The Magnetic Field Profile in Strongly Magnetized Neutron Stars

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arXiv: 1612.05795

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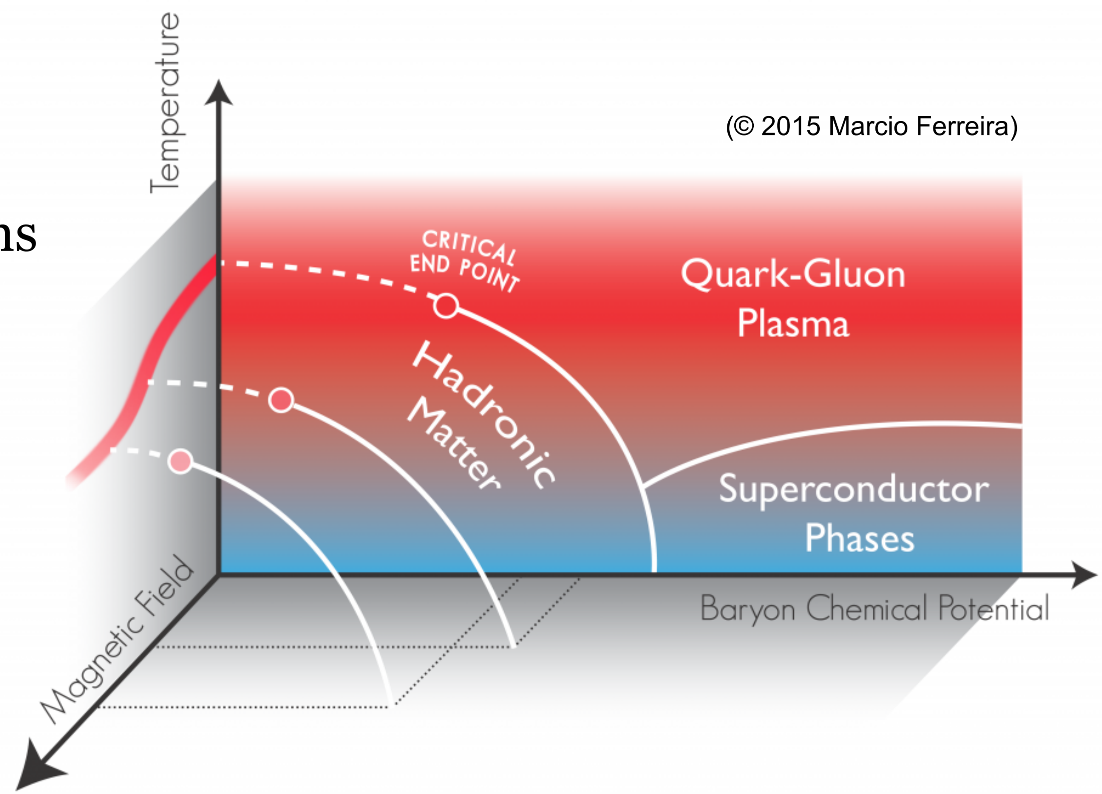
✯ Motivation

- understand how B changes inside neutron stars to calculate

- changes in EoS stiffness
- changes in population
- possible phase transitions



- transport properties (thermal and electric conductivities), etc.
- temperature profiles (for fixed entropy per baryon)

Franzon, Dexheimer, and Schramm Phys. Rev. D (2016)

✯ Ad hoc B profiles from literature

- as a function of baryon density:

$$B^*(n_B/n_0) = B_{surf} + B_0 \left[1 - e^{-\beta(n_B/n_0)^\gamma}\right]$$

Bandyopadhyay, Chakrabarty and Pal
Phys. Rev. Let. (1997)

- as a function of chemical potential:

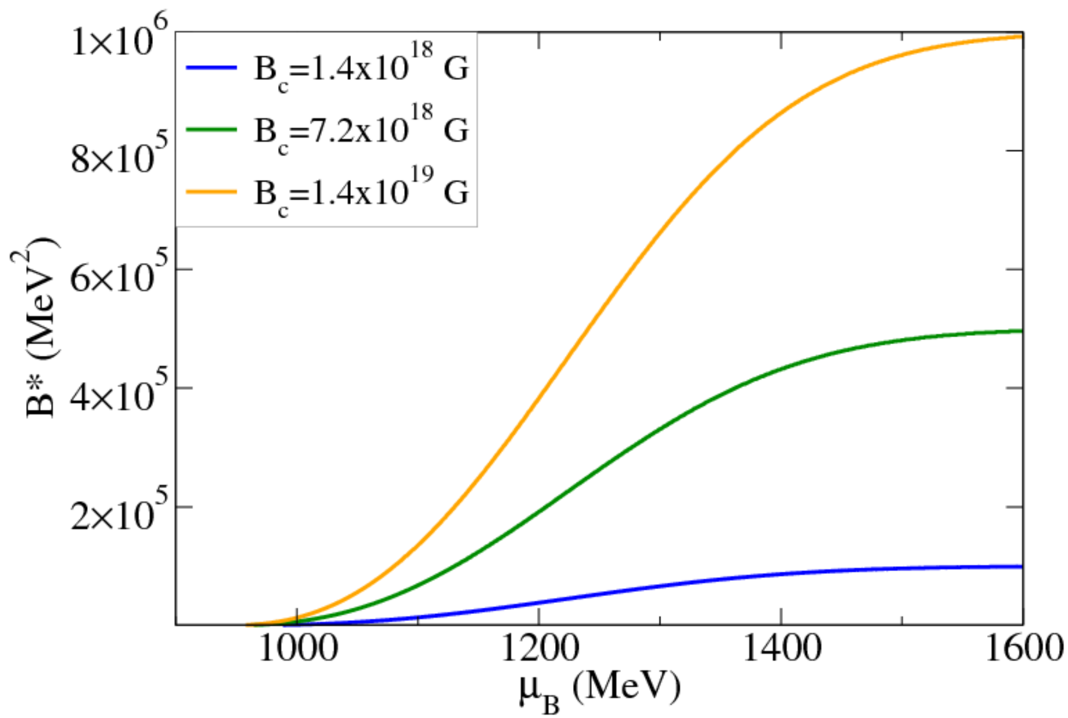
$$B^*(\mu_B) = B_{surf} + B_c \left[1 - e^{b\frac{(\mu_B - 938)^a}{938}}\right]$$

Dexheimer, Negreiros and Schramm
Eur. Phys. J. A (2012)

and others

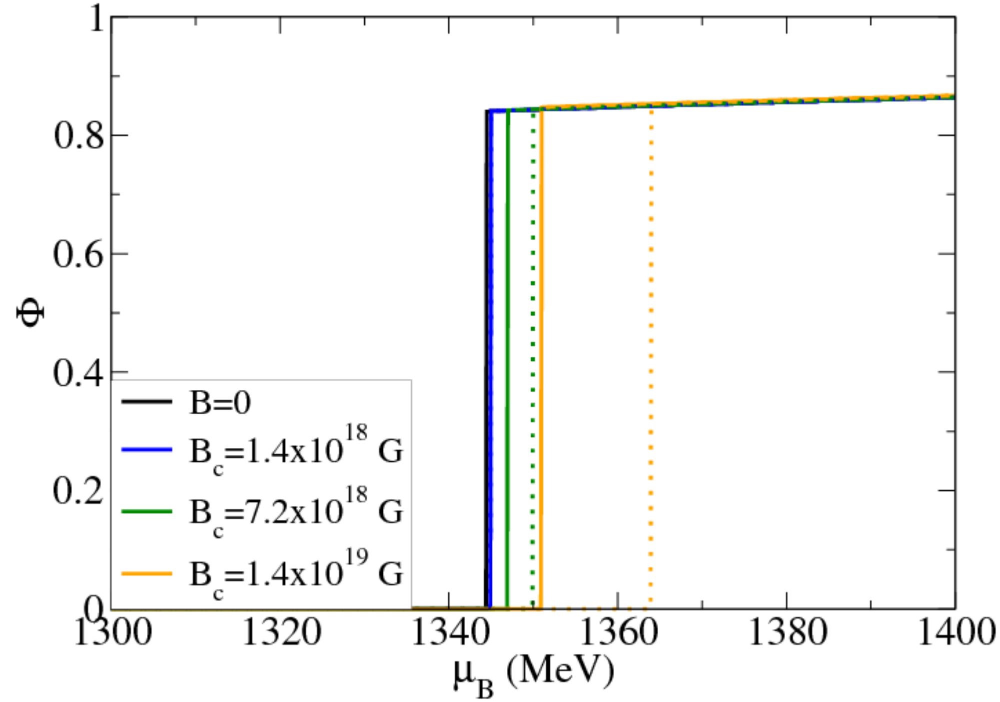
- do not fulfill Maxwell's equations

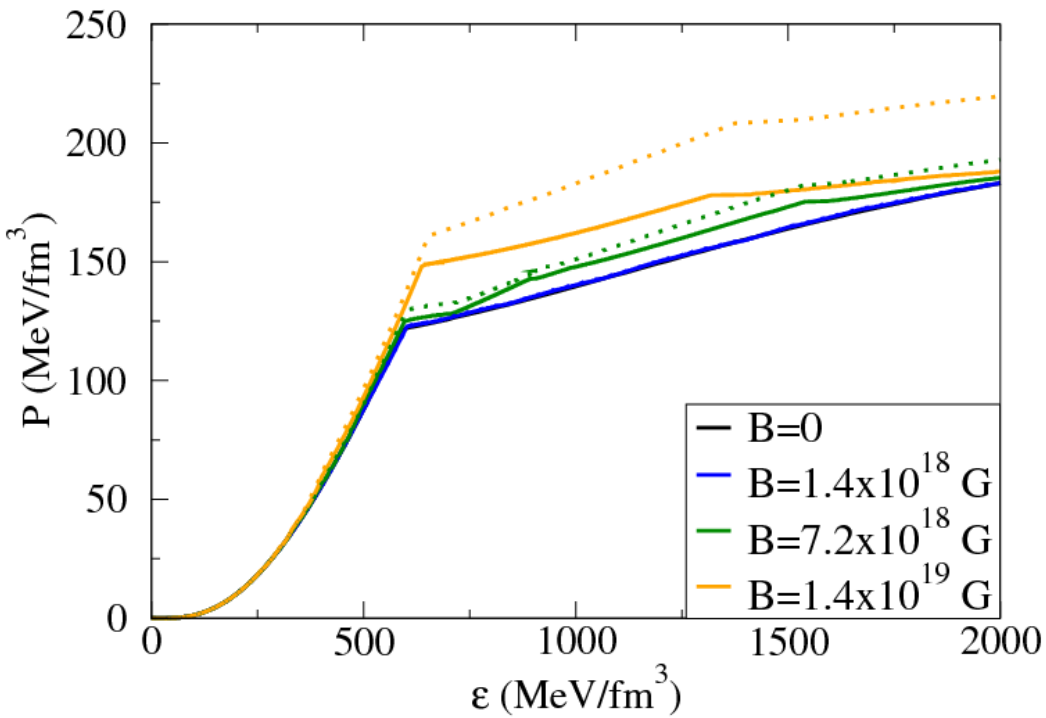
Menezes and Alloy
arXiv:1607.07687 (2016)



✯ Ad hoc B-profile effects on chiral (CMF) EOS

- Phi signals deconfinement which is pushed to larger chemical potentials by B
- effect increased by AMM (dotted line)
- equation of state gets stiffer with B





✭ Ingredients

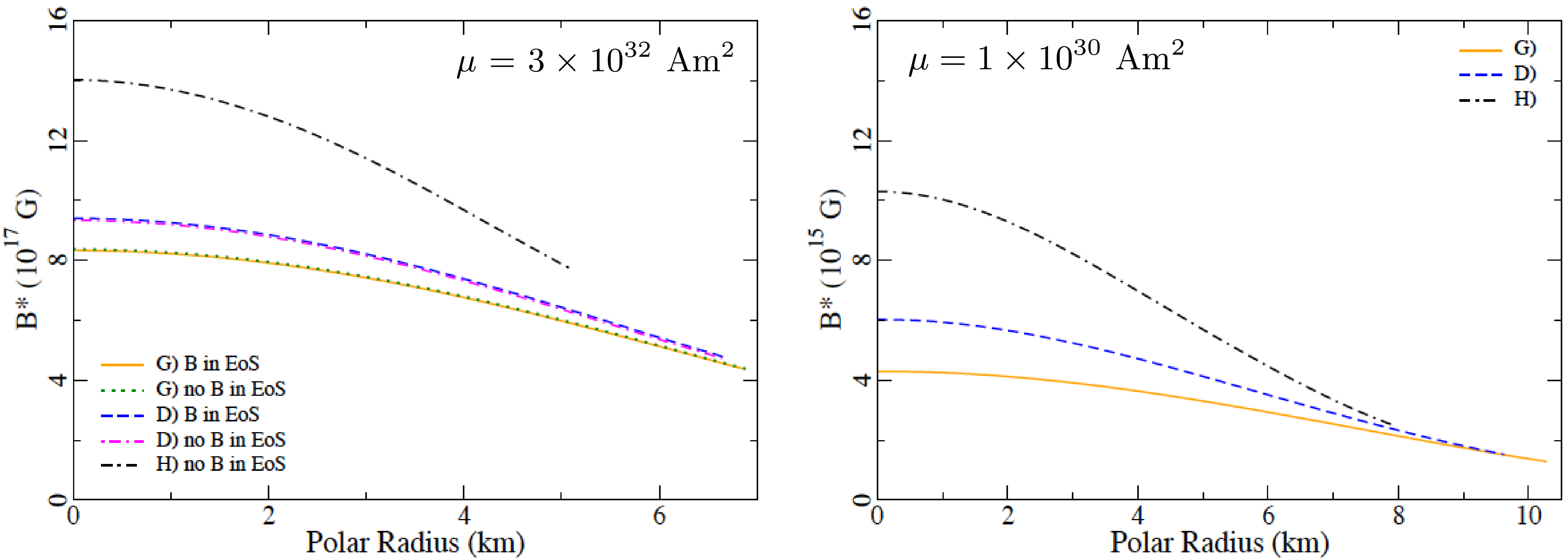
- EoS's:

- include magnetic field effects
- respect nuclear and astro constraints
- possess different degrees of freedom
  1) hadronic: G-model (many-body forces (MBF) among nucleons simulated by non-linear self-couplings)
  2) hybrid: D-model (chiral (CMF) model with nucleons, hyperons, quarks)
  3) quarks: **H-model** (3-flavor NJL model with vector-isoscalar interaction)

- General relativity:

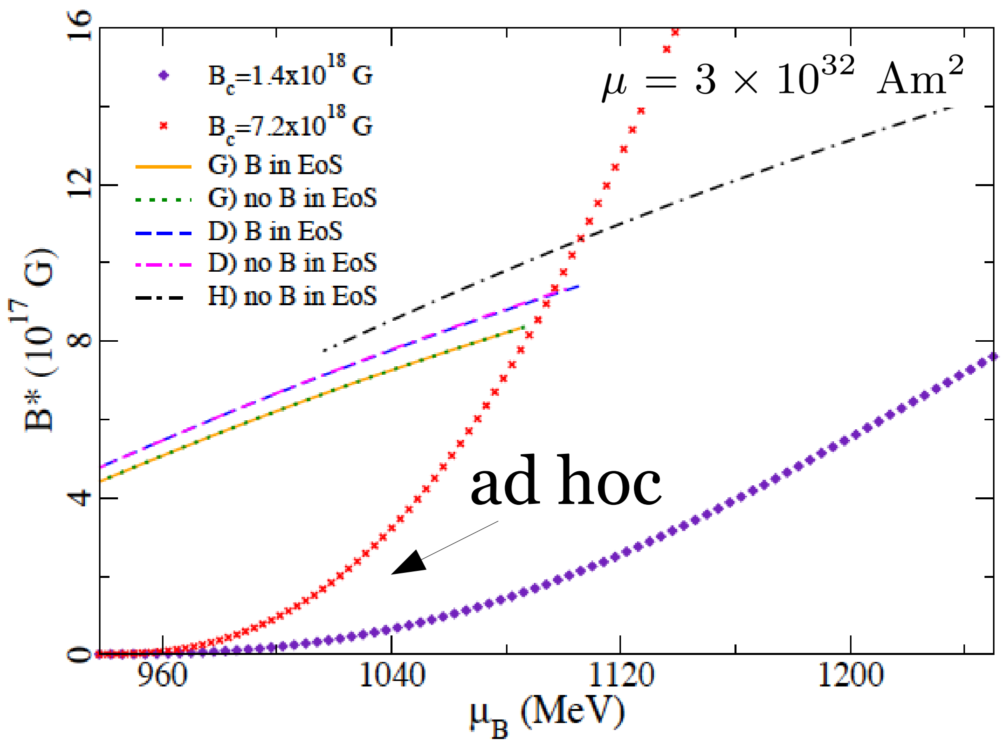
- equilibrium configurations from Einstein-Maxwell's field equations in spherical polar coordinates
- assumes a poloidal magnetic field configuration produced self-consistently by a macroscopic current (stellar radius, angle theta, and dipole magnetic moment μ)
- LORENE C++ class library for numerical relativity

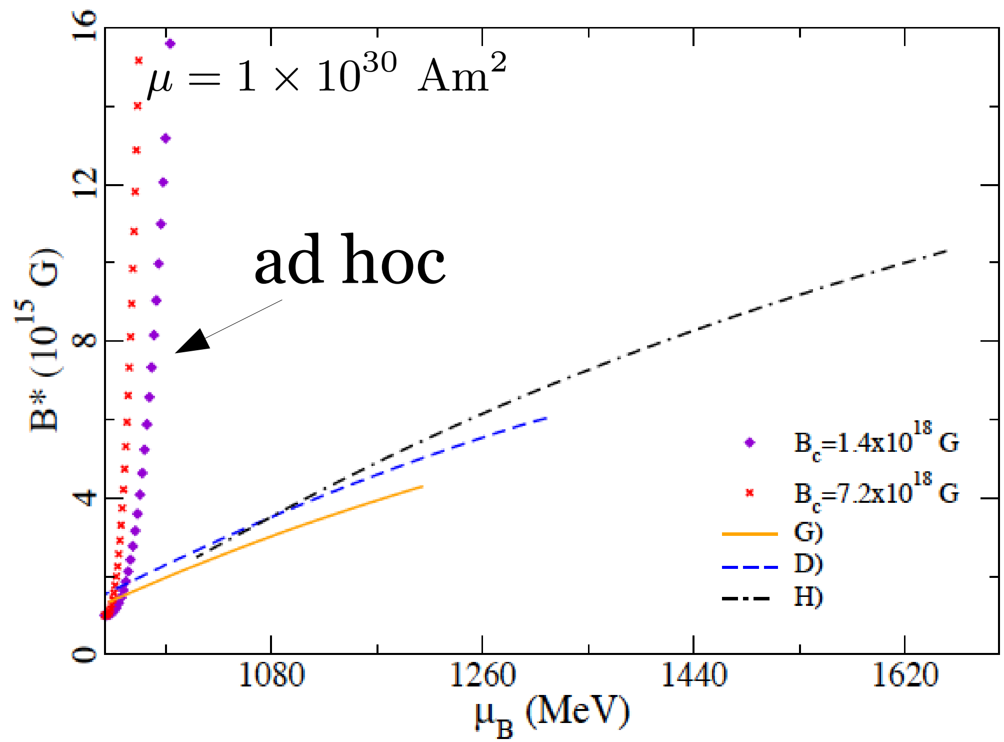
✫ B-profile versus macroscopic quantity in a massive star



- B in EoS makes very little or no difference in profile
- different EoS's show different magnetic field strengths, but have approximately the same profile shape (for any μ)

✯ B-profile versus macroscopic quantity in a massive star



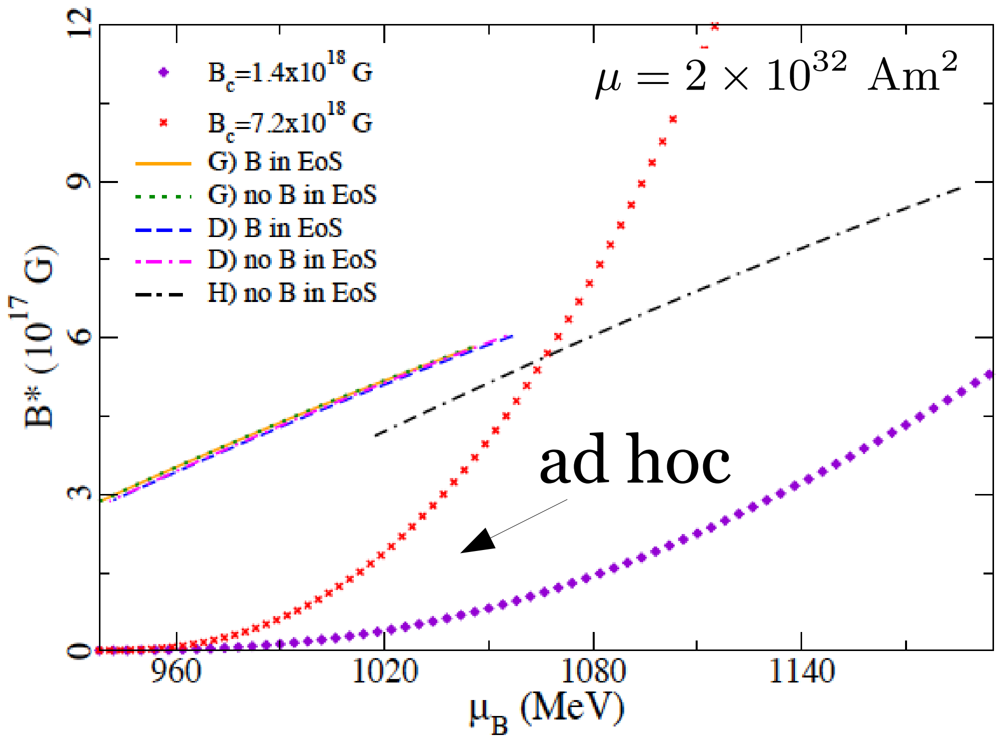


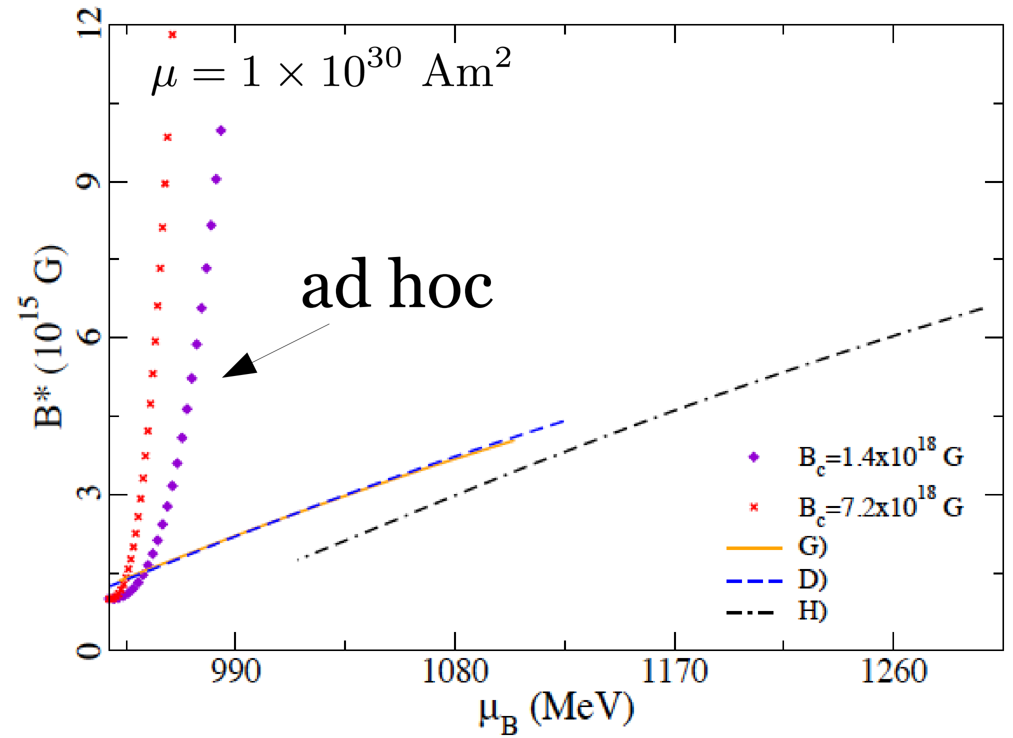
- the B profile is quadratic with respect to chemical potential

$B^*(\mu_B) = (a + b\mu_B + c\mu_B^2)\ \mu,$ with $a = -1.68 \times 10^{-14}$, $b = 2.80 \times 10^{-17}$, $c = -8.92 \times 10^{-21}$ and

μ_B given in MeV and μ in A.m² to produce B^* in G

☆ B-profile versus macroscopic quantity in a lower mass star





- the B profile is still quadratic with respect to chemical potential but with coefficients $a = -2.60 \times 10^{-14}$, $b = 4.16 \times 10^{-17}$ and $c = -1.35 \times 10^{-20}$

- nuclear EoS's overlap

✯ Summary and Outlook

- we provide the first realistic magnetic-field profile for the EoS of magnetized neutron stars

- our profile is obtained from the solution of Einstein's equations and does not violate Maxwell’s equations

- our results allow anyone to include a B profile in any neutron star EoS in a simple way to study changes in stiffness, population, phase transitions, temperature, transport properties, etc. due to B effects in their models

- we are currently analyzing the effects of the B profile in a phase diagram for neutron star matter

Magnetic Field in EOS at T=0

- B in the z-direction
- x, y energy levels quantized
- anomalous magnetic moment (AMM)

$$E^*_{i_{\nu s}} = \sqrt{k_{z_i}^2 + \left(\sqrt{m_i^{*2} + 2\nu|q_i|B^*} - s_i\kappa_i B^*\right)^2}$$

$$E^*_{i_s} = \sqrt{k_i^2 + \left(m_i^{*2} - s_i\kappa_i B^*\right)^2}$$

maximum Landau level

$$\nu_{max} = \frac{{E^*_{i_s}}^2 + s_i\kappa_i B^* - m_i^{*2}}{2|q_i|B^*}$$

$\kappa_i \rightarrow$ coupling strength of baryons with electromagnetic field tensor