Dense matter equation of state in neutron stars & supernovae

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Phase diagram of strongly interacting matter

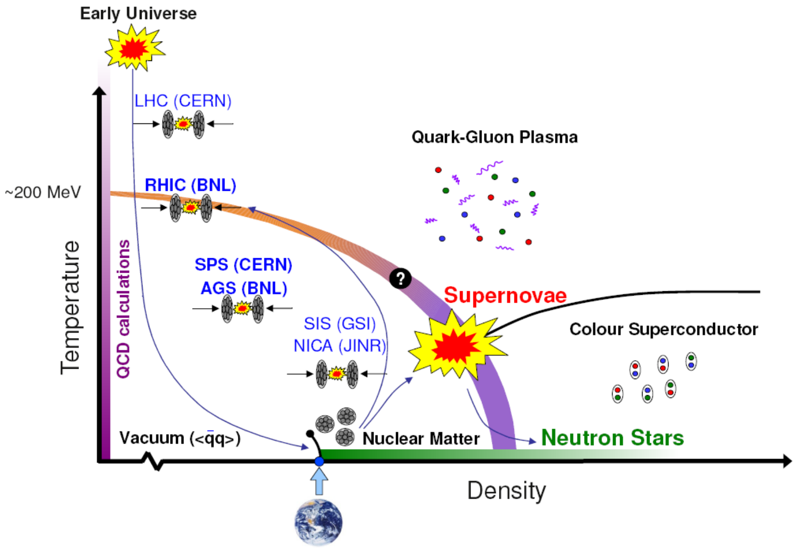
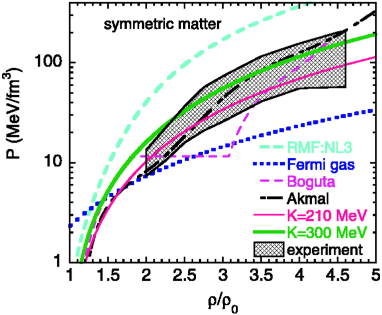
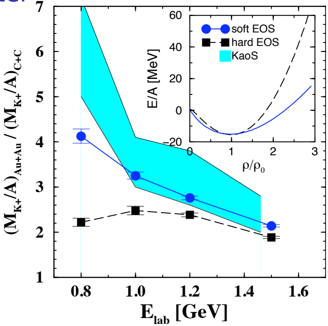


Fig.: Fredrik Sandin

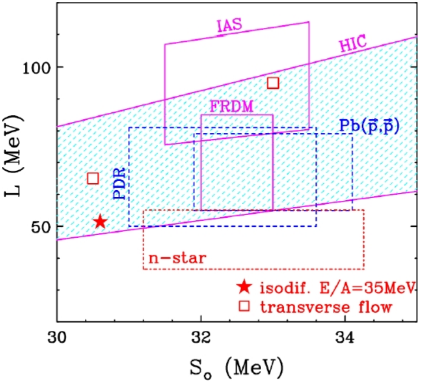
Heavy-ion data: Isospin symmetric matter





- Giant monopole resonances (Youngblood et al. PRL 82, 1999):
  $K_0 = 9n_b^2 \frac{d^2}{dn_b^2} E(n_b)|_{n_0} = 231 \pm 14$ MeV, $n_b \sim n_0$
- Multistep K$^+$ production (Chr. Sturm et al., RL 86, 2001): $K \lesssim 200$ MeV for $n_b \lesssim (2-3)n_0$
- Elliptic and transverse flow (P. Danielewicz, R. Lacey, W.G. Lynch, Science 298, 2002)
- $T \gtrsim 100$ MeV, $Y_p \sim 0.5$, timescales $t \sim 10^{-24}$ s
- Transport models:
  $U(n_b) = \alpha \left(\frac{n_b}{n_0}\right) + \beta \left(\frac{n_b}{n_0}\right)^\gamma \rightarrow E(n_b) = \frac{1}{n_b} \int U(n_b) dn_b$, $p = n_b^2 \frac{d}{dn_b} E(n_b)$

Heavy-ion data: Isospin asymmetric matter



- Symmetry energy S_0 and density dependence L at $n_b \lesssim n_0$
- $E(n_b, \delta) = E(n_b, \delta = 0) + S(n_b)\delta^2$, $\delta = \frac{n_n + n_p}{n_b}$, $L = 3n_0 \frac{dS(n_b)}{dn_b}|_{n_0}$
- n/p ratios and isospin diffusion (HIC), nuclear binding energies via finite-range droplet model (FRDM), Isobaric Analog States (IAS), neutron skin thickness ($P_b(\vec{p}, \vec{p})$), and Pygmy Dipole Resonances (PDR)

Fig.: Tsang et al., Physical Review C 86, 1 (2012)

Conditions in a core collapse supernova

- Typical conditions after core-bounce:
  $T \sim 10$ MeV
  $Y_p \lesssim 0.3$
  $n_b \gtrsim n_0$
- Timescales $\lesssim ms$
- Typical supernova EoSs cover:
  $T : (0 - \geq 100)$ MeV
  $Y_p : 0.01 - \geq 0.5$
  $n_b : (10^5 - \geq 10^{15})\ \frac{\mathrm{g}}{\mathrm{cm}^3}$

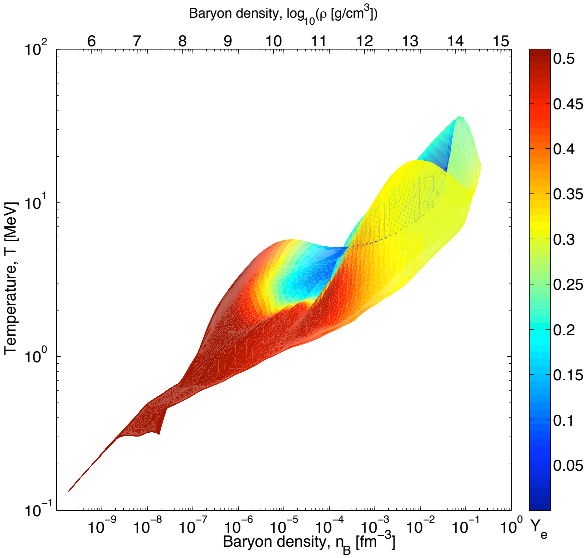
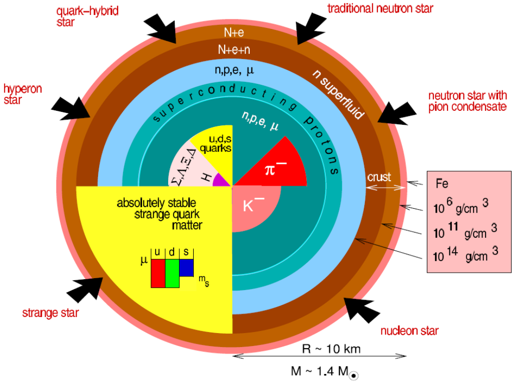


Figure: Fischer et al., ApJS 194, 39 (2011): Phase space covered in a core collapse simulation for a 15 $M_\odot$ progenitor

Neutron stars

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

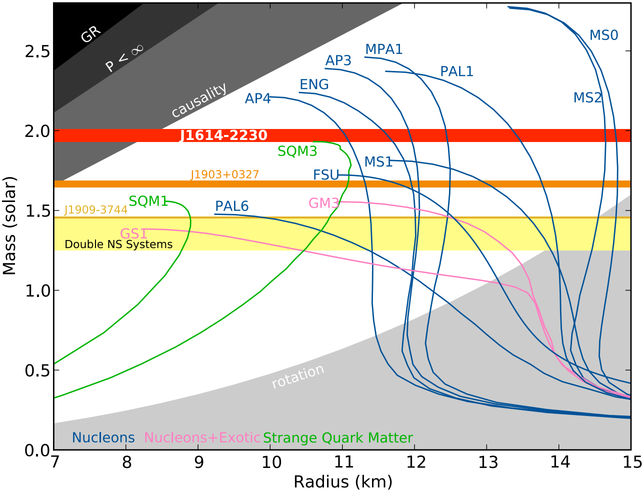
- Low temperatures: $T \sim (0.1-10)$ keV
- Large central densities: $n_b \gg n_0$
- Large isospin asymmetry: $Y_p \ll 0.5$
- Timescales $t \gg s$



Neutron stars consist of bulk nuclear matter in mechanical, thermal, and weak equilibrium. Their masses and radii are governed by general relativity and the nuclear equation of sate $p = f(n_b)$

Figure: F. Weber

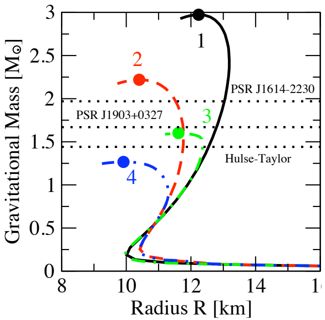
Neutron star masses (Demorest et al., Nature 467 (2010))



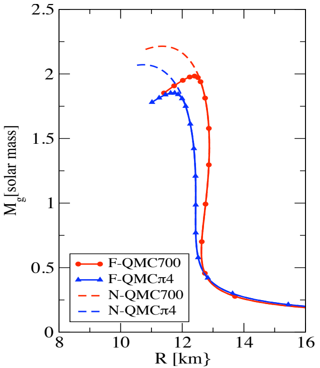
- Soft equations of state (hadronic & quark) are ruled out

Hyperons in neutron stars

- Large uncertainties in YY interaction, TBF with hyperons
- Microcsopic calculations: Inclusion of hyperons softens the EoS (BHF, Schulze & Rijken PRC 84 (2011))
- Low maximum masses of hyperon stars ($< 1.4\ M_\odot$)



- Quark meson-coupling model (Rikovska-Stone et al., NPA, Vol 792 (2007); Whittenbury et al., arXiv:1204.2614)
- SU(3) non-linear sigma model (Dexheimer and Schramm, PRC, Vol. 18 (2010))
- Relativistic Mean Field (Bednarek and Manka, J. Phys. G, 36 (2009), Weissenborn et al. NPA, Vol. 881 (2012))

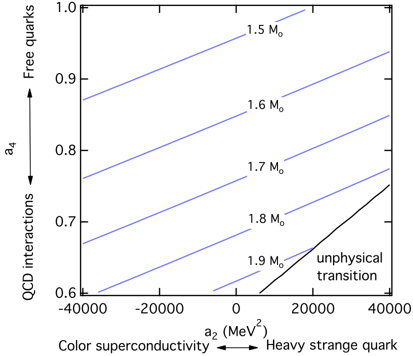


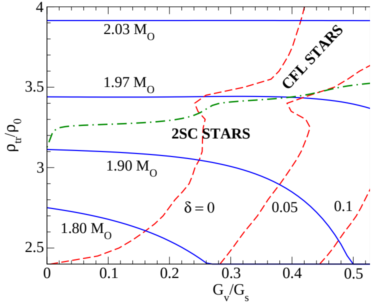
Figures: top: I. Vidana et al., EPL, Vol. 94, 2011, bottom: J. Rikovska Stone et al., NPA, Vol 792, 2007

Quark matter in neutron stars

- Bag models: Ozel et al., ApJL 724 (2010), Weissenborn et al., ApJL 740 (2010)
- Nambu-Jona-Lasinio models: Bonnano & Sedrakhian, Astron. & Astrophys. 539 (2012), Blaschke et al. Phys. Rev. C 80 (2009)
- $O(\alpha_s^2)$ Perturbative QCD: Kurkela et al. Phys. Rev. D 81 (2010)
- Dyson-Schwinger: Klaehn et al. (Phys. Rev C 82 (2010), Chen et al. (Phys. Rev. D 84, (2011)

Figures: Ozel et al., ApJL 724 (2010), Bonnano & Sedrakhian, Astron. & Astrophys. 539 (2012)





Hybrid equation of state

- Hadronic model: RMF TM1 ($M \sim 2.2\,M_\odot$)
- Quark model: Bag model

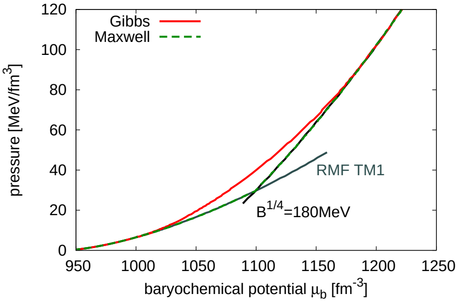
$$p = -\Omega_{QM}$$
$$p = \sum_i \left(p_i - \alpha_s \frac{\mu_i^4}{2\pi^3} + \Delta^2 \frac{\mu_i^2}{\pi^2} \right) - B$$

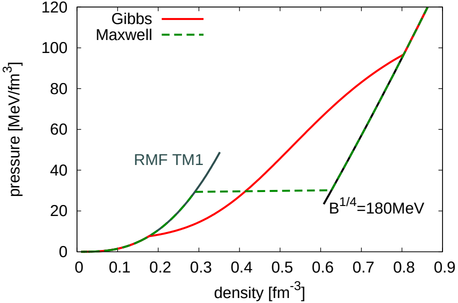
- $T^q = T^h\ p^q = p^h,\ \mu_i{}^q = \mu_i{}^h$

$\mu_s = \mu_d$

- Local charge neutrality: Maxwell transition
- Global charge neutrality: Gibbs transition
- Mixed phase with quark fraction

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





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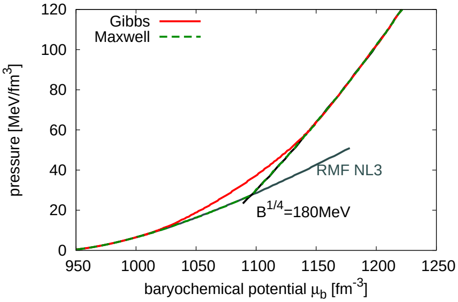

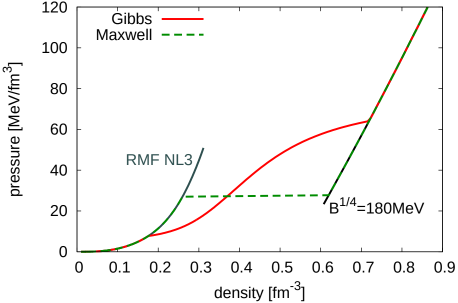

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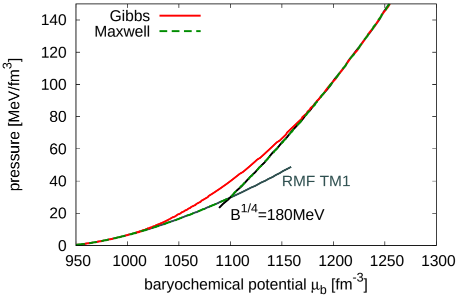

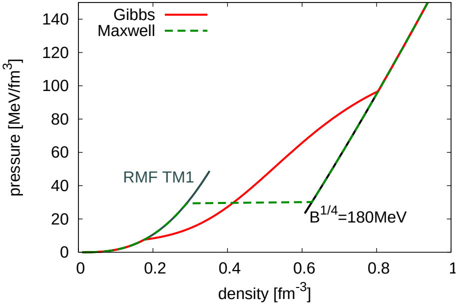

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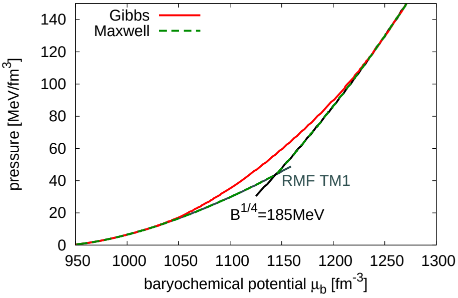

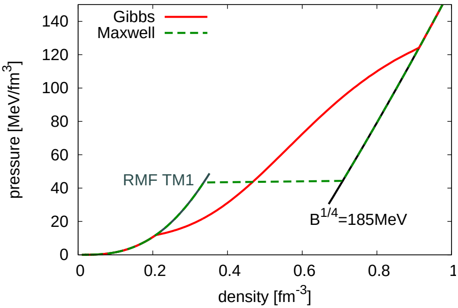

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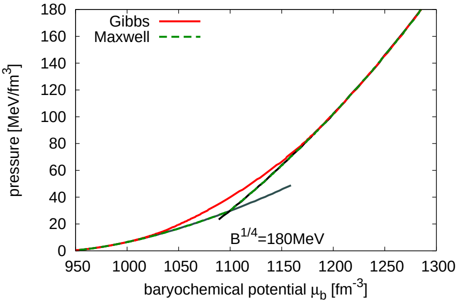

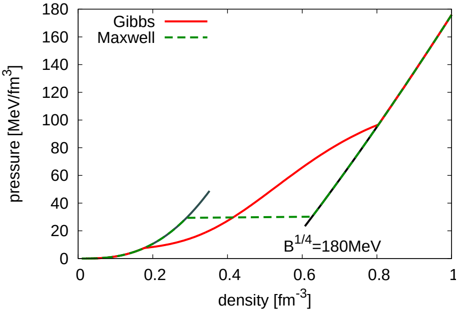

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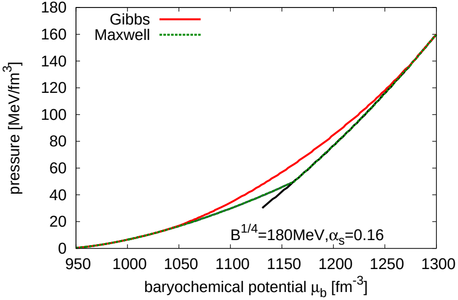
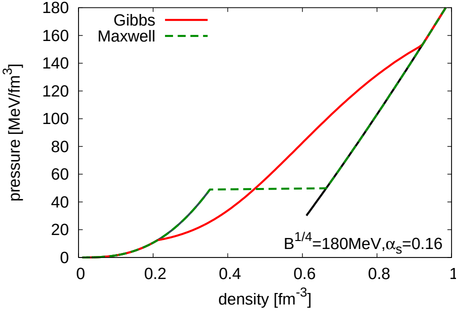
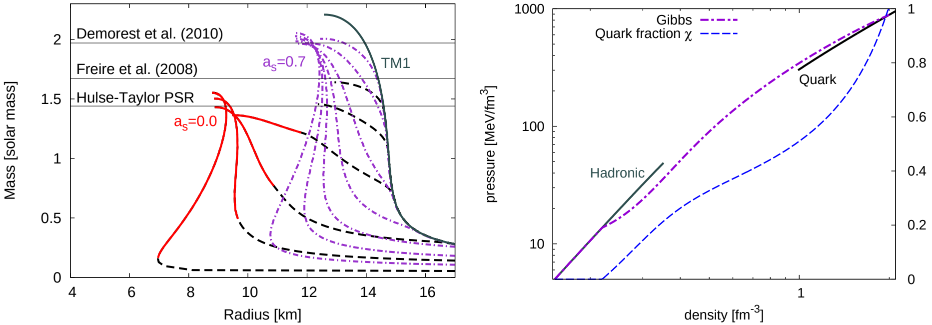




Massive hybrid stars



- Stiff quark EoSs can be very similar to stiff nucleonic EoSs (Alford et al., ApJ 629 (2005))
- Not only the stars' masses but also their radii are similar
- How to distinguish hybrid stars from neutron stars?
- Cooling? Viscosity? Supernovae $\rightarrow p = f(n_b, Y_p, T)$!

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
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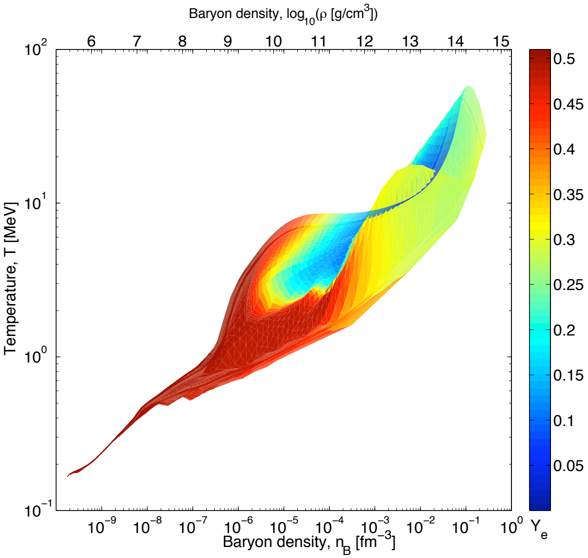


Figure: Fischer et al., ApJS 194, 39 (2011): Phase space covered in a core collapse simulation for a 40 $M_\odot$ progenitor

Quark and hyperon matter in core collapse supernovae

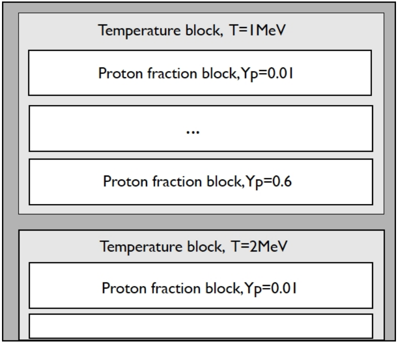
- Migdal, Chernoustan, Mishustin, Phys. Lett. B 83 (1979)
- Takahara and Sato, Astrophys. and Space Science 119 (1986)
- Drago and Tambini, Journal of Phys. G 25 (1999)

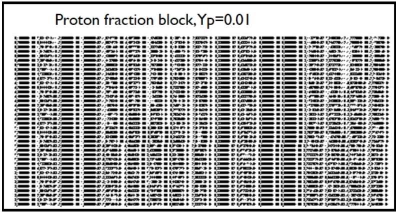
- Gentile et al., Astrophys. Journal 414 (1993)
- Pons et al., ApJ 513 (1999), Pons et al., Phys.Rev.Lett. 86 (2001)
- Nakazato et al., Phys. Rev. D 77 (2008)
- Sumiyoshi et al., ApJL, 690 (2009)
- I.S. Fischer et al., Phys. Rev. Lett. 102 (2009)
- ...

- Ishizuka et al., Journal of Phys. G 35 (2008)
- H. Shen et al., Astrophys. Journal Suppl. 197 (2011)
- Oertel, Fantina, and Novak, Phys. Rev. C 85 (2012)

Supernova equations of state

- Supernova simulations implement informations on nuclear matter properties in form of tables
- Typical size of tables $\lesssim$ 100 MB
  - 30 - 90 Temperature blocks with:
  - $\sim$ 70 Proton fraction blocks with:
  - $\sim$110 density values
  - $\sim$18 quantities for each density
- Lattimer and Swesty, Nucl. Phys. A 535 (1991), H.Shen et al. Prog. Th. Phys. 100 (1998), G. Shen et al., Phys. Rev. C 83 (2011), Hempel et al. Astrophys. J. 748 (2012), Steiner et al. arXiv1207.2184





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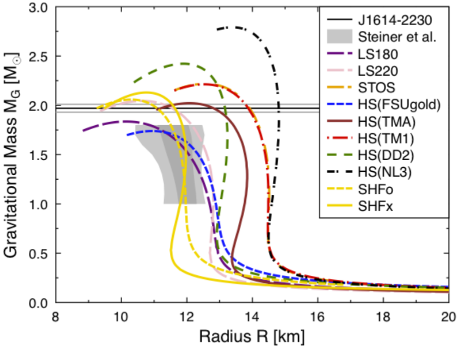
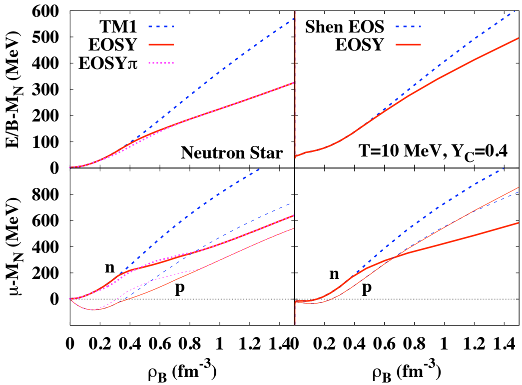


Fig.: M. Hempel

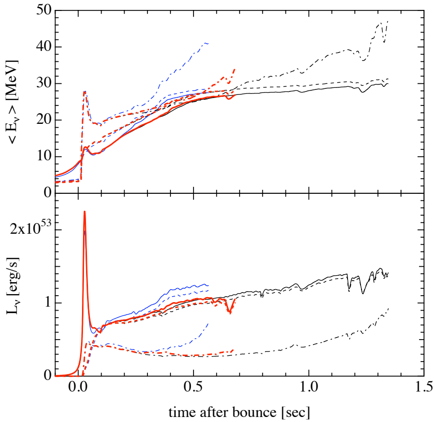
Hyperons in core-collapse of light progenitor stars



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

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

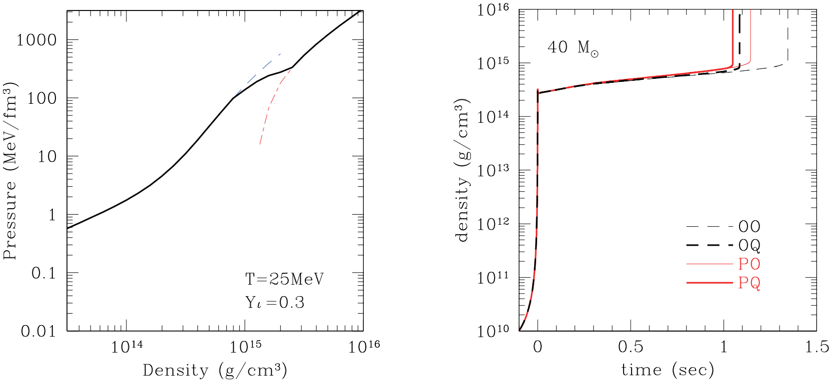
Hyperons in core-collapse SNe of massive progenitor stars



- Core-collapse supernova simulation of $40M_{\odot}$ progenitor with hyperon EoS from Ishizuka et al., JPG. 35 (2008)
- Comparison to H.Shen EoS and Lattimer-Swesty EoS ($K_0 = 180$ MeV)
- Hyperons appear around 500ms after core bounce and accelerate black hole production

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

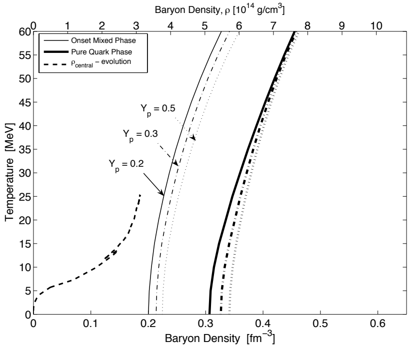
Quark matter in core-collapse SNe of massive progenitor stars

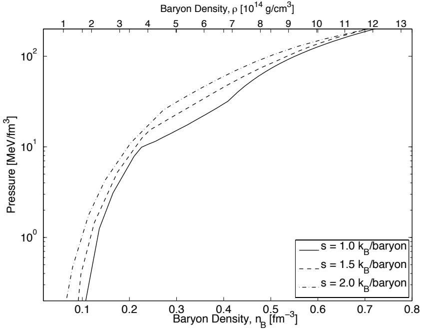


- H.Shen et al. EoS with strange quark matter and thermal pions
- Quark bag model: $B^{1/4} \sim 209$ MeV ($M_{max} \sim 1.8$ M$_\odot$)
- Core-collapse supernova simulation of 40M$_\odot$ progenitor
- Black hole formation $\sim$ 0.07ms after onset of phase transition

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

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

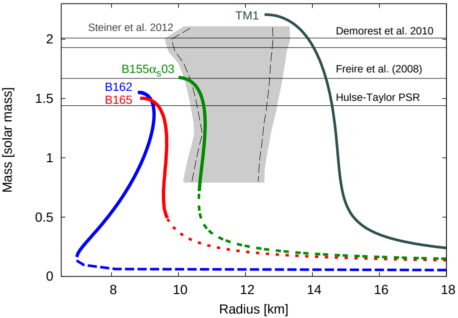


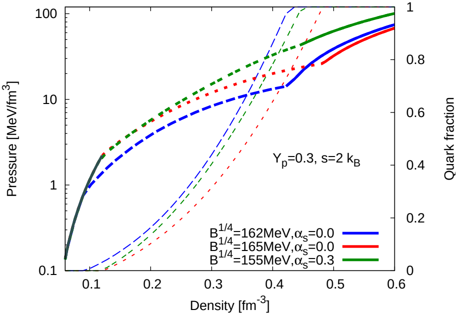


- H.Shen EoS & phase transition to quark matter with PNJL model ($M_{max} \sim 2\,M_{\odot}$)
- Deconfinement to up and down quark matter, strangeness appears later
- 1D Supernova simulation of a 15 $M_{\odot}$ progenitor
- GR hydrodynamics and Boltzmann neutrino transport in 1D (Liebendoerfer et al. 2004)
- Due to high critical density no phase transition during post-bounce accretion phase

Fischer et al., Physics of Atomic Nuclei 75 (2012)

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



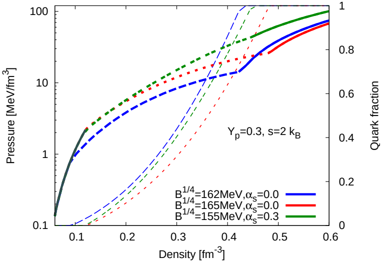


- H.Shen et al. EoS with quark bag model $\Omega_{QM} = \sum_{i=u,d,s,e} \Omega_i + \alpha_s \frac{\mu^4}{4\pi^3} + B$
- Progenitors: 10.8 $M_\odot$, 13 $M_\odot$, and 15 $M_\odot$
- 1D GR hydrodynamics and Boltzmann neutrino transport (Liebendoerfer et al. 2004)
- $B^{1/4} = 162$MeV, 165MeV and $B^{1/4} = 155$MeV & $\alpha_s = 0.3$

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

Core-collapse and second shock

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



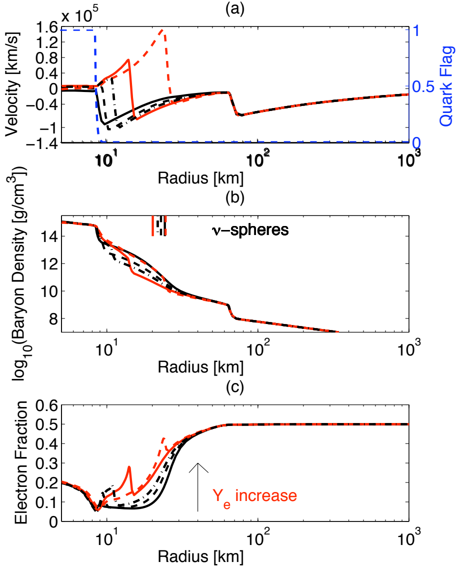
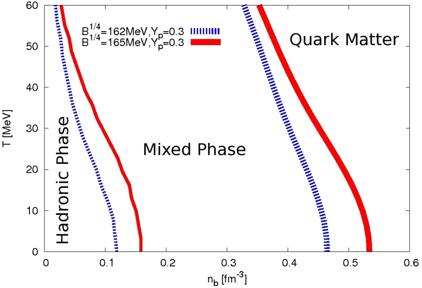
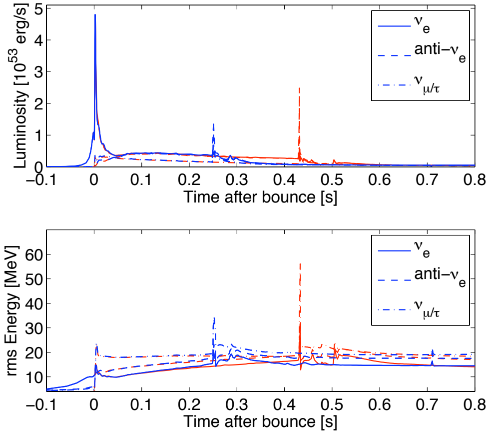


Fig: T.Fischer, $B^{1/4} = 165$ MeV, $10 M_\odot$ progenitor

First and Second Neutrino Bursts





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

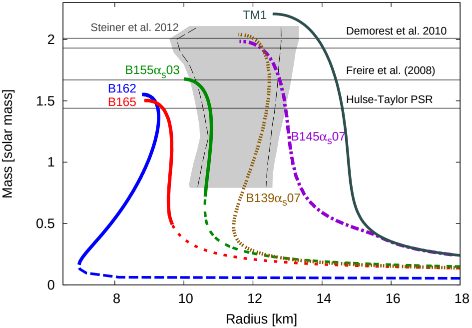
Fig: T.Fischer, Neutrino luminosities and rms neutrino energies, at 500km for 10 $M_\odot$ progenitor

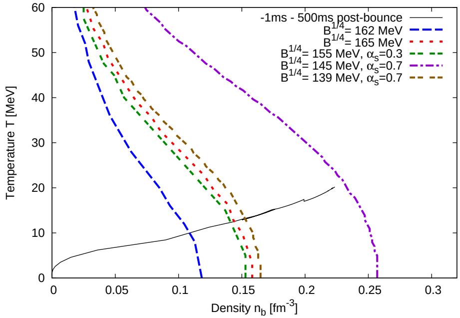
Parameter study (Fischer et al., ApJS 194, 39 (2011))

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:
  - 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
- Second neutrino burst detectability in Icecube and Superkamiokande (Dasgupta et al., PRD 81, 10 (2010))
- Nucleosynthesis study (Nishimura et al., ApJ. 758, 9 (2012))

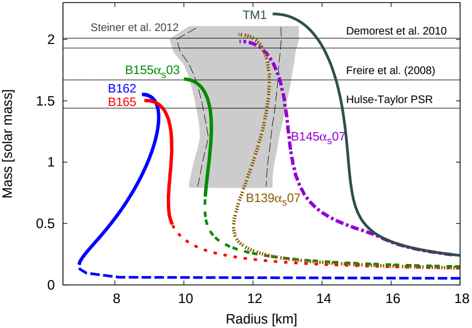
Quark matter in core-collapse SN of light progenitors - stiff EoS

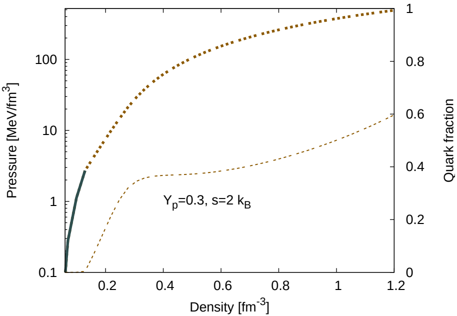




- For $B^{1/4} = 145$ MeV & Collapse of 15 $M_\odot$ and 30 $M_\odot$ progenitors
- Phase transition too late $\sim$ 1 s after bounce $\rightarrow$ No second collapse
- For $B^{1/4} = 139$ MeV: Earlier phase transition, but no second collapse

Quark matter in core-collapse SN of light progenitors - stiff EoS





- For $B^{1/4} = 145$ MeV & Collapse of 15 $M_\odot$ and 30 $M_\odot$ progenitors
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Summary & Conclusion

- Variety of studies for quark matter and hyperons in neutron stars and core-collapse supernovae
- Need more input on high density nuclear matter and hyperon interactions from heavy ion experiments
- Softening of the quark or hyperon EoS impacts the duration and spectrum of the supernova neutrino signal
- **But**: EoSs have to be stiff at high density! Only a few studies use EoSs which reproduce a neutron star mass of $M_{NS} = 1.97 \pm 0.04 \mathrm{M}_\odot$
- Can we be able to distinguish between effects from (stiff) hyperonic, quark,or hadronic EoSs ?

With

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