恒星進化から超新星爆発にわたる連続的なニュートリノ光度の計算と内部物理量との関係性

Continuous ν emission from massive star and supernova & relationship between ν’s and stellar interior

Chinami Kato (TUS)

collaborators: Akira Ito (Waseda), Ryuichiro Akaho (Waseda), Hiroki Nagakura (NAOJ)

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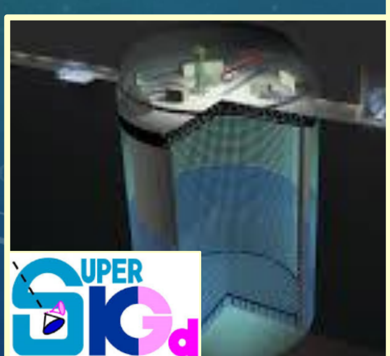
Development of ν observation

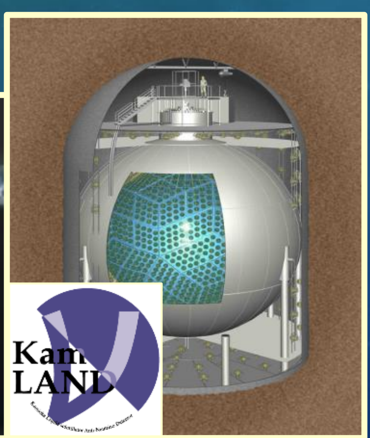
✓low background at low-energy neutrino (~MeV)

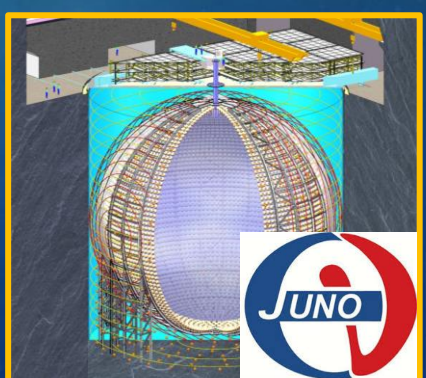
✓various neutrino detection channel

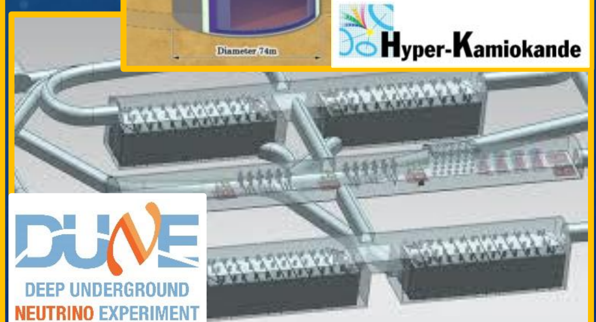
e.g. inverse-β decay
nuclear coherent scattering
nuclear charged current

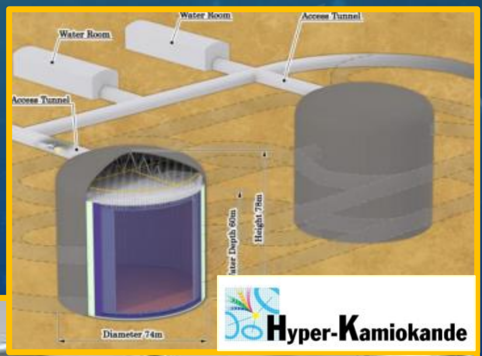
✓all flavor neutrino observation











Continuous ν emission & detection

✓ efficient neutrino emission from deep interior

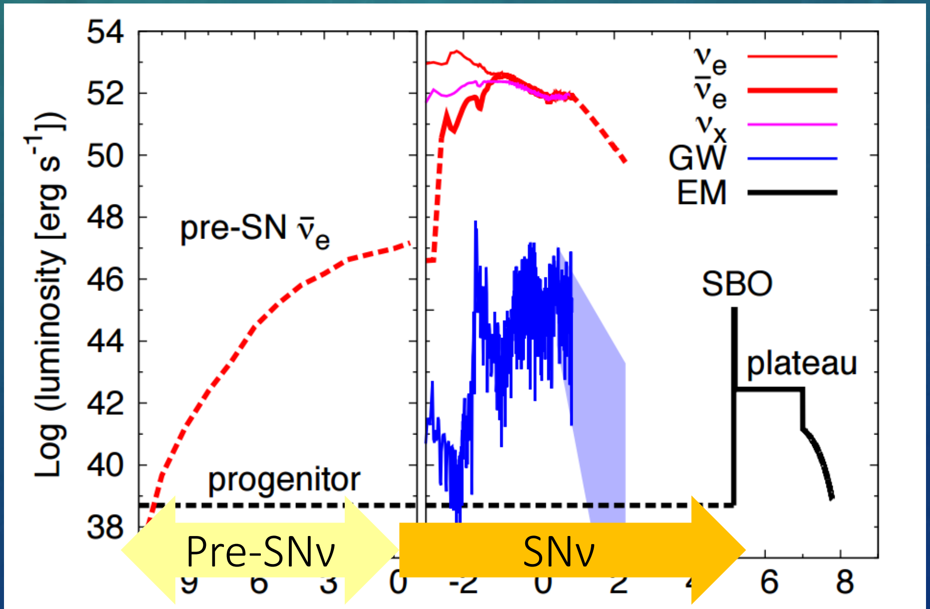
➡ key physics on massive star evolution and SN dynamics

✓ observational development

➡ long-time ν observation

(a few days before and a few minutes after SN)

consistent theoretical treatment of ν's throughout evolution



Nakamura 2016

Combination of preSN & SN neutrinos

Feel free to add more!!

✓ PreSN neutrino obs.

- progenitor type (e.g., ECSNe/FeCCSNe)
- Si-shell burning time
- progenitor structure

✓ SN neutrino obs.

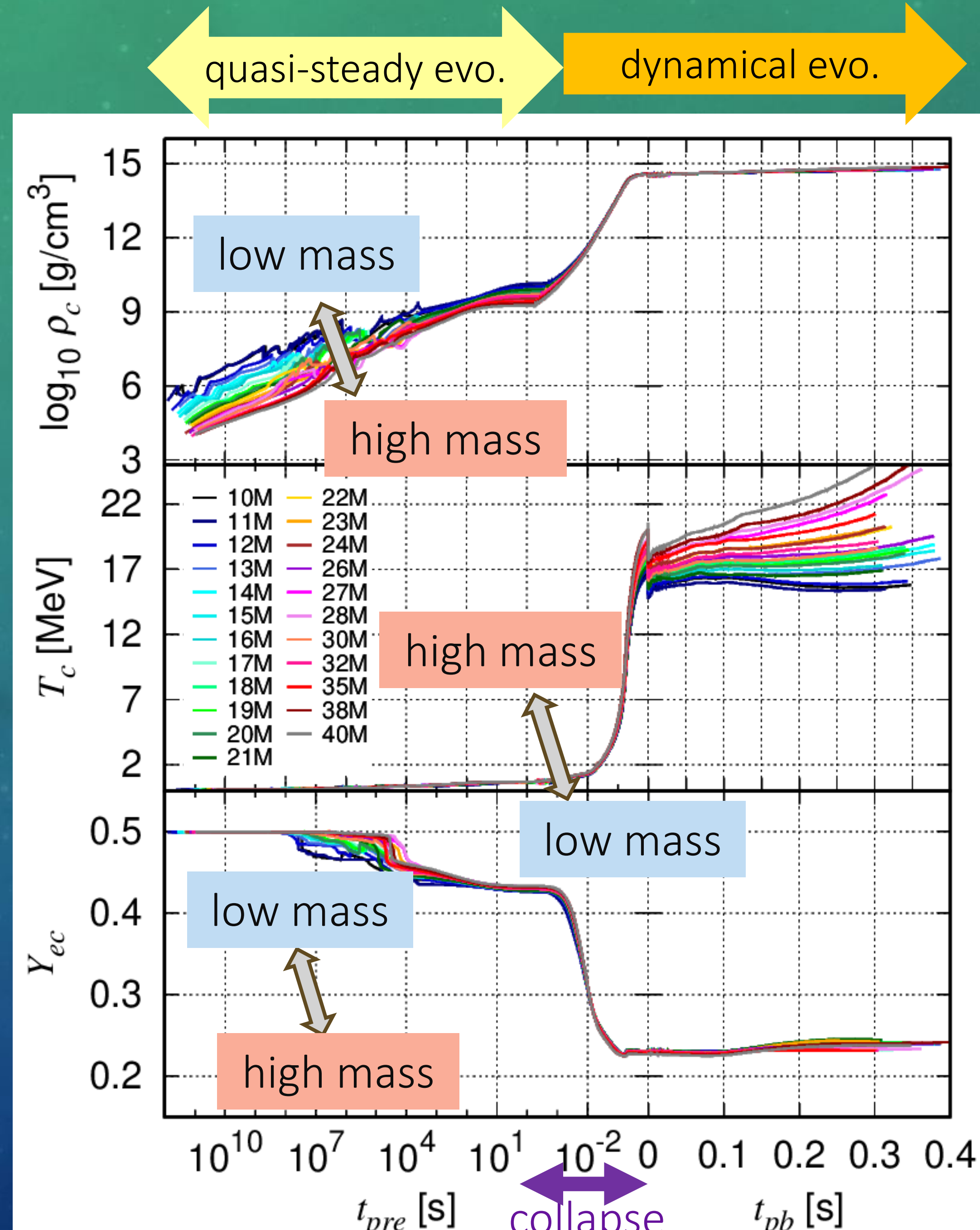
- progenitor structure
- BH formation
- bounce time
- multi-dimensional properties (e.g, SASI/LESA)
- explosion energy
- neutrino mass hierarchy
- beyond standard model

How about the combination of these two observation?

Stellar models

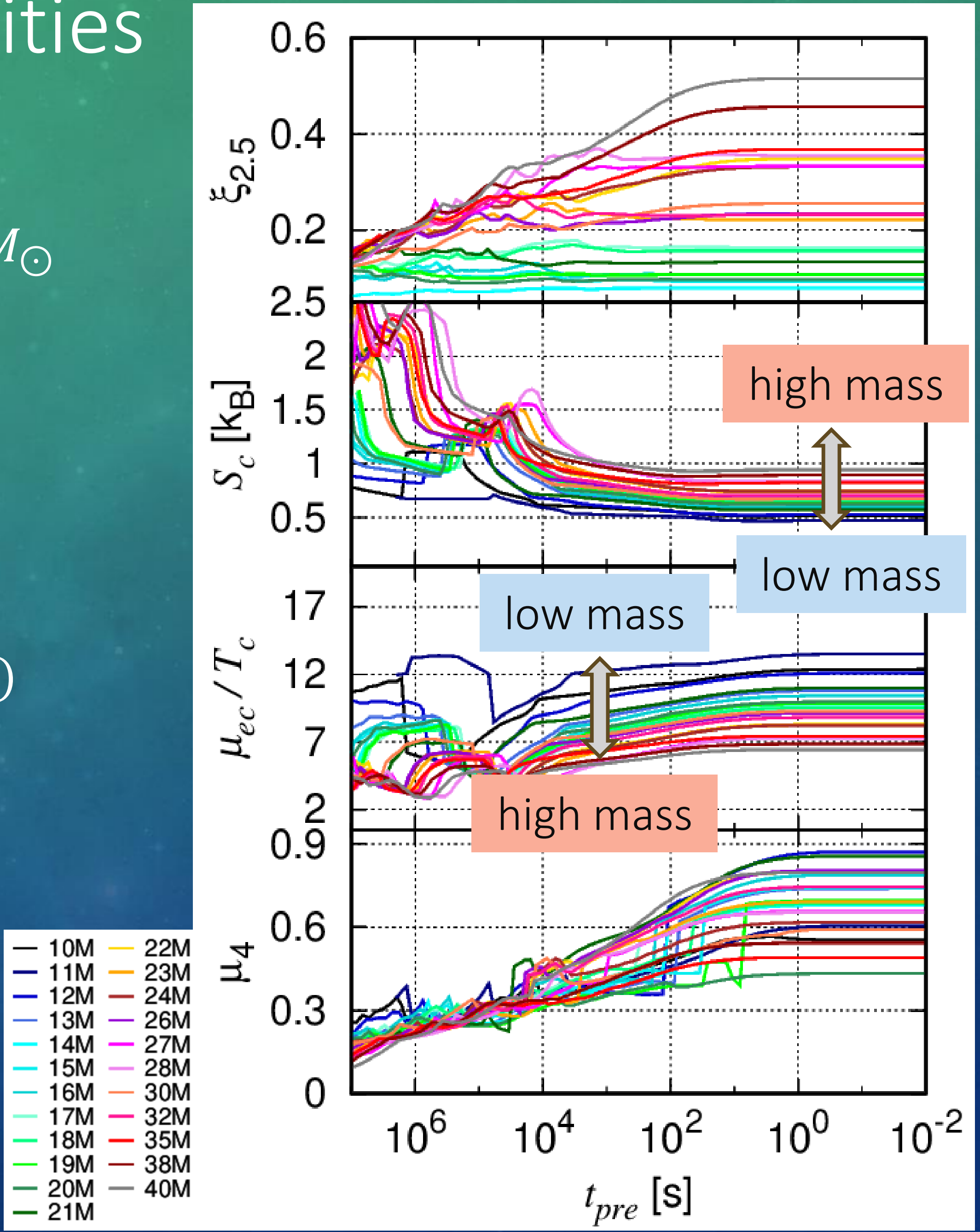
23 initial mass models

- ✓ $10M_{\odot} - 40M_{\odot}$
- ✓ solar metallicity
- ✓ quasi-steady evo.
  - ➡ HOSHI codes
    (1D quasi-steady code)
- ✓ dynamical evo.
  - ➡ Akaho codes
    (1D full GR rad+hydro code)



Important quantities

- ✓ compactness $\xi_{2.5}$
  $\xi_{2.5} = M/R(M)$ at $M = 2.5M_{\odot}$
- ✓ central entropy S_c
- ✓ degeneracy μ_{ec}/T_c
- ✓ Ertl's parameter μ_4
  $\mu_4 = dM/dr$ at $M(S = 4k_B)$
- ✓ CO core mass M_{co}
- ✓ Iron core mass M_{Fe}



Neutrino emission

✓ quasi-steady evolution: postprocess manner
(hydro quantities → NSE composition → ν emission)

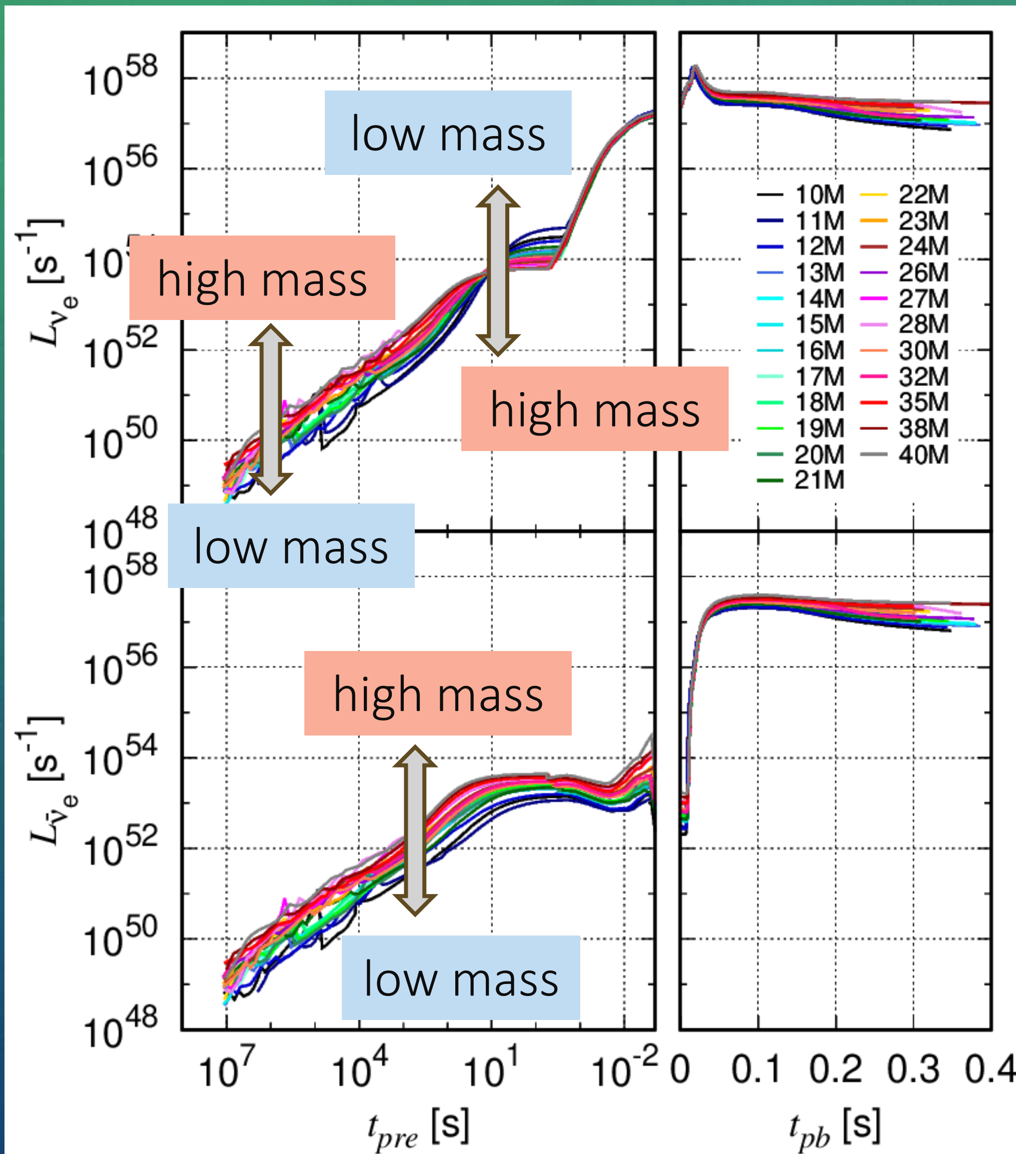
✓ dynamical evolution: ν_e ➡ transport results
$\bar{\nu}_e, \nu_x$ ➡ postprocess manner

✓ neutrino reaction

Neutrino emission process		Post process	Transport
pair	$e^- + e^+ \rightarrow \nu + \bar{\nu}$	✓	✓
EC by free p	$e^- + p \rightarrow n + \nu_e$	✓	✓
EC by nuclei	$(Z, A) + e^- \rightarrow (Z-1, A) + \nu_e$	✓	✓
β^- decay	$(Z, A) \rightarrow (Z+1, A) + e^- + \bar{\nu}_e$	✓	
PC by nuclei	$(Z, A) + e^+ \rightarrow (Z+1, A) + \bar{\nu}_e$	✓	
β^+ decay	$(Z, A) \rightarrow (Z-1, A) + e^+ + \nu_e$	✓	
PC by nuclei	$e^+ + n \rightarrow p + \bar{\nu}_e$		✓
Brems	$N + N \leftrightarrows N + N + \nu + \bar{\nu}$		✓

Transport calc. include scattering with nuclei/e^-/nucleon

Neutrino number luminosities



✓ ν_e: ECs by free p & nuclei

➡ high T, ρ, Y_e

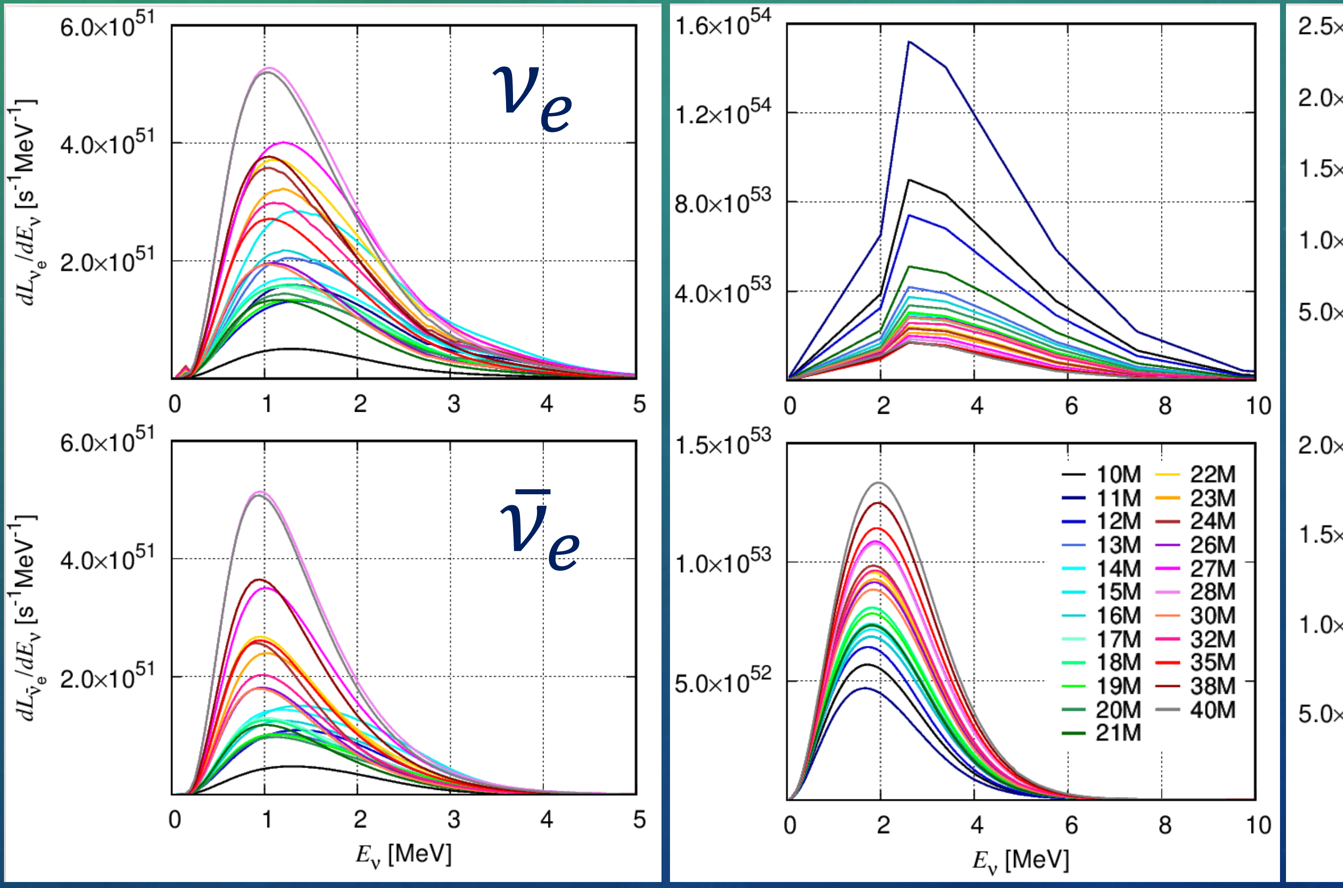
✓ $\bar{\nu}_e$: pair & β^-decay

➡ high T

relatively low ρ, Y_e

Neutrino spectrum

✓ Average energy is independent of initial mass



-1h collapse 200ms

Neutrino oscillation & detector info.

✓ terrestrial neutrino flux

$$F_{\bar{\nu}_e} = pF^0_{\bar{\nu}_e} + (1-p)\,F^0_{\bar{\nu}_x}$$
$$F_{\nu_e} = pF^0_{\nu_e} + (1-p)\,F^0_{\nu_x}$$

p	$\bar{\nu}_e$	ν_e
NO	0.675	0.0234
IO	0.024	0.3007

✓ detector information

detector: SK-Gd, KamLAND, JUNO, DUNE

reaction: inverse-β decay ($\bar{\nu}_e$), CC reaction for Ar (ν_e)

distance: 200pc

detector	volume	Energy threshold(ν)
SK-Gd	32kt	5.3MeV
KamLAND	1kt	1.8MeV
JUNO	20kt	1.8MeV
DUNE	40kt	10 MeV

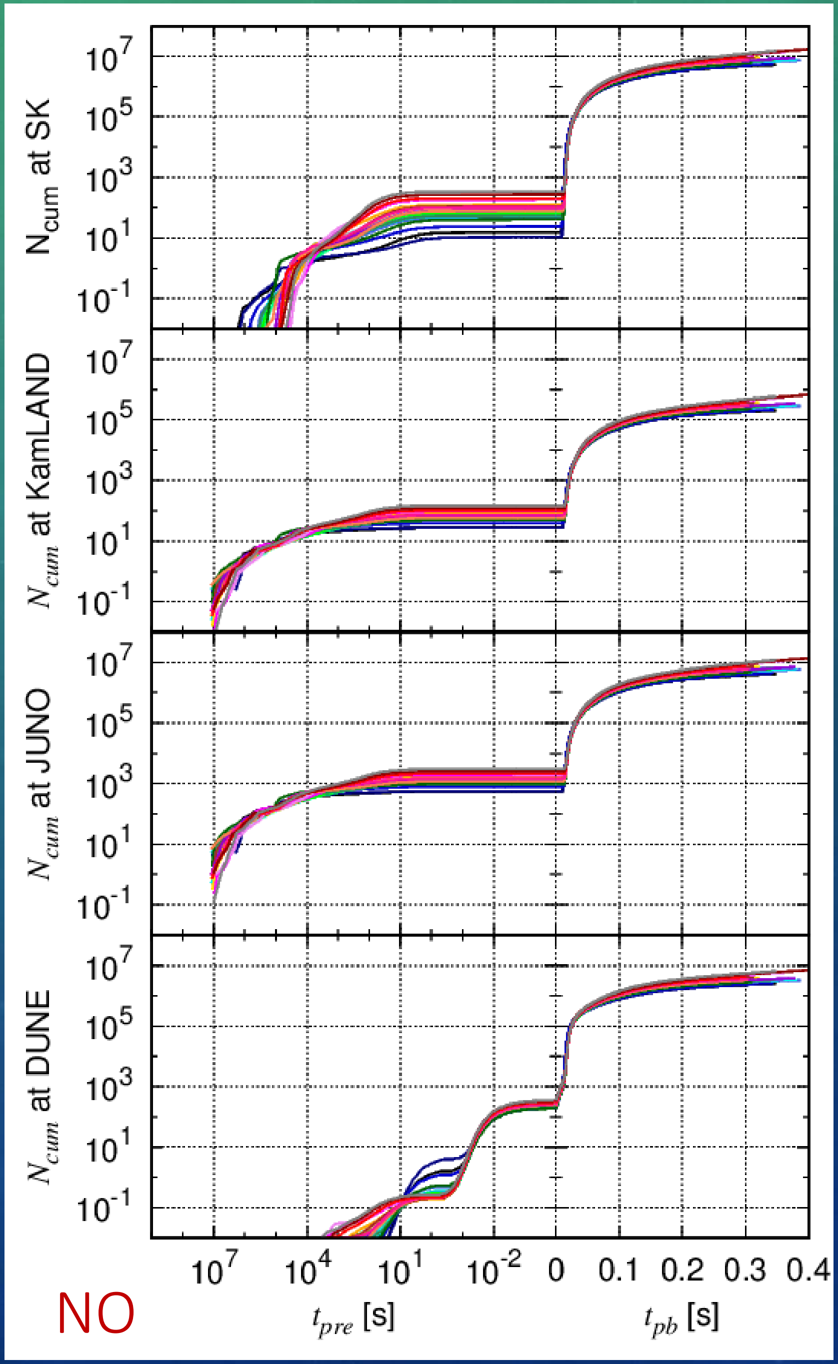
Neutrino events

✓ PreSN ν events: O(10)-O(1000)
SN ν events: O(10^6)-O(10^7)

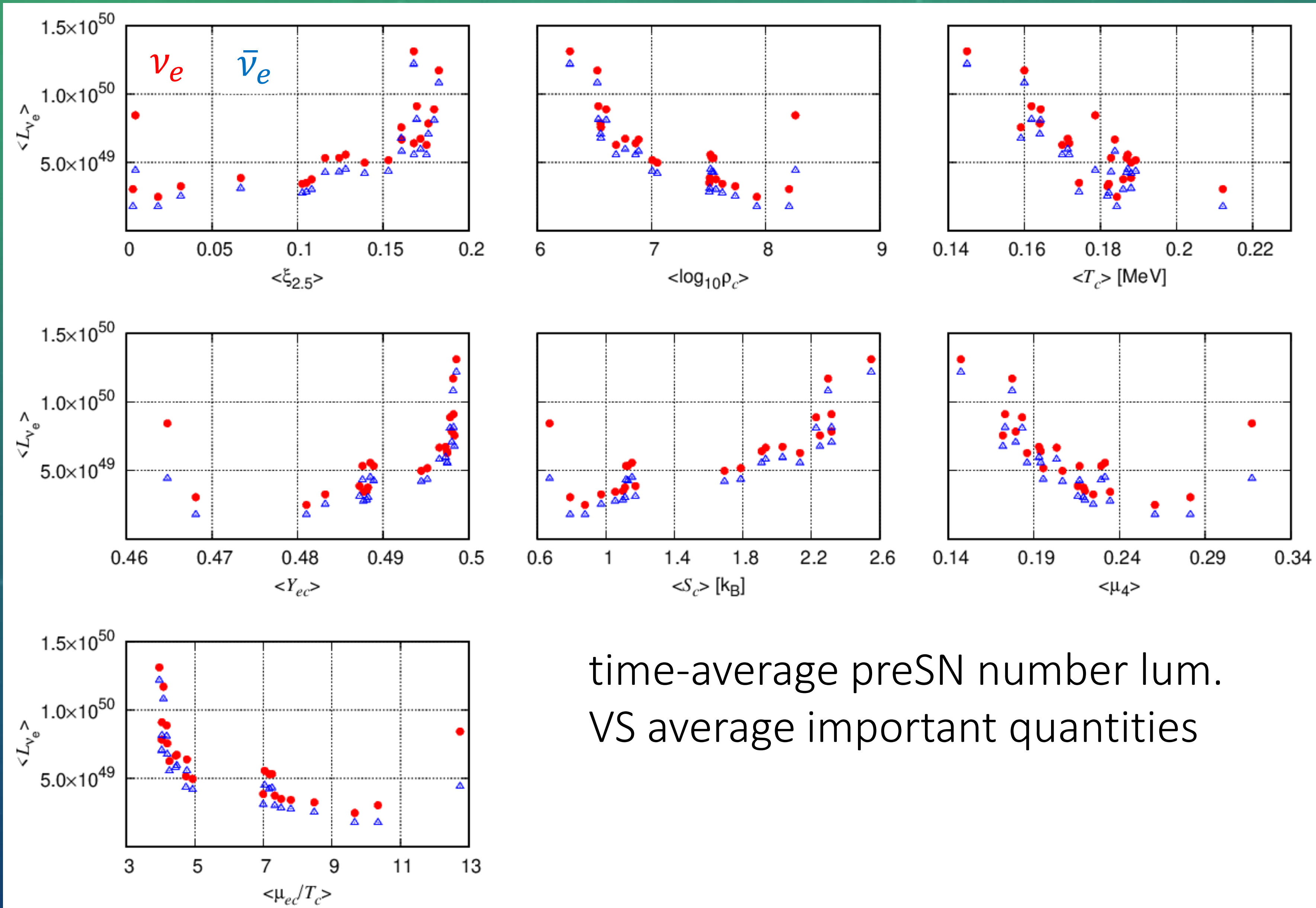
✓ SK events in preSN phase
➡ high energy threshold
➡ large mass dependence
➡ high-energy neutrino info.?

Ex) total event at JUNO

mass	Pre collapse	After collapse
$10M_{\odot}$	557	4.1×10^6
$15M_{\odot}$	1111	6.1×10^6
$24M_{\odot}$	1423	7.4×10^6



Correlation1: average preSN lum. VS important quantities

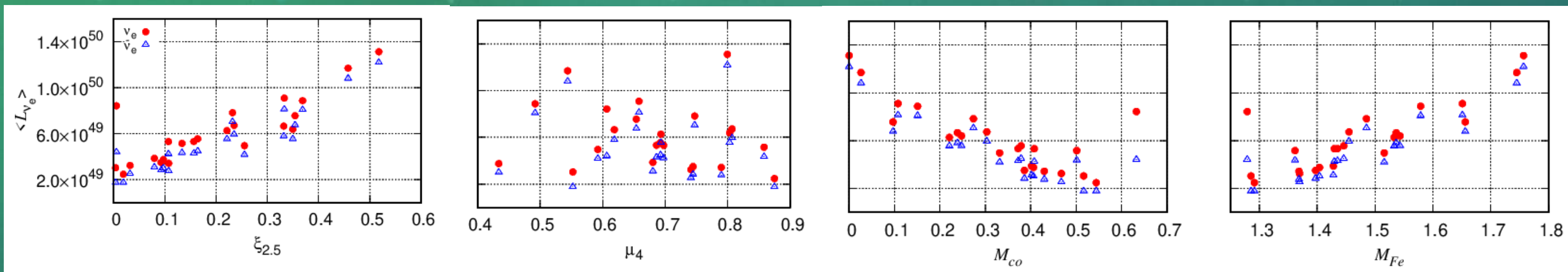


time-average preSN number lum.
VS average important quantities

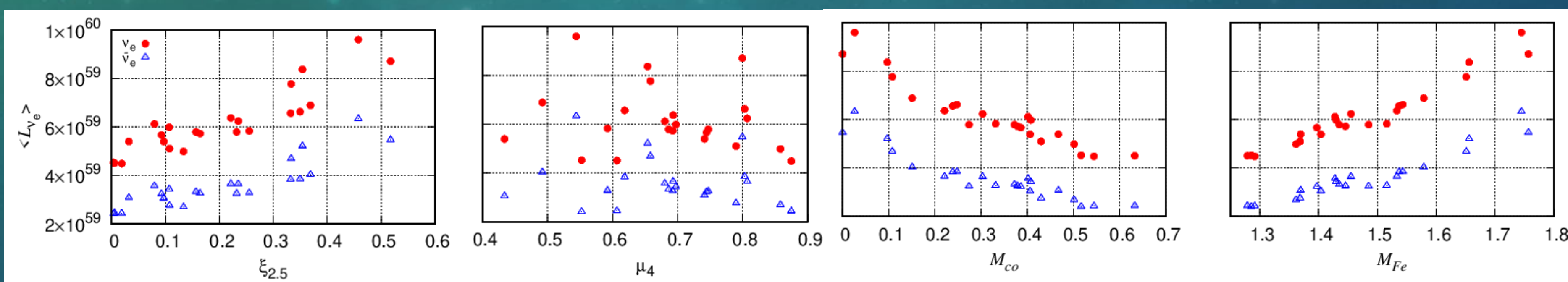
Correlation2: average lum. VS important quantities

PreSN ν

Important quantities at collapse



SN ν



✓average neutrino number luminosity correlates with neutrino luminosity except μ_4

Summary & future works

Summary

✓ long-term ν observation era! ➡ consistent theoretical treatment

✓ systematic estimation of neutrino luminosities and spectrum from a few days before to a few hundreds ms after bounce

✓ PreSN ν events: O(10)-O(1000)

- SN ν events: O(10^6)-O(10^7)

✓ clear correlations between average ν lum. and several important quantities

Future works

✓ continuation of current correlation studies

✓ connection to PNS phase

✓ creation of public database