A Novel Approach to Model Hybrid Stars

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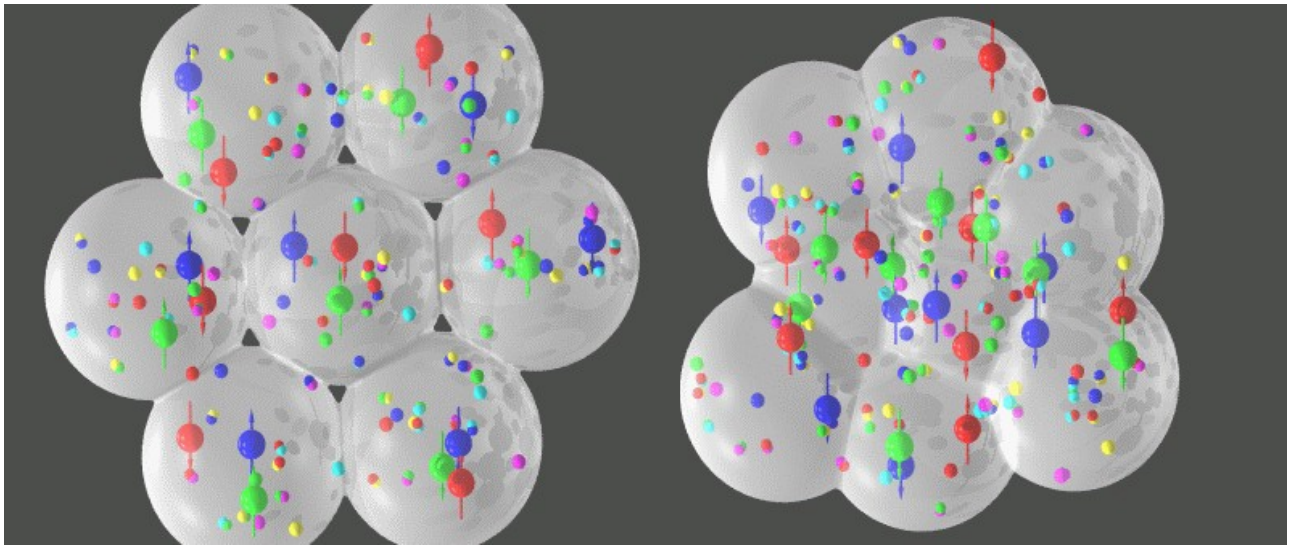
HIC for FAIR

Neutron Stars:

- giant nuclei → nuclear constraints
- several times saturation density → different particles ($\sim 3.5\rho_0$)
  ↓
  massive stars!
- fast rotation Dexheimer et al. Astrophys.J. 2008, Negreiros at al. PRC 2010, Negreiros et al. E-print 2011
- high magnetic fields
- …
- deconfinement to quark matter ($\sim 3.7\rho_0$)



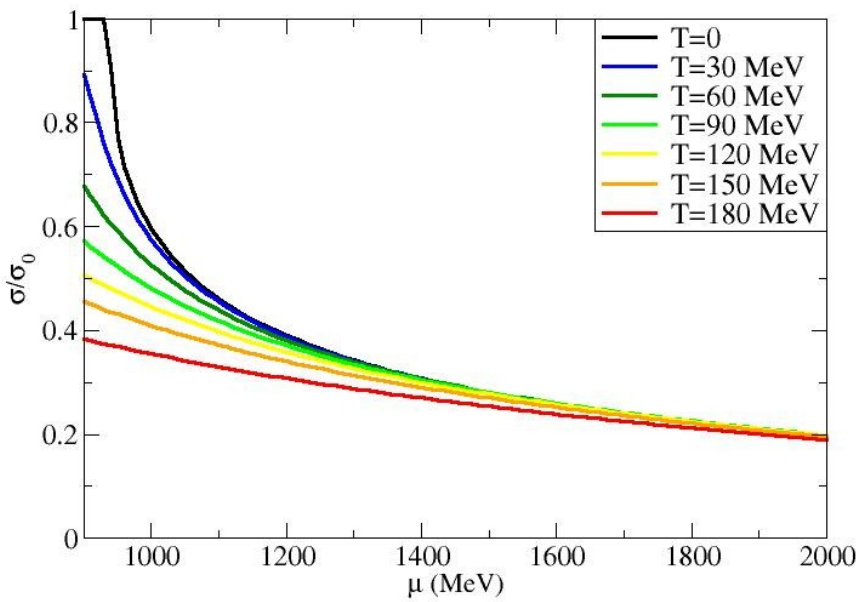
increase of density ρ_B

SU(3) Non-Linear Sigma Model:

Dexheimer et al. Astrophys.J. 2008

- effective quantum relativistic model → mean field
- describes hadrons interacting via meson exchange (σ, δ, ζ, ω, ρ, ϕ)
- constructed from symmetry relations → allow it to be chiral invariant → masses from interaction with medium

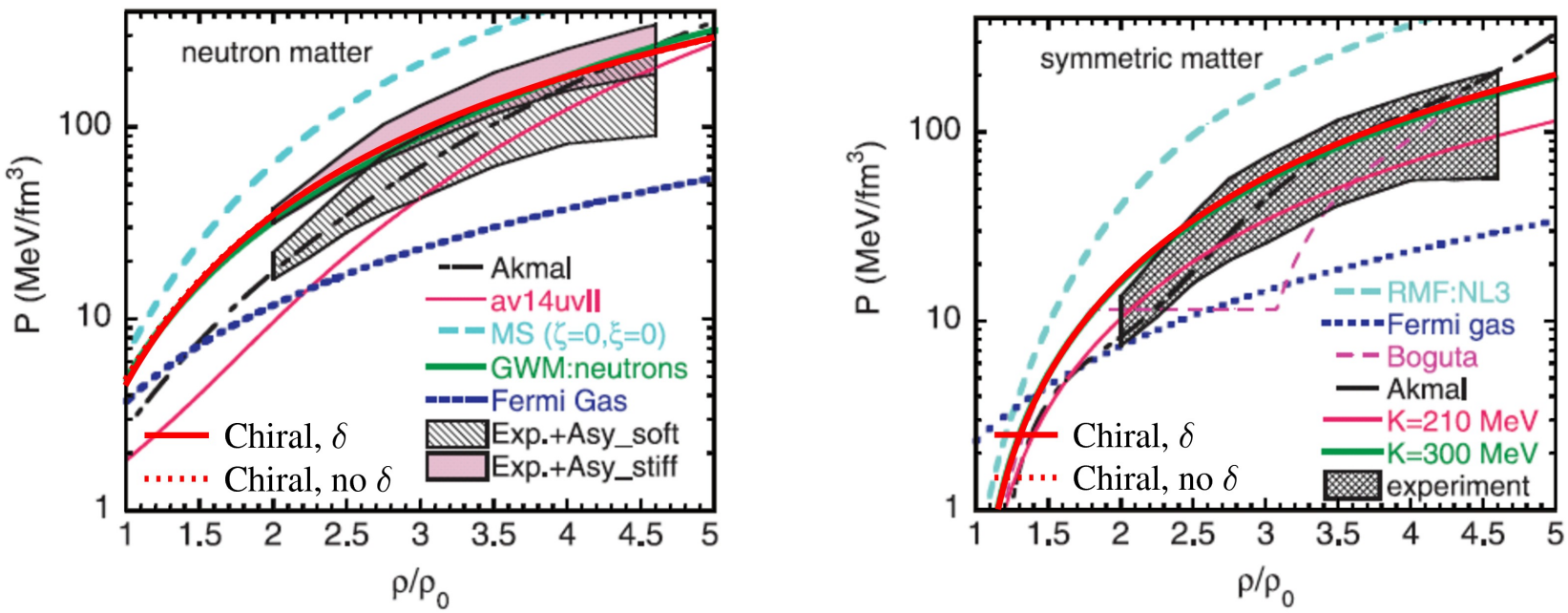
$$m_b^* = g_{b\sigma}\sigma + g_{b\delta}\tau_3\delta + g_{b\zeta}\zeta + \delta m_b$$



- chiral symmetry spontaneously broken in nature
- no parity doublets
- pseudo-Goldstone bosons (pseudo-scalar mesons)

Parameter Fitting:

- coupling constants reproduce: standard nuclear constrains, baryon vacuum masses, hyperon potentials, pion and kaon decay constants

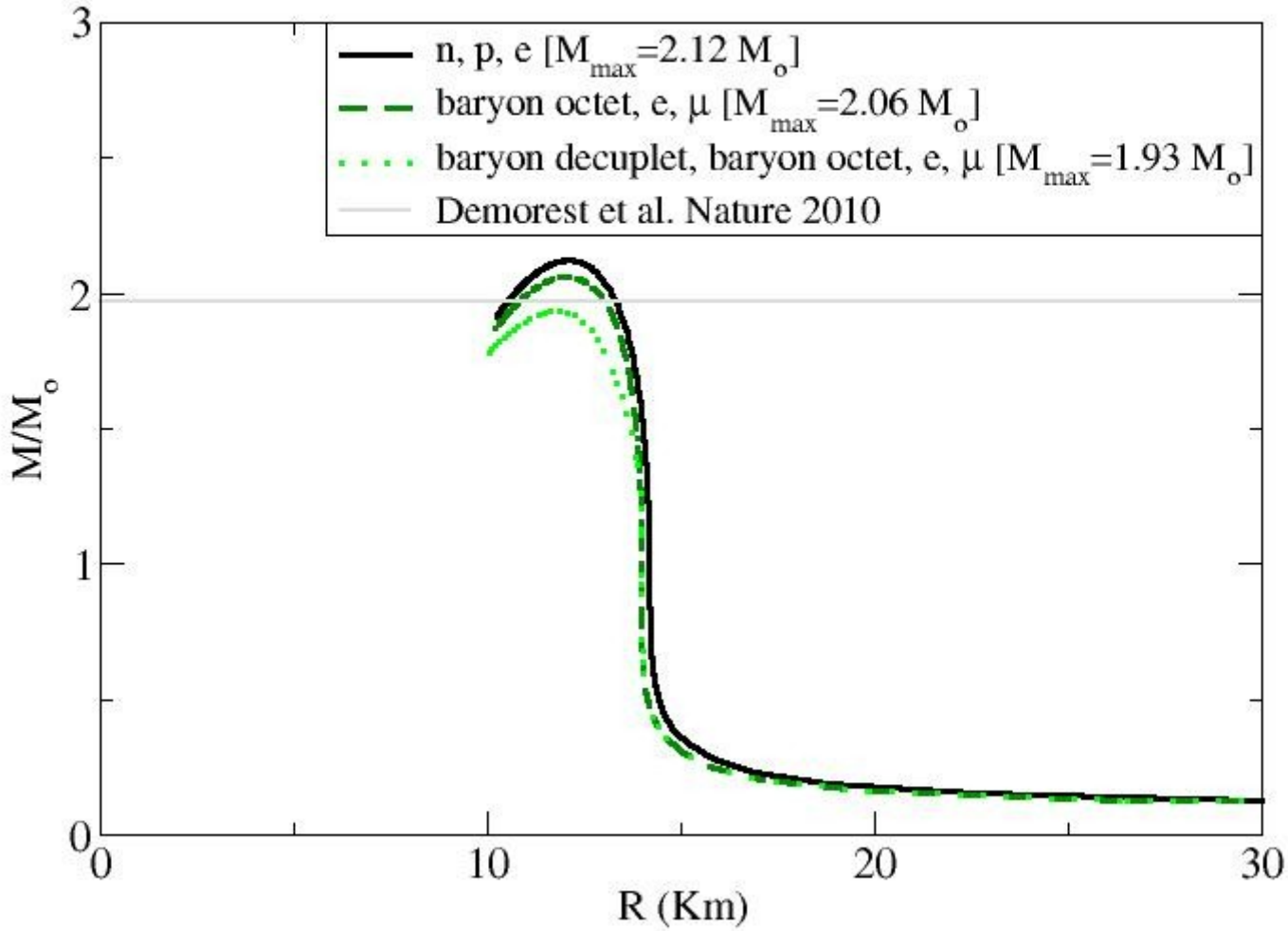


Danielewicz et al. Science 2002

- nuclear matter saturation properties (ρ_0=0.15 fm^{-3}, $E_{sym\ 0}$=29.56 MeV, L_0=88.18 MeV, p_0=4.52 MeV/fm^3, B=-16.00 MeV, K_0=298 MeV)

- inclusion of the delta meson (scalar-isovector) ($E_{sym\ 0}$=32.47 MeV, L_0=93.85 MeV, p_0=4.82 MeV/fm^3)

Inclusion of Gravity (TOV):

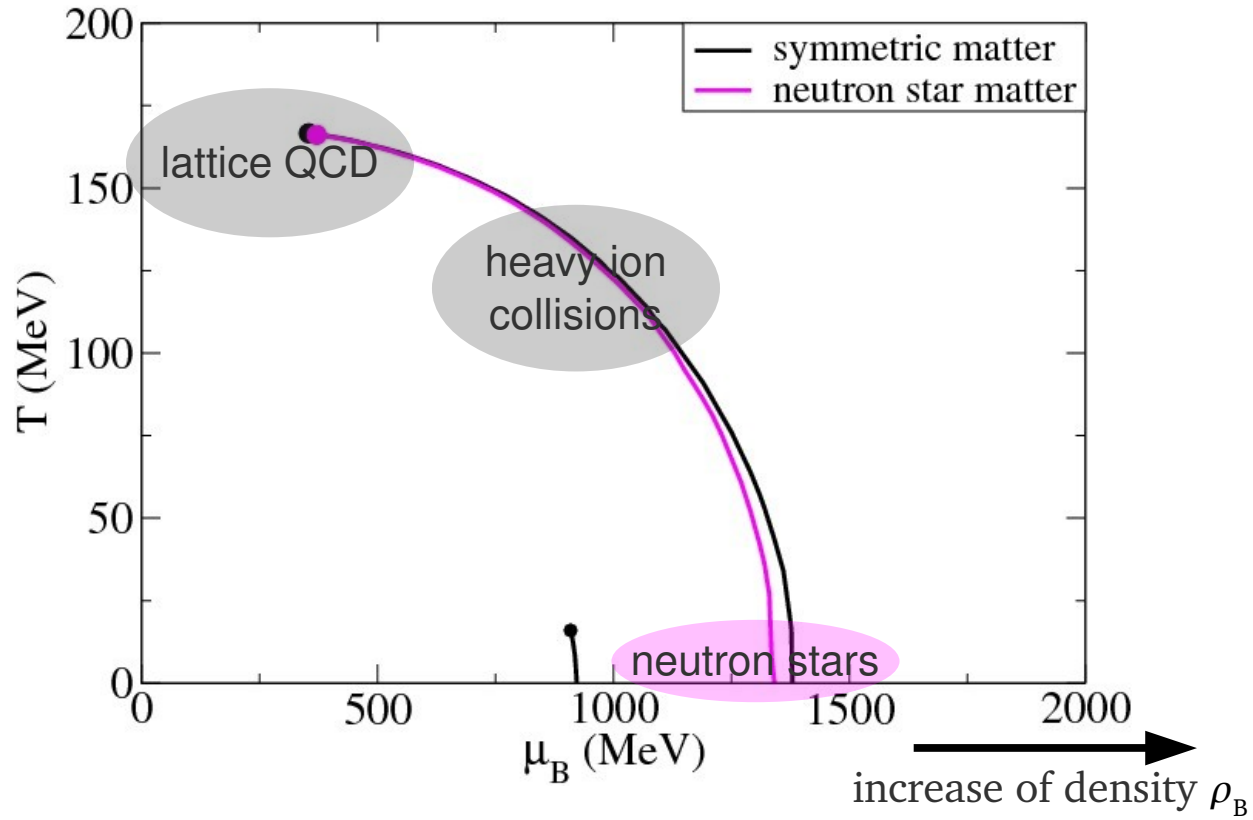


- new degrees of freedom make EOS softer (star less massive!)

Extended SU(3) Non-Linear Sigma Model:

Dexheimer et al. Phys. Rev. C 2010

- hadronic matter (n, p, Λ, … e, μ)
- quark matter (u, d, s)
- different orders of phase transition
- liquid-gas phase transition
- order parameters σ, Φ
- effective masses
- potential for Φ (deconfinement)



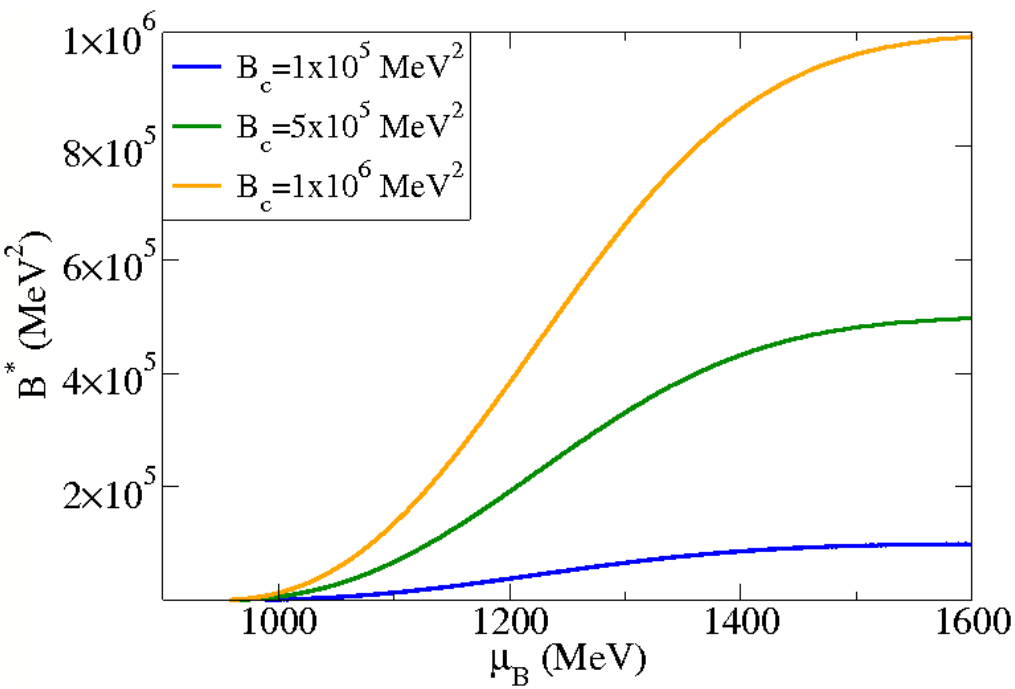
$$m_b^* = g_{b\sigma}\sigma + g_{b\delta}\tau_3\delta + g_{b\zeta}\zeta + \delta m_b + g_{b\Phi}\Phi^2$$

$$m_q^* = g_{q\sigma}\sigma + g_{q\delta}\tau_3\delta + g_{q\zeta}\zeta + \delta m_q + g_{q\Phi}(1-\Phi)$$

$$U = (a_0\, T^4 + a_1\, \mu^4 + a_2\, T^2\mu^2)\phi^2 + a_3\, T_0^4 \quad \ln\left(1 - 6\phi^2 + 8\phi^3 - 3\phi^4\right)$$

Inclusion of Magnetic Field:

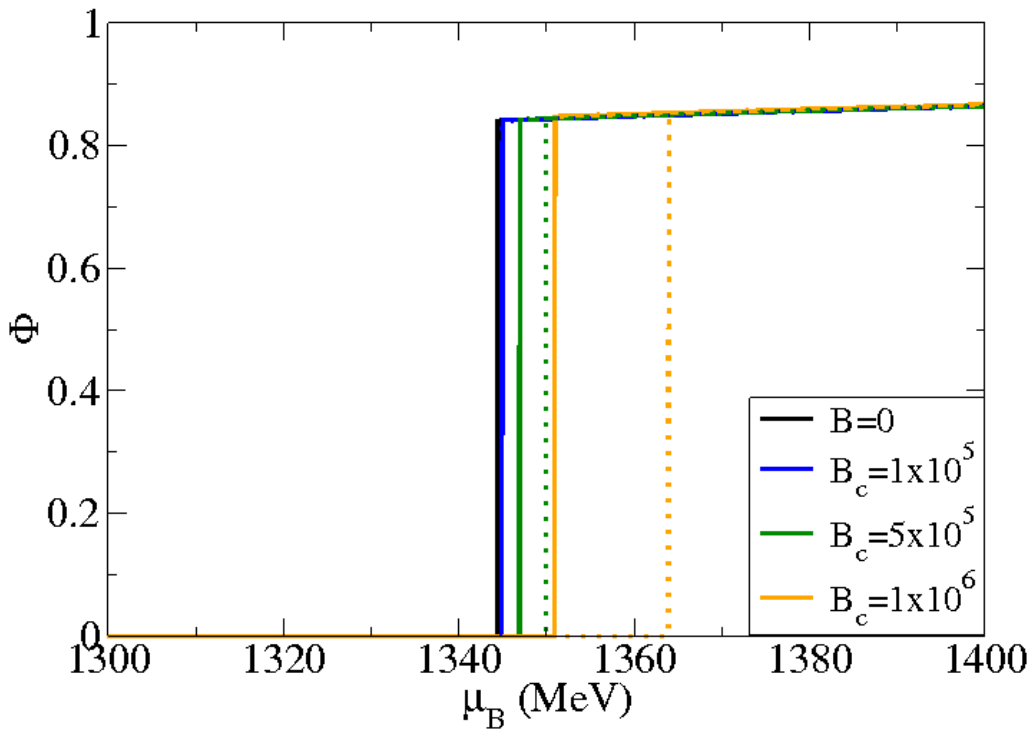
- affects density in which phase transition occurs?
- magnetic field in z-direction
  $B(\mu_B)$: $B_{surf}=69.25\ MeV^2=10^{15}G \rightarrow B_c$
- quantization of energy levels (only charged particles)
- anomalous magnetic moment (effect on non-charged particles)

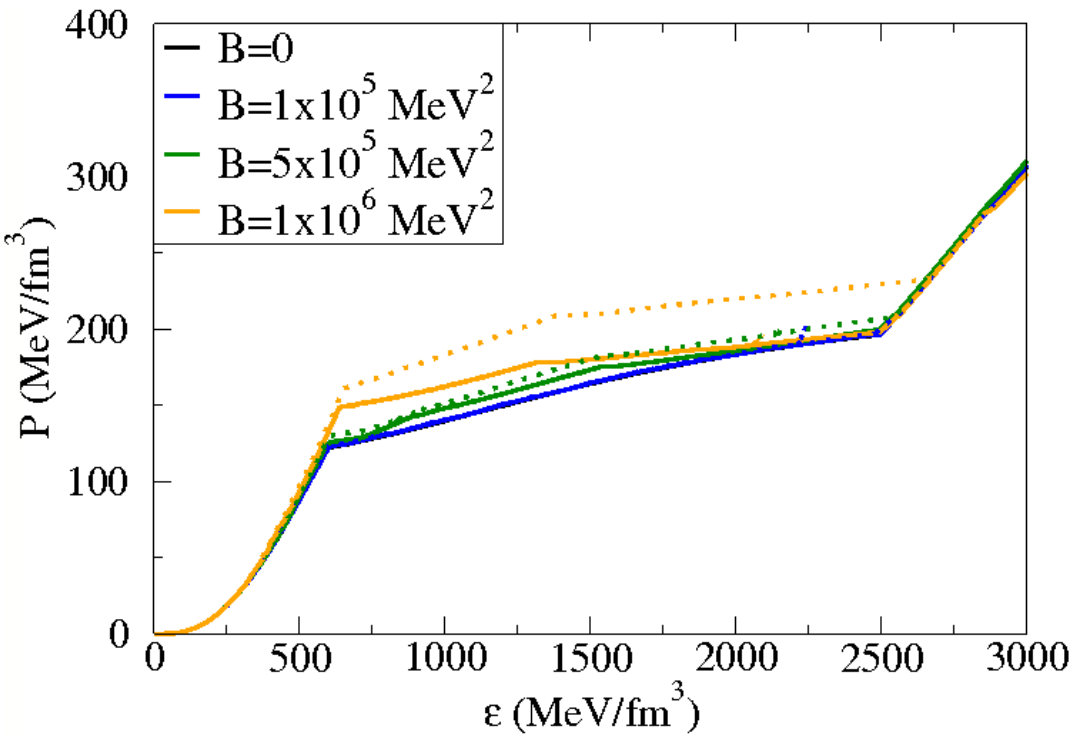


$1\ MeV^2=1.444 \times 10^{13}\ G$

Phase Transition:

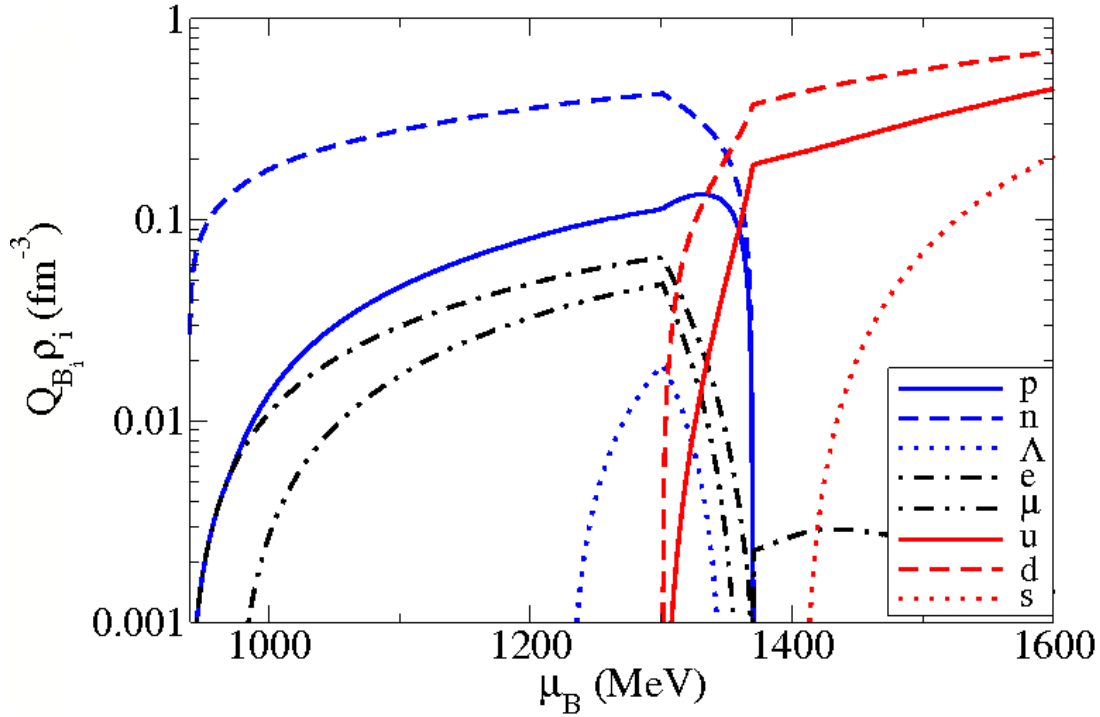
- Φ → deconfinement
- associated with chiral symmetry restoration
- B delays deconfinement
- effect increased by anomalous magnetic moment (dotted line)
- $P_{matter} \times \epsilon_{matter}$
- Gibbs construction
- EOS gets stiffer





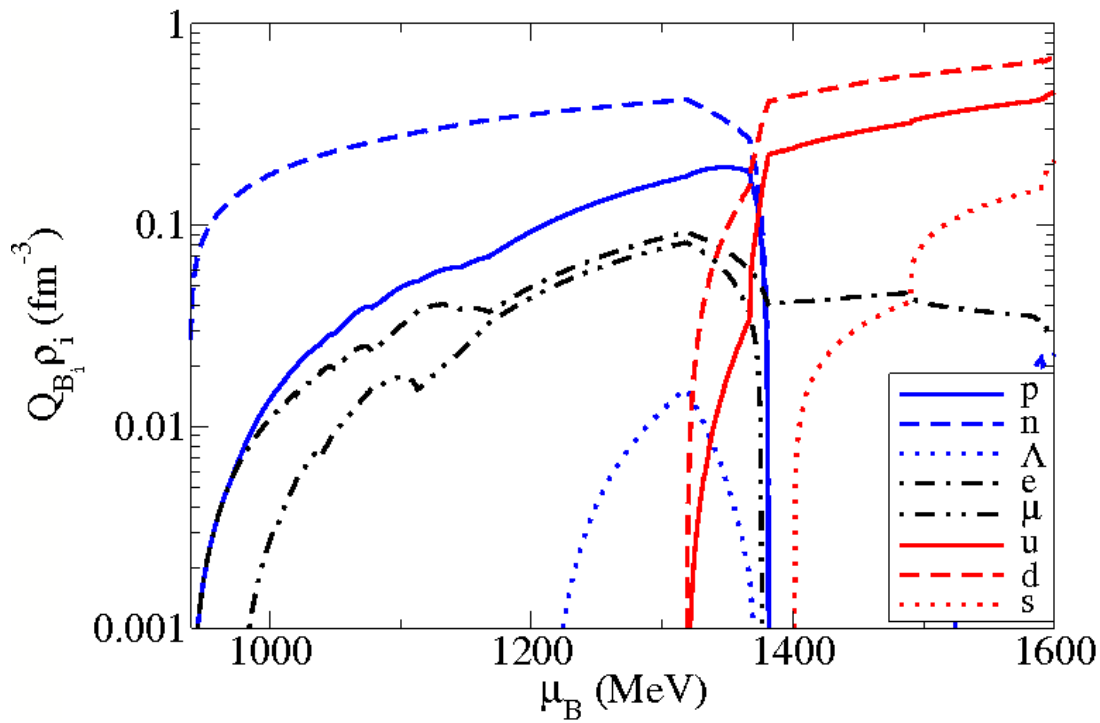
Population:

- no magnetic field
- $B = 1 \times 10^6$ MeV^2 (1.444×10^{19} G) with anomalous magnetic moment



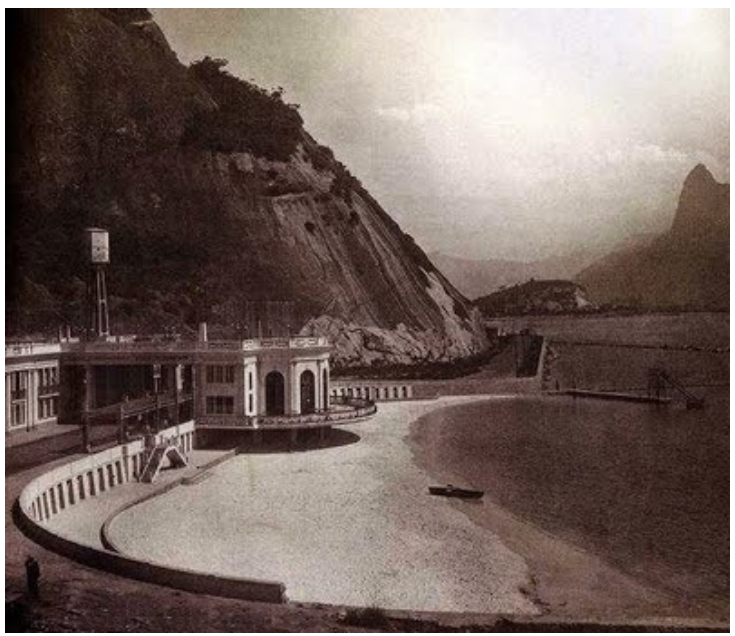
- charged particles
- e quark phase
- level thresholds

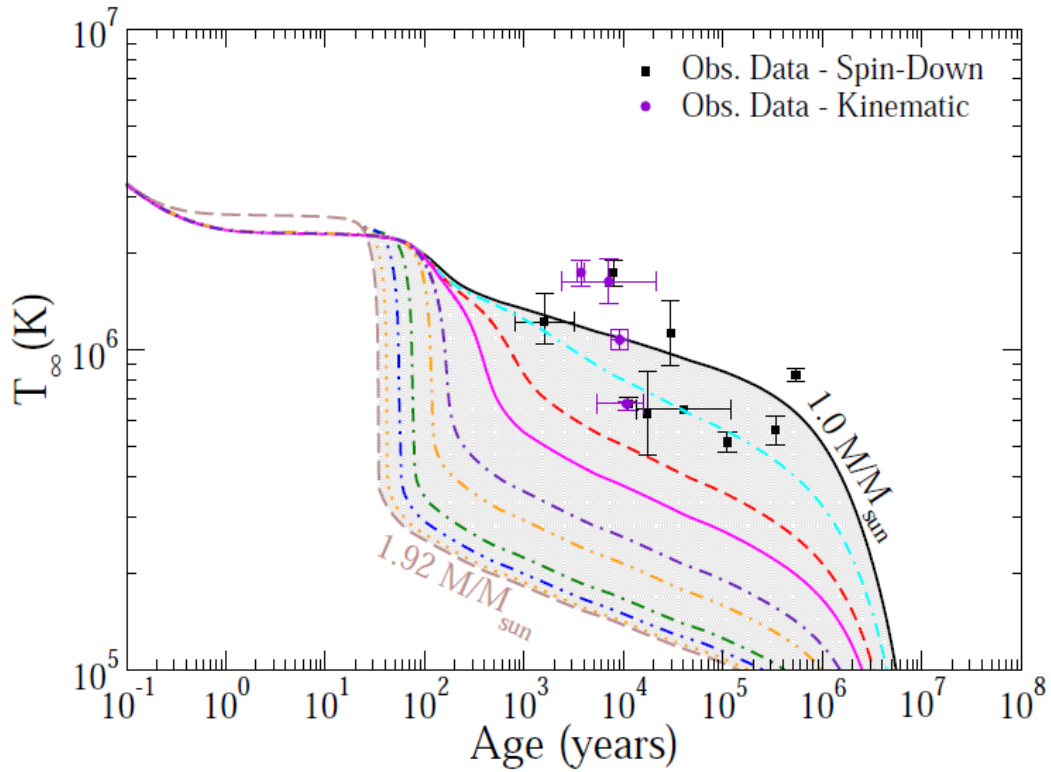
- enough to change cooling?



Cooling:

- neutrino emission: direct Urca process ($M>1.2\ M_\odot$)
  modified Urca process
  Brehmstrahlung
- photon emission
- same for quarks

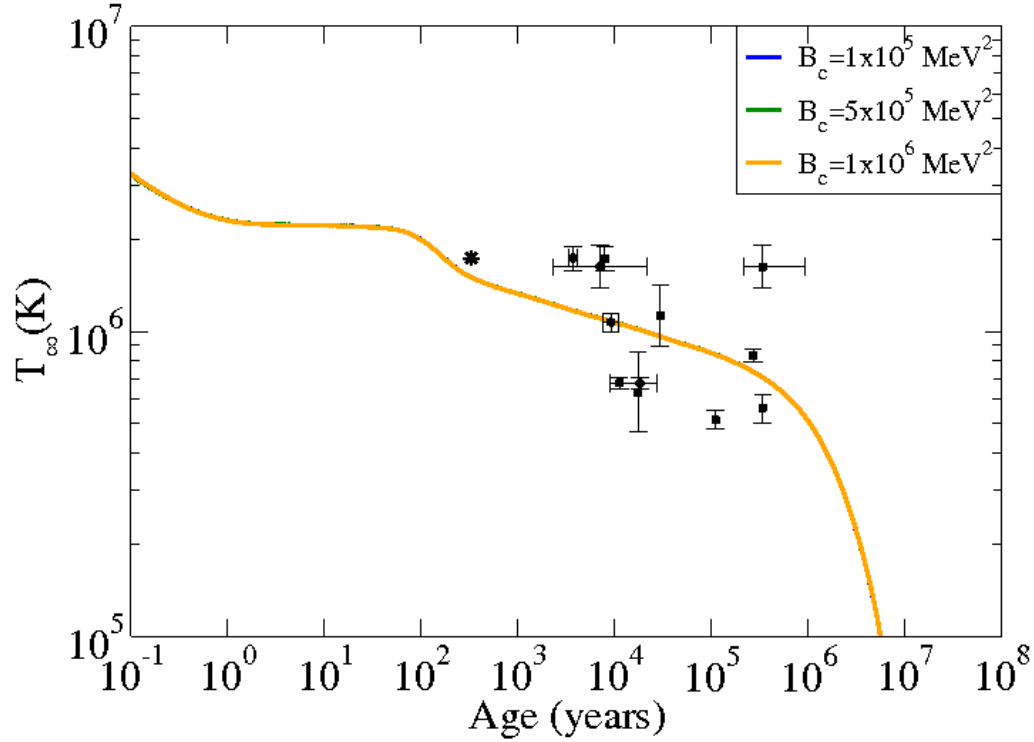


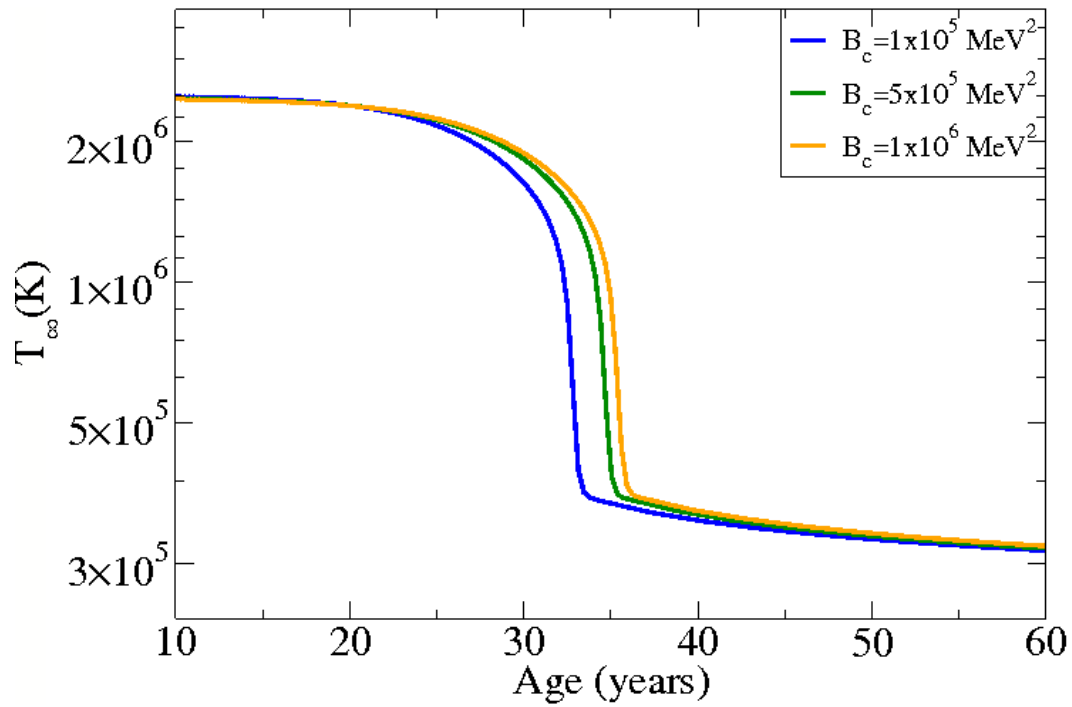


"the energy disappears in the nucleus of the supernova as quickly as the money disappeared at that roulette table" George Gamow

Cooling with Magnetic Field:

- 1.1 solar masses
- 1.93 solar masses (maximum mass for B=0)
- with anomalous magnetic moment
- cools slower



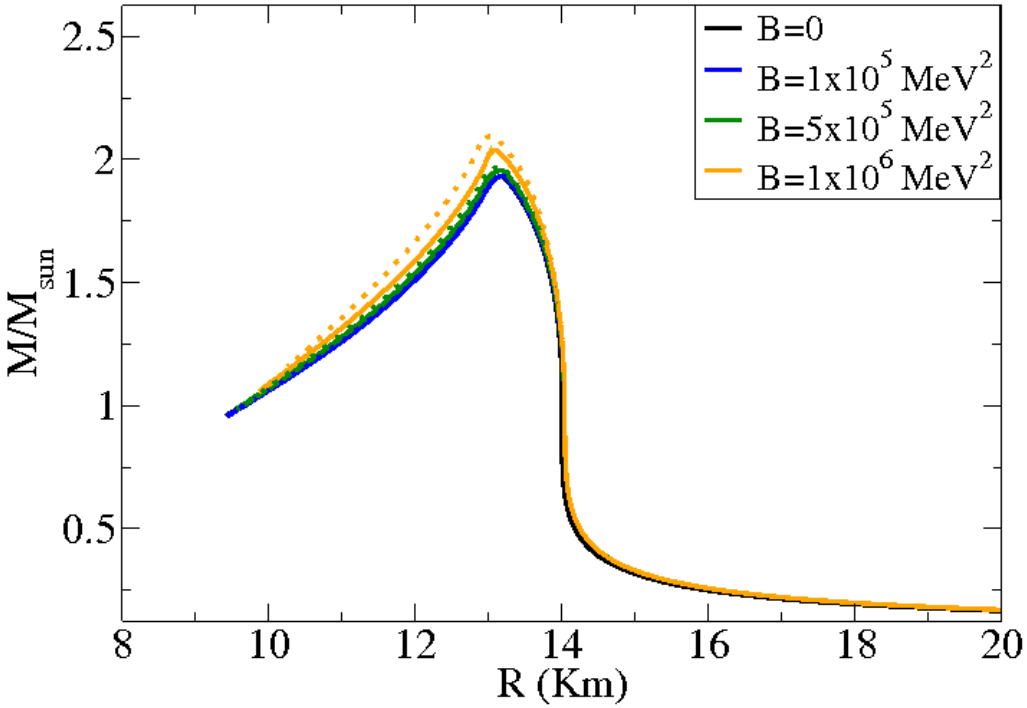


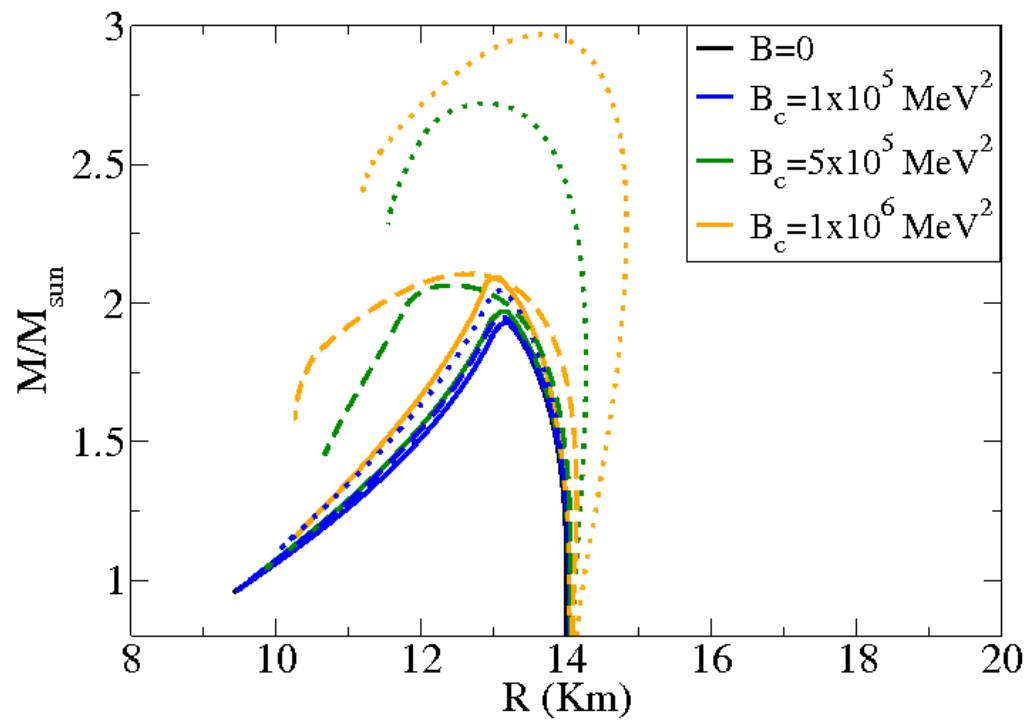
TOV:

- magnetic field increases star masses (more with anomalous magnetic moment)
- extra term in pressure?

$$T^{\mu\nu} = \frac{1}{4\pi}\begin{pmatrix} \frac{1}{2}B^{*2} & 0 & 0 & 0 \\ 0 & \frac{1}{2}B^{*2} & 0 & 0 \\ 0 & 0 & \frac{1}{2}B^{*2} & 0 \\ 0 & 0 & 0 & -\frac{1}{2}B^{*2} \end{pmatrix}$$

- with anomalous magnetic moment
- $\epsilon_{\text{matter}}+B^{*2}/8\pi$, $P_{\text{matter}}+B^{*2}/24\pi$ (dashed line)
- $\epsilon_{\text{matter}}+B^{*2}/8\pi$, $P_{\text{matter}}+B^{*2}/8\pi$ (dotted line)





Conclusions:

- chiral SU(3) non linear sigma model consistent with nuclear matter constraints
- extended chiral SU(3) non linear sigma model changes degrees of freedom naturally for high density/temperature
- allows to study high density matter (any temperature)
- reproduces massive stars
- at T=0 high magnetic field delays phase transition
- EOS gets stiffer (different energy distribution)
- even more massive stars
- without cylindrical TOV there are different possibilities
- magnetic field has small effect on cooling (delay)

Our Lagrangian:

$$L = L_{Kin} + L_{Int} + L_{Self} + L_{SB} - U,$$

$$L_{Int} = -\sum_i \bar{\psi}_i[\gamma_0(g_{i\omega}\omega + g_{i\phi}\phi + g_{i\rho}\tau_3\rho) + M_i^*]\psi_i,$$

$$L_{Self} = -\frac{1}{2}(m_\omega^2\omega^2 + m_\rho^2\rho^2 + m_\phi^2\phi^2)$$

$$\boxed{+g_4\left(\omega^4 + \frac{\phi^4}{4} + 3\omega^2\phi^2 + \frac{4\omega^3\phi}{\sqrt{2}} + \frac{2\omega\phi^3}{\sqrt{2}}\right)}$$

$$+k_0(\sigma^2 + \zeta^2 + \delta^2) + k_1(\sigma^2 + \zeta^2 + \delta^2)^2$$

$$+k_2\left(\frac{\sigma^4}{2} + \frac{\delta^4}{2} + 3\sigma^2\delta^2 + \zeta^4\right) + k_3(\sigma^2 - \delta^2)\zeta$$

$$+k_4 \quad \ln\frac{(\sigma^2-\delta^2)\zeta}{\sigma_0^2\zeta_0},$$

$$L_{SB} = m_\pi^2 f_\pi\sigma + \left(\sqrt{2}m_k^2 f_k - \frac{1}{\sqrt{2}}m_\pi^2 f_\pi\right)\zeta,$$

Introduction Magnetic Field:

$$B^* = B_{surf} + B_c[1 - e^{b_1(\frac{\mu_B - 939}{939})^{b_2}}]$$

69.25 MeV^2=10^{15}G

$$E^*_{i_{\nu s}} = \sqrt{k^2_{z_i} + \left(\sqrt{m^{*2}_i + 2\nu|q_i|B^*} - sk_iB^*\right)^2})$$

$$E^*_{i_s} = \sqrt{k^2_i + \left(m^{*2}_i - sk_iB^*\right)^2}$$

$$\nu_{max} = \frac{E^{*2}_{i_s} + sk_iB^* - m^*_i}{2|q_i|B^*}$$

- anomalous magnetic moment has effect on non-charged fermions (k_i determines the coupling strength of baryons with electromagnetic field tensor)

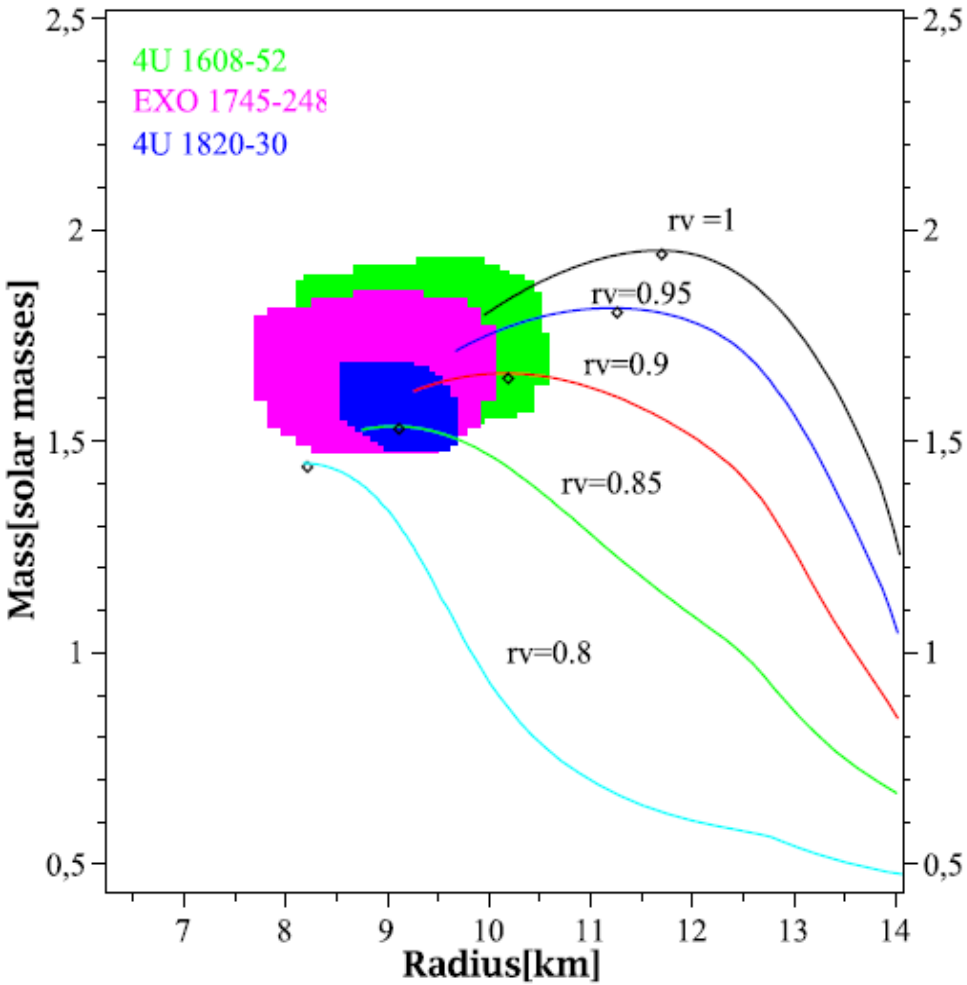
- Thermal Balance and Thermal Energy Transport Equation:

$$\frac{\partial(le^{2\phi})}{\partial m} = -\frac{1}{\rho\sqrt{1-2m/r}}\left(\epsilon_\nu e^{2\phi} + c_v \frac{\partial(Te^{\phi})}{\partial t}\right)$$

$$\frac{\partial(Te^{\phi})}{\partial m} = -\frac{(le^{\phi})}{16\pi^2 r^4 \kappa\rho\sqrt{1-2m/r}}\,.$$

  - boundary conditions: luminosity l vanishes at star's center, surface luminosity determined by mantle temperature and temperature outside the star
  - microscopic input: neutrino emissivity $\epsilon_\nu(r,T)$, specific heat $c_v(r,T)$ and thermal conductivity $\kappa(r,T)$

⋆ Inclusion of Δ Resonances:



$$r_v = \frac{g_{\Delta\omega}}{g_{N\omega}}$$

- Schurhoff et al. APJ 2010
- Oezel Phys. Rev. D 2010