Multidimensional Supernova Simulations with a concentration on Equation of State (EOS)

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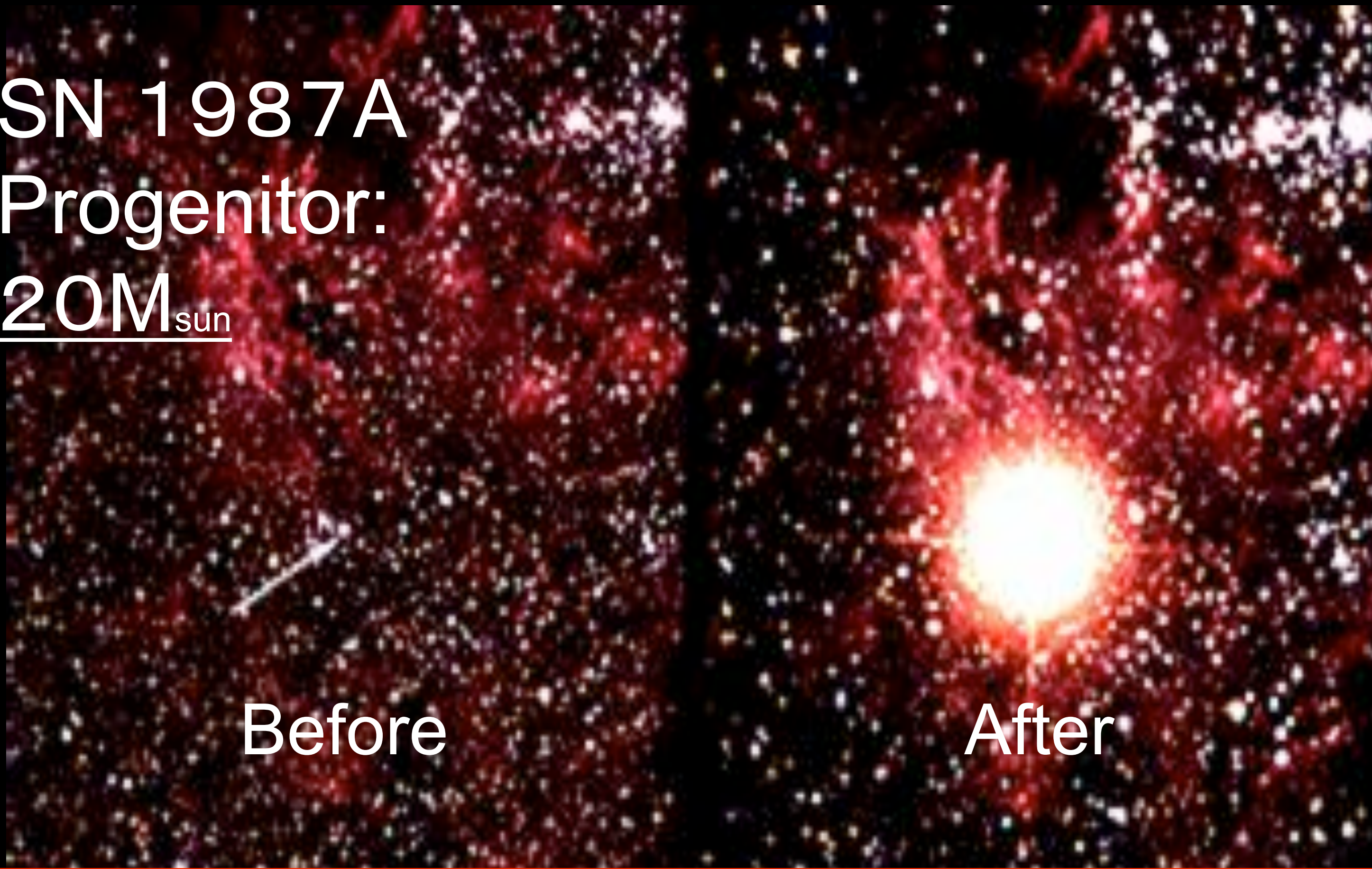
The supernova shocks reach to the stellar surface somehow… with its kin. E of 10^{51} erg !



But… we don't understand the mechanism of explosion over these 40 years ! (the supernova problem)

Neutrino heating mechanism

- Best-studied and most promising way to explode stars($> 10M_{sun}$).

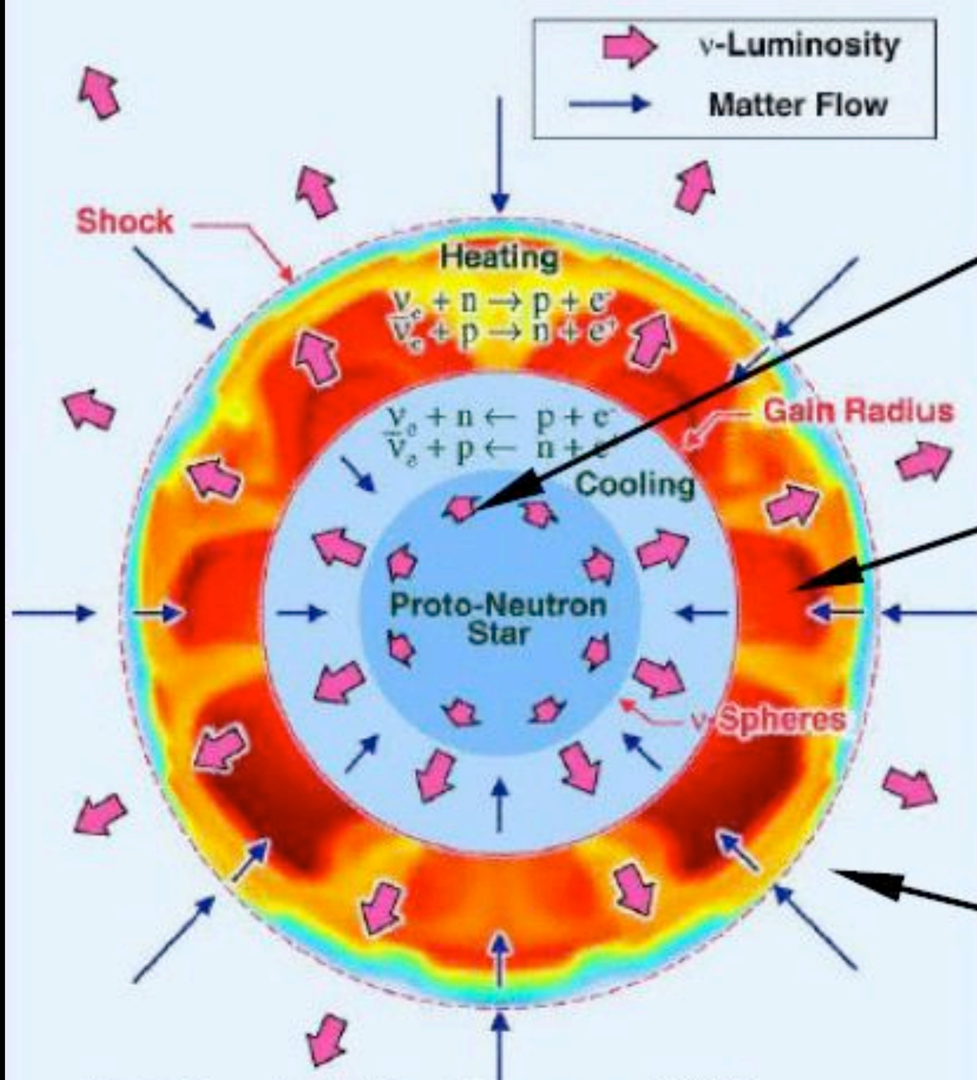


Illustration adapted from Mezzacappa (2003)

(Wilson ´82, Bethe & Wilson '85)

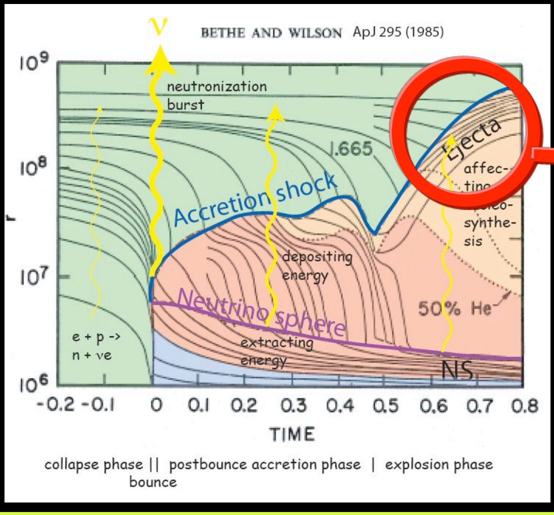
neutrinos diffuse out of opaque proto-neutron star ($\tau_\nu \sim 1$)

neutrinos heat matter in semi-transparent ($\tau_\nu \sim 1$) post-shock region ---> convection with coexisting downflows and rising hot bubbles sets in

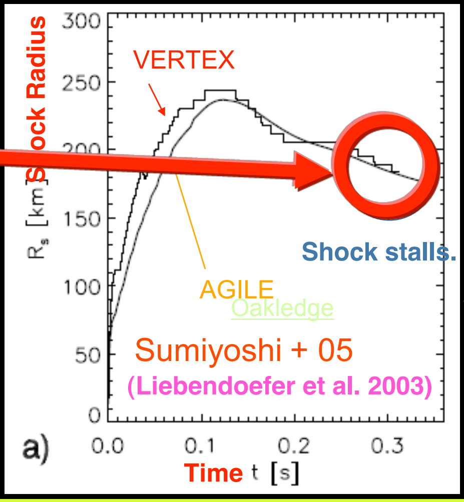
neutrinos stream freely through stellar envelope ($\tau_\nu << 1$)

Looking back 20+ Years of Modeling & Theory

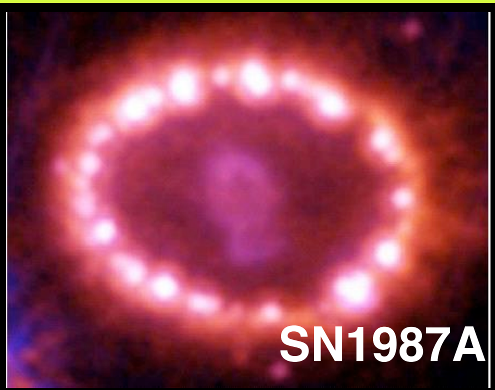
- Neutrino-heating mechanism (Wilson '82,Bethe'85) in spherical symmetry fails to explode massive stars with iron cores.



~20 years



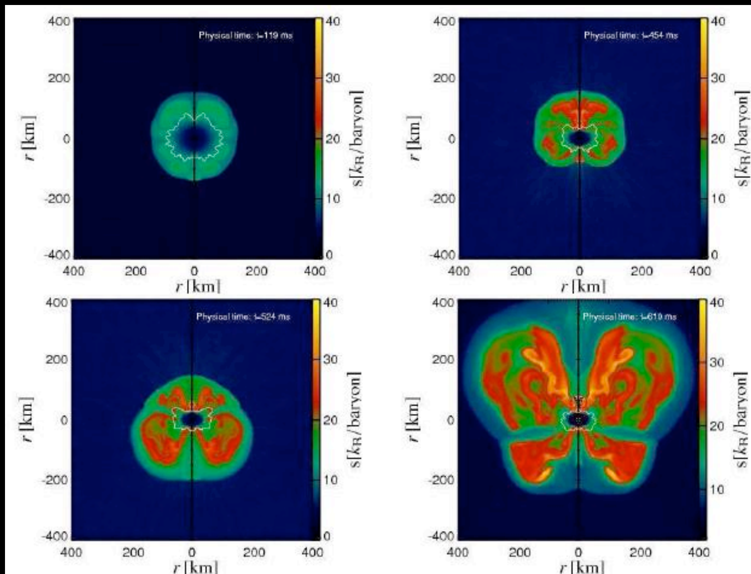
Doing-best simulations, but..



- CC SNe are generally aspherical. (Wang+.01,02)
- Multidimensional explosions are favorable for reproducing the synthesized elements. (Nagataki+.97, Maeda+.03, Kifonidius+.07,Maeda+08…)

Multidimensional modeling is crucial !

2D neutrino-driven explosion (Garching):

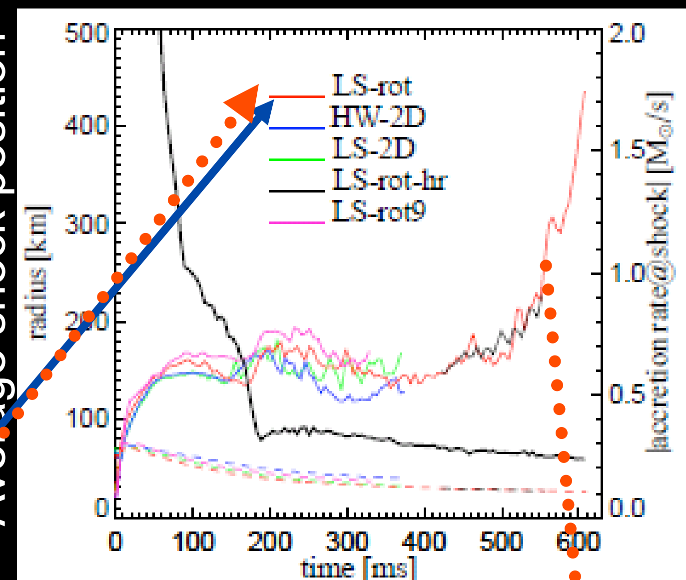


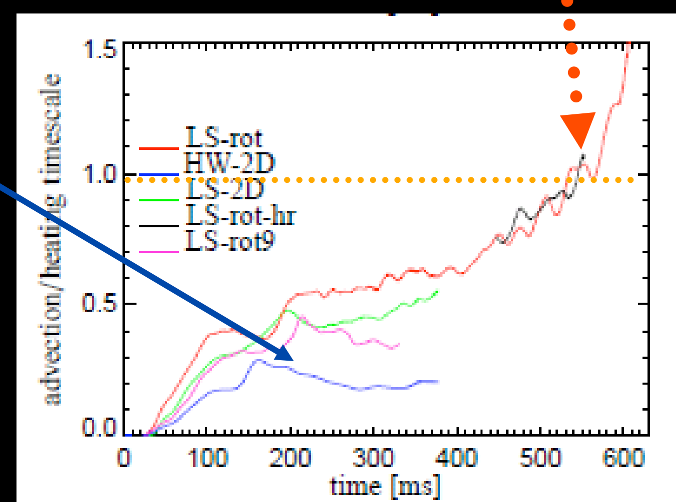
(15Ms by Woosley & Weaver (95))

Marek and Janka (09)

(Ray-by-Ray accurate Boltzmann transport)

Average shock position





EOS table

		K(MeV)
• Wolff-Hillebrandt	Hillebrandt et al. 1984, AA	263
• Lattimer-Swesty EOS (LS) – Based on liquid drop model	Lattimer Swesty, 1991, NPA	180
• Relativistic EOS (Shen) – Based on RMF(relativisitic mean field) + Thomas Fermi	Shen et al., 1998, NPA, PTP	281
• Nuclear experiment	Shlomo et al. (06)	240±20

✓ The first success of neutrino-driven exp. in 2D

✓ Weak explosion (~10^{50}erg) at the end of simulations. (1-2 orders of magnitude less than obs.)

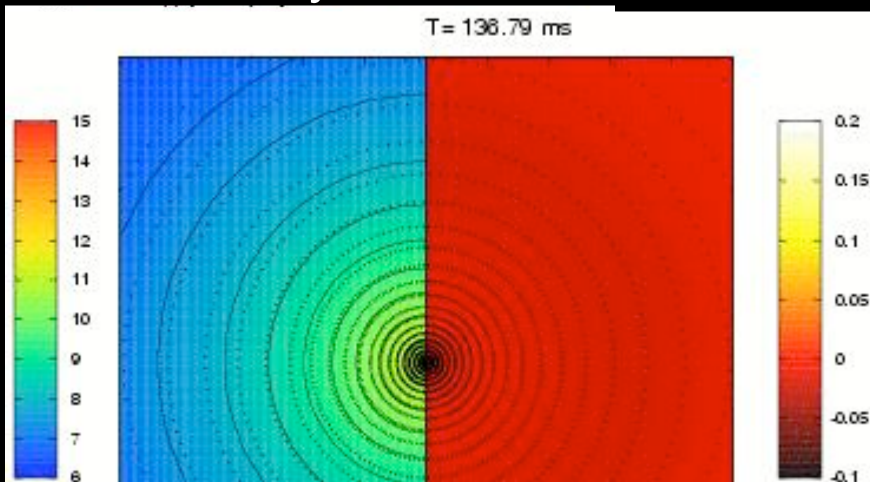
✓ **only for a softer EOS. (Accurate nuclear EOS !!)**

A la carte of recent 2D exploding models

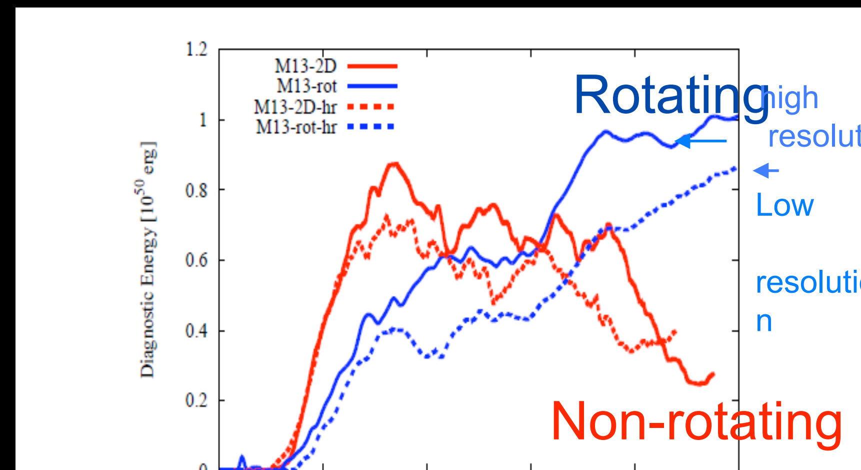
✓ Rapidly-rotating 13 Msun star (Tokyo)

Suwa, Kotake, Takiwaki, Whitehouse, Liebendoefer, Sato (10)

density v/c



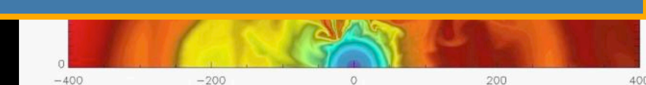
Time evolution of explosion energy



☆ Fundamental problems remained !

✓ The obtained explosion energies are typically underpowered by 1or 2-orders-magnitudes compared to observation (SN kinetic energy of 10^{51} erg).

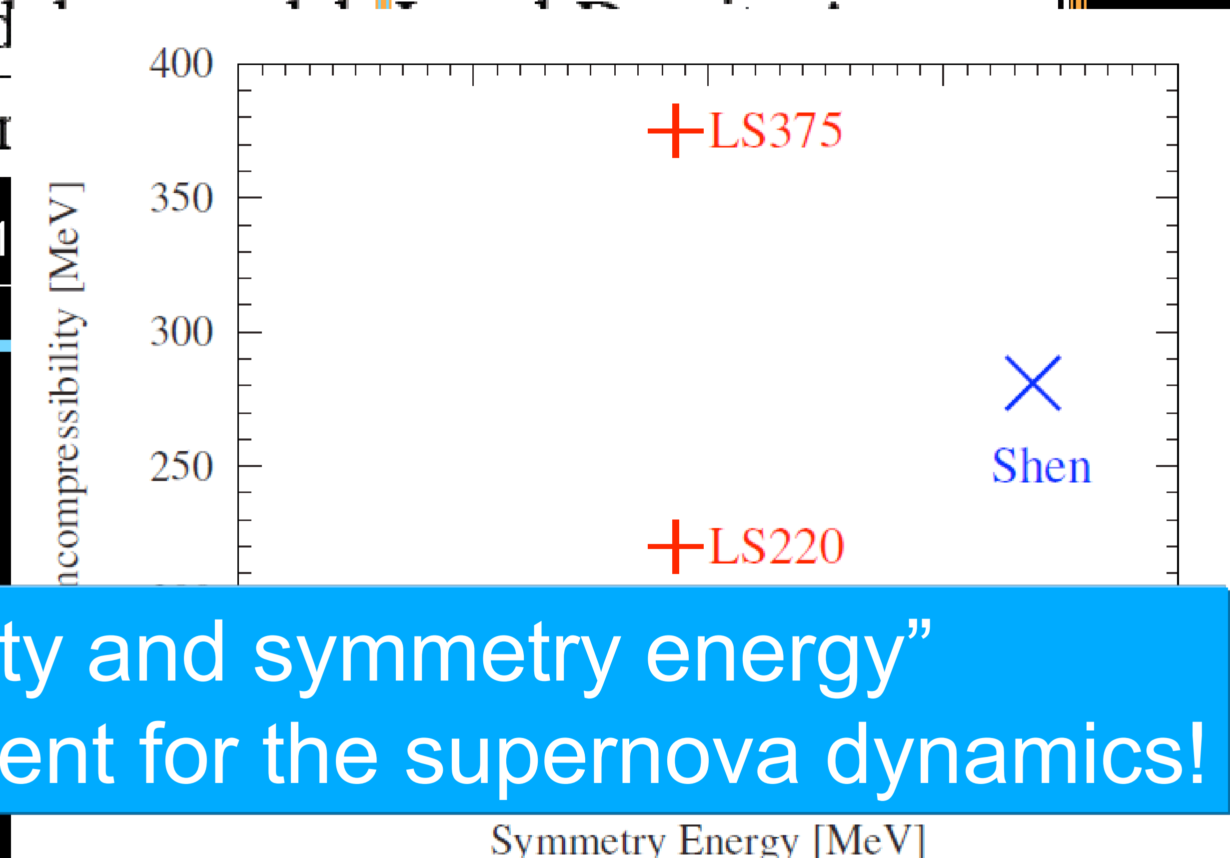
✓ All of the exploding models assume a very soft nuclear EOS (K=180 MeV).



Two representative EOSs in recent supernova simulations

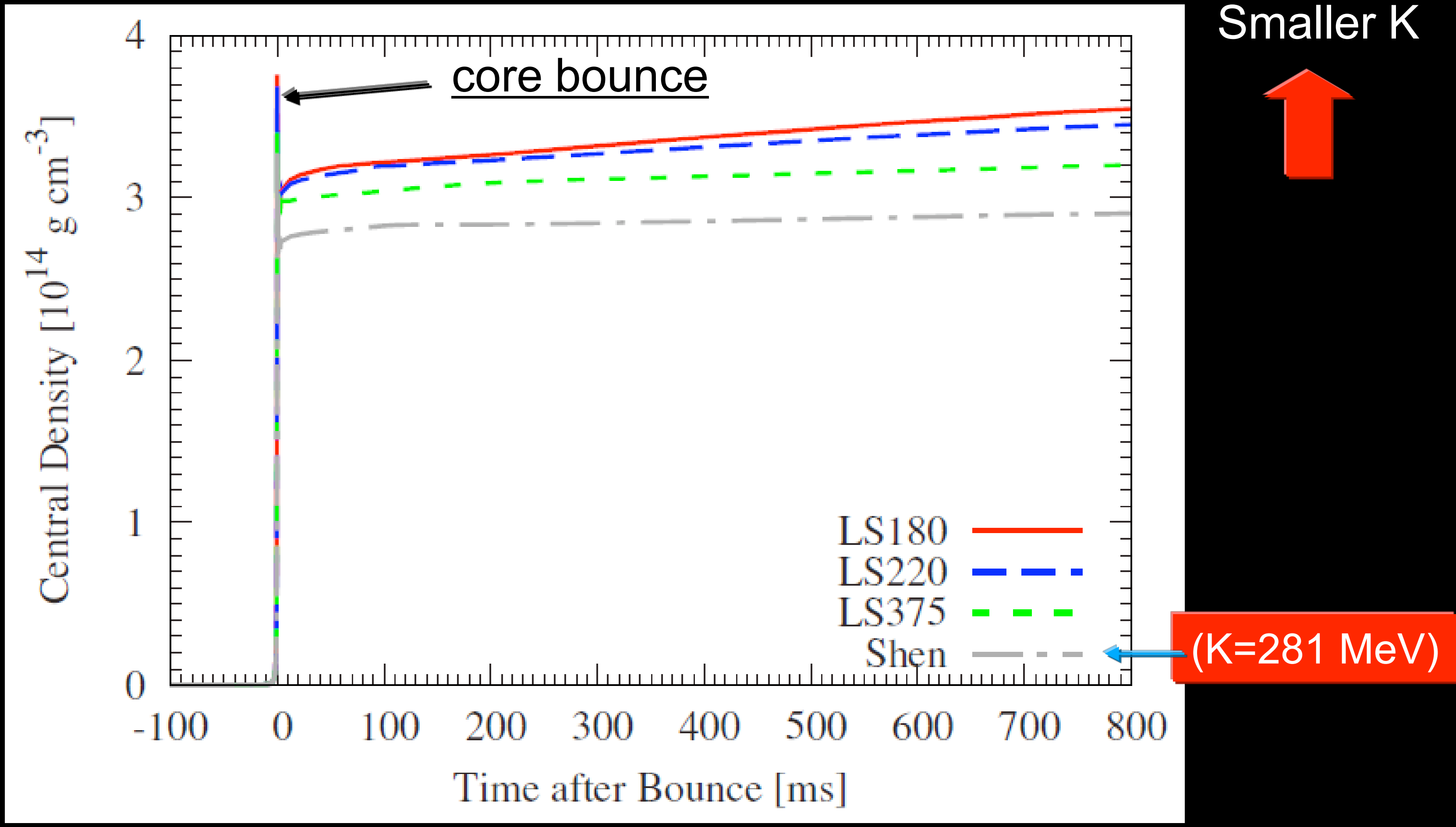
(Lattimer & Swesty'91)
NPA535(1991)331

	LS-EOS	Shen-EOS
Model	Compressible liquid	Rel. Mean Field +
Bulk EOS	"Skyr	
incompressibility	K = 1	



"Incompressibility and symmetry energy"
is a key ingredient for the supernova dynamics!

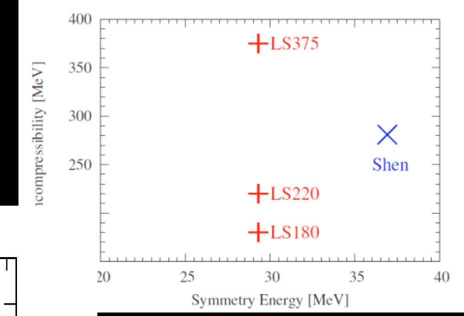
Impacts of EOSs in 1D models

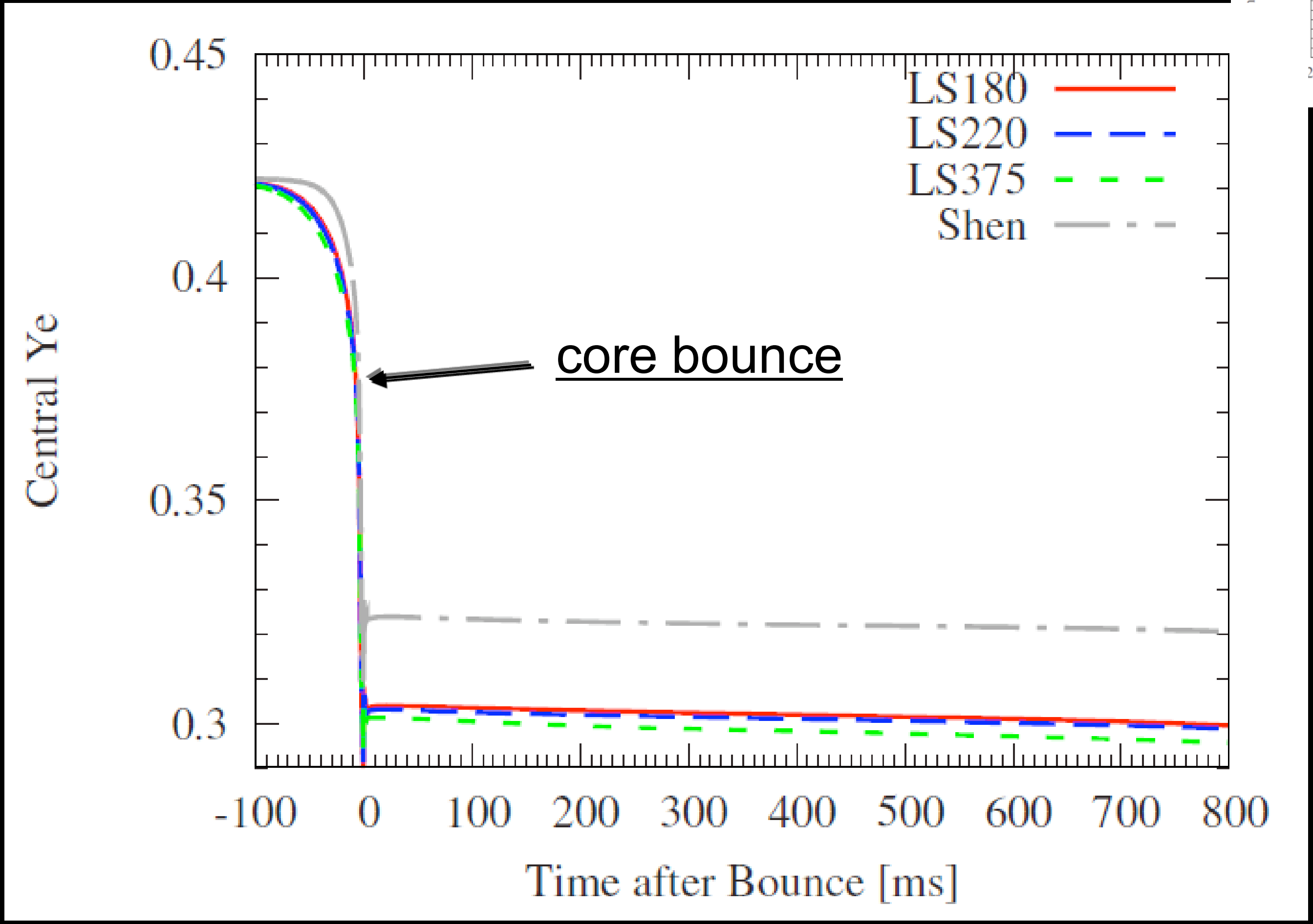


✓ The central density becomes higher for softer EOSs with smaller K.

✓ The symmetry energy is also pivotal to determine the post-bounce evolution of supernova cores.

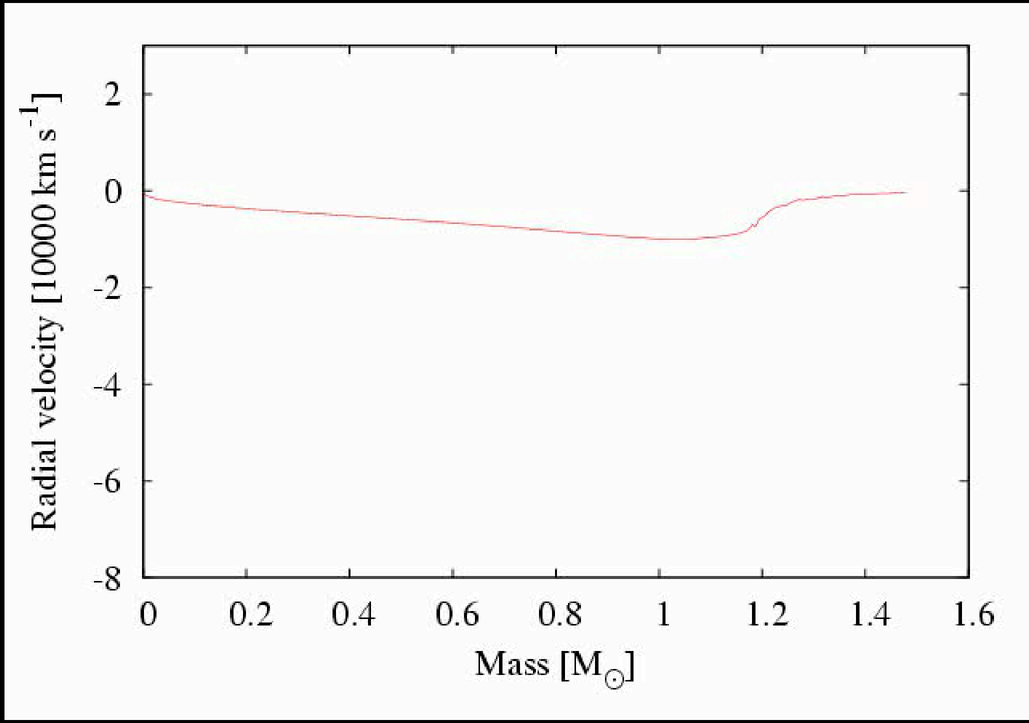
What is role of “symmetry energy” ?



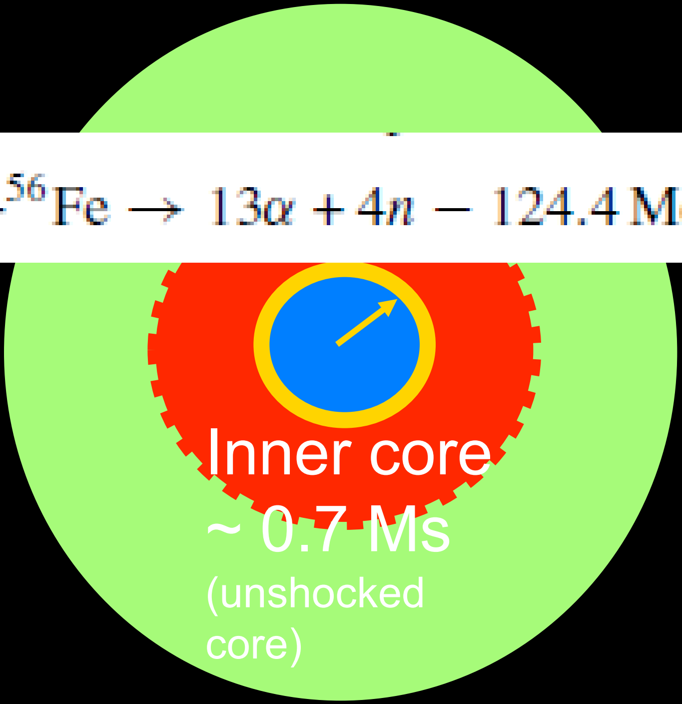


✓Ye(# of electrons /# of baryons) becomes larger for the Shen EOS that has larger symmetry energy (38 MeV) than LS’s (28 MeV).

Dynamics near bounce



Iron core = 1.4 Ms



$$\gamma + {}^{56}\mathrm{Fe} \rightarrow 13\alpha + 4n - 124.4\,\mathrm{MeV}$$

✓The initial shock position is given ~ $M_{\mathrm{ic}} \sim 0.7 M_\odot \left(\frac{Y_e}{0.34}\right)^2$ $Y_e = \frac{n_e}{n_b}$

✓ During the shock-passage in the iron core, the kinetic energy of the shock gets small due to the photo-dissociation at

Mass outside the inner core

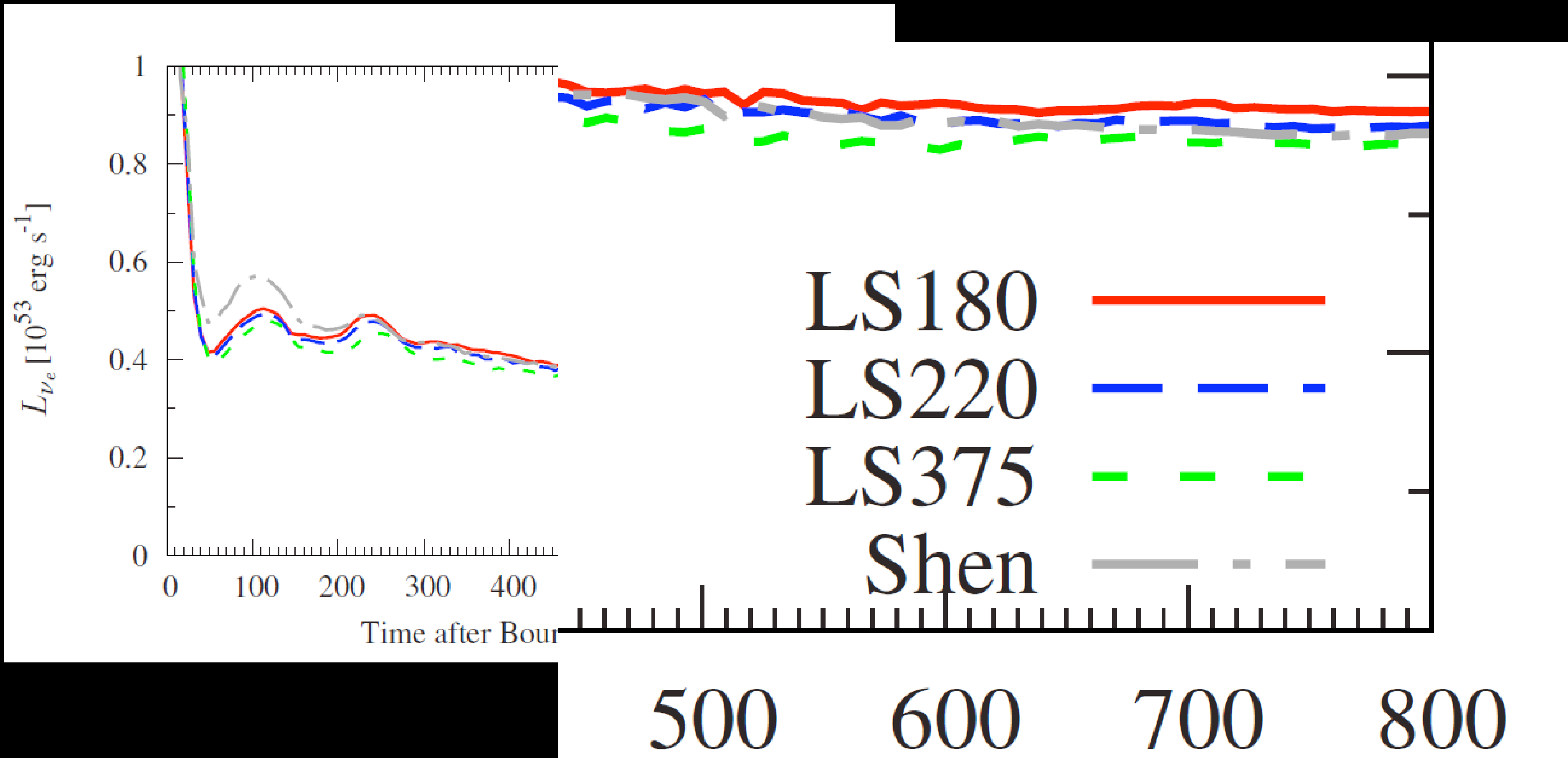
$E_{\mathrm{loss}} \sim 10^{50}\mathrm{erg}/\mathrm{M}_\odot \left(\frac{\Delta M}{0.1 M_\odot}\right)^{-1}$

✓ Larger Ye leads to more massive inner core.

✓ **Larger symm. energy** can help to produce neutrino-driven explosions !

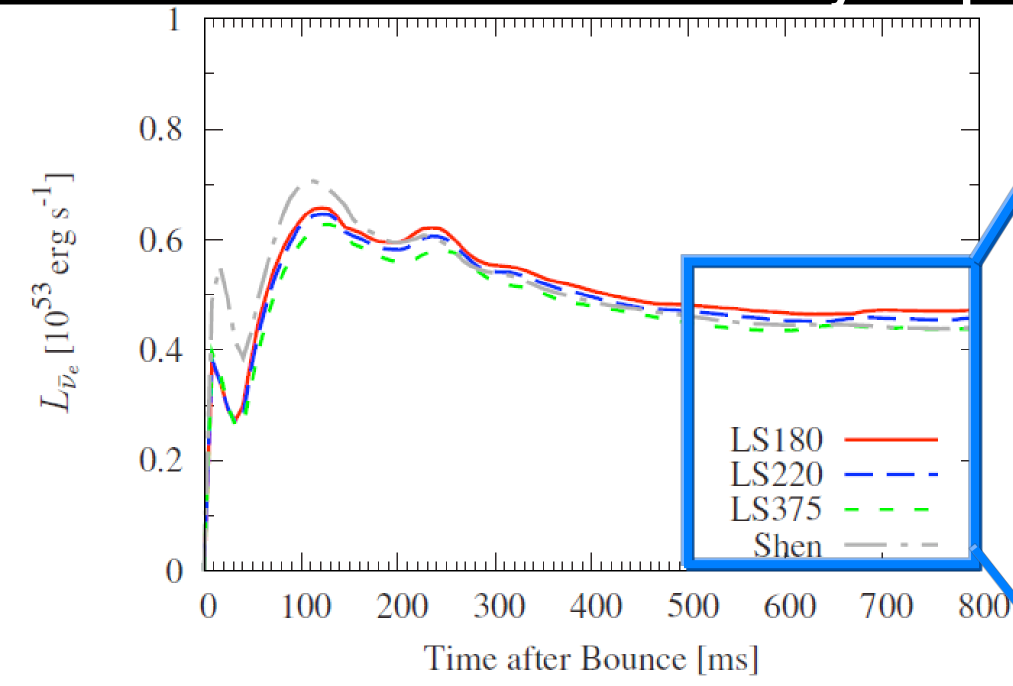
What is the role of “K” ?

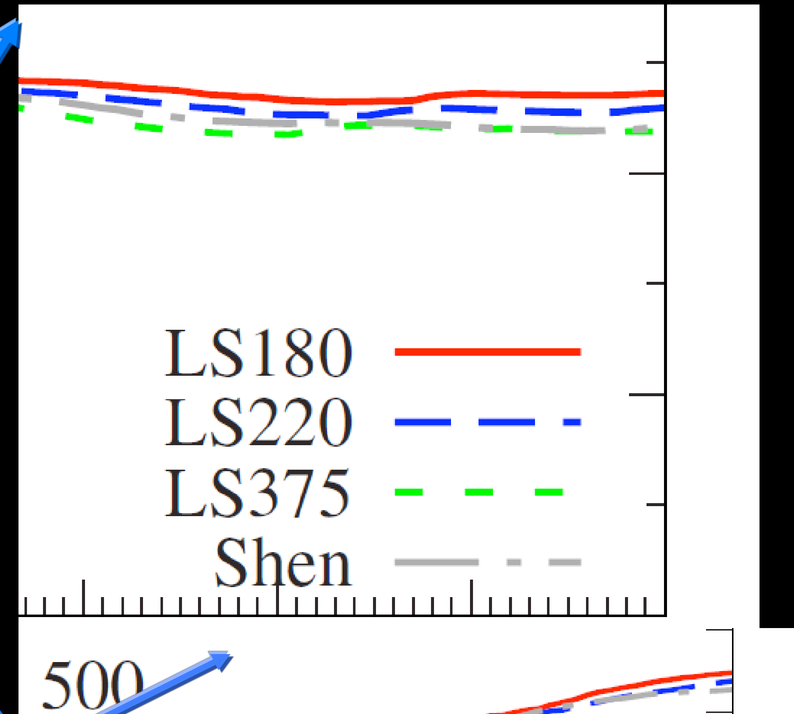
Electron neutrino luminosity vs. postbounce time



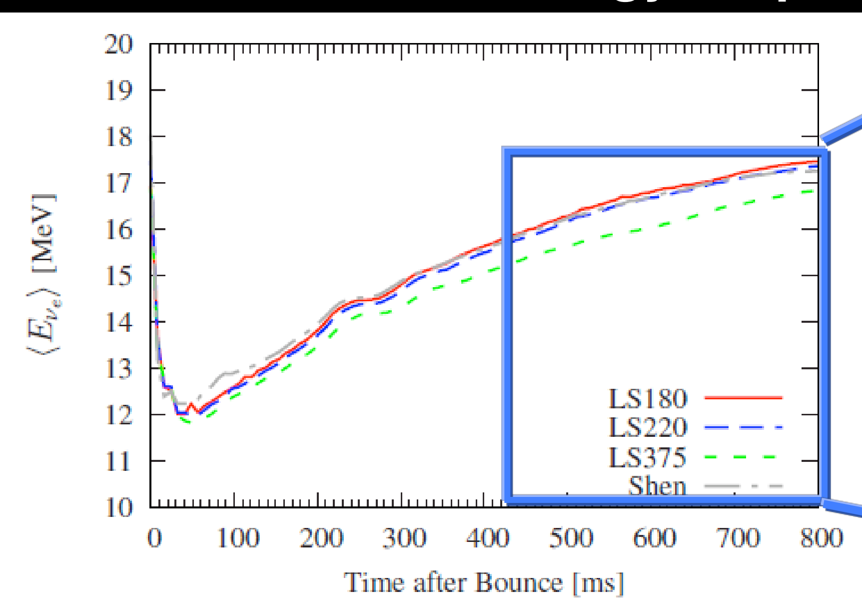
✓ Neutrino luminosity becomes higher with smaller **“K”, simply because the PNS can be more** compact to realize higher temperature inside.

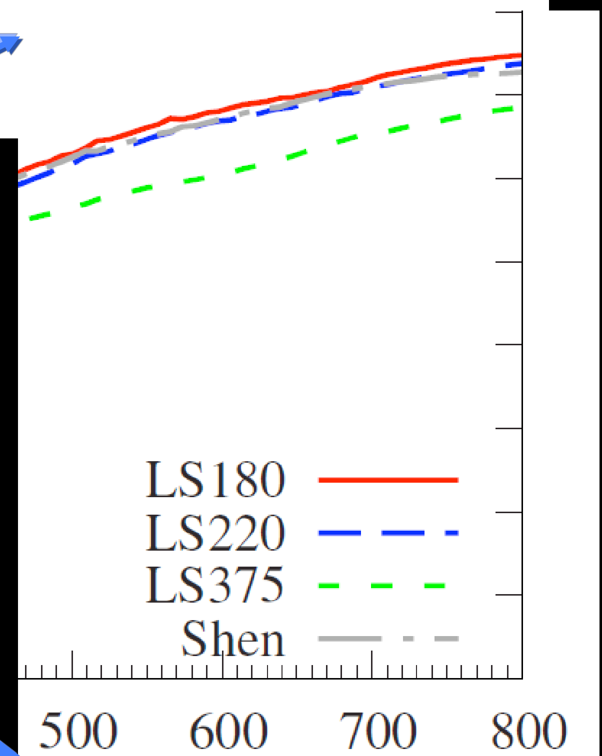
Anti-electron neutrino luminosity vs. postbounce time





Electron neutrino energy vs. postbounce time

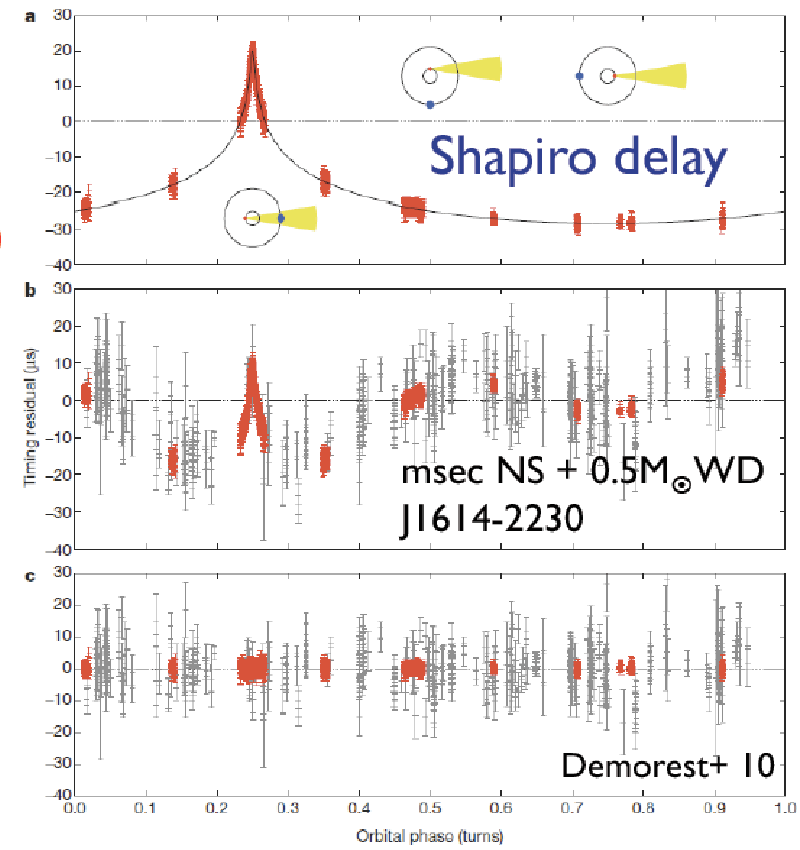




To summarize the impacts of EOSs on SN dynamics

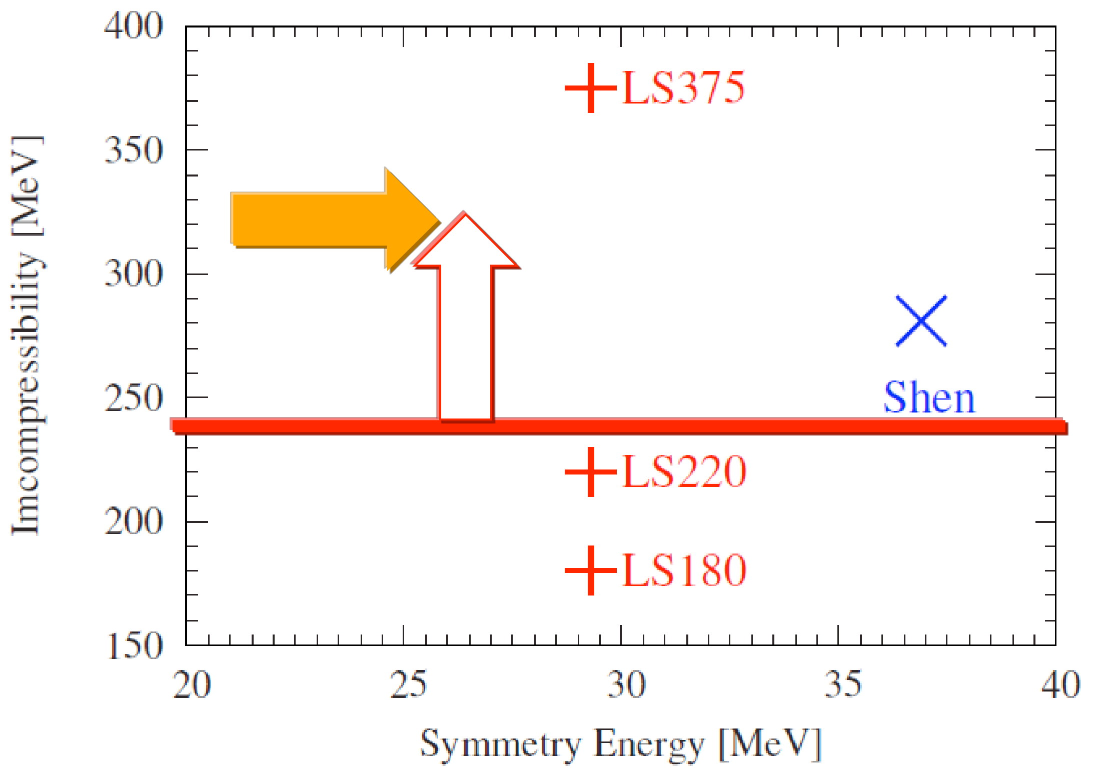
Larger symmetry energy & Smaller incompressibility is the best combination to blow up massive stars !

Demorest et al. Nature; Volume: 467,; Pages: 1081–1083



M_{ns} ~(1.97±0.04)$M_\odot$

Final question is the symmetry energy !
(As soon as you get the answer, let me know!)



Our 2D model with K=180MeV LS EOS

✓ $15M_{sun}$ progenitor by Woosley et al. (2002)

✓ After bounce, the bounce shock stalls.

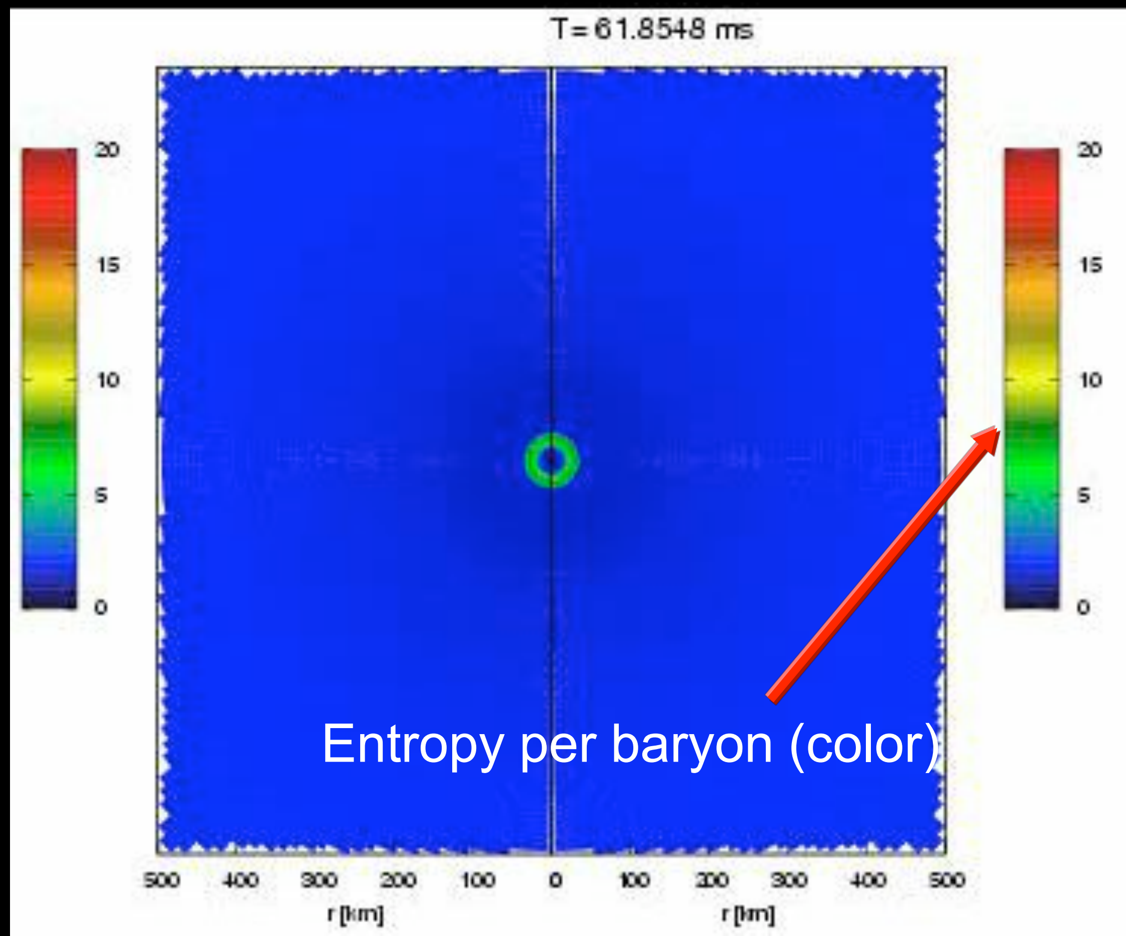
✓ "Standing Accretion Shock Instability (SASI)" is observed

: "low-modes" oscillations of the stalled shock

✓ The traveling timescales of matter in the neutrino-heated regions become longer due to non-radial oscillations.

✓ At around 300 ms after bounce, the neutrino-driven explosion sets in.

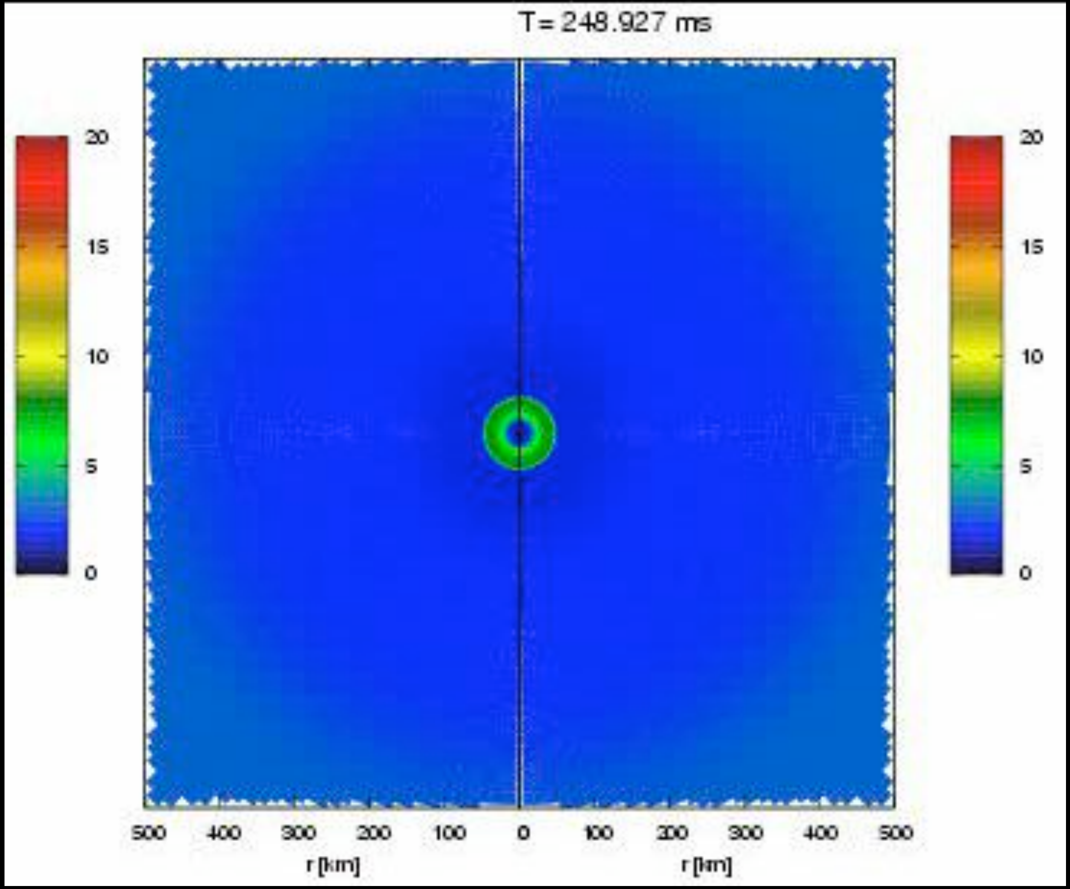
Right panel is zoom up in the central region



2D model with SHEN EOS

✓ The SASI continues.
but .we have not observed
the shock-revival yet.

✓ This model seems not
to be exploding …



☆In 2D, it's more easier to obtain explosions than 1D.

(because the non-radial motions can elongate the neutrino-heating timescales)

☆ In 3D, one might expect a more favorable situation!

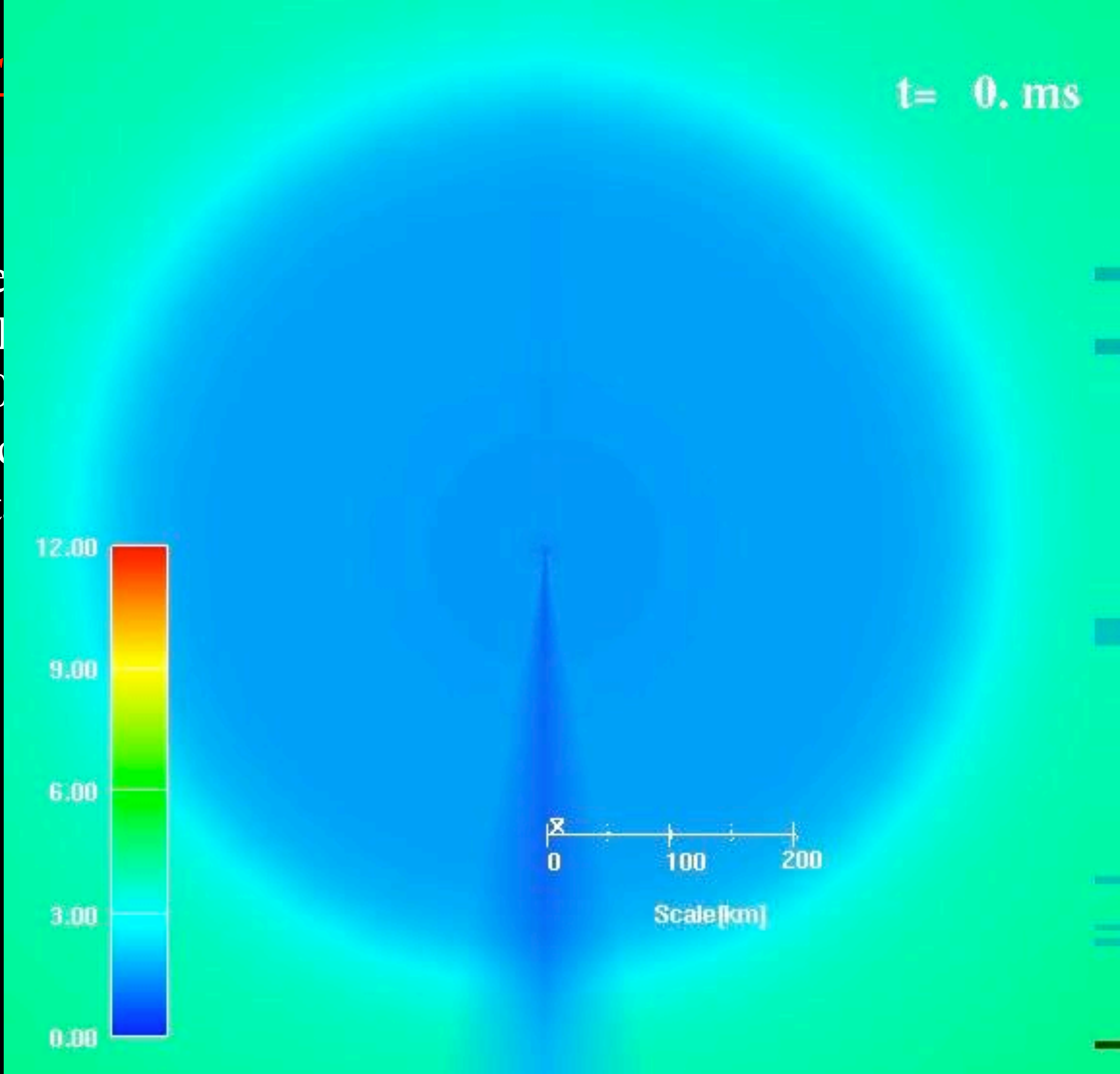
(because matter can travel freely in the azimuthal(φ) direction!)

3D Results

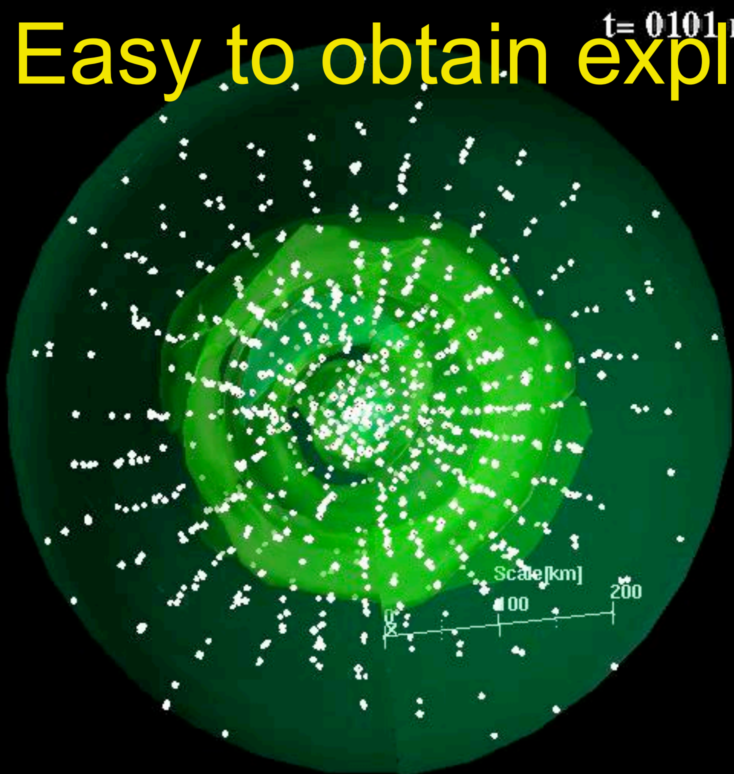
✓13 Ms proge

✓ Numerical I

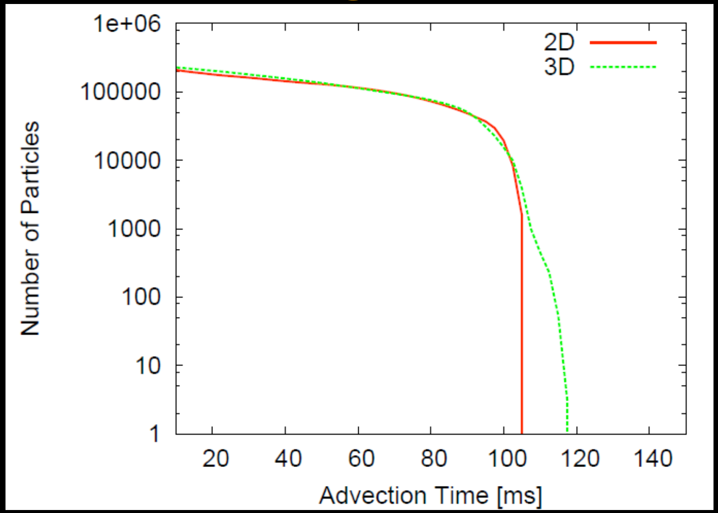
- Grid: 30
- Processo
- Non-rot



Easy to obtain explosions in 3D ?(Yes or No!)

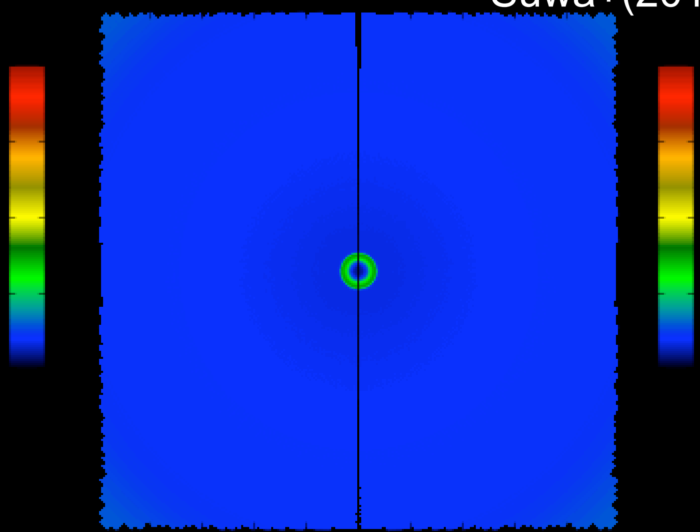


✓ **For working the neutrino-heating mechanism**



The advection timescales become longer in 3D than in 2D.

Suwa+(2010)



✓ **For the hydrodynamic point of view, it may be more easier for 2D.**

(because matter motions can be concentrated along the special direction)

Please stay tuned for our high resolution 3D simulations.

Conclusions

☆Larger symmetry energy & Smaller incompressibility is the best combination to blow up massive stars !

☆**With currently available EOSs, only weak explosions have been obtained in the state-of-the-art 2D simulations. (e.g., Marek & Janka (2009), Suwa, KK et al. (2010))**

☆ **3D supernova simulations equipped with accurate EOSs can be the only solution to understand the supernova mechanism.**

Thank you very much !