# Diagnosing the Structure of Massive Stars with Galactic SN Neutrinos
## (ニュートリノで探る系内超新星親星のコア構造)

Horiuchi, KN et al., J. Phys. G., 44, 114001 (2017) *(arXiv:1708.08513)*

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新学術「地下素核研究」第4回超新星ニュートリノ研究会　Jan. 8-9, 2018

# 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** |

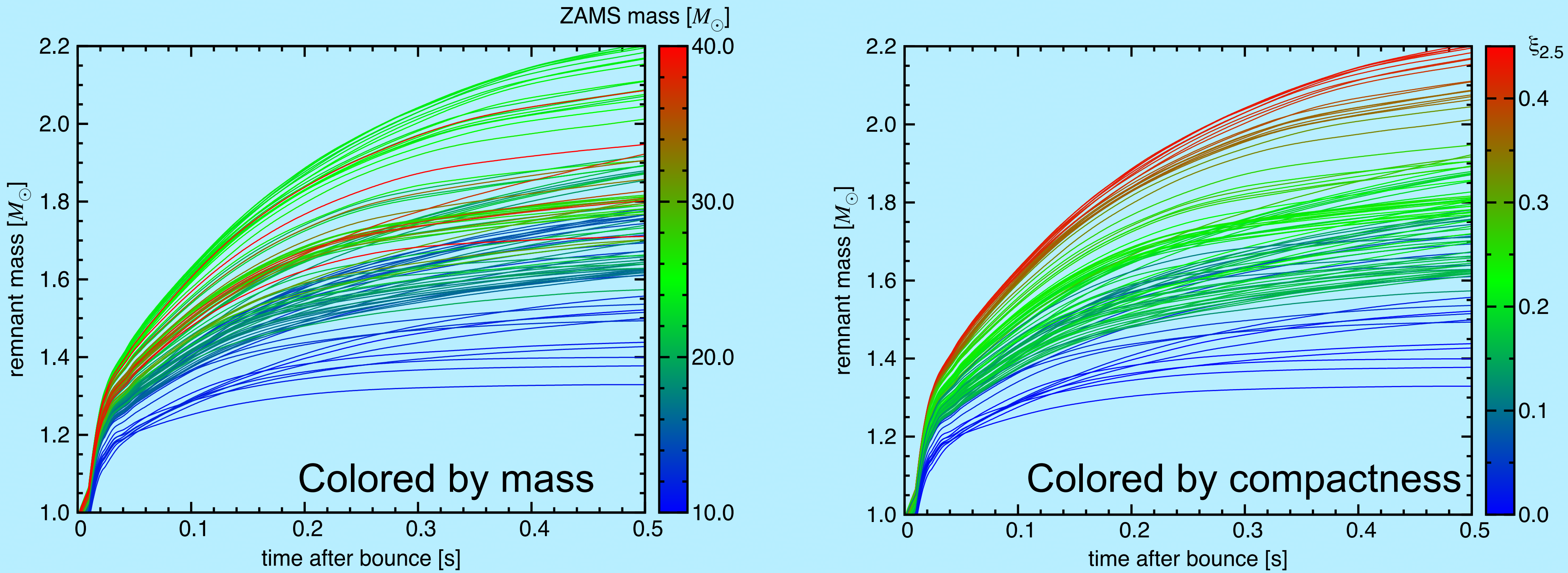
# Systematic feature of CCSNe – NS mass

- ✓ 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 – $\nu$ 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.**

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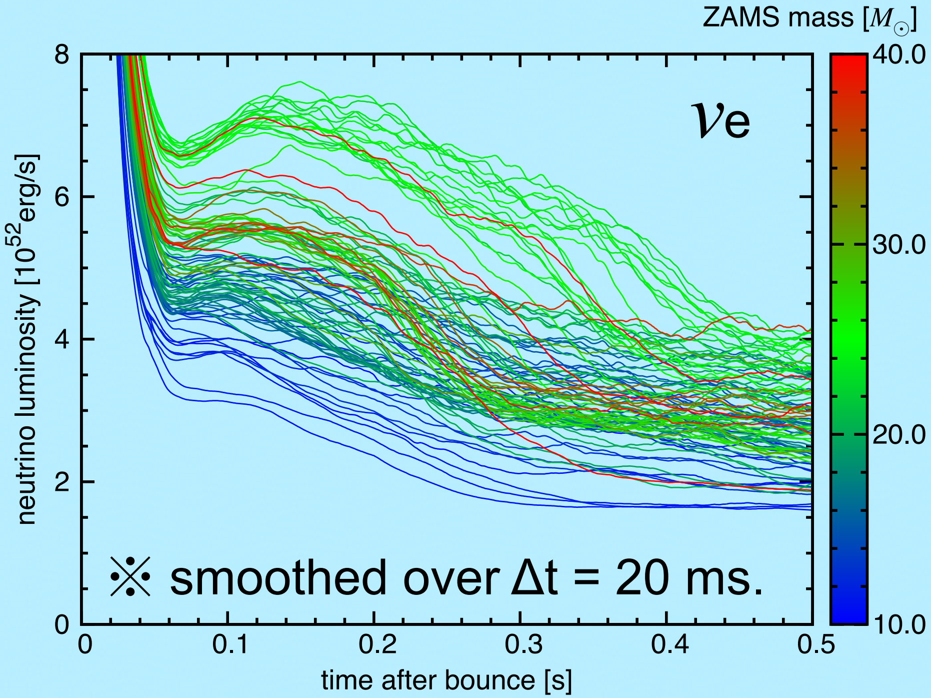


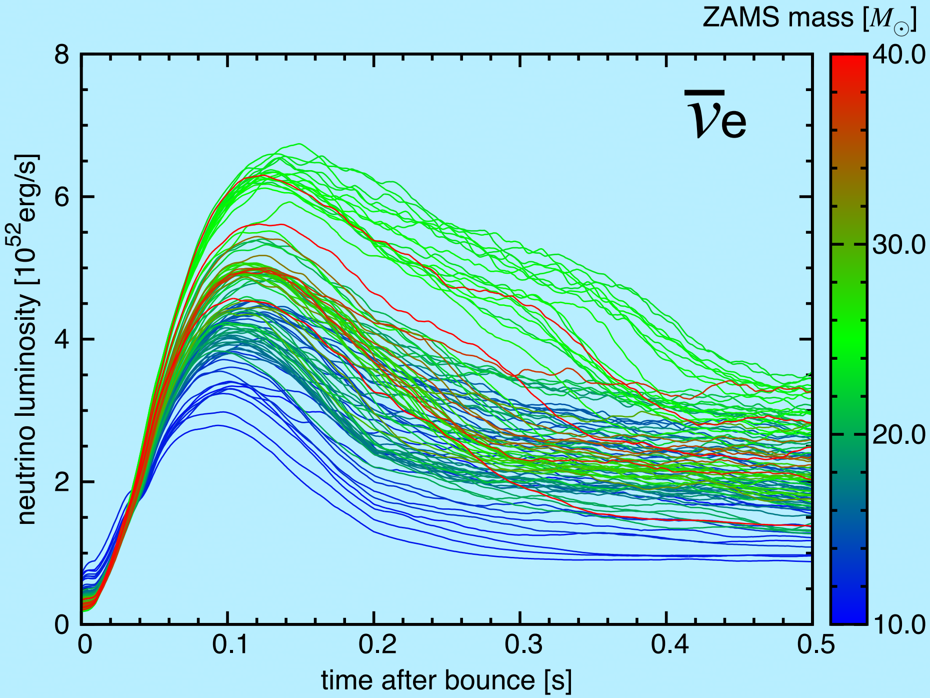

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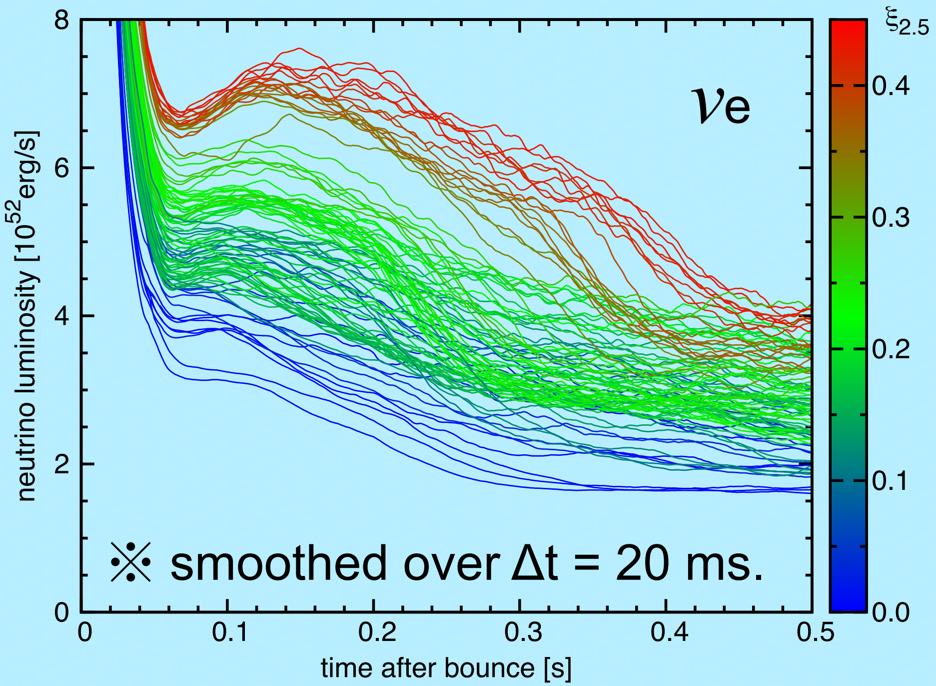
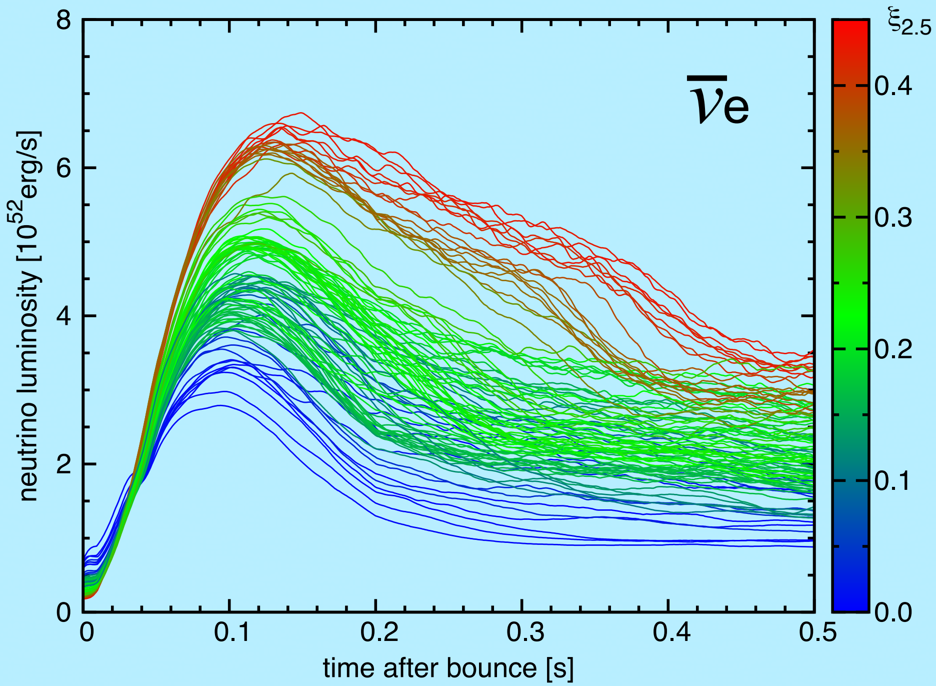
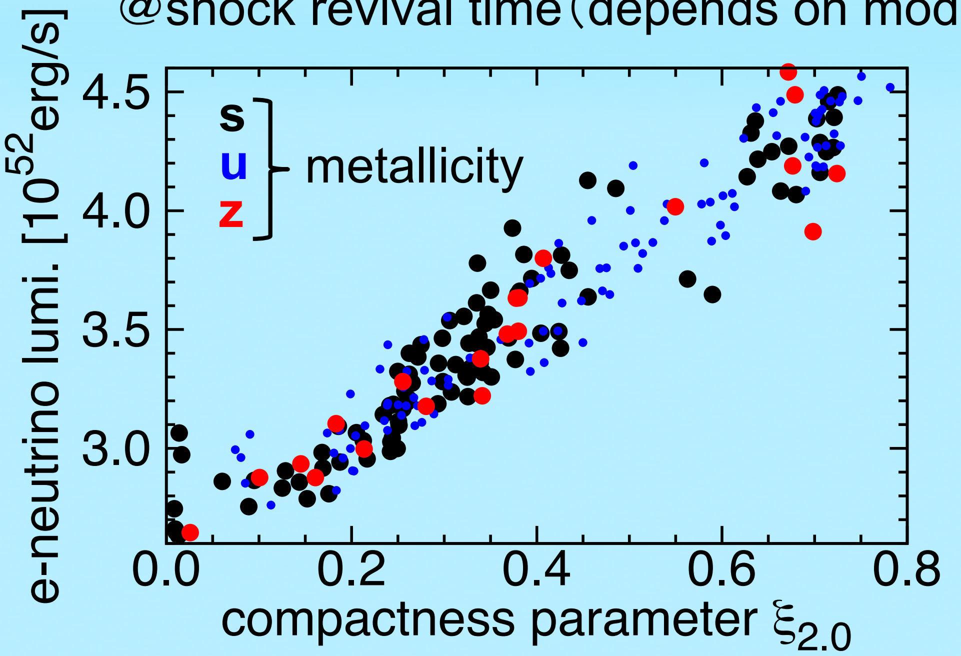


# Compactness - $L\nu$, $M_{PNS}$

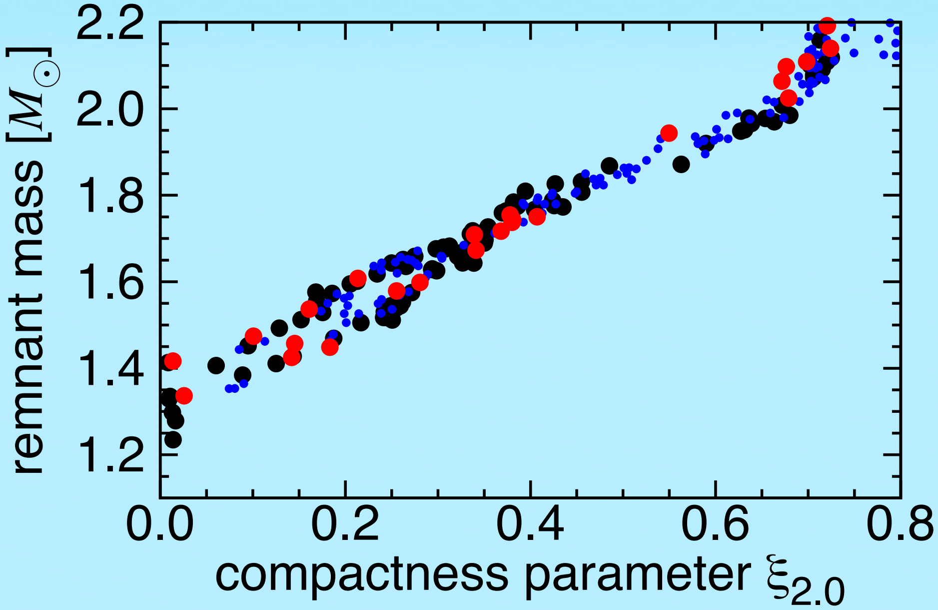
**e-neutrino luminosity**

@shock revival time (depends on models)




**PNS mass**

@final simul. time (depends on models)

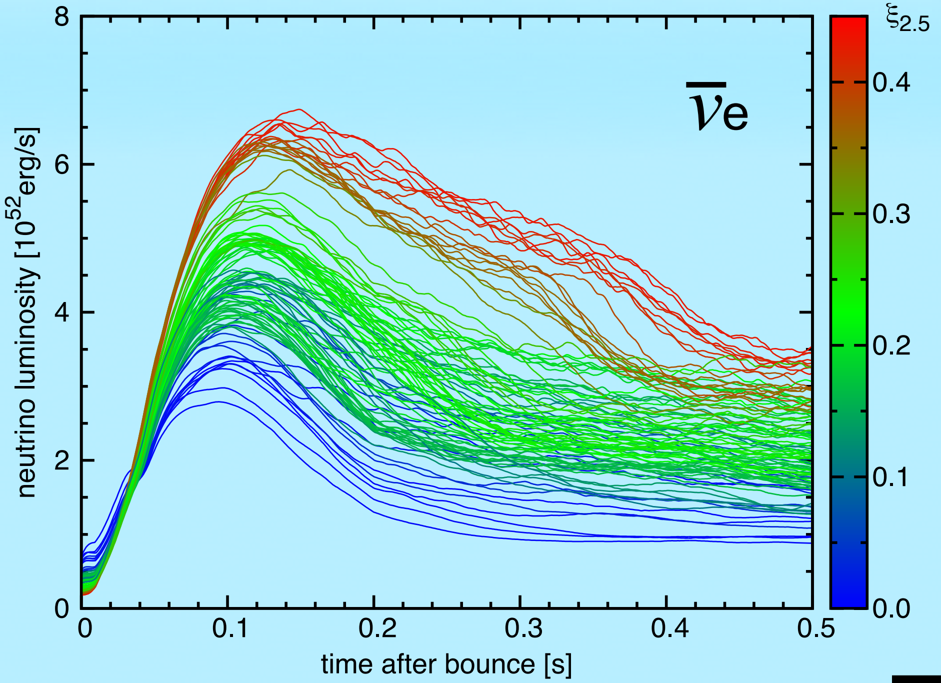



Both have a good linear correlation to the compactness.

# Progenitor structure from Galactic SN $\nu$

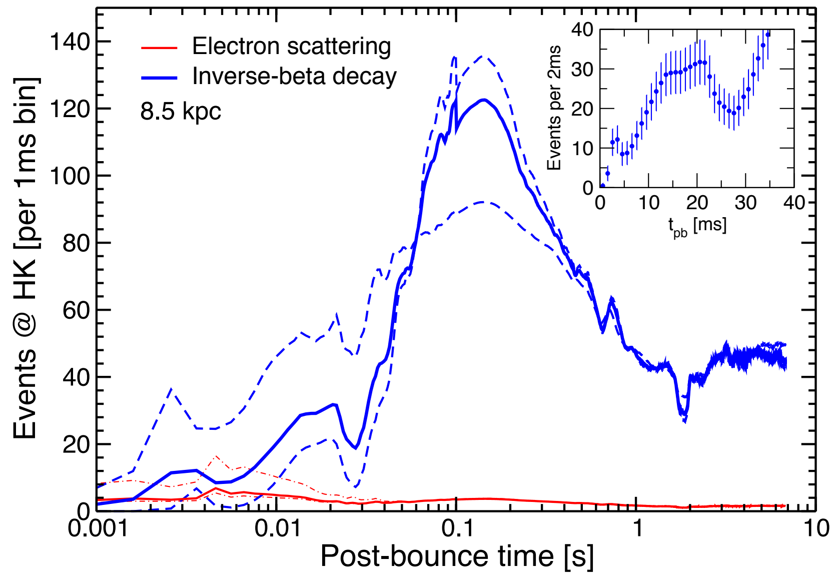
*Horiuchi, KN+17*

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 indicator**.

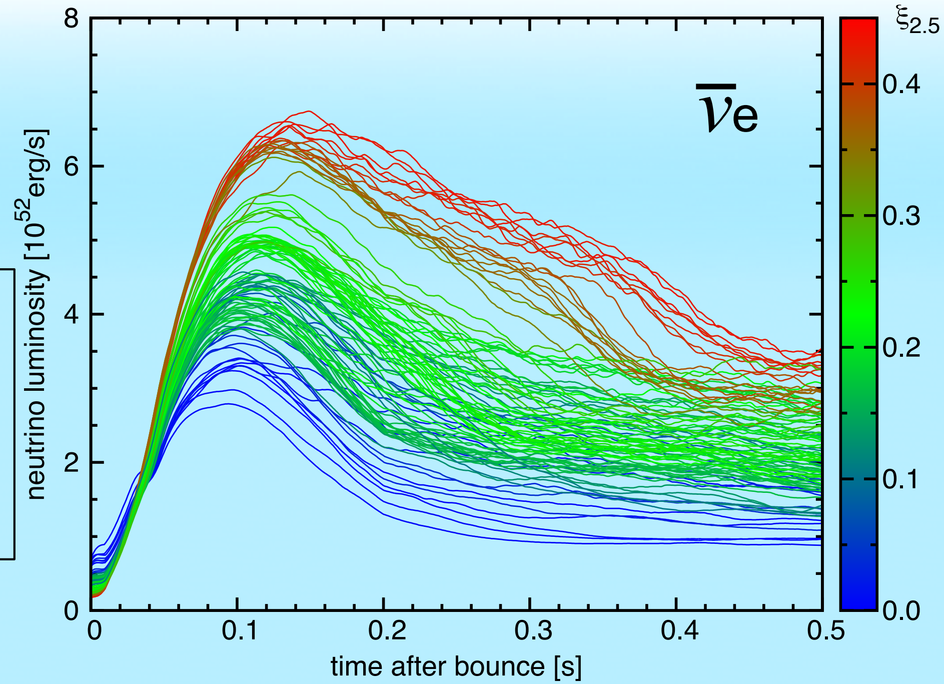
# Progenitor structure from Galactic SN $\nu$

*Horiuchi, KN+17*

**1) Reliable template**

CCSN models with
approximated/simplified scheme.

Code development
- sophisticated transport scheme
- detailed reactions
- effective GR




**2) Distance-independent indicator**

Detection event number $\propto D^{-2}$,
but large uncertainty in the distance to SN (progenitor).

New distance-independent indicator

# 1) Code Development

Neutrino reactions

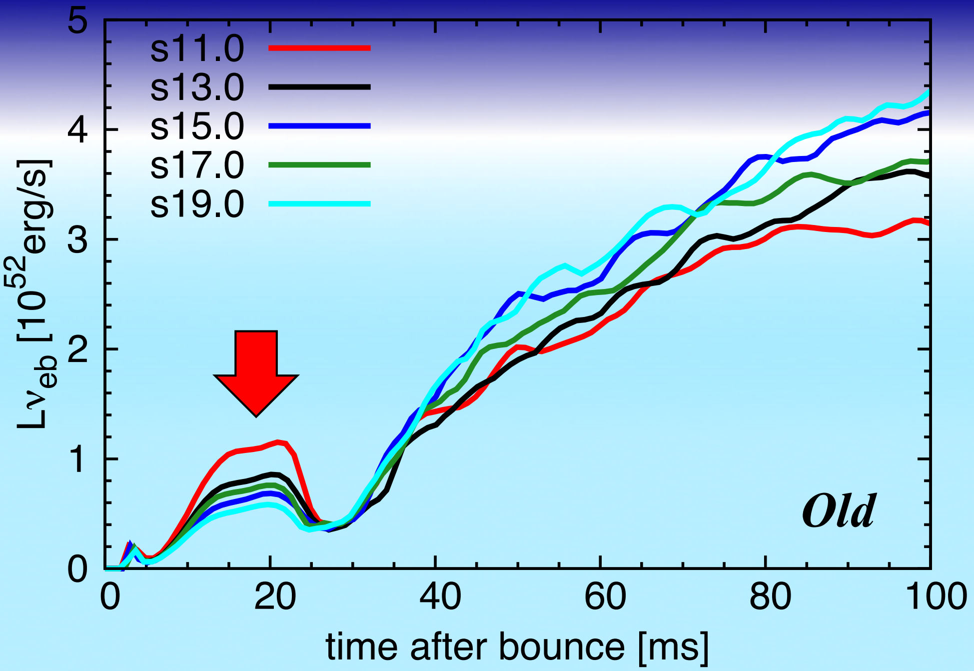
Bumps in $\bar{\nu}_e$ light curves.
(unrealistic)

$\nu_x$

Current scheme employs
IDSA ($\nu_e$, $\bar{\nu}_e$) + Leakage ($\nu_x$).
$\nu_x$ information is necessary
for neutrino oscillation.

General relativistic effects

cannot be ignored even in
exploding (NS forming) cases.



# 1) Code Development

Neutrino reactions

Bumps in $\bar{\nu}_e$ light curves.
(unrealistic)

Detailed reactions including ES.
→ bumps disappear.

$\nu_x$

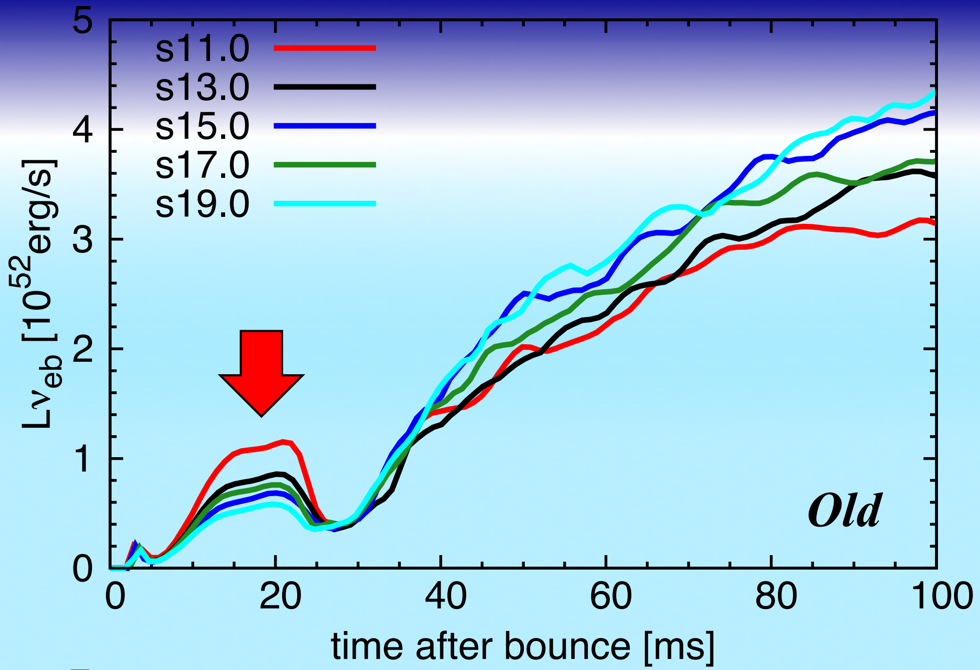
Current scheme employs
IDSA ($\nu_e$, $\bar{\nu}_e$) + Leakage ($\nu_x$).
$\nu_x$ information is necessary
for neutrino oscillation.

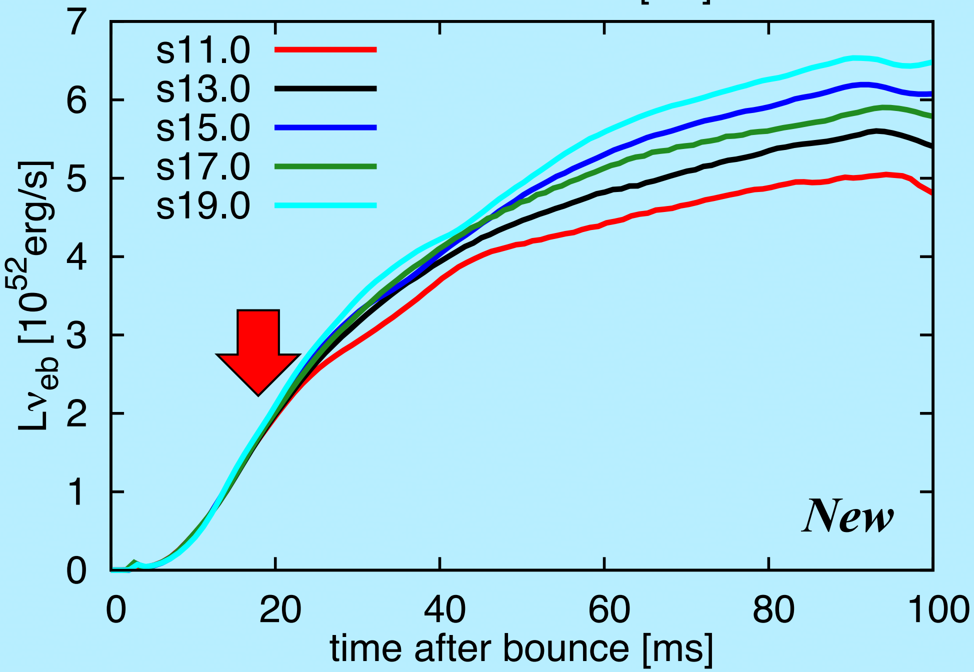
IDSA ( $\nu_e$ , $\bar{\nu}_e$ and $\nu_x$ )

General relativistic effects

cannot be ignored even in
exploding (NS forming) cases.

effective GR potential



# 2) Distance-independent indicator

Early phase（t < ~50 ms）:

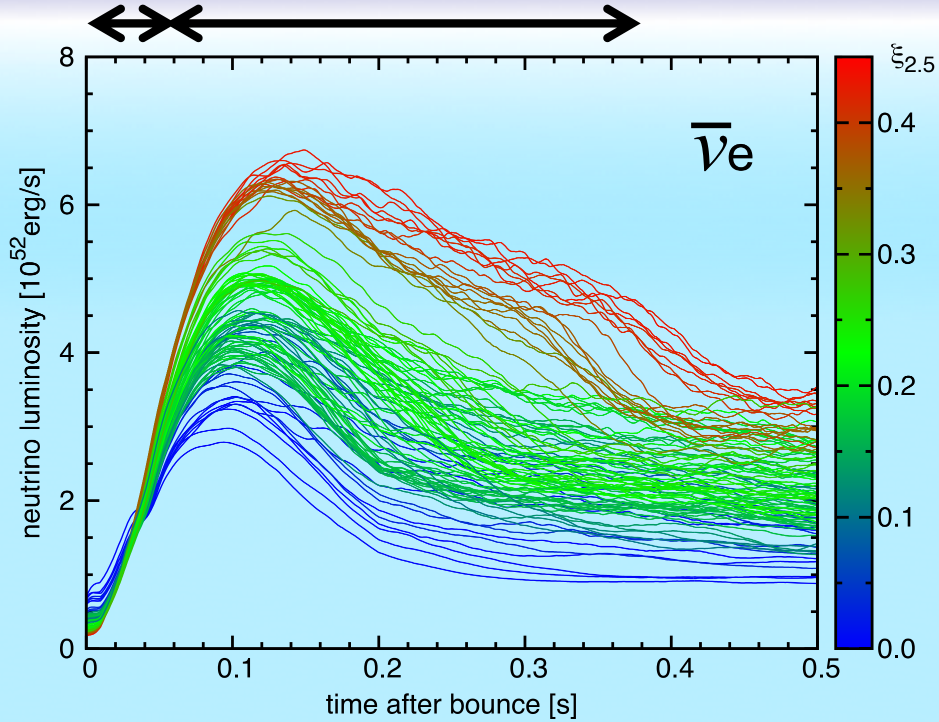
Diffusive neutrino dominant.

Less dependent on compactness.

Later phase:

Accretion neutrino dominant.

Monotonically dependent on compactness.



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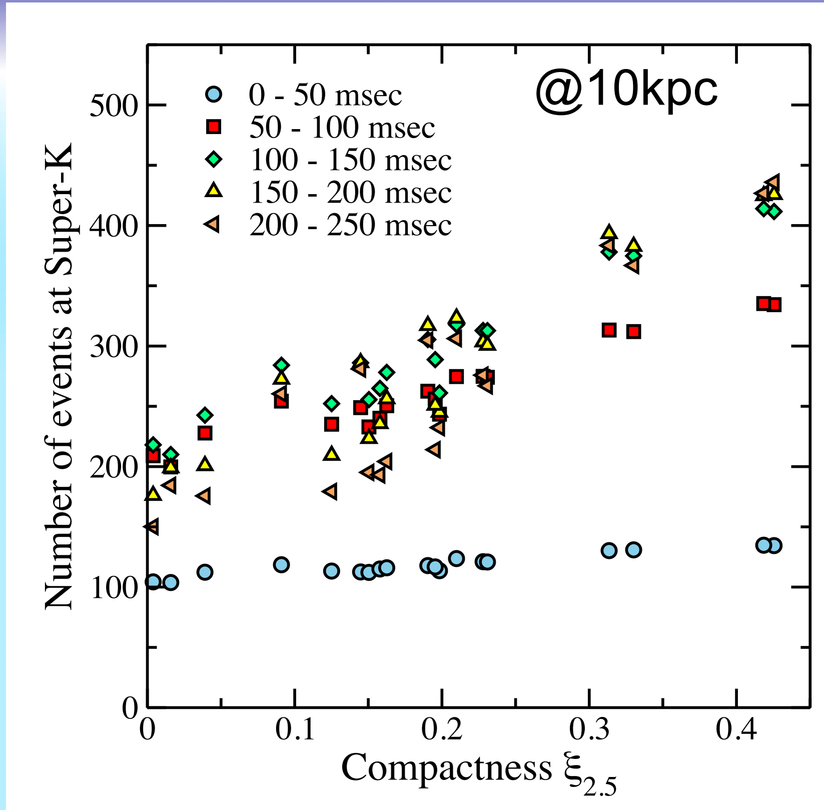



Distance-independent, compactness-dependent index.

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

Ratio of neutrino detection numbers between two phases.

# Time-integrated IBD events (SK, 10 kpc)

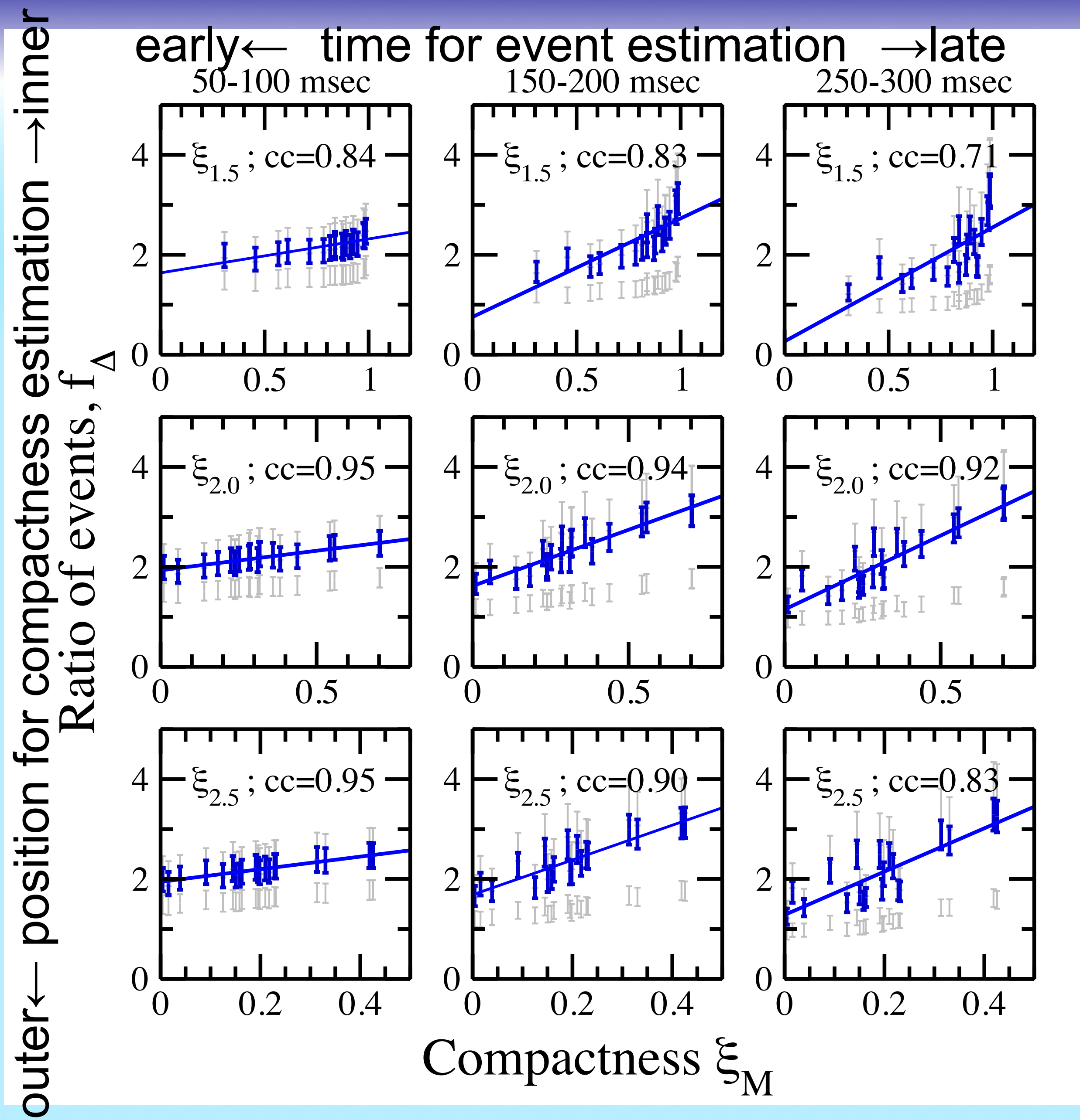
Event number ratio to N(0-50 msec).

flat ←→ steep.
Note that our method is not suitable for much later phase.

Degenerate in high $\xi_{1.5}$.

Best CC in $\xi_{2.0}$.

Blue : MSW mixing.
Gray : $P(\overline{\nu}_e)$ = 0 & 1.

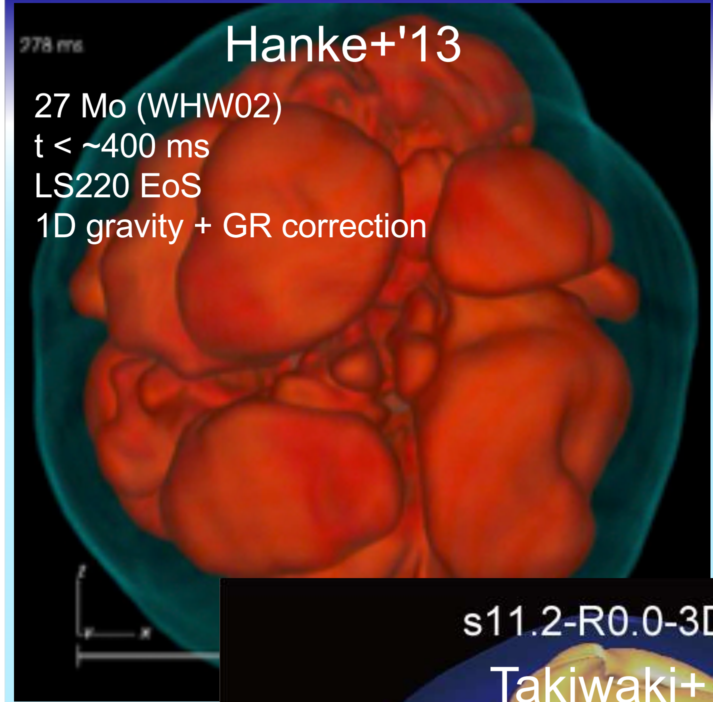


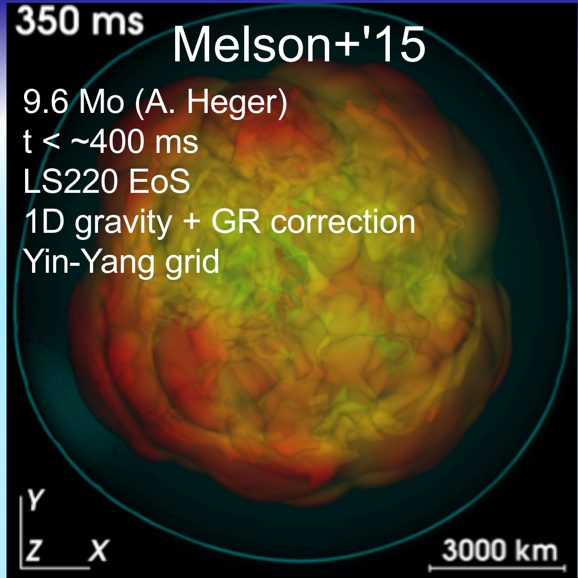
# Short summary & discussions

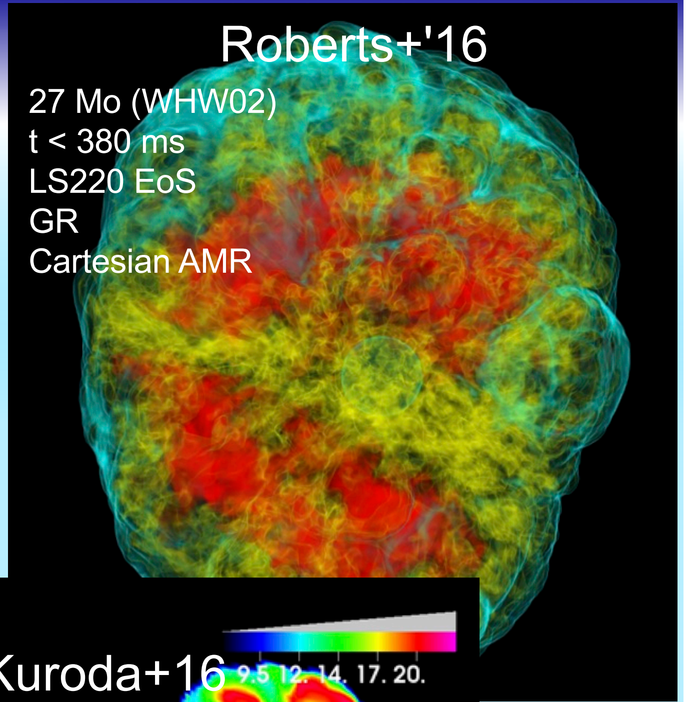
- ✓ We have explored the systematic features of CCSN using ~400 numerical models.
- ✓ The compactness-observables correlation suggests that we could infer the progenitor structure (even before explosion).
- ✓ The ratio $N_{\mathrm{acc.}}/N_{\mathrm{diff.}}$ can be a good distance-independent indicator.

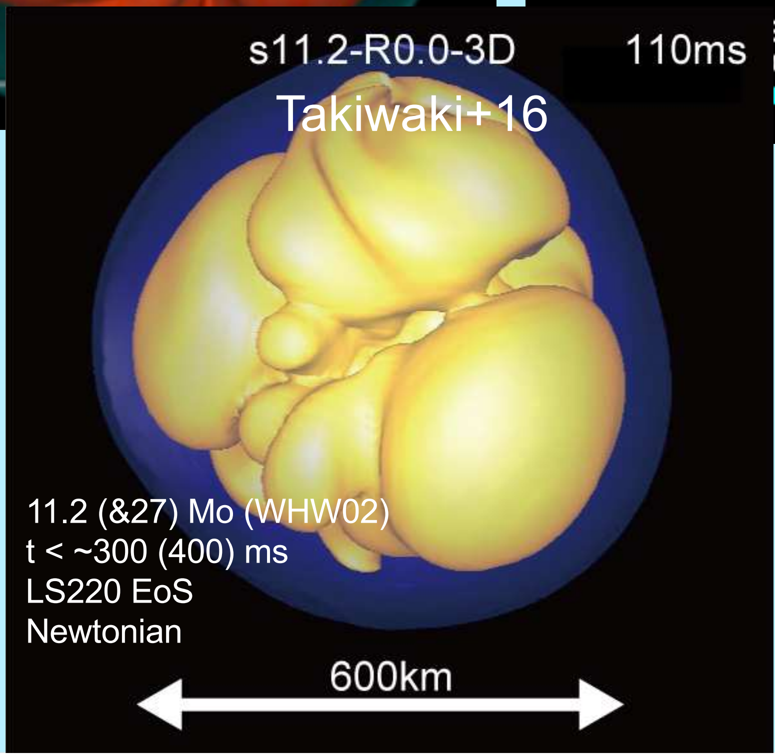
- ✓ Additional neutrino flavor mixing beyond MSW,
- ✓ Simulations should be in 3D including rotation, B-field, …

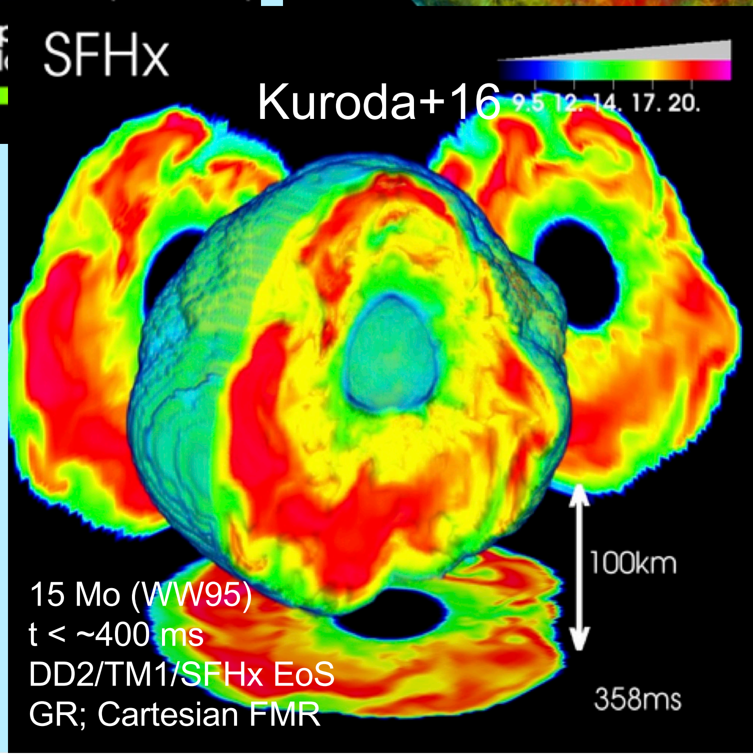
# 3D CCSN Simulations



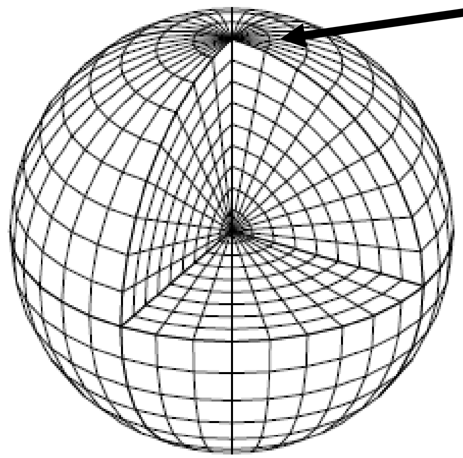



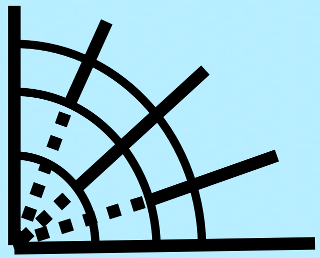
# Mesh coarsening scheme



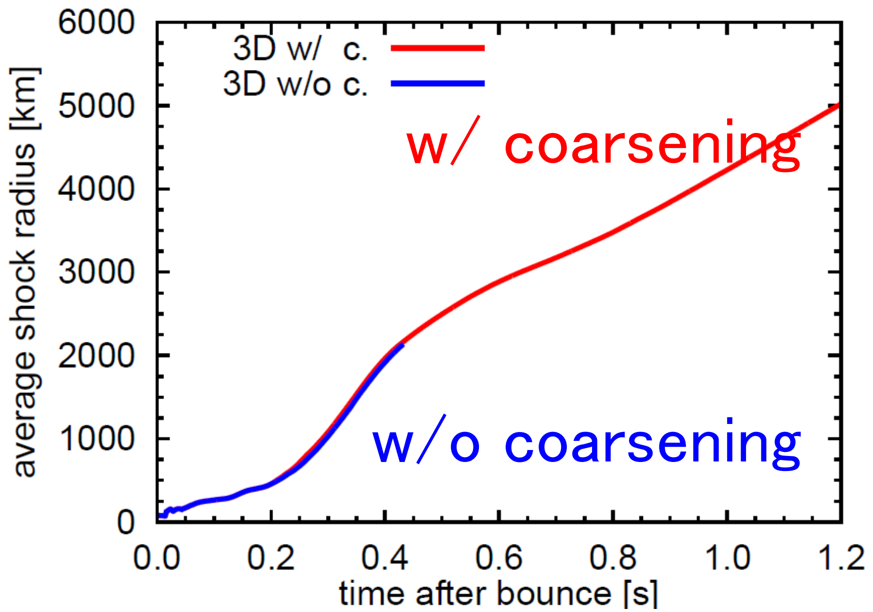
Too much small cell width around the polar.

→ Simulation time step $\Delta t$ is very small.

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



⇒ Estimate $\Delta t$ in "coarsened grid".



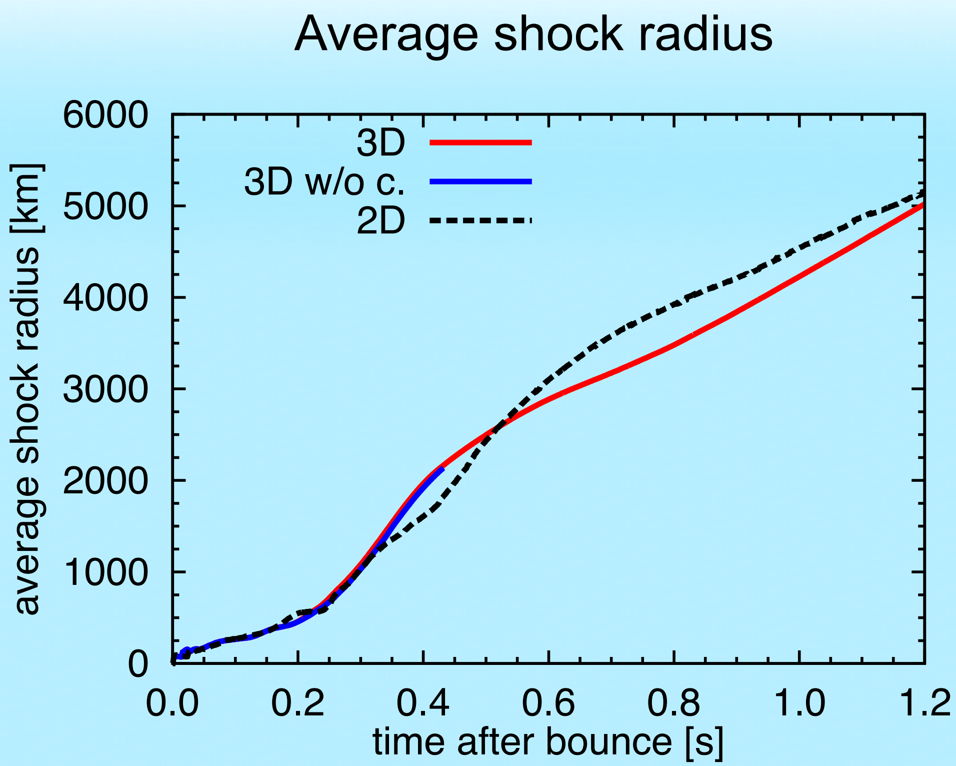

3D test calculation.

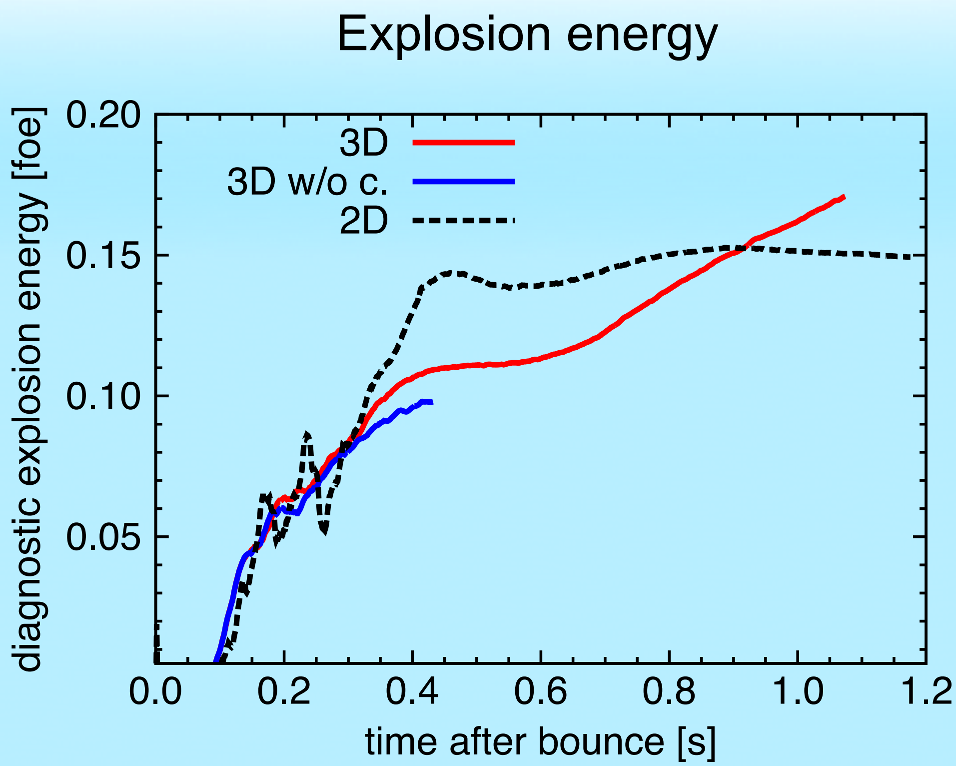
Averaged (or space-integrated) values such as shock radius show good agreement.

(preliminary)

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

# Preliminary result of 3D simulation




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

→More energetic in 3D.

# Rotation of Massive Star Cores

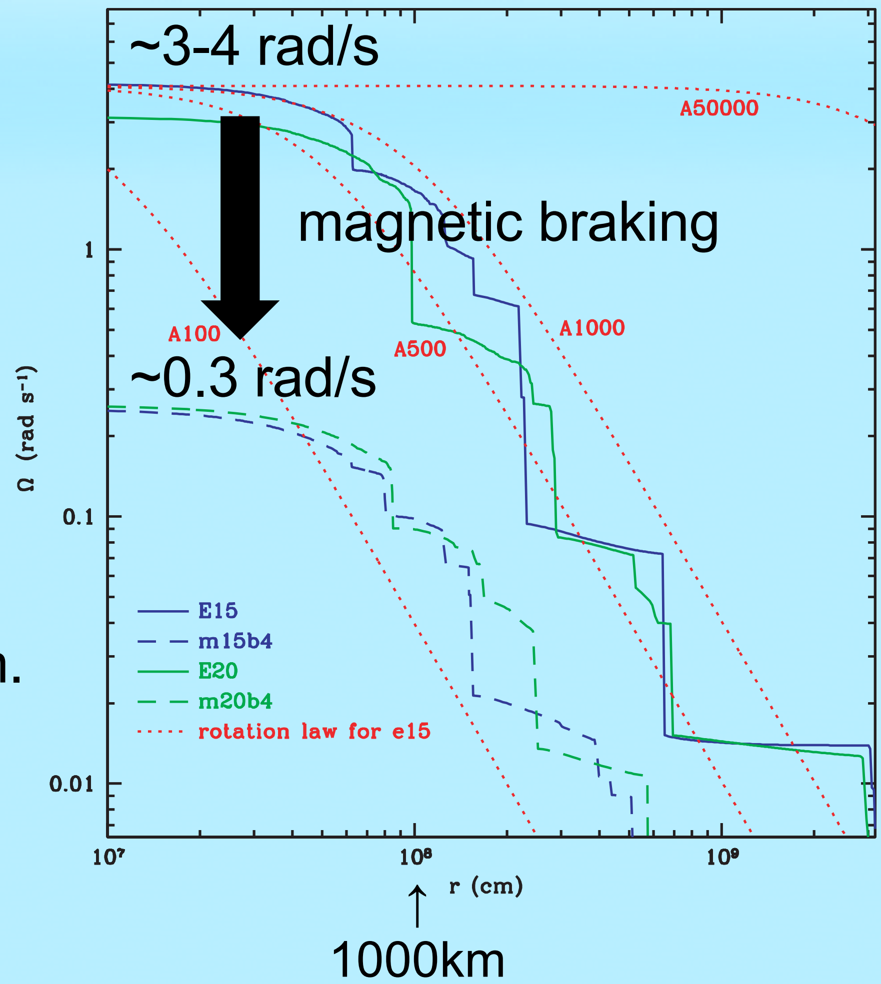
- ✓ Rotation of massive star core is unknown.
- ✓ Theoretical (numerical) prediction.
  *Zwerger & Muller '97*
  *Woosley & Weaver '95*
  *Heger+ '00, '03.*

M=15, 20 Mo, $v_{ini}$ = 200 km/s

Nearly rigid rotation within ~1000km.

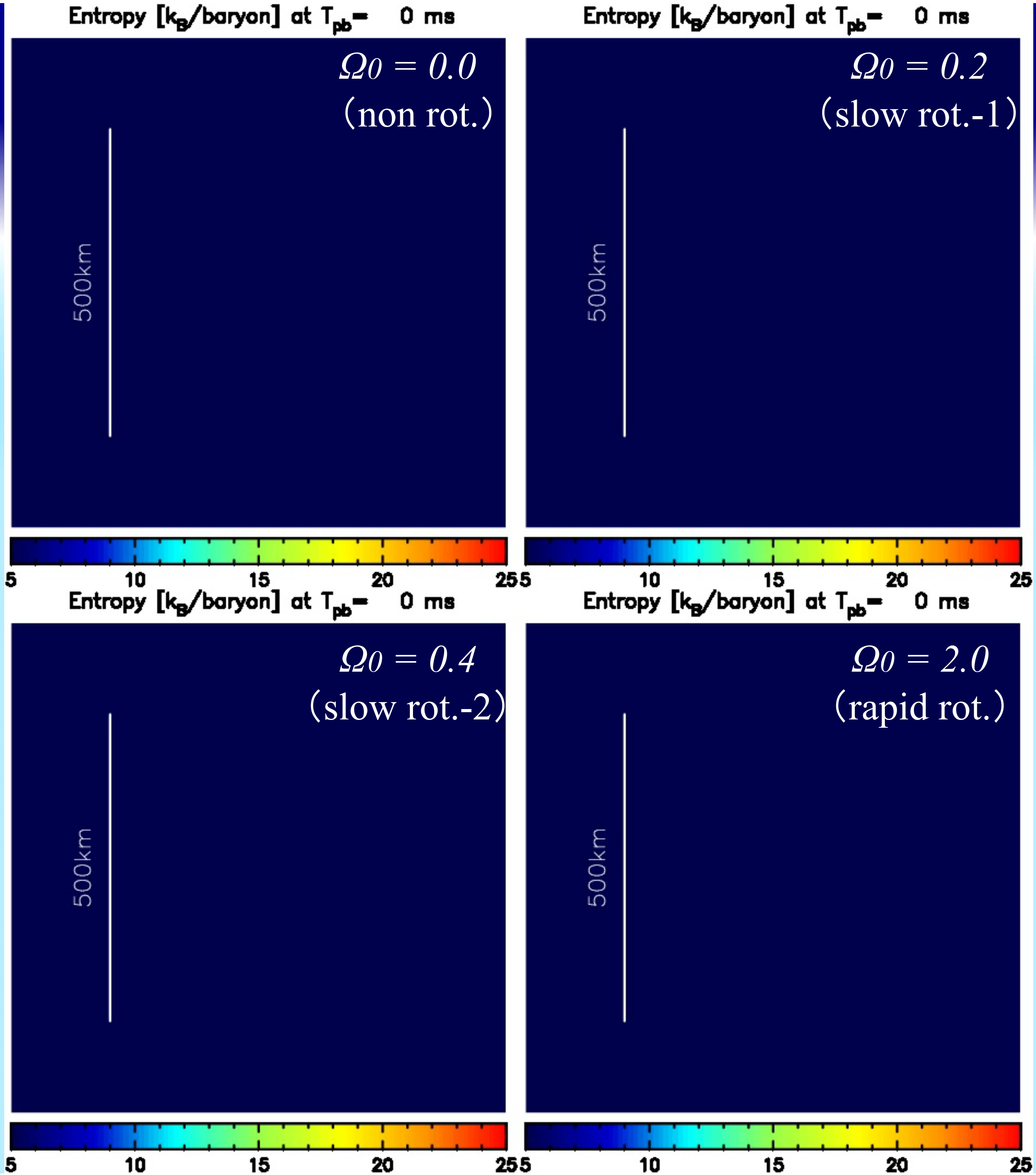
0.3 (w/ B-field) - 3.0 (w/o) rad/s.

Angular momentum distribution based on calculations of stellar evolution



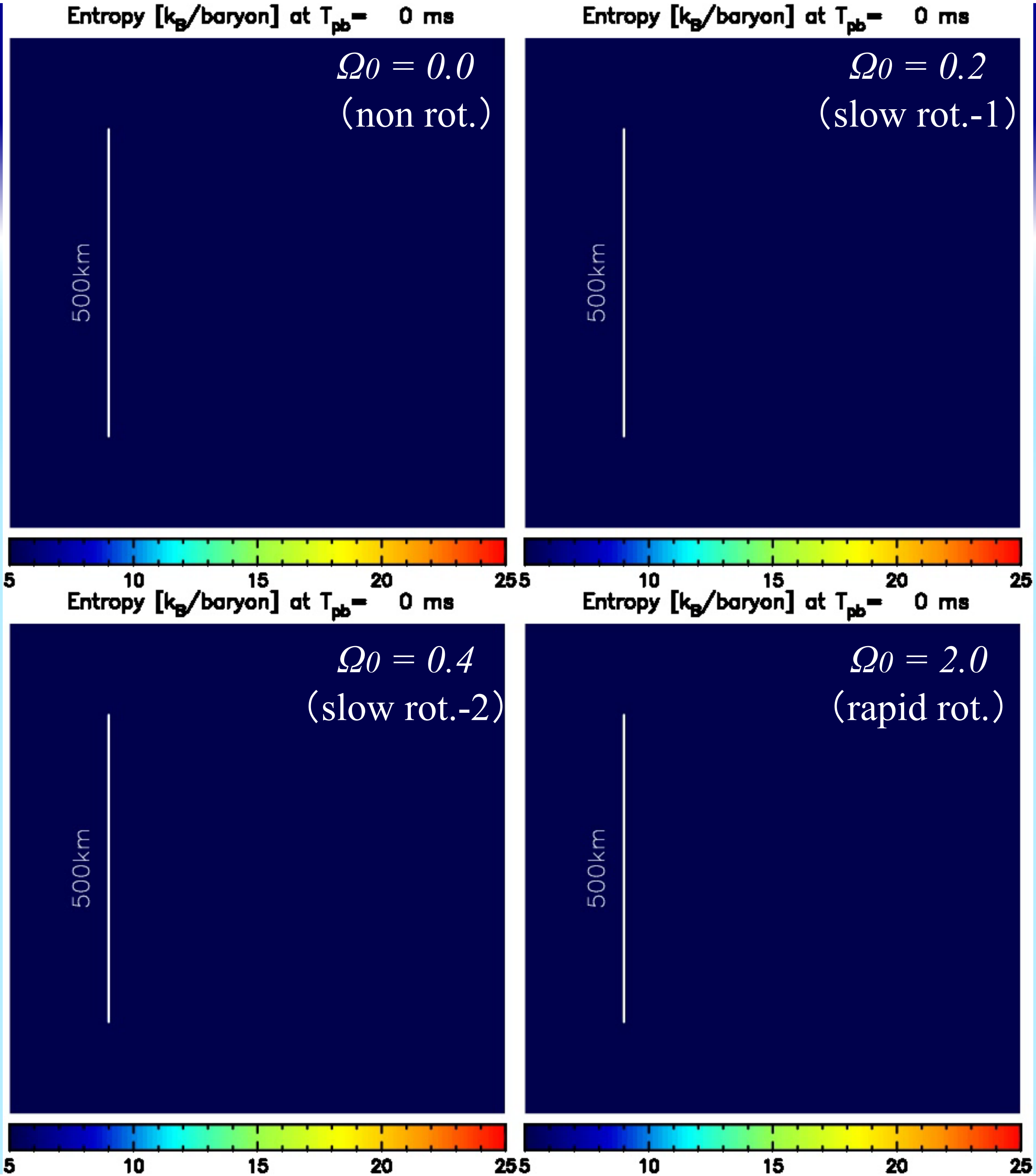
# s11.2

- ✓ s11.2 model with different $\Omega_0$ [rad/s].
- ✓ All models turns to shock expansion at ~300 ms.
- ✓ $\Omega_0$=2.0 model presents oblate structure just after core bounce.



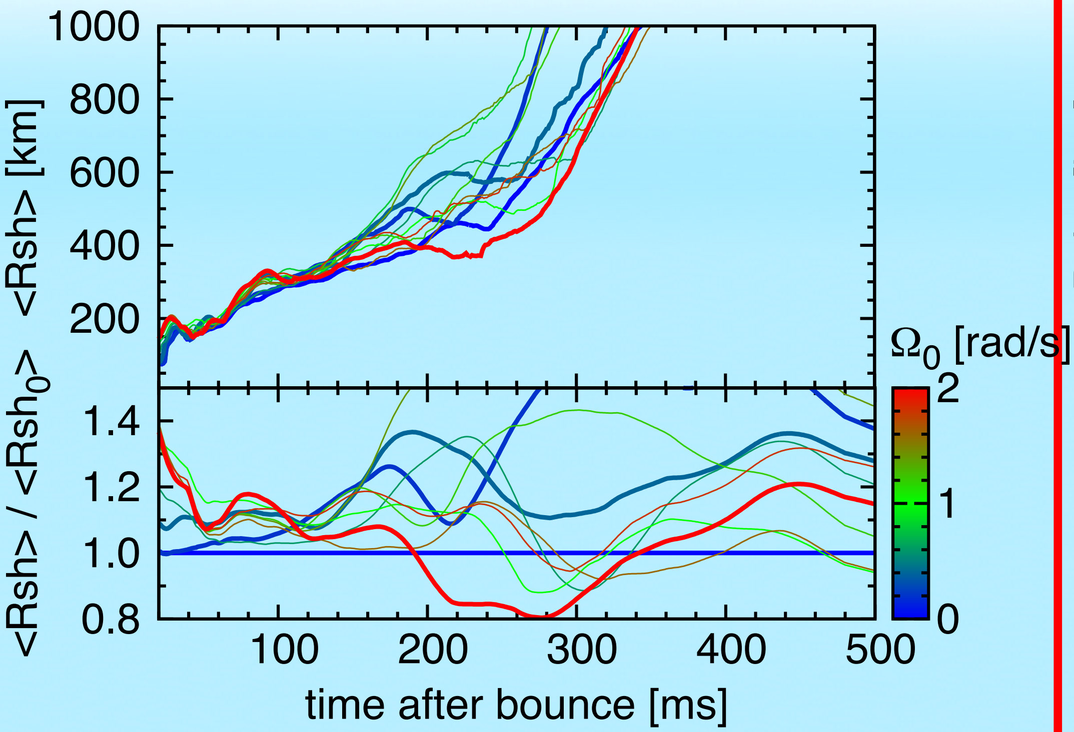
s15.0

- ✓ s15.0 model with different $\Omega_0$ [rad/s].
- ✓ Non-rotating model does not explode.
- ✓ Slowly rotating models successfully revive the shock.
- ✓ Rapidly rotating model might explode.

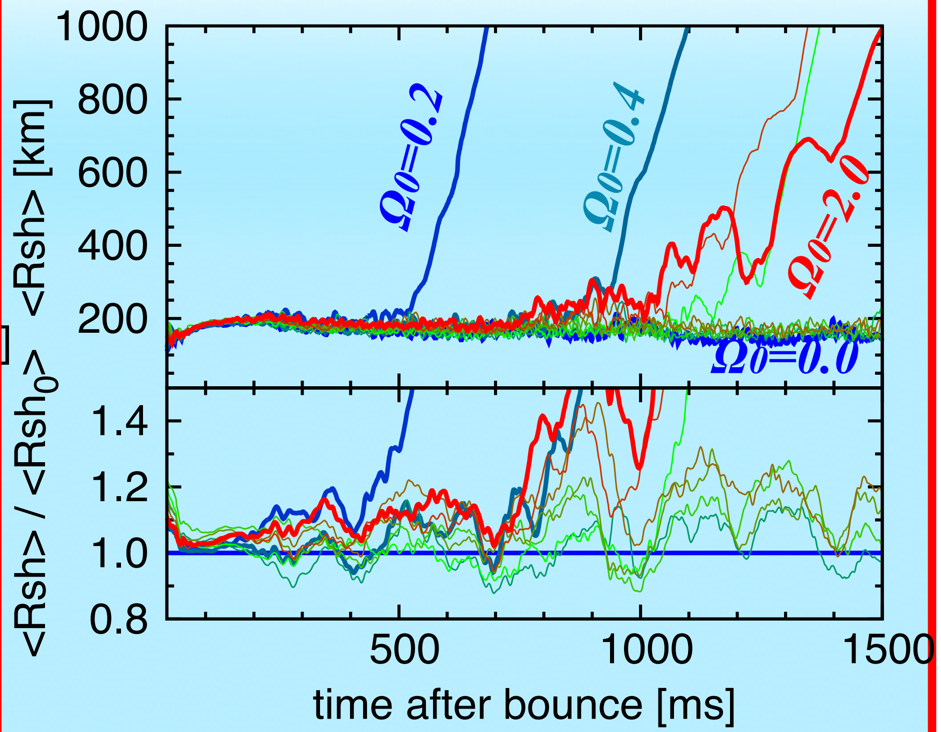


# Angle-averaged shock radius

s11.2




s15.0

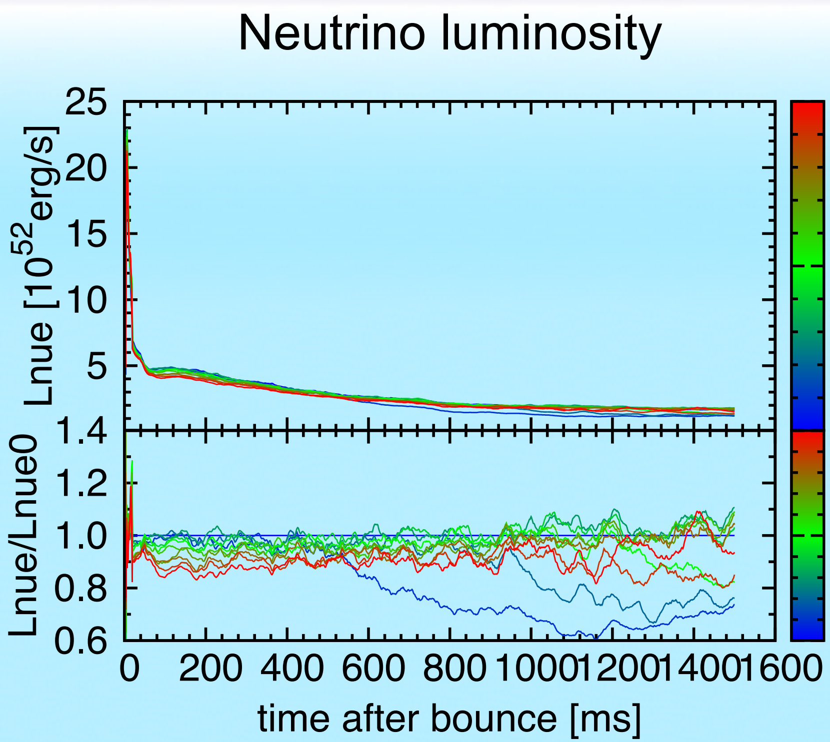


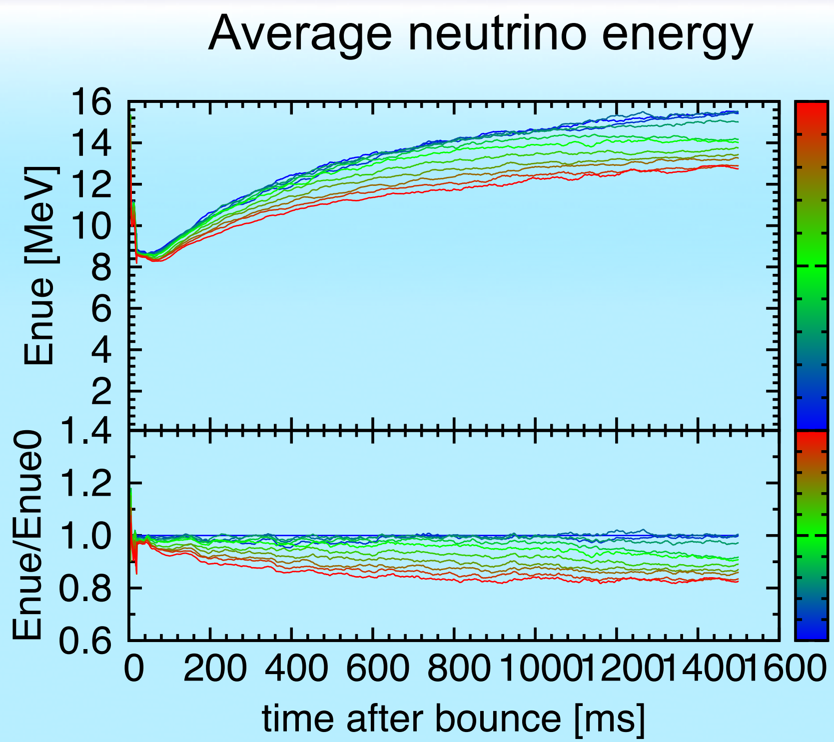

The core of s11.2 progenitor is surrounded by dilute envelope.
→ Rotation effect is weak.

Rotation strongly affects dynamics. Shock revival time is not aligned with rotation speed.

# Neutrino luminosities and average energies

s15.0




Rapid rotation ($\Omega_0$ = 2.0 rad/s) reduces neutrino luminosity and average energy up to ~20 %.

# Summary & discussions

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- ✓ The compactness-observables correlation suggests that we could infer the progenitor structure (even before explosion).
- ✓ The ratio $N_{acc.}/N_{diff.}$ can be a good distance-independent indicator.

- ✓ Additional neutrino flavor mixing beyond MSW,
- ✓ Simulations should be in 3D including rotation, B-field, …
  - 3D CCSN models from multiple progenitors are being available.
  - (Very) rapid rotation affects neutrino properties.
- ✓ Uncertainty in the nuclear physics → Nakazato-san's talk.