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 $> 10M_{\text{solar}}$ make a gravitational collapse and, possibly, a supernova explosion.
- Stars with $> 25M_{\text{solar}}$ 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 $\rho_0$ (saturation density of nuclear matter), and a lot of neutrinos are emitted.
Hydrodynamics & neutrinos

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: $\nu_e, \bar{\nu}_e, \nu_\mu ( = \nu_\tau ), \bar{\nu}_\mu ( = \bar{\nu}_\tau )$

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.
  - $\mu_n = \mu_u + 2\mu_d$, $\mu_p = 2\mu_u + \mu_d$
  - $P_H = P_Q$
- $\beta$ equilibrium ($\nu$ 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 \( \mu_B \) for high T are lower for high T
  \(
  \rightarrow \text{Consistent to well known properties.}
  \)
Maximum mass of hybrid stars

- $1.8M_\odot$ for our EOS with $\pi$ and Quark
- $2.2M_\odot$ for Shen EOS
- That WAS consistent to observations of compact stars.
Evolution of the central density

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

• Bag constant is assumed to be very low
  ~ 90 MeV/fm$^3$
• Transition density is very low.
• Core collapse $\rightarrow$ bounce (as ordinary)
• Shock is launched but stalled (as ordinary)
• But, core collapse again $\rightarrow$ bounce again
• Shock propagates $\rightarrow$ successful explosion
Low bag constant case

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

![Graph showing mass vs. radius and temperature vs. baryon density with different B values and Yp values.]

- saturation density
Our result

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

• Confirming 2\textsuperscript{nd} bounce and shock formation

\[ s = 4.0k_B \]
\[ Y_\ell = 0.35 \]

Mix $\rightarrow$ Quark

Hadron $\rightarrow$ Mix
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?

Phase diagram

\[ T \begin{array}{c}
\uparrow

\rho

\approx 10\text{MeV}
\end{array} \begin{array}{c}
\downarrow

\rho_0

\rho_{\text{max}}
\end{array} \]

Collapse trajectory

\[ T \begin{array}{c}
\uparrow

\rho

\rho_0

\rho_{\text{max}}
\end{array} \begin{array}{c}
\downarrow

Y_p = 0

Y_p = 0.5
\rho_0
\end{array} \]

• Comments welcome!