Strange matter in neutron stars and core-collapse supernovae

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9th International Conference on High Energy Density Laboratory Astrophysics
Florida State University, Tallahassee, Florida
April 30-May 4, 2012

MICHIGAN STATE UNIVERSITY

comp star

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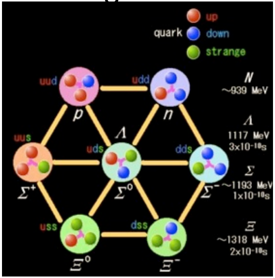
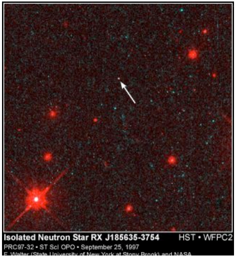
Strangeness



Supernovae

?????

Neutorn Stars



Born in

Can contain

Neutron stars:

- Radius $\sim$ 10km
- Mass $\sim (1-3)\,M_\odot$

- $\rho_b \gg 2.7 \cdot 10^{14}\,\mathrm{g/cm^3}$
  $n_b \gg 0.16\,\mathrm{fm}^{-3}$

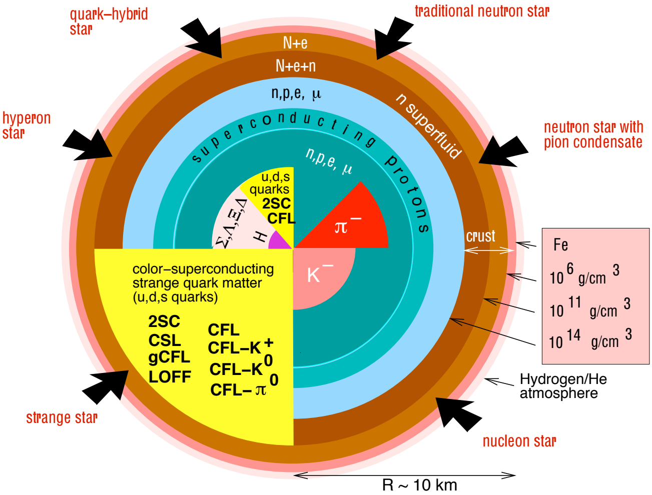
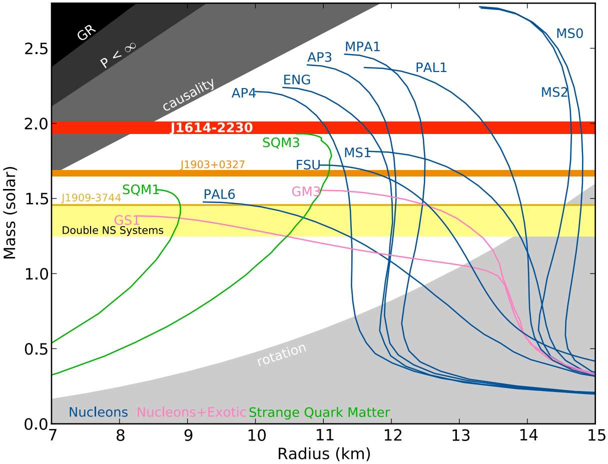


Figure: F. Weber

Neutron star masses (Demorest et al., Nature 467 (2010)



- High neutron star masses → stiff nuclear EoS at high densities

Hybrid stars

- Quark bag model:

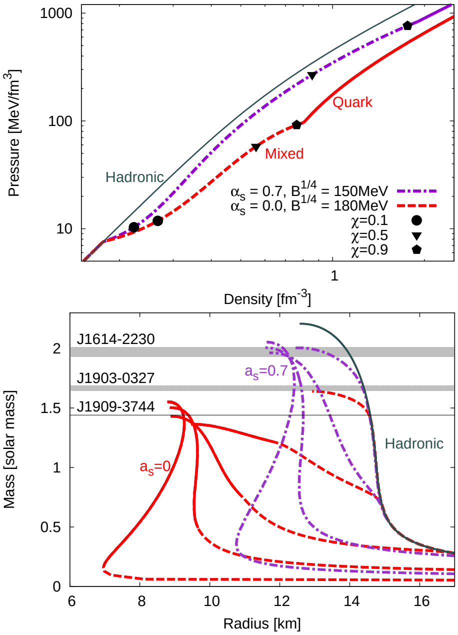
  $\Omega_{QM} = \sum_i \Omega_i + \alpha_s \mu_i^4/(2\pi^3) + B$

  i=up, down, strange quarks

- Weak, thermal, hydrostatic equilibrium, global charge neutrality (Gibbs condition)

- Quark-hadron mixed phase with quark volume fraction:

  $\chi = \frac{V_Q}{V_Q+V_H}, \quad 0 < \chi < 1$

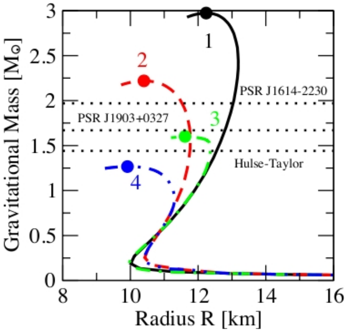


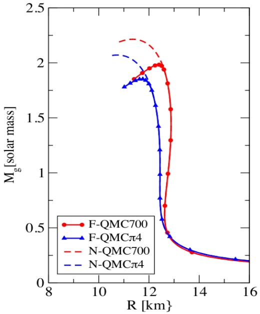
S. Weissenborn, I. S., G. Pagliara, M. Hempel, J. Schaffner-Bielich, ApJL 740 (2011); Oezel et al., ApJL 724 (2010)

Hyperon stars

- Microscopic calculations (BHF): Inclusion of hyperons softens the EoS (Schulze & Rijken PRC 84, 2011)
- Maximum masses: $\lesssim 1.4\ M_\odot$
- Uncertainties: e.g. Hyperon-hyperon interaction

- Quark meson-coupling model (J. Rikovska Stone et al., NPA, Vol 792 (2007))
- Relativistic mean field: repulsive vector meson interaction among hyperons (Weissenborn et al., NPA 881 (2012))





Figures: top: I. Vidana et al., EPL, Vol. 94 (2011), bottom: J. Rikovska Stone et al., NPA, Vol 792 (2007)

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

- Typical supernova EoSs cover:
  T : $(0- \geq 100)$ MeV
  Y_p : $0.01- \geq 0.5$
  n_b : $(10^5- \geq 10^{15})\ \frac{\mathrm{g}}{\mathrm{cm}^3}$
- Lattimer and Swesty, Nucl. Phys. A 535 (1991),
  Shen et al. Prog. Th. Phys. 100 (1998),
  Hempel et al. Astrophys. J. 748 (2012), ...

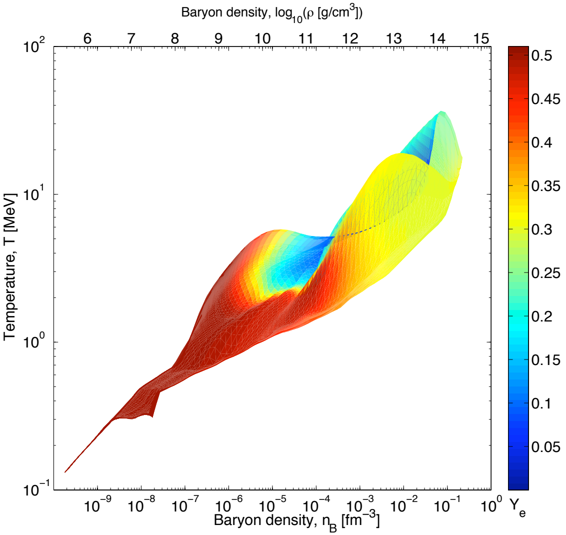
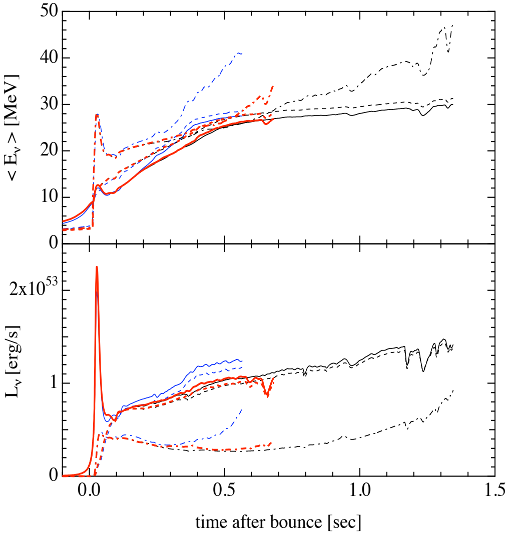


Figure: Fischer et al., ApJS 194, 39 (2011): Phase space covered in a core collapse simulation for a 15 $M_\odot$ progenitor

Massive progenitor stars

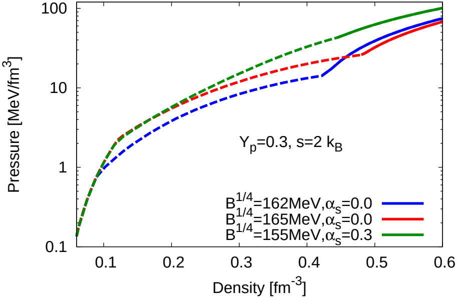
- Progenitor: $40M_{\odot}$
- Soft hyperon/quark EoS accelerates black hole formation
- Figure: Sumiyoshi et al., ApJL, 690 (2009)
  Shen EoS with hyperons
  Comparison to normal **Shen et al.** and Lattimer-Swesty EoSs

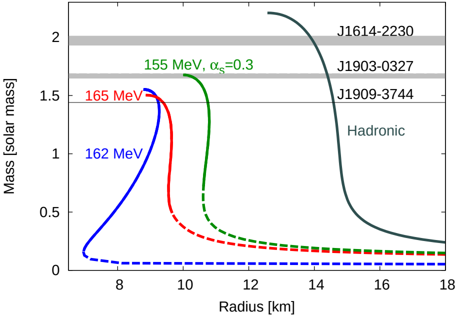


Nakazato et al., ApJ 745 (2012), Shen et al., ApJS 197 (2011) Nakazato et al., Astrophys.J. 721 (2010), Ohnishi et al., Phys.Lett.B 704 (2011), Nakazato et al., Phys.Rev.D 77 (2008)

Light and intermediate progenitor stars

- Shen EoS with strange quark matter
- Quark bag model with:
  $B^{1/4} = 162\text{MeV}$, $B^{1/4} = 165\text{MeV}$, $\alpha_s = 0$
  $B^{1/4} = 155\text{MeV}$, $\alpha_s = 0.3$
- Quark hadron mixed phase with Gibbs conditions
- Progenitors: 10.8 $M_\odot$, 13 $M_\odot$, and 15 $M_\odot$ (Woosley et al. 2002)
- 1D GR hydrodynamics and Boltzmann ν-transport (Liebendoerfer et al. 2004)

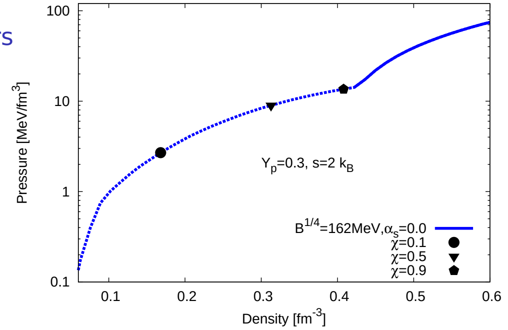


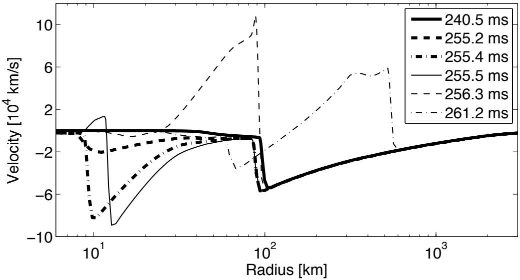


I. S., T. Fischer, M. Hempel, G. Pagliara, J. Schaffner-Bielich, A. Mezzacappa, F.-K. Thielemann, M. Liebendoerfer, PRL 102, 081101 (2009);
Fischer et al., ApJS 194, 39 (2011)

Light and intermediate progenitors

- Mixed phase at core bounce in the center of the proto neutron star
- Softening of the mixed phase EoS for growing χ
- Collapse of proto neutron star
- Stiffening of quark EoS halts collapse
- Formation of second shock wave





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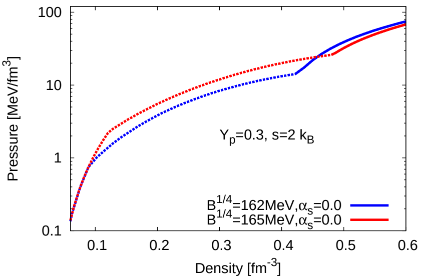
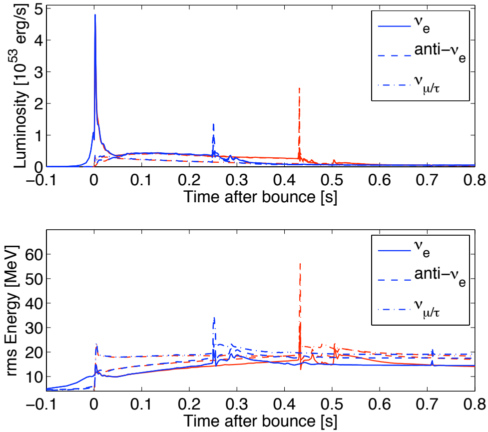
First and Second Neutrino Bursts





- Second shock wave passes neutrinospheres $\rightarrow$ second neutrino burst dominated by antineutrinos
- For $B^{1/4}$=165MeV second neutrino burst is $\sim$200 ms later than for $B^{1/4}$=162MeV

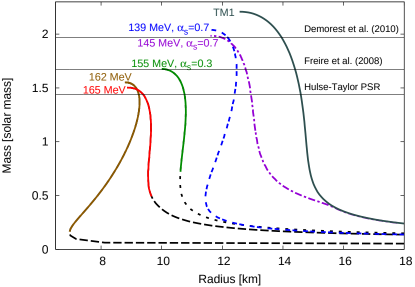
Fig: T.Fischer, Neutrino luminosities and rms neutrino energies, at 500km for 10 $M_\odot$ progenitor

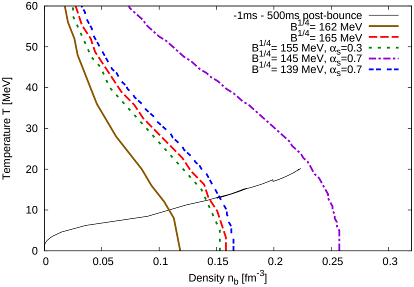
Results (Fischer et al., ApJS 194, 39 (2011))

Prog. $M_\odot$	$B^{1/4}$ MeV	t_{pb} ms	ρ_c 10^{14}g/cm^3	T_c MeV	M_{pns} $M_\odot$	E_{expl} 10^{51}erg	$M_{\max}$ $M_\odot$
10.8	162	240	6.61	13.14	1.431	0.373	1.55
10.8	165	428	6.46	14.82	1.479	1.194	1.50
13	162	235	6.49	13.32	1.465	0.232	1.55
13	165	362	7.23	16.38	1.496	0.635	1.50
15	162	209	7.52	17.15	1.608	0.420	1.55
15	165	276	7.59	16.25	1.641	u	1.50
15	155, $\alpha_s = 0.3$	326	5.51	17.67	1.674	0.458	1.67

- Higher critical density:
  - Longer accretion on proto neutron star
  - More massive proto neutron star with deeper gravitational potential
  - Stronger second shock and larger explosion energies
  - Second neutrino burst later with larger peak luminosities
- More massive progenitor: earlier onset of phase transition and more massive proto neutron star

High mass hybrid stars for SN EoS - Preliminary





- For $B^{1/4} = 145$ MeV & Collapse of 15 $M_\odot$ and 30 $M_\odot$ progenitors
- Phase transition too late $\sim$ 1 s after bounce $\rightarrow$ No second collapse
- For $B^{1/4} = 139$ MeV: Earlier phase transition, but no second collapse
- Appearance of quark matter might still visible in neutrino signal

I. S., T. Fischer, M. Hempel, G. Pagliara, J. Schaffner-Bielich, F.-K. Thielemann, M. Liebendoerfer, arXiv:1112.6328

Summary

- Strange matter (quarks/hyperons) can populate the interior of massive neutron stars
- Quarks/hyperons in supernovae:
- Late onset & softening of EoS $\rightarrow$ Shorter neutrino signal in black hole formation
- Early quark onset & softening+stiffening $\rightarrow$ Two-peak neutrino signal
- Stiff quark EoSs $\rightarrow$ So far no second collapse
- Further studies: Nucleosynthesis (N.Nishimura et al. (arXiv:1112.5684), 3D simulations ...

With

- T. Fischer
- M. Hempel
- M. Liebendoerfer
- A. Mezzacappa
- G. Pagliara
- J. Schaffner-Bielich
- F.-K. Thielemann

Intermediate progenitor stars

& Hyperons

- Shen EoS with hyperons and thermal pions ($M_{max} \sim 1.63\ M_{\odot}$)
- Adiabatic collapse of an iron core from
- Progenitor: 15 $M_{\odot}$
- No ν-transport

- Small hyperon fraction ~ 0.1
- No effect on the supernova dynamics

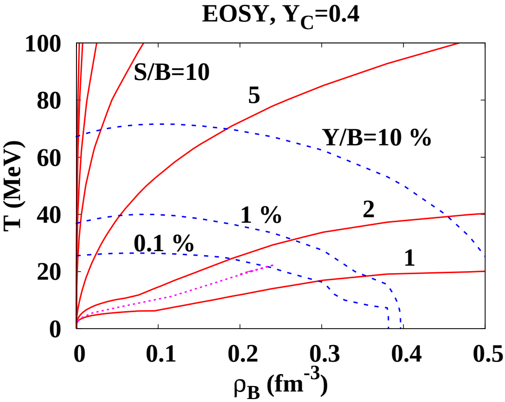


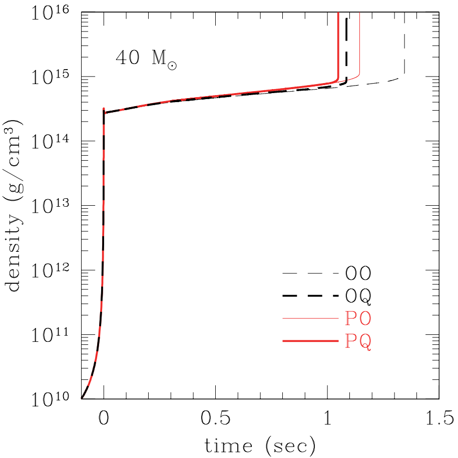
Figure: Ishizuka et al., JPG. 35 (2008)

Massive progenitor stars

& Quark matter

- Shen EoS with strange quark matter and thermal pions
- Bag model, $B^{1/4} \sim 209$ MeV ($M_{max} \sim 1.8\ M_\odot$)
- 1D supernova simulation with ν-transport
- Progenitor: 40 $M_\odot$

- Quark matter softens EoS
- Shorter black hole formation time



Figures: Nakazato et al., Phys.Rev.D 77 (2008)
Nakazato et al., Astrophys.J. 721 (2010), Ohnishi et al., Phys.Lett.B 704 (2011)