Signals of the QCD phase transition in core-collapse supernovae

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MICRA2009
Niels Bohr International Academy, Copenhagen
24-28 August, 2009

Helmholtz Research School Quark Matter Studies

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Published in PRL 102, 081101 (2009)

Punchline

Put in quark matter in the core collapse supernova and let it explode

Punchlines

A (quark matter) phase transition during the early postbounce phase of a core collapse supernova can causes a second shock wave. The latter can lead to the explosion of the star and is accompanied by a second neutrino burst which can give informations about the characteristics of the phase transition.

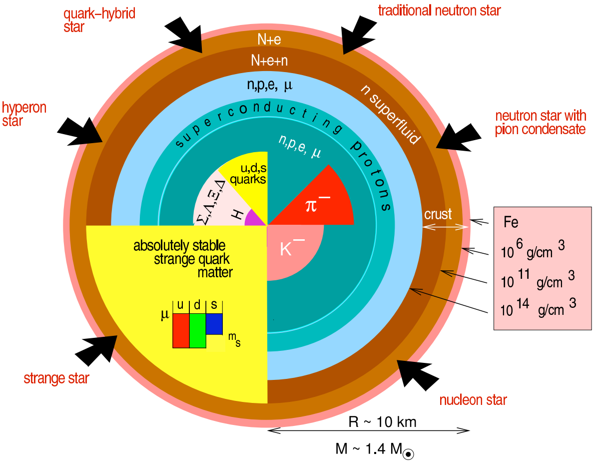

quark–hybrid star
traditional neutron star
hyperon star
neutron star with pion condensate
strange star
nucleon star
N+e
N+e+n
n,p,e, μ
n superfluid
superconducting protons
n,p,e, μ
u,d,s quarks
Σ,Λ,Ξ,Δ
H
π⁻
K⁻
crust
absolutely stable strange quark matter
μ
u
d
s
m_s
Fe
10^6 g/cm^3
10^11 g/cm^3
10^14 g/cm^3
R ~ 10 km
M ~ 1.4 M⊙

Fig: F. Weber

Production of exotic matter in core-collapse supernovae

- Gentile et al. (ApJ, 414, 1993):
  - Phase transitions to quark matter in core collapse SN with GR hydrodynamics code.
  - Formation of a second shock
  - No neutrino transport. Investigation of only a few ms after bounce
- A. Drago and U. Tambini (JPG, 25, 1999):
  - Finite T EoS for quark matter including neutrinos
  - No dynamical calculations of the collapse.
- Ishizuka et al. (JPG. 35,2008):
  - EoS by Shen with hyperons.
  - Adiabatic collapse of iron core of 15 $M_\odot$ star: Hyperon fraction very small (10^{-3}), no effect on the dynamics
  - No neutrino transport.
- Nakazato et al. (Phys.Rev.D, 77, 2008);
  - EoS by Shen with phase transition to quark matter
  - Core collapse SN of a 100 $M_\odot$ progenitor with Boltzmann neutrino transport
  - Very high critical densities ($> 5n_0$) $\longrightarrow$ phase transition shortened time until black hole formation
  - No second shock

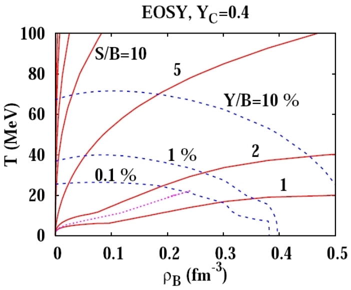


Figure 6. Hyperon fraction contours and adiabatic paths in supernova matter at $Y_C = 0.4$ from the hyperonic EOS table without pions (EOSY). The contours of the fixed number fraction of hyperons (sum of strange baryons) are shown by dashed lines. The solid lines denote the contour of fixed entropy per baryon (isentropy). The dotted line shows the trajectory of the dense matter at center during core collapse and bounce.

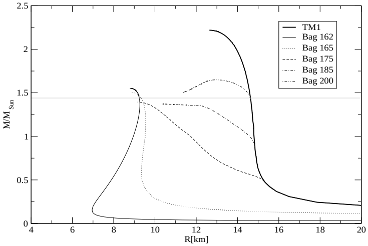
Initial Setup

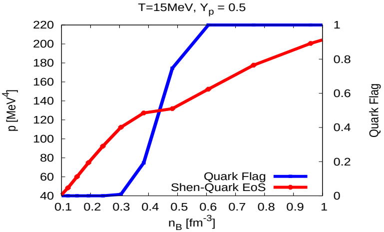
- Quark EoS: MIT Bag model:

$$p(\mu_i, T) = \sum_i p_F(\mu_i, T) - B$$

$$\epsilon(\mu_i, T) = \sum_i \epsilon_F(\mu_i, T) + B, \; i = u, d, s$$

- Hadronic EoS: relativistic mean field by Shen et al.
- Phase transition modelled by a Gibbs construction (mixed phase of quarks and hadrons)





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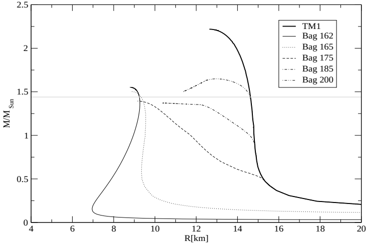
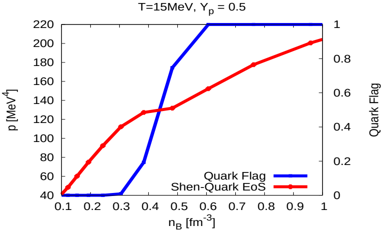
- Phase transition modelled by a Gibbs construction (mixed phase of quarks and hadrons)

- Bag parameter:
  - Usually chosen between 145-200 MeV
  - $eos1 : B^{1/4} = 162$ MeV,
    $eos2 : B^{1/4} = 165$MeV
    $\longrightarrow$ low critical density and maximum compact star mass $M_{max} > 1.44\, M_{\odot}$





Initial Setup

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$$
\begin{aligned}
p(\mu_i, T) &= \sum_i p_F(\mu_i, T) - B \\
\epsilon(\mu_i, T) &= \sum_i \epsilon_F(\mu_i, T) + B,\ i = u, d, s
\end{aligned}
$$

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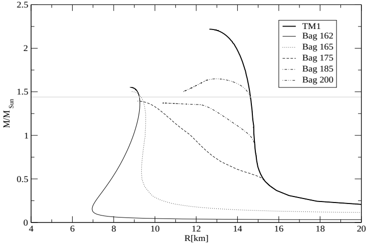
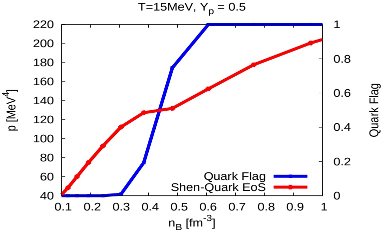
- Progenitors: 10 $M_\odot$ and 15 $M_\odot$ (Woosley et al. 2002)

- GR hydrodynamics and Boltzmann neutrino transport in spherical symmetry (Liebendoerfer et al. 2004)





Core-collapse and formation of second shock

- First stage like in normal SN scenarios: Core collapse, formation of a shock, energy loss due to dissociation of nuclei and emission of ν_e burst $\longrightarrow$ formation of a standing accretion shock

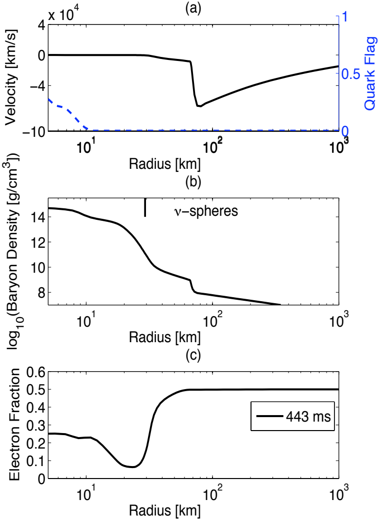


Fig: T.Fischer, $B^{1/4} = 165$ MeV, $10 M_\odot$ progenitor

Core-collapse and formation of second shock

- Mixed phase of quarks and hadrons appears at core bounce in the center of the PNS

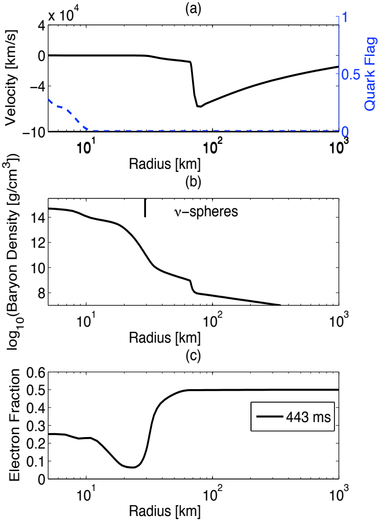


Fig: T.Fischer, $B^{1/4} = 165$ MeV, $10 M_{\odot}$ progenitor

Core-collapse and formation of second shock

- Mixed phase of quarks and hadrons appears at core bounce in the center of the PNS
- Soft EoS causes PNS starts to collapse

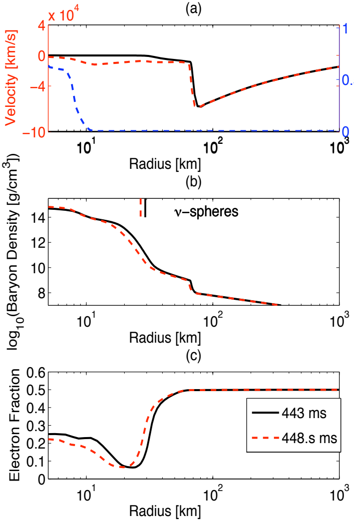


Fig: T.Fischer, $B^{1/4} = 165$ MeV, $10\mathrm{M}_\odot$ progenitor

Core-collapse and formation of second shock

- At central density 4-5n_0 pure quark matter appears
- Stiff quark EoS halts the collaps
- Subsonic accretion front between hydrostatic quark core and subsonically infalling mixed phase

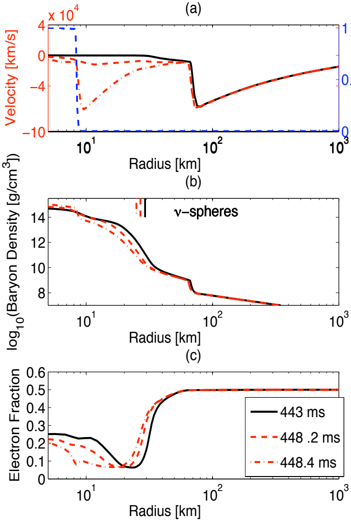


Fig: T.Fischer, $B^{1/4} = 165$ MeV, 10M$_\odot$ progenitor

Core-collapse and formation of second shock

- Accretion front moves to the surface of the PNS
- Supersonically infalling hadronic matter turns subsonic front into a shock front

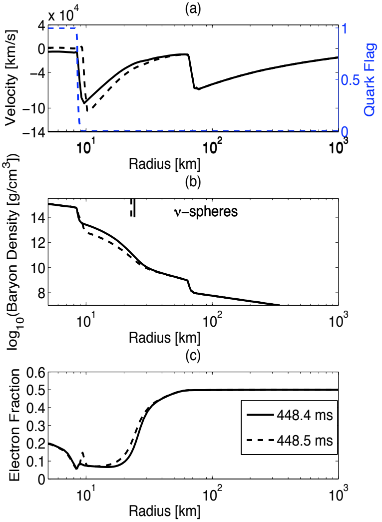
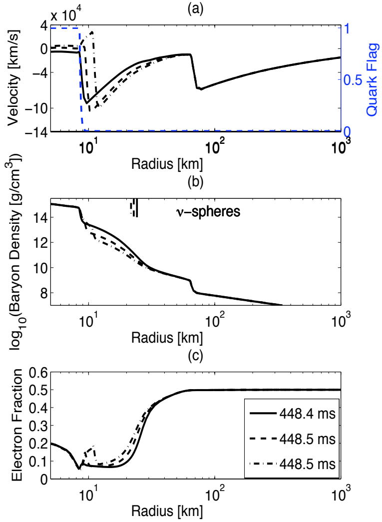


Fig: T.Fischer, $B^{1/4} = 165$ MeV, $10M_\odot$ progenitor

Core-collapse and formation of second shock



- At the surface of PNS $\longrightarrow$ shock front detaches and accelerates
- Shock heating of deleptonized hadronic matter leads to an increase in Y_e and $\bar{\nu_e}$ production

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

Core-collapse and formation of second shock

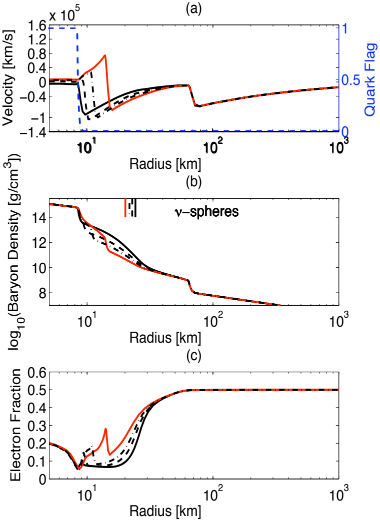


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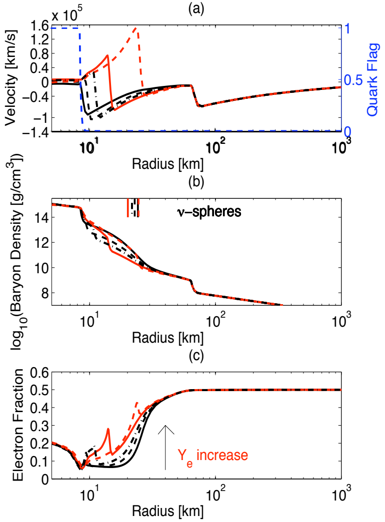
Fig: T.Fischer, $B^{1/4} = 165$ MeV, $10M_\odot$ progenitor

Core-collapse and formation of second shock



- At the surface of PNS $\longrightarrow$ shock front detaches and accelerates
- Shock heating of deleptonized hadronic matter leads to an increase in Y_e and $\bar{\nu_e}$ production
- When shock reaches the neutrino sphere a second neutrino burst is released
- Second shock overruns the first standing accretion shock $\longrightarrow$ explosion

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

Velocity profile

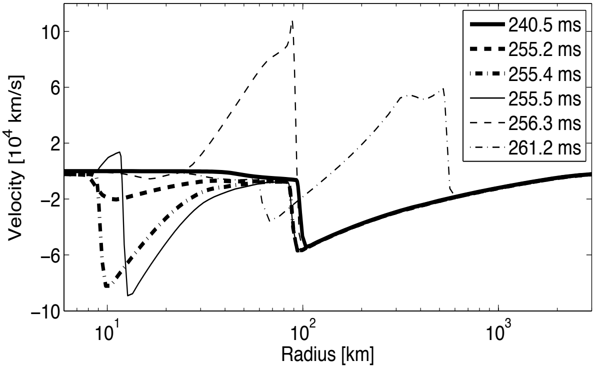


Fig: T.Fischer, velocity profile for $B^{1/4} = 162$ MeV, $10M_\odot$ progenitor

Production of second neutrino burst

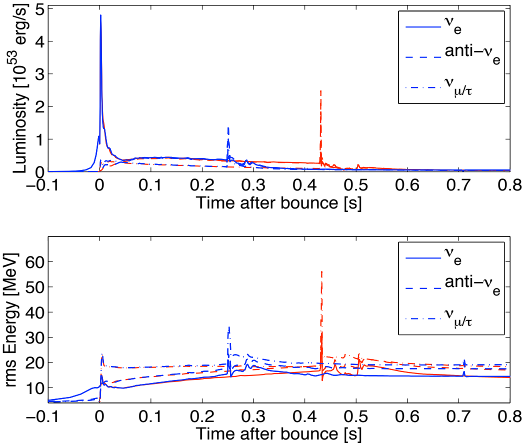


Fig: T.Fischer, Neutrino Signal for different Bag constants, $10M_{\odot}$ progenitor

Results

Prog. [$M_\odot$]	EoS	t_{pb} [ms]	M_Q [$M_\odot$]	M_{mix} [$M_\odot$]	M_{pns} [$M_\odot$]	E_{expl} [10^{51}erg]	BE [10^{53}erg]	M_G [$M_\odot$]
10	*eos1*	255	0.850	0.508	1.440	0.44	3.33	1.25
10	*eos2*	448	1.198	0.161	1.478	1.64	4.07	1.38
15	*eos1*	209	1.146	0.320	1.608	0.42	3.26	1.30
15	*eos2*	330[1]	1.496	0.116	1.700	u[2]	4.28	1.46

- Models *eos*1 and *eos*2 evolve in qualitatively similar way
- Larger Bag constant (*eos*2)
  - Longer proto neutron star accretion time due to higher critical density
  - More massive proto neutron star with deeper gravitational potential
  - Stronger second shock and larger explosion energies
  - Second neutrino burst 200 ms later with larger peak luminosities
- More massive progenitor: earlier onset of phase transition and more massive proto neutron star

[1] moment of black hole formation

[2] black hole formation before positive explosion energy is achieved

Summary

Prog. $[M_\odot]$	EoS	t_{pb} [ms]	M_Q $[M_\odot]$	M_{mix} $[M_\odot]$	M_{pns} $[M_\odot]$	E_{expl} $[10^{51}$erg]	BE $[10^{53}$erg]	M_G $[M_\odot]$
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- Test of early phase transition in post bounce phase of a core collapse supernova in spherical symmetry
- Phase transition leads to the formation of a second shock wave
- Energy of second shock wave is sufficient to drive a supernova explosion
- A second neutrino burst dominated by $\bar{\nu}_e$ is released which will be observable by present day and future neutrino detectors
- Compact star masses are in the range of $\sim 1.3 - \sim 1.5 M_\odot$
- Properties of second shock (onset and strength) and second neutrino burst (time and luminosity) are related to the critical density

[3] moment of black hole formation

[4] black hole formation before positive explosion energy is achieved

Outlook and / on the open problems

- Construction of a stiffer quark EoS to reach higher maximum mass Hybrid stars
- Late phase transitions after successfull SN explosion due to standard mechanism
- Gravitational wave emission
- Study of effects on r-process
- Systematic study of
  - Progenitor model
  - Mixed phase configuration (M.Hempel,arXiv:0907.2680; M.Hempel and G.Pagliara, arXiv:0907.3075)
  - Transition density to Quark Matter

  in regard to their influence on the evolution of the postbounce evolution
- Study strangeness production via
  - Inclusion of Hyperons
  - Two step process (first deconfinement to ud quark matter, followed by transition to sqm)
- Verification of the presented results by other groups
- Study of different approaches to the quark EoS (e.g. NJL-Modell)
- Compatibility of large quark core with observations (e.g. long time cooling)

Thank you for Attention

Backup Slides

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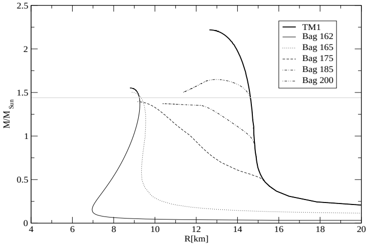

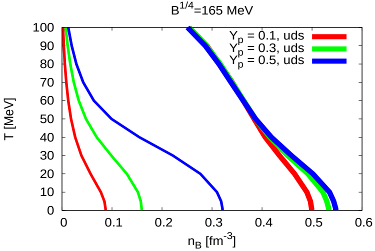

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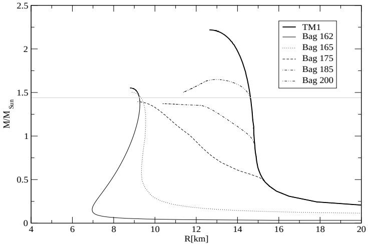
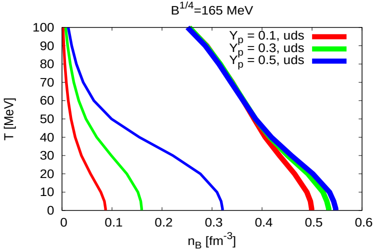
- Progenitors: 10 $M_\odot$ and 15 $M_\odot$
- GR hydrodynamics and Boltzmann neutrino transport in spherical symmetry ($\longrightarrow$ S. Scheidegger's Talk)





Equation of State for Quark matter

- Quark EoS: MIT Bag model:

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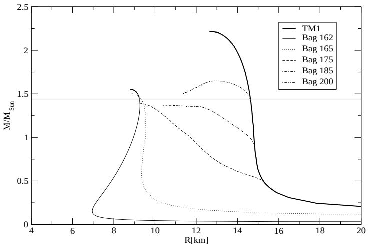
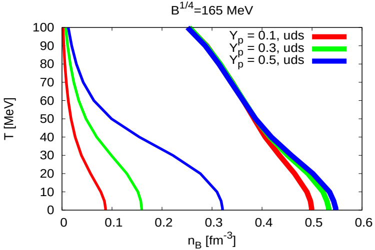
- Hadronic EoS: relativistic mean field by Shen et al.
- Phase transition modelled by a Gibbs construction (mixed phase of quarks and hadrons, no finite size effects included)

$$p^H(\mu_B, \mu_c) = p^Q(\mu_B, \mu_c)$$
$$\mu^Q_{B,e,\nu} = \mu^H_{B,e,\nu}$$
$$\rho_e = (1-\chi)\,\rho^H_c(\mu_B, \mu_c) + \chi \rho^Q_c(\mu_B, \mu_c)$$

χ: quark fraction

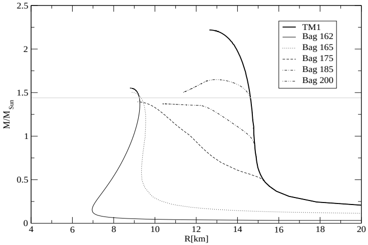


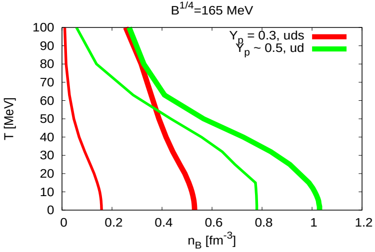


Bag parameter

- There are two main differences to heavy ion collisions:

1. Supernova matter is isospin asymmetric ($Y_p < 0.5$) $\longrightarrow$ low proton fraction favors phase transition
2. Supernova timescales are $\sim$ ms $\longrightarrow$ matter is in weak equilibrium to reactions producing strangeness





Signals from QCD phase transition in core collapse SN (arXiv:0809.4225)

Second neutrino burst

- Second shock propagates into deleptonized hadronic phase with low $Y_e \sim 0.1$
- Shock heating of matter decreases electron degeneracy $\longrightarrow$ weak equilibrium is restored at $Y_e \geq 0.2$
- When shock reaches neutrino sphere a second neutrino burst of all neutrino flavors is released, dominated by $\bar{\nu}_e$

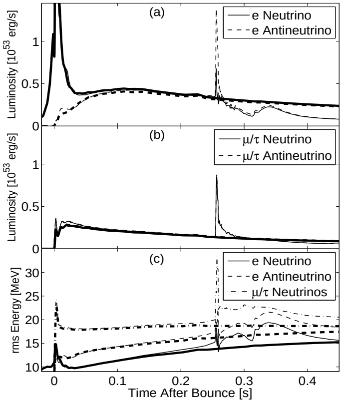


Fig:Neutrino luminosities and rms-energies at 500 km distance, $B^{1/4} = 162$ MeV, $10 M_{\odot}$ progenitor

Production of second neutrino burst

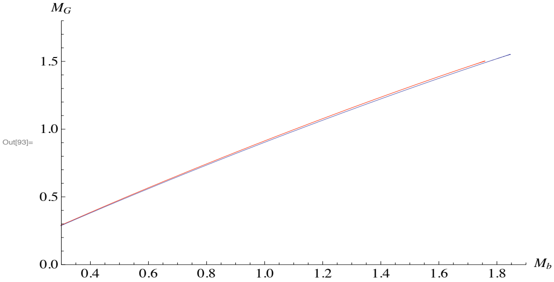


Fig.: G. Pagliara; Baryonic vs. gravitational mass configuration of hybrid stars with eos2 for the cold beta stable case (black line) and T=0.1 $Y_p = 0.3$ (red line)

Long time cooling of hybrid stars (preliminary results)

In collaboration with J. Henderson

- At high density quarks can form Cooper pairs $\longrightarrow$ Color superconductivity (CSC)
- Depending on T and μ_b many different pairing possibilities $\longrightarrow$ many different phases
- For paired quarks the interaction is exponentially suppressed by $\sim e^{-\Delta(T)/T}$ with the pairing energy $\Delta(T)$
- CSL phase: all quark flavors form Cooper pairs (uu, dd, ss) (suppression factor from *A.Schmitt et al., Phys.Rev.D 73, 2006*)

Result: Depending on $\Delta(T)$ hybrid stars can stay hot for a longer time

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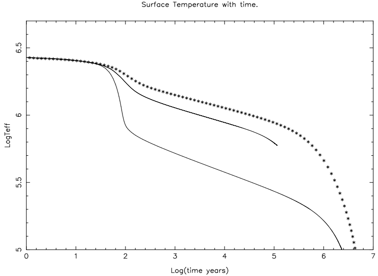
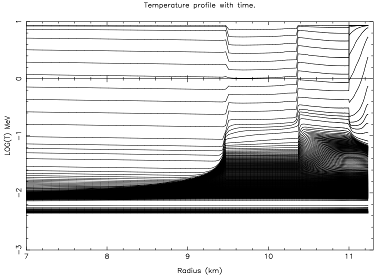
Fig.:Cooling curve and temperature profile for hybrid star with CSL phase and $\Delta(T=0) \sim 5$ MeV





Long time cooling of compact stars

- Cooling stages: Thermal relaxation stage ($t < 10 - 100$ y), Neutrino cooling ($t \leq 10^5$y), Photon cooling ($t > 10^5$y)
- Energy-balance equation

$$\frac{e^{-\lambda-2\phi}}{4\pi r^2}\frac{\delta}{\delta r}(L_r e^{2\phi}) = -Q_\nu + Q_h - \frac{c_T}{e^\phi}\delta T \delta t$$

r: radial coordinate,Q_ν: neutrino emissivity, Q_h: reheating sources, c_T: heat capacity per unit volume, L_r: local luminosity, ϕ: gravitational redshift, λ: gravitational distortion of radial scales

- Energy transport

$$\frac{L_r}{4\pi\kappa r^2} = e^{-\lambda-\phi}\frac{\delta}{\delta r}(Te^\phi) \quad (1)$$

κ thermal conductivity

- Input: Equation of state, Neutrino emissivity, Heat capacity and Thermal conductivity
- Atmosphere model for neutron star. effects from superfluidity and magnetic fields

Name	Process	Emissivity (erg cm^{-3} s^{-1})	
Modified Urca cycle (neutron branch)	$n+n \to n+p+e^- + \bar{\nu}_e$ $n+p+e^- \to n+n+\nu_e$	$\sim 2\times10^{21}\, R T_9^8$	Slow
Modified Urca cycle (proton branch)	$p+n \to p+p+e^- + \bar{\nu}_e$ $p+p+e^- \to p+n+\nu_e$	$\sim 10^{21}\, R T_9^8$	Slow
Bremsstrahlung	$n+n \to n+n+\nu+\bar{\nu}$ $n+p \to n+p+\nu+\bar{\nu}$ $p+p \to p+p+\nu+\bar{\nu}$	$\sim 10^{19}\, R T_9^8$	Slow
Cooper pair formations	$n+n \to [nn]+\nu+\bar{\nu}$ $p+p \to [pp]+\nu+\bar{\nu}$	$\sim 5\times10^{21}\, R T_9^7$ $\sim 5\times10^{19}\, R T_9^7$	Medium
Direct Urca cycle	$n \to p+e^- + \bar{\nu}_e$ $p+e^- \to n+\nu_e$	$\sim 10^{27}\, R T_9^6$	Fast
π^- condensate	$n+ < \pi^- > \to n+e^- + \bar{\nu}_e$	$\sim 10^{26}\, R T_9^6$	Fast
K^- condensate	$n+ < K^- > \to n+e^- + \bar{\nu}_e$	$\sim 10^{25}\, R T_9^6$	Fast