# *Emergence of hyperons in failed supernovae with short neutrino bursts*

## *the fate of more massive stars*

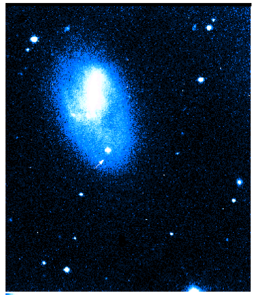
SN1987A

A. K. Mann, "Shadow of a star"


**K. Sumiyoshi** (Numazu College of Technology)

With K. Nakazato, C. Ishizuka, K. Tsubakihara
A. Ohnishi, S. Yamada and H. Suzuki

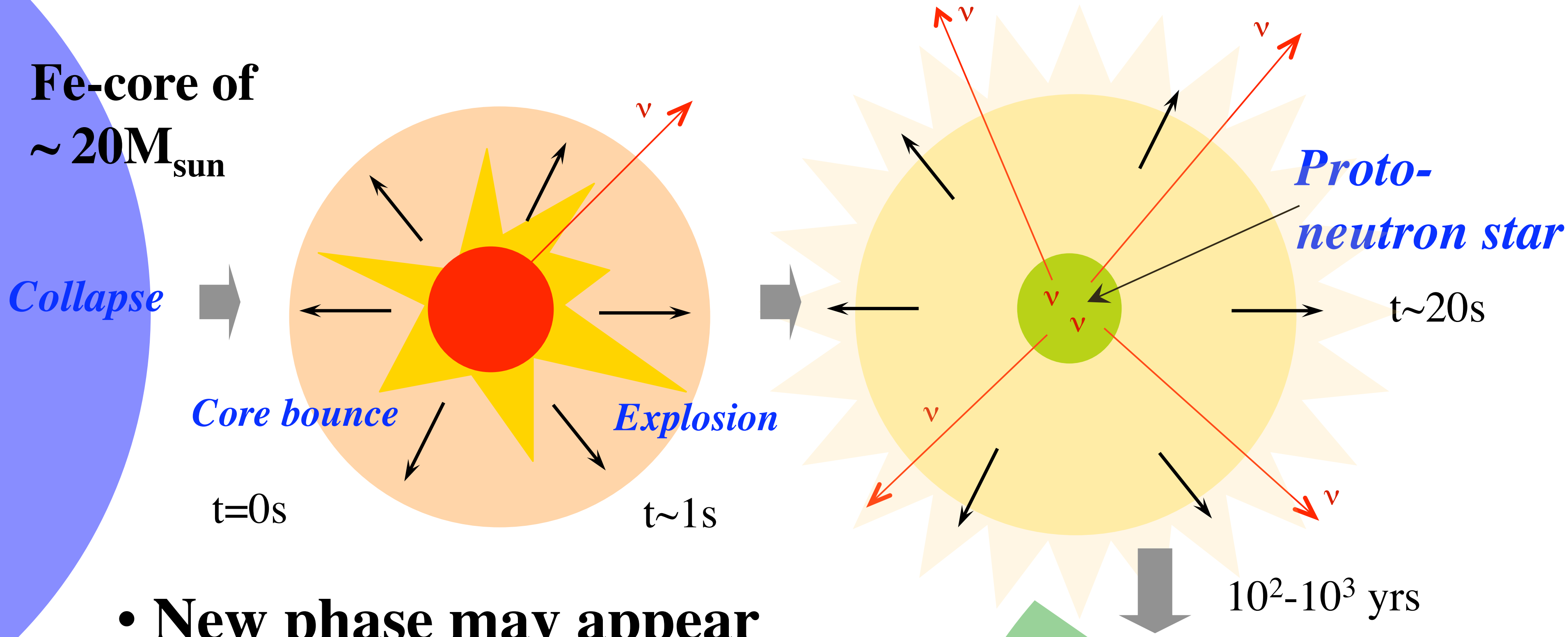

SN 1997D



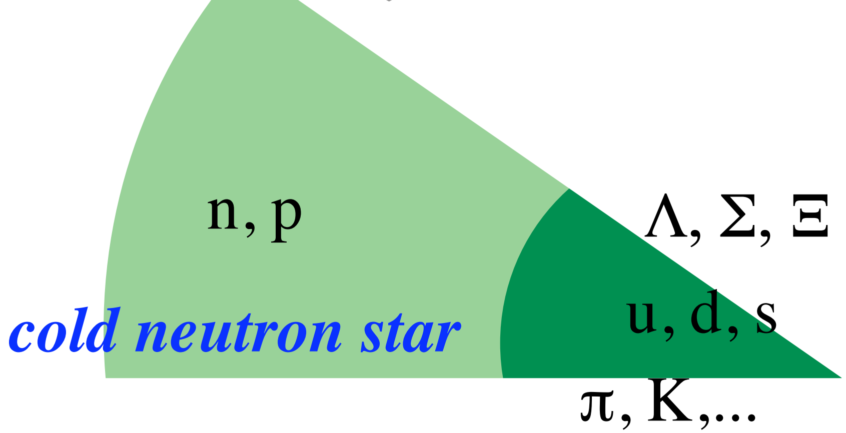
From http://www.oso.chalmers.se/~duilia/sn.html

- Gravitational collapse of massive stars ~$40M_{sun}$
  - high $\rho$, T toward black hole formation
- Unique neutrino bursts as a probe of EOS

# When and how strangeness appear?

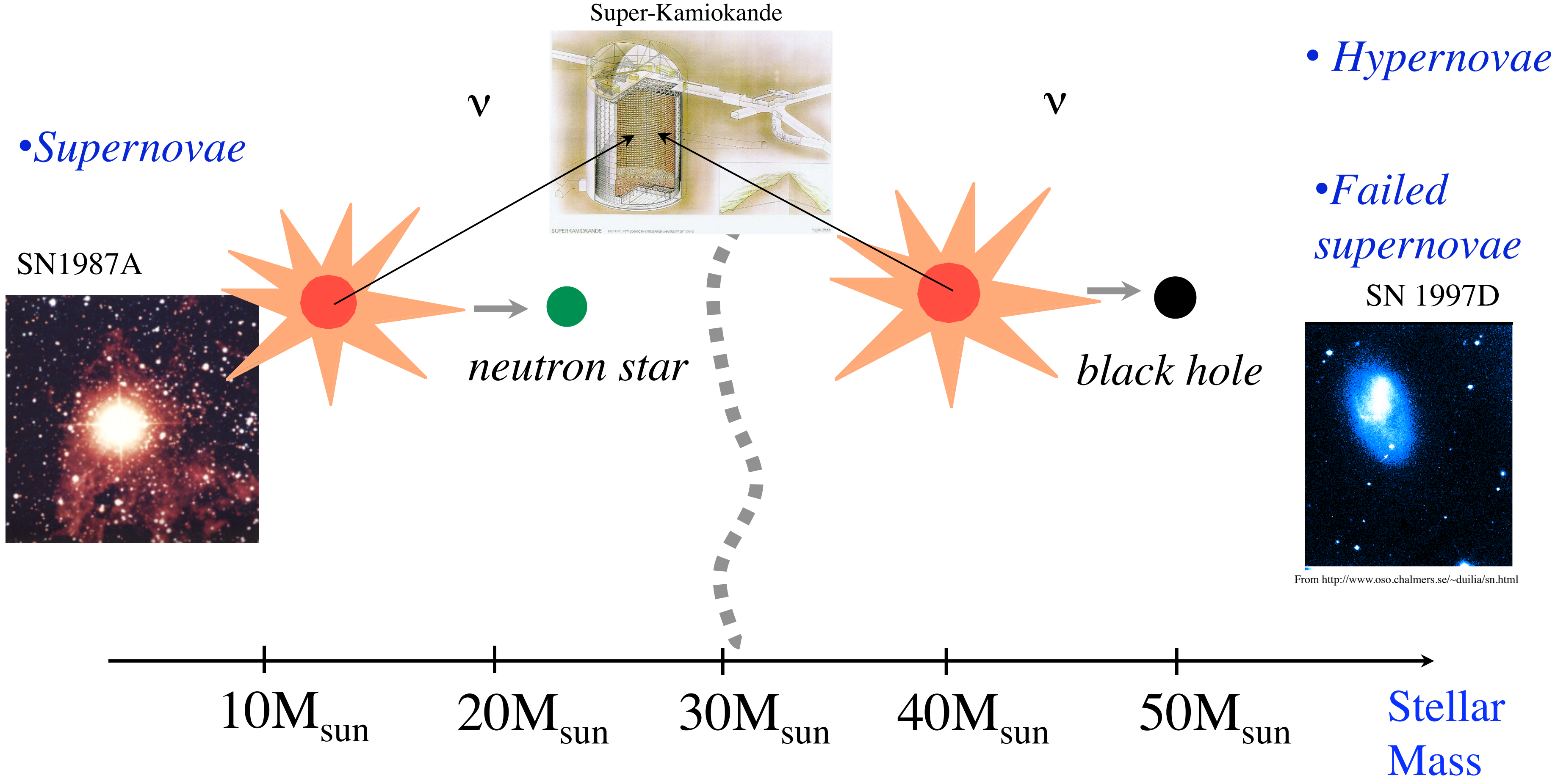



- **New phase may appear in proto-NS:** hot, ν-trapped
  - ν-emission for ~20 sec
- **Supernova neutrinos**
  - EOS information

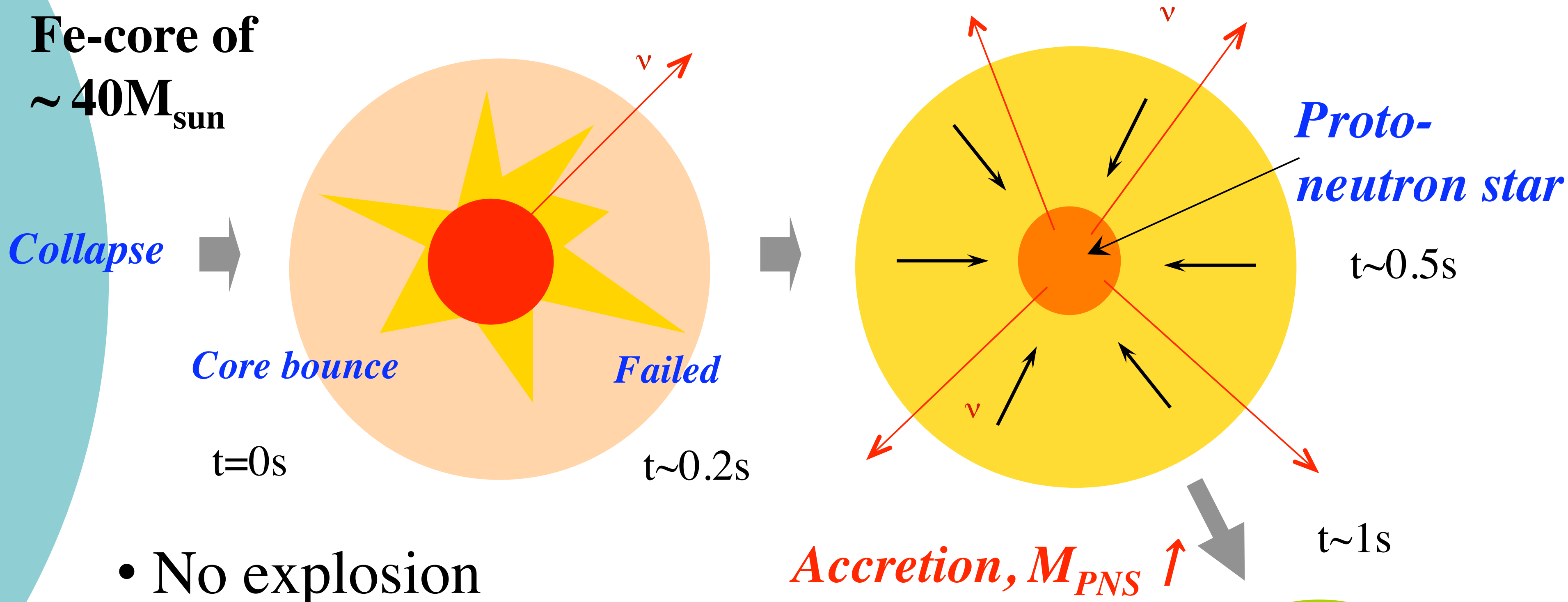


# Mass range of massive stars

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



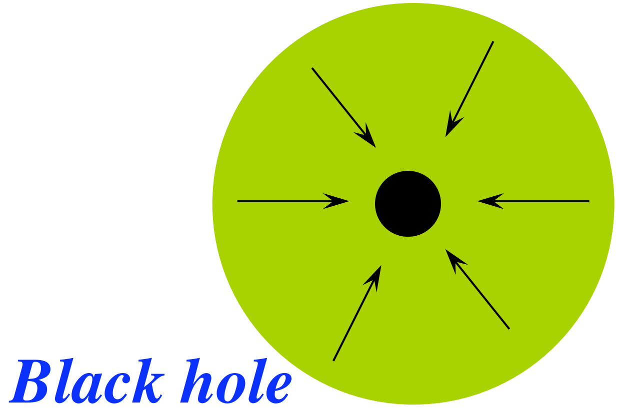
# Black hole formation from massive stars




- No explosion
- Mass of proto-NS increases

  High density and temperature in 1s
- Hyperons/quarks appear

→ Simulations with EOS tables



# *EOS tables for supernova simulations*

Cover wide range: $\rho=10^5\sim10^{15}$ g/cm$^3$

$T=0\sim100$ MeV

$Y_e=0\sim0.55$

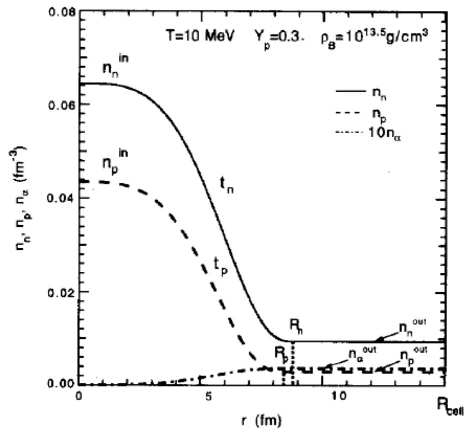
# Relativistic EOS tables for supernovae

**Public on the web**

## Shen-EOS

Shen, Toki, Oyamatsu & Sumiyoshi, (1998) NPA, PTP

- Relativistic Mean Field (TM1) + Local-Density Approx.
  - **Relativistic many body calculations**
    - Based on relativistic Brueckner Hartree-Fock theory
  - **Inputs: exp. data of n-rich unstable nuclei**
    - Nuclear structure: mass, charge radius, neutron skin,…
- EOS data table (~60MB) covers ($\rho$, $Y_p$, T)




## Hyperon-EOS

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

Ohnishi's talk

- Extension of Shen-EOS table
  - **RMF with strange baryons ($\Lambda$, $\Sigma^{-0+}$, $\Xi^{-0}$ )** Schaffner-Mishustin (1996)
    - Interaction: TM1 & meson-hyperon from potentials

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

- Tables available for cases with $U_\Sigma$= -30 ~ +90 MeV, with/without pions

# Sets of EOS for numerical simulations

- EOS at $(\rho, T, Y_e)$

*Energy, pressure, composition, chemical potentials, entropy…*

| EOS table | Framework | Nucleons | Hyperons | Quarks | Ref. |
|---|---|---|---|---|---|
| Shen EOS | RMF | n, p, $\alpha$, nuclei | - | - | Shen 1998, NPA |
| Hyperon EOS | RMF in SU(3) | n, p, $\alpha$, nuclei | $\Lambda$, $\Sigma$, $\Xi$ | - | Ishizuka 2008, JPG |
| Quark EOS | RMF + MIT bag model | n, p, $\alpha$, nuclei | - | u, d, s | Nakazato 2008, PRD |
| LS-EOS | Ext. of liquid drop model | n, p, $\alpha$, nuclei | - | - | Lattimer 1991, NPA |

# Comparison of 3 sets of EOS

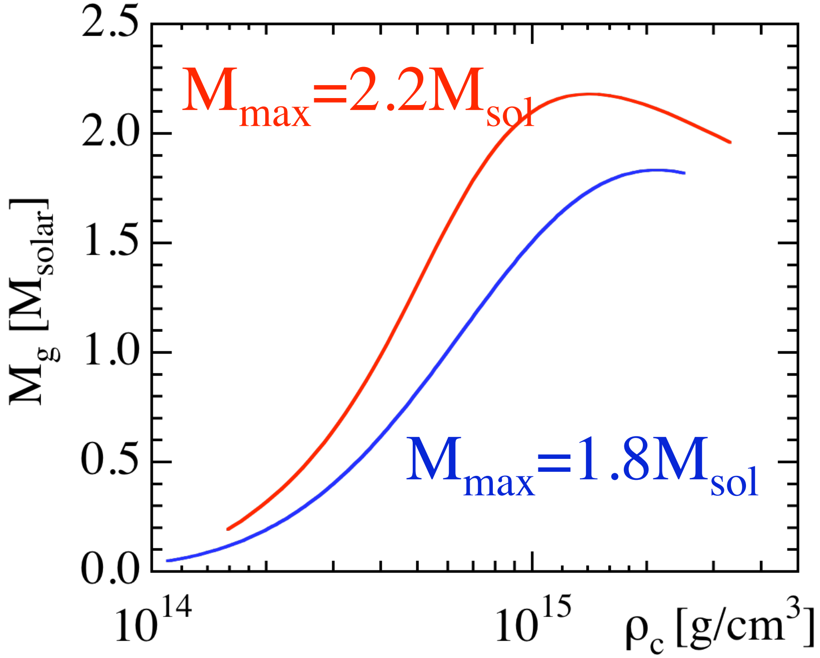
## Shen-EOS vs LS-EOS

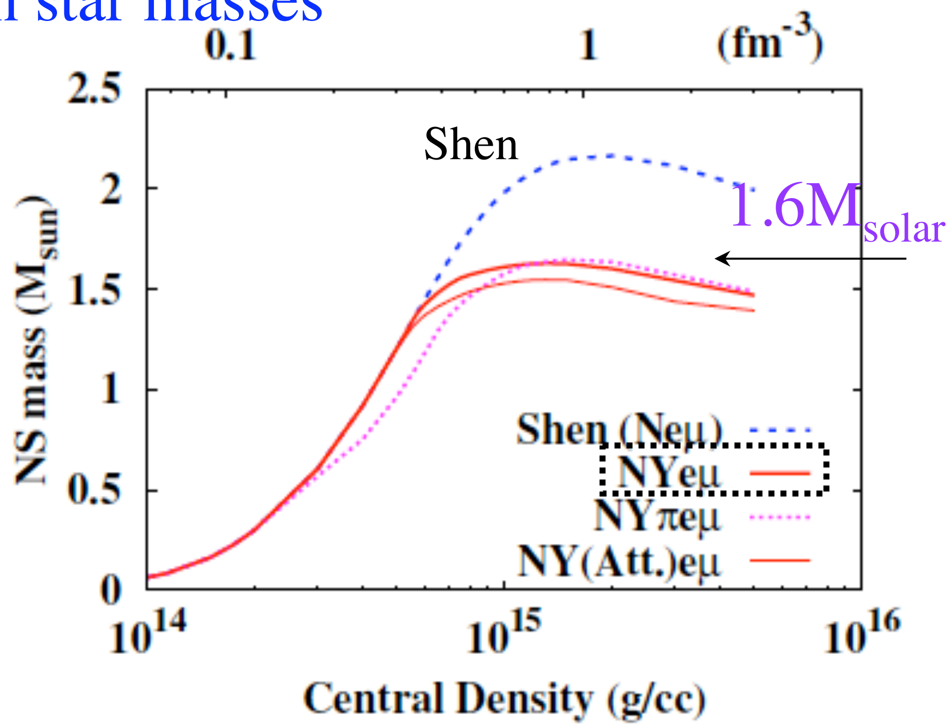
- Relativistic EOS is stiff cf. non-rel
  - Shen-EOS: K=281 MeV
  - LS-EOS: K=180 MeV

## Shen-EOS vs Hyperon-EOS

- Softening due to hyperons
  - Mixture starts from ~2-3$\rho_0$
  - Smaller maximum mass

cold neutron star masses




Sumiyoshi et al. NPA730 (2004)

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

## *Collapse of a massive star: $40M_{sun}$*

So quick and drastic

# Our numerical simulations

- General relativistic ν-radiation hydrodynamics

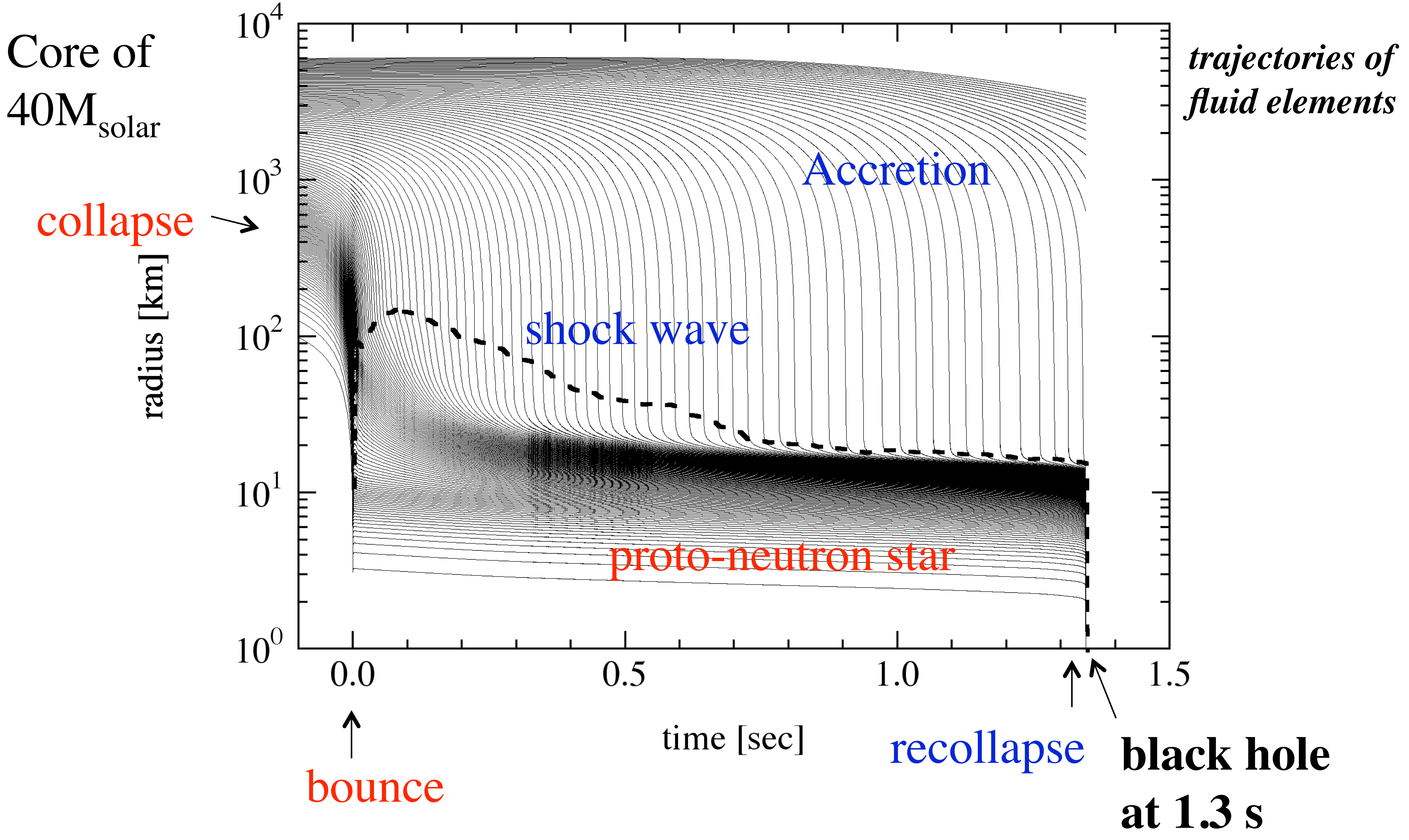
Yamada, ApJ (1997) Sumiyoshi et al. (2005)

  - Solve Boltzmann eq. for neutrinos (1D: spherical symmetry)
  - Supernova simulations: collapse, bounce, birth of NS/BH
- EOS tables + neutrino reactions with compositions
- Evaluation of neutrino flux, energy spectrum

- Initial condition
  - Fe-core of massive stars ($40M_{sun}$, $50M_{sun}$)
- EOS: Shen-EOS, LS-EOS, Hyperon, Quark

*Thanks for supercomputing resources at JAERI/Tokai, YITP, RCNP and NAOJ*

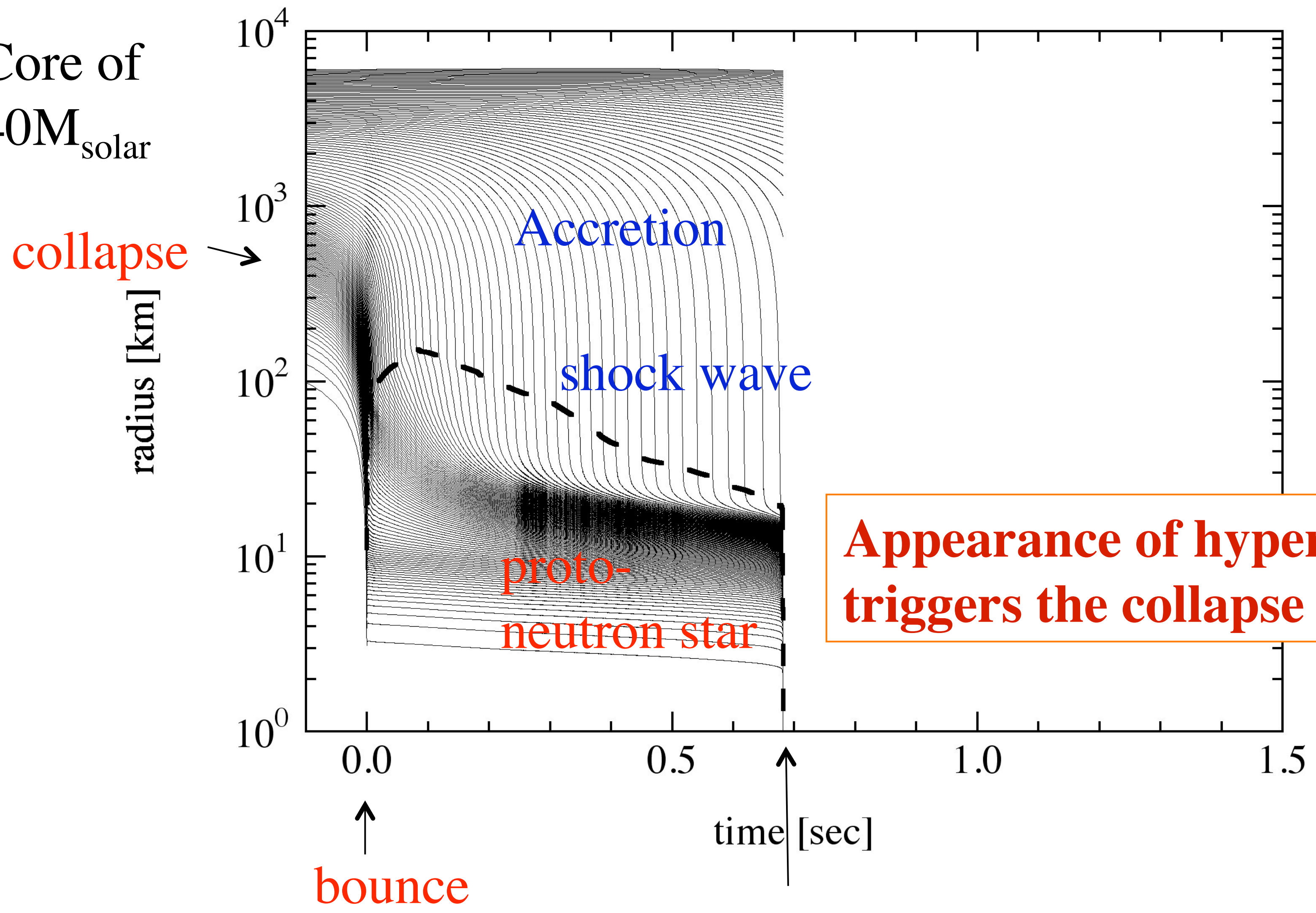
# Collapse toward black hole: Shen-EOS




Sumiyoshi et al., PRL 97 (2006) 091101

# More quick: Hyperon-EOS

Core of 40M$_{solar}$

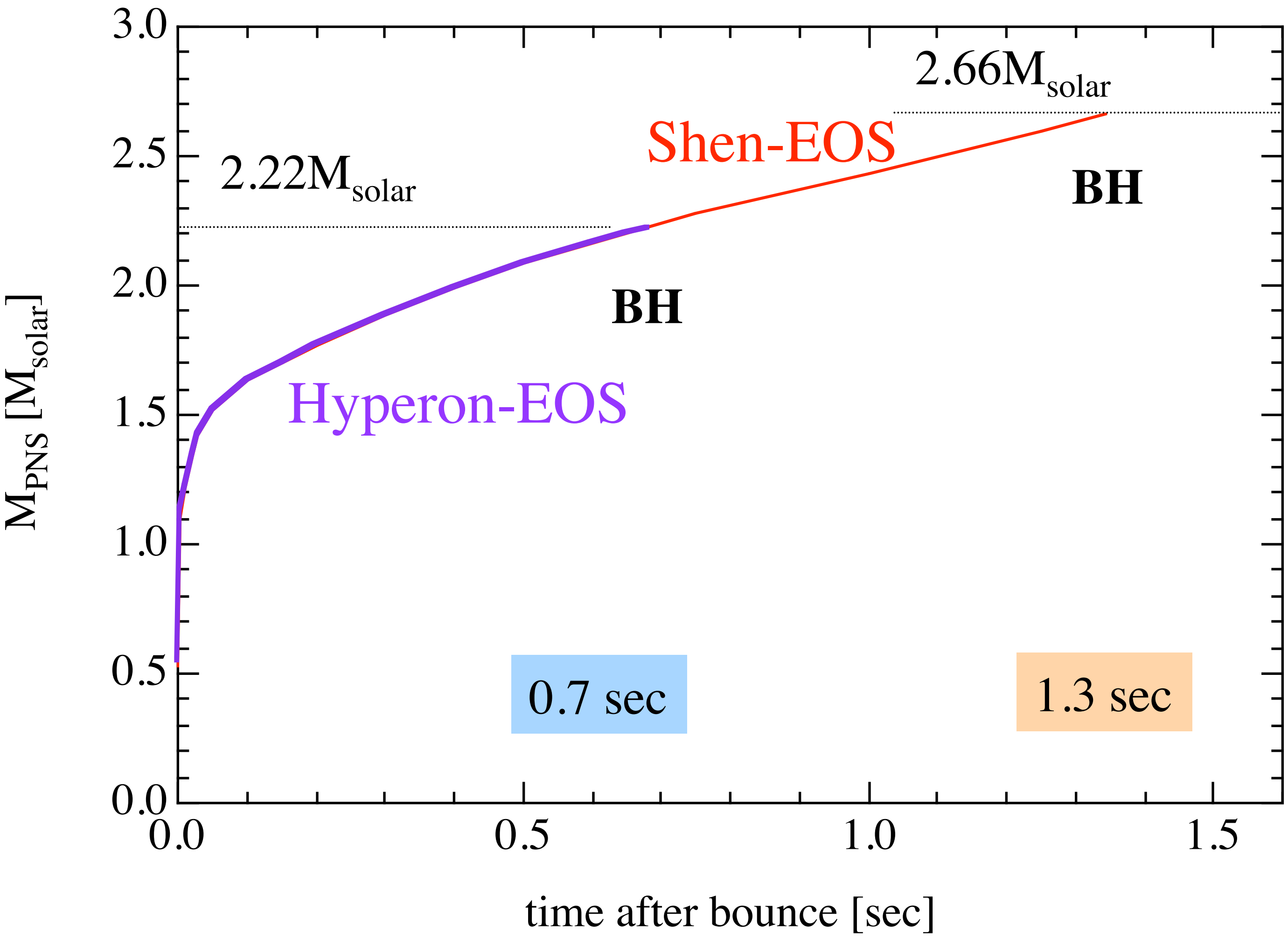



Appearance of hyperons triggers the collapse to BH

**black hole at 0.7 s**

Sumiyoshi et al., ApJ 690 (2009) L43

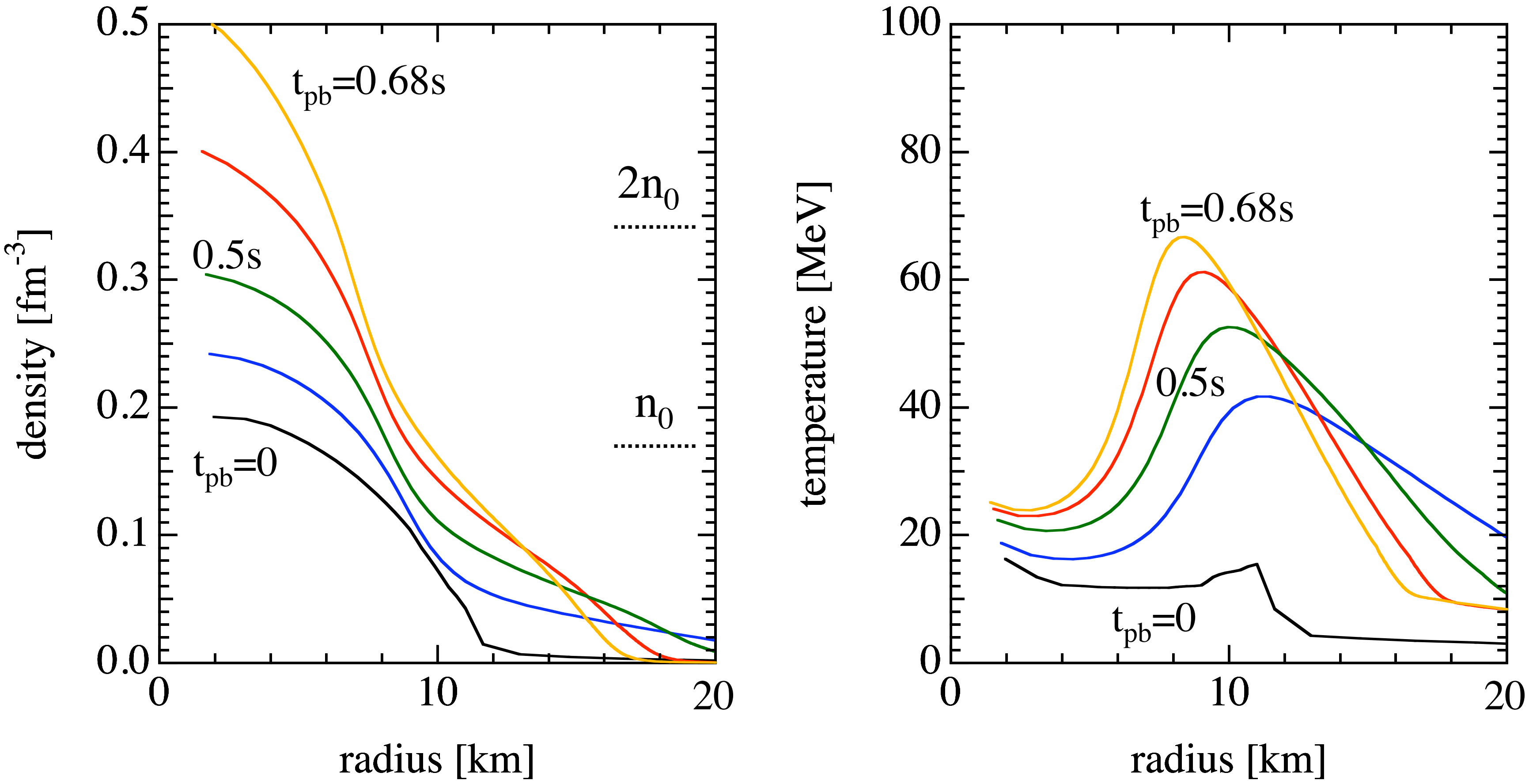
# Increase of proto-neutron star mass




Sumiyoshi et al., ApJ (2007), ApJL (2009)

# Profile of ρ, T after core bounce

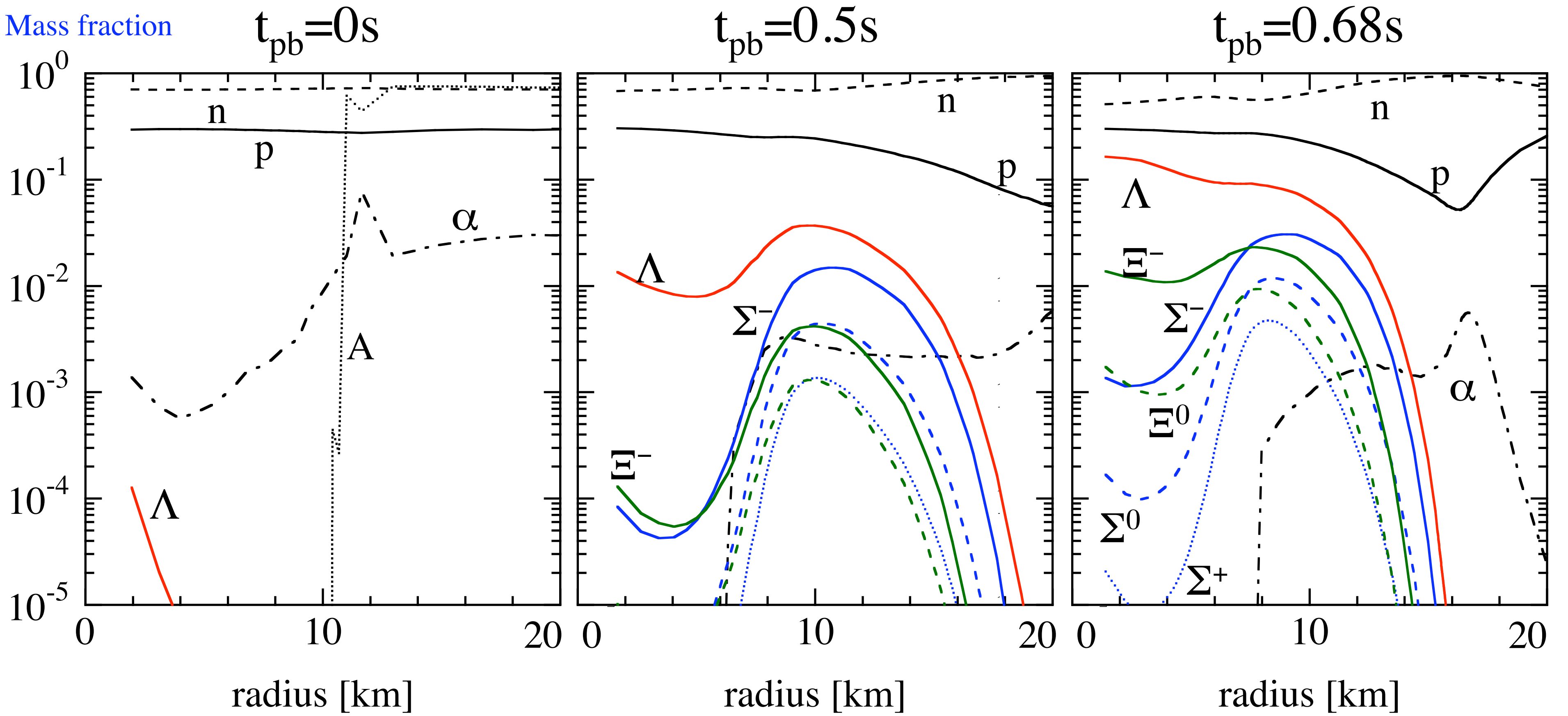
Hyperon-EOS




$t_{pb}$=0, 0.3, 0.5, 0.65, 0.68s

Sumiyoshi et al., ApJL (2009)

# Appearance of hyperons in proto-neutron star



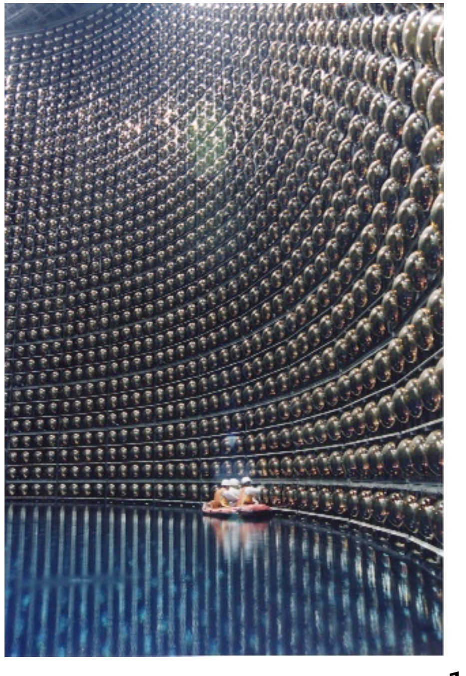

- Mixture of hyperons in 0.5s after bounce
  - Softer than Shen-EOS → Earlier collapse → Shorter ν-burst

Sumiyoshi et al., ApJL (2009)

# *Neutrino astronomy*

to explore EOS
with strangeness

2002 Nobel Prize: Prof. Koshiba



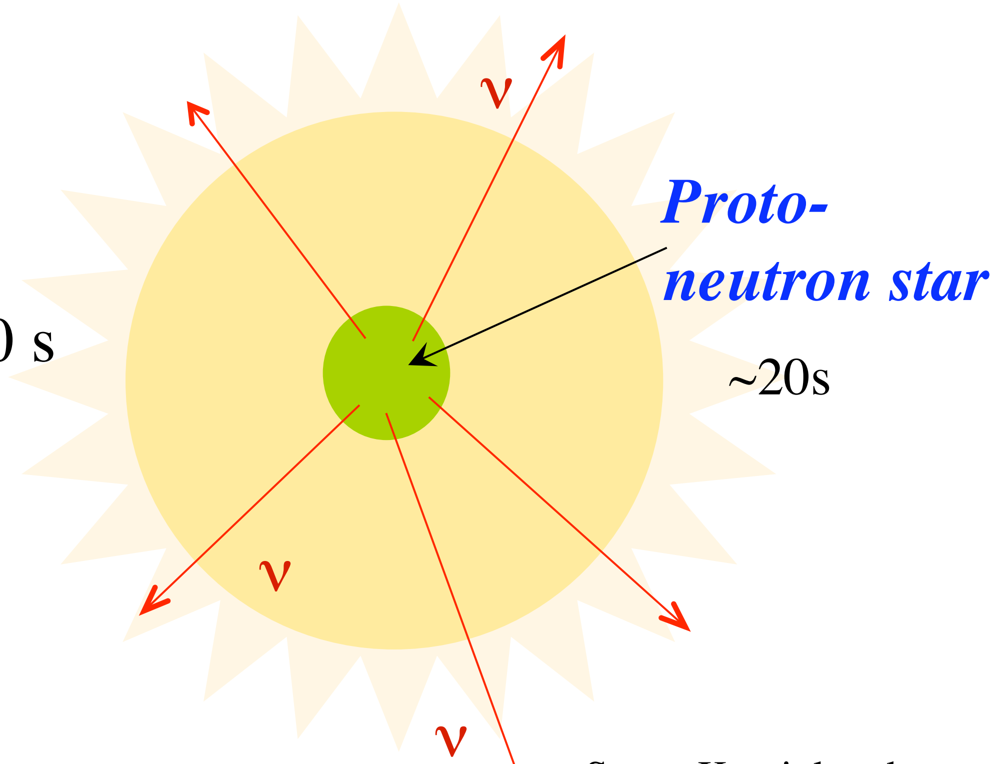
Super-Kamiokande, ICRR

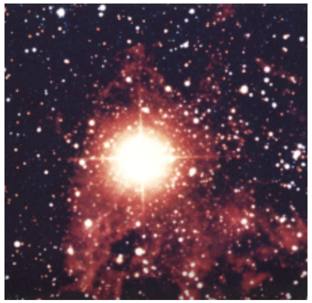
# Supernova neutrinos as a probe EOS

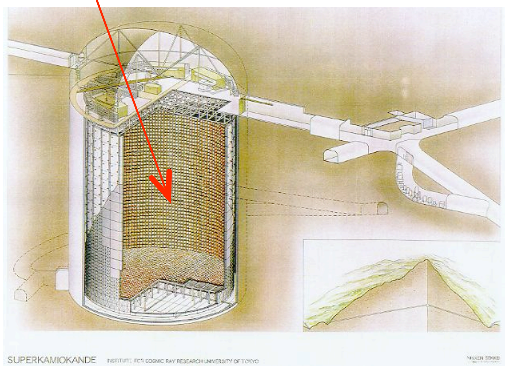
**Stars with ~ $20M_{sun} \rightarrow$ NS**

- Proto-neutron star (PNS) cools down by emitting $10^{57}$ neutrinos
- Supernova neutrinos last in ~20 s
  - SN1987A: 11 $\nu$
  - a next Galactic SN: $10^4$ $\nu$

- Neutrinos are emitted from hot and dense matter
- We can probe EOS by neutrino signals
  - Hyperons, quarks?





SN1987A

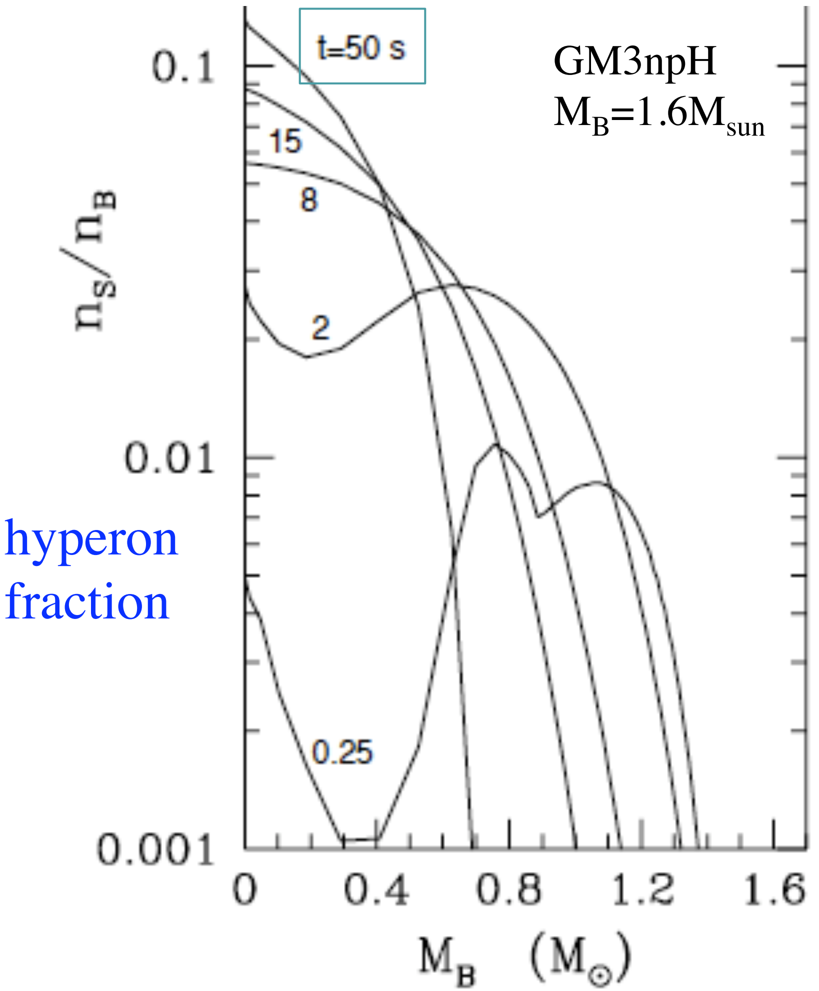
Super-Kamiokande


# Supernova ν from proto-NS

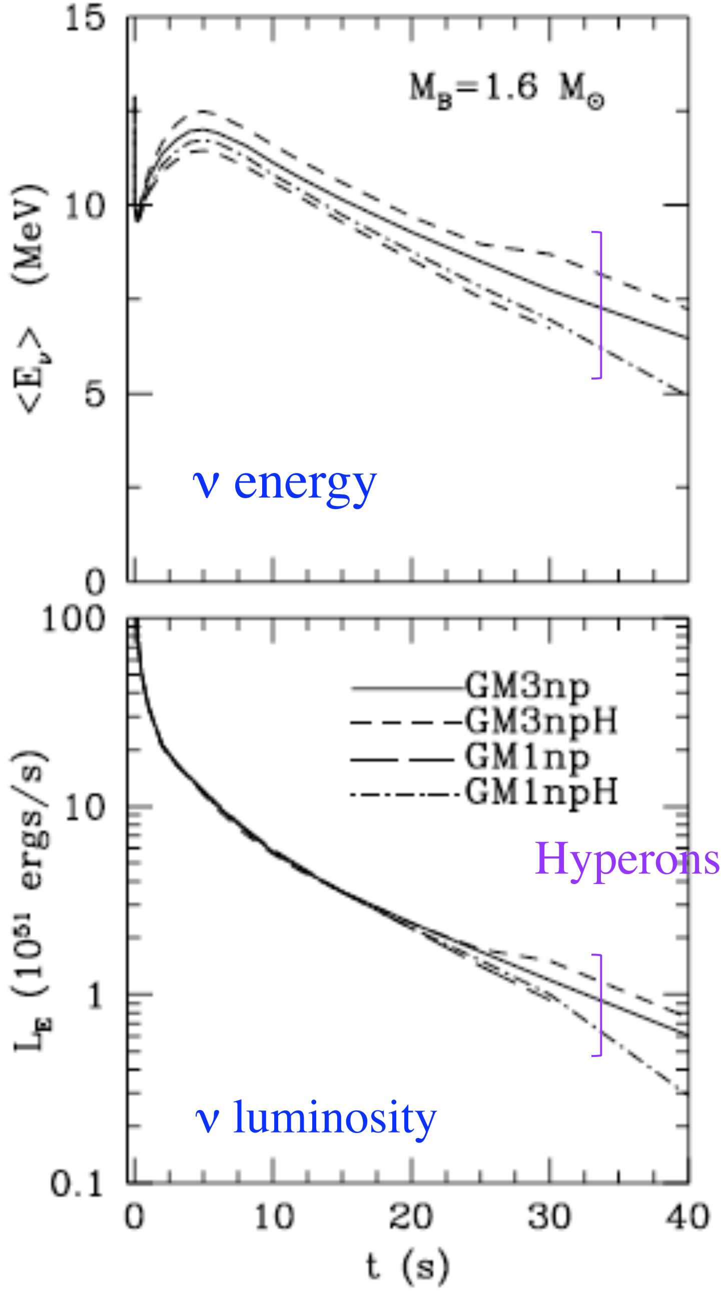
- Hyperons appear at late phase

  ν-trapping → threshold high

- EOS difference, but flux is small




Pons et al. ApJ (1999)



# Neutrinos from failed supernovae

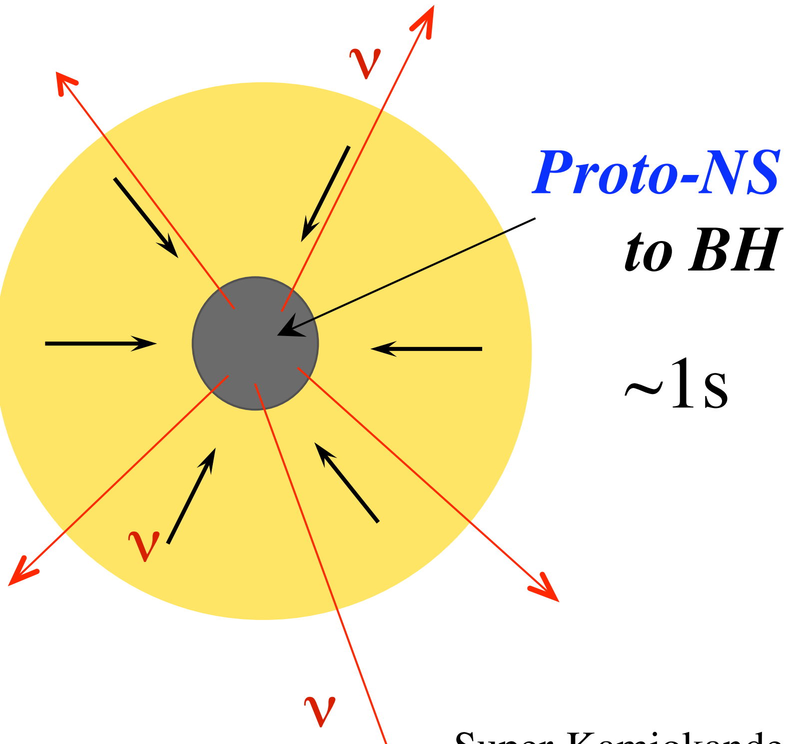
**Stars with ~ 40$M_{sun}$→BH**

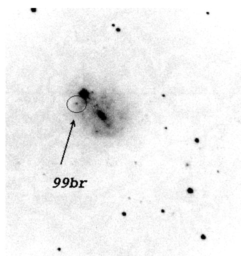
- Without any optical display

- Different from supernova ν
    - Short within ~1 sec
    - Energy, flux increase

~$10^4$ ν events for galactic cases

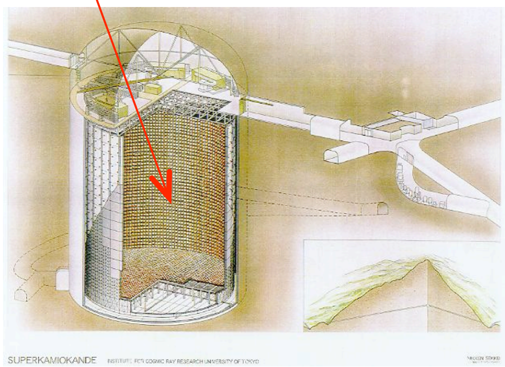
- Chance to see:
    - the birth of black hole
    - emergence of hyperons
    - transition to quarks



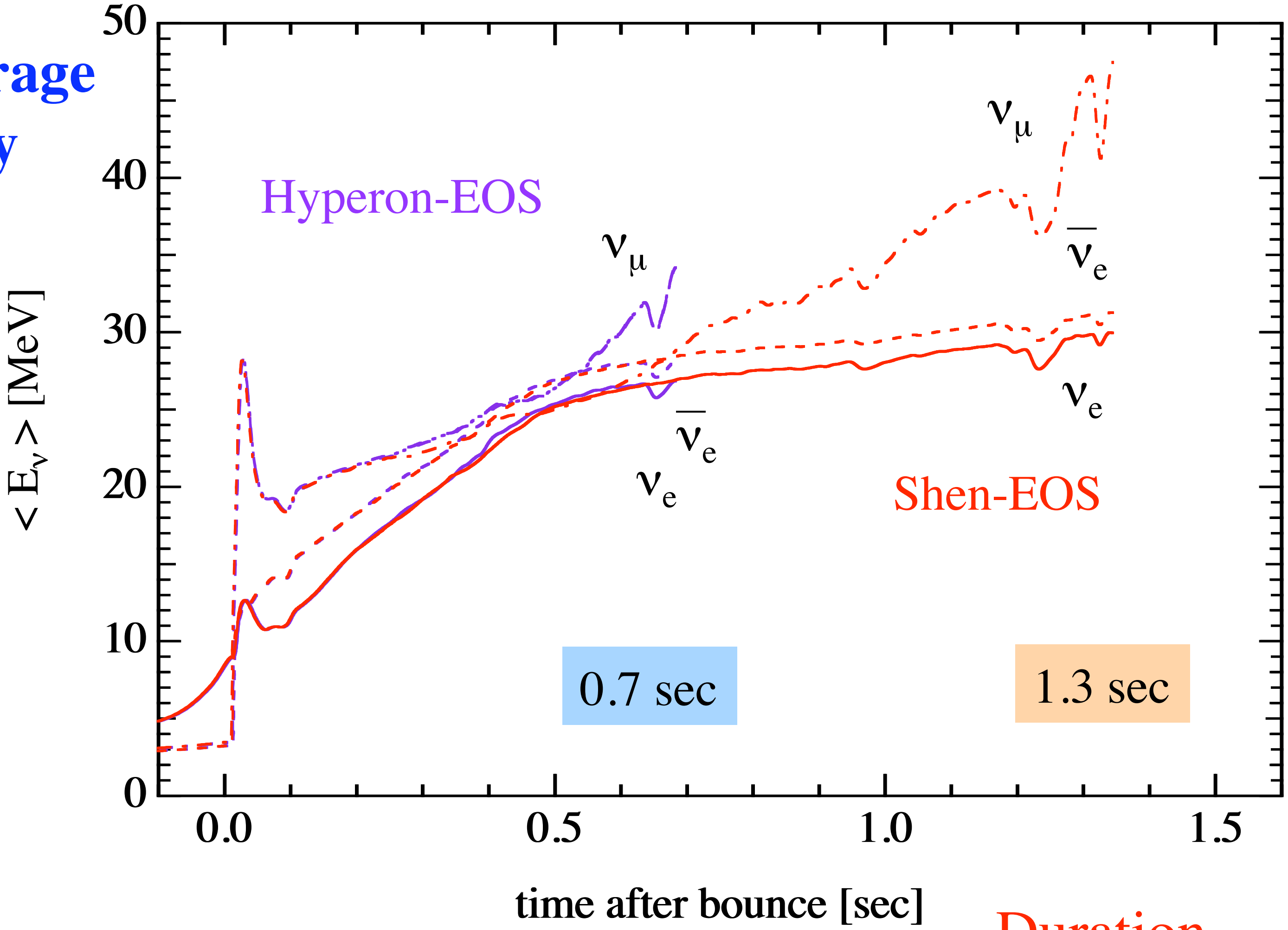

SN1999br

Super-Kamiokande



# Time evolution of average energy of neutrinos

ν-average energy



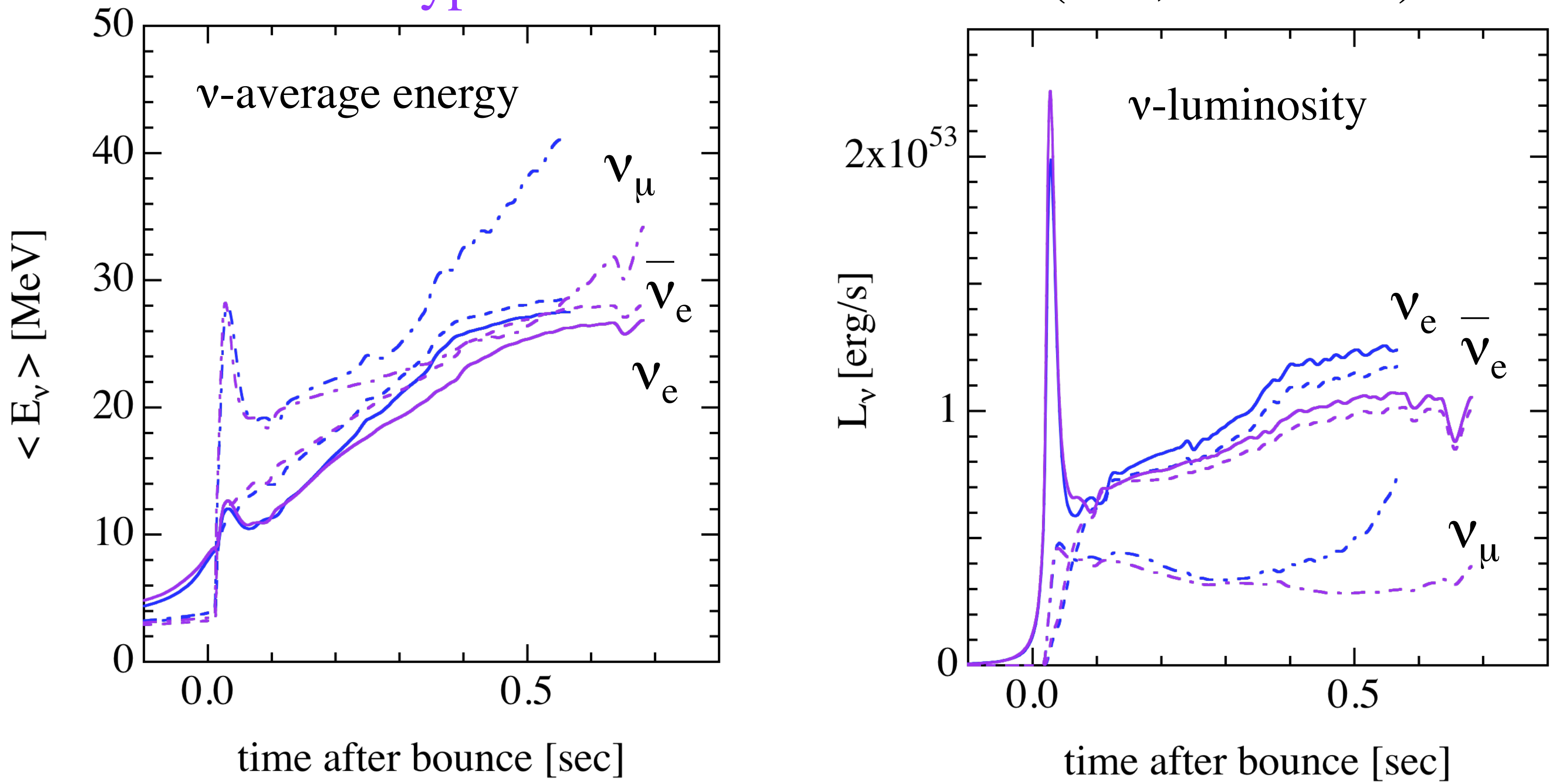

$40M_{sun}$

Duration
→ Hyperon emergence

Sumiyoshi et al., ApJL (2009)

# Can we distinguish hyperon-mixture？

Hyperon-EOS & LS-EOS (soft, nucleonic)

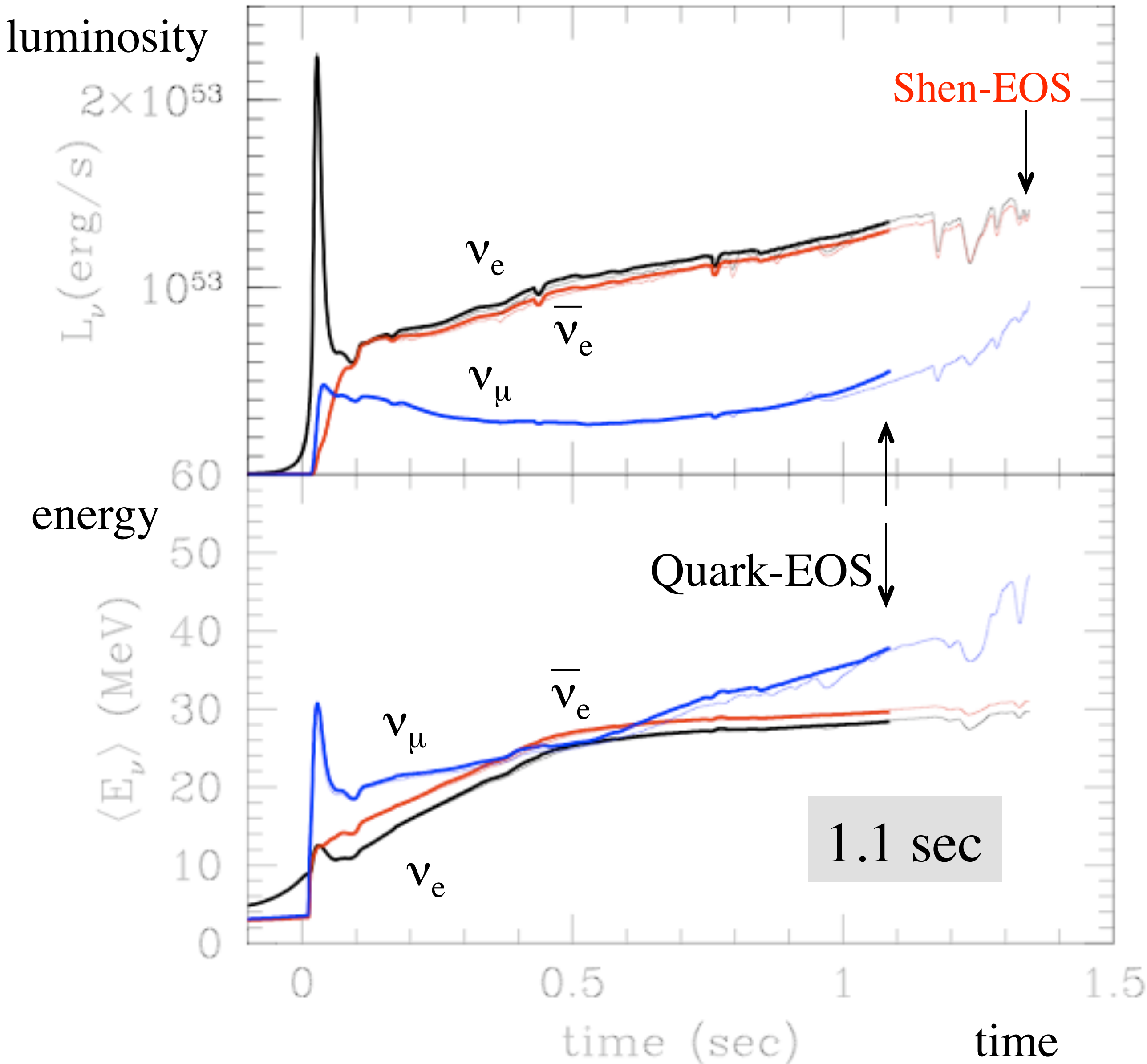



- Energy difference in μ, τ-type ν → ν-oscillation → detectable
  - Temperature effect

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

# A case of quark EOS

Nakazato (2008) PhD, PTP




$40M_{sun}$

Extension of Shen
RMF+MIT bag

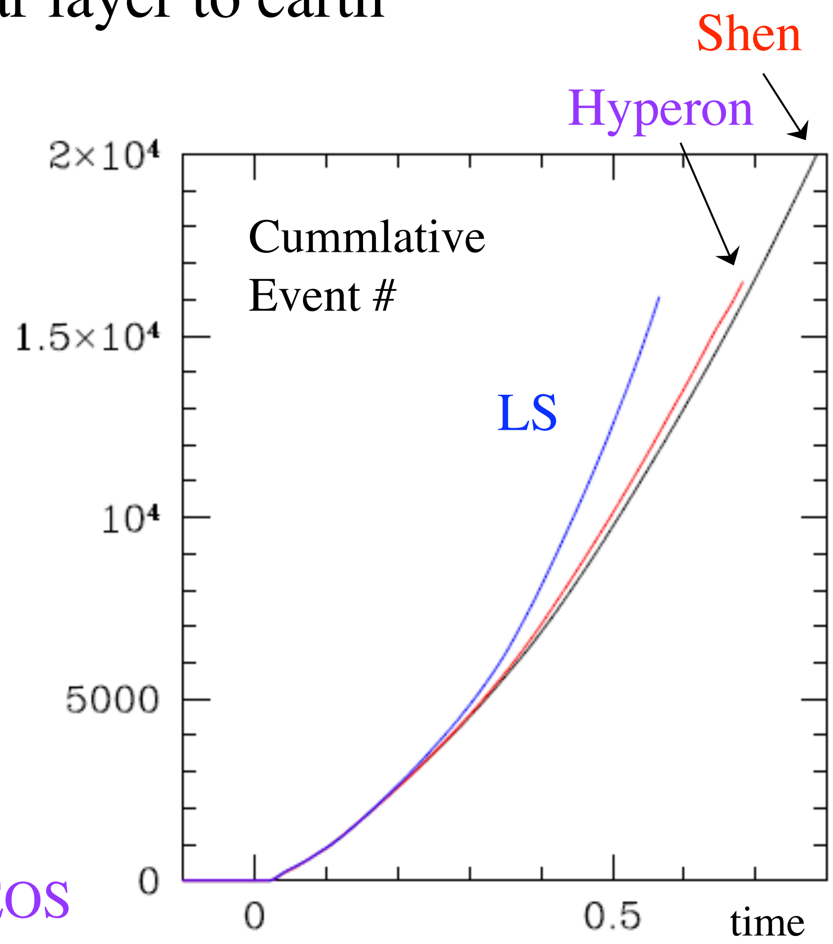
$B^{1/4}$=209 MeV
$M_{NSmax}=1.8M_{sun}$

quarks appear
only final moment

# Evaluation of neutrino detections

Nakazato et al.
PRD 2008, 2009

- 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

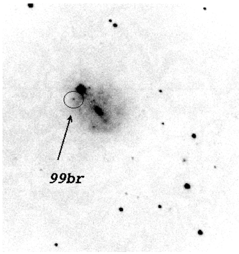
| ν-mixing | LS | Hyperon | Shen |
|---|---|---|---|
| Normal, $\sin^2\theta_{13}=10^{-8}$ | 16086 | 16490 | 49513 |
| Inverted, $\sin^2\theta_{13}=10^{-2}$ | 12136 | 9952 | 30992 |

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

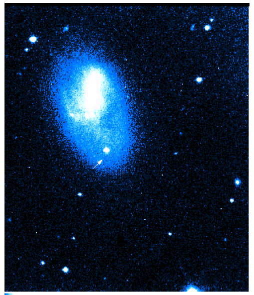
Nakazato et al. Submitted to PRL (2009)

# Feasible targets in astronomy

SN1999br




SN 1997D



From http://www.oso.chalmers.se/~duilia/sn.html

- > ~30$M_{sun}$: ~30% of massive stars
  - Obs: 2 faint supernovae, a BH with 24-33$M_{sun}$
- Monitoring disappearance of ~$10^6$ massive stars
  - planned to find a quiet death yearly Kochanek et al. ApJ 2008
- Search far galaxies by large ν-detectors (5Mt)

Kistler al. 2008

| Coverage | Distance (1pc~3ly) | SN event rates | ν event # Super-Kam. | ν event # Deep-TITAND |
|---|---|---|---|---|
| Our galaxy | 10kpc | ~0.03 /yr | ~10000 | ~$10^6$ |
| LMC, SMC | 50kpc | ~0.03 /yr | ~400 | ~$4x10^4$ |
| M31 | ~1Mpc | ~0.08 /yr | ~1 | ~100 |
| M83 | ~4Mpc | ~0.3 /yr | ~0.1 | ~10 |

# Summary: ν bursts from failed supernovae

- Quick dynamics toward BH from $40M_{sun}$ stars
  - High ρ and T within ~1 s to have strangeness
- Short (~1s) and energetic neutrino bursts
  - Different signals from ordinary supernovae (~20s)
- End of neutrino burst is determined by EOS
  - Appearance of exotics is the trigger to the BH formation
- Popular as ordinary supernovae from $\sim 20M_{sun}$ stars
  - Detection is feasible: $\sim 10^4$ ν events for super-Kamiokande

- Further studies using more sets of EOS, massive stars
  - Constrain EOS by neutrino bursts in black hole formation

## Thanks for collaboration with

- Supernova research
  - S. Yamada
  - K. Nakazato
  - H. Suzuki
- RMF-EOS table
  - H. Shen
  - K. Oyamatsu
  - H. Toki
- Extension of EOS table
  - A. Ohnishi
  - C. Ishizuka
  - K. Tsubakihara
- Supercomputing
  - S. Chiba
  - T. Maruyama
- Numerical simulations
  - K. Kiuchi
  - K. Kotake
  - N. Ohnishi
- Many body theories
  - M. Takano
  - H. Kanzawa

and others…

*Also Supercomputing resources at JAEA, YITP, RCNP, NAOJ*