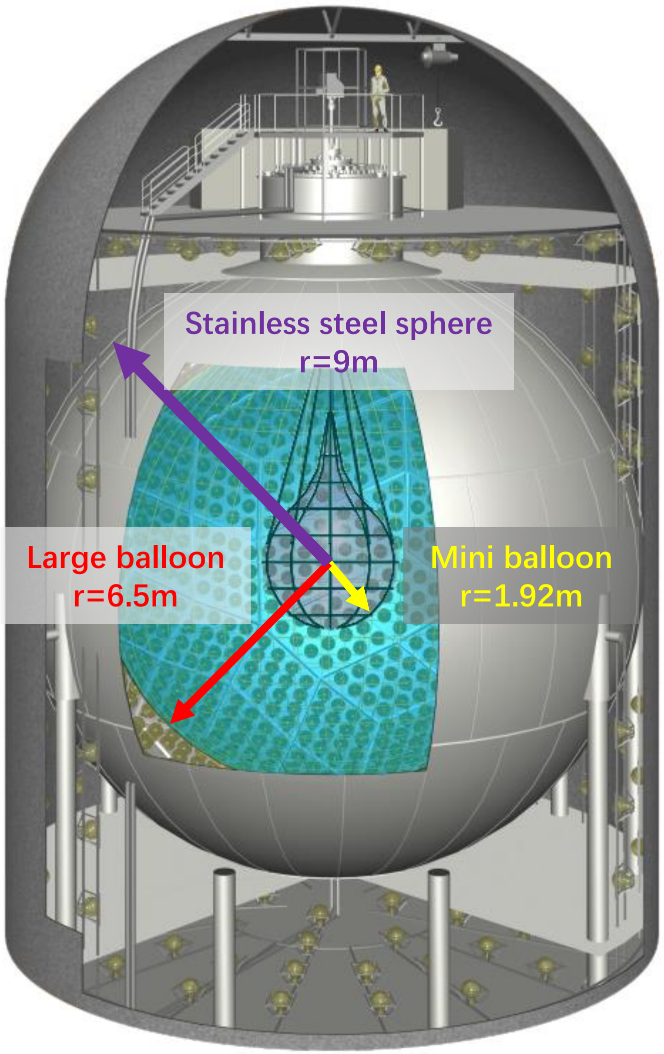
Scheme of IBD interactions, with neutron captured by Hydrogen / Gadolinium

Core-Collapse Supernova Candidates



Nearby core-collapse supernova candidates. Colored labels show the star's spectral type. Masses and distances of the stars are shown in parenthesis. [Mukhopadhyay et al., *Astrophys. J.* 899 (2020)]

KamLAND



liquid scintillator detector located in the Kamioka mine

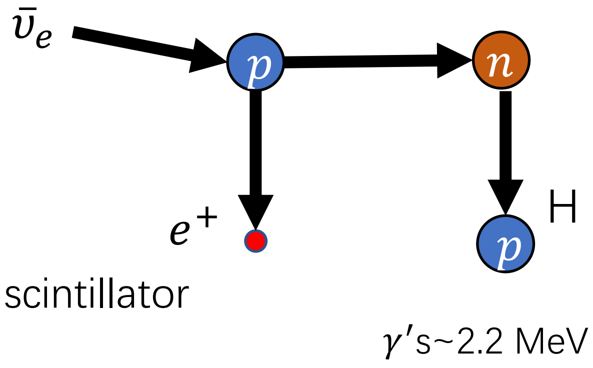
- 1000 m of rock overburden, (2700 m.w.e.)

Outer detector

- Cylinder tank equipped with 20-inch PMTs
- Filled with pure water
  - Muon veto based on Cherenkov lights
  - Shields gamma rays and fast neutrons

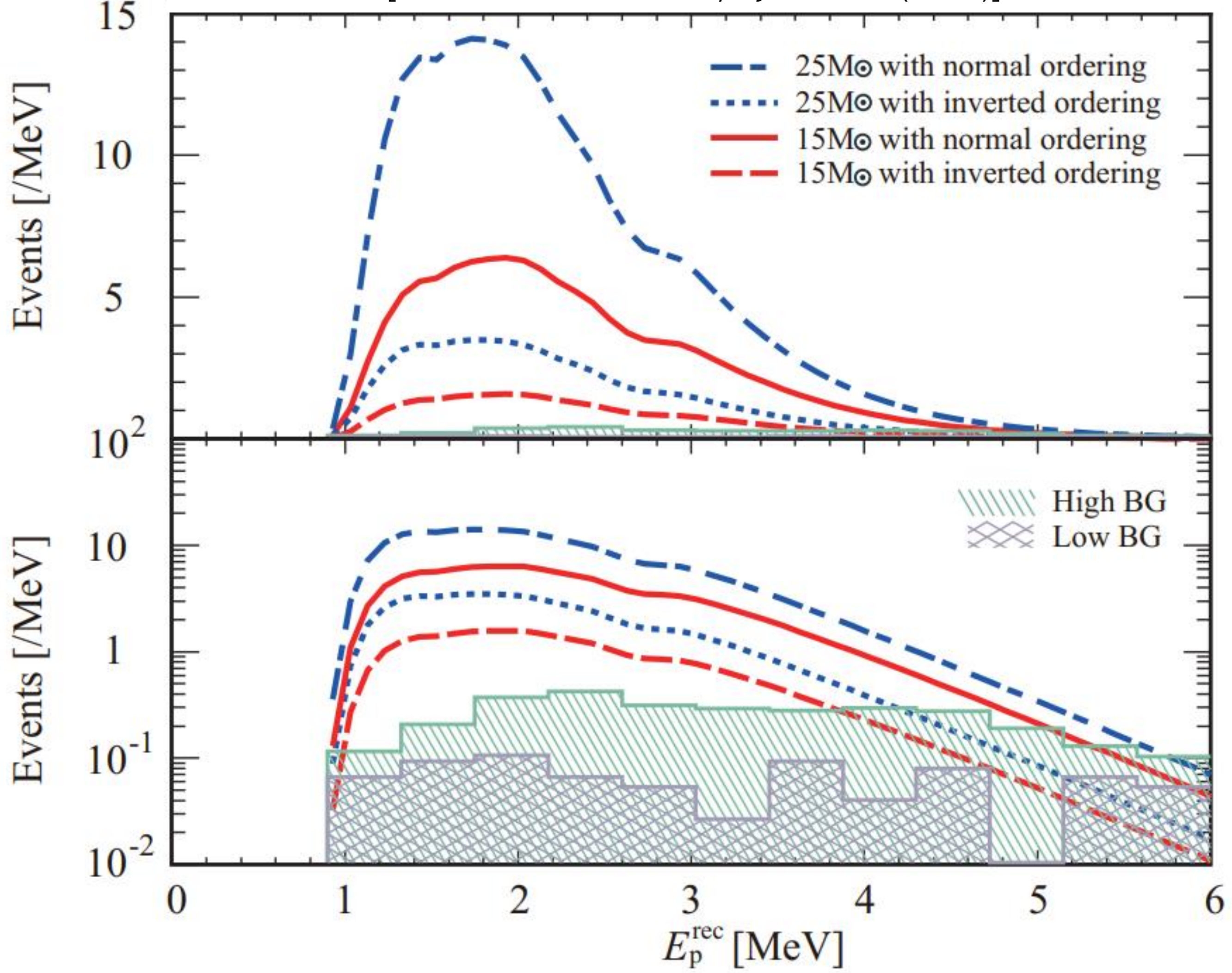
Inner detector

- Mini balloon (r=1.92m) with 745kg Xe
  - Neutrinoless double beta decay
- Large balloon (r=6.5m) with 1-kton liquid scintillator
  - IBD interactions
- Stainless steel sphere (r=9m) filled with mineral oil
  - Gamma shielding
- ~500 20-inch PMTs and ~1300 17-inch PMTs



Pre-Supernova Neutrinos in KamLAND

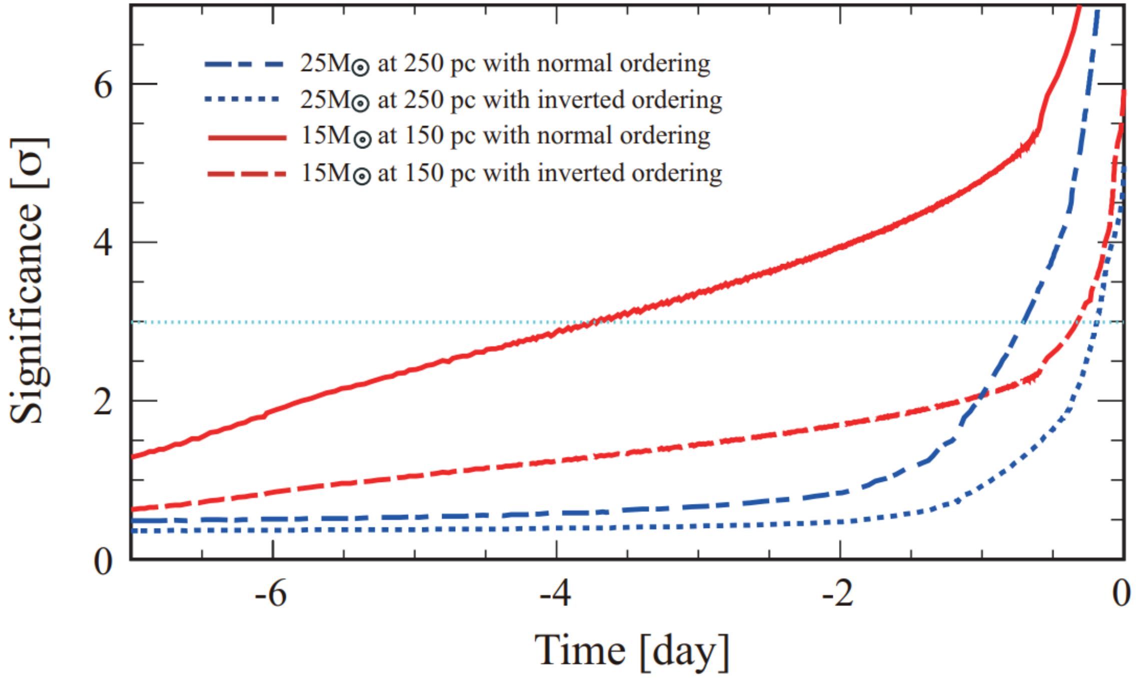
[K. Asakura et al. *Astrophys. J.* 818 (2016)]



- The integrated pre-SN neutrino energy spectrum over the last 48 hours before core-collapse.
  - Odrzywolek pre-SN model [Odrzywolek & Heger, *Acta Phys. Pol. B*, 41 (2010)]
- The background sources include
  - Accidental coincidences
  - $\alpha - n$
  - **Reactor neutrinos** and Geo-neutrinos (dominant)
- Low BG: low-reactor phase
  - Since the Great East Japan Earthquake
- High BG: high-reactor phase
  - Assuming reactor power plants restart

Pre-SN Sensitivity of KamLAND (Previous)

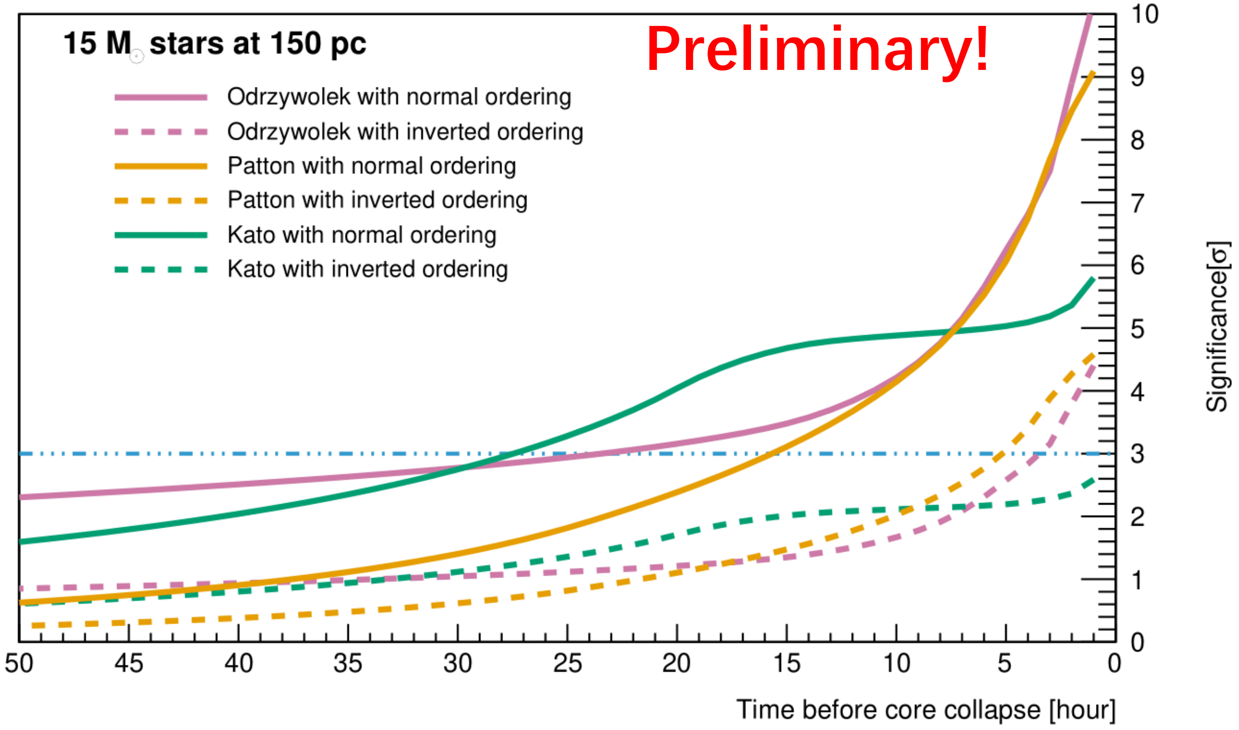
- The KamLAND collaboration has established a pre-SN alert system in 2015.
  - Report will be sent to GCN/ACTel if a promising signal of pre-SN is found.
- The expected discovery significance to pre-SN neutrinos is as shown below [K. Asakura et al. *Astrophys. J.* 818 (2016)]



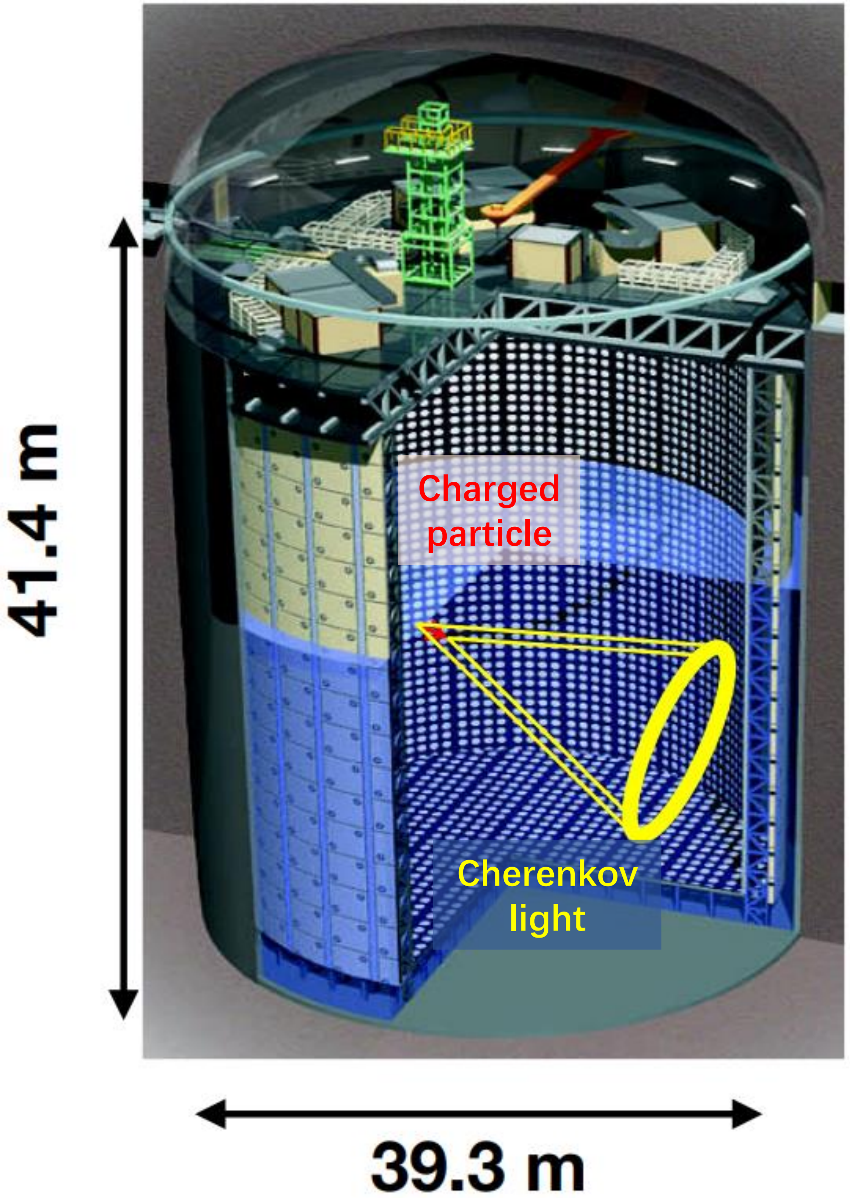
Odrzywolek model Odrzywolek & Heger, *Acta Phys. Pol. B*, 41 (2010)

Pre-SN Sensitivity of KamLAND

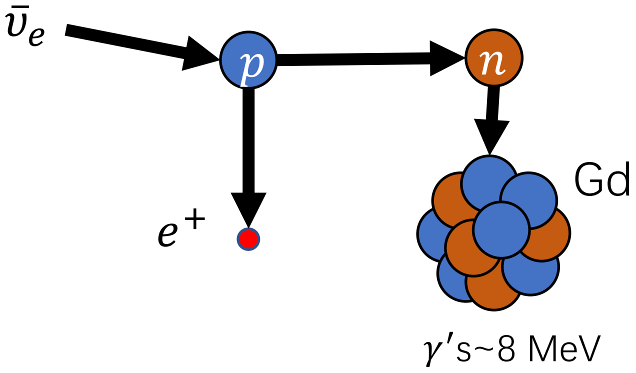
- Patton model [K.M. Patton et al. *Astrophys. J.* 840 (2017)] and Kato model [C. Kato et al. *Astrophys. J.* 848 (2017)] are taken into consideration.
- Analysis window optimized considering the three pre-SN models and both neutrino mass orderings. [see 齊藤さん's poster]
  - Optimal analysis window is 24-hour.
- Background rate $\sim \mathbf{0.007\ /hour}$ (as of 2023/02/01)
  - Expected number of background = 0.18 in 24 hours
  - About 2.5 times of that in 2015.



Super-Kamiokande (SK-Gd)

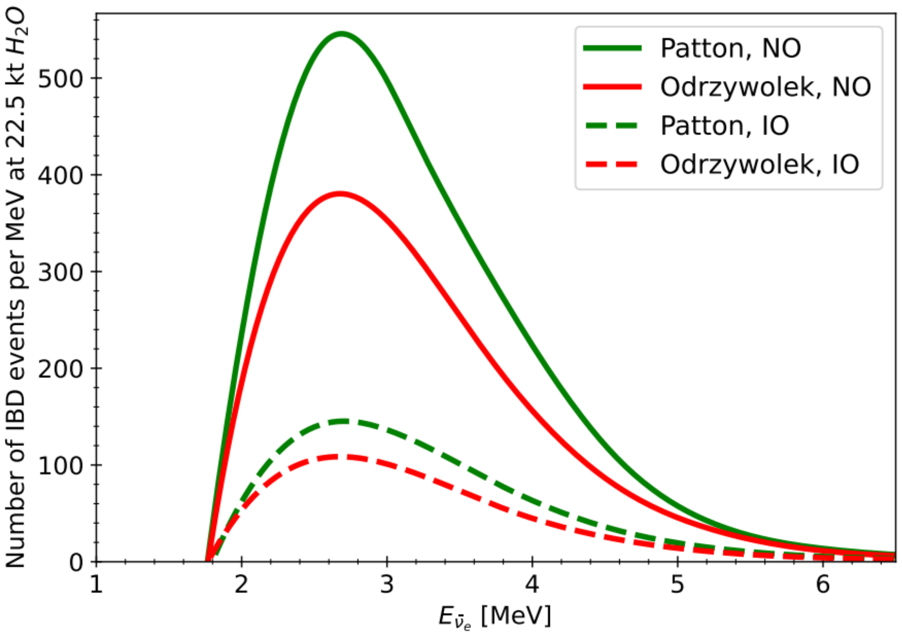


- 50-kton water Cherenkov detector located in the Kamioka mine
  - 1000 m of rock overburden, (2700 m.w.e.)
  - Inner detector: >11000 20-inch PMTs
- Multiple physics targets, expanding from solar neutrinos (~MeV) to atmospheric neutrinos (~TeV).
- SK-Gd: upgrade Super-K by dissolving Gadolinium to water
  - Better neutron tagging capability



- Physics targets extended!
  - Supernova relic neutrino (SRN)
  - Reduction of background for proton decay
  - $\nu/\bar{\nu}$ discrimination
  - Galactic supernovae (pointing accuracy)
  - **pre-supernova ν**

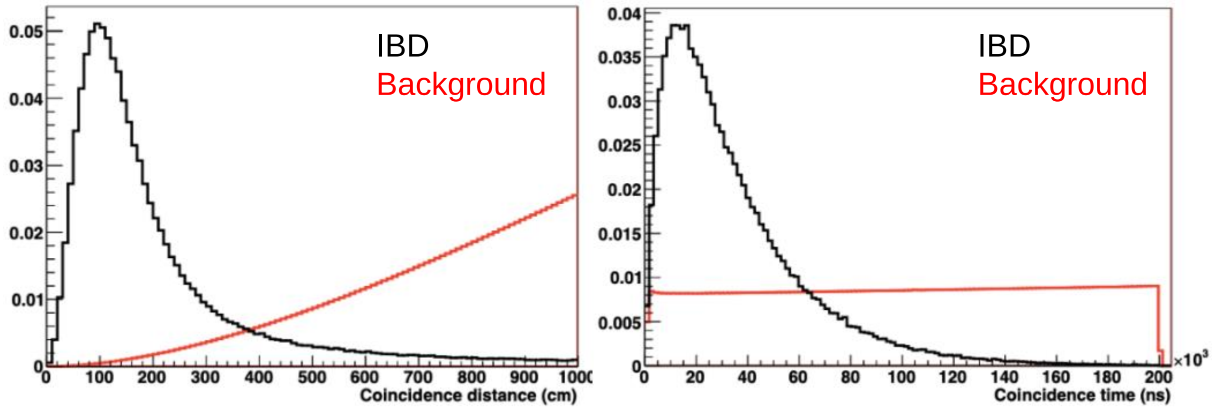
Pre-Supernova Neutrinos in SK-Gd



- The integrated pre-SN neutrino energy spectrum over the last 8 hours before core-collapse. [L.N. Machado et al. *Astrophys. J.* 935 (2022)]
  - Assuming stars with 15 $M_\odot$ at 150 pc

- Background sources
  - Accidental coincidences (radioactive decays, dark noise and uncorrelated events)
  - Radioactive Contaminations (decay of radioisotopes ^{238}U, ^{232}Th and ^{235}U distributed in the detector after Gd loading)
  - **Reactor neutrinos** and geoneutrinos

- Selection is optimized using Boosted Decision Tree method.



Coincidence distance (left) and time (right) between products from IBD events for simulated signal (black) and background (red)

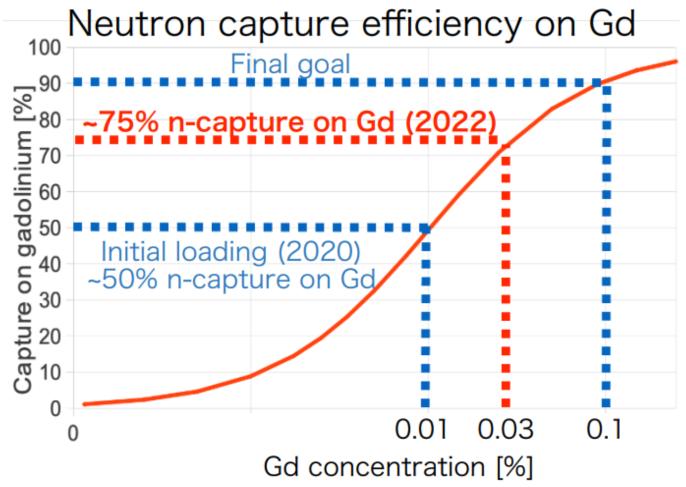
Pre-SN Sensitivity of SK-Gd (Previous)

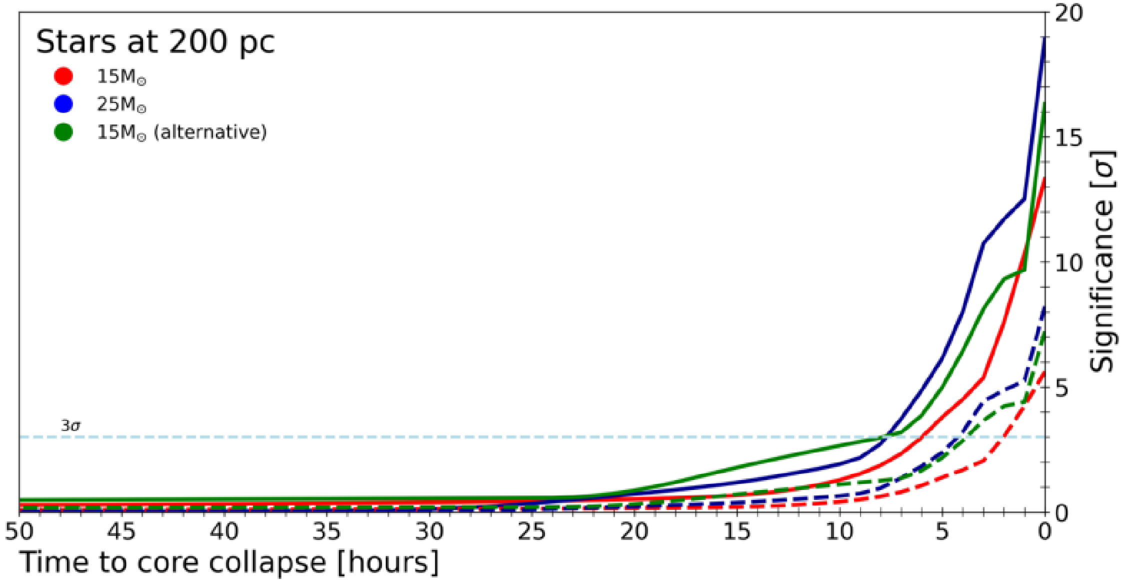
2019 Before Gd loading

- The Super-Kamionkande collaboration published the first article of studies on sensitivity of SK-Gd for pre-SN. [C. Simpson et al. *Astrophys. J.* 885 (2019)]

2020 Gd concentration = 0.01%

- A pre-SN alert system was developed, with optimized selection of candidate events. [L.N. Machado et al. *Astrophys. J.* 935 (2022)]
- The expected discovery significance of SK-Gd with 0.01% Gd is as shown below.





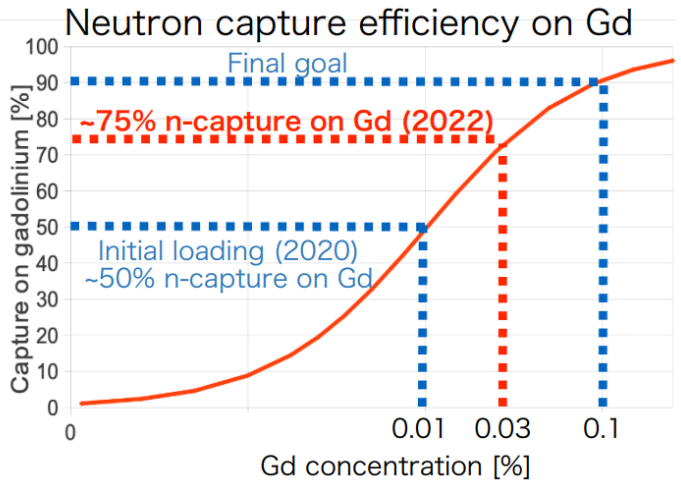
Odrzywolek 15x solar mass Odrzywolek & Heger, *Acta Phys. Pol. B*, 41 (2010)
Odrzywolek 25x solar mass
Patton 15x solar mass K.M. Patton et al. *Astrophys. J.* 840 (2017)

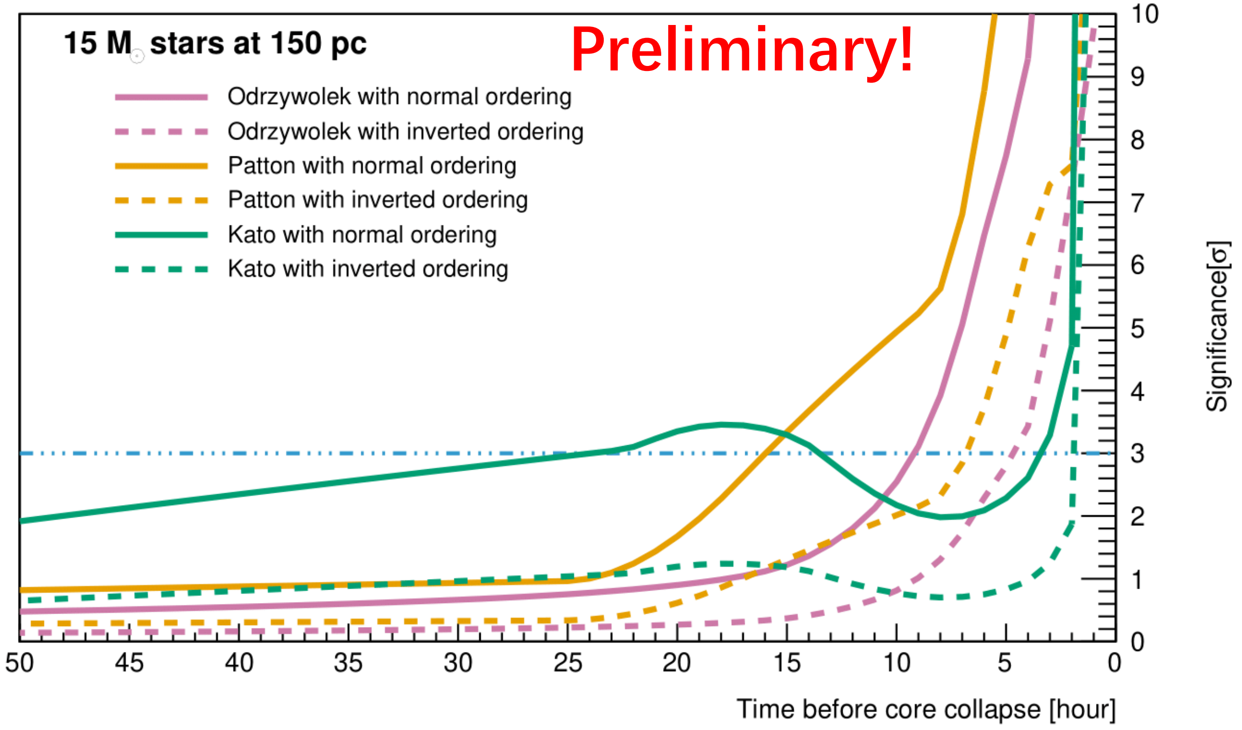
Dashed lines for inverted ordering

Pre-SN Sensitivity of SK-Gd

Now(since 2022) Gd concentration = 0.03%

- Joint pre-SN alert system in development.
- Event selection optimized for 0.03% Gd. —— optimal analysis window is 8-hour
- Background rate ~0.45 /hour (as of 2023/02/01) —— expect 3.6 events in 8 hours
- Preliminary sensitivity to pre-SN neutrinos:





Method for the Joint Search

- Without explicit reference to a pre-SN model, the monitor performs a test of significance between data and background.
- Super-K and KamLAND are Poisson counting experiments, in terms of pre-SN neutrinos.
  - Count pre-SN neutrino-like events over a time period.
  - Compare the counts to expected number of background.

Frequentist approach:

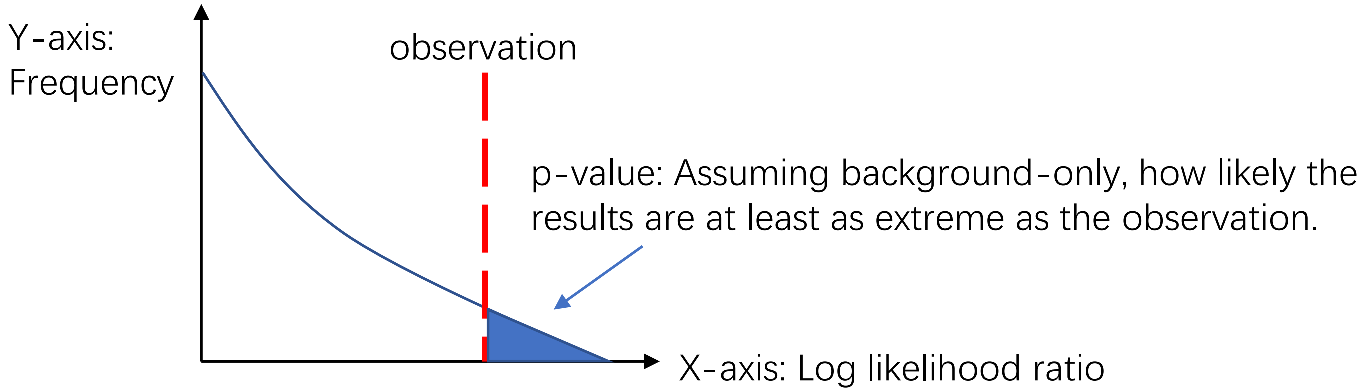
- The likelihood function is a product of two Poisson probabilities.

$$\mathcal{L} = Poisson\left(n_{SK}^{obs} \middle| S_{SK} + B_{SK}\right) \times Poisson\left(n_{KL}^{obs} \middle| S_{KL} + B_{KL}\right)$$

SK for Super-Kamiokande; KL for KamLAND

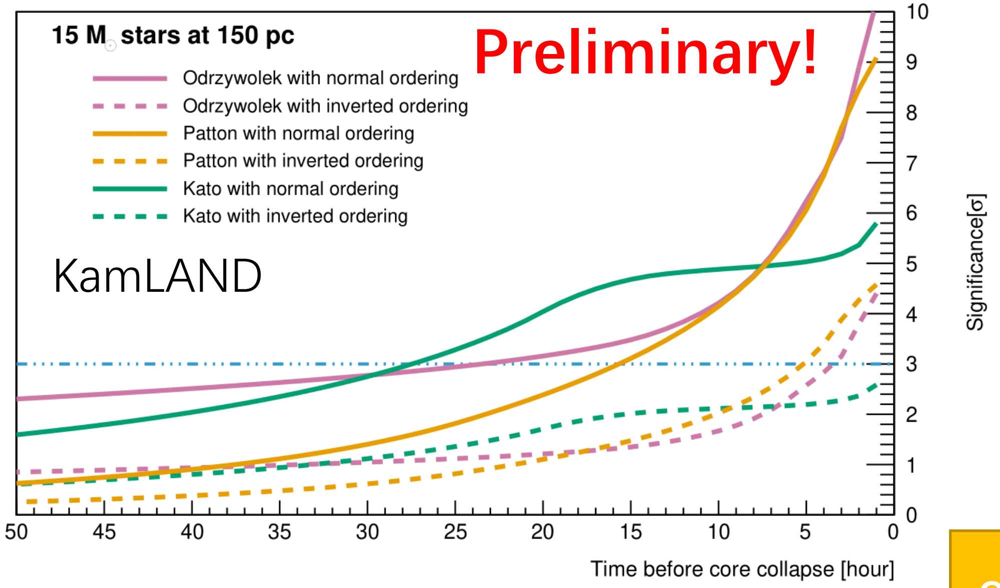
- n^{obs}: observed numbers of candidates
- S: parameters represent signal contributions
- B: parameters represent background contributions

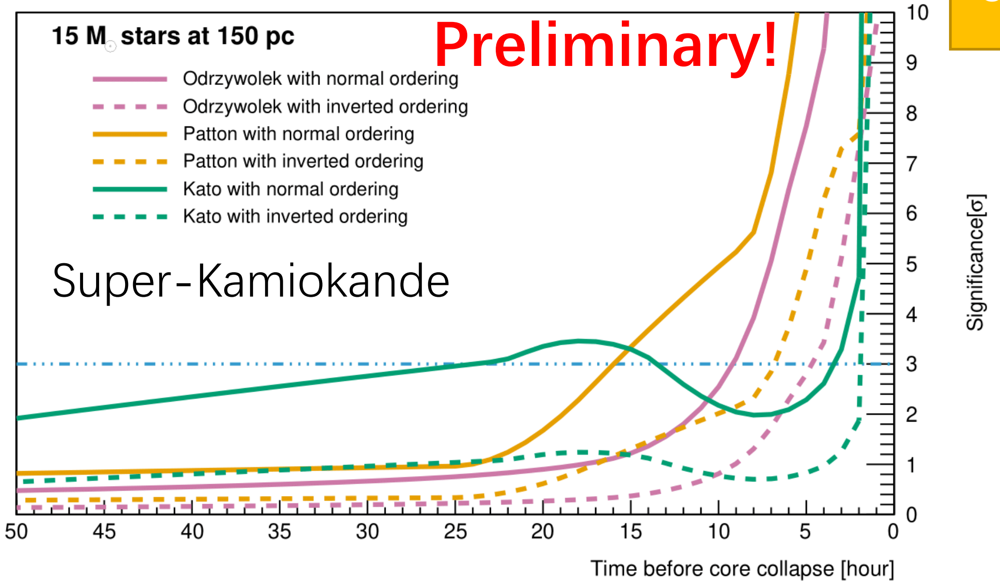
- Test statistics: log likelihood ratio
- Find the p-value and convert to significance

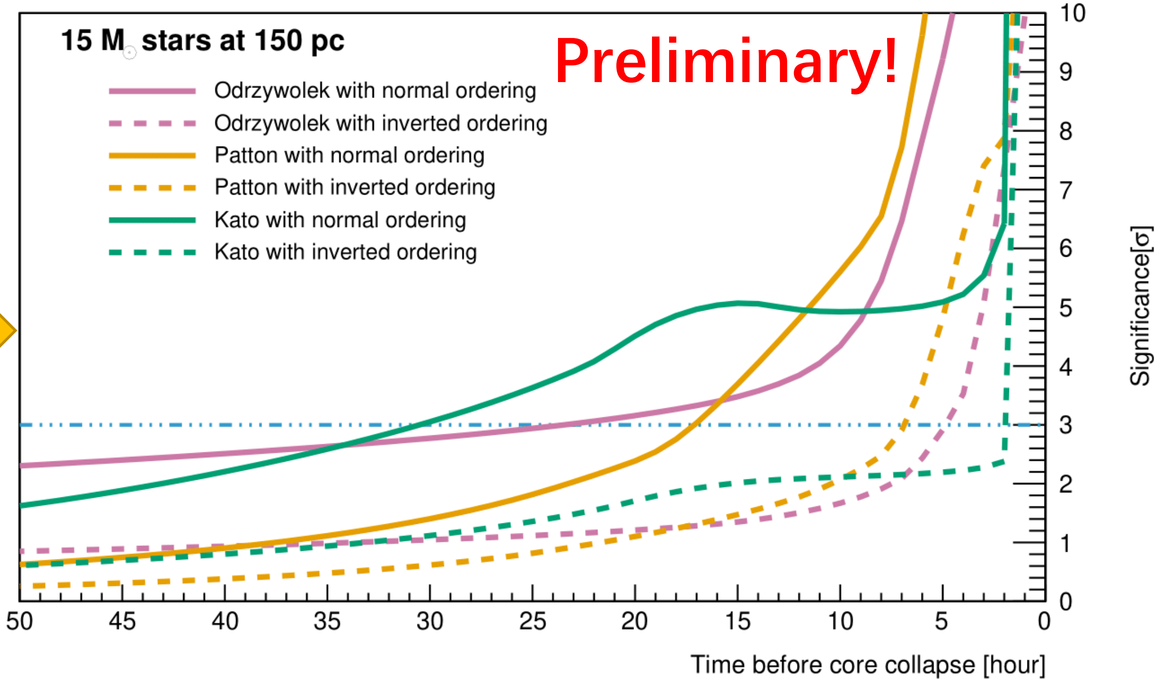


Distribution of test statistics assuming background-only

Combined Sensitivity





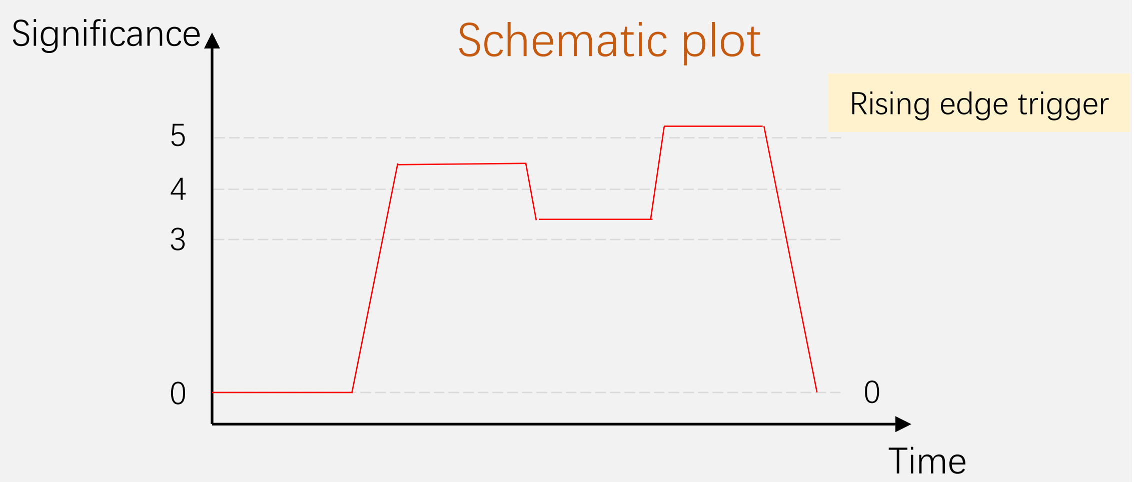


- KamLAND can resolve a signal early because of low background rate.
- Super-K's large size help increasing significance.
- **Combined**: Taking benefits from both detectors!

False Alarm Rate

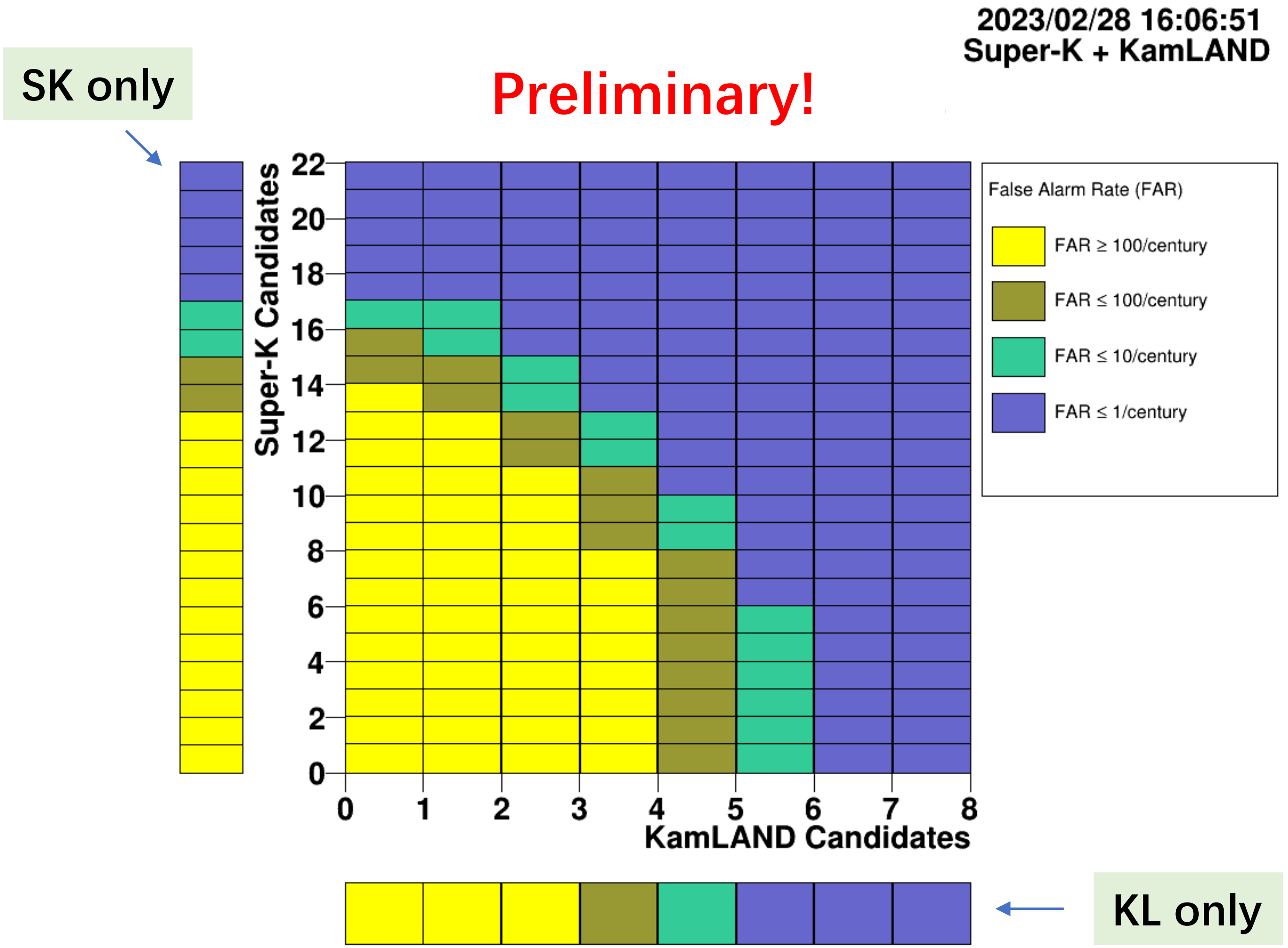
- **Difficulties** in interpreting the results to the false positive rate.
  - Significance level = 3σ doesn't mean the false positive rate = 0.3% !
  - **NOT independent** measurements
  - The "**Look Else-where Effects**"
- How many times we get false positive in a century? —— "**False Alarm Rate**"

- Toy Monte-Carlo simulation.
  - Generate a time-series of random events assuming background-only for 1 million years
  - Simulate what the alert system does
  - Count false positives —— how many times the alarm is triggered.



Significance Level = 3σ —— 1 false alarm
Significance Level = 4σ —— 2 false alarms
Significance Level = 5σ —— 1 false alarm

False Alarm Rate



- False Alarm Rate
  - Assuming background-only hypothesis true
  - How frequently we find the results as extreme as the given combination of number of events.

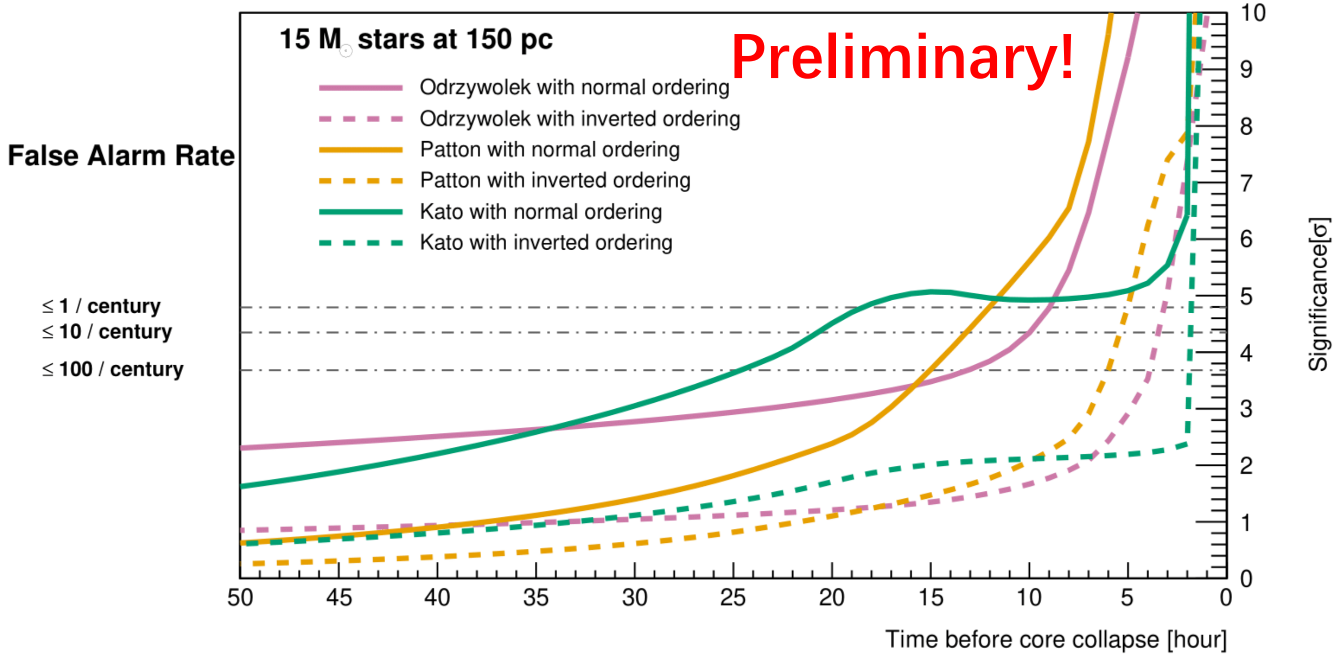
- When the observation is in the blue regions
  - reject background-only hypothesis
  - with false alarm rate no more than 1 per century
  - Galactic CCSN frequency ~3.2 per century [S.M. Adams et al. *Astrophys. J.* 778 (2013)]

Sensitivity with False Alarm Rate

Optimal analysis window
KamLAND: 24 hours
Super-K: 8 hours

Using background rate as of 2023/02/01
KamLAND: ~ 0.007 /hour 0.18 events in 24 hours
Super-K: ~ 0.45 /hour 3.6 events in 8 hours

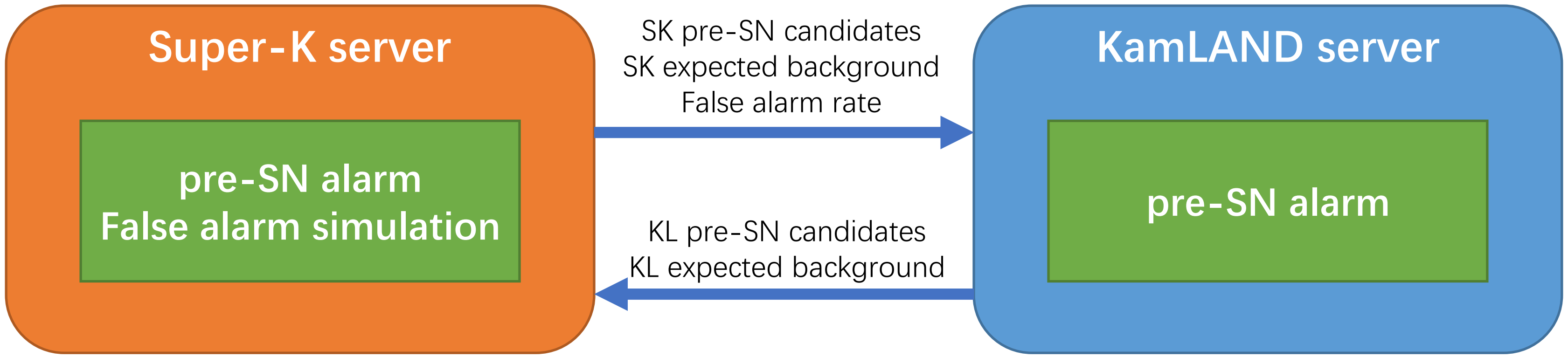
Evolution of the significance level in joint alarm system



Assuming stars with 15 solar mass at 150 pc, we can claim a significant pre-SN signal with false alarm ≤ 1/century,

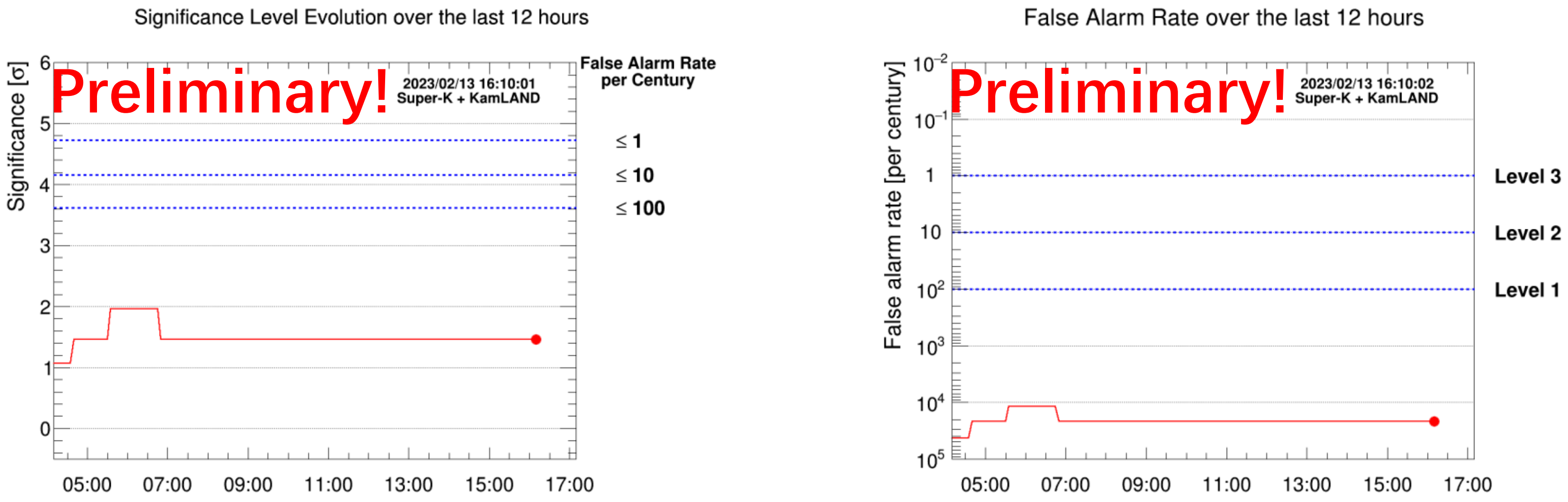
- 9 hours before core-collapse, for all models with normal ordering
- 2 hours before core-collapse, for all models with inverted ordering

We are testing the alert system on Super-K server and KamLAND server.



It shall be online soon, to provide discovery significance of current observations and the corresponding false alarm rate.

- The form of these information is not determined yet. The plots below are examples.
- Updates every 5 minutes.
- Will be linked to GCN. (may begin with GCN circular)



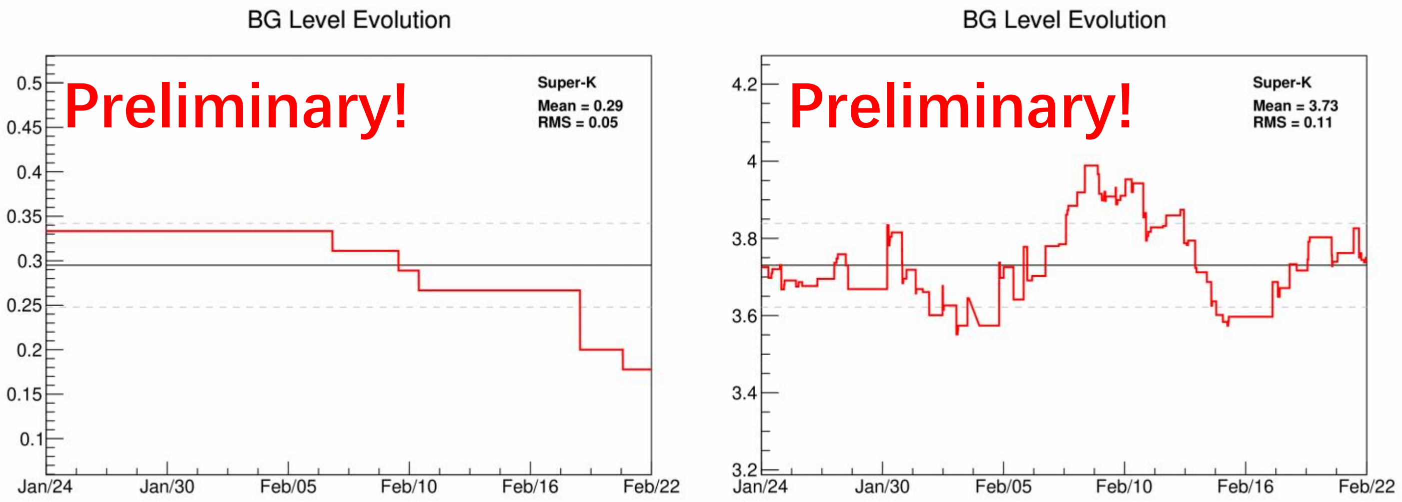
Significance (left) and the corresponding false alarm rate (right) of the joint search of pre-SN neutrinos

Concern of Reactor Neutrino Background

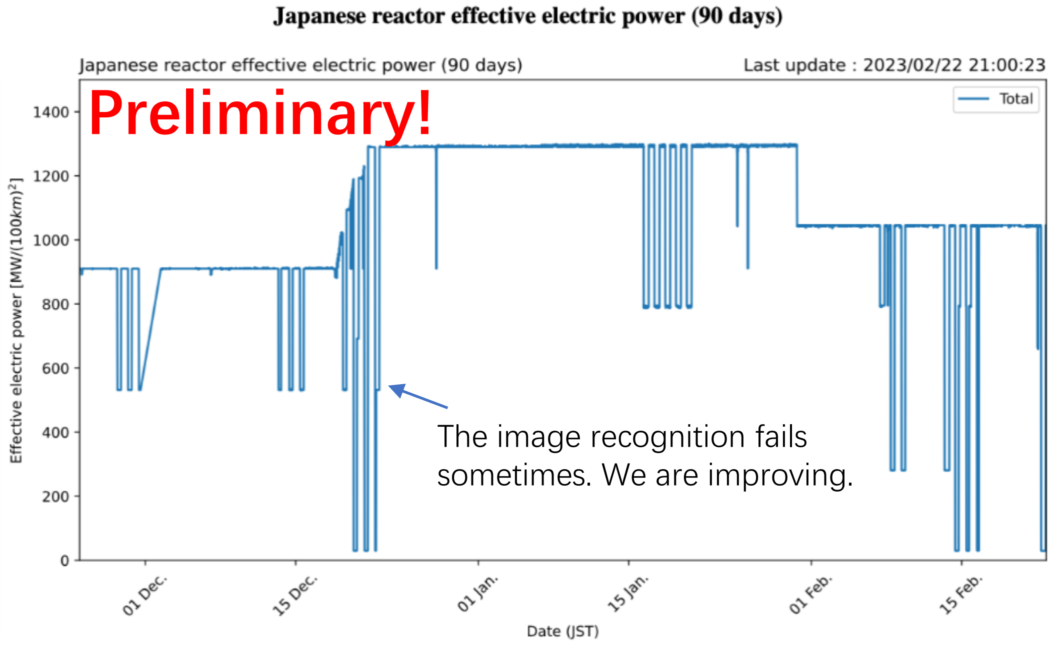
Concerning the potential changes in reactor neutrino background, both Super-K and KamLAND update their background measurements constantly, using candidate events over a previous time period as background measurements.

- Super-K uses data over the past one month
- KamLAND uses data over the past three months

KamLAND also developed a reactor electric power monitor based on public web sites of power companies. It could be an extra reference to avoid sending wrong alerts.



Expected numbers of background in KamLAND (left) and Super-K (right)



Effective reactor electric power (weighted by distance to Kamioka) of commercial reactors in Japan

Summary

- Before a core-collapse supernova, a large amount of neutrinos are emitted, —— pre-supernova neutrinos
  - Neutrinos from the Si-burning phase are potentially detectable by the Super-Kamiokande experiment and the KamLAND experiment.
  - Such a neutrino signal can give an early warning of a CCSN.

- Super-Kamiokande is running with 0.03% Gd (SK-Gd phase). A pre-SN alarm got to work in 2021.
- KamLAND established a pre-SN alarm in 2015, providing a semi-realtime result of pre-SN search to the community.

- Combining the measurements from Super-K and KamLAND, we can take benefits from the low background rate in KamLAND and the large size of Super-K.
- Assuming a star with $15M_{\odot}$ at 150 pc, it is expected that we can issue an early warning with false alarm $\leq 1/$century,
  - 9 hours before core-collapse, with normal ordering
  - 2 hours before core-collapse, with inverted ordering

- Currently (March 2023), a joint pre-SN alert system combining the two alarms is developed. We have been testing the system. And it will be online soon.

Stay Tuned! Thank you!

Backup

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Test Statistics for the Joint Search

Test statistic: log likelihood ratio

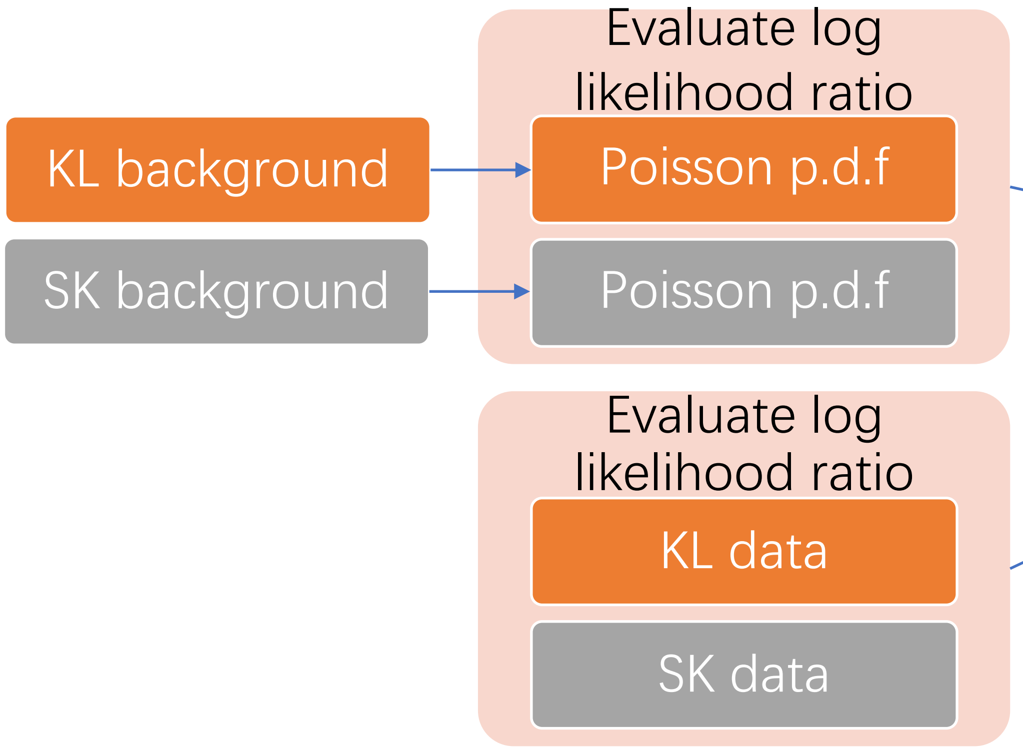
$$-2\ln\lambda = -2\ln[\frac{\max(\mathcal{L}|_{S=0})}{\max(\mathcal{L})}]$$

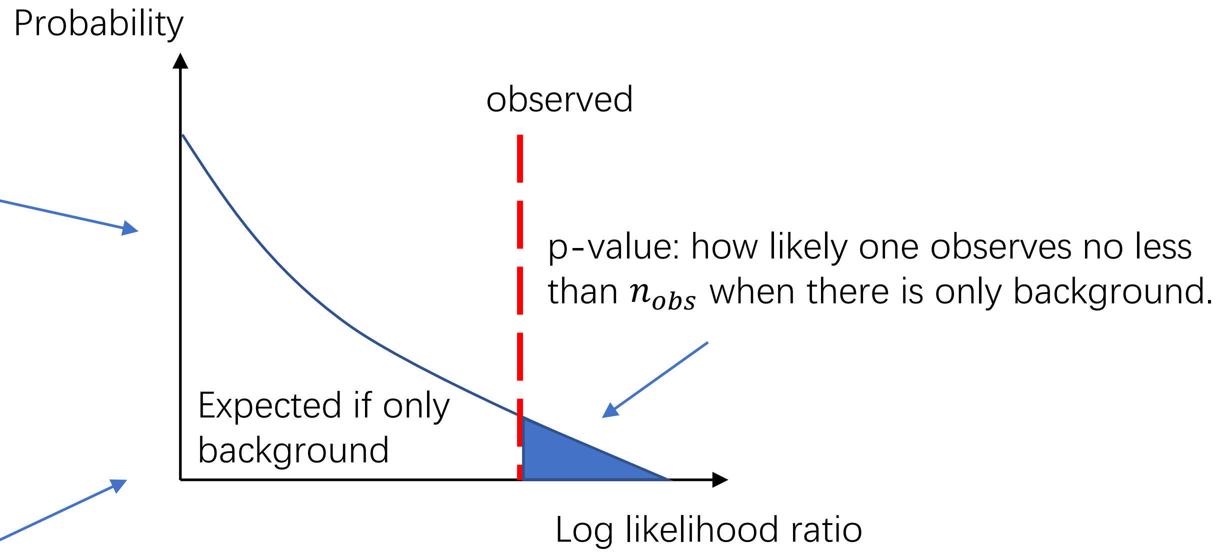
$$\mathcal{L} = \prod_{KL,\,SK} Pois(n_{obs}|S+B)$$

- n_{obs}: observed numbers of events at KamLAND or Super−K
- S: adjustable parameters represent signal contribution (fixed to 0 in NULL hypothesis)
- B: expected background (sampling weeks or months of previous data, updates every week)
- Systematic uncertainties are currently neglected.

Frequentist Approach

- Usually, one generates a large amount of MC under the background-only assumption, and calculate for each MC the log likelihood ratio.
- Without systematic uncertainty, the distribution of number of events (background-only) is a Poisson distribution.

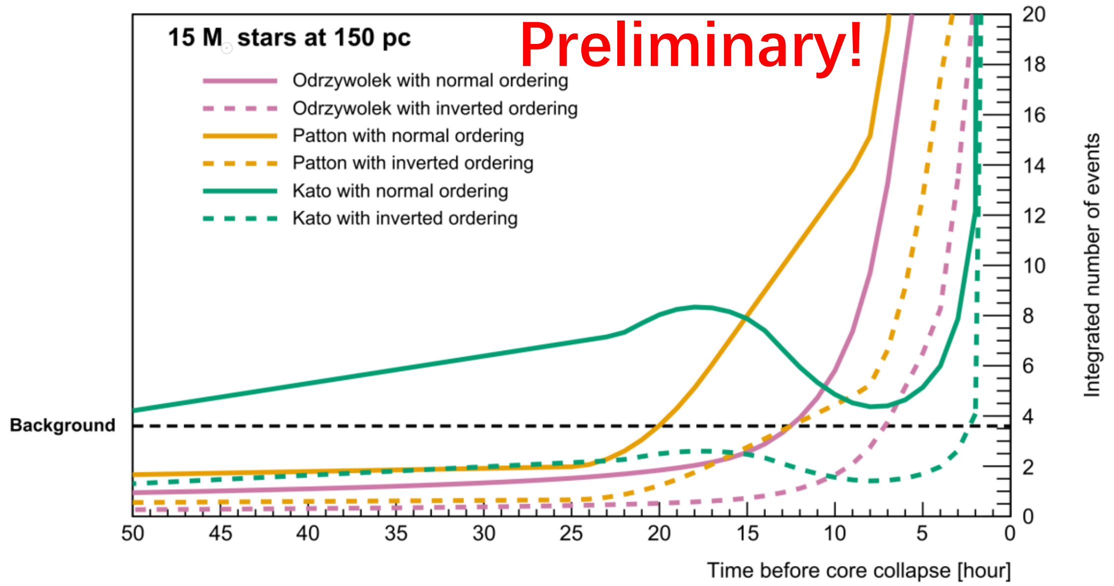




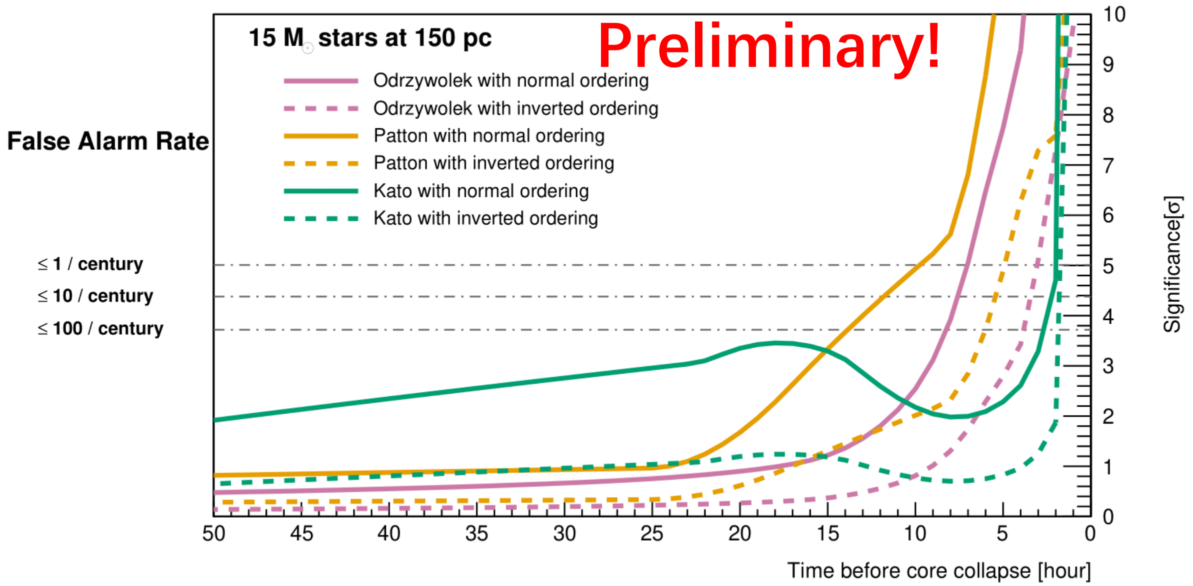
Find p-value (tail probability)
Convert p-value to z-score

Expected Number of Events in Analysis Window

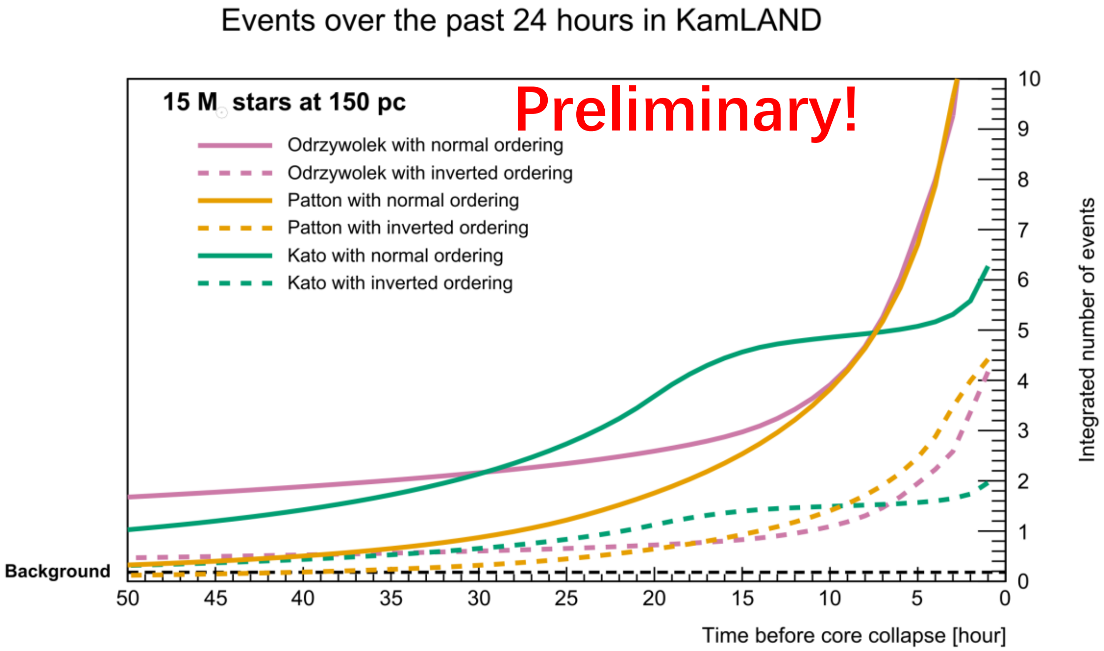
Events over the past 8 hours in Super-K

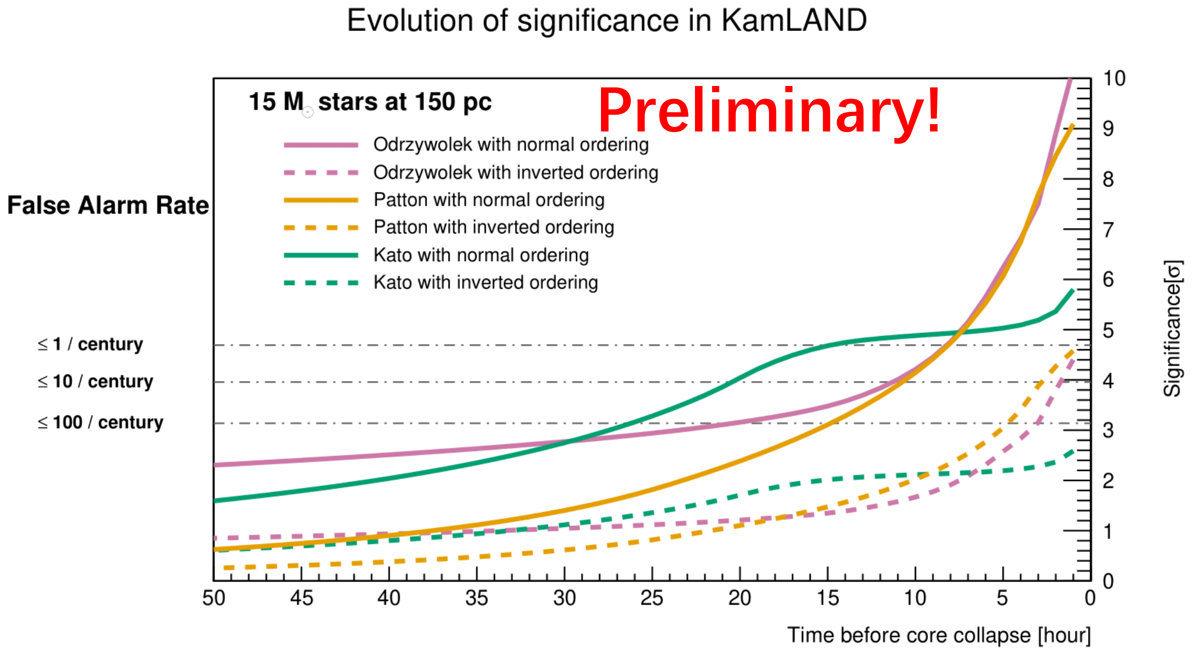


Evolution of significance in Super-K

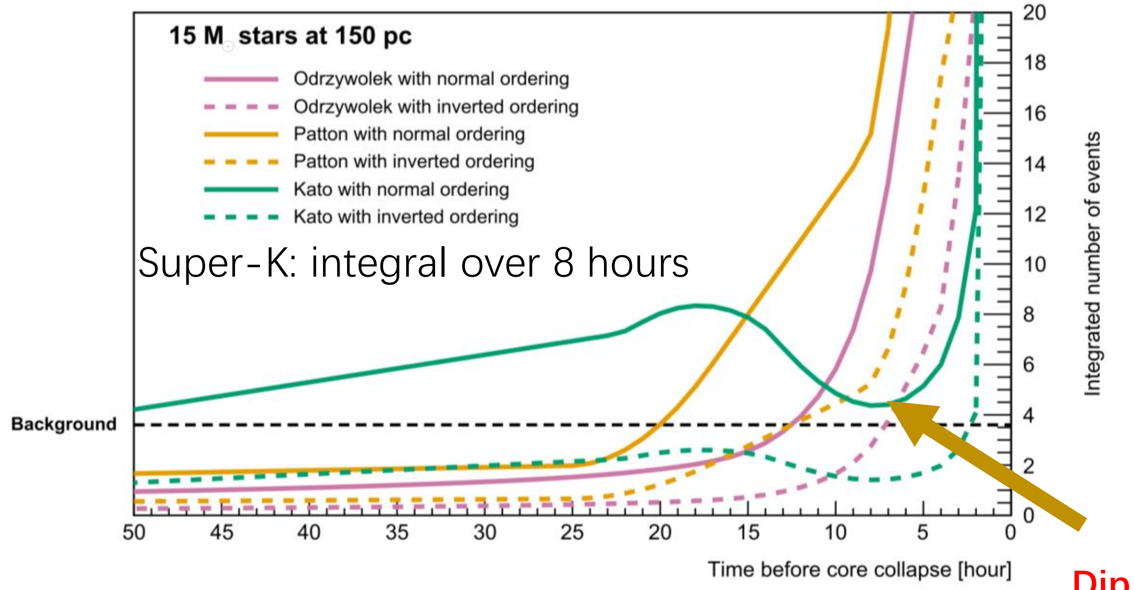


Expected Number of Events in Analysis Window

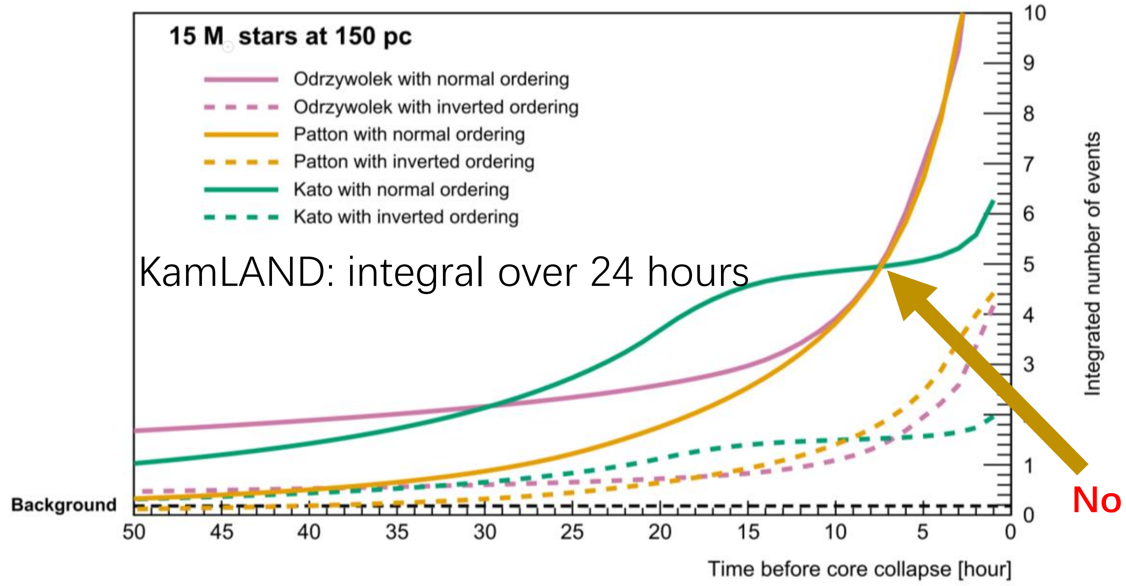




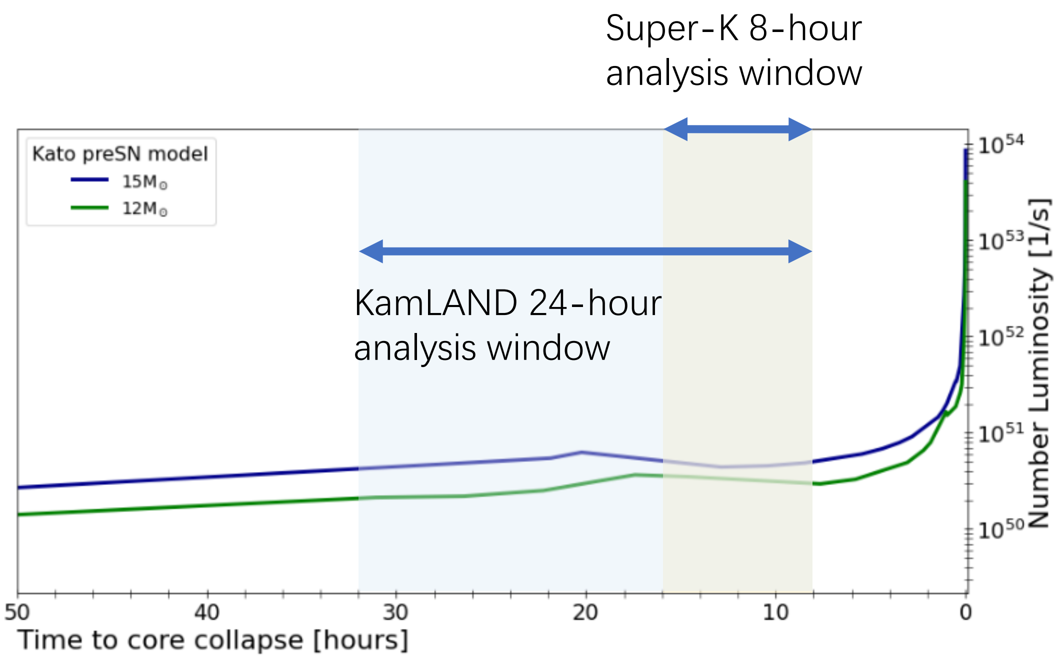
Dip



Dip at ~7 hr



No obvious dip



Time evolution prior to the core collapse of the neutrino number luminosity.

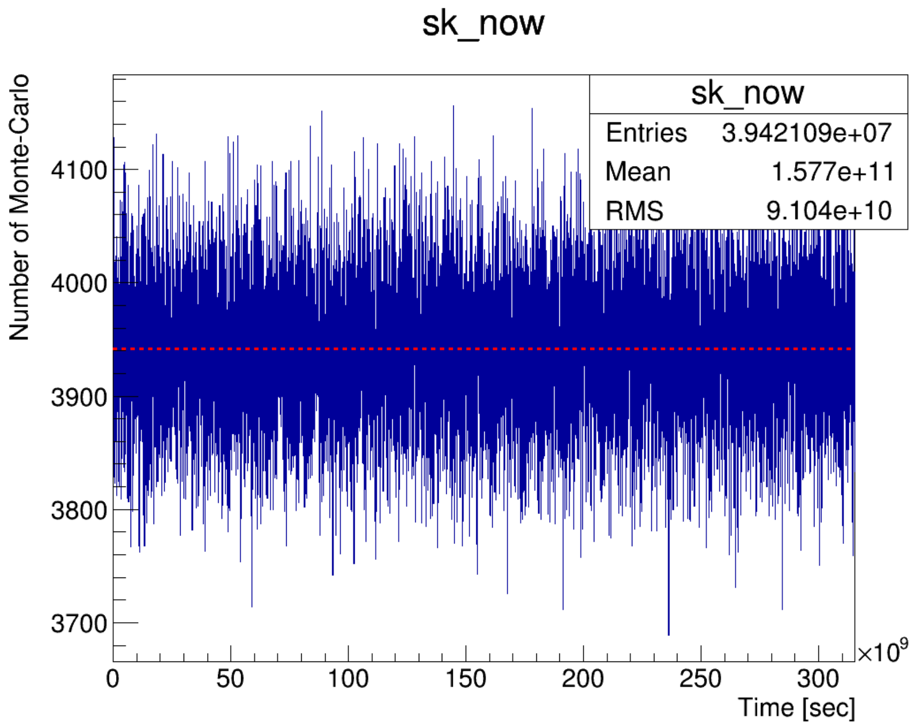
The bump/dip structure in Super-K plot is due to the behavior of Kato model.

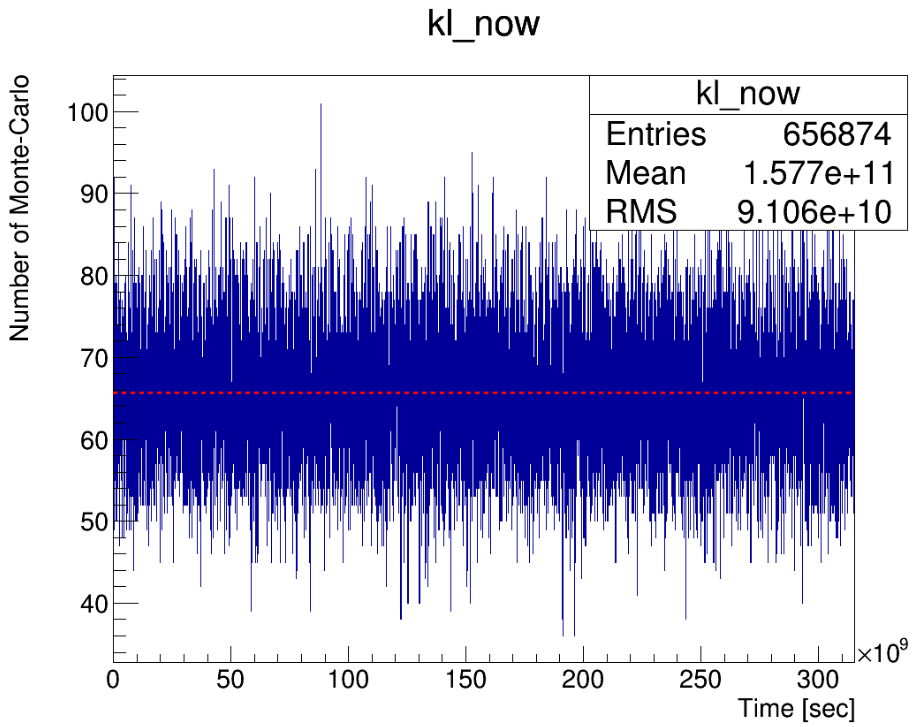
KamLAND does not have the same structure due to wide analysis window.

Toy MC sanity check

Using background rate as of 2023/02/01
KamLAND: ~ 0.007 /hour 0.18 in 24 hours
Super-K: ~ 0.45 /hour 3.6 in 8 hours

- Toy SuperK (background-only):
  - expected number of event: 3.942×10^7
  - monte-carlo: $39{,}421{,}090$ events
- Toy KamLAND (background-only):
  - expected number of event: 6.57×10^5
  - monte-carlo: $656{,}874$ events



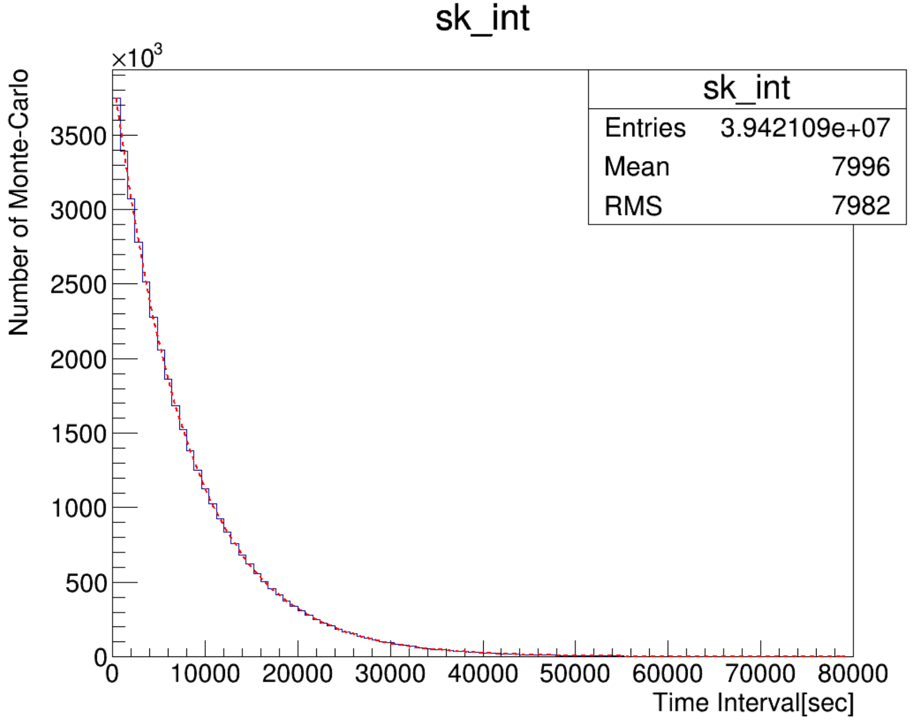


Distributions of numbers of event per year

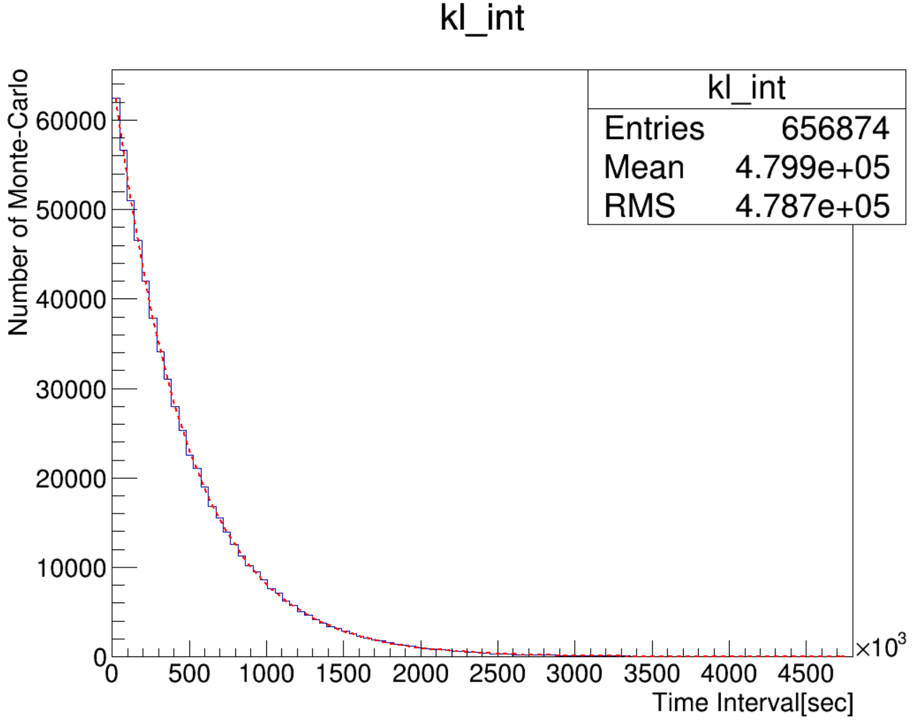
Toy MC sanity check

Using background rate as of 2023/02/01
KamLAND: ~ 0.007 /hour 0.18 in 24 hours
Super-K: ~ 0.45 /hour 3.6 in 8 hours

- Toy SuperK (background-only):
  - expected mean time interval: 8000
  - monte-carlo mean: 7996
  - monte-carlo RMS: 7982



- Toy KamLAND (background-only):
  - expected mean time interval: 4.8×10^5
  - monte-carlo mean: 4.799×10^5
  - monte-carlo RMS: 4.787×10^5

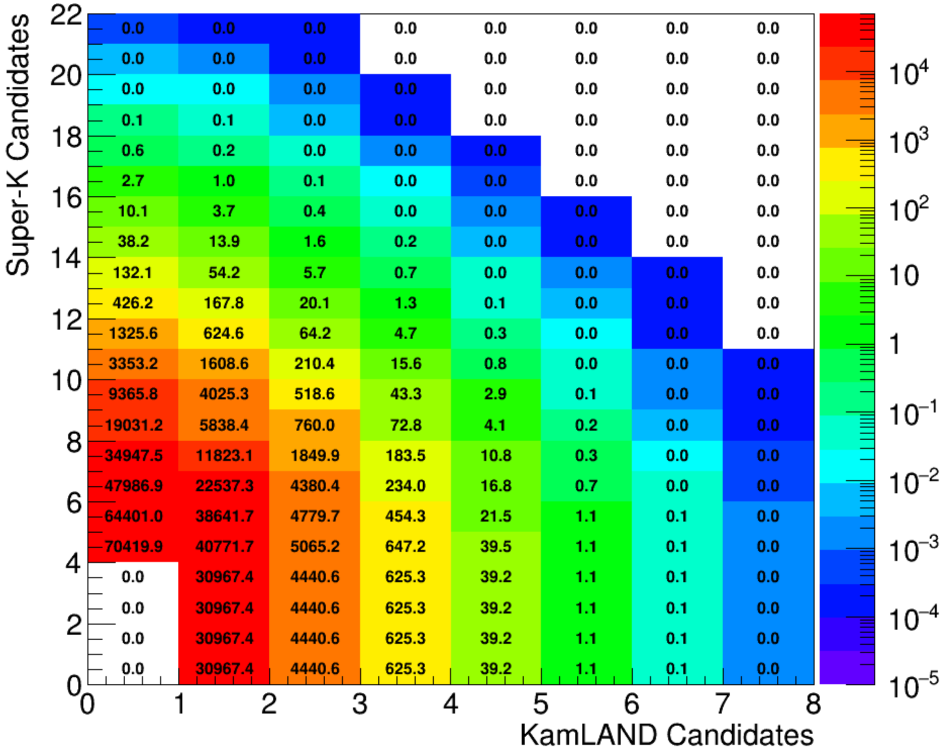


Distributions of time intervals between two adjacent events

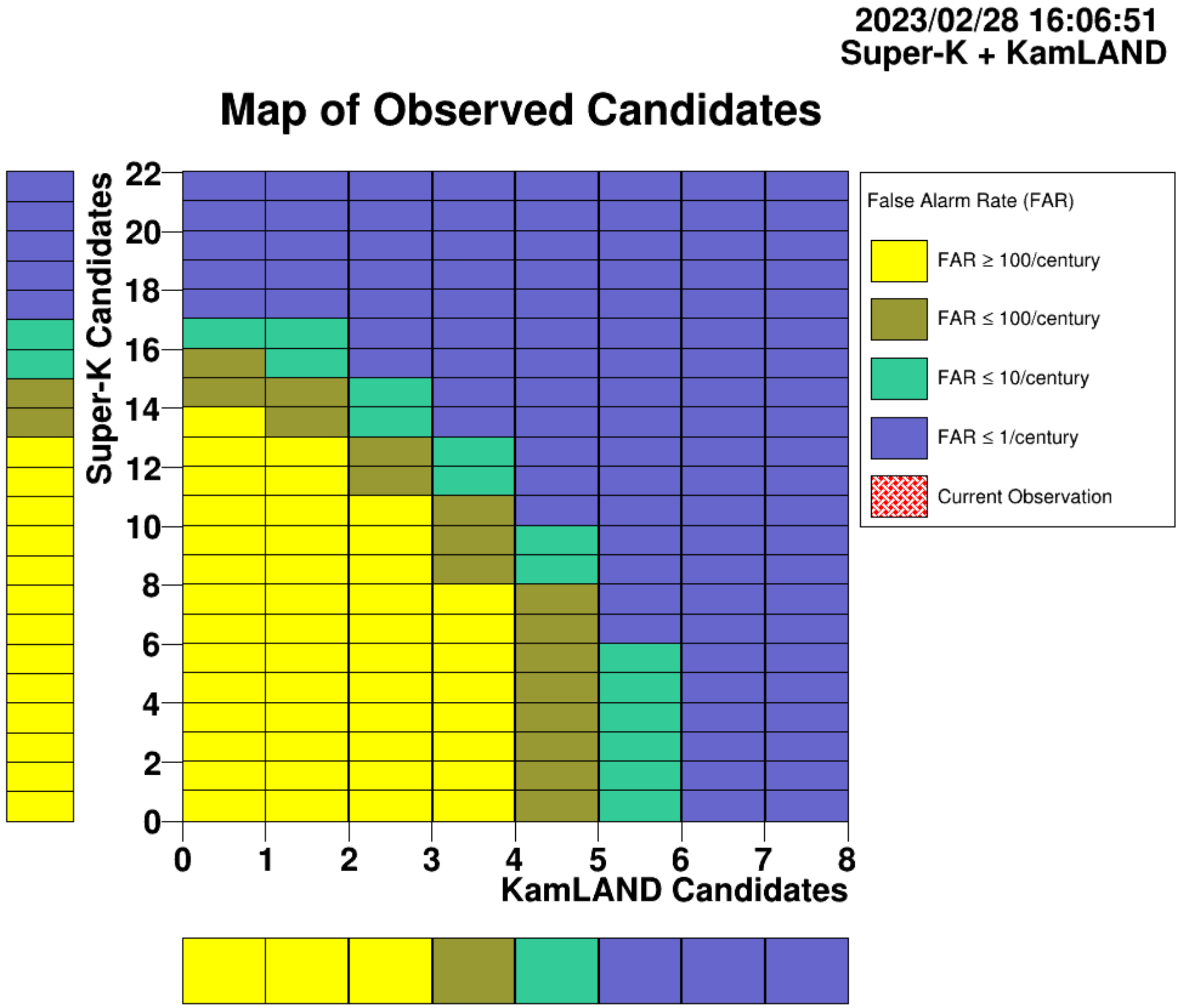
False alarm rate (SK+KL)

Counts in 8 hours at SuperK

z-axis: false alarms per century

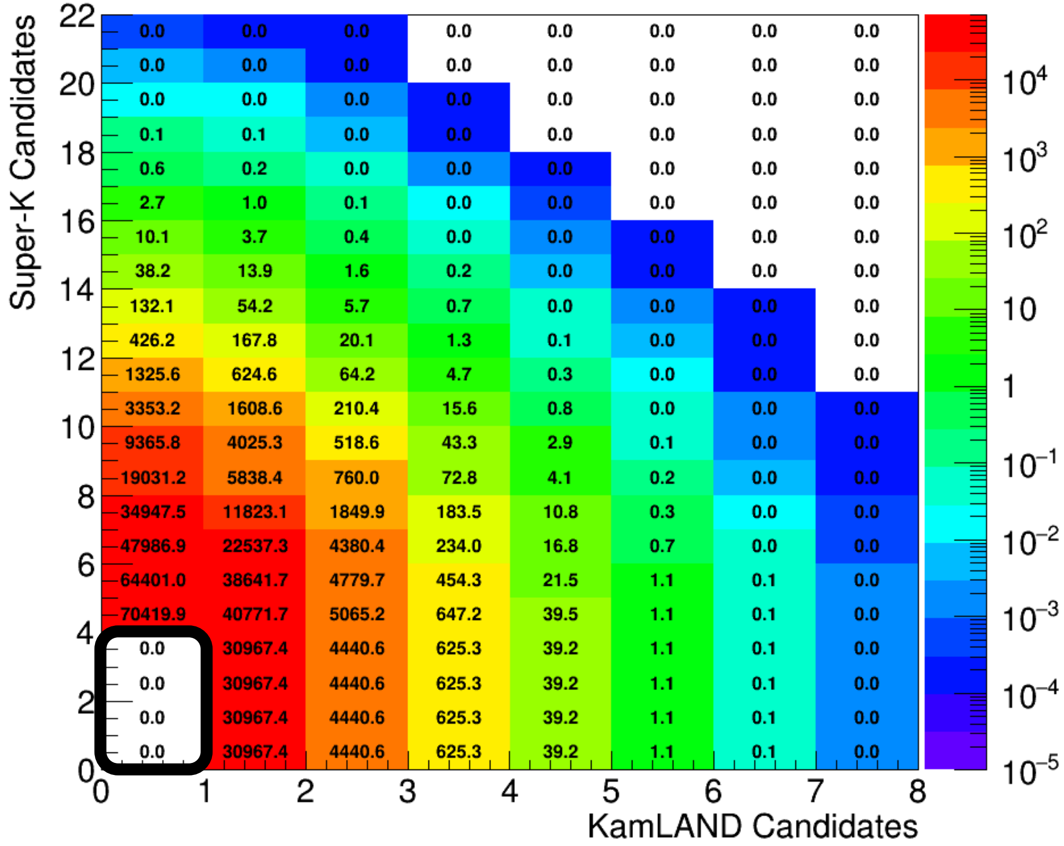


Counts in 2 days at KamLAND



False alarm rate (SK+KL)

Using background rate as of 2023/02/01
KamLAND: ~ 0.007 /hour 0.18 in 24 hours
Super-K: ~ 0.45 /hour 3.6 in 8 hours

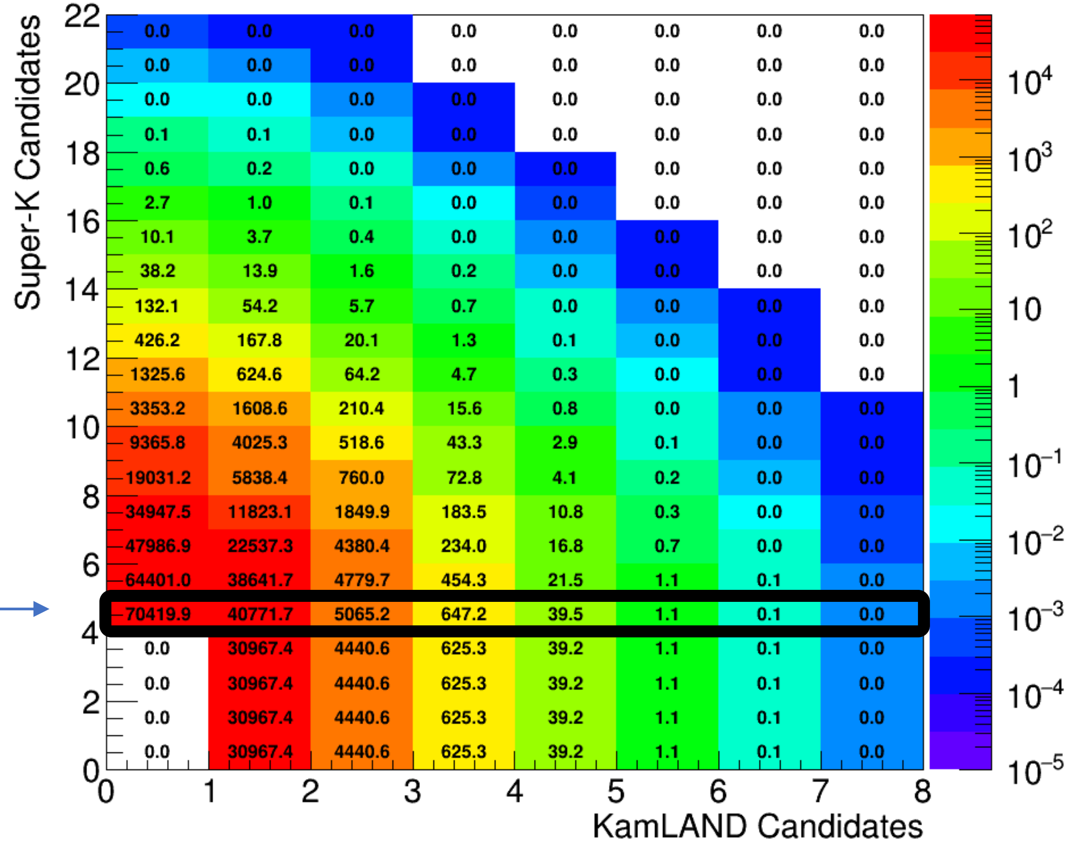


Actually, false alarm rates in this region are N/A, because significance = 0.
When setting significance level = 0, the term “false alarm” is undefined.

False alarm rate (SK+KL)

Using background rate as of 2023/02/01
KamLAND: ~ 0.007 /hour   0.18 in 24 hours
Super-K: ~ 0.45 /hour   3.6 in 8 hours

Most probable number for Super-K

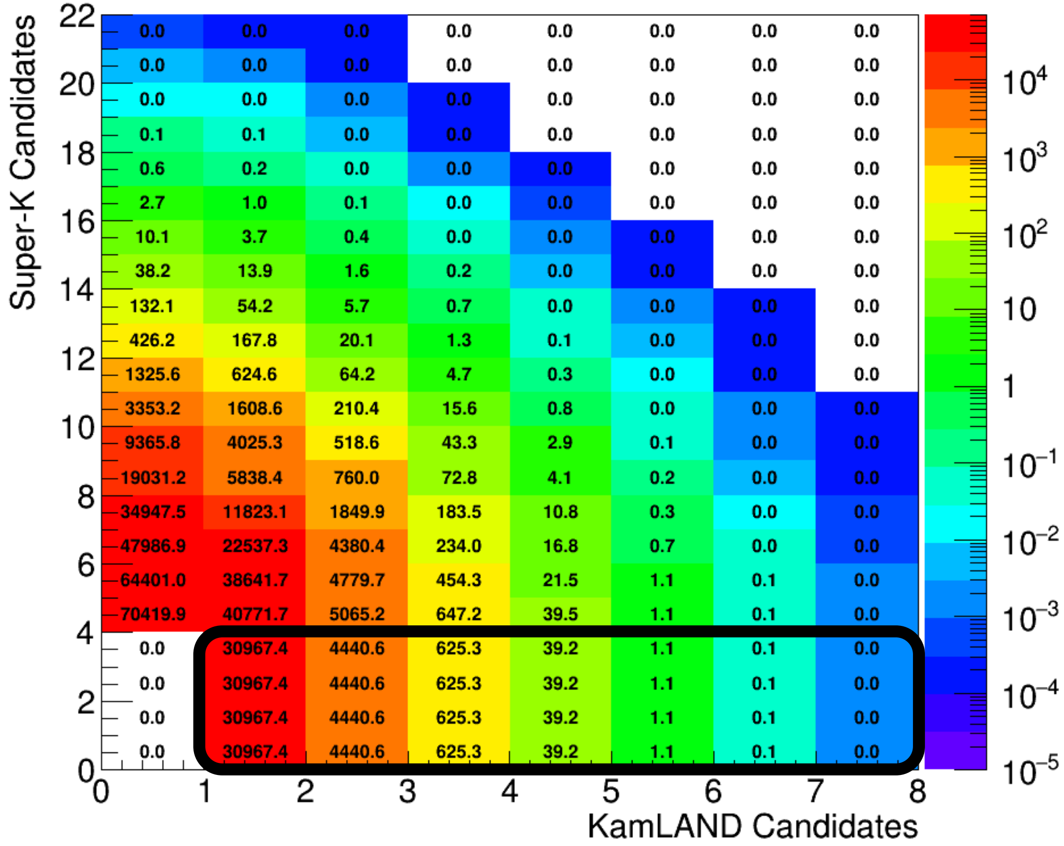


When background-only hypothesis is true, we expect the case “Super-K observes 4 events in 8 hours” most commonly happens.

So, “Super-K obverses 0 event” is rare, compared to “Super-K obverses 4 events”.

False alarm rate (SK+KL)

Using background rate as of 2023/02/01
KamLAND: ~ 0.007 /hour   0.18 in 24 hours
Super-K: ~ 0.45 /hour   3.6 in 8 hours



For each column, false alarm rates in this region are the same, as the significances are the same.

(Super-K observed<Super-K expected background)