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Pre-SN neutrino emission from massive stars and its importance for multi-messengers

Chinami Kato

Tohoku university

Collaborators

S. Yamada (Waseda), H. Nagakura (Princeton),

S. Furusawa (TUS), K. Takahashi (MPI), T. Yoshida (UT),

H. Umeda (UT), K. Ishidoshiro (Tohoku)

Historical SN neutrino observation

Supernovae

violent explosions of the progenitors with $M_{\mathrm{ZAMS}} > 8\ M_{\odot}$ at the end of their lives

"SN1987A"

- 23th, Feb, 1987
- LMC
- $20\ M_{\odot}$
- ～50kpc

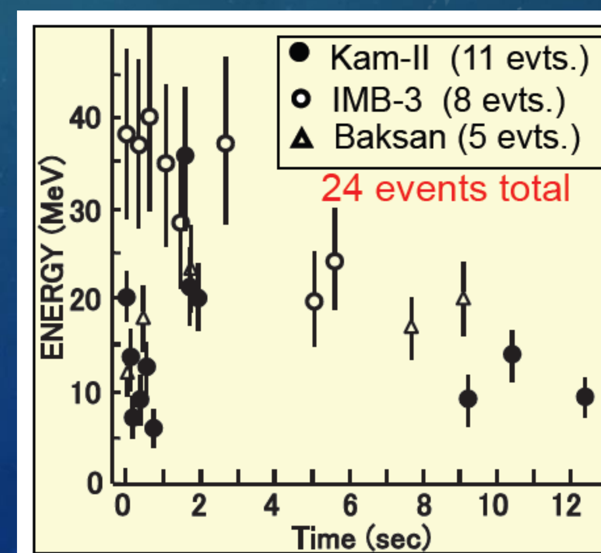
✓11 events @ Kamiokande Ⅱ

We found luminosity and average energy

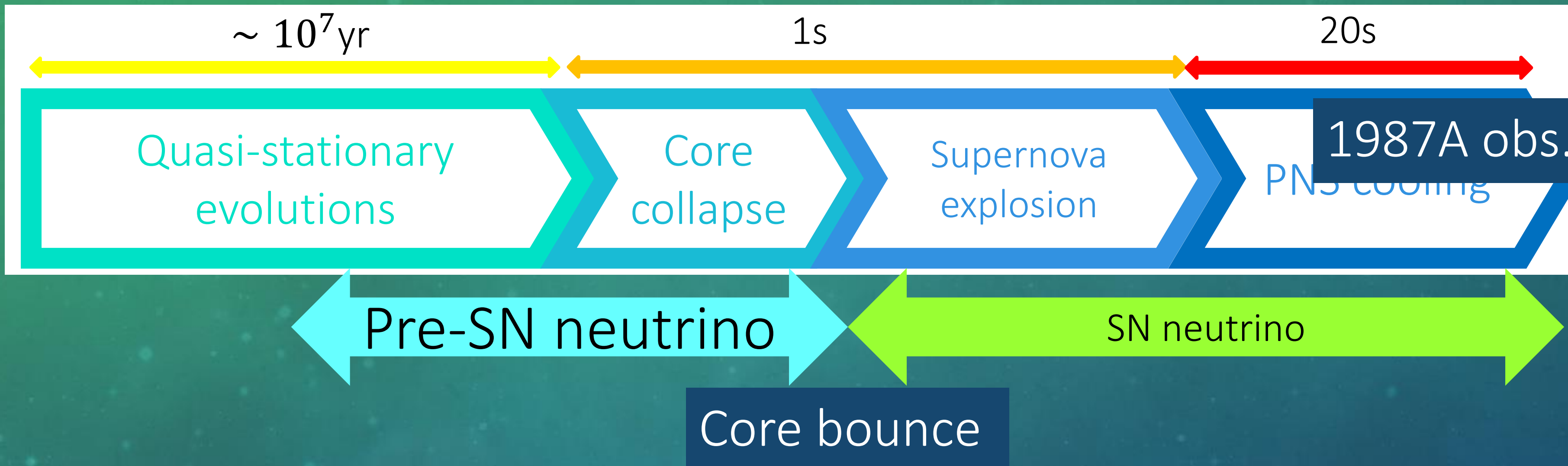
$L_{\nu_e} \sim 5 \times 10^{52}$[ergs] $E_{\nu_e} \sim 10 - 15$ [MeV]

✓'neutrino astronomy' began !

ν's give us information about high T & ρ regions



Massive star evolution & ν emissions



Pre-SN neutrinos

- ✓ ν's emitted from the core before core bounce
- ✓ They decide evolutionary paths
- ✓ typical average energy: ~ a few MeV

  ⇒ It seemed to be difficult to detect them

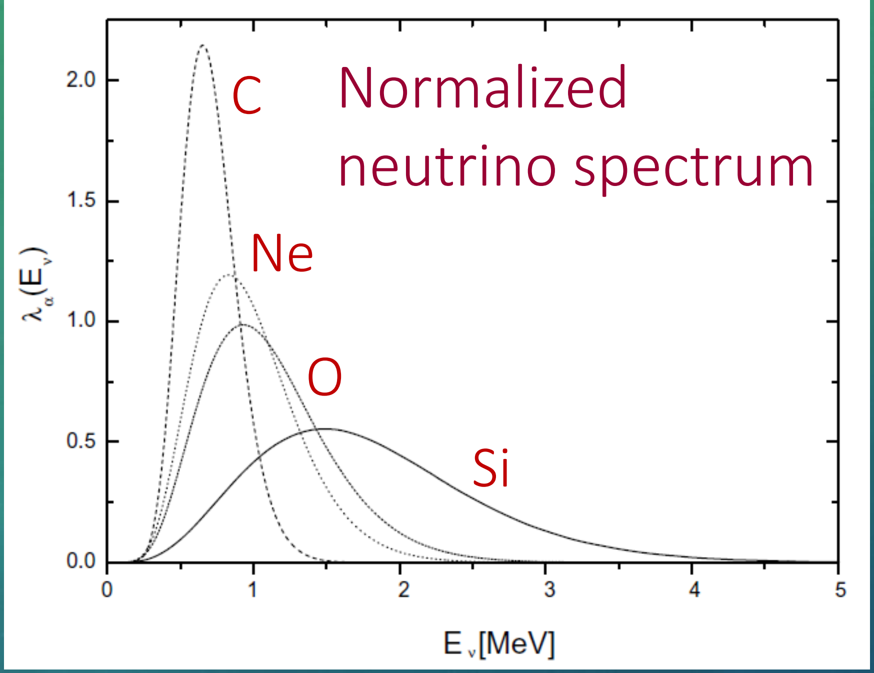
Previous great study

A. Odrzywolek et al.(2004)

Idea paper of pre-SN neutrino observation

✓20M⊙ C, Ne, O, Si burning

✓pair-annihilation



Observation of pre-SN neutrinos is come into the view !!!!

Detector	Reactions	Event rate (day^{-1})
Borexino	$\bar{\nu}_e + p \to e^+ + n$	0.34
	$\nu_e + e^- \to \nu_e + e^-$	0.49
	$\bar{\nu}_e + e^- \to \bar{\nu}_e + e^-$	0.19
	$\nu_{\mu,\tau} + e^- \to \nu_{\mu,\tau} + e^-$	0.03
	$\bar{\nu}_{\mu,\tau} + e^- \to \bar{\nu}_{\mu,\tau} + e^-$	0.026
KamLAND	$\bar{\nu}_e + p \to e^+ + n$	1.6
	$\nu_e + e^- \to \nu_e + e^-$	1.7
	$\bar{\nu}_e + e^- \to \bar{\nu}_e + e^-$	0.65
	$\nu_{\mu,\tau} + e^- \to \nu_{\mu,\tau} + e^-$	0.11
	$\bar{\nu}_{\mu,\tau} + e^- \to \bar{\nu}_{\mu,\tau} + e^-$	0.09
SNO	$\bar{\nu}_e + p \to e^+ + n$	2.2
	$\bar{\nu}_e + d \to e^+ + n + n$	0.004
	$\nu_x + d \to \nu_x + p + n$	0.038
	$\bar{\nu}_x + d \to \bar{\nu}_x + p + n$	0.032
Super-K	$\bar{\nu}_e + p \to e^+ + n$	41
UNO	$\bar{\nu}_e + p \to e^+ + n$	560
Hyper-K	$\bar{\nu}_e + p \to e^+ + n$	687

Event/day @1kpc

Importance of pre-SN ν observations

1. Proof of stellar evolution theory
   - convection property
   - nuclear burning process
   - progenitor type
   - EOS
2. SN alarm
3. neutrino physics
   - mass hierarchy

etc.

Outline

1. Massive star evolution
   & typical properties of pre-SN neutrinos
2. Importance 1: Proof of stellar evolution theory
3. Importance 2: SN alarm
4. Discussion for observation of pre-SN neutrinos
5. Summary & Future prospects

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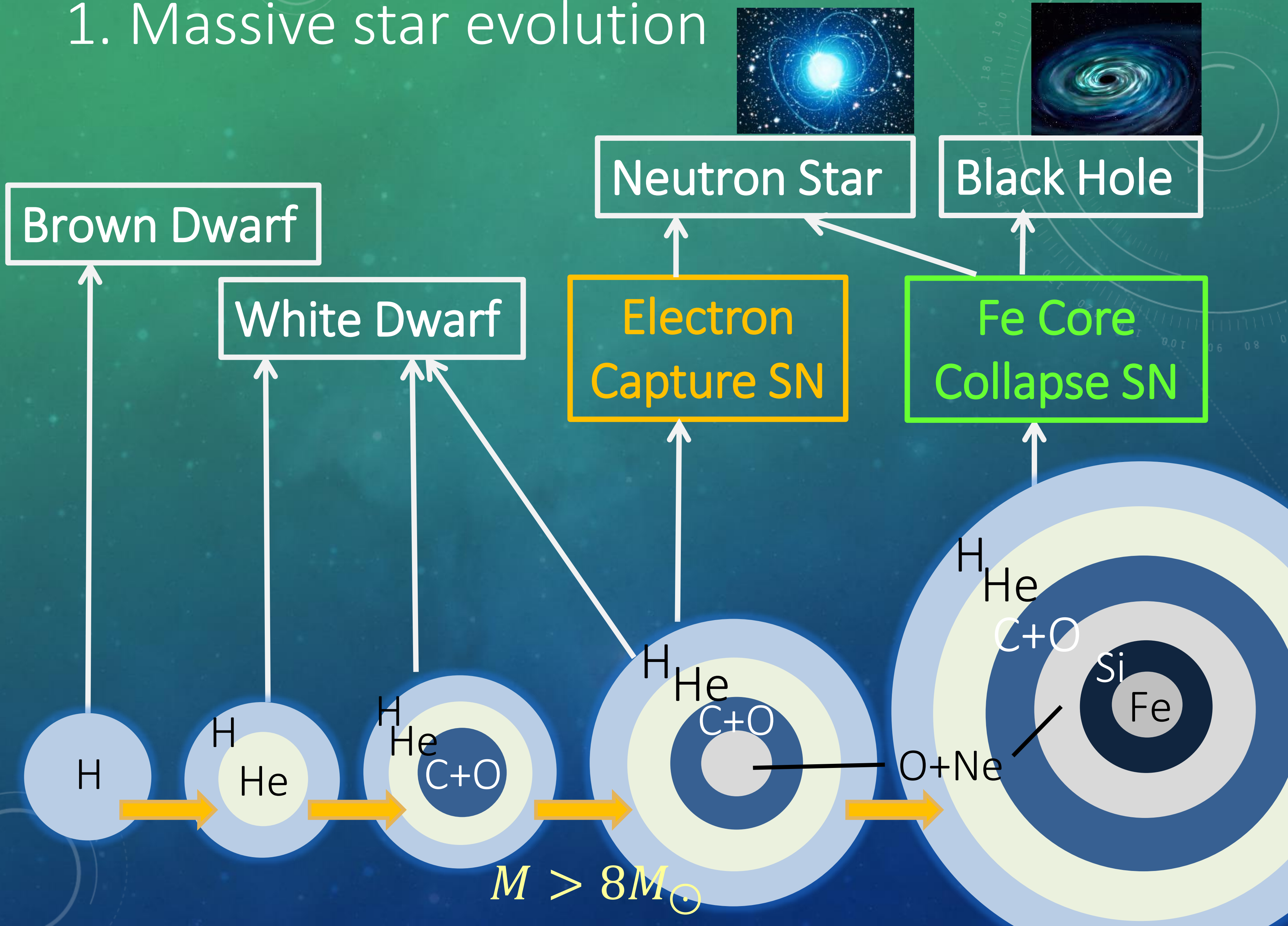
1. Massive star evolution



1. Neutrino emission from massive stars

✓ Thermal emission

1. Pair annihilation

$$e^- + e^+ \rightarrow \nu_e + \overline{\nu_e}$$

2. Plasmon decay

$$\gamma^* \rightarrow \nu_e + \overline{\nu_e}$$

✓ Electron capture by free p

$$e^- + p \rightarrow n + \nu_e$$

✓ Nuclear reactions

1. electron capture (EC)

$$(Z, A) + e^- \longrightarrow (Z-1, A) + \nu_e$$

2. β^+ decay

$$(Z, A) \longrightarrow (Z-1, A) + e^+ + \nu_e$$

3. positron capture (PC)

$$(Z, A) + e^+ \longrightarrow (Z+1, A) + \bar{\nu}_e$$

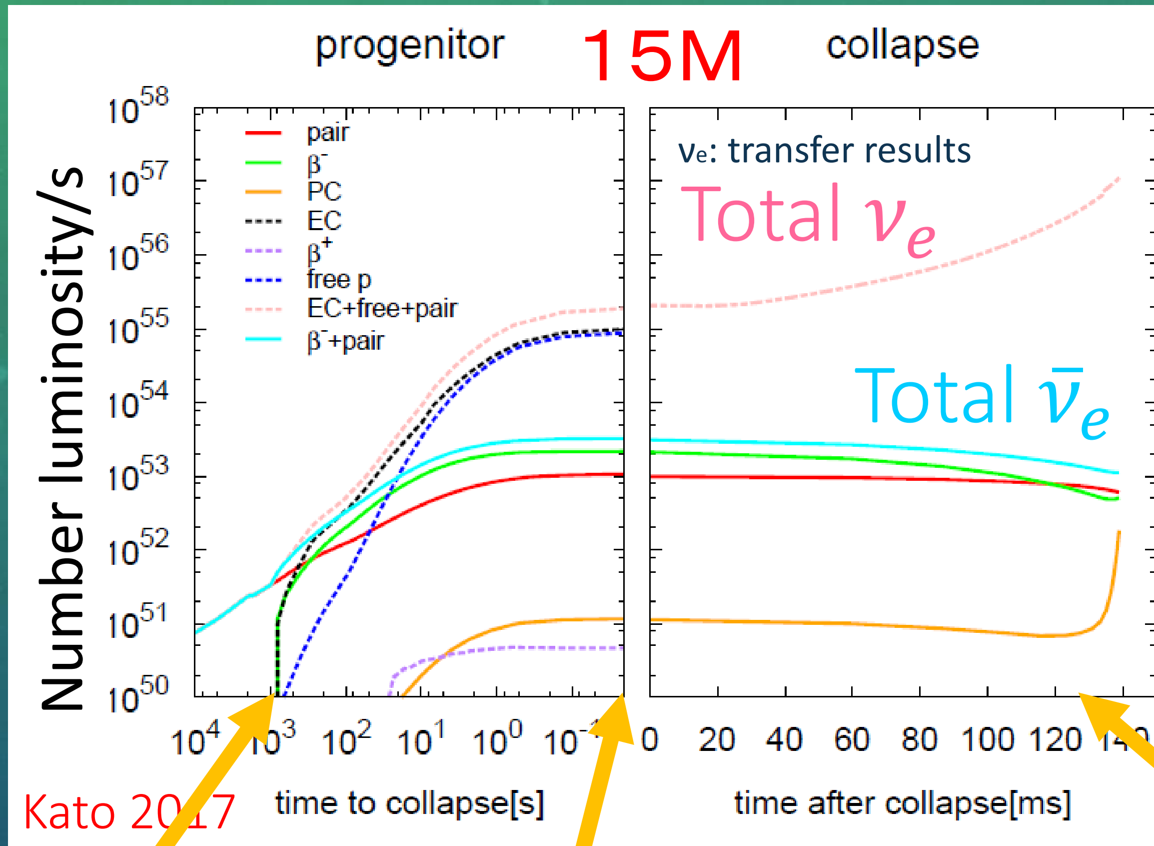
4. β^- decay

$$(Z, A) \longrightarrow (Z+1, A) + e^- + \bar{\nu}_e.$$

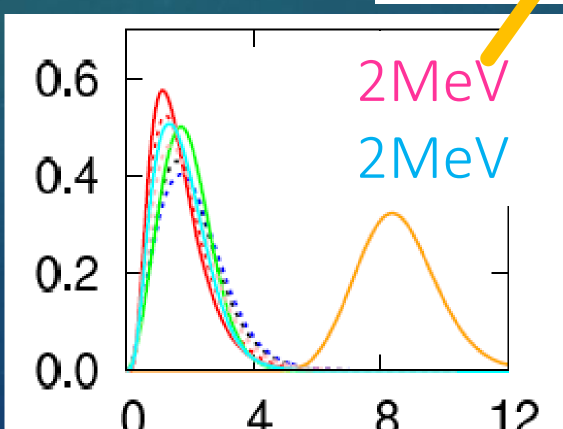
Neutrino emission: T, ρ, Ye, Xi

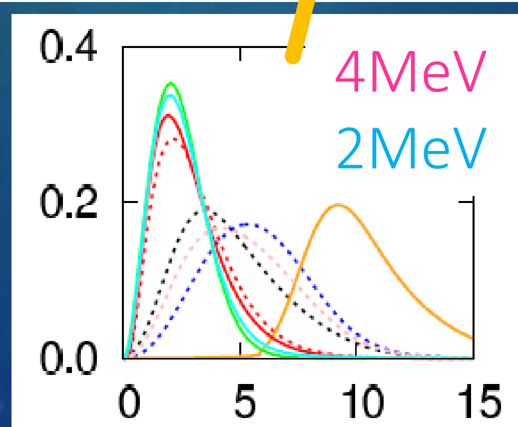
Odrzywolek 2004・2007・2009, Kato 2015・2017, Patton 2015

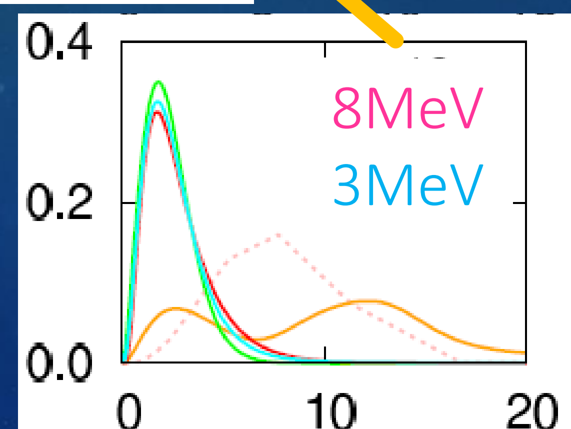
1. Typical pre-SN neutrino properties



Normalized spectra







1. Typical pre-SN neutrino properties

	detector	15 $M_\odot$ normal	15 $M_\odot$ inverted
$\bar{\nu}_e$	Super-K	89.9	20.3
		(88.3, 1.61)	(19.9, 0.41)
	KamLAND	44.3	10.1
		(44.2, 0.15)	(10.1, 0.03)
	Hyper-K	363	37.7
		(353, 9.84)	(35.9, 1.82)
	JUNO	894	204
		(891, 3.07)	(203, 0.63)
ν_e	DUNE(5MeV)	169	2142
		(57.8, 111)	(713, 1429)
	DUNE(10.8MeV)	69.3	895
		(6.27, 63)	(80.1, 815)

Kato 2017

Progenitor phase

Collapsing phase

- ✓ d = 200pc
- ✓ Inverse-β decay ($\bar{\nu}_e$) liquid Ar reaction (ν_e)
- ✓ neutrino oscillation

✓ $\bar{\nu}_e$: progenitor phase
ν_e: collapse phase

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2. Nuclear burning & convective property

✓ shell burning affects neutrino emissions

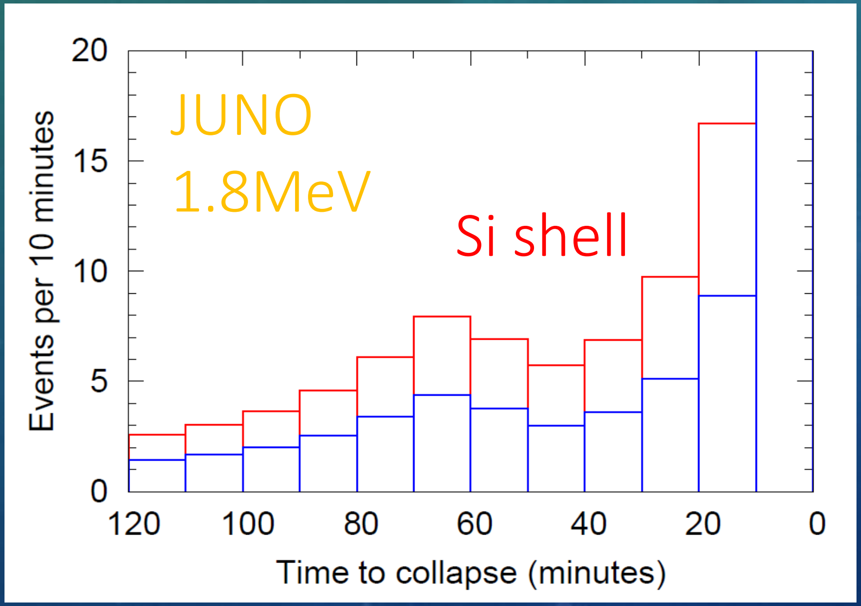
shell burning ⇒ core expansion

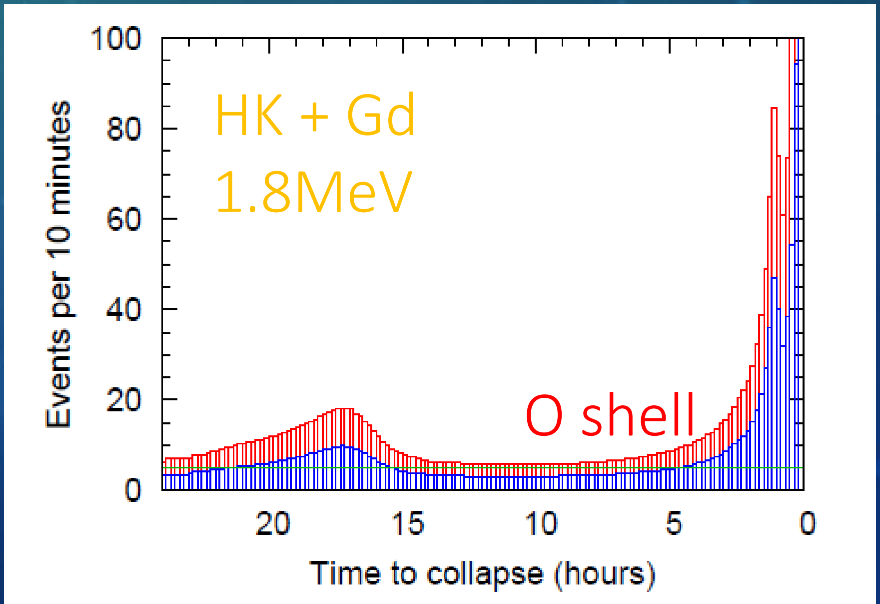
⇒ T & ρ ↓

⇒ neutrino emissions ↓

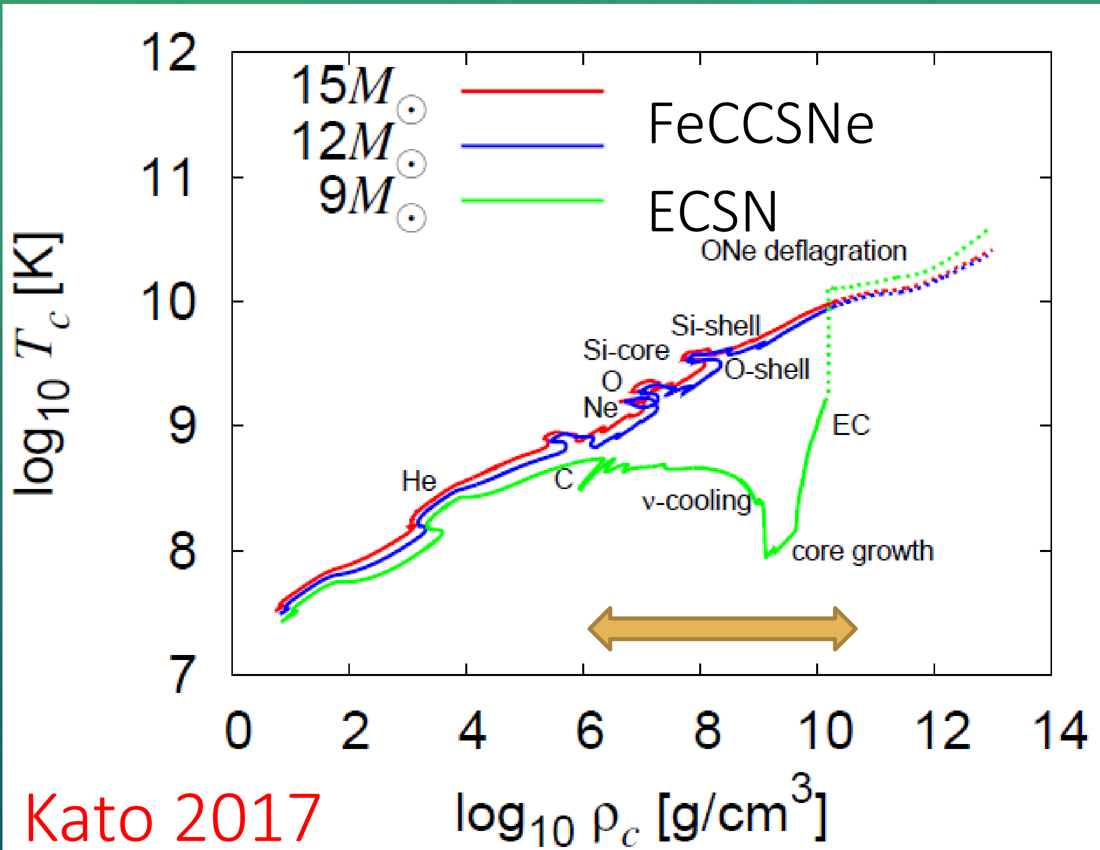
✓ We confirm the existence of shell burning

Yoshida 2015



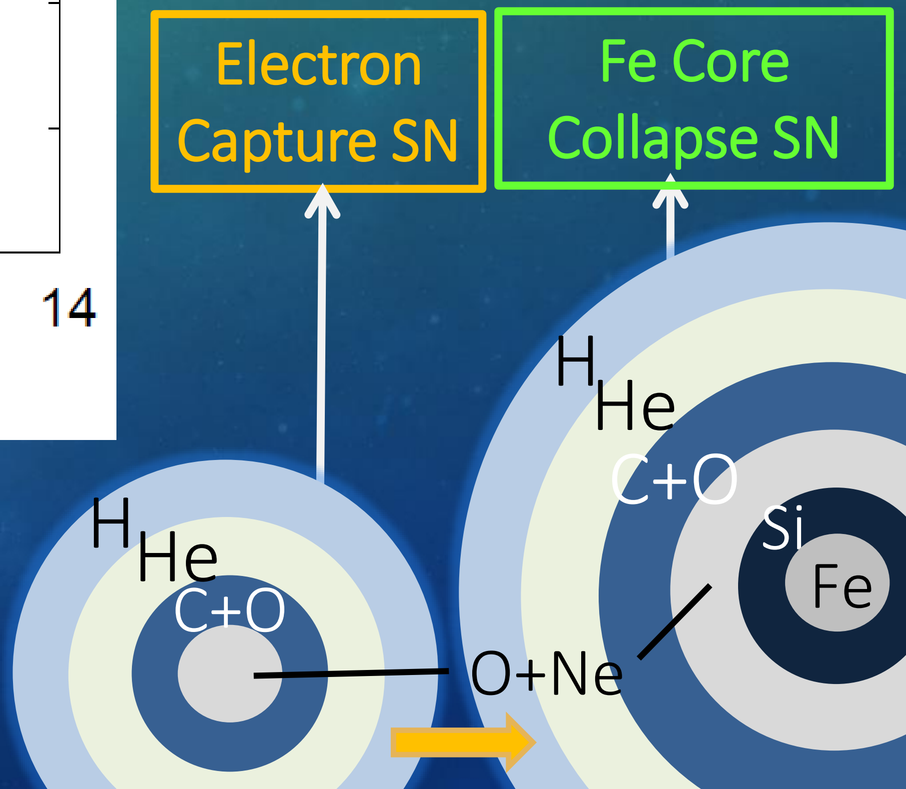


2. Progenitor difference



✓The mass boundary of two progenitors is quite uncertain

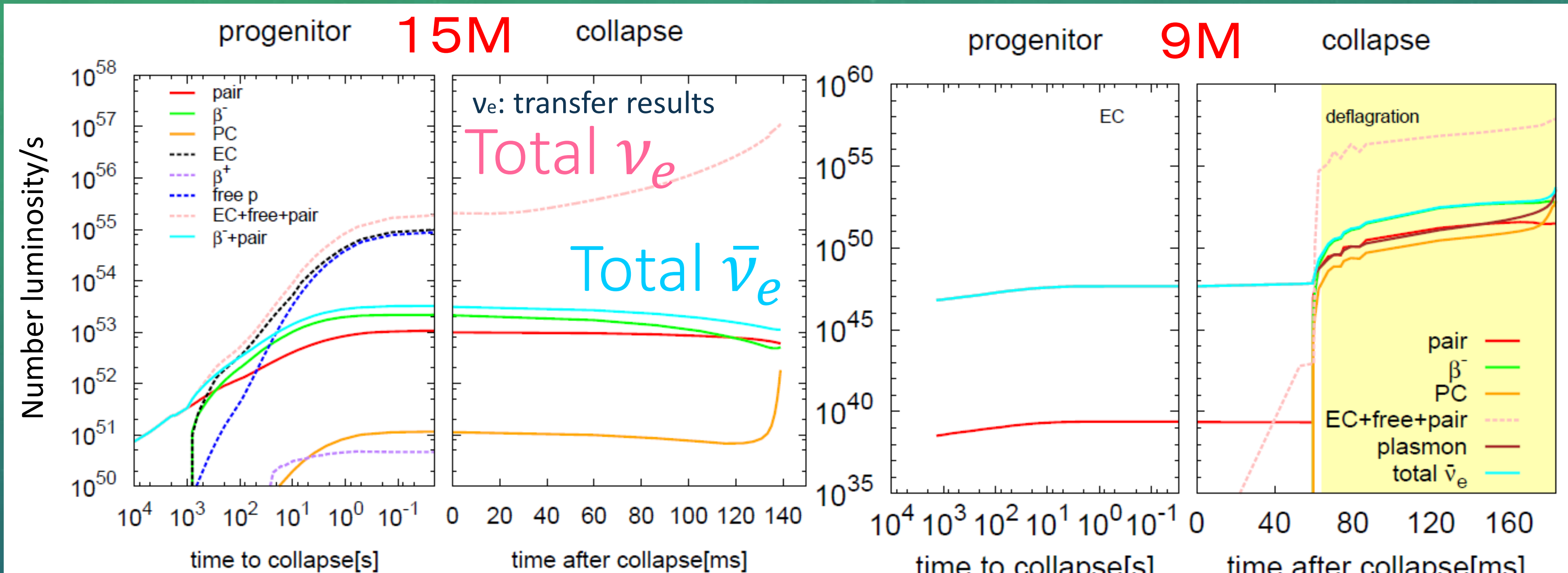
Boundary: $M = M_{up}$



✓The evolution in late phase is quite different

ECSNe: drastically T increase

2. Progenitor difference



non-detectable : ECSN
detectable : FeCCSN

detector	9 $M_\odot$		15 $M_\odot$	
	normal	inverted	normal	inverted
Super-K	0.93	0.03	89.9 (88.3, 1.61)	20.3 (19.9, 0.41)
KamLAND	0.05	0.002	44.3 (44.2, 0.15)	10.1 (10.1, 0.03)
Hyper-K	11.6	0.42	363 (353, 9.84)	37.7 (35.9, 1.82)
JUNO	0.98	0.04	894 (891, 3.07)	204 (203, 0.63)

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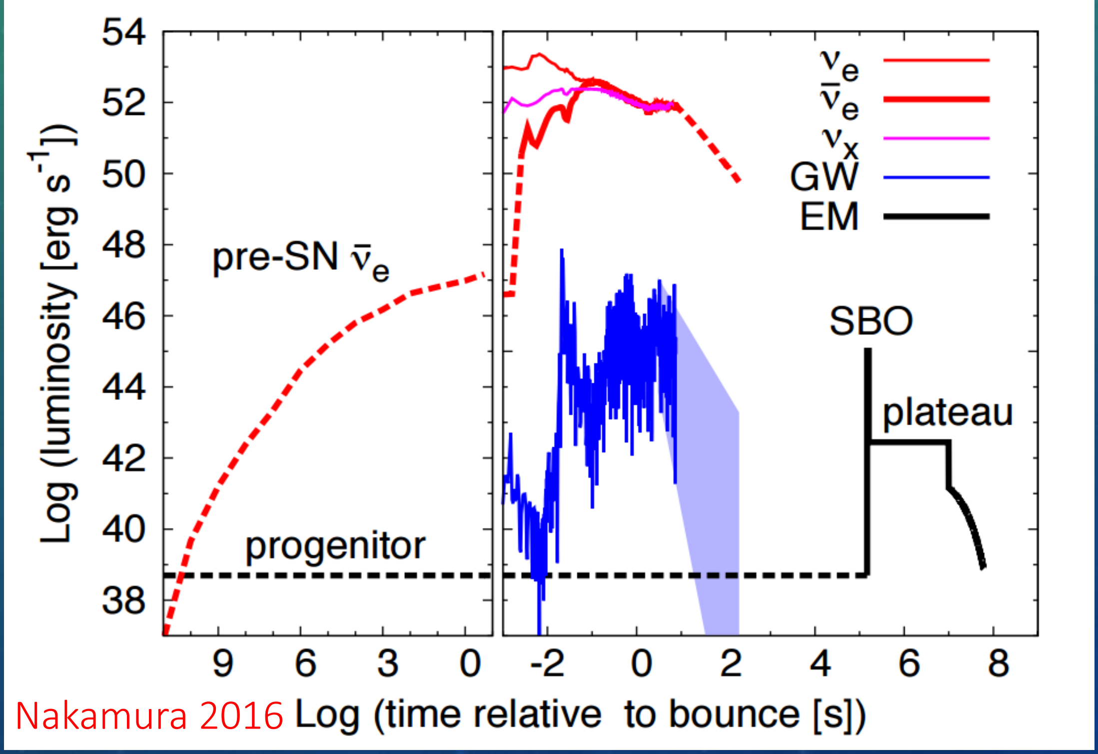
3. Multi-messenger & SN alarm

Galactic supernova rate : a few / 100years

⇒ We must not miss next SN !

Multi-messenger study of SNe : neutrino, GW, EM wave

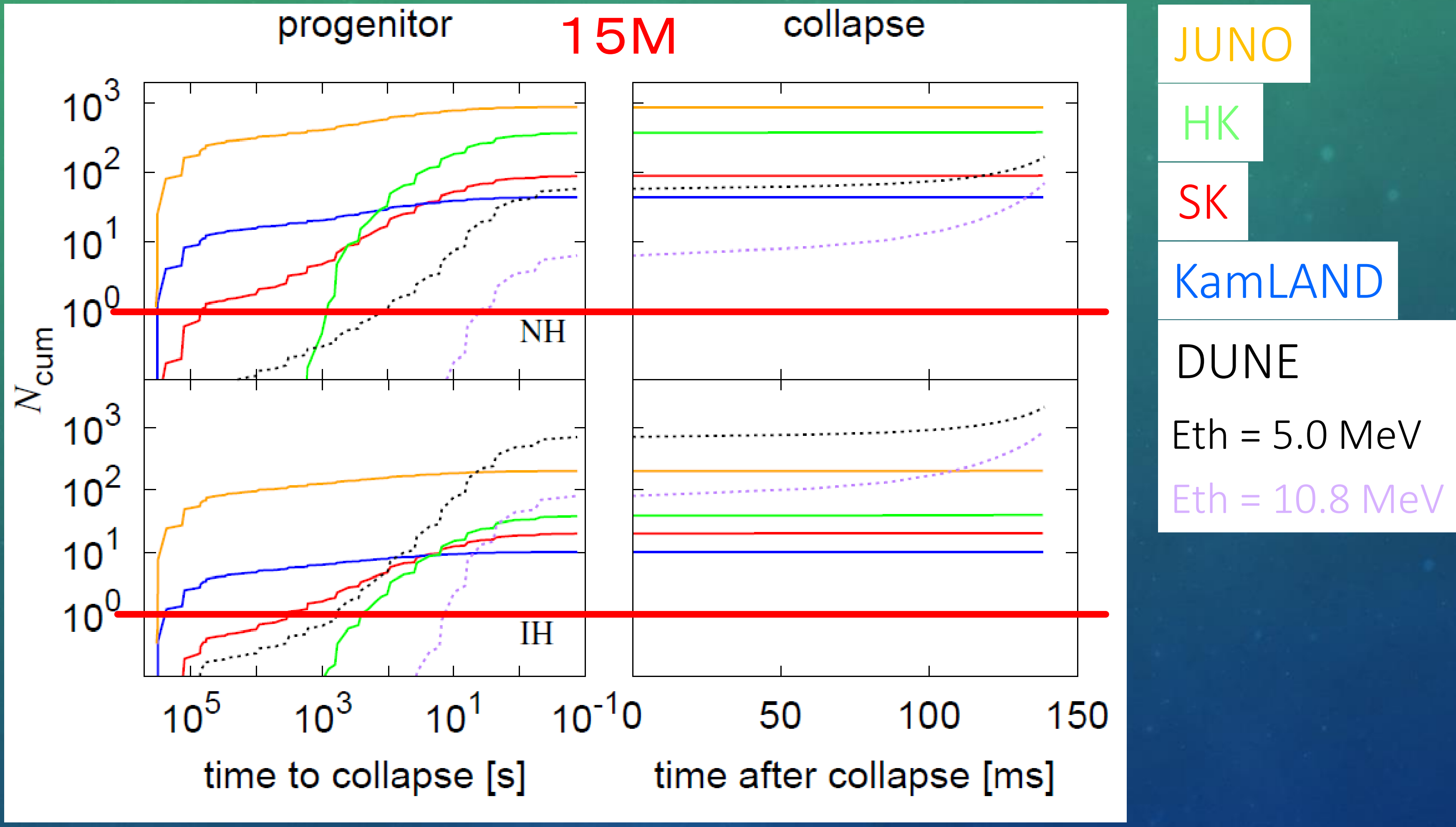


Nakamura 2016

Findings by SN neutrinos

- ✓ mechanism of SNe
- ✓ nucleosynthesis
- ✓ EOS
- ✓ BH formation
- ✓ neutrino physics etc.

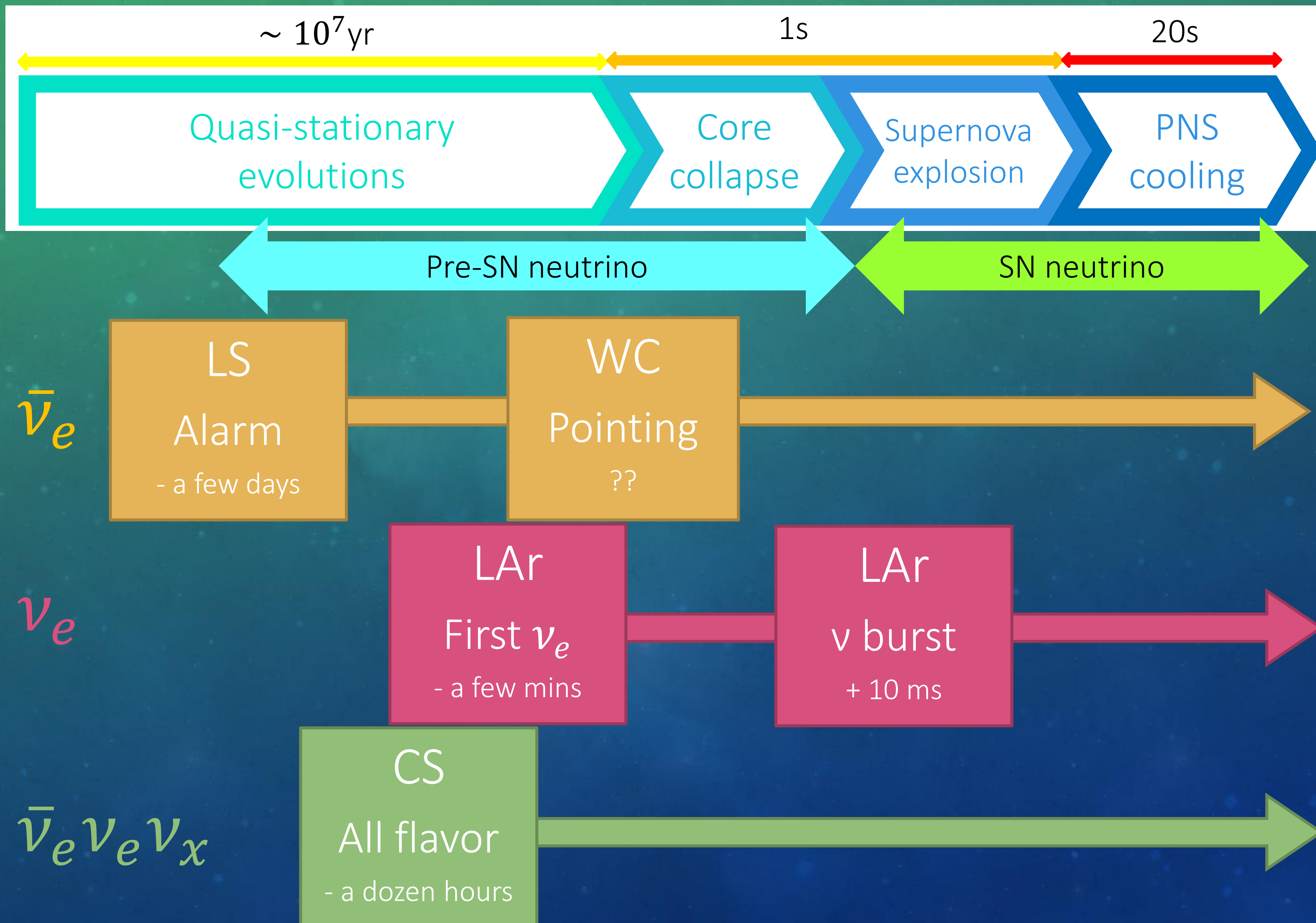
3. Time evolution of neutrino events



✓ $\bar{\nu}_e$: ~6 days before @ LS / ν_e : ~20 min before @ DUNE

✓ $\nu_e > \bar{\nu}_e$ in collapse phase (IH) ⇒ detail information

3. Strategy of SN alarm for FeCCSNe @ 200pc



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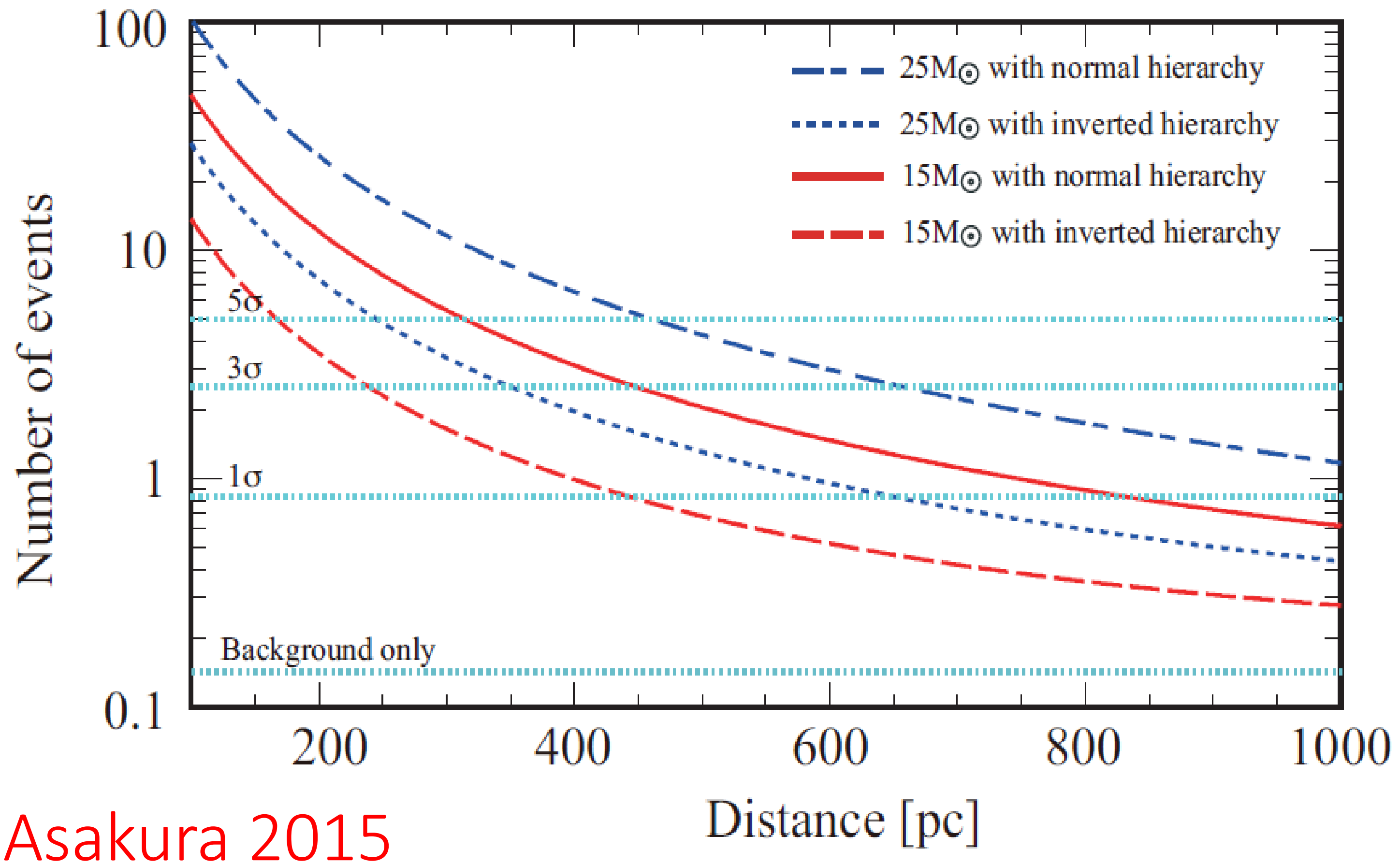
4. Discussion for pre-SN neutrino obs.

Observable distance @KamLAND



Asakura 2015

Detectable range: ≲ a few hundreds pc

4. Discussion for pre-SN neutrino obs.

Candidate RSGs : 39 (d < 1kpc)

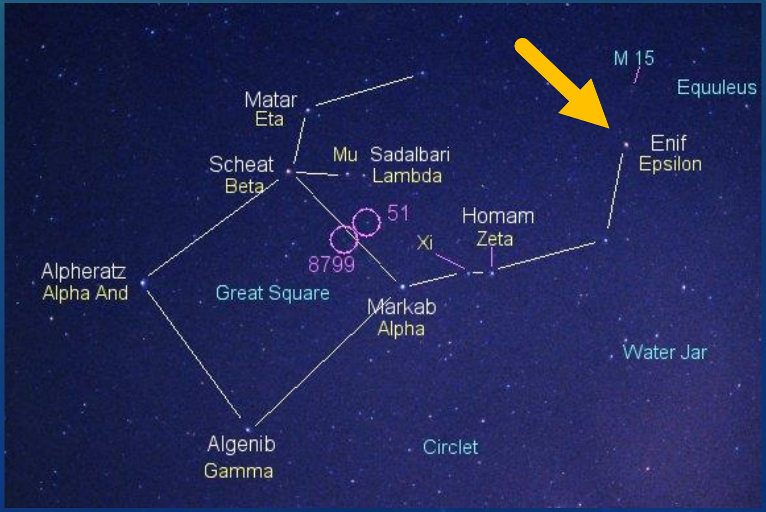
Nakamura 2016

Betelgeuse (200pc)

Antares (160pc)

Lambda Velorum (190pc)

Epsilon Pegasi (150pc)



5. Summary

✓ Observations of pre-SN neutrinos come into the view due to the development of low background technique !!

✓ Evidence of stellar evolution theory

- confirmation of shell burning
- distinguishability of two types of SN progenitors

✓ SN alarm (200 pc)

- a few days before ($\bar{\nu}_e$ @ LS)
- source pointing ($\bar{\nu}_e$ @ WC)
- detail information during collapse (ν_e @ LAr)

5. Future prospects

✓ Detail background discussion

✓ Systematic study ($8 - 25M_{\odot}$)

✓ Pointing by pre-SN neutrinos

When is the first detection of pre-SN ν's ?

⇒ Only god knows…

@Japanese shrine (Dazaifu)

Thank you for your attention!