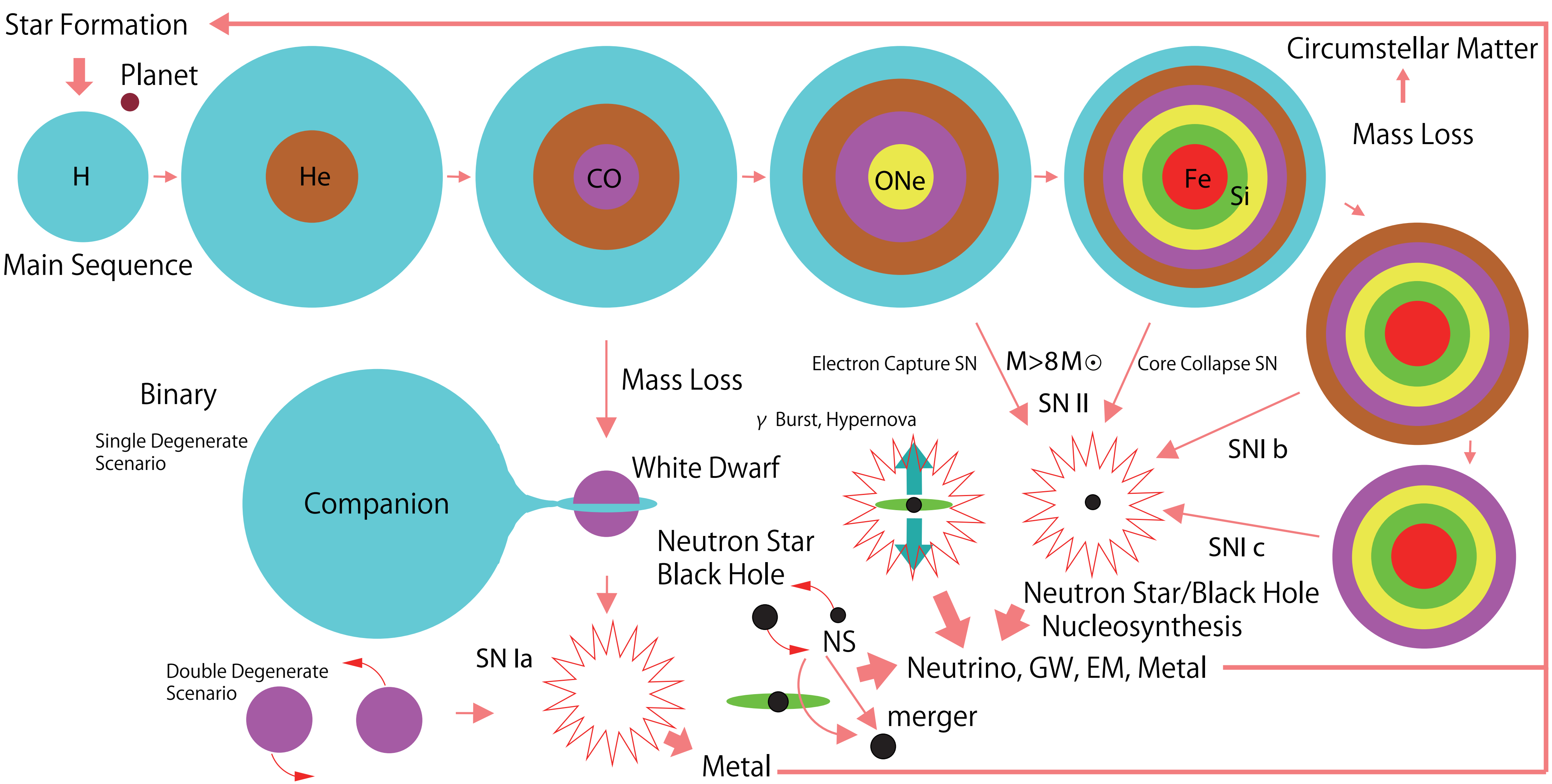
E02 group: Theoretical research on supernova neutrinos in connection with nuclear physics and cosmic chemical evolution

Hideyuki Suzuki (Tokyo Univ. of Science)



Massive stars: Core-collapse → NS/BH formation, ν emission, metal ejection
NS+NS/BH binaries: merger → metal(r-process elements) ejection
some WDs in binaries: Type Ia SNe → metal ejection

Core Members	Hideyuki Suzuki (Tokyo U. Science)
	Shoichi Yamada (Waseda U.)
	Masatoshi Takano (Waseda U.)
	Ken'ichiro Nakazato (Kyushu U.)
	Takuji Tsujimoto (NAOJ)
Collaborators	Hajime Togashi (RCNP)
	Wakana Iwakami (PD at Waseda and TUS)

Talks in this symposium

- Galactic and cosmic chemical evolutions, and their connection to neutrino astronomy: T. Tsujimoto (NAOJ)
- Boltzmann simulations of CCSNe and PNS cooling and their applications to collective neutrino oscillations: S.Yamada (Waseda)
- Burst and Cosmic Background Neutrinos from Core-Collapse Supernovae: K. Nakazato (Kyushu)
- Probing supernova interiors with neutrinos: Y. Suwa (Tokyo)

Grants for related research (FY2020-2021,2022-2023)

- T. Yoshida (UT, YITP): stellar evolution and nucleosynthesis
  大質量星における４０Ｋと中質量元素の元素合成：後期進化の対流混合による影響
- K. Nakamura (Fukuoka U.): 3D SN models and DSNB
  現実的な３次元超新星モデルに基づく超新星背景ニュートリノ解析
- C. Kato (TUS): collective neutrino oscillation
  ニュートリノ集団振動を考慮した超新星ニュートリノスペクトルの構築
  物質中のニュートリノ集団振動の非線形挙動と超新星ニュートリノに与える影響の調査
- Y. Suwa (U. Tokyo): long term SN neutrinos
  超新星ニュートリノ後期放射の理論計算および背景ニュートリノ探査の新手法開発

Workshops

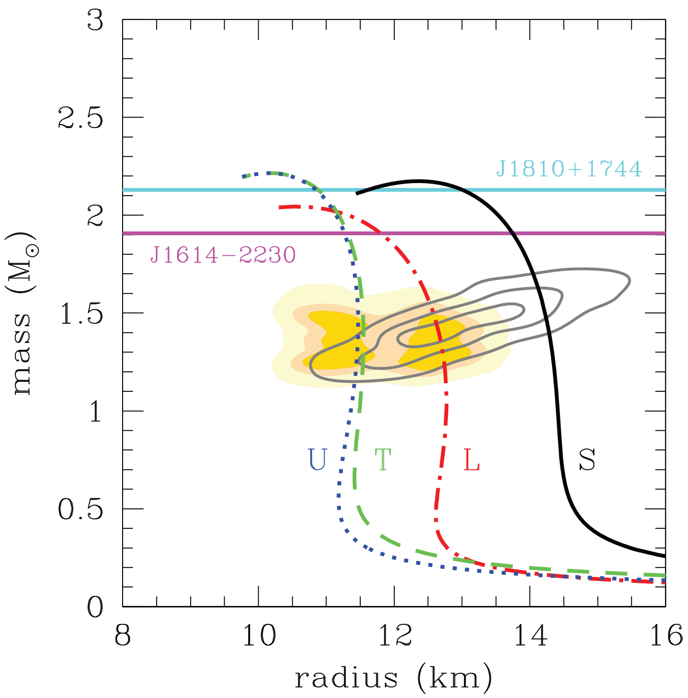
- International workshop “The Evolution of Massive Stars and Formation of Compact Stars: from the Cradle to the Grave” 2020.2.26-2.28 at Waseda
- 6th-10th Workshop for Supernova Neutrinos with C01 group
  2020.1.6-1.7 at Kashiwa
  2021.1.7-1.8 Online
  2022.1.6-1.7 at Waseda
  2023.3.2-3.3 at Kyushu
  2024.2.29-3.1 at Okayama

About 50 papers

Topics related to nuclear physics

SN explosion, SN neutrinos, NS/BH formation
⇐ Equation of states (EOS) for the high density matter with finite temperature for supernova simulations (hydrodynamics and neutrino transfer)
$\rightarrow P(\rho, T, Y_{\rm e}), X_i(\rho, T, Y_{\rm e})(i = {\rm n}, {\rm p}, {\rm A}, \alpha), \mu_i(\rho, T, Y_{\rm e})(i = {\rm p}, {\rm n}, {\rm e}), \cdots$

Togashi, Takano, Nakazato, Suzuki+'17: New EOS table

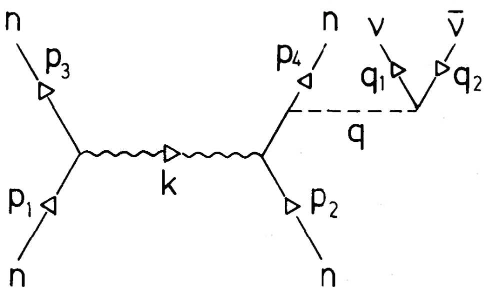


R-M relations of Neutron Stars with several EOSs (Nakazato+'22)

T: Togashi EOS
cluster variational method starting from bare nuclear forces (AV18 potential + UIX three body potential)
consistent with GW, X-ray, NS mass observations
It is used as one of the standard EOSs in the SN simulations.
In addition to thermodynamic quantities, nucleon effective mass and correlation function between nucleons are also obtained.

Many body effects for the neutrino interaction rates with matter should be included consitently with EOS.

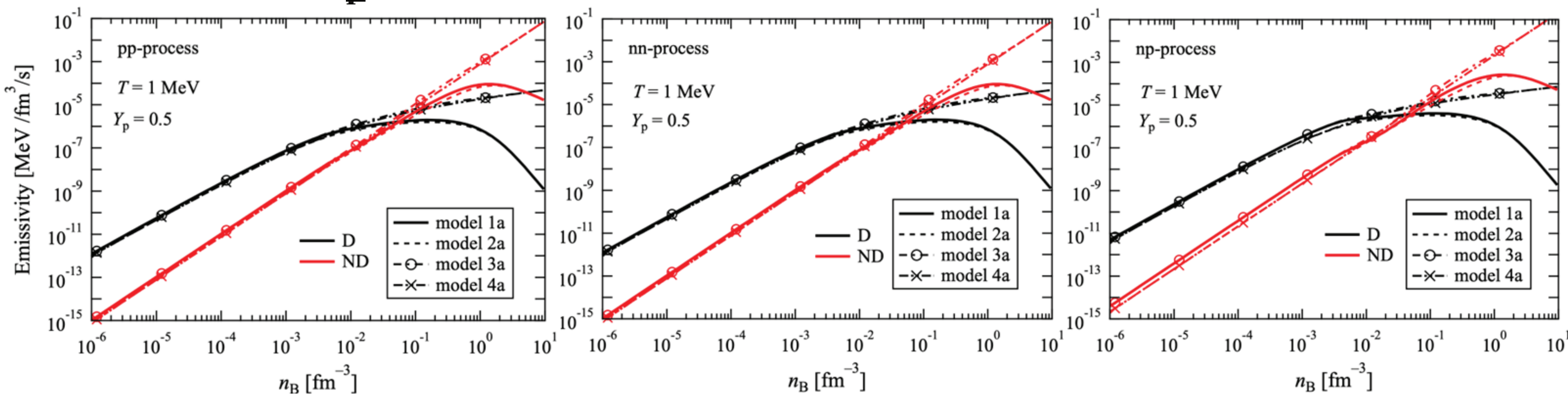
Results of Takano group: Neutrino emissivity consistent with nuclear EOS



Nucleon bremsstrahlung processes are important source for ν_x.
Update from Friman & Maxwell'79 treatment
NN interaction: One Pion Exchange model → correlations between nucleons and effective mass of nucleons obtained from cluster variational calculations.

Bremsstrahlung Emissivity

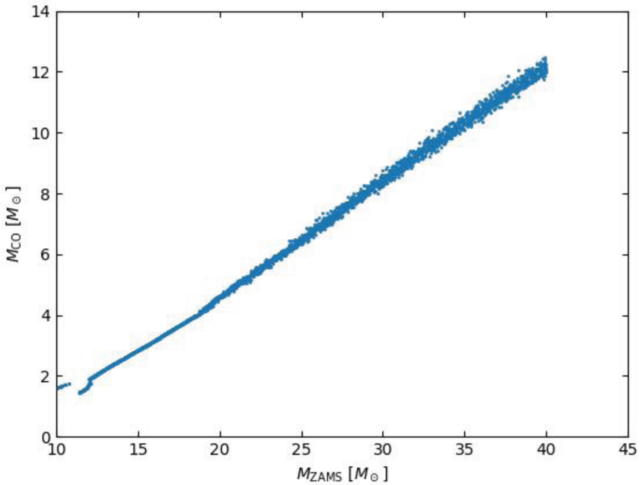
$T = 1$ MeV, $Y_p = 0.5$



In the high density region, neutrino emission rates by nucleon bremsstrahlung processes (line 1a) are smaller than previous estimations (line 4a).
It is not so important for the sufficiently opaque regions, but the semi-transparent region should be calculated with the new rates. We will incorporate the new rate into our SN and PNSC simulations.

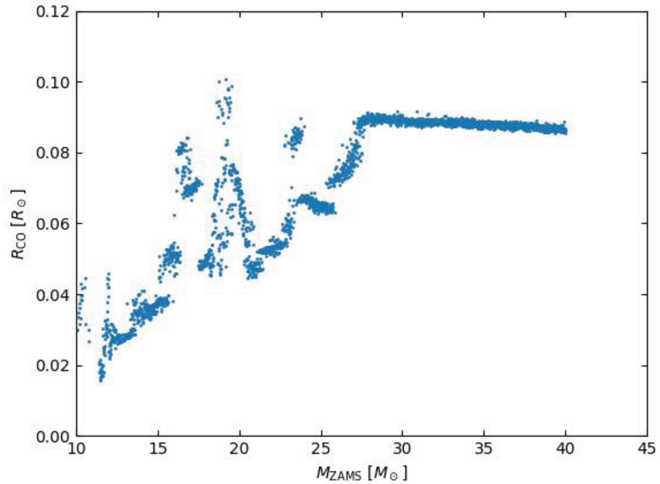
On going: Estimation of Diffuse Supernova Neutrino Background and Chemical Evolution with Population synthesis codes (SSE/BSE) + fitting of Müller's 1D SNE model

$M_{\rm CO}$



$M_{\rm ZAMS}$

$R_{\rm CO}$



$M_{\rm ZAMS}$

Detailed Presupernova Stellar models by MHLC'16 ($M_{\rm ZAMS}$ vs. $M_{\rm CO}, R_{\rm CO}$)

$M_{\rm CO}$: smooth function of $M_{\rm ZAMS}$

$R_{\rm CO}, M_{\rm Fe}/R_{\rm Fe}$, explodability: not monotonic functions of $M_{\rm ZAMS}$

DSNB and chemical evolution $\Leftarrow$ yields from various stars

detailed stellar evolution and 2D/3D SNE simulations: time-consuming

$\Downarrow$

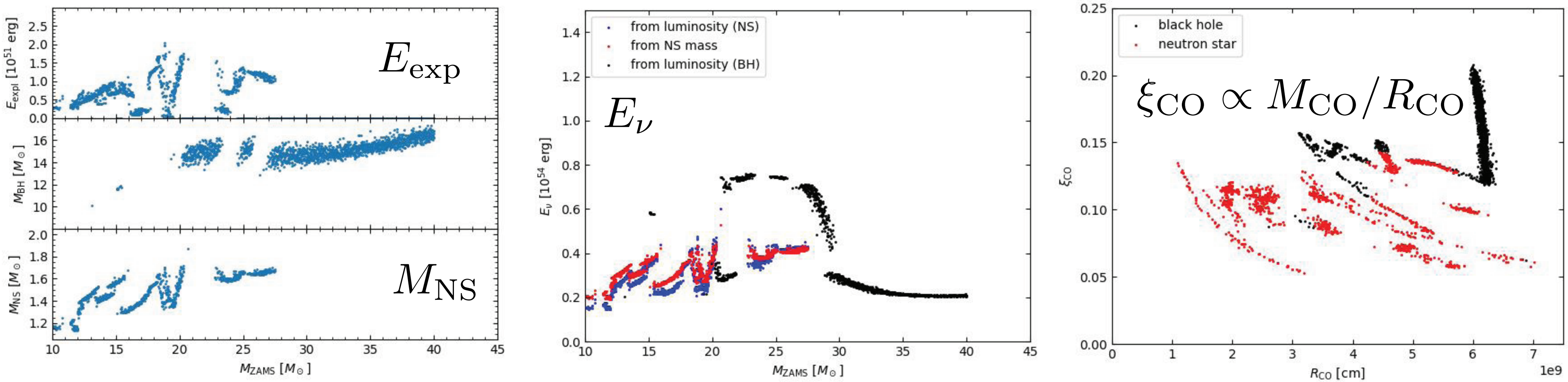
Population synthesis code (Hurley's SSE/BSE code) with fitting formula for detailed stellar evolution

Müller's 1D SNE model with parameters calibrated by multidimensinal SNE simulations

Preliminary results by H. Nakamura (MT 2024, TUS)

1D Müller's model for CCSNe (assuming $E_{\nu_e} + E_{\bar{\nu}_e} = 4E_{\nu_x}$)

Presupernova density profile $\Rightarrow$ Explodability, $M_{\rm NS}, E_{\rm exp}, E_\nu$ and so on.



$M_{\rm ZAMS}$ $M_{\rm ZAMS}$ $R_{\rm CO}$

done: rough fitting of results of Müller's model in order to incorporate them into population synthesis codes

todo: Calibration of Müller's parameters and re-fitting

Summary

Towards a conprehensive understanding of supernova neutrinos including diffuse supernova neutrino background and cosmic chemical evolution

- 2D/3D supernova simulations with Boltzmann neutrino tranfer
- analysis concerning the collective neutrino oscillation
- long-term evolution of proto neutron star with various EOSs
- insights from the observational data of supernova neutrino burst
- models of the galactic and cosmic chemical evolution and diffuse supernova neutrino background
- neutrino emission rates by nucleon bremsstrahlung processes consistent with EOS
- updates of population synthesis code by incorporating 1D Müller's SN model to estimate the neutrino emission and metal ejection