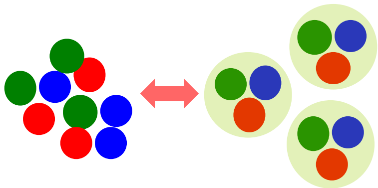
Supernovae and neutron stars: playgrounds of dense matter and neutrinos

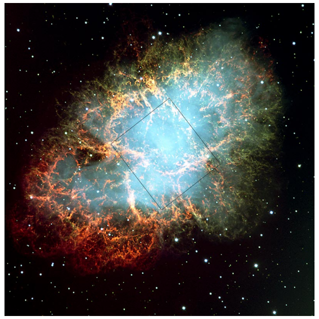
Quarks and Hadrons



K. 'Sumi'yoshi

Numazu College of Technology
Japan

Crab nebula



hubblesite.org

- Explosive phenomena: wide range of conditions
- Neutrino burst signals: probe inside compact stars

Numazu near Mt. Fuji

Wikipedia (trimmed)

Hot & dense matter in supernova explosions

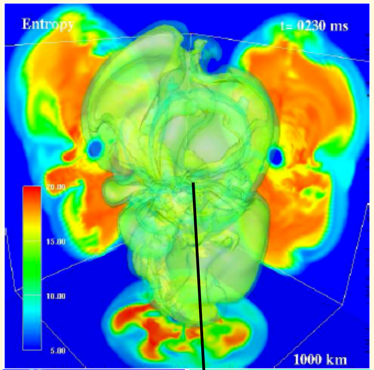
(1) Explosion or not? with EOS and neutrino

(2) Neutrino signals to probe exotic phase?

SN1987A

Mann "Shadow of a Star"

3D Simulations

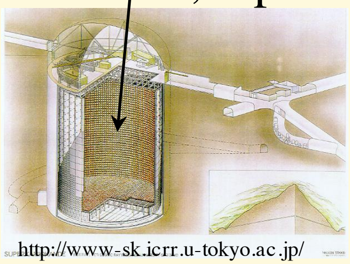


ApJ 2012 Takiwaki

ν

ν Neutrino burst

Kamioka, Japan

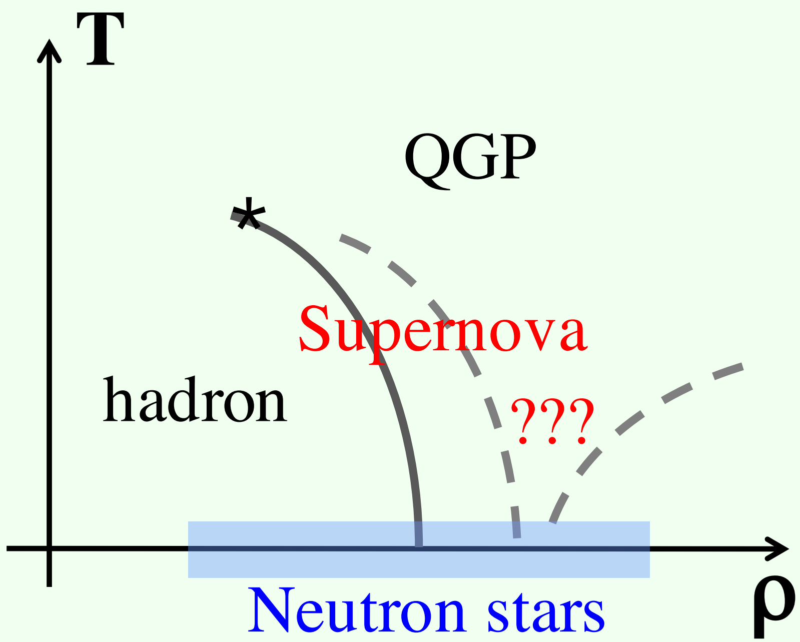


http://www-sk.icrr.u-tokyo.ac.jp/

Gran Sasso, Italy

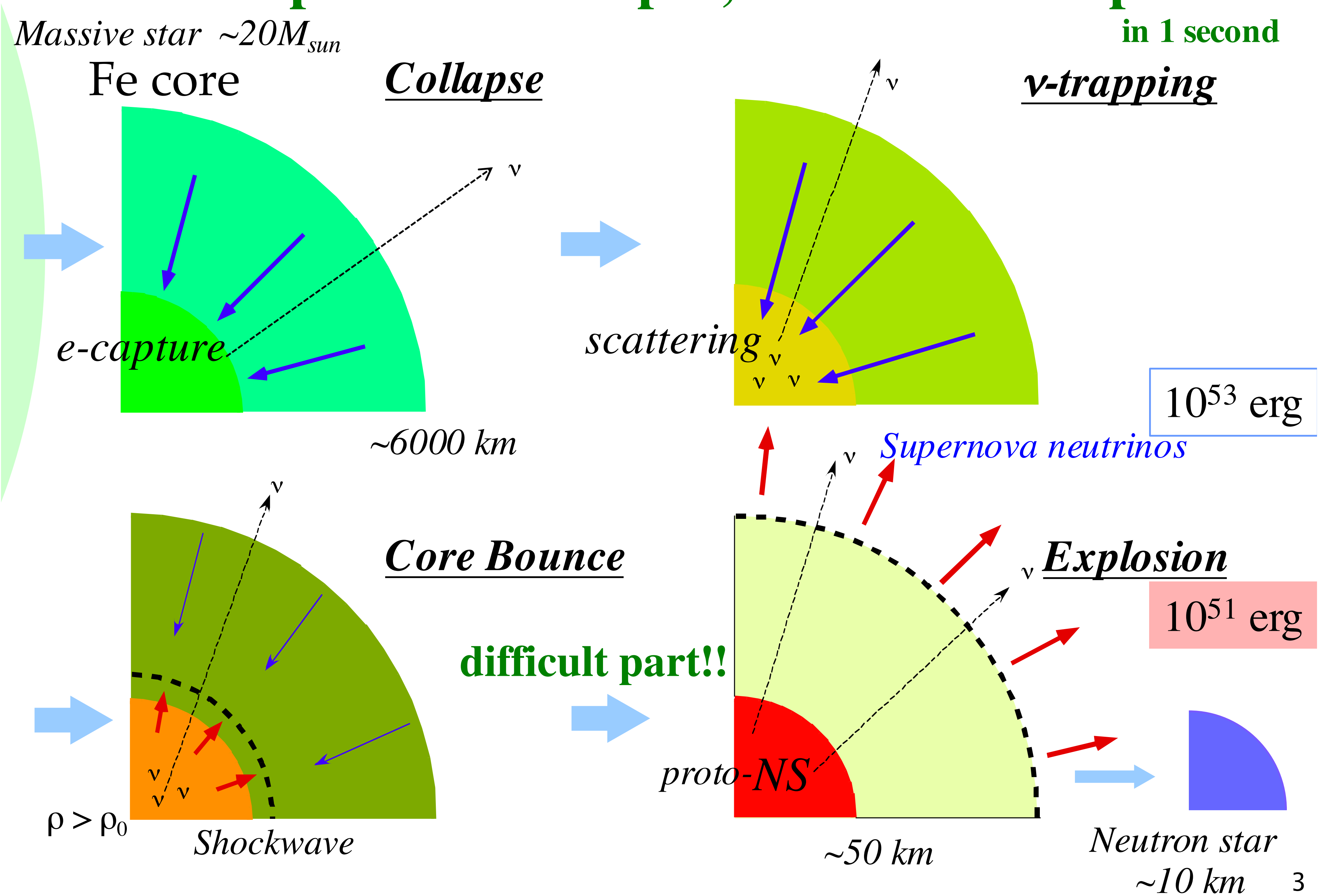
https://www.lngs.infn.it/en/lvd

QCD phase diagram



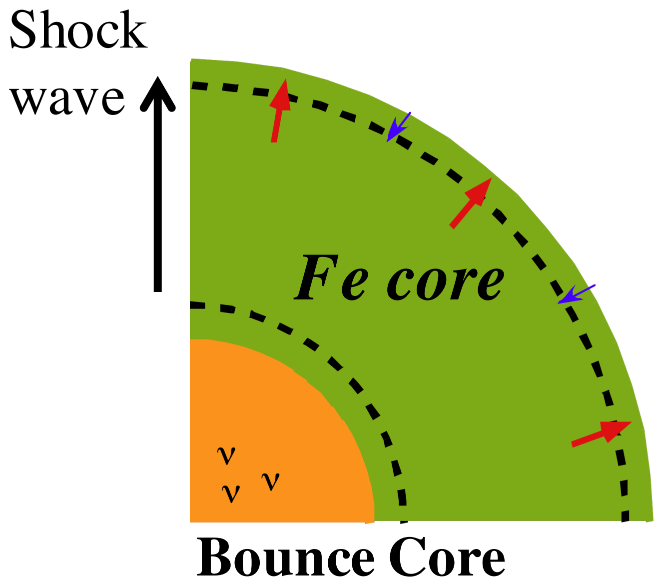
(3) Which region in ρ-T plane?

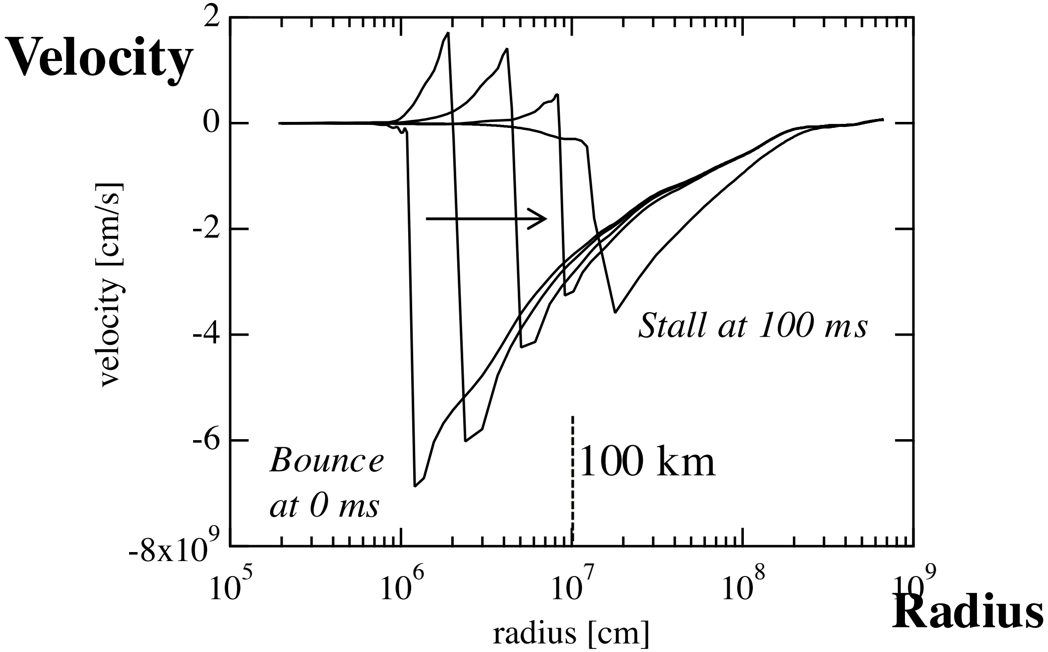
Core-collapse SNe: collapse, bounce and explosion



Difficulties: shock wave stalls on the way

1. Initial shock energy is used up by Fe dissociation
2. No explosion occurs in spherical (1D) simulations





How to revive the stalled shock wave?

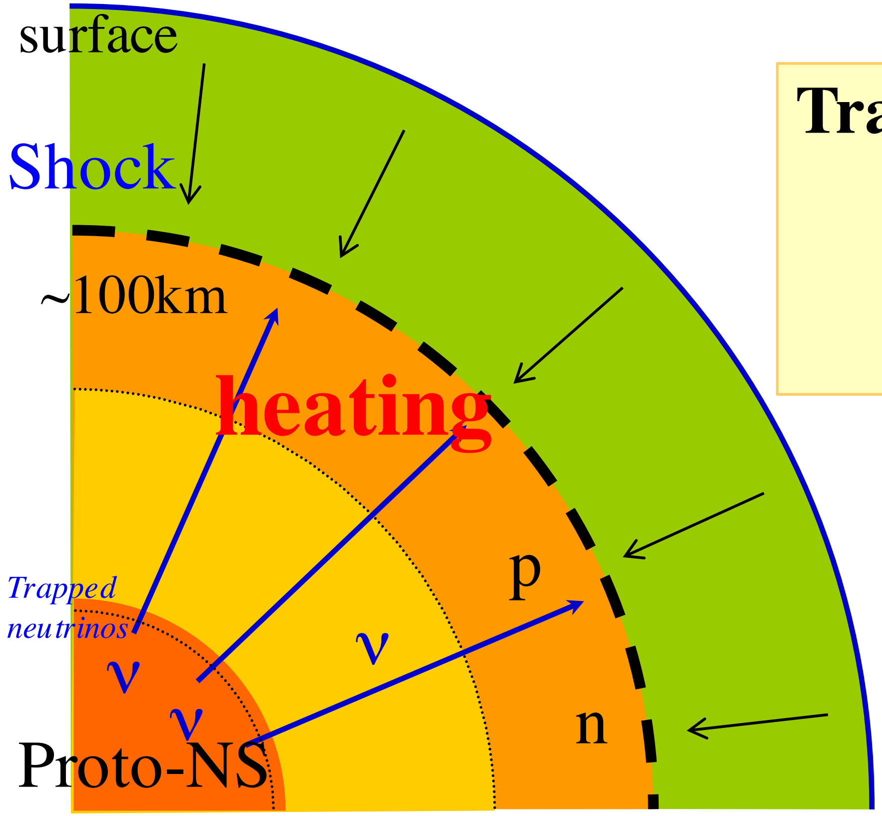
- Neutrino heating mechanism
- Multi-dimensional effects

Neutrino heating mechanism for revival of shock

Heating by neutrino absorption

$\nu_e + n \rightarrow e^- + p,$

$\bar{\nu}_e + p \rightarrow e^+ + n$



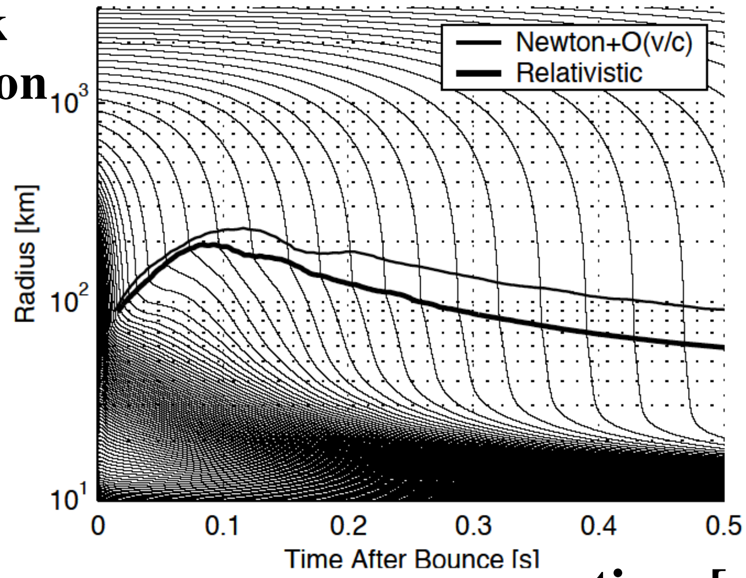
100ms after bounce

Transfer of energy from ν Janka A&A (1996)

$$E_{\nu-heat} \sim 2\times10^{51}\left(\frac{\Delta M}{0.1M_{solar}}\right)\left(\frac{\Delta t}{0.1s}\right)erg$$

No explosion by modern 1D simulations

Shock position



time [s]

Liebendörfer et al. (2000)

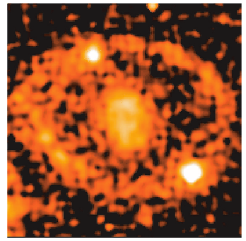
Neutrino energy/flux from trapped neutrinos

Explosions mechanism in 2D & 3D

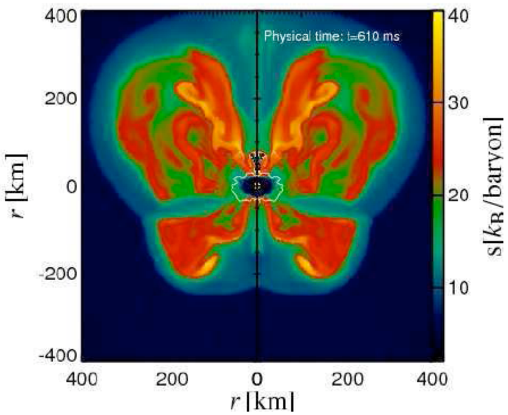
- Convection, SASI, rotation, magnetic etc - Observations

neutrino-heating with hydro instabilities

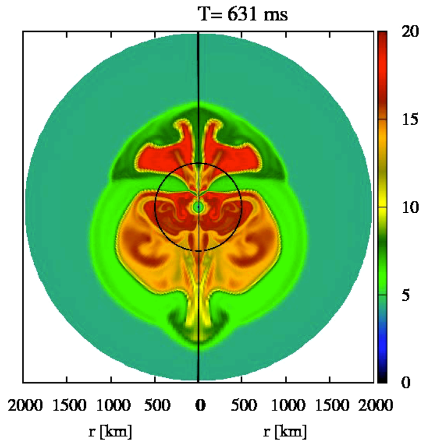
SN1987A



Wang (2002)



Marek et al, ApJ (2009)

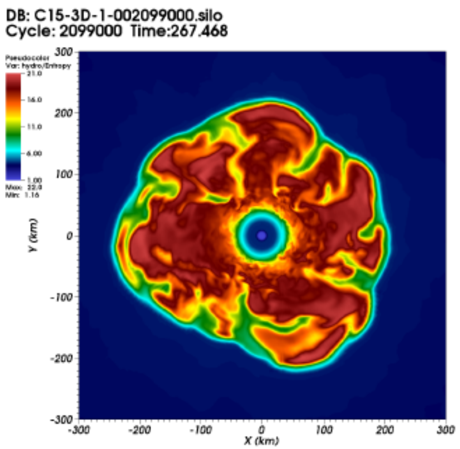


Suwa et al. (2010) PASJ

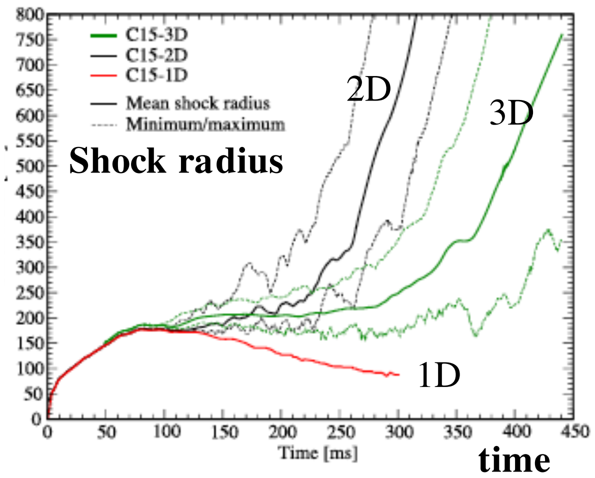
Deformation of shock
Convection

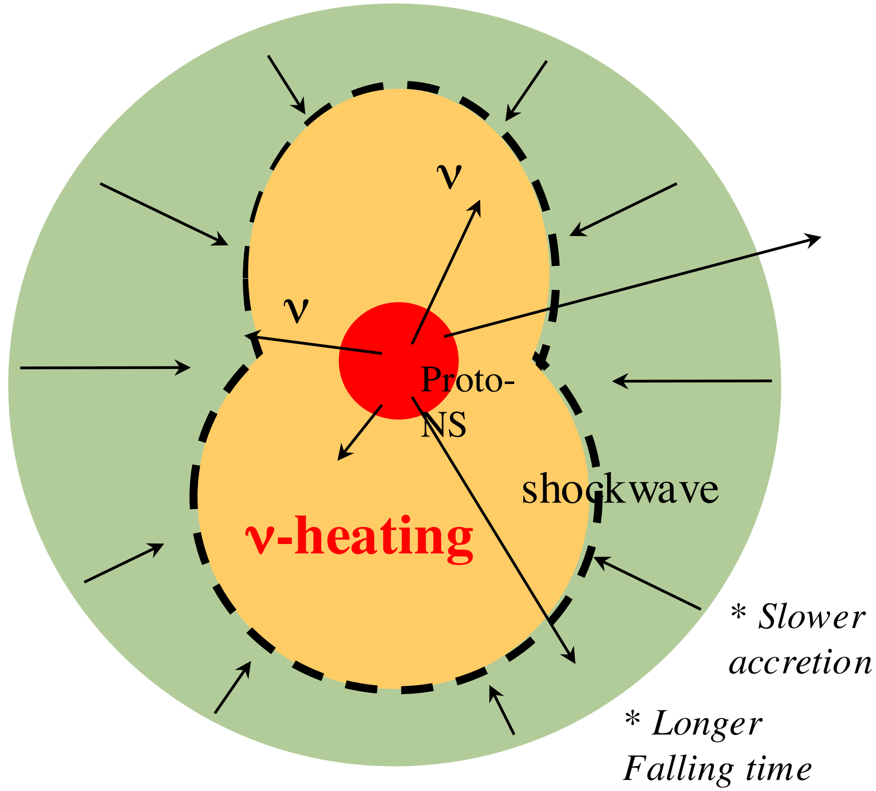
→

Enough time
for ν-heating



Lentz ApJ (2015)





** Slower accretion*

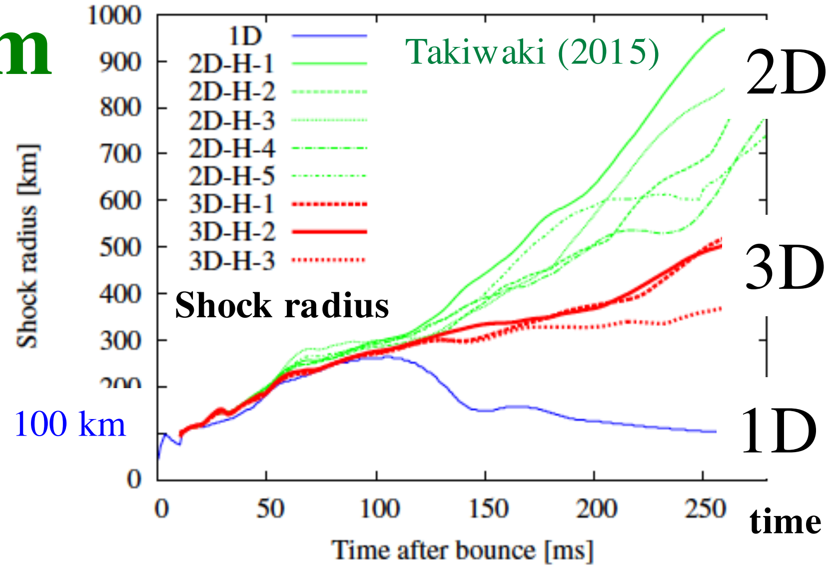
** Longer Falling time*

Issues of explosion mechanism

- **What is main trigger?**

2D vs 3D, Low explosion energy? 10^{50} erg

- Evaluation of neutrino-heating
- Dependence on nuclear physics



- **To clarify the mystery we need full simulations**

Nuclear Physics

- Equation of state
- Neutrino reactions

  at 10^5-10^{15} g/cm^3, ~10^{11} K

Astrophysics

- Hydrodynamics
- Neutrino transfer
- General Relativity

Supercomputing technology

- Numerical simulations of core-collapse supernovae

  Huge supercomputing power is necessary

K-Computer, Japan

Supernova issues: neutrino transfer

From approximate to exact
neutrino-radiation hydrodynamics

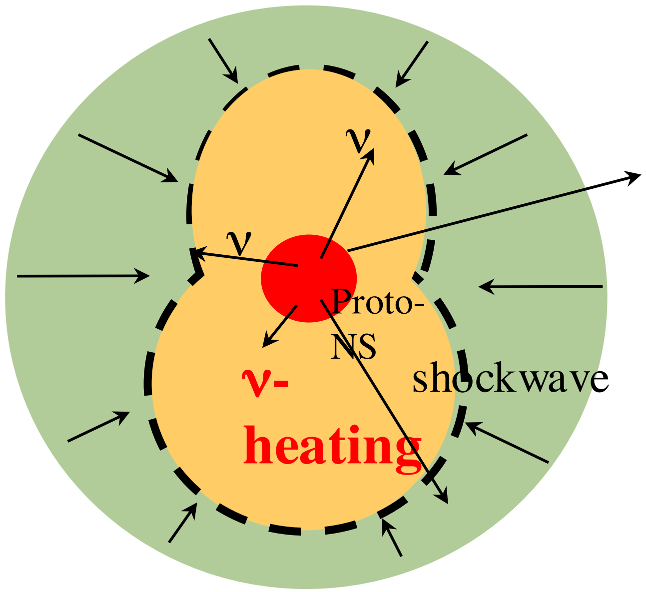
Nagakura et al., ApJS (2014, 2016)
Sumiyoshi et al., ApJS (2012, 2015)

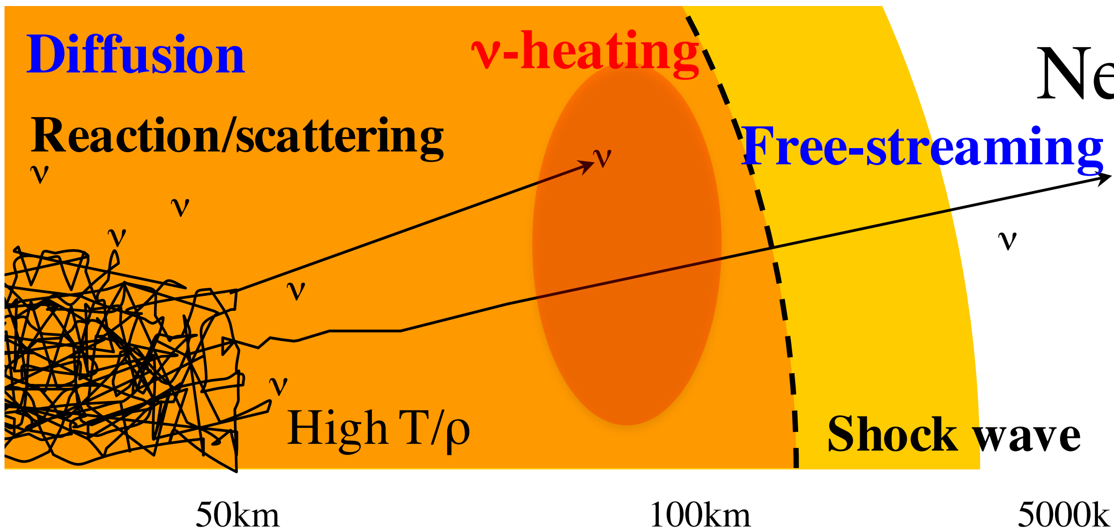
ν-transfer to determine ν-heating

2D/3D hydrodynamics + neutrino heating

- Neutrino flux & heating
  - ν-trapping, emission, absorption
- From diffusion to free-streaming
  - Intermediate regime is important

→ From approximate to exact





Need to solve Boltzmann eq.

$$\frac{1}{c}\frac{\partial f_\nu}{\partial t} + \vec{n}\cdot\vec{\nabla} f_\nu = \frac{1}{c}\left(\frac{\delta f_\nu}{\delta t}\right)_{collision}$$

formidable so far

New code solves 6D Boltzmann eq.

$$f_\nu(r,\theta,\phi;\ \varepsilon_\nu,\theta_\nu,\phi_\nu;\ t)$$

Sumiyoshi & Yamada, ApJS (2012)

Boltzmann eq.

$$\frac{1}{c}\frac{\partial f_\nu}{\partial t} + \vec{n}\cdot\vec{\nabla} f_\nu = \frac{1}{c}\left(\frac{\delta f_\nu}{\delta t}\right)_{collision}$$

Time evolution + Advection = Collision

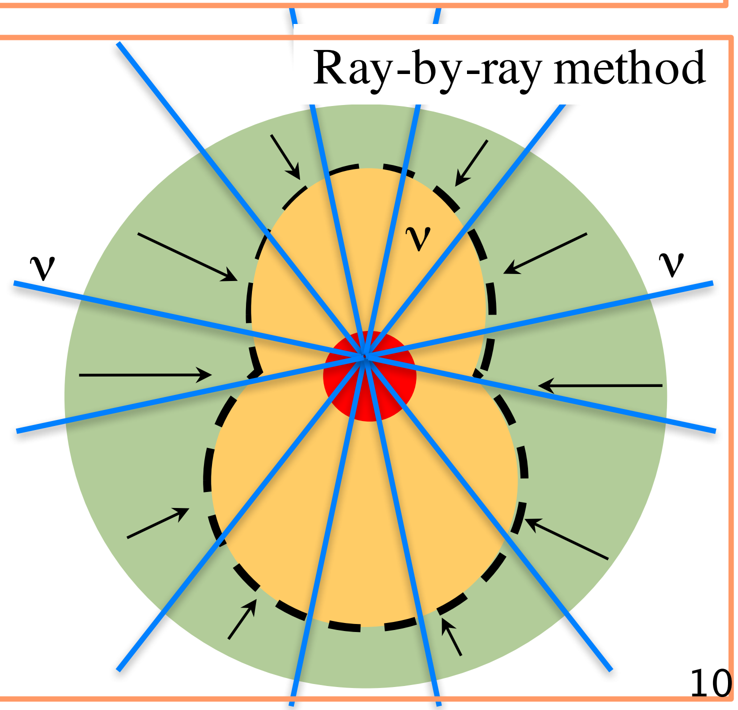
- Collision Term is tough
  - Energy, angle dependent
  - Stiff, non-linear
  - Frame dependent

  → Huge computation

- Approximations used so far
  - 2D/3D: Diffusion, Ray-by-Ray method

    (1D spherical: 1st principle calculations)
- Comparison with Ray-by-ray
  - Local ν-heating ~20% difference

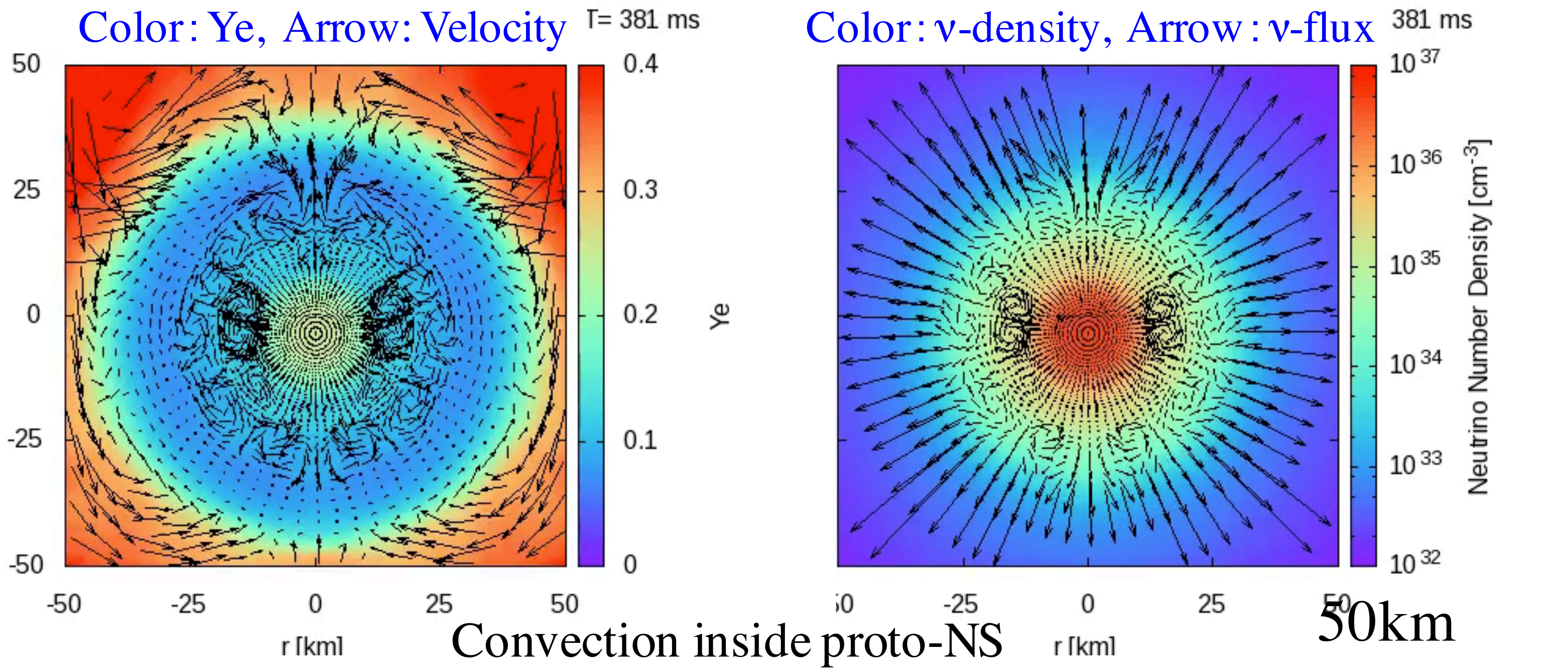
Sumiyoshi et al. ApJS (2015) *Background fix*



Our code: Neutrino-radiation hydrodynamics

Nagakura et al. ApJS (2014, 2016)

- 6D Boltzmann solver ＋ 2D Hydrodynamics + 2D gravity
  - Relativistic effects: Doppler, angle aberration, moving mesh
  - Neutrino transfer in fluid flow (from diffusion to free-streaming)



Non-radial neutrino flux in the whole region cf. Ray-by-ray approx.

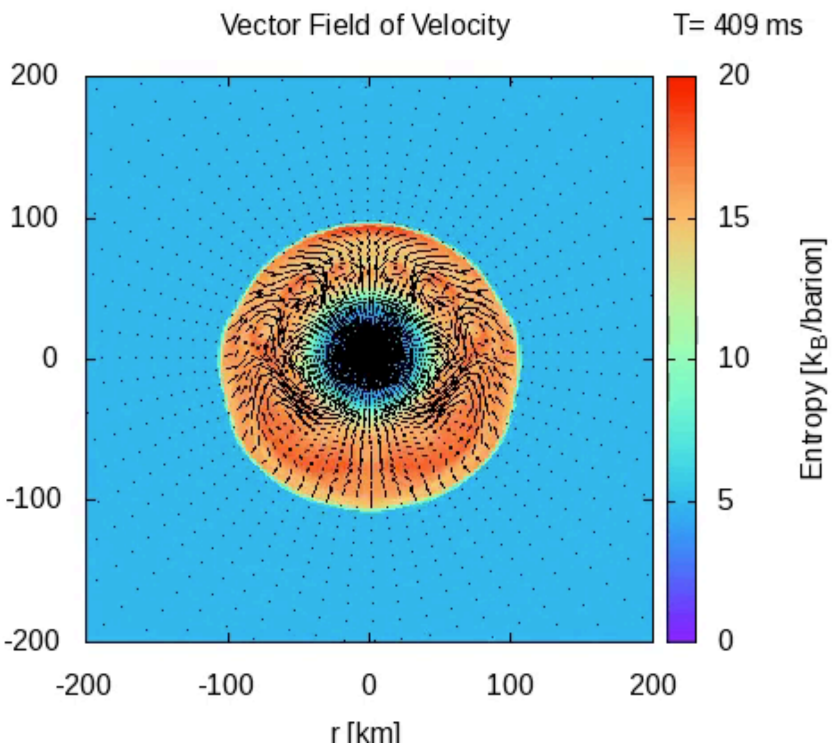
Figure by Iwakami

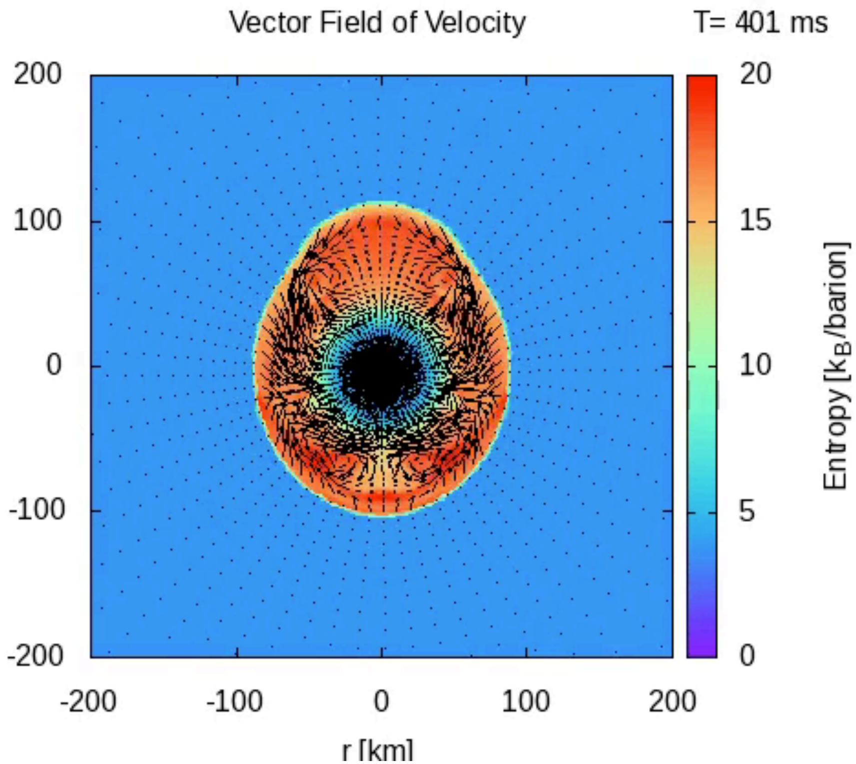
First results of long-term evolution

Nagakura, Iwakami et al. (2016)

- 2D dynamics depends ρ-profiles of massive stars

$11.2M_{sun}$ **Color: entropy, Arrow: Velocity** $15M_{sun}$





with Furusawa EOS table with NSE & GSI e-capture rates

(RMF-TM1, "extended Shen EOS")

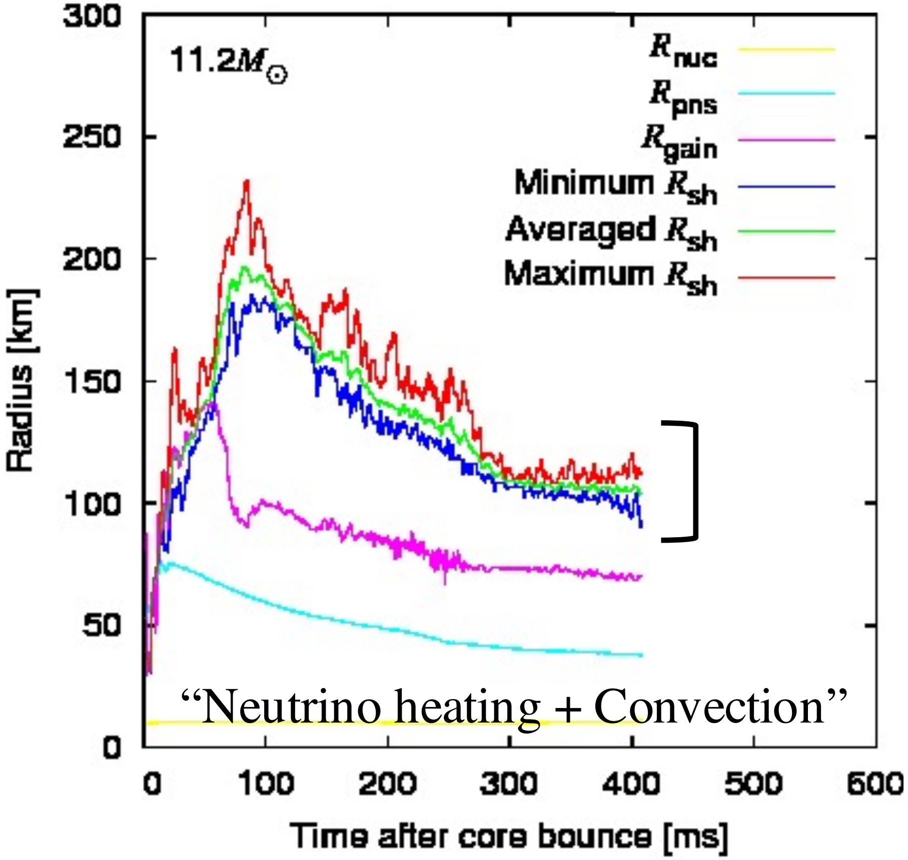
K-Computer, Japan

No explosion found in 2D Hydro+Boltzmann

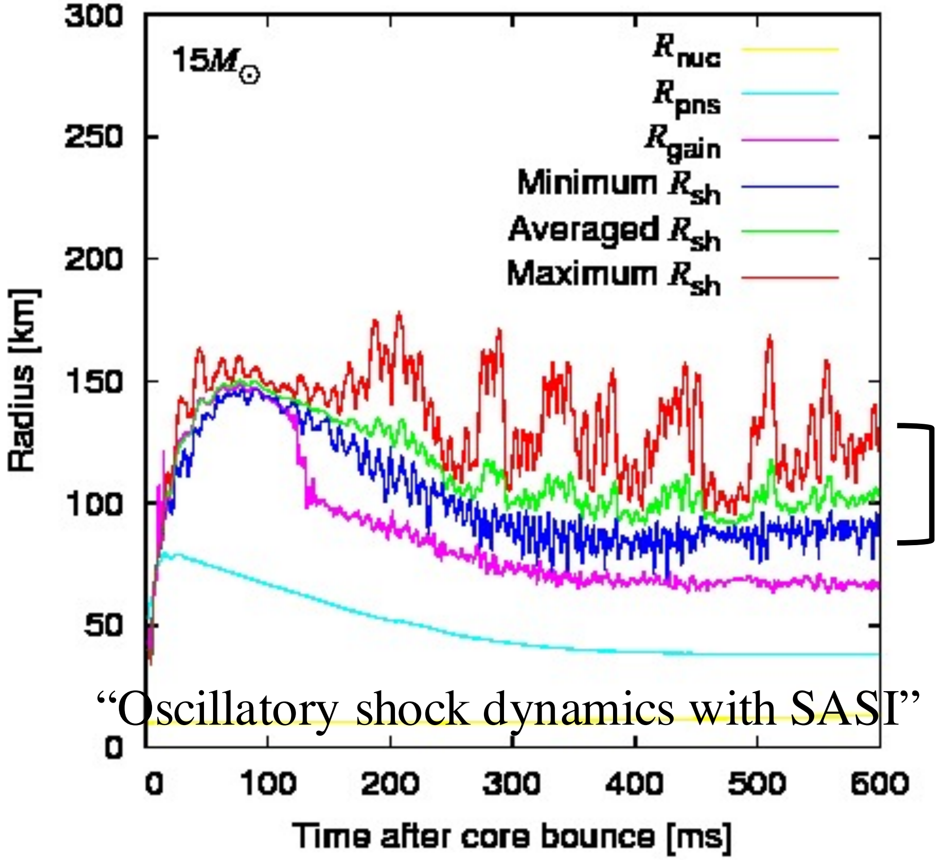
Nagakura, Iwakami et al. (2016)

- No revival of shock in 2 models

Shock position 11.2M_{sun}



Shock position 15M_{sun}



Need further study: Nuclear physics, General Relativity?

Supernova issues: Equation of State

effects on explosion?

EOS table for supernova simulations

- Data covers wide range
  - ρ : $10^{5.1} \sim 10^{16}$ g/cm^3
  - Y_p : $0 \sim 0.65$
  - T : $0 \sim 400$ MeV
- Consistent framework
- Experiments of nuclei
- Observations of neutron stars

Models	Framework	Reference	
Nucleon benchmark 1990's~	Skyrme Hatree-Fock Extended Liquid-Drop Relativistic Mean Field	Wolff-Hillebrandt Lattimer-Swesty Shen	LS-EOS Shen-EOS
Nucleon updates 2000's~	Relativistic Mean Field Nuclear many body	G. Shen, Oertel, Peres Togashi, Constantinou	
Nucleon updates+NSE	Relativistic Mean Field Mixture of nuclei	Hempel, Steiner, Fischer Furusawa	Hempel Furusawa
Nucleon +Hyperon	Relativistic Mean Field Hyperon interactions	Ishizuka Gulminelli, Oertel, Banik	Hyperon
Nucleon +Quark	Relativistic Mean Field Bag model	Nakazato Sagert, Fischer	Quark

Based on Oertel, Hempel, Klaehn & Typel (2016)

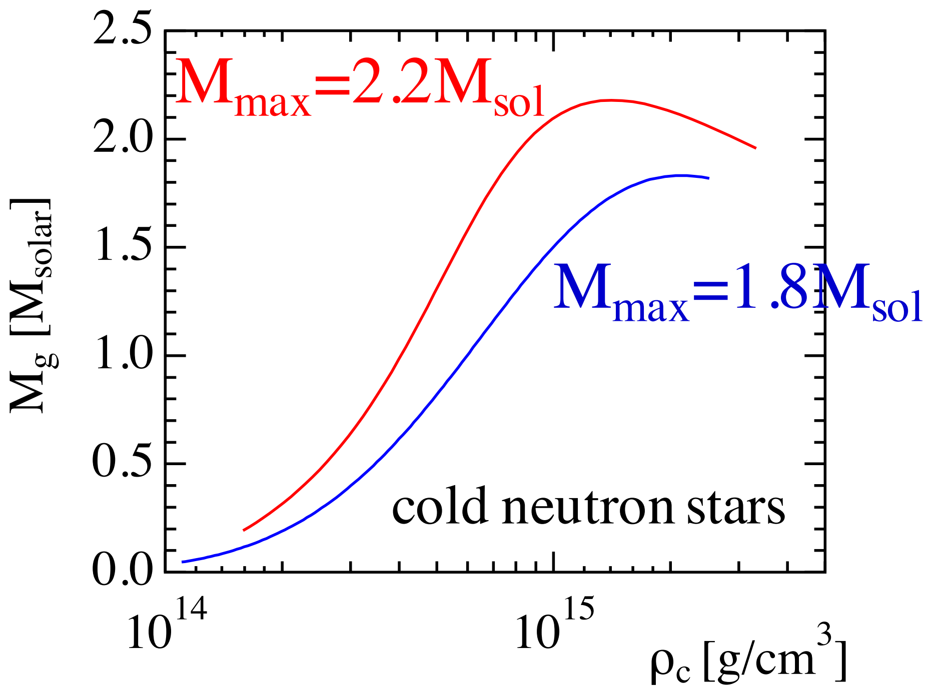
Comparison of EOS sets: benchmark

- Difference in stiffness & symmetry energy

	LS-EOS	Shen-EOS
K [MeV]	180, 220, 375	281
A_{sym} [MeV]	29.3	36.9

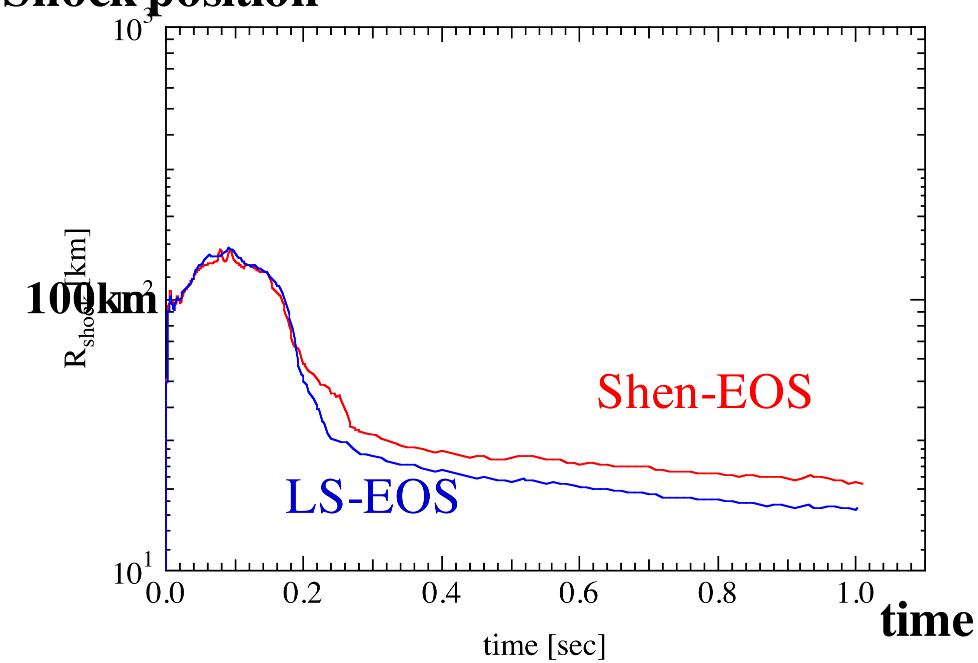
- Two representatives
- Extremes in modern sense

180, 220: Frequently used for many simulations



Sumiyoshi (2004)

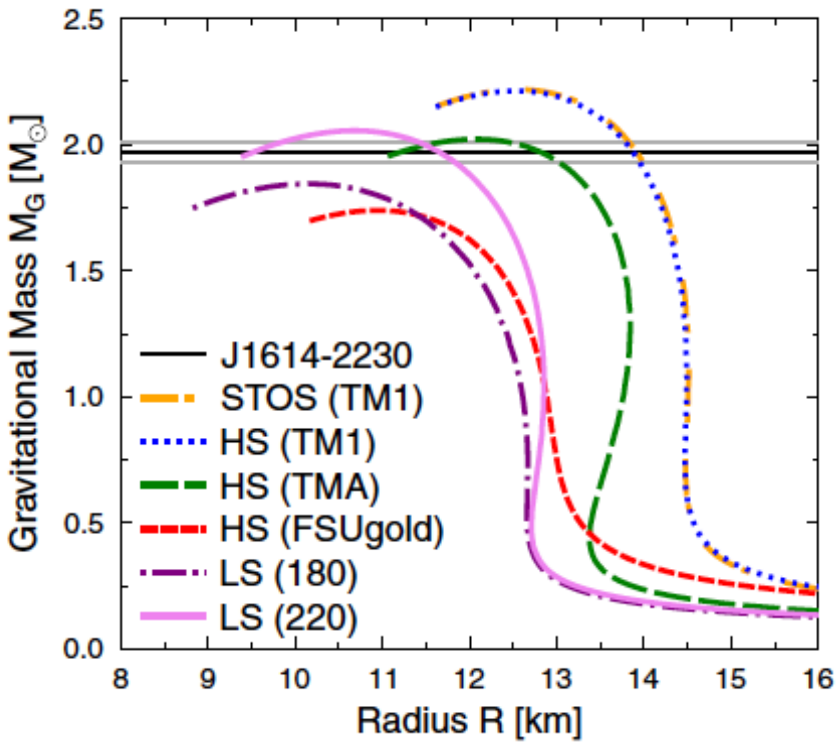
Shock position



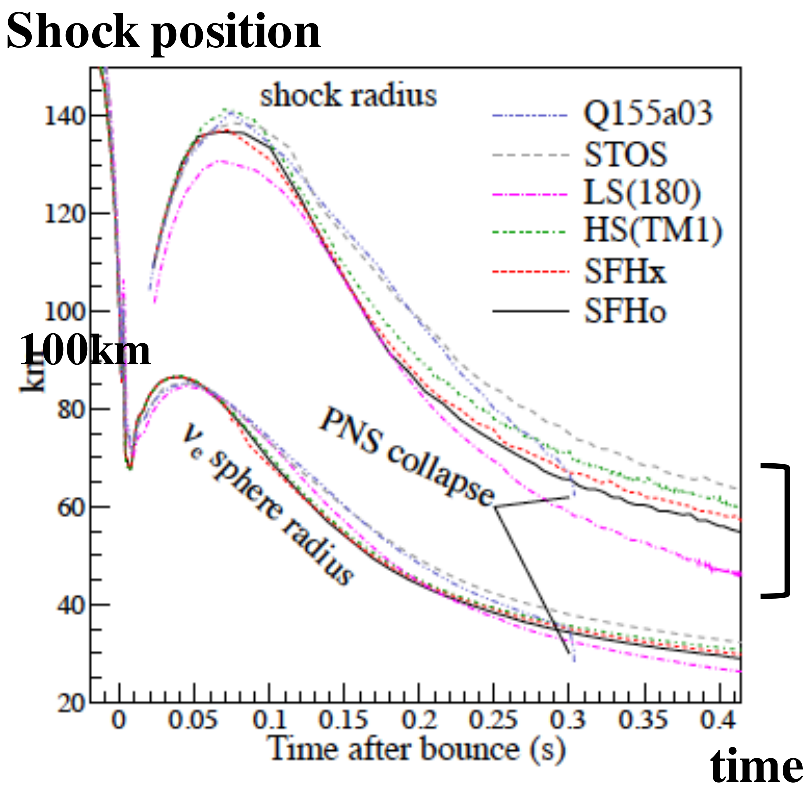
$15M_{solar}$ Sumiyoshi et al. (2005)

Comparison of EOS sets: more recent

- Choice of nuclear interaction (stiffness, radius, …)
- No explosion with various EOS tables



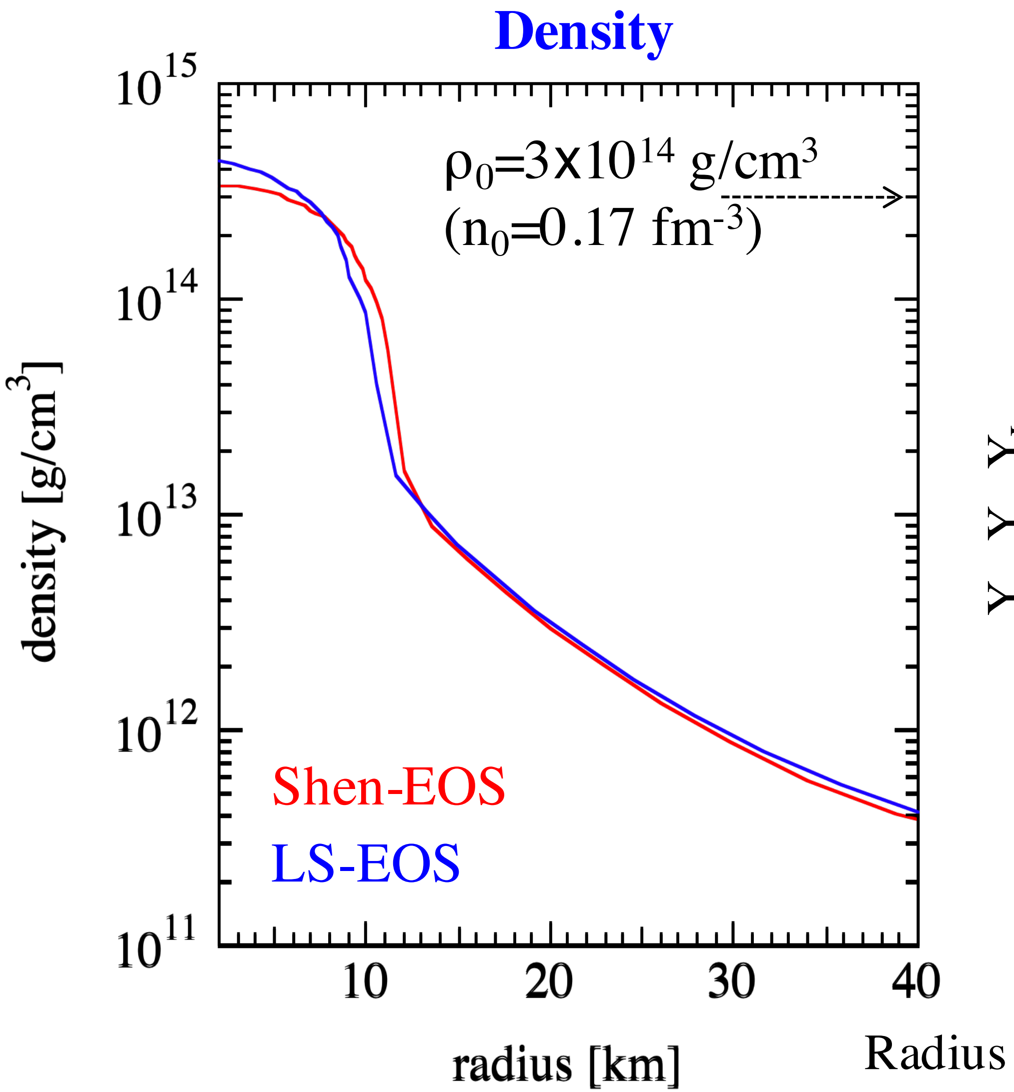
Hempel (2012)

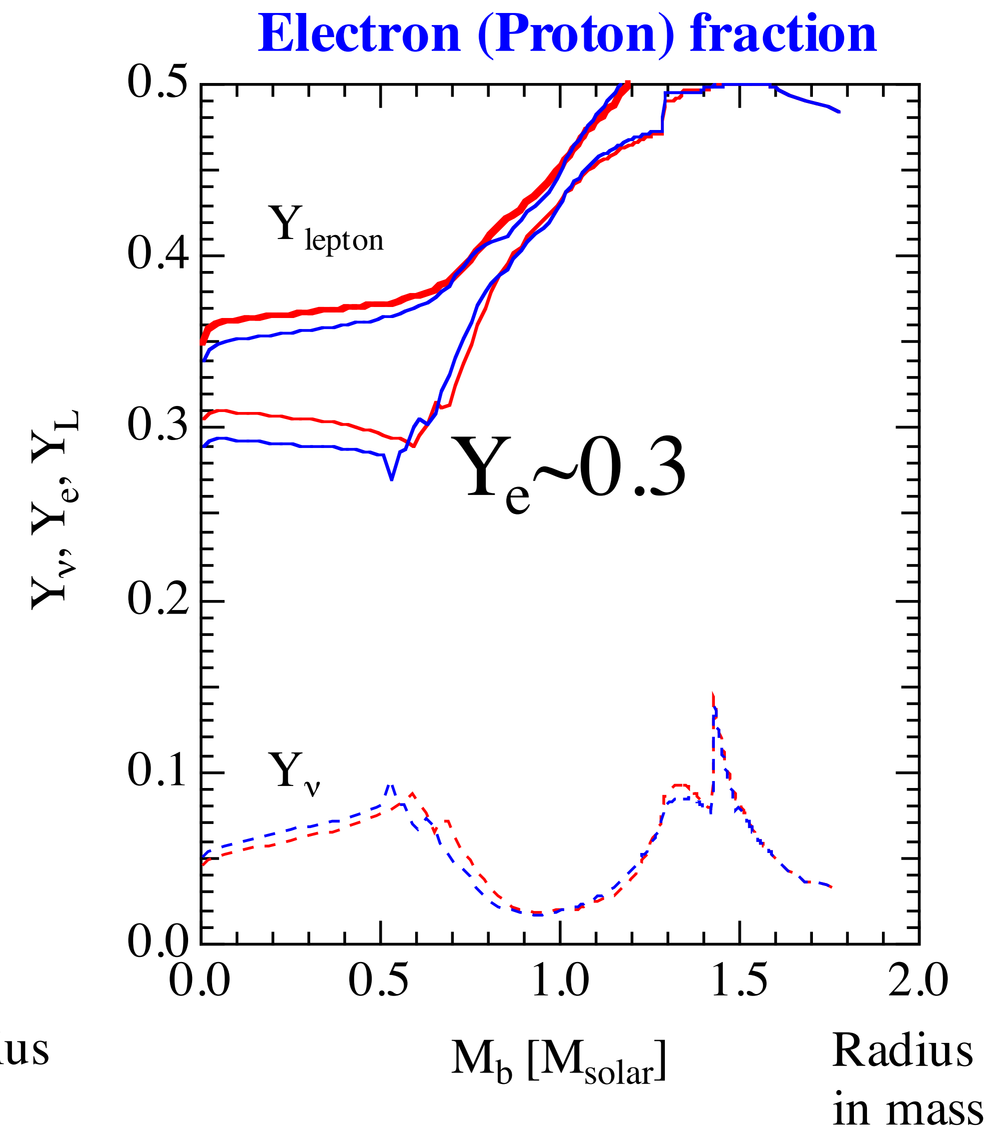


$11.2M_{solar}$ Steiner et al. (2013)

Supernova profiles at core bounce: t_{pb}=0 ms

ρ: just above ρ_0, T~10 MeV, Y_p: not so neuron-rich yet



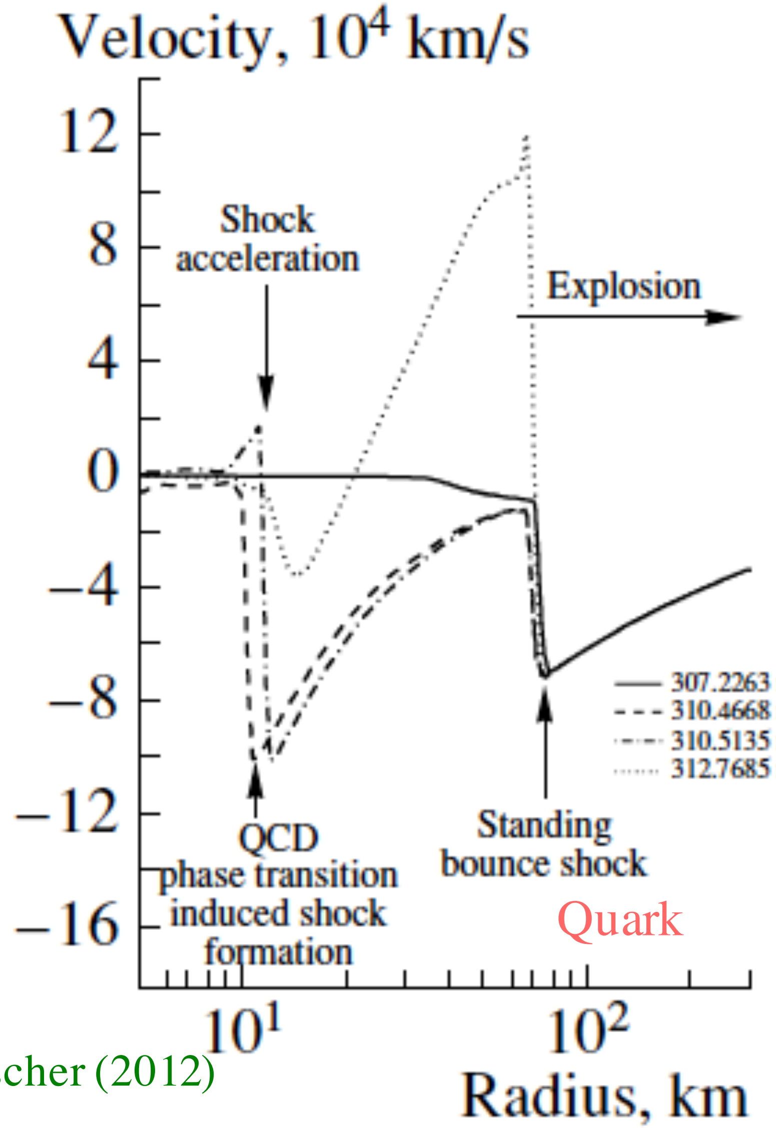


Sumiyoshi et al. ApJ 629 (2005) 922.

Explosion with quark EOS

Sagert (2009), Fischer (2012)

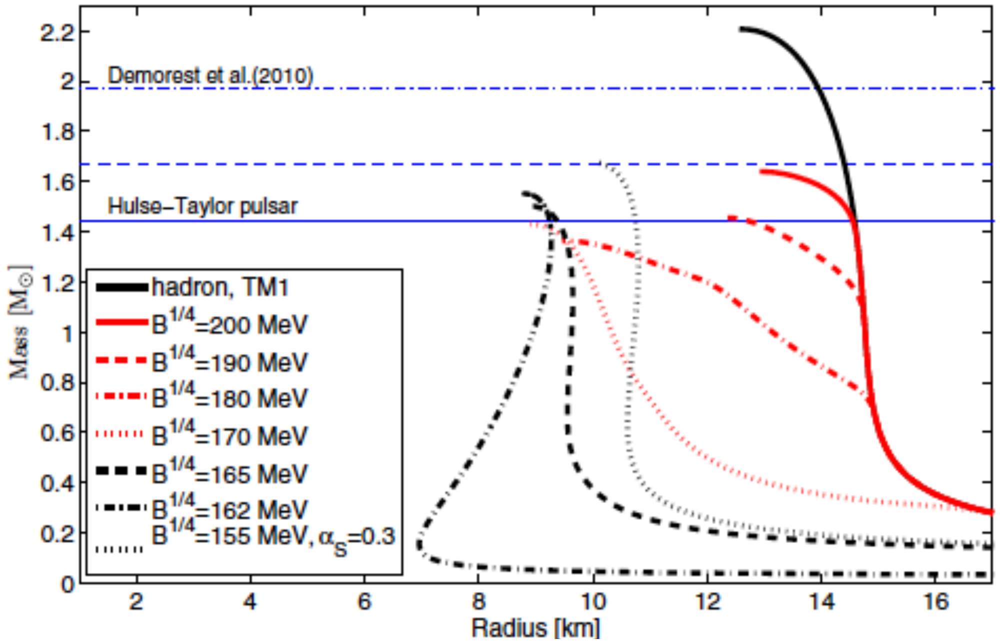
- 2nd collapse & bounce

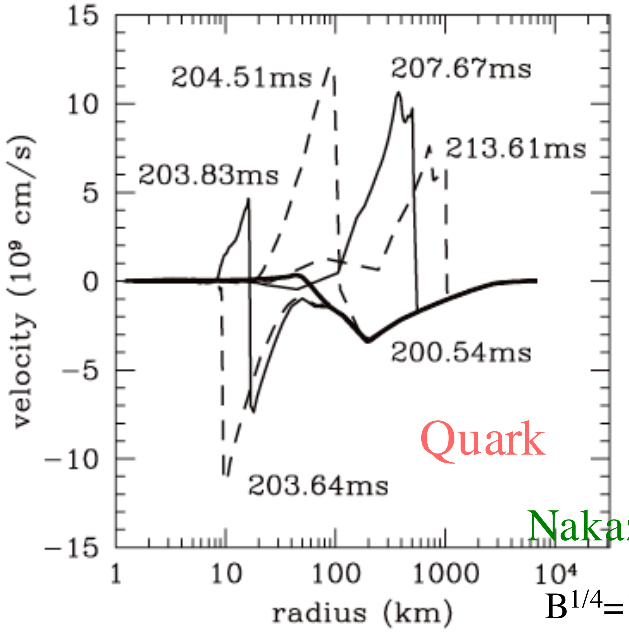


Fischer (2012)

$B^{1/4}$=155 MeV, α_s=0.3

Neutron star mass and radius



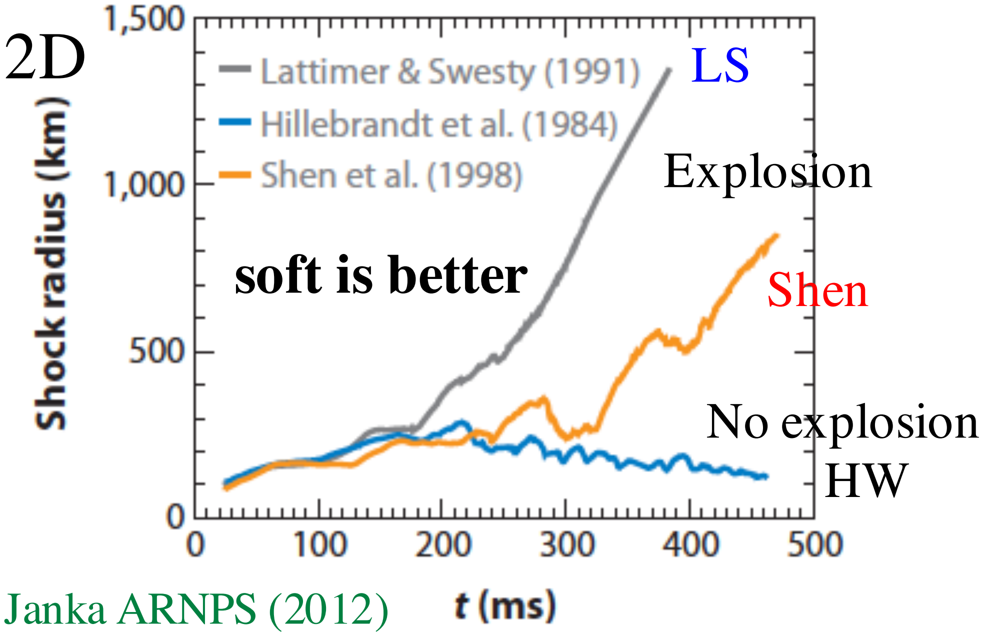


But for Soft EOS

Nakazato (2013)

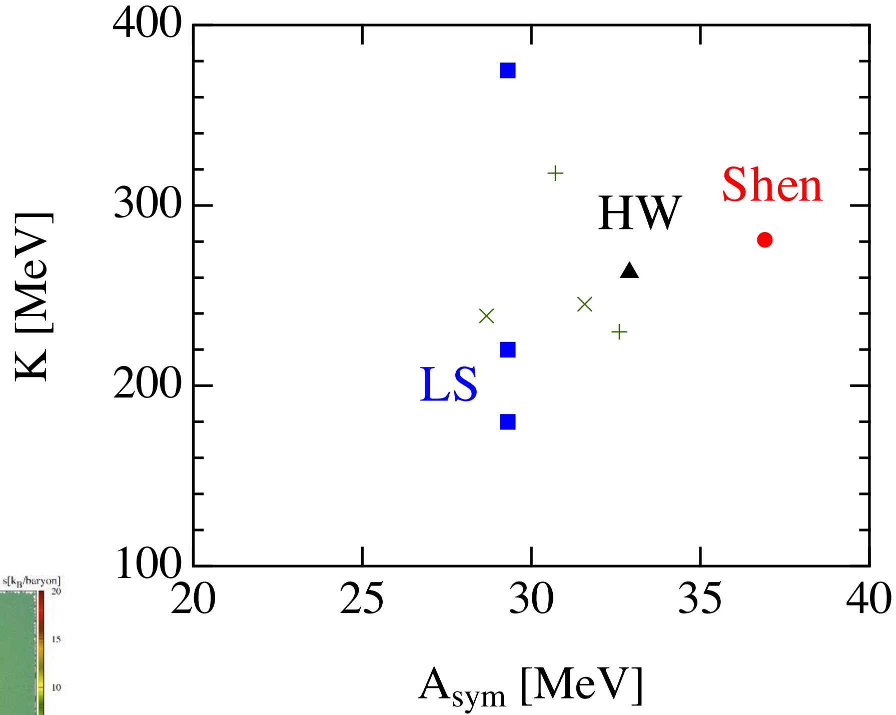
$B^{1/4}$=162 MeV

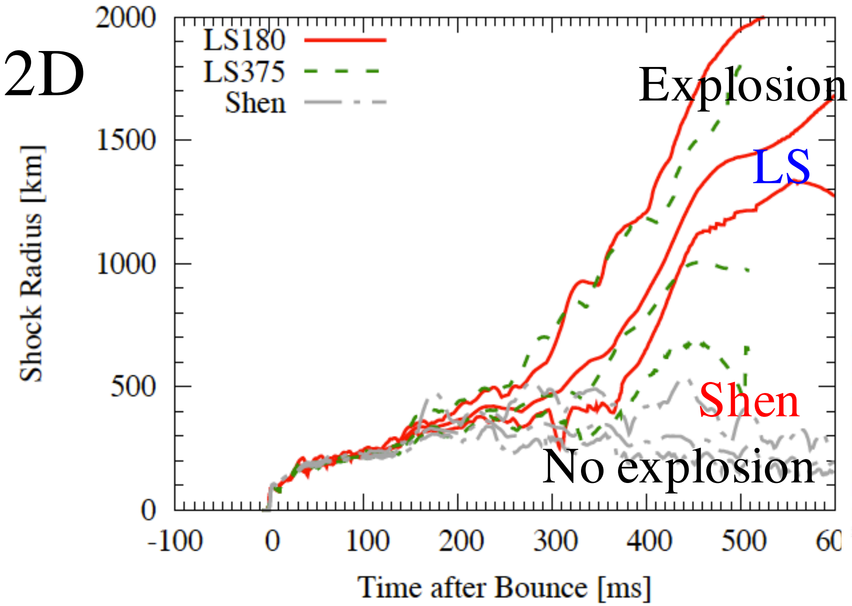
EOS effects in multi-D: larger than 1D?

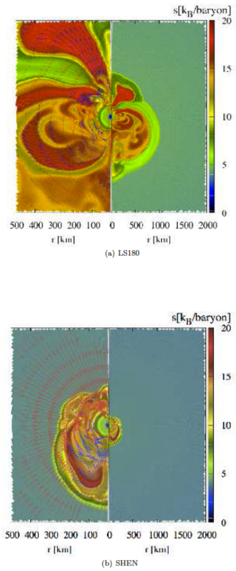


Janka ARNPS (2012)

Need more systematic studies







Suwa et al. ApJ (2013)

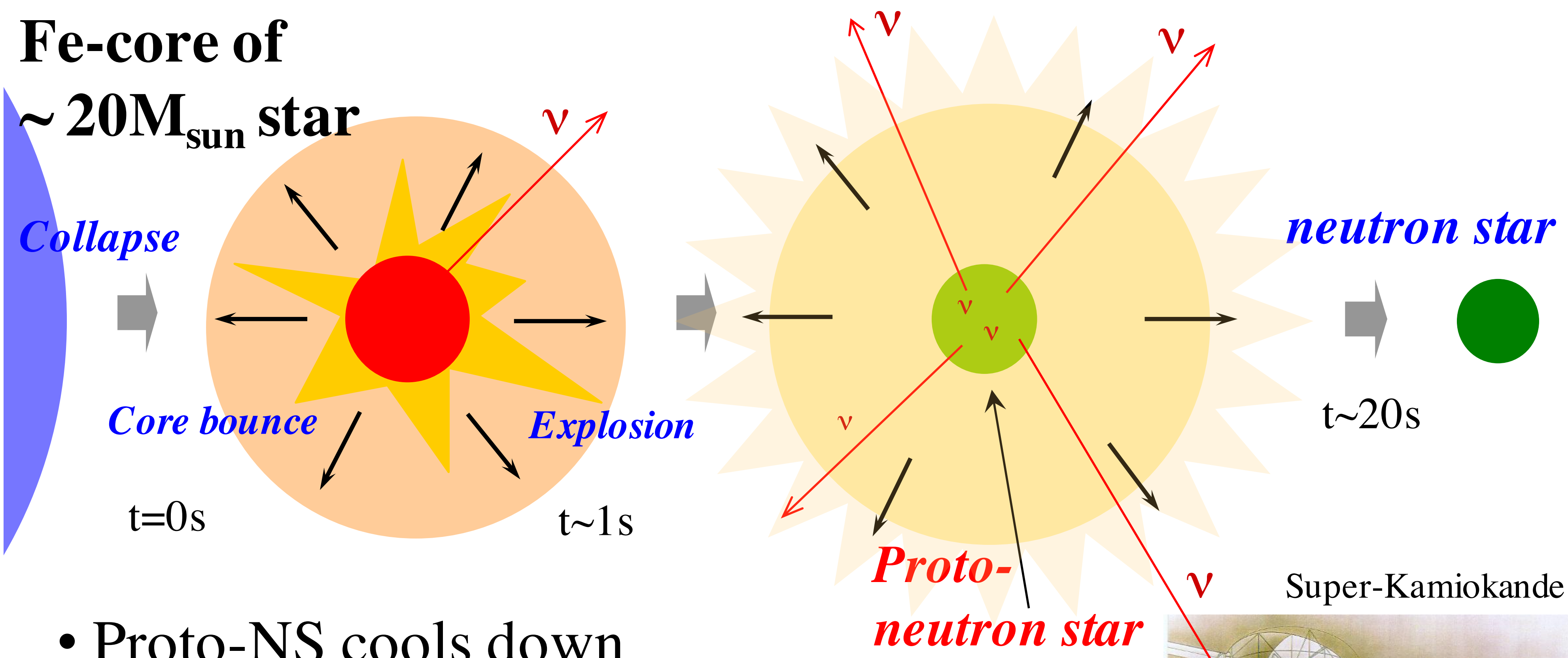
In 3D, LS 220MeV so far

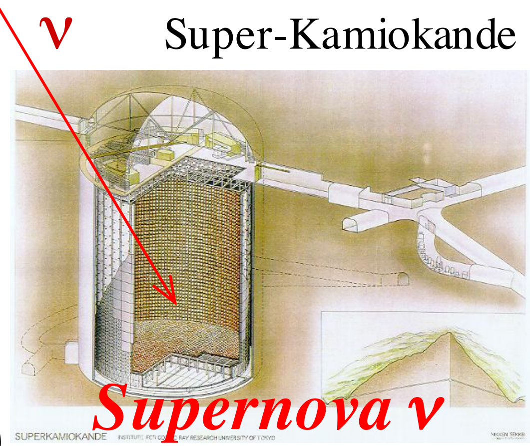
Takiwaki (2012), Hanke (2013), Bruenn (2014), Lentz, Melson (2015) Robert (2016)

Neutrino burst to probe EOS

Proto-neutron star vs black hole formation

Supernova neutrinos as a probe EOS





- Proto-NS cools down
  by emitting 10^{57} ν in ~20 sec

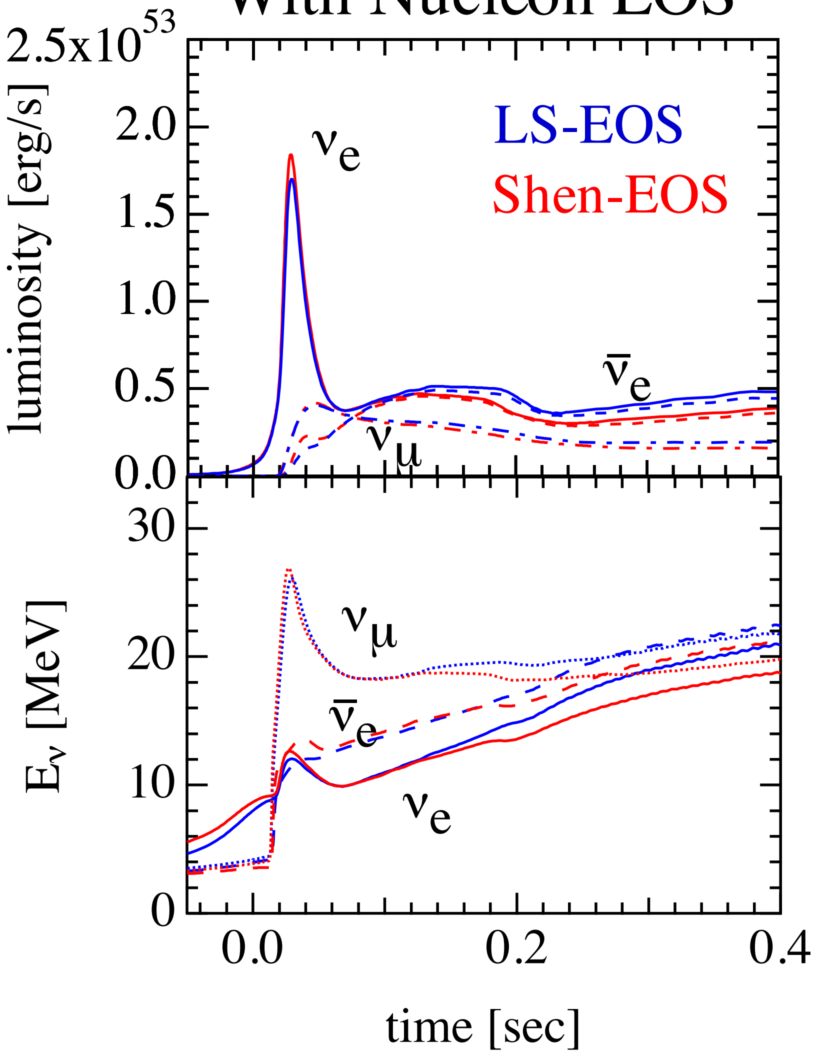
- a next Galactic SN: 10^4 ν (SN1987A: 11 ν)

- ν emitted from hot and dense matter (EOS)

Neutrino bursts after core bounce

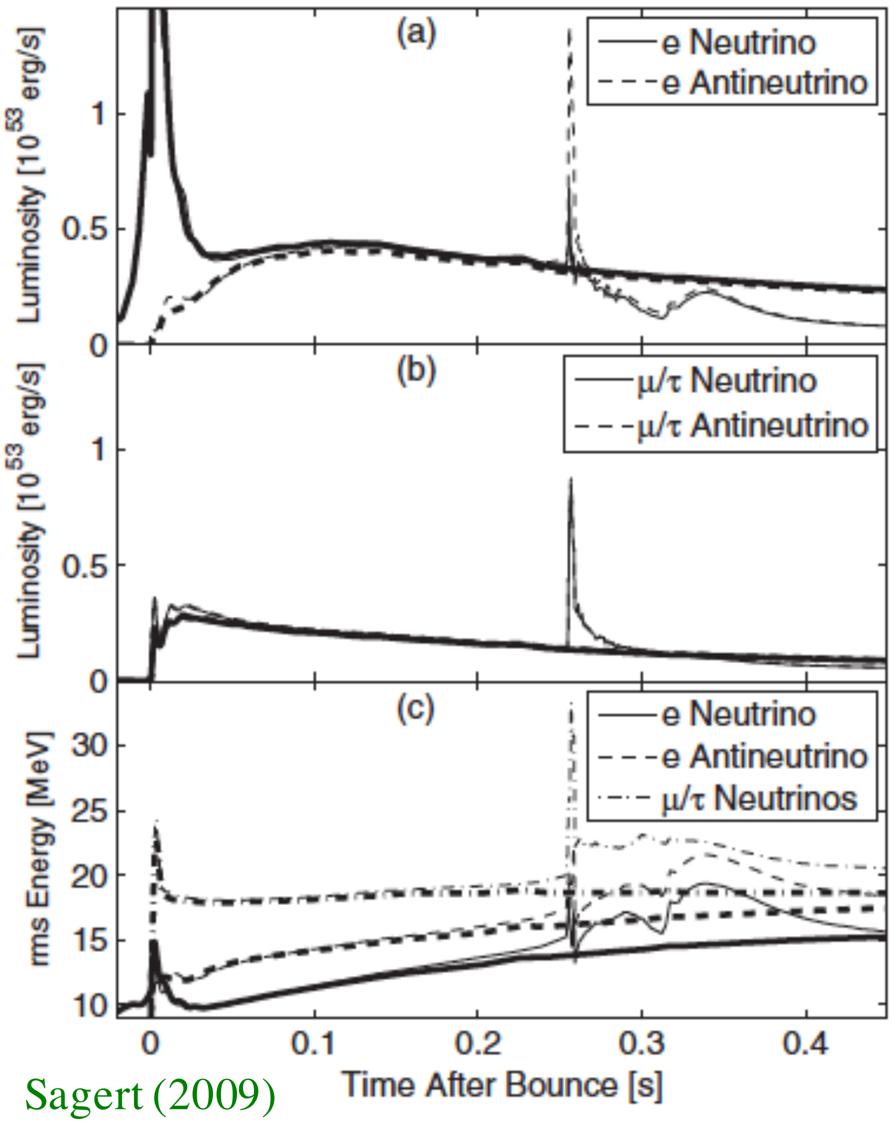
- Reflects EOS stiffness and composition

With Nucleon EOS



Sumiyoshi et al. (2005)

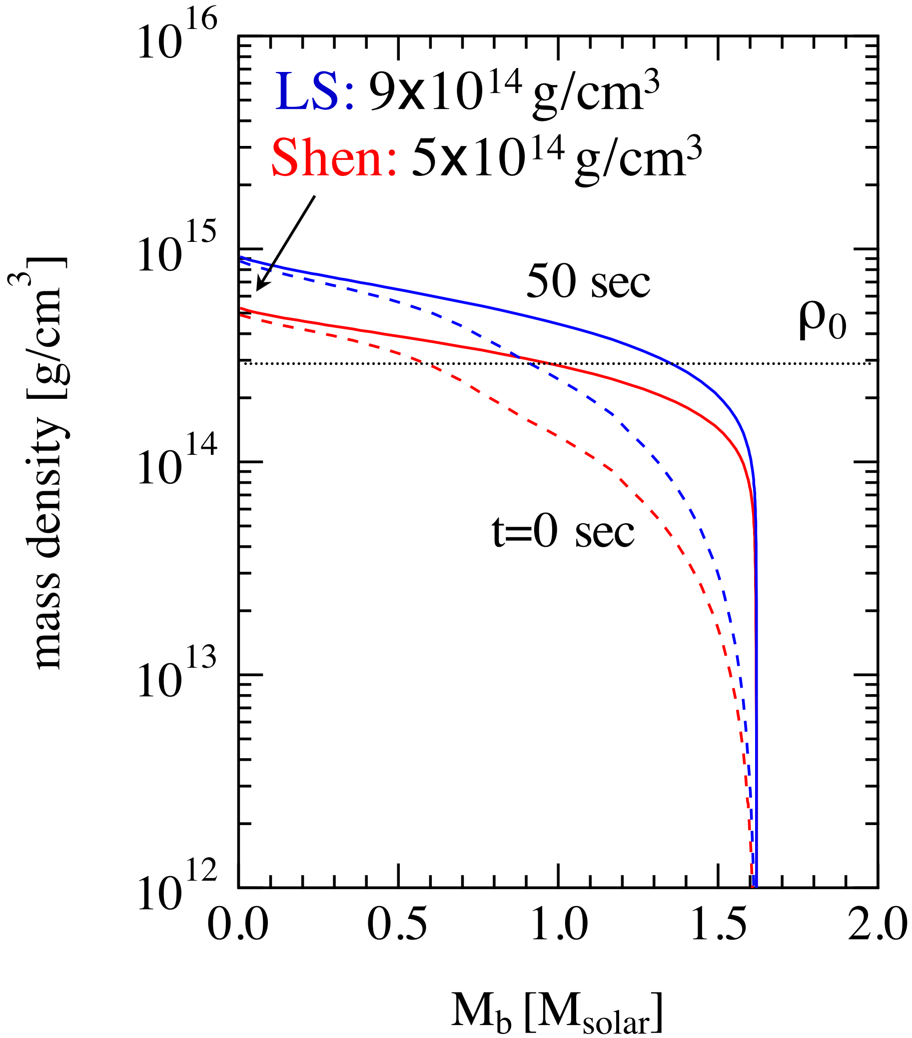
With Quark EOS

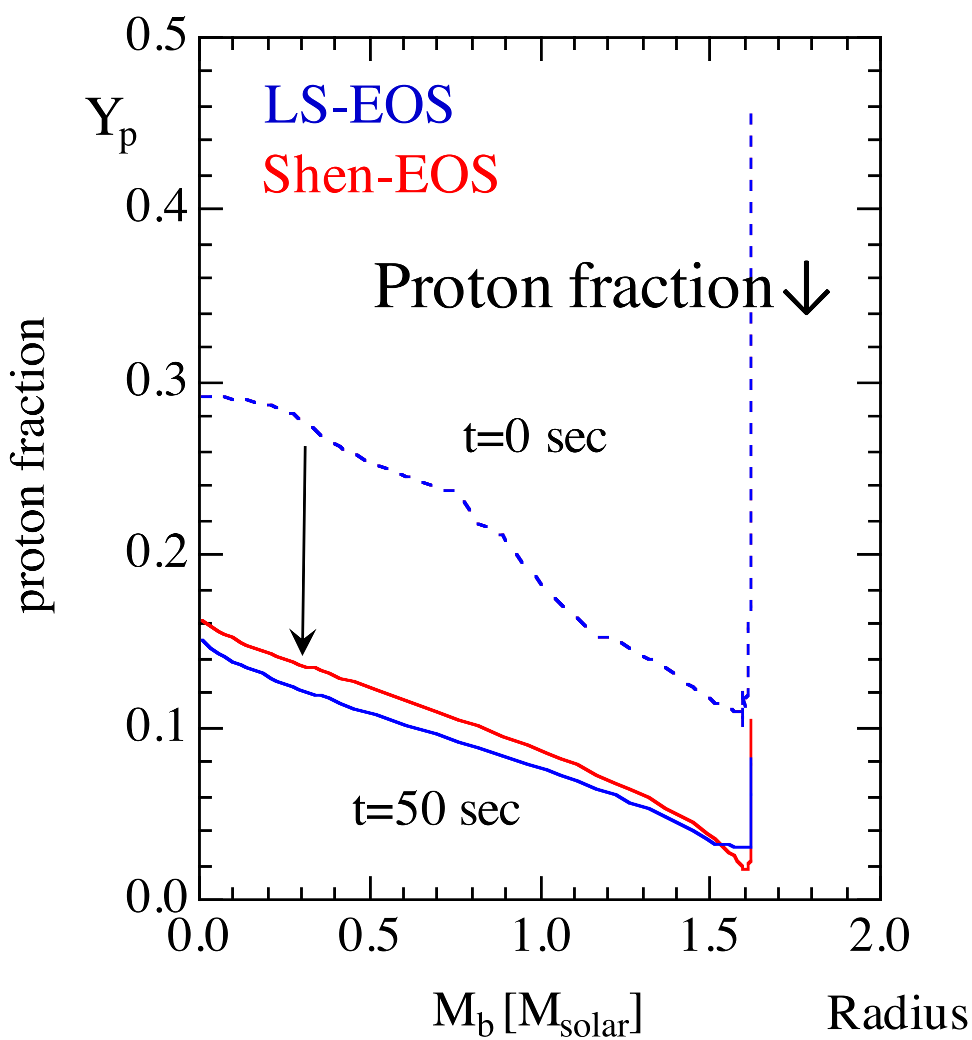


Sagert (2009)

EOS differences appear in proto-neutron stars

Trapped neutrinos escape ⇒ pressure↓, density, temperature↑



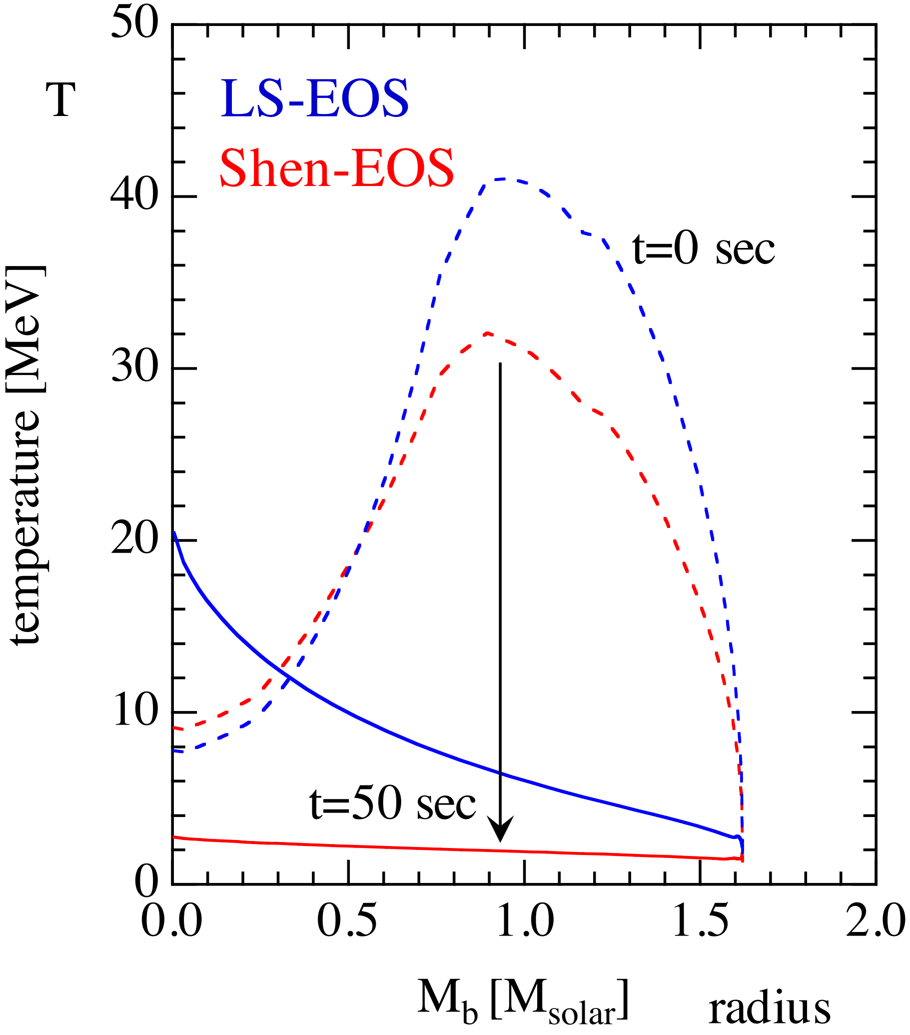


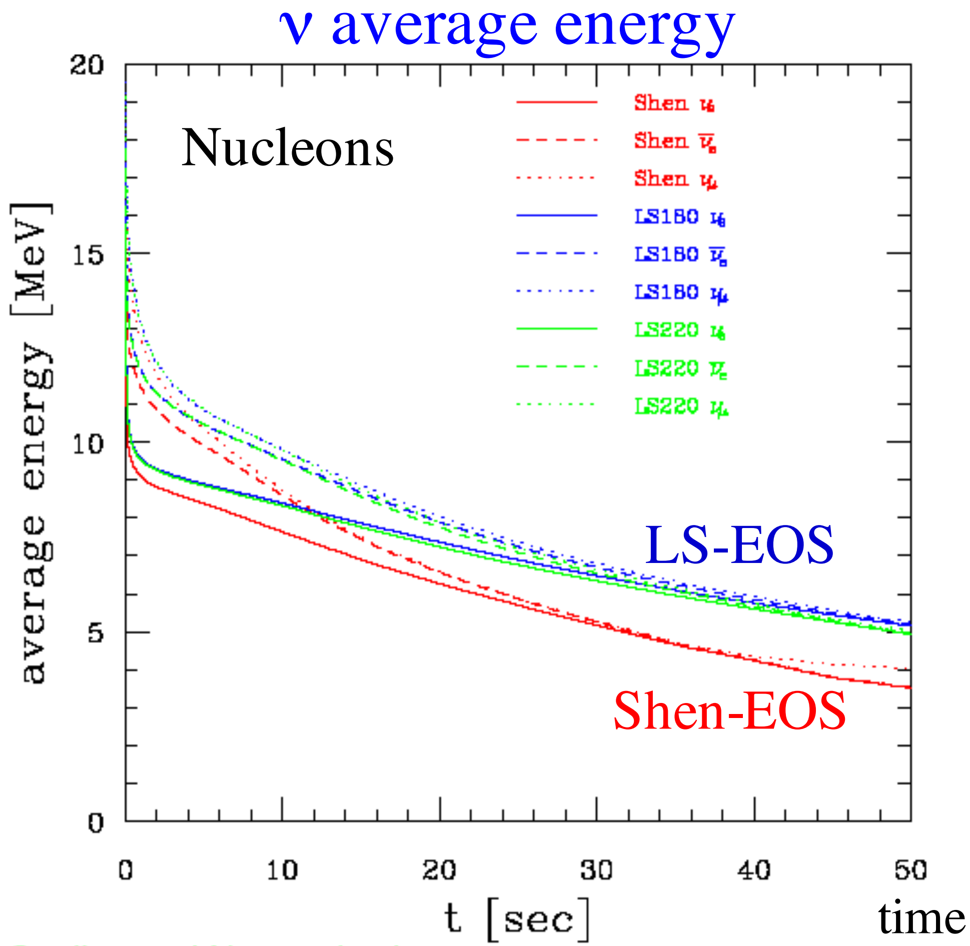
Sumiyoshi et al. A&A (1995)
H. Suzuki (2005)

Proto-NS cooling Simulation started from t_{pb}=0.4 sec

Supernova ν from proto-neutron star

Temperature difference ⇒ Average energy difference





Last for ~20s, E_ν, L_ν decrease

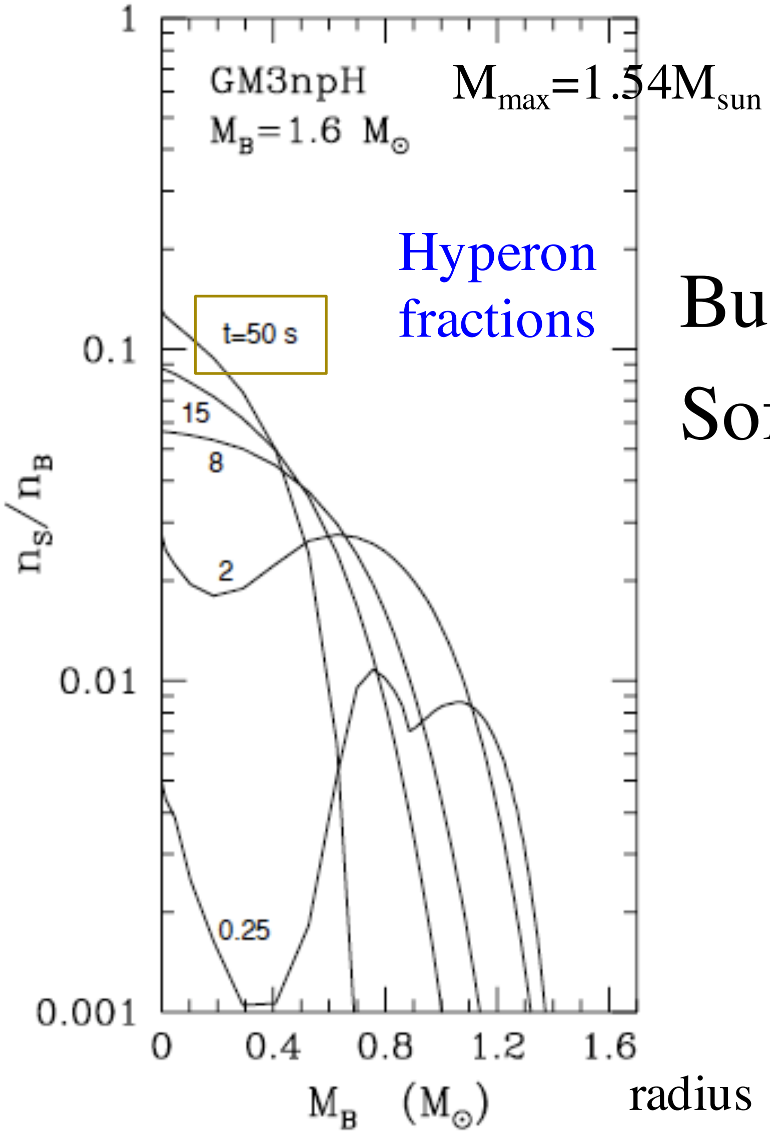
Sumiyoshi et al. A&A (1995), H. Suzuki (2005)

Suzuki, Ono, Sumiyoshi, Yamada (2004)

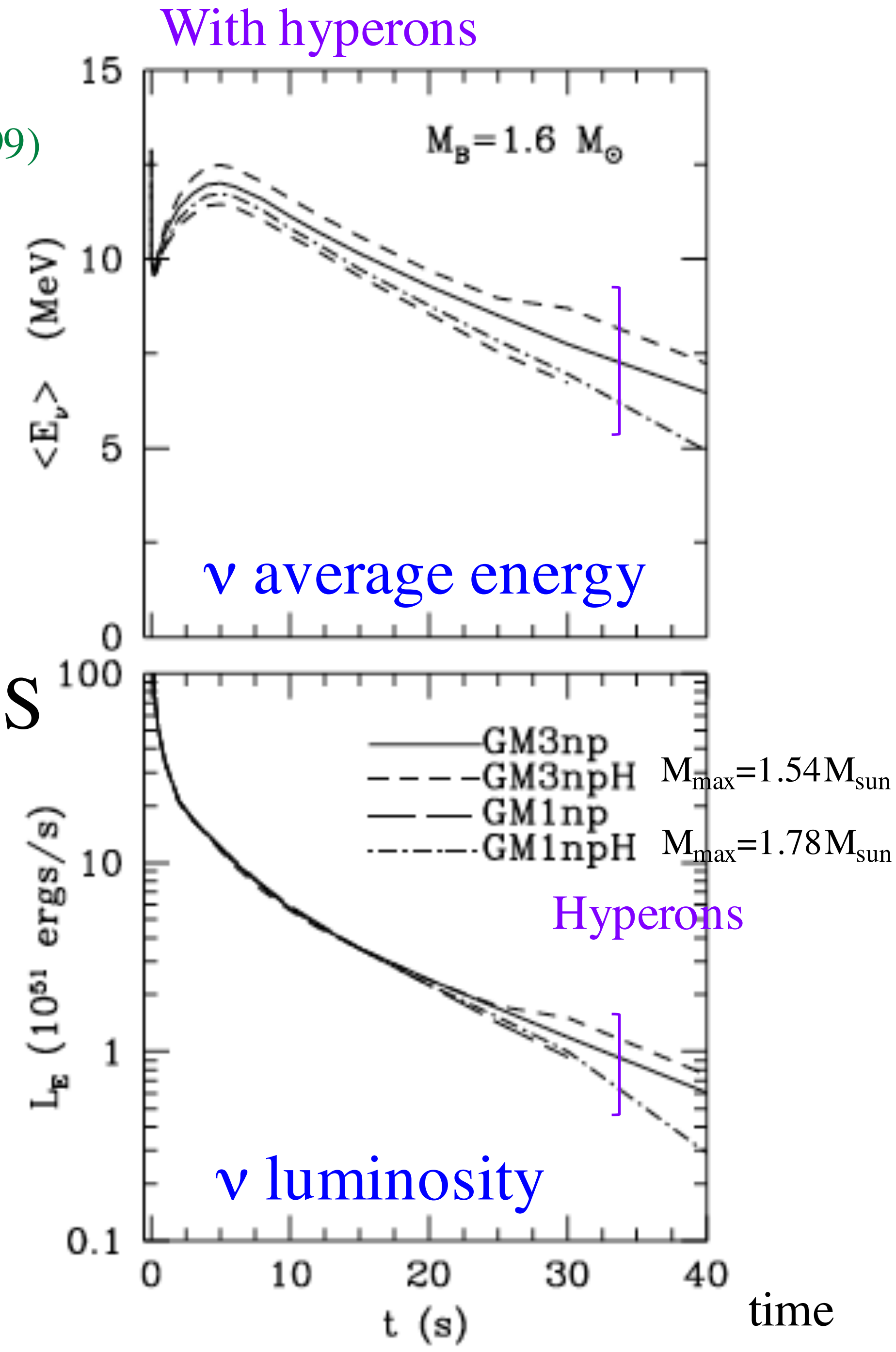
Hyperons in proto-NS

Pons et al. ApJ (1999)

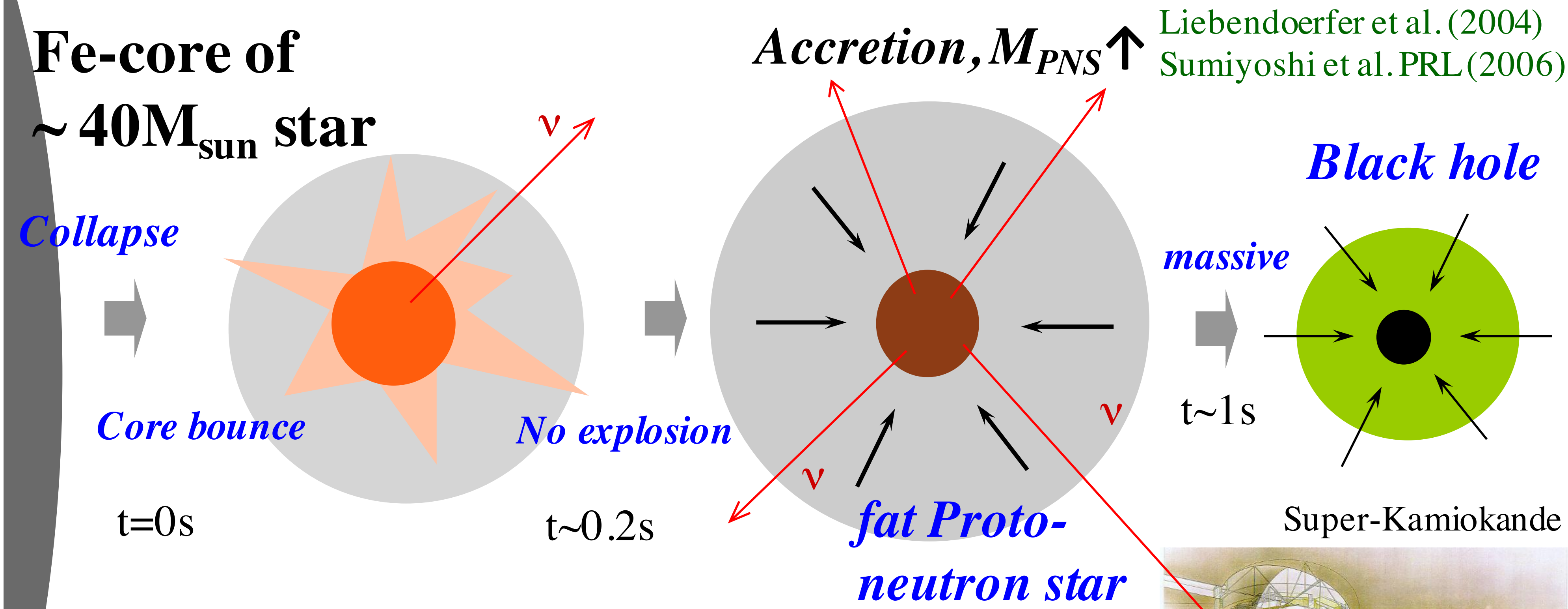
appear late at ~50s

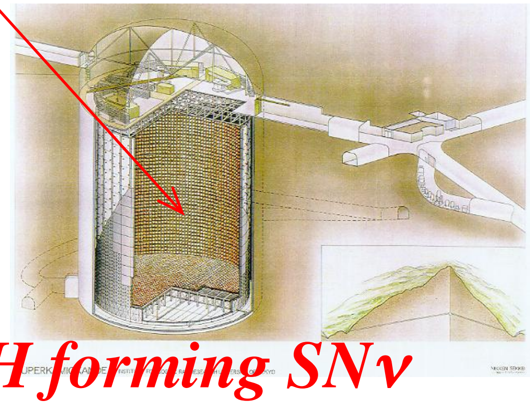


But for Soft EOS



More massive stars lead to black holes

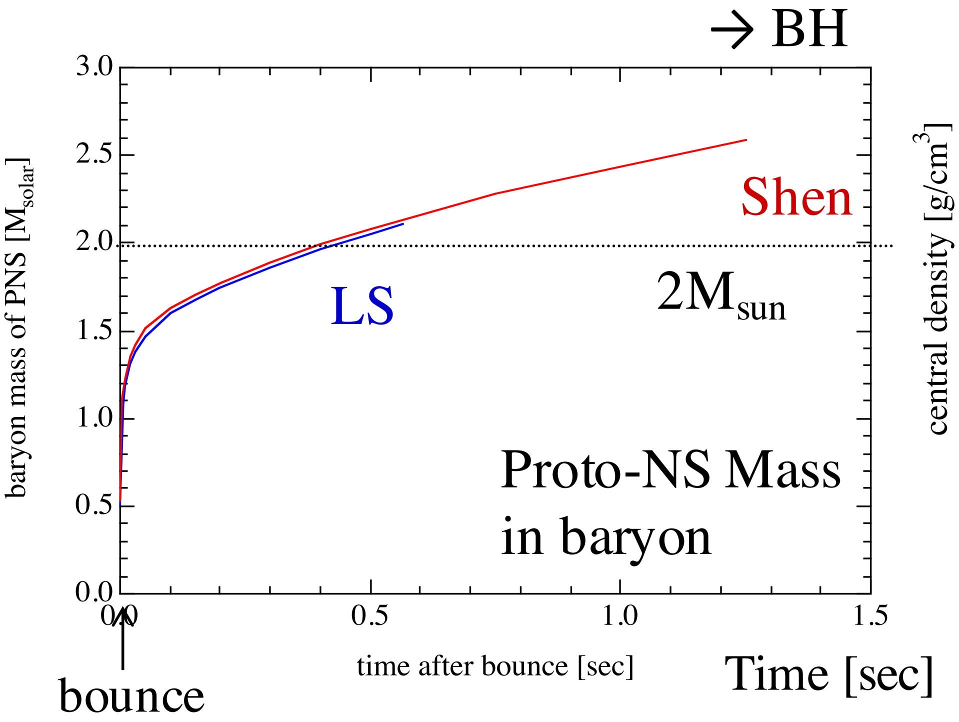


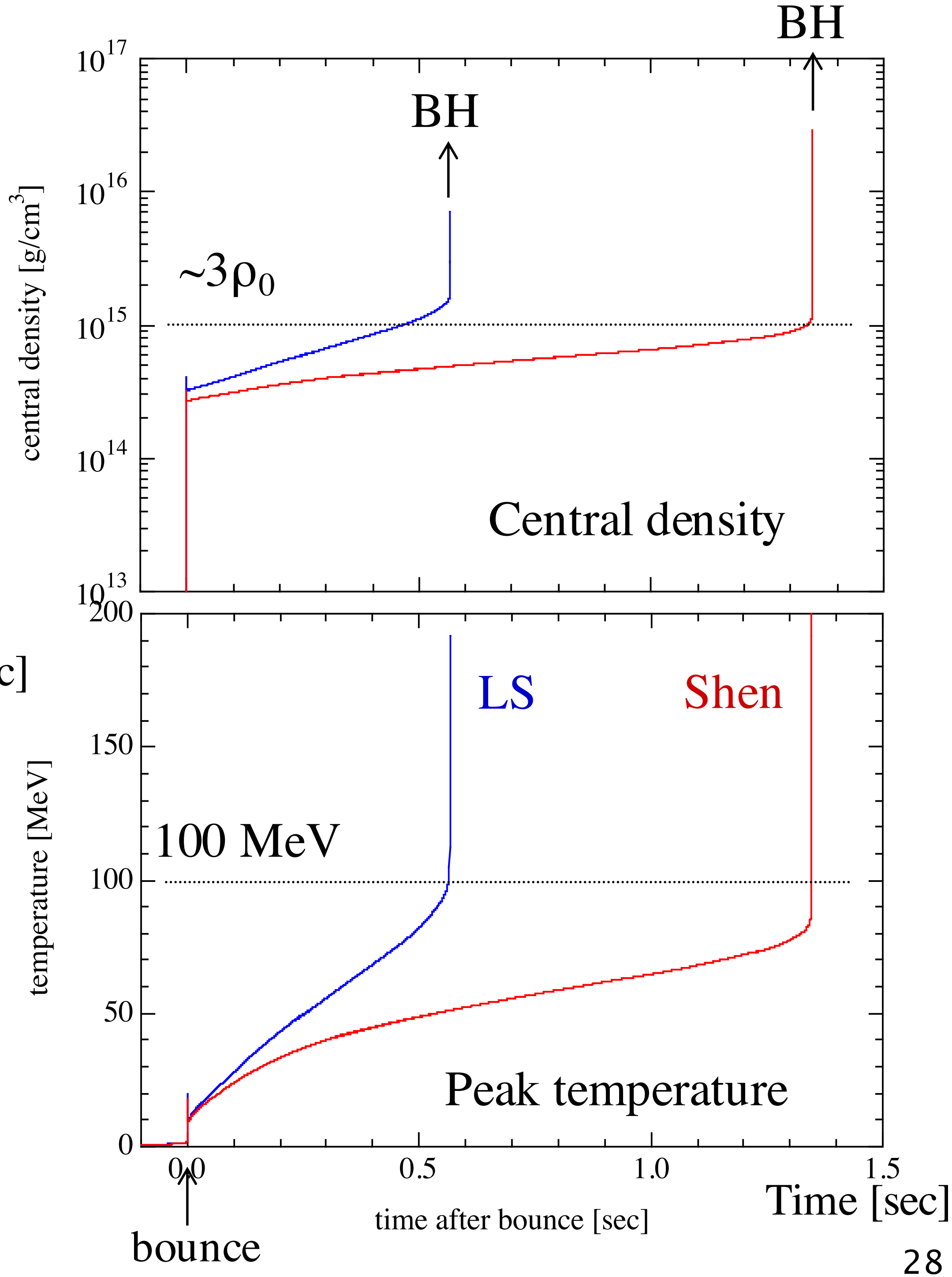


A Galactic case: 10^4 ν

- Massive proto-NS to black hole in ~1s
- No display, but neutrino burst
- Chance to see black hole formation
- Probe of EOS at high ρ and T

proto-NS becomes massive





Extreme conditions:

– density > ~3ρ_0

– temperature > 100 MeV

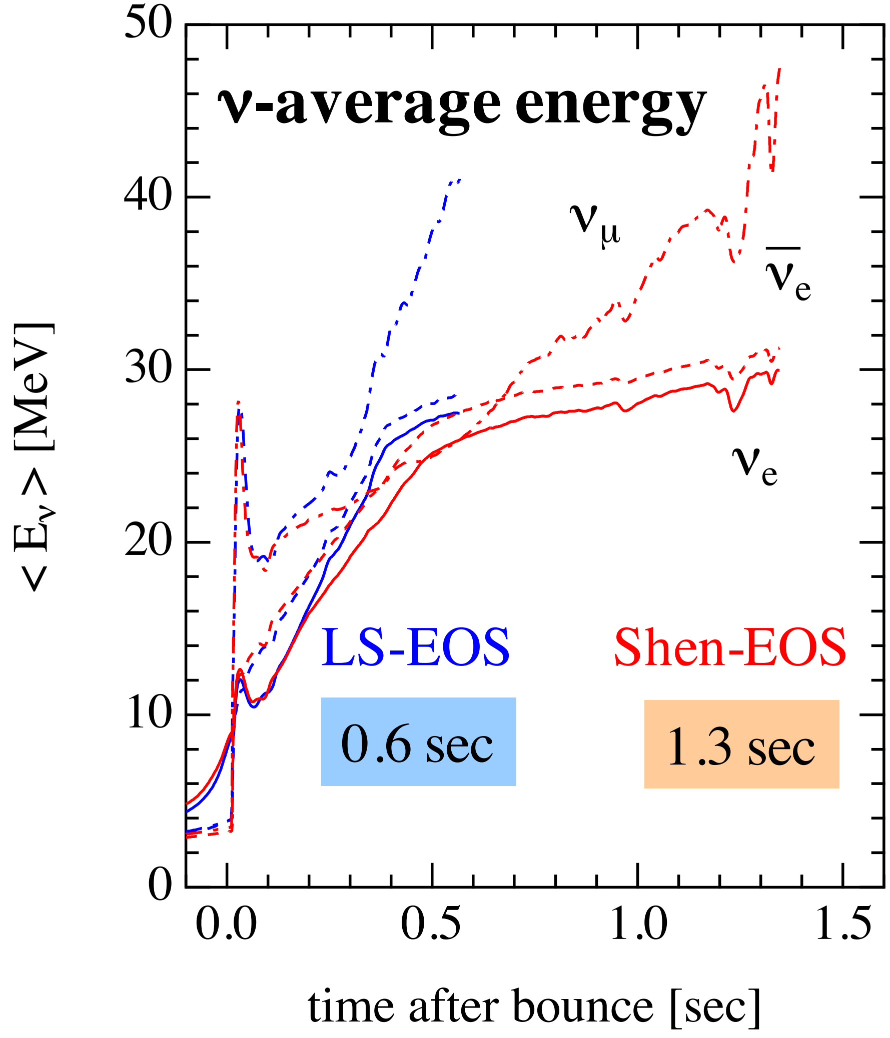
before black hole formation

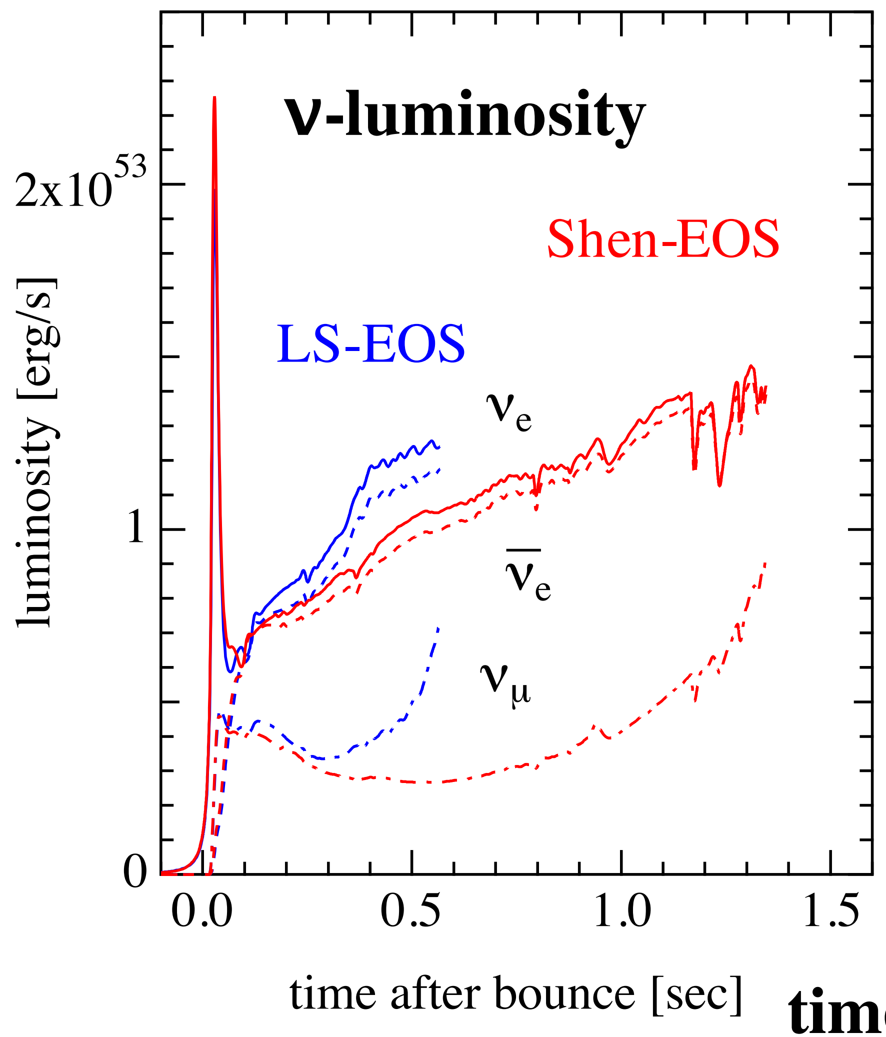
- Exotic phase may appear
  - hyperon, quarks

Sumiyoshi et al. ApJ 2007

Neutrino emission till black hole formation

Short duration (~1s) **E_ν, L_ν increase**





time

Soft EOS → Early Collapse

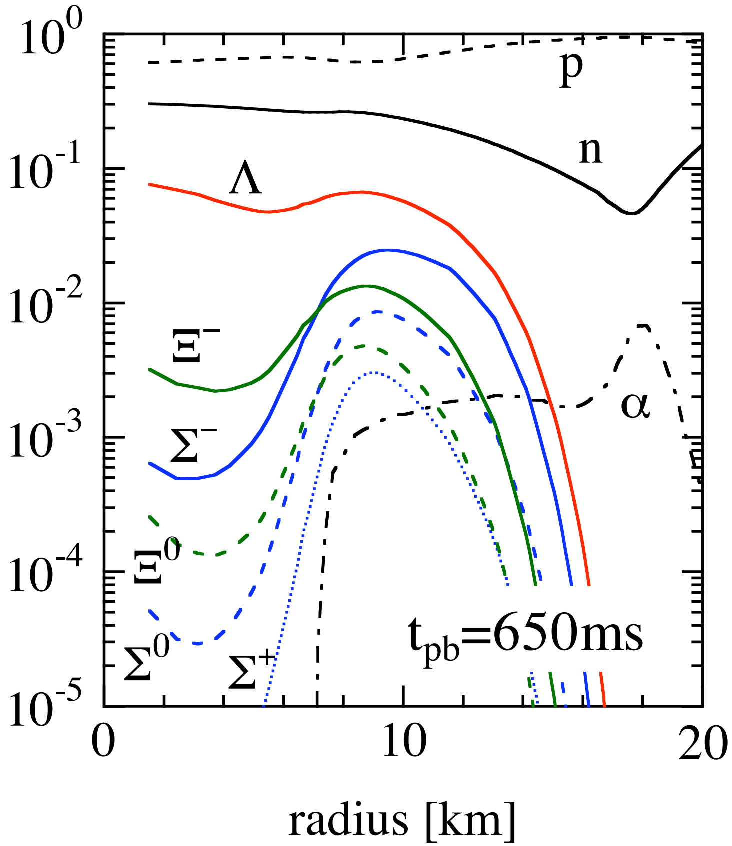
$40M_{sun}$

Sumiyoshi et al., ApJ (2007)

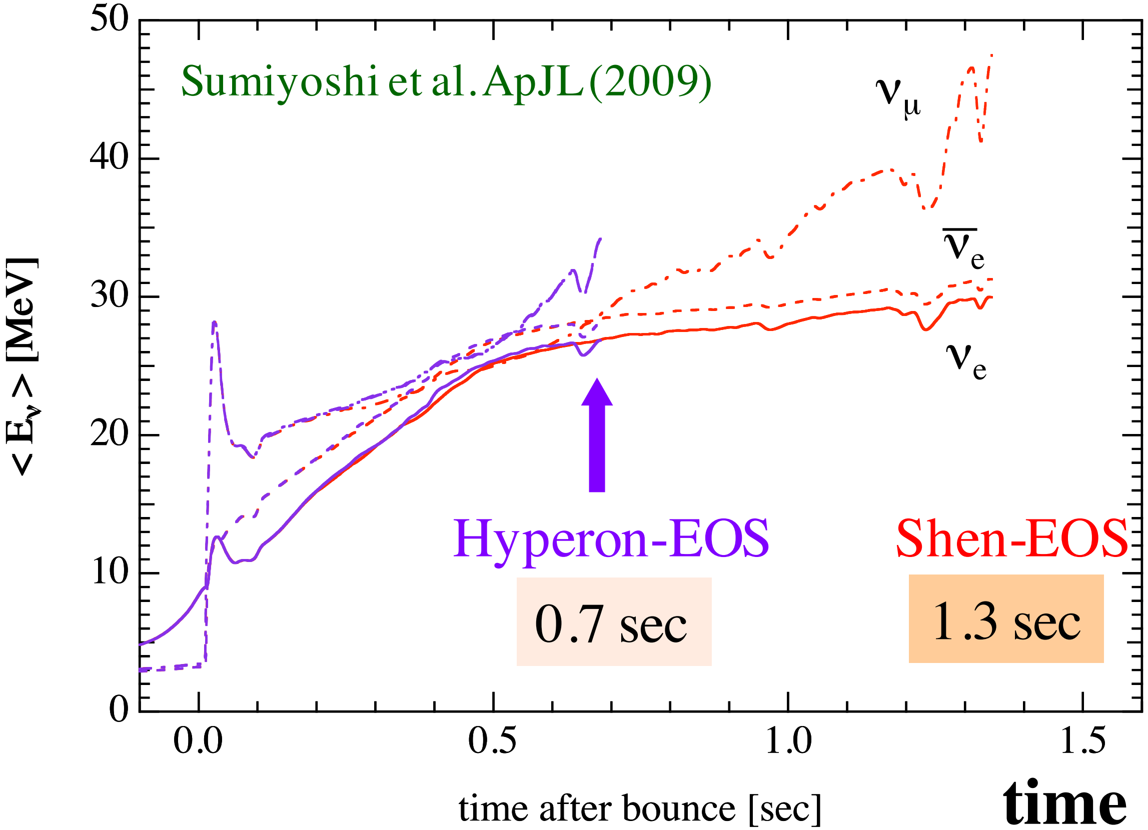
Hyperons appear at high ρ and T

- Exotic phase triggers the re-collapse to black hole

Composition inside proto-NS



ν-average energy



time

- Probe exotic matter by neutrinos (but for soft EOS)

Hyperon-EOS: $M_{NSmax}=1.6M_{sun}$

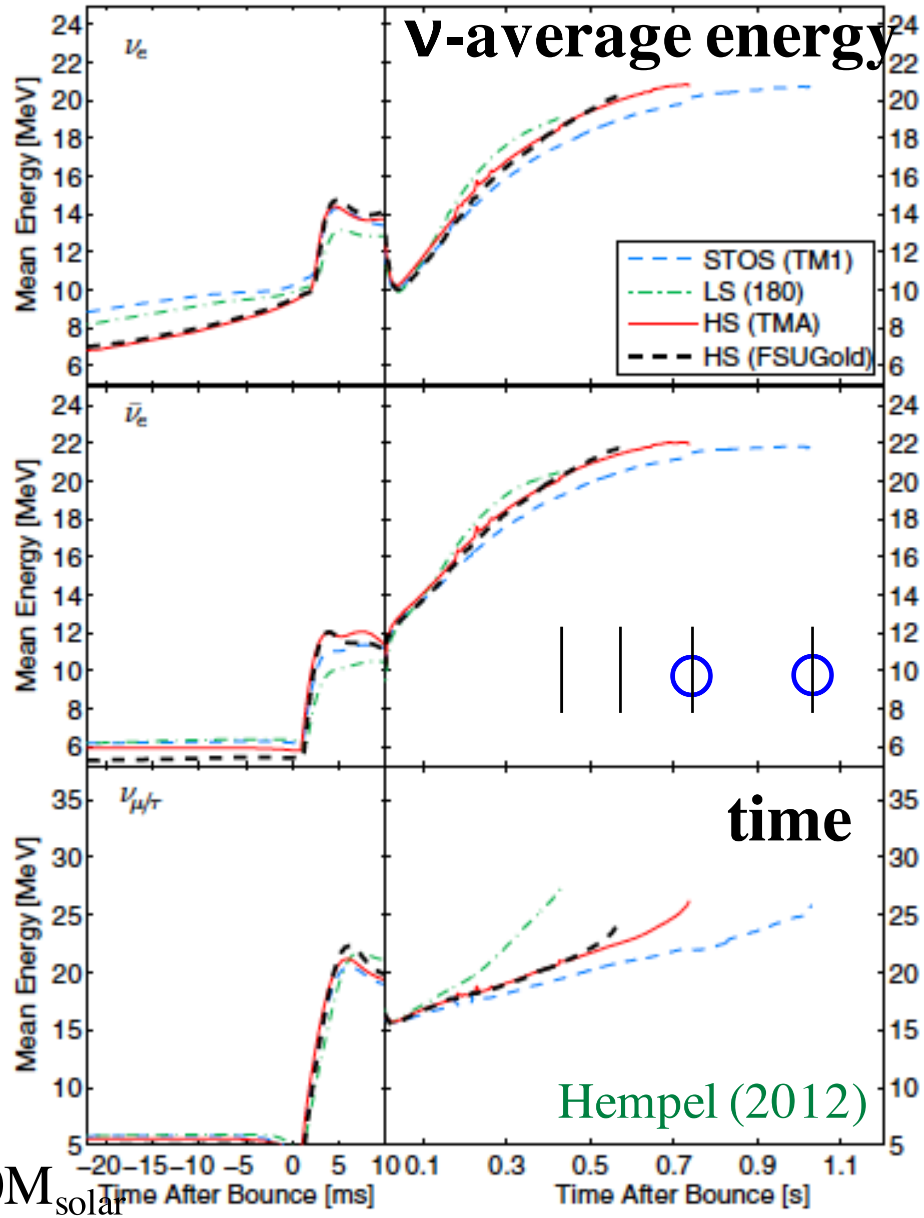
$40M_{solar}$

Sumiyoshi et al., ApJL (2009), Nakazato et al. PRD (2010)

Difficult to distinguish?

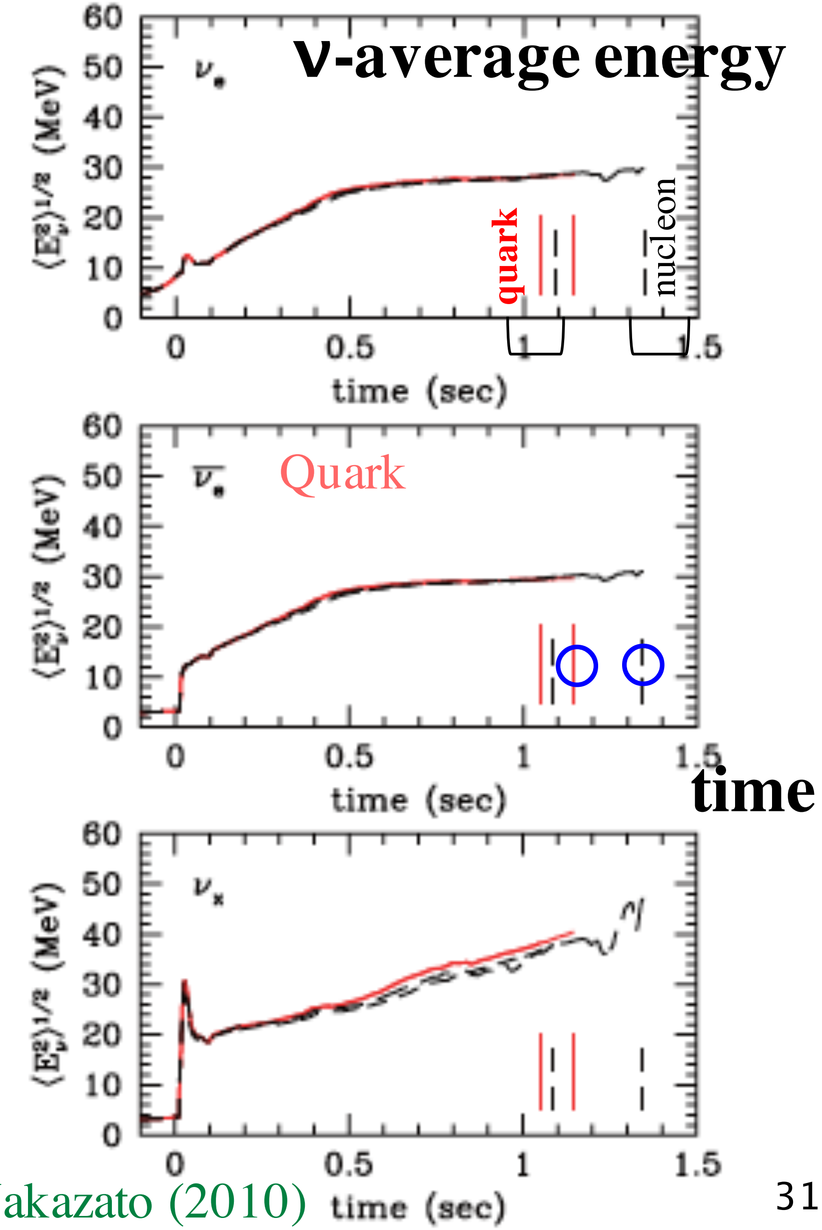
EOS with NS $2M_{sun}$ ○

With Nucleon EOS



$40M_{solar}$

With Quark EOS



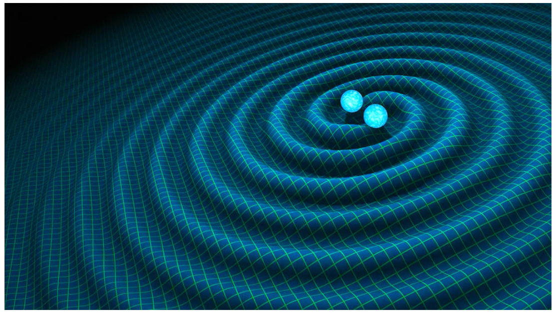
Nakazato (2010)

Extreme conditions in ρ-T plane

Supernova, Black hole formation

& Neutron star merger

R. Hurt/Caltech-JP

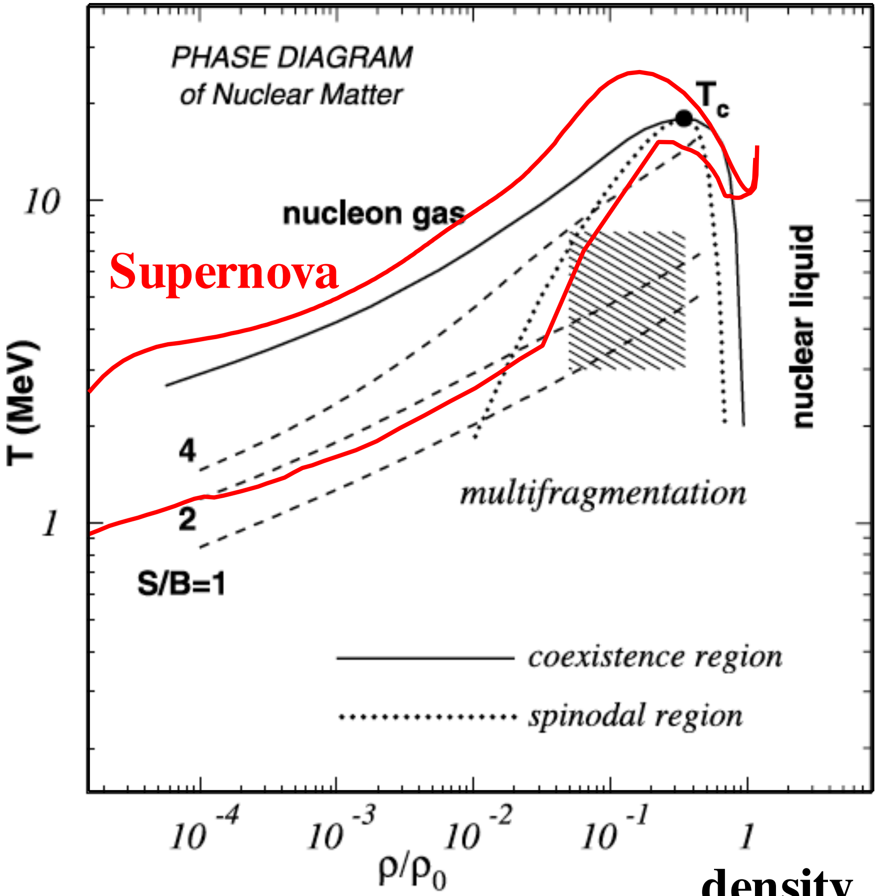


http://www.nasa.gov/

Supernova explosion (~20M_{sun}) ~ heavy ion collision

- Near the boundary between nuclei and gas

temperature



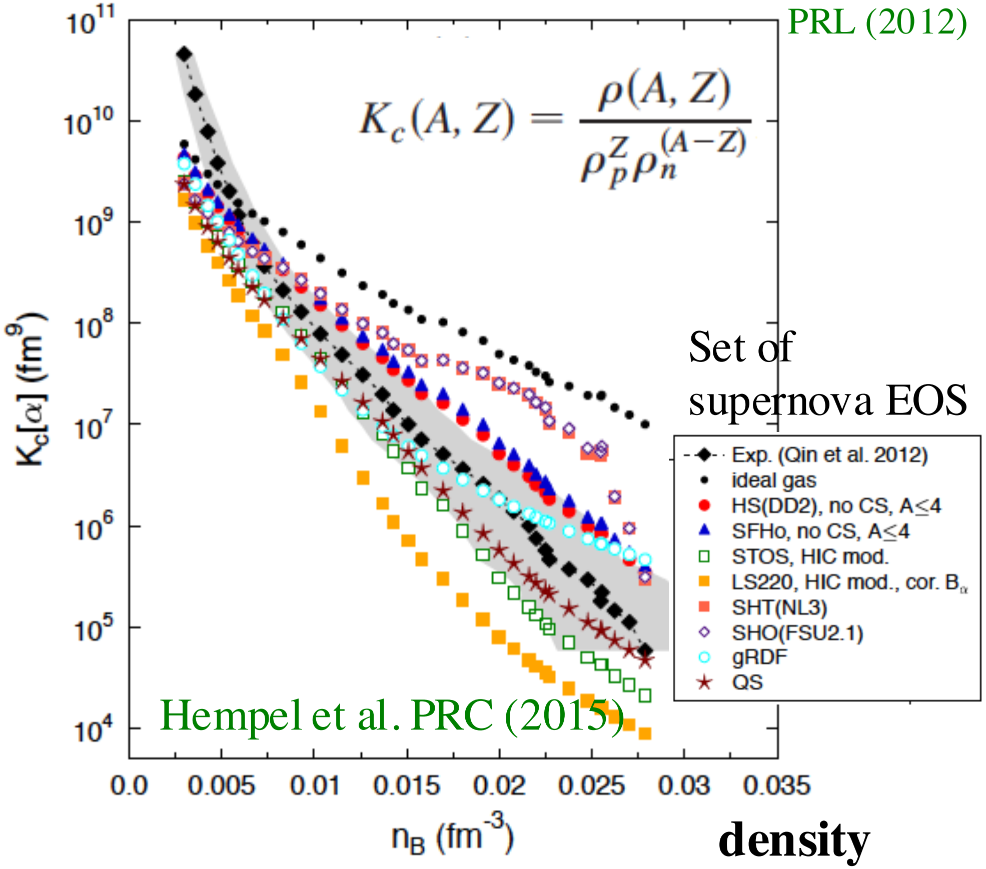
density

Botvina-Mishustin NPA (2010)
Buyukcizmeci NPA (2013)

- Composition from experiments

From ^{40}Ar, ^{64}Zn with ^{112,124}Sn 47AMeV at Texas A&M Qin et al. PRL (2012)

abundance



Set of supernova EOS

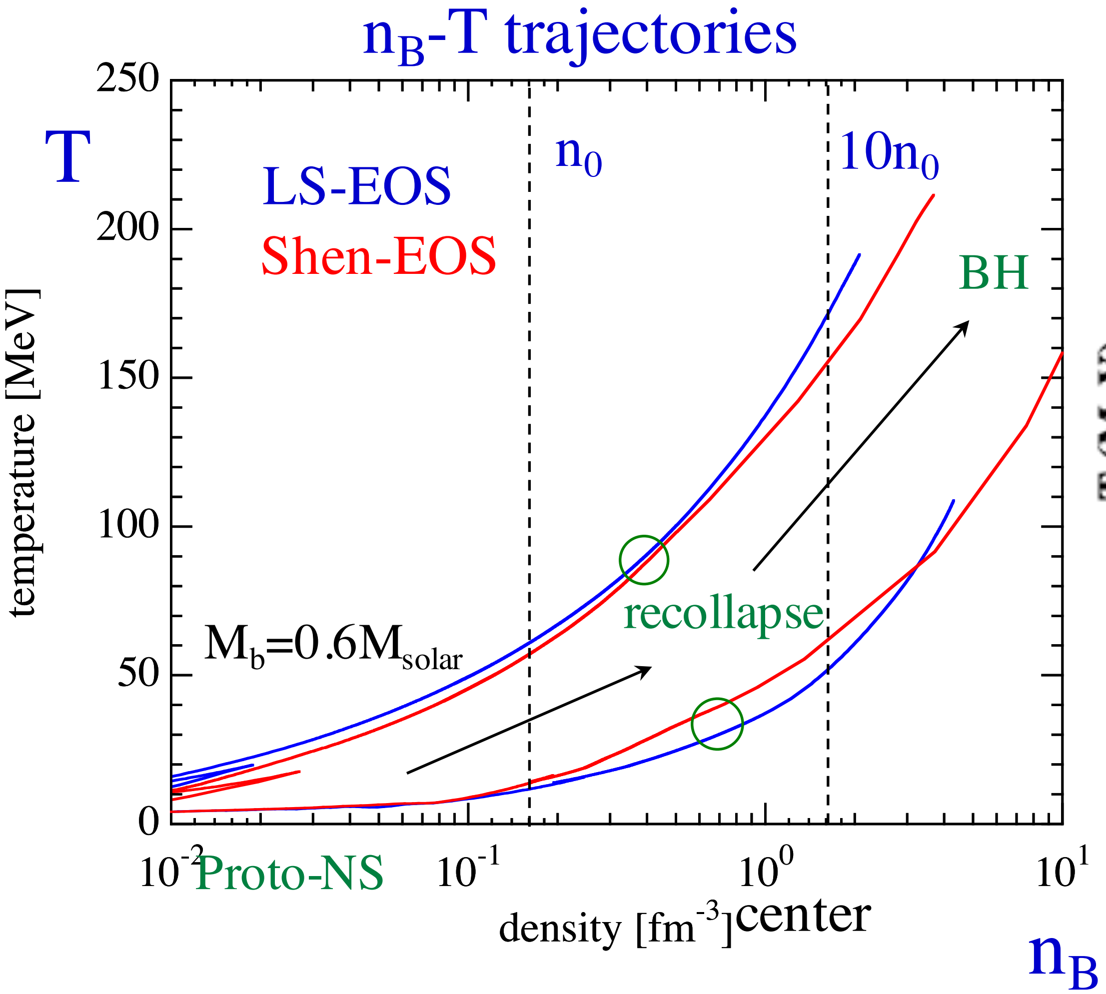
density

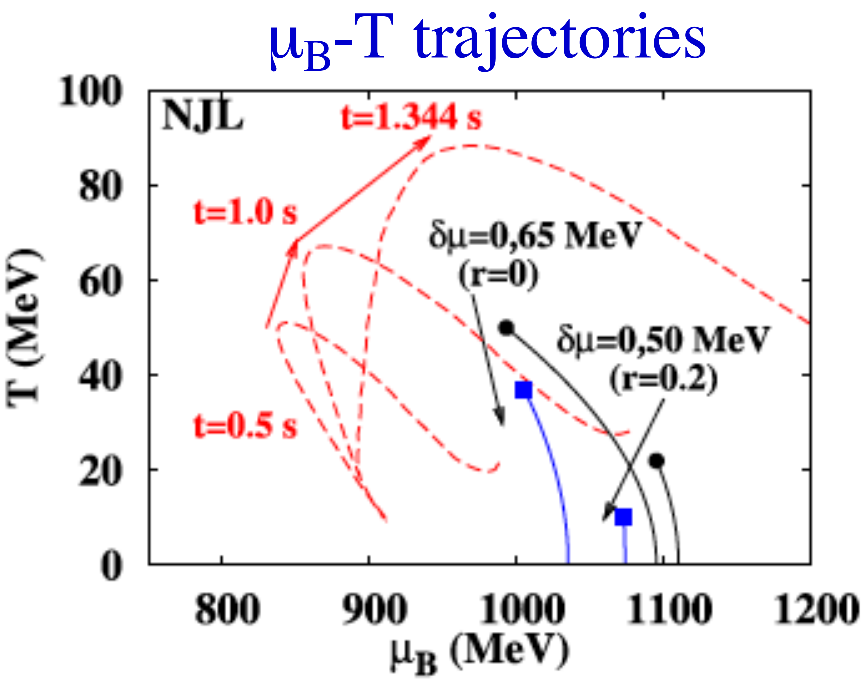
- Light nuclei (d, t, He)
  - Affect explosion or not?

Furusawa, Fischer

Failed supernovae (~$40M_{sun}$) black hole formation

- Very high ρ-T just before collapse to black hole





$40M_{solar}$

Sumiyoshi et al., ApJ (2006)

- Critical point sweep?

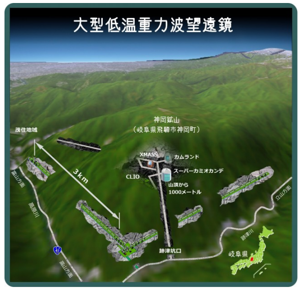
Ohnishi (2011)

- Black hole forming cases (GRB, collapsar, …)

Neutron star merger

- Target of gravitational waves
  - Probe of neutron star EOS
- Possible r-process site
  - Afterglow (kilonova)
- Hyper-massive neutron star
  - Black hole formation

KAGRA

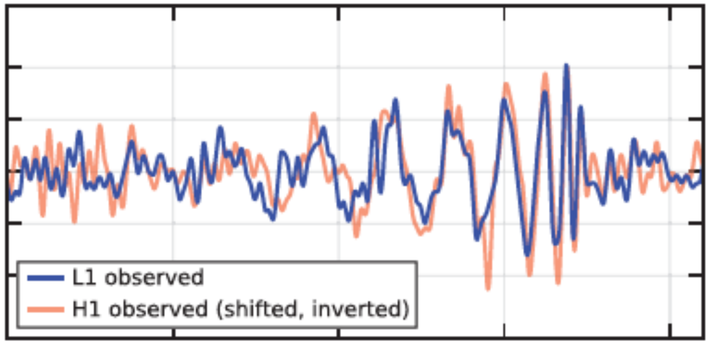


http://gwcenter.icrr.u-tokyo.ac.jp/

LIGO

http://www.ligo.org

BH merger GW150914



Abbott et al. PRL (2016)

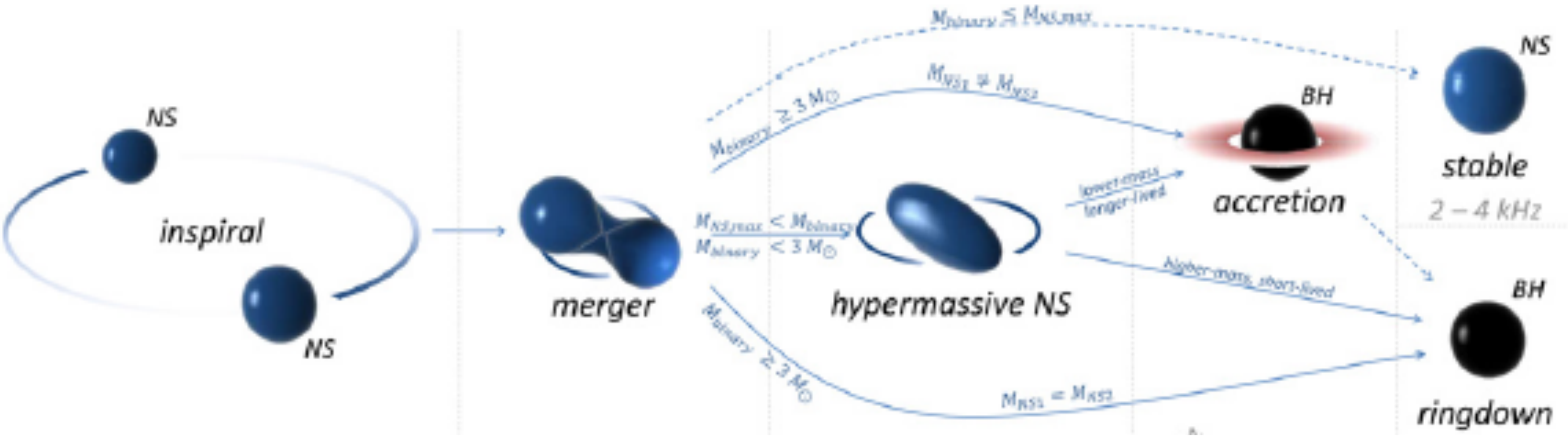
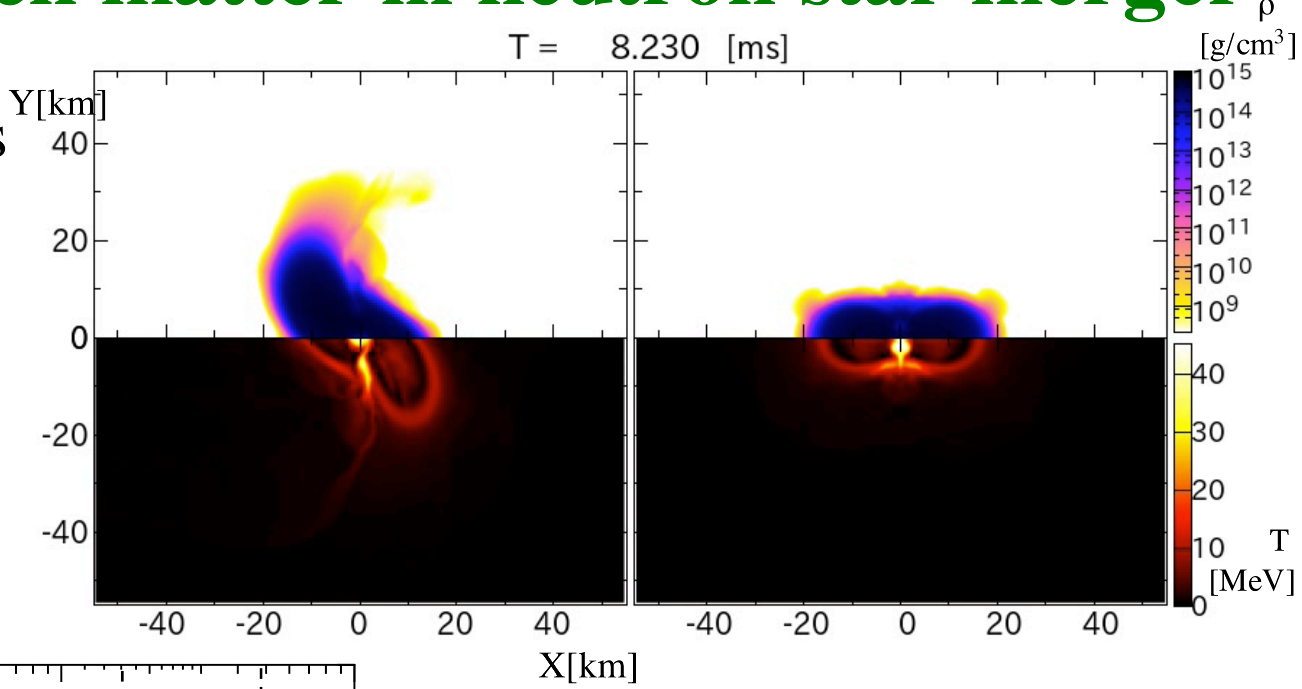
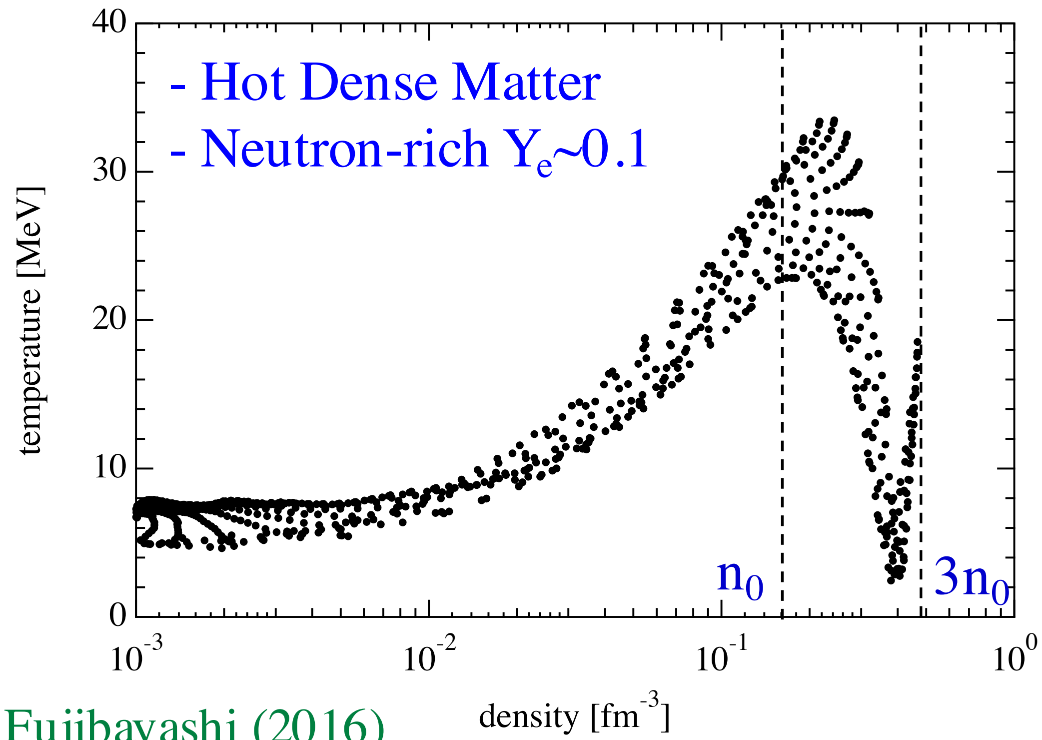


Figure from Bartos et al. CQG (2013)

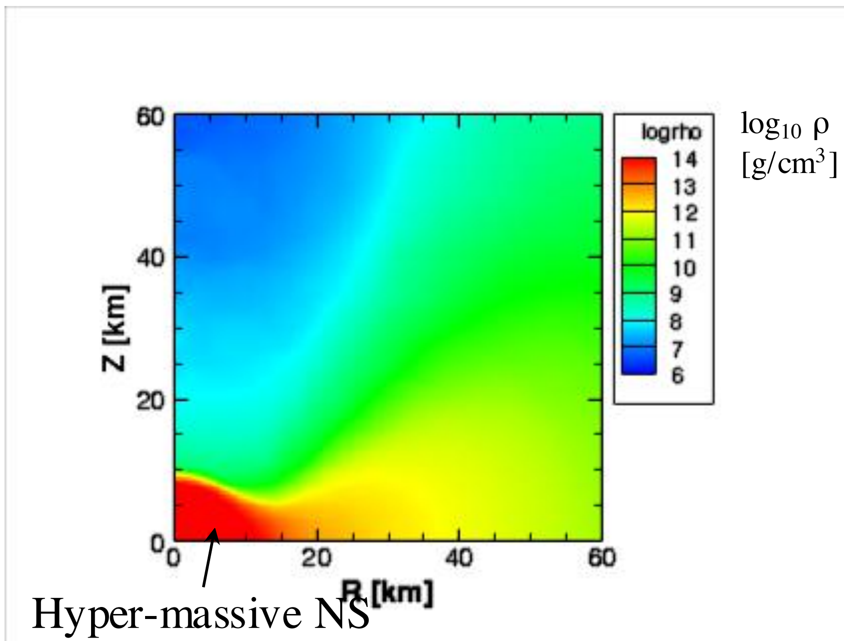
Hot-Dense, n-rich matter in neutron star merger

- Merger of binary NSs
  - 1.35M + 1.35M
- Rotating hot NS
  - $M \sim 2.6 M_{sun}$
  - Hempel DD2 EOS
  - $M_{max} \sim 2.4 M_{sun}$





Fujibayashi (2016)



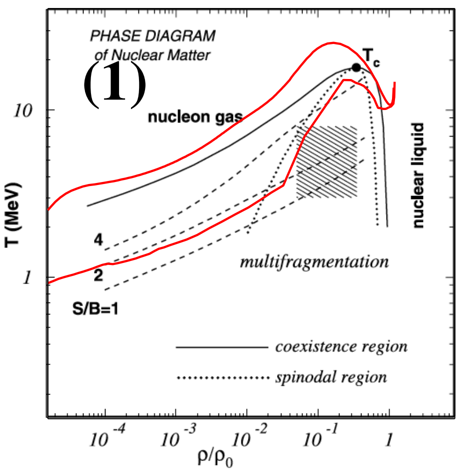
Sekiguchi et al. PRD (2015)

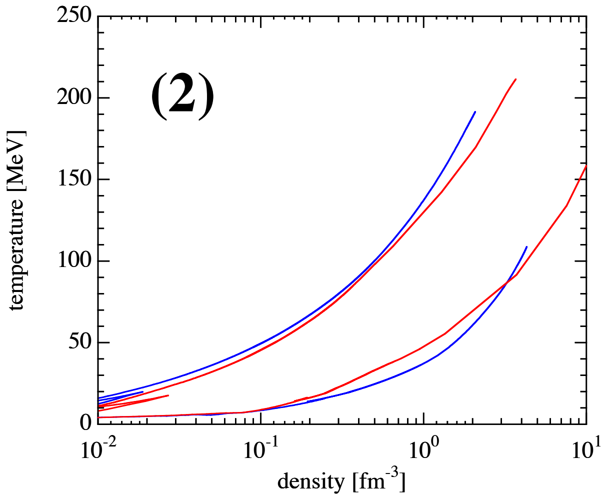
Extreme conditions in explosive phenomena

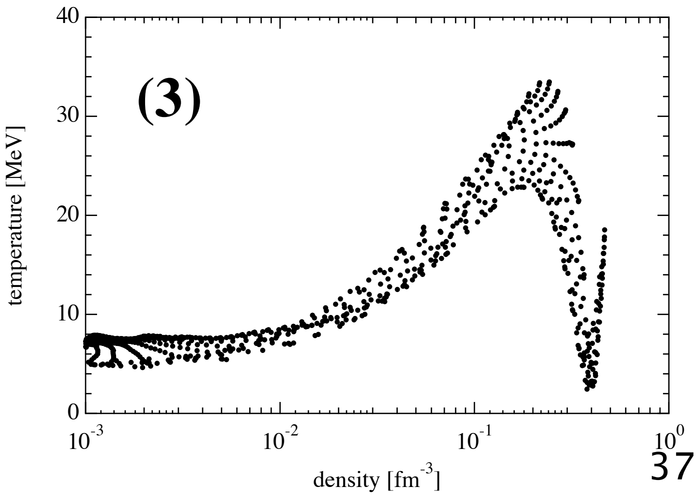
- **Core-collapse supernovae by ν-heating in 2D/3D**
  - 6D Boltzmann eq. solver & EOS tables to explore
- **Neutrino signals to probe EOS and exotics**
  - Supernova neutrinos ~20s, black hole forming neutrino ~1s

Wide range of (ρ, T, Y_p) conditions

1. **Core-collapse supernovae: hot-dense matter**
   1. Moderate Just above ρ_0, neutrino trapped matter
2. **Black hole forming supernovae**
   1. Extreme condition just before recollapse to black hole
3. **Neutron star merger & BH forming objects**







Compact stars in Kyoto, this fall

Oct. 17 – Nov. 18, 2016 @ Yukawa Institute TP

NPCSM 2016: YITP long-term workshop on "Nuclear Physics, Compact Stars, and Compact Star Mergers 2016", Oct.17 (Mon) - Nov.18 (Fri), 2016, YITP, Kyoto, Japan

http://www2.yukawa.kyoto-u.ac.jp/~npcsm/index.cgi

Compact star, dense matter, QCD phase diagram, NS merger & more!

Project in collaboration with

- Numerical simulations
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  - H. Okawa
  - A. Harada
  - S. Yamada
- Supernova research
  - T. Takiwaki
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  - K. Kotake
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- Supercomputing
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K-Computer, Japan