Systematic Features of CCSNe Based on Multi-D Simulations

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SN Workshop at Ringberg Castle   July 24-28, 2017

Systematic CCSN study

O'Connor & Ott '11,'13; Ugliano+'12; Ertl+'16; Sukhbold+'16

- Explosion properties (NS/BH mass, Eexp, etc.) strongly depend on the stellar structure and exhibit large variety.
- They are correlated to compactness parameter.

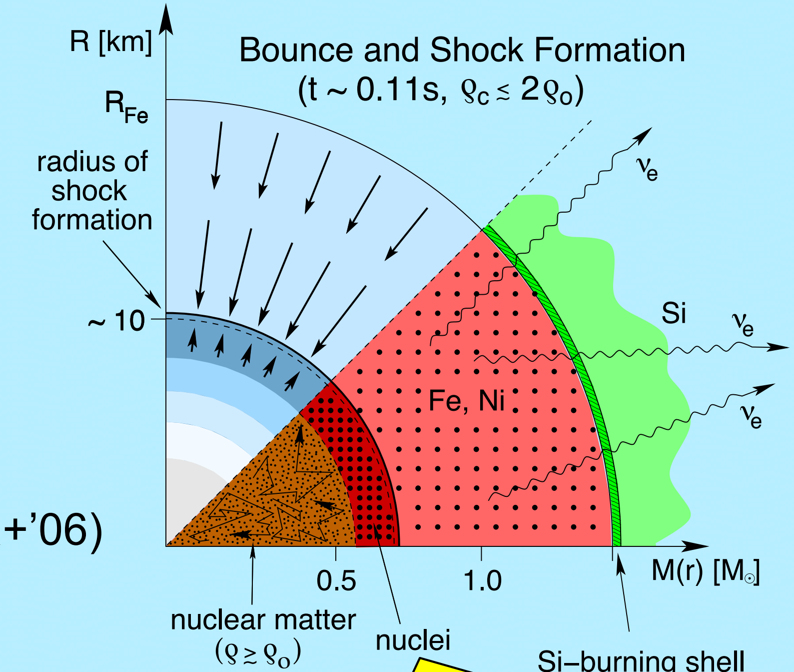
Compactness parameter
(*O'Connor & Ott 2011*)

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

- All of these studies are based on 1D simulations.

Explosion mechanism of CCSN

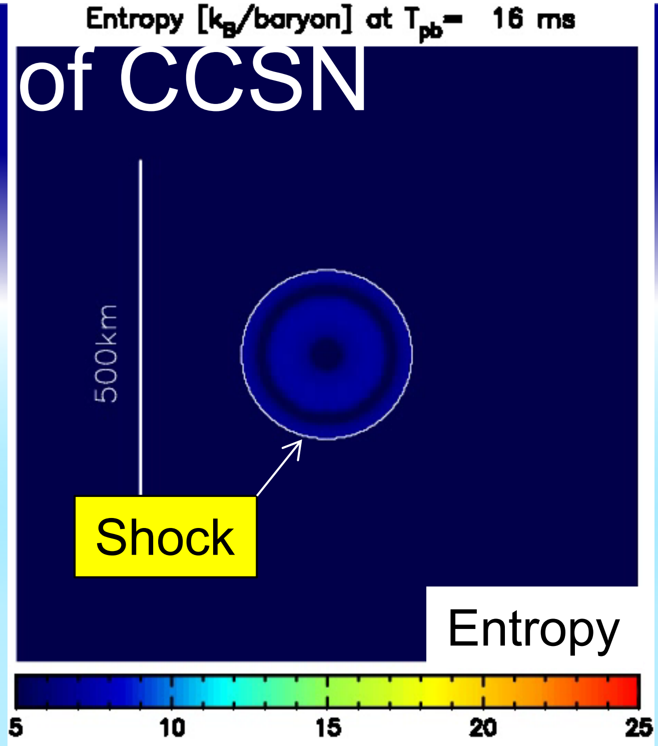
- Core-collapse supernova
  - Final fate of massive stars (>~10Mo)
  - Unclear mechanism of explosion
  - **Neutrino heating mechanism**
  - Convection, SASI

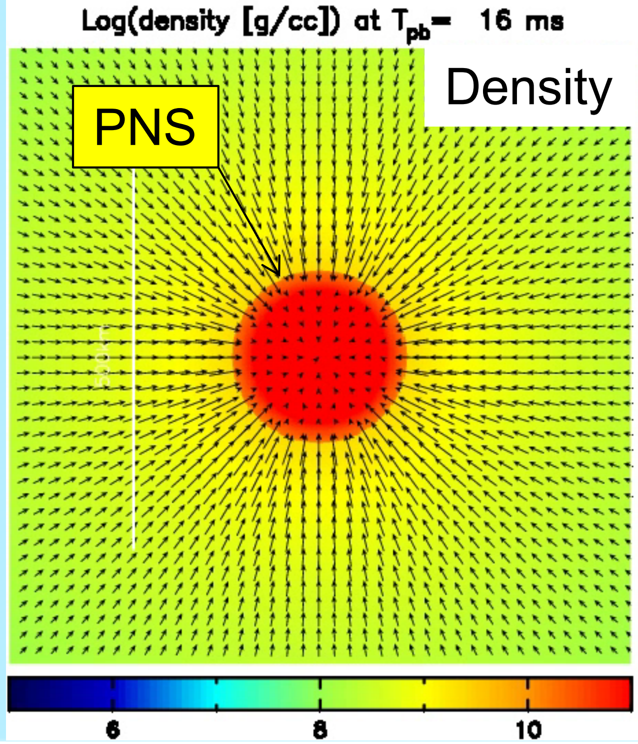


(Janka+'06)

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

ex.)
M = 17 Mo
Z = Zo





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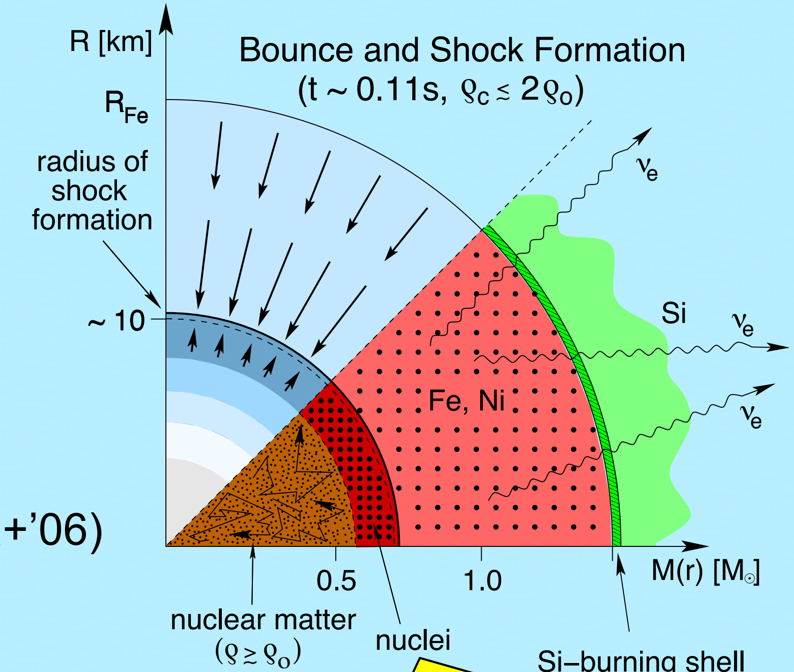

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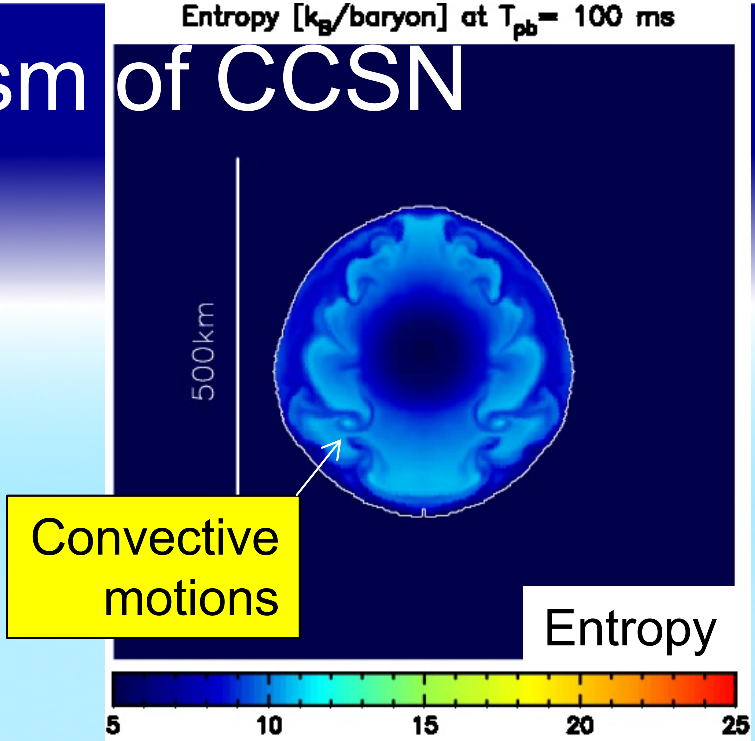

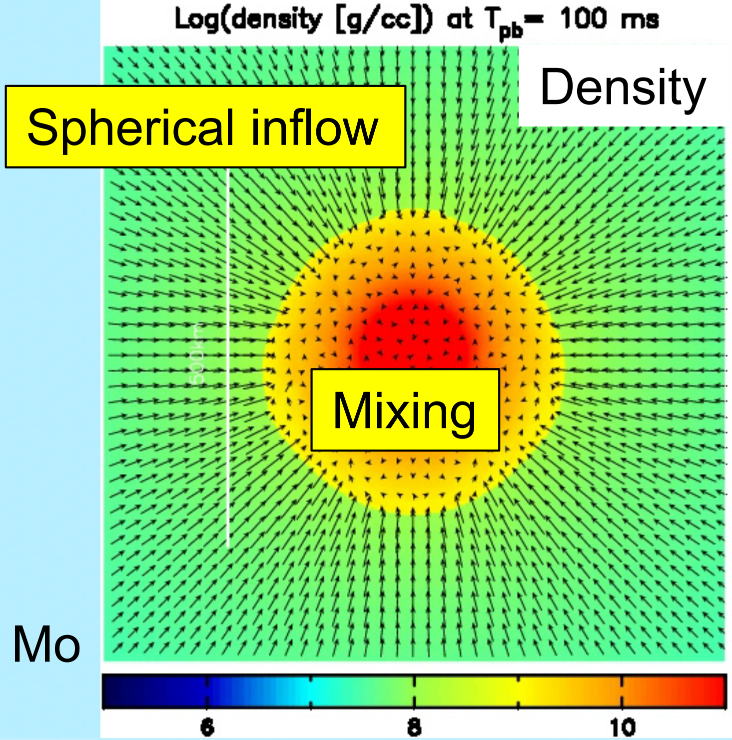

ex.)
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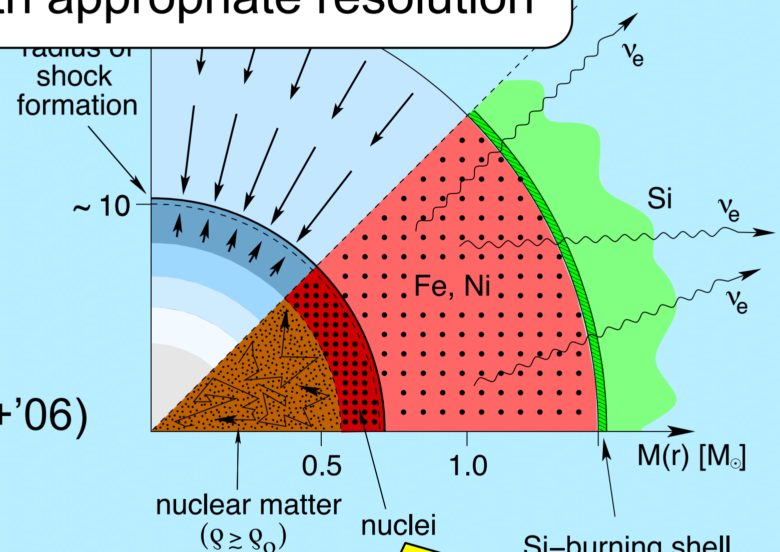
Z = Zo

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



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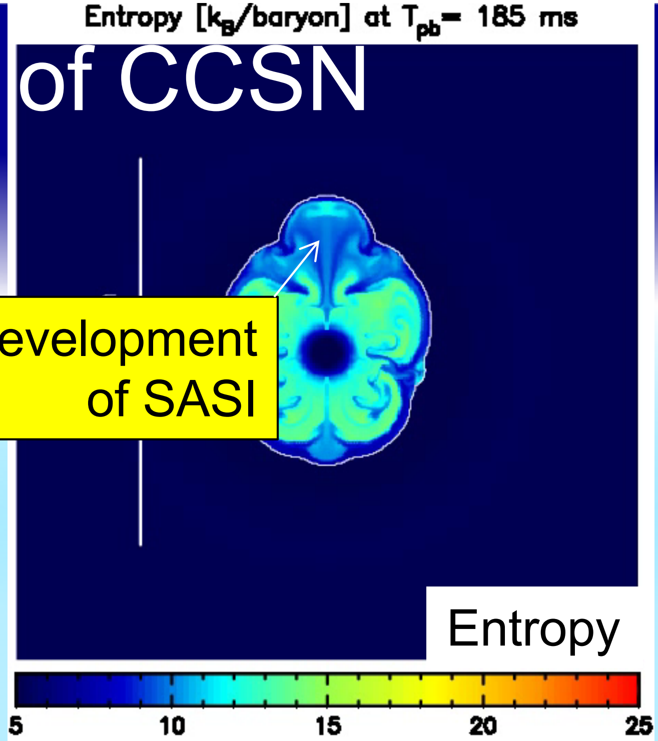
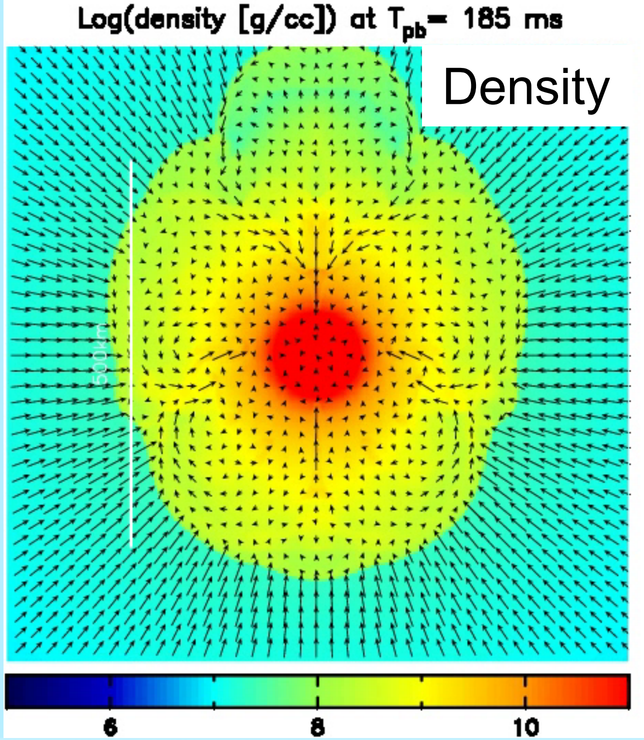
Development of SASI



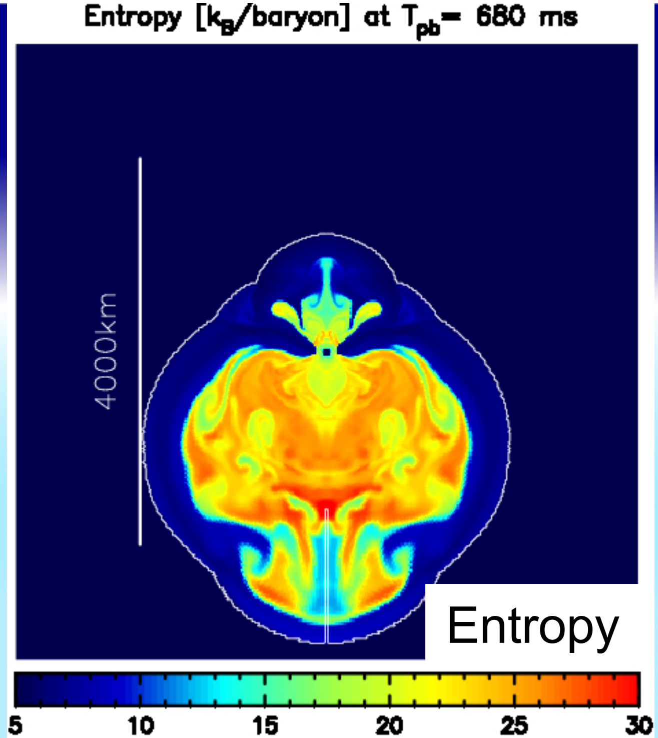


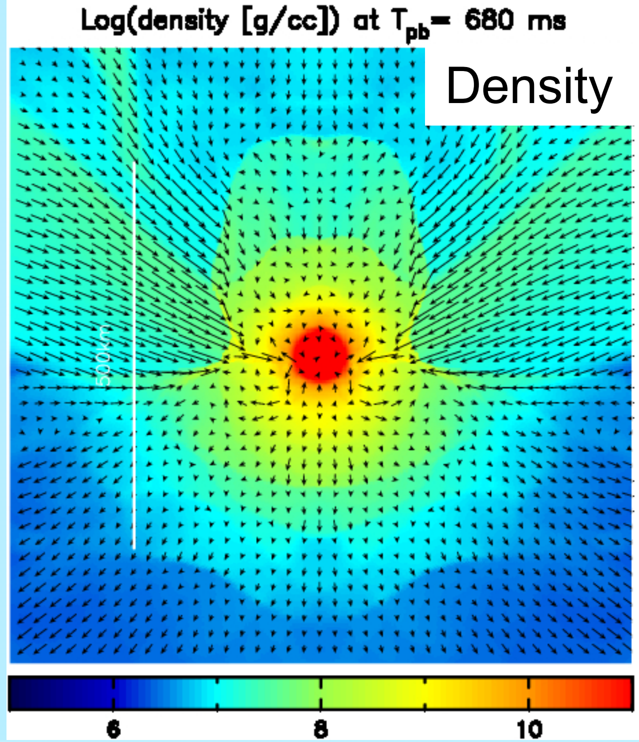
Systematic features of CCSNe

KN et al., PASJ (2015)

- **Numerical code**
  - **2D**, n(r)*n(θ) = 384*128
    r = 0-**5000 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)
- **Nuclear reactions**
  - 13α (He-Ni) network
- **Progenitor model**
  - M = 10.8-75 Mo, Z = 0-1 Zo, w/o rotation & B-field.
    378 models (Woosley, Heger, & Weaver '02)

・ Numerical computations were carried out on
Cray XC30（96 cores × 2.5 days / model）.





*All progenitors are from *Woosley, Heger & Weaver (2002)*

Solar-metallicity (Z=Zo) models

s10.8 - 40.0 （#100）

Metal-poor (Z=$10^{-4}$$Z$o) models

u11.0 - 22.8 / u23.0 - 46.8 / u47.0 - 58.8
（#240）

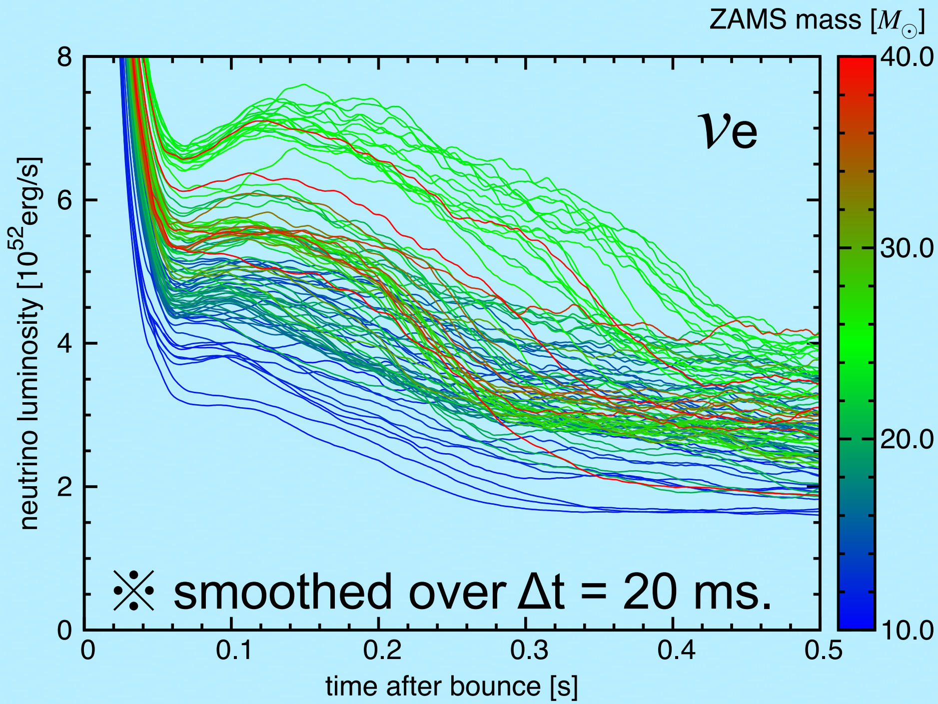
Zero-metallicity (Z=0) models

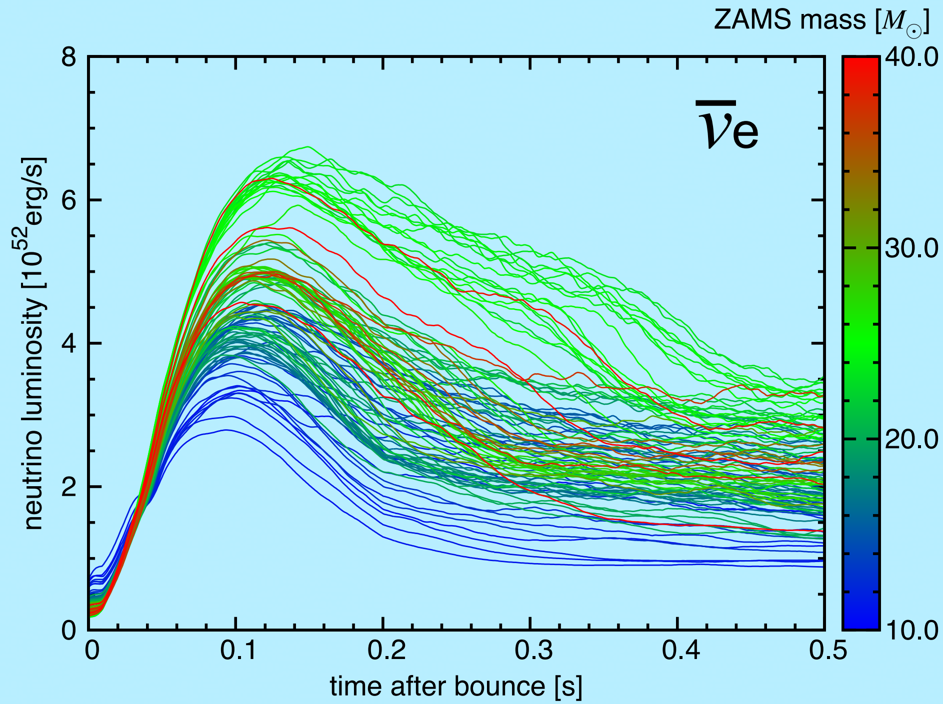
z11.0 - 40.0 （#30）

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.



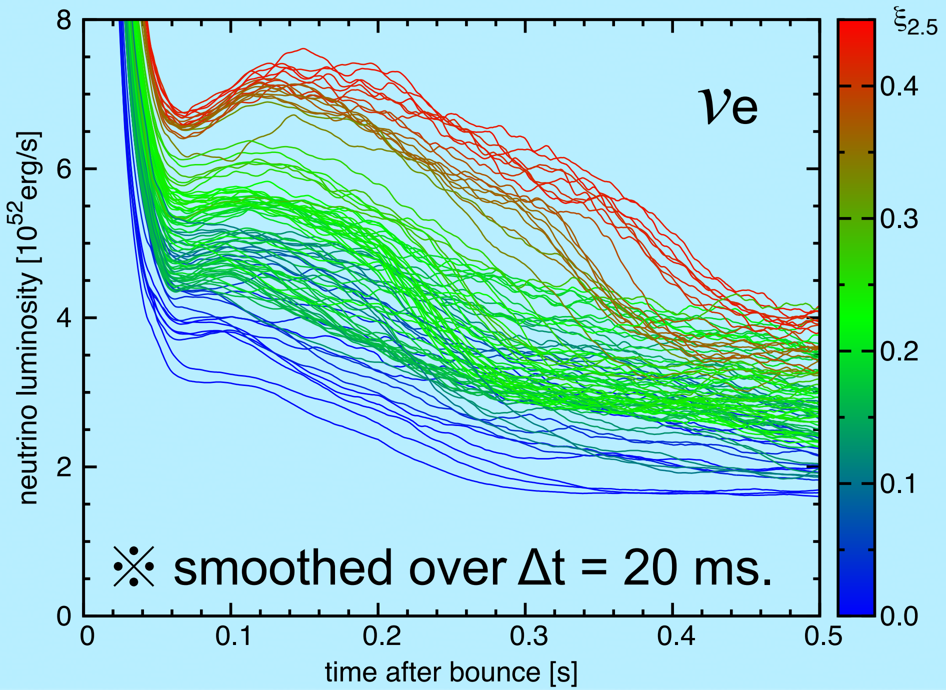


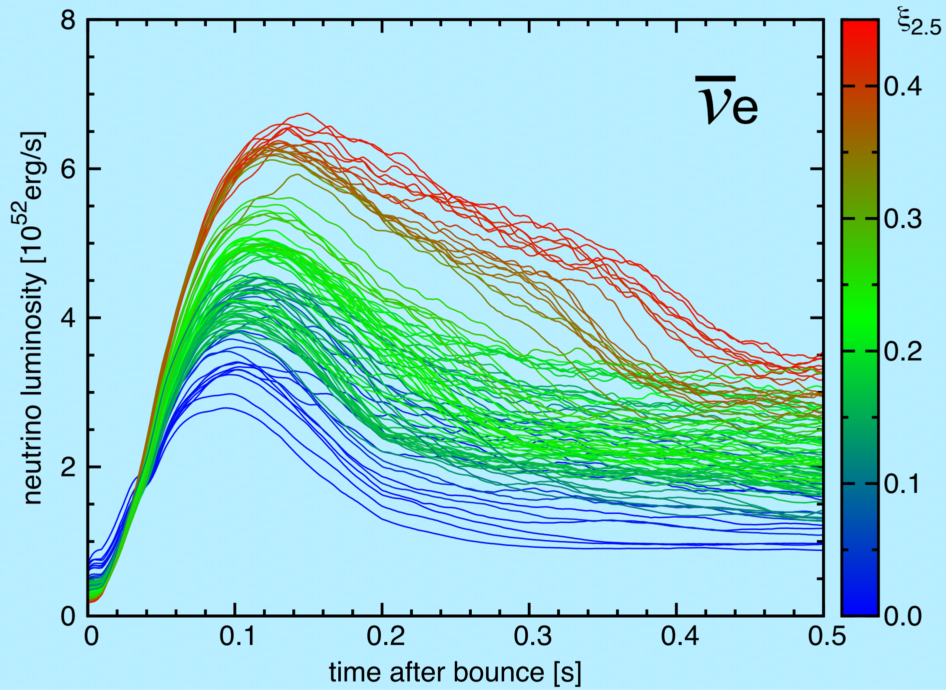
Time evolution of neutrino luminosity

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

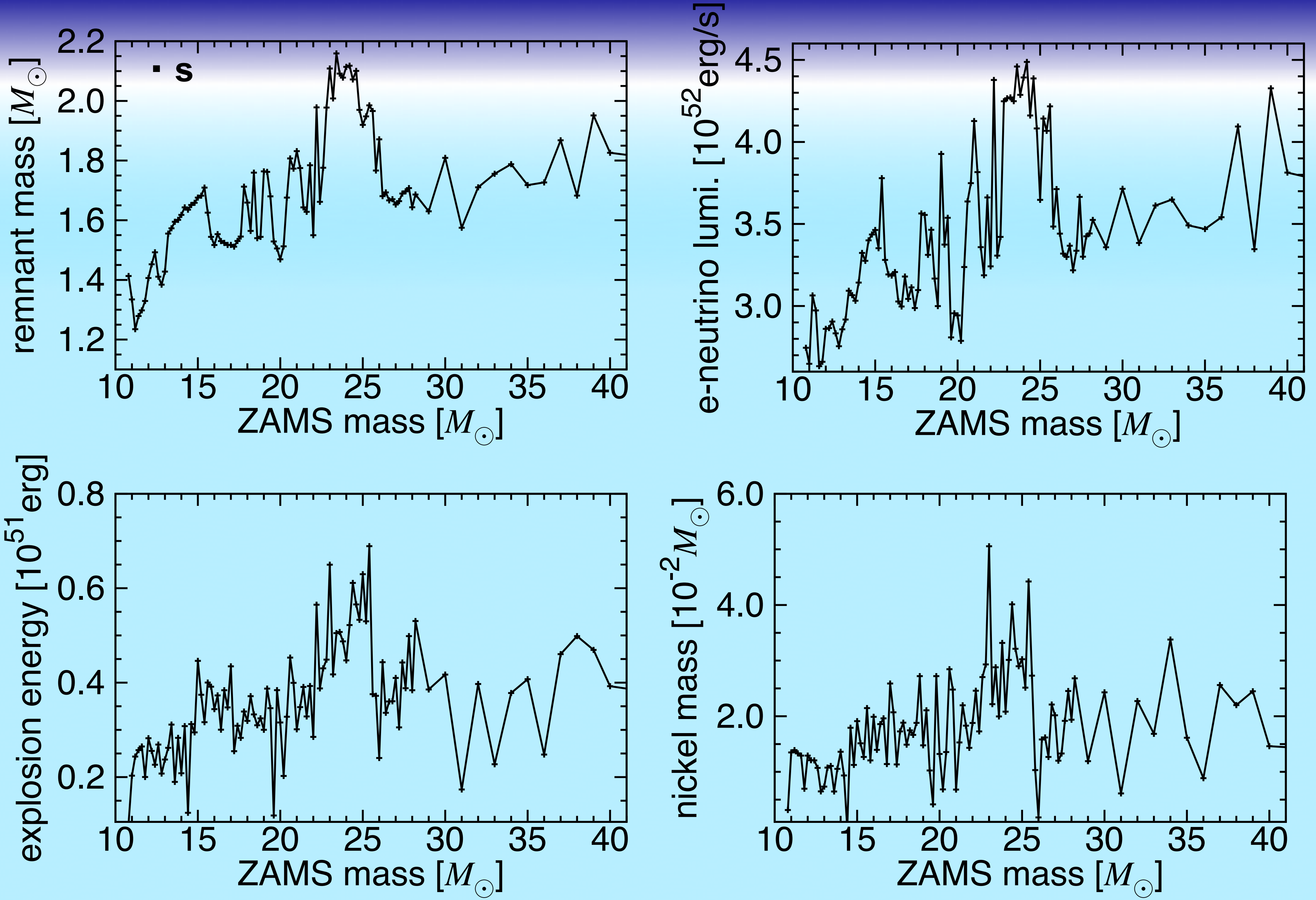
Compactness parameter
(*O'Connor & Ott 2011*)

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

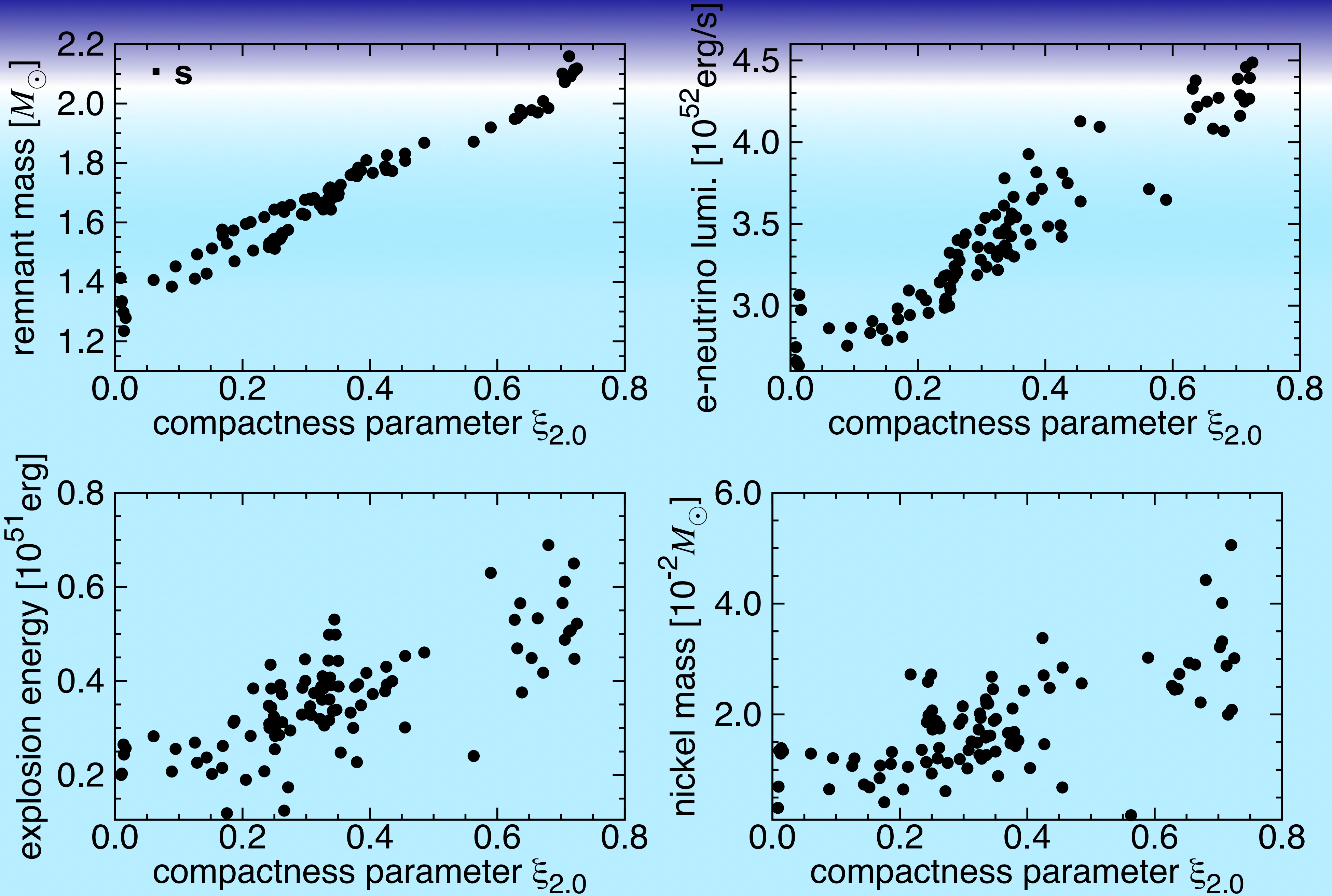




CCSN properties v.s. ZAMS mass



CCSN properties v.s. compactness



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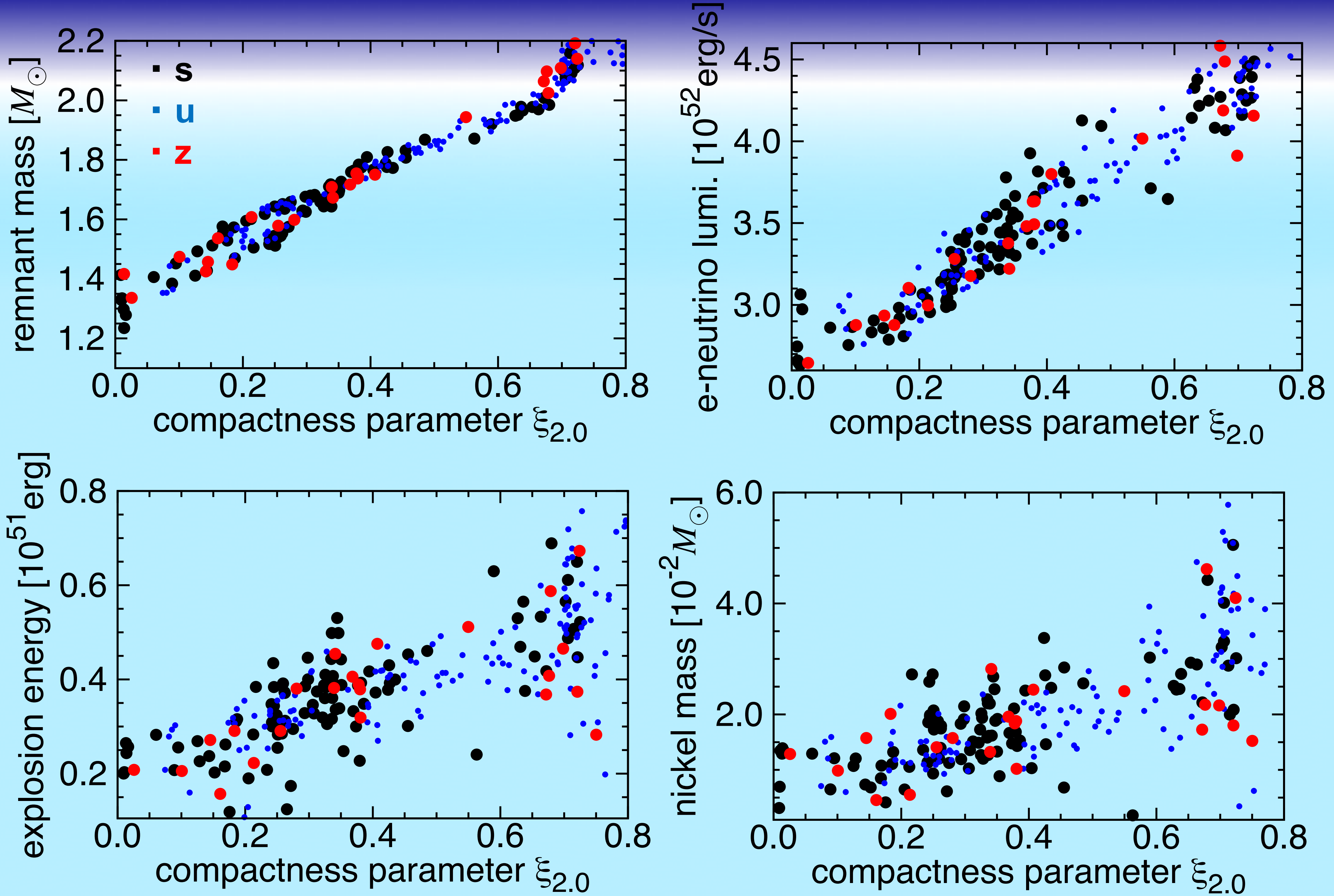
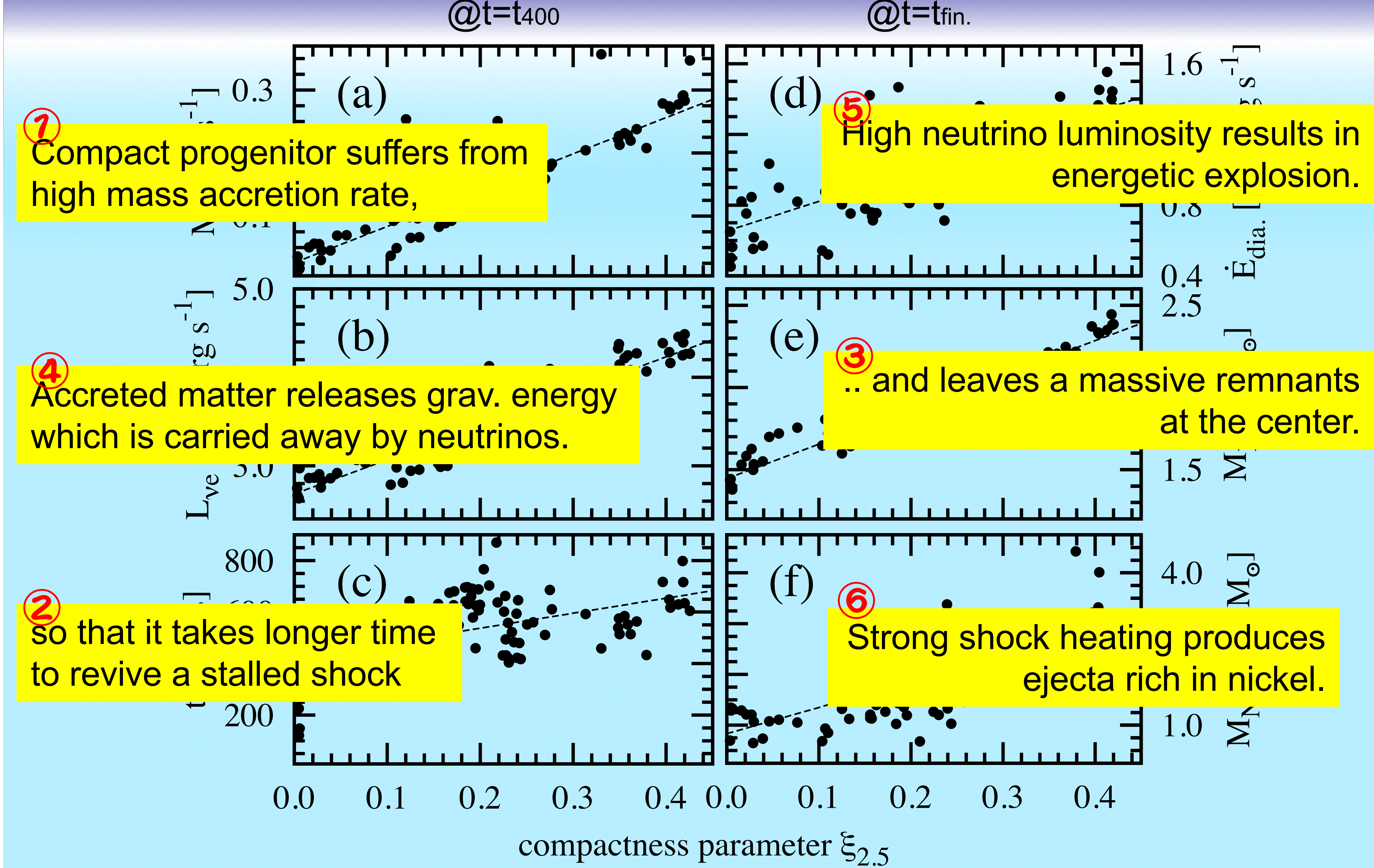


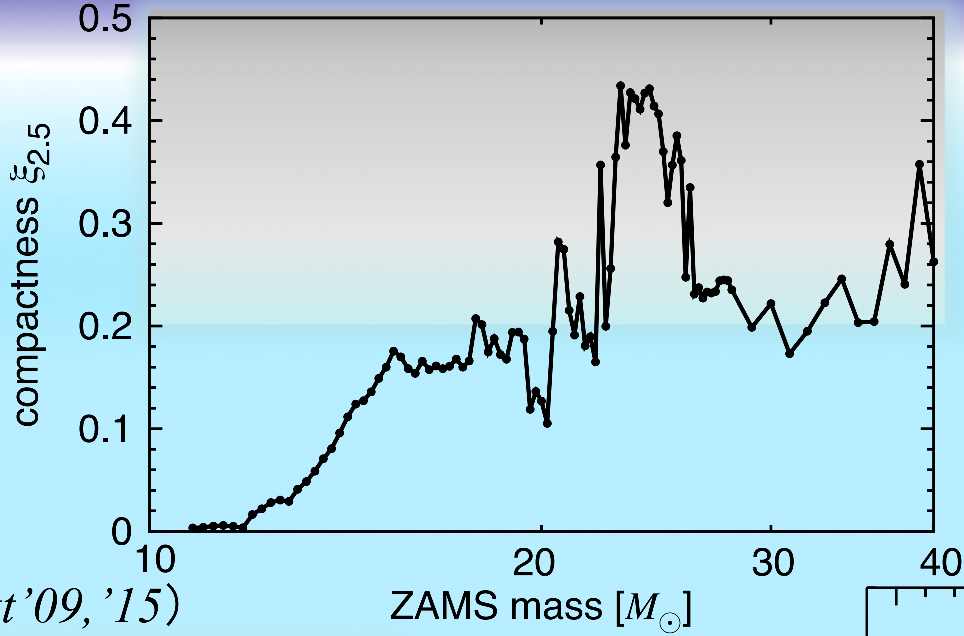
Compilation of CCSNe Simulations for 101 Solar-metallicity Progenitors



RSG problem & SN rate problem

Horiuchi+'14; Sukhbold+'16

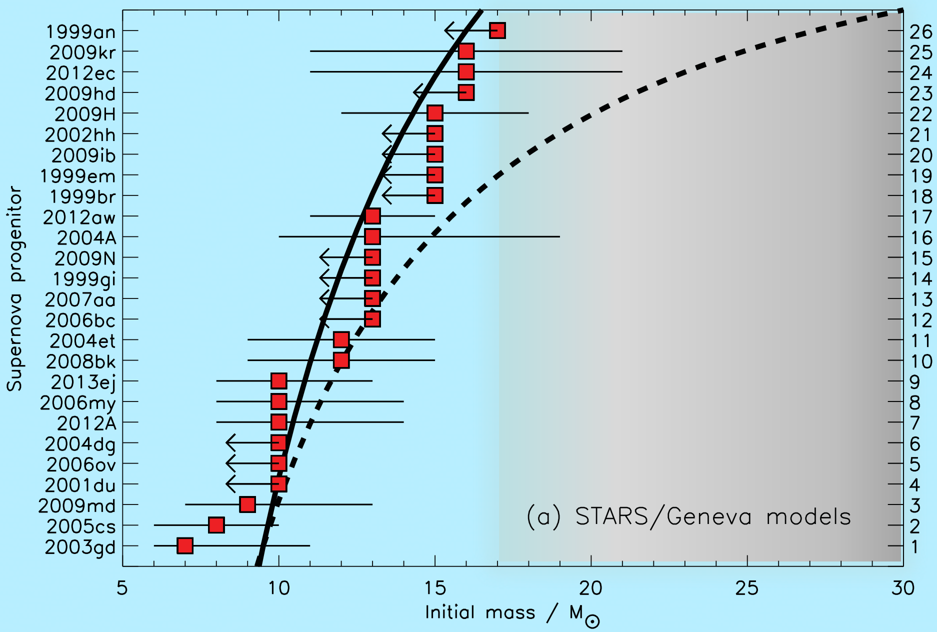
Critical $\xi_{2.5} \sim 2.0$

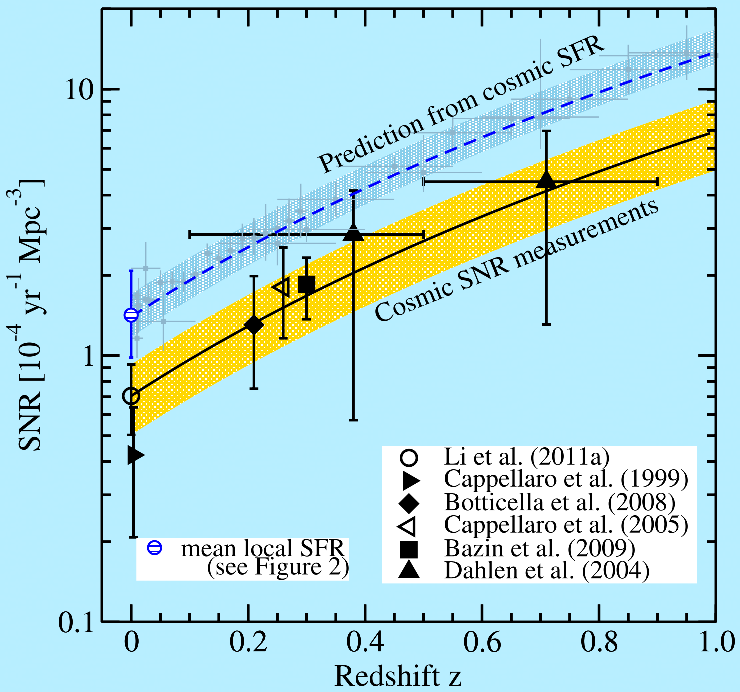


~50% of massive stars

SNR problem (*Horiuchi+'11*)

RSG problem (*Smartt'09, '15*)





Short summary

We have demonstrated 2D ab initio CCSN simulations

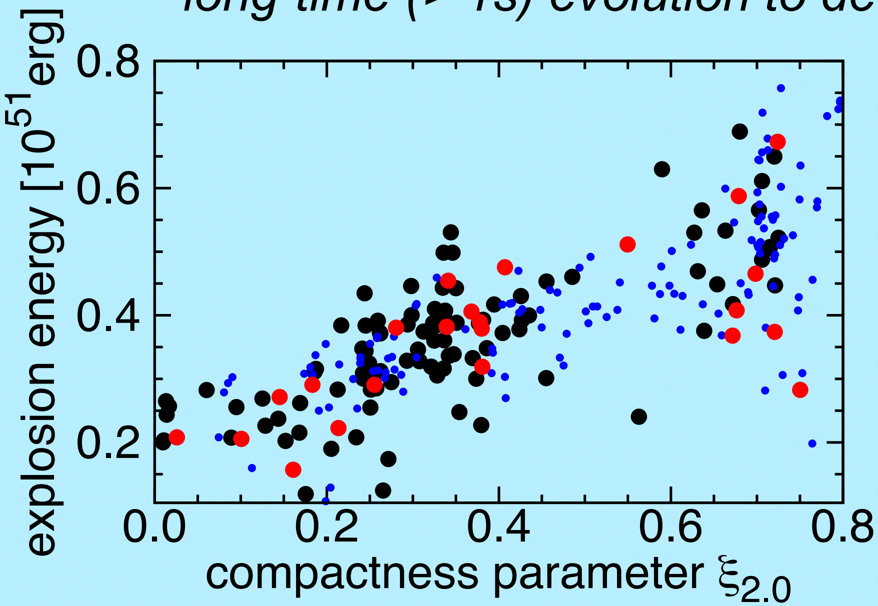
- taking account of neutrino transport and hydro. instabilities
- for ~400 progenitors covering M = 10.8 - 75 Mo and Z = 0 - Zo.

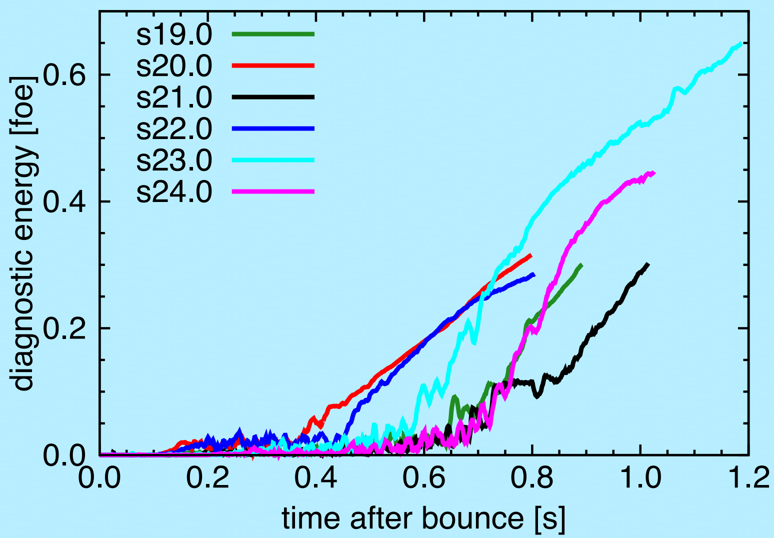
CCSN properties are well characterized by the compactness parameter

- M_{PNS}, $L_{\nu e}$ (& $L_{\bar{\nu}e}$), E_{exp}, M_{Ni} (, GW)
- $\xi \equiv \dfrac{M/\ M_\odot}{R(M)/1000\mathrm{km}}$

Next step:

- *long-time (> 1s) evolution to determine final explosion energy*



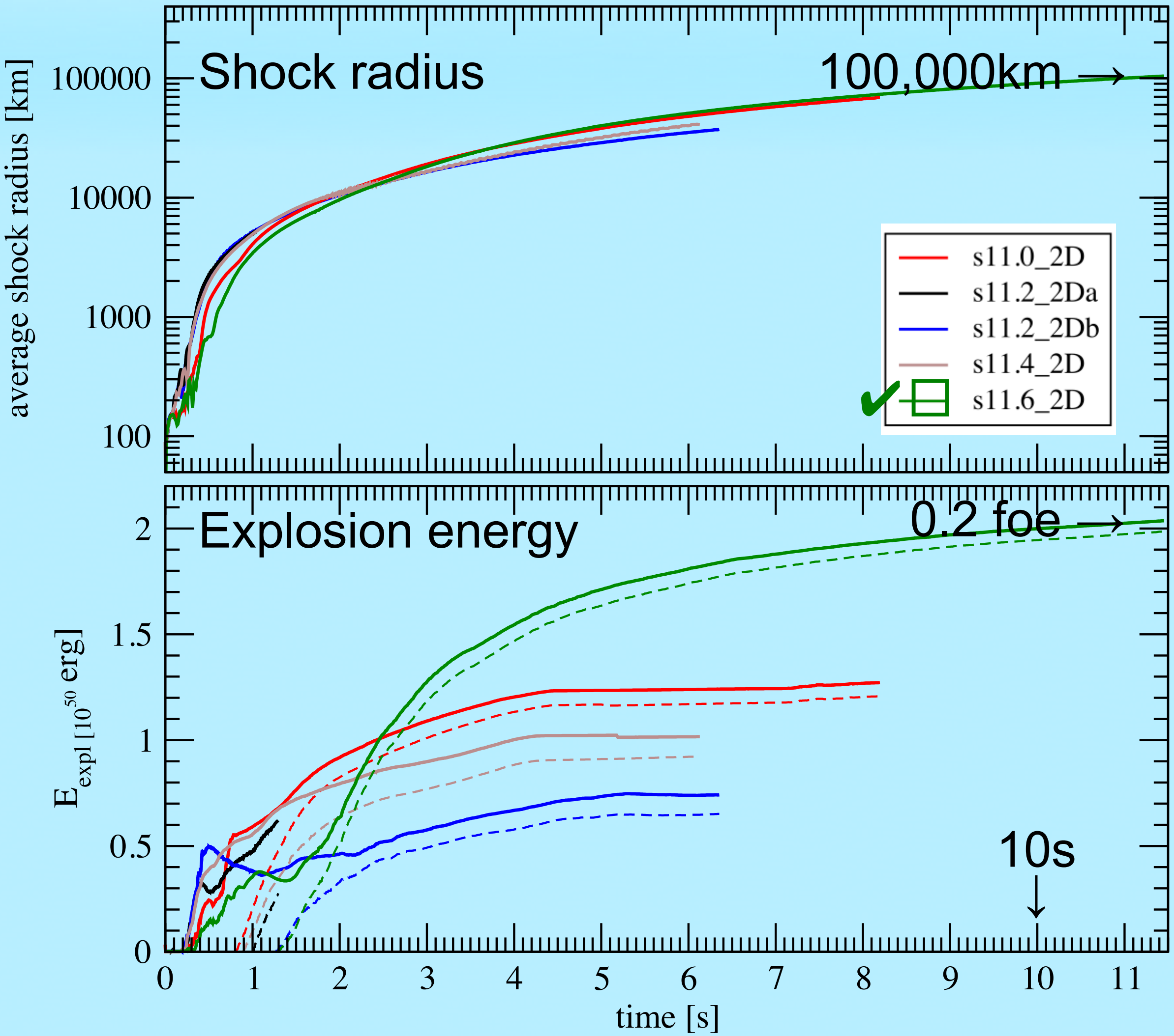


Long-term 2D CCSN simulation

- **B. Mueller '15**
  M = 11.0 - 11.6 Mo
  2D, n(r)*n(θ) = 550*128

  Explosion energy is
  converged
  at small value
  (<~0.2 foe).

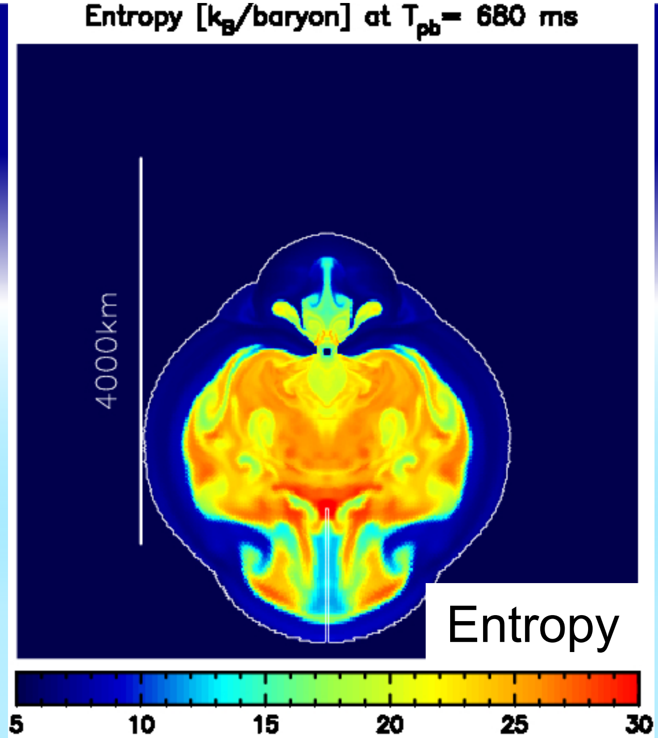
R < 100,000 km, t < 6−11 s

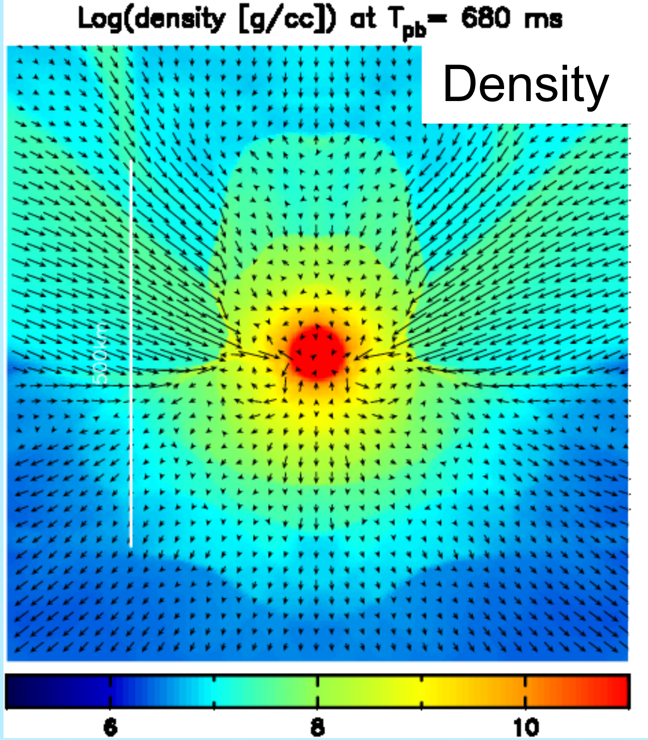


Long-term CCSN simulation

- **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）





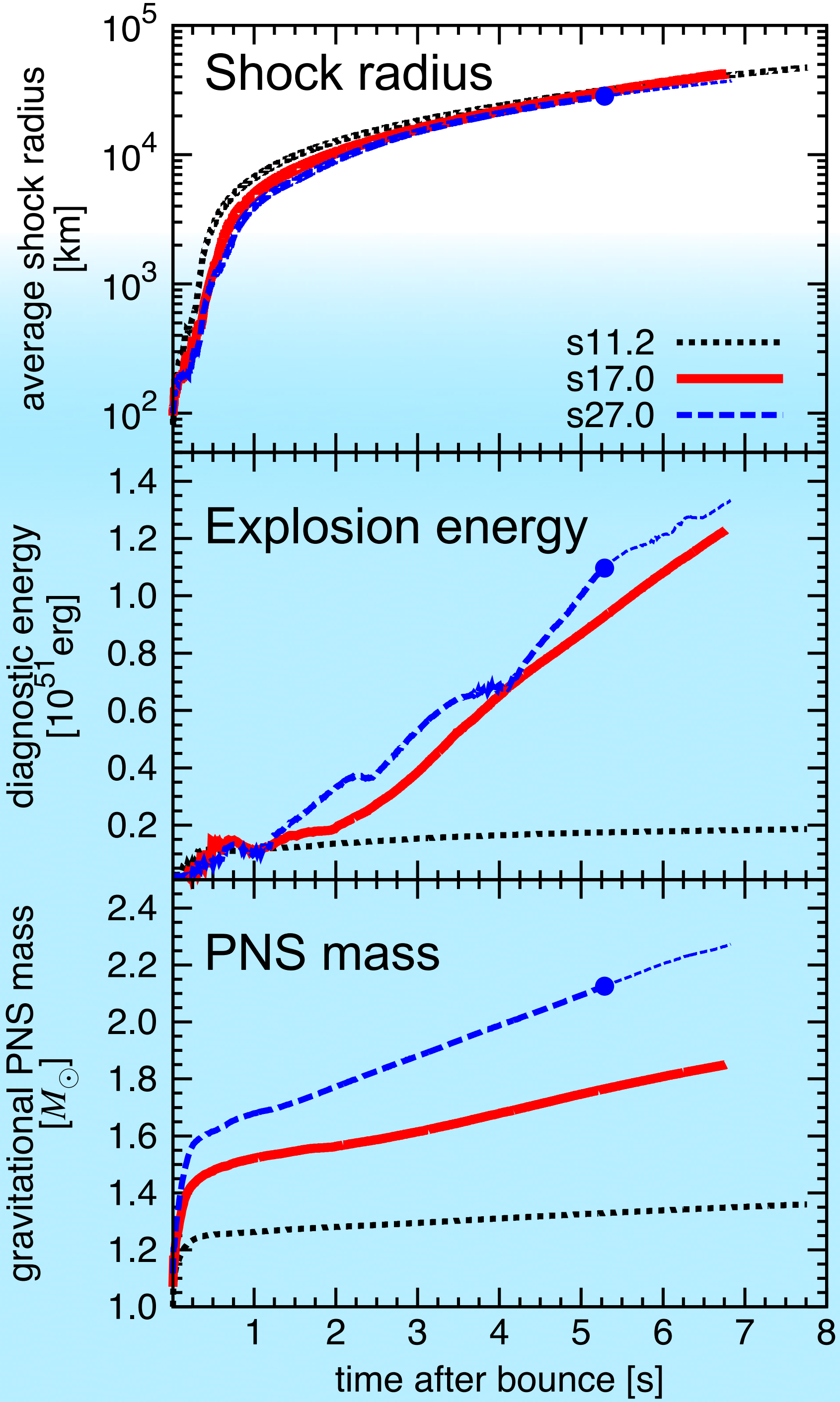
Results

- ✓ 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

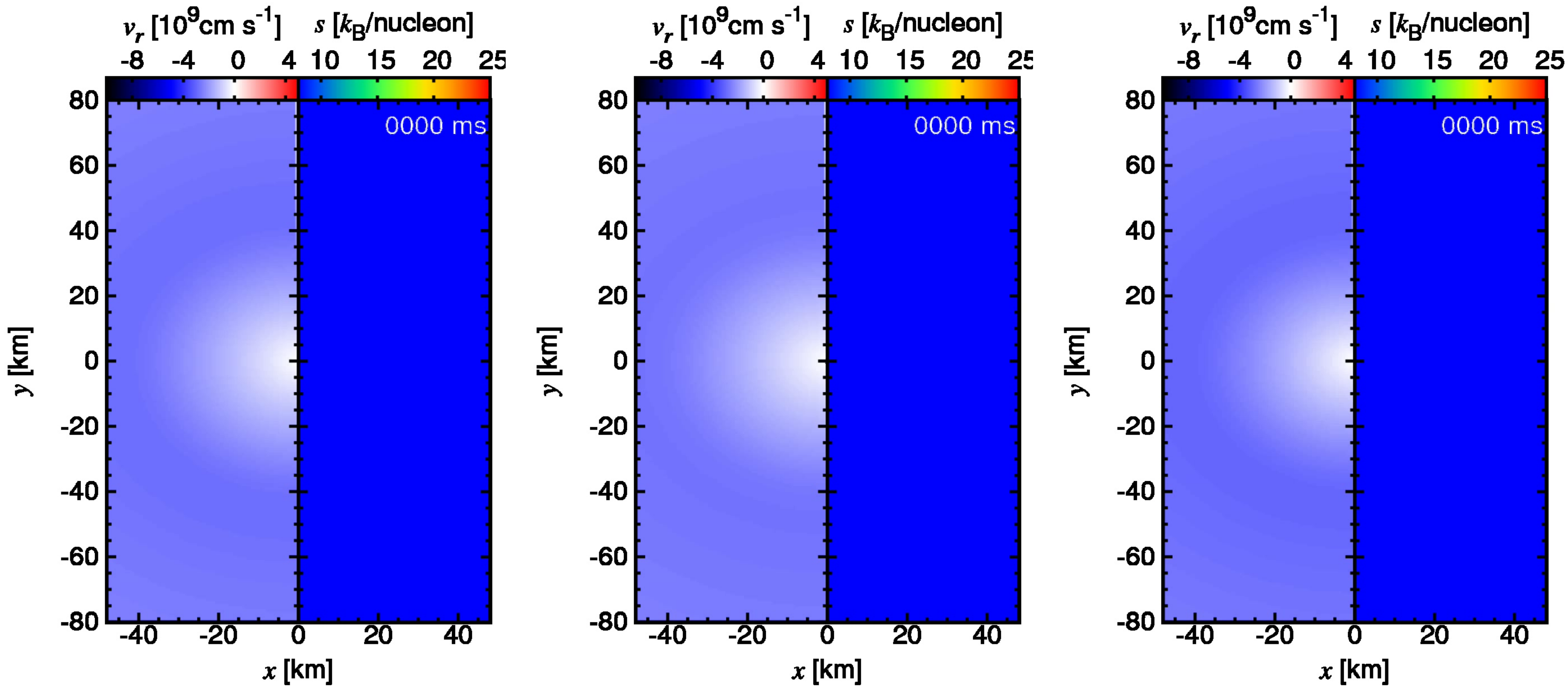
- ✓ **s27.0 model**
  is similar to s17.0 models, but the PNS mass reaches the limit（M_{PNS} = 2.13 Mo）predicted by 1D GR simulation.
  (O'Connor & Ott '11; KN+'15)



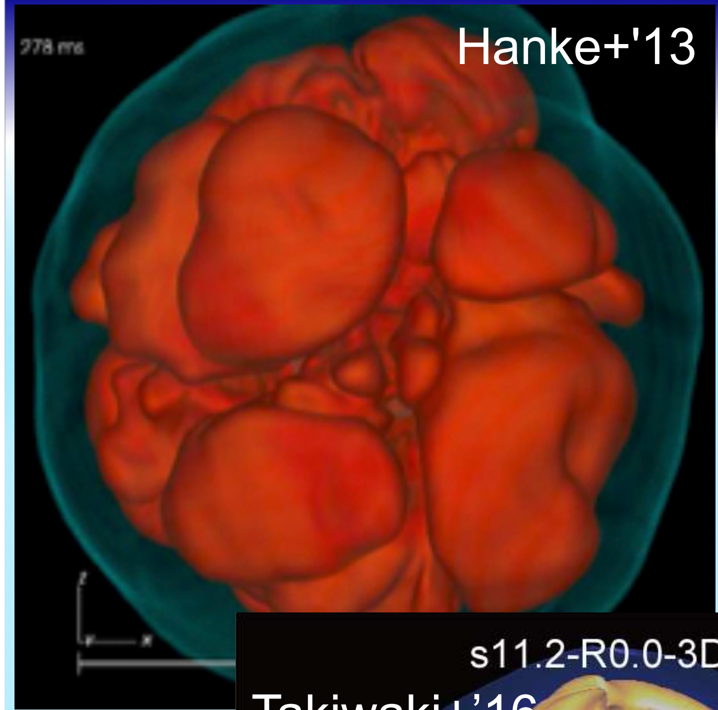
Mass accretion onto the central PNS

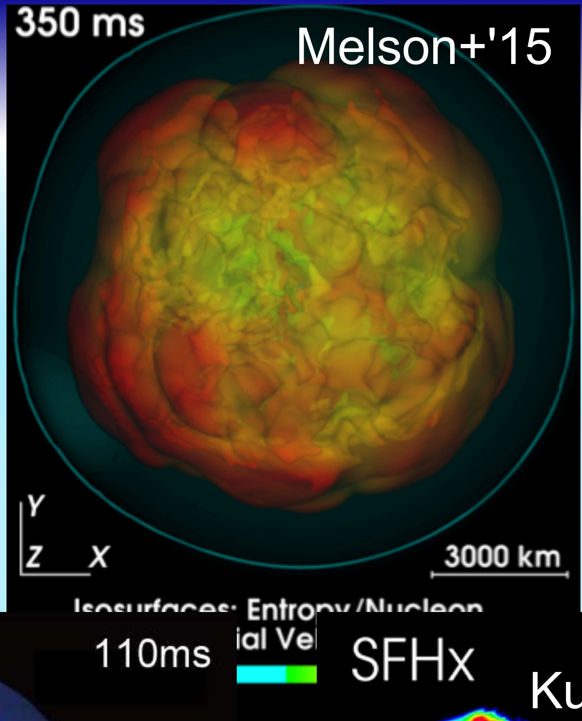
- ✓ In s17.0 & s27.0 models, a cold downflow keeps hitting the PNS.
  → The PNS mass increases and ν luminosity keeps high,
  → resulting in continuous growth of the explosion energy.

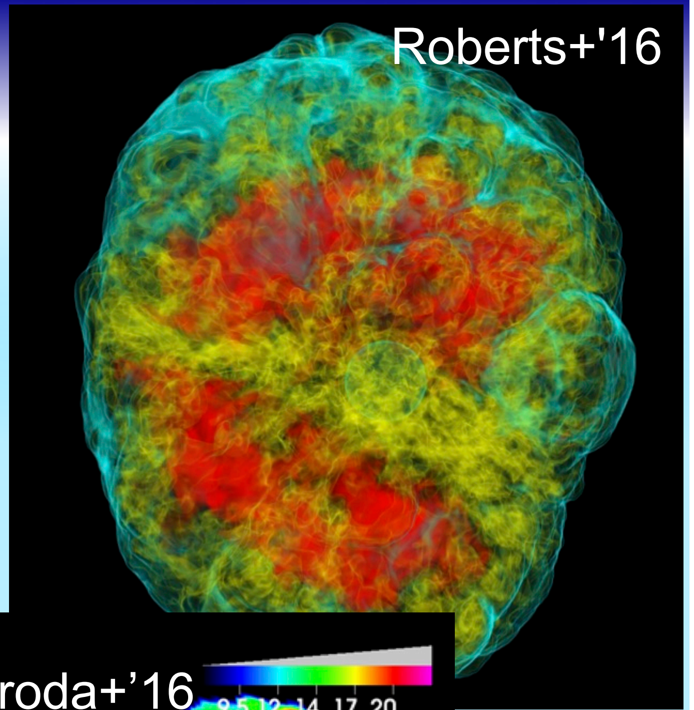
s11.2 s17.0 s27.0

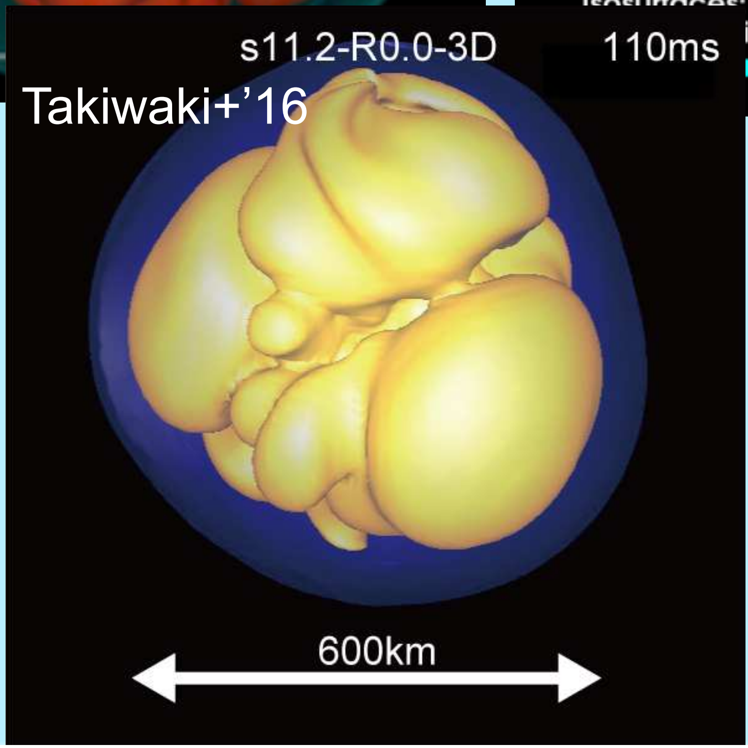


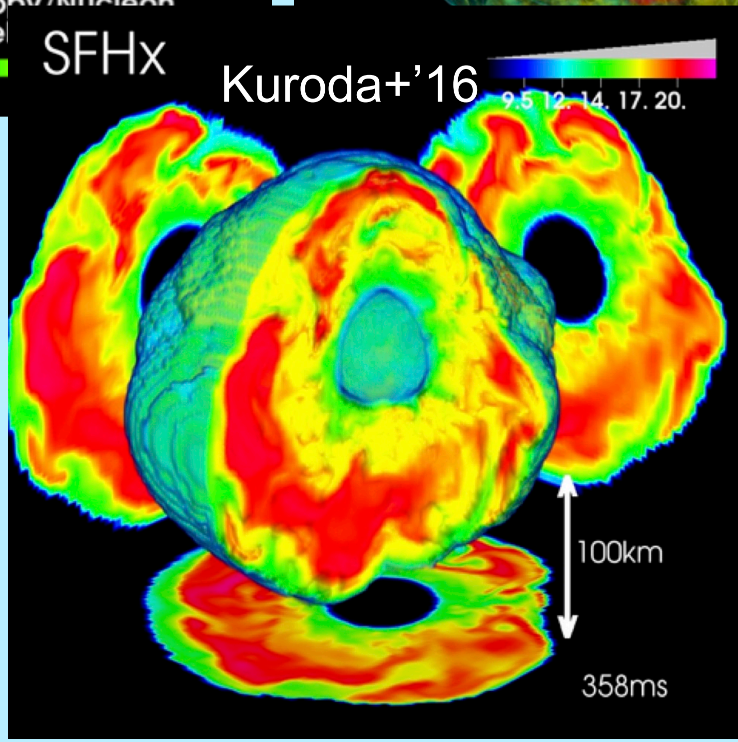
3D CCSN Simulations



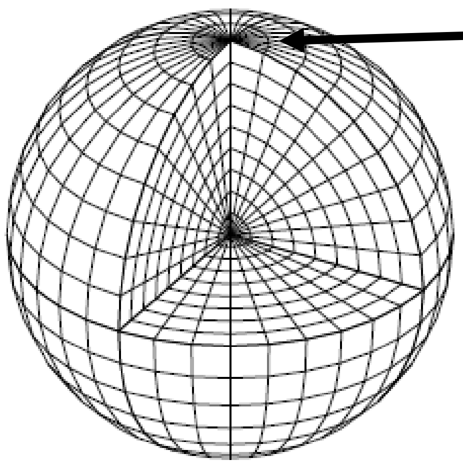








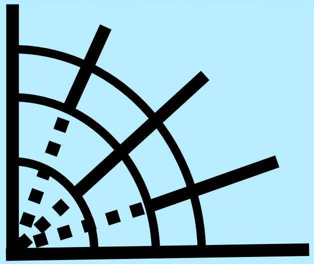
Mesh coarsening scheme

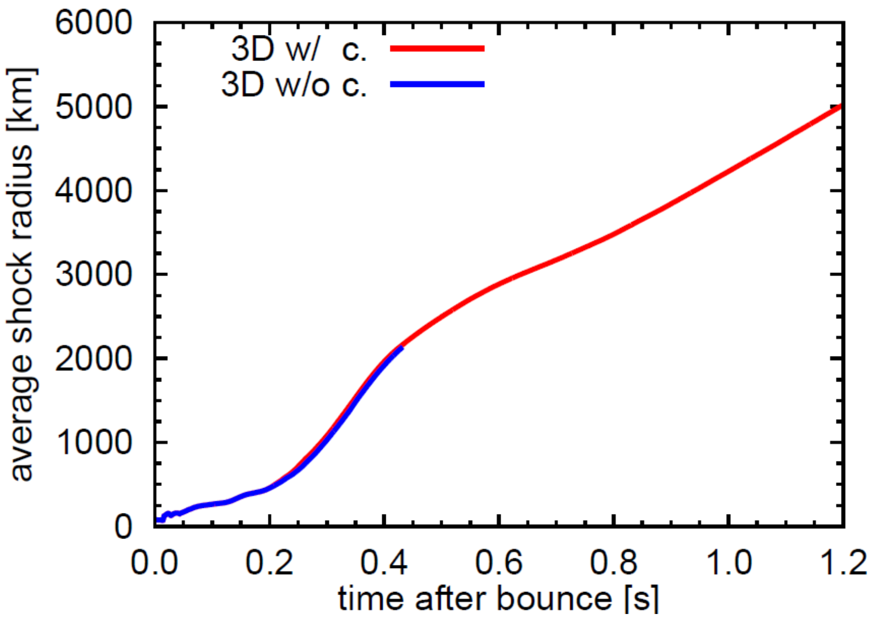


very small cell width L along the pole

→ very small time step Δt.

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



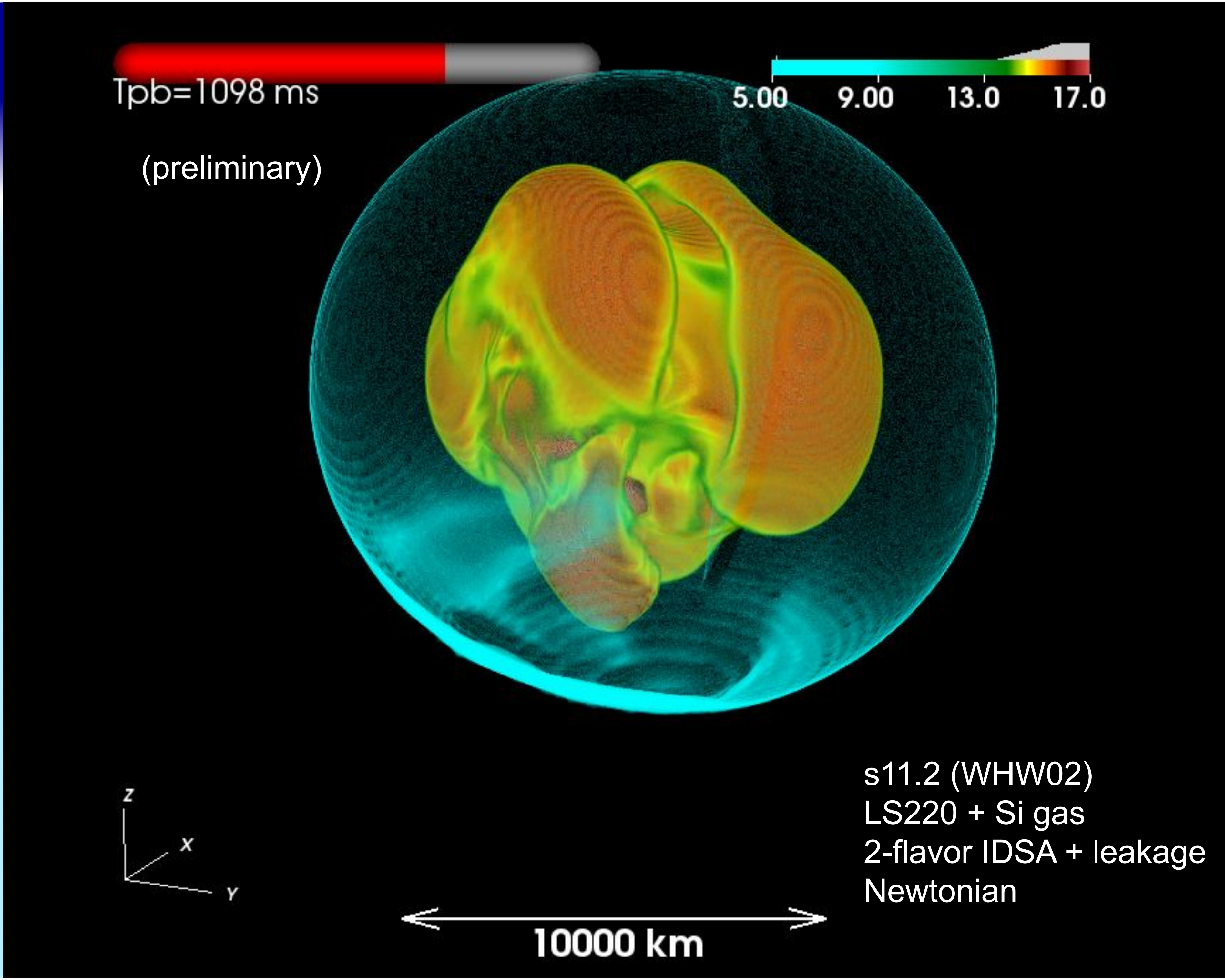


1) Hydrodynamics is solved in fine grid.

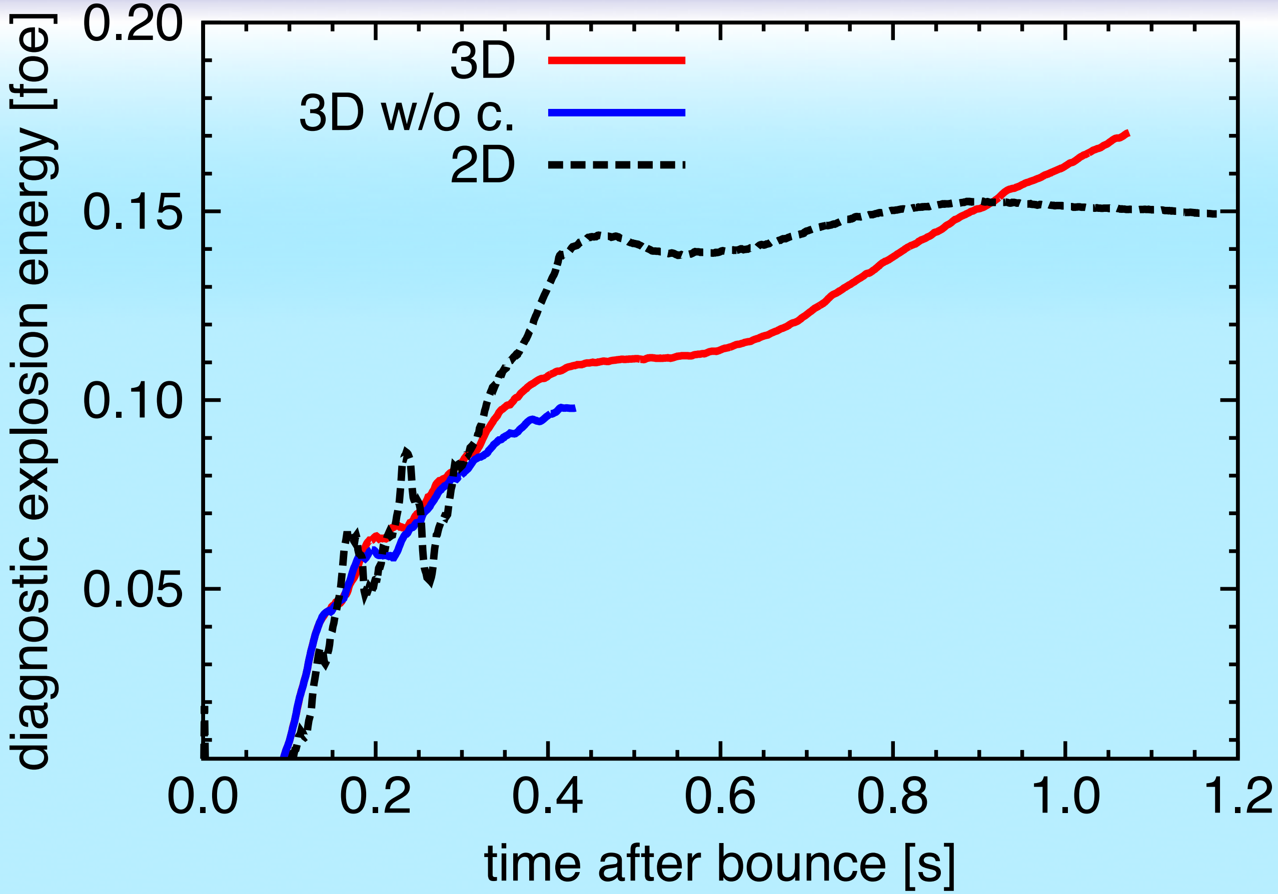
2) Then some meshes are coarsened (averaged over the "large" cell).

3) Δt is determined in the "large" cell.

Preliminary result from test calculations.


Tpb=1098 ms
5.00
9.00
13.0
17.0
(preliminary)
s11.2 (WHW02)
LS220 + Si gas
2-flavor IDSA + leakage
Newtonian
Z
X
Y
10000 km

Explosion energy



Small explosion energy in 2D（~10^{50} erg, Mueller'15)
→ possibly becomes larger in 3D.

Summary

- **1. Systematic CCSN study based on 2D simulations.** R<5,000km, t<~1s.
  KN+'15 PASJ, 67 (6) 107
  SN properties (neutrino luminosity, PNS mass, etc.) **are well characterized by compactness parameter ξ.**
  But explosion energy is still growing.

- **2: Long-term 2D simulations.** R<100,000km, t~10s.
  KN+'16 MNRAS, 461 (3) 3296
  For three progenitors with small/middle/large ξ.
  → **Explosion energy reaches 10^{51}erg**, but **not converged**.
  2D seems to be problematic.

- **3. Toward a long-term 3D CCSN simulation.**
  KN+, in prep.
  With mesh coarsening scheme.
  → s11.2 progenitor shows larger explosion energy.