Systematic Features of CCSN neutrinos

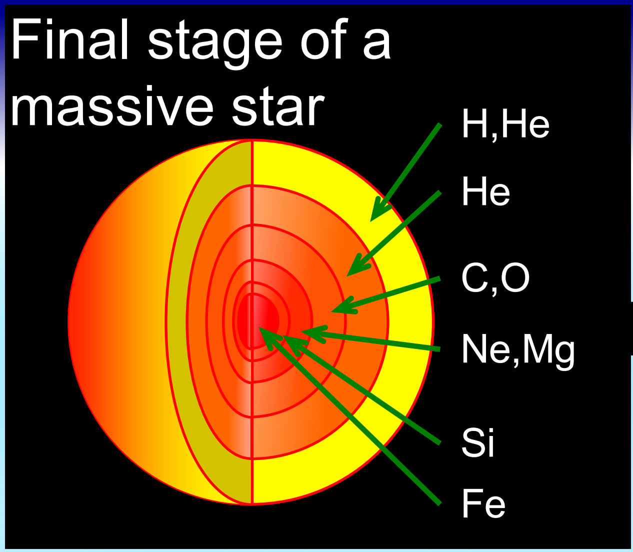
Ko Nakamura (Fukuoka Univ.)

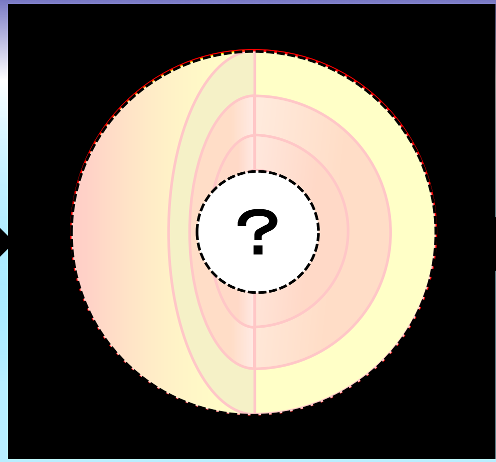
T. Takiwaki (NAOJ) , S. Horiuchi (Virginia Tech.),

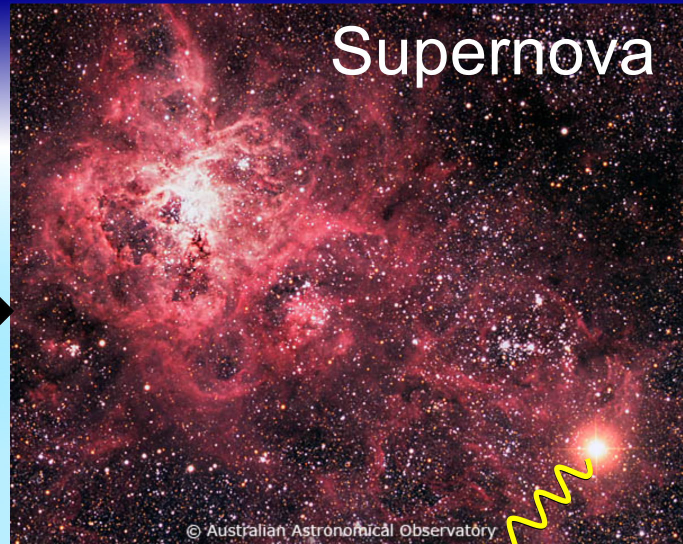
M. Tanaka (Tohoku Univ.), K. Kotake (Fukuoka Univ.)

International Symposium on Revealing the history of the universe
with underground particle and nuclear research
@ Tohoku Univ.   Mar. 7-9, 2019

How to create a Core-collapse SN (CCSN)







Basic equations:

$$\frac{d\rho}{dt} + \rho\nabla\cdot\mathbf{v} = 0$$

$$\rho\frac{d\mathbf{v}}{dt} = -\nabla P - \rho\nabla\Phi$$

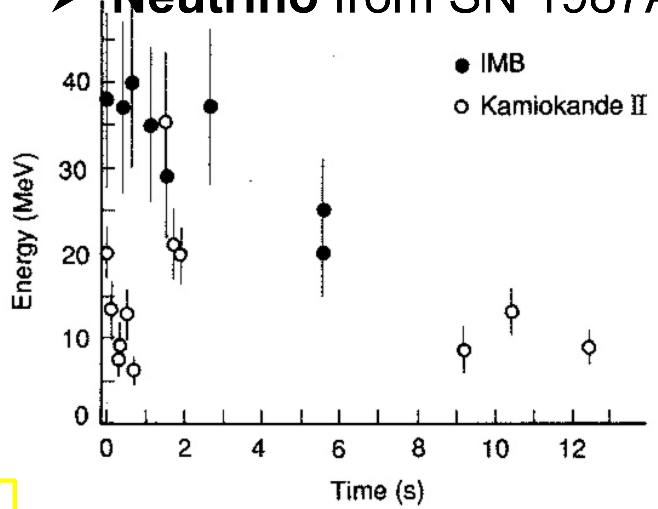
$$\frac{\partial e^*}{\partial t} + \nabla\cdot[(e^* + P)\mathbf{v}] = -\rho\mathbf{v}\cdot\nabla\Phi + Q_E$$

$$\frac{dY_e}{dt} = \Gamma_N$$

Energy and electron fraction change due to neutrino interactions.

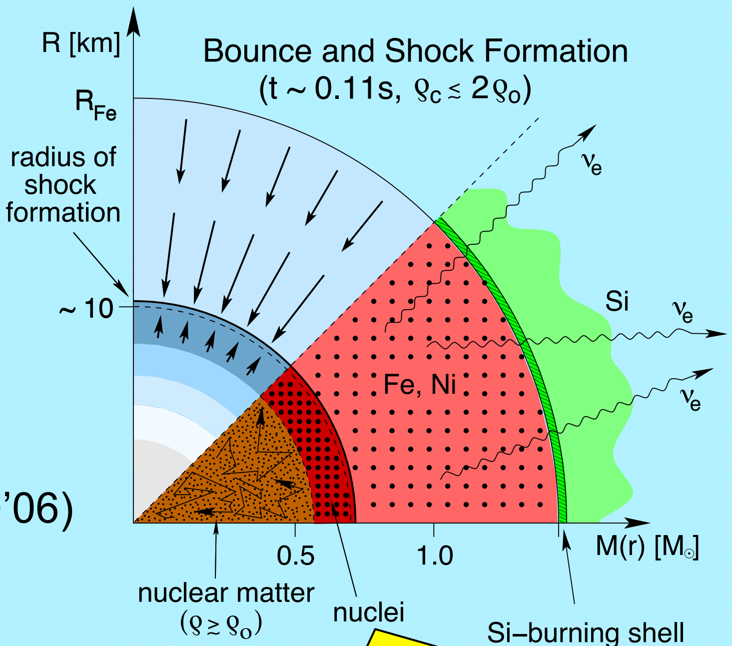
$$\triangle\Phi = 4\pi G\rho$$ + EOS.

- **Neutrino** from SN 1987A



Explosion mechanism of CCSN

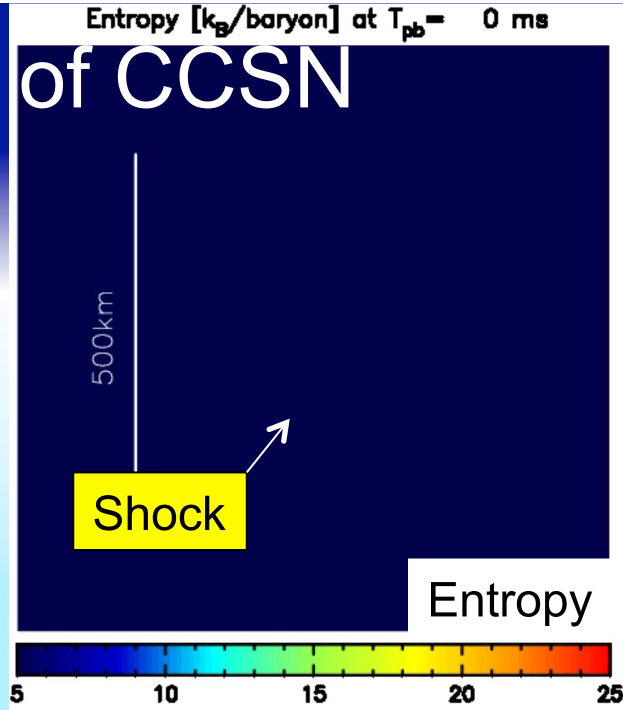
- Core-collapse supernova
  - Final fate of massive stars (>~10Mo)
  - Unclear mechanism of explosion
  - **Neutrino heating mechanism**
  - Convection, SASI

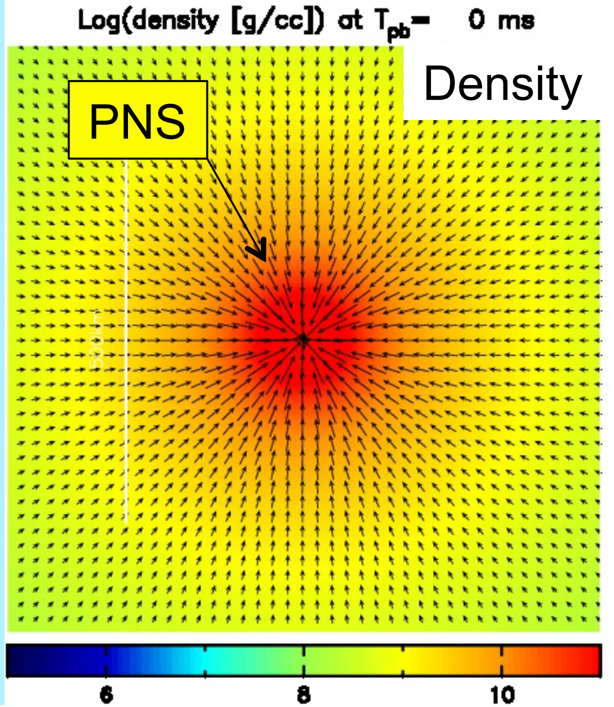


(Janka+'06)

$\nu_e + n \rightarrow p + e^-$,
$\bar{\nu}_e + p \rightarrow n + e^+$, etc.

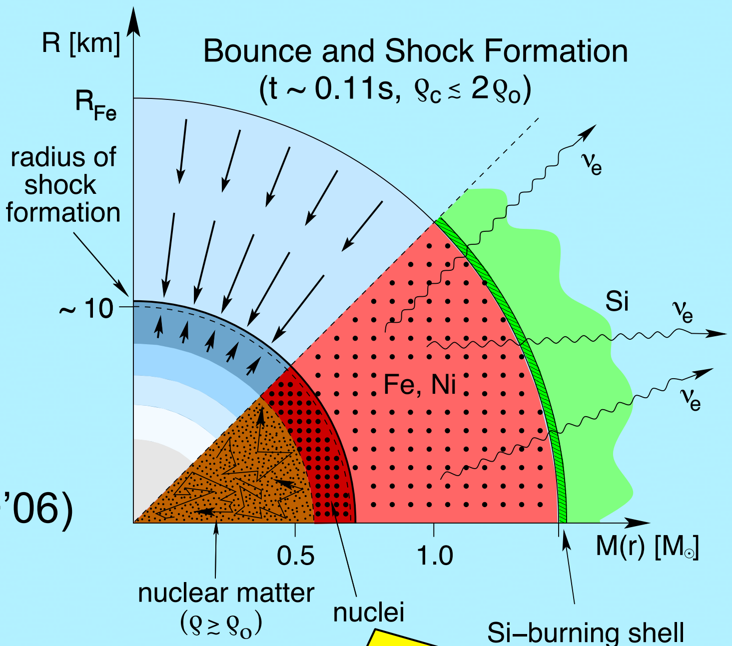
ex.)
M = 17 Mo
Z = Zo





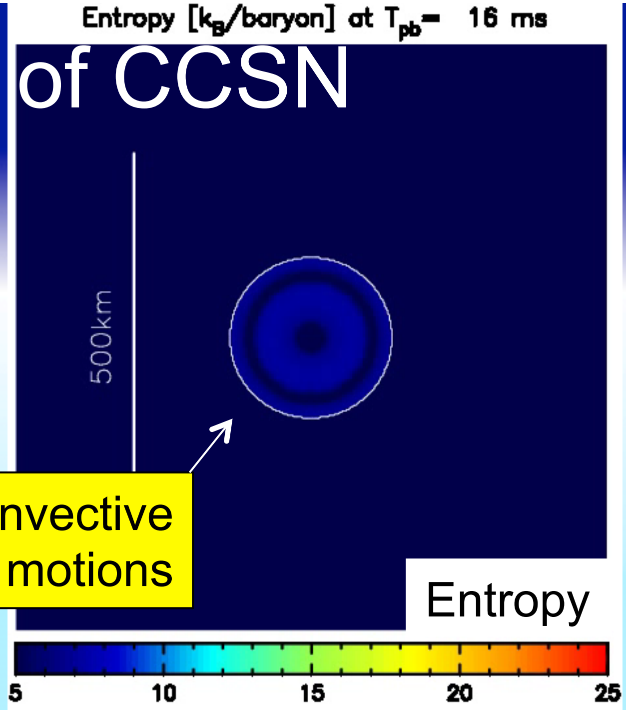
Explosion mechanism of CCSN

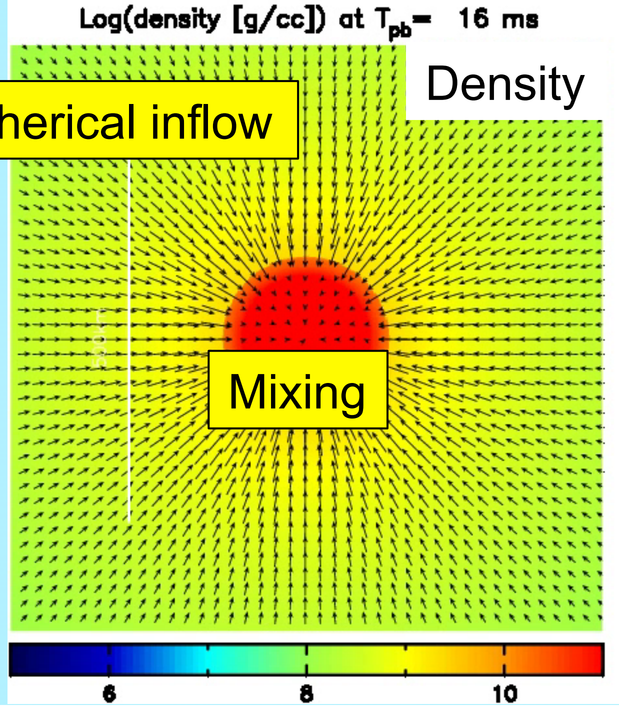
- Core-collapse supernova
  - Final fate of massive stars（>~10Mo）
  - Unclear mechanism of explosion
  - **<u>Neutrino heating mechanism</u>**
  - Convection, SASI



(Janka+'06)

$\nu_e + n \rightarrow p + e^-$,
$\bar{\nu}_e + p \rightarrow n + e^+$, etc.

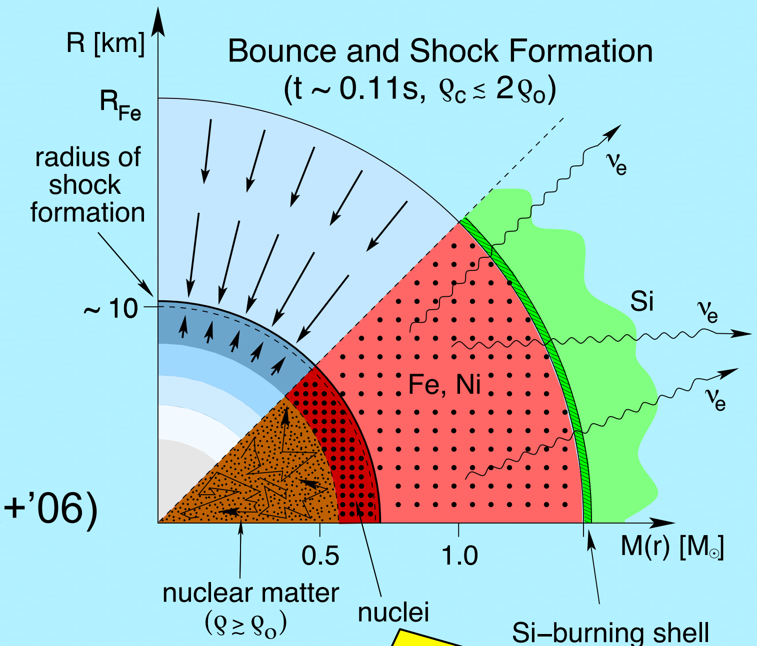




ex.)
M = 17 Mo
Z = Zo

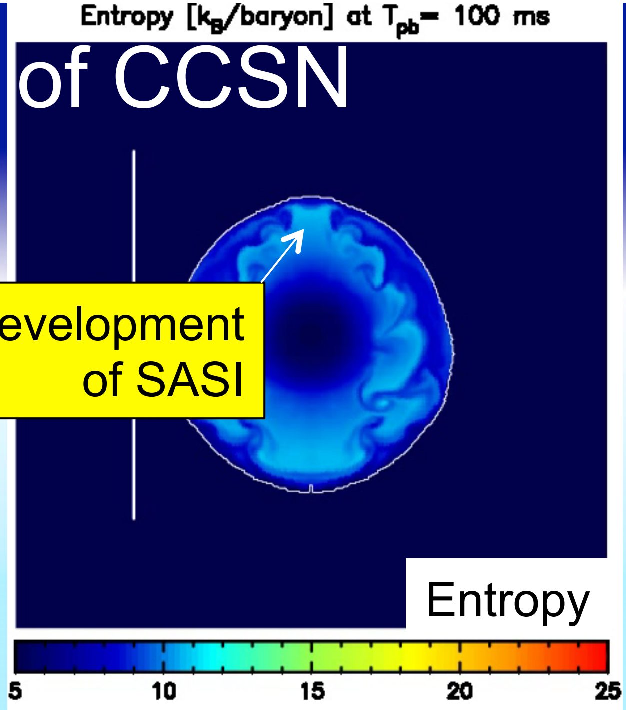
Explosion mechanism of CCSN

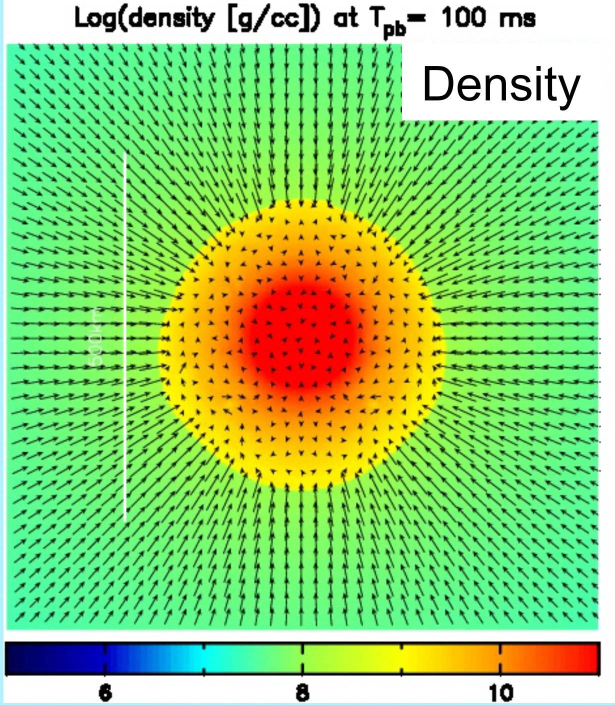
- Core-collapse supernova
  - Final fate of massive stars (>~10Mo)
  - Unclear mechanism of explosion
  - **Neutrino heating mechanism**
  - Convection, SASI



(Janka+'06)

$\nu_e + n \rightarrow p + e^-$,
$\bar{\nu}_e + p \rightarrow n + e^+$, etc.





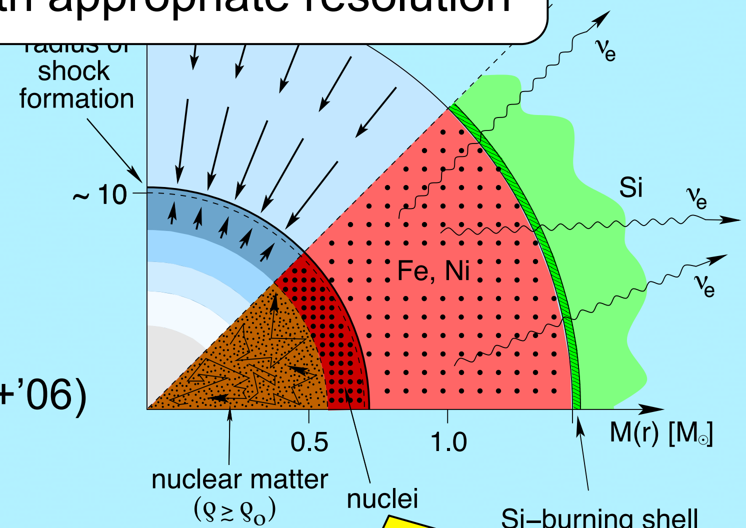
ex.)
M = 17 Mo
Z = Zo

Explosion mechanism of CCSN

Neutrino transport
from interior of PNS to outside of the shock
Energy distribution
to solve energy-dependent reactions

– **Neutrino heating mechanism**
– Convection, SASI

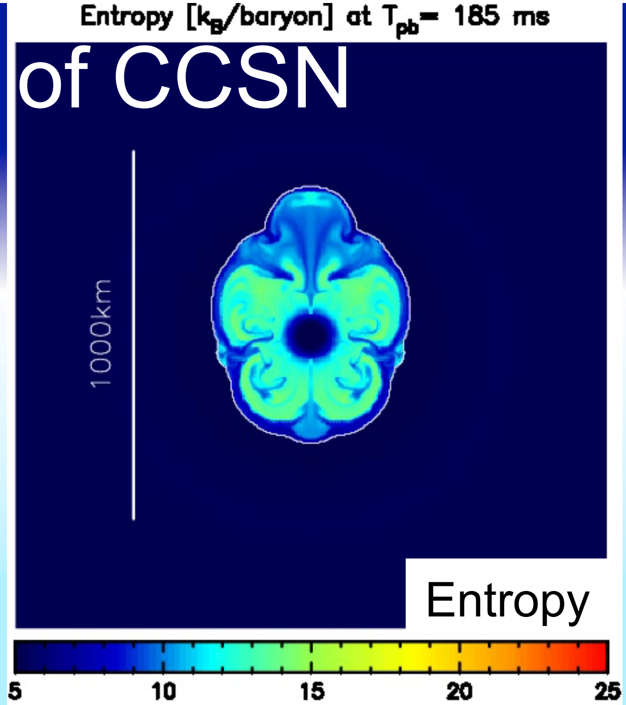
~~1D~~/**2D**/3D
with appropriate resolution

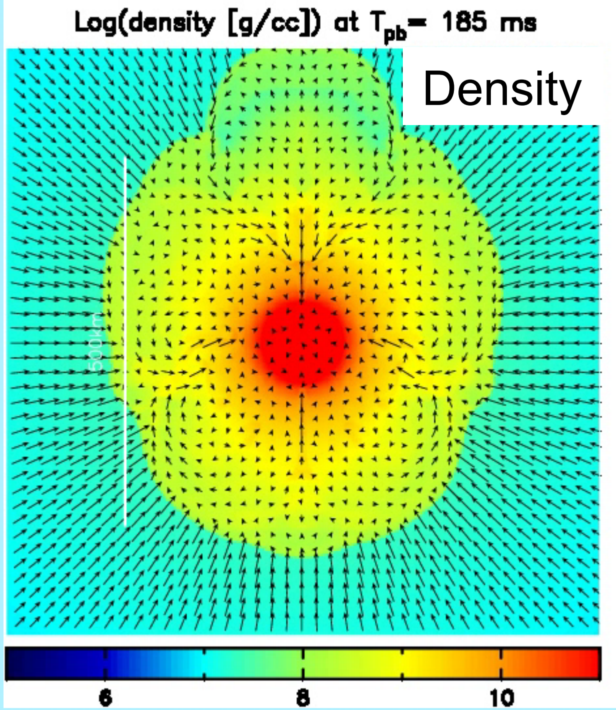


(Janka+'06)

$\nu_e + n \rightarrow p + e^-$,
$\bar{\nu}_e + p \rightarrow n + e^+$, etc.

ex.)
M = 17 Mo
Z = Zo

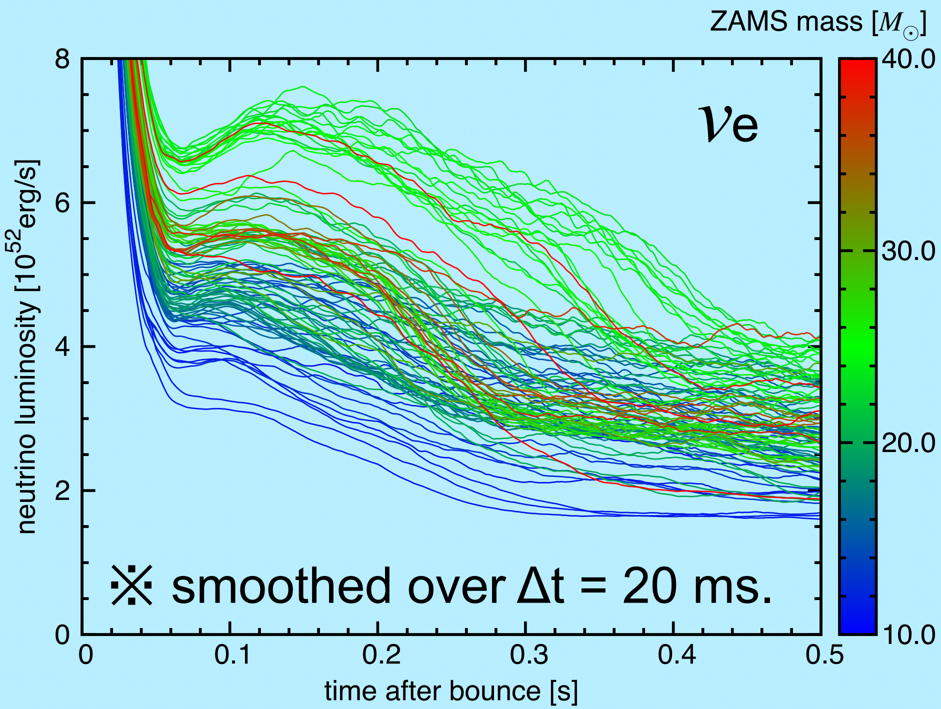


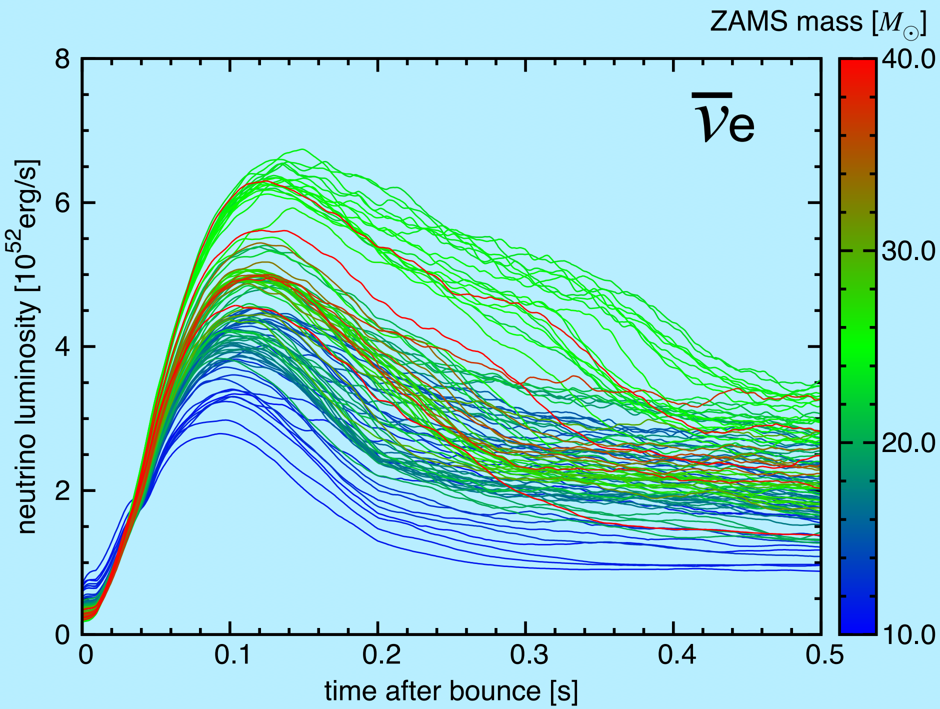


Time evolution of neutrino luminosity

- ✓ Showing 101 models with solar metallicity.
  The other models with lower metallicity have a similar trend (not shown here).

- ✓ The difference of $L\nu$ is **more than double**.
  2-6 $\times 10^{52}$ erg/s @ t = 200 ms.





Compactness parameter

What determines the CCSN properties is ...
mass accretion onto the PNS!

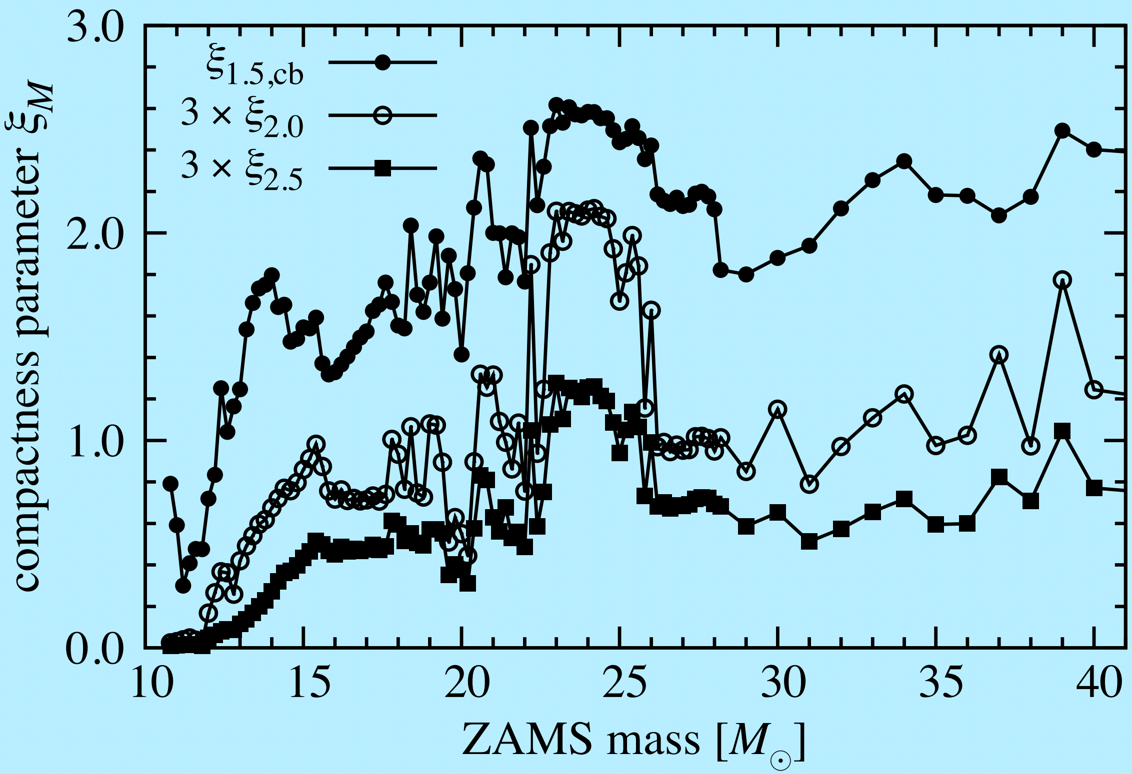
*Too much accretion leads to
BH formation and/or failed explosion.

(*Not too much) Mass accretion ↗
→PNS mass ↗
→ν luminosity ↗
→Explosion energy ↗
→^{56}Ni mass ↗

Compactness parameter

(O'Connor & Ott '11)

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



Time evolution of neutrino luminosity

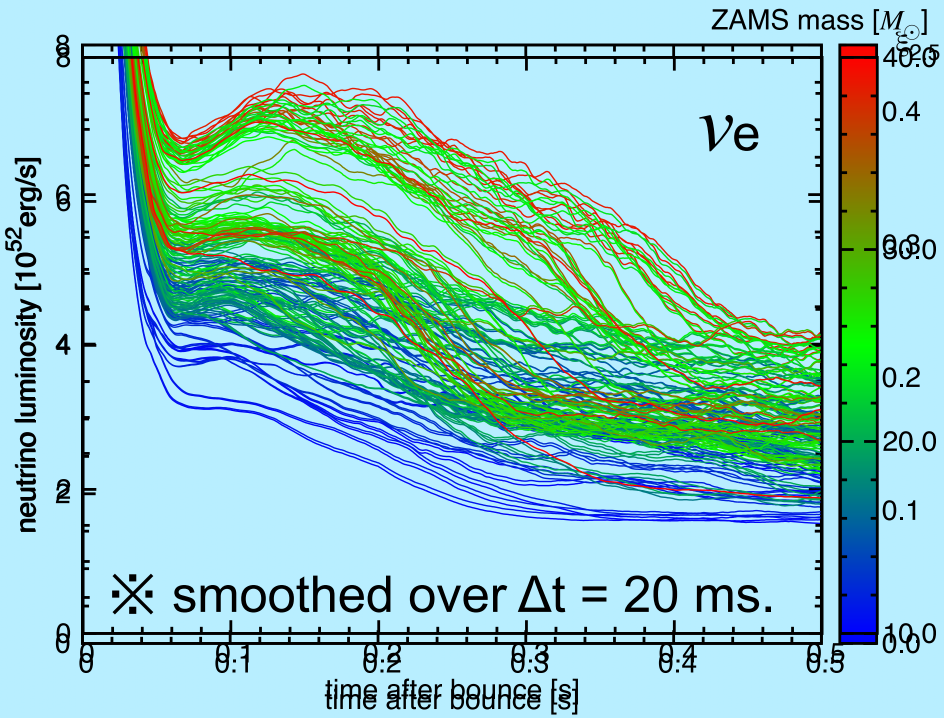
- ✓ Showing 101 models with solar metallicity.
  The other models with lower metallicity have a similar trend (not shown here).

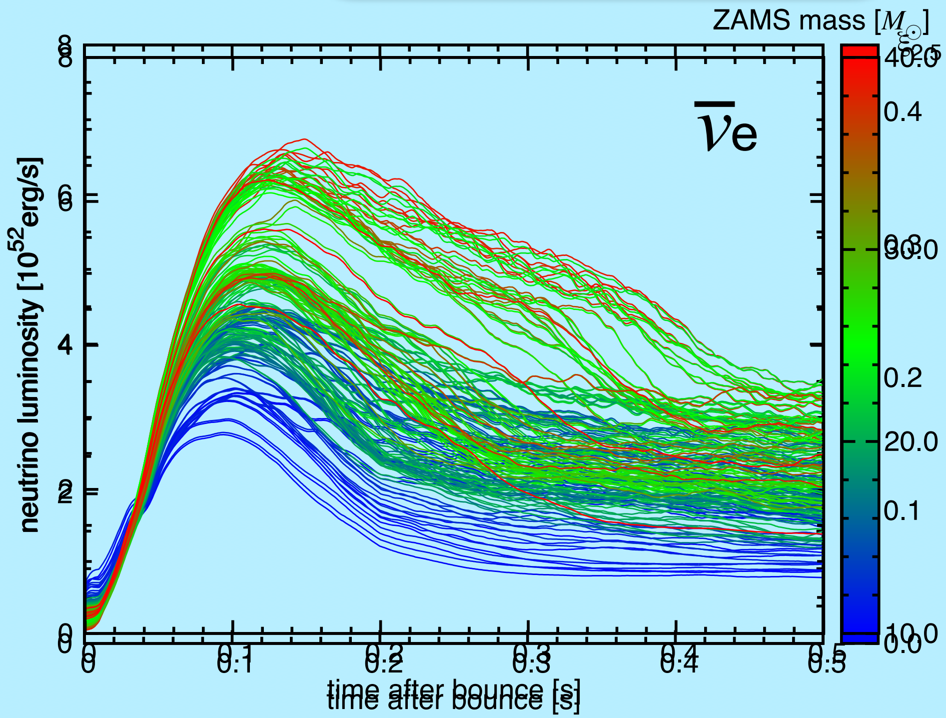
- ✓ The difference of *Lν* is **more than double**.
  2-6 × 10^{52} erg/s @ t = 200 ms.

- ✓ The compactness-colored lines show a **monotonic trend**.

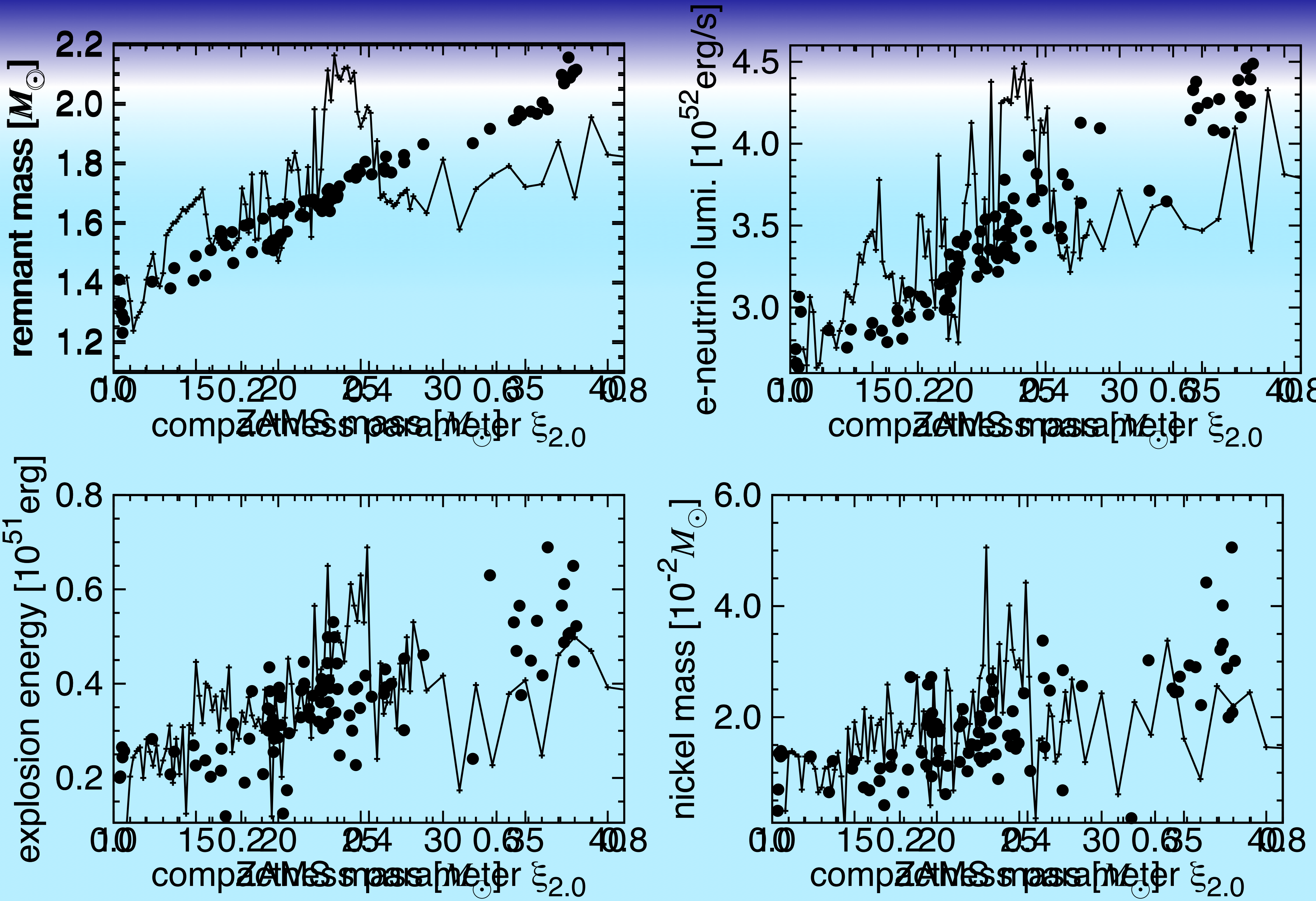
Compactness parameter
(*O'Connor & Ott 2011*)

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

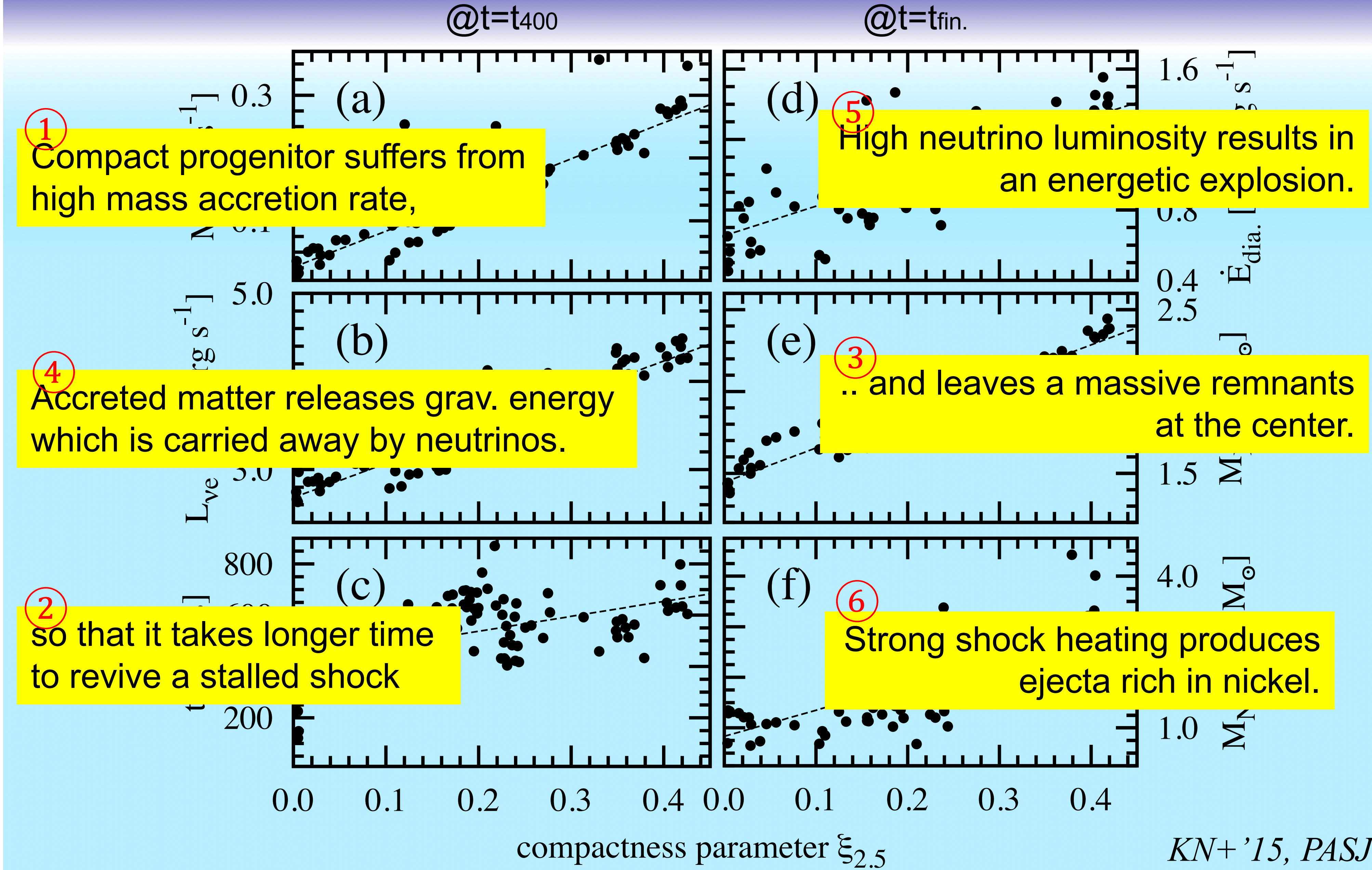




CCSN properties as a function of the compactness



Compilation of CCSNe Simulations for 101 Solar-metallicity Progenitors

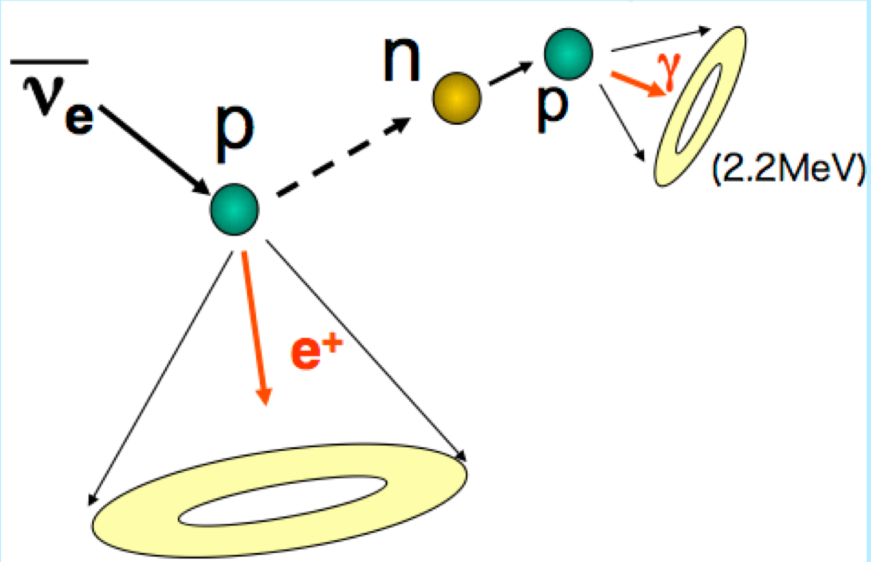


KN+'15, PASJ

Neutrino signals & detectors

✓ Water-Cherenkov detector
- Super Kamiokande (-Gd)
- Hyper Kamiokande

✓ Reaction channels
- inverse beta decay
- electron scattering



Gd-loaded SK can drastically suppress the background noise (*Beacom & Vagins '04*).

Neutrino signals & detectors

✓ Water-Cherenkov detector
- Super Kamiokande (-Gd)
- Hyper Kamiokande

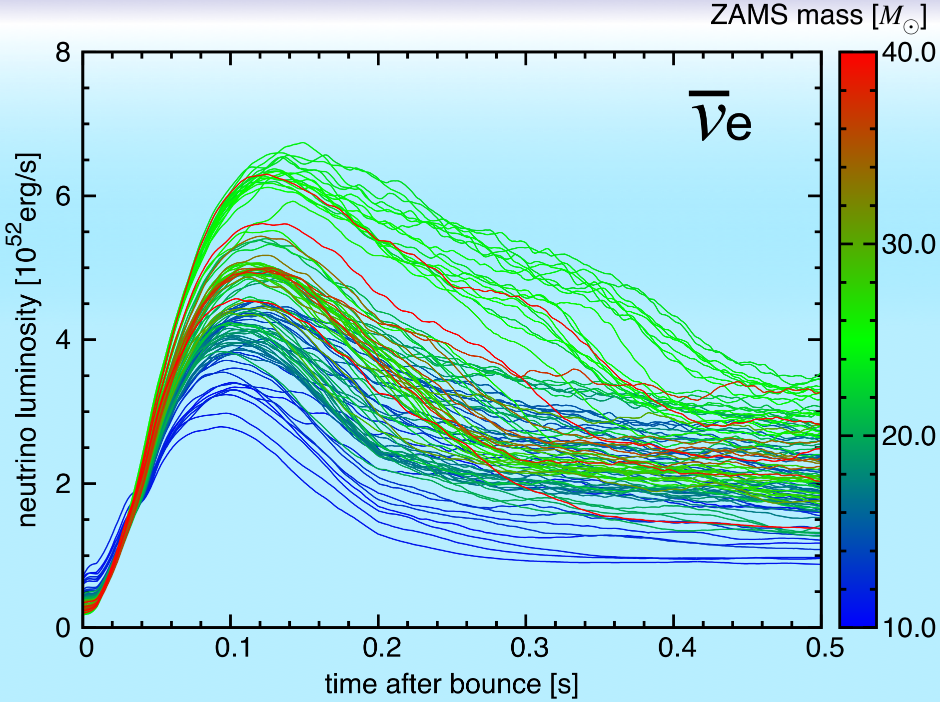
✓ Reaction channels
- inverse beta decay
- electron scattering

✓ Observed event rate:

$$\frac{dN_e}{dT_e} = \underbrace{N_t}_{\text{Number of targets}} \int_{E_{\min}}^{\infty} dE_\nu \frac{dF_\nu}{dE_\nu}(E_\nu) \frac{d\sigma}{dT_e}(E_\nu, T_e)$$

Number of targets

$$\frac{dF_\nu}{dE_\nu}(E_\nu) = \frac{\underline{L_\nu}}{4\pi \underline{d^2} \langle \underline{E_\nu} \rangle} \underline{f(E_\nu)}$$



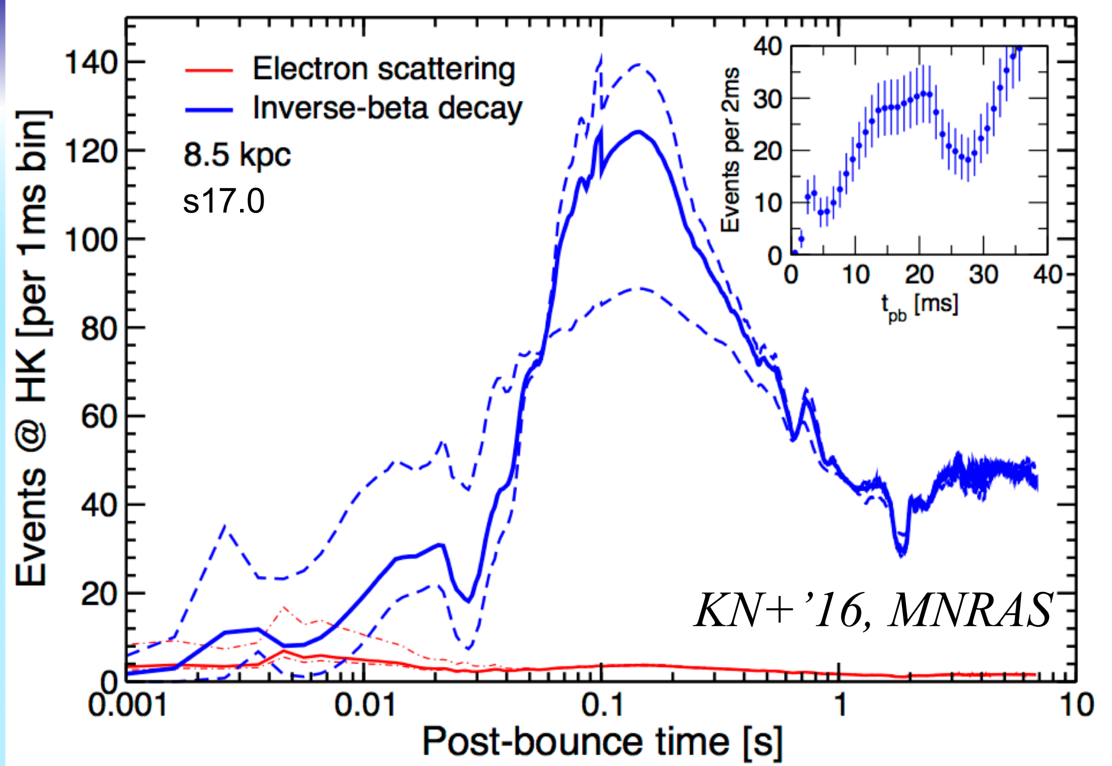
Galactic event @ 8.5 kpc

- ✓ Water-Cherenkov detector
  - Super Kamiokande (-Gd)
  - Hyper Kamiokande
- ✓ Reaction channels
  - inverse beta decay
  - electron scattering
- ✓ Observed event rate:

$$\frac{dN_e}{dT_e} = \underbrace{N_t}_{\text{Number of targets}} \int_{E_{\min}}^{\infty} dE_\nu \frac{dF_\nu}{dE_\nu}(E_\nu) \frac{d\sigma}{dT_e}(E_\nu, T_e)$$

Number of targets

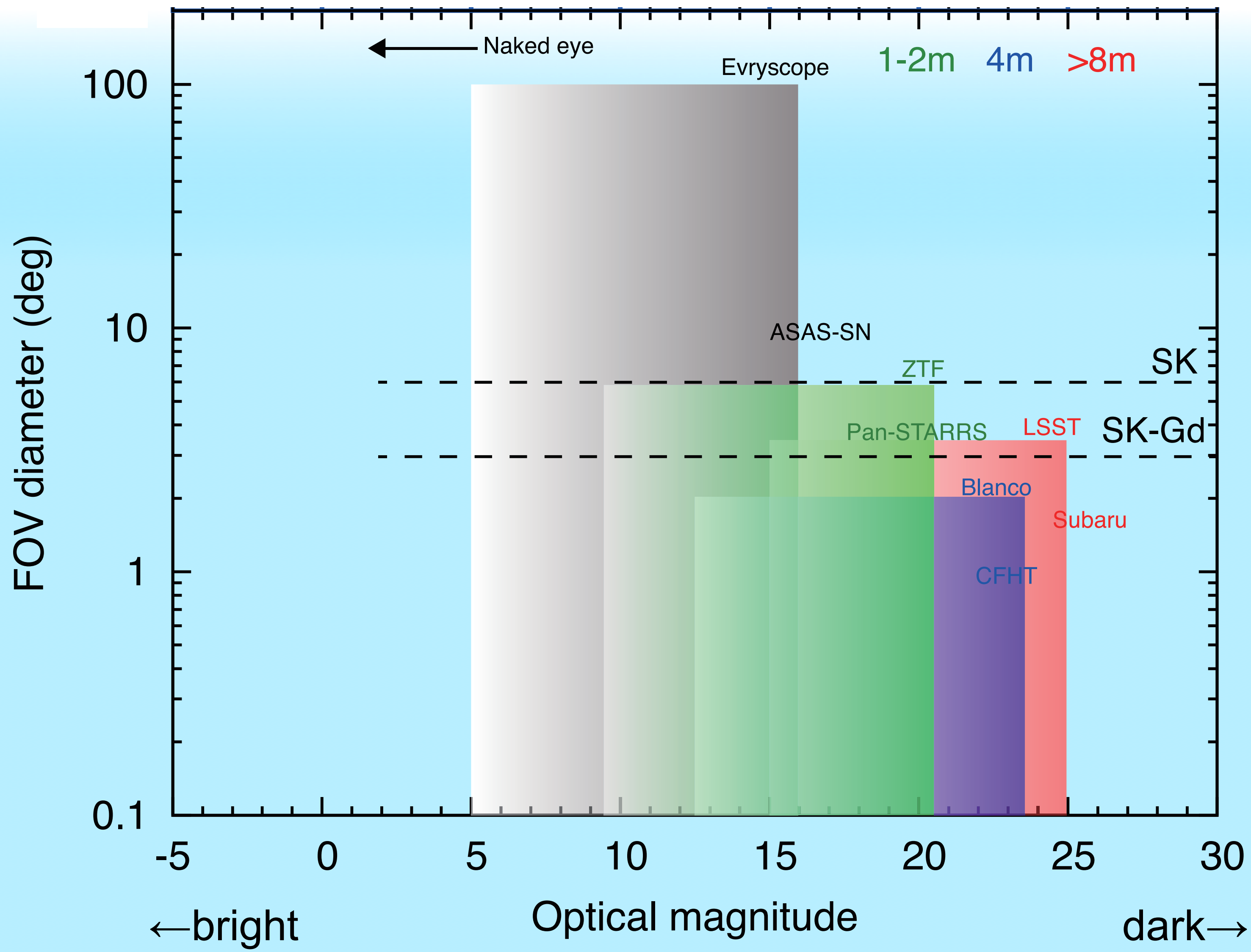
$$\frac{dF_\nu}{dE_\nu}(E_\nu) = \frac{L_\nu}{4\pi d^2 \langle E_\nu \rangle} f(E_\nu)$$



- ✓ Timing information (via IBD):
  the bounce time within ±3.0 ms (HK)
  at 95% confidence level.
- ✓ Pointing information (via e⁻ scattering):
  ~ 6° (SK), ~ 3° (SK-Gd), ~ 2° (HK)
  ~ 0.6° (HK-Gd)

Field of views (FOV) of optical telescopes

KN+'16, MNRAS



Time sequence of observations

(pre-SN neutrino)

neutrino burst

SBO

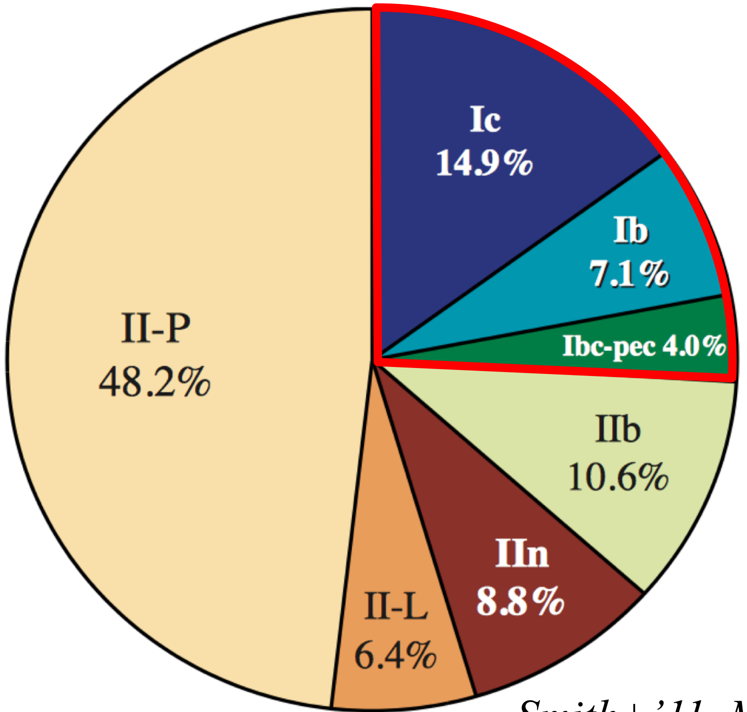
Red Supergiant (RSG) progenitor
→ **Type II SN**

$R^* \sim 10^{13\text{-}14}$ cm, shock velocity ~ 10^9 cm/s
→ $\Delta t \sim R^*/v \sim 10^{4\text{-}5}$ s **(a few hours - a day)**

Distribute ALERT !
(SN Early Warning System; SNEWS)

Wolf-Rayet (WR) progenitor
→ **Type Ib/c SN**

$R^* \sim 10^{11}$ cm
→ $\Delta t \sim R^*/v \sim 100$ s **(a few minutes) !**

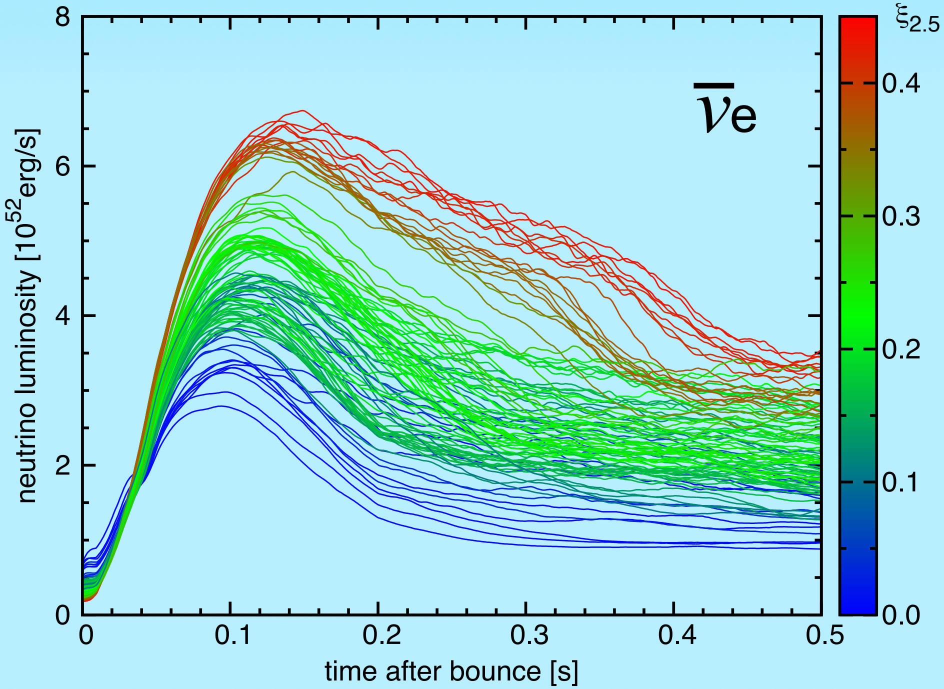


Smith+'11, MNRAS

Core-Collapse SN Fractions

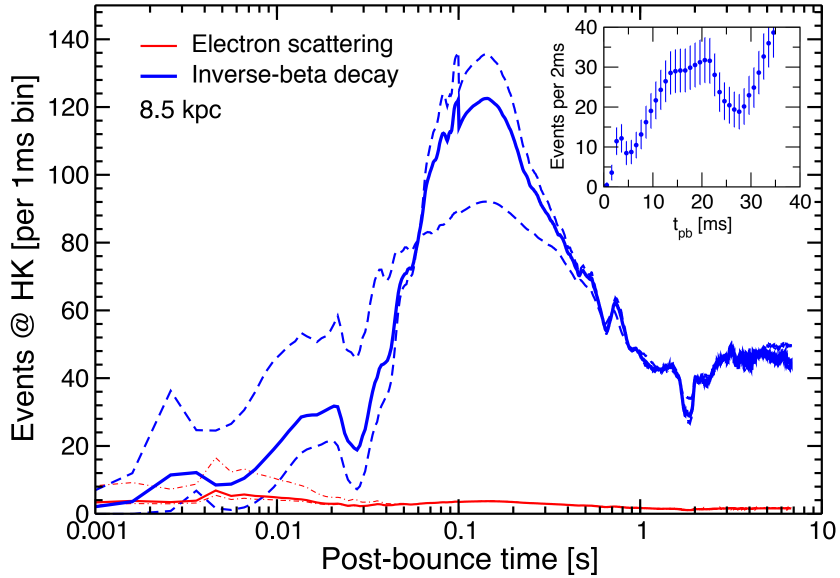
Pinning down the progenitor compactness

Template of neutrino light curves
from numerical simulations



Expected detection events

KN+'16, MNRAS

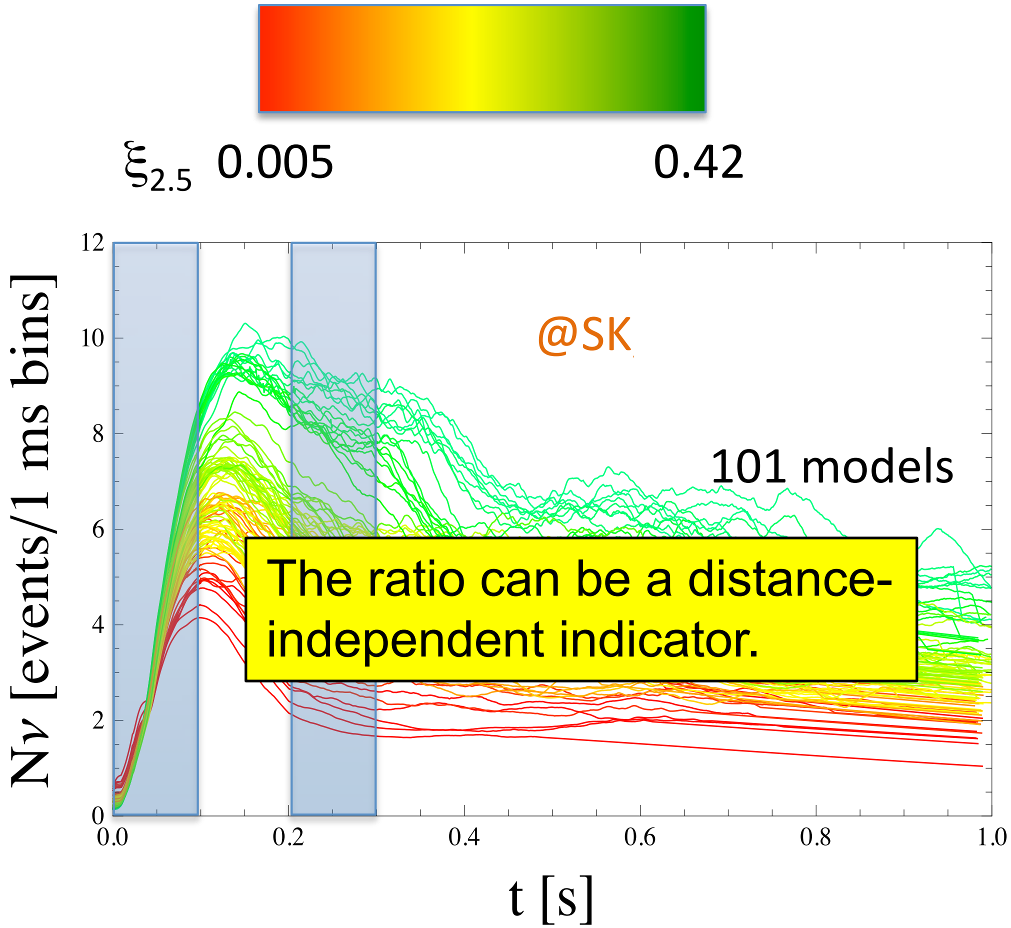


Uncertainty (1) - distance

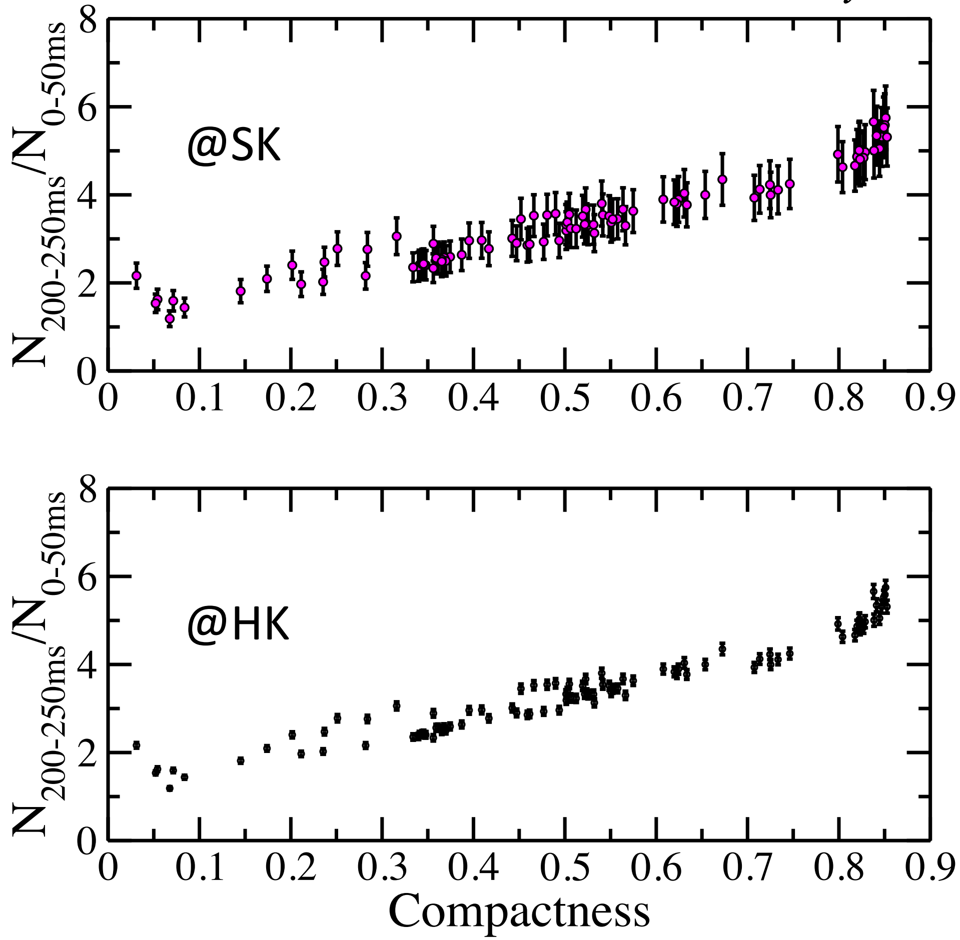
✓ Observed event rate depends on the distance to SN.

$$\frac{dN_e}{dT_e} = N_t \int_{E_{\min}}^{\infty} dE_\nu \underline{\frac{dF_\nu}{dE_\nu}(E_\nu)} \frac{d\sigma}{dT_e}(E_\nu, T_e) \qquad \underline{\frac{dF_\nu}{dE_\nu}}(E_\nu) = \frac{L_\nu}{4\pi \underline{d^2} \langle E_\nu \rangle} f(E_\nu)$$

Horiuchi, KN+'17, J. Phys. G



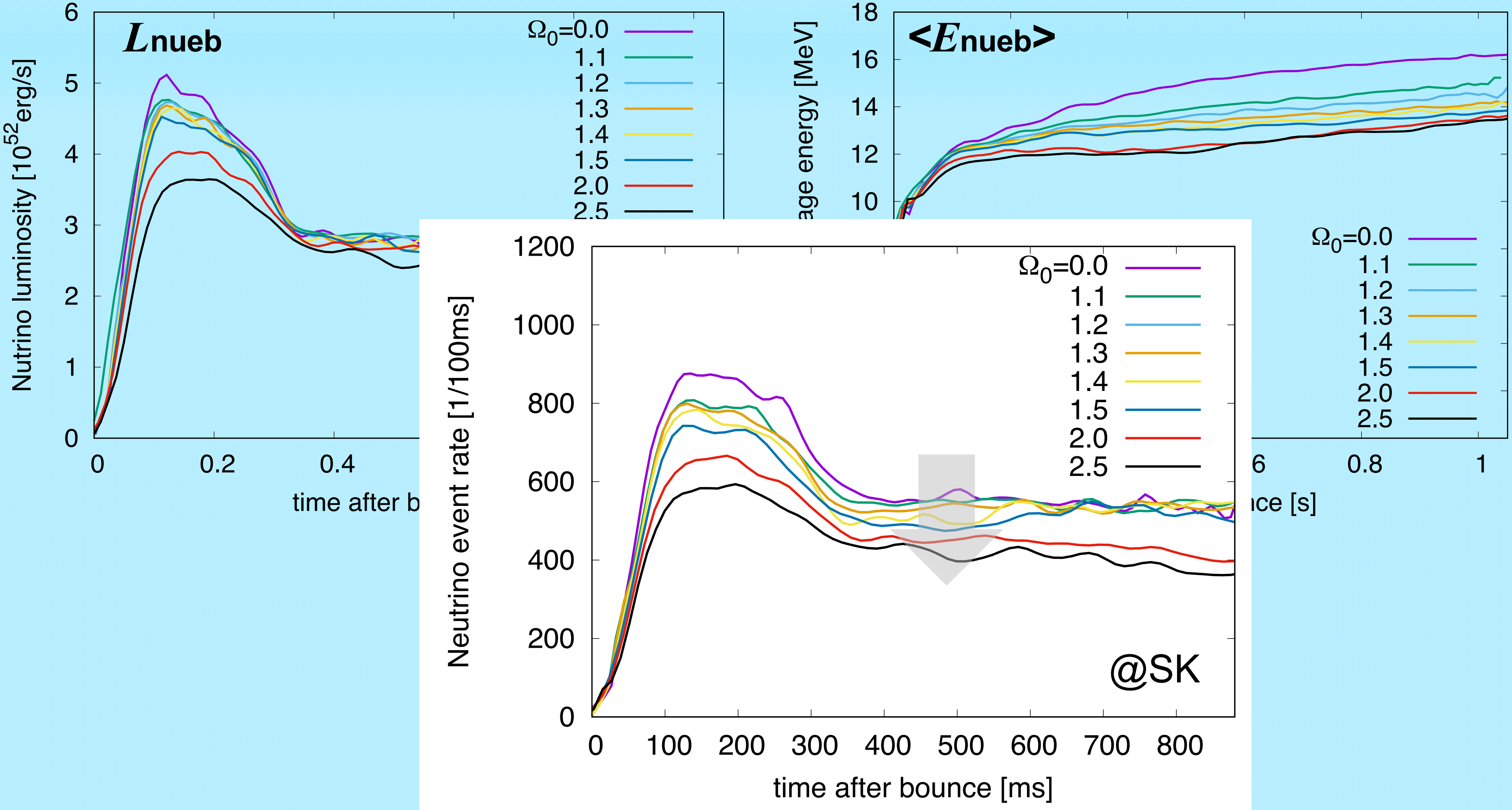
The ratio can be a distance-independent indicator.



Uncertainty (2) - rotation

✓ Core rotation affects SN neutrino properties.

2D simulations for s20.0 progenitor with initial Ω_0 = 0.0 - 2.5 rad/s.



Summary

- ✓ Systematic study of CCSN properties (neutrino, explosion energy, etc.):
  - Numerical simulations covering a wide range of progenitor mass (10.8 - 75 $M_{\rm sun}$, ~400 models) are demonstrated.
  - Compactness is a good index of the explosion properties.

- ✓ Neutrinos from a Galactic CCSN:
  - The could tell us the compactness of CCSN progenitor,
  - as well as the core bounce time ($\pm$ 3.0 ms by HK),
  - and the direction to the CCSN (~ 6° by SK, ~ 3° by SK-Gd, ~ 2° by HK).

- ✓ Possible uncertainties in pinning down the compactness:
  - distance to the CCSN
  - rotation