Title: Progress of EOS tables for neutrino-radiation hydrodynamics of core-collapse

Date: Jun 21, 2011 03:00 PM

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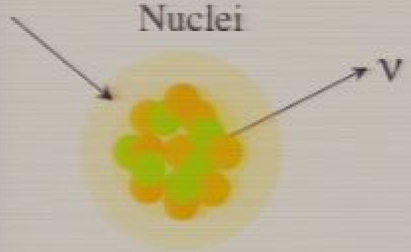
Abstract: I would like to overview the progress of the EOS tables for core-collapse supernovae and their influence clarified by these EOS developments. Some topics I try to cover include the neutrino signal from the black hole formation as well as the composition in supernova cores. We would to like hear needs and comments from users of the series of Shen EOS tables for further developments. I would like to report also on recent development of our numerical code of the neutrino-transfer calculation in 3D.

Progress of supernova simulations with the Shen equation of state



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Supernova

Crab nebula

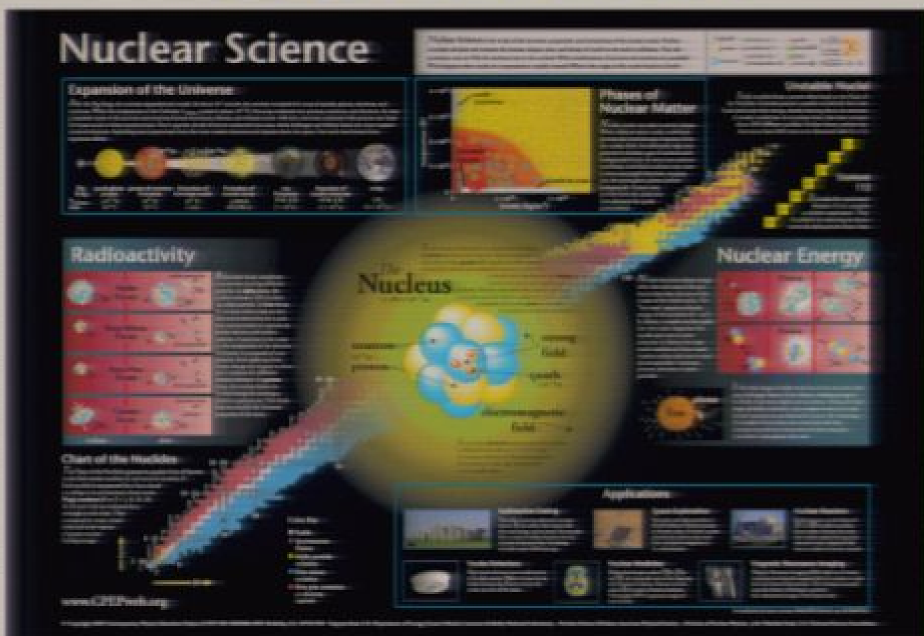
Applications of nuclear physics in astrophysics

- Series of the Shen EOS tables
- Neutrino bursts as a probe of EOS

Focus of Interests

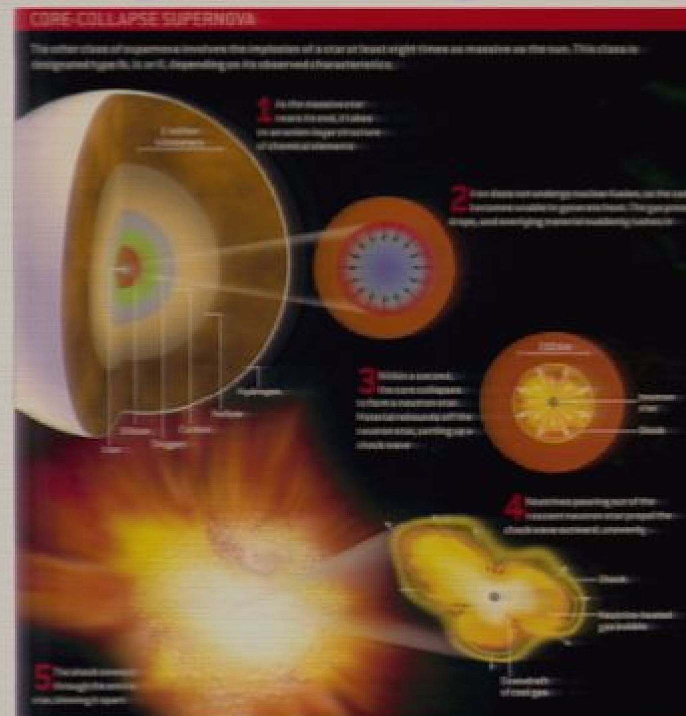
- Interplay of nuclear physics and astrophysics

Nuclei and matter



http://www.lbl.gov/abc/wallchart/index.html

Supernova explosions



Scientific American (2006

How are they related to each other?

Microphysics determines the outcome.

Updates on the Shen EOS

extension with compositions

Supernova EOS covering the wide range

- Tables of EOS so far
  - Wolff-Hillebrandt EOS (1985)
  - Lattimer-Swesty EOS (1991)
    - *Extension of liquid-drop models (Skyrme-like)*
  - H. Shen, Toki, Oyamatsu & Sumiyoshi EOS (1998)
    - *Relativistic Mean Field approach*

- Extensions to high densities
  - Hyperons — Ishizuka, H. Shen
  - Quarks — Schäffner, Nakazato
    - *RMF SU(3), MIT Bag model* — *also Baldo-Schulz et al.*
- Extension to low densities
  - Mixture of nuclei — G. Shen, Hempel, Furusawa
    - *NSE, Virial expansion* — *also Newton, Botvina, Blinnikov*

Extensions of Shen EOS tables

- Appearance of hyperons & quarks

Ishizuka et al. JPG (2006), Nakazato et al. PRD (2008

EOS table	Framework	Nucleons	Hyperons	Quarks	Max. NS
Shen EOS 1998, NPA	RMF	n, p, α, nuclei	-	-	$2.2M_{sun}$
Hyperon EOS 2008, JPG	RMF in SU(3)	n, p, α, nuclei	Λ, Σ, Ξ	-	$1.6M_{sun}$
Quark EOS 2008, PRD	RMF + MIT bag model	n, p, α, nuclei	-	u, d, s	$1.8M_{sun}$

- Mixture of nuclei in NSE

Furusawa et al. arXiv:1103.612

NSE EOS 2011, (ApJ)	RMF + NSE	n, p, α, NSE of nuclei	-	-	$2.2M_{sun}$

- Updates of Shen EOS (range, grids, Λ)

Shen et al. arXiv:1105.1666

Extensions of Shen EOS table

Hyperon-EOS

Ishizuka, Ohnishi, Tsubakihara, Sumiyoshi, Yamada (2008) J. Phys. G

- Relativistic Mean Field with strange baryons
  - Interaction: TM1 & meson-hyperon potentials — Schaffner-Mishustin (199
  - Experimental data of hyper-nuclei (Λ, Σ^{-0+}, Ξ^{-0})

$$U_\Lambda^{(N)} = -30 \text{ MeV}, \quad U_\Sigma^{(N)}(\rho_0) \simeq +30\text{MeV}, \quad U_\Xi^{(N)}(\rho_0) \simeq -15\text{MeV}$$

- Tables available for cases with U_Σ= -30 ~ +90 MeV, with/without pions
- Minimal model with Λ by H. Shen (2011)

Quark-EOS

Nakazato, Sumiyoshi & Yamada (2008) PRD

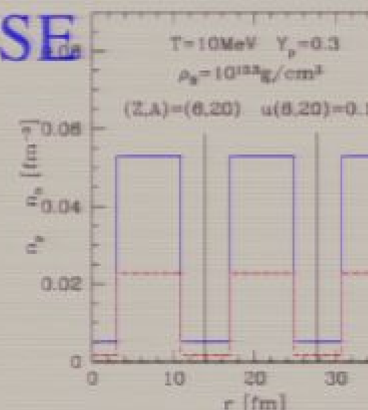
- Relativistic Mean Field + MIT bag model
  - Interaction: TM1 & Bag constant (B=250 MeV/fm^3)
  - Gibbs condition for mixed phase

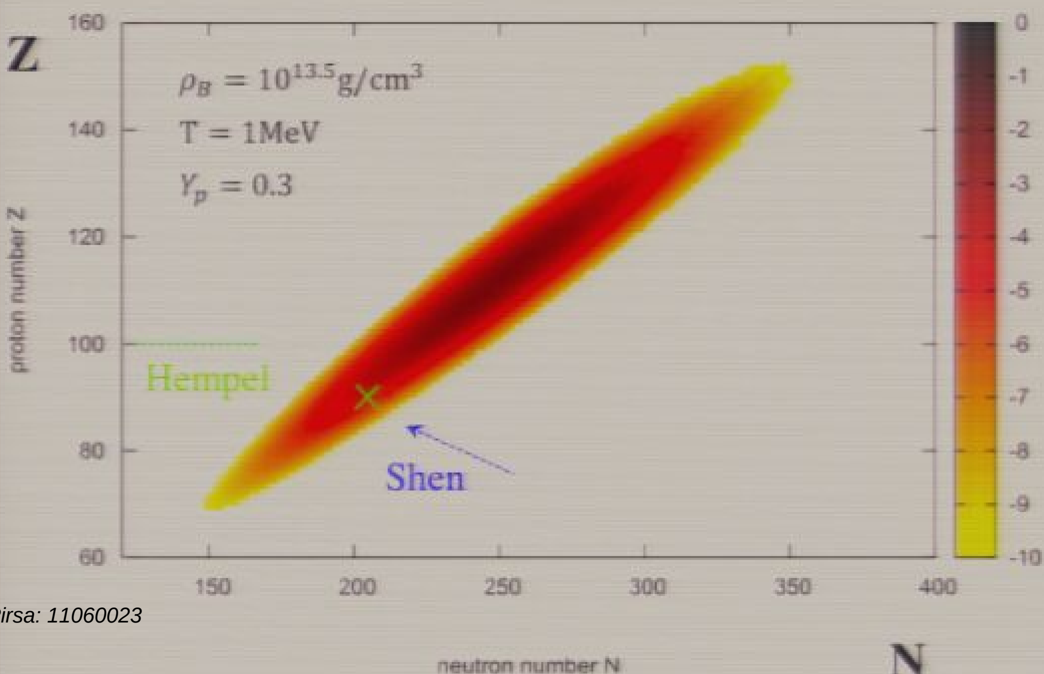
Extensions of Shen EOS table II

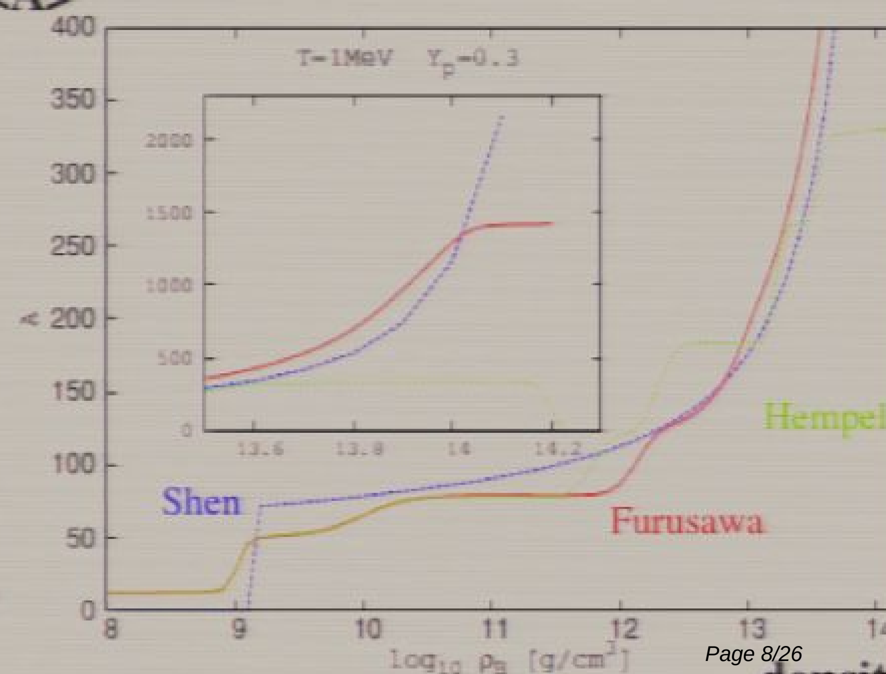
Furusawa-EOS

Furusawa, Yamada, Sumiyoshi & Suzuki (2011) arXiv:1103.6129 (Ap

- Relativistic Mean Field with Mixture of nuclei in NSE
  - Interaction: TM1 for uniform matter
  - Nuclear mass data & Compressible liquid drop model
  - Smooth connection from NSE to uniform matter
  - Provide <A>, <A²> for neutrino-reactions







Comparison of 3 sets of EOS

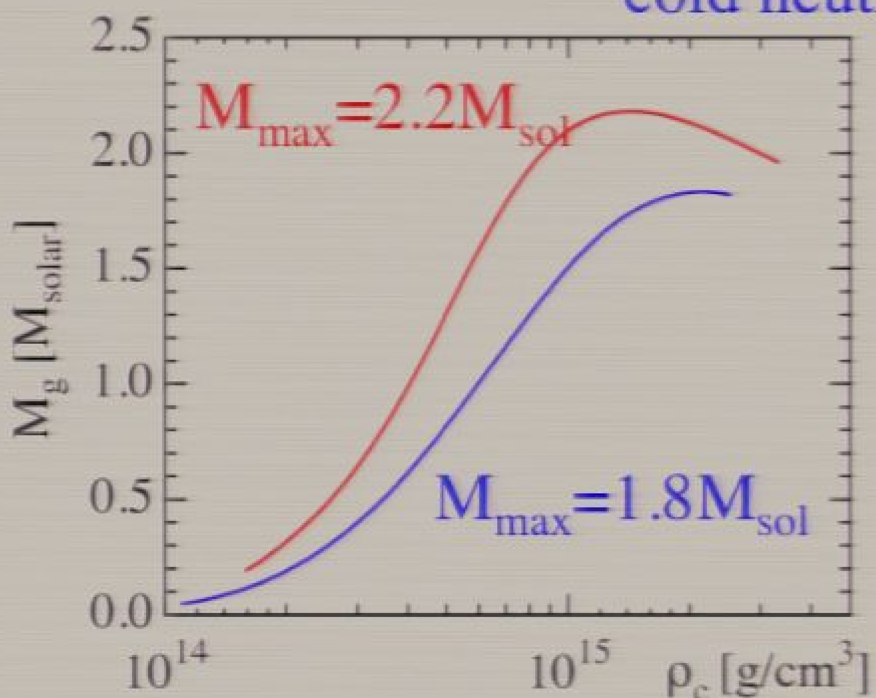
Shen-EOS vs LS-EOS

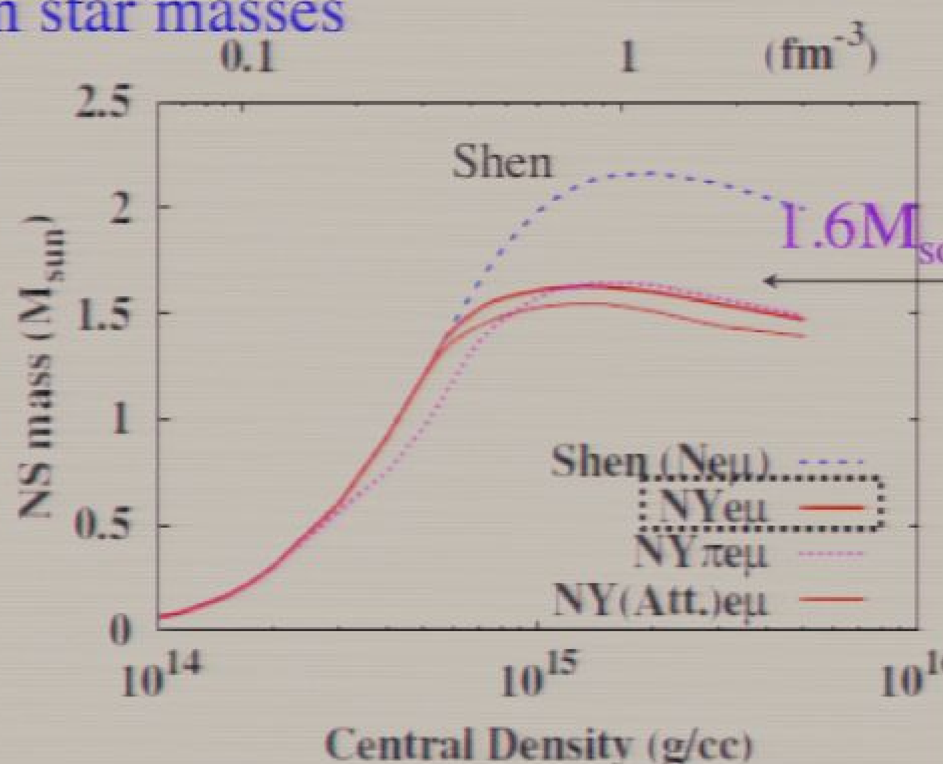
- Relativistic EOS is stiff cf. non-rel
  - Shen-EOS: K=281 MeV
  - LS-EOS: K=180 MeV

Shen-EOS vs Hyperon-EO

- Softening due to hyperons
  - Mixture starts from ~2-3ρ_0
  - Smaller maximum mass

cold neutron star masses





Sumiyoshi et al. NPA730 (2004)

Ishizuka, et al. 2008, J. Phys. G

Influence of EOS on supernova neutrinos

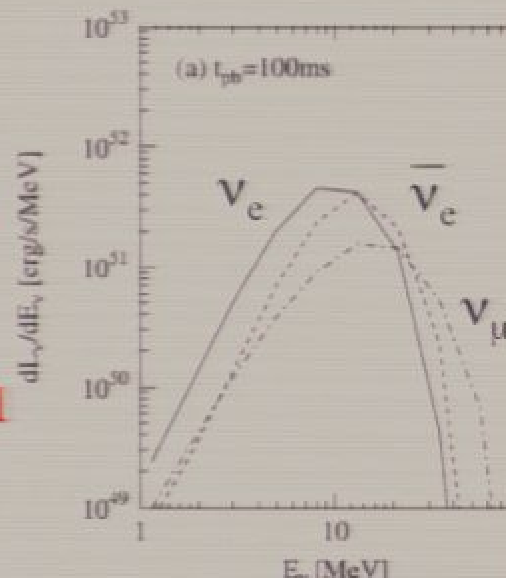
The birth of neutron star / black hole

Our numerical simulations in 1D

- General relativistic ν-radiation hydrodynamics

Yamada, ApJ (1997) Sumiyoshi et al. (2005)

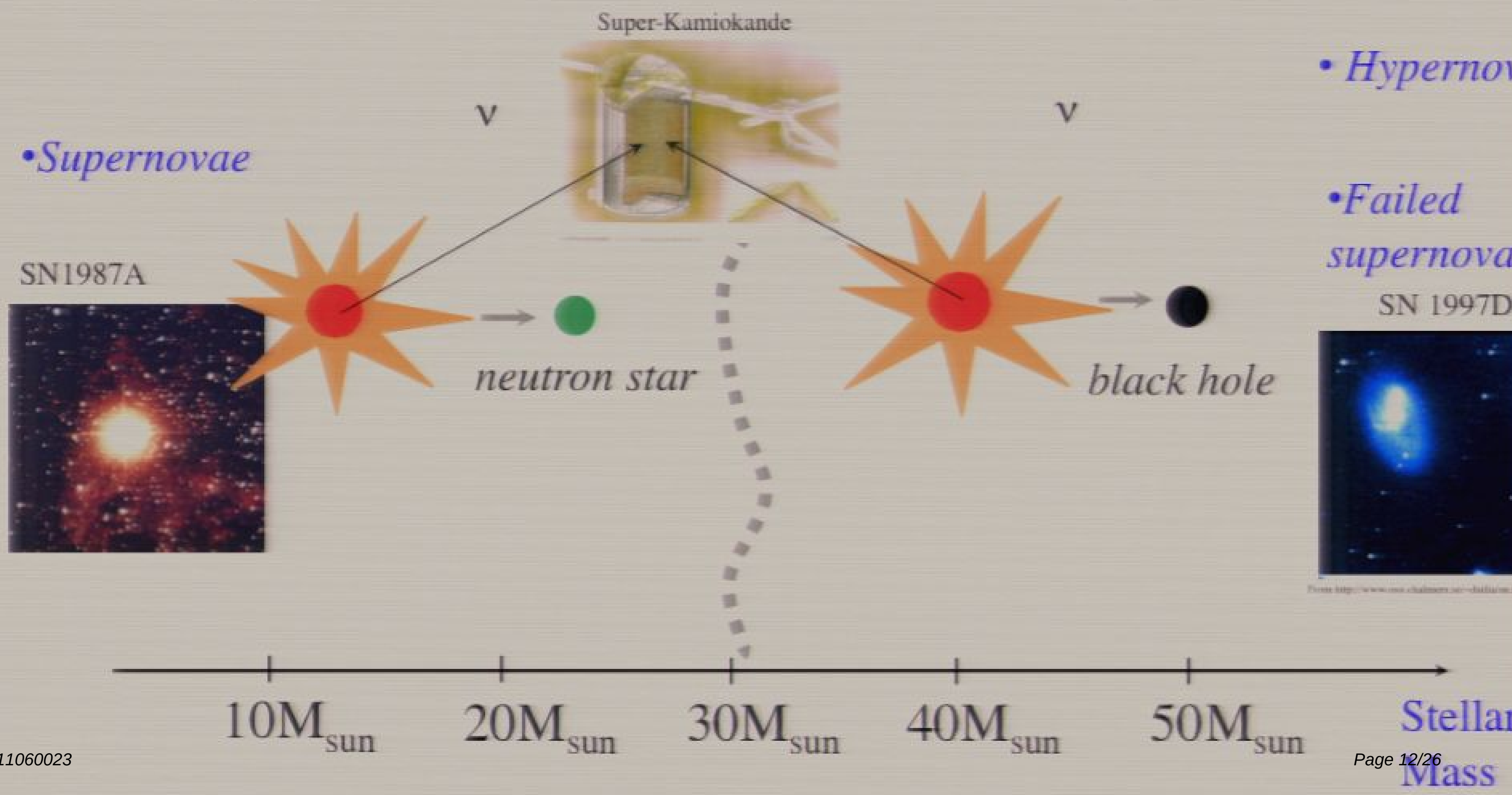
  - GR Boltzmann eq. for neutrinos
  - GR Hydrodynamics Full implicit method
  - EOS: Shen-EOS, LS-EOS, Hyperon, Quark
  - Neutrino reactions: Bruenn + extensions
  - Collapse of Massive stars
- Examine the influence of microphysics
  - Core collapse mechanism, ν-emission
- Evaluation of neutrino energy spectrum
  - Obs. of Supernova ν in birth of NS/BH



Supercomputing resources at YITP, RCNP, UT, KEK, NAOJ and JAERI/Tokai

Explore the fate of massive stars by ν

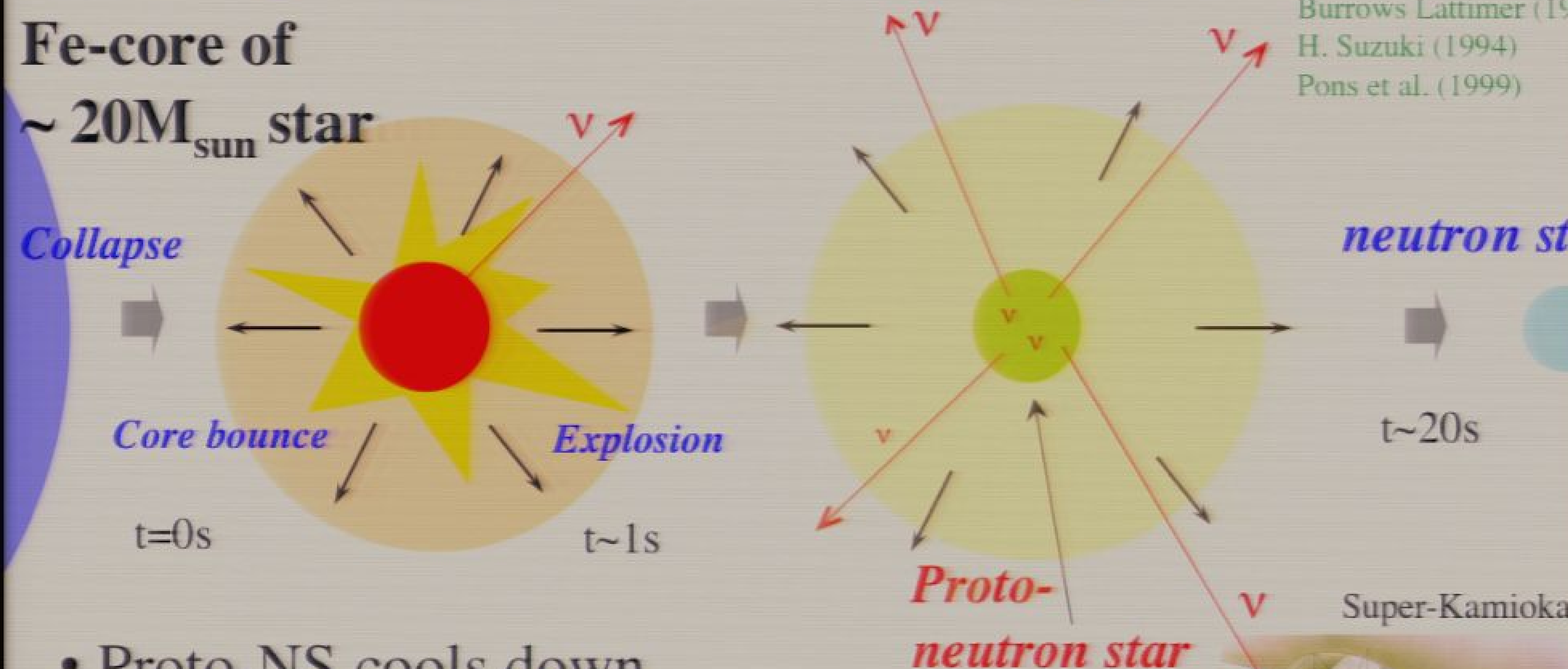
- There are more massive stars ~40M_{sun} (~30 % of massive stars
- They lead to the black hole formation with neutrino bursts



Supernova neutrinos as a probe EOS

Burrows Lattimer (19
H. Suzuki (1994)
Pons et al. (1999)

Fe-core of
~ $20M_{sun}$ star



- Proto-NS cools down

  by emitting 10^{57} ν in ~20 sec

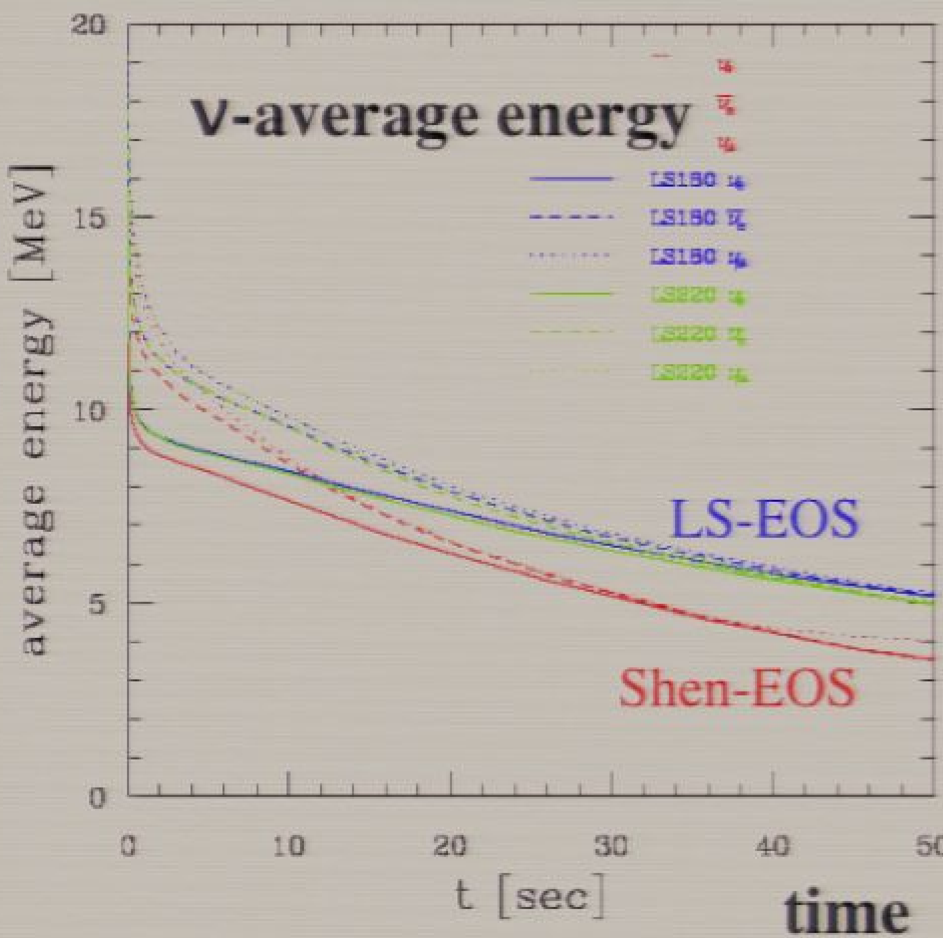
- a next Galactic SN: 10^4 ν (SN1987A: 11 ν)

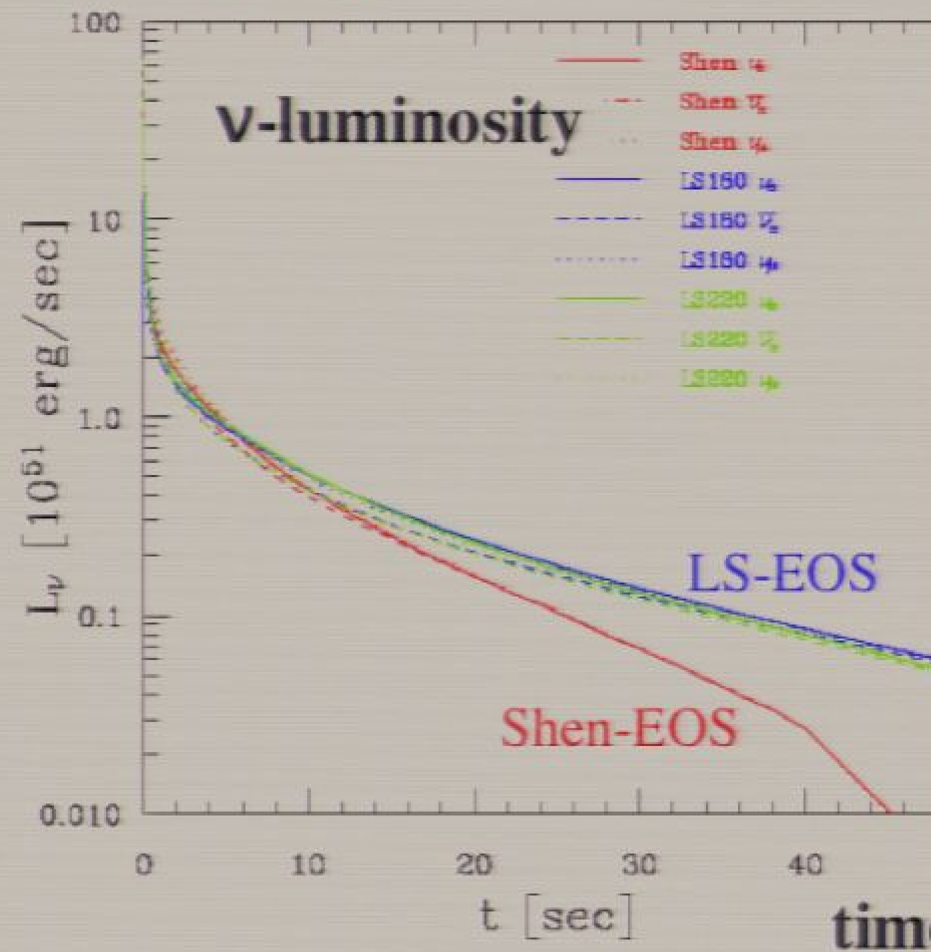
- ν emitted from hot and dense matter (EOS)

Neutrinos from proto-neutron star

Burrows, Pons, H. Suzuk

ν-bursts for ~20sec E_ν, L_ν decrease

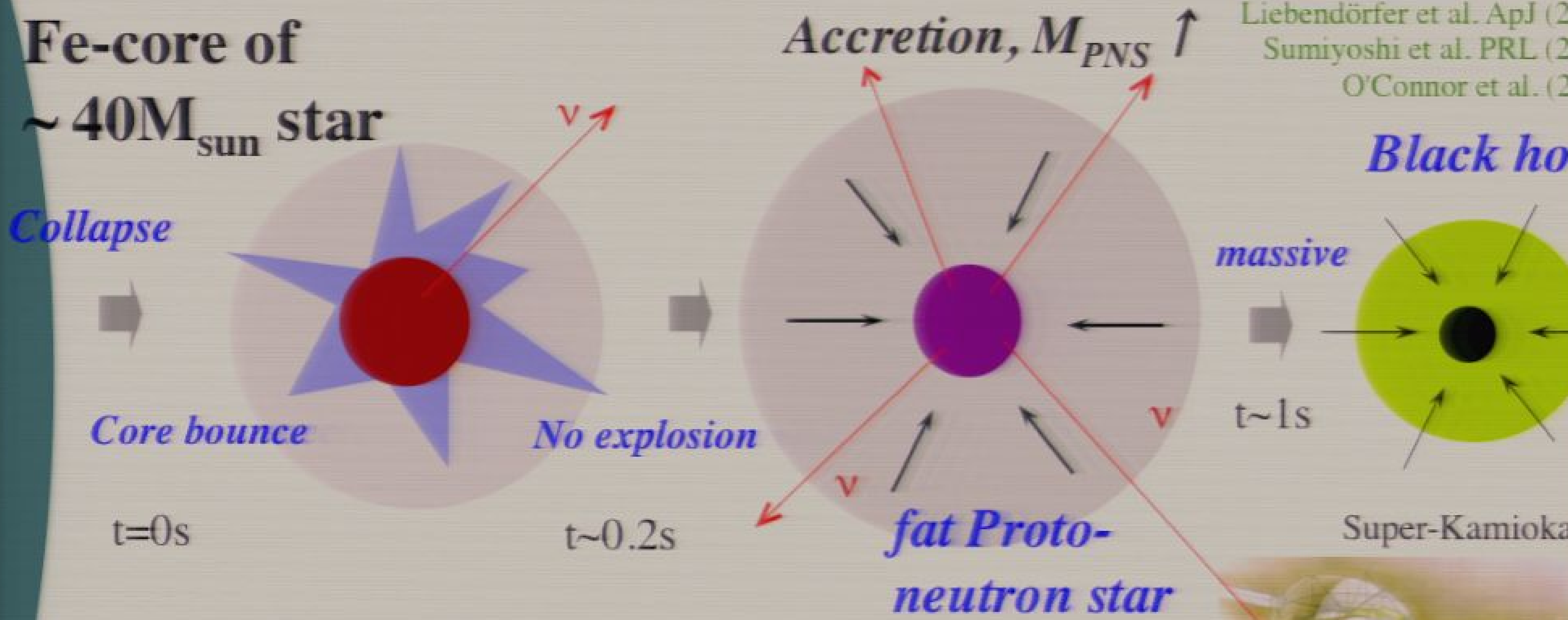


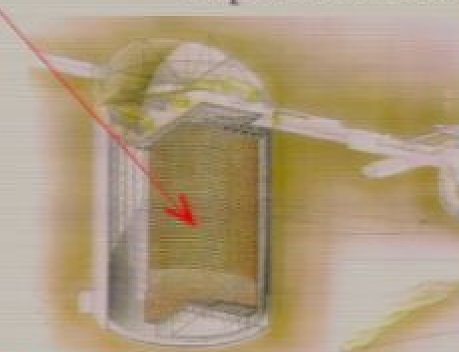


numerical simulation of cooling of proto-NS

Suzuki, Ono, Sumiyoshi, Yamada (2004)

More massive stars lead to black holes



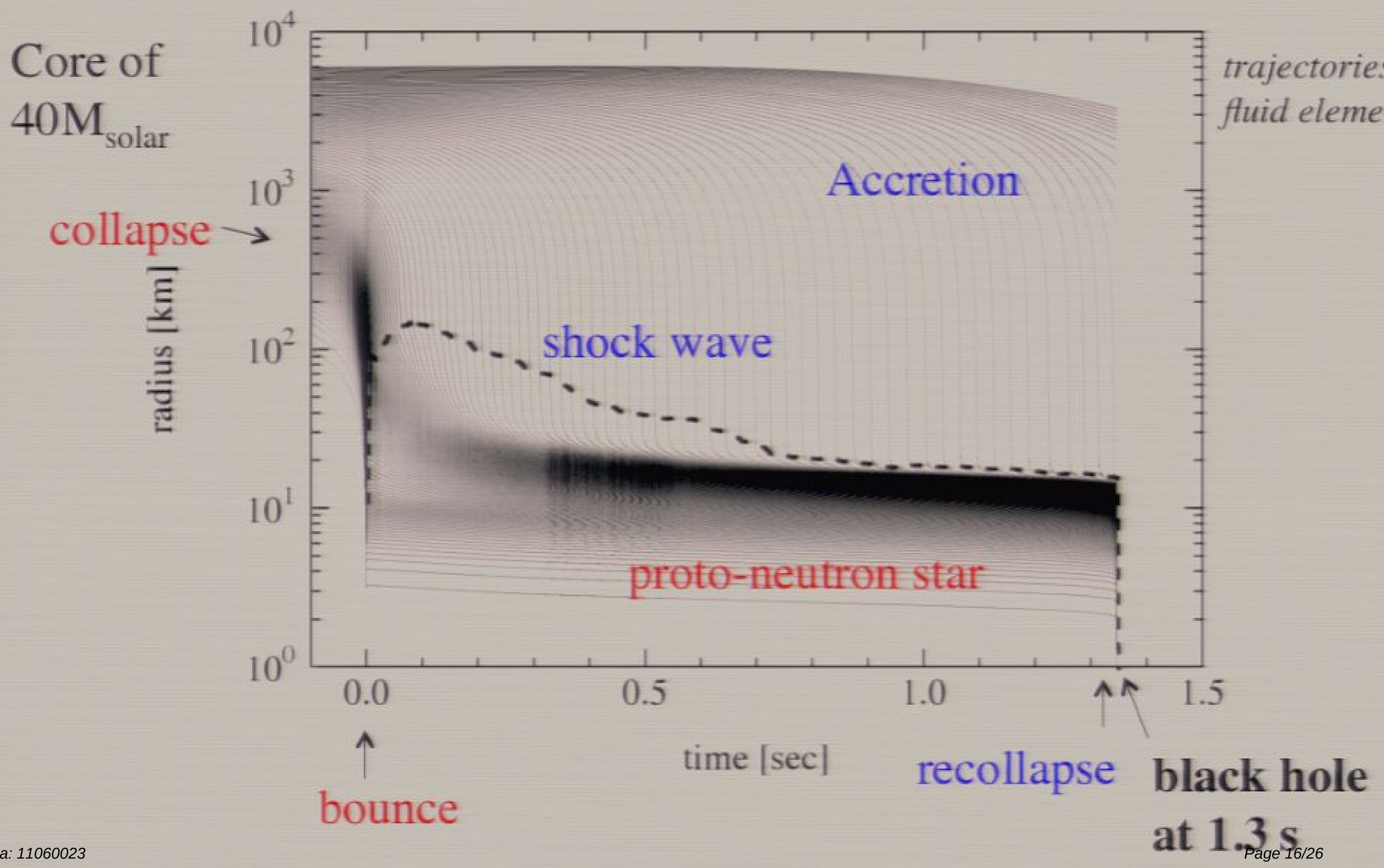


failed supernova ν

A Galactic case: 10^4 ν

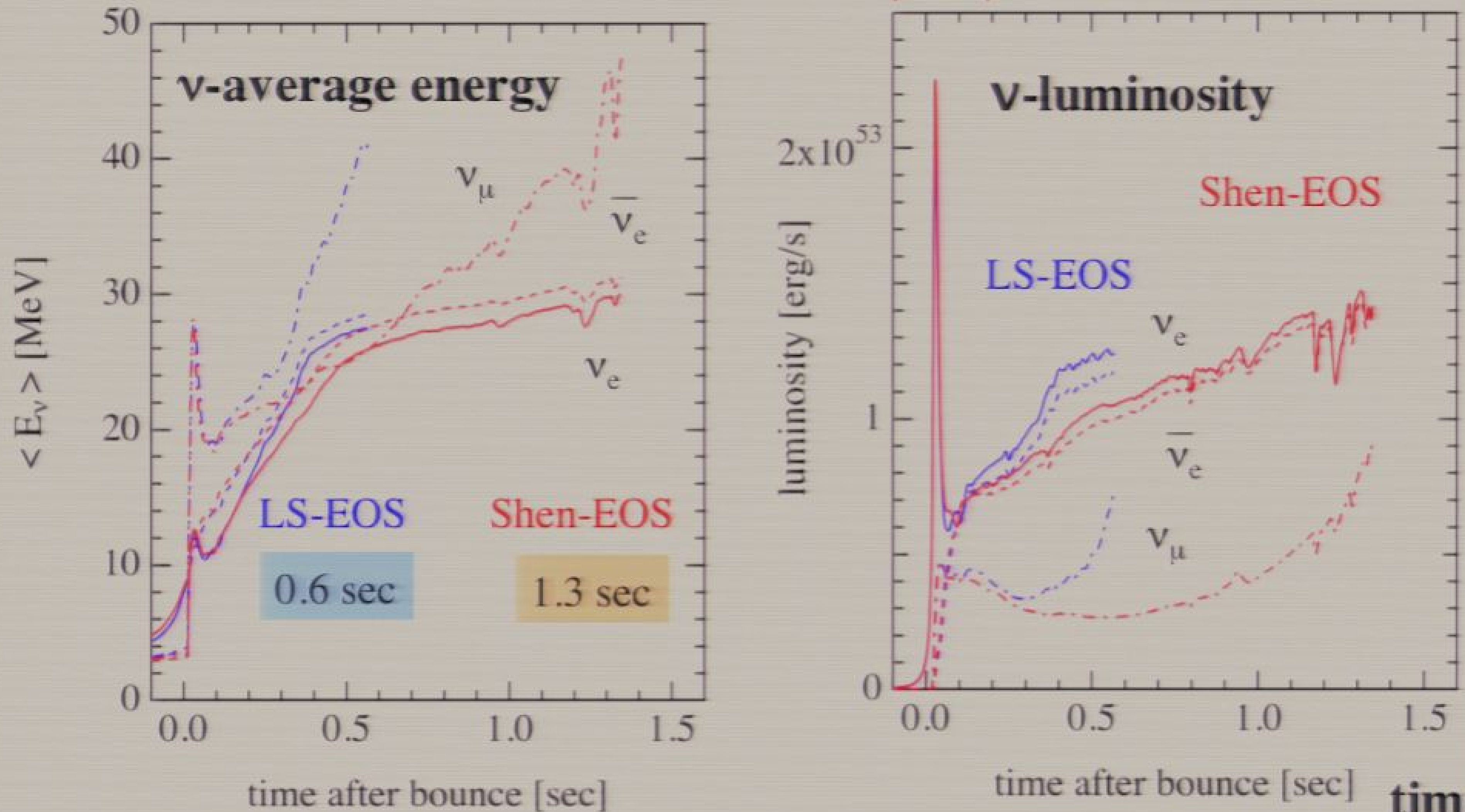
- Massive proto-NS to black hole in 1s
- No display, but neutrino burst
- Chance to see black hole formation
- Probe of EOS at high ρ and T

Collapse toward black hole: Shen-EOS



Neutrino emission till black hole formation

Short duration (~1s) **E_ν, L_ν increase** 40M



time

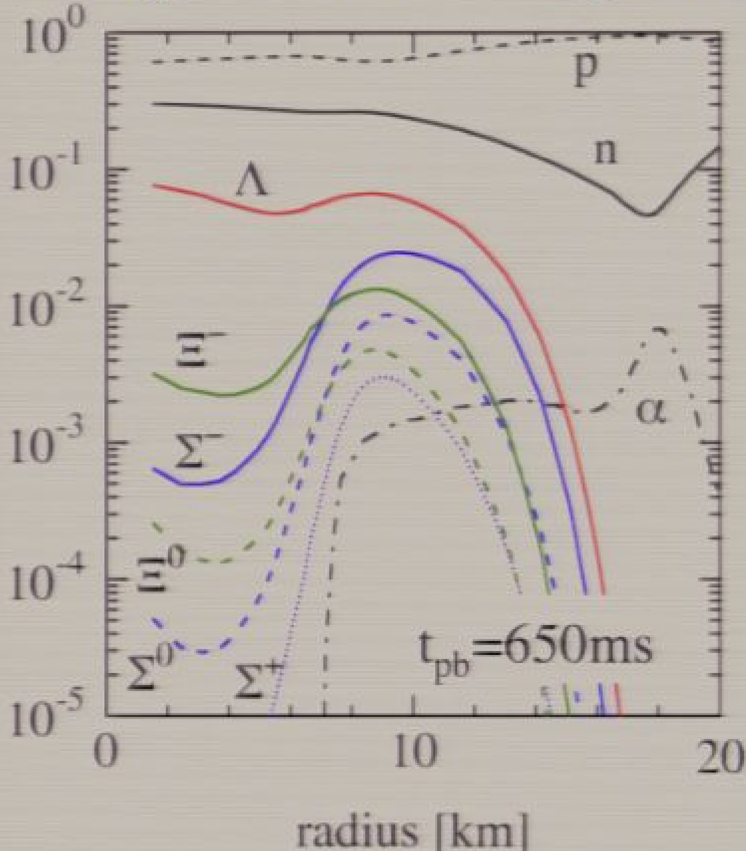
Soft EOS→ Earlier Collapse: duration of ν burst

Sumiyoshi et al., ApJ (2007)

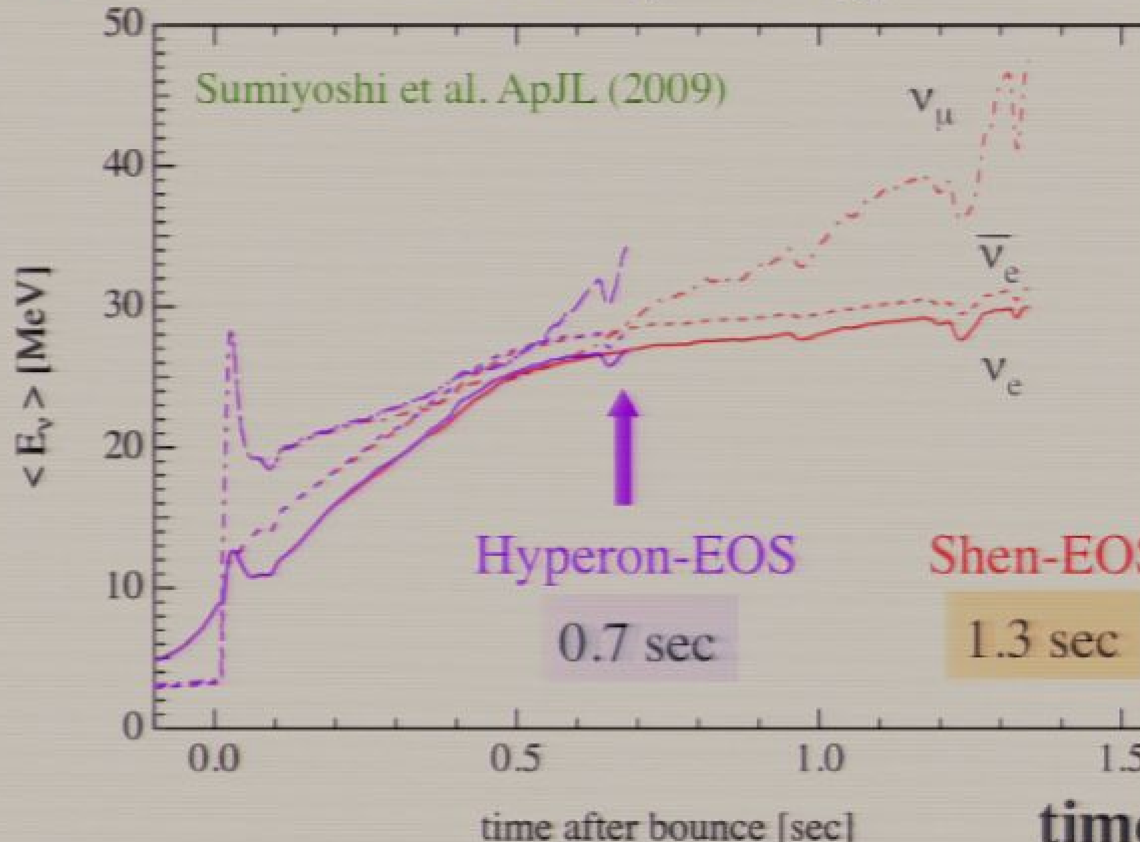
Hyperons appear at high ρ and T

triggers the re-collapse to black hole

Composition inside proto-NS



ν-average energy

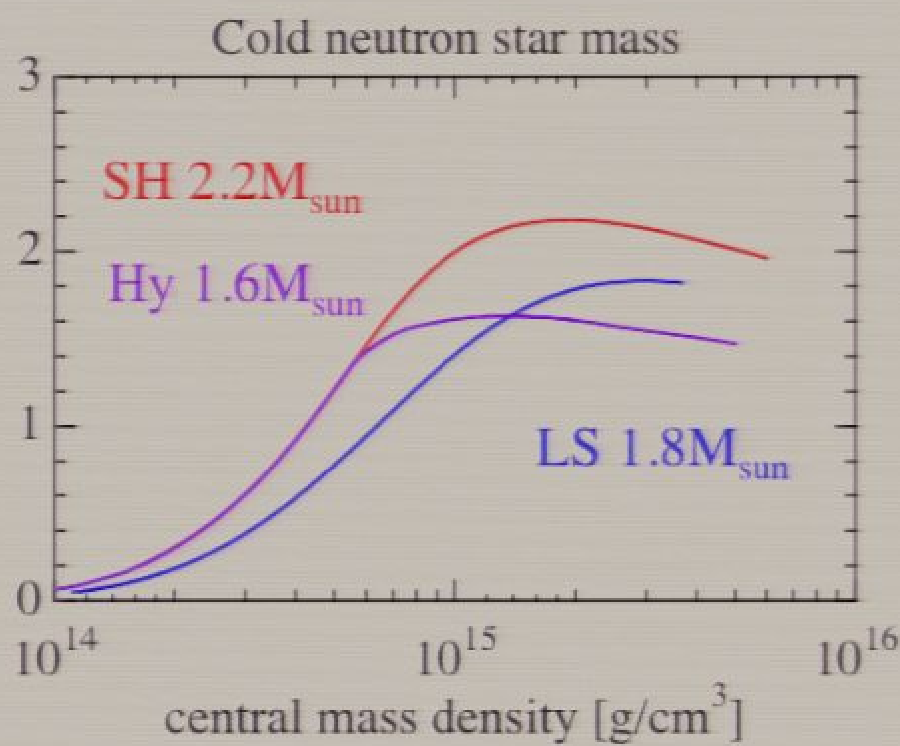


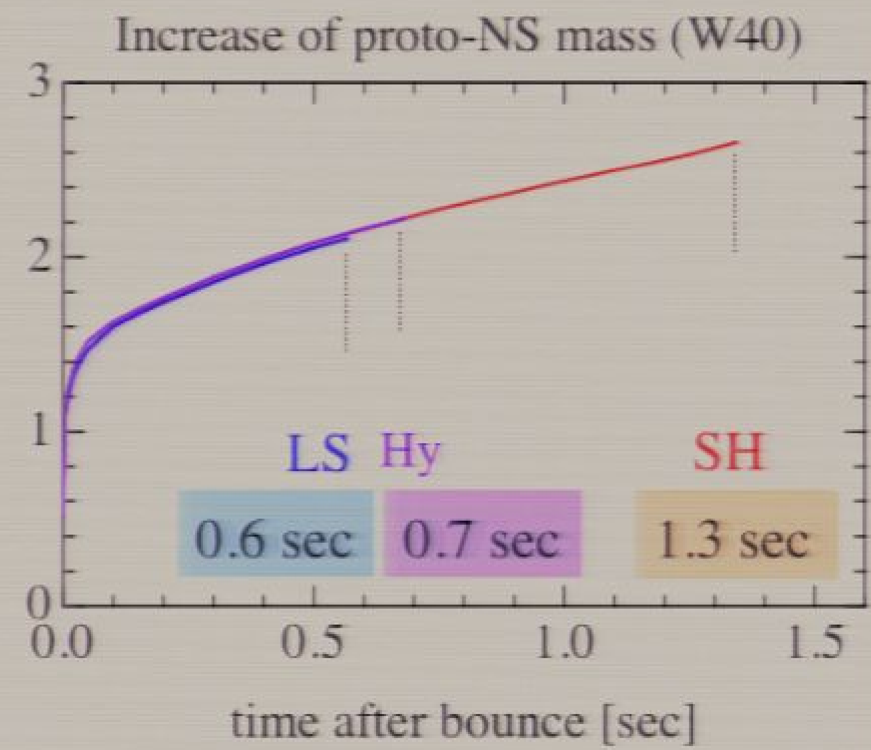
time

- Probe exotic matter by detection of neutrinos

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

EOS effect on duration till BH formation



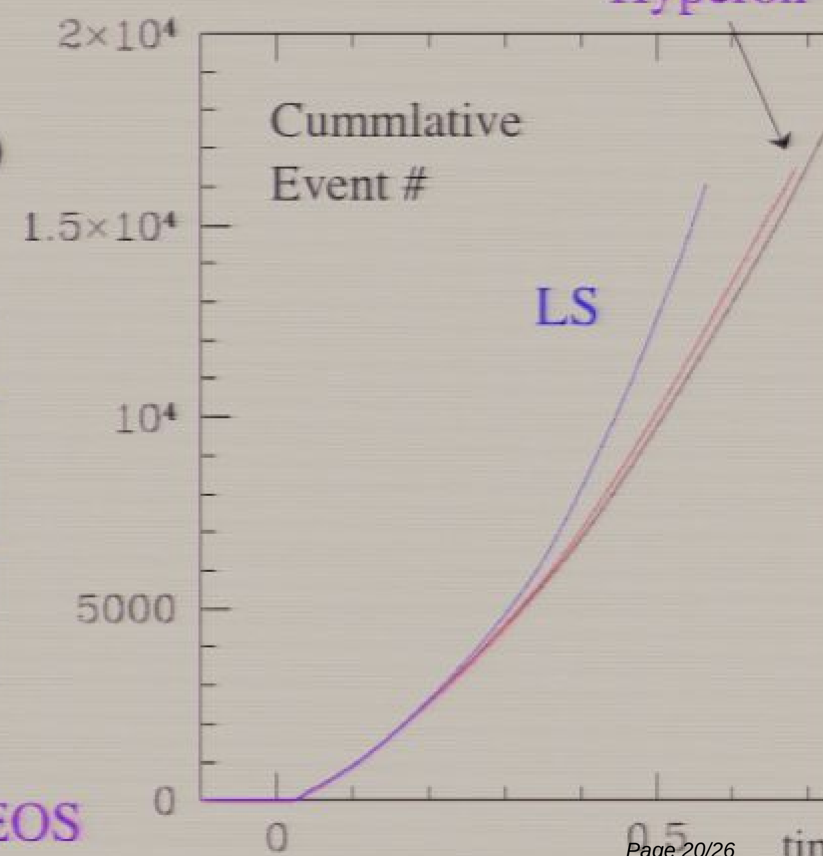


- Roughly corresponds to maximum cold neutron star
  - Note: proto-NS contains neutrinos at finite temperature
- More than 1 sec for stiff EOS
  - Progenitor determines the mass increase

Evaluation of neutrino detections

Nakazato et a
PRD 2008, 200

- Event numbers of detection: large enough
  - Events at Galaxy center (~10kpc), Super-Kamiokande
  - Neutrino oscillations: from stellar layer to earth
- Distinguish different EOSs
  - Duration of ν-burst (softness)
  - Energy difference (composition)



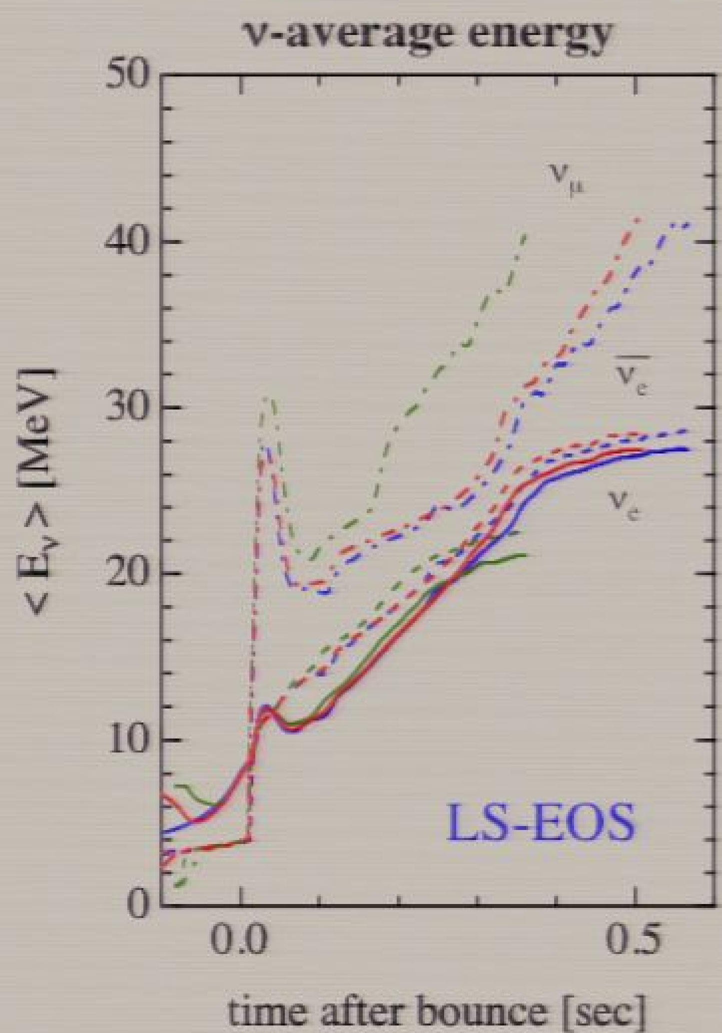
- ν event number

ν-mixing	LS	Hyperon	Shen
Normal, $\sin^2\theta_{13}=10^{-8}$	16086	16490	49513
Inverted, $\sin^2\theta_{13}=10^{-2}$	12136	9952	30992

Kolmogolov-Smirnov tests to distinguish two time profile: possible to distinguish Hyperon-EOS

Nakazato et al. PRD (2010)

Progenitor dependence



Duration

H40: 0.36s

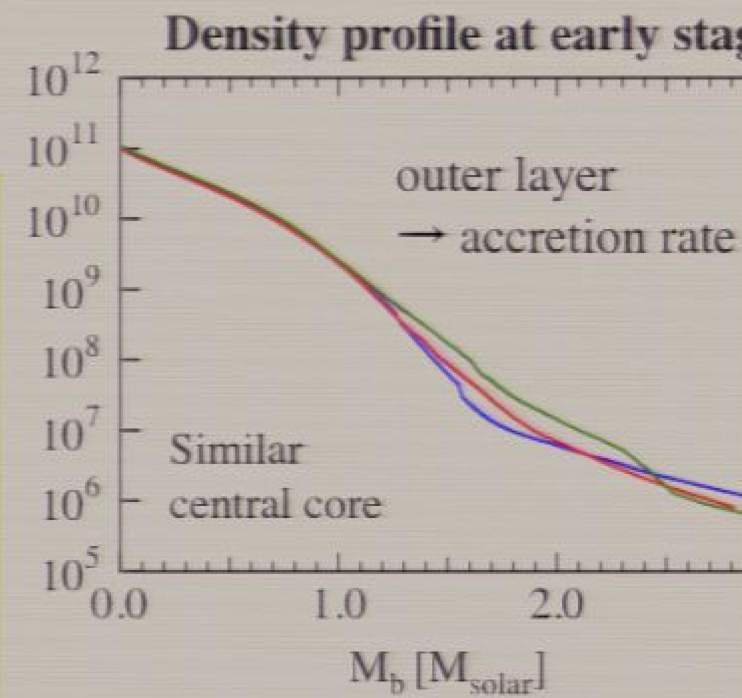
T50: 0.51s

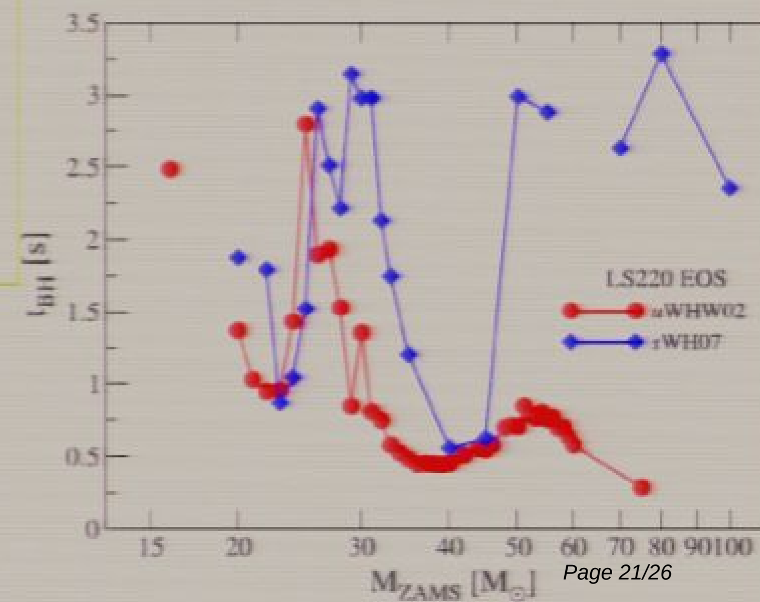
W40: 0.57s

slope ρ(r)

→

difference





- Need studies using stellar models

See Fischer-Liebendörfer, O'Connor-Ott

Summary

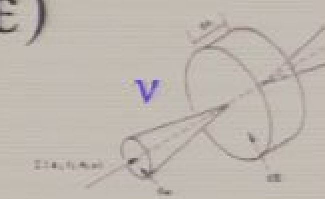
- **Progress of the series of the Shen EOS**
  - Extensions with hyperons and quarks
  - Extensions with multi-composition of nuclei
  - Refine with wider range and regular grids

- **Influence of EOS on neutrino bursts**
  - Supernova neutrinos from proto-neutron stars (~20 s
  - Neutrino bursts from failed supernovae (~1 s)
    - Softness determines the duration, energy spectra
    - Enough event numbers for galactic events
  - Systematic studies with stellar models

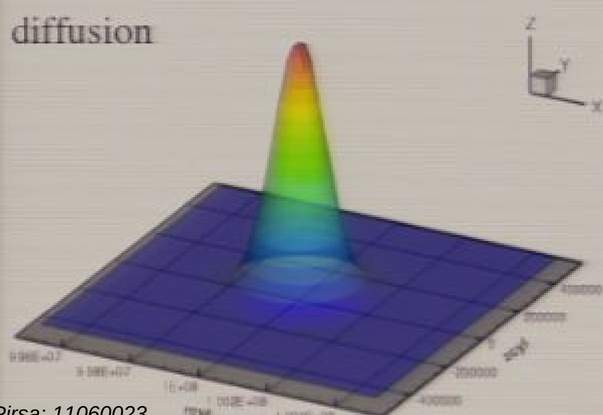
Project on ν-radiation transfer in 3D

Sumiyoshi, Yamada (2011) submitted to A

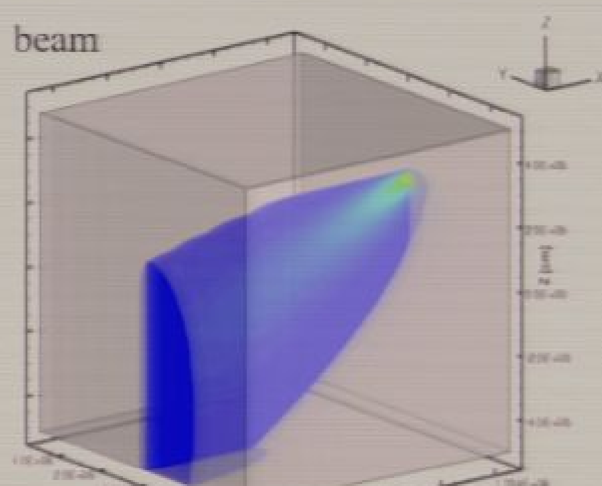
- New numerical code to solve Boltzmann equation in 3D
  - Neutrino distribution in 6D $(r, \theta, \phi, \theta_\nu, \phi_\nu, \varepsilon)$
  - EOS table and neutrino reactions
- Computational challenge
  - Large sparse-block matrix (implicit method)
    - Parallel algorithm, matrix solver
- Validated code: applied to supernova cores

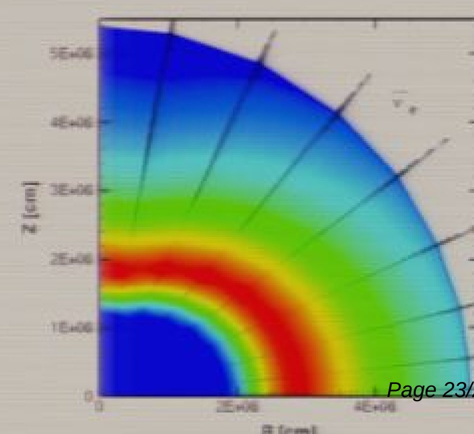


diffusion



beam





Defor
core

This project is done in collaboration with

- Supernova research
  - S. Yamada
  - K. Nakazato
  - H. Suzuki
- RMF-EOS table
  - H. Shen
  - K. Oyamatsu
  - H. Toki
  - A. Ohnishi
  - C. Ishizuka
- Supercomputing
  - S. Hashimoto
  - H. Matsufuru
  - T. Sakurai
- Numerical simulations
  - K. Kotake
  - T. Takiwaki
  - H. Nagakura
  - S. Furusawa

Category 5: Origin and structure of matter and universe
Subject 3: Supernova explosion & Black hole

HPCI Strategic Program Field 5
"The origin of matter and the universe"

10Pflops supercomputer at AICS, Kobe

ranking 1st position in top 500, June 20, 2011

Project on ν-radiation transfer in 3D

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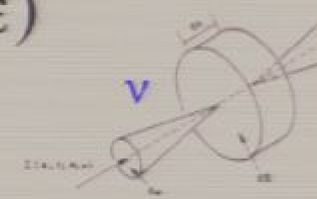
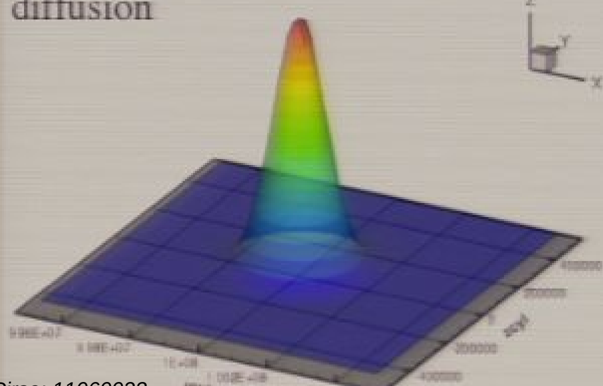


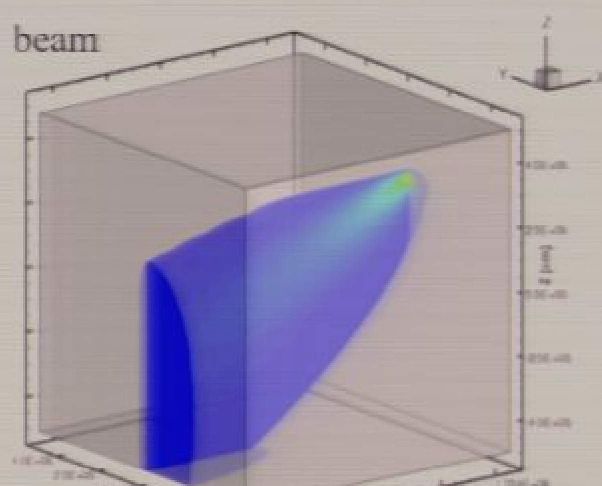
- Computational challenge
  - Large sparse-block matrix (implicit method)
    - Parallel algorithm, matrix solver

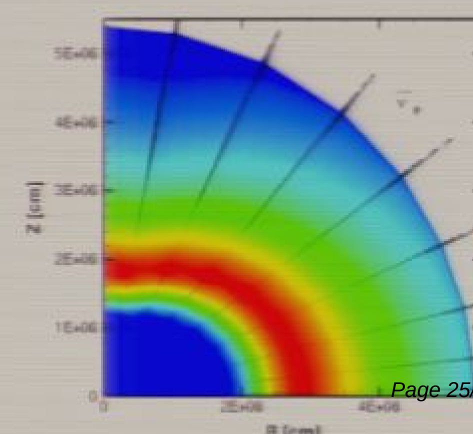
- Validated code: applied to supernova cores

diffusion



beam



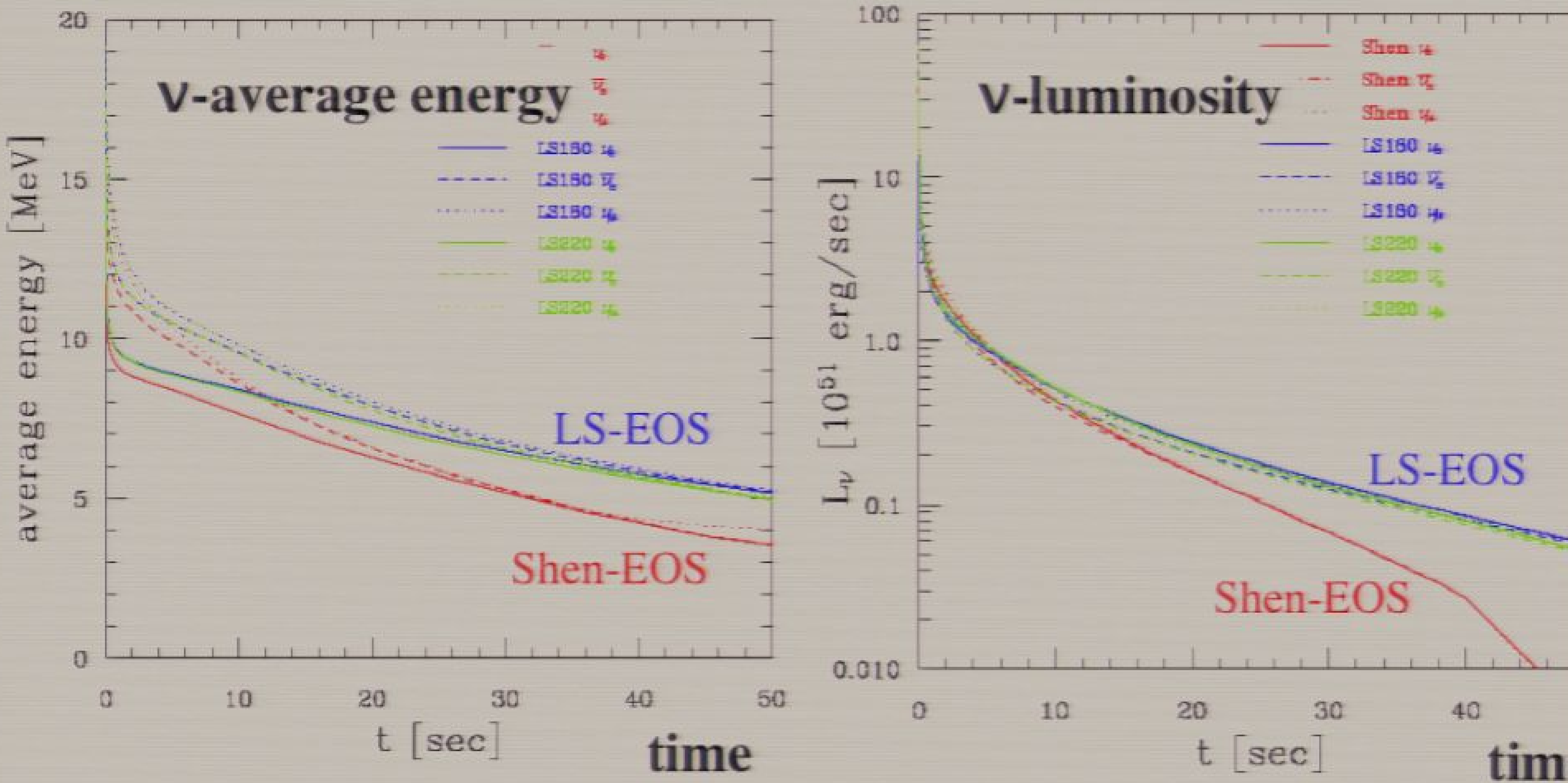


Deform core

Neutrinos from proto-neutron star

Burrows, Pons, H. Suzuk

ν-bursts for ~20sec E_ν, L_ν decrease



numerical simulation of cooling of proto-NS

Suzuki, Ono, Sumiyoshi, Yamada (2004)