Supernova Explosion and Black Hole Formation with QCD phase transition

～ along my research history ～

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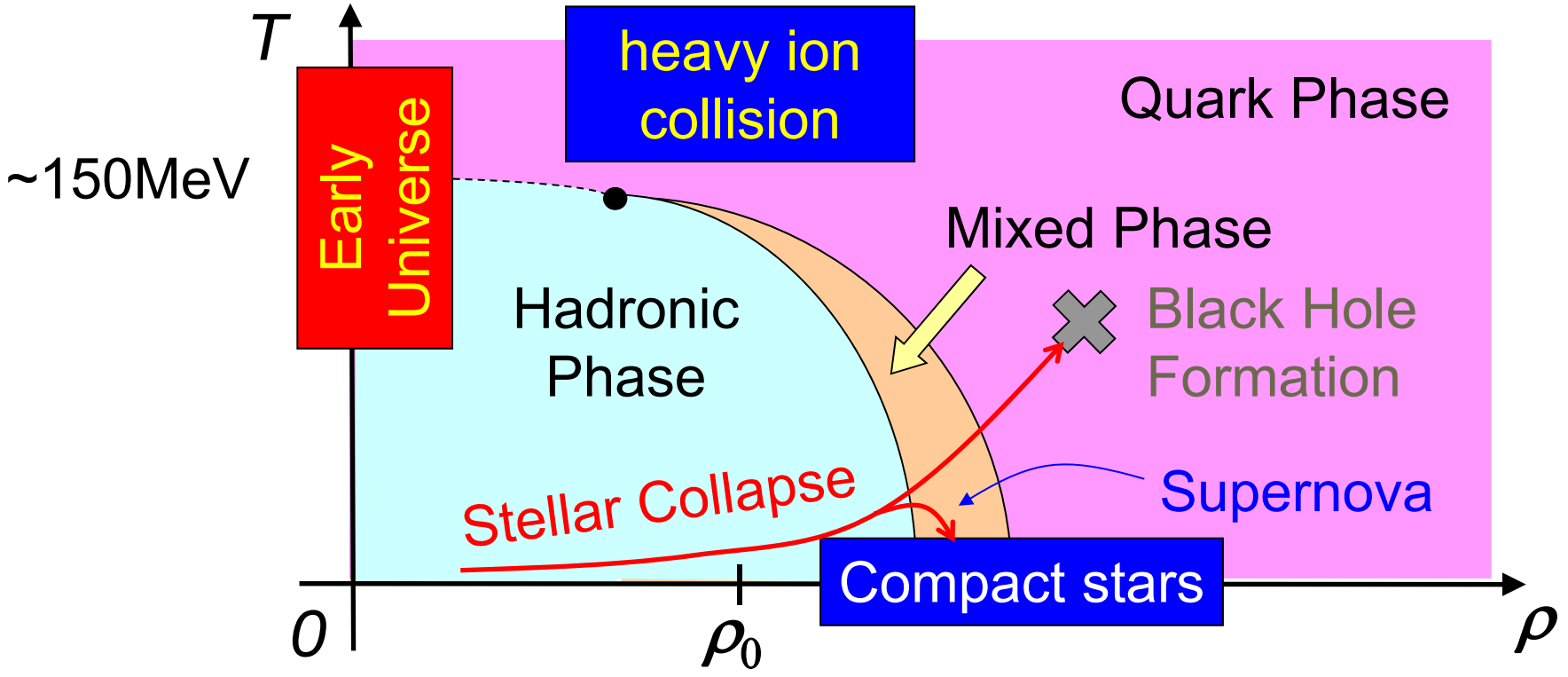
Quarks and Compact Stars @ Peking University, Oct. 21, 2014

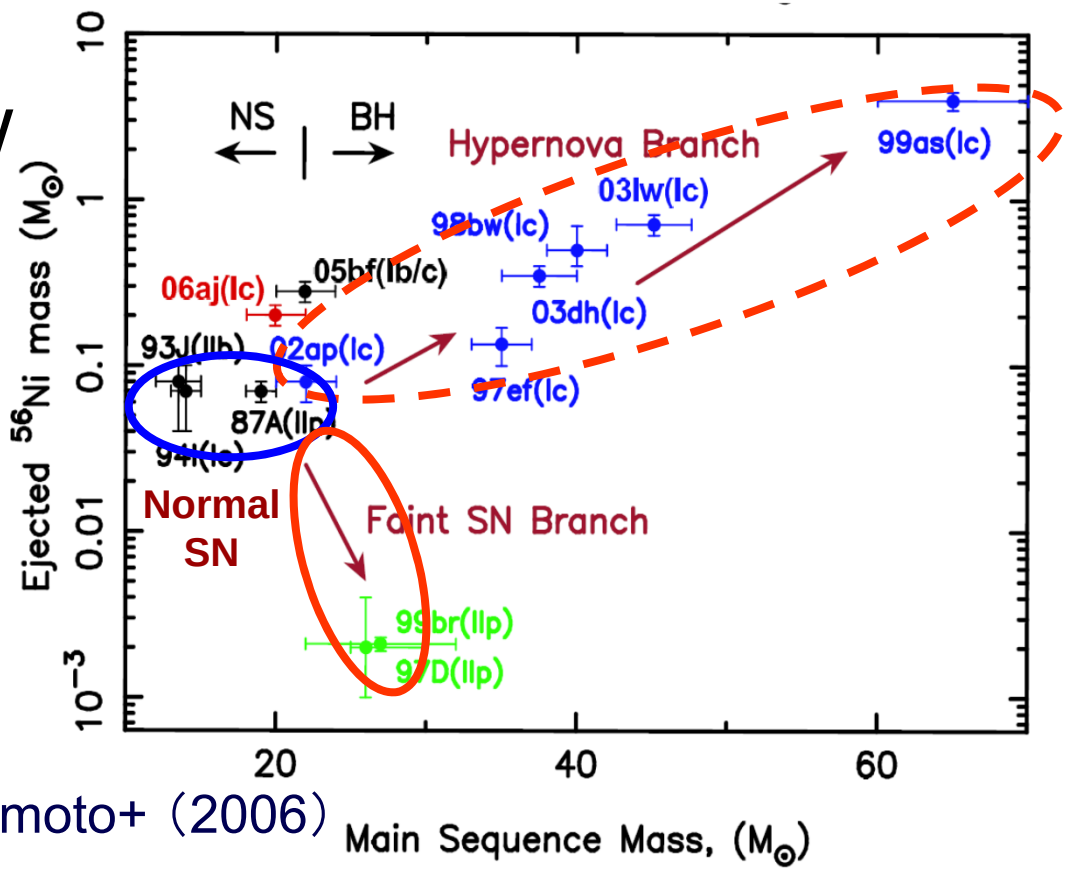
At the beginning

- from 2006, as my PhD project.
- Basic idea:
  - Collapsing core would be enough hot and dense to undergo QCD transition.



Fates of massive stars

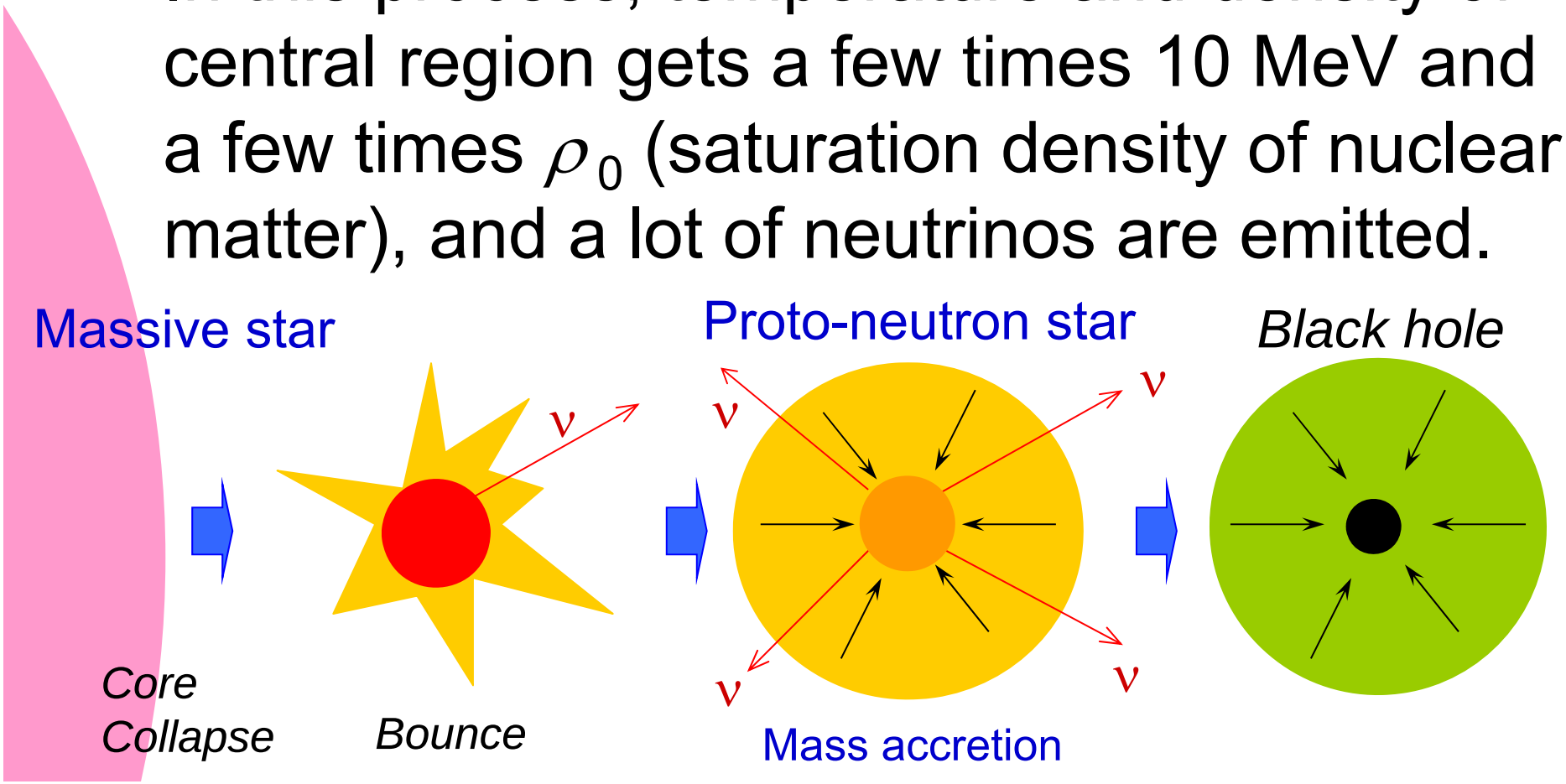
- Stars with > 10M_{solar} make a gravitational collapse and, possibly, a supernova explosion.
- Stars with > 25M_{solar} are thought to form a black hole（BH）.
- Observations show 2 branches.
  - Hypernovae （Rapid rotation）
  - Faint or Failed Supernovae （Weak rotation）



Nomoto+（2006）

Failed supernova neutrinos

- Failed supernova progenitor makes bounce once and recollapse to the black hole.
- In this process, temperature and density of central region gets a few times 10 MeV and a few times ρ_0 (saturation density of nuclear matter), and a lot of neutrinos are emitted.



Hydrodynamics & neutrinos

Yamada, Astrophys. J. **475** (1997), 720
Yamada et al., Astron. Astrophys. **344** (1999), 533
Sumiyoshi et al., Astrophys. J. **629** (2005), 922

Spherical, Fully GR Hydrodynamics

metric : Misner-Sharp (1964) mesh : 255 non uniform zones

+

Neutrino Transport (Boltzmann eq.)

Species : ν_e , $\bar{\nu}_e$, ν_μ (= ν_τ) , $\bar{\nu}_\mu$ (= $\bar{\nu}_\tau$)

Energy mesh : 14 zones (0.9 – 350 MeV)

Reactions : $e^- + p \leftrightarrow n + \nu_e$, $e^+ + n \leftrightarrow p + \bar{\nu}_e$, $\nu + N \leftrightarrow \nu + N$,

$\nu + e \leftrightarrow \nu + e$, $\nu_e + A \leftrightarrow A' + e^-$, $\nu + A \leftrightarrow \nu + A$,

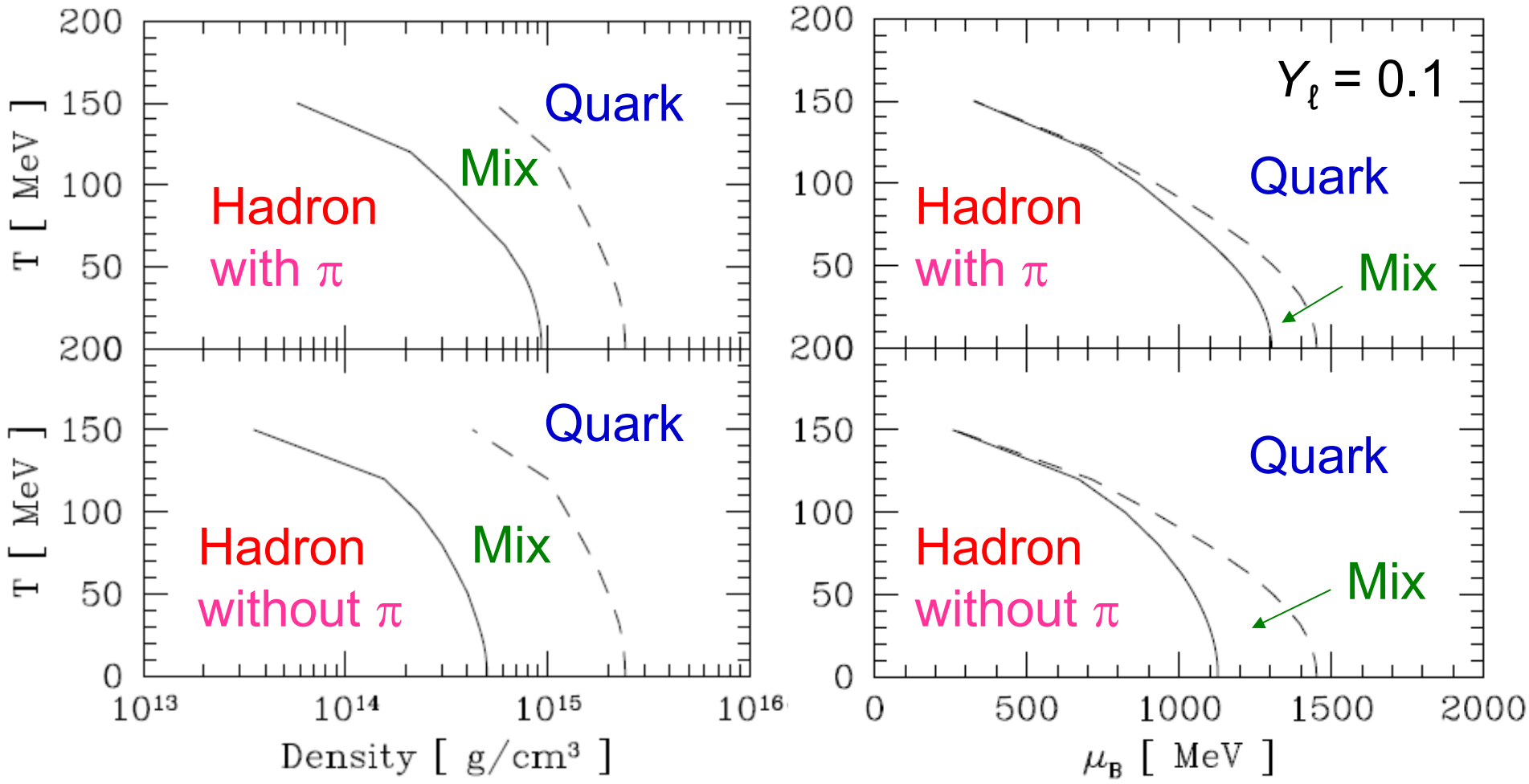
$e^- + e^+ \leftrightarrow \nu + \bar{\nu}$, $\gamma^* \leftrightarrow \nu + \bar{\nu}$, $N + N' \leftrightarrow N + N' + \nu + \bar{\nu}$

Hadron-quark mixed EOS

Nakazato et al., PRD **77** (2008a), 103006

- Shen EOS (1998) (+ π) for Hadronic phase
- MIT Bag model (Chodos et al. 1974) for Quark phase
  - Bag constant: B = 250 MeV/fm^3
- Gibbs conditions are satisfied in Mixed phase.
  - $\mu_n = \mu_u + 2\mu_d$, $\mu_p = 2\mu_u + \mu_d$
  - $P_H = P_Q$
- β equilibrium (ν trapping) is assumed in Mixed and Quark phase.
  - $\mu_d = \mu_s$, $\mu_p + \mu_e = \mu_n + \mu_\nu$

Phase diagram of EOS

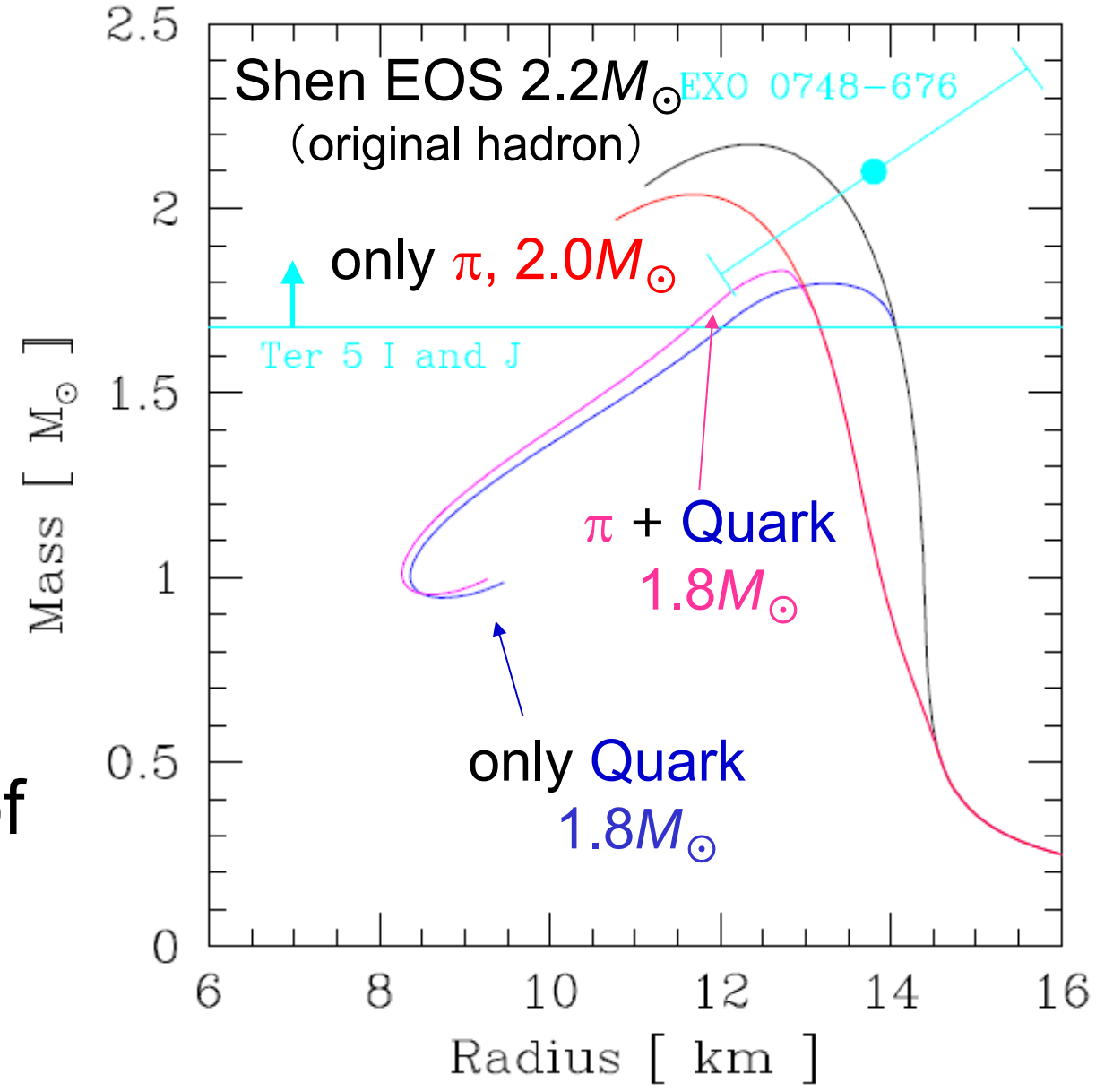


- $\rho_{\text{trans.}}$ and $\mu_{\text{B trans.}}$ are lower for high T

→ Consistent to well known properties.

Maximum mass of hybrid stars

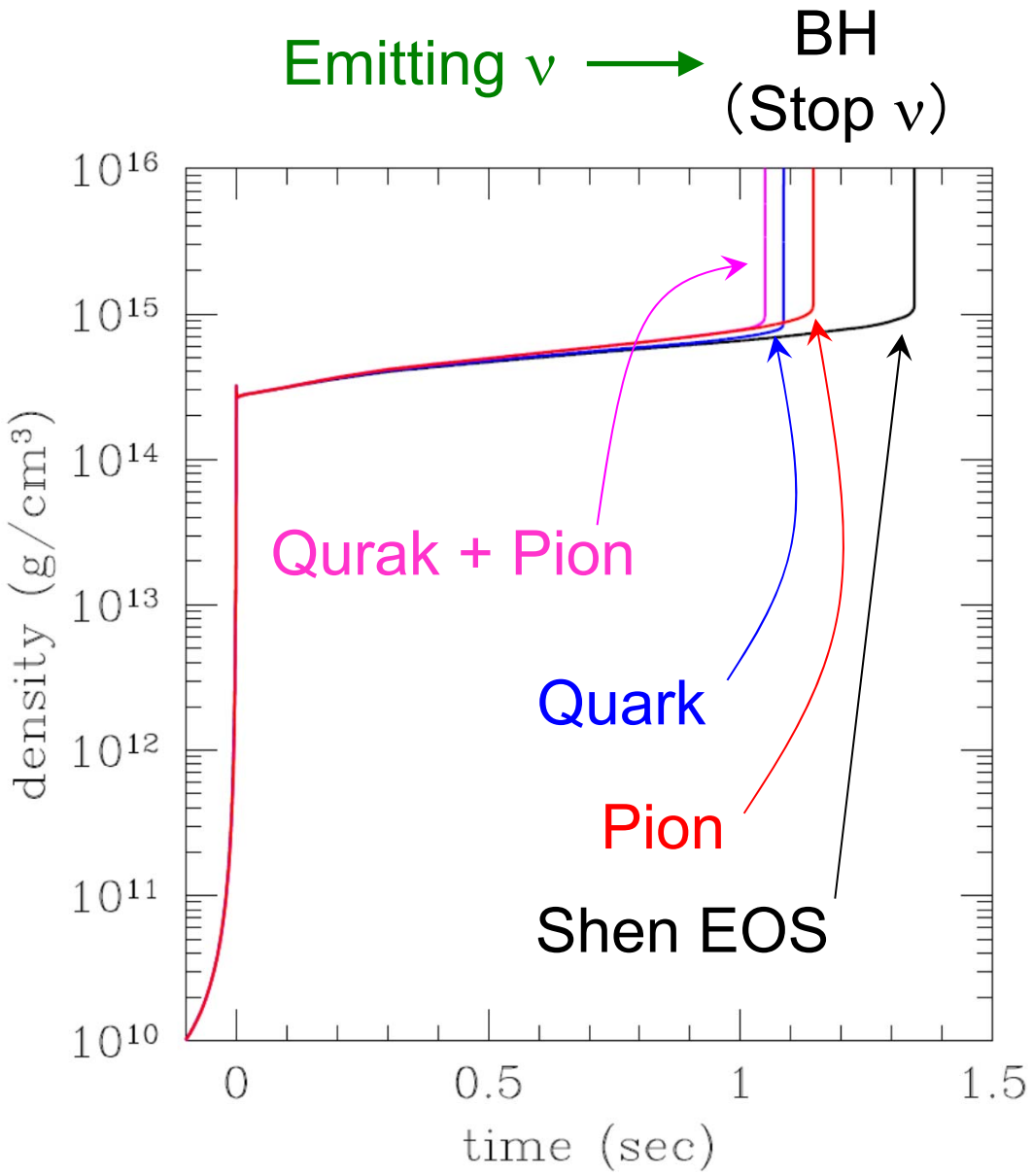
- $1.8M_\odot$ for our EOS with π and Quark
- $2.2M_\odot$ for Shen EOS
- That **WAS** consistent to observations of compact stars.



Evolution of the central density

$40M_{\odot}$ model

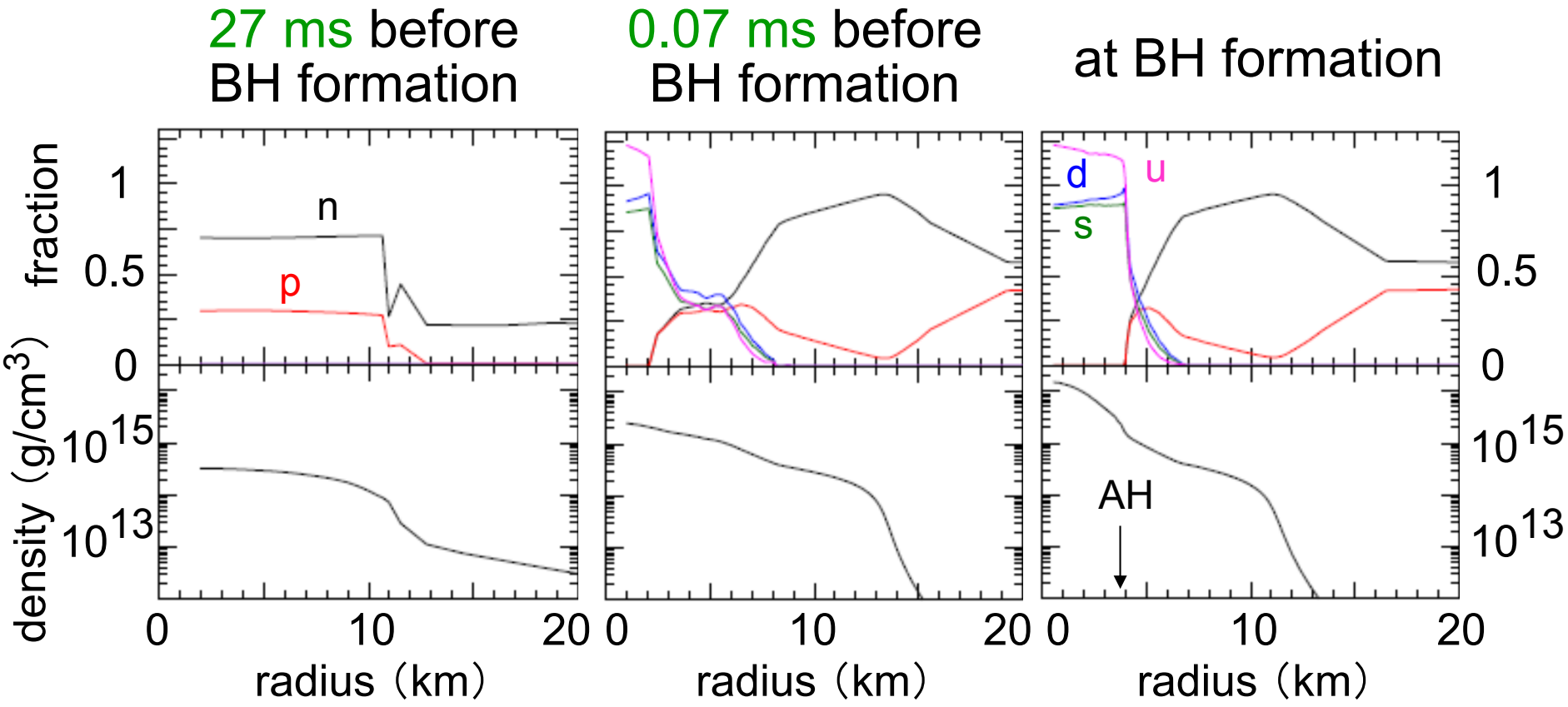
- QCD transition fastens the BH formation.
- Thus it shortens the duration of neutrino emission because EOS gets softer.



Compositions

$40M_{\odot}$ model

Nakazato et al., Astrophys. J. **721** (2010b), 1284



- Quark transition occurs at the very late phase and trigger the black hole formation.

Shock in 2008

- M. Liebendoerfer and T. Fischer
- March, workshop at Ringberg castle.
  - They and we were studying same theme.
  - We had already submitted a paper on BH.
- August, e-mail form M. Liebendoerfer.
  - They reported a successful SN explosion.
- What is different?

Bag Constant

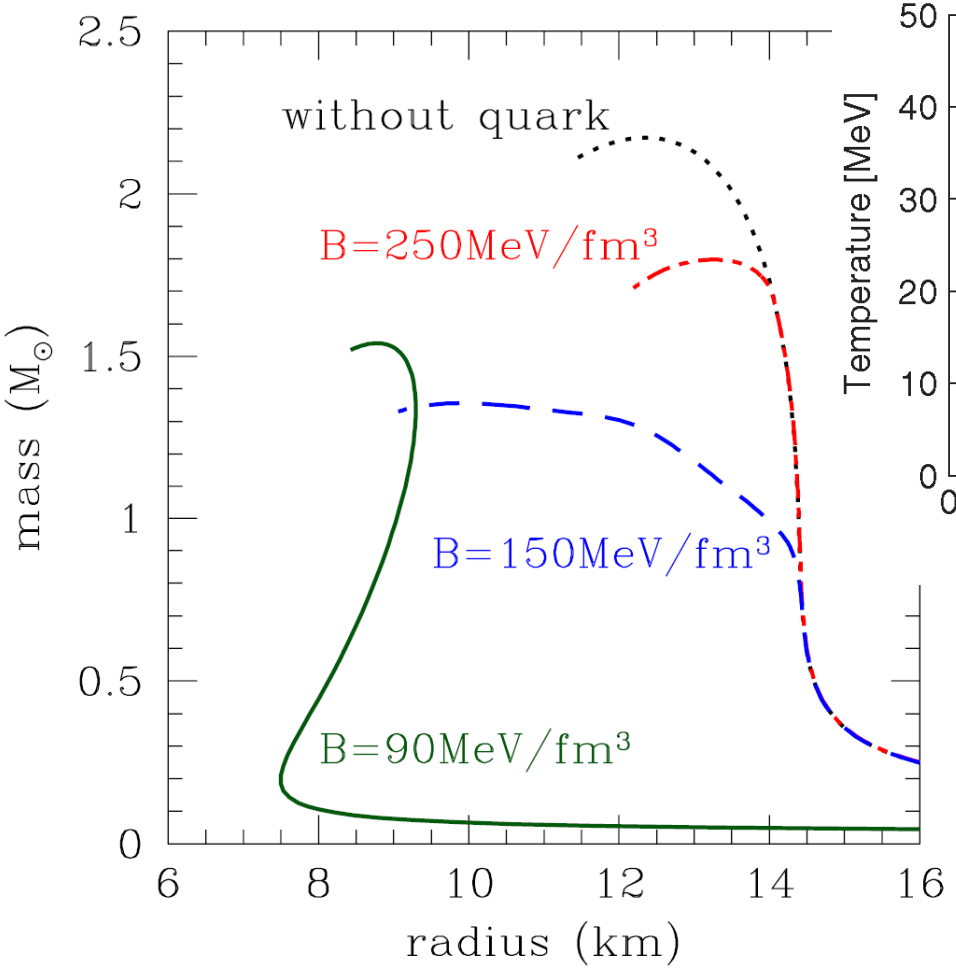
QCD scenario for SN explosion

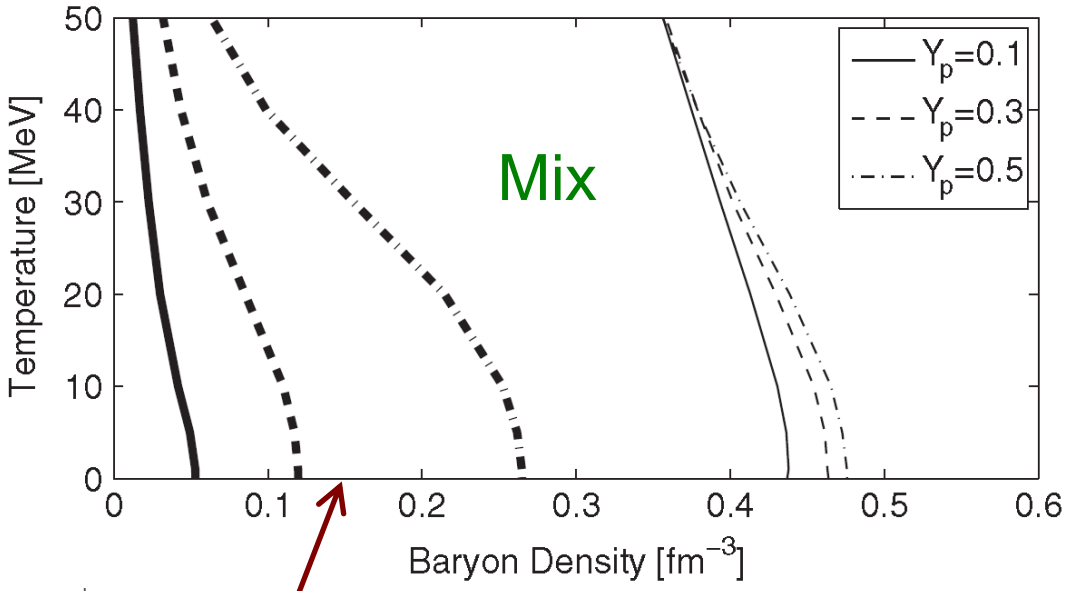
Sagert et al., Phys. Rev. Lett. **102** (2009), 081101
Fischer et al., Astrophys. J. Suppl. **194** (2011), 39

- Bag constant is assumed to be very low
  ~ 90 MeV/fm^3
- Transition density is very low.

- Core collapse → bounce (as ordinary)
- Shock is launched but stalled (as ordinary)
- But, core collapse again → bounce again
- Shock propagates → successful explosion

Low bag constant case





saturation density

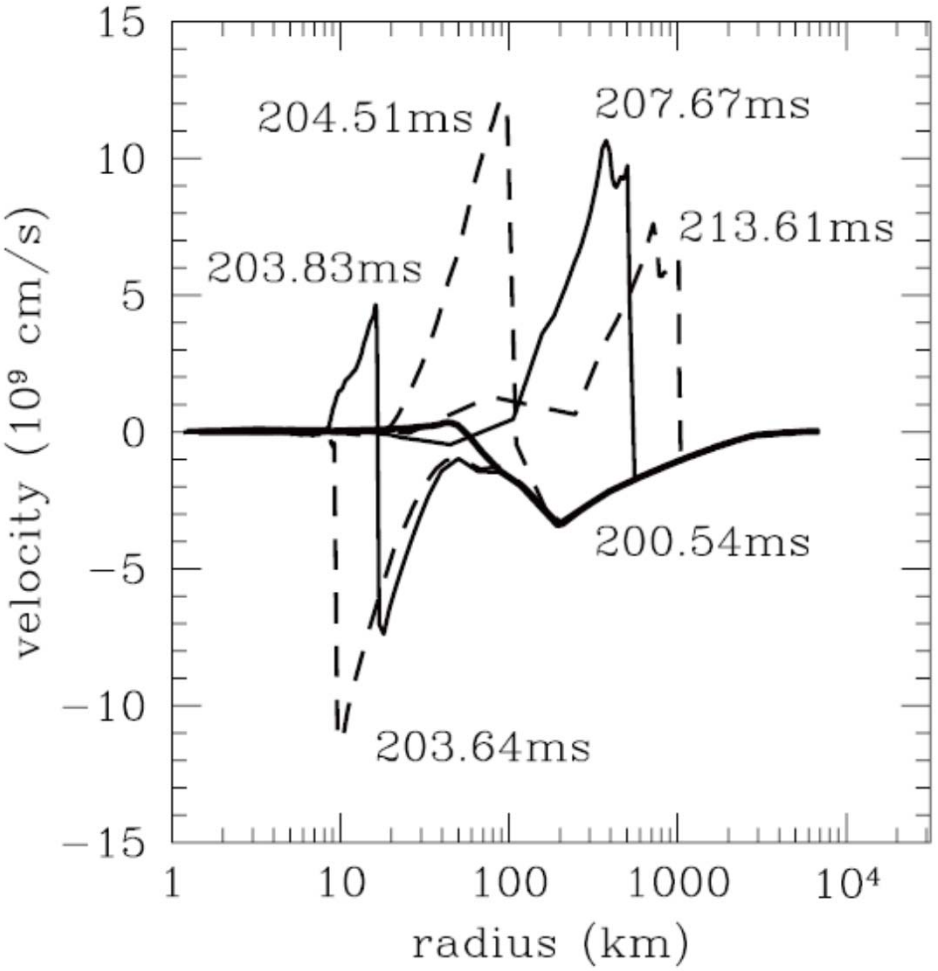
- The maximum mass WAS somewhat low.
- Critical density is very low.

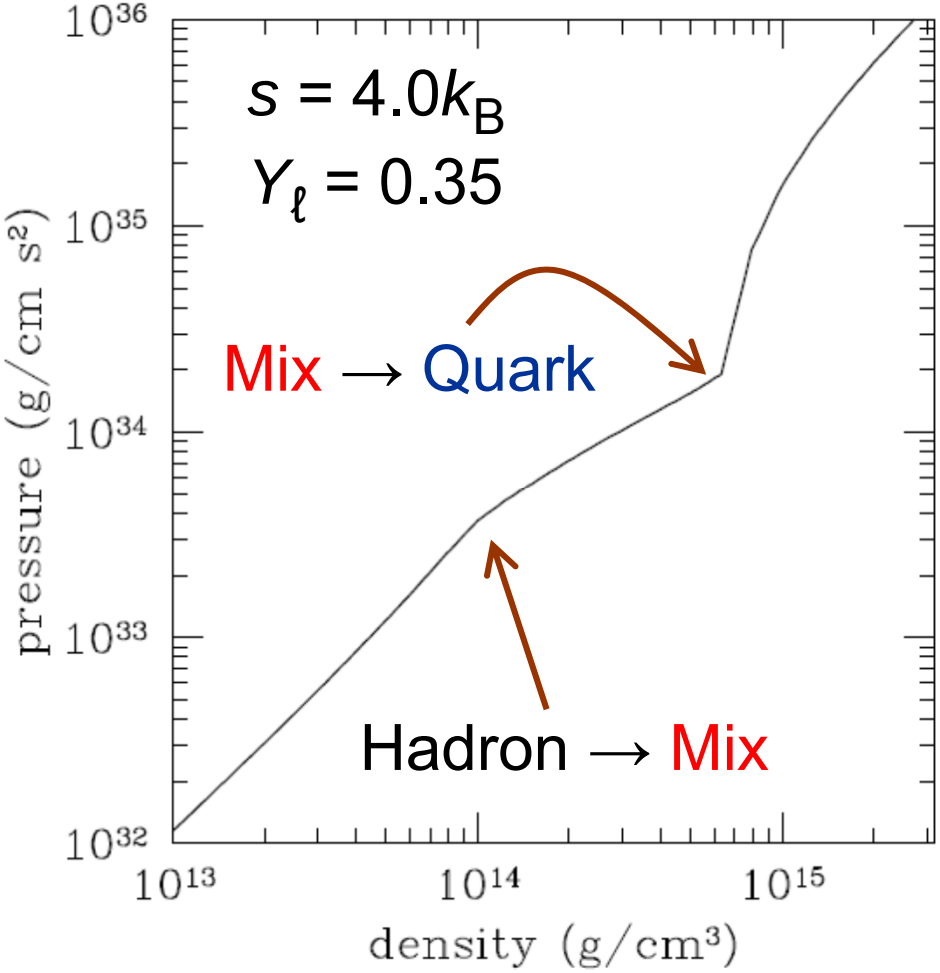
Our result

$15M_{\odot}$ model

Nakazato et al., Astron. Astrophys. **558**（2013b）, A50

- Confirming 2nd bounce and shock formation



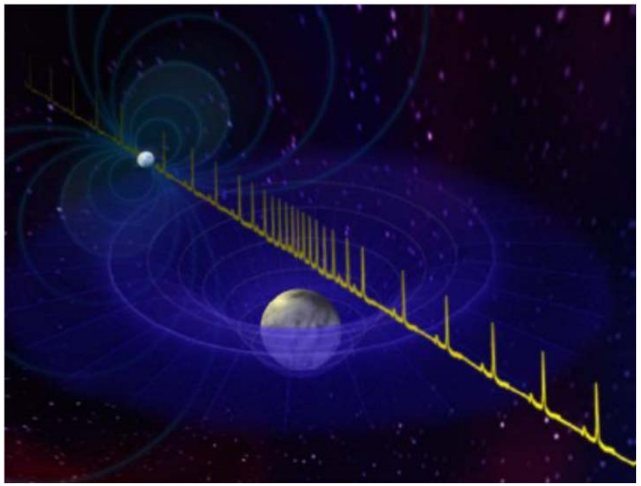


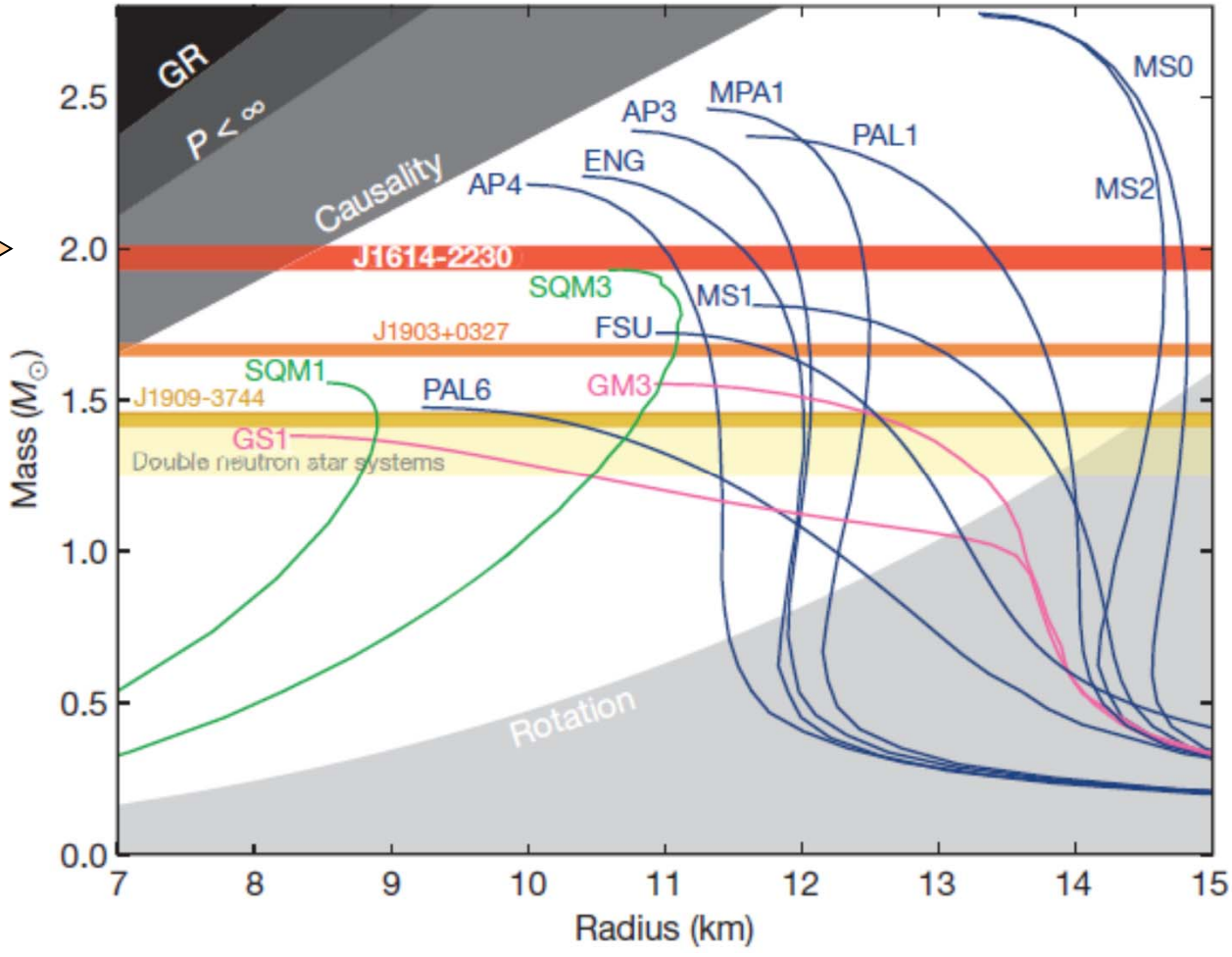
Shock in 2010

- Pulsar J1614-2230, $M = 2M_{\odot}$

Demorest et al., Nature **467**（2010）, 1081

Shapiro delay

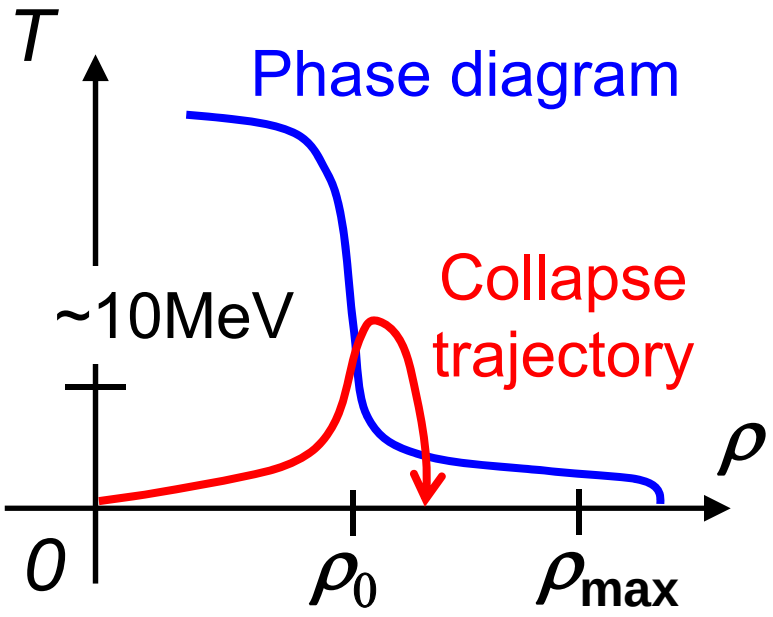


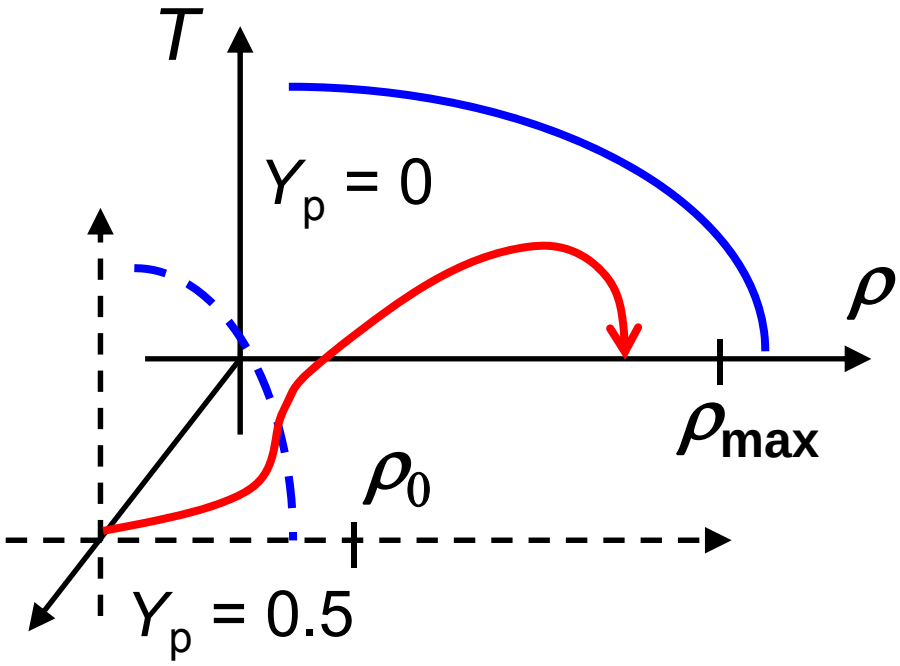


Outlook

- Is QCD scenario hopeless?
- Discussion in workshop at Prerow（2014）.

  → possibly back to ``neutron'' stars?





- Comments welcome!