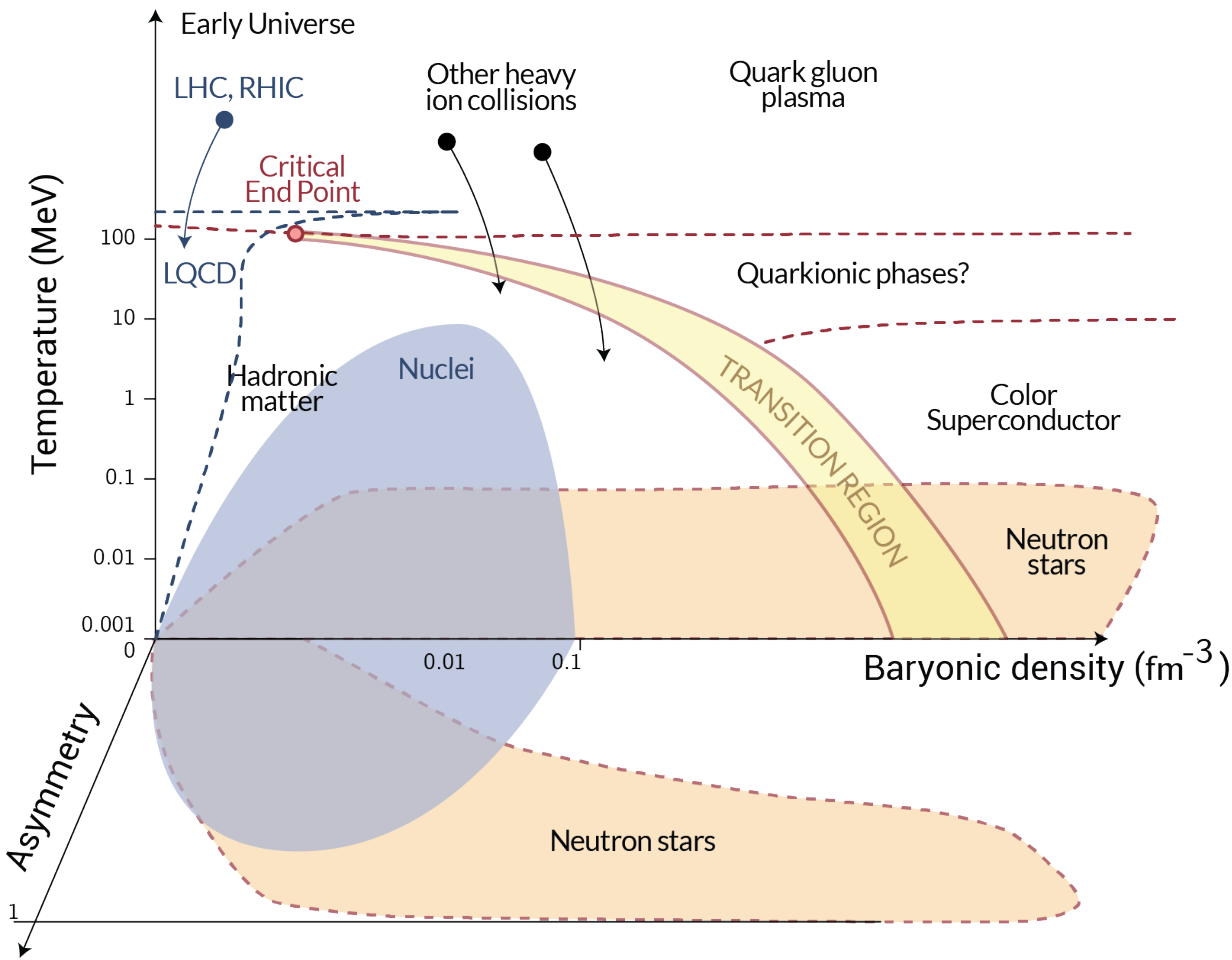
Neutron Stars : composition and observation

Débora Peres Menezes (UFSC)
04/10/2021



Early Universe
LHC, RHIC
Other heavy ion collisions
Quark gluon plasma
Critical End Point
LQCD
Quarkionic phases?
Temperature (MeV)
100
10
1
0.1
0.01
0.001
0
Hadronic matter
Nuclei
TRANSITION REGION
Color Superconductor
Neutron stars
0.01
0.1
Baryonic density (fm^{-3})
Asymmetry
1
Neutron stars

Can NS be described by

quark matter - MIT, NJL, NJLv ?

hadronic+quark matters in hybrid stars ?

nature physics

Letter | Open Access | Published: 01 June 2020

Evidence for quark-matter cores in massive neutron stars

Eemeli Annala, Tyler Gorda, Aleksi Kurkela, Joonas Nättilä & Aleksi Vuorinen

Nature Physics **16**, 907–910(2020) | Cite this article

Abstract

The theory governing the strong nuclear force—quantum chromodynamics—predicts that at sufficiently high energy densities, hadronic nuclear matter undergoes a deconfinement transition to a new phase of quarks and gluons[1]. Although this has been observed in ultrarelativistic heavy-ion collisions[2,3], it is currently an open question whether quark matter exists inside neutron stars[4]. By combining astrophysical observations and theoretical ab initio calculations in a model-independent way, we find that the inferred properties of matter in the cores of neutron stars with mass corresponding to 1.4 solar masses ($M_\odot$) are compatible with nuclear model calculations. However, the matter in the interior of maximally massive stable neutron stars exhibits characteristics of the deconfined phase, which we interpret as evidence for the presence of quark-matter cores. For the heaviest reliably observed neutron stars[5,6] with mass $M \approx 2M_\odot$, the presence of quark matter is found to be linked to the behaviour of the speed of sound c_s in strongly interacting matter. If the conformal bound $c_s^2 \leq 1/3$ (ref. [7]) is not strongly violated, massive neutron stars are predicted to have sizable quark-matter cores. This finding has important implications for the phenomenology of neutron stars and affects the dynamics of neutron star mergers with at least one sufficiently massive participant.

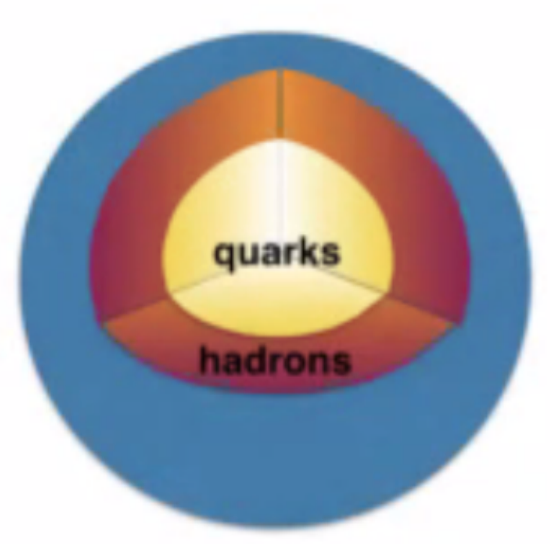
Estrelas hadrônicas, híbridas, de quarks

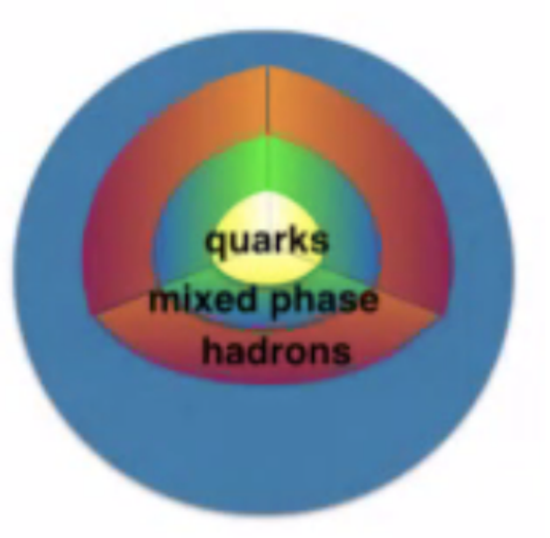
1969 - estrelas híbridas (possibilidade de um caroço supercondutor)
Ivanenko + Kurdgelaidze

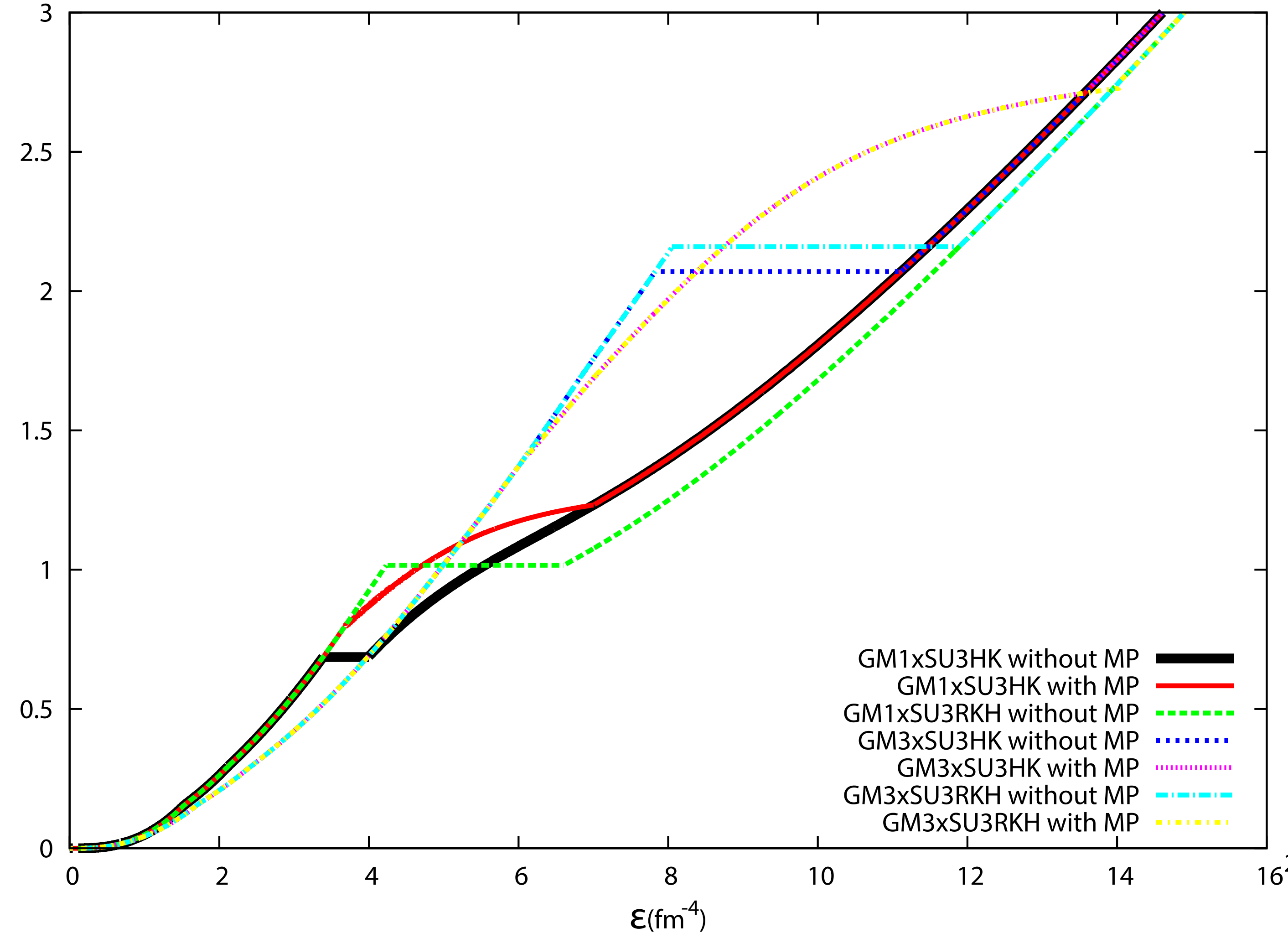
1970 - estrelas de quarks - Itoh

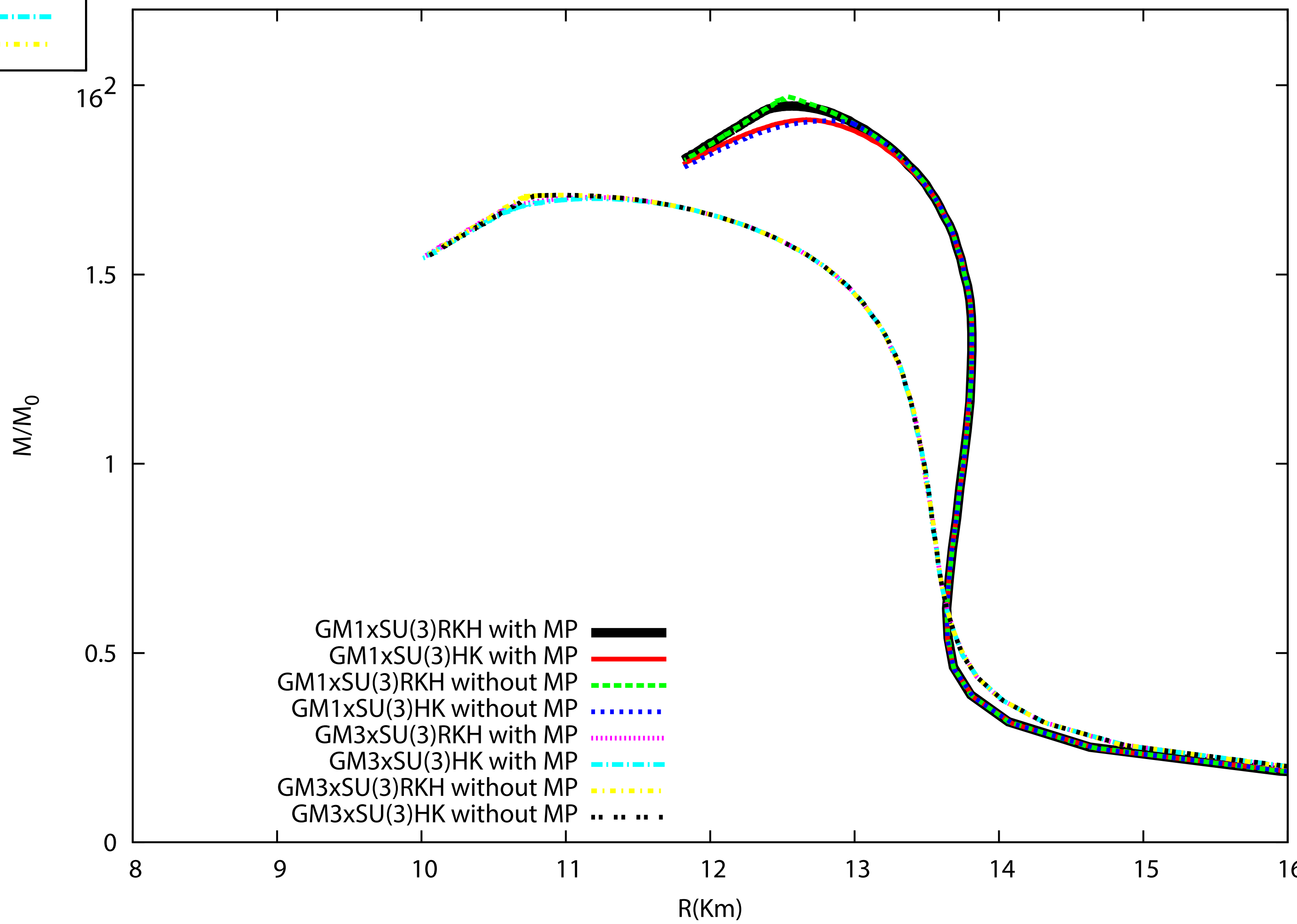
conjectura de Bodmer (1971) - Witten (1984)
estrelas estranhas

estrelas híbridas - com ou sem fase mista

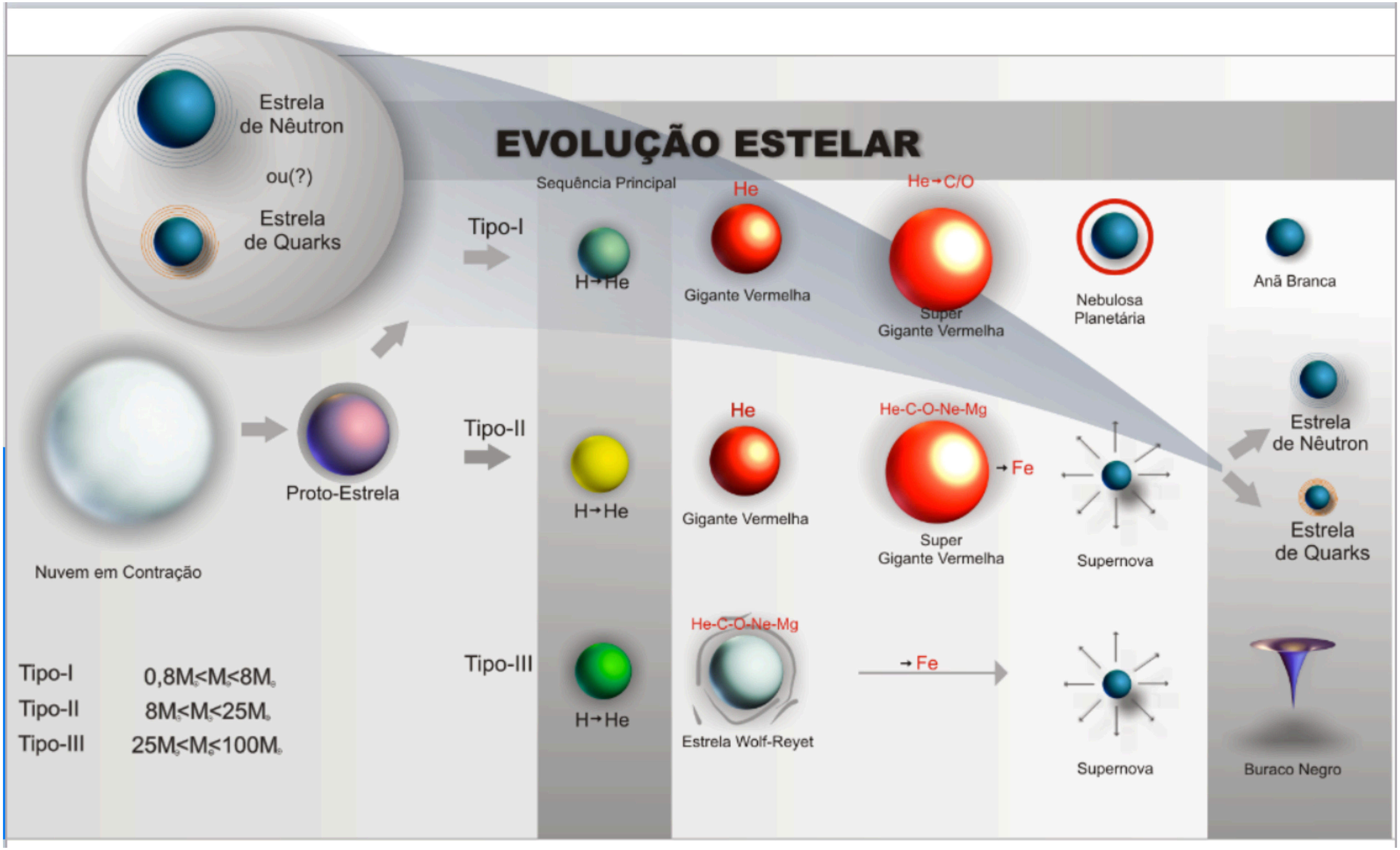






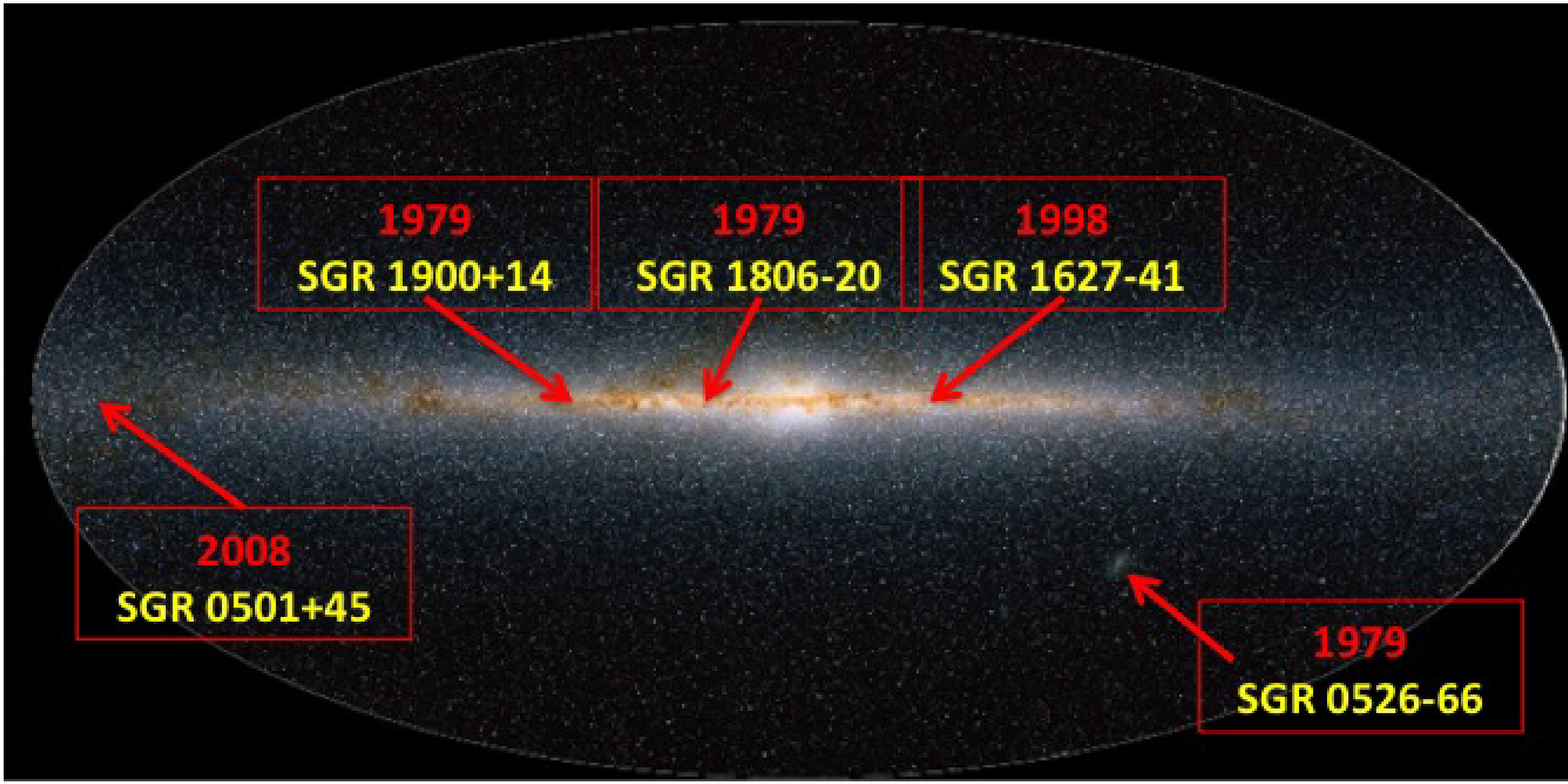


M.G. de Paoli and D.P. Menezes, Int.J. Mod.Phys. D 19, 1525-1529 (2010)



Msc. Thesis - James Rudinei Torres

Quark star candidates



Courtesy picture: C. Kouveliotou and Chengmin Zhang

Quark stars - Stability window

Two-flavor quark matter (2QM) must be unstable :

$E/A > 930$ MeV (Fe binding energy)

Three-flavor quark matter (SM) must be stable:

$E/A \leq 930$MeV

From microscopic physics
(quantum and nuclear phys.)
to macroscopic properties
(astronomical observations)

Equation of state → **hydrostatic equilibrium**

↖ ↓

stellar properties

Free Fermi gas

$$\mathcal{L}_0 = \bar{\psi}(i\gamma^\mu \partial_\mu - m)\psi$$

$$\downarrow$$

$$\partial_\mu \left(\frac{\partial \mathcal{L}}{\partial(\partial_\mu \psi)} \right) - \frac{\partial \mathcal{L}}{\partial \psi} = 0 \quad \longrightarrow \quad (i\gamma^\mu \partial_\mu - m)\psi = 0$$

$$T_{\mu\nu} = -g_{\mu\nu}\mathcal{L} + \partial_\nu \psi \left(\frac{\partial \mathcal{L}}{\partial(\partial^\mu \psi)} \right)$$

$$\downarrow$$

$$\mathcal{E} =< T_{00} >, \quad p = \frac{1}{3} < T_{ii} >$$

Free Fermi gas

$$\mathcal{E} = \frac{\gamma}{2\pi^2}\int_0^{k_F} \mathbf{k}^2 dk \sqrt{\mathbf{k}^2 + M^2}$$

$$p = \frac{\gamma}{6\pi^2}\int_0^{k_F} dk \frac{\mathbf{k}^4}{\sqrt{\mathbf{k}^2 + M^2}}$$

MIT Bag Model

$$\mathcal{E} = \frac{6}{2\pi^2}\int_0^{k_F} \mathbf{k}^2 dk \sqrt{\mathbf{k}^2 + M^2} + Bag$$

$$p = \frac{6}{6\pi^2}\int_0^{k_F} dk \frac{\mathbf{k}^4}{\sqrt{\mathbf{k}^2 + M^2}} - Bag$$

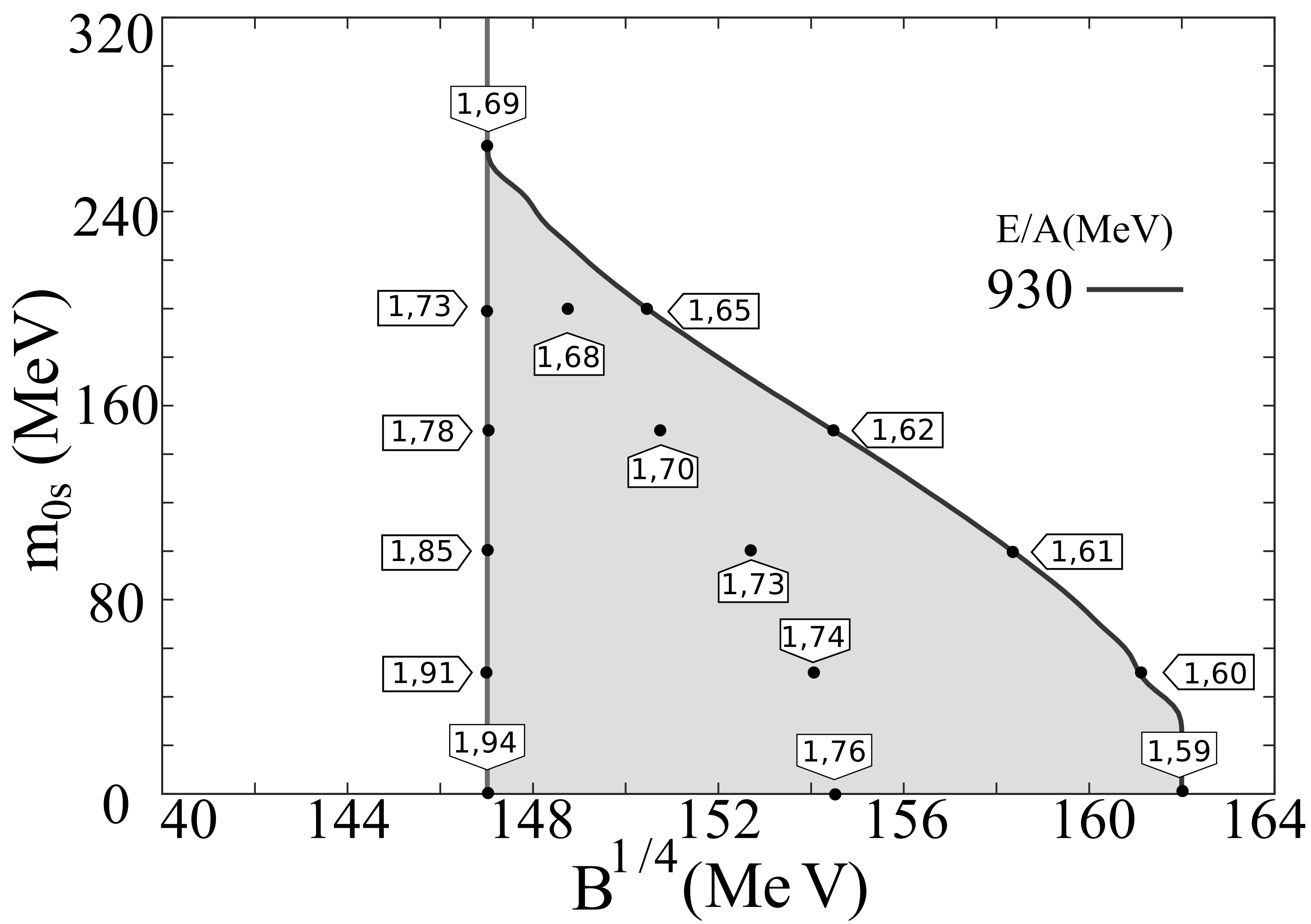
Charge neutrality

$$\frac{2}{3}\rho_u - \frac{1}{3}\rho_d - \frac{1}{3}\rho_s - \rho_e = 0$$

Chemical equilibrium

$$\mu_u^* + \mu_e = \mu_d^* = \mu_s^*$$

Quark Stars - MIT Bag Model



J.R. Torres and DPM, Europhysics Letters,101 (2013) 42003

Density dependent mass quark model

$$m_i = m_{i0} + m_I \equiv m_{i0} + \frac{D}{\rho_b^{1/3}} + C\rho_b^{1/3}$$

$$\rho_b = \frac{1}{3}\sum_i \rho_i, \quad \rho_i = \frac{g_i \nu_i^3}{6\pi^2}, \quad g_i = 6$$

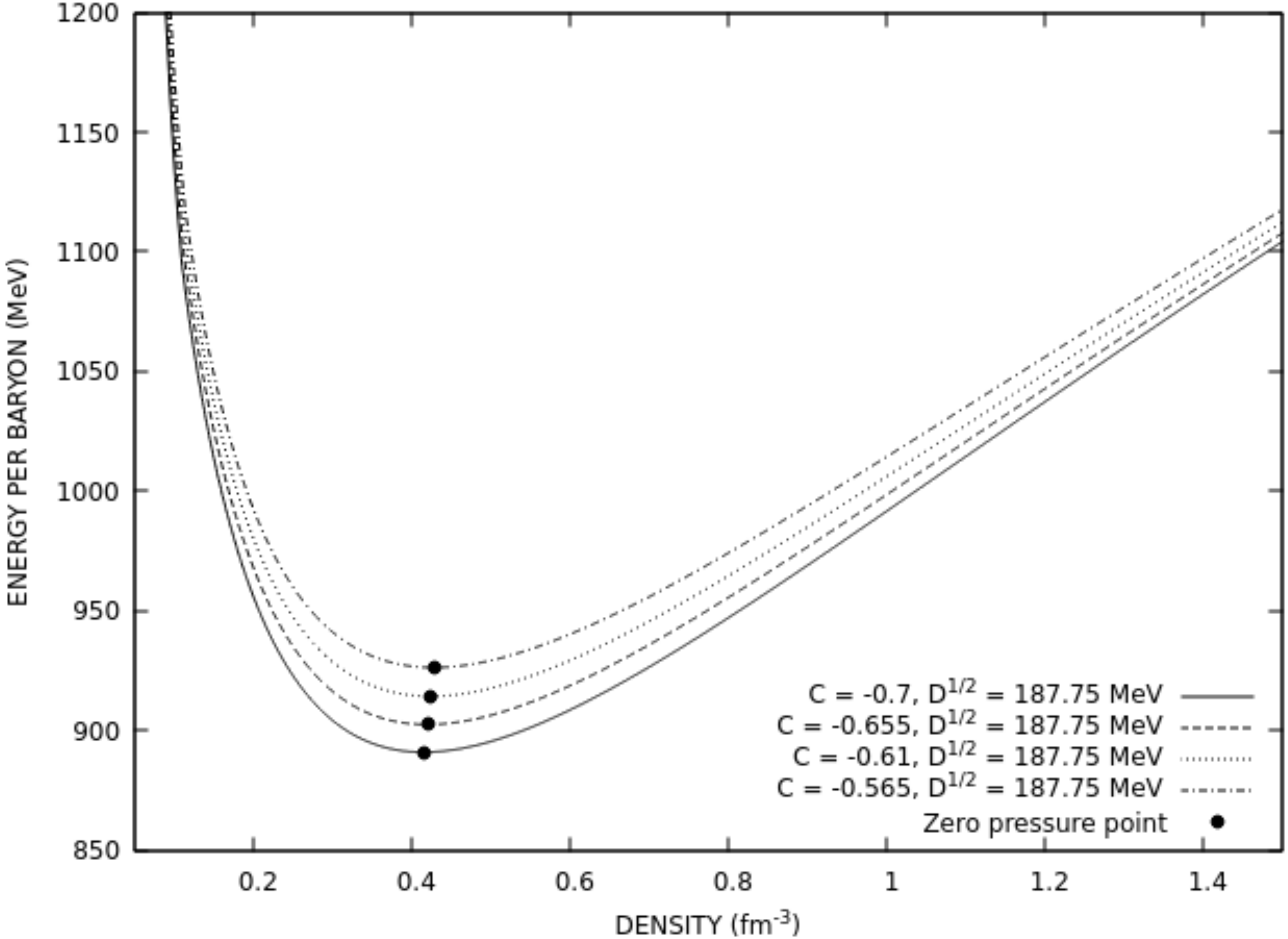
$$\nu_i = \sqrt{\mu_i^{*2} - m_i^2}$$

$$\mathcal{E} = \Omega_0 - \sum_i \mu_i^* \frac{\partial \Omega_0}{\partial \mu_i^*}$$

$$p = -\Omega_0 + \sum_{i,j} \frac{\partial \Omega_0}{\partial m_j} n_i \frac{\partial m_j}{\partial \rho_i}$$

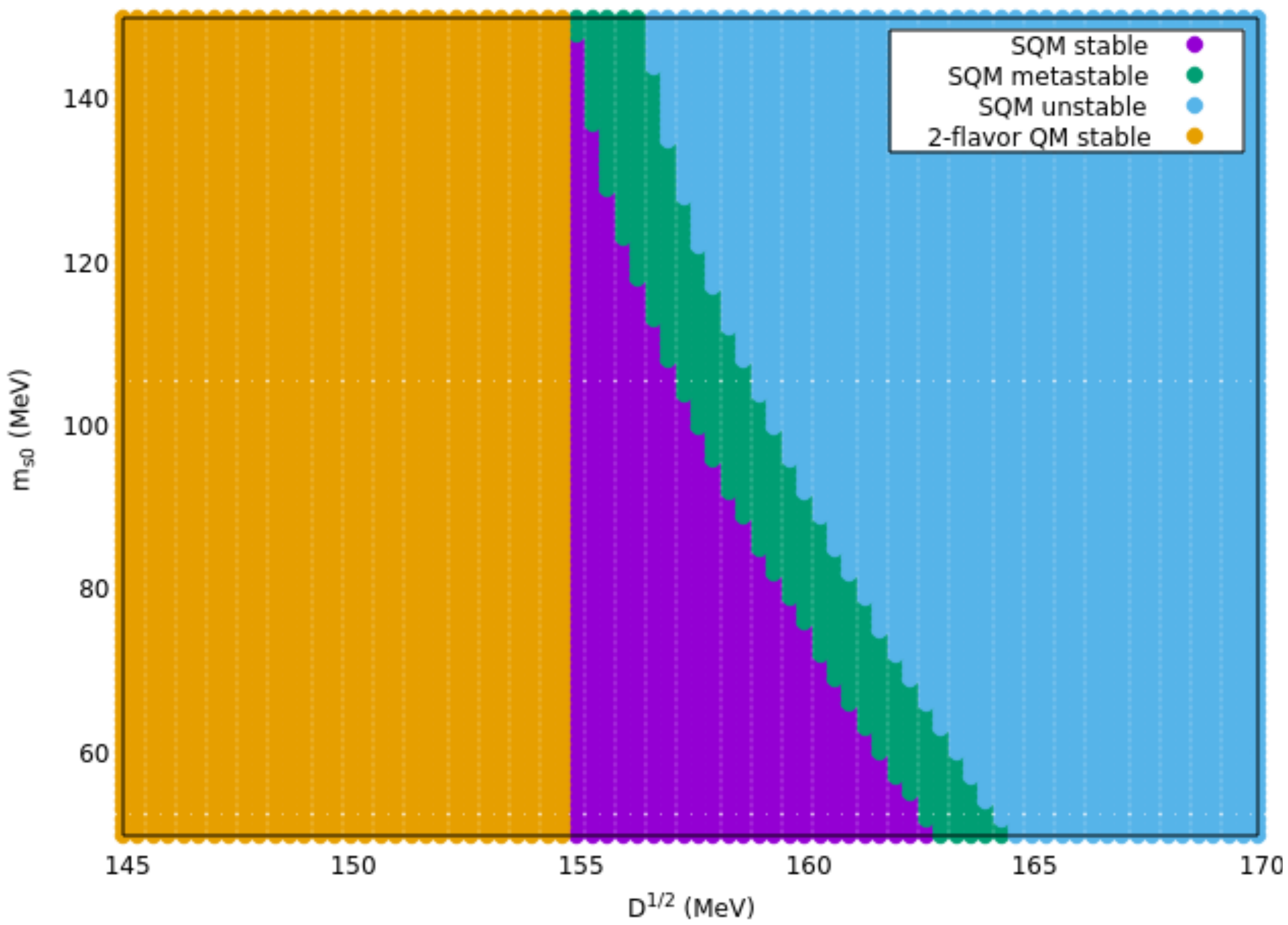
$$\Omega_0 = -\sum_i \frac{g_i}{24\pi^2} \left[\mu_i^* \nu_i \left(\nu_i^2 - \frac{3}{2} m_i^2 \right) + \frac{3}{2} m_i^4 \ln \frac{\mu_i^* + \nu_i}{m_i} \right]$$

$$\mu_i = \mu_i^* + \frac{1}{3} \frac{\partial m_I}{\partial n_b} \frac{\partial \Omega_0}{\partial m_I}$$

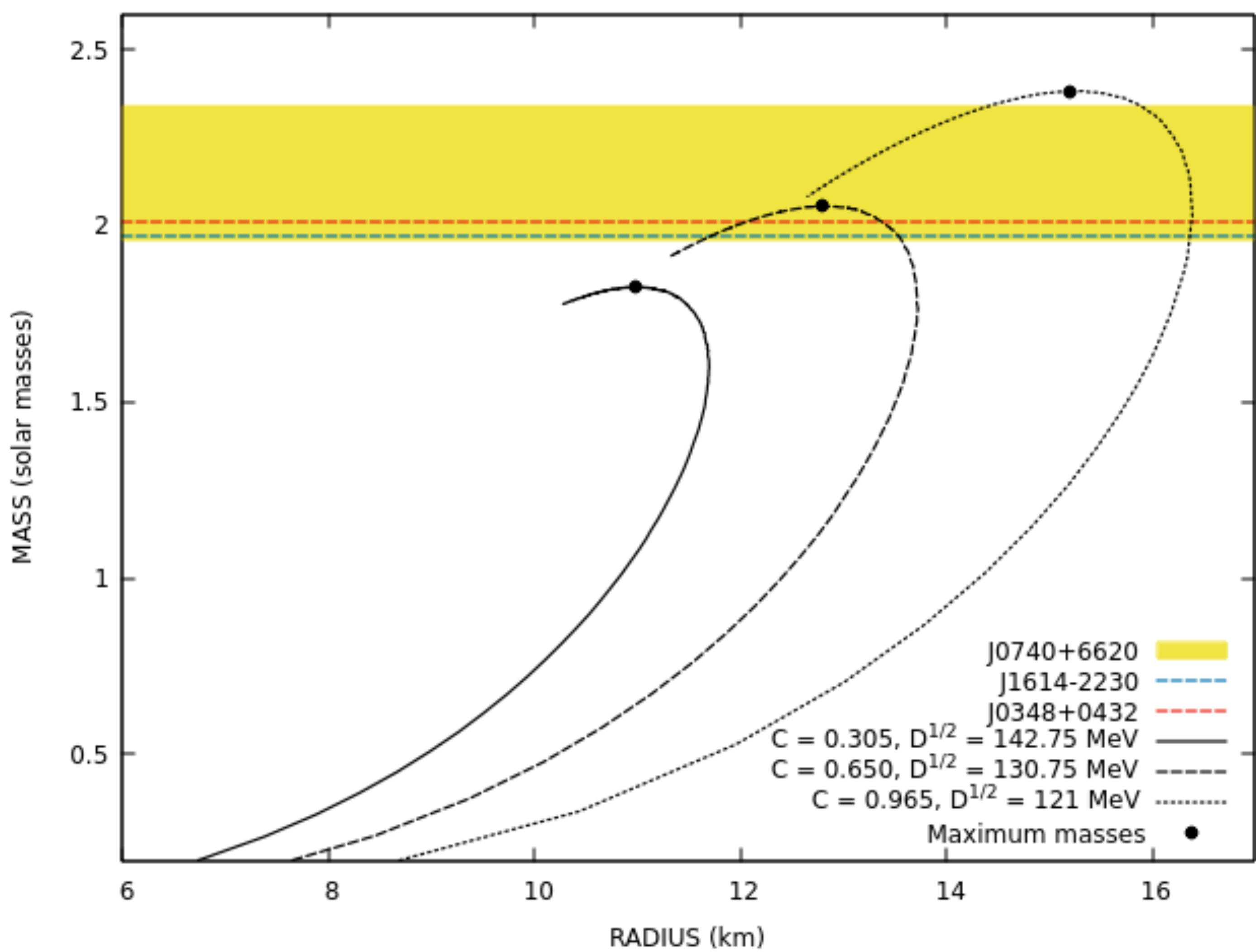


ENERGY PER BARYON (MeV)
1200
1150
1100
1050
1000
950
900
850
0.2
0.4
0.6
0.8
1
1.2
1.4
DENSITY (fm-3)
C = -0.7, D1/2 = 187.75 MeV
C = -0.655, D1/2 = 187.75 MeV
C = -0.61, D1/2 = 187.75 MeV
C = -0.565, D1/2 = 187.75 MeV
Zero pressure point

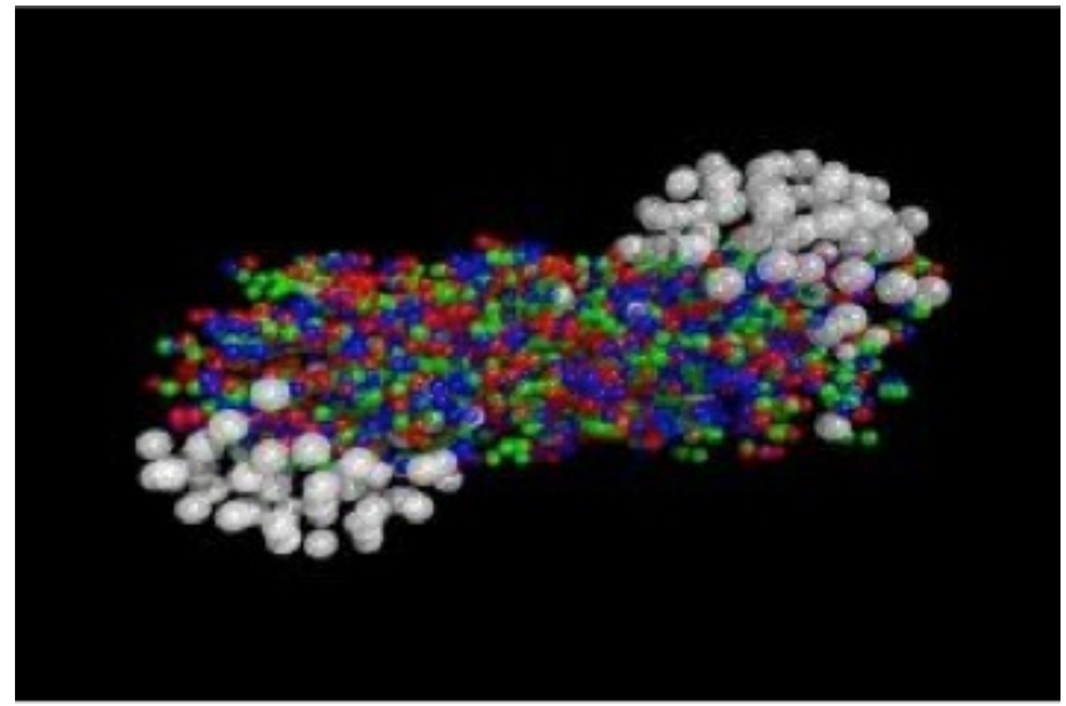
Quark Stars - DDQM



Betânia C. Backes, E. Hafemann, I. Marzola and DPM, J.Phys.G48, 055104 (2021)



Motivation: why magnetic fields?



Magnetars - $eB \simeq 0.5 m^2_\pi$

$m^2_\pi \simeq 3.5 \times 10^{18}$ G

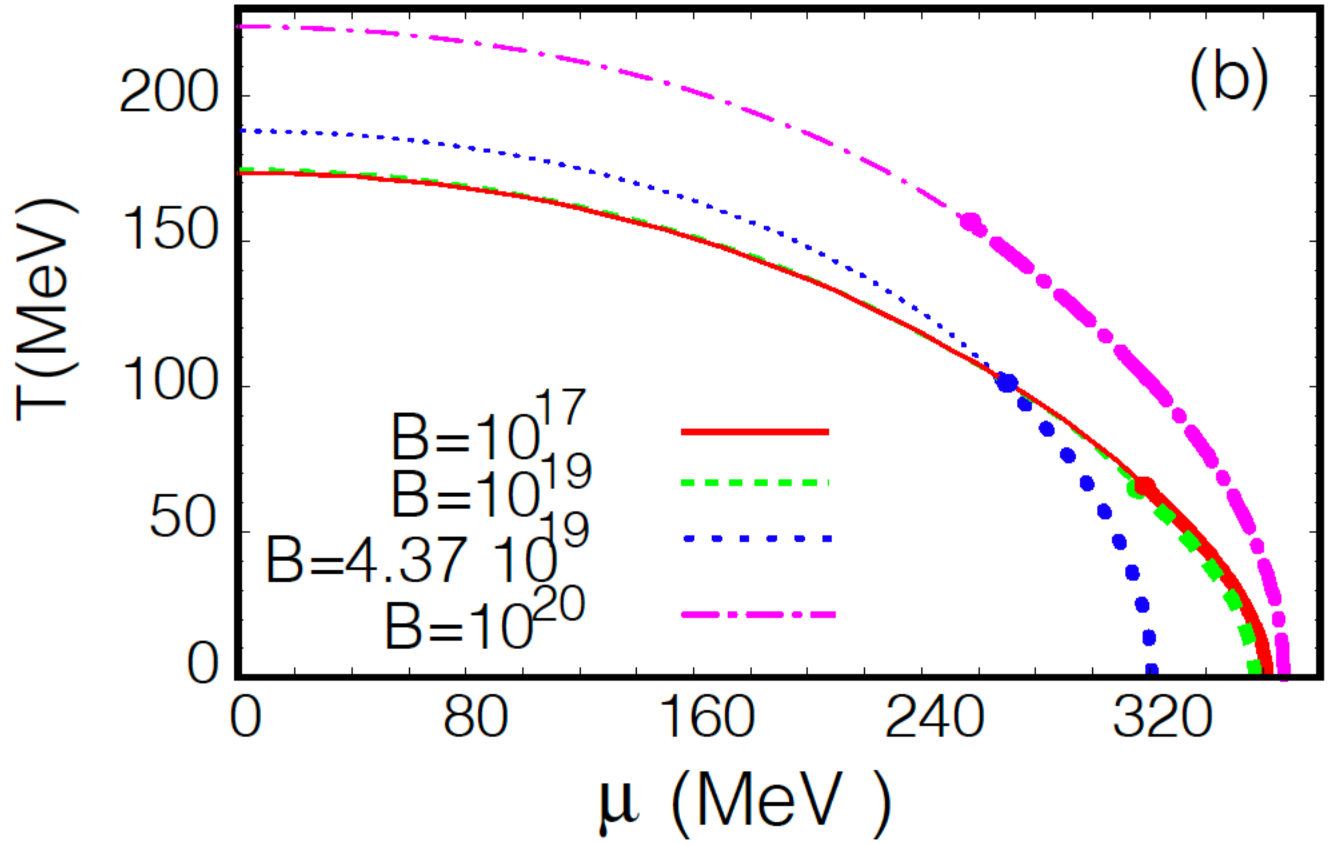
Non-central HIC - $eB \simeq 5 - 15 m^2_\pi$

Early Universe - $eB \simeq 30 m^2_\pi$

in natural units: $eB = 1\ \mathrm{GeV}^2 \quad B = 1.69 \times 10^{20}\mathrm{G}$

Heaviside-Lorentz, Gaussian and natural units lead to different conversions!

QCD Phase Diagram - NJL model



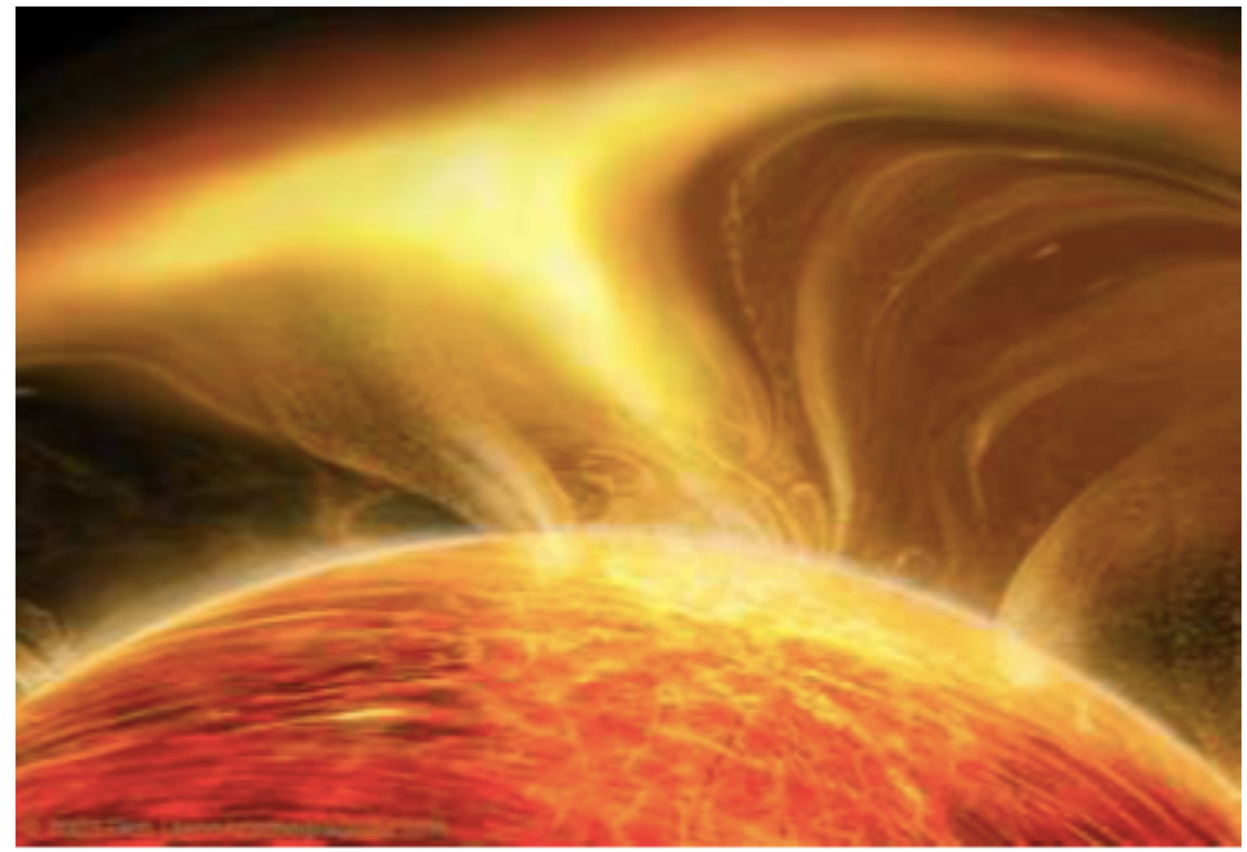
T_c decreases at high μ; size of 1^{st} order line increases with B;
T_{pc} (cross-over) increases at $\mu = 0$

S.S. Avancini, D.P. Menezes, M.B. Pinto and C. Providência; Phys. Rev. D 85, 091901(R) (2012).

Pulsars x Magnetars

Crab nebula pulsar/ Chandra

$$B = 10^{12}\ G$$

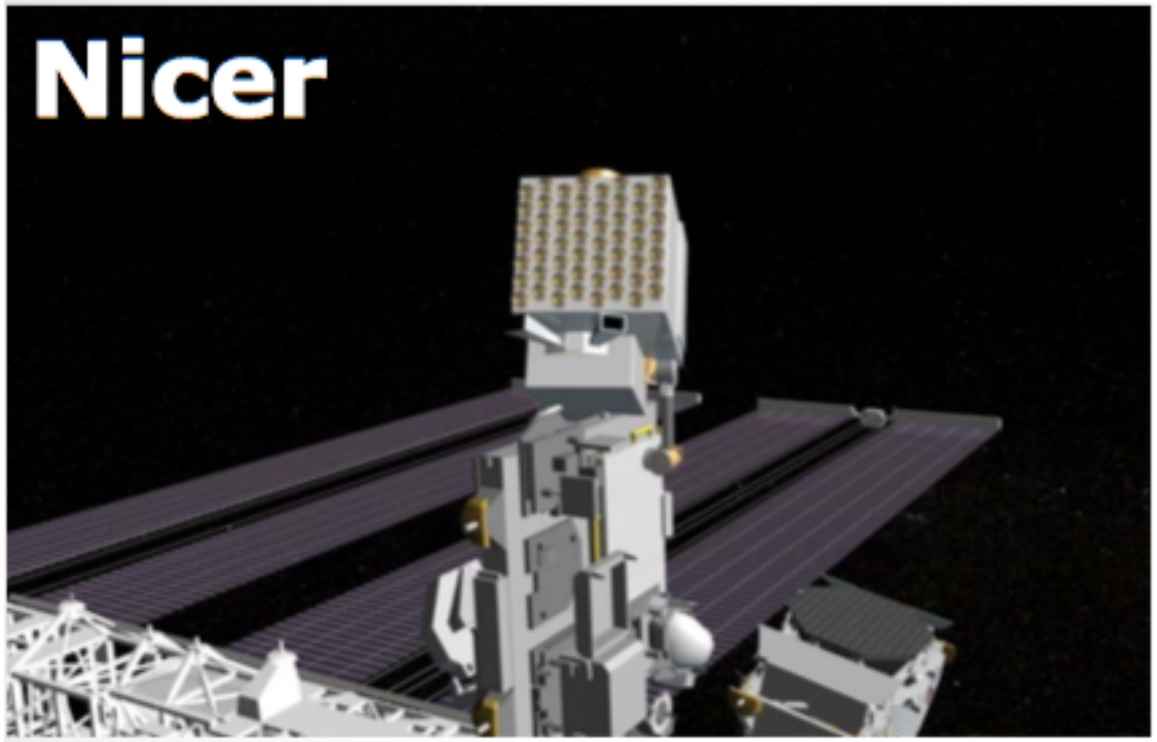


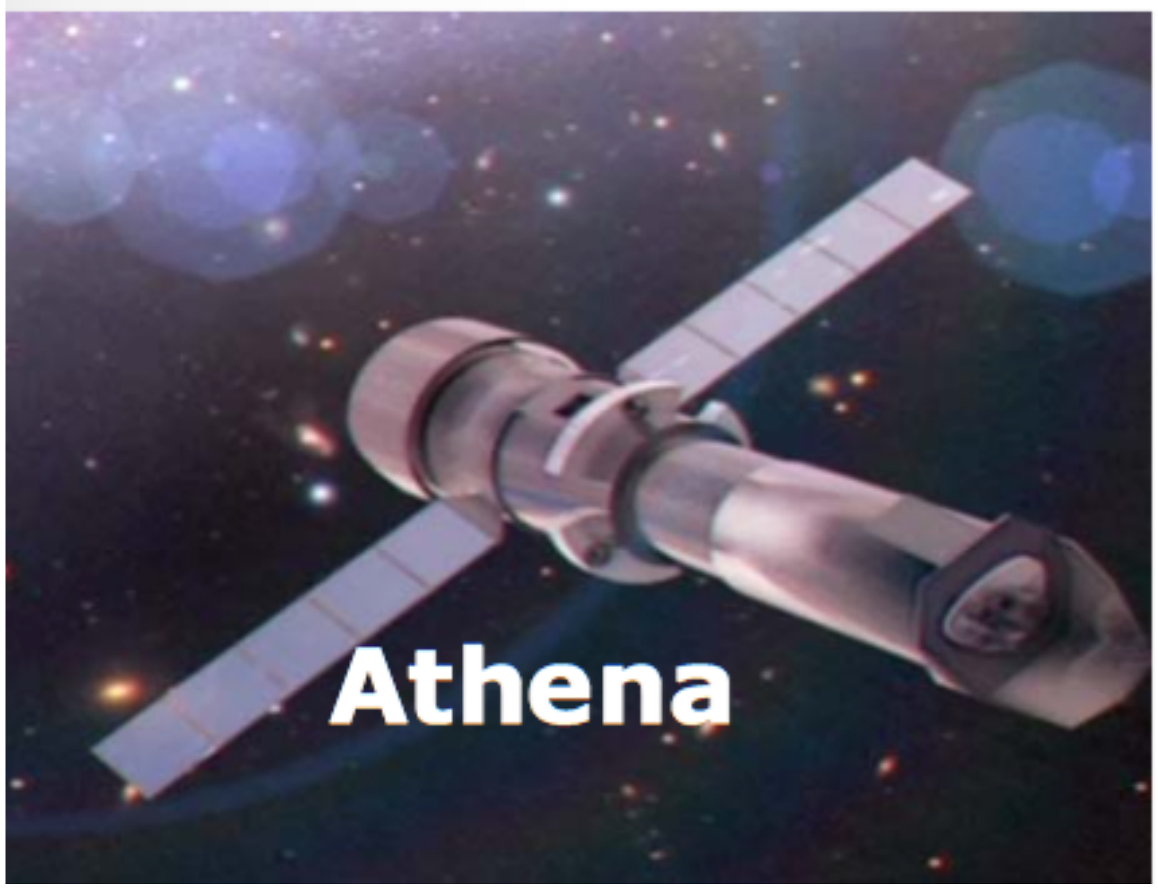
Just my imagination

$$B = 10^{15}\ G$$

magnetic field at the surface

NS interior composition explorer - 06/2017





Advanced telescope for high energy astrophysics to be launched in 2030

Main NS manifestations:

$$M = M_{\odot} \simeq 10^{30}\ Kg$$

$$R \simeq 10 Km$$

$$\rho = M/R^3 \simeq 10^{18} Kg/l$$

- Pulsars - powered by rotation energy (1900 observed in radio-frequency)

- Accreting X-Ray Binaries powered by gravitational energy rotation periods 0.0015-1000 s)

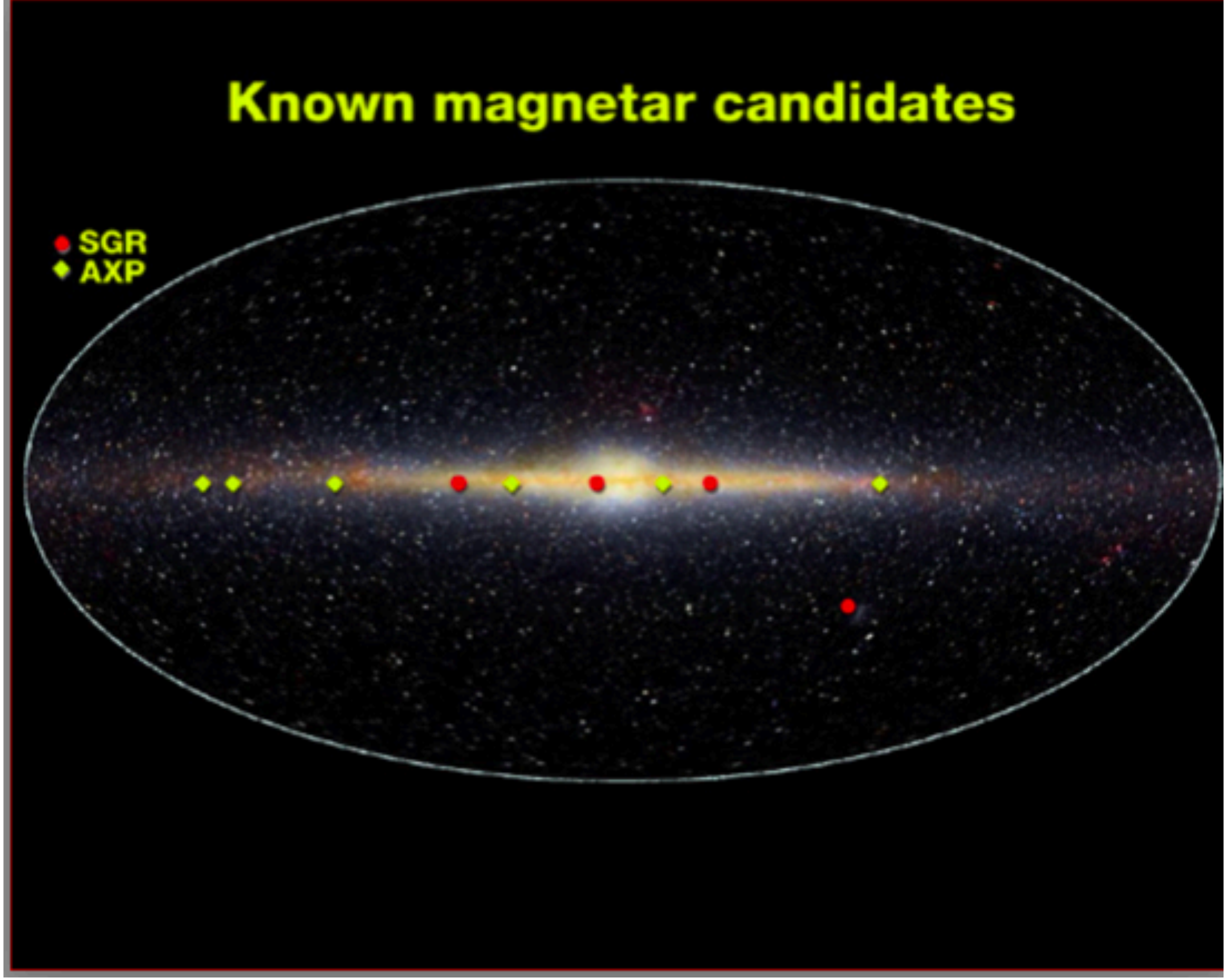
Magnetars don't fit into these categories! They are normally isolated NS whose main power source is the magnetic field.

There are 2 classes of magnetars (29):

http://www.physics.mcgill.ca/~pulsar/magnetar/main.html

- Soft gamma-ray repeaters (discovered in 1979 as transient X-ray sources and giant flares - 11 confirmed, 4 candidates);

- Anomalous X-ray pulsars (identified in 1990 as a class of persistent
- X-ray with no sign of a binary companion - 12 confirmed,
- 2 candidates);



Courtesy picture: C. Kouveliotou and Chengmin Zhang

The formalism - hadronic matter - chaotic EoS

Luiz Laércio Lopes and DPM, JCAP 08, 002 (2015)

$$\mathcal{L}_{QHD} = \sum_b \bar{\psi}_b \Big[\gamma^\mu (i\partial_\mu - e_b A_\mu - g_{b,\omega}\omega_\mu - g_{b,\rho}\frac{1}{2}\vec{\tau}\cdot\vec{\rho}_\mu) - (m_b - g_{b,\sigma}\sigma)\Big]\psi_b + \frac{1}{2}m_v^2\omega_\mu\omega^\mu$$
$$+\frac{1}{2}m_\rho^2\vec{\rho}_\mu\cdot\vec{\rho}^{\,\mu} + \frac{1}{2}(\partial_\mu\sigma\partial^\mu\sigma - m_s^2\sigma^2) - U(\sigma) - \frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{1}{4}\Omega^{\mu\nu}\Omega_{\mu\nu} - \frac{1}{4}\mathbf{P}^{\mu\nu}\cdot\mathbf{P}_{\mu\nu},$$

$$U(\sigma) = \frac{1}{3!}\kappa\sigma^3 + \frac{1}{4!}\lambda\sigma^4$$

non-linear terms

$$\mathcal{L}_{lep} = \sum_l \bar{\psi}_l[i\gamma^\mu(\partial_\mu - e_l A_\mu) - m_l]\psi_l$$

leptons - free Fermi gas

MFA - Euler-Lagrange - eqs. of motion

$$[\gamma_0(i\partial^0 - g_{b,\omega}\omega_0 - g_{b,\rho}\rho_0) - \gamma_j(i\partial^j - e_b A^j) - M_b^*]\Psi = 0$$

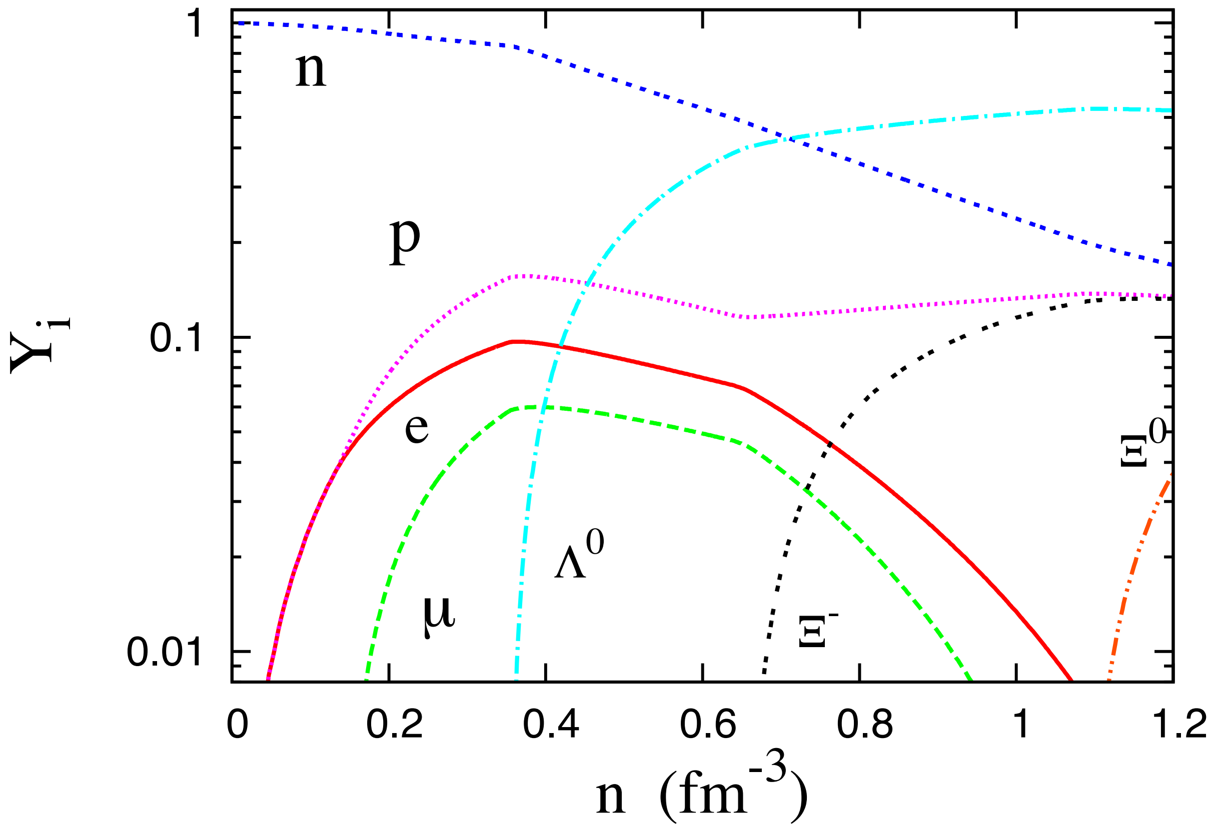
$$M_b^* \doteq m_b - g_{b,\sigma}\sigma_0, \quad A_2 = A_3 = 0; A_1 = -B_0 y$$

$$E_b = \sqrt{k_z^2 + M_b^{*2} + 2\nu|e|B_0} + g_{b,\omega}\omega_0 + g_{B,\rho}\frac{\tau_3}{2}\rho_0, \quad E_l = \sqrt{k_z^2 + m_l^2 + 2\nu|e|B_0}$$

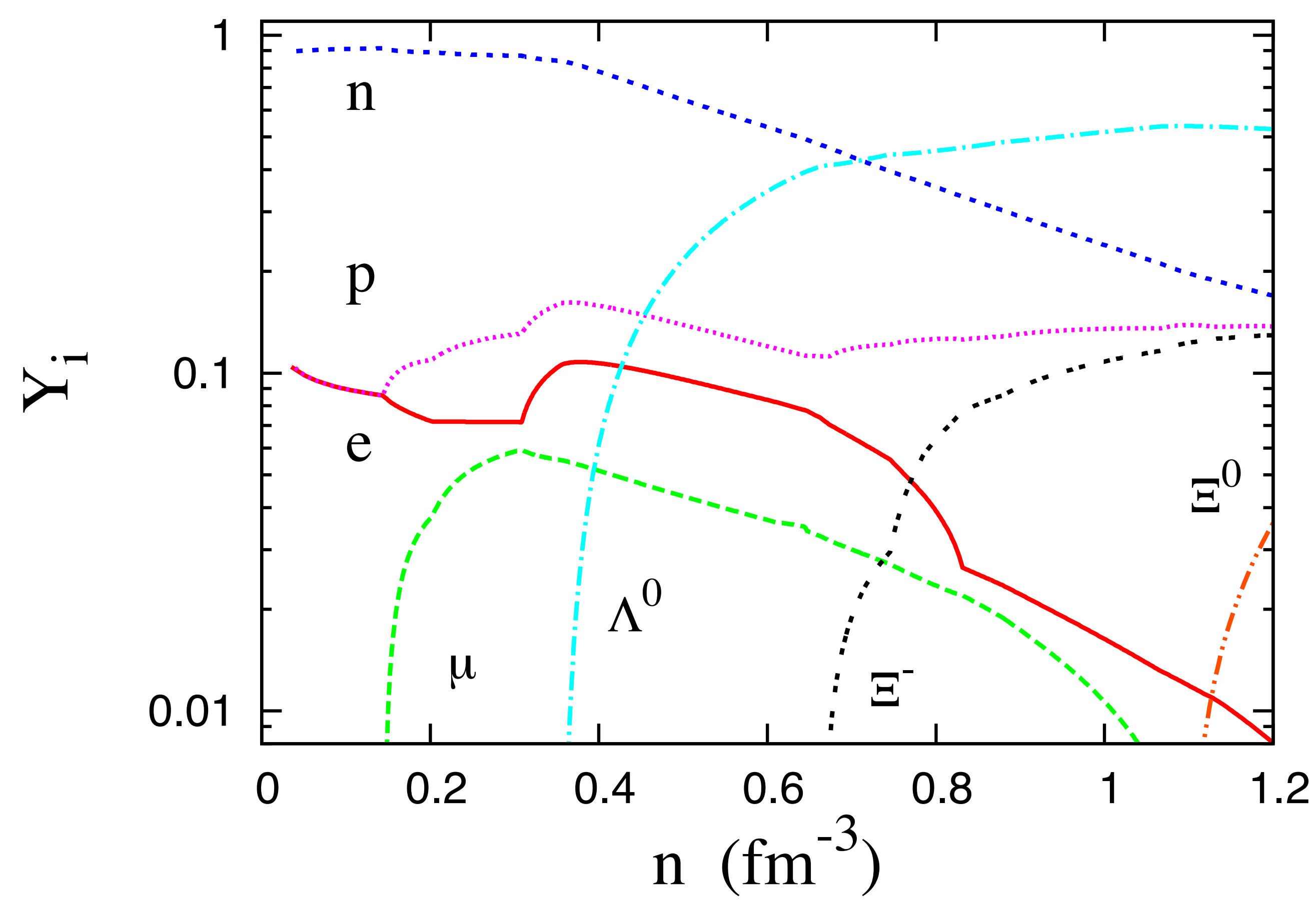
$$\epsilon = \frac{|e|B_0}{2\pi^2}\sum_\nu \eta(\nu)\int_0^{k_f}\sqrt{k_z^2 + M_b^* + 2\nu|e|B_0}dk_z$$

$$\epsilon = \frac{1}{\pi^2}\int_0^{k_f}\sqrt{k^2 + M_b^*}k^2 dk$$

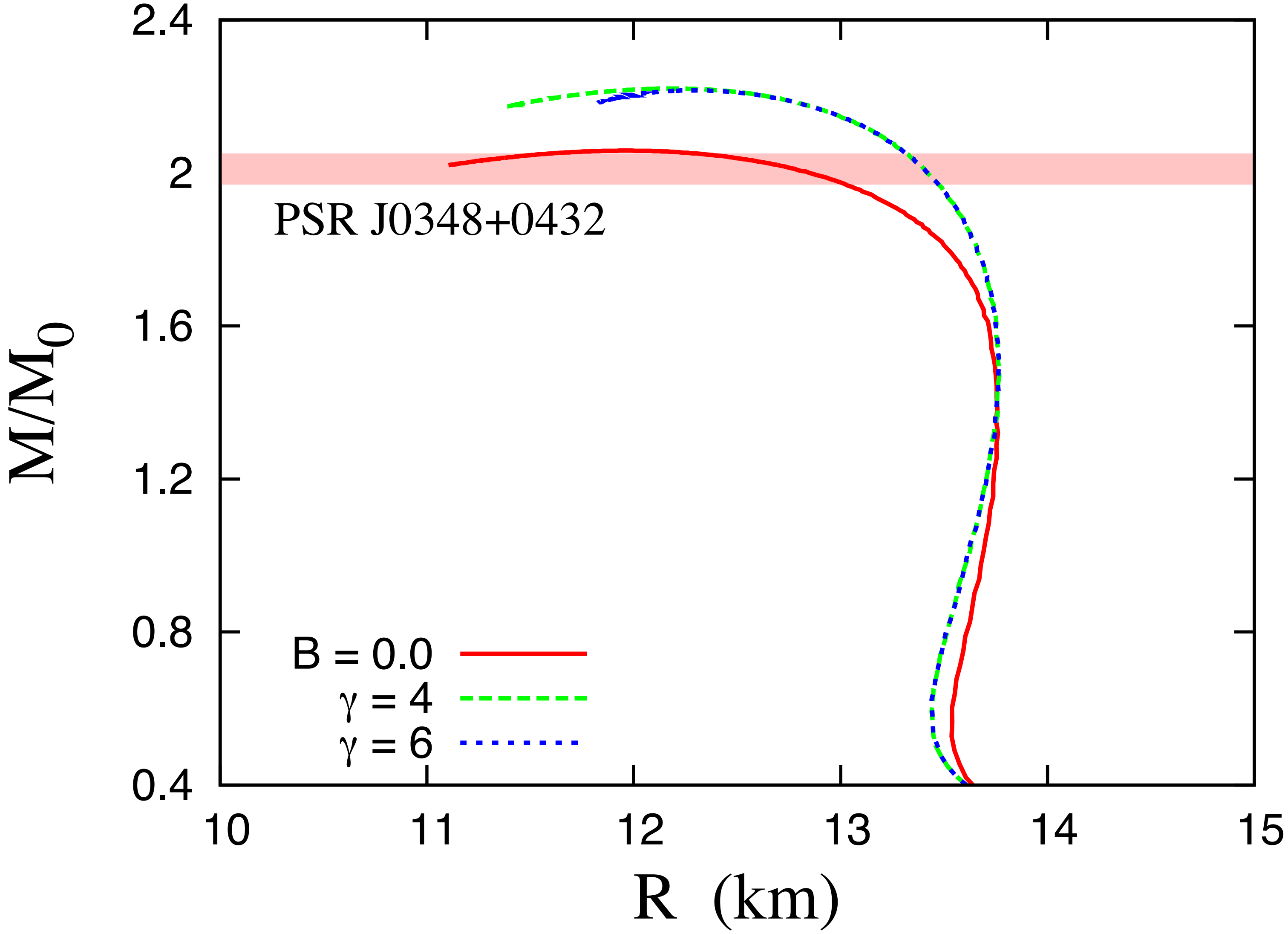
$$\epsilon_m = \frac{1}{2}\left(m_s^2\sigma_0^2 + m_v^2\omega_0^2 + m_\rho^2\rho_0^2\right) + U(\sigma)$$



B=0



$B = 3 \times 10^{18} G$



γ	$M/M_\odot$	$R(km)$	$\epsilon_c\ (Mev/fm^3)$	$B_c\ (\times 10^{18} G)$
$B = 0.0$	2.06	11.96	1122	0.0
4	2.21	12.18	1063	2.84
6	2.21	12.27	1046	2.79

Neutron star oscillations

Before the merging, tidal interactions can excite the fluid modes by resonance;

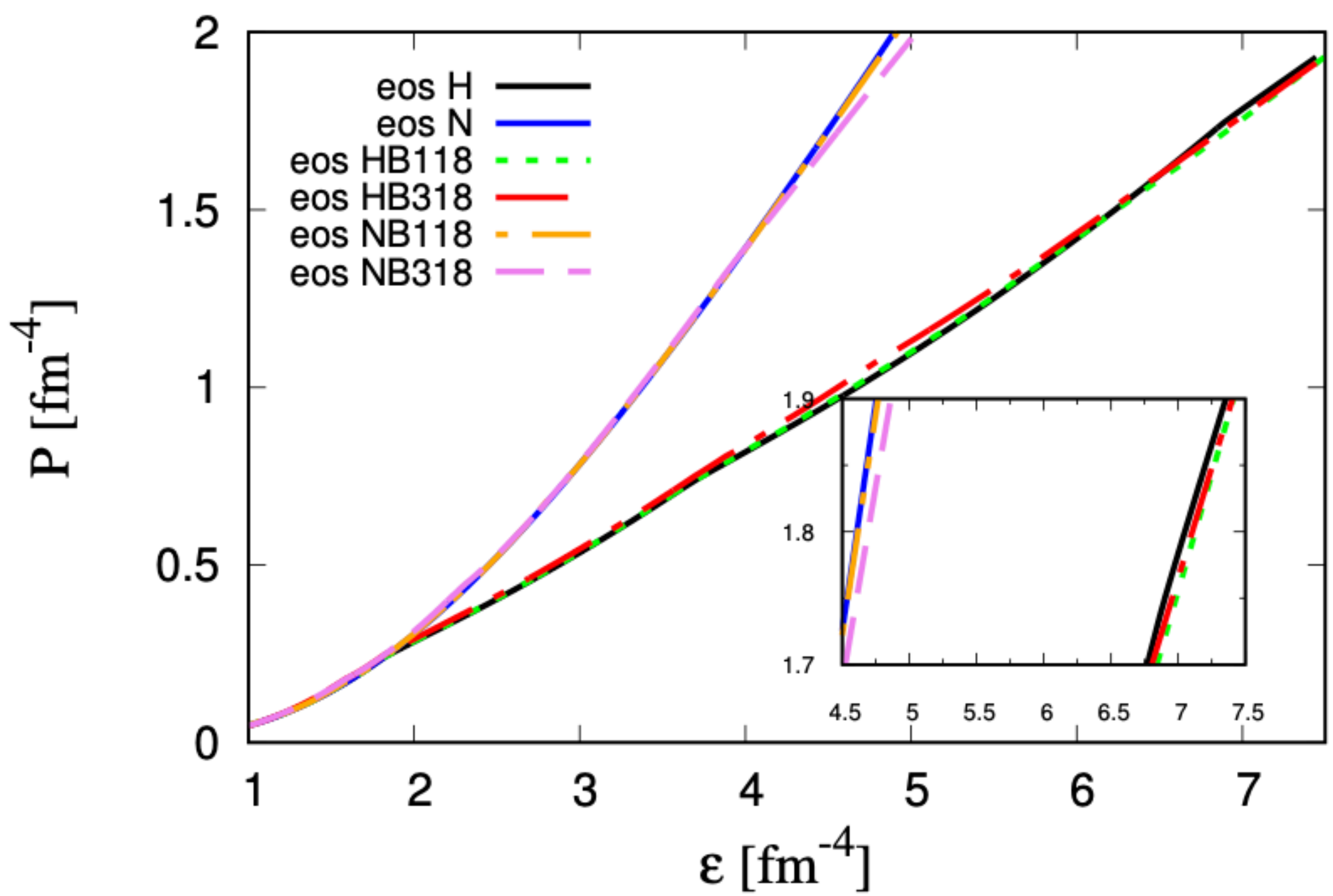
oscillation modes perturb the metric;

quadruple modes dominate the emission of GW;

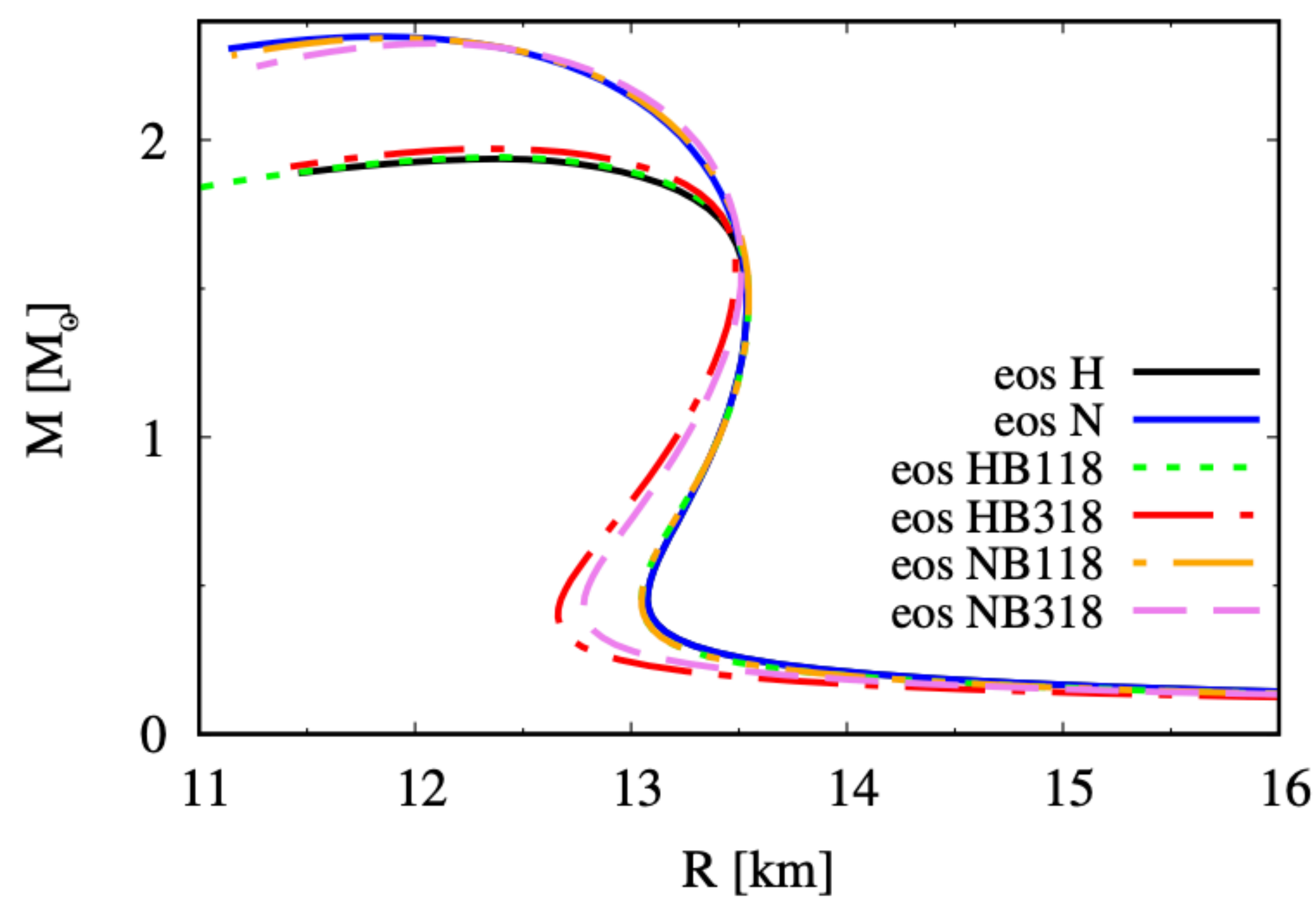
non-radial oscillations can be calculated and their frequency computed;

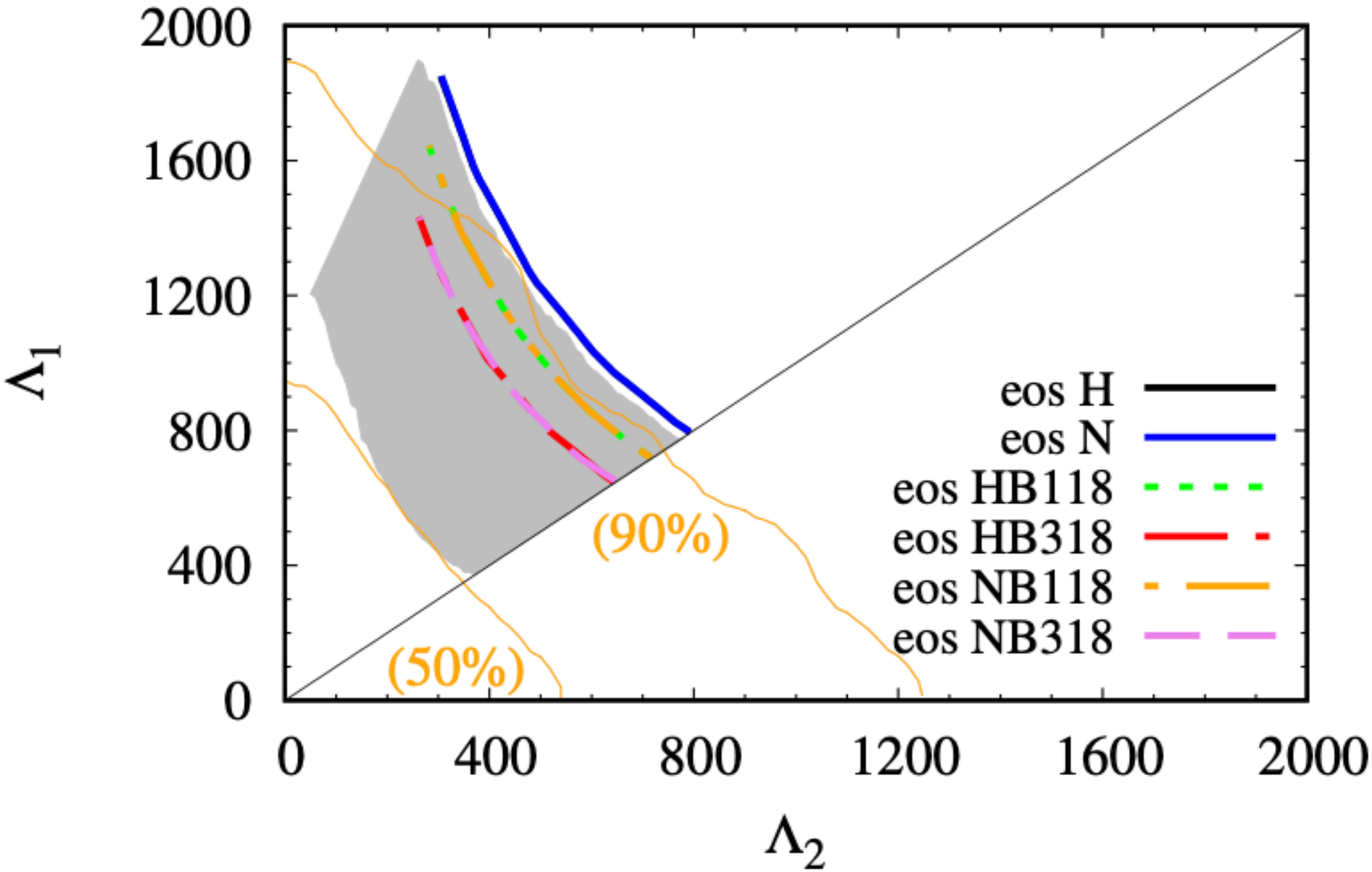
a family of modes can be calculated;

we look at the fundamental mode (around 2 kHz), which are expected to be detected by the Einstein telescope.

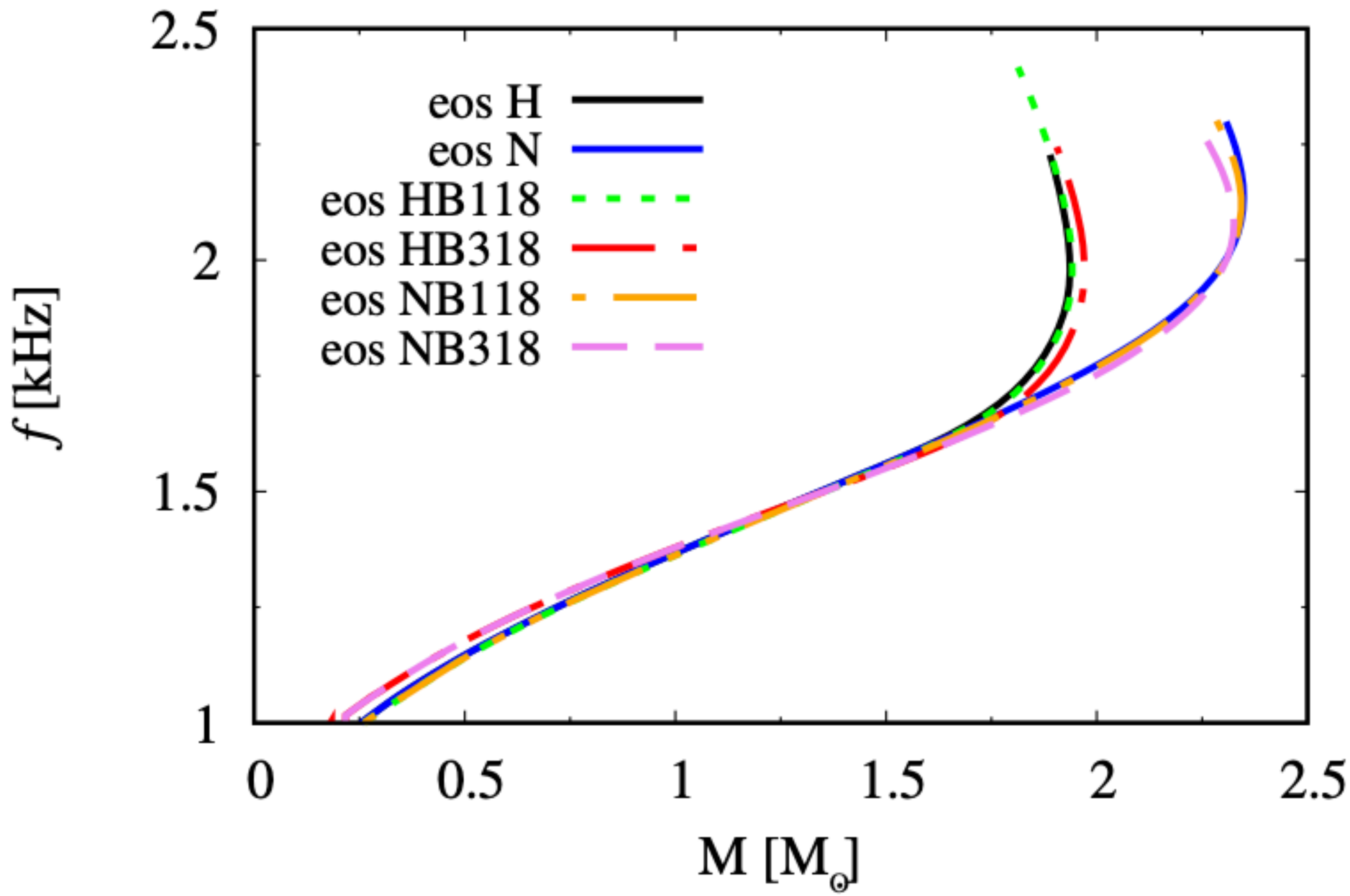


Cesar V. Flores, Luiz L. Lopes, Luis B. Castro and DPM, EPJC 80, 1142 (2020); arXiv:1905.11170





2000
1600
1200
800
400
0
0
400
800
1200
1600
2000
Λ_1
Λ_2
(90%)
(50%)
eos H
eos N
eos HB118
eos HB318
eos NB118
eos NB318



frequencies generated by massive stars are very sensitive to their EOS

f-mode is only sensitive to very strong Bs

Uncertainties concerning EOS to describe magnetars:

Can magnetars be part of binary systems?
How strong is B inside the star?

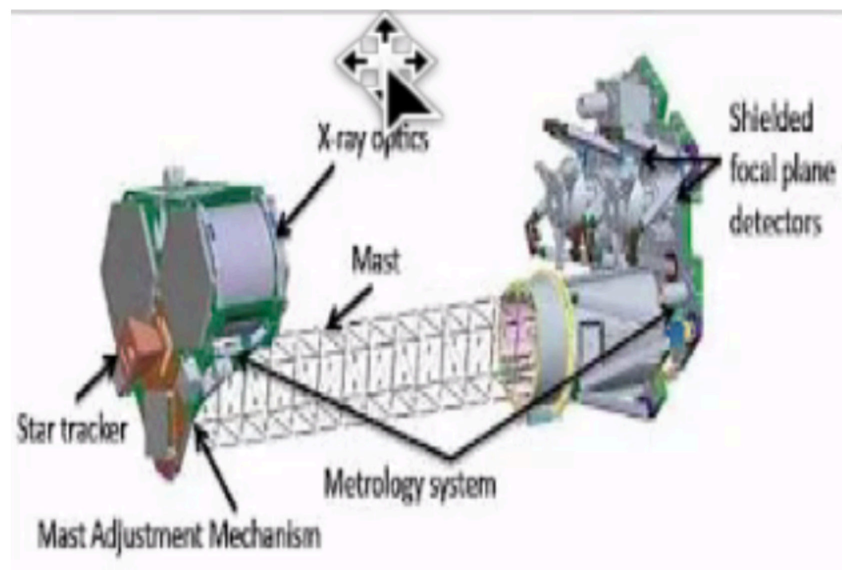
Although low B's do not affect the EOS and the macroscopic properties, they affect the crust-core transition, with many consequences:

- **can explain glitches,**
- **different Love number and tidal polarizabilities.**

density dependent B not really justified, but calculations with LORENE may produce too large B's at the surface and too big crusts.

Space Observatories (X- ray telescopes)

XMM Newton
X-ray multi-mirror mission
European Space Agency
1999-2022
in orbit

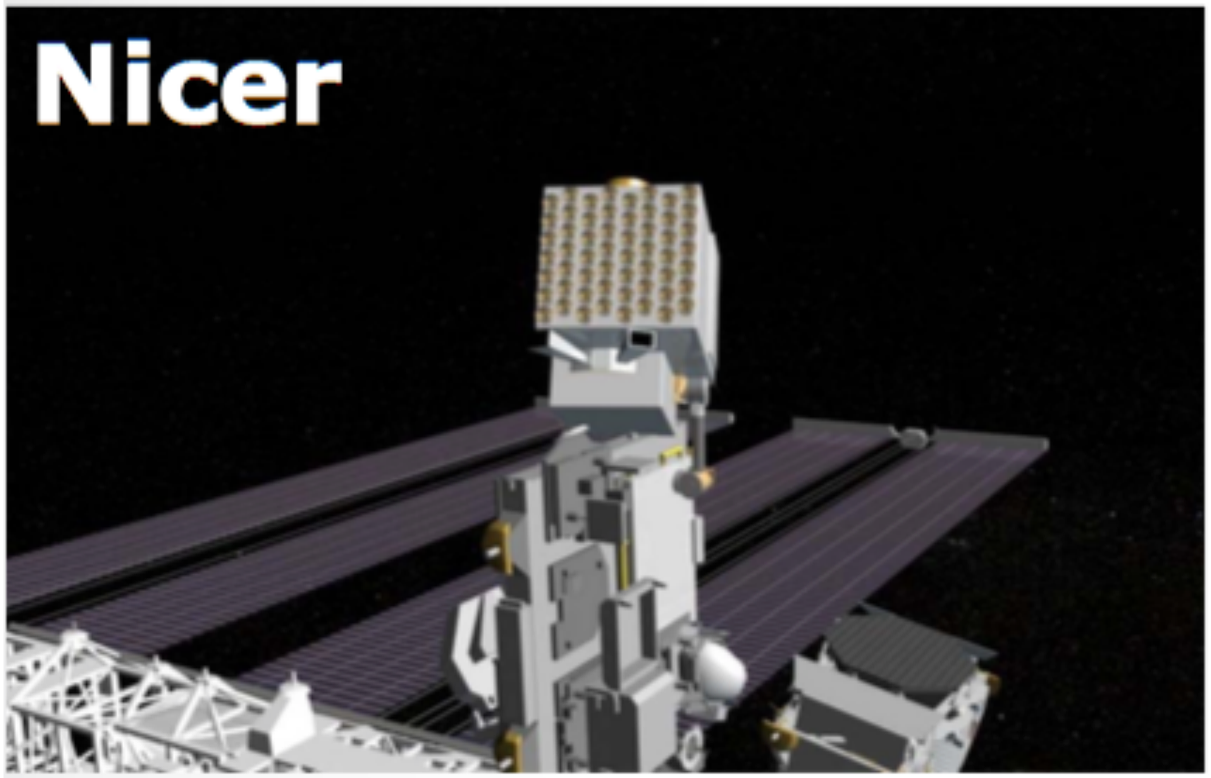


NuSTAR
Nuclear Spectroscopy Telescope Array
NASA - launched in 2012

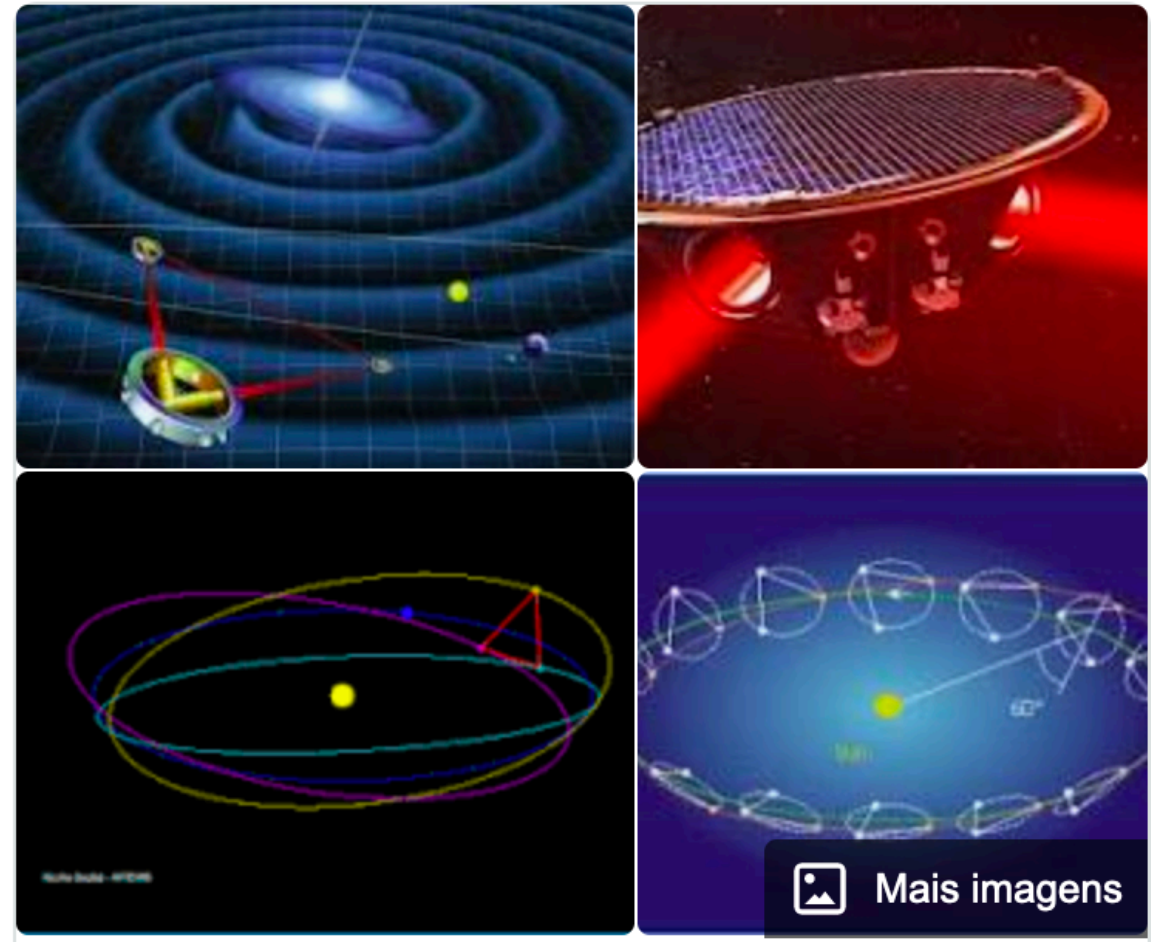
Chandra
Earth-satellite
NASA
1999-2021

The Future ???

2017



2030



Evolved Laser Interferometer Space Antenna

2034

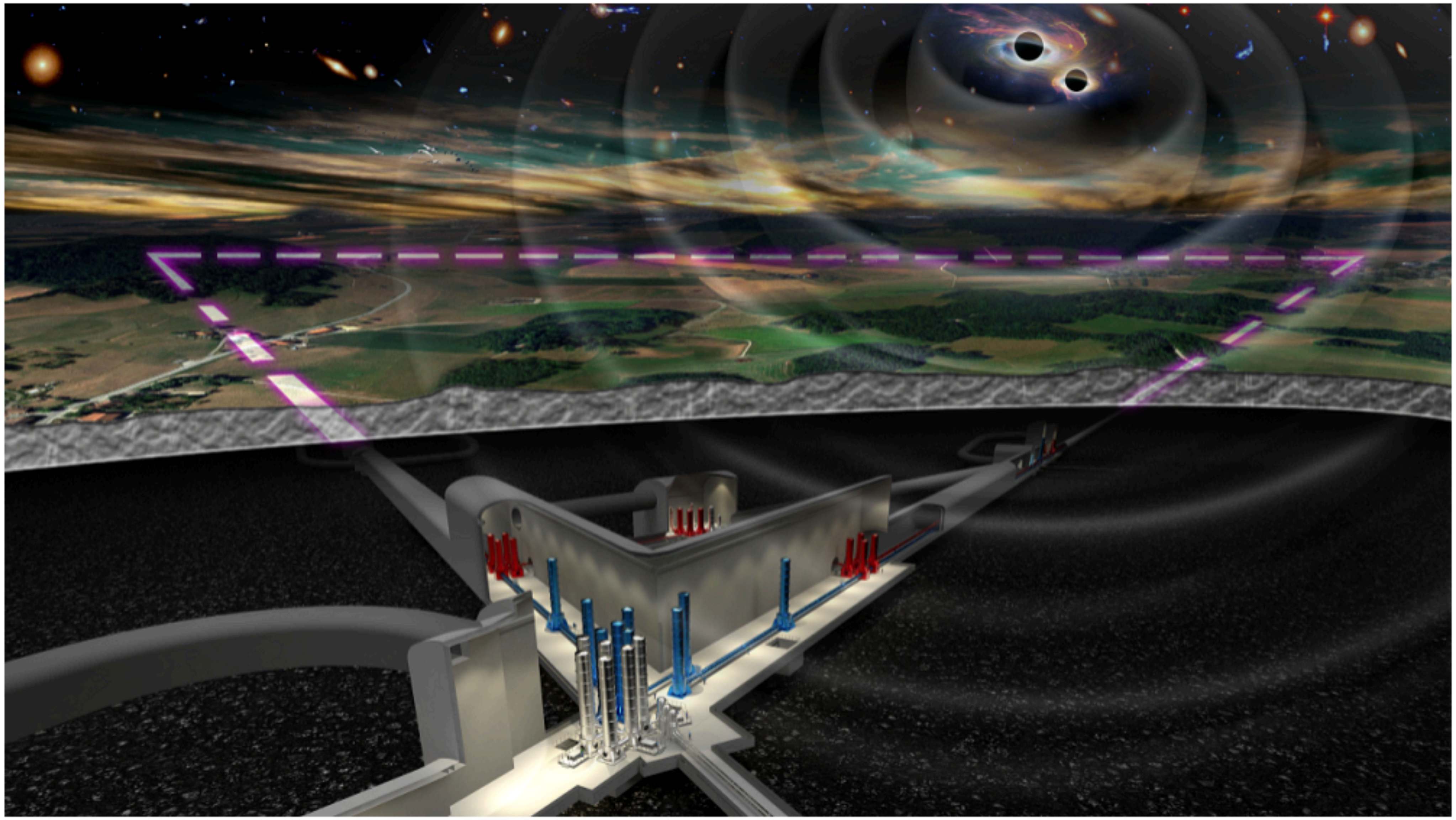
A Evolved Laser Interferometer Space Antenna ou Antena Espacial de Interferômetro a Laser, ou ainda como é conhecida pela abreviação de cada uma de suas primeiras letras, eLISA, é um sistema de três satélites da Agência Espacial Europeia com previsão de lançamento em 2034. Wikipédia

ET EINSTEIN TELESCOPE

The ET (Einstein Telescope) project Web Site

EGO

ET - underground infrastructure - 3rd generation gravitational wave observatory - 2030 ?



Final Remarks

Hadron physics is a very rich field, with many aspects still to be investigated

Different (T, chemical potential) of the QCD phase diagram can be described

In general, it involves multidisciplinary areas (thermodynamics, statistical mechanics, astrophysics,…)

Modelling hadronic matter properly remains a challenge and NS are excellent laboratories

The quest for the holy grail (EOS and a good formalism) continues…

Physics is an empirical science

It is not physics unless it can be tested empirically

It is not proved unless it is verified experimentally

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