超新星爆発へ向けた親星からの予兆
～前兆ニュートリノの放出と観測可能性

The sign from the progenitors for the supernova explosions
～the emissions of pre-SN neutrinos and their detection possibilities

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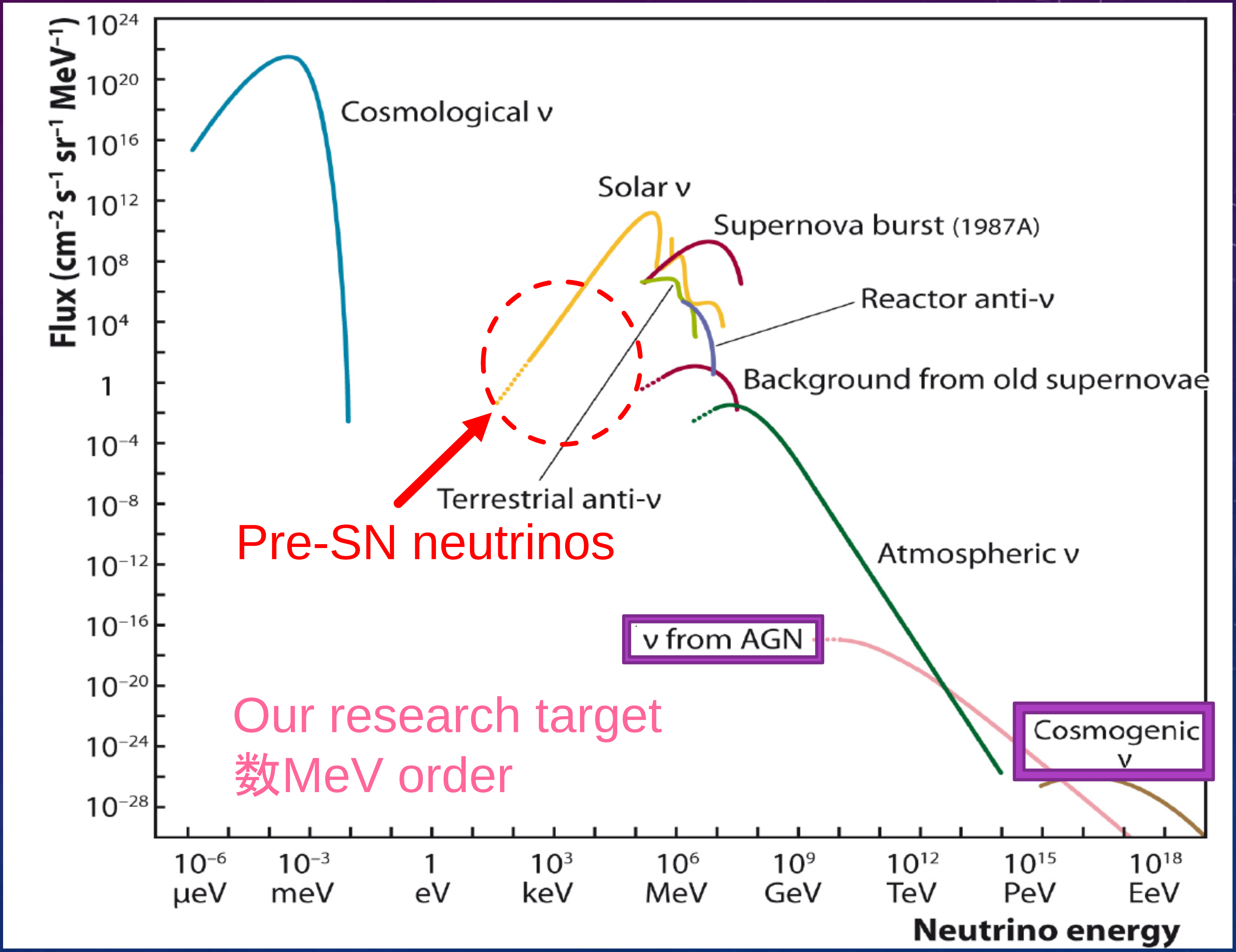
Collaboration with S. Yamada(Waseda), H. Nagakura (Caltech), S. Furusawa(Frankfurt), K. Takahashi (UT), T. Yoshida (UT), H. Umeda (UT), K. Ishidoshiro (Tohoku)

Our target

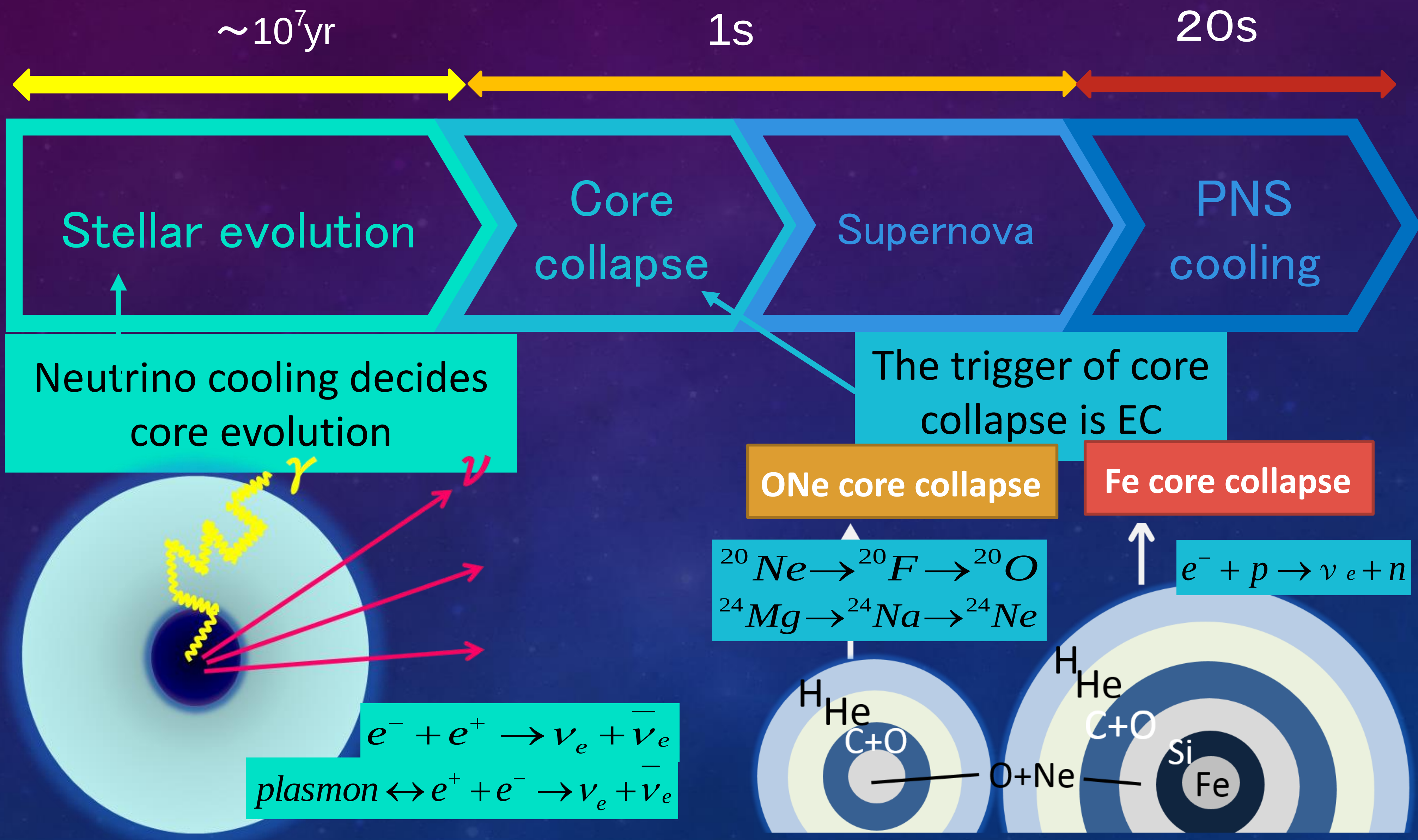


Flux (cm⁻² s⁻¹ sr⁻¹ MeV⁻¹)
10²⁴
10²⁰
10¹⁶
10¹²
10⁸
10⁴
1
10⁻⁴
10⁻⁸
10⁻¹²
10⁻¹⁶
10⁻²⁰
10⁻²⁴
10⁻²⁸
Cosmological ν
Solar ν
Supernova burst (1987A)
Reactor anti-ν
Background from old supernovae
Terrestrial anti-ν
Pre-SN neutrinos
Atmospheric ν
ν from AGN
Cosmogenic ν
Our research target
数MeV order
10⁻⁶ μeV
10⁻³ meV
1 eV
10³ keV
10⁶ MeV
10⁹ GeV
10¹² TeV
10¹⁵ PeV
10¹⁸ EeV
Neutrino energy

Outline

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

Massive Star Evolution & Neutrino



Massive Star Evolution & Neutrino

$\sim 10^7$yr | 1s | 20s

Stellar evolution → Core collapse → Supernova → PNS cooling

Neutrinos give energy to stalled shock

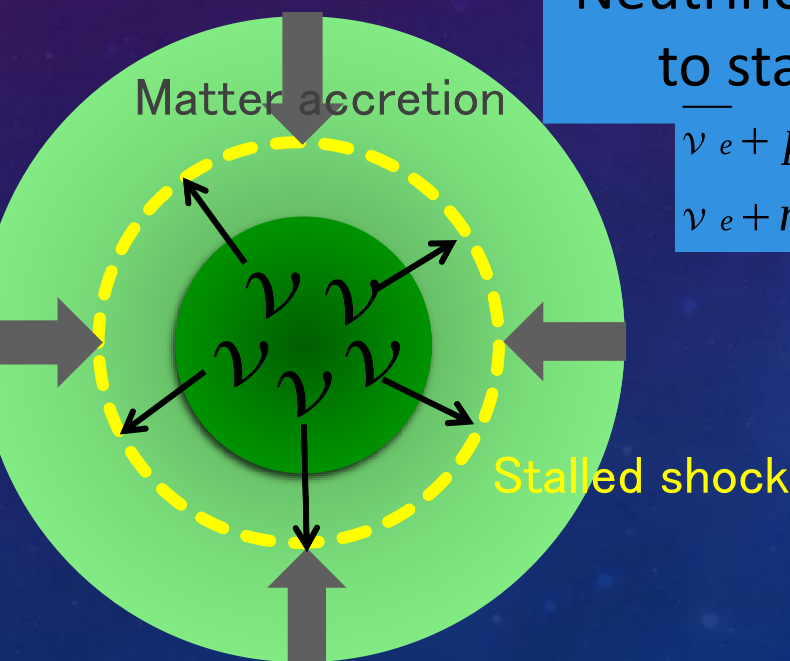
$$\bar{\nu}_e + p \to e^+ + n$$

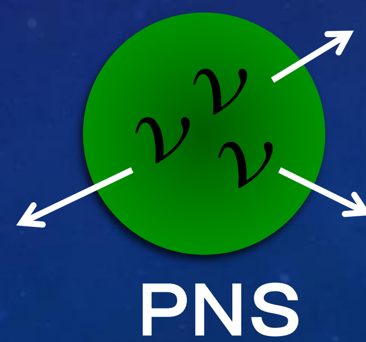
$$\nu_e + n \to e^- + p$$

Neutrinos cool PNS towards NS

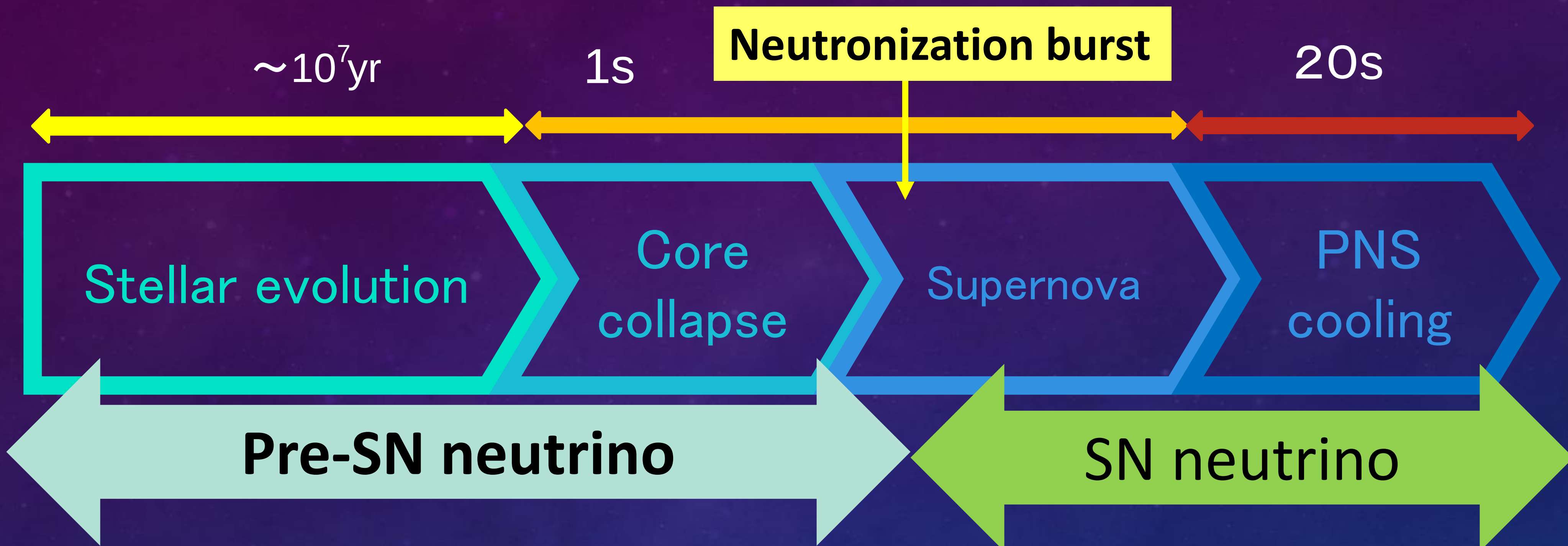
$$n \to p + e^- + \bar{\nu}$$

$$n + N \to p + N + e^- + \bar{\nu}$$





Importance of observations



Pre-SN neutrino

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

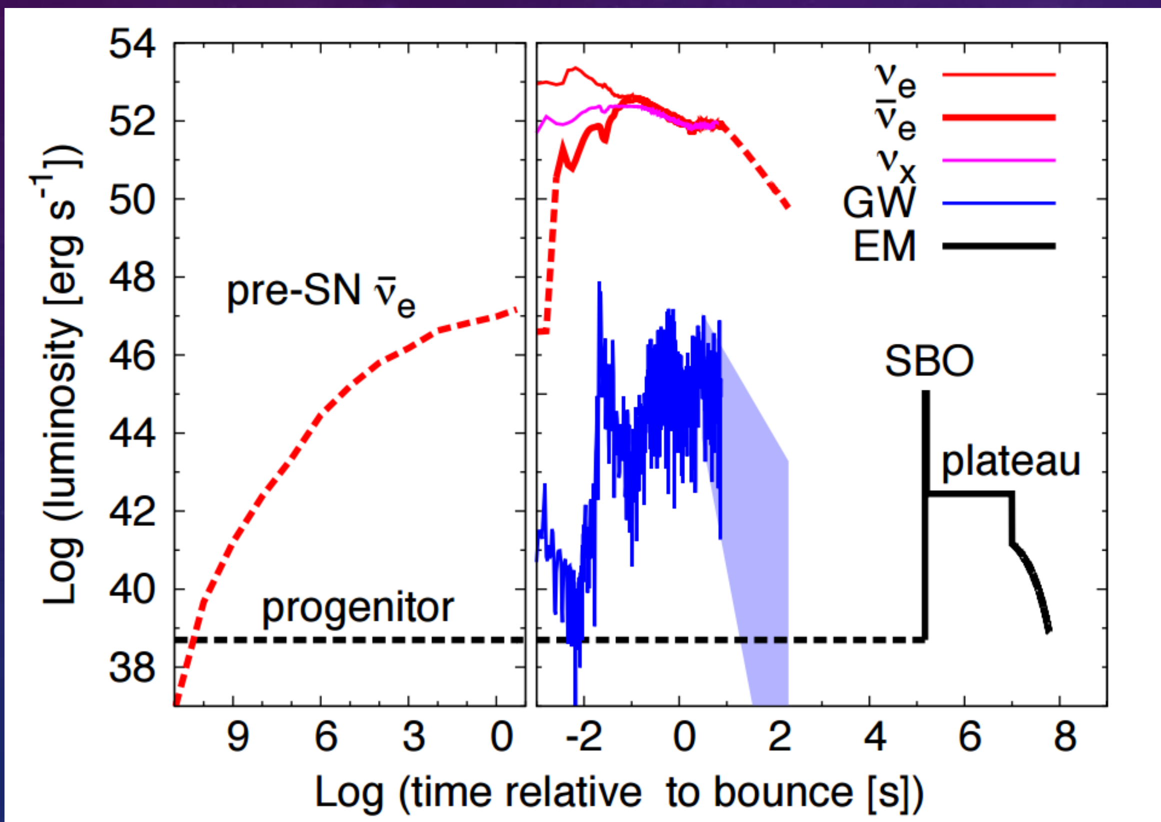
SN neutrino

- ✓ 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:

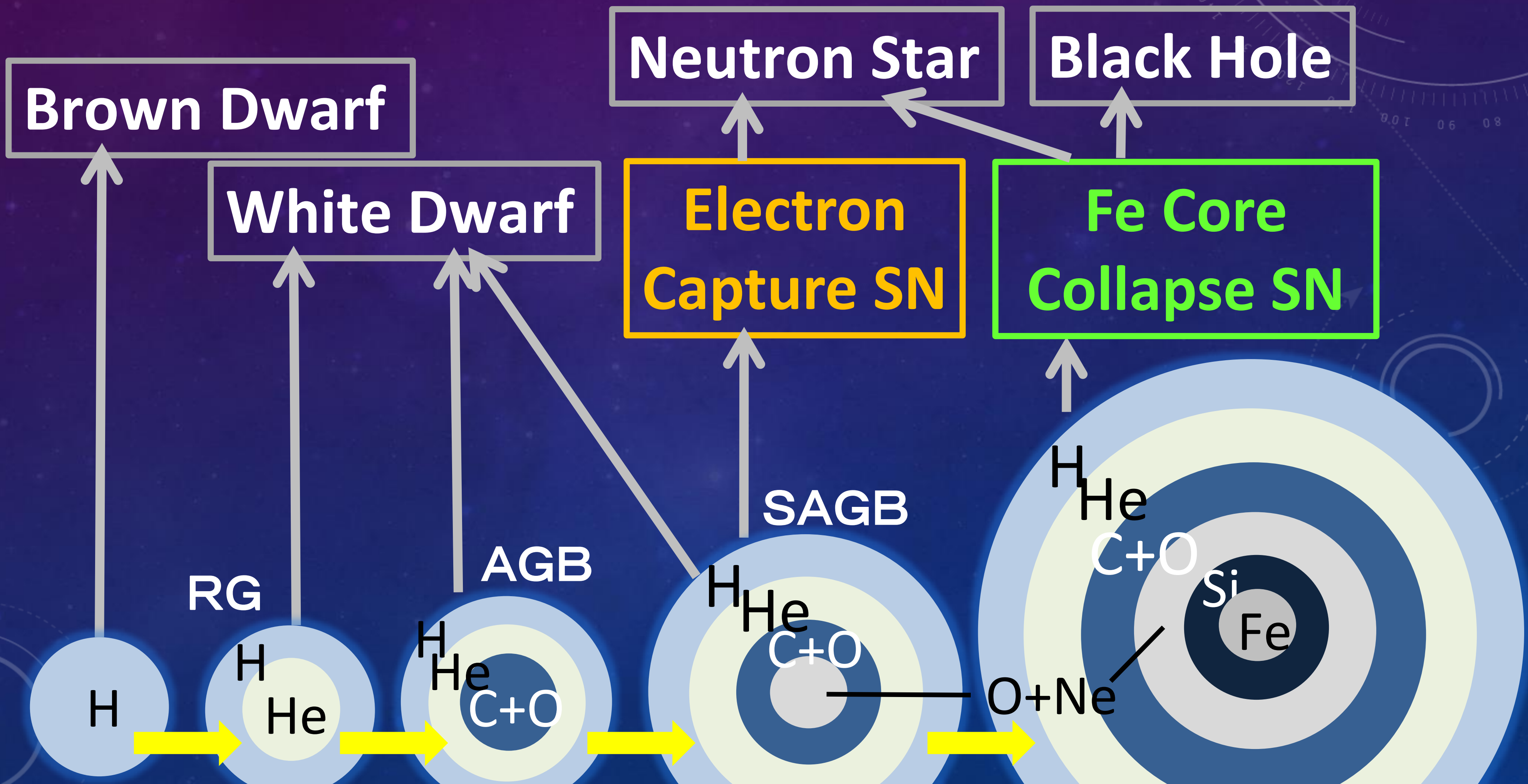
the first alert for SN !

✓warning system: SNEWS

"SuperNova Early warning system"

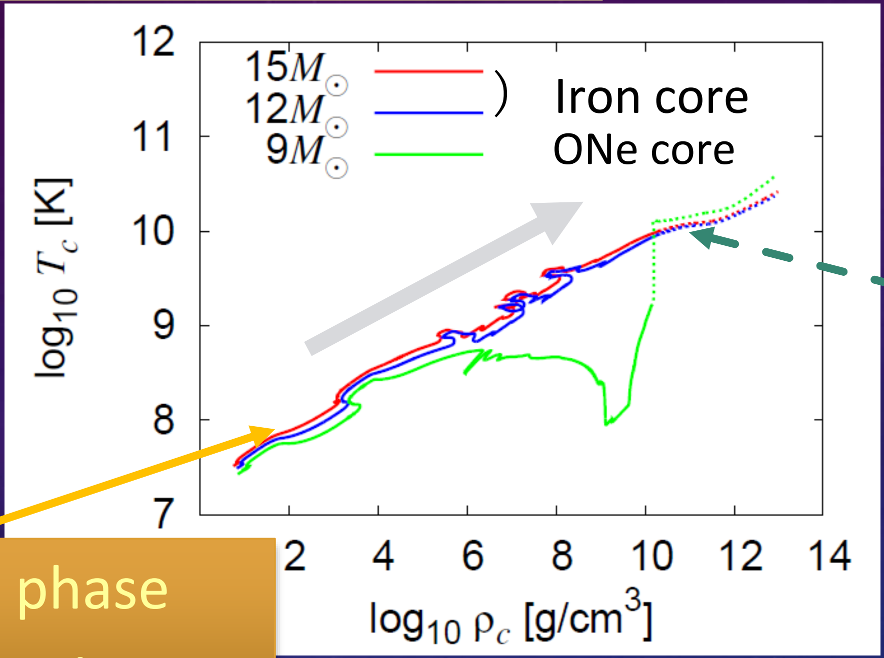
Purpose of present research

Can we detect pre-SN neutrinos ?



METHODS

Step.1 Back ground calculation



Collapsing phase
C. Kato et al.

H.Nagakura(Caltech) et al.

Stellar evolution phase
K. Takahashi et al.

Step.2 neutrino spectrum & luminosity

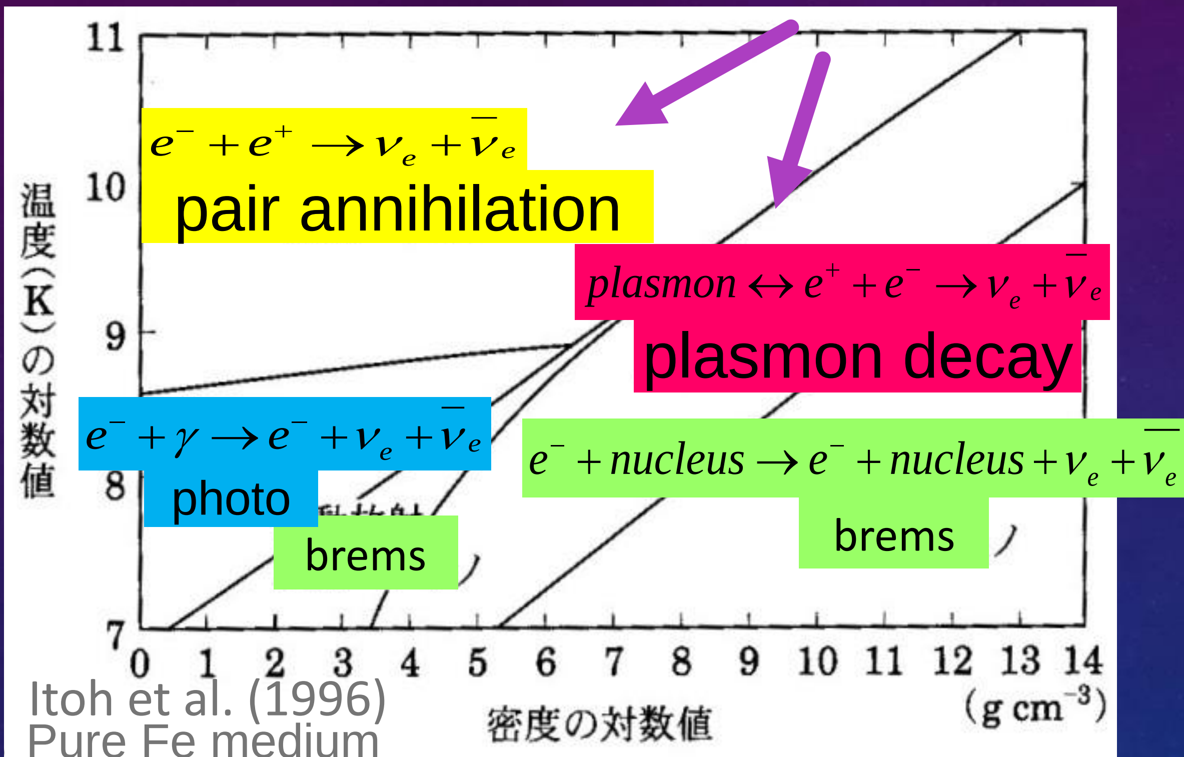
Post process

density
temperature
Ye
ve distribution

luminosity & spectrum

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),

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

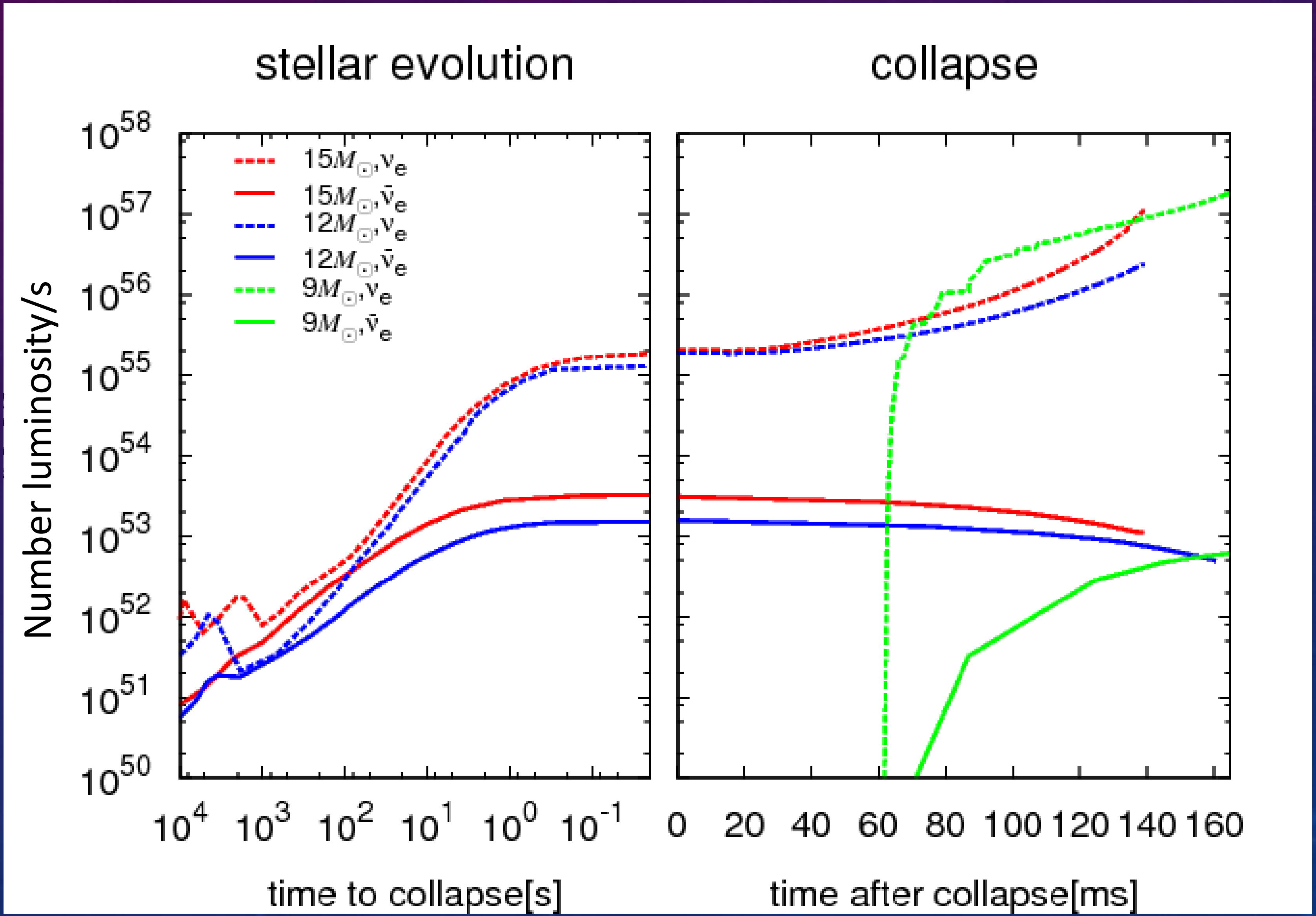
4. β^- decay (β^-),

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

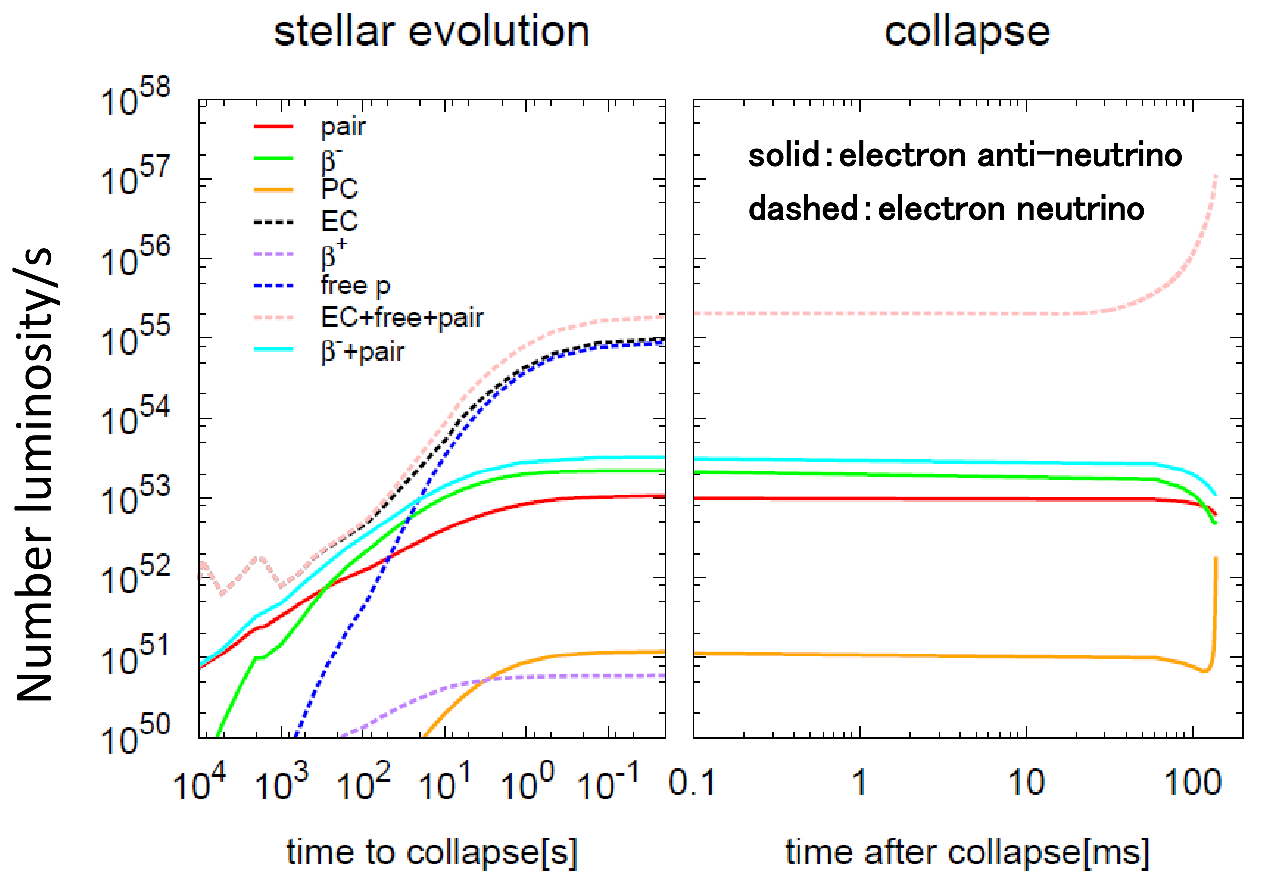
✓ electron capture by free proton

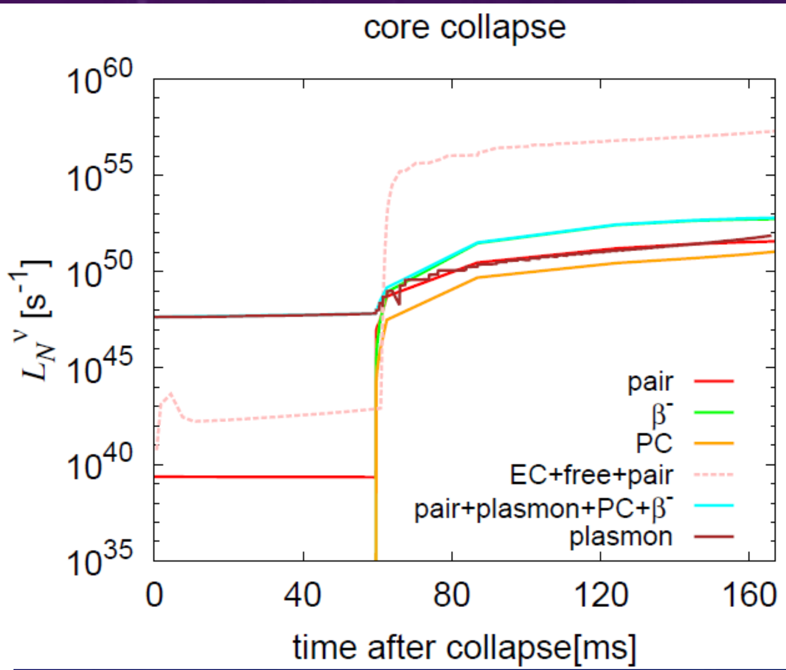
$$e^- + p \rightarrow n + \nu_e$$

Neutrino luminosities



Neutrino luminosities



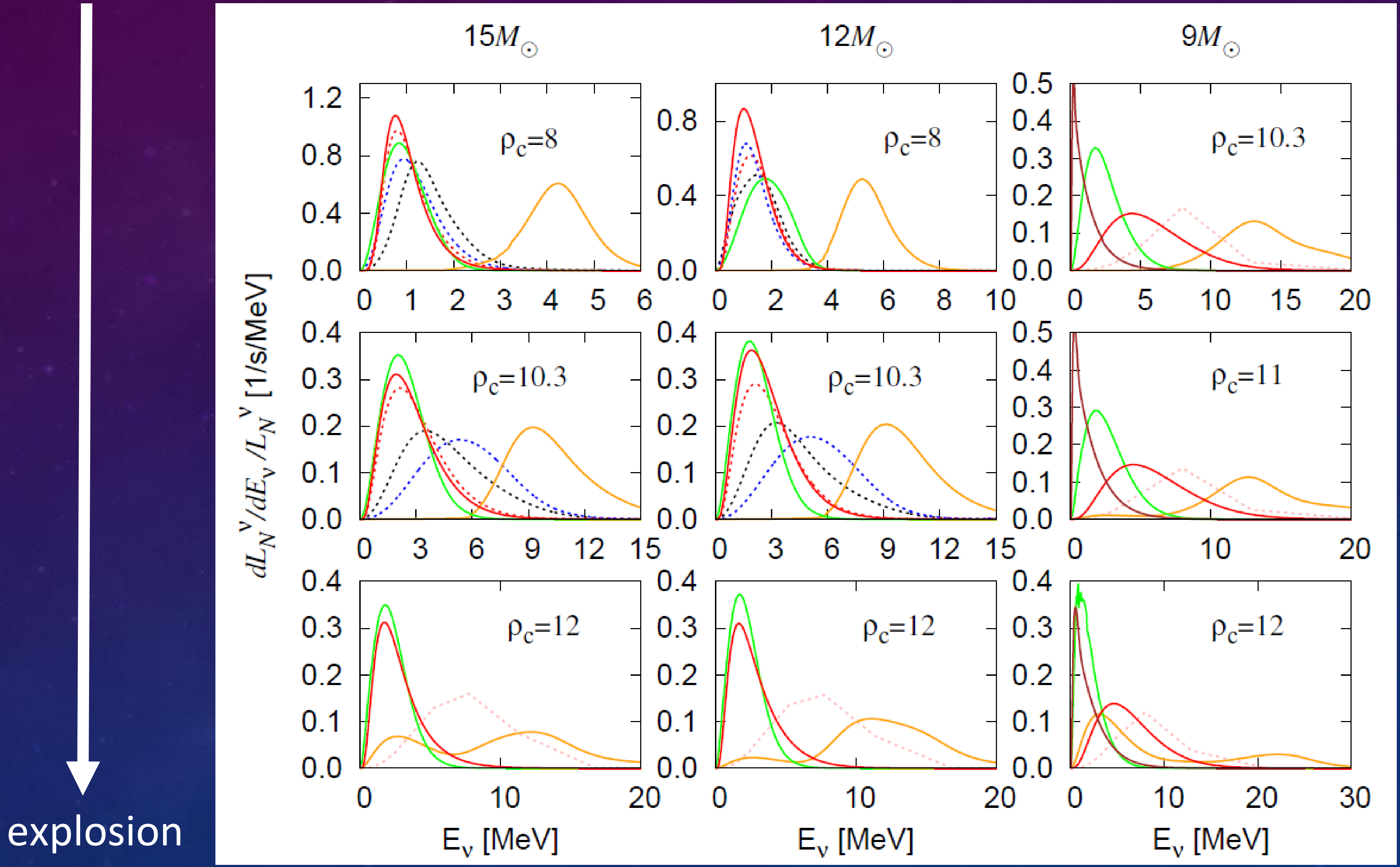


Electron Capture SN

explosion

Fe Core Collapse SN

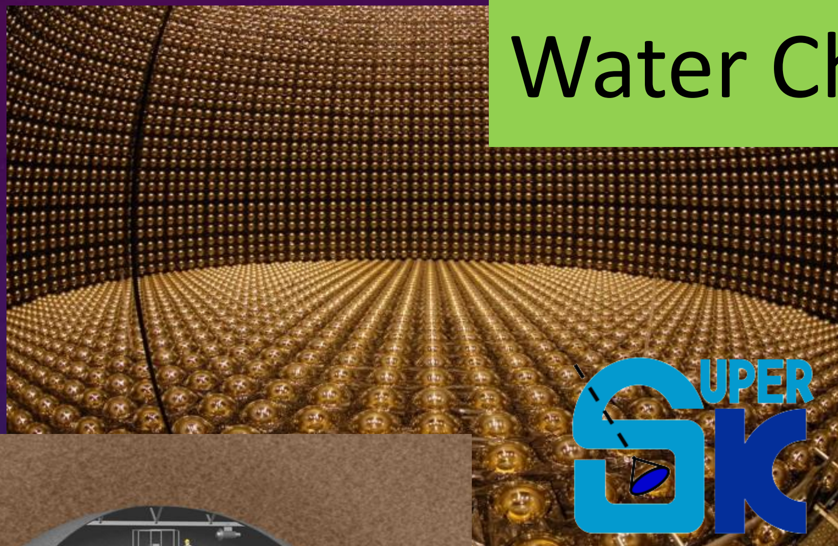
Spectrum



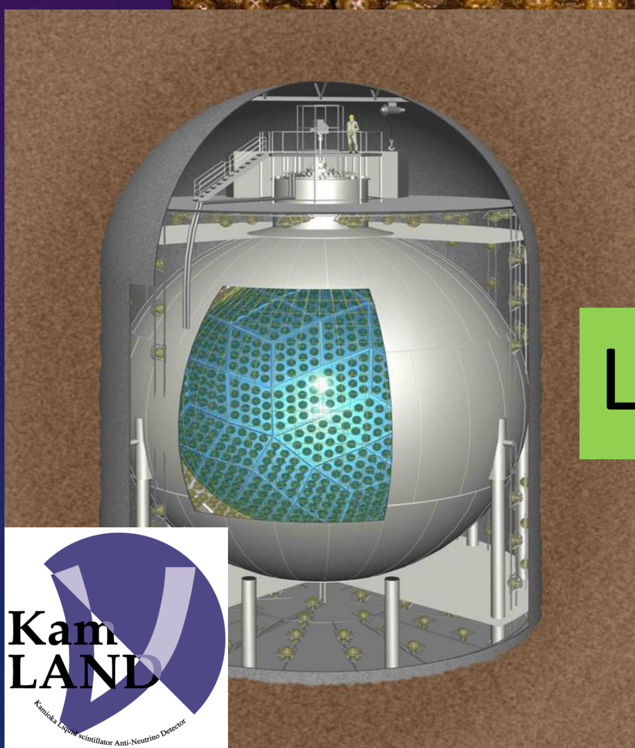
explosion
$15M_\odot$
$12M_\odot$
$9M_\odot$
ρ_c=8
ρ_c=8
ρ_c=10.3
ρ_c=10.3
ρ_c=10.3
ρ_c=11
ρ_c=12
ρ_c=12
ρ_c=12
$dL_N^\nu/dE_\nu/L_N^\nu$ [1/s/MeV]
E_ν [MeV]
E_ν [MeV]
E_ν [MeV]

Neutrino detectors

Water Cherenkov



Liquid scintillator

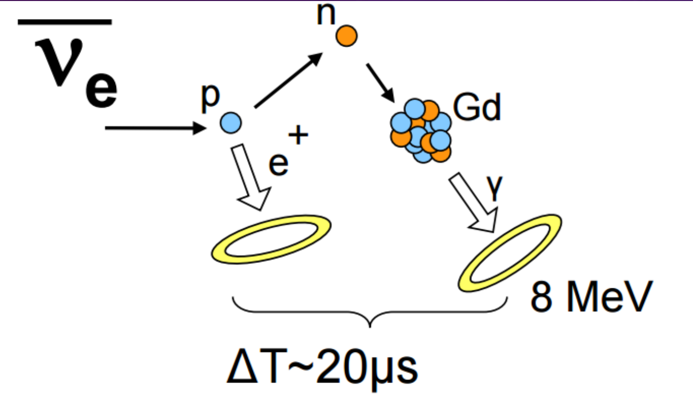


Neutrino detectors

✓low background

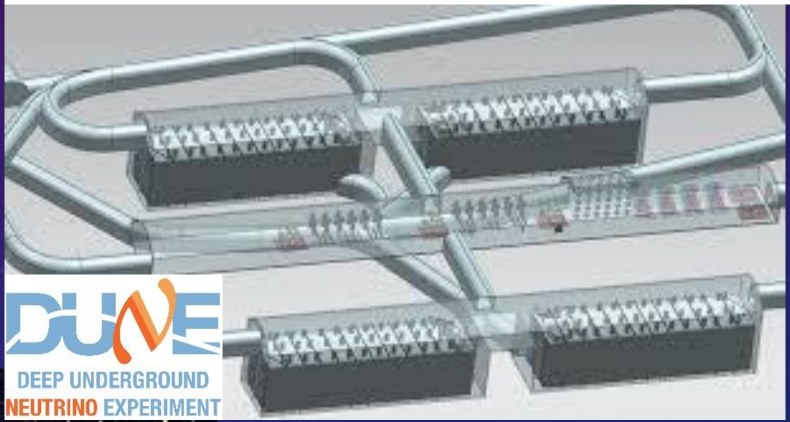
EX) SK+Gd

GADZOOKS!計画 Beacom and Vagins PRL93,171101 (2004)
(Gadolinium Antineutrino Detector Zealously Outperforming Old Kamiokande, Super!)



✓ν_e detection

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



宇宙の歴史をひもとく地下素粒子原子核研究

文部科学省研究費補助金　新学術領域　領域番号2603(平成26年～30年度)

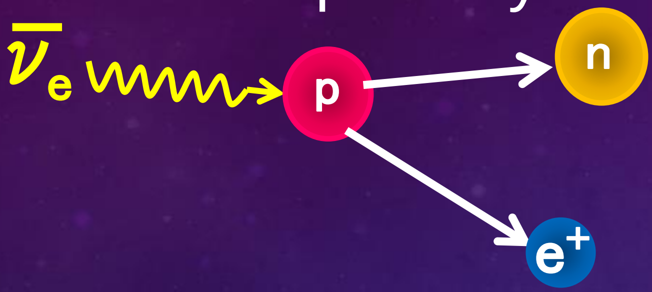
C02 近傍天体ニュートリノ包括的観測体制の構築と天体活動の研究

研究目的: 本研究の目的は，ベテルギウス，太陽や地球など近傍天体起源のニュートリノを観測を通じて，我々を形作る元素が天体内部でどのように作られるかや地球の熱源，宇宙の歴史のまさに「今」を究明する．特にベテルギウスなど近傍超新星爆発に焦点を当てて，超新星爆発前に放出される前兆ニュートリノと全種類の超新星ニュートリノを観測して超新星爆発にいたる天体活動を解明する．そのために，神岡の極低バックグランド下で稼働する3台のニュートリノ検出器（ Super-Kamiokande, KamLAND, XMASS) を同時かつ相補的に活用する体制を構築する．なかでも，KamLANDは世界で唯一，爆発前のケイ素燃焼反応起源(前兆)ニュートリノを検出する能力を持っている．本研究では，近傍天体ニュートリ

Set up of estimation

✓ reaction

Inverse-β decay



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

Survival probability

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

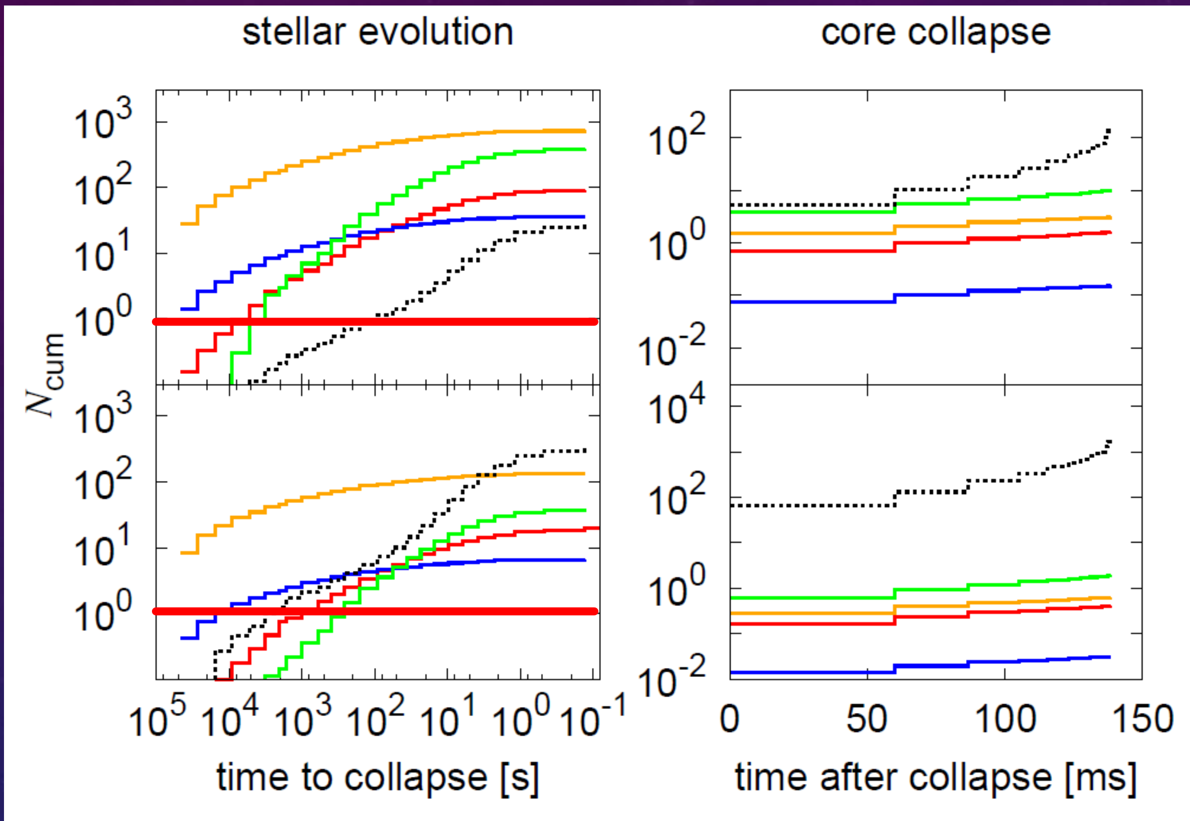
✓ Neutrino oscillation

- adiabatic oscillation
- 3 flavor mixing

R=200pc

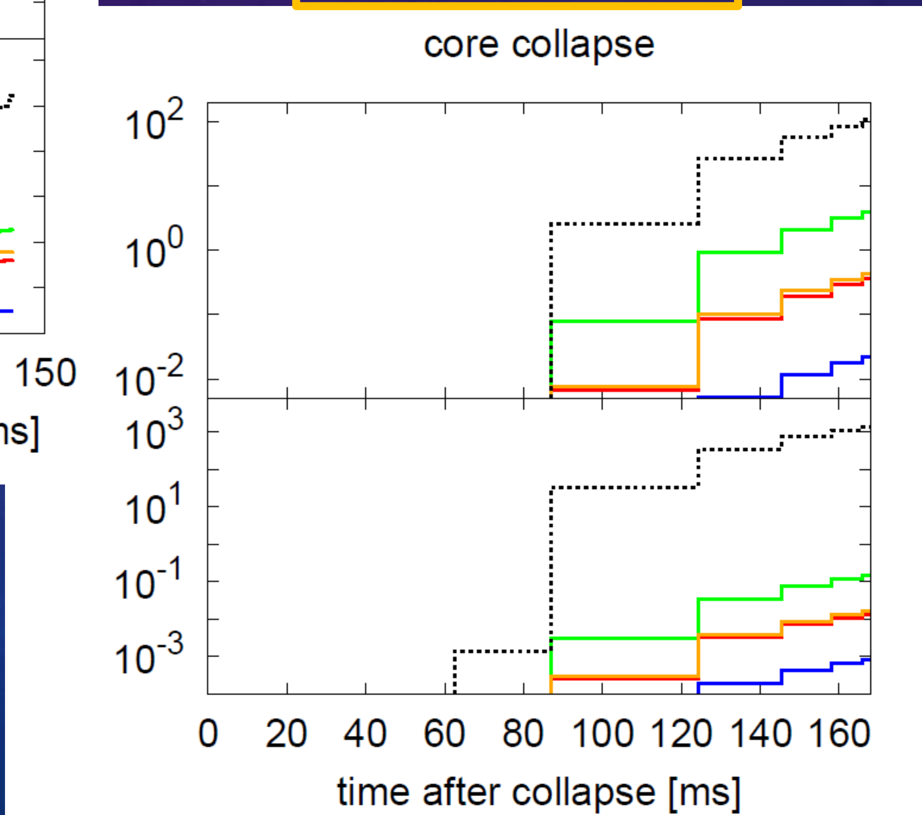
	SK	HK	KamLAND	JUNO	DUNE
threshold (MeV)	5.3	8.3	1.8	1.8	5.0
target number N	2.1×10^{33}	3.6×10^{34}	8.5×10^{31}	1.7×10^{33}	6.0×10^{33}

Event numbers



Fe Core Collapse SN

Electron Capture SN



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
nueb	KamLAND	0.05	0.002	23.7	5.22	36.0	6.64
nueb	Hyper-K	11.7	0.43	87.6	11.4	392	40.2
nueb	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

Summary & future work

- ☑ We focus on the 2 different types SN progenitors.
- ☑ At first, we calculate the background hydrodynamic values
- ☑ By post-process calculation, we get continuous neutrino luminosity from stellar evolution phase until core bounce.
- ☑ anti-neutrinos: 2 types of progenitors by pre-SN neutrinos

  alert for following SN

  neutrinos: give information about core of both progenitors

- ☑ calculate neutrino luminosities & spectrum about many progenitor initial masses
- ☑ detail physics derived from the observations

Future study

Continuous neutrino spectrum & luminosity calculation of whole massive star evolutions