Presupernova Neutrinos Relating to the Final Evolution of Massive Stars

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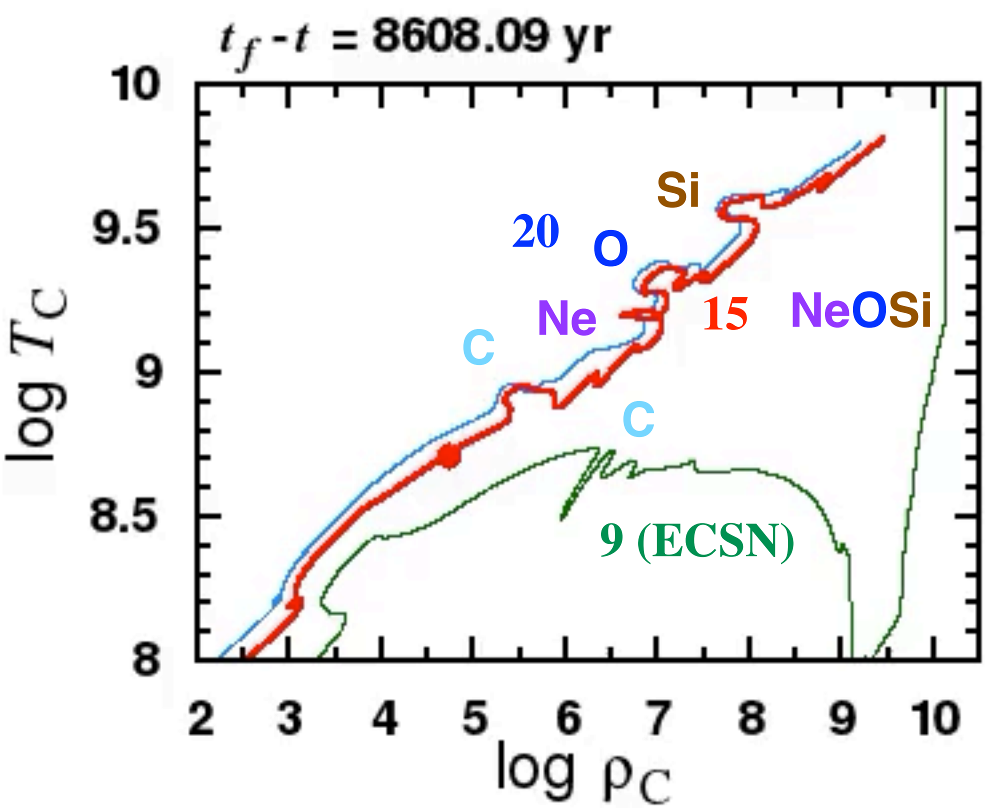
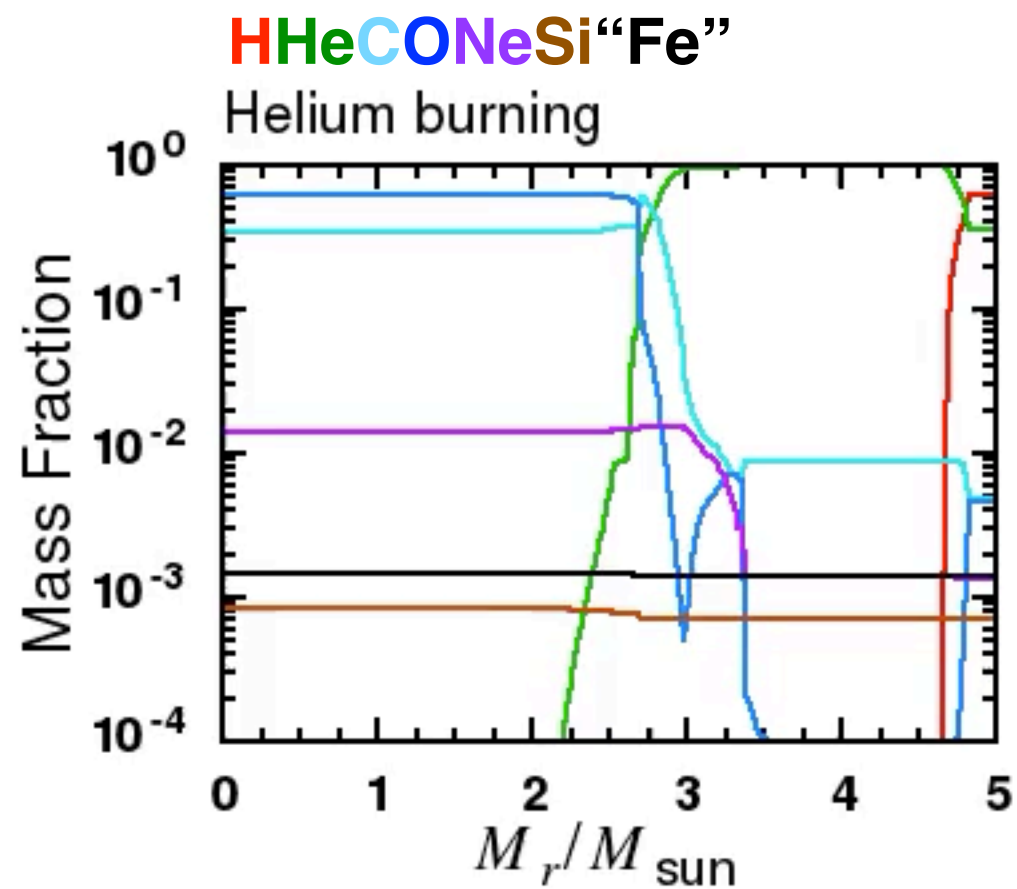
Advanced Evolution of Massive Stars

- **Massive stars** → $M \gtrsim 8\ M_\odot$ **stars**
  Fe core formation and core collapse (CC)

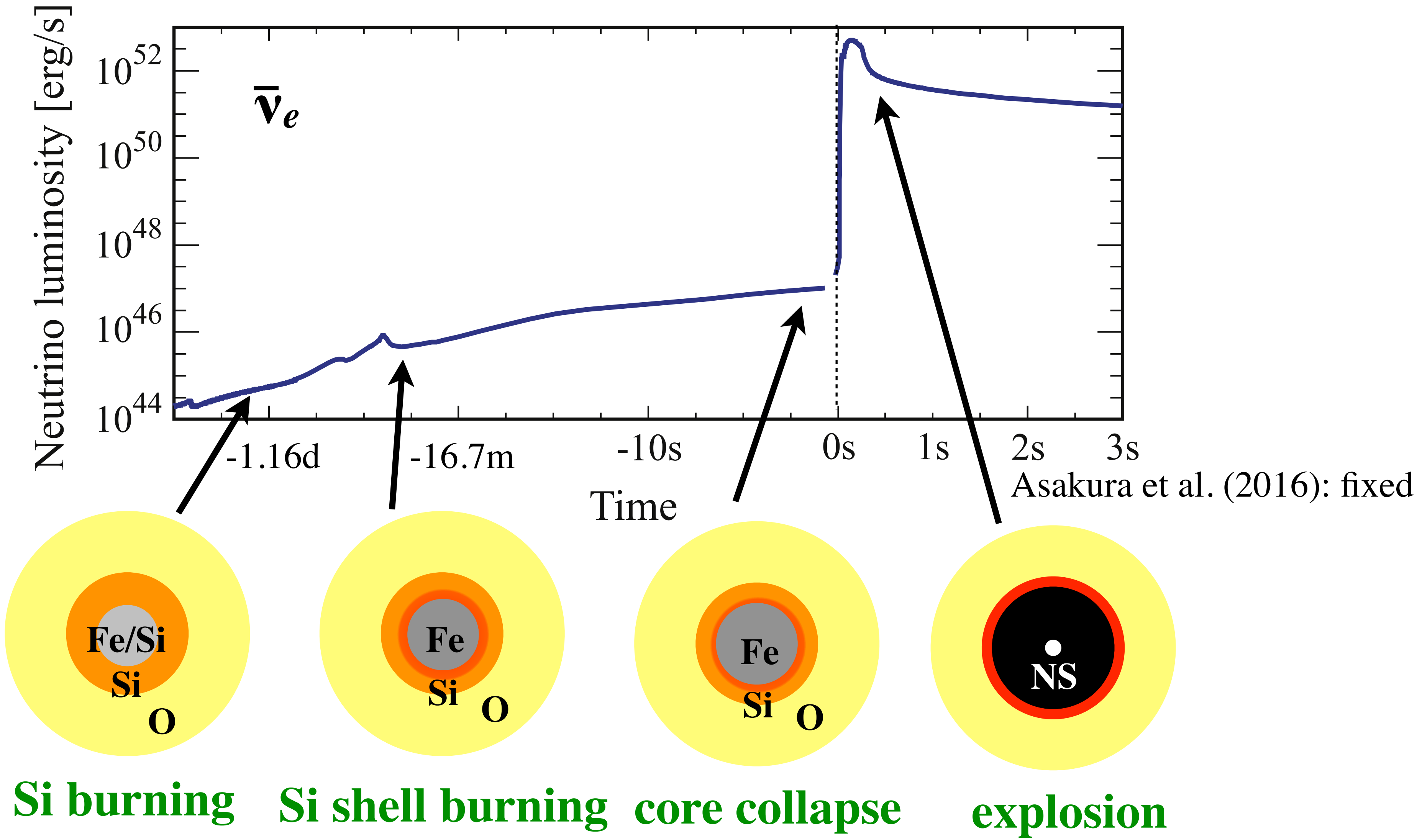
  Low-mass end → **ONe core formation**
  and an electron capture (EC) supernova (SN)

- **Advanced evolution of a 15 $M_\odot$ star** (Yoshida et al. 2016)





Neutrinos from a Presupernova (PreSN) Star



- **PreSN neutrinos from a nearby SN (at hundreds pc) are detectable.**
- **PreSN neutrino events can be SN alarms.**

Studies on PreSN Neutrinos

- **Pioneering studies**

  e.g., Odrzywołek et al. (2004); Misiaszek et al. (2006); Odrzywołek et al. (2007); Odrzywołek (2009)

- **PreSN neutrino spectra using detailed stellar structure and evolution**

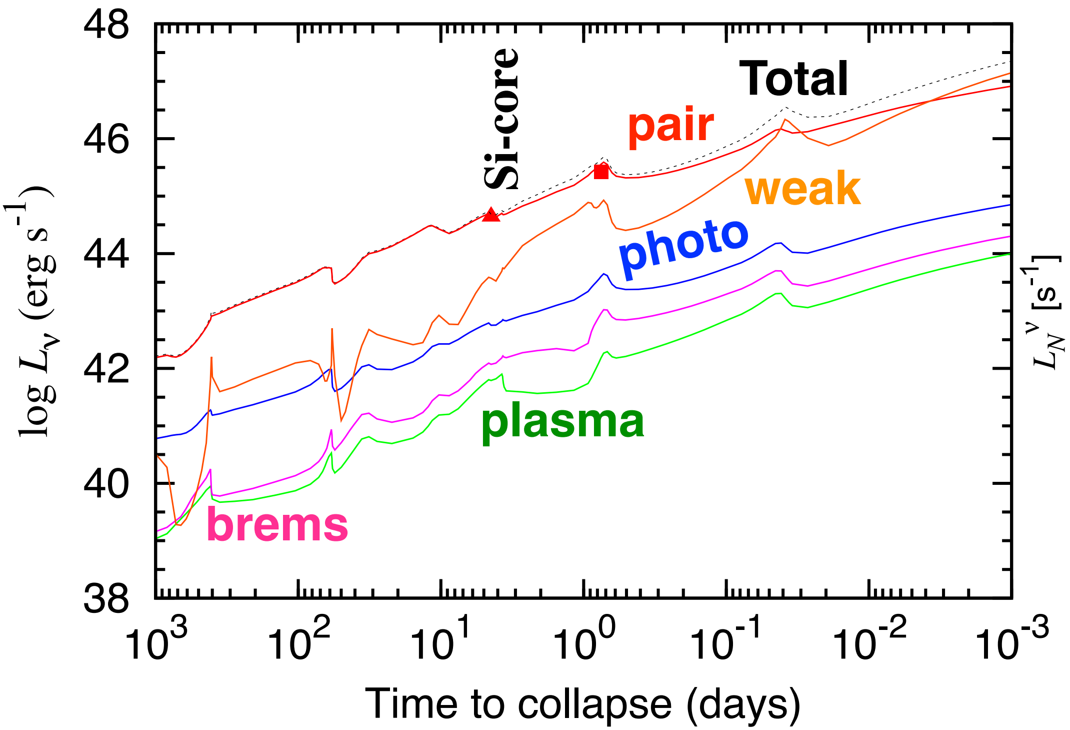
  Odrzywołek & Heger (2010); Kato et al. (2015); Yoshida et al. (2016); Kato et al. (2017); Patton et al. (2017a,b), Yoshida et al. (2019a, in prep.)

- **Supernova alarm**

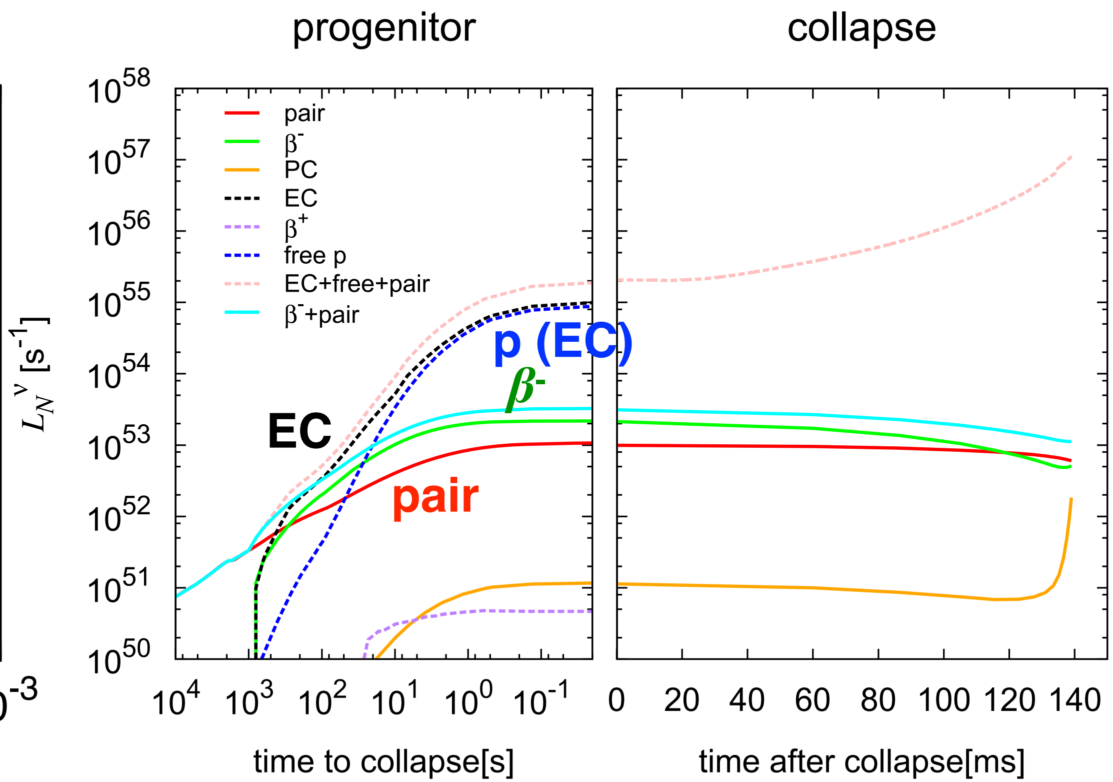
  Asakura et al. (2016); Yoshida et al. (2016)

Neutrino Sources

- **Neutrino sources of a 15$M_\odot$ star**



(Yoshida et al. 2016)

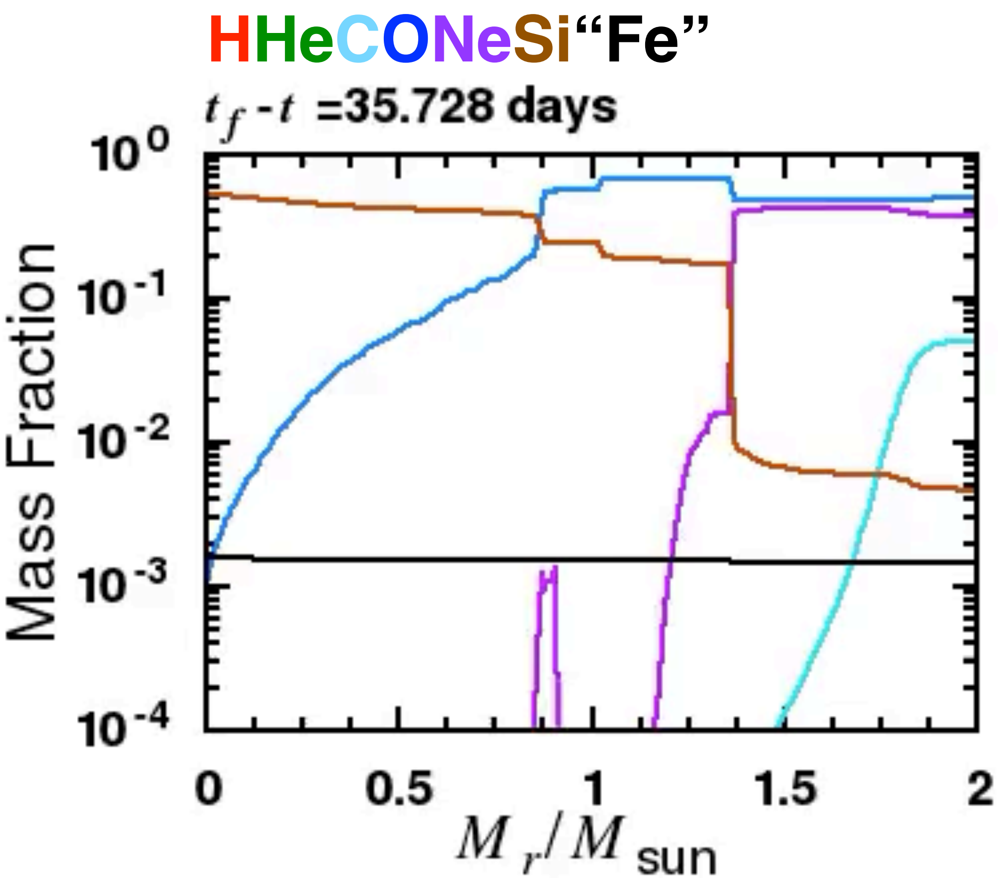


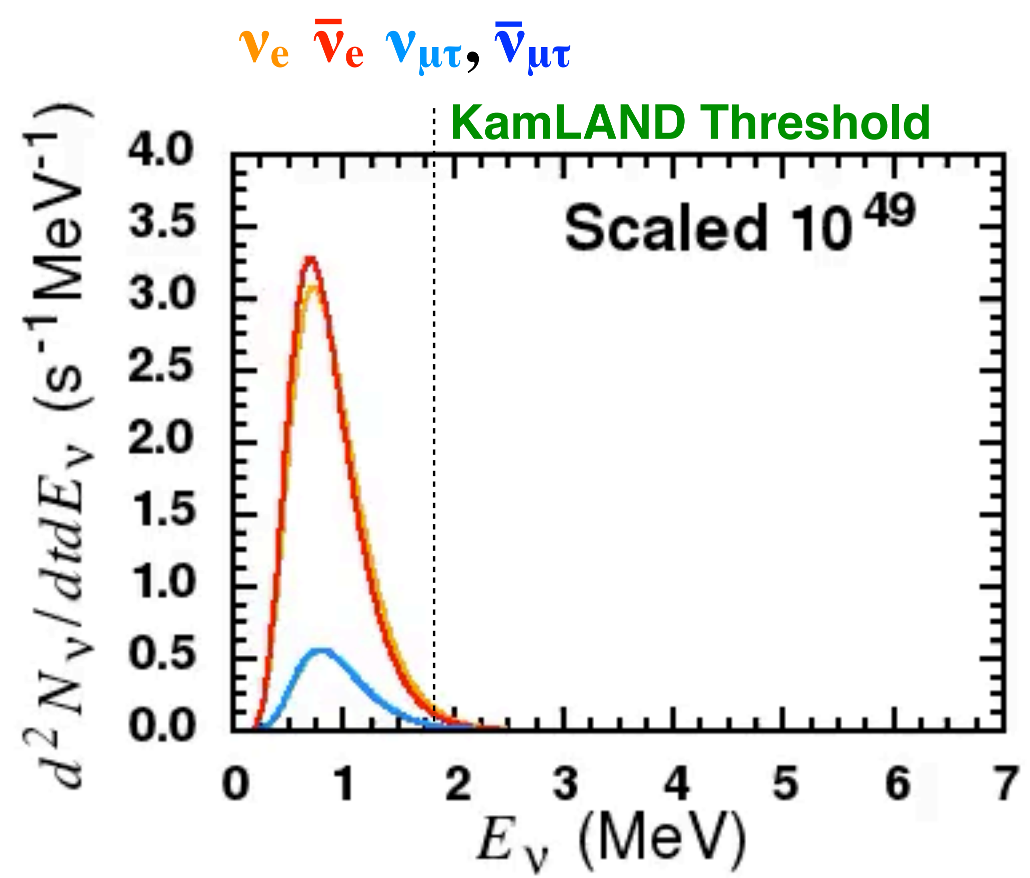
(Kato et al. 2017)

- **$\bar{\nu}_e$ ➡ Pair neutrinos for days to minutes**
  Neutrinos through β^- decays from minutes
- **ν_e ➡ Electron capture neutrinos from minutes**

Spectra of Pair Neutrinos

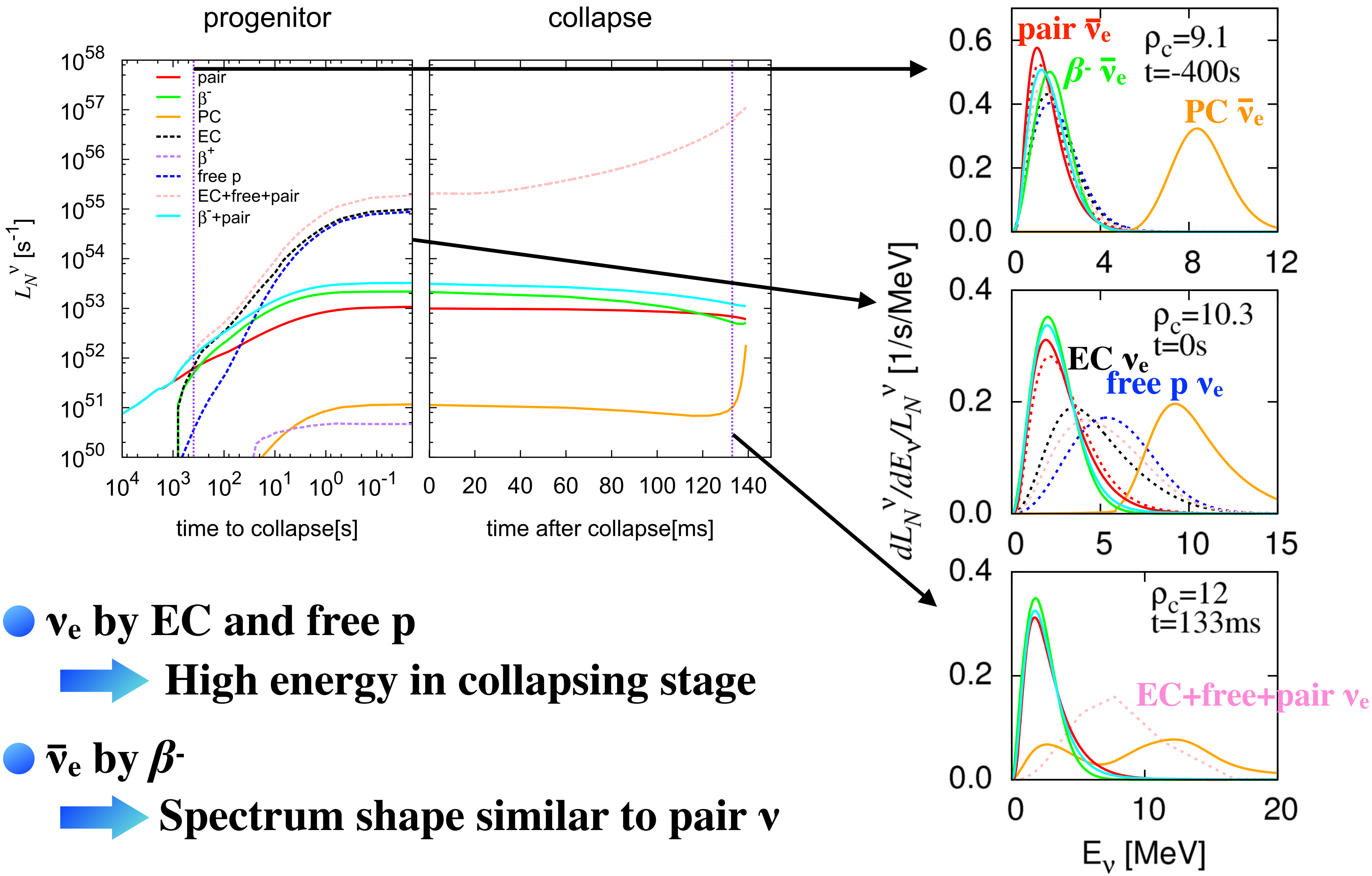
- Evolution of spectra of pair neutrinos produced in a $15M_{\odot}$ star (Yoshida et al. 2016)
  - Core Si burning (4.4 days)
  - O-shell burning (16—11 hours) ➡ Decrease in ν flux
  - Si-shell burning and core collapse (1 h~)





Neutrino Spectra in Collapse

- **Neutrino spectra in the collapsing stage of a 15$M_\odot$ star** (Kato et al. 2017)



- **ν_e by EC and free p**
  - ➡ **High energy in collapsing stage**
- **$\bar{\nu}_e$ by β^-**
  - ➡ **Spectrum shape similar to pair ν**

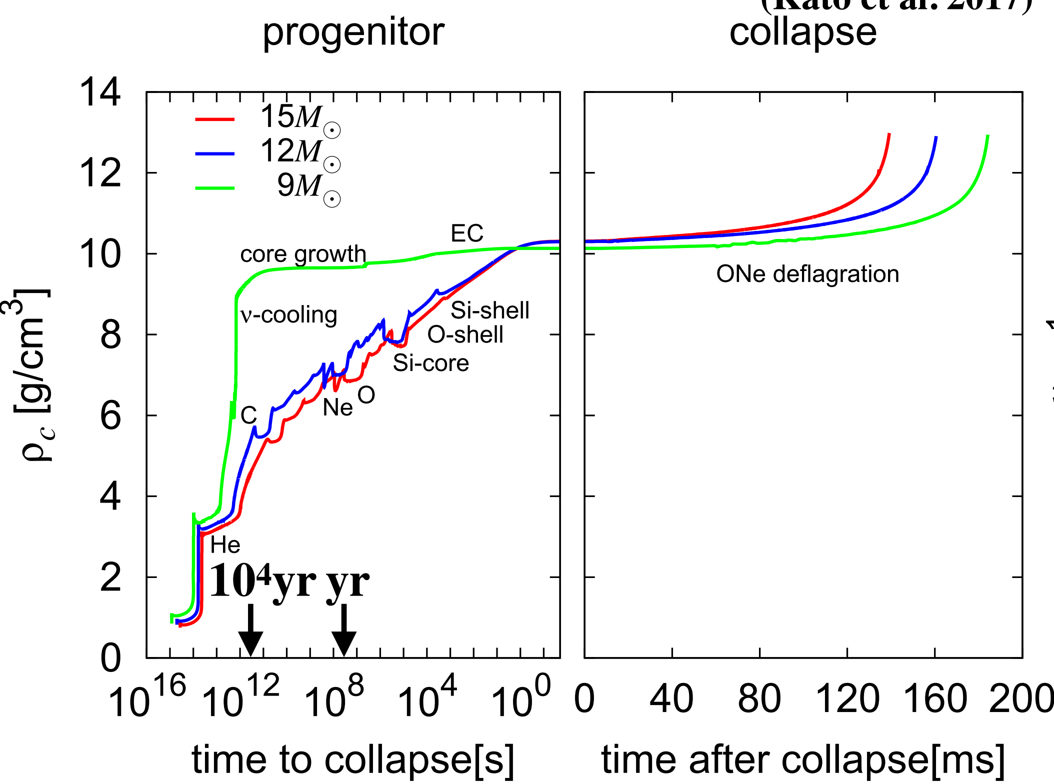
Neutrinos from EC SN Progenitor

- **EC SN progenitor (9 $M_\odot$ star)** **(Takahashi et al. 2019)**

  ONe core → Core growth → ^{20}Ne EC → O ignition and deflagration → Fe core formation and collapse (~ 0.1 s) → EC SN

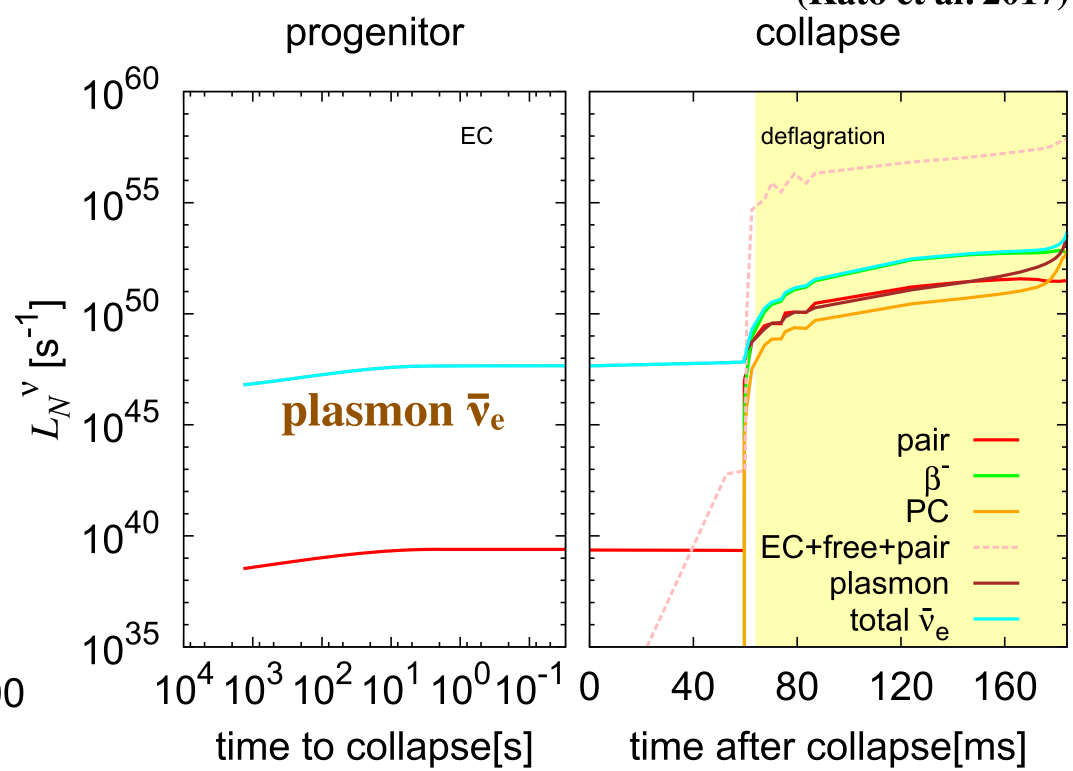
Evolution of central density

(Kato et al. 2017)



Neutrino emission rate

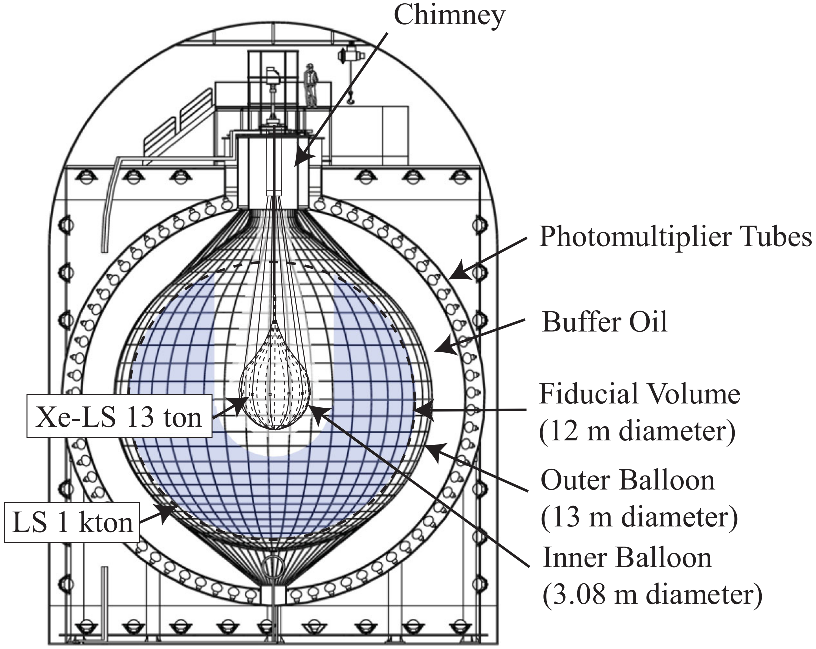
(Kato et al. 2017)



- **Degenerate ONe core ➡ Plasma ν: ~10^{-5} of pair ν from CC SNe**
- **Fe core formation and collapse (~ 0.1 s) ➡ EC ν_e and β^- $\bar{\nu}_e$**

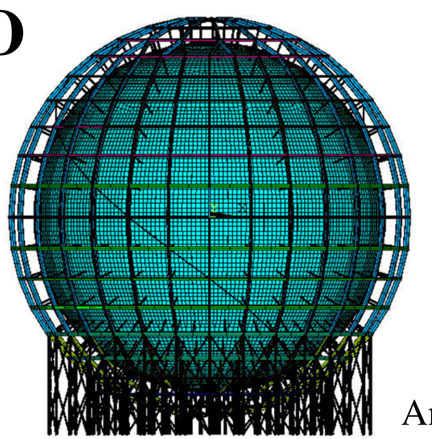
PreSN ν Detection by KamLAND and JUNO

- $\bar{\nu}_e$ events through $p + \bar{\nu}_e \to n + e^+$
- **KamLAND**



(Gando et al. 2013)

- **JUNO**



An et al. (2015)

- $N_{\mathrm{Proton}} = 5.98 \times 10^{31}$ (Gando et al. 2013)
- **Detection efficiency** (Asakura et al. 2016)

  $\varepsilon_{\mathrm{live}}=0.903$: mean livetime-to-runtime ratio

  - **Average**: $\varepsilon_S(\varepsilon_p)=0.64$
  - **No Baloon**: $\varepsilon_S(\varepsilon_p) \sim 0.9$
- $P_{\alpha e}$: Transition probability of $\bar{\nu}_\alpha \to \bar{\nu}_e$

  $P_{ee} = 0.68$ for normal

  $P_{ee} = 0.02$ inverted
- $N_{\mathrm{Proton}} = 1.19 \times 10^{33}$

Massive Star Models

Evolution of massive stars from H burning until core collapse

- **HO**ngo **S**tellar **H**ydrodynamics **I**nvestigator (**HOSHI**) code
  (e.g., Takahashi et al. 2016, 2018)

- **Initial mass and metallicity: 9 - 40$M_\odot$, Z = 0.014 ($Z_\odot$)**
  9-28, 30, 32, 35, 38, 40 $M_\odot$
  → **25 models**

- **4 different convection overshoot treatments**
  → **Strong (L) / weak (M) until He burining**
  On (ov,c) / off ( ) after He burning

→ **100 massive star models ($L_{ov,c}$, L, $M_{ov,c}$, M)** **(Yoshida et al. 2019b, in prep.)**
98 core-collapse SN progenitors
(2 white dwarfs from 9 $M_\odot$ stars (models $M_{ov,c}$ and M))

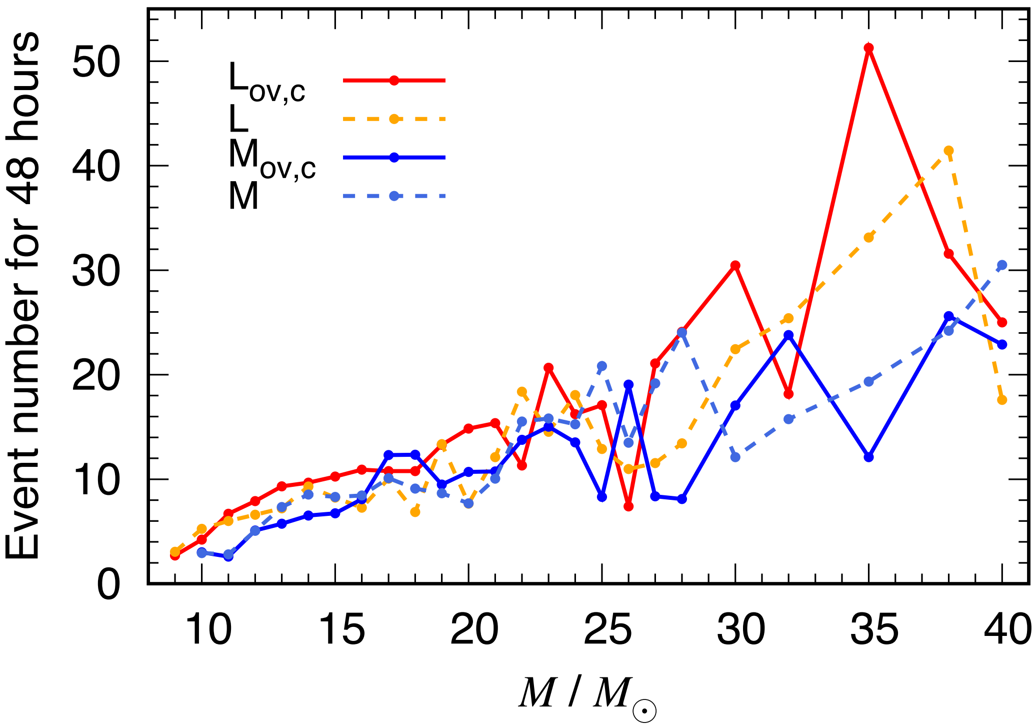
→ **Applications to presupernova neutrino events by KamLAND**
(Yoshida et al. 2019a, in prep.)

Stellar Mass and Convection Dependence

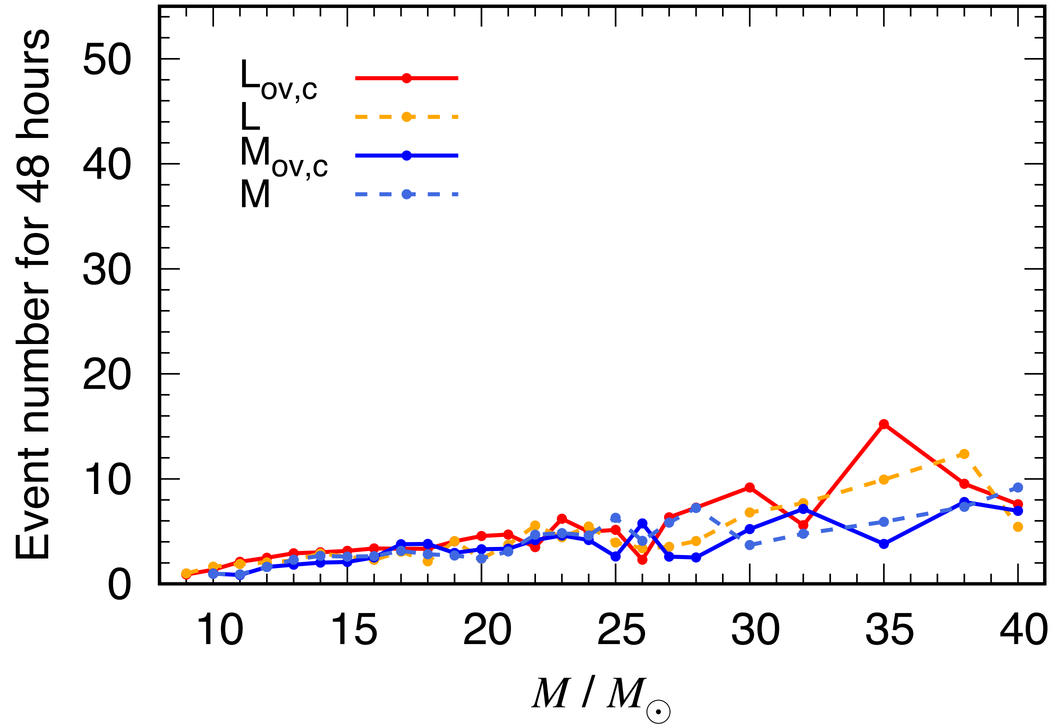
- **Neutrino events by KamLAND for 48 hours** (Yoshida et al. 2019a, in prep.)
  - **Pair neutrinos**
  - **Efficiency: Average, energy window: $0.9 < \varepsilon_p < 3.5$ MeV**

***d* = 200pc (~ Betelgeuse)**

Normal ordering



Inverted ordering



- **Several to tens events**
- **~ 10+ events**

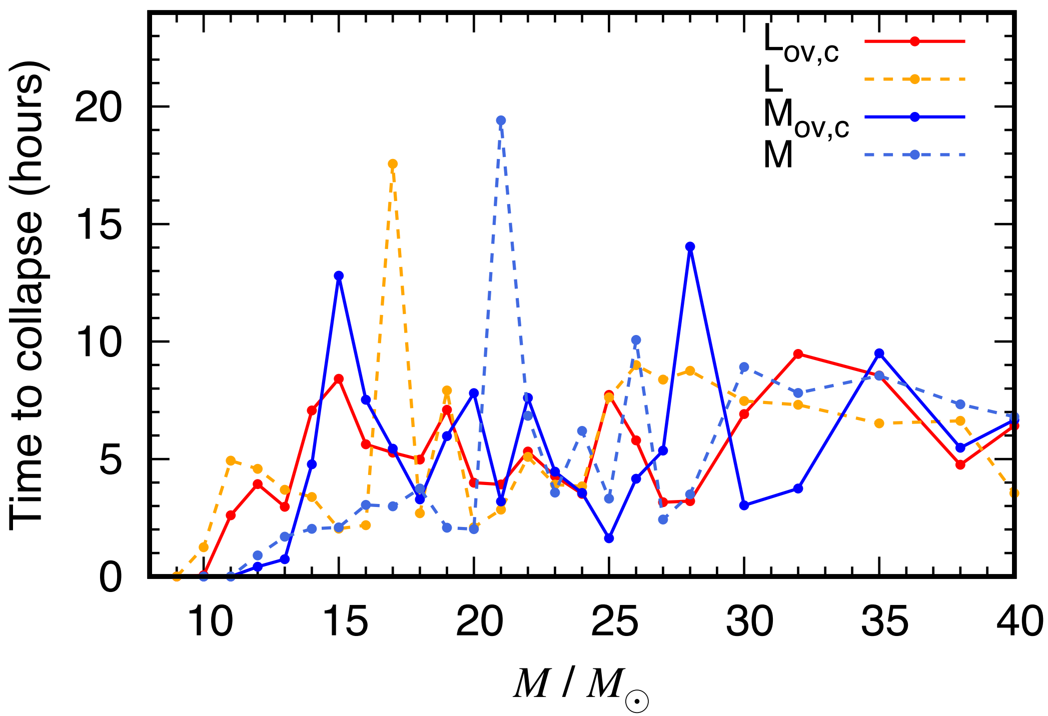
SN Alarm by KamLAND

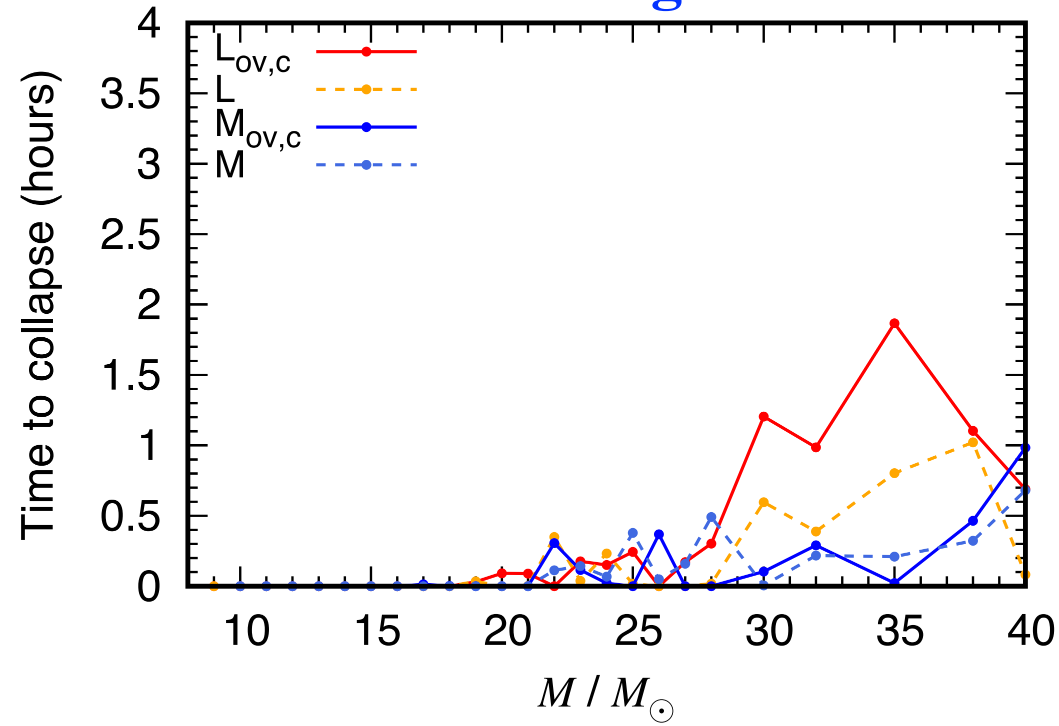
- **Detection efficiency: Average**

Three $\bar{\nu}_e$ events for 48 hour with $0.9 < \varepsilon_p < 3.5$ MeV by KamLAND
(3.7σ significance in *low* background) **(Yoshida et al. 2019a, in prep.)**

***d* = 200pc (~ Betelgeuse)**

Normal ordering **Inverted ordering**





- **Normal** → **A few to ~20 hours before core-collapse**

Inverted → **~ a few hours before core-collapse**

SN Alarm by KamLAND

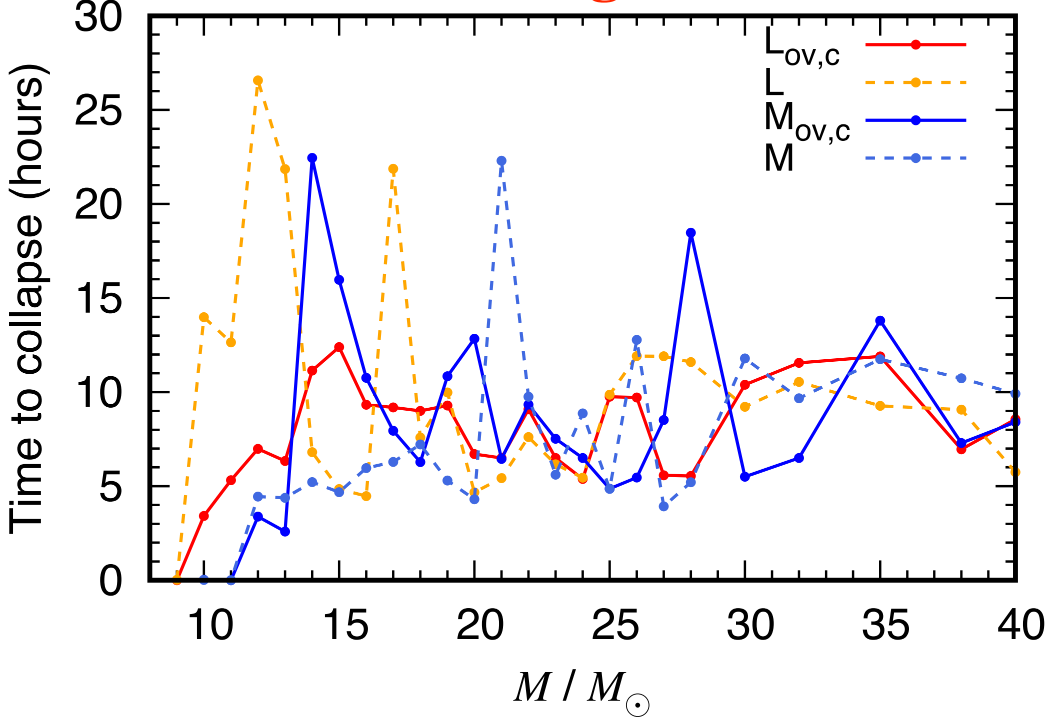
- **Detection efficiency: No Baloon**

Three $\bar{\nu}_e$ events for 48 hour with $0.9 < \varepsilon_p < 3.5$ MeV by KamLAND

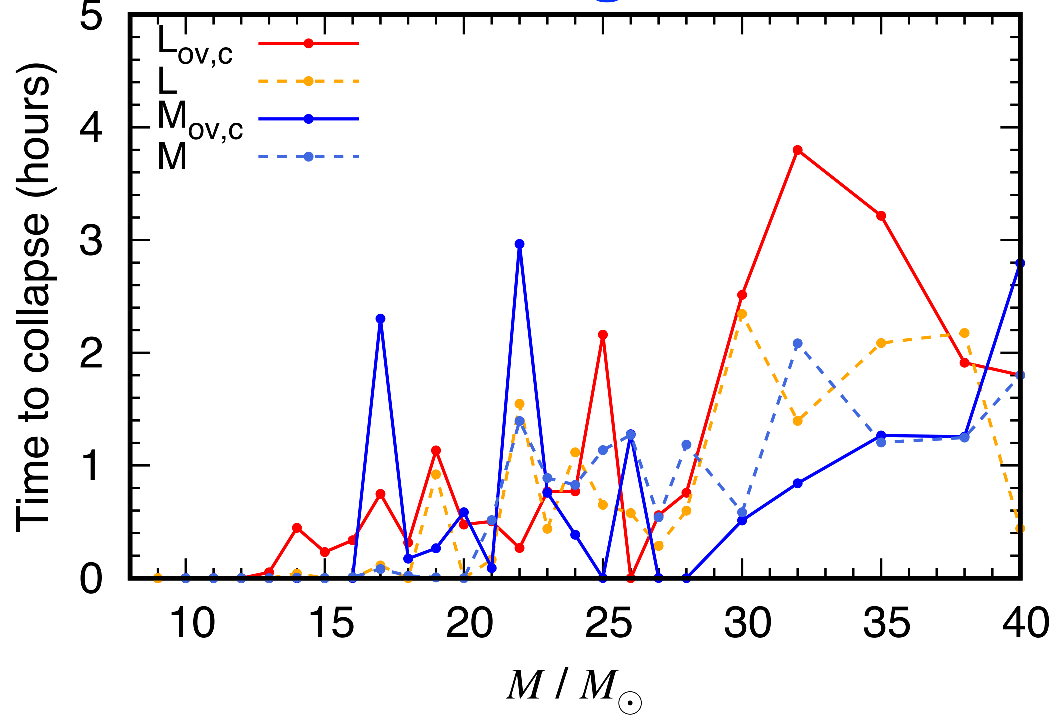
***d* = 200pc (~ Betelgeuse)**

(Yoshida et al. 2019a, in prep.)

Normal ordering



Inverted ordering



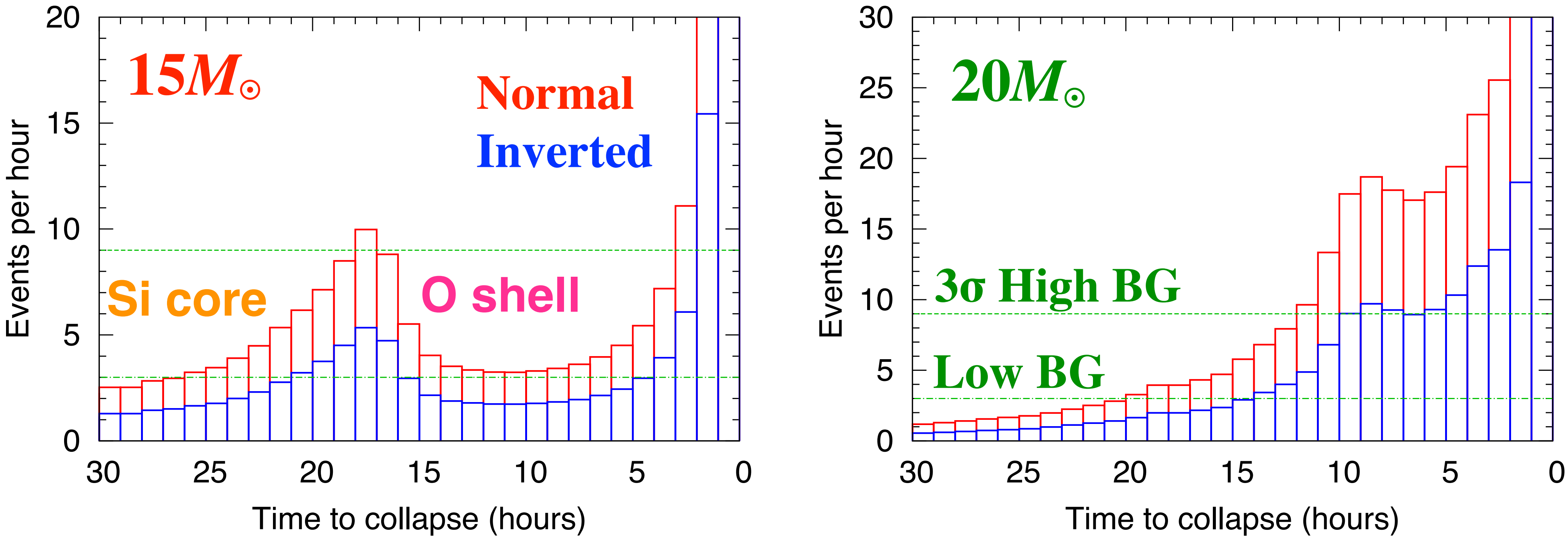
- **Normal**

12$L_{ov,c}$ ➡ Three events would be observed just before O shell burning.

Neutrino Events Revealing Burning Processes

- **Time evolution of preSN neutrino events *per hour* by JUNO**
  d = 200pc (~ Betelgeuse)

(Yoshida et al. 2016)



- **3σ level of high background (BG) → Reactor neutrino is considered.**
- **8 - 17 hours before collapse ➡ Decrease in the neutrino events**

  ➡ Si core burning → O shell burning

The central burning processes will be observed by neutrinos.

Summary

Neutrinos from neighboring preSN stars (*d* ~ 200 pc) will be detectable.

- **Neutrinos from a core collapse SN progenitor**
  - ➡ **From Si core burning for a few days through pair neutrino process**
    Time variation by shell burnings would be observed.
  - ➡ **EC ν_e and β^- $\bar{\nu}_e$ dominate for the last several minutes.**
- **Neutrinos from an electron capture SN progenitor**
  - ➡ **EC ν_e and β^- $\bar{\nu}_e$ dominate for ~ 0.1 s.**
    Explosion mechanism may be able to be specified.
- **Expected neutrino events from a preSN star**
  - ➡ **Up to several tens neutrino events by KamLAND for 48 hours**
  - ➡ **Time variation by O shell burning would be observed by JUNO.**
- **SN alarm by preSN neutrinos**
  - ➡ **Up to ~20 hours before SN explosion by KamLAND**
    Complicated stellar mass dependence