Neutrino 2026: XXXII International Conference on Neutrino Physics and Astrophysics @University of California, Irvine

Comprehensive Neutrino Light Curves and Spectra: From Pre-supernova Evolution to Early Supernova Phase

arXiv: 2603.09810

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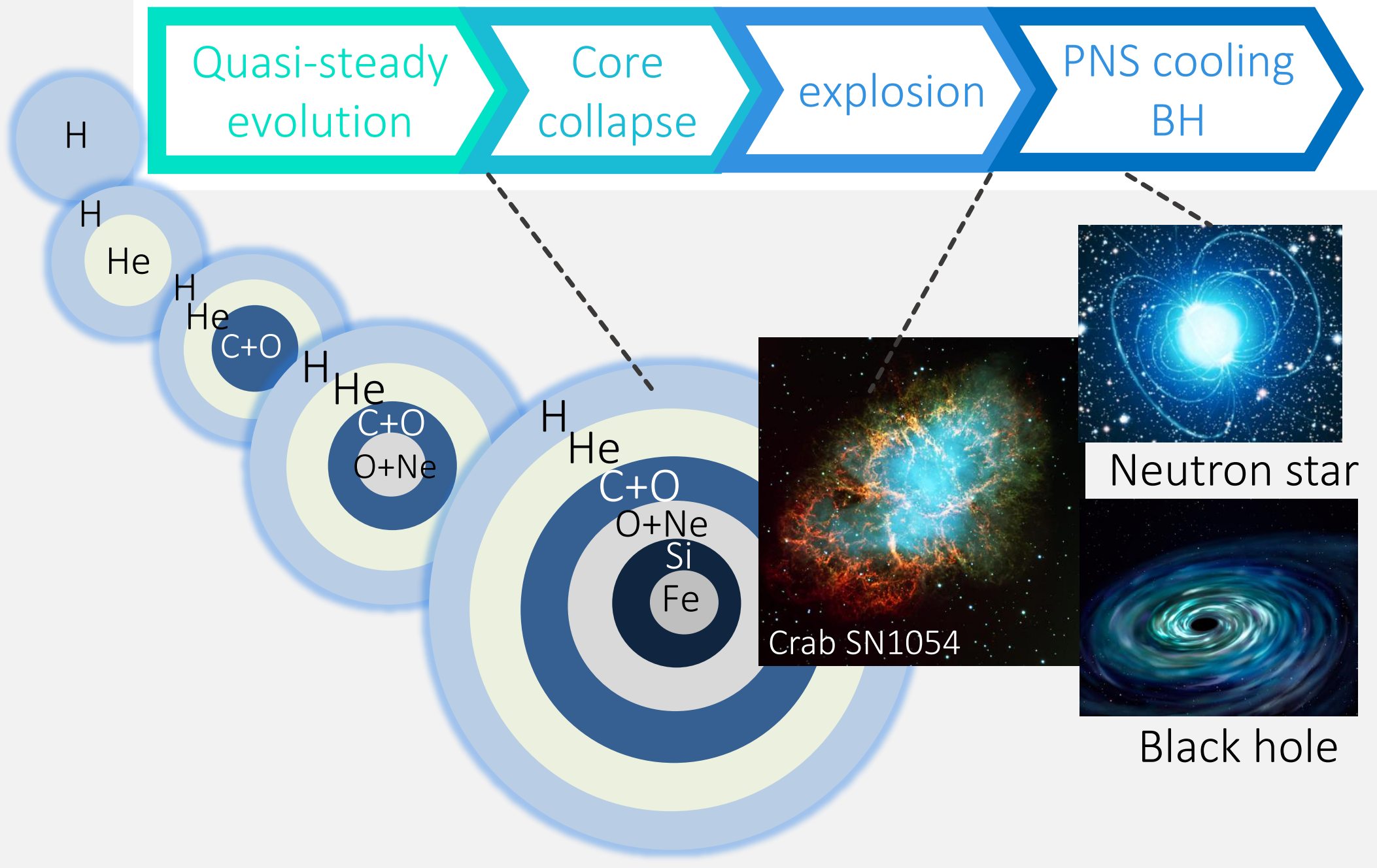
Abstract

Recent advances in neutrino observation techniques have opened the door to pre-supernova (preSN) neutrinos emitted from progenitors of core-collapse supernova. They can serve not only as progenitors of the subsequent explosion, but also as powerful tools for addressing unresolved questions in stellar evolution theory. In this study, for the first time, we comprehensively calculate the neutrino luminosities and spectra from several days before the explosion to 200 ms after core bounce. We also investigate correlations between neutrino emission and key physical parameters in progenitors, and discuss what information on progenitors and explosion dynamics can be obtained by connecting observations of preSN and SN neutrinos.

Introduction

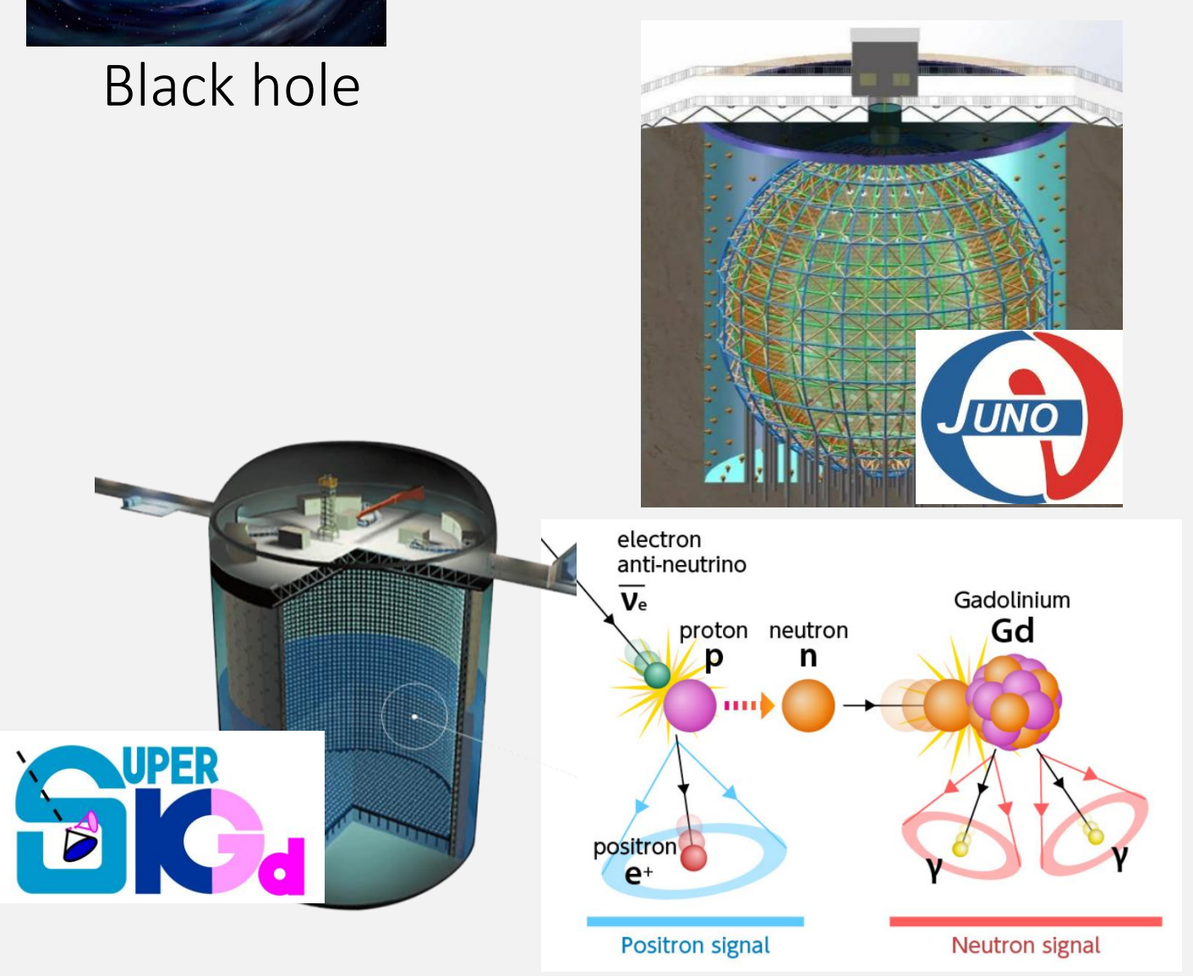
✓Progenitors in core-collapse supernova (CCSN)

The progenitors of CCSN are massive stars with initial masses above $8M_\odot$. Neutrinos (ν's) play an extremely important role throughout the evolution of massive stars. e.g., core cooling and assistance / the explosion mechanism



✓Observation of MeV neutrino

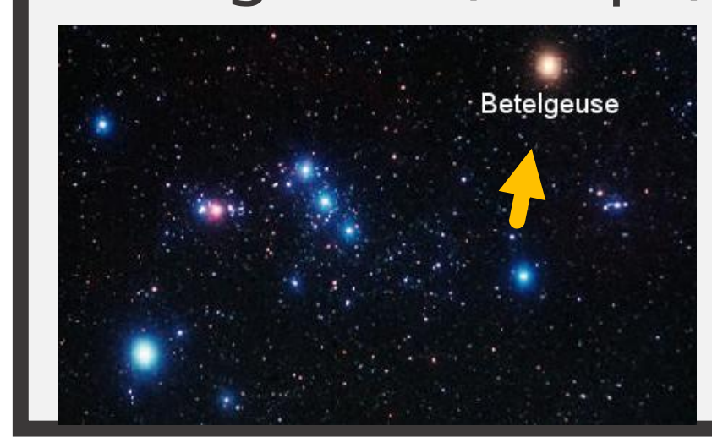
Observational techniques for MeV ν's have advanced remarkably, for example, BG reduction.
e.g., SK-Gd / liquid scintillator detectors



✓New observational target: preSN ν's

With advances in observational techniques, the observation of preSN ν's emitted from progenitors before explosion has come within reach. Such observations may provide direct constraints on the progenitor. They also play an important role as an alert for the upcoming explosion.

Betelgeuse (200pc)



Antares (160pc)

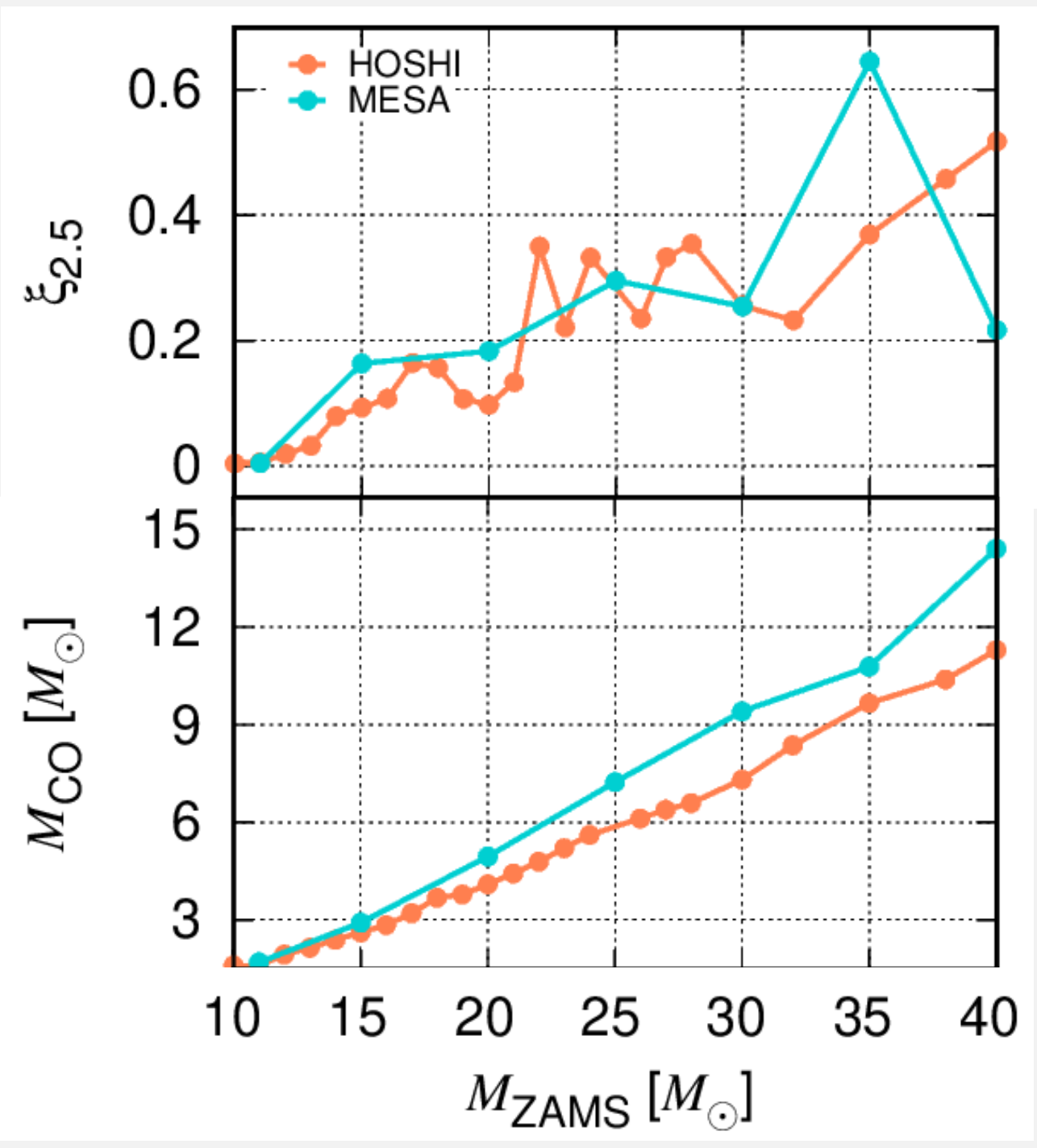
Expectation of PreSN ν observation (NO, Kato 2020a)

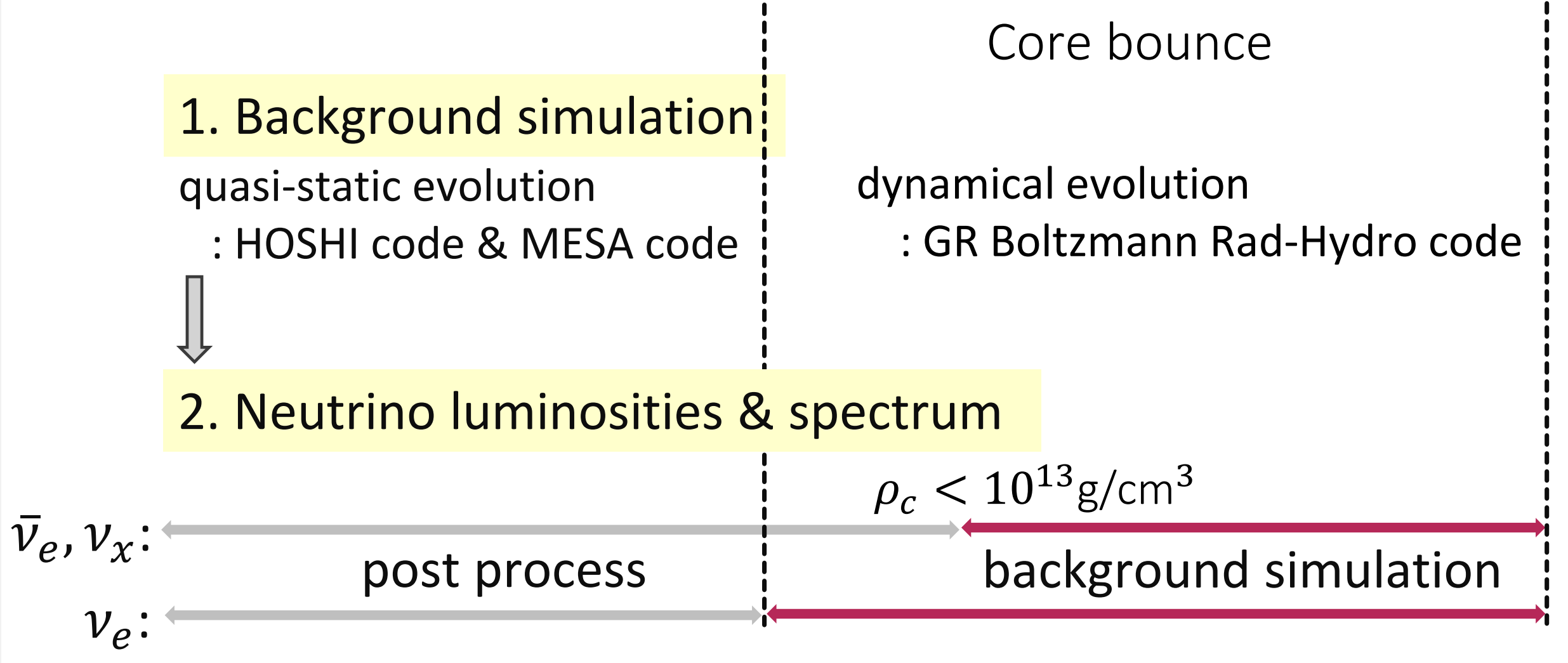
	# of events (2days)	first detection (d=200pc)	max distance (2days)
SK-Gd	54-58	0.2-10hr	320-430pc
JUNO	341	62hr	960pc

Methods and Models

✓Methods

- 28 models of 10–40$M_\odot$
- solar metallicity
- single stars
- ν luminosities and spectra:
  t_{pb}~ -160 yrs - 200 ms





1. Background simulation
quasi-static evolution
: HOSHI code & MESA code

dynamical evolution
: GR Boltzmann Rad-Hydro code

2. Neutrino luminosities & spectrum

$\rho_c < 10^{13}$g/cm^3
$\bar{\nu}_e, \nu_x$: post process | background simulation
ν_e: post process | background simulation

✓Key parameters for progenitors

The compactness ($\xi_{2.5}$) and The CO core mass (M_{co}) are better indicator than the initial mass (M_{ZAMS}) for characterizing the progenitor structures and explosion dynamics. We then investigate their correlation with ν emission.

Summary and Future works

✓ We computed long-term ν light curves and spectra from preSN evolution to 200 ms after bounce.

✓ Time-integrated ν numbers correlate with key parameters of progenitors such as M_{co} and $\xi_{2.5}$.

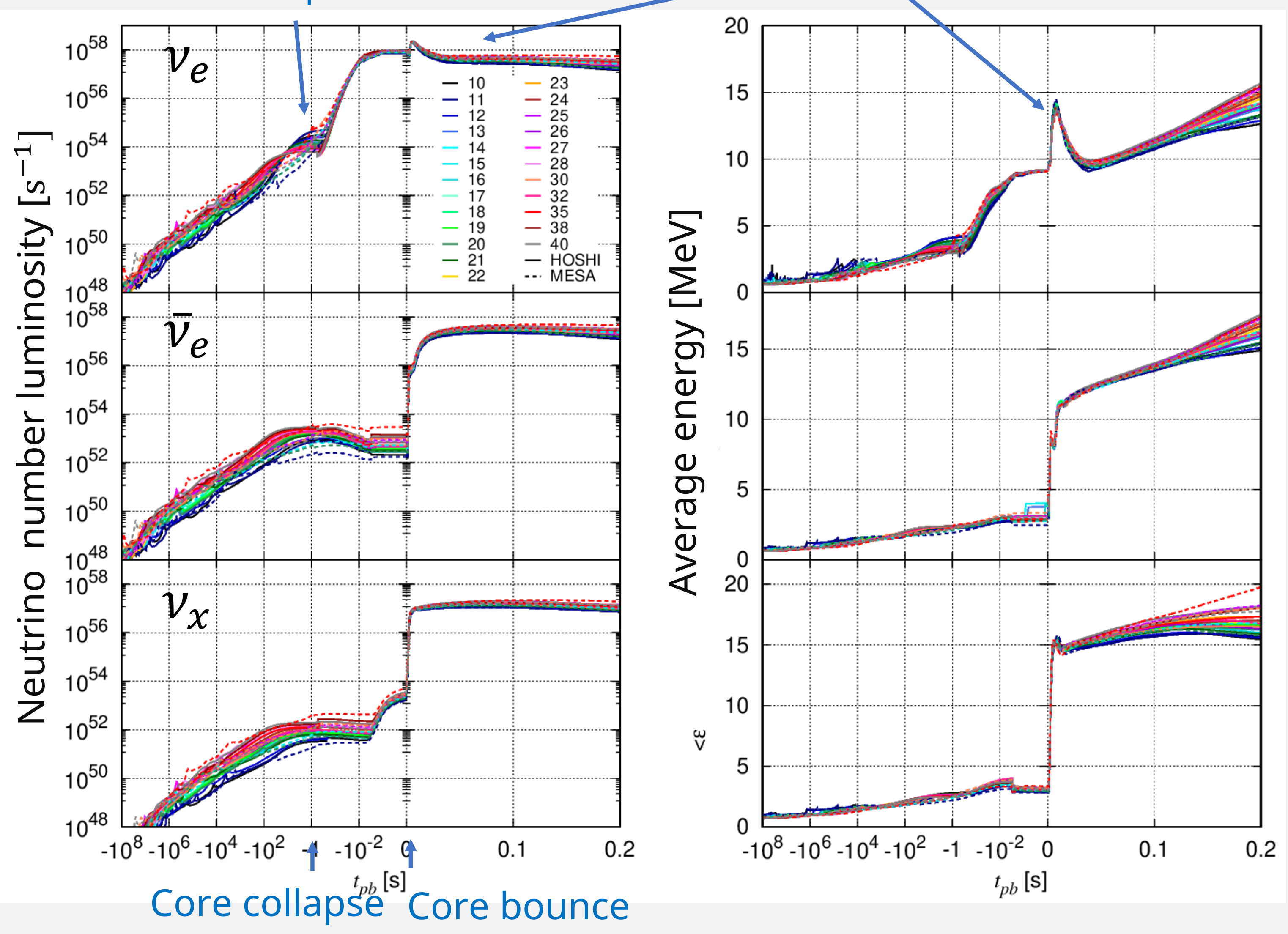
✓ Future work will test the robustness of these correlations against progenitor-physics uncertainties.

Results

✓Long-term preSN and SN ν emissions

Because of the numerical difference in the unstable phase

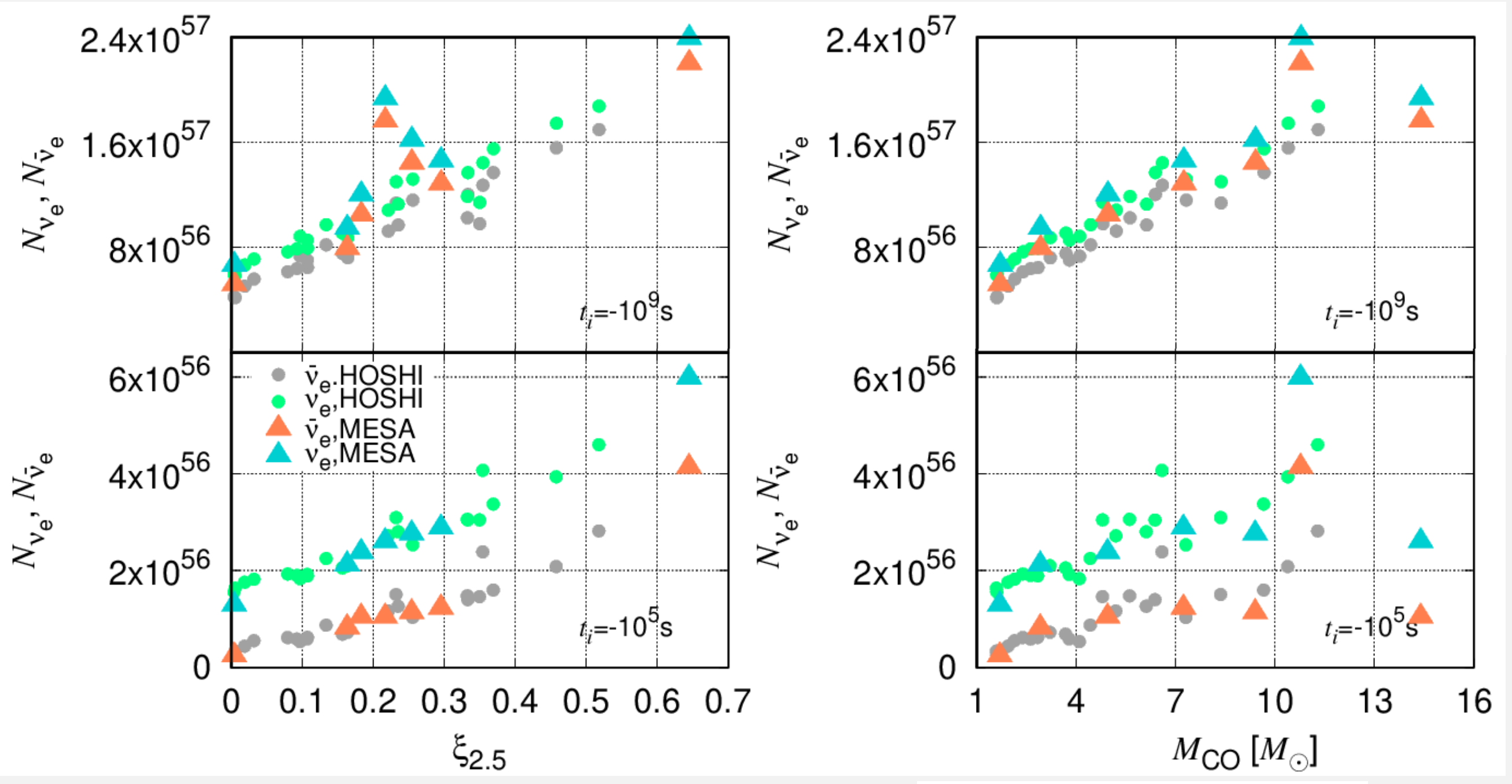
Neutronization burst



Core collapse Core bounce

✓Correlation between ν emission and key parameters

・Time-integrated preSN ν number VS $M_{co}/\xi_{2.5}$

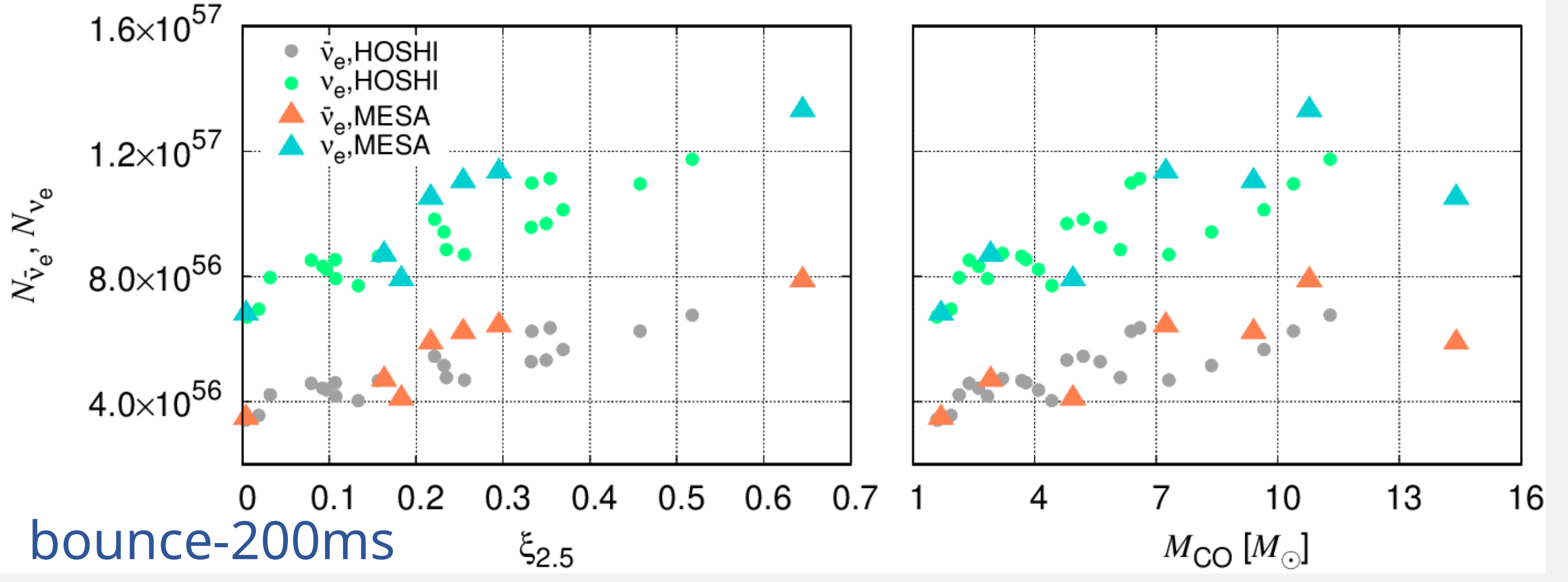


The time-integrated ν number
➡ t_i=$-10^9, -10^5$s
t_f=0 s (bounce)

$$N(t_i)=\int_{t_i}^{t_f} L_\nu^N(t)\,dt,$$
$$E(t_i)=\int_{t_i}^{t_f} L_\nu^E(t)\,dt,$$

* $\xi_{2.5}$: the inner-core structure → correlation with N_ν over ~1 day
* M_{co} : long-term shell evolution → correlation with N_ν over ~10^9 s
* The ν-emitting region << M_{co} in extended-core models
→ M_{co} ≠ the ν emitting boundary
= proxy for progenitor evolution

・Time-integrated SN ν number VS $M_{co}/\xi_{2.5}$



bounce-200ms

* clear correlation between N_ν and $\xi_{2.5}$ in early SN phase

✓Synergy of preSN & SN ν observations

- PreSN and SN ν's impose independent constraint on progenitor structures.
- Combining observational results of both phases enables a more robust reconstruction of the progenitor.
- Discrepancies between the two constraints may indicate missing physics in progenitor or SN models.