Development of alarm method incorporating pre-supernova neutrino light curve

2025/3/3

11th Supernova Neutrino Workshop

Research center for neutrino science

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GPPU

PHYSICS FOR THE UNIVERSE GRADUATE PROGRAM ON

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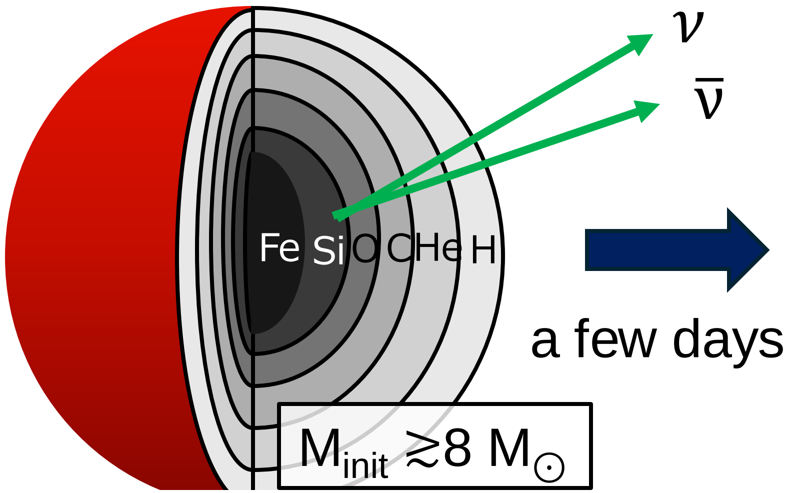
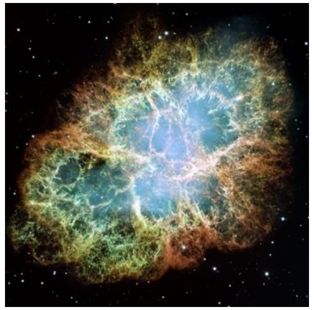
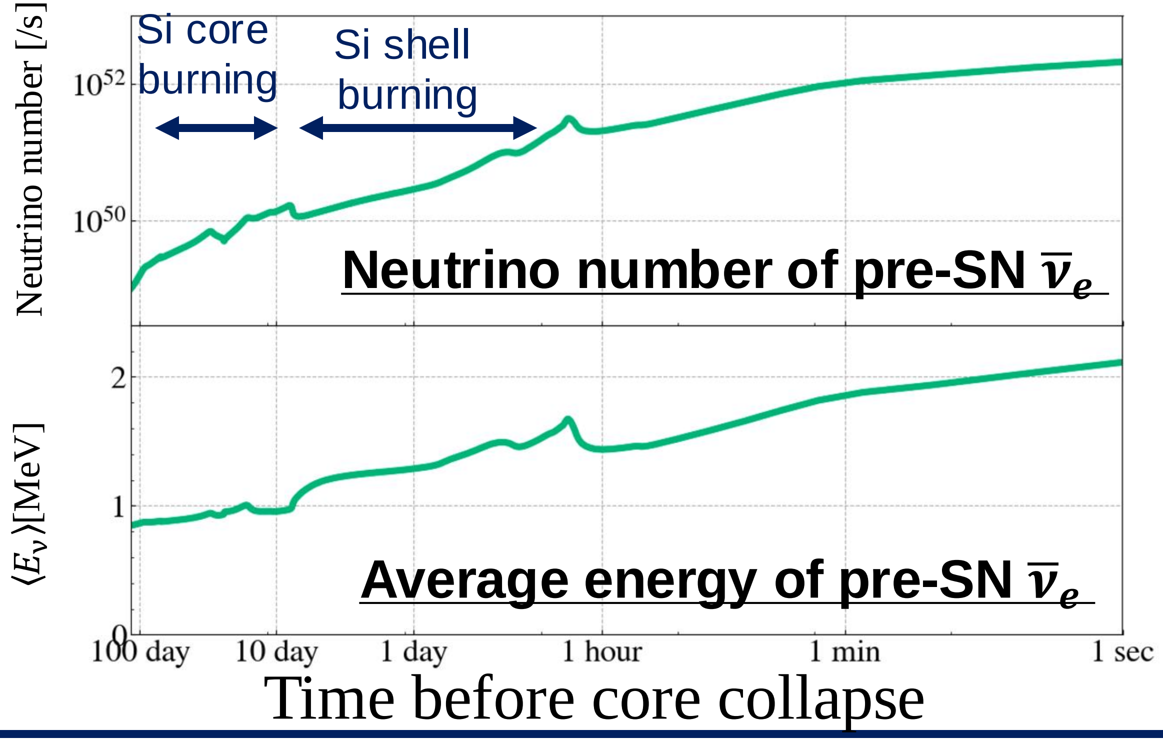
Pre-supernova neutrino





Core collapse supernova (CCSN)



Pre-supernova neutrino (Pre-SN ν)

All flavor neutrinos are predominantly emitted during the last stage of massive ($M > 8\ M_\odot$) stars

- Thermal pair production
- Nuclear weak interactions

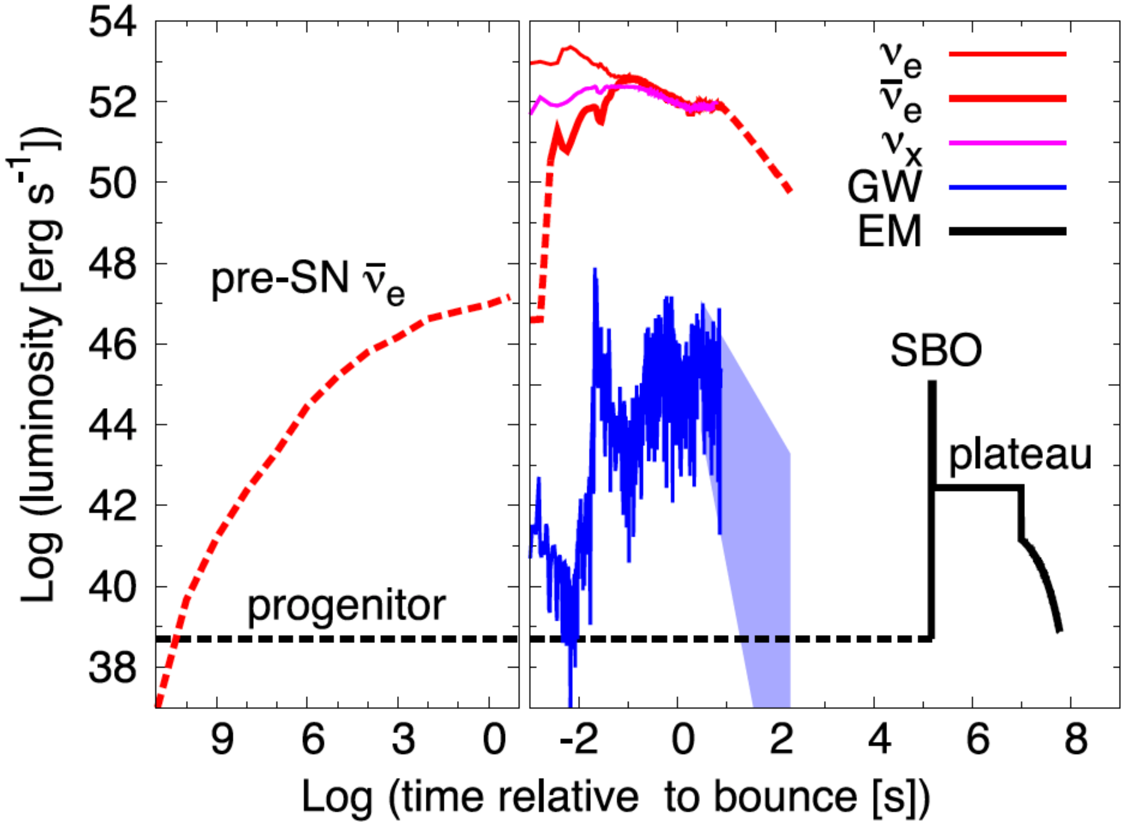
Pre-SN ν flux is calculated from star evolution simulations(**Pre-SN model**)

Motivation for detecting Pre-SN ν

Alarm system to CCSNe (Pre-SN ν alarm)

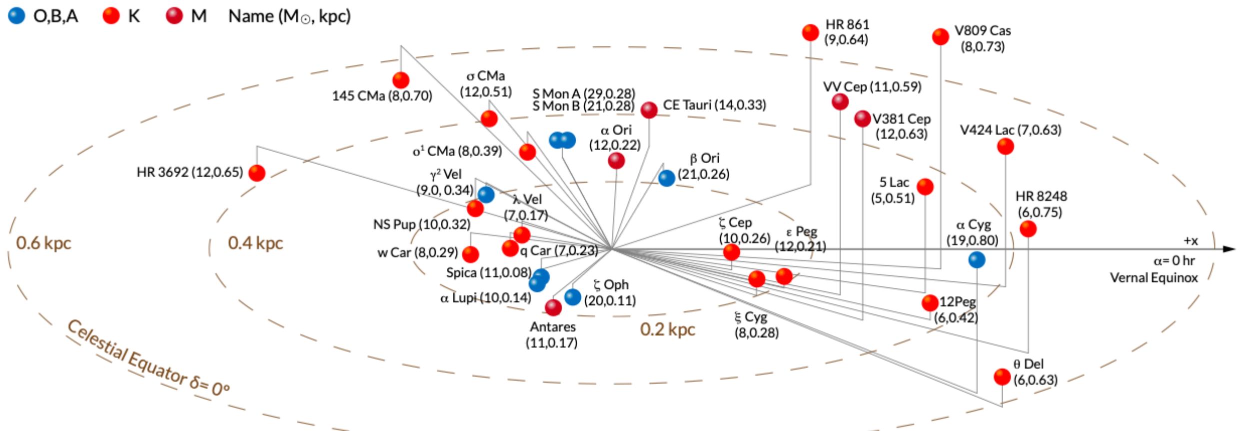
Pre-SN alarm

Pre-SN ν issues alarm to **neutrino**, **gravitational wave (GW)** and **electromagnetic (EM)** CCSN observations



Nakamura et al. 2016

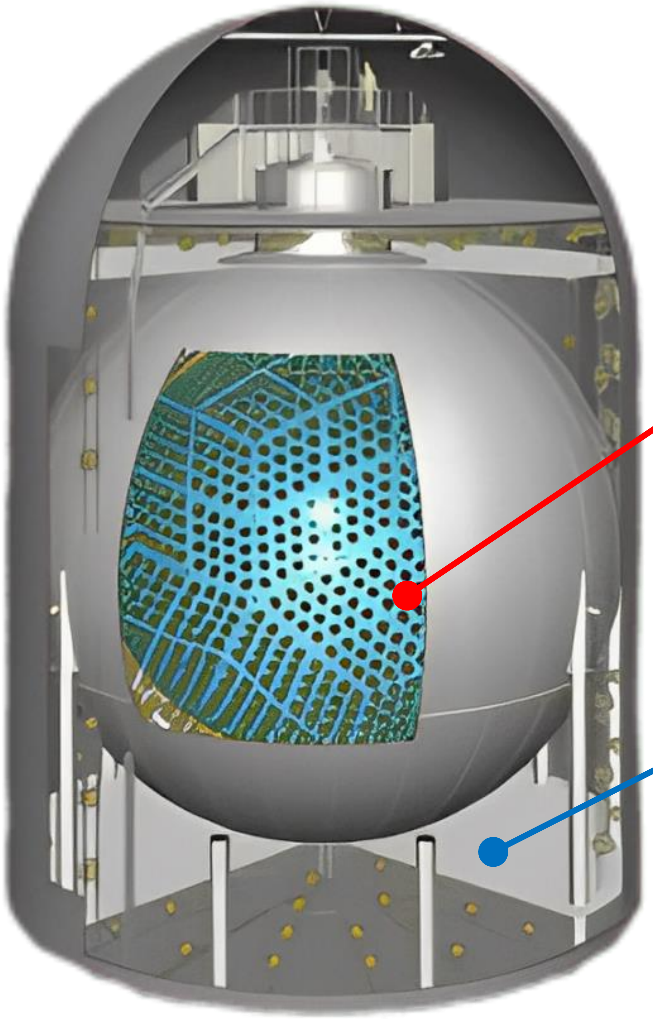
- Pre-SN ν are emitted before core collapse
  - **EM** detectors **observe stars before and during core collapse** due to stelar evolution
  - **ν** and **GW** detectors prevent CCSN data unavailability due to maintenance or calibration works
- Alarm distance $\lesssim$ 1 kpc
  - restrict number of CCSN candidate stars to ~ 30
  - **All CCSN candidate is covered** by aligning telescope worldwide with these star



Mainak Mukhopadhyay *et al* 2020 *ApJ* **899** 153

KamLAND (Kamioka Liquid scintillator Anti Neutrino Detector)

KamLAND is a large liquid scintillator ν detector located at Kamioka mine in Gifu prefecture



Inner detector

Event detection

1 kton liquid scintillator
1325 17inch + 554 20inch PMTs

Outer detector

Shield + Active veto

3.2 kton water Cherenkov detector
140 20inch PMTs

Detection channel of pre-SN $\bar{\nu}_e$

KamLAND has potential to detect pre-SN $\bar{\nu}_e$ via inverse beta decay

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

- Energy threshold

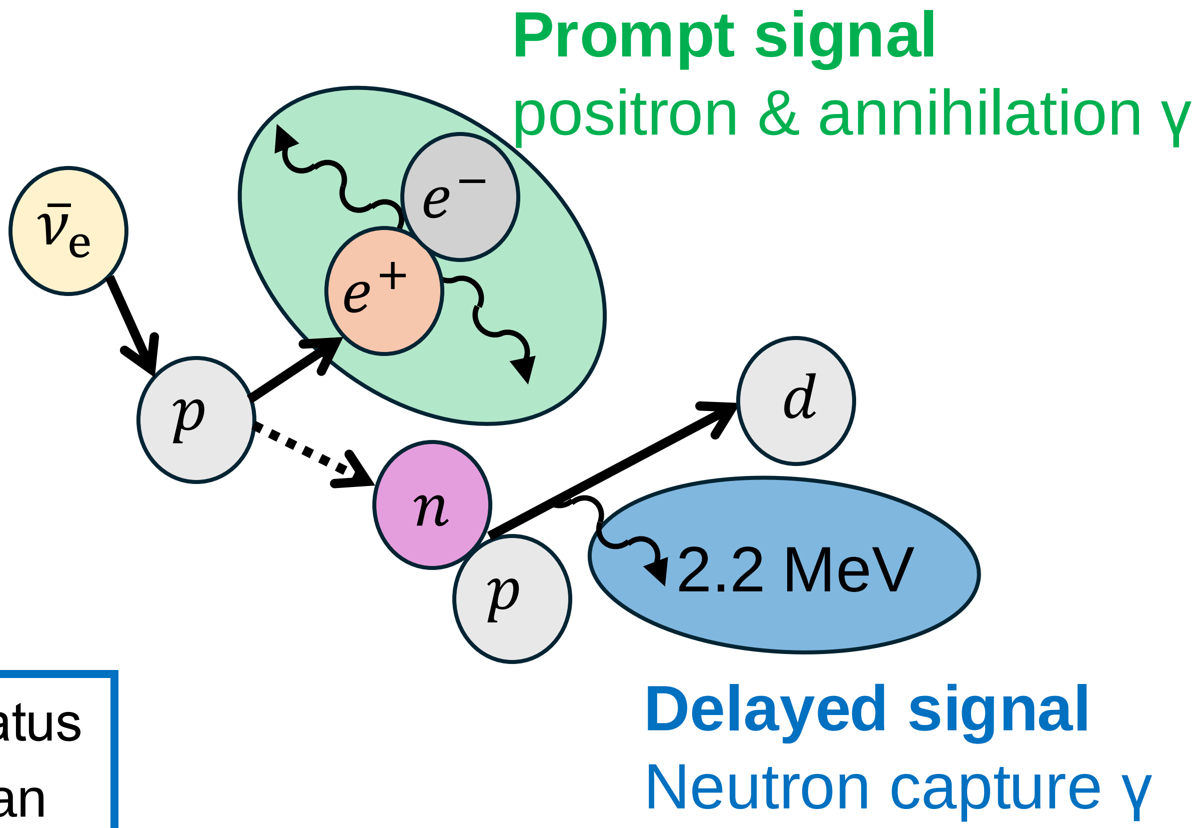
  → **Low energy threshold**: $E_\nu \gtrsim 1.8\ \mathrm{MeV}$

<ins>Delayed coincidence</ins>

- Time/Spatial correlation between prompt & delayed signals

  → **Low background(BG) rate: 0.22 /day**

BG rate depends on reactor's operational status
Assumption: Reactor in Wakasa-bay & Korean are operating



Goal of my study

Goal of my study

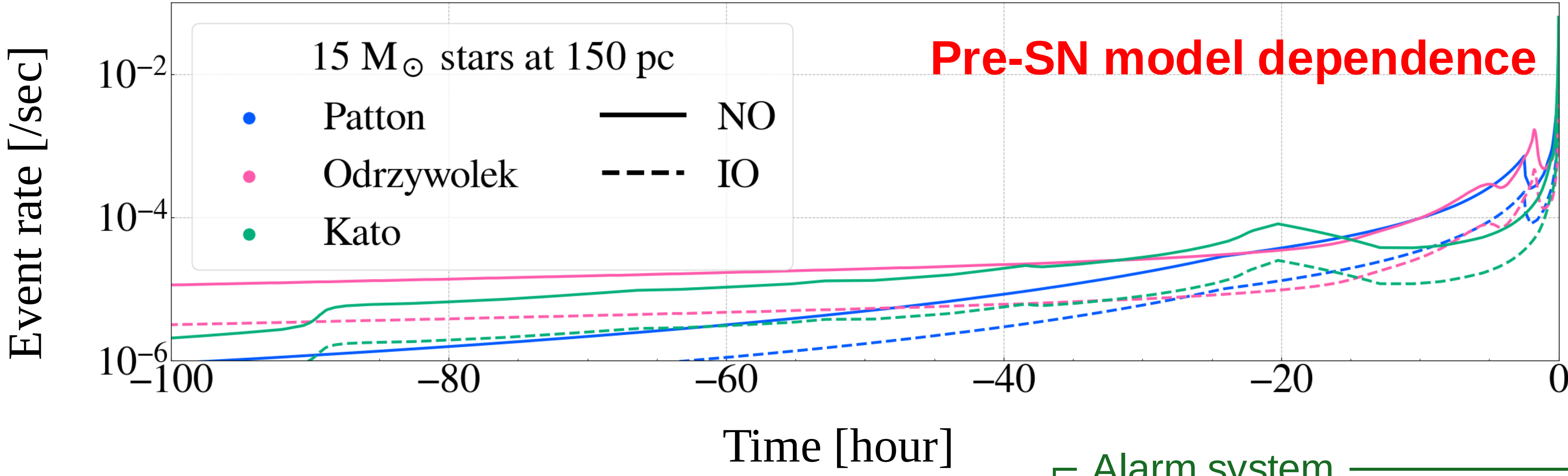
Issue alarm for Betelgeuse (Pre-SN candidate star)

Conventional alarm method

- ✓ Significance evaluation based on statistical excess of observed event rate from background one (**Rate analysis**)
- ✗ Not sensitive to Betelgeuse, inverted mass ordering (IO)

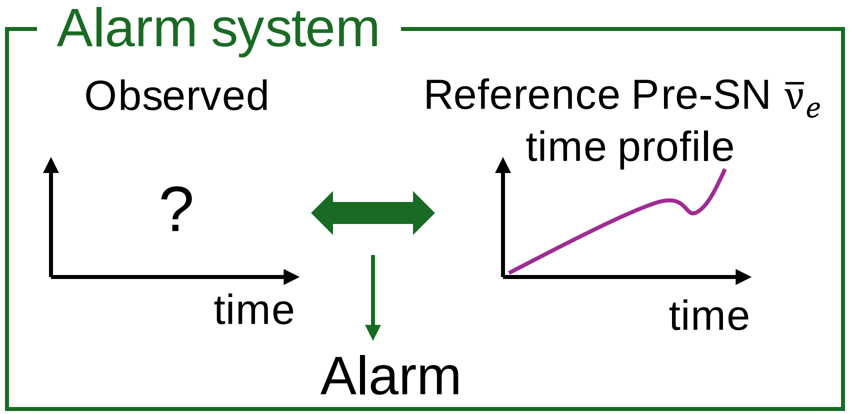
Alarm method incorporating time evolution of observed pre-SN $\bar{\nu}_e$ rate (**Rate+Time analysis**)

Time evolution of expected pre-SN $\bar{\nu}_e$ rate



Note: Time evolution of real pre-SN $\bar{\nu}_e$ rate **does not always match** that calculated from pre-SN model

Rate+Time analysis requires pre-SN time profile calculated from pre-SN model



Does **Rate+Time analysis issue earlier than Rate analysis** if pre-SN $\bar{\nu}_e$ signal **differ from reference pre-SN model**?

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Alarm methodology(1/2)

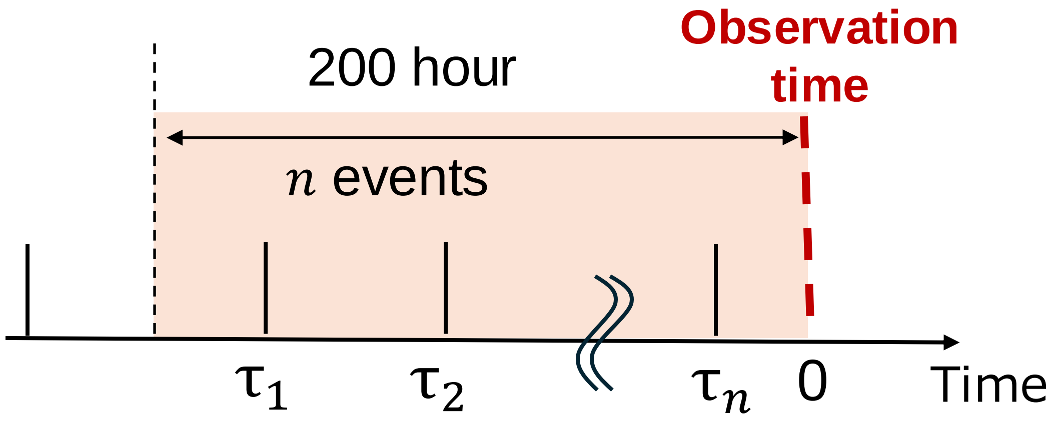
Rate+Time analysis is based on hypothesis test using log likelihood ratio (LLR)

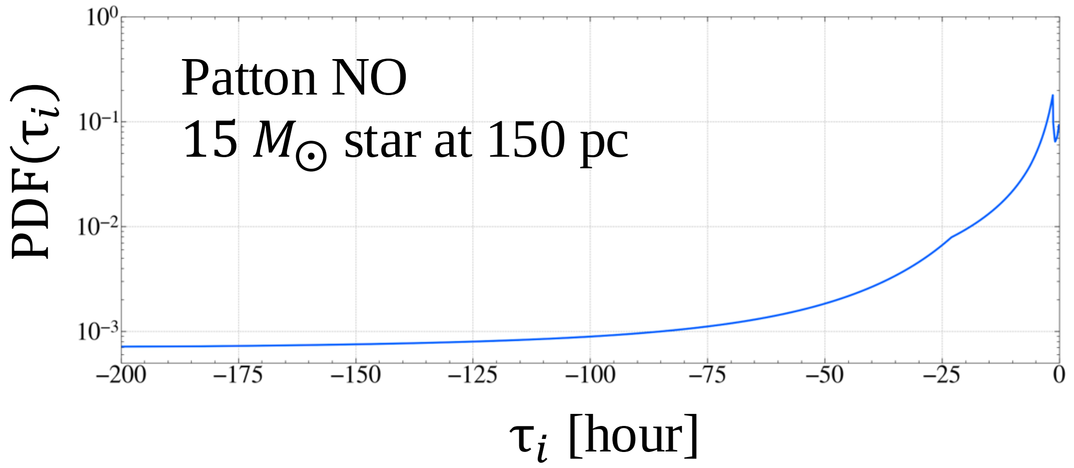
$$\mathrm{LLR} = \log \frac{\mathrm{Likelihood}_{\mathrm{BG+Signal}}(n, \tau_i)}{\mathrm{Likelihood}_{\mathrm{BG\ Only}}(n, \tau_i)}$$

$$\mathrm{Likelihood} = \boxed{\mathrm{PDF}(n)} \prod_{i=1}^{n} \boxed{\mathrm{PDF}(\tau_i)}$$

Poisson PDF
(λ=expected number
of event within 200 hour)

Event time PDF
(right bottom figure)



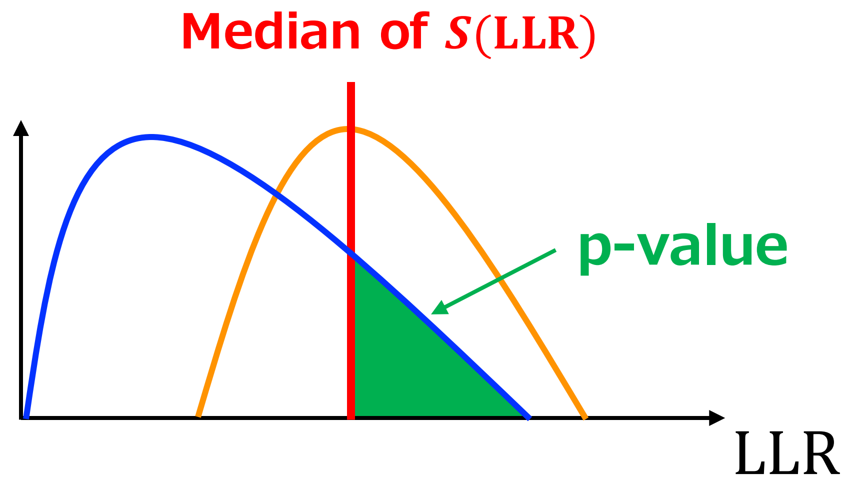


Expected event number and trend of increasing event time depend on pre-SN model (**Reference model**)

Alarm methodology(2/2)

$$\mathrm{LLR} = \log \frac{\mathrm{Likelihood}(\mathrm{BG} + \mathrm{Signal})}{\mathrm{Likelihood}(\mathrm{BG\ Only})}$$

n & τ_i generated using Monte Carlo method (MC) are substituted into LLR function and create LLR distribution



$B(\mathrm{LLR})$ LLR distribution when pre-SN $\bar{\nu}_e$s absent

$S(\mathrm{LLR})$ LLR distribution when pre-SN $\bar{\nu}_e$s arrive in addition to background events

Significance is calculated from **p-value**

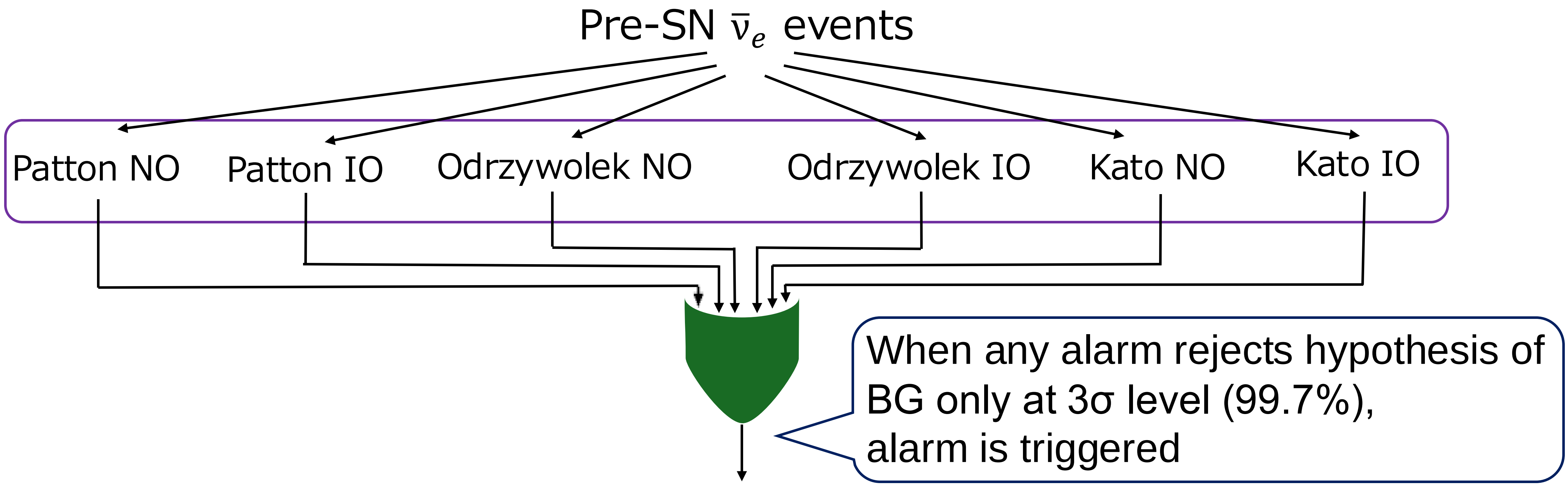
p-value quantifies the strength of evidence **to reject hypothesis of BG only**

Alarm system

Alarms using various **reference model** are set in parallel

- Using log likelihood function with specific **reference model**
- Assuming $15\ M_{\odot}$ star at 150 pc

System design



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Alarm time

Evaluation of significance using MC simulated events

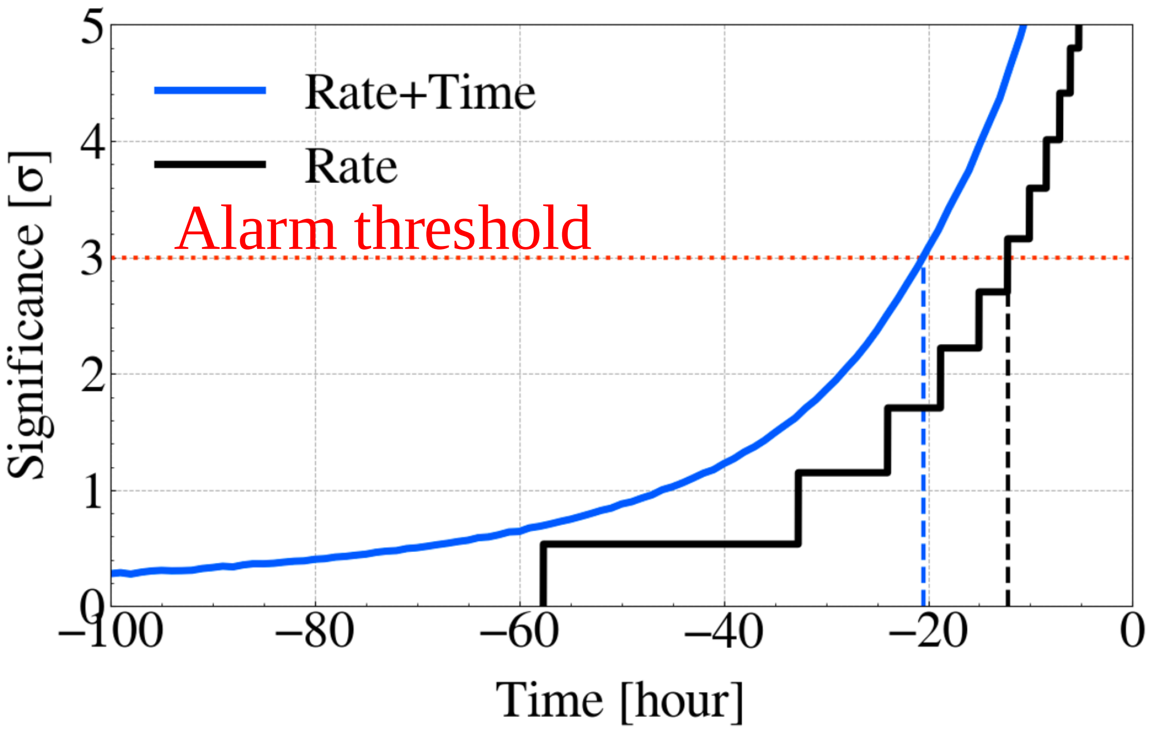
Alarm time: Time until alarm rejects hypothesis of BG only at 3σ level (99.7%)

Rate:	-12.3 hour
Rate+Time:	-20.5 hour

Signal model

(Target pre-SN model for significance evaluation):
Patton NO, 15 $M_{\odot}$ at 150 pc

Time evolution of significance



Rate+Time analysis issues earlier than Rate analysis

Pre-SN model robustness(1/2)

Alarm significance evaluation from various **reference** and **signal model**

Reference model: Characterize the shape of likelihood function

Signal model: Target for significance evaluation

Both model assumes $15\ M_{\odot}$ star at 150 pc

Alarm time [hour] (**Red**: the earliest alarm time in particular signal model)

		Signal model					
		Patton		Odrzywolek		Kato	
Reference model		NO	IO	NO	IO	NO	IO
Patton	NO	**-20.5**	**-7.3**	-82.5	-7.3	-36.5	-2.2
	IO	-20.3	**-7.3**	-71.4	-6.8	-34.7	-1.8
Odrzywolek	NO	-18.2	-5.4	**-97.5**	-7.9	-37.0	-1.7
	IO	-19.2	-6.3	-95.4	**-8.3**	-36.9	-1.8
Kato	NO	-19.7	-6.4	-94.5	-7.9	**-38.3**	**-2.7**
	IO	-20.1	-6.9	-87.9	-7.4	-37.1	**-2.7**
Rate analysis		-12.3	-2.5	-81.6	-4.8	-26.7	-0.1

Alarm is issued at the earliest when reference model = signal model

Pre-SN model robustness(2/2)

Real pre-SN $\bar{\nu}_e$ signal may **not** match **the same** time evolution as **reference model**

Alarm significance evaluation with **reference model** ≠ **signal model**

Alarm time [hour] (**Red**: the earliest alarm time in particular signal model)

		Signal model					
		Patton		Odrzywolek		Kato	
Reference model		NO	IO	NO	IO	NO	IO
Patton	NO			-82.5	-7.3	-36.5	**-2.2**
	IO			-71.4	-6.8	-34.7	-1.8
Odrzywolek	NO	-18.2	-5.4			**-37.0**	-1.7
	IO	-19.2	-6.3			-36.9	-1.8
Kato	NO	-19.7	-6.4	**-94.5**	**-7.9**		
	IO	**-20.1**	**-6.9**	-87.9	-7.4		
Rate analysis		-12.3	-2.5	-81.6	-4.8	-26.7	-0.1

Rate+Time Analysis with reference model ≠ signal model issues earlier than Rate analysis

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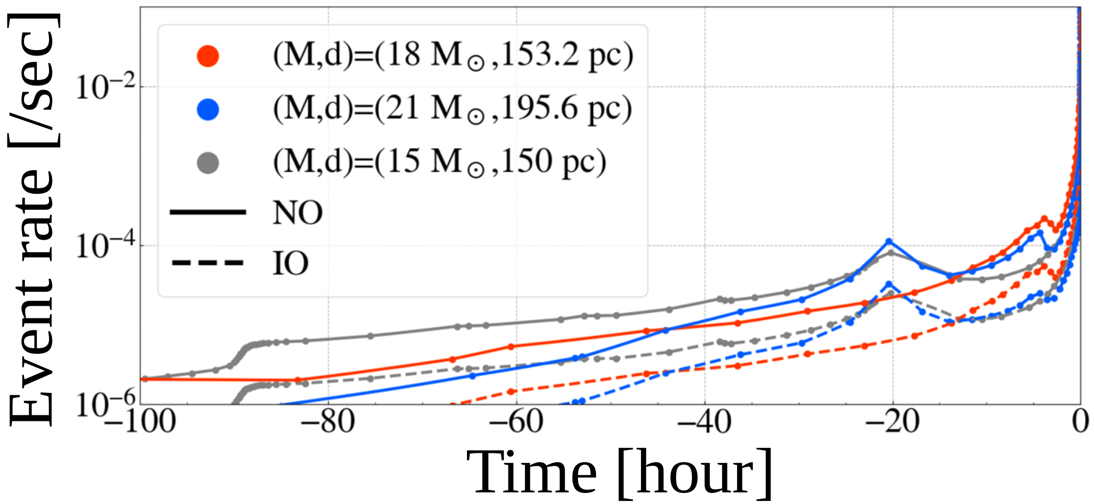
Alarm significance of Betelgeuse(1/2)

<u>Betelgeuse</u>

- Initial mass M [1]: $18 - 21\ M_{\odot}$
- Distance from Earth d [1]: $168.1^{+27.5}_{-14.9}$ pc

[1]Joyce et al. (2020)

Time evolution of expected pre-SN $\bar{\nu}_e$ event rate



Alarm significance evaluation
from <u>two typical case</u> (from Kato simulation)

$(M, d) = (18\ M_{\odot}, 153.2\ \mathrm{pc}), (21\ M_{\odot}, 195.6\ \mathrm{pc})$

Alarm Significance of Betelgeuse(2/2)

- Rate+Time analysis **issue alarms for Betelgeuse with IO, unlike Rate analysis**
- Rate+Time analysis is expected to alarm **at least 1.1 hours** before Betelgeuse's core collapse

Alarm time [hour] (**Red**: the earliest alarm time in particular signal model)

Reference model ($15\ M_\odot$ star at 150 pc)		Signal model $(18\ M_\odot, 153.2\ \mathrm{pc})$ NO	$(18\ M_\odot, 153.2\ \mathrm{pc})$ IO	$(21\ M_\odot, 195.6\ \mathrm{pc})$ NO	$(21\ M_\odot, 195.6\ \mathrm{pc})$ IO
Patton	NO	-17.9	-2.5	-23.5	**-1.1**
	IO	-16.9	**-2.6**	**-23.6**	-1.0
Odrzywolek	NO	-18.4	-1.0	-22.1	-0.3
	IO	-18.7	-1.7	-22.8	-0.5
Kato	NO	**-19.1**	-1.6	-23.0	-0.8
	IO	-18.1	-2.0	-23.3	**-1.1**
Rate analysis		-11.6	N/A	-18.6	N/A

Contents

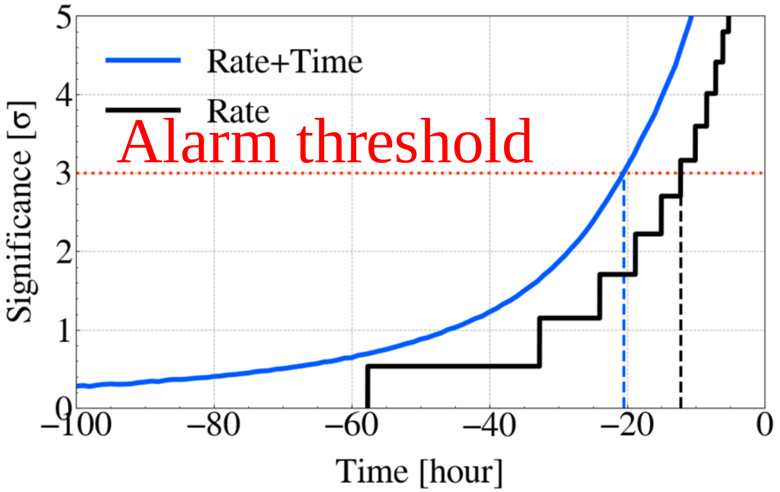
Summary

Pre-SN neutrino

- produced before a few days from supernova explosion
- alarm to neutrino, gravitational wave and electromagnetic wave detector

Development of alarm method incorporating time evolution of observed pre-SN $\bar{\nu}_e$ rate (**Rate+Time analysis**)

✓ check pre-SN model robustness



Accomplishments

Rate+Time analysis **issue alarms for Betelgeuse with IO** **unlike Rate analysis**

Implementable when KamLAND data taking restarts from 2027

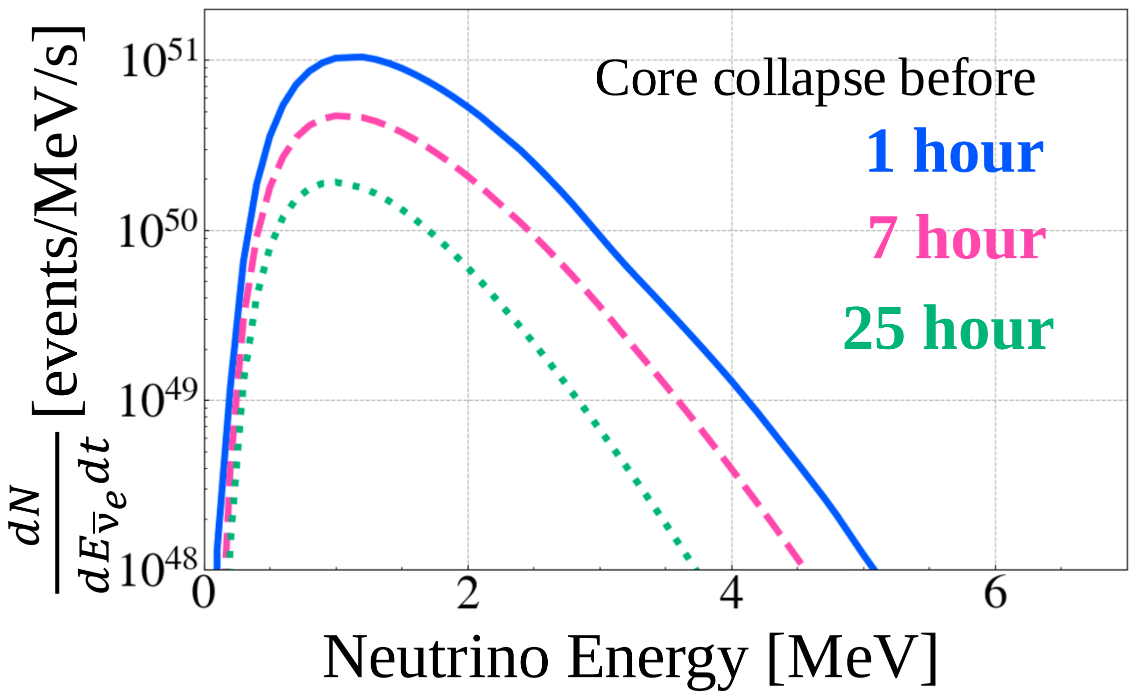
Prospect

- Alarm sensitivity evaluation with false alarm rate (FAR)
- Application of Rate+Time analysis to SK-Gd
- Alarm sensitivity evaluation for other stars (Mainak Mukhopadhyay et al)
- Using energy spectrum

$$\mathcal{L} = \mathrm{PDF(Rate)} \times \mathrm{PDF(Time)} \times \mathbf{PDF(Energy)}$$

		Does pre-SN $\overline{\nu}_e$ come?	
		Yes	No
Does alarm trigger?	Yes		FAR
	No		

Energy spectrum



Back up