Multi-D Simulation of CCSNe

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Outline

- ✓ 2D (short-term) simulations for systematic study of CCSNe.
  KN+, PASJ, 67, 107 (2015)
- ✓ 2D long-term simulations.
  KN+ in prep.
- ✓ 3D long-term simulations.

- ◆ Multi-messenger astronomy
  KN+, MNRAS, 461, 3296 (2016)
- ◆ Explosive nucleosynthesis
  Eichler, KN+, J. of Phys. G accepted.
- ◆ Neutrino from Galactic CCSN
  Horiuchi, KN+, J. of Phys. G, 44, 114001 (2017)
- ◆ Diffuse SN neutrino background
  Horiuchi, Sumiyoshi, KN+, MNRAS submitted.
- ◆ NS kick
  KN+ in prep.

Numerical simulations of CCSNe

Space:	3D, ~10^{13} cm (RSG)	1D or 2D, ~10^{9} cm (Fe core+Si,O)
Neutrino:	Boltzmann, Detailed reactions	Approximated, Standard reactions
Gravity:	GR	Newtonian (+GR correction)

Systematic study using a huge number of progenitors

	Space	Neutrino	Gravity	Model #
Ugliano+'12	1D	gray	effective GR	~100
O'Connor+'13	1D	M1	GR	32
Nakamura+'15	**2D**	IDSA+leakage	Newtonian	~**400**

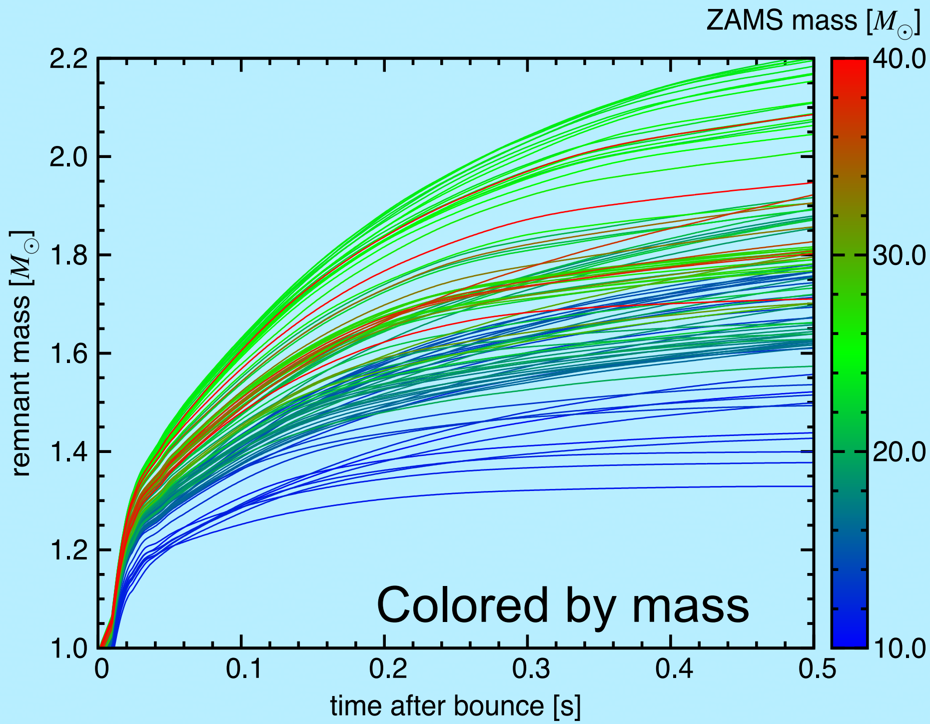
Systematic feature of CCSNe – NS mass

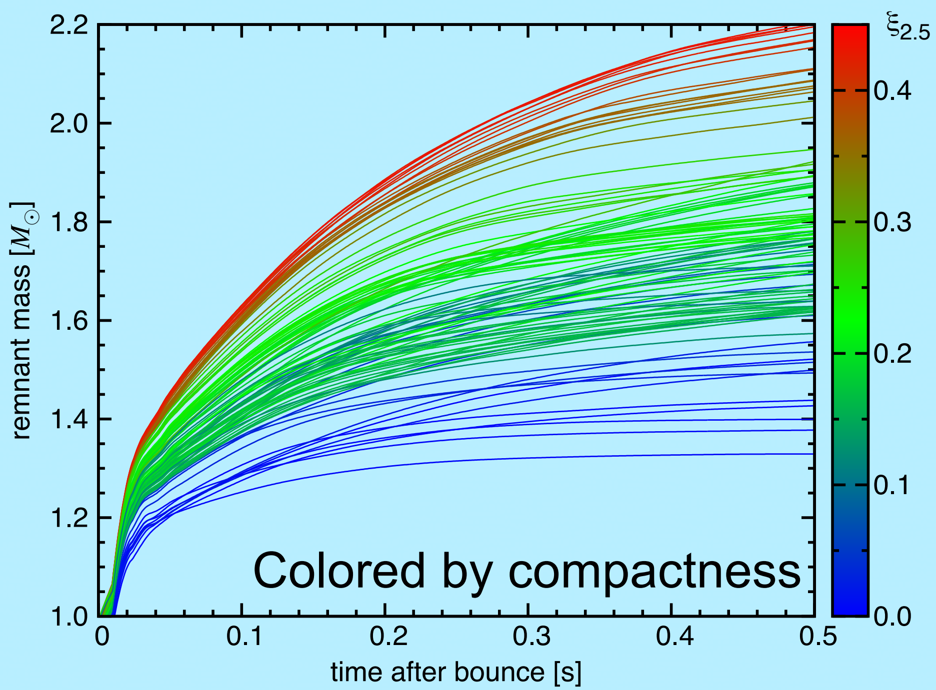
- ✓ Focusing on 101 models with solar metallicity.
  (Metal-poor models also show a similar trend.)
- ✓ PNS mass has a large dependence on models,
  from ~1.3Mo to >2Mo→BH formation.
- ✓ **Monotonic trend in compactness-colored figure.**

Compactness parameter
(O'Connor & Ott 2011)

$$\xi_M \equiv \frac{M/M_\odot}{R(M)/1000\mathrm{km}}$$

characterizing progenitor structure.





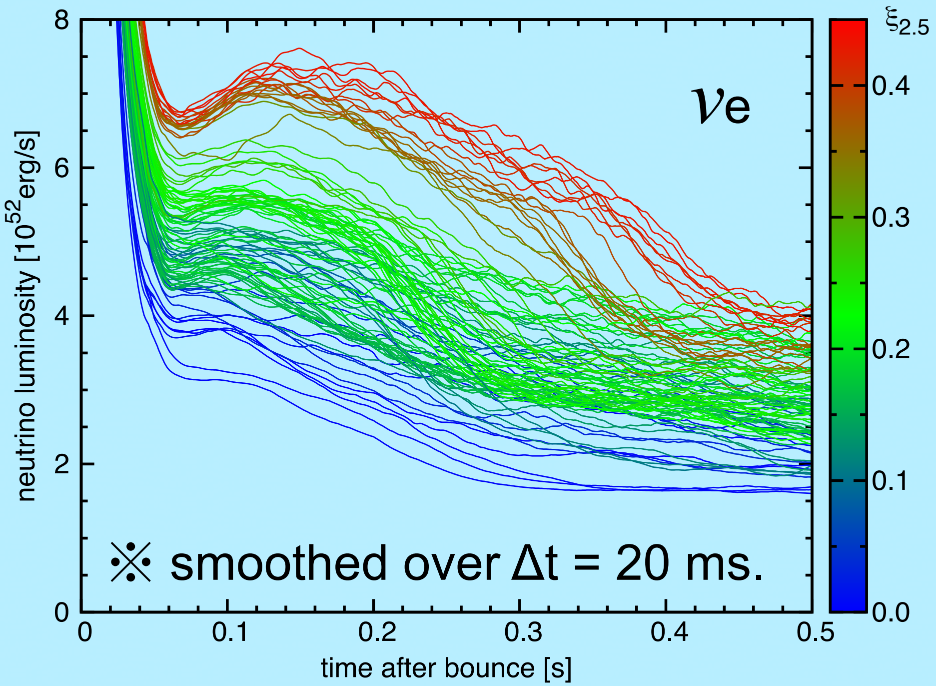
Systematic feature of CCSNe – ν luminosity

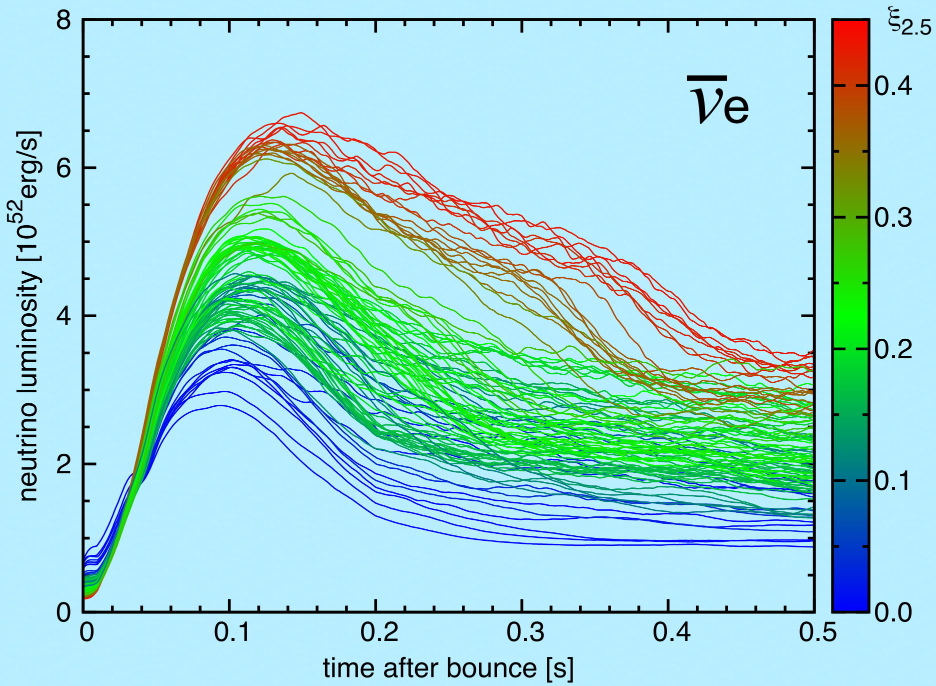
- ✓ Focusing on 101 models with solar metallicity.
  (Metal-poor models also show a similar trend.)
- ✓ Difference is more than double.
  2-6 $\times 10^{52}$ erg/s @ t = 200 ms.
- ✓ **Monotonic trend in compactness-colored figure.**

Compactness parameter
(*O'Connor & Ott 2011*)

$$\xi_M \equiv \frac{M/M_\odot}{R(M)/1000\mathrm{km}}$$

characterizing progenitor structure.

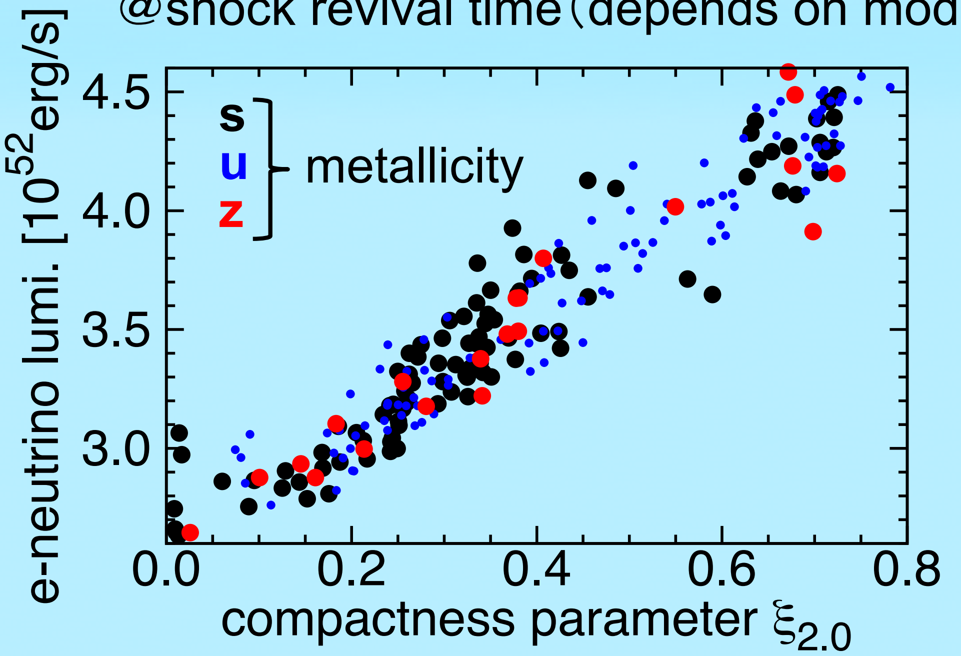




Compactness - $L\nu$, $M_{\rm PNS}$

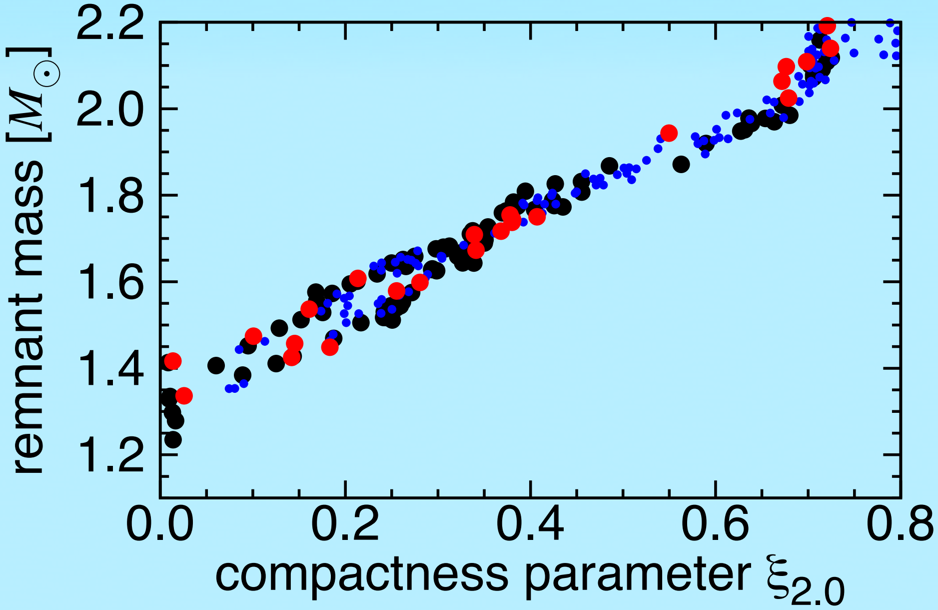
e-neutrino luminosity

@shock revival time (depends on models)



PNS mass

@final simul. time (depends on models)



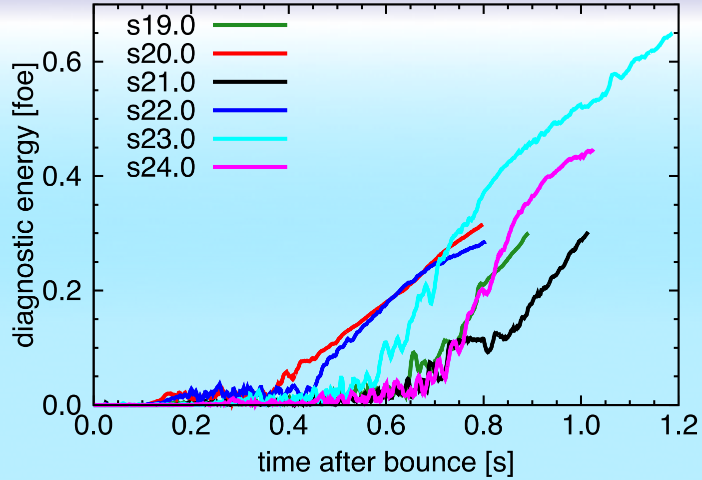
Both have a good linear correlation to the compactness.

Compactness – *Eexp.*

- **<u>Step 1: Short-term simulations of CCSN cores.</u>**
  KN+'15 PASJ, 67 (6) 107

  R<5,000km, t<1.5s

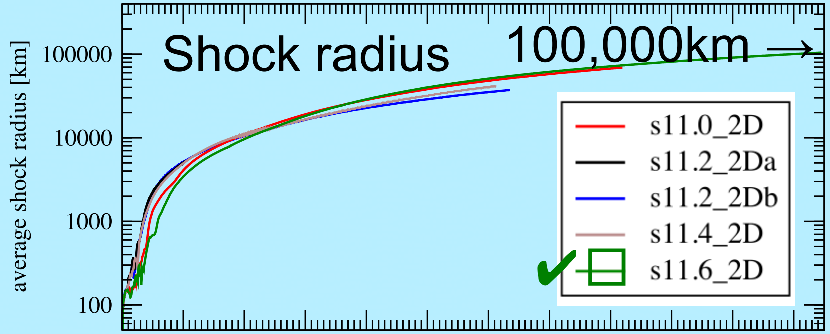
  CCSN properties (ν luminosity, PNS mass, etc.)
  show good correlations to the compactness ξ.
  → But simulations were too short to find final explosion energies and Ni yields.

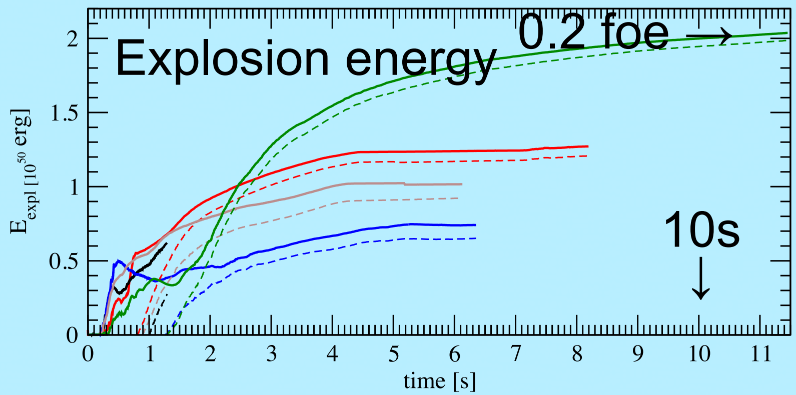


- **<u>B. Mueller '15</u>**

  R < 100,000 km, t < 6−11 s

  COCONUT (GR hydro.) - FMT (ν) code
  M = 11.0 - 11.6 Mo
  2D, n(r)*n(θ) = 550*128





2D Long-term CCSN simulation

- **Numerical code**
  - **2D**, n(r)*n(θ) = 1008*128

    r=0-**100,000 km**, θ=0-π
  - Neutrino transport

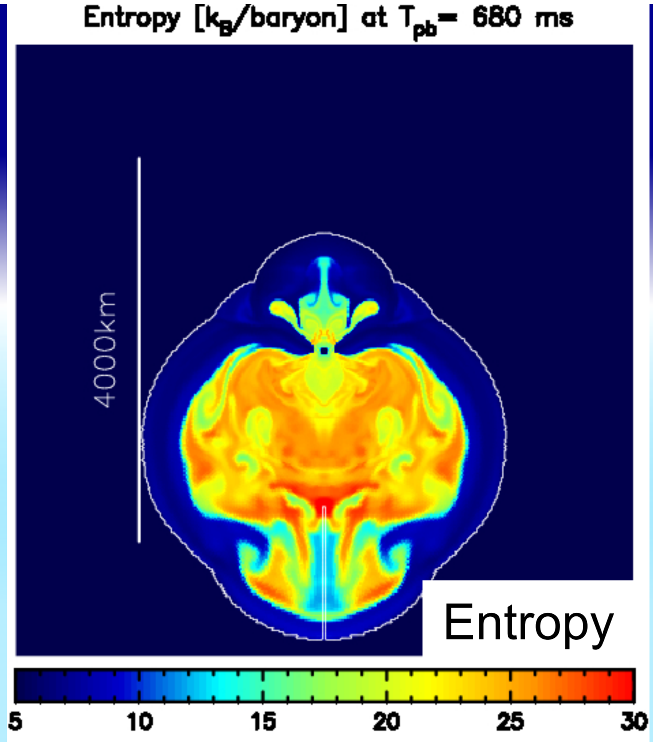
    $\nu e, \overline{\nu e}$: **IDSA spectral transport** (Liebendoerfer+09)

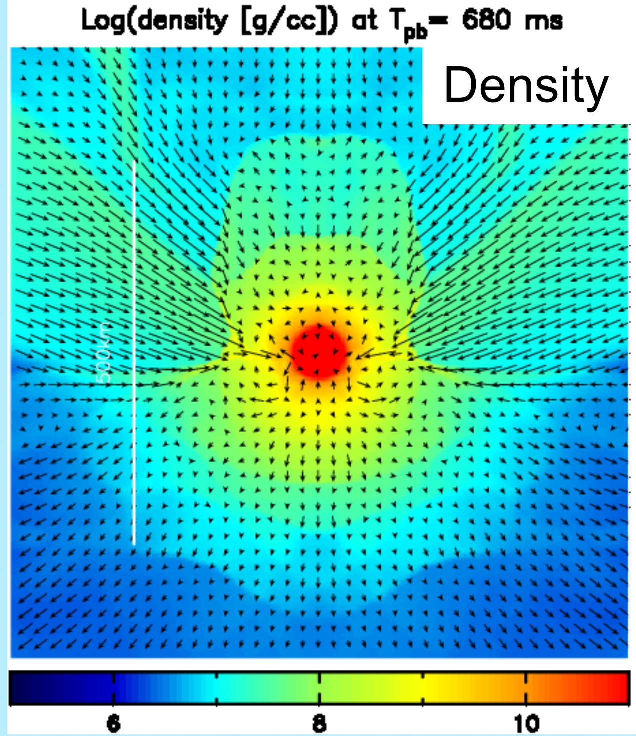
    νx : **leakage scheme**

    with 20 energy bins (< 300 MeV)
- **EoS**
  - LS220 (Lattimer & Swesty '91) + Si gas
- **Nuclear reactions**
  - 13α (He-Ni) network
- **Progenitor model**
  - **M = 11.2, 17, 27 Mo**, Z = Zo, w/o rotation & B-field

    (Woosley, Heger, & Weaver '02)

・ Numerical computations were carried out on Cray XC30（576 cores × 20 days / model）





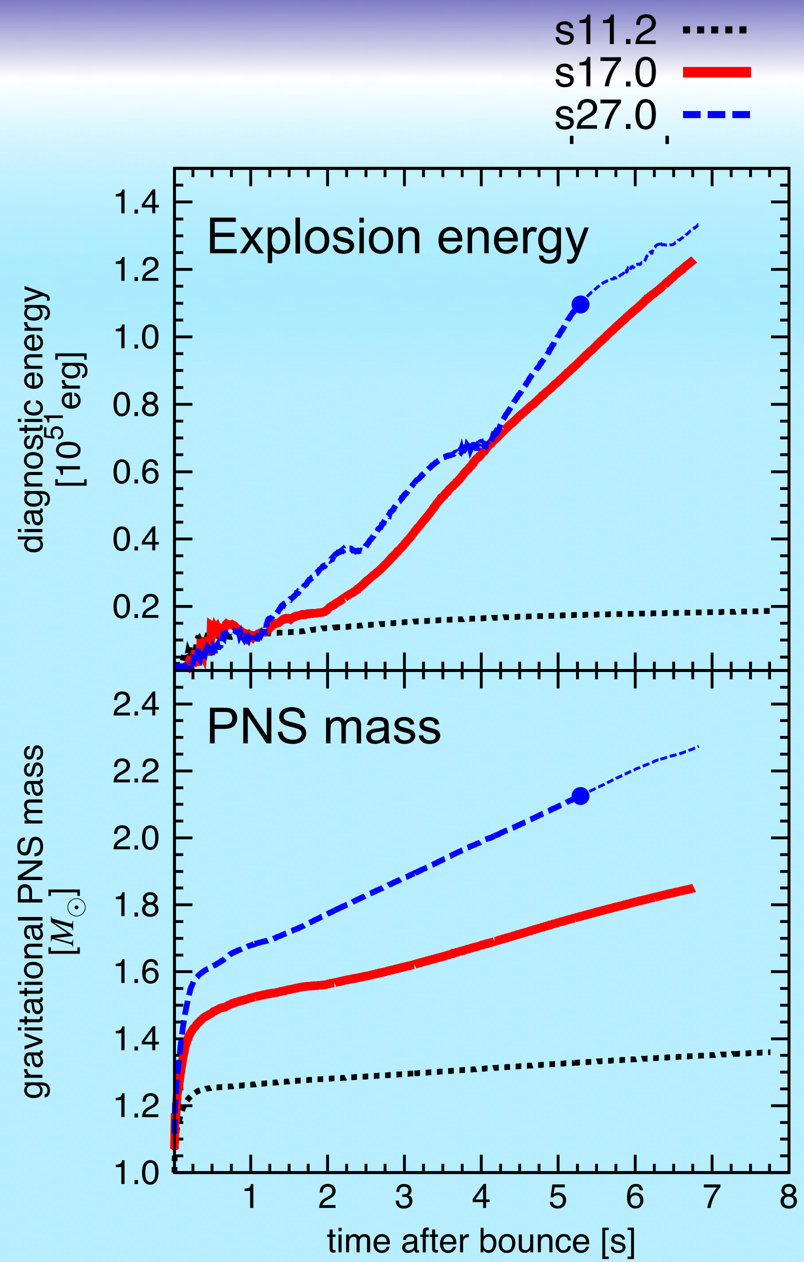
KN+ in prep.

✓ All models exhibit shock revival.
The shock reaches at r = 100,000 km
(nearly the bottom of He layer)
within t = 7-8 s.

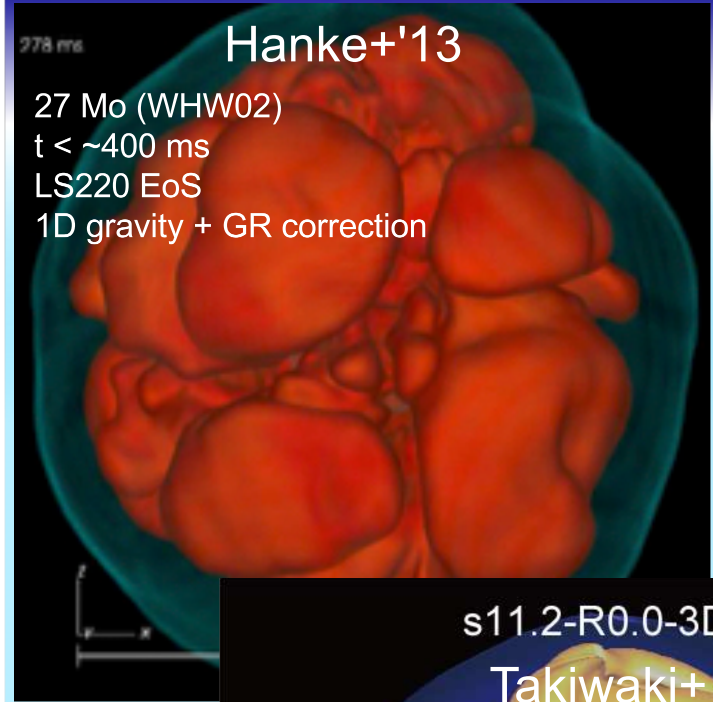
✓ **s11.2 model**
shows almost converged E_{exp} & M_{PNS}.
E_{exp} = 0.19 foe, M_{PNS} = 1.36 Mo

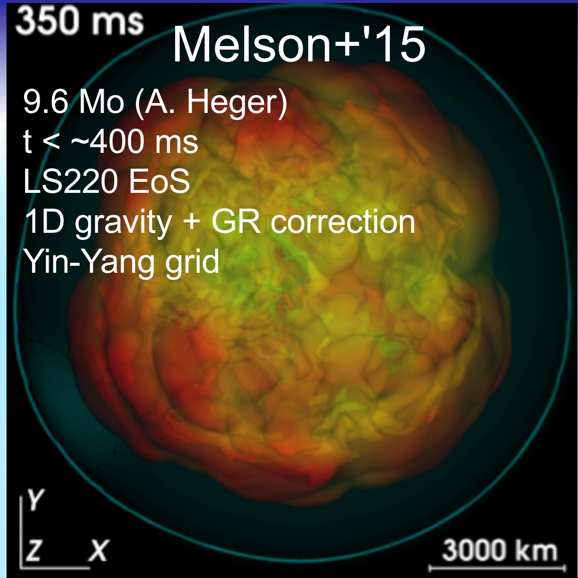
✓ **s17.0 model**
shows still growing E_{exp} & M_{PNS} at t ~ 7s.
E_{exp} = = 1.23 foe, M_{PNS} = 1.85 Mo

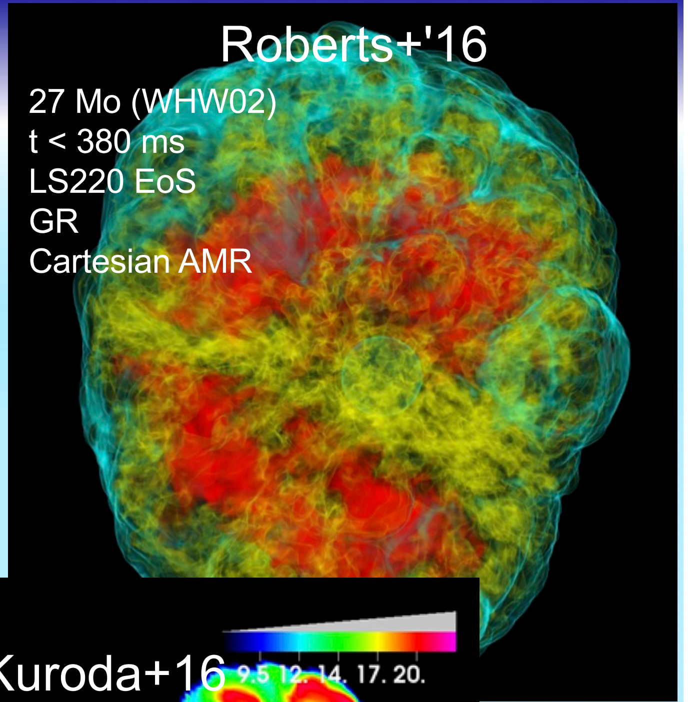
✓ **s27.0 model**
is similar to s17.0 models, but the PNS
mass reaches the limit（M_{PNS} = 2.13 Mo）
predicted by 1D GR simulation.
(O'Connor & Ott '11; KN+'15)

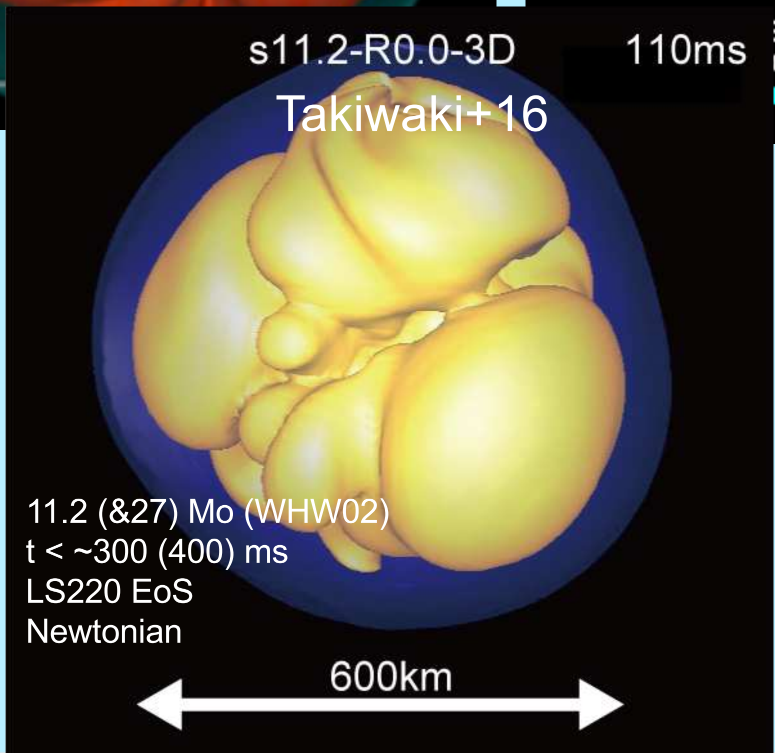


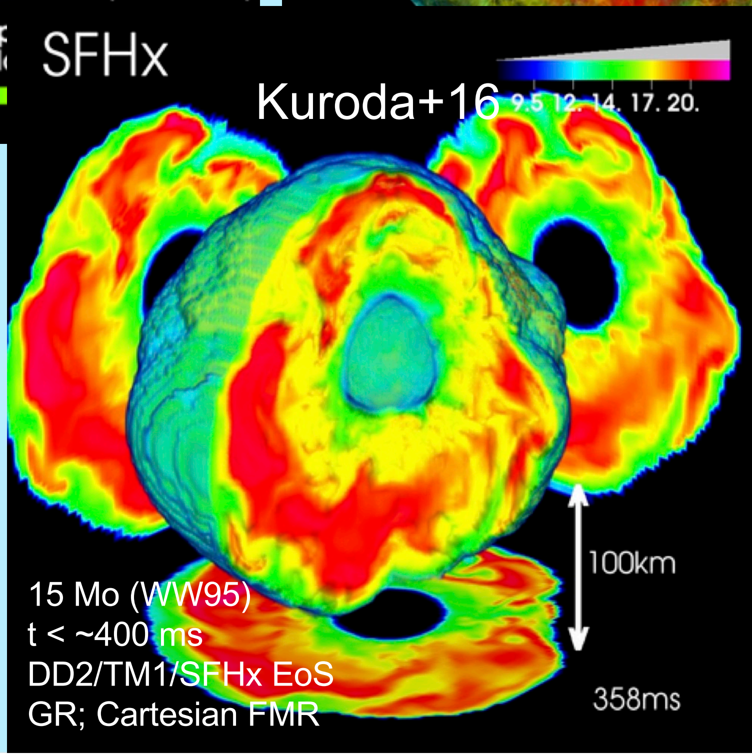
3D CCSN Simulations



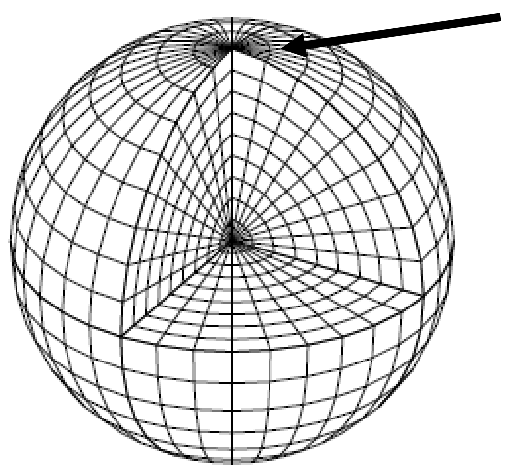








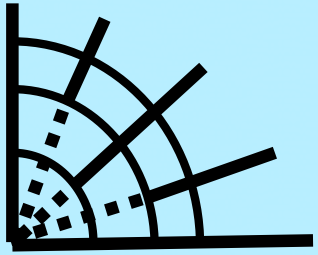
Mesh coarsening scheme



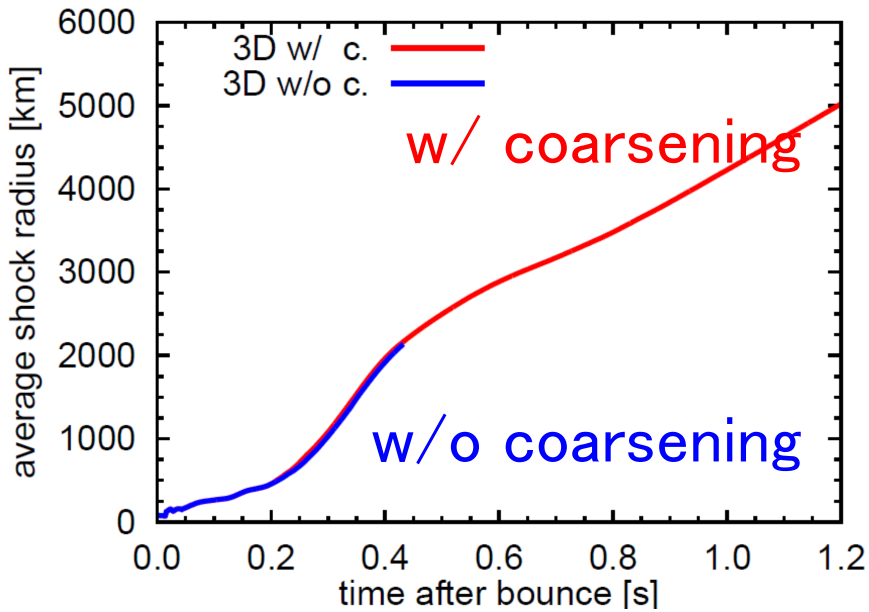
Too much small cell width around the polar.

→ Simulation time step Δt is very small.

$$L \sim r\Delta\theta\Delta\phi \qquad \Delta t \sim L/c_{\mathrm{s}}$$



⇒ Estimate Δt in "coarsened grid".



3D test calculation.

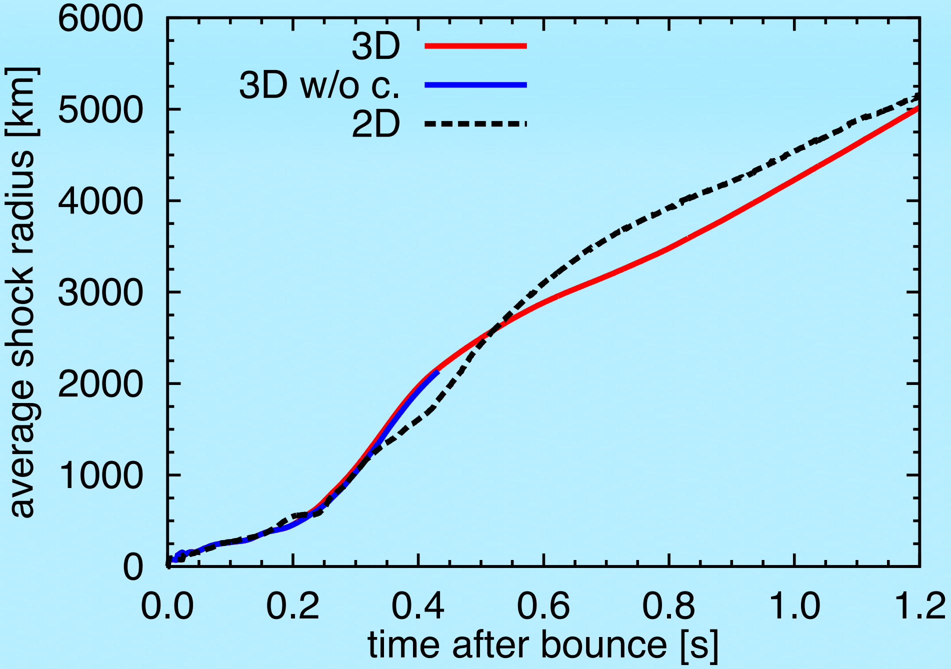
Averaged (or space-integrated) values such as shock radius show good agreement.

(preliminary)

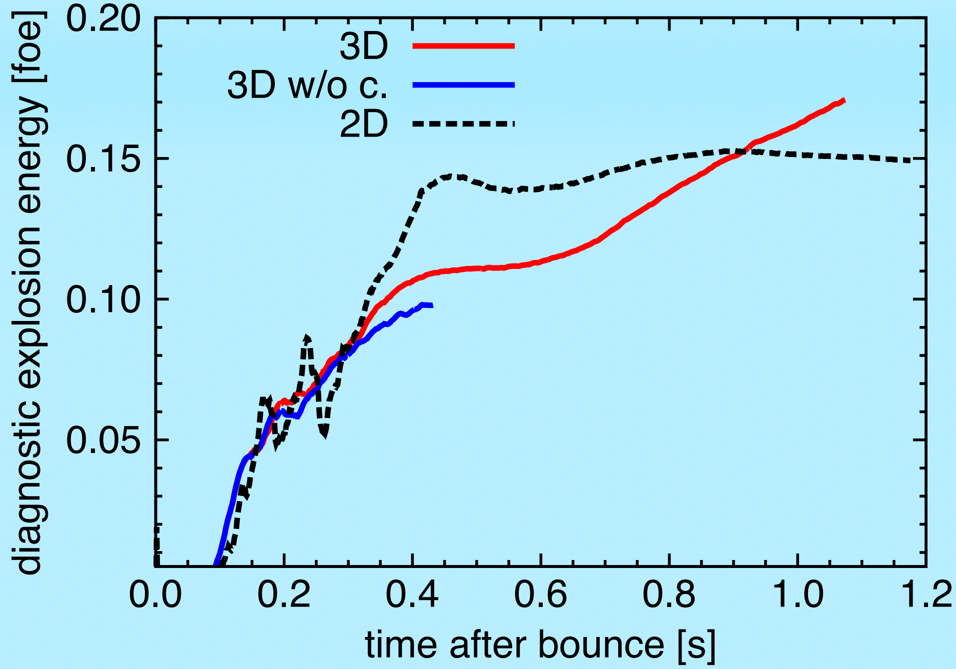
s11.2 (WHW02)
LS220 + Si gas
2-flavor IDSA + leakage
Newtonian

Preliminary result

Average shock radius



Explosion energy



2D long-term simulation results in low-energy explosion（~10^{50}erg, Mueller'15）.

→More energetic in 3D.

Outline

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- ◆ Neutrino from Galactic CCSN

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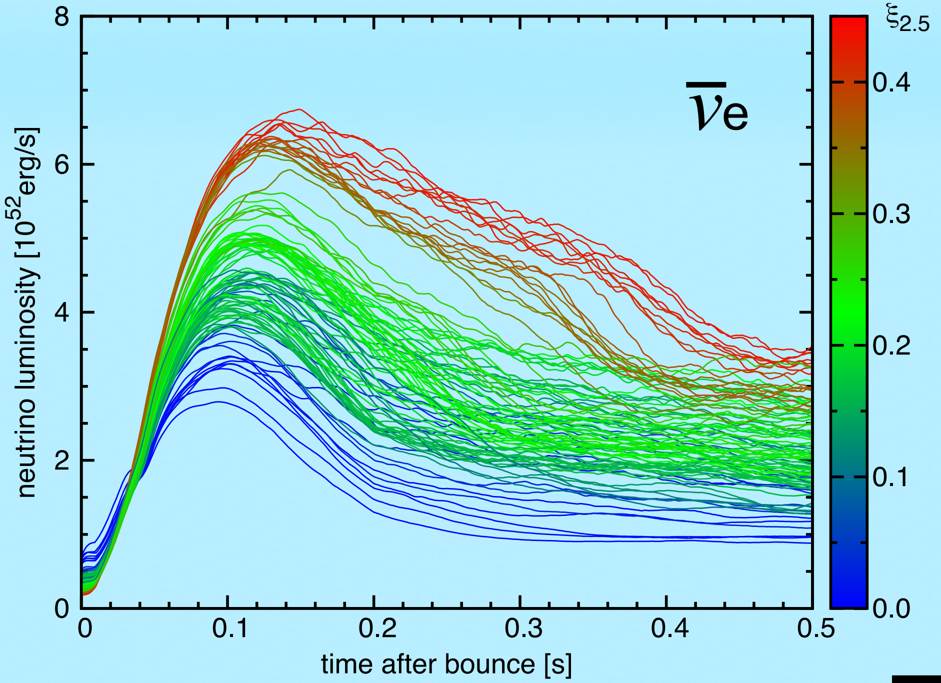
- ◆ NS kick

  KN+ in prep.

Progenitor structure from Galactic SN ν

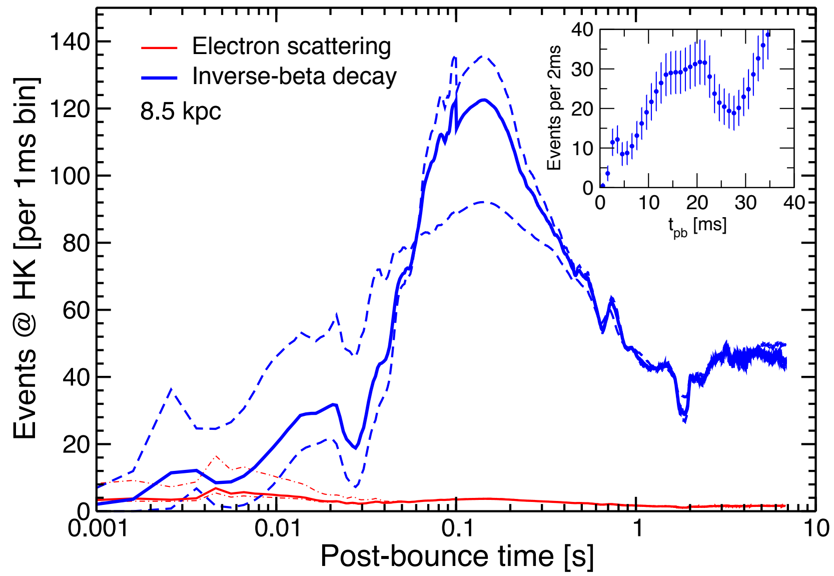
Horiuchi, KN+17

Template of SN neutrino
from hundreds of CCSN simulations.



ex.）Expected SN neutrino detection

Fig.4 in Nakamura+16



Progenitor structure (compactness) is determinable ？
YES ! if we have **reliable template** & **distance-independent index**.

Progenitor structure from Galactic SN ν

Horiuchi, KN+17

Early phase（t < ~50 ms）:

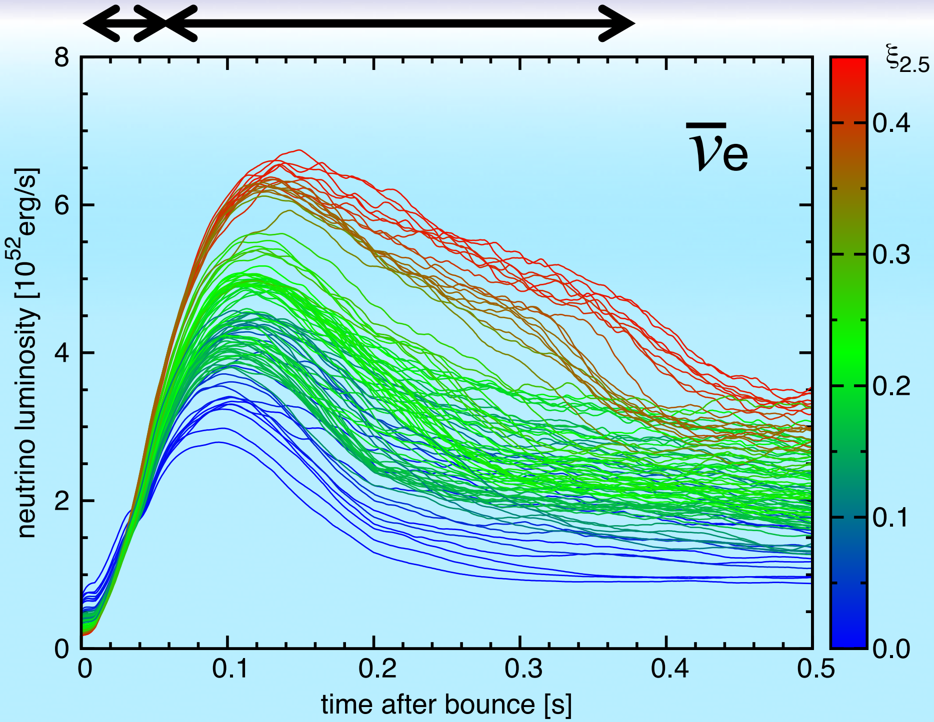
Diffusive neutrino dominant.

Less dependent on compactness.

Later phase:

Accretion neutrino dominant.

Monotonically dependent on compactness.



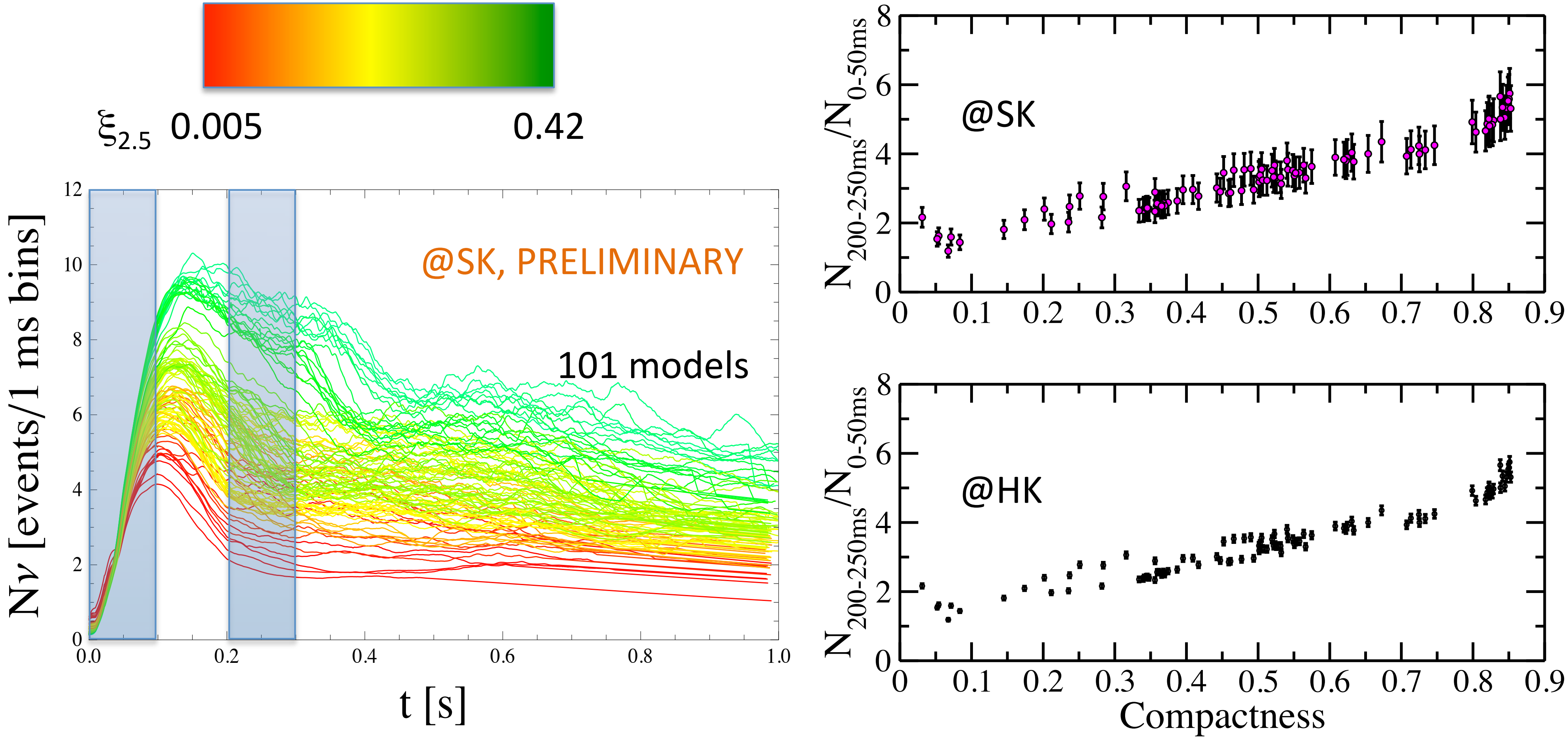
Distance-independent, compactness-dependent index.

$$\frac{\int^{\text{acc.}} L\nu \, \mathrm{dt}}{\int^{\text{diff.}} L\nu \, \mathrm{dt}} \sim \frac{N_{\text{acc.}}}{N_{\text{diff.}}}$$

Ratio of neutrino detection numbers between two phases.

Progenitor structure from Galactic SN ν

Horiuchi, KN+17



Hyper-Kamiokande can determine the progenitor compactness.

Diffuse SN neutrino background

Horiuchi, Sumiyoshi, KN+17

Background of SN neutrino in cosmic history.

$$\frac{d\phi}{dE} = c \int R_{\rm CC}(z) \frac{dN}{dE'} (1+z) \left| \frac{dt}{dz} \right| dz \,, \qquad (14)$$

where $E' = E(1+z)$ and $|dz/dt| = H_0(1+z)[\Omega_m(1+z)^3 + \Omega_\Lambda]^{1/2}$.

Core-collapse（CCSN+BH）event rate

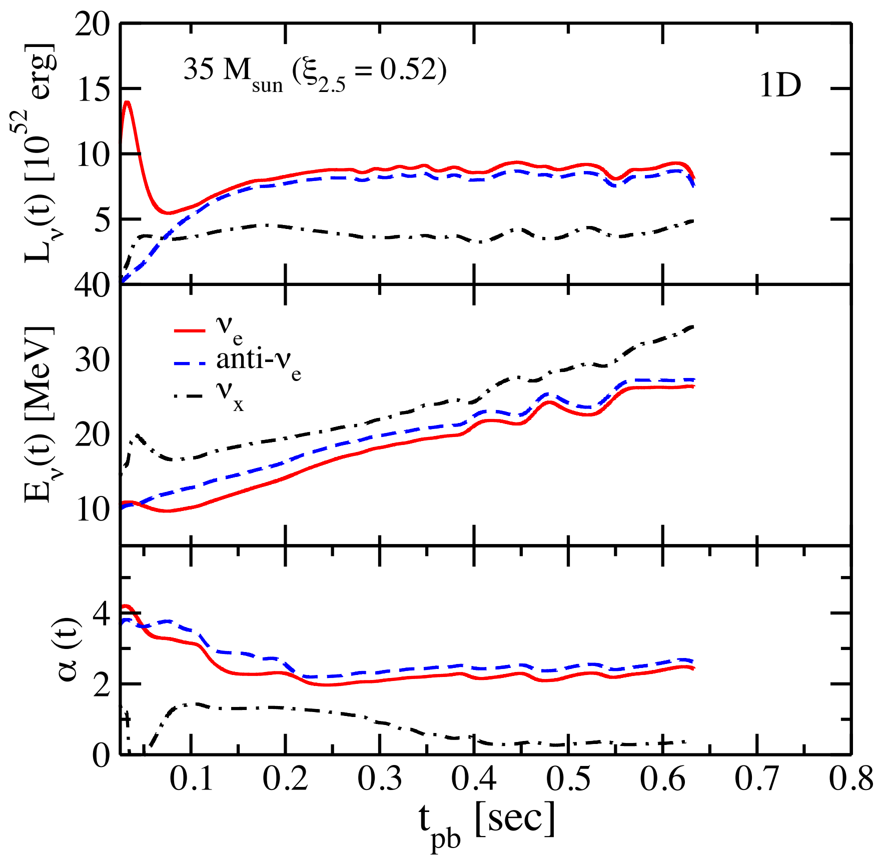
$$R_{\rm CC}(z) = \dot{\rho}_*(z) \frac{\int_8^{100} \psi(M) dM}{\int_{0.1}^{100} M\psi(M) dM}$$

Average neutrino spectrum per event is estimated from simulations.

$$dN/dE' = dN/dE(1+z)$$

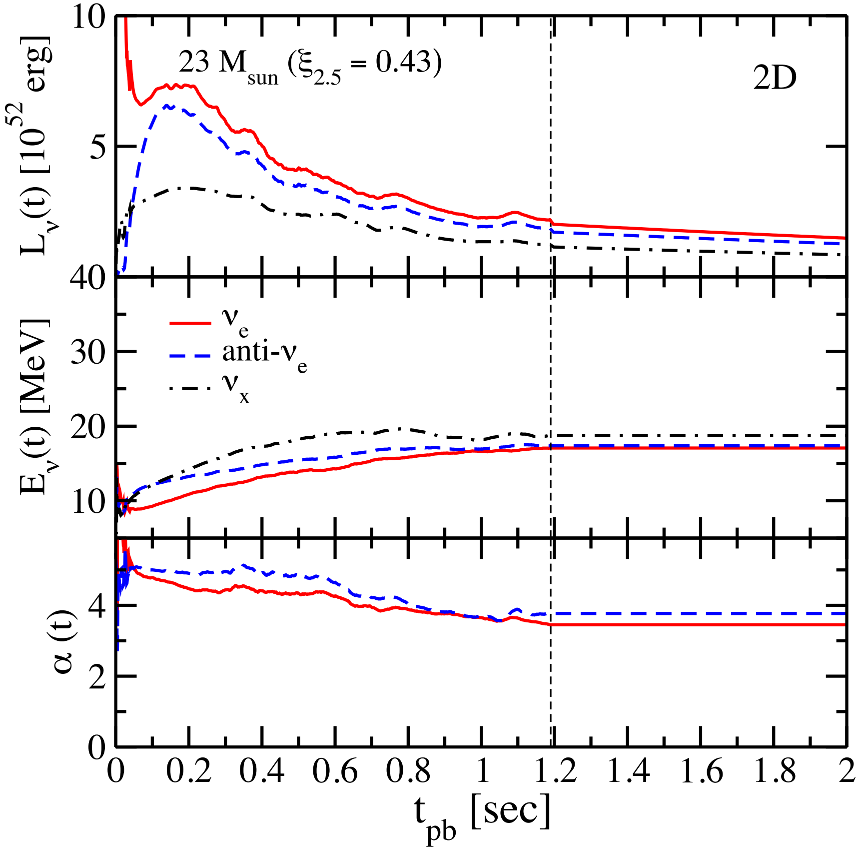
Diffuse SN neutrino background

Horiuchi, Sumiyoshi, KN+17



Time evolution of neutrino spectral parameters for the core collapse of the 35Mo progenitor leading to black hole formation at 630 msec post bounce.

simulation←→extrapolation

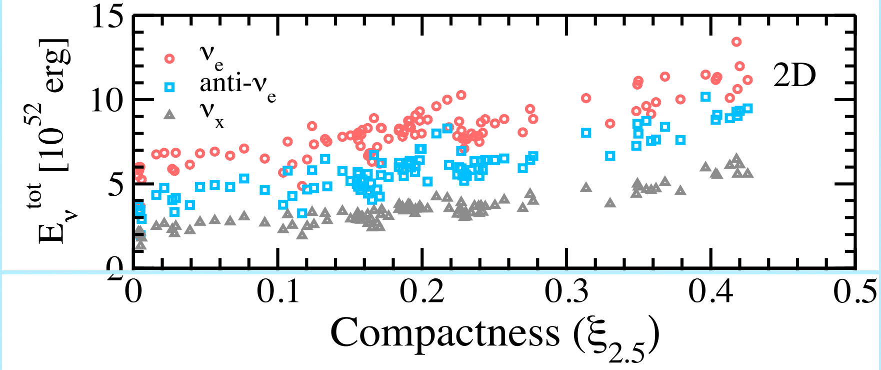


Time evolution of neutrino spectral parameters for the core collapse of the 23Mo progenitor leading to CCSN explosion.

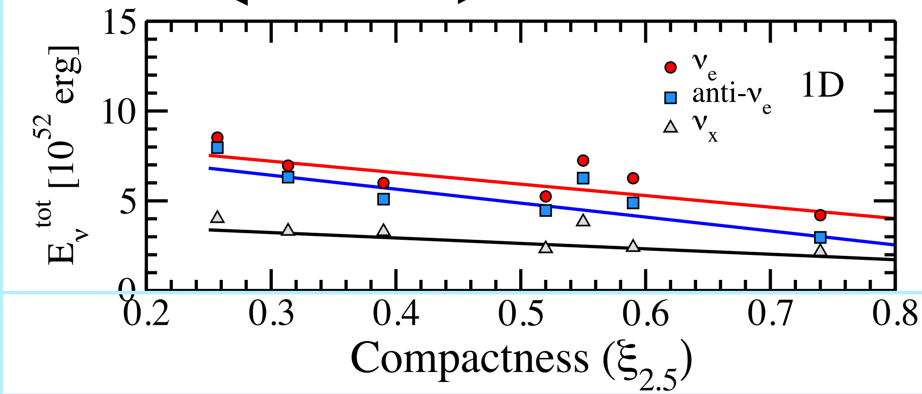
Diffuse SN neutrino background

Horiuchi, Sumiyoshi, KN+17

CCSN



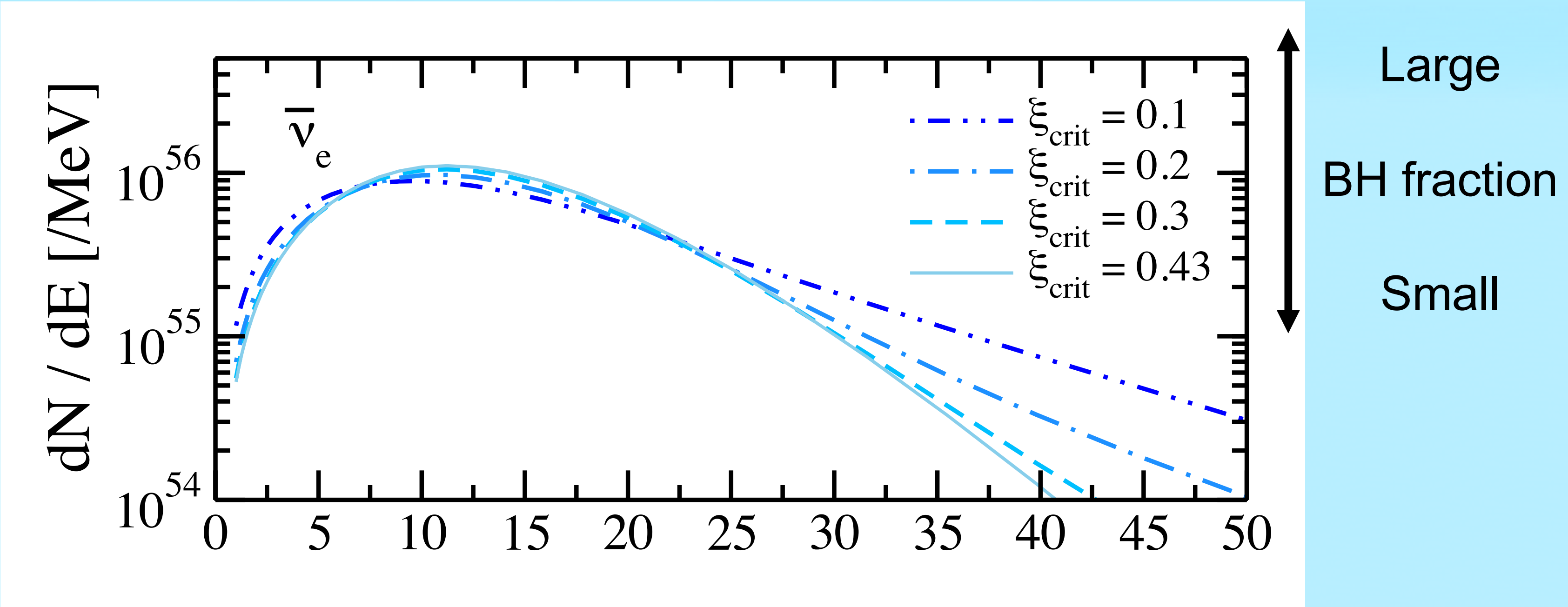
?



BH

Diffuse SN neutrino background

Horiuchi, Sumiyoshi, KN+17



Weighted average neutrino spectra of $\bar{\nu}e$, based on 101 2D core-collapse simulations and a collection of simulations of collapse to black holes.

Diffuse SN neutrino background

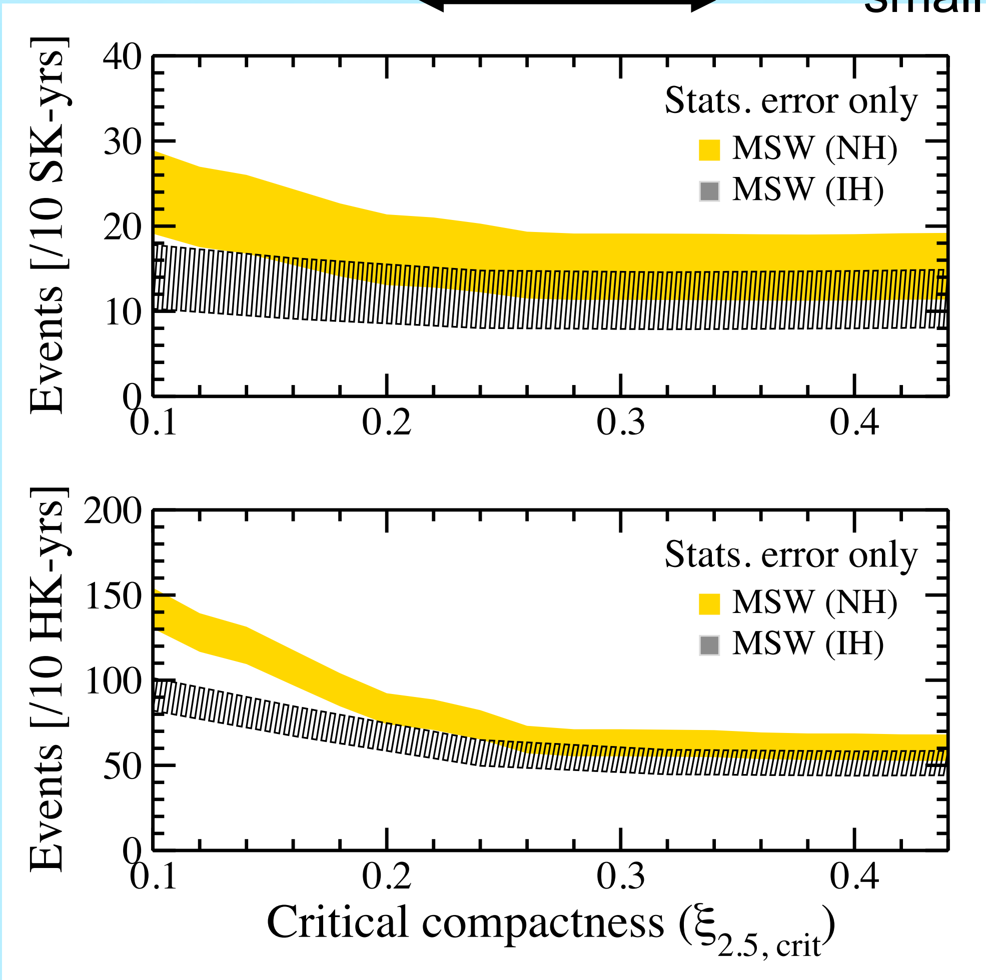
Horiuchi, Sumiyoshi, KN+17

Prediction for DSNB detection by Super- & Hyper-Kamiokande.

10-yr HK obs. can give a restriction of ξ_{crit}.

large contribution from BHs

small



Predicted DSNB event rate per 10 years in SK (22.5 kton inner volume, top panel) and in HK (374 kton inner volume, bottom panel) as functions of the critical compactness.

Summary

✓ 2D (short-term) simulations for systematic study of CCSNe.

CCSN properties are well characterized by compactness.

✓ 2D long-term simulations.

Some models presents too energetic (>10^{51} erg) explosions.

✓ 3D long-term simulations.

*T*o find converged values of explosion energy and PNS mass.

◆ Multi-messenger astronomy *KN+, MNRAS, 461, 3296 (2016)*

Neutrino, gravitational wave, and EM wave from Galactic CCSN.

◆ Explosive nucleosynthesis ***Eichler, KN+, J. of Phys. G accepted***

Explosive nucleosynthesis based on 2D long-term CCSN simulations.

◆ Neutrino from Galactic CCSN ***Horiuchi, KN+, J. of Phys. G (2017)***

CCSN neutrino as a probe of CCSN core structure.

◆ Diffuse SN ν background ***Horiuchi, Sumiyoshi, KN+, MNRAS submitted***

Critical compactness above which massive stars collapses to BH.

◆ NS kick *KN+ in prep*

Correlation between NS kick velocity and NS mass.