原子核による前兆ニュートリノ放出

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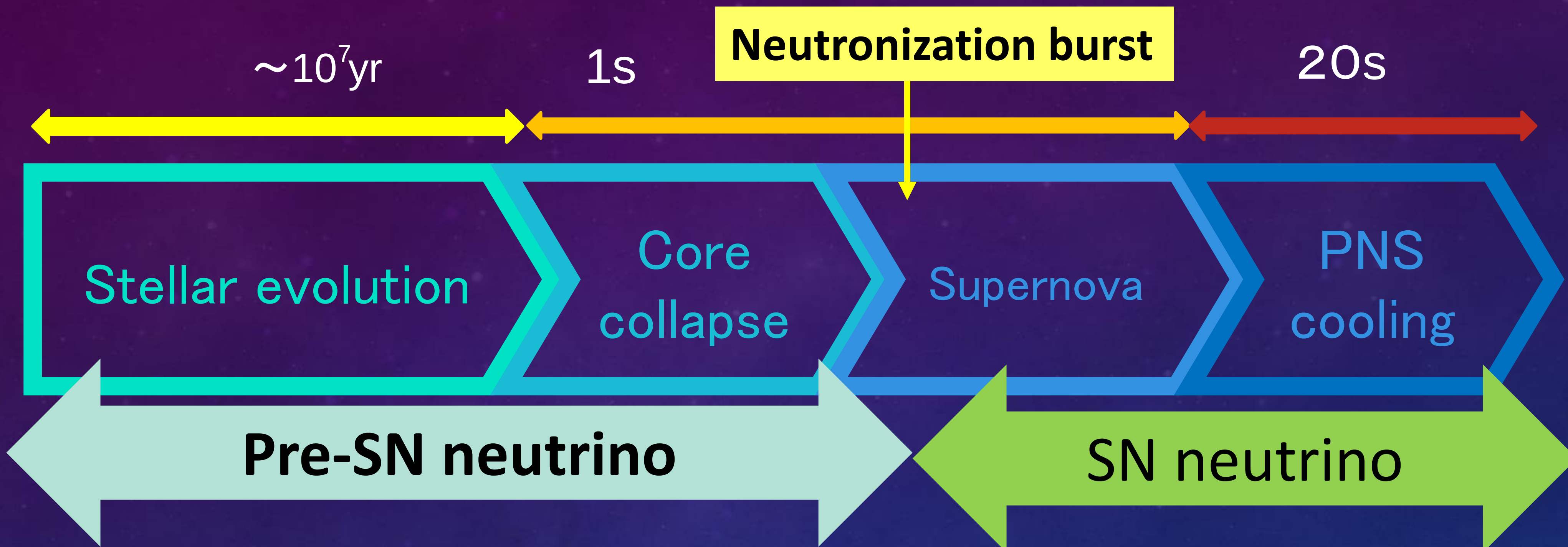
Outline

- ☑ Introduction
- ☑ Purpose
- ☑ Methods
- ☑ Results
- ☑ Summary & Future work

Importance of observations



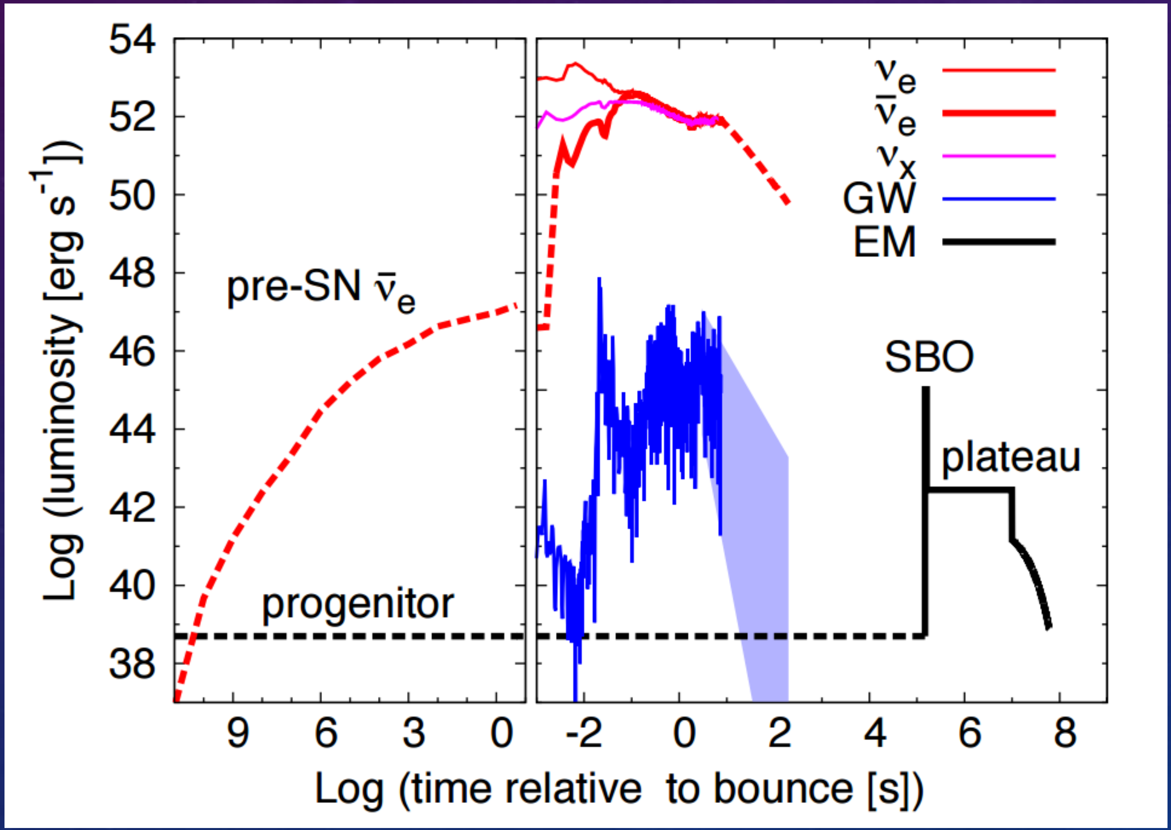
✓ structure of SN progenitor
- progenitor type
- convection property
- nuclear burning process
- EOS etc.

✓ mechanism of SN explosion
✓ nucleosynthesis of heavy nuclei
✓ EOS
✓ BH formation etc.

Importance of observations

Galactic supernova rate : a few / 100years

⇒ We must not miss one chance !



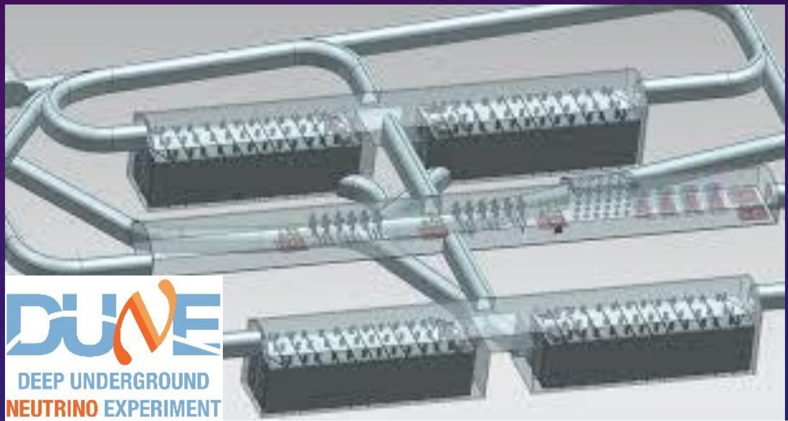
Nakamura et al.(2016)

✓Multi-messenger:

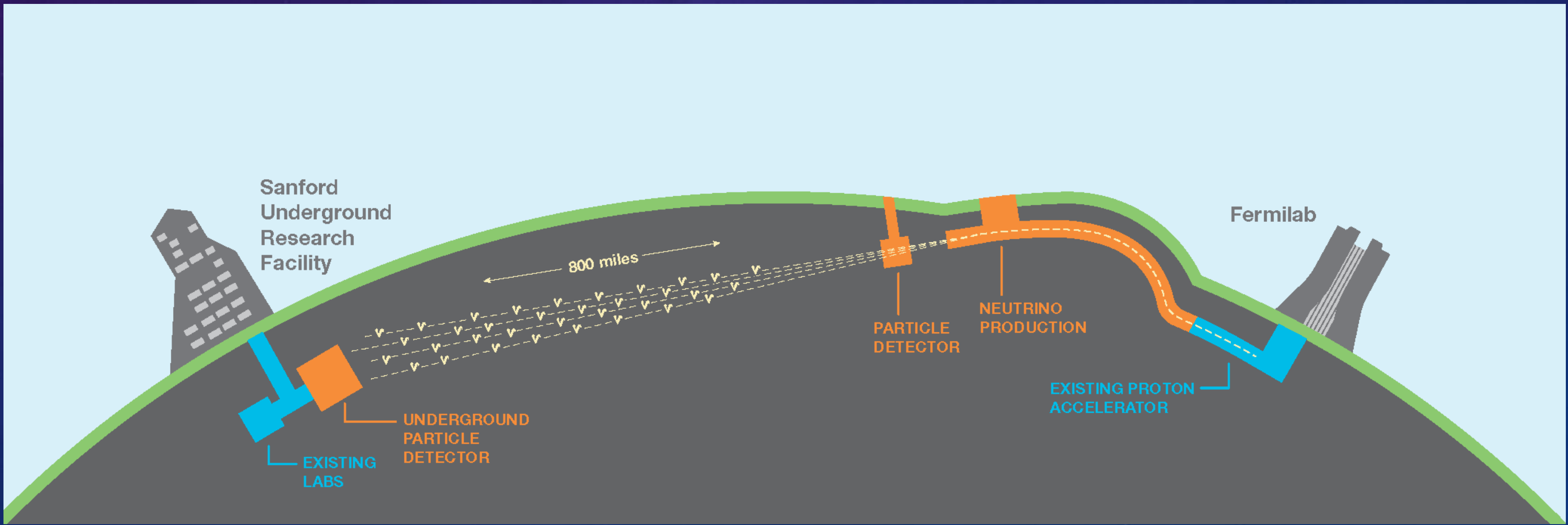
the first alert for SN !

DUNE

- ✓ ν_e detection
- ✓ 40kt liquid-Argon
- ✓ ~5MeV for ν_e
- ✓ ~3000 ν_e for SN @ GC



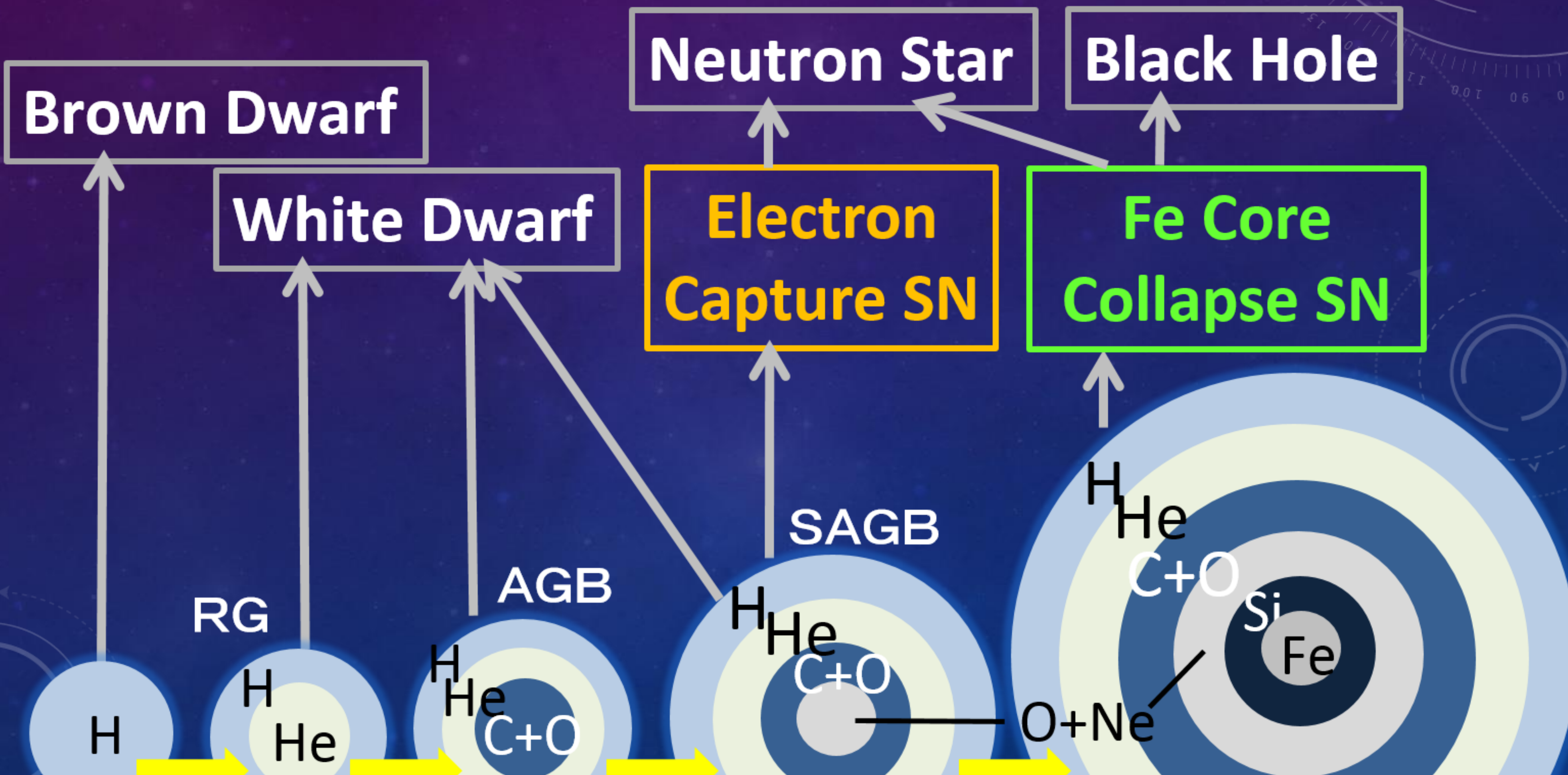
$$^{40}\mathrm{Ar} + \nu_e \longrightarrow e^- + ^{40}\mathrm{K}^*$$



Purpose of this talk

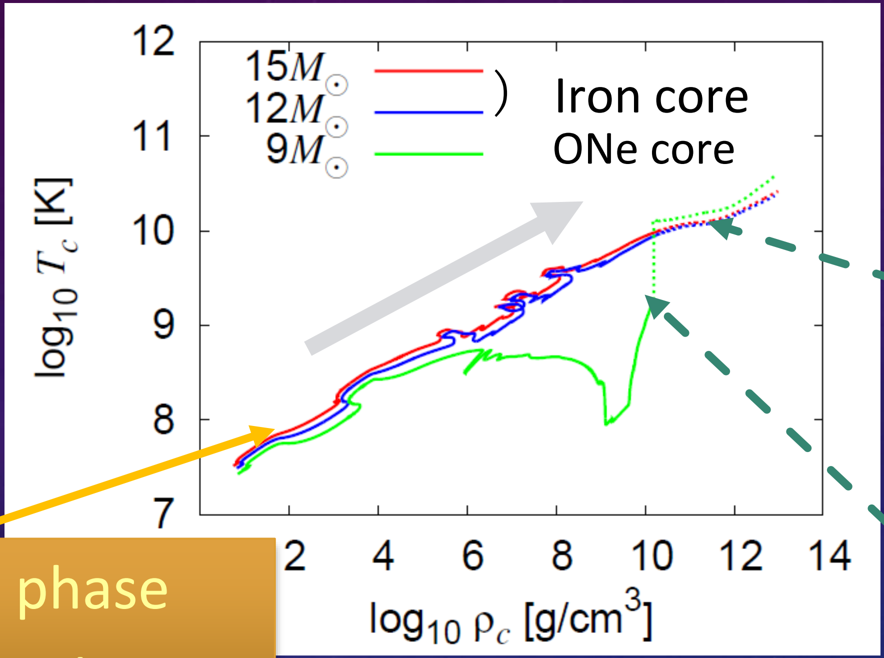
Can we detect electron neutrinos ?

If we can, what can we derive from the observations?



Methods

Step.1　Back ground calculation



switching point

$\log_{10}\rho = 10.3$

Collapsing phase

C. Kato et al.

H.Nagakura(Caltech) et al.

Collapsing phase

K.Takahashi et al.

Stellar evolution phase

K. Takahashi et al.

Step.2　neutrino spectrum & luminosity

Post process

density

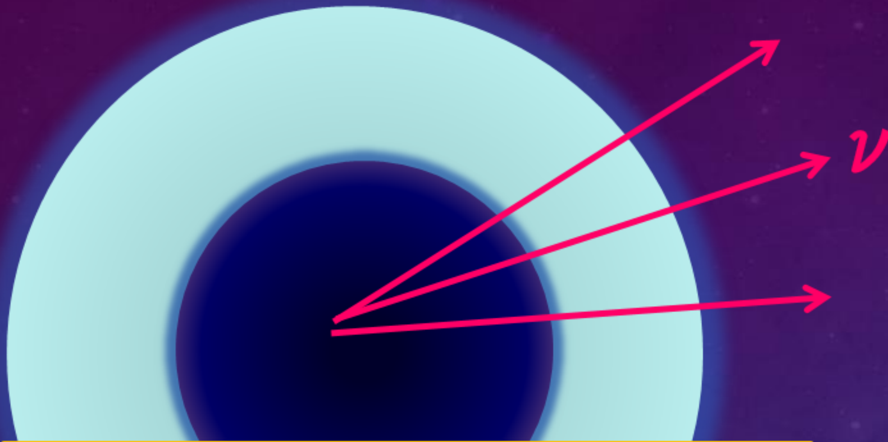
temperature

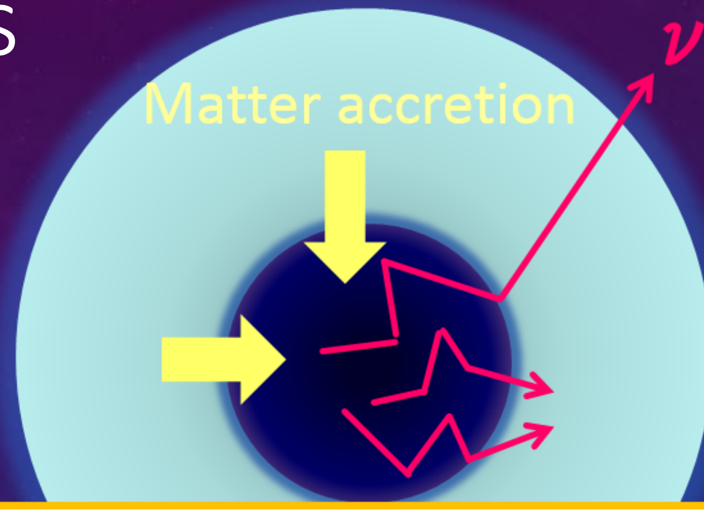
Ye

ve distribution

luminosity & spectrum

Methods





Stellar evolution phase	Core collapse phase
Central density : $\sim 10^{10}$ [g/cm³]	Central density : $\sim 10^{12}$ [g/cm³]
➡ free streaming	➡ neutrino trapping

✓ Fermi-Blocking effects & neutrino interactions

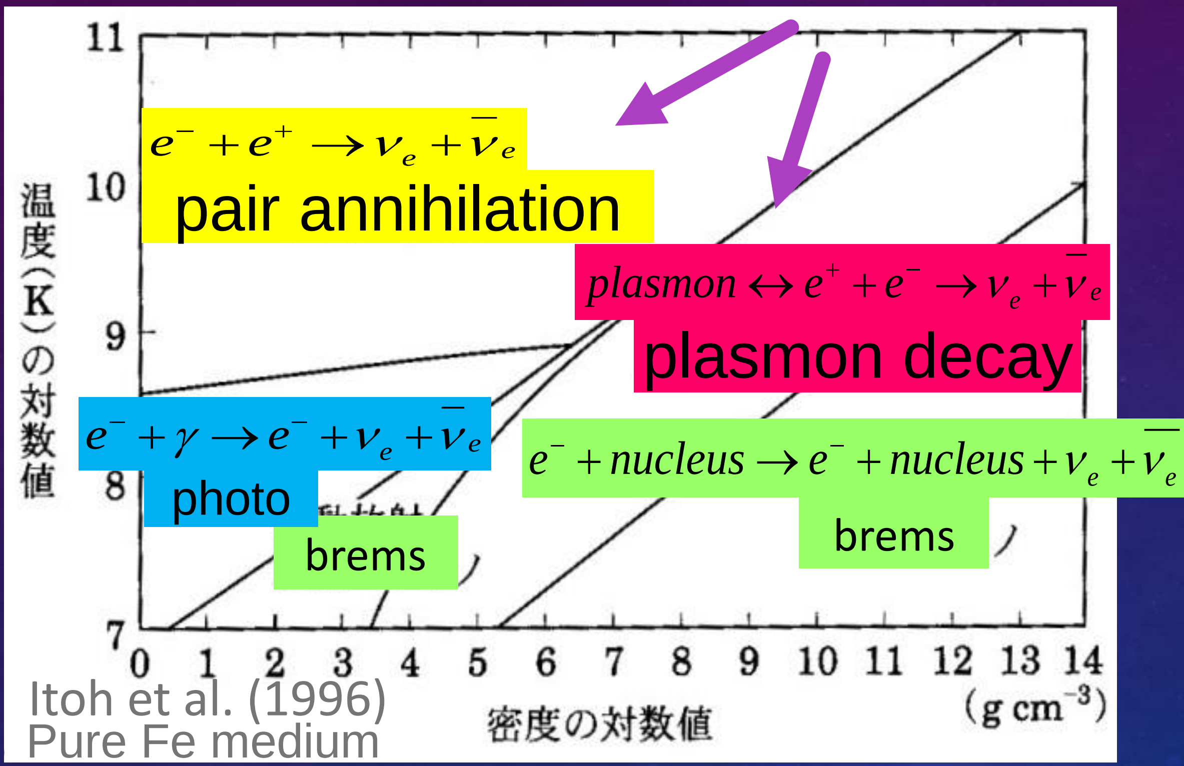
$\Rightarrow$ importance of neutrino transport

Electron scattering $\nu_e + e^- \rightarrow \nu_e + e^-$ Proton capture $\overline{\nu}_e + p \rightarrow n + e^+$

✓ dynamically unstable ⇒ hydrodynamic simulation

Neutrino emission processes

✓ thermal neutrino



✓ nuclear weak interaction

1. Electron capture (ec),

$$(Z, A) + e^- \rightarrow (Z-1, A) + \nu.$$

2. β^+ decay (β^+),

$$(Z, A) \rightarrow (Z-1, A) + e^+ + \nu.$$

3. Positron capture (pc),

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

4. β^- decay (β^-),

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

✓ electron capture by free proton

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

Weak tables

Total decay rate & neutrino energy loss

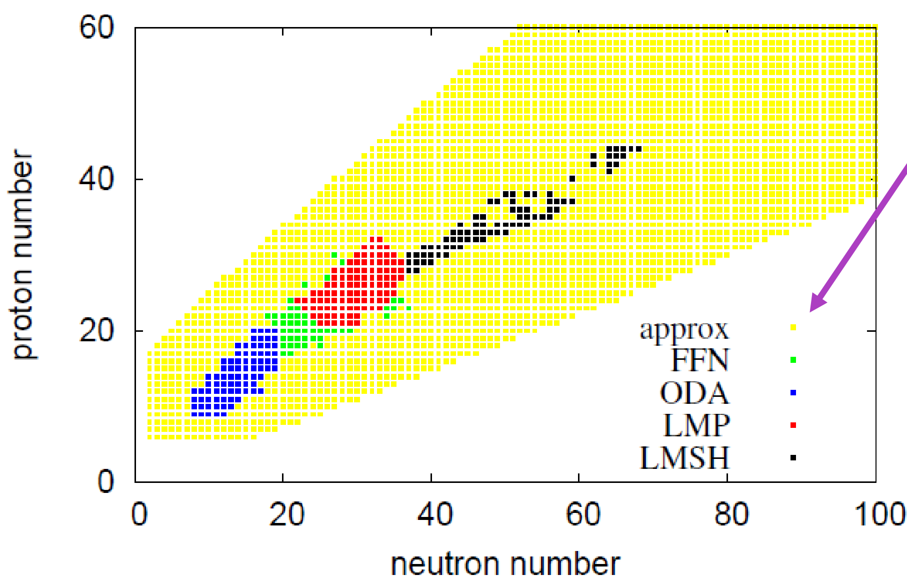
Table	range	reaction	ref
LMSH	$65 \leq A \leq 112$	EC	Langanke et al. (2003)
LMP	$45 \leq A \leq 65$	EC,β^+,PC,β^-	Langanke et al. (2001)
ODA	$17 \leq A \leq 39$	EC,β^+,PC,β^-	Oda et al. (1994)
FFN	$21 \leq A \leq 60$	EC,β^+,PC,β^-	Fuller et al. (1985)
TACHI	$7 \leq A \leq 330$	~~EC,β^+~~,β^-	Tachibana & Yamada (1995)

Fuller 1985, Langanke 2003

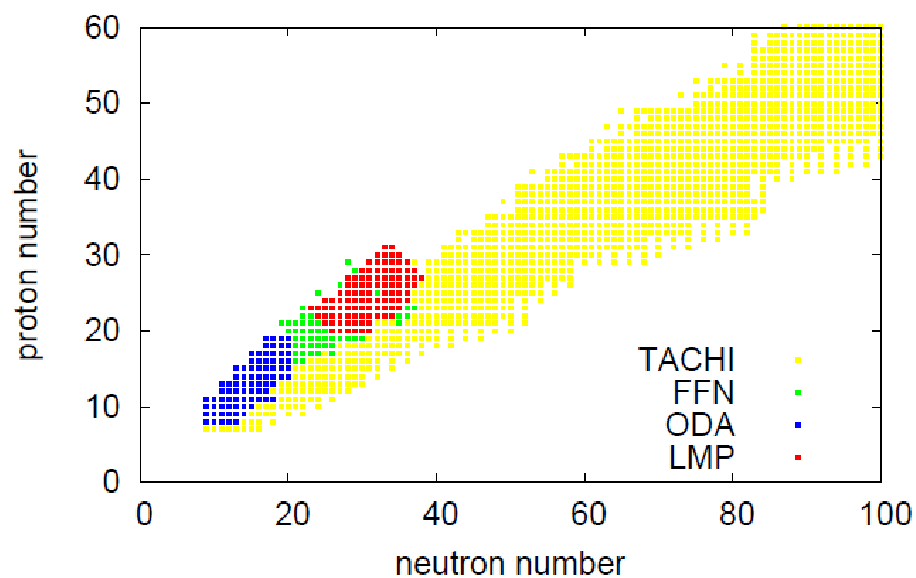
$$Q^{\nu_e}_{N,\mathrm{EC}} = \sum_i \frac{X_i\rho}{m_pA_i}\frac{\ln 2\cdot B}{K}\left(\frac{T}{m_ec^2}\right)^5 \times \left[F_4(\eta)-2\chi F_3(\eta)+\chi^2F_2(\eta)\right]$$

$$Q^{\nu_e}_{E,\mathrm{EC}} = \sum_i \frac{X_i\rho}{m_pA_i}\frac{\ln 2\cdot B}{K}\left(\frac{T}{m_ec^2}\right)^6 \times \left[F_5(\eta)-2\chi F_4(\eta)+\chi^2F_3(\eta)\right]$$

EC



β^-



Neutrino spectrum by nuclear weak interaction

Spectrum shape : effective Q-value

Langanke 2001, Sullivan 2015, Patton 2015

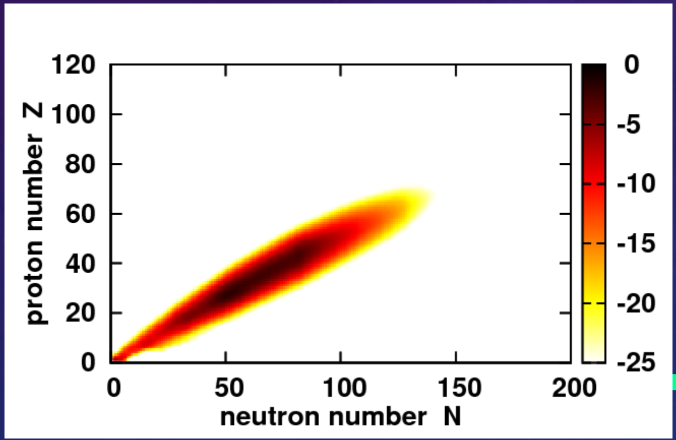
Averaged energy

$$\langle E_{\nu,\bar{\nu}} \rangle = \frac{\int_0^\infty \left(\frac{d\lambda}{dE_\nu}\right) E_\nu dE_\nu}{\int_0^\infty \left(\frac{d\lambda}{dE_\nu}\right) dE_\nu} = \frac{\mathcal{E}^{\nu,\bar{\nu}}}{\lambda^{EC,PC} + \lambda^{\beta^\pm}}$$

ε, λ are given by tables

$$\phi_{EC,PC} = N_{EC,PC} \frac{E_\nu^2 (E_\nu - Q)^2}{1 + \exp\left((E_\nu - Q - \mu_e)/kT\right)} \times \Theta(E_\nu - Q - m_e)$$

$$\phi_\beta = N_\beta \frac{E_\nu^2 (Q - E_\nu)^2}{1 + \exp\left((E_\nu - Q + \mu_e)/kT\right)} \times \Theta(Q - m_e - E_\nu) \ ,$$



Normalized by total decay rate

$$\lambda^i = \int_0^\infty \phi_i dE_\nu \quad i = EC, PC, \beta^\pm$$

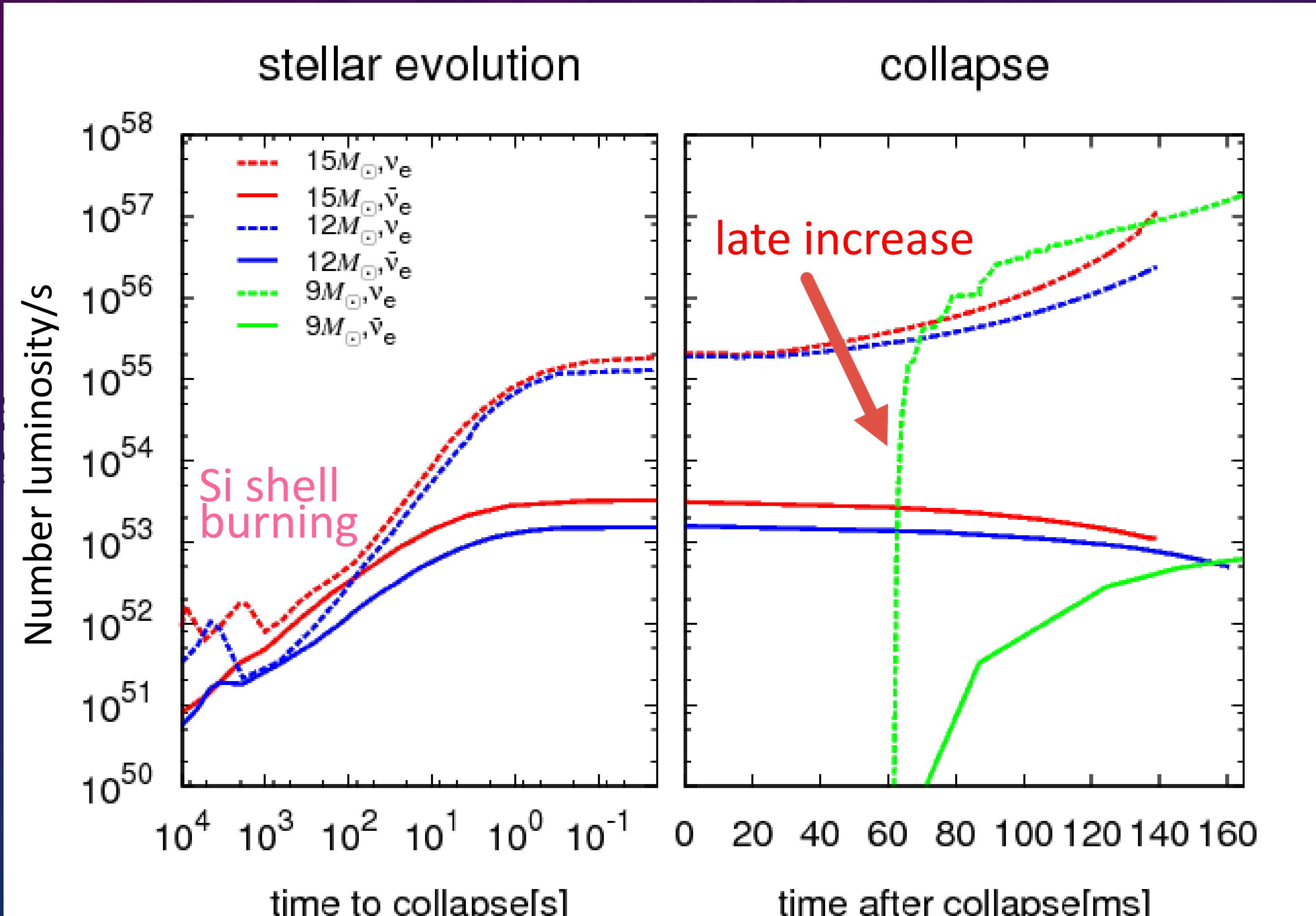
$$\Phi_{\nu,\bar{\nu}} = \sum_k X_k \phi_k \frac{\rho}{m_p A_k}$$

X is given by NSE composition

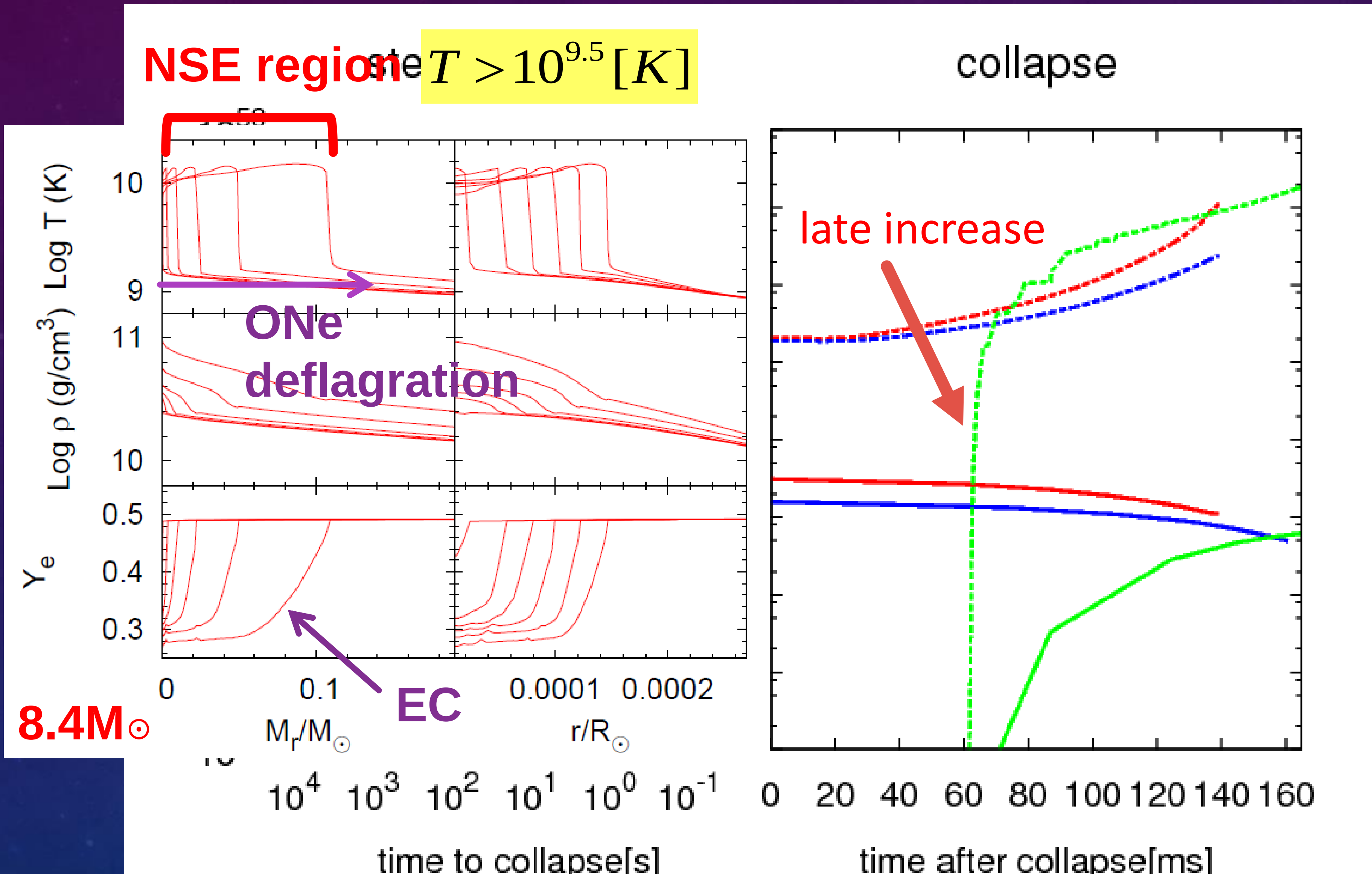
(Furusawa2013 EOS)

μe, T, ρ are given by background calculation

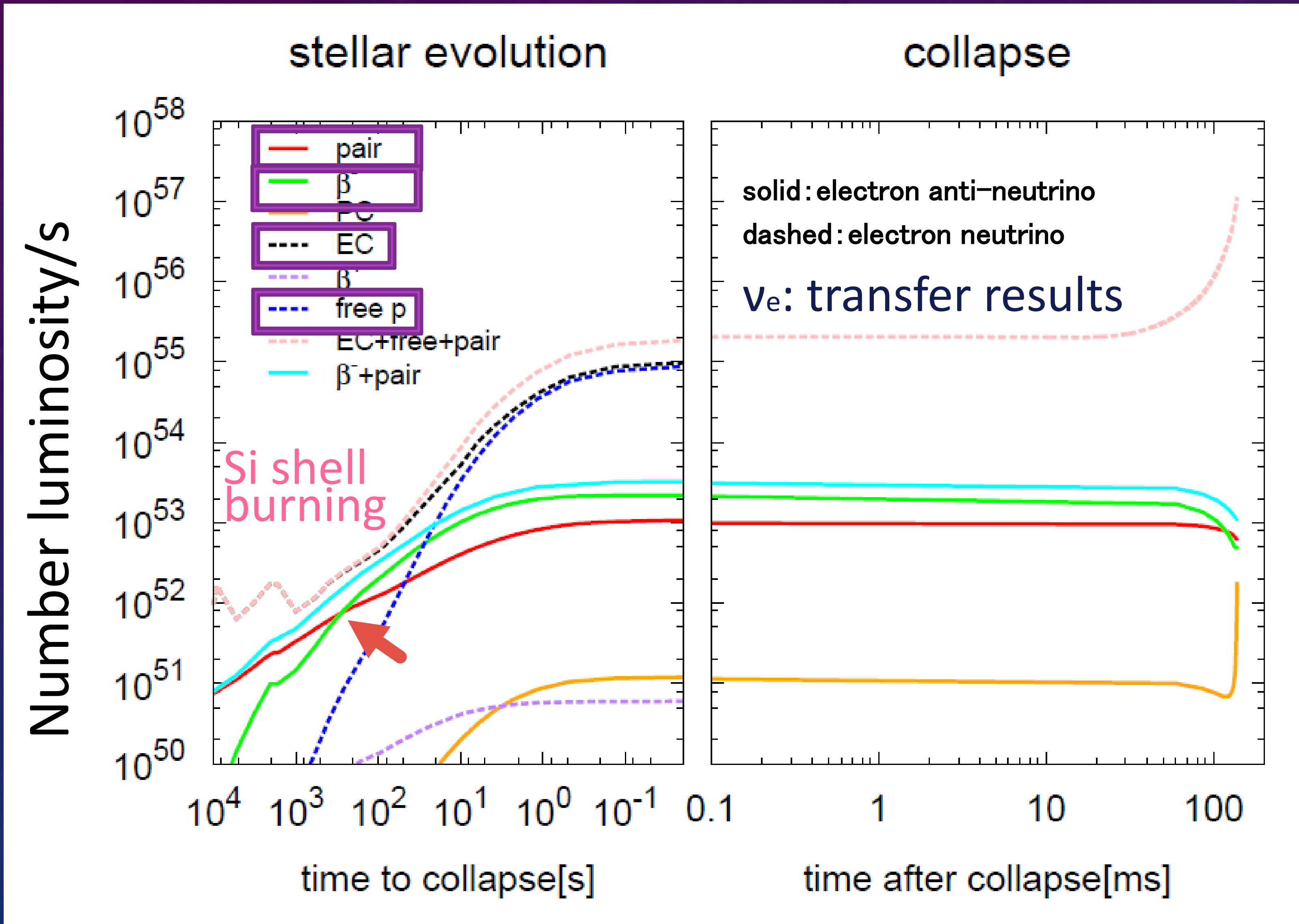
Neutrino luminosities



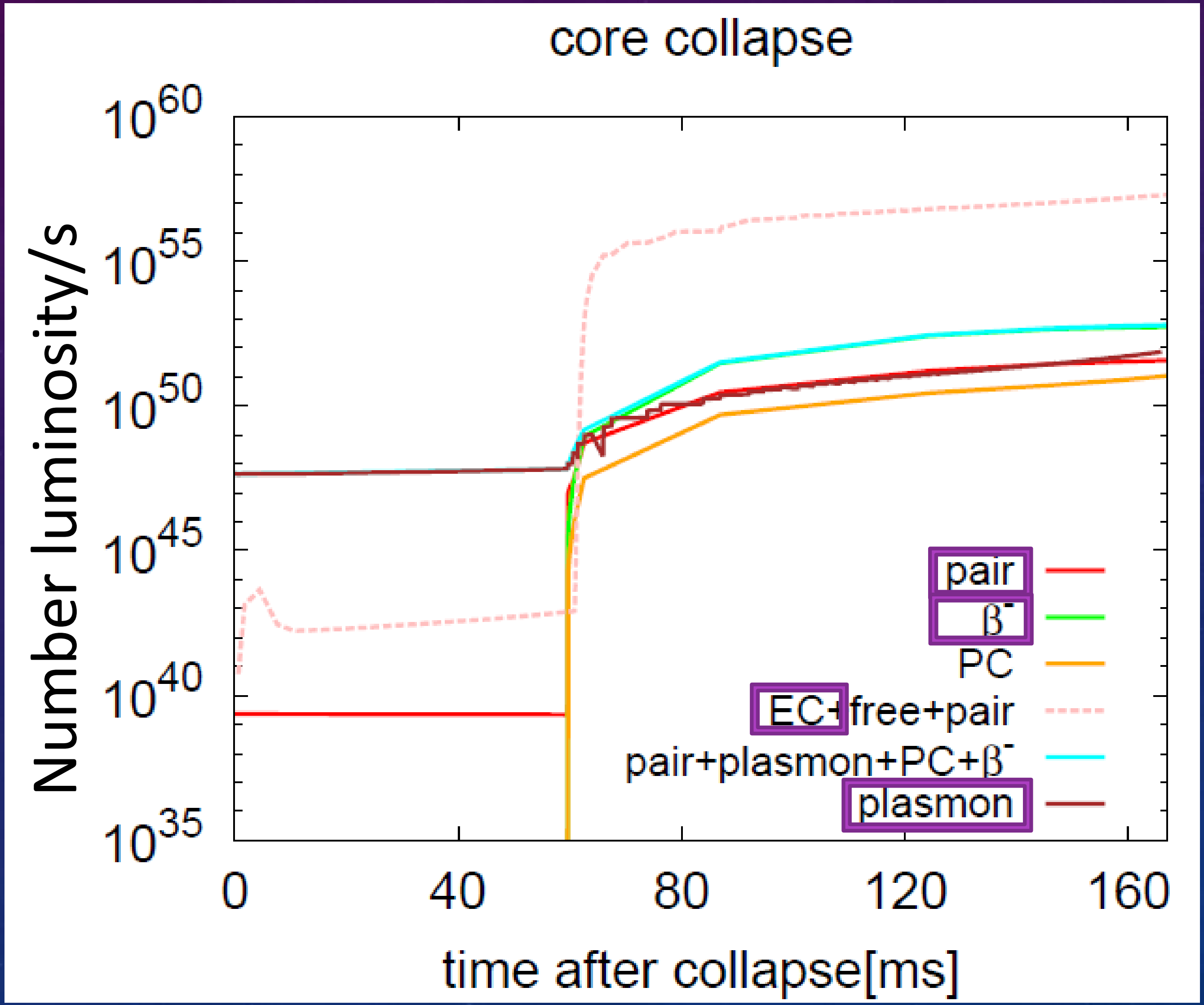
Neutrino luminosities



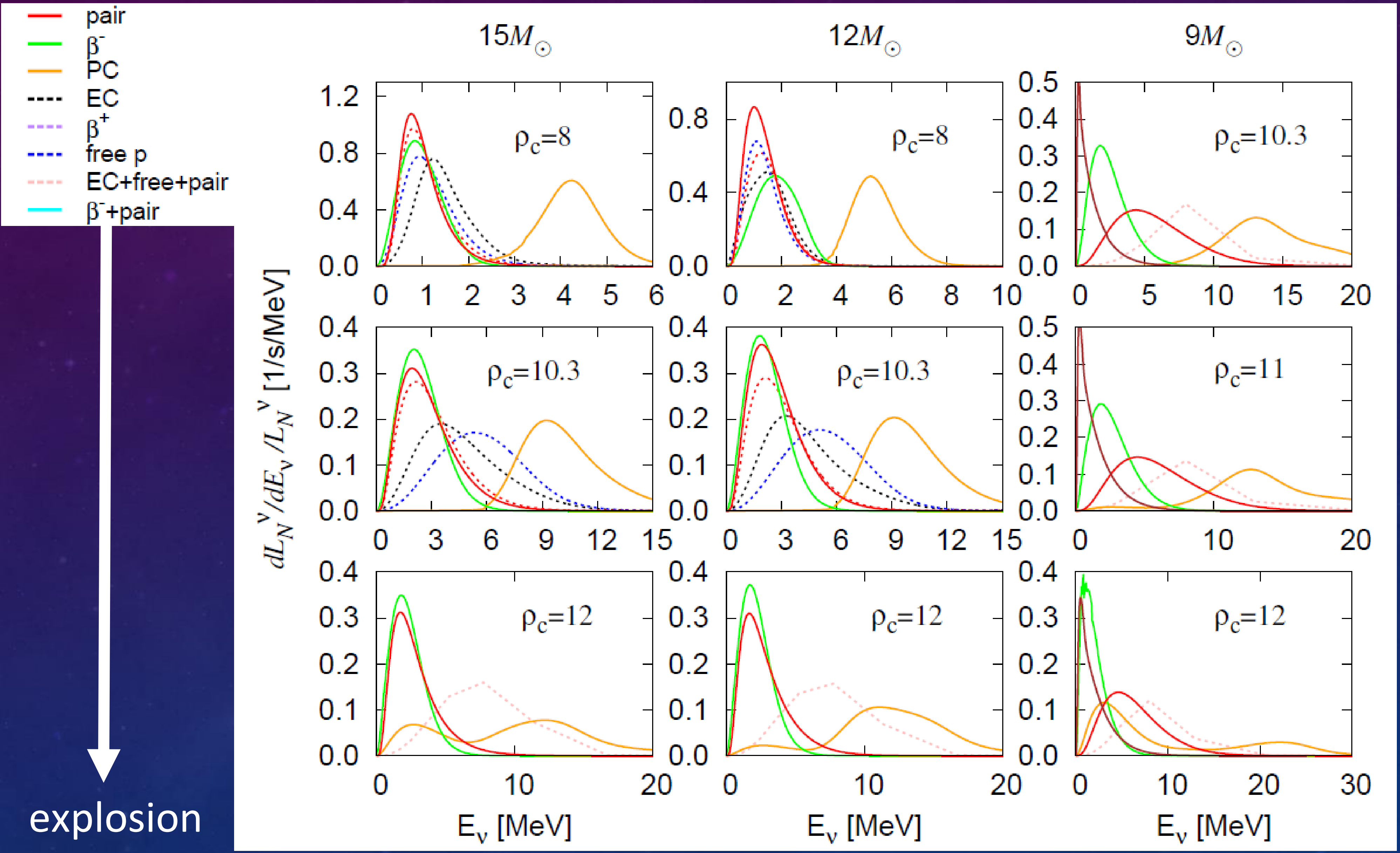
Neutrino luminosities



Neutrino luminosities



Spectrum



explosion

Dominant nuclei

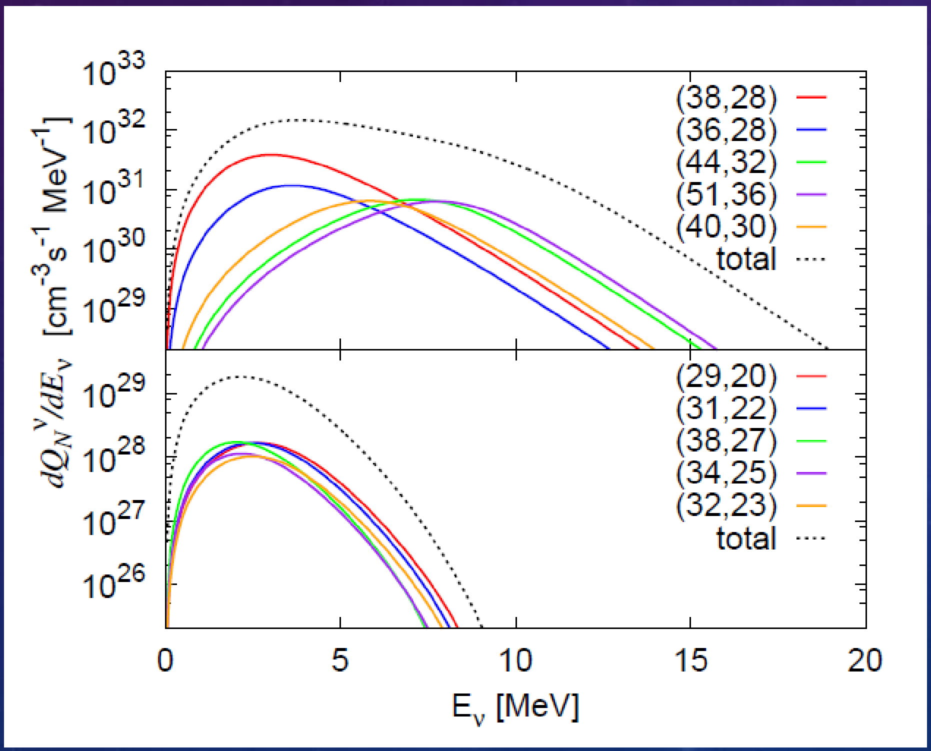
EC			β^-		
(N,Z)	X_i	R_i	(N,Z)	X_i	R_i
(38,28)	7.76×10^{-2}	10.57	(29,20)	1.88×10^{-2}	3.64×10^{-2}
(36,28)	1.99×10^{-2}	11.89	(31,22)	1.29×10^{-2}	5.56×10^{-2}
(44,32)	5.88×10^{-3}	32.59	(38,27)	4.60×10^{-3}	1.78×10^{-1}
(51,36)	7.85×10^{-3}	26.37	(34,25)	9.78×10^{-3}	5.20×10^{-2}
(40,30)	5.32×10^{-3}	30.04	(32,23)	6.05×10^{-3}	7.62×10^{-2}

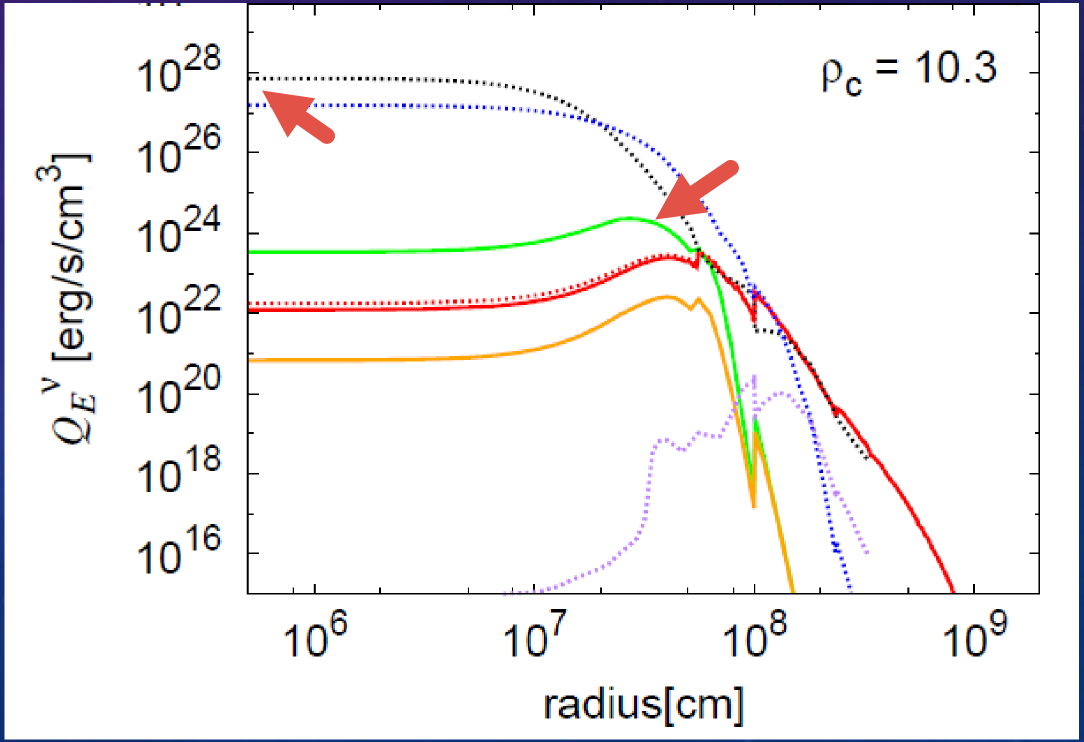
nuclei near magic number

⇒ stable

⇒ ・small weak rates

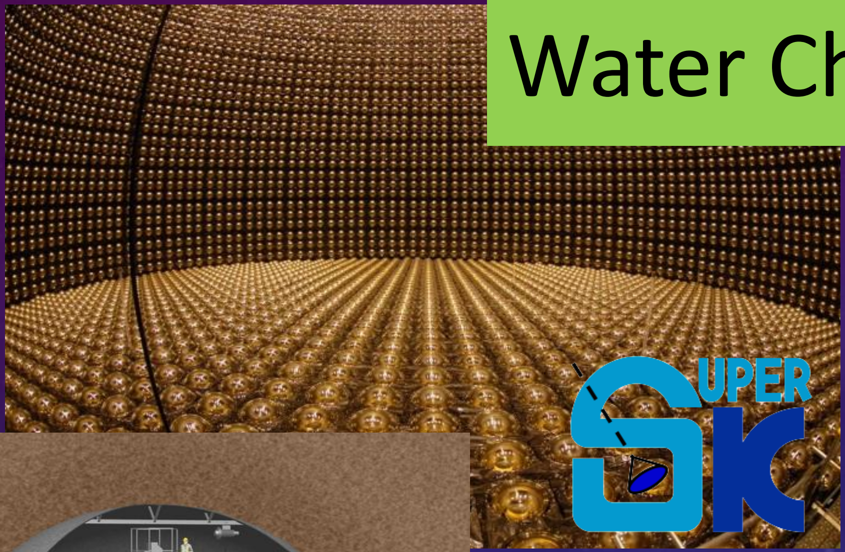
・large mass fractions

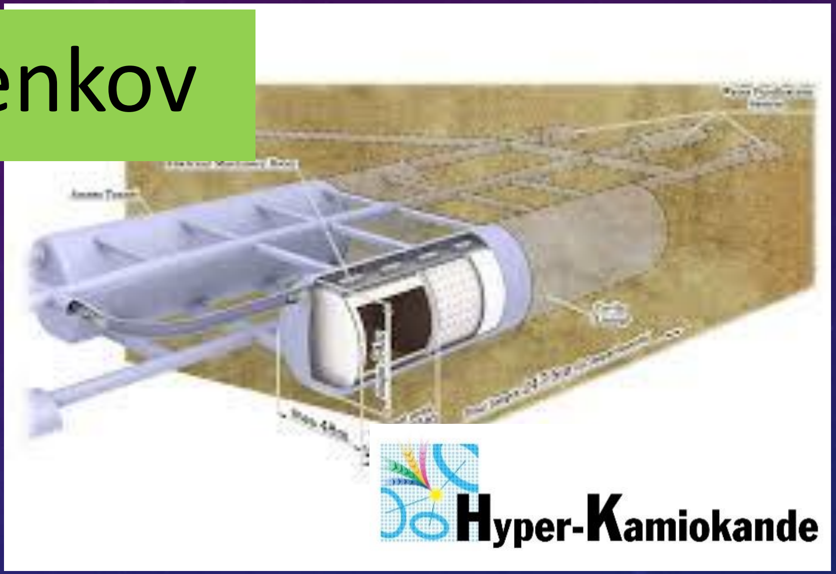




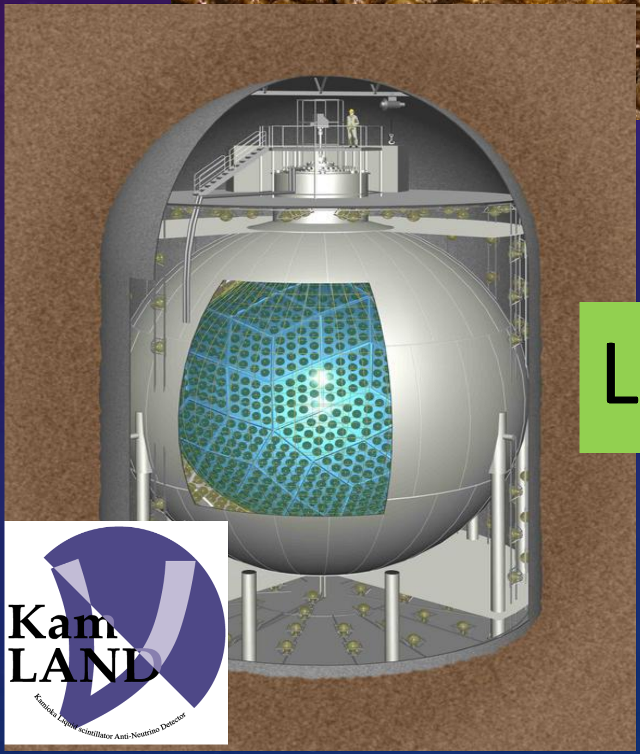
Neutrino detectors

Water Cherenkov





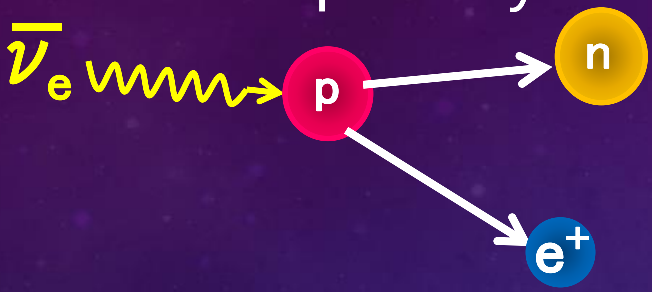
Liquid scintillator



Set up of estimation

✓ reaction

Inverse-β decay



$$^{40}\mathrm{Ar} + \nu_e \longrightarrow e^- + ^{40}\mathrm{K}^*$$

✓ Neutrino oscillation

- adiabatic oscillation
- 3 flavor mixing

Survival probability

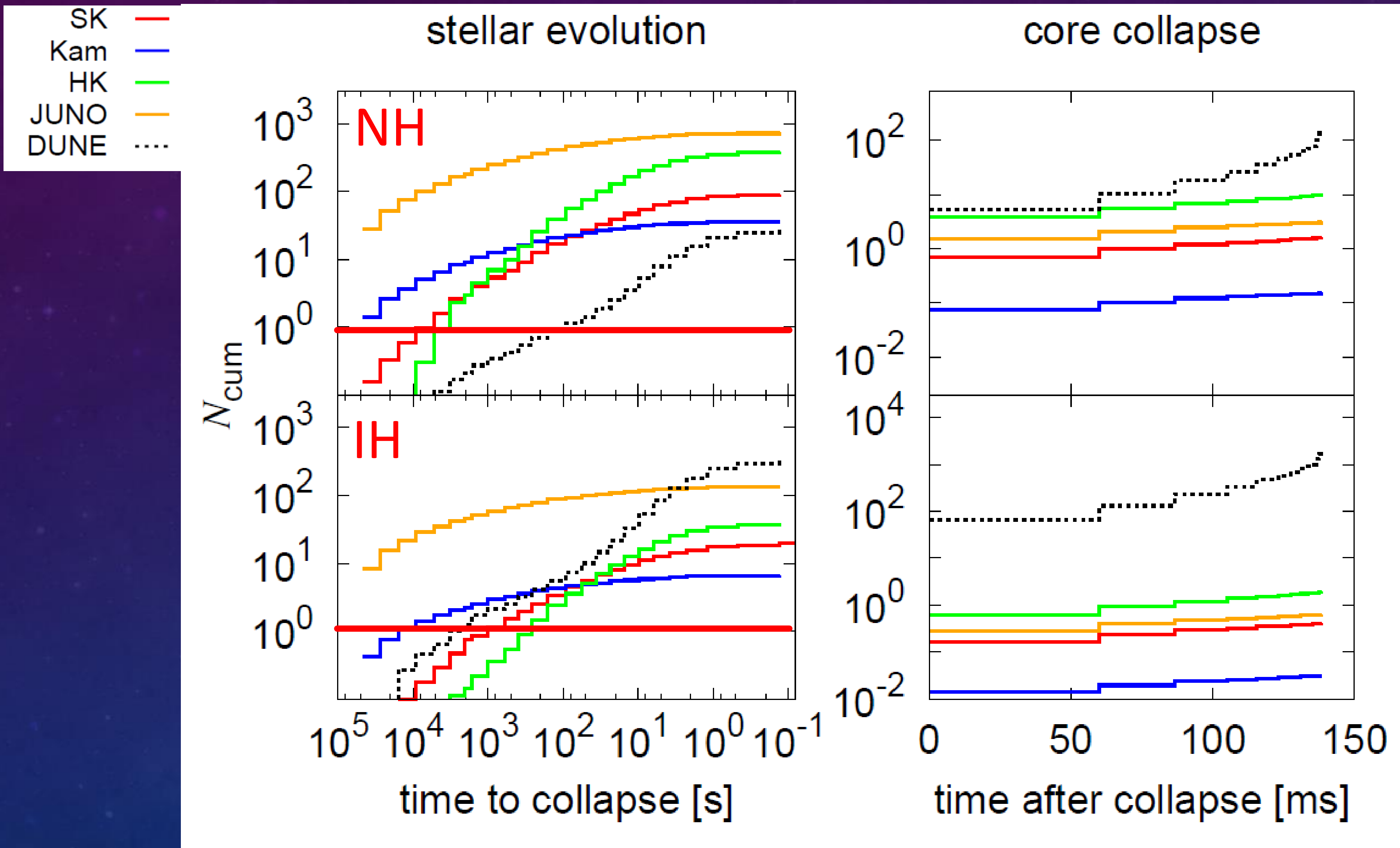
	$\bar{\nu}_e$	νe
normal	0.675	0.0234
inverted	0.024	0.3007

R=200pc

	SK	HK	KamLAND	JUNO	DUNE
threshold (MeV)	5.3	8.3	1.8	1.8	5.0
target number N	2.1×10^{33}	3.6×10^{34}	8.5×10^{31}	1.7×10^{33}	6.0×10^{33}

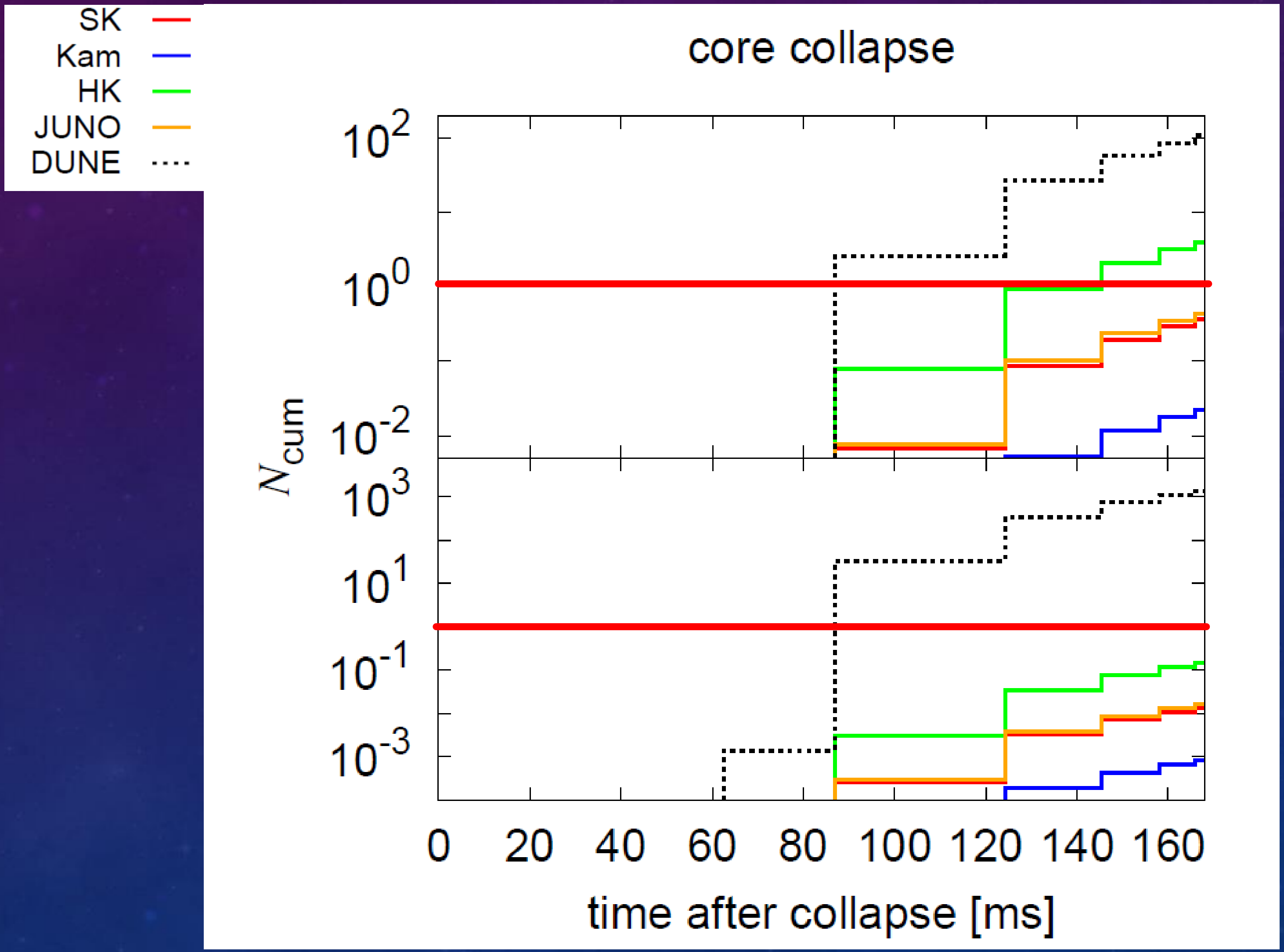
Fe Core Collapse SN

Event numbers



Electron Capture SN

Event numbers



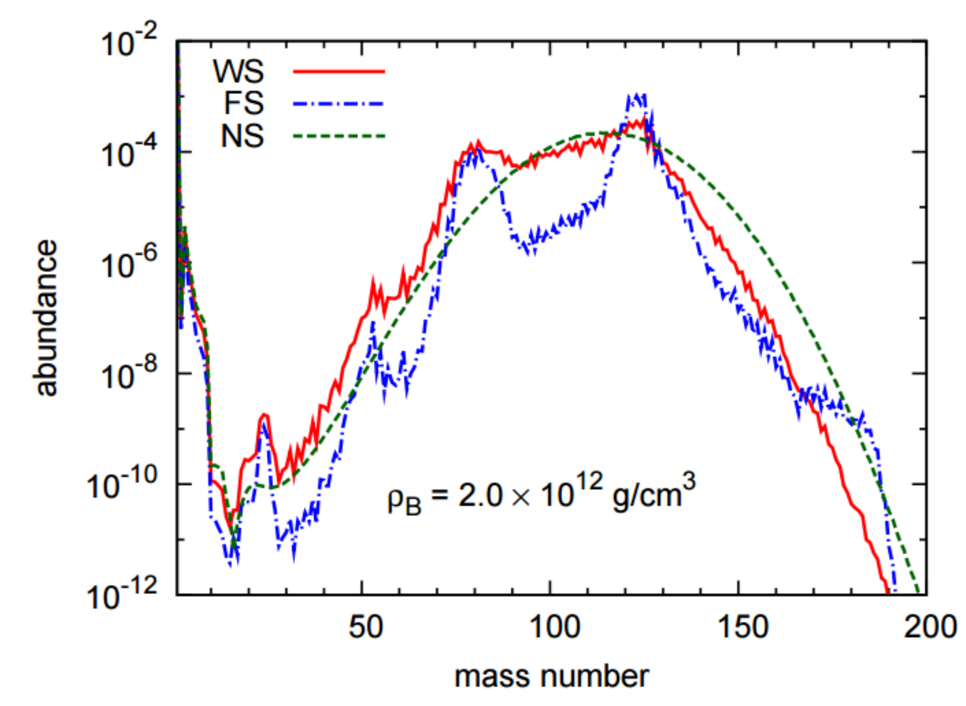
Number of events

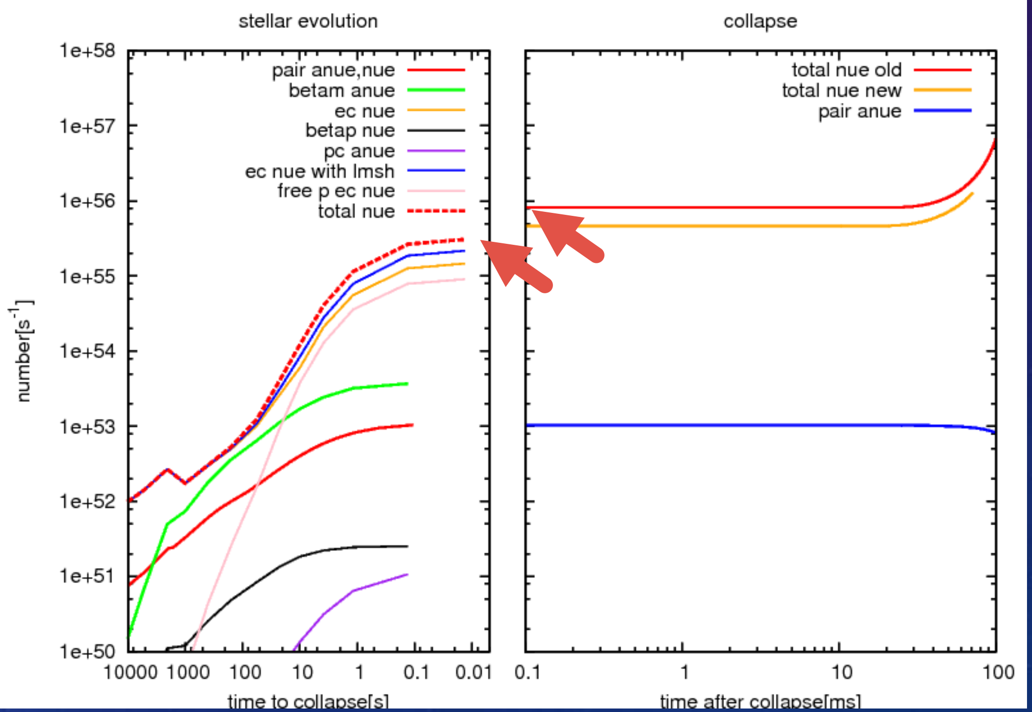
	detector	$9\ M_\odot$		$12\ M_\odot$		$15\ M_\odot$	
		normal	inverted	normal	inverted	normal	inverted
nueb	Super-K	0.94	0.03	30.5	8.42	90.9	20.2
	KamLAND	0.05	0.002	23.7	5.22	36.0	6.64
	Hyper-K	11.7	0.43	87.6	11.4	392	40.2
	JUNO	0.98	0.04	477	105	725	134
nue	DUNE	211	2716	104	1332	187	2385

- Anti-neutrinos : we can distinguish 2 types of progenitors, the alert for SN
- Neutrinos : we can get core information regardless of progenitor types

Uncertainty

☑ EOS (NSE composition)



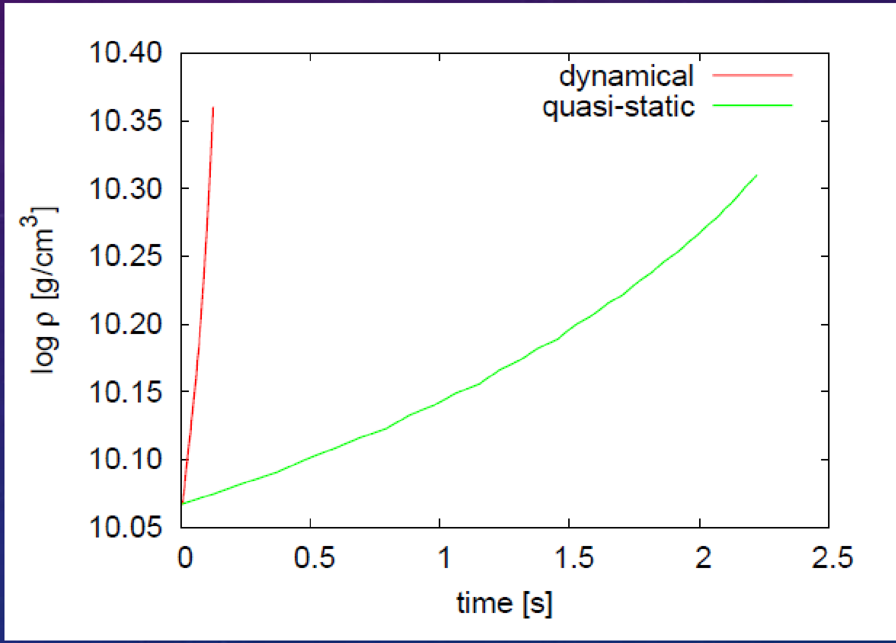


Furusawa 2017

Uncertainty

☑ switching time of 2 type simulation

・EOS's used in 2 calculation is different



☑ weak rate

・Tachibana tables are given assuming the terrestrial condition (their data are dominant at $\log_{10} \rho > 11$)

・Data for β- is not enough

Summary

☑ We focus on the 2 different types SN progenitors.

☑ At first, we calculate the background HD values

☑ By post-process calculation, we get continuous neutrino luminosity from SE phase until core bounce.

☑ $\overline{\text{ve}}$: 2 types of progenitors by pre-SN neutrinos
alert for following SN

ve: give information about core of both progenitors

Future works

☑ systematic study : calculate neutrino luminosities & spectrum about many progenitor initial masses

☑ detail physics derived from the observations

- constraint for Ye in CC phase by ν_e observation
  - ✓EOS (dynamical evolution, composition)
  - ✓weak rate

☑ continuous neutrino luminosities from pre-SN to PNS cooling

☑ Fade out of neutrino luminosities

physics of PNS⇒NS

Thank you for listening !