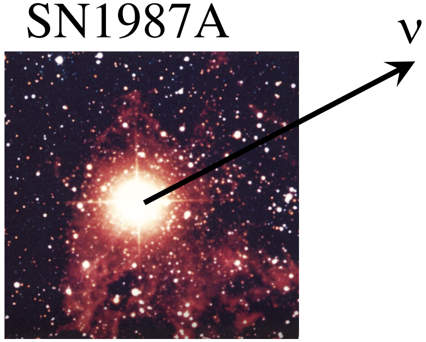
Neutrino emission and equation of state in core-collapse supernovae

SN1987A



A.K.Mann

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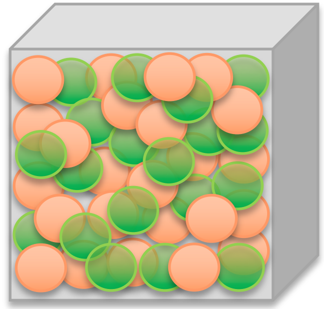
EOS



Topics on supernova neutrinos and dense matter

- Extensions beyond Shen EOS table and its effect
- Extract information from supernova neutrinos

Our approach to supernovae

EOS tables

- Relativistic mean field frameworks
  - Extensions based on Shen-EOS
- Microscopic many body theories
  - Based on nuclear interactions (VM, DBHF)
    - Composition, Weak reaction rates

Approximate → Realistic

Numerical codes

- Simulations based on Boltzmann eq. 2D by Harada
  - 1D GR Boltzmann radiation hydrodynamics code
  - 1D GR FLD proto-NS cooling code
- Examine nuclear physics, neutrino signals

→ Clarify role of nuclear physics in supernovae

Topics of EOS and supernova neutrinos

- Update of EOS table I: revised Shen EOS

  Sumiyoshi et al. arXiv:1908.02928

  - RMF with density-dependent symmetry energy
  - Effects on supernovae, BH formation, Proto-NS

- Update of EOS table II: microscopic approaches

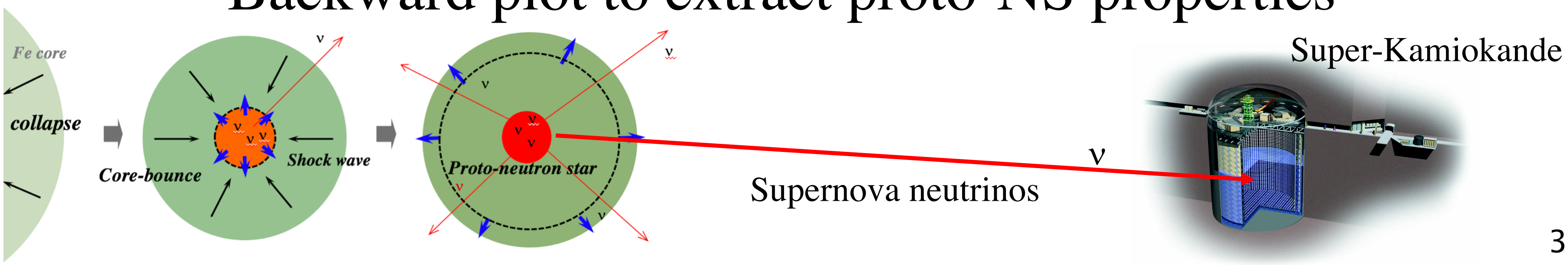
  Togashi, Furusawa (2017, 2019)

  - Variational method (non-relativistic)
  - Dirac Brückner Hartree-Fock theory (relativistic)

- Proto-NS in detection of supernova neutrinos

  Suwa et al. ApJ (2019) arXiv:1904.09996

  - Long duration of neutrino bursts > 50 sec
  - Backward plot to extract proto-NS properties



Update of EOS table I : symmetry energy of RMF

Sumiyoshi et al. arXiv: 1908.02928

- 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

```
cccccccccccccccccccccccccccccccccccccc
 Temperature=  1.000000E-01

5.100000E+00  7.581421E-11 -2.00000
5.200000E+00  9.544443E-11 -2.00000
5.300000E+00  1.201574E-10 -2.00000
5.400000E+00  1.512692E-10 -2.00000
5.500000E+00  1.904367E-10 -2.00000
5.600000E+00  2.397456E-10 -2.00000
5.700000E+00  3.018218E-10 -2.00000
5.800000E+00  3.799711E-10 -2.00000
5.900000E+00  4.783553E-10 -2.00000
6.000000E+00  6.022137E-10 -2.00000
6.100000E+00  7.581421E-10 -2.00000
6.200000E+00  9.544443E-10 -2.00000
6.300000E+00  1.201574E-09 -2.00000
6.400000E+00  1.512692E-09 -2.00000
6.500000E+00  1.904367E-09 -2.00000
6.600000E+00  2.397456E-09 -2.00000
```

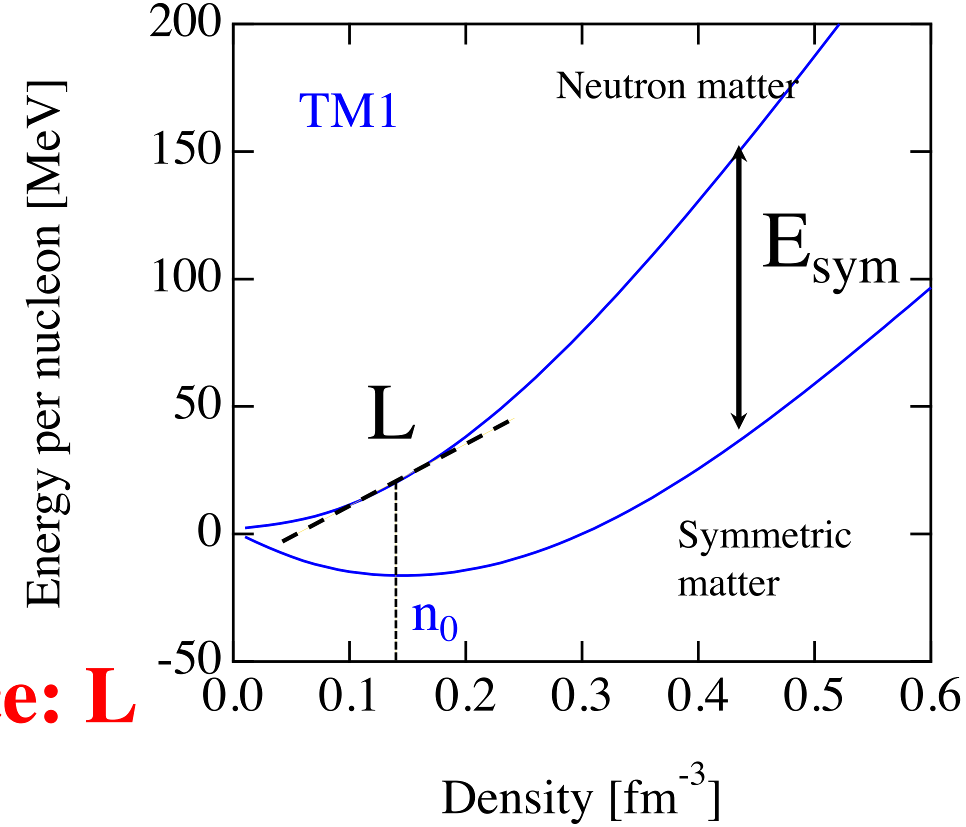
http://user.numazu-ct.ac.jp/~sumi/eos

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

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

by nuclear structure calculations
limited knowledge in 1994

Sugahara-Toki NPA (1994)



→ Extend density-dependence: L

Density dependence of symmetry energy

- Additional term for iso-vector meson in RMF
  - Non-linear meson term

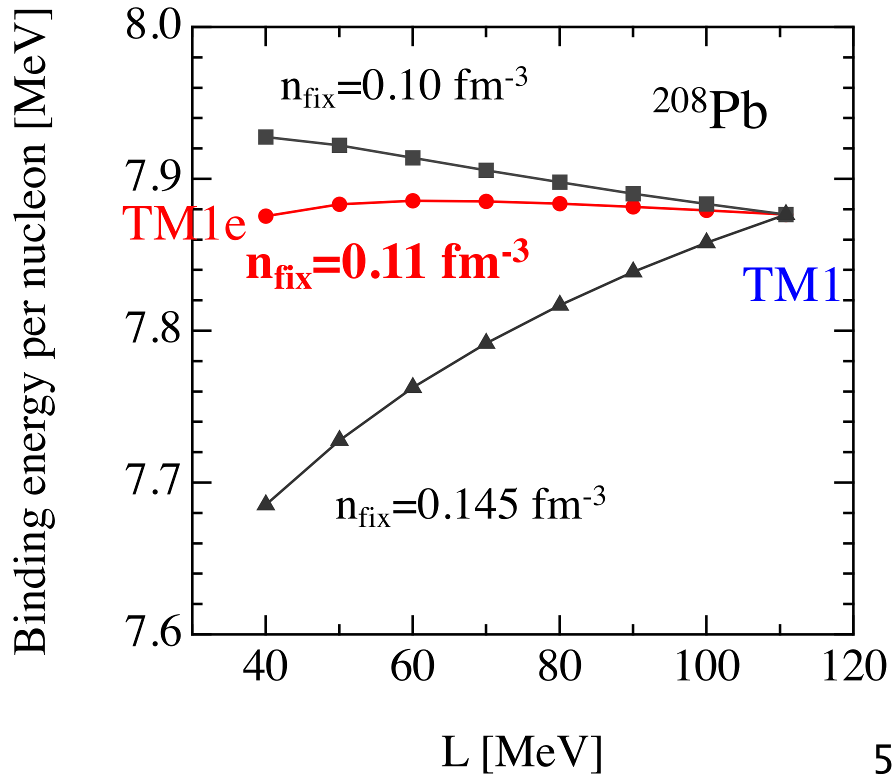
Bao, Hu, Zhang, Shen PRC (2014)

$$-\frac{1}{3}g_2\sigma^3-\frac{1}{4}g_3\sigma^4+\frac{1}{4}c_3(\omega_\mu\omega^\mu)^2+\Lambda_v\left(g_\omega^2\omega_\mu\omega^\mu\right)\left(g_\rho^2\rho_\mu^a\rho^{a\mu}\right)$$

Incompressibility	Dirac Brueckner HF	Density-dependent symmetry energy
Boguta-Bodmer	Sugahara-Toki	Horowitz-Piekarewicz

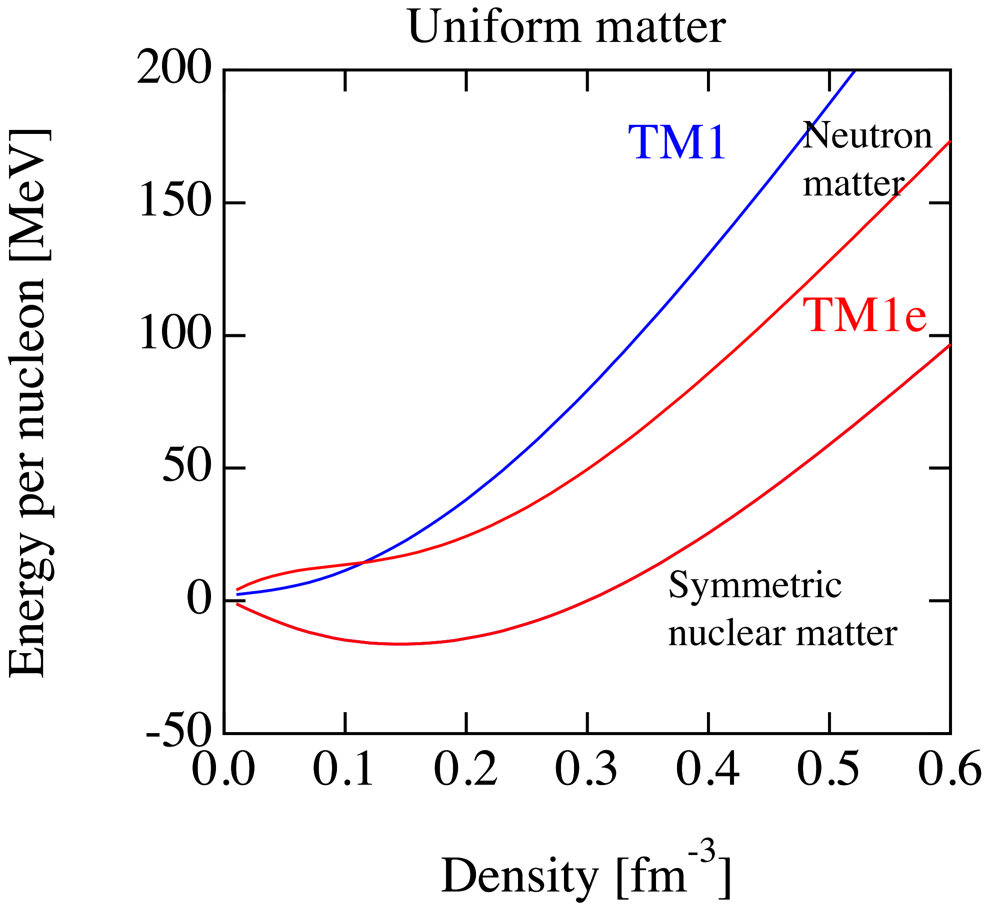
- Same symmetric matter
  - Good properties of nuclei
- Same value of E_{sym}
  - But at n_B=0.11 fm^{-3} < n_0
- Study by changing L

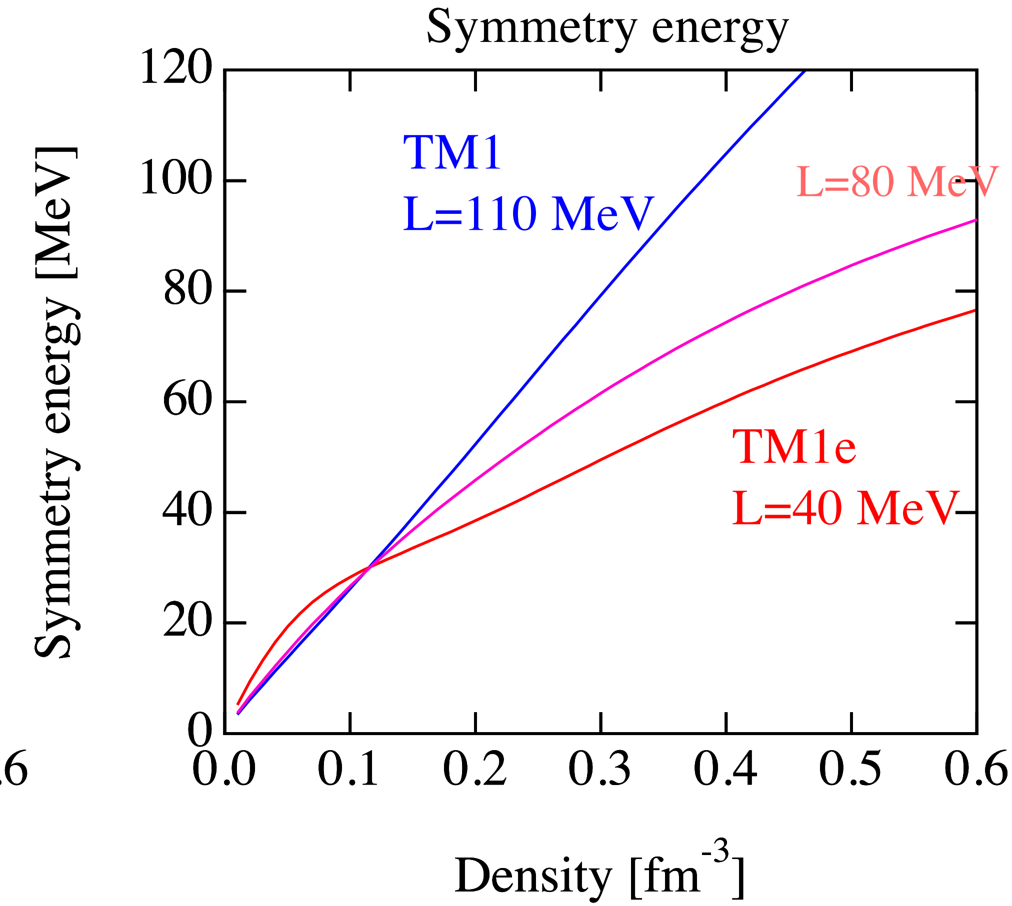
TM1e : L=40 MeV



RMF calculations: change density-dependence, L

- Change of neutron matter, same symmetric matter



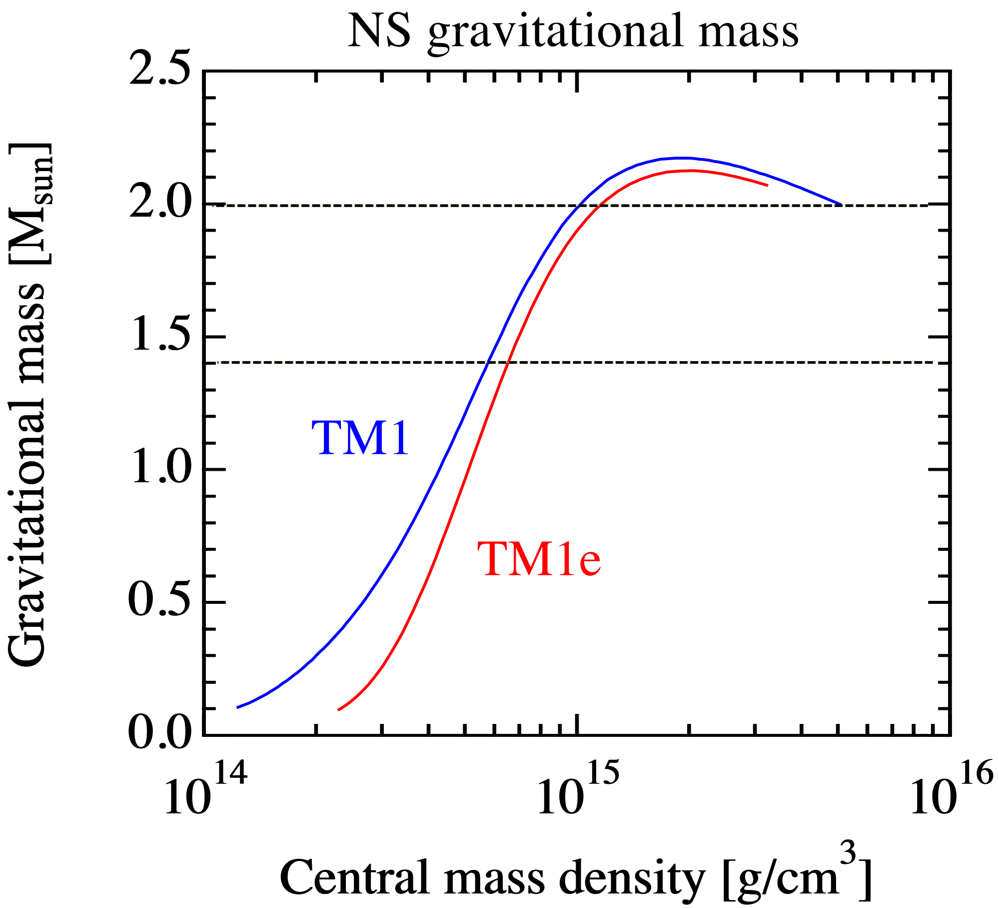


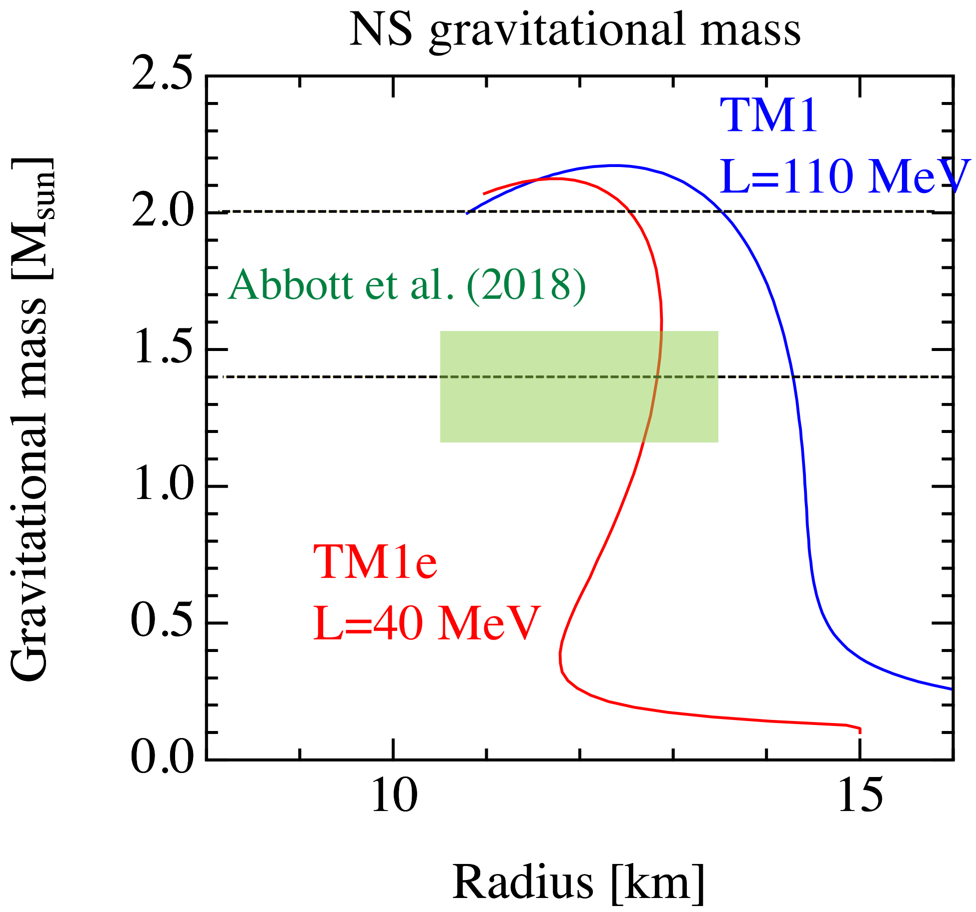
	L [MeV]	E_{sym} [MeV]
TM1	110.8	36.89
TM1e	40	31.38

Sumiyoshi et al. (2019)

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

- Similar maximum mass, smaller radius





Togashi
Shen, Hu, Sumiyoshi (2019)

Shen, Furusawa

Numerical codes

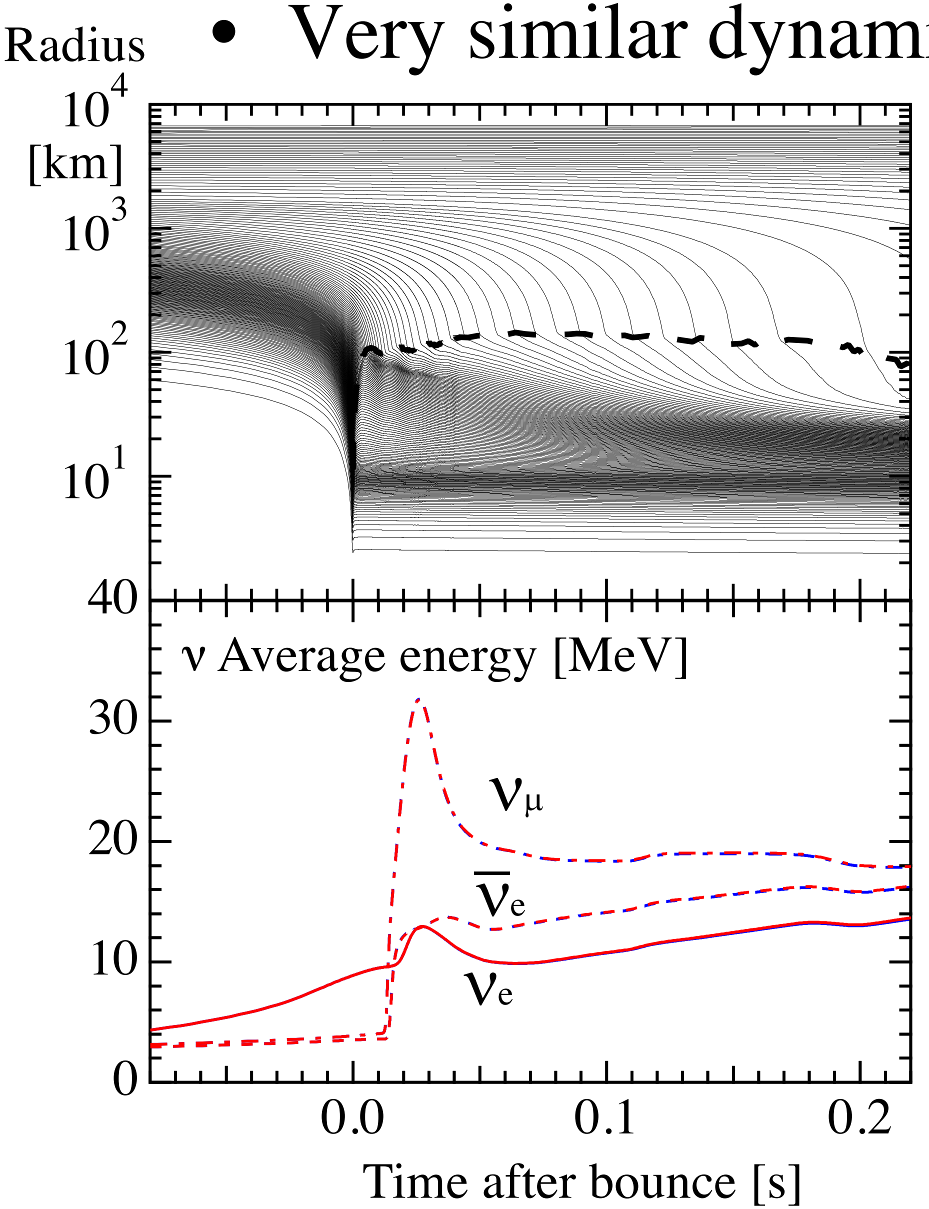
Sumiyoshi et al. arXiv: 1908.02928

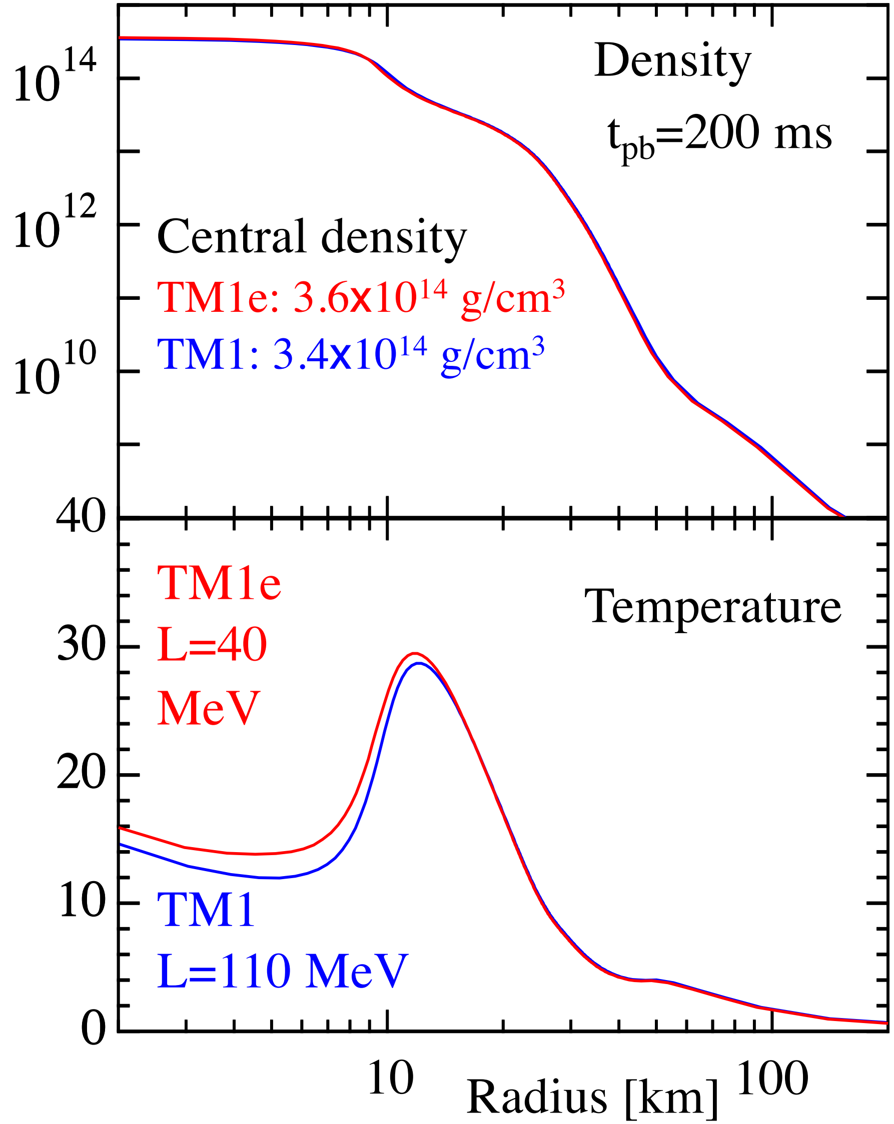
- 1D GR neutrino-radiation hydrodynamics
  - Collapse of massive stars to 200 ms after bounce
  - 15M_{sun} WW95, 11.2M_{sun}, 15M_{sun} WHW02
  - 40M_{sun} WW95, 50M_{sun} TUN07
- 1D GR Flux-limited diffusion, quasi-static structure
  - Thermal evolution of proto-NS cooling
  - Initial condition with Y_e, S-profile (0.3 s after bounce)
  - Additional proto-NS models for M_{NS}=1.2, 2.1M_{sun}
- Data table of TM1e EOS for uniform matter
  - Use of TM1 Shen EOS for low density $< 10^{14}$ g/cm^3
  - Working on full TM1e EOS table

Shen, Furusawa

Applications to supernovae: small L

- Very similar dynamics, a little high temperature





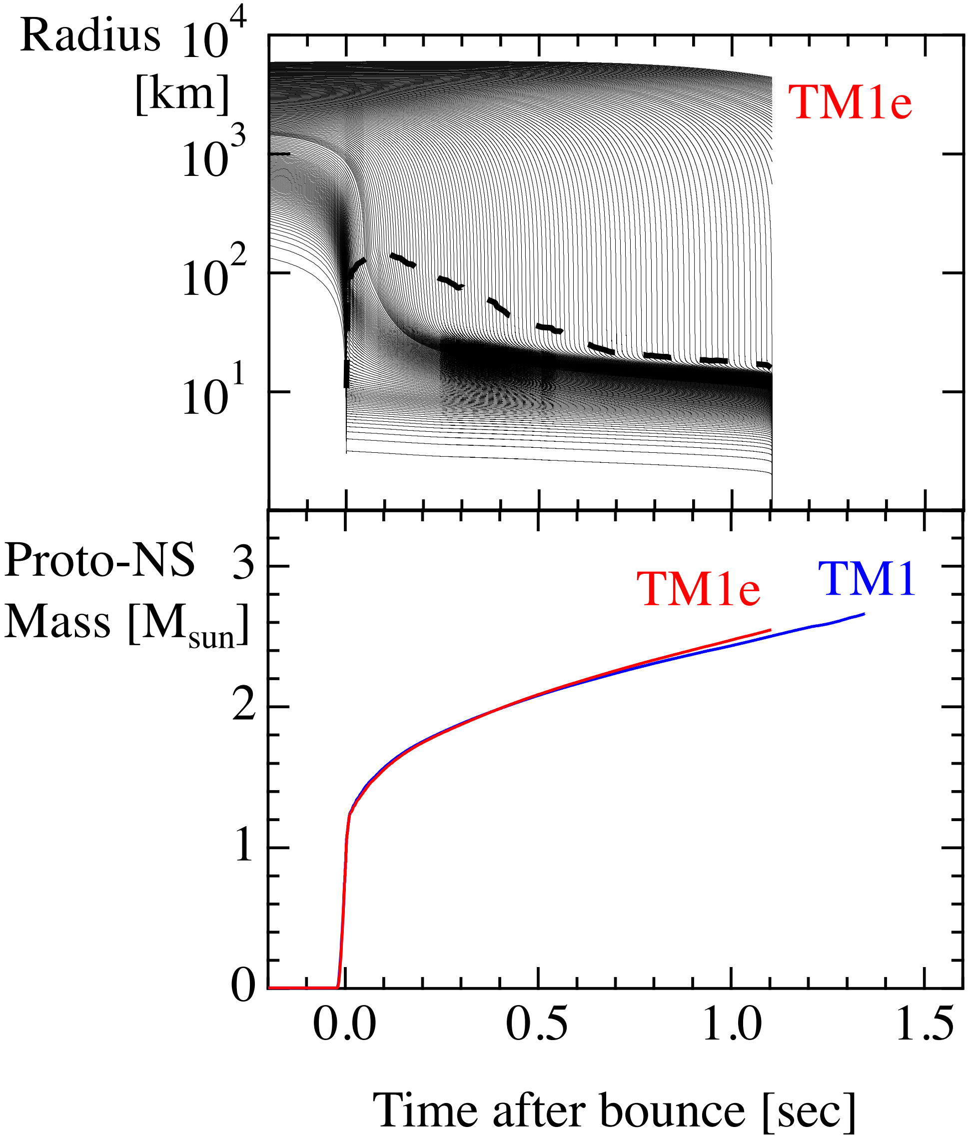
Sumiyoshi et al. 1908.02928

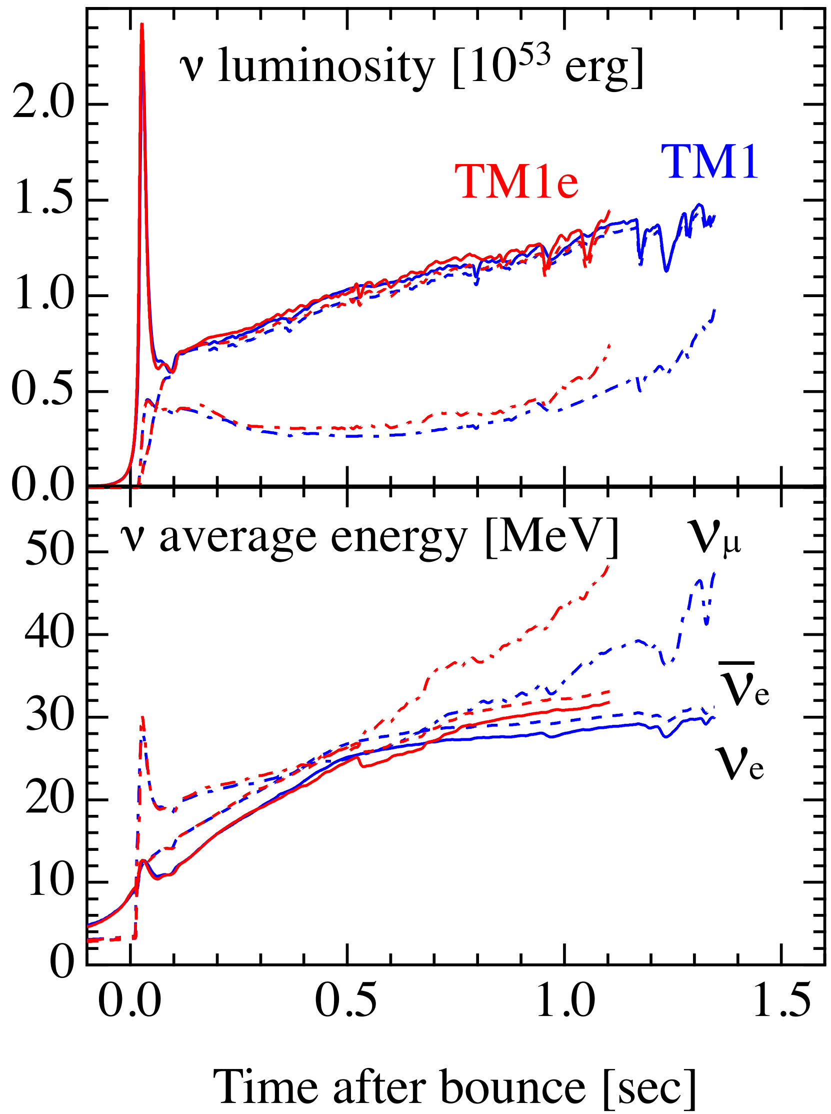
1D GR ν-radhyd

15M_{sun} (WW95)

Applications to black hole formation: small L

- Shorter duration till recollapse: small M_{max}



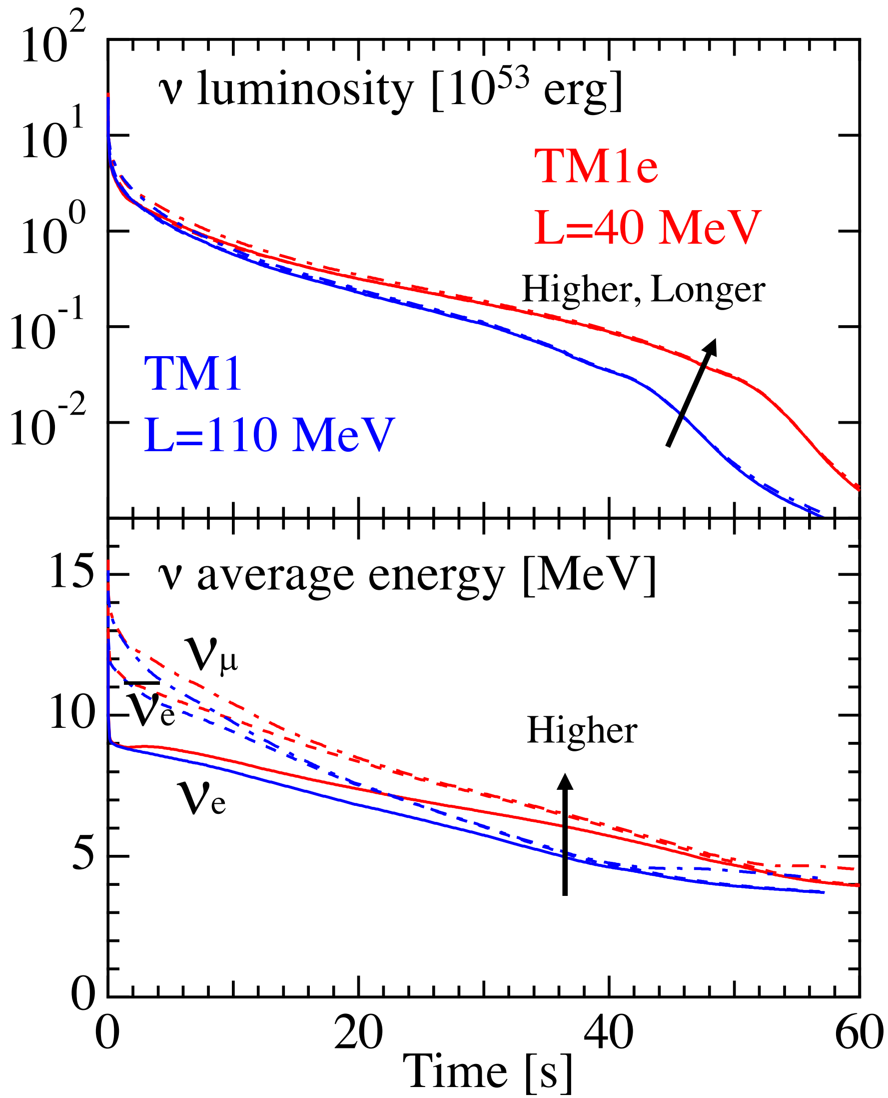


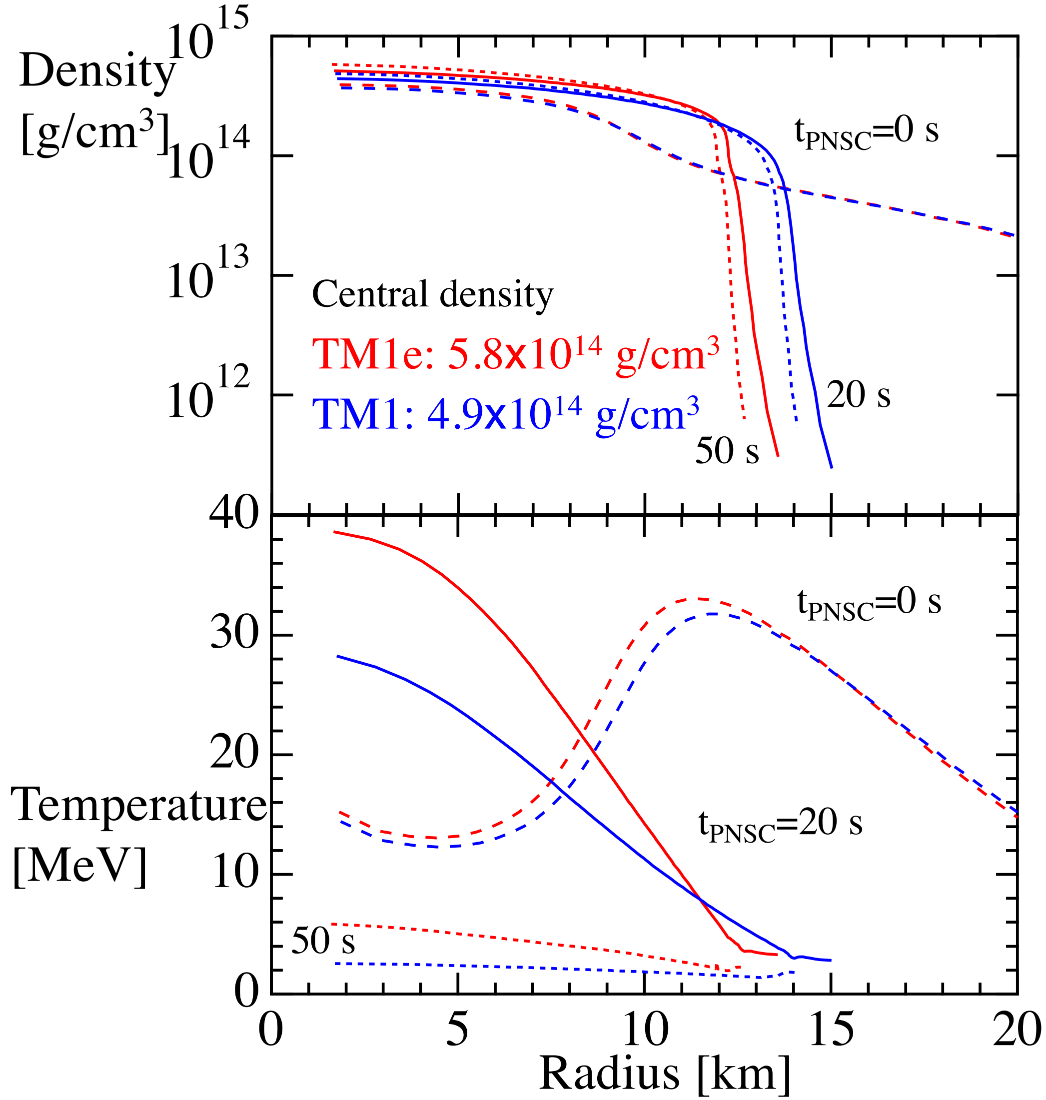
Sumiyoshi et al. 1908.02928

1D GR ν-radhyd 40M_{sun} (WW95)

Applications to proto-neutron star cooling: small L

- Differences in neutrinos, density, temperature



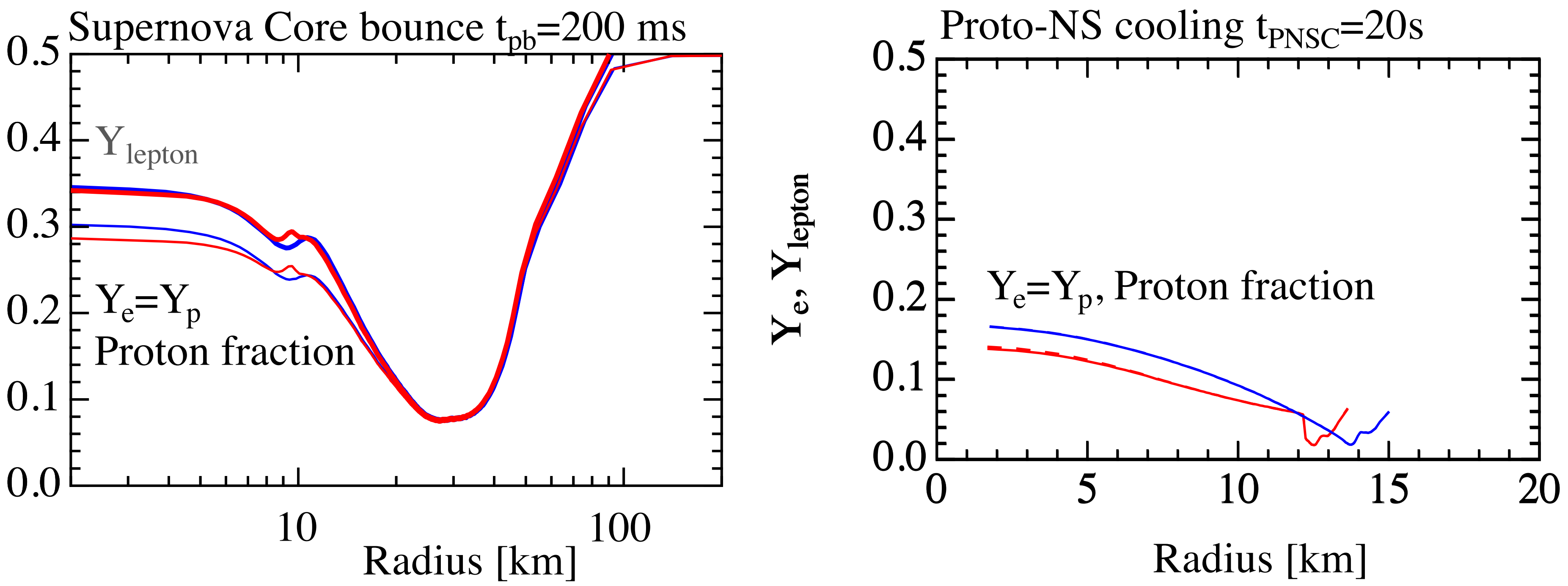


Nakazato, Sumiyoshi et al. 1908.02928

1D GR FLDν proto-NS cooling

EOS effects when matter becomes neutron-rich

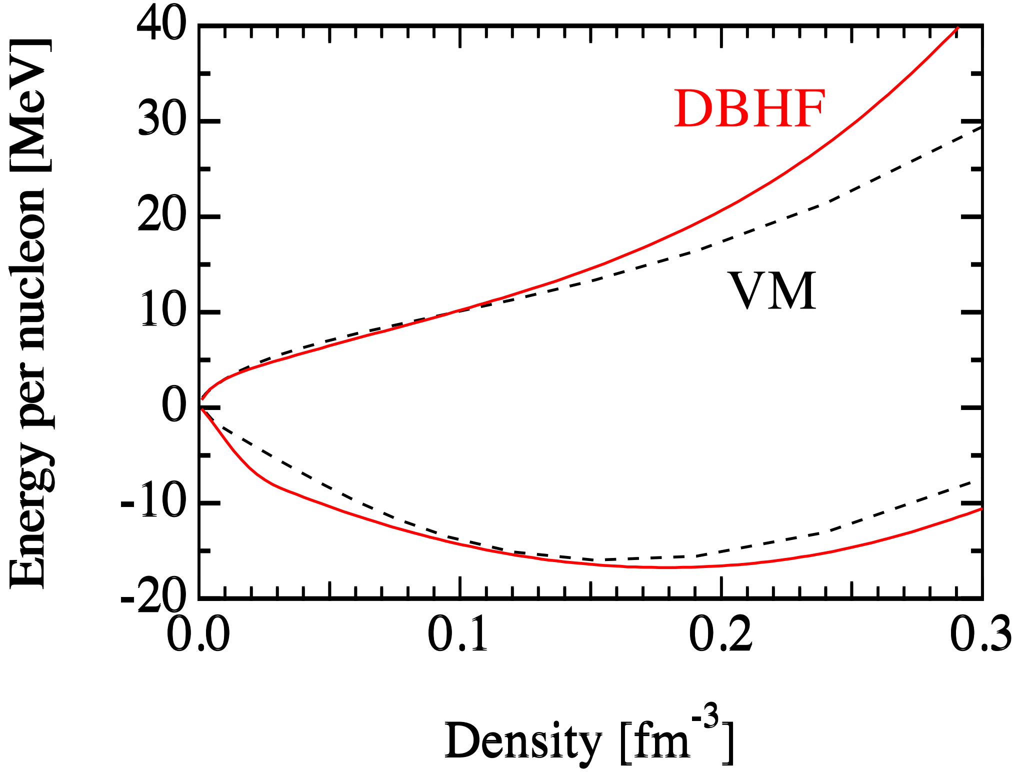
- Minor difference around core bounce till 200 ms
  - Not so neutron-rich at moderate density → Small difference
- Difference appears at late stage in proto-neutron star
  - Effects on neutron star formation and neutrino emission

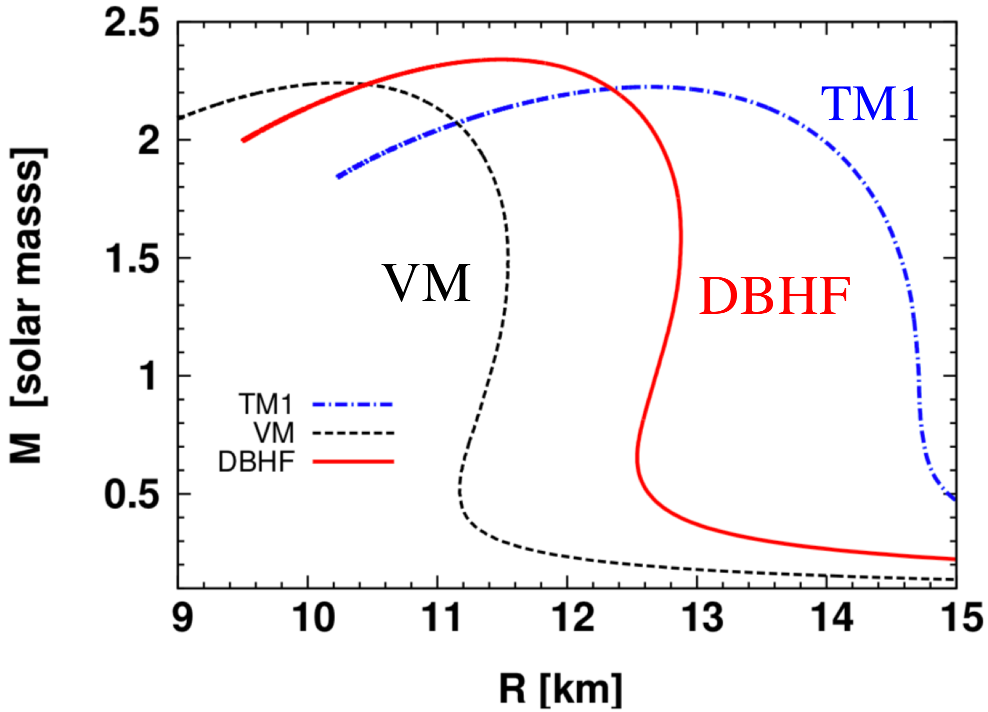


Sumiyoshi et al. 1908.02928

Update of EOS table II: microscopic approaches

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



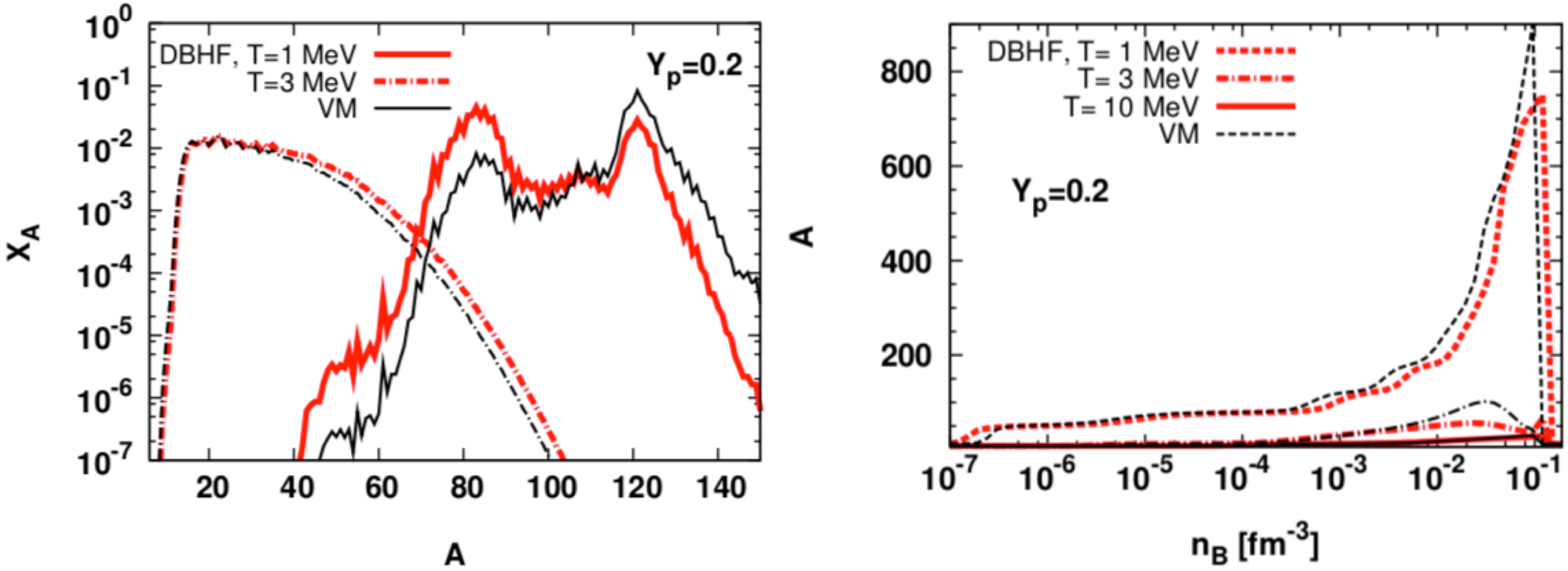


Non-relativistic vs relativistic (ex. LS vs Shen)

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



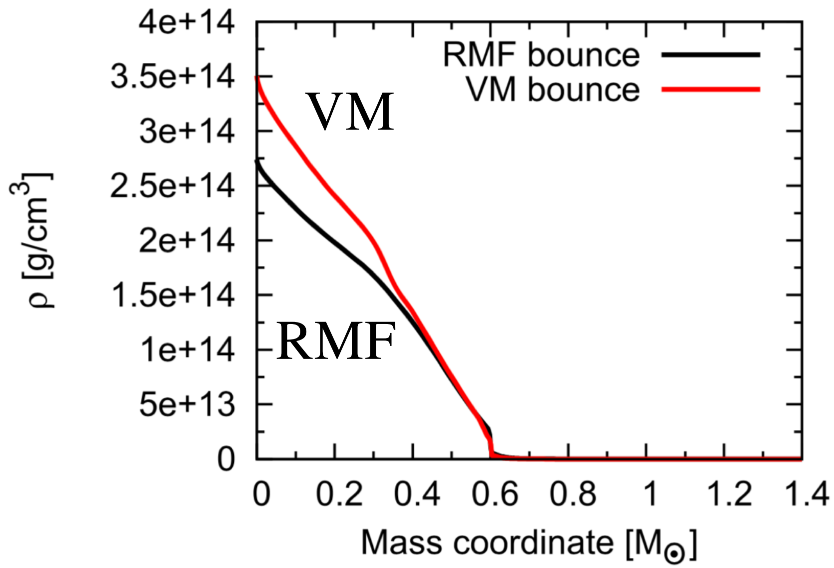
Different compositions (mass fractions, nuclear abundance)

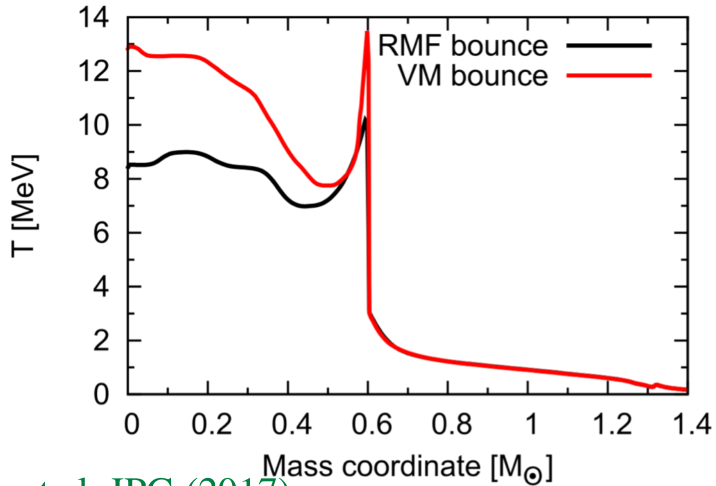
Furusawa et al. (2019)

Applications to supernovae: Variational Method

Togashi, NPA (2017), Furusawa JPG (2017)

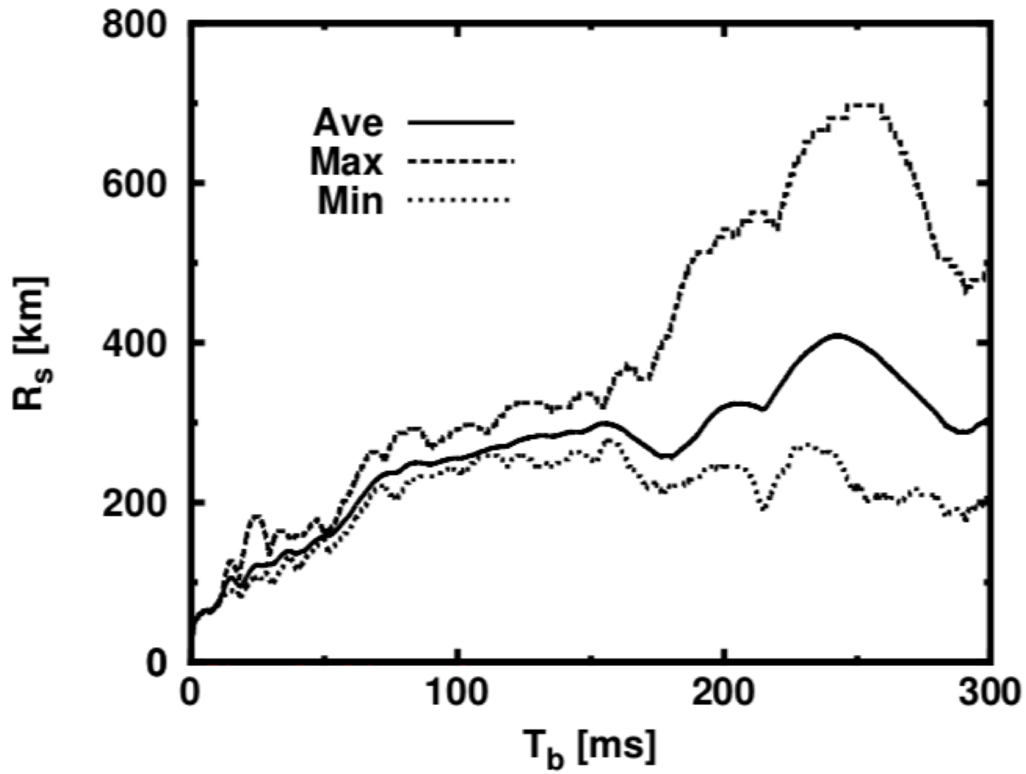
- 1D: RMF vs VM
  - WHW02, 11.2M_{sun}





Furusawa et al. JPG (2017)

- 2D: VM EOS



Possible early kick of proto-NS arXiv:1907.04863

Nagakura et al. ApJ (2017)

Explore more on EOS by 2D simulations

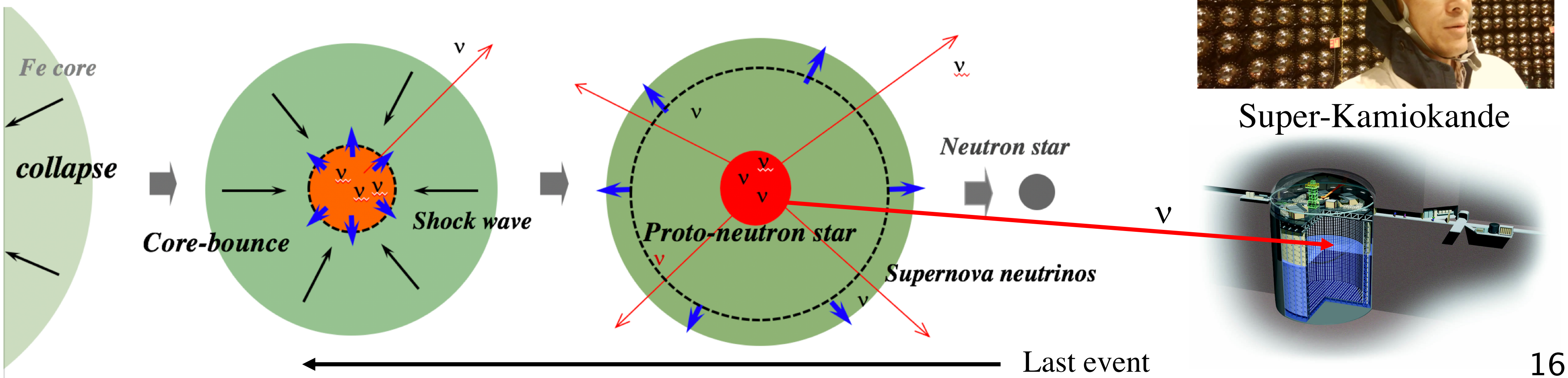
Detection of supernova neutrinos

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

- 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

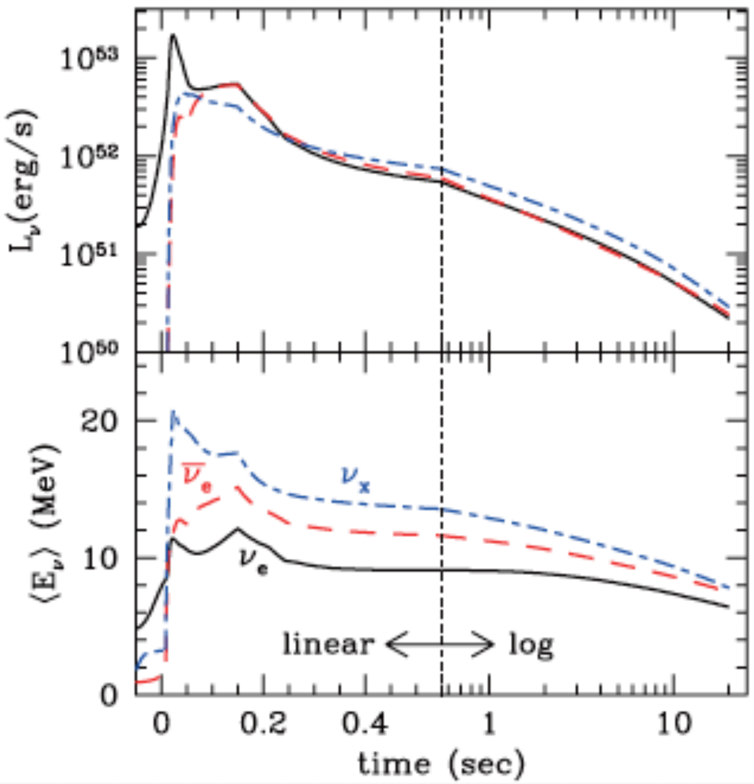
Super-Kamiokande



Supernova neutrino data database

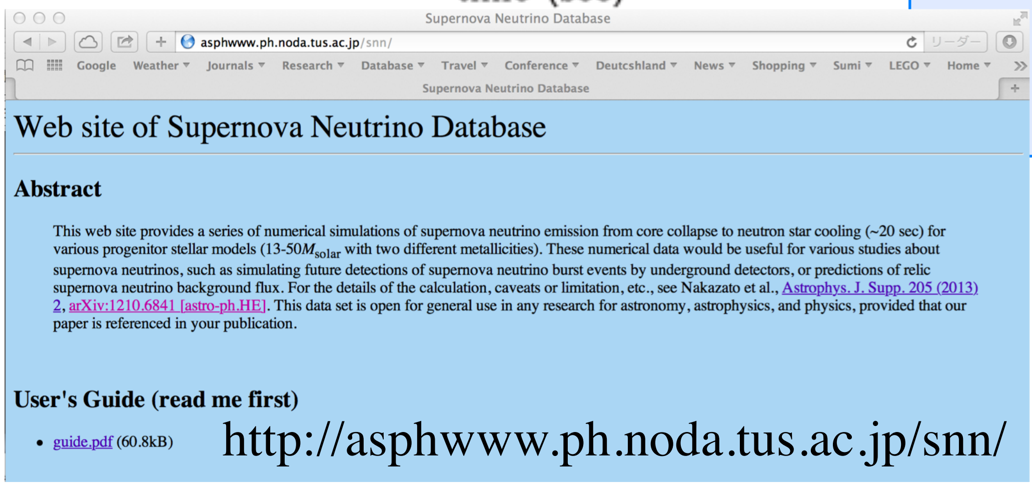
Nakazato et al. ApJ 2013

- 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/

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)

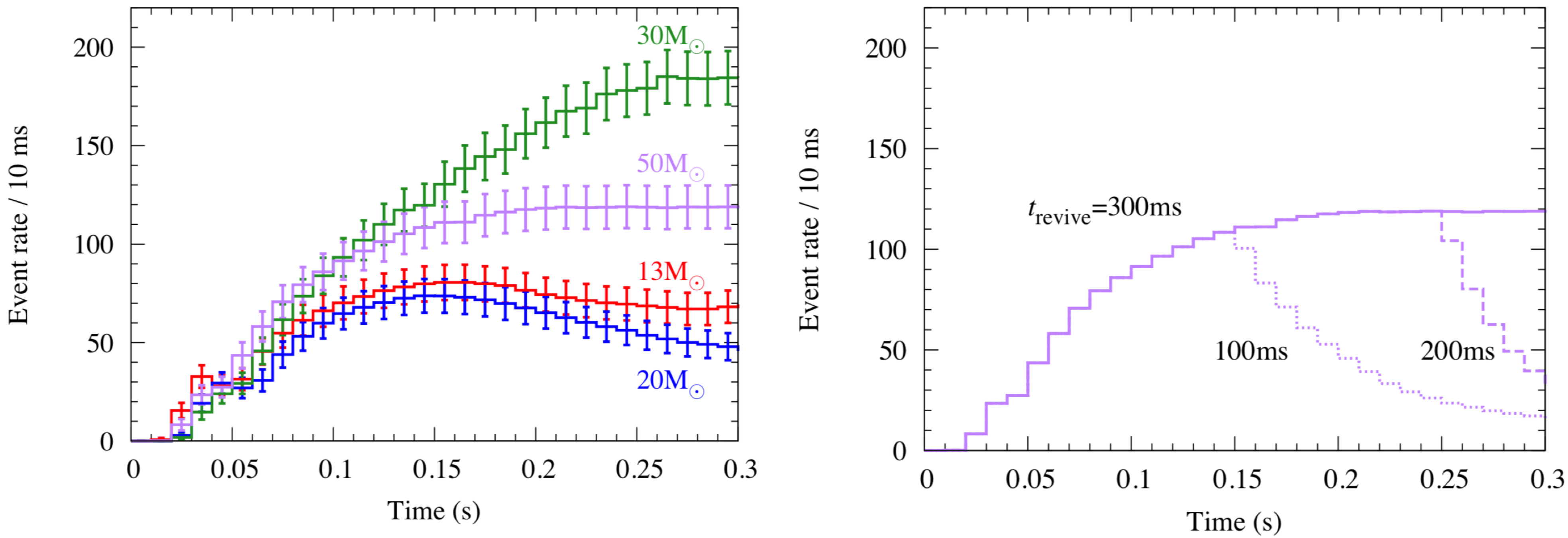
http://asphwww.ph.noda.tus.ac.jp/snn/

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)

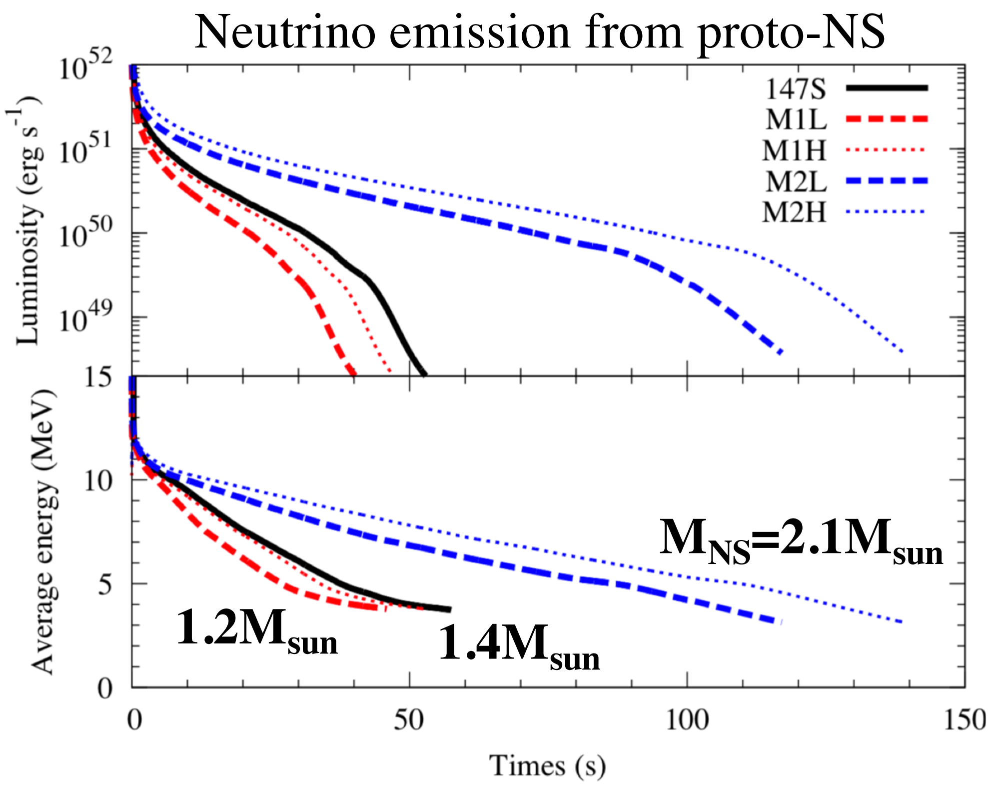


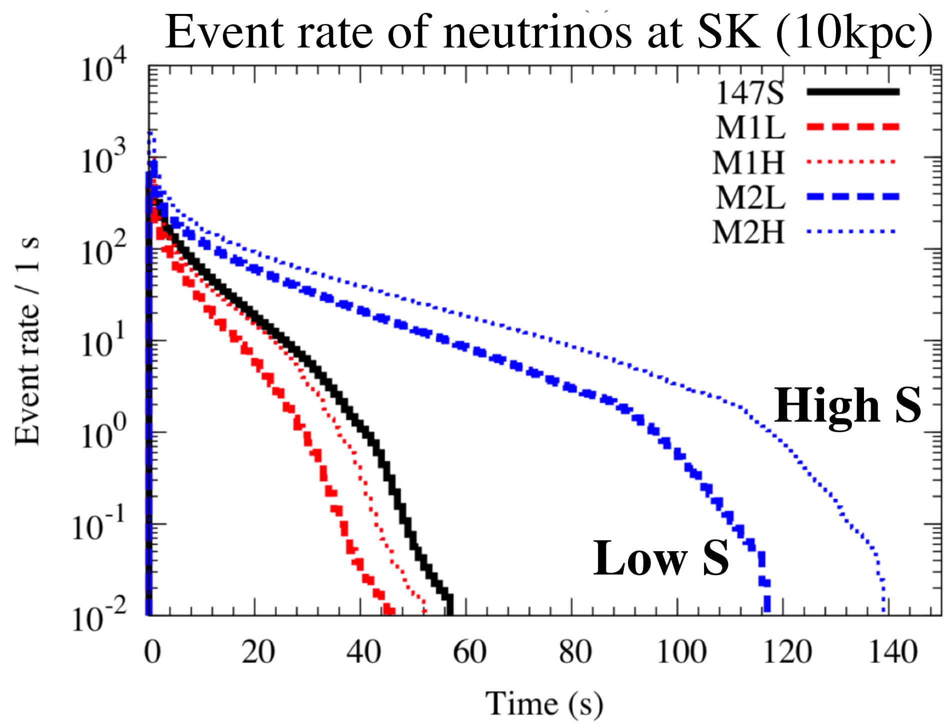
- At early phase phase around core bounce
  - Depends on matter accretion from progenitor
  - May have more variations due to 2D/3D effects, Less EOS dependent

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



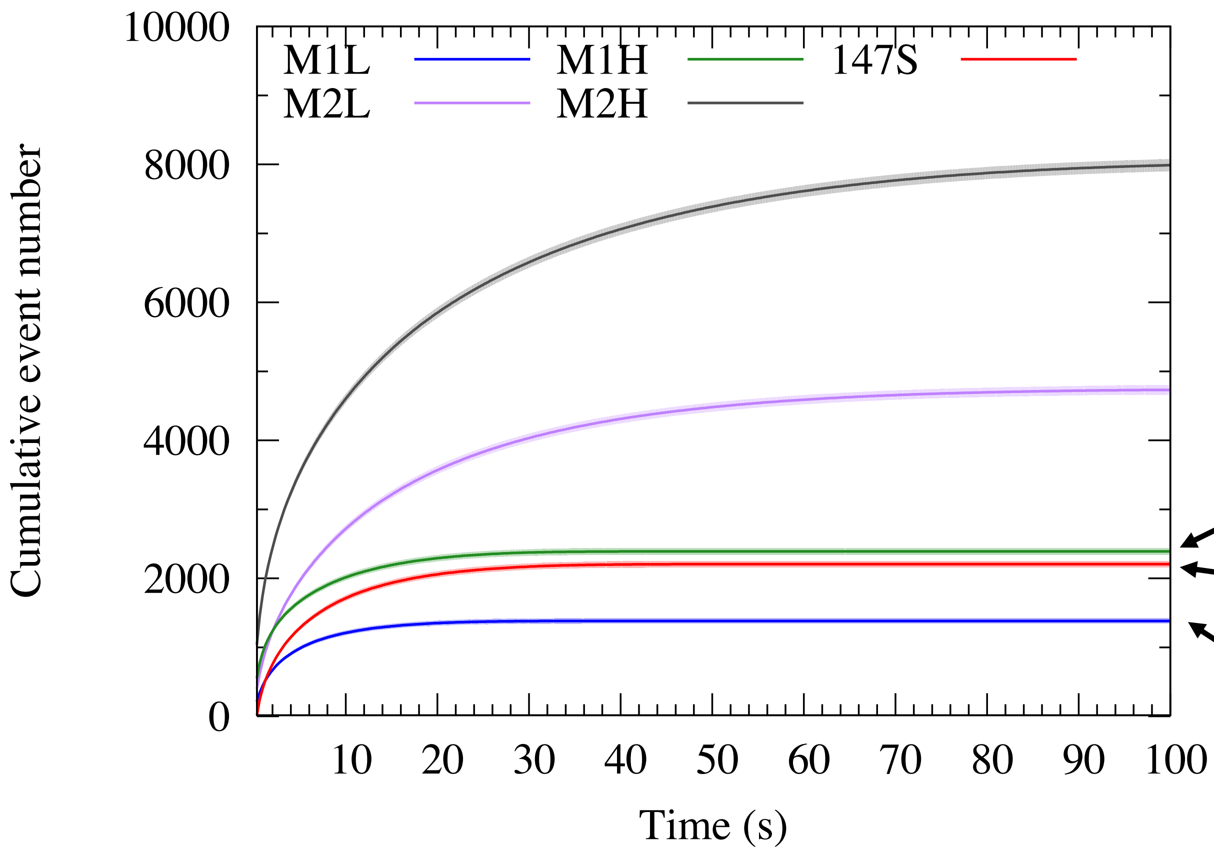


- At late phase due to proto-NS cooling
  - Simple emission of all flavors from diffusion (indep. of ν-osc.)
  - May have convection, More EOS dependent

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

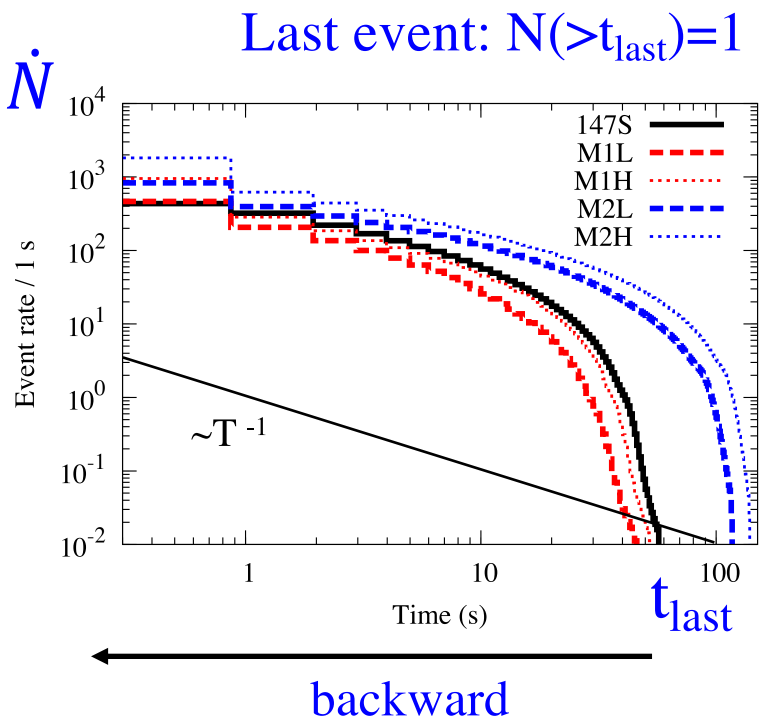
But, depends on initial profiles?

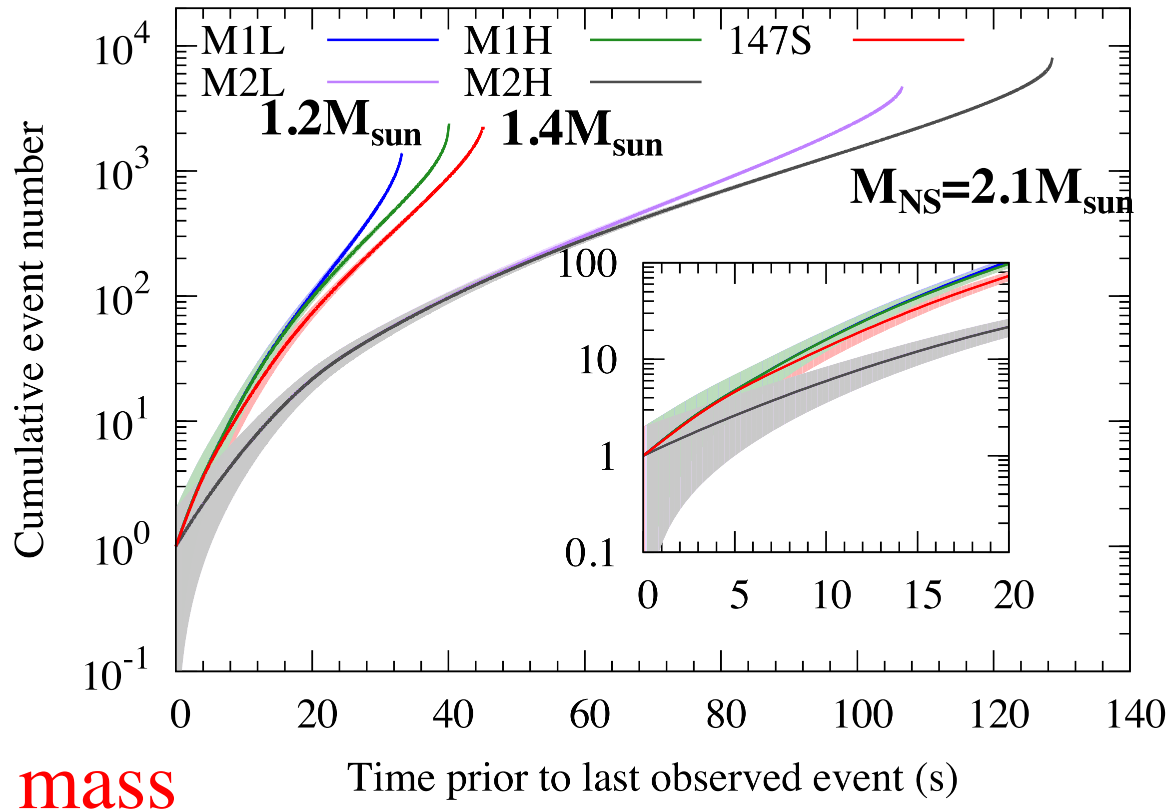
- We plot time backward: less sensitive initial cond.

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

Topics of EOS and supernova neutrinos

- Update of EOS table I: revised Shen EOS

  Sumiyoshi et al. arXiv:1908.02928
  - RMF with density-dependent symmetry energy
  - Major effects at late stage in Proto-NS
    - *Working on full table with low densities*
- Update of EOS table II: microscopic approaches

  Togashi, Furusawa (2017, 2019)
  - Variational method (non-relativistic)
  - Dirac Brückner Hartree-Fock theory (relativistic)
    - *Applications to 2D simulations*
- Proto-NS in detection of supernova neutrinos

  Suwa et al. ApJ (2019) arXiv:1904.09996
  - Long duration of neutrino bursts over 50 sec
  - Backward time plot to extract proto-NS properties
    - *EOS dependence, connection to early phase*

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, Y. Takahira

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

Innovative areas on Gravitational Wave: Genesis

Gravitational Wave Physics and Astronomy Genesis