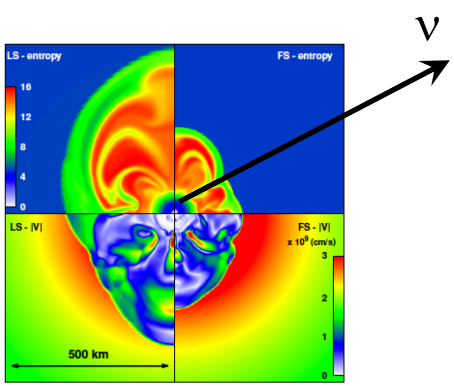
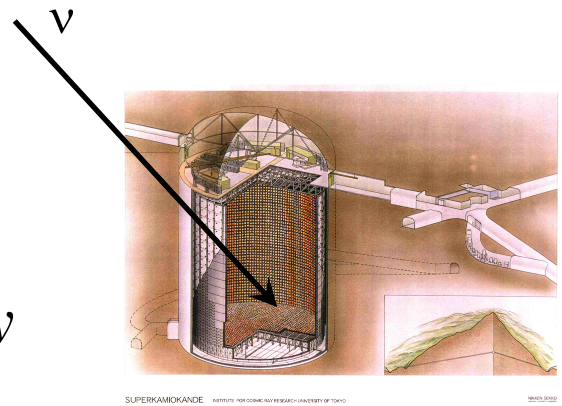
CCSN simulations with full Boltzmann transport
status report of group C02 of GW-genesis I



K. 'Sumi'yoshi

National Institute of Technology
Numazu College, Japan

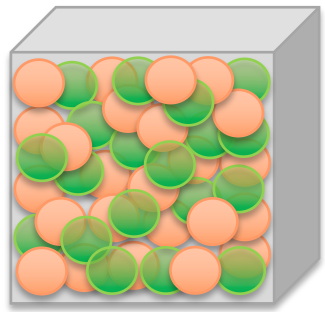


SK

Progress of supernova simulations and applications

- SN neutrino detections at Super-Kamiokande
- Improvement of Equation of State tables

EOS

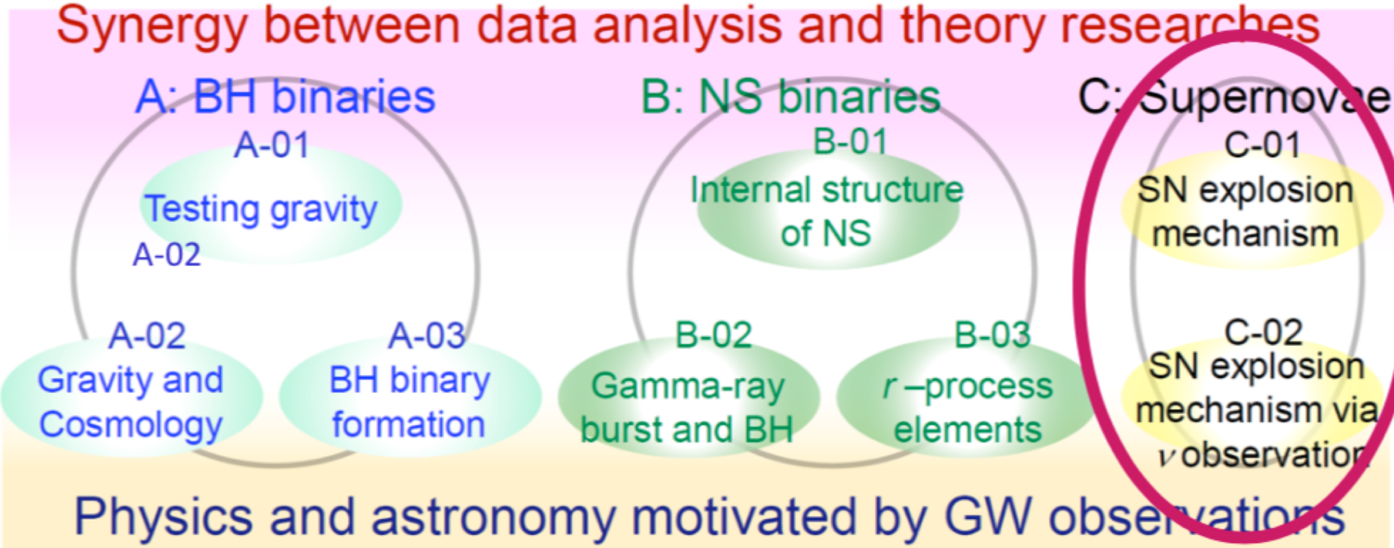


Gravitational wave physics and astronomy: genesis

Gravitational Wave Physics and Astronomy Genesis

2017 - 2021

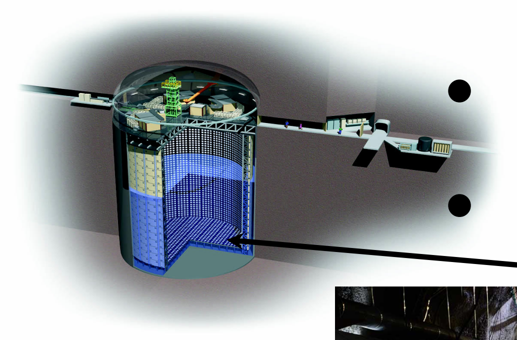
KAKENHI by JSPS



C01 : Supernova mechanism by Gravitational Waves (Kotake)

C02 : Supernova mechanism by Neutrinos (Vagins)

- Obs: KAGRA, Super-Kamiokande + Gd
- Theory: Supernova simulations



SK

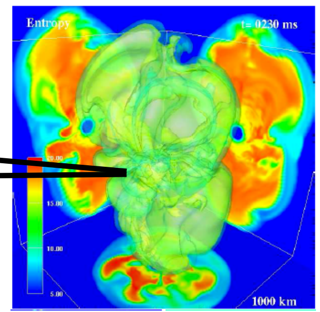
KAGRA

ν

GW

Extract information

Takiwaki



Simulations

C02: Supernova mechanism from neutrinos

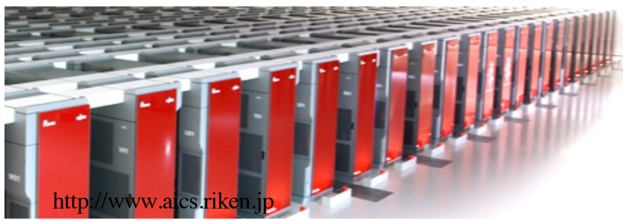
- Observation: Super-Kamiokande (SK) + Gd
- Theory: predictions of supernova neutrinos

→ Extract the supernova mechanism

- – Information on progenitor, neutron star / black hole
- – Properties of dense matter, equation of state (EOS)

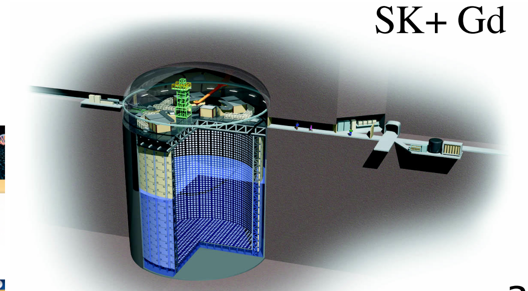
- Connecting theory with observations

1. Supernova modeling by sophisticated simulations
2. Providing template of neutrino bursts at SK



Post-K (Fugaku) , Japan

SK+ Gd



C02: Supernova mechanism via ν-observation

Research members

- M. Vagins
- Y. Koshio
- theory • K. Sumiyoshi
- thoery • H. Matsufuru
- thoery • A. Harada

Targeted research (Koubo)

- W. Horiuchi ν-reactions
- S. Ando relic SNν
- Y. Suwa proto-NSν
- S. Furusawa SN-EOS
- H. Togashi SN-EOS

Close collaborators

- R. Wendell, S. Ito, Y. Kato, M. Nakahata, K. Nishijma
- S. Yamada, K. Nakazato ν-oscillations, proto-NS
- H. Nagakura, S. Horiuchi

Ingredients in supernova mechanism

Nuclear Physics ~ fm=10^{-15} m

- Equation of state
- Neutrino reactions
- Nuclear data

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

Astrophysics >1000 km=10^{6} m

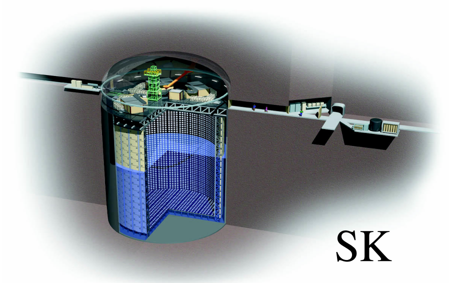
- Stellar models
- Hydrodynamics
- Neutrino transfer
- General Relativity

Dynamics of supernova explosions

- *Prediction of supernova neutrinos → Event rates*

C02 Theory report on

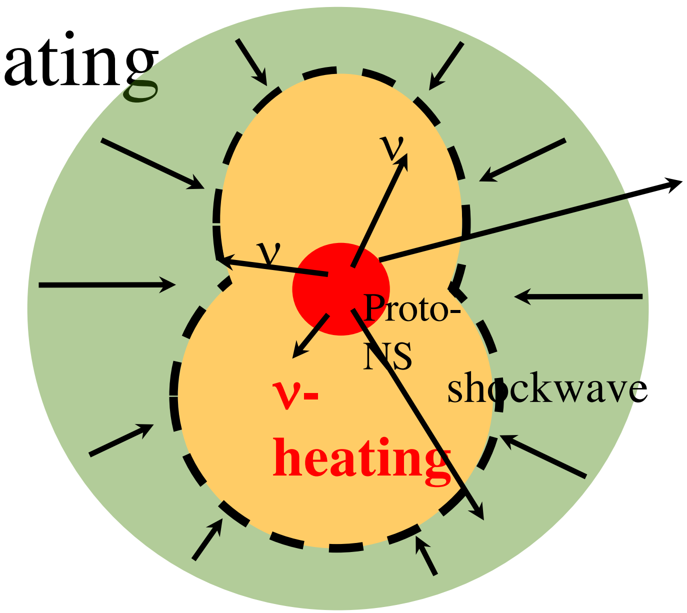
1. Supernova modeling by Boltzmann equation **Harada**
2. Event rates of neutrino bursts at SK
3. Influence of equation of state



SK

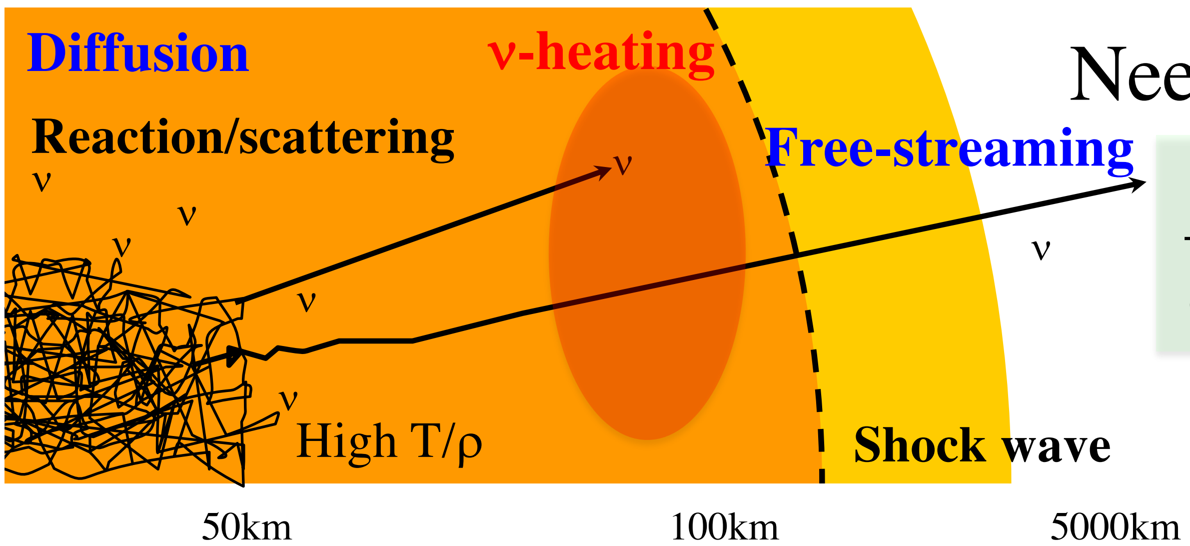
Remaining issues: neutrino transfer

2D/3D explosions occur with neutrino-heating



- Heating sensitive to ν-transfer
  - ν-trapping, emission, absorption
- From diffusion to free-streaming
  - Intermediate regime is important

We replace approximate ones to the exact method



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

Numerical code to solve 6D Boltzmann eq.

Sumiyoshi & Yamada, ApJS (2012)

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

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

→ Huge computation

Average by angle integral

$$\frac{1}{c}\frac{\partial E_\nu}{\partial t}+\frac{1}{c}\nabla\cdot\vec{F}_\nu=Q_\nu^0$$

$$\frac{1}{c}\frac{\partial \vec{F}_\nu}{\partial t}+c\nabla\cdot\vec{P}_\nu=\vec{Q}_\nu^1$$

Diffusion, Moment methods

- Check and develop approximations
  - Diffusion, Ray-by-Ray method, M1 closure relation

Sumiyoshi (2015)
Richers (2017)
Harada (2019)

- Provide all: energy, angle, space distributions
  - Directional dependence, Neutrino collective oscillations

Yamada
Delfan Azari

- Complemental to each other with approximate methods
  - Expensive: resolution, time evolution

Works with C02

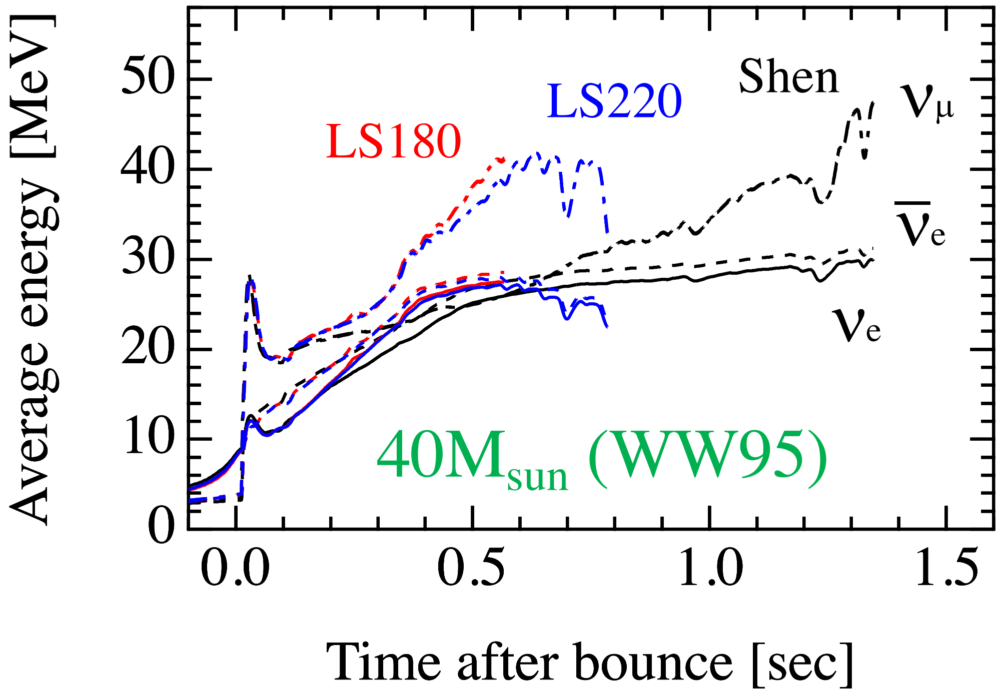
Numerical code by Boltzmann solver

First principle calculation *Yamada et al. (1997, 1999) Sumiyoshi et al (2005)*

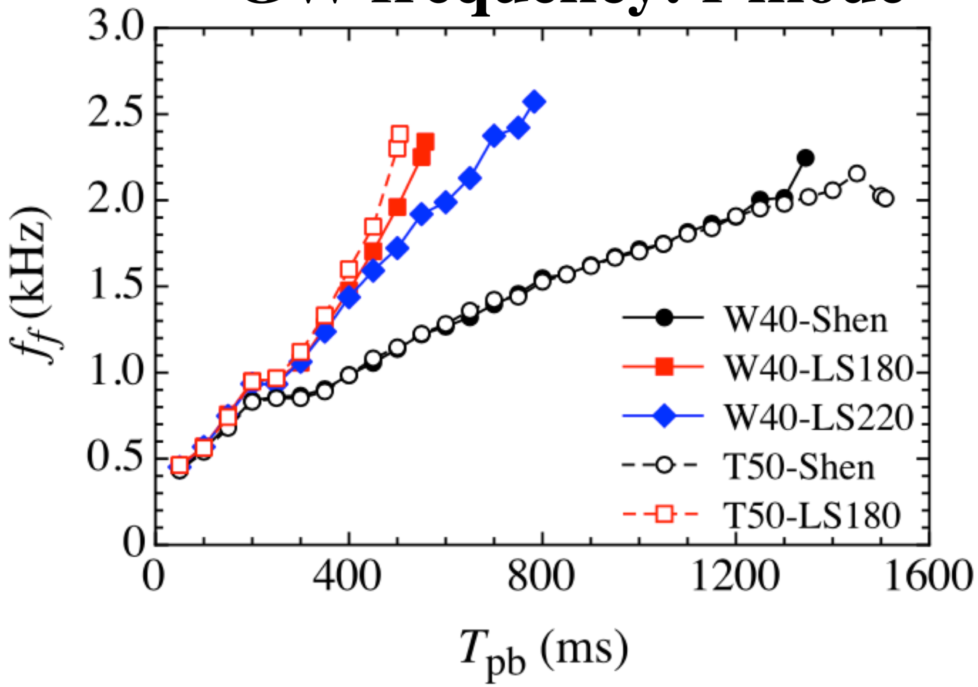
- spherical GR neutrino-radiation hydrodynamics
  - Prediction of neutrino signals (Supernova ν database)
  - Examine nuclear physics: EOS, ν-reactions
  - Black hole formation (relic SNν)

GPU by Matsufuru

Neutrino burst from BH formation



GW frequency: f-mode



Sumiyoshi et al. 1908.02928

Sotani & Sumiyoshi PRD (2019)

Numerical code by 6D Boltzmann solver

Nagakura et al. (2014, 2017, 2019)

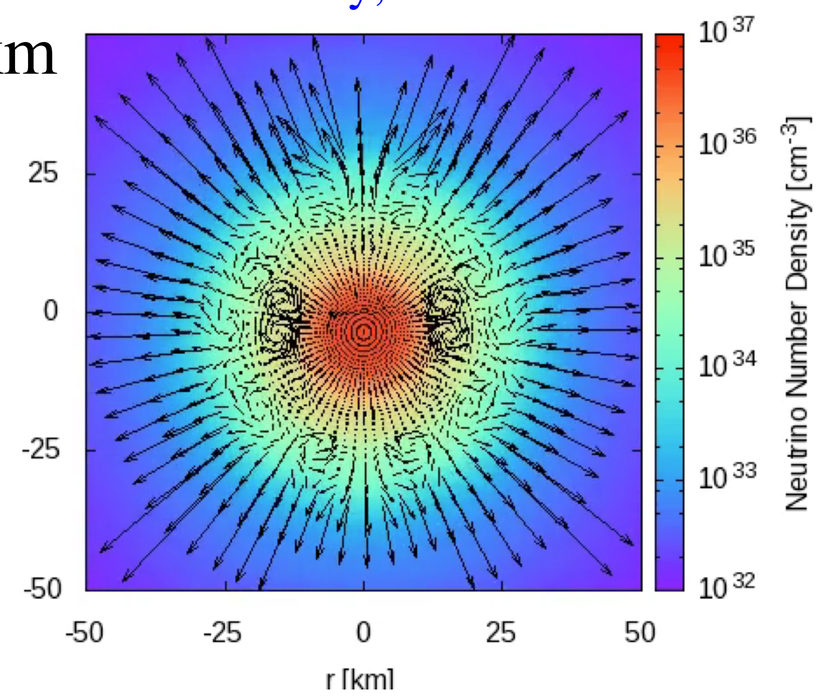
- 2D (axial) neutrino-radiation hydrodynamics
  - Relativistic effects: Doppler shift, angle aberration
  - Moving mesh for kick of proto-NS

Now extended to 3D

ν-flux in convection

Color : ν-density, Arrow : ν-flux

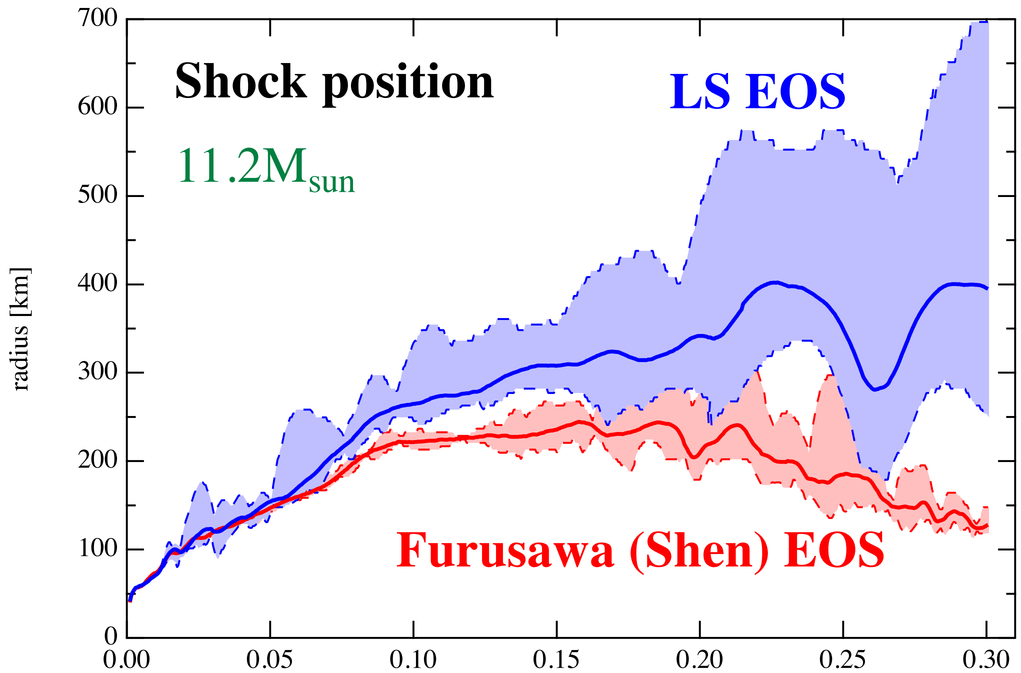
50km



proto-NS region

Figure by Iwakami

Different shock dynamics: 2 EOS



Time after bounce

Nagakura et al. ApJ (2018)

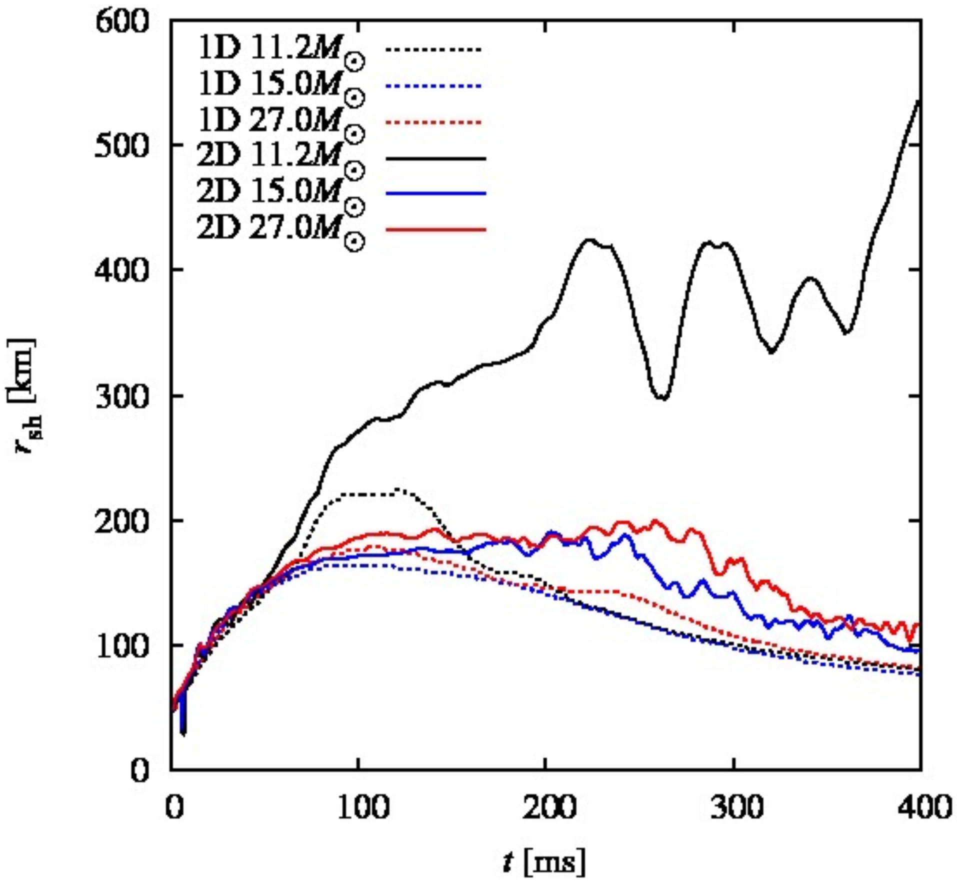
More Results of 6D Boltzmann solver

- different stellar models, rotation with updated EOS

Talk by Harada

Average Shock Radius

Lattimer-Swesty EOS



Furusawa-Togashi EOS

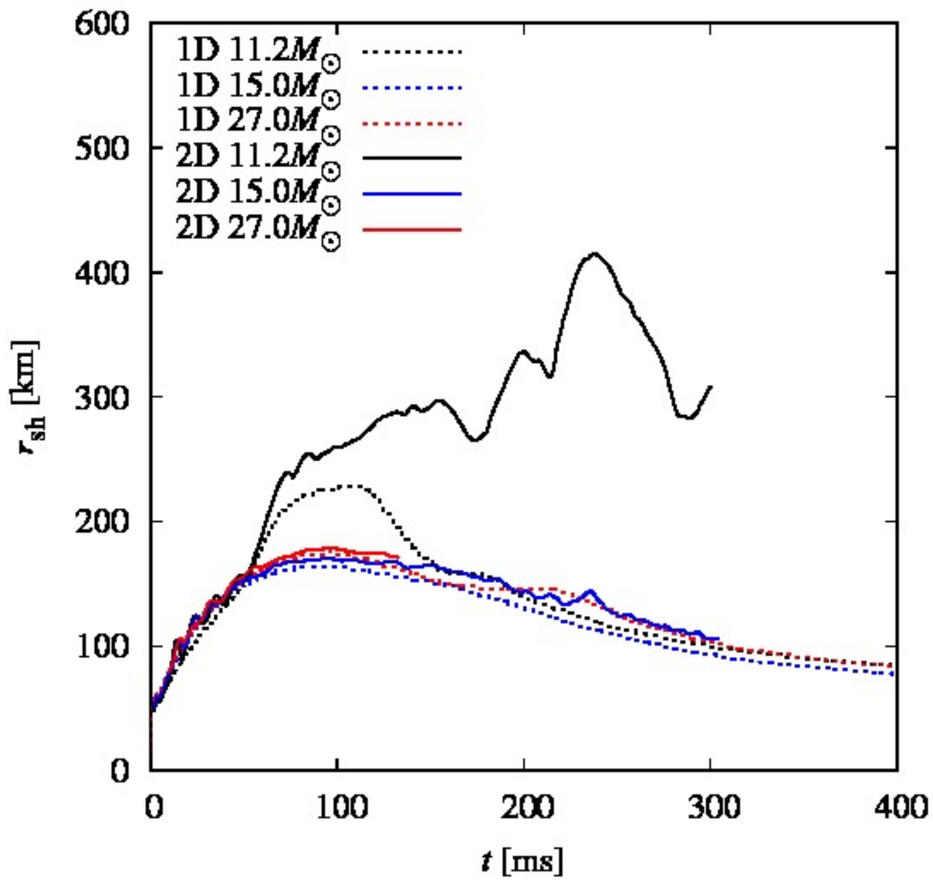


Figure by Iwakami (2019)

Detection of supernova neutrinos

Suwa et al. ApJ (2019)

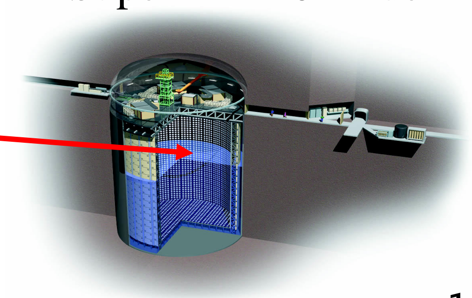
nuLC

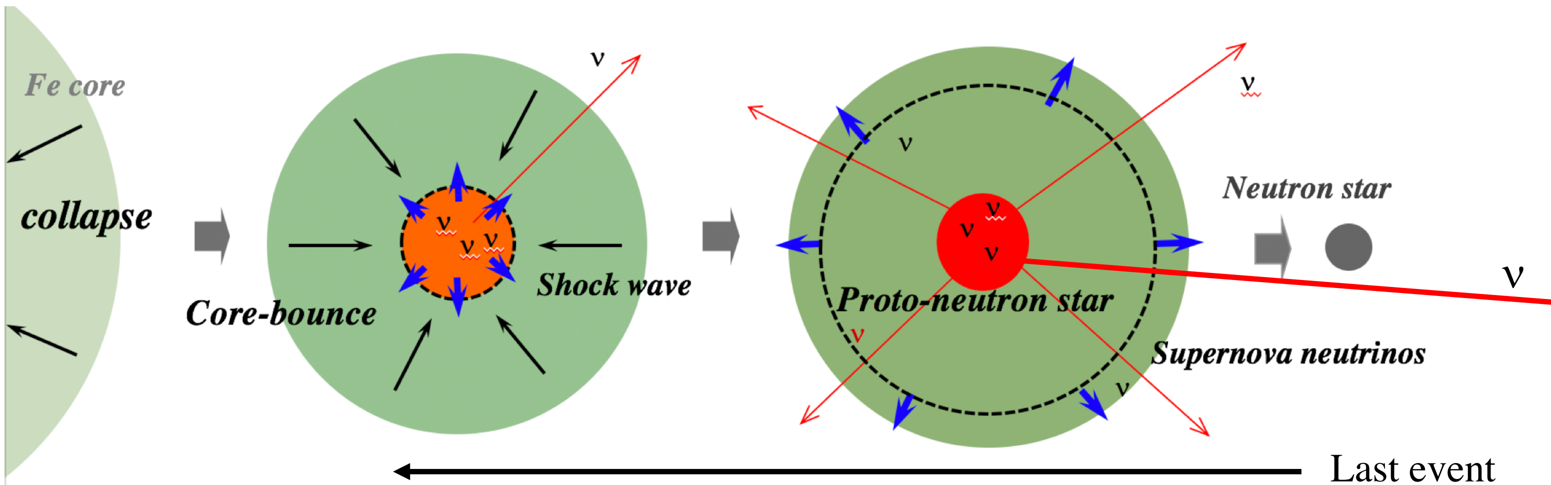
slack

- We want to extract information of supernovae
  - Progenitor, proto-neutron star, equation of state
- Prediction of event rates at Super-Kamiokande
  - Templates of neutrino signals (like Grav. Wave)
  - Supernova neutrino database   Nakazato et al. ApJ 2013
- Determine proto-NS properties?
  - Backward time plot of events

Working with SK members

Super-Kamiokande

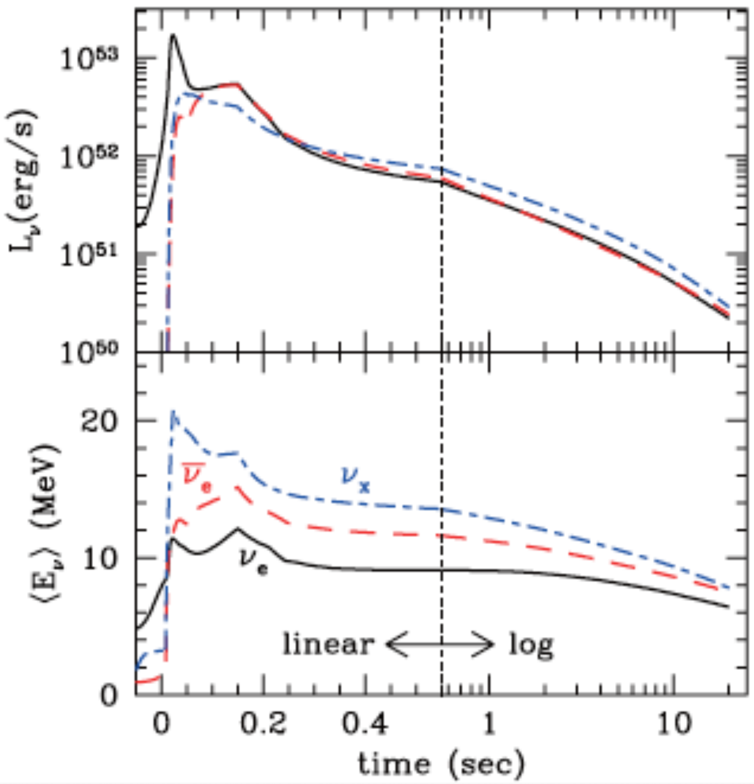




Supernova neutrino data database

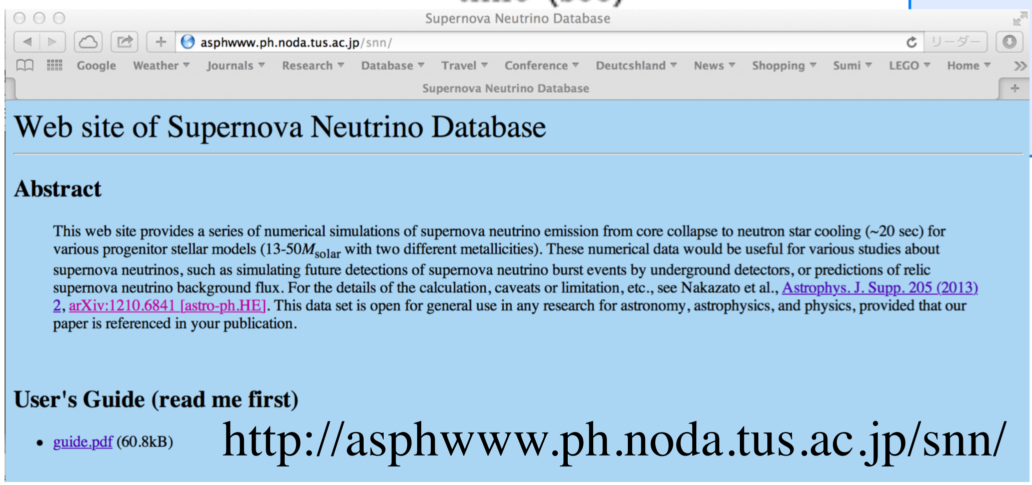
Nakazato et al. ApJ 2013

- Set of neutrino emission from supernova simulations



- Cover series of progenitors
  - 13-50M_{sun}, Z=0.02, 0.004
- 1D GR ν-radiation hydro
- 1D GR FLD proto-NS cooling
- Connect two phases
  - Obtain central object
  - Connect smoothly emission
  - Parameter: shock revival time

Shen EOS (and extensions)



Supernova Neutrino Database

asphwww.ph.noda.tus.ac.jp/snn/

Google Weather Journals Research Database Travel Conference Deutschland News Shopping Sumi LEGO Home

Supernova Neutrino Database

Web site of Supernova Neutrino Database

Abstract

This web site provides a series of numerical simulations of supernova neutrino emission from core collapse to neutron star cooling (~20 sec) for various progenitor stellar models (13-50M_{solar} with two different metallicities). These numerical data would be useful for various studies about supernova neutrinos, such as simulating future detections of supernova neutrino burst events by underground detectors, or predictions of relic supernova neutrino background flux. For the details of the calculation, caveats or limitation, etc., see Nakazato et al., Astrophys. J. Supp. 205 (2013) 2, arXiv:1210.6841 [astro-ph.HE]. This data set is open for general use in any research for astronomy, astrophysics, and physics, provided that our paper is referenced in your publication.

User's Guide (read me first)

- guide.pdf (60.8kB)

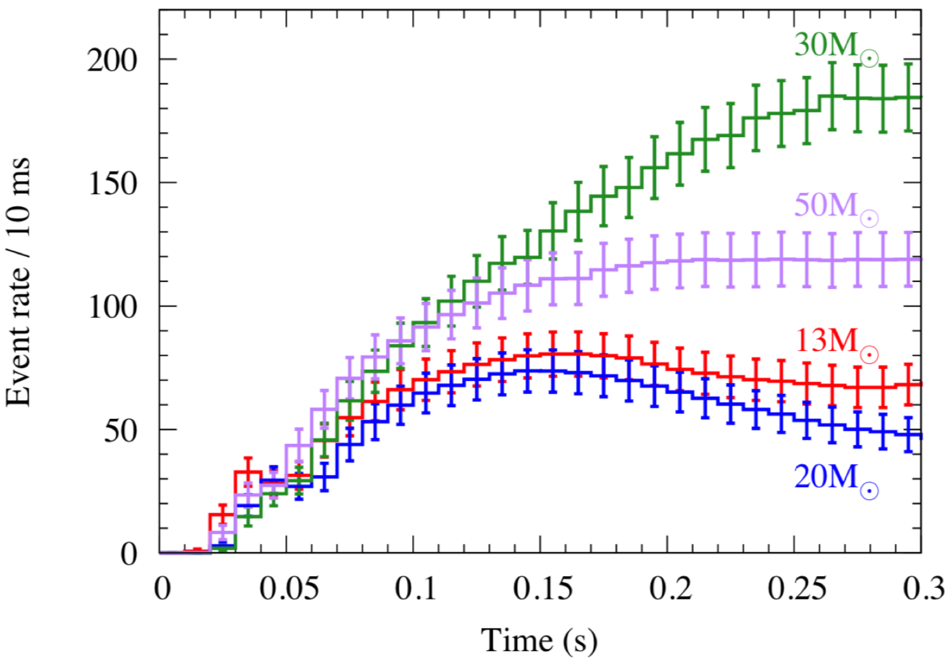
http://asphwww.ph.noda.tus.ac.jp/snn/

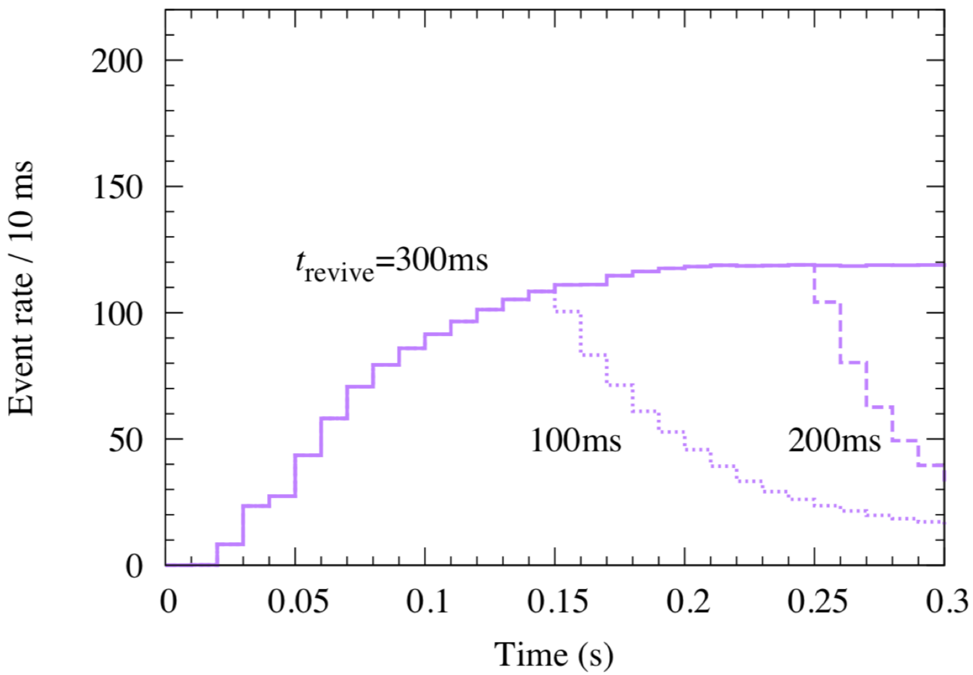
Additional proto-NS models for different NS masses

Prediction of supernova neutrino events

- Different progenitor stars, shock revival time
  - At Super-Kamiokande, full volume, 10kpc

Predicted event rates at SK (Inverse beta decay, No oscillation)





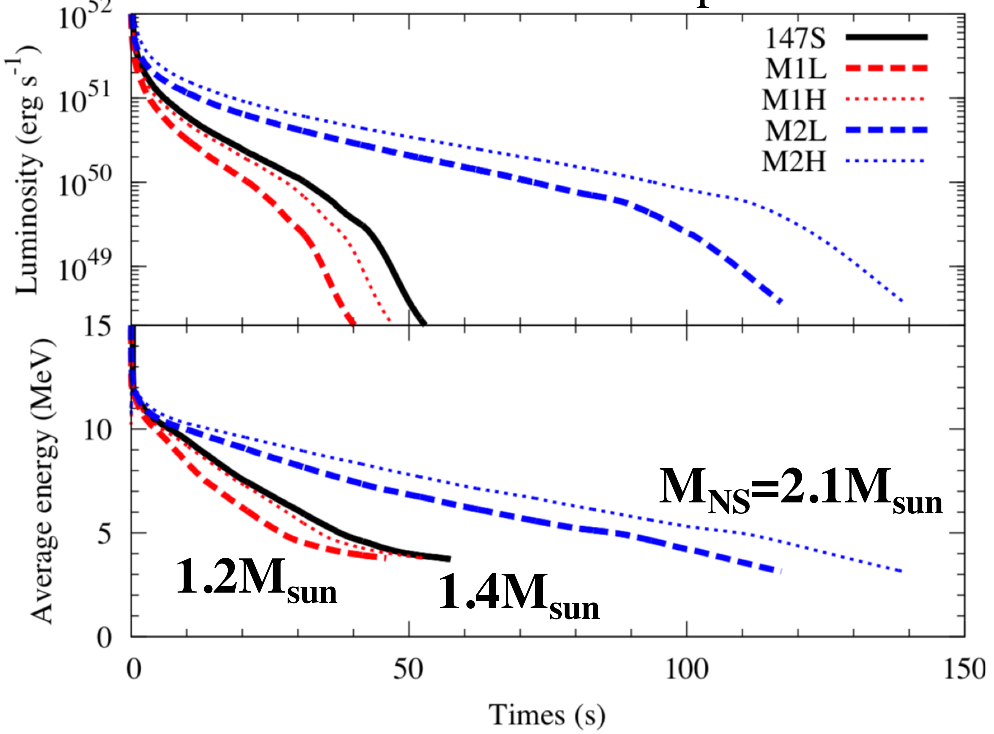
- At early phase phase around core bounce
  - Depends on matter accretion from progenitor
  - May have more variations due to 2D/3D effects, Less EOS dependent

Suwa et al. ApJ (2019); arXiv:1904.09996

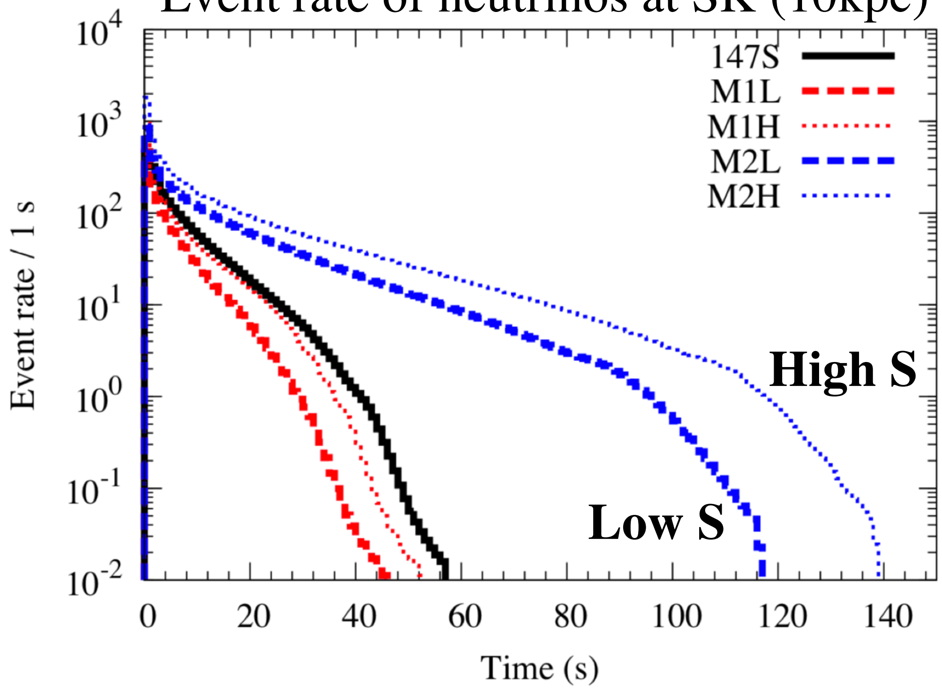
How long we can detect neutrino burst?

- Long term evolution of proto-NS cooling > 50 sec
  - Massive proto-NS emits neutrinos over 100 sec

Neutrino emission from proto-NS



Event rate of neutrinos at SK (10kpc)

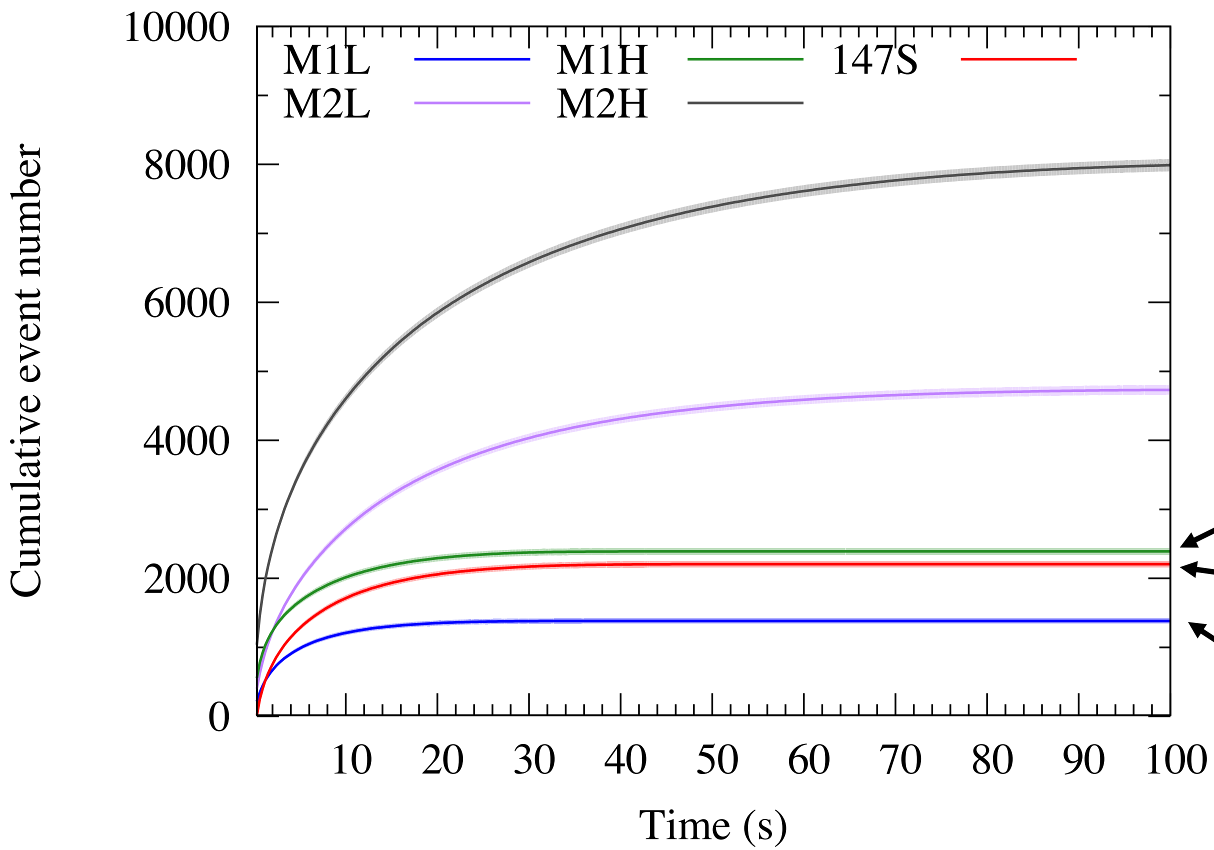


- At late phase due to proto-NS cooling
  - Simple emission of all flavors from diffusion (indep. of ν-osc.)
  - May have convection, More EOS dependent

Suwa et al. ApJ (2019); arXiv:1904.09996

Extract proto-NS properties from neutrinos

- Cumulative event numbers for proto-NS models
  - Different curves toward the total event number



Large event # for massive NS

M_{NS}=2.1M_{sun}, High S

M_{NS}=2.1M_{sun}, Low S

M_{NS}=1.2M_{sun}, High S

M_{NS}=1.4M_{sun}, SNνDB

M_{NS}=1.2M_{sun}, Low S

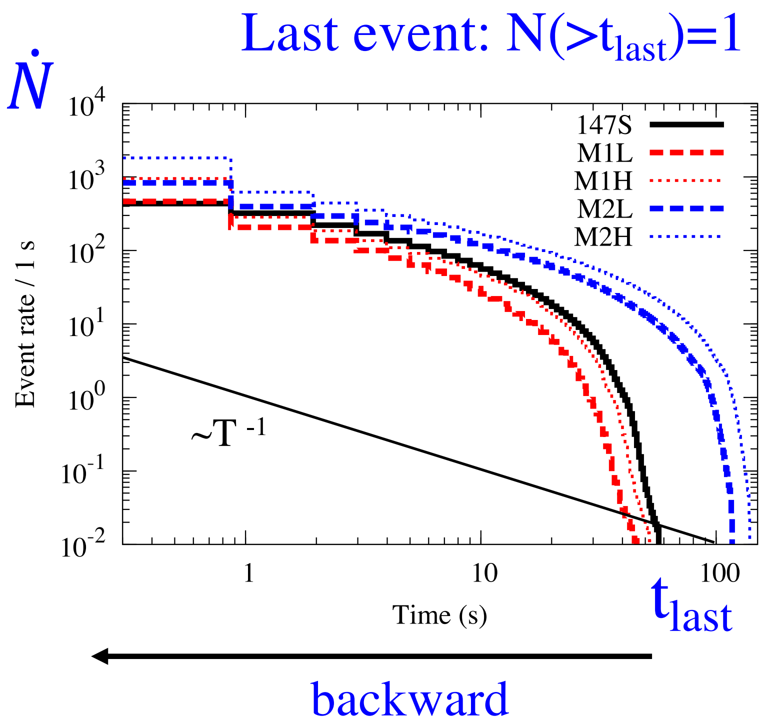
But, depends on initial profiles?

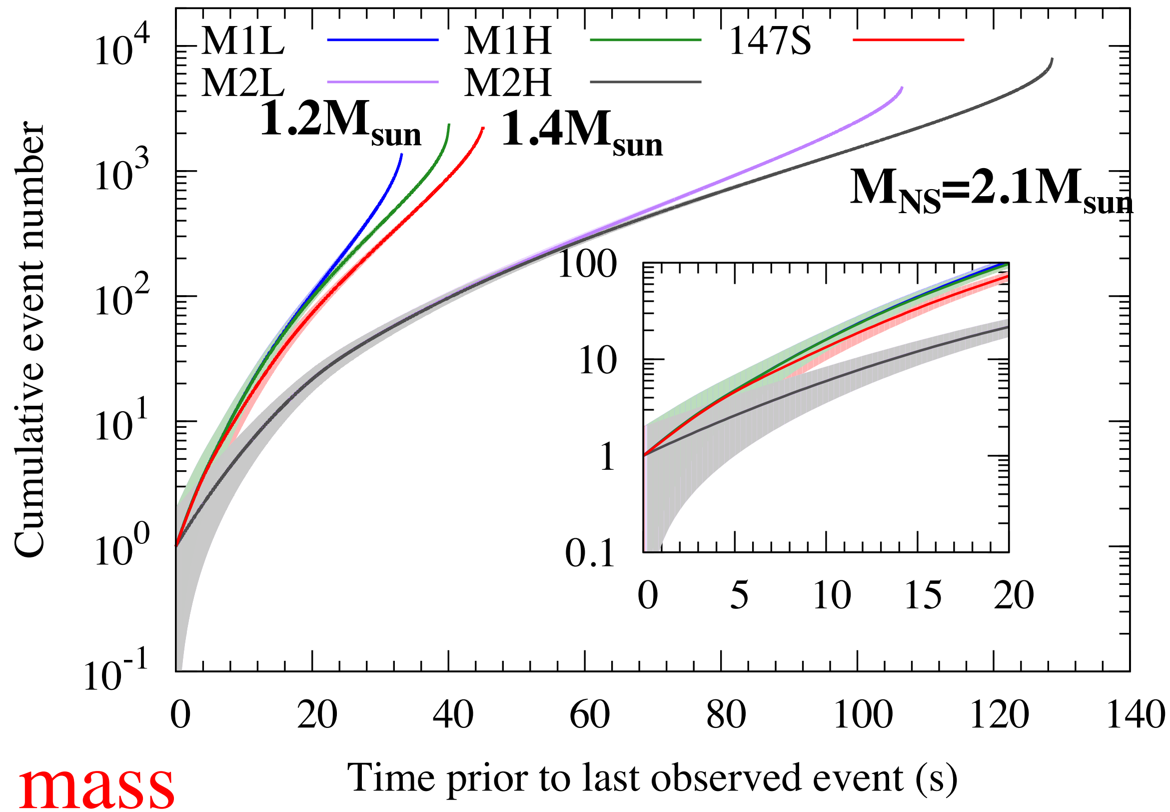
- We plot time backward: less sensitive initial cond.

Suwa et al. ApJ (2019); arXiv:1904.09996

Extract proto-NS properties from neutrinos

- Backward time plot from the last event
  - Cumulative event number $N(>t) = \int_t^\infty \dot{N} dt$





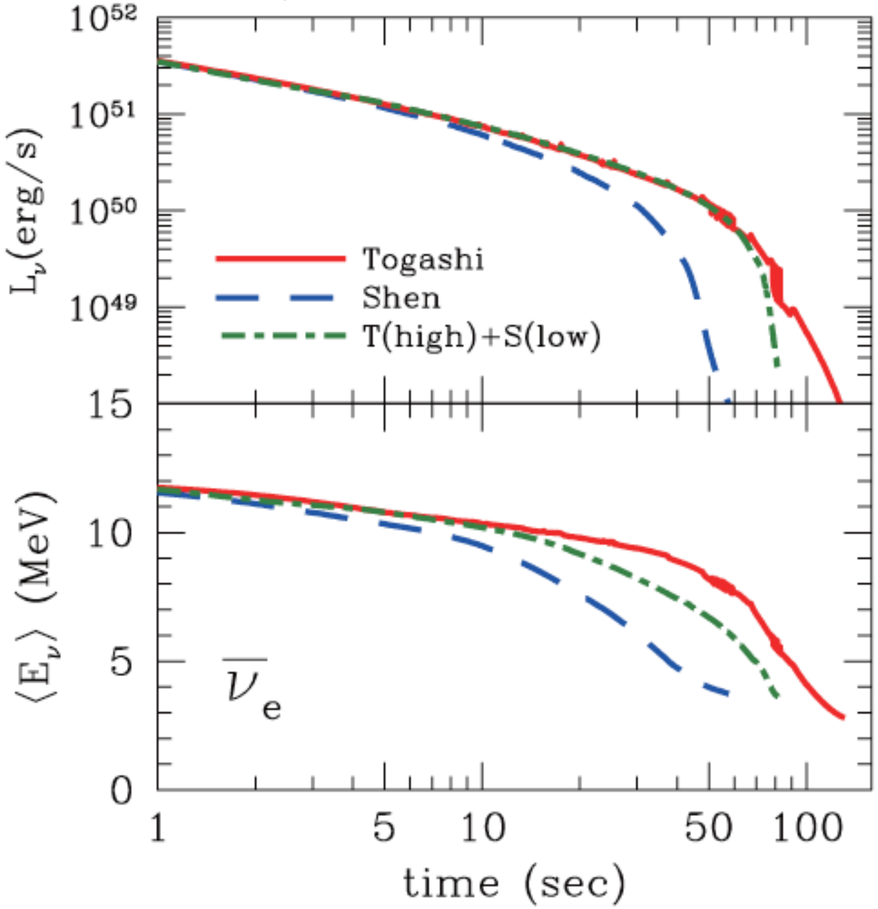
- Determine proto-NS mass
- Less sensitive to initial profiles (early phase)
  - Need to check EOS dependence

Suwa et al. ApJ (2019); arXiv:1904.09996

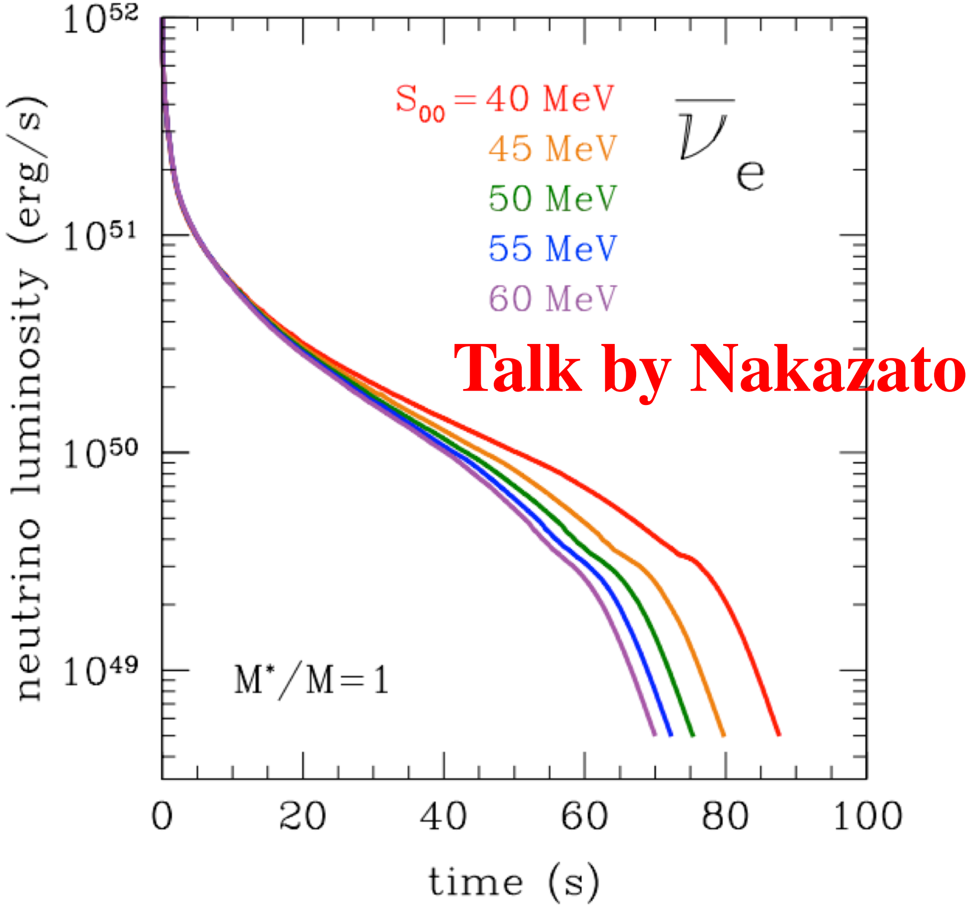
supernova neutrino: dependence on EOS

- ν-emission from proto-neutron star cooling

Togashi EOS vs Shen EOS



Symmetry energy at $2\rho_0$



Nakazato et al. PRC 2018

Nakazato et al. arXiv:1905.00014

Need further analysis on proto NS mass EOS, neutrino reactions

Progress of supernova EOS tables

- Mean field frameworks
  - Non-relativistic formula: Lattimer-Swesty
  - Relativistic mean field: Shen-EOS

- Microscopic many body theories
  - Variational method (VM) **Togashi**
  - Dirac-Brueckner Hartree-Fock (DBHF) **Furusawa**

- Systematic study of EOS effects
  - Nuclear saturation parameters (K, L etc)
  - Parameters in mean fields

Togashi

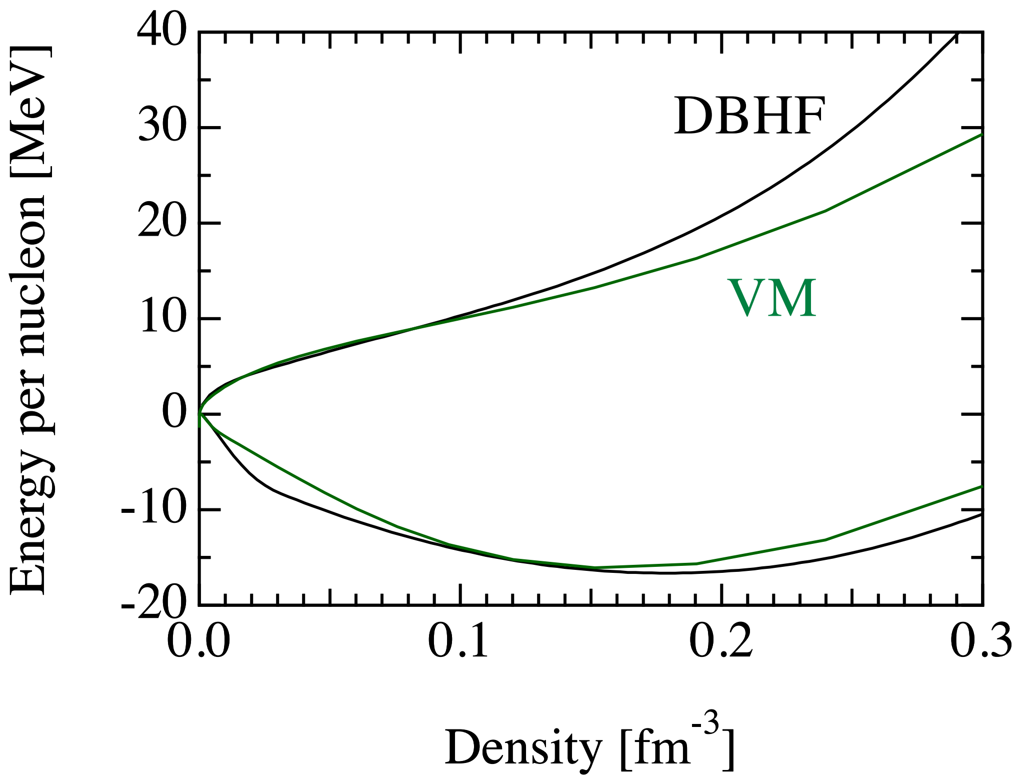
Nakazato

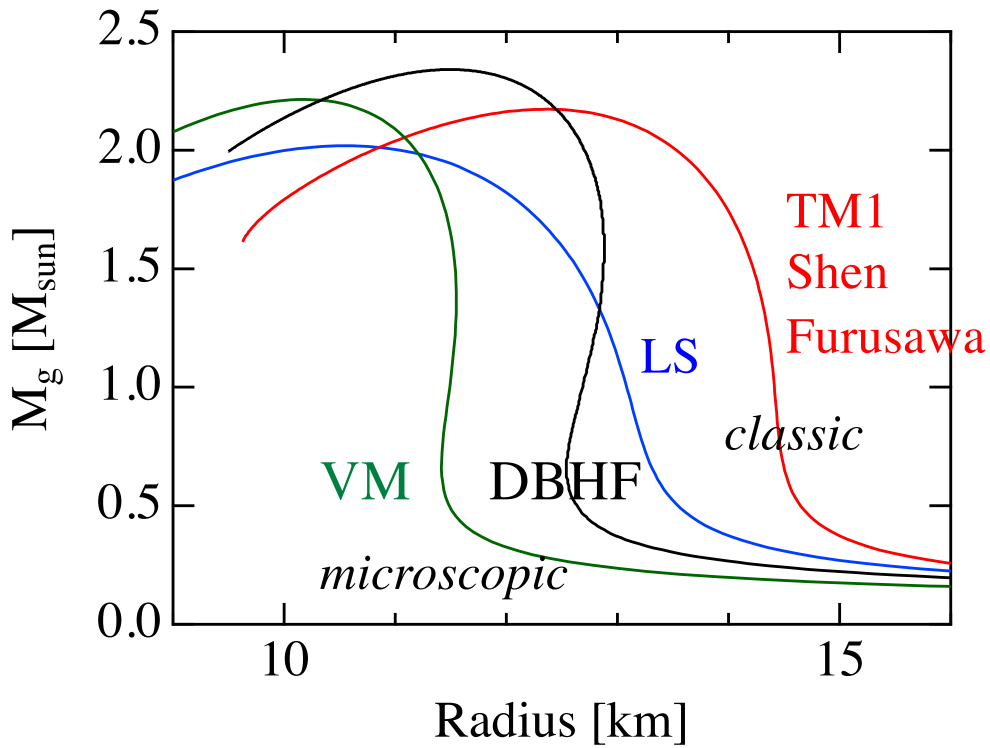
Classic → Realistic

Classic → Variations

Progress of EOS table I: microscopic approaches

- Variational method (VM) Togashi, NPA (2017), Furusawa JPG (2017)
  - Two-body AV18 + three-body UIX
- Dirac Brückner-Hartree Fock theory (DBHF)
  - Two-body Bonn-A, Saturation Katayama PRC (2013), Furusawa (2019)



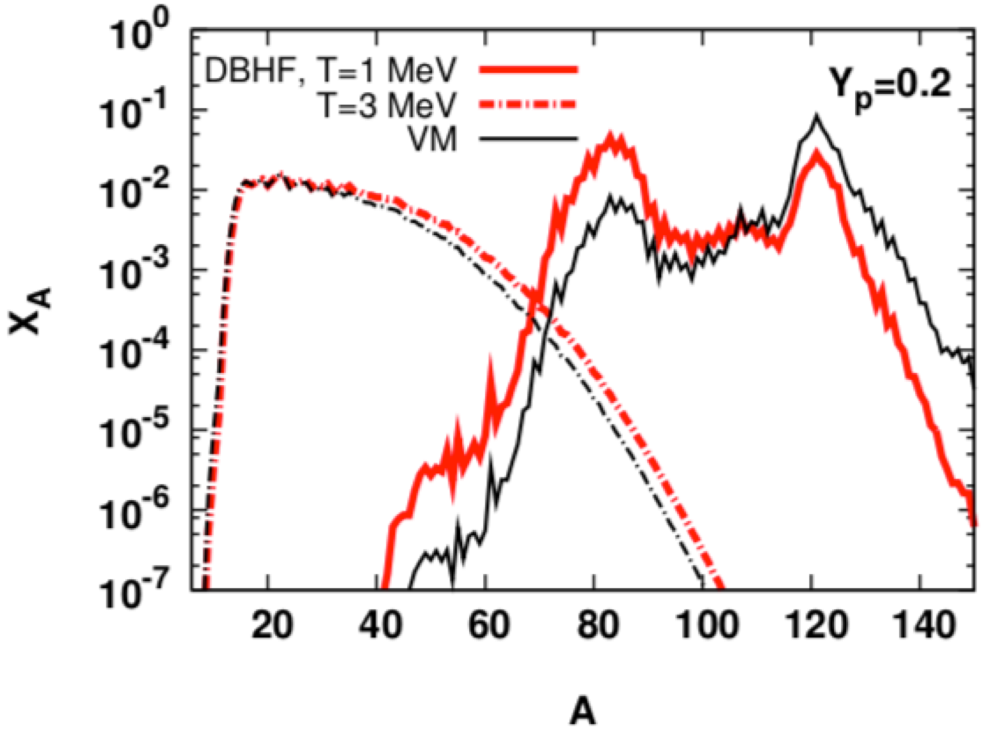


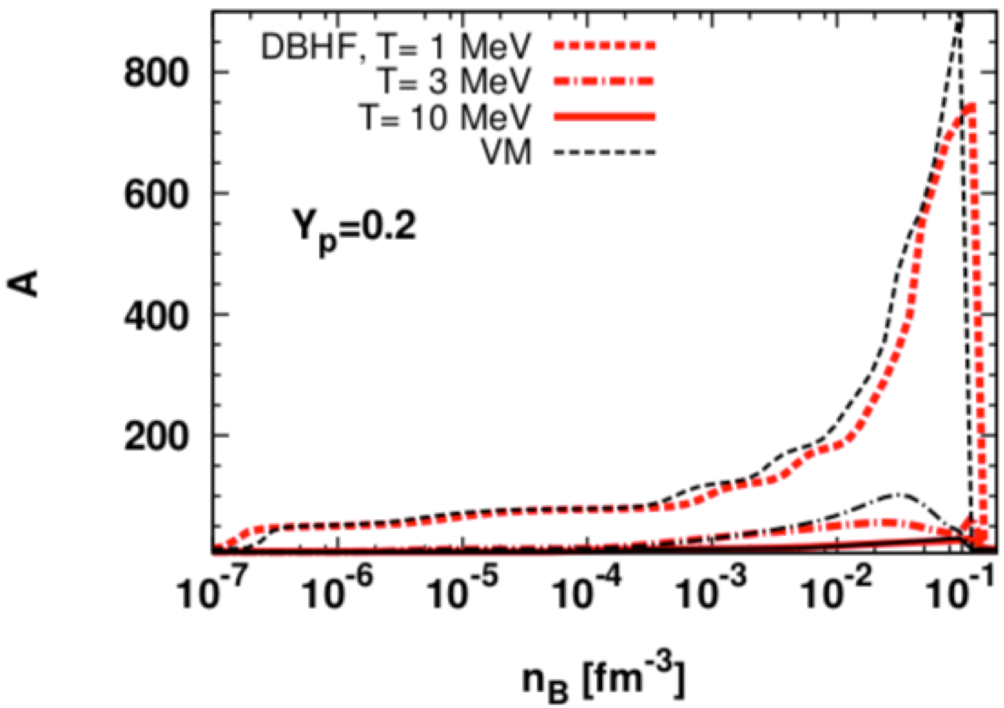
Non-relativistic vs Relativistic (ex. LS vs Shen)

EOS table with microscopic approaches

Togashi et al. (2017), Furusawa et al. (2017, 2019)

- Energy of uniform matter from VM, DBHF
- NSE mixture of nuclei with liquid drop model





Different compositions (mass fractions, nuclear abundance)

Talk by Furusawa

Furusawa et al. (2019)

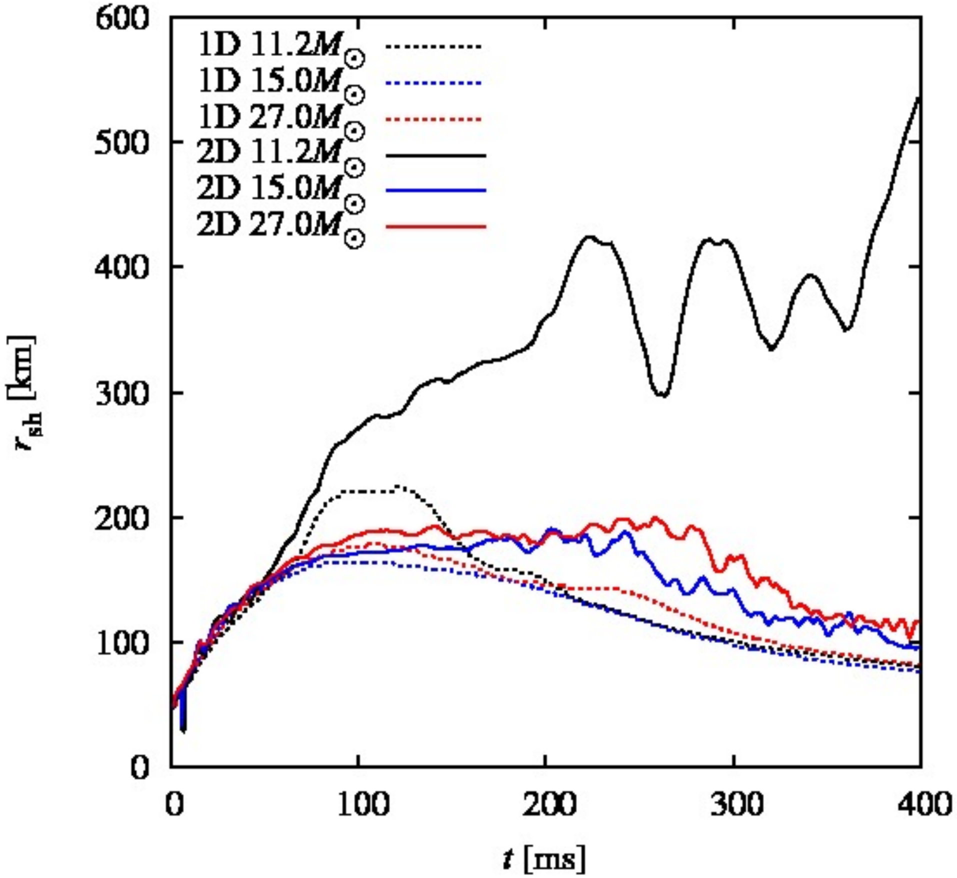
More Results of 6D Boltzmann solver

- different stellar models, rotation with updated EOS

Talk by Harada

Average Shock Radius

Lattimer-Swesty EOS



Furusawa-Togashi EOS (VM)

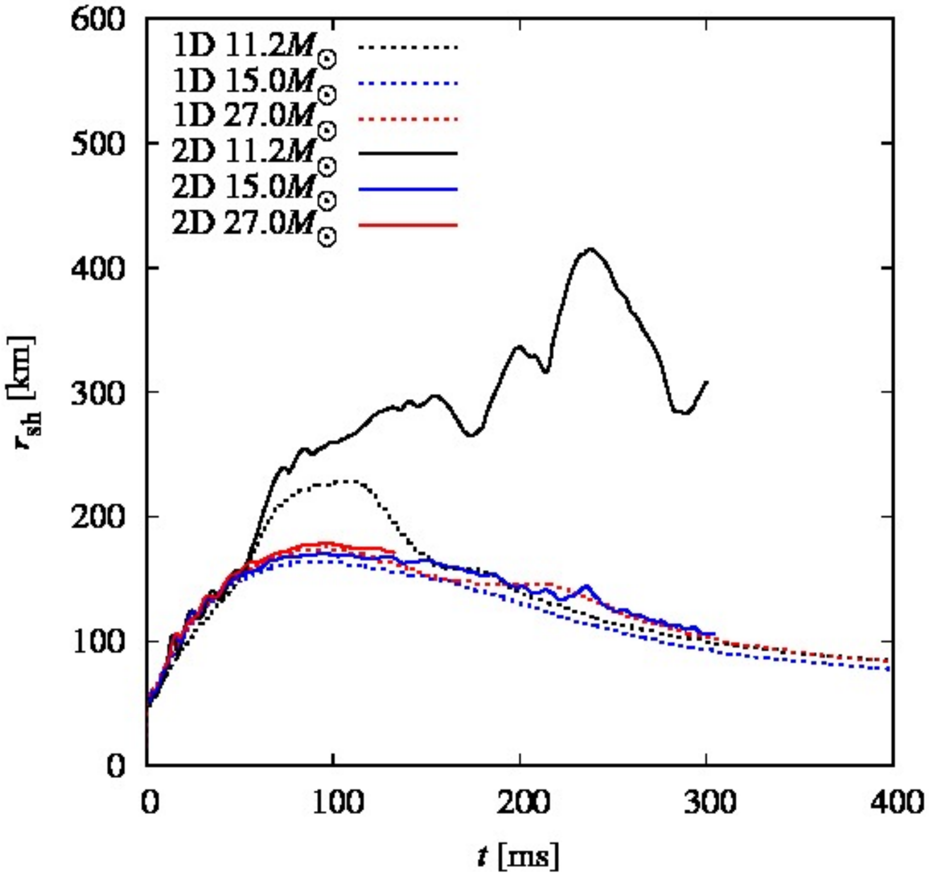
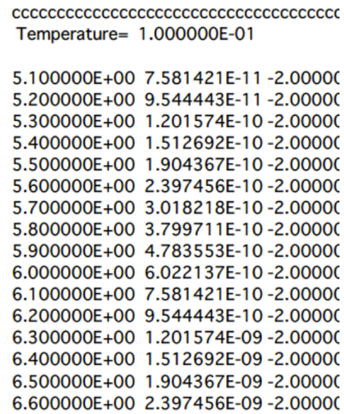


Figure by Iwakami (2019)

Progress of EOS table II : symmetry energy in RMF

Sumiyoshi et al. arXiv: 1908.02928


```
cccccccccccccccccccccccccccccccccccccccc
 Temperature=  1.000000E-01

5.100000E+00 7.581421E-11 -2.0000(
5.200000E+00 9.544443E-11 -2.0000(
5.300000E+00 1.201574E-10 -2.0000(
5.400000E+00 1.512692E-10 -2.0000(
5.500000E+00 1.904367E-10 -2.0000(
5.600000E+00 2.397456E-10 -2.0000(
5.700000E+00 3.018218E-10 -2.0000(
5.800000E+00 3.799711E-10 -2.0000(
5.900000E+00 4.783553E-10 -2.0000(
6.000000E+00 6.022137E-10 -2.0000(
6.100000E+00 7.581421E-10 -2.0000(
6.200000E+00 9.544443E-10 -2.0000(
6.300000E+00 1.201574E-09 -2.0000(
6.400000E+00 1.512692E-09 -2.0000(
6.500000E+00 1.904367E-09 -2.0000(
6.600000E+00 2.397456E-09 -2.0000(
```

http://user.numazu-ct.ac.jp/~sumi/eos

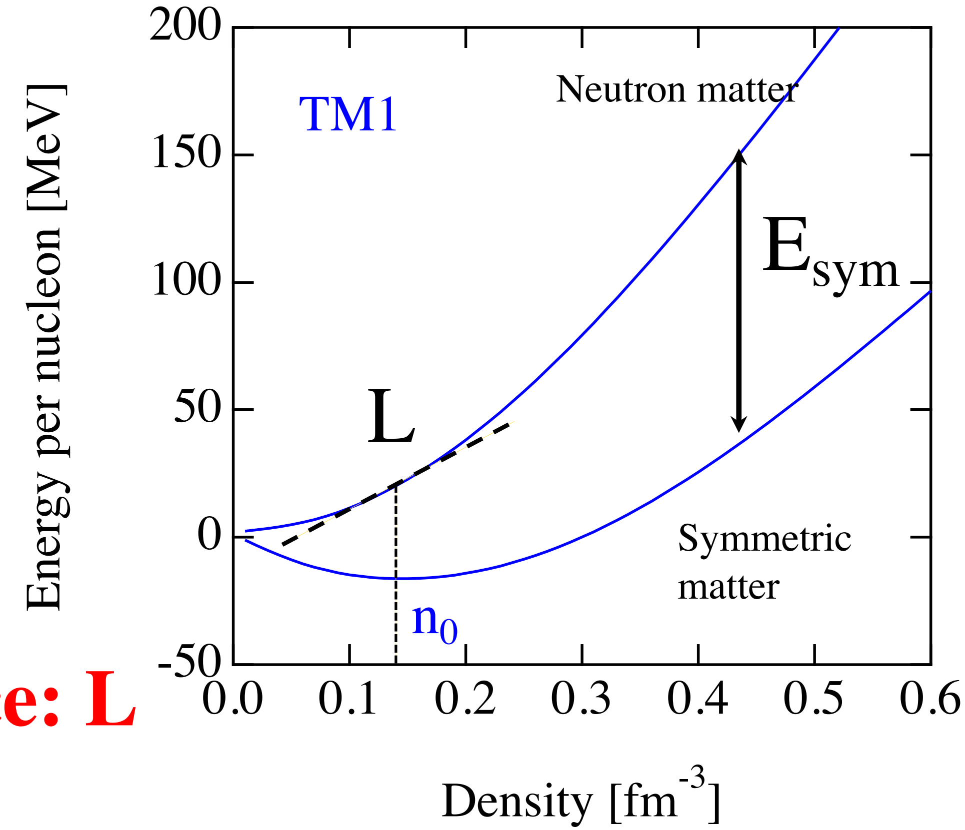
- Shen EOS (1998,2011) PTP, NPA, ApJS
  - Relativistic mean field (RMF) theory: TM1
  - Benchmark with LS EOS: many applications
    - Extended with mixture of nuclei (Furusawa)
  - Large symmetry energy

$$E_{sym}(n_0) = 37 \text{ MeV}$$

$$L = 3n_B \frac{\partial E_{sym}}{\partial n_B} = 110 \text{ MeV}$$

by nuclear structure calculations
limited knowledge in 1994

Sugahara-Toki NPA (1994)

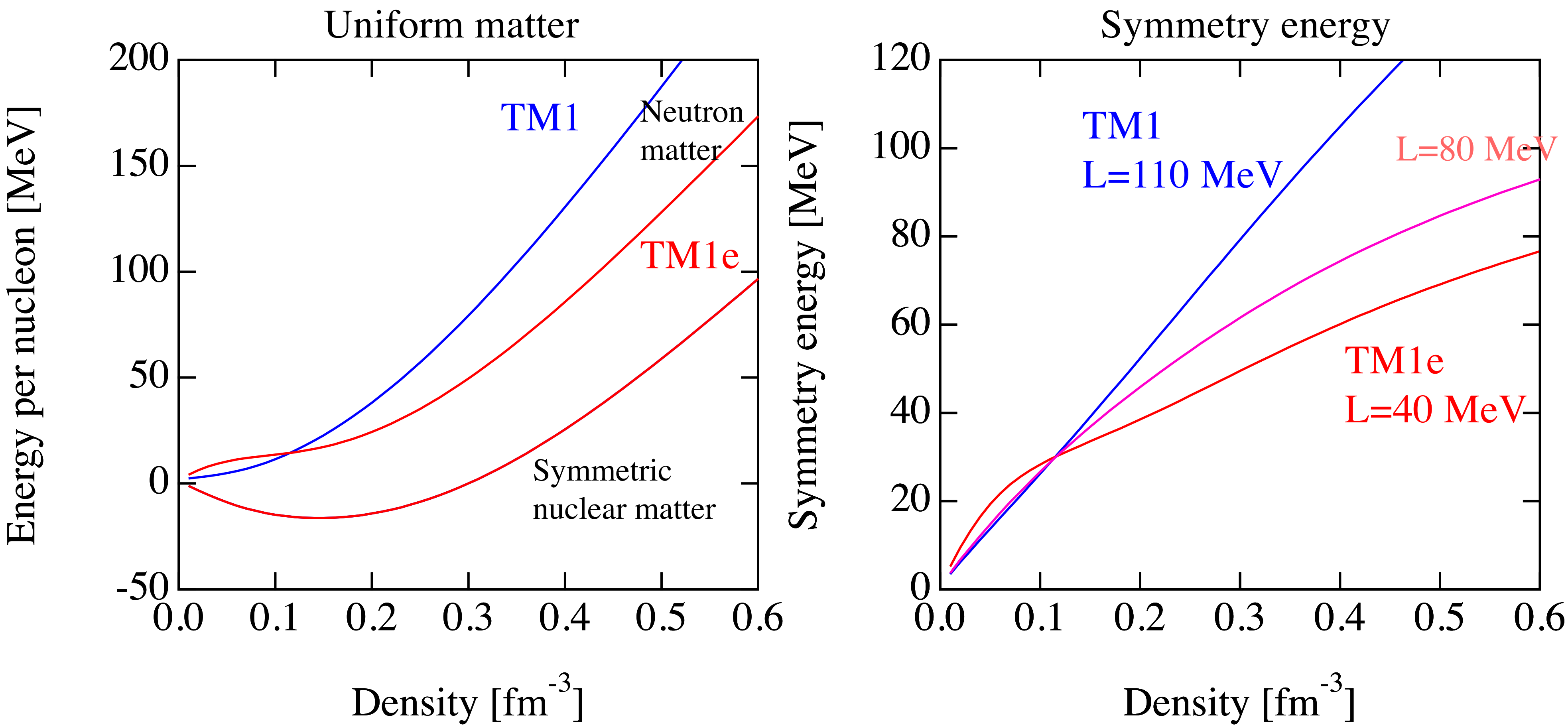


→ Extend density-dependence: L

RMF calculations: change density-dependence, L

Bao & Shen (2014)

- Change of neutron matter, same symmetric matter

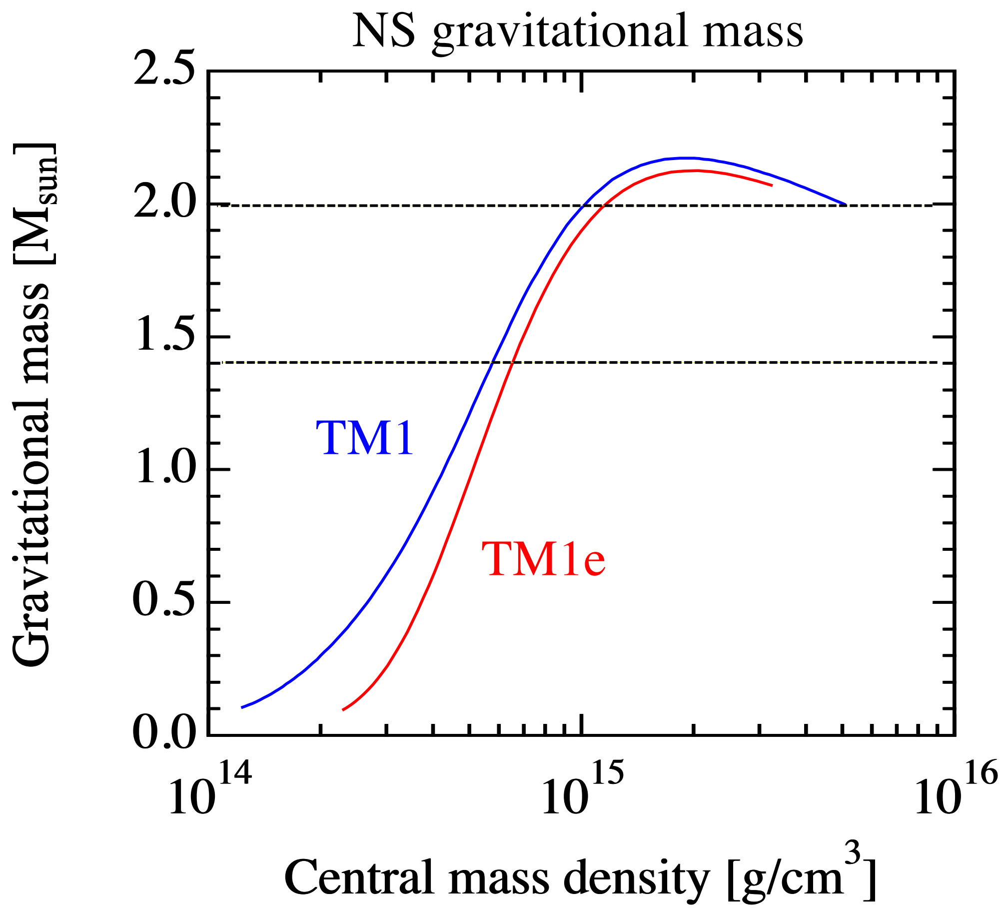


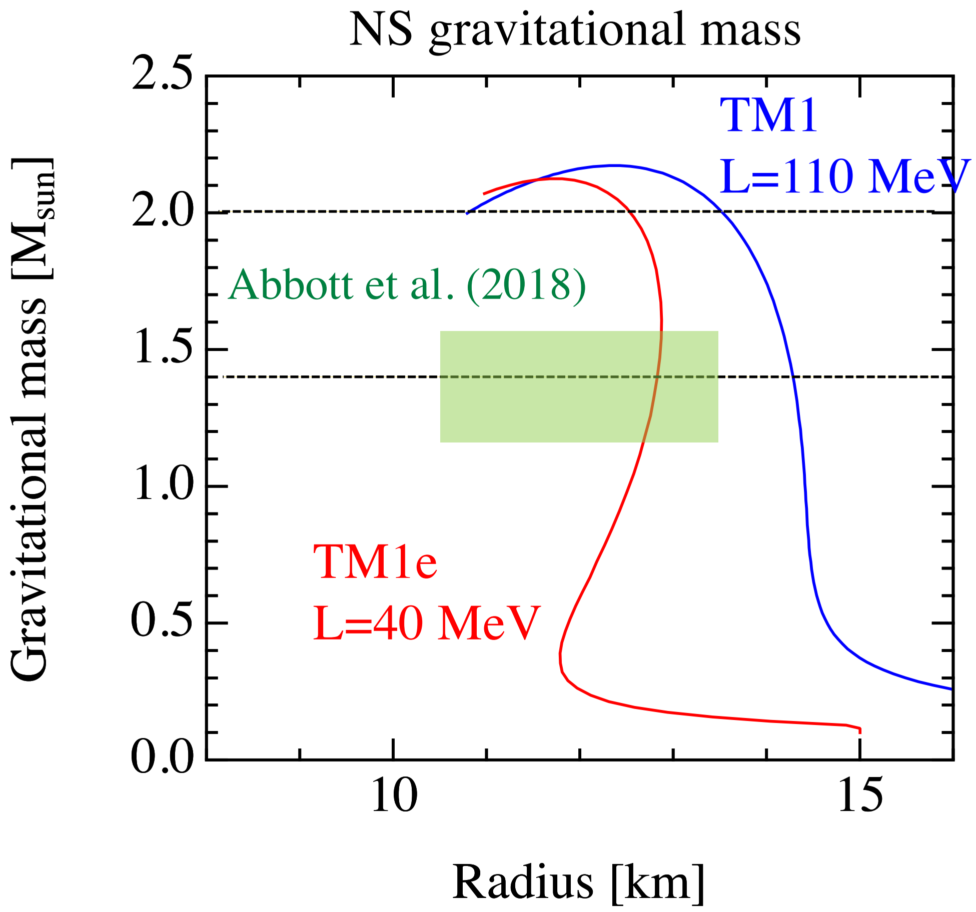
	L [MeV]	E_{sym} [MeV]
TM1	110.8	36.89
TM1e	40	31.38

Sumiyoshi et al. (2019)

Neutron star properties: L=110 → 40 [MeV]

- Similar maximum mass, smaller radius



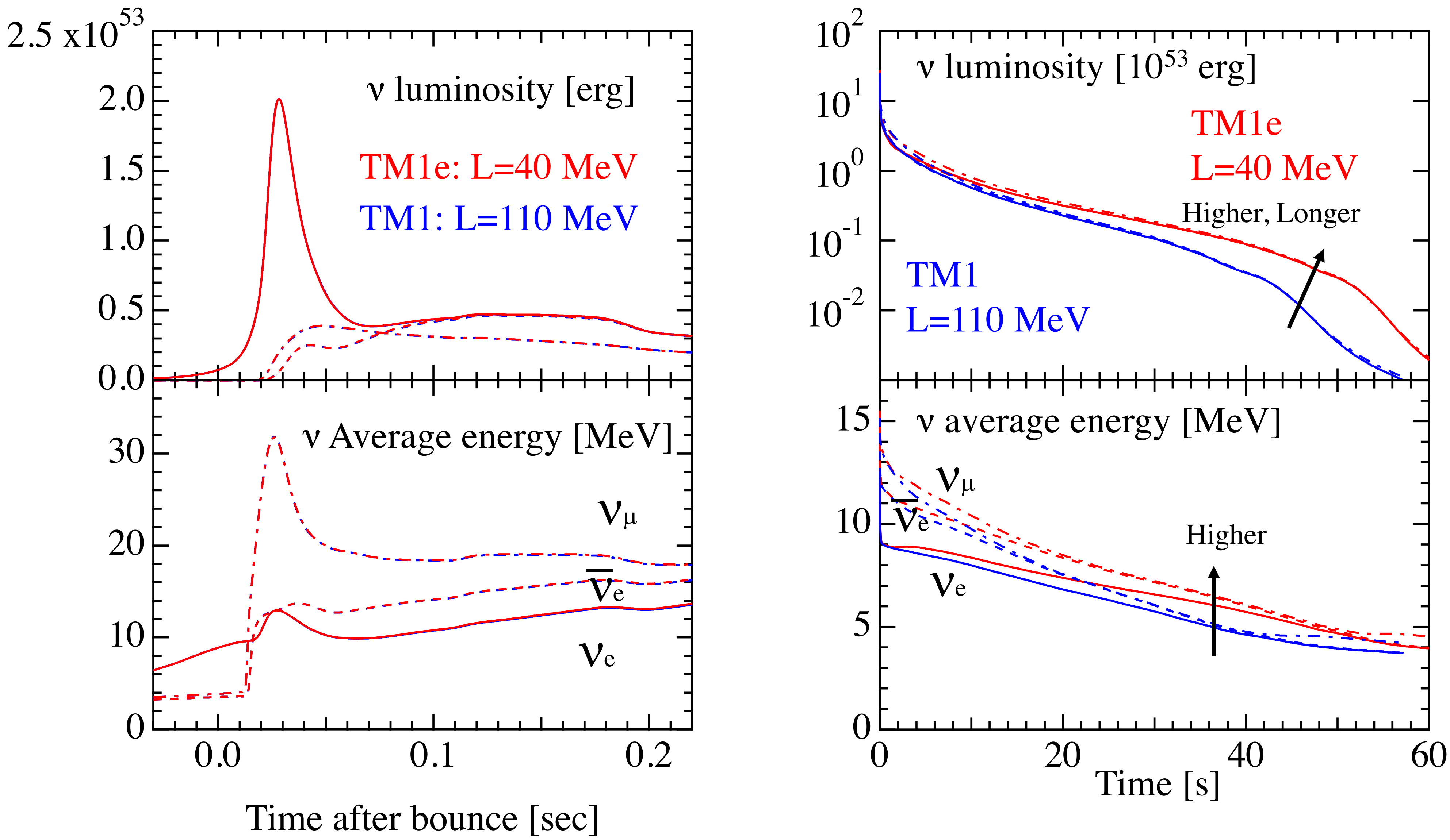


Togashi
Hu, Shen, Sumiyoshi (2019)

Shen, Furusawa

Neutrino burst in supernova & proto-NS : small L

- Very similar at bounce, Different at late phase of proto-NS



Sumiyoshi et al. 1908.02928 $15M_{sun}$ (WW95) Proto-NS cooling

Supernova & neutrino : progress report of C02

- ν-radiation hydrodynamics by Boltzmann
  - 1D spherical: supernova neutrino database
  - 2D axial: hydrodynamics with 6D Boltzmann
    - more models for different mass, EOS etc **Talk by Harada**
- Detection of supernova neutrinos at SK

  Suwa et al. ApJ (2019)
  - Long duration of neutrino bursts over 50 sec
  - Backward time plot to extract proto-NS properties
    - *EOS dependence, connection to early phase*
- Update of EOS tables: microscopic, systematics
  - Variational method, Dirac Brückner Hartree-Fock

    Togashi, Furusawa (2017, 2019)
  - Revised Shen EOS with small L

    Sumiyosh et al. (2019)

Projects in collaboration with

- Numerical simulations
  - A. Harada
  - W. Iwakami
  - H. Okawa
  - H. Nagakura
  - S. Yamada
- Supernova research
  - Y. Suwa
  - K. Nakazato
  - T. Takiwaki
  - K. Kotake
  - K. Takahashi
- Supercomputing
  - H. Matsufuru, A. Imakura
- EOS tables
  - S. Furusawa, H. Togashi
  - H. Shen, J. Hu,
  - K. Oyamatsu, H. Toki
- Super-Kamiokande
  - Y. Koshio, R. A. Wendell
  - M. Mori, M. Harada

Supported by

- *MEXT and JICFuS*
- *for K-computer and Post-K machine*

Grant-in-Aid for Scientific Research
(15K05093, 17H06357, 17H06365, 19K03837)

K-Computer *Post-K (Fugaku) , Japan*

Innovative areas on Gravitational Wave: Genesis

Gravitational Wave Physics and Astronomy Genesis