Signals of quark matter in core-collapse supernovae

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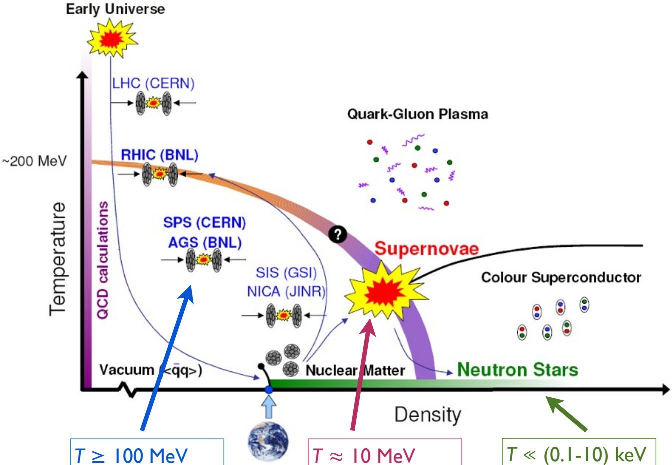
(A) Phase diagram of strongly interacting matter



$T \geq 100$ MeV
$n_b \leq n_0, Y_p \approx 0.5$
$t \approx (10^{-23}\text{-}10^{-21})$ s

$T \approx 10$ MeV
$n_b \geq n_0, Y_p \leq 0.3$
$t \approx$ ms

$T \ll (0.1\text{-}10)$ keV
$n_b \gg n_0, Y_p \ll 0.5$
$t \gg$ s

Fig.: Fredrik Sandin

Conditions in a core collapse supernova - 15 $M_\odot$

- Typical conditions after core-bounce:
  $T \sim 10$ MeV
  $Y_p \lesssim 0.3$
  $n_b \gtrsim n_0$

- Typical supernova EoSs cover:
  $T : (0- \geq 100)$ MeV
  $Y_p : 0.01- \geq 0.5$
  $n_b : (10^5- \geq 10^{15})\ \frac{\mathrm{g}}{\mathrm{cm}^3}$

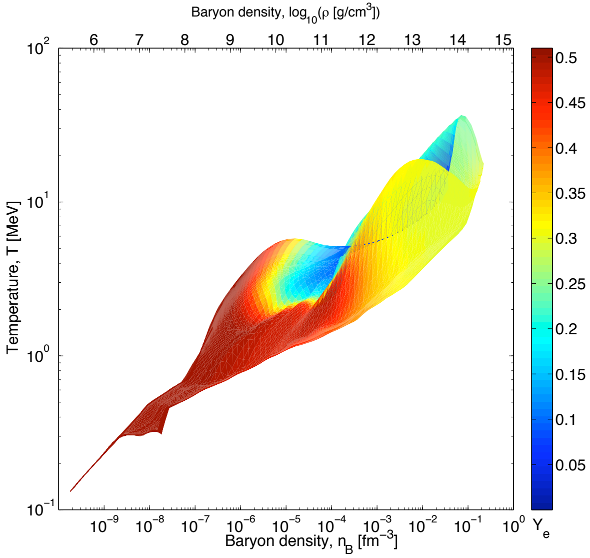


Figure: Fischer et al., ApJS 194, 39 (2011): Phase space covered in a core collapse simulation for a 15 $M_\odot$ progenitor

Conditions in a core collapse supernova - 40 $M_\odot$

- Typical conditions after core-bounce:
  $T \sim 10$ MeV
  $Y_p \lesssim 0.3$
  $n_b \gtrsim n_0$

- Typical supernova EoSs cover:
  $T : (0 - \geq 100)$ MeV
  $Y_p : 0.01 - \geq 0.5$
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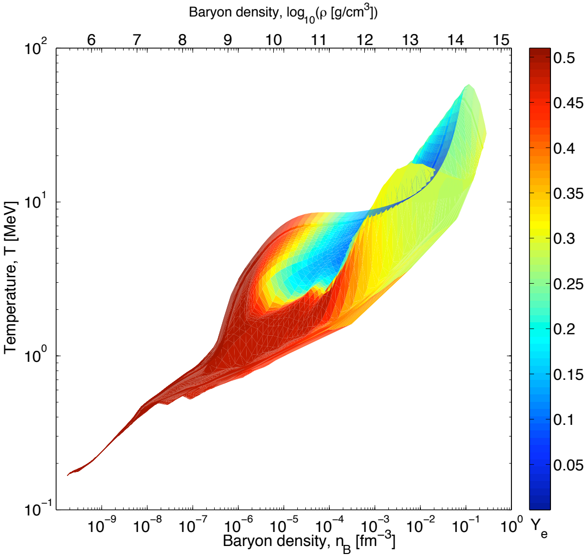


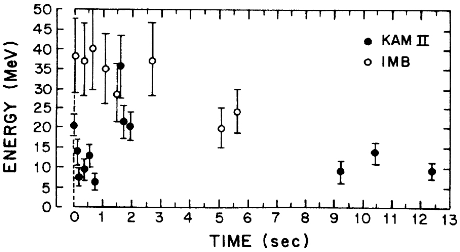
Figure: Fischer et al., ApJS 194, 39 (2011): Phase space covered in a core collapse simulation for a 40 $M_\odot$ progenitor

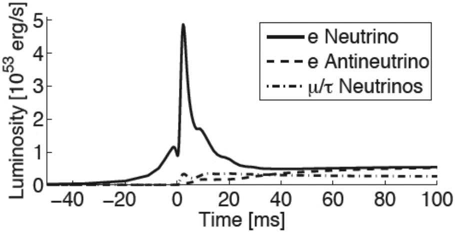
Supernova observables

- Neutrino signal, gravitational waves, impact on nucleosynthesis, ...

SN1987A:

- Supernova explosion of $20M_\odot$ progenitor
- Detection of 24 neutrinos during ca. 13 s
- Estimated for emitted energy: $\sim 2 \cdot 10^{53}$ erg
- Next galactic supernova: IceCube and Superkamiokande will observe $\sim 10^3$ neutrinos





Figures: Hirata et al., Phys. Rev. D, Vol. 38, 2 (1988)

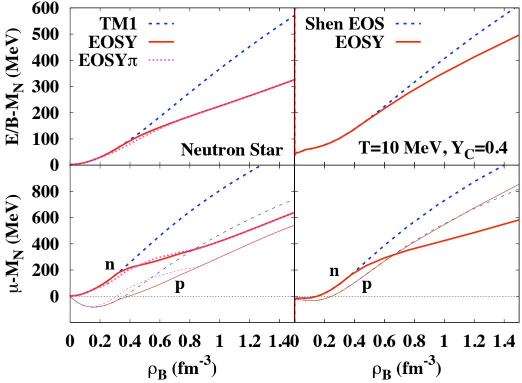
Quark and hyperon matter in core collapse supernovae

- Migdal, Chernoustan, Mishustin, Phys. Lett. B 83 (1979)
- Takahara and Sato, Astrophys. and Space Science 119 (1986)
- Drago and Tambini, Journal of Phys. G 25 (1999)

- Gentile et al., Astrophys. Journal 414 (1993)
- Pons et al., ApJ 513 (1999), Pons et al., Phys.Rev.Lett. 86 (2001)
- Nakazato et al., Phys. Rev. D 77 (2008)
- Sumiyoshi et al., ApJL, 690 (2009)
- I.S. Fischer et al., Phys. Rev. Lett. 102 (2009)
- ...

- Ishizuka et al., Journal of Phys. G 35 (2008)
- Shen et al., Astrophys. Journal Suppl. 197 (2011)
- Oertel, Fantina, and Novak, Phys. Rev. C 85 (2012)
- Perez, Oertel, Novak, Phys. Rev. D 87 (2013)
- Gulminelli, Raduta, Oertel, Margueron, Phys. Rev. C 87 (2013)

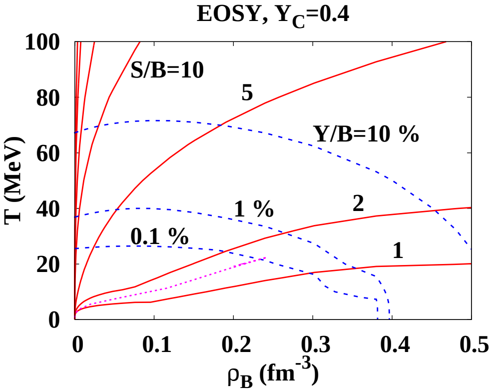
Hyperons in core-collapse of light progenitor stars



- Shen et al. supernova EoS (RMF TM1, $M_{max} \sim 2.1 M_\odot$) (STOS) extended to hyperons and thermal pions ($M_{max} \sim 1.6 M_\odot$)
- $(U_\Lambda, U_\Sigma, U_\Xi)$ =(-30MeV, +30MeV, -15MeV)

Figure: Ishizuka et al., JPG. 35 (2008)

Hyperons in core-collapse of light progenitor stars



- Simulation an adiabatic collapse of an iron core from 15 $M_\odot$ progenitor
- No neutrino transport
- Small hyperon fraction $\sim$ 0.1 % has no effect on the supernova dynamics

Figure: Ishizuka et al., JPG. 35 (2008)

Hyperons in core-collapse SNe of massive progenitor stars

- 1D GR core-collapse SN simulation for a $40M_\odot$ progenitor
- Boltzmann neutrino transport

- STOS supernova EoS extended to hyperons and thermal pions ($M_{max} \sim 1.6\ M_\odot$)
- $(U_\Lambda, U_\Sigma, U_\Xi)$ =(-30MeV, 30MeV, -15MeV)
- Comparison to **STOS EoS** and Lattimer-Swesty EoS ($K_0 = 180$ MeV)
- Hyperons appear $\sim$ 500 ms post-bounce and accelerate black hole formation

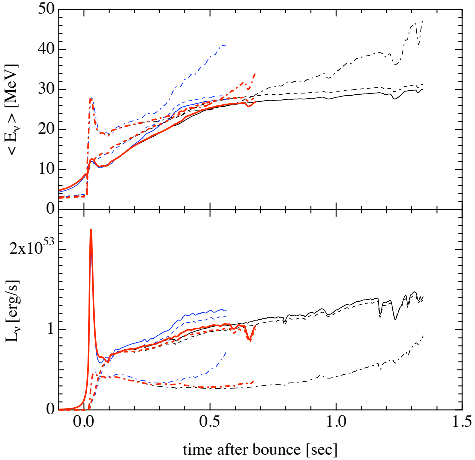
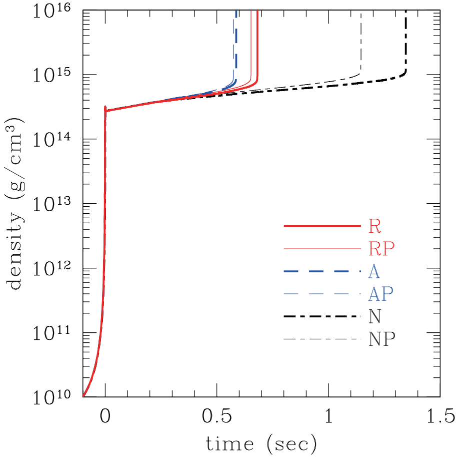


Figure: Sumiyoshi et al., ApJL, 690 (2009)

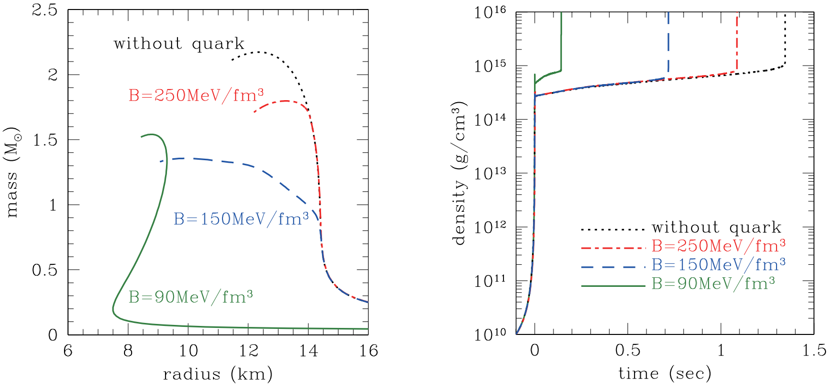
Hyperons in core-collapse SNe of massive progenitor stars



- Variation of stiffness in hyperon EoS via Σ hyperon potential
- $A = U_{\Sigma}^{(N)}$ =-30MeV; $R = U_{\Sigma}^{(N)}$ =+30MeV

Figure: Nakazato et al. ApJ, 745 (2012)

Quark matter in core-collapse SNe of massive progenitor stars

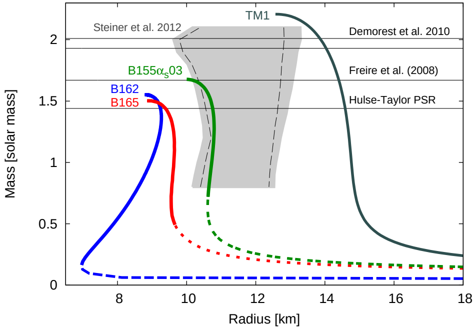


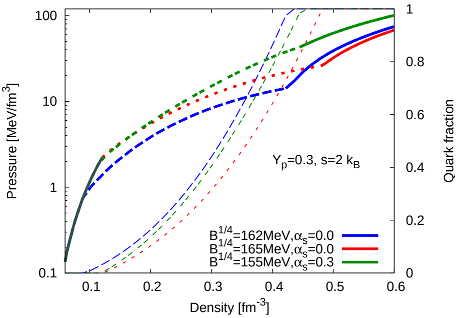
- Core-collapse supernova simulation of $40M_\odot$ progenitor
- STOS EoS with strange quark matter with quark bag model
- Parameters: $B^{1/4} = 90, 150, 250$ MeV/fm^3 (162, 184, 209 MeV)
- For $B^{1/4} = 150$ MeV/fm^3 and 250 MeV/fm^3 quarks do not appear until just before the black hole formation
- Impact on the duration of the ν-signal but not the luminosities and spectrum

Figures: Nakazato et al., A&A (2013)

Similar studies: Nakazato et al., Astrophys. J. 721 (2010), Ohnishi et al., Phys. Lett. B 704 (2011)

Quark matter in core-collapse SNe of light progenitors - Soft EoS

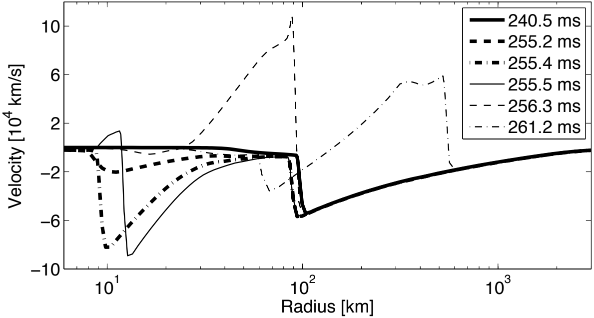




- Core-collapse supernova simulation of 10.8 $M_\odot$, 13 $M_\odot$, and 15 $M_\odot$ progenitors
- STOS EoS with strange quark matter
- Quark Bag model: $p = \sum_i (p_i - \alpha_s \frac{\mu_i^4}{2\pi^3}) - B$
- Parameters: $B^{1/4} = 162$ MeV, 165 MeV and $B^{1/4} = 155$ MeV & $\alpha_s = 0.3$

Sagert et al., PRL 102, 081101 (2009); Fischer et al., ApJS 194, 39 (2011)

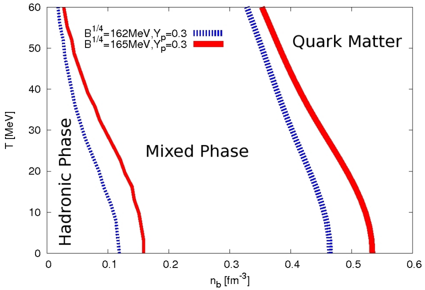
Second Shock Wave from Phase Transition

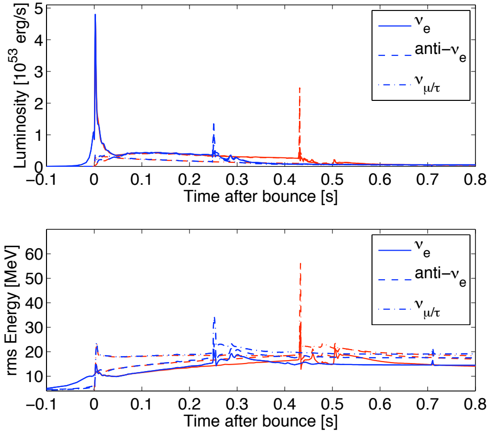


- Mixed phase is present after core-bounce
- Collapse of the proto neutron star to pure quark matter 200ms - 400ms after core bounce
- Formation of second shock wave which leads to the explosion of the star

Sagert et al., PRL 102, 081101 (2009); Fischer et al., ApJS 194, 39 (2011)

First and Second Neutrino Bursts

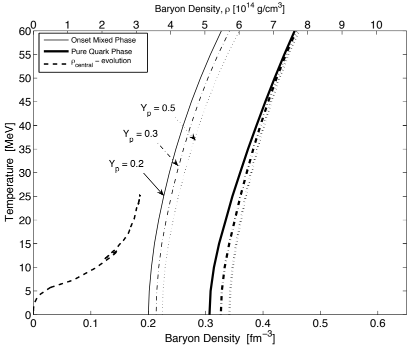


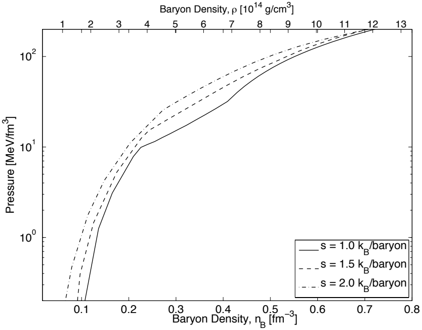


- Second shock wave passes neutrinospheres $\rightarrow$ second neutrino burst dominated by antineutrinos
- For $B^{1/4} = 165$ MeV second neutrino burst is $\sim$ 200ms later than for $B^{1/4} = 162$ MeV
- Second collapse confirmed by Nakazato et al., A&A (2013) for $B^{1/4} = 162$ MeV and 15 $M_\odot$ progenitor

Fig: T.Fischer, Neutrino luminosities and rms neutrino energies, at 500 km for 10 $M_\odot$ progenitor

Stiff Quark EoS in core-collapse SNe - Bag



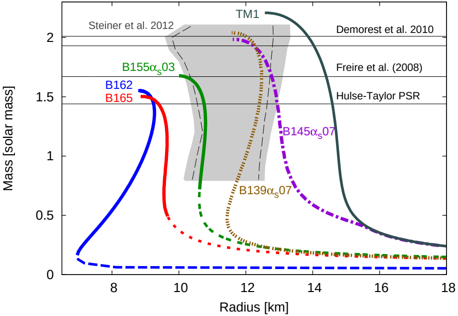


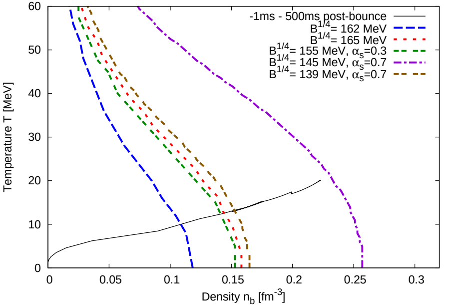
- STOS EoS + quark matter with PNJL ($M_{max} \sim 2\,M_\odot$)
- 1D Supernova simulation of a 15 $M_\odot$ progenitor
- Strange quarks appear at high density
- Due to high critical density no phase transition during post-bounce accretion phase

Figures: Fischer et al., PAN 75 (2012)

Stiff Quark EoS in core-collapse SNe - Bag

- 1D GR simulation of core collapse of 15 $M_\odot$ and 30 $M_\odot$ progenitors
- For $B^{1/4} = 145$ MeV, $\alpha_s = 0.7$:
  $\rightarrow$ Phase transition ~ 1 s after core-bounce
  $\rightarrow$ No second collapse and impact on SN dynamics
- For $B^{1/4} = 139$ MeV, $\alpha_s = 0.7$:
  $\rightarrow$ Earlier phase transition to quark-hadron mixed phase
  $\rightarrow$ No second collapse due to stiffness of EoS





Figures: Sagert et al.,Acta Phys. Pol. B 43 (2012)

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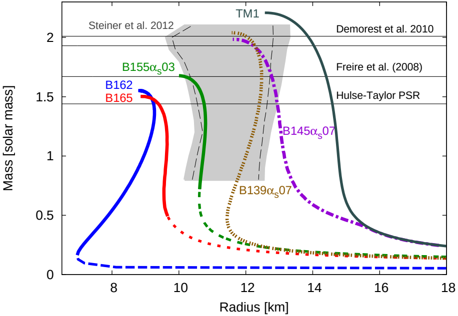

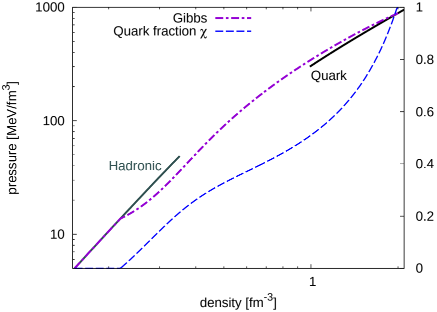

Figures: Sagert et al.,Acta Phys. Pol. B 43 (2012)

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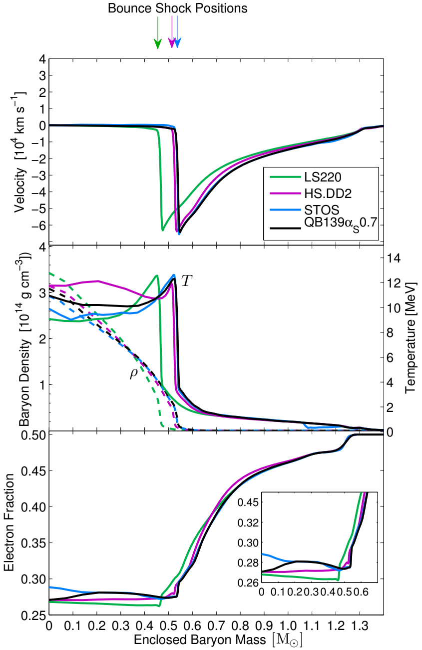

Figure: Fischer et al. arXiv:1307.6190

Summary

- Quark-hadron phase transitions (and the appearance of hyperons) are studied on their effects in core-collapse supernovae
- If the appearance of strangeness leads to a softening of the EoS signals might be strong:
  - Shorter duration of neutrino signal and higher neutrino energies and luminosities during black hole formation
  - Second collapse and formation of second shock wave in case of a low-density first order quark-hadron phase transition
    $\leftrightarrow$ observable via a second neutrino peak
- But: Most tested EoSs do not fulfill the $2\,M_\odot$ requirement. The question remains whether stiff quark or hyperon EoSs could also leave a significant imprint on signals of core-collapse supernovae