PHASE TRANSITIONS INSIDE OF ROTATING NEUTRON STARS

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COLLABORATORS

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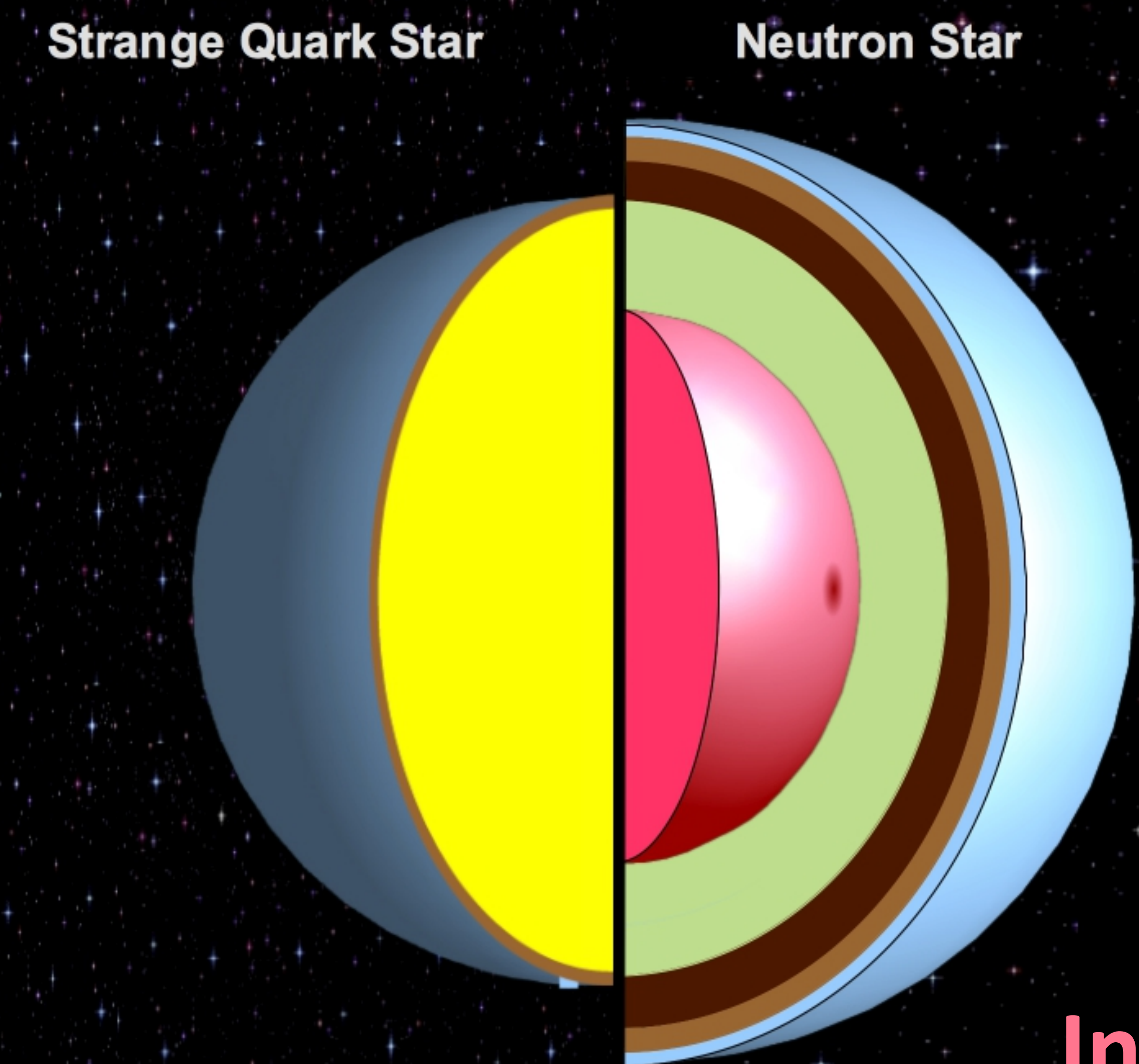
OUTLINE

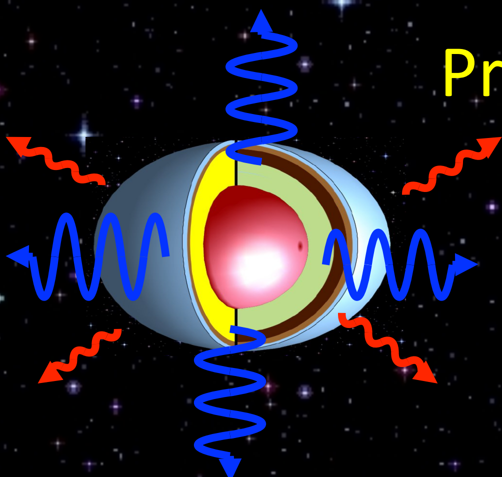
- Introductory remarks concerning rotation
- Rotation-driven particle re-population phenomena
  - Neutron-to-proton ration & Direct Urca process
  - Hyperons
  - Quark-hadron phase transition
- Geometrical structures
  - Transport properties
- Summary



Introductory Remarks

SN Ib, Ic, SN II

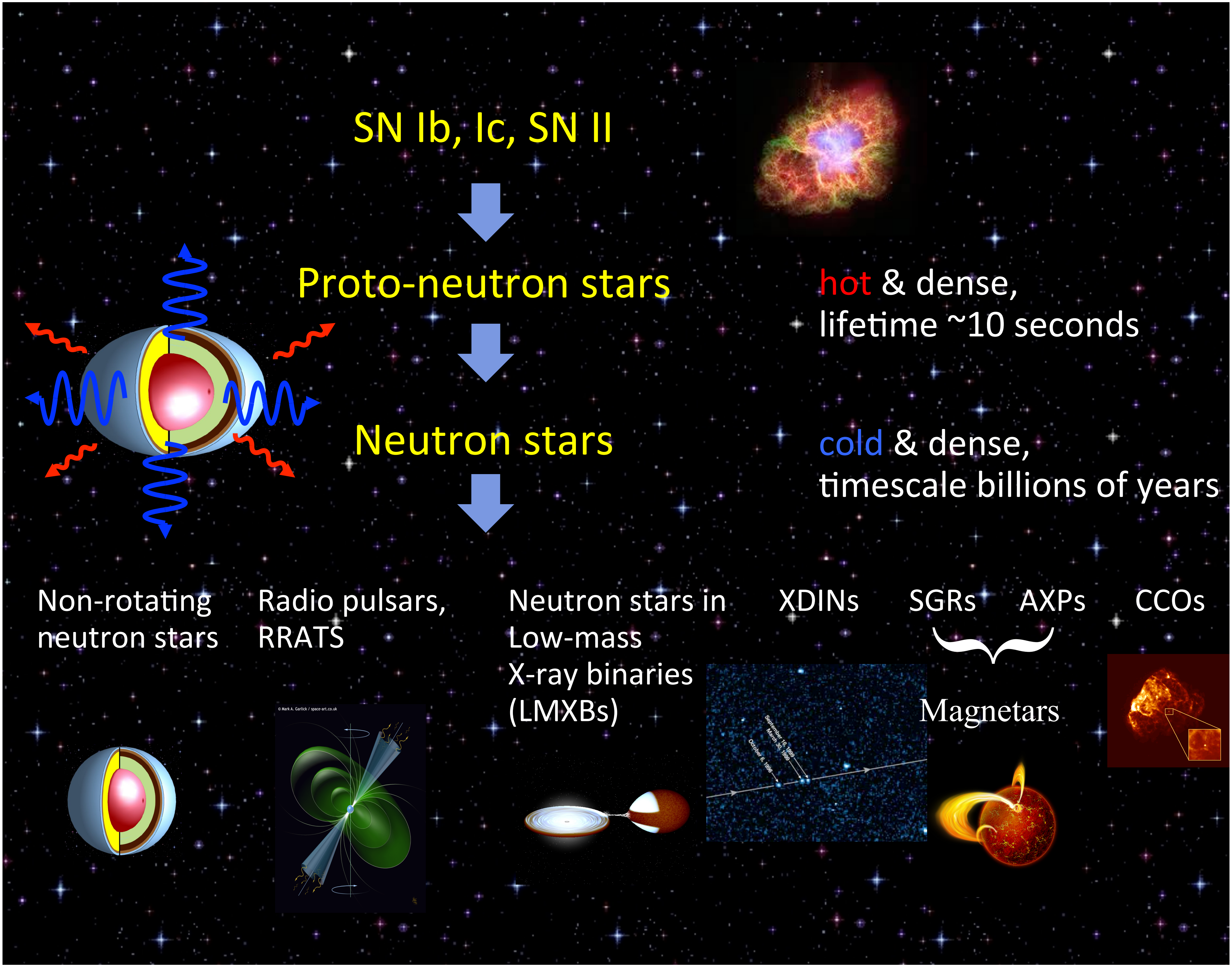
Proto-neutron stars



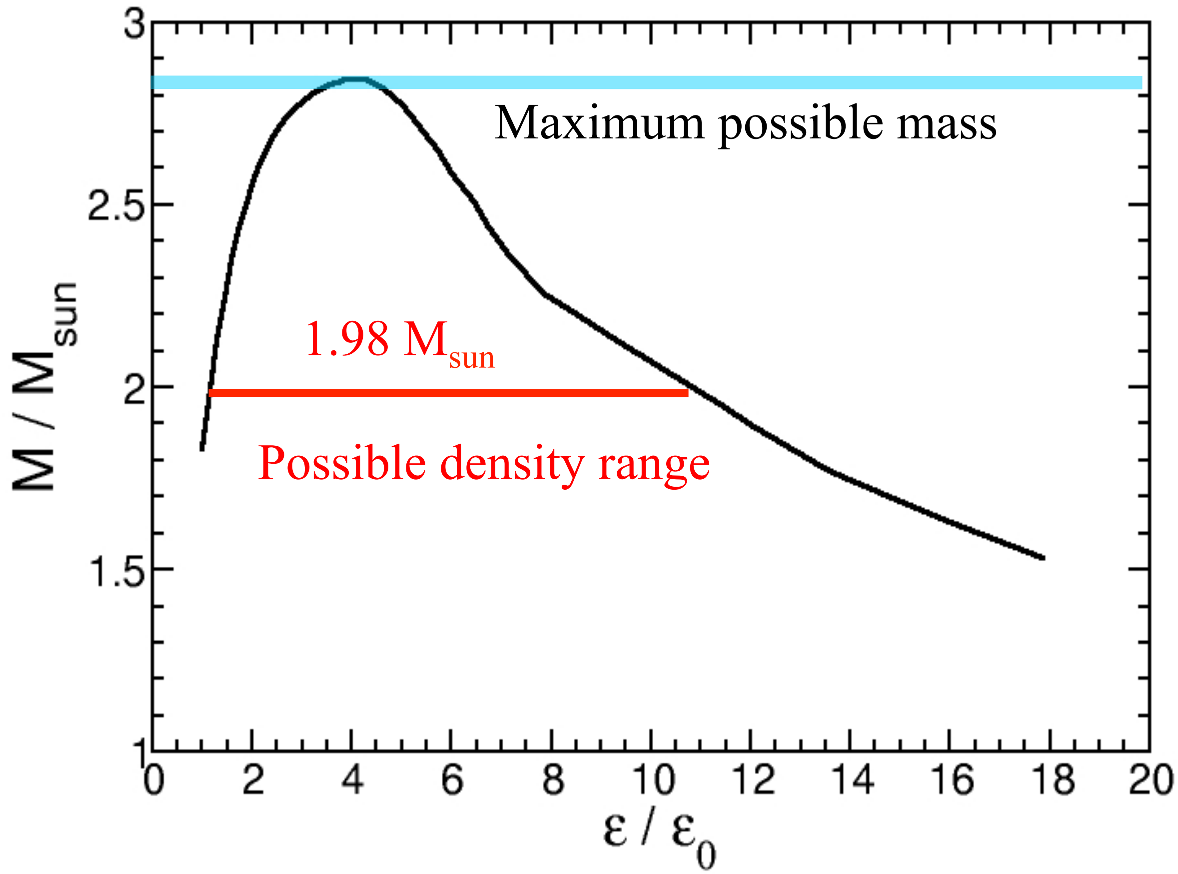
hot & dense,
lifetime ~10 seconds

Neutron stars

cold & dense,
timescale billions of years


SN Ib, Ic, SN II
Proto-neutron stars
hot & dense,
lifetime ~10 seconds
Neutron stars
cold & dense,
timescale billions of years
Non-rotating
neutron stars
Radio pulsars,
RRATS
Neutron stars in
Low-mass
X-ray binaries
(LMXBs)
XDINs
SGRs
AXPs
Magnetars
CCOs

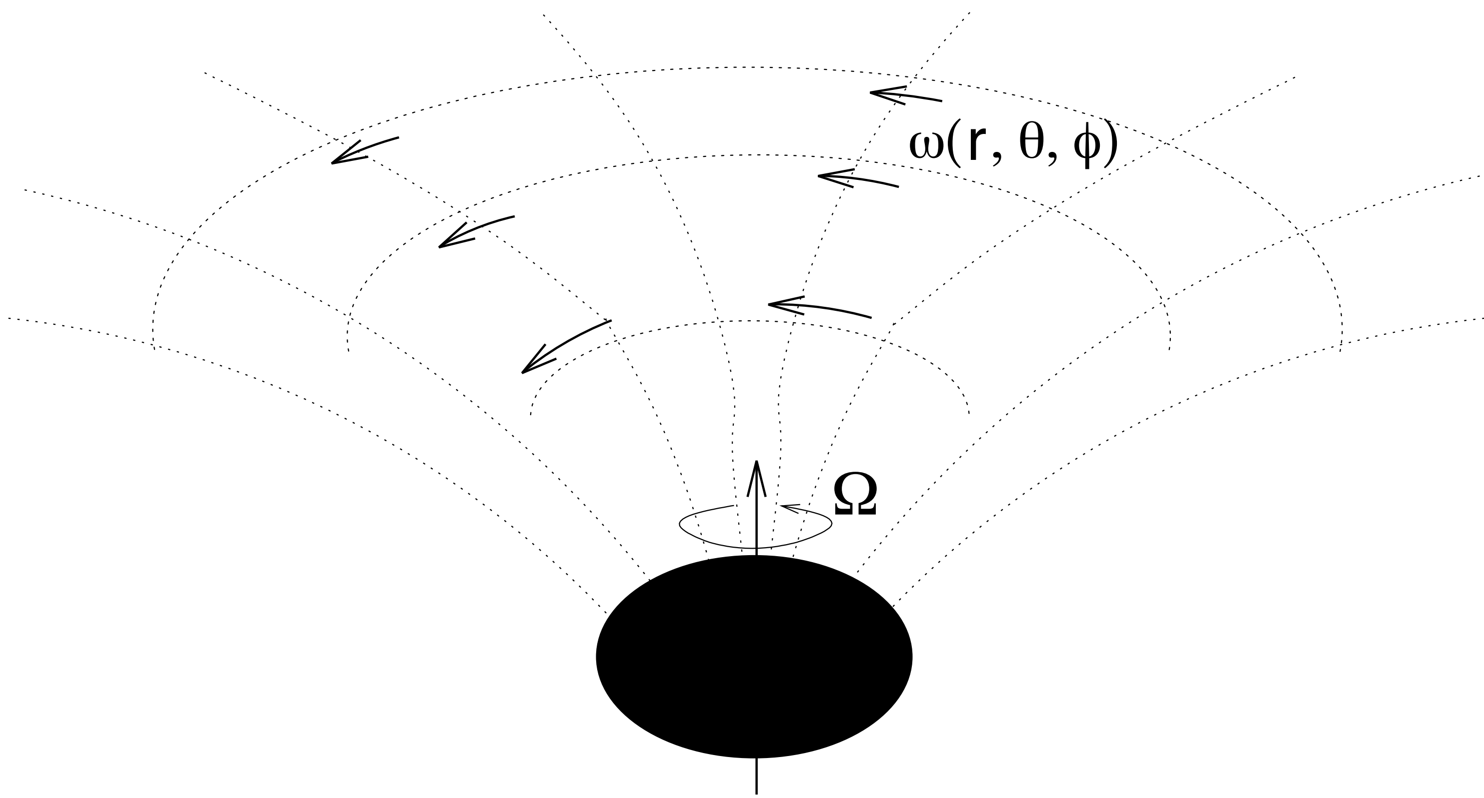
The maximum possible **central densities** of neutron stars



Oliver Hamil, SDSU (2010)

See also Rhoades & Ruffini (1974), Hartle (1978), Lattimer & Prakash (2010)

Rotation in General Relativity



- Frame dragging (Lense—Thirring effect)
- Rotational deformation (→ 2-D problem)
- Define limits on stable rapid rotation

Einstein's Field Equations for Rotating Compact Objects

- Metric: $ds^2 = -\,e^{-2\nu}\,dt^2 + e^{2(\alpha+\beta)}\,r^2\,\sin^2\theta\,(d\varphi - N^\varphi\,dt)^2 + e^{2(\alpha-\beta)}\,(dr^2 + r^2\,d\theta^2)$

- Christoffel symbols:
  $\Gamma^\sigma{}_{\mu\nu} = g^{\sigma\lambda}\,(\partial_\nu g_{\mu\lambda} + \partial_\mu g_{\nu\lambda} - \partial_\lambda g_{\mu\nu})\,/\,2$

- Riemann tensor:
  $R^\tau{}_{\mu\nu\sigma} = \partial_\nu \Gamma^\tau{}_{\mu\sigma} - \partial_\sigma \Gamma^\tau{}_{\mu\nu} + \Gamma^\kappa{}_{\mu\sigma}\Gamma^\tau{}_{\kappa\nu} - \Gamma^\kappa{}_{\mu\nu}\Gamma^\tau{}_{\kappa\sigma}$

- Ricci tensor: $R_{\mu\nu} = R^\tau{}_{\mu\sigma\nu}\,g^\sigma{}_\tau$

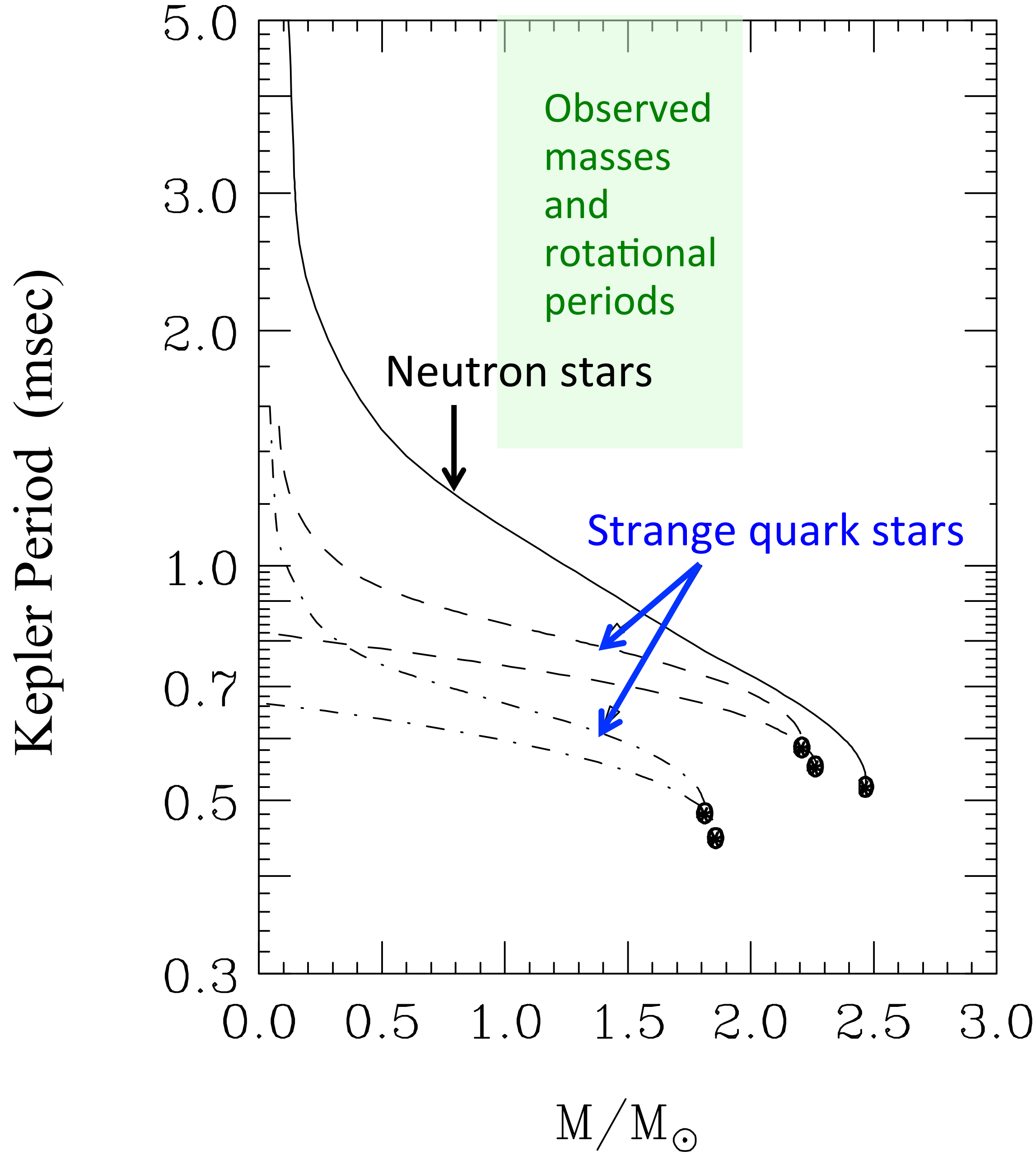
- Scalar curvature: $R = R_{\mu\nu}\,g^{\mu\nu}$

- Kepler frequency: $\Omega_K = r^{-1}\,e^{\nu-\alpha-\beta}\,U_K + N^\varphi$

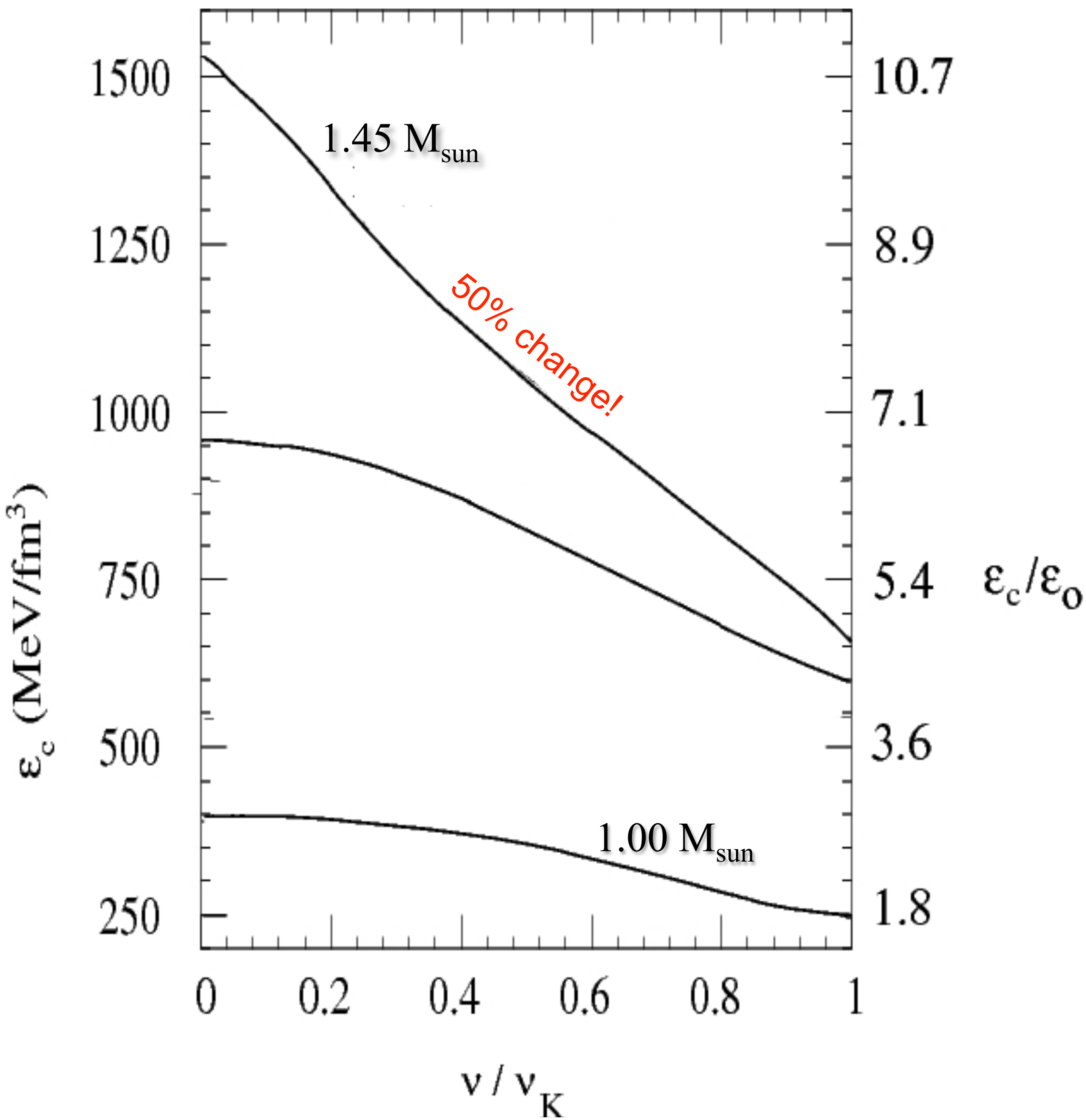
- Differential rotation/uniform rotation

Stellar properties: M, R_p, R_{eq}, I, z, Ω_K, ω, P, ε, ρ

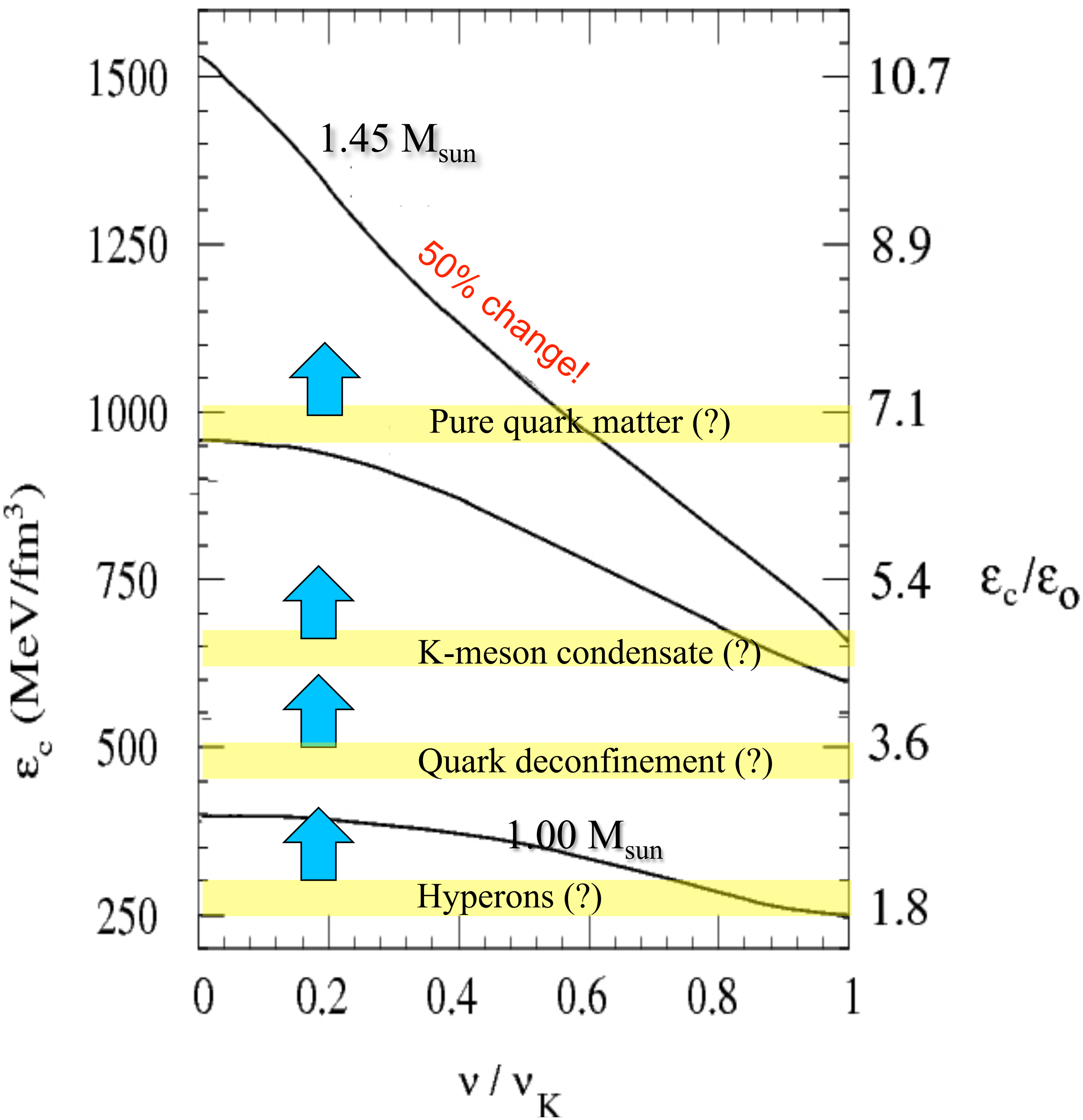
The maximum possible **rotational periods**

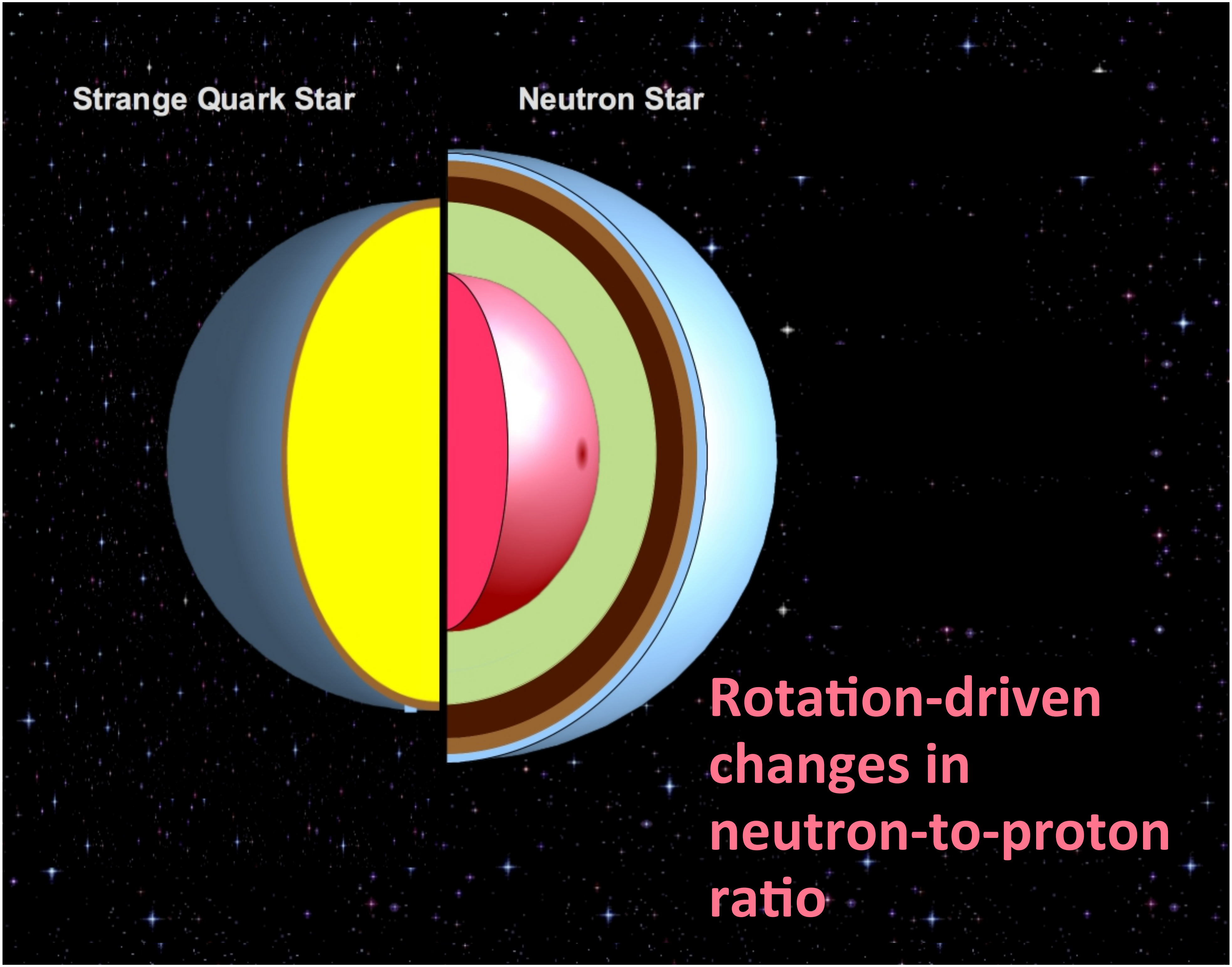


Frequency dependence of a neutron star's **central** density

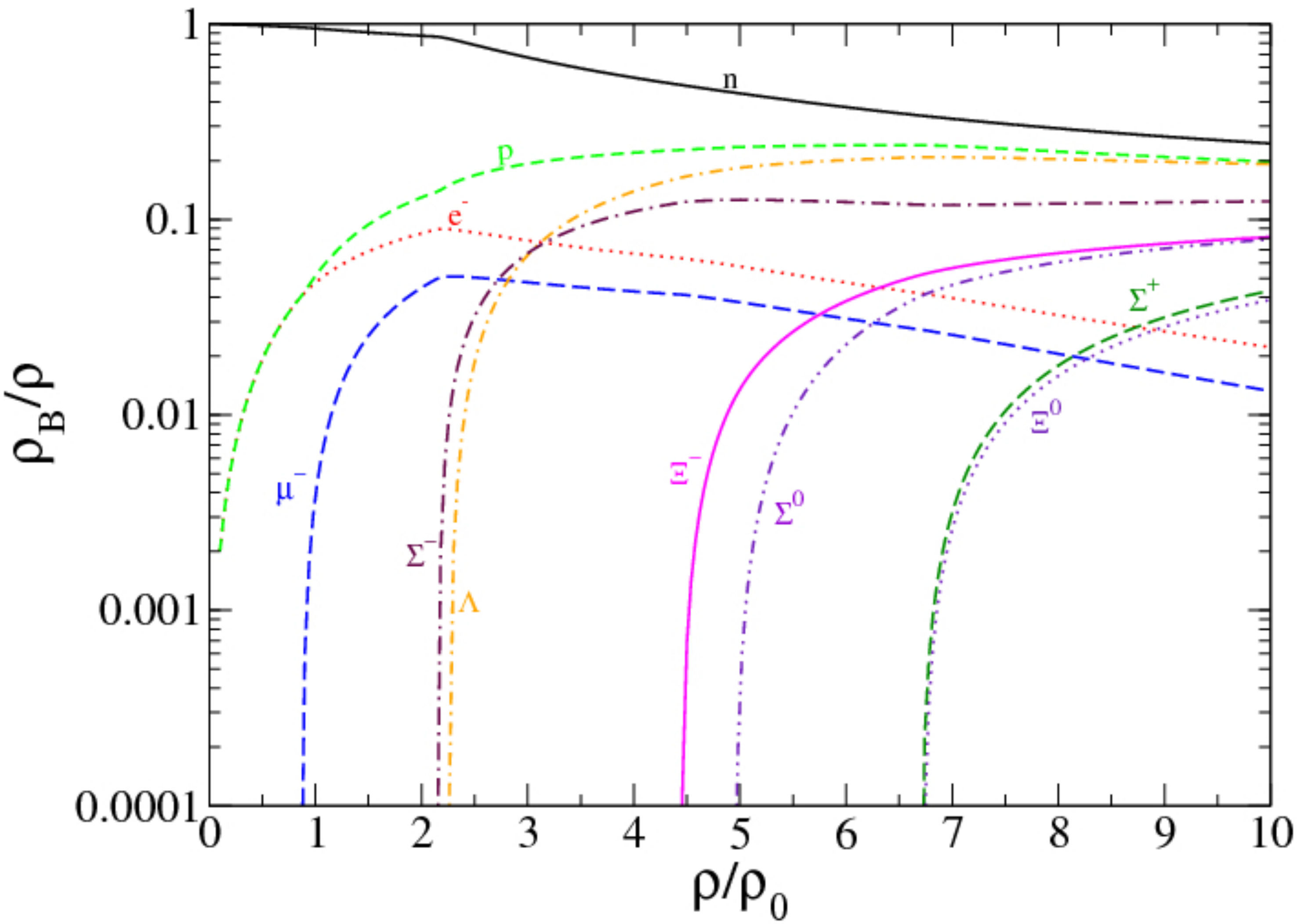


Frequency dependence of a neutron star's **central** density

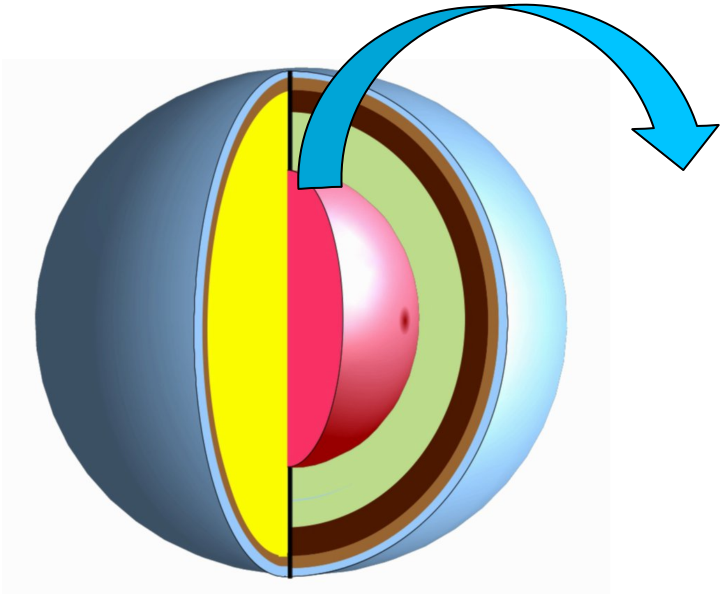



Strange Quark Star
Neutron Star
Rotation-driven changes in neutron-to-proton ratio

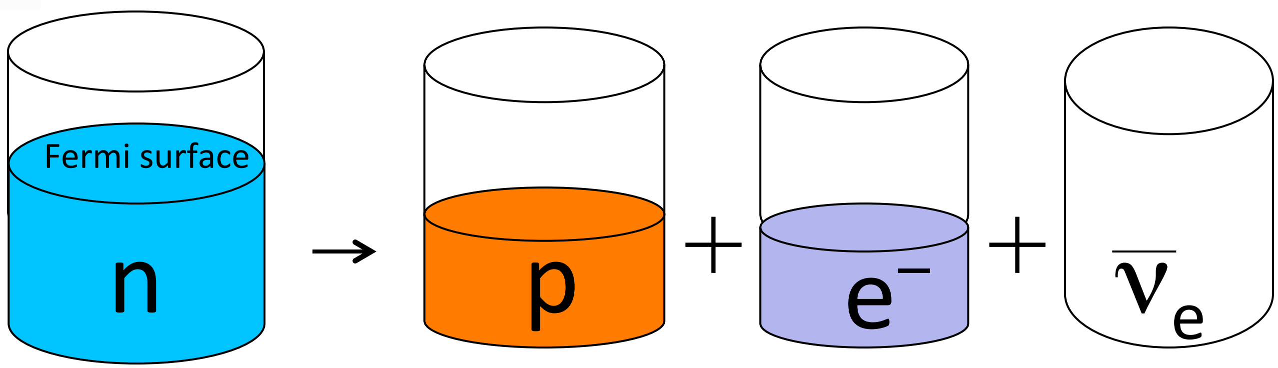
Sample composition of NS matter

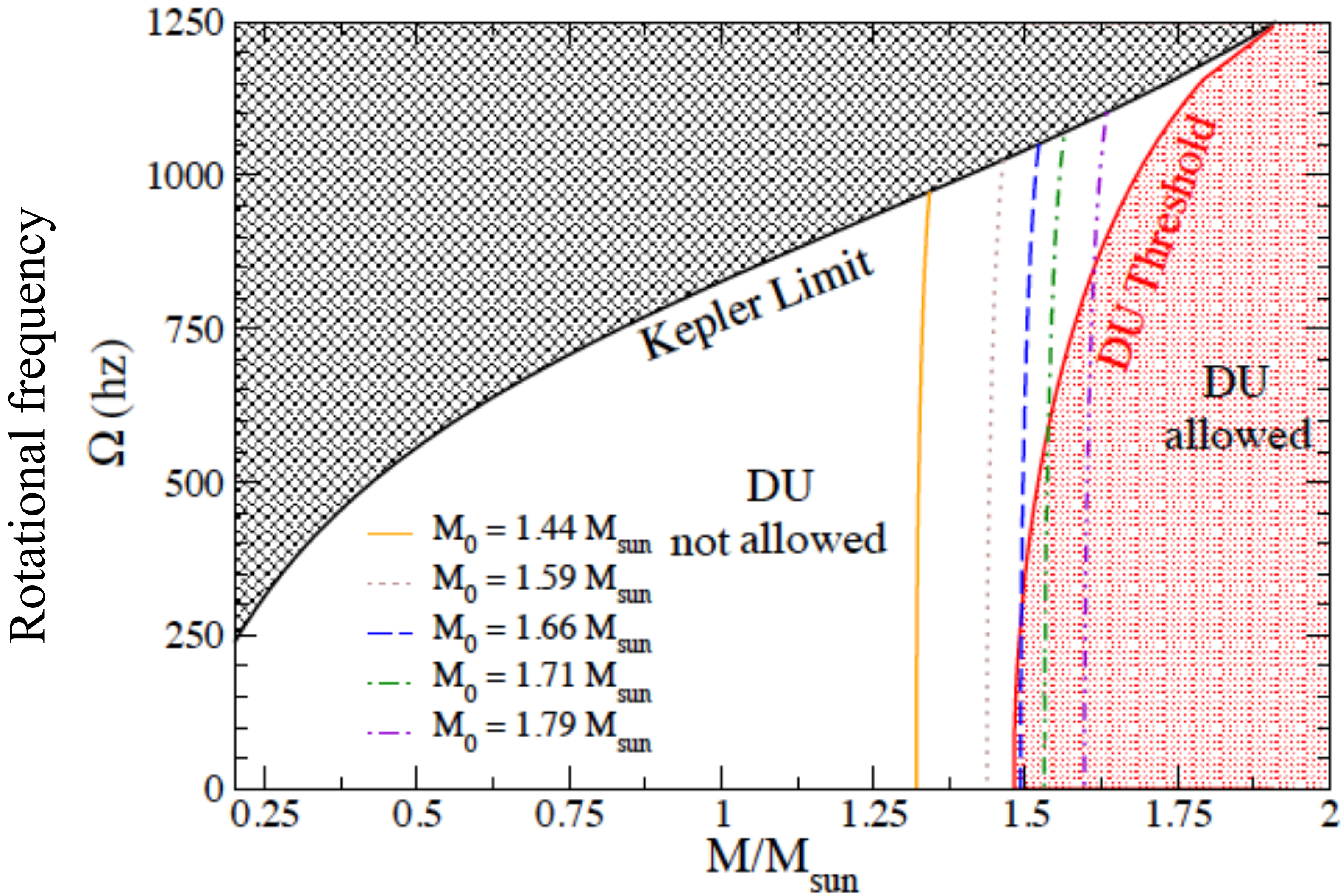


Rotation-driven onset of **Direct Urca Process** in stellar core

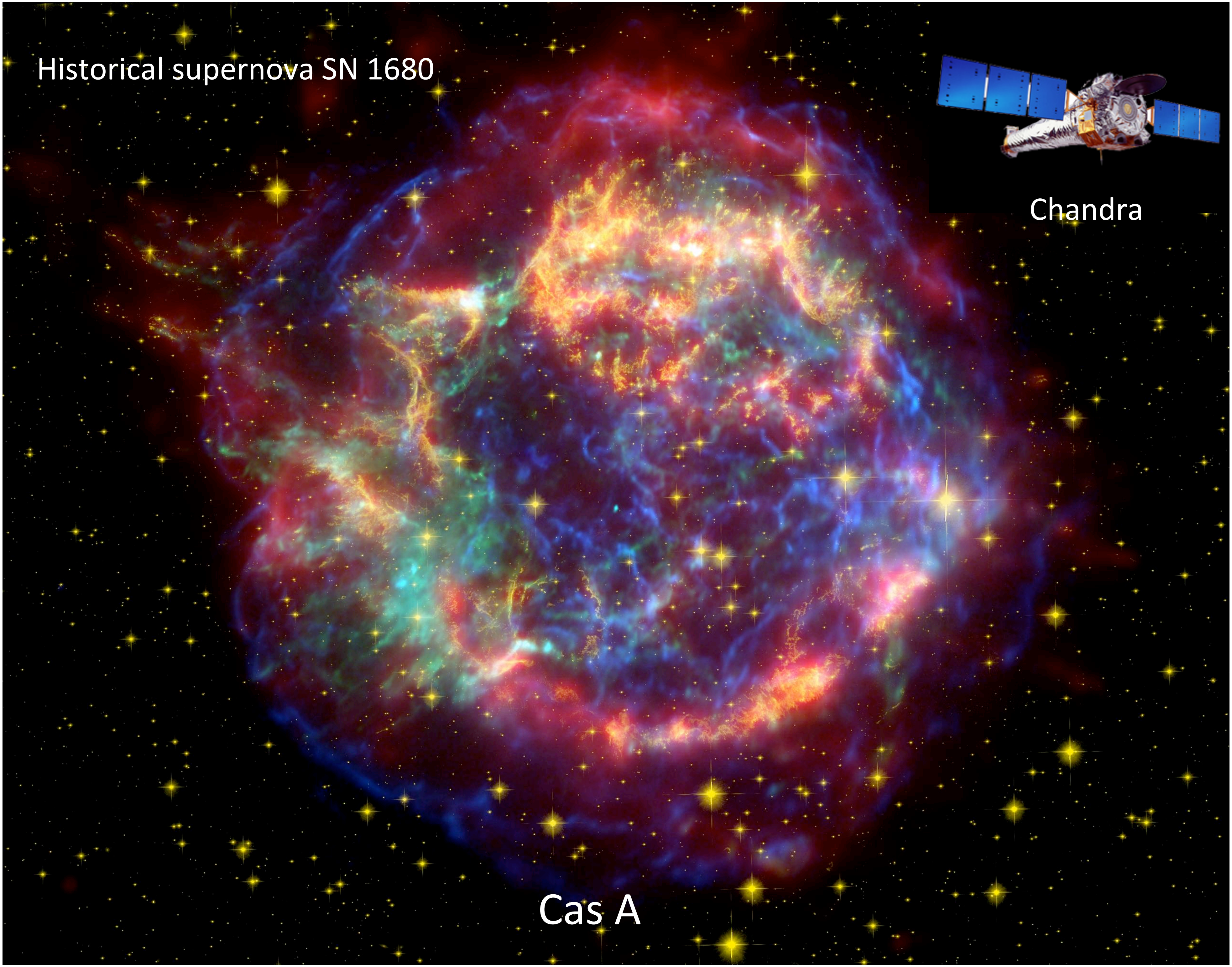


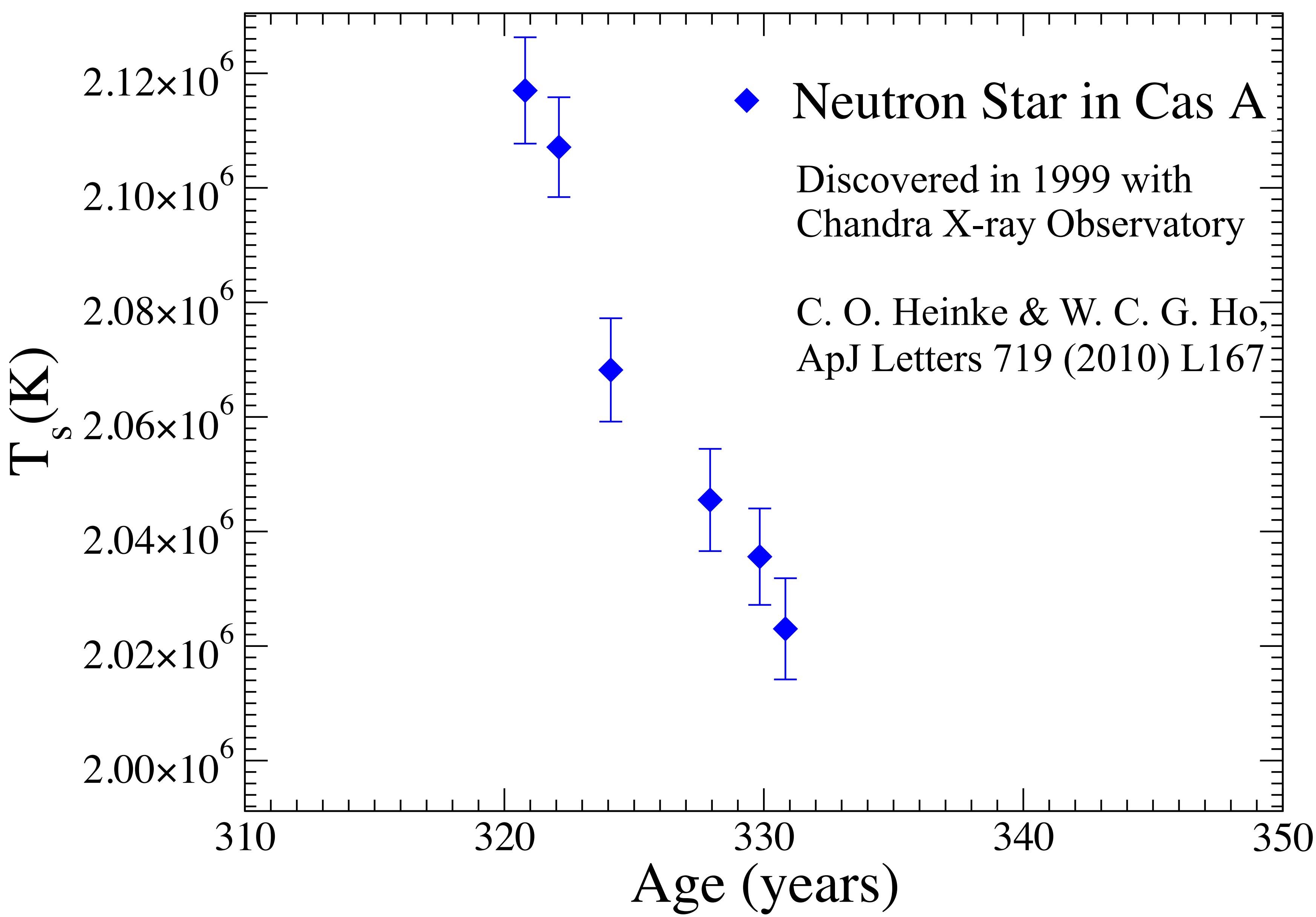
$$n \longrightarrow p + e^- + \bar{\nu}_e$$



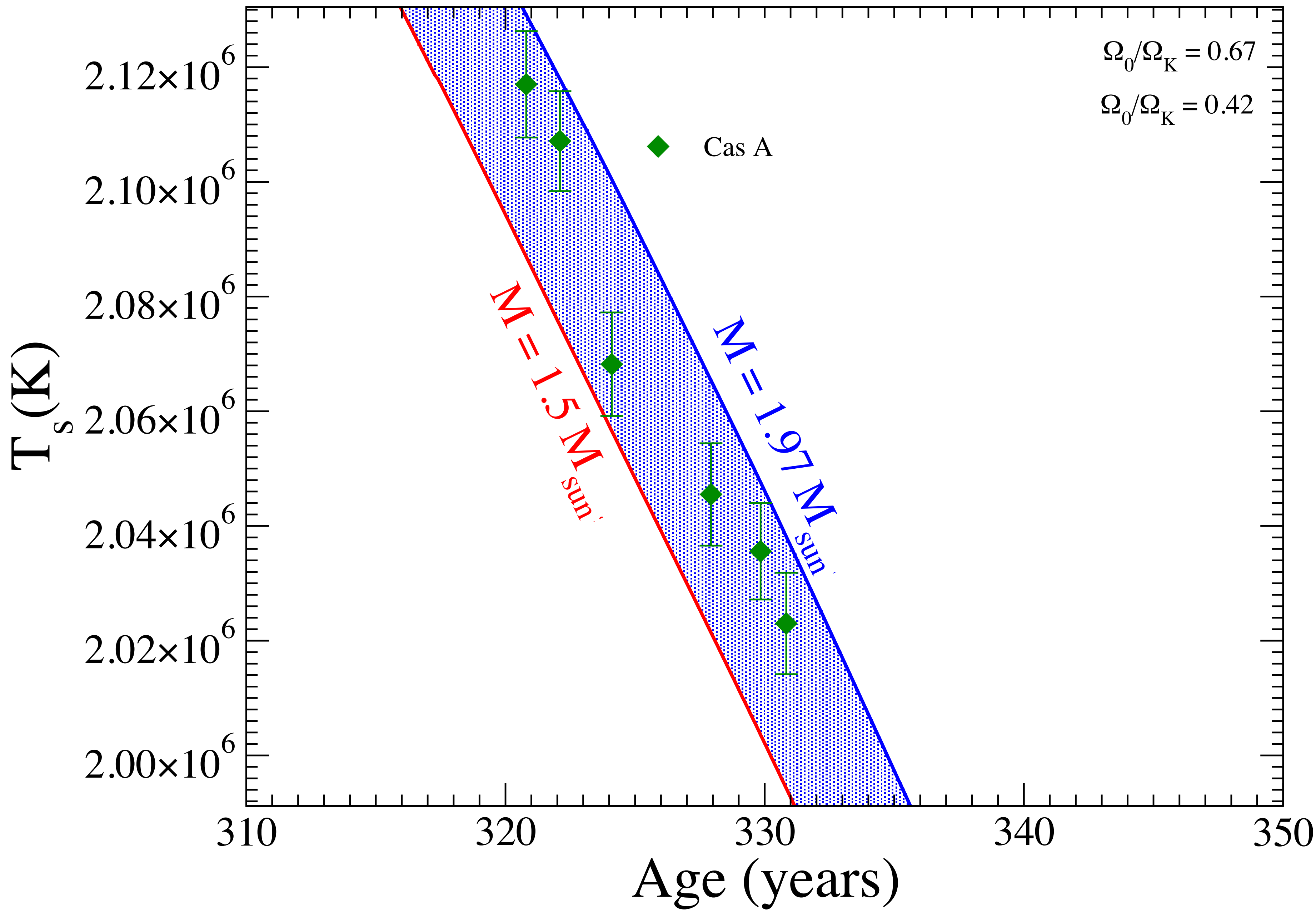


R. Negreiros, S. Schramm, FW (2012)


Historical supernova SN 1680
Chandra
Cas A



Neutron Star in Cas A
Discovered in 1999 with
Chandra X-ray Observatory
C. O. Heinke & W. C. G. Ho,
ApJ Letters 719 (2010) L167
T_s (K)
2.12×10^6
2.10×10^6
2.08×10^6
2.06×10^6
2.04×10^6
2.02×10^6
2.00×10^6
310
320
330
340
350
Age (years)



R. Negreiros, S. Schramm, FW (2012)

Selected for a Viewpoint in *Physics*
PRL **106,** 081101 (2011) PHYSICAL REVIEW LETTERS week ending 25 FEBRUARY 2011

Rapid Cooling of the Neutron Star in Cassiopeia A Triggered by Neutron Superfluidity in Dense Matter

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[4]*Joint Institute for Nuclear Astrophysics, National Superconducting Cyclotron Laboratory and, Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA*
(Received 29 November 2010; published 22 February 2011)

We propose that the observed cooling of the neutron star in Cassiopeia A is due to enhanced neutrino emission from the recent onset of the breaking and formation of neutron Cooper pairs in the $^3P_2$ channel. We find that the critical temperature for this superfluid transition is $\simeq 0.5 \times 10^9$ K. The observed rapidity of the cooling implies that protons were already in a superconducting state with a larger critical temperature. This is the first direct evidence that superfluidity and superconductivity occur at supranuclear densities within neutron stars. Our prediction that this cooling will continue for several decades at the present rate can be tested by continuous monitoring of this neutron star.

See also D. Yakovlev et al., MNRAS 411 (2011) 1977

PHYSICAL REVIEW C **85**, 022802(R) (2012)

Cooling of the neutron star in Cassiopeia A

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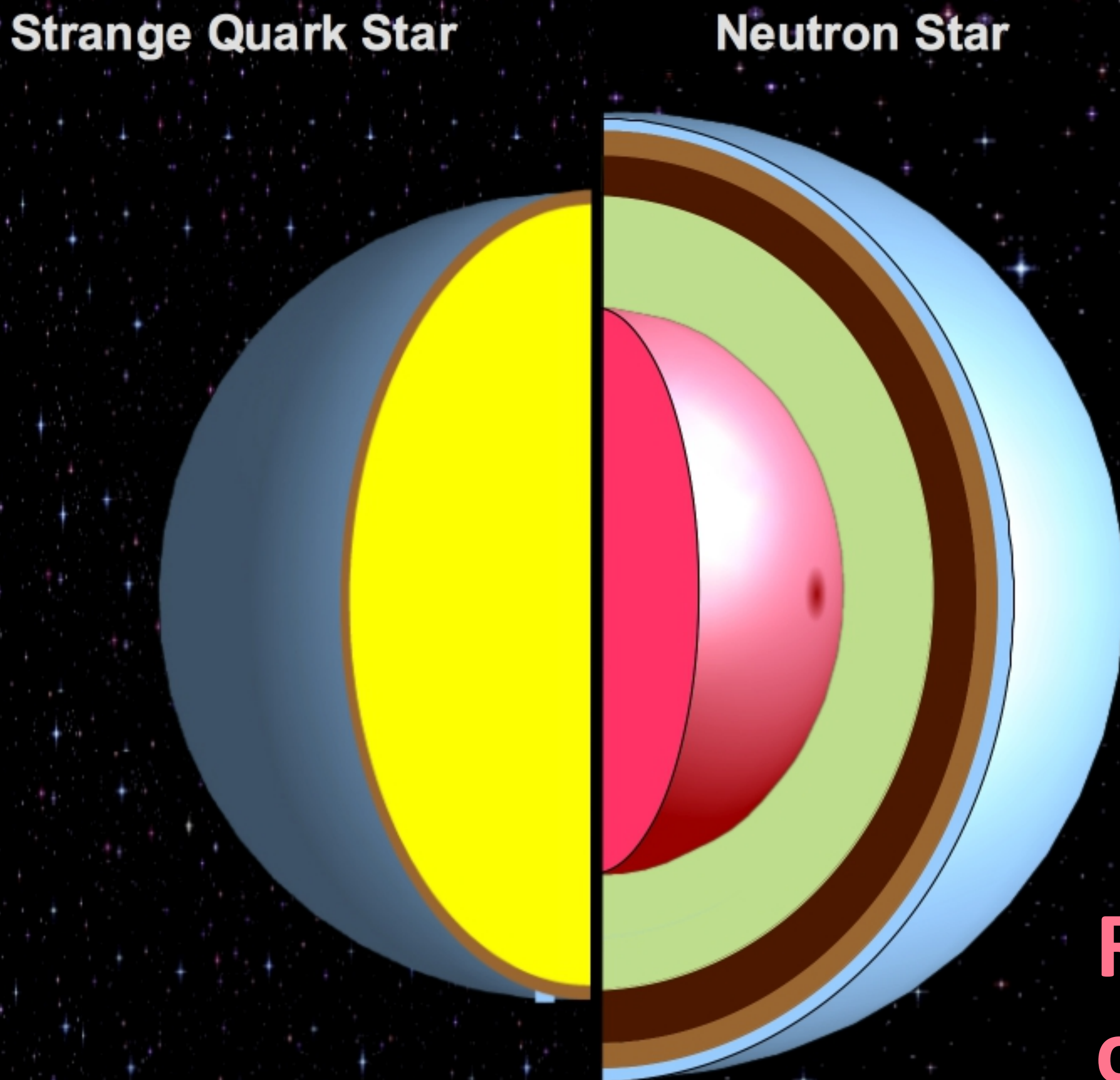
[5]*ExtreMe Matter Institute (EMMI) and Research Division, GSI Helmholtzzentrum für Schwerionenforschung, Planckstraβe 1, 64291 Darmstadt, Germany*
[6]*Department of Physics, San Diego State University, San Diego, California 92182, USA*
(Received 20 August 2011; published 27 February 2012)

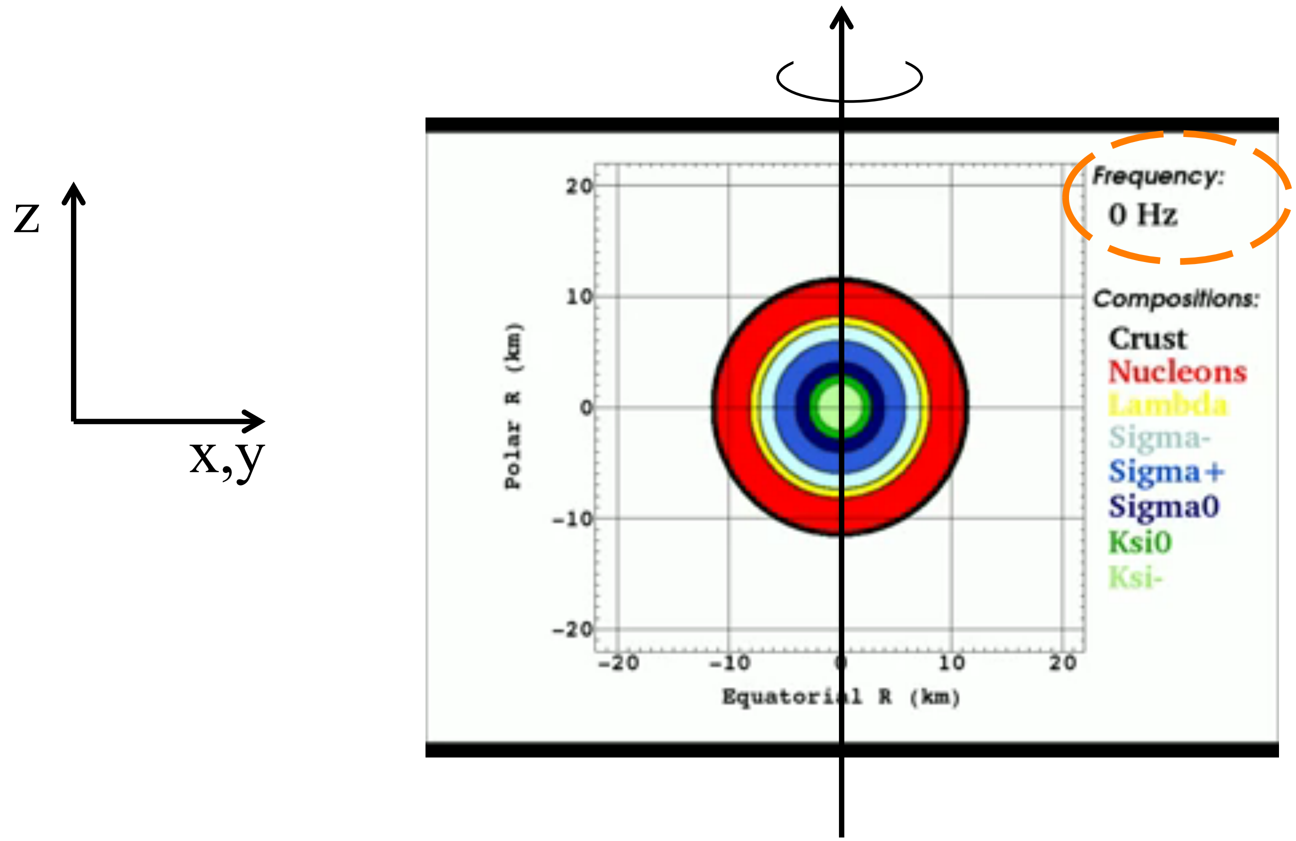
We demonstrate that the high-quality cooling data observed for the young neutron star in the supernova remnant Cassiopeia A over the past 10 years—as well as all other reliably known temperature data of neutron stars—can be comfortably explained within the "nuclear medium cooling" scenario. The cooling rates of this scenario account for medium-modified one-pion exchange in dense matter and polarization effects in the pair-breaking formations of superfluid neutrons and protons. Crucial for the successful description of the observed data is a substantial reduction of the thermal conductivity, resulting from a suppression of both the electron and nucleon contributions to it by medium effects. In a few more decades of continued monitoring of Cassiopeia A, the observed data may allow one to put additional constraints on the efficiency of different cooling processes in neutron stars.

DOI: 10.1103/PhysRevC.85.022802 PACS number(s): 97.60.Jd, 95.30.Cq, 26.60.−c



Rotation-driven changes in hyperons population

Rotation-driven compositional changes inside of neutron stars



Crust
Nucleons
Lambdas
Sigma$^-$
Sigma$^+$
Sigma^0
Xi^0
Xi$^-$

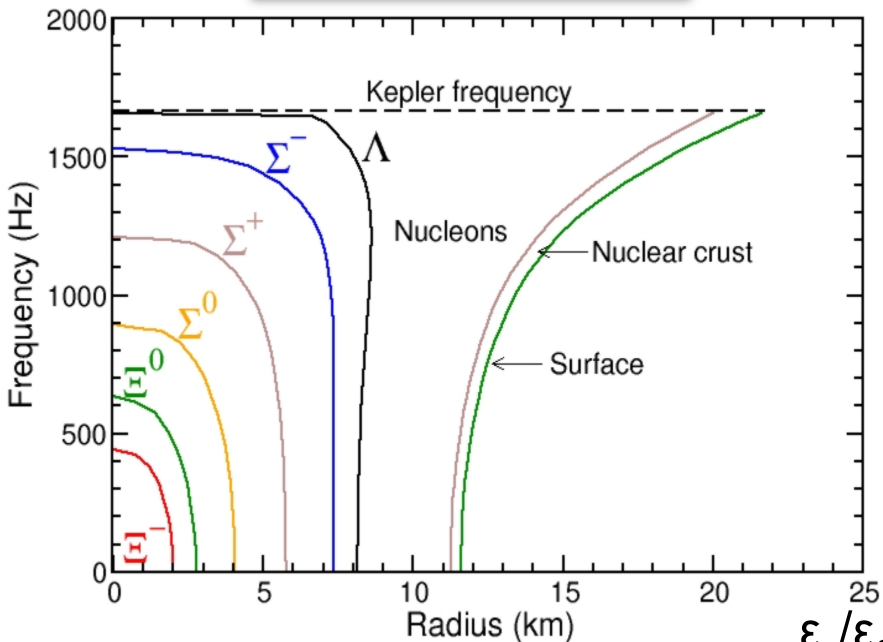
Jirina Stone (ORNL) & FW, 2012

Data: DDRMF (Hofmann, Keil, Lenske)

Model Composition of a M=1.7 M_{sun} Neutron Star

Equatorial direction

$\varepsilon_c/\varepsilon_0$=3 @ $v=v_K$



$\varepsilon_c/\varepsilon_0$=7 @ v=0

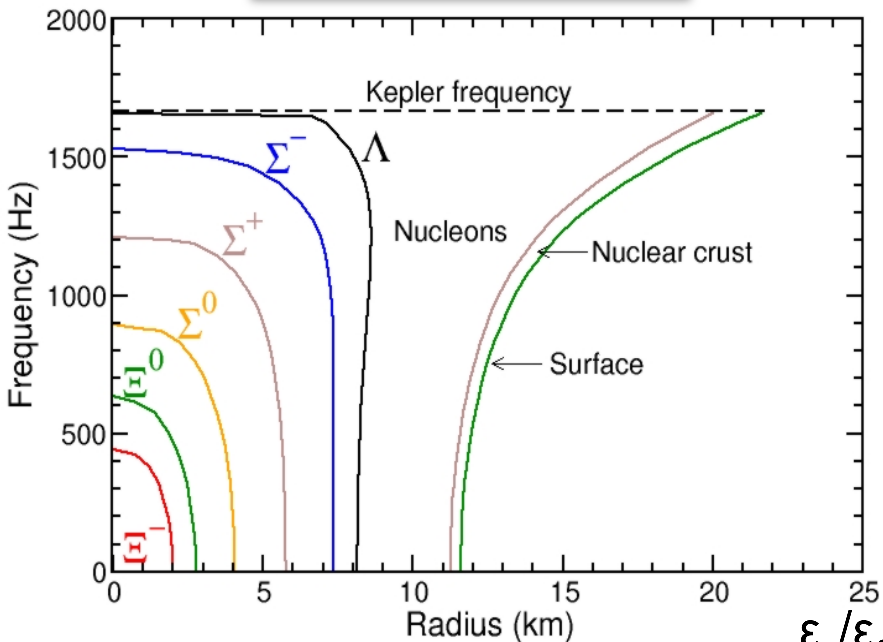
Rosenfield, (SDSU, 2008); Equation of state: DDRMF, Hofmann, Keil, Lenske.

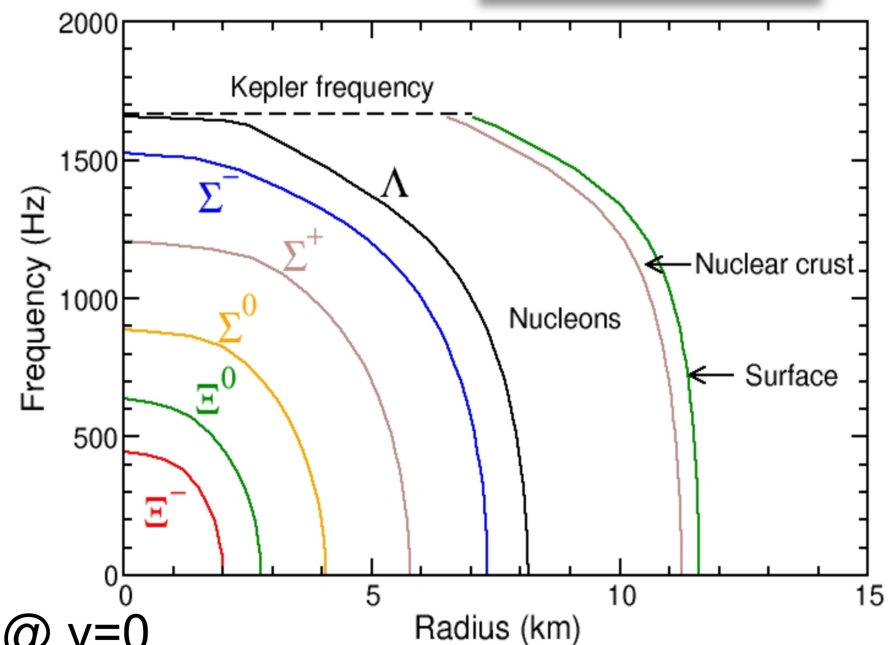
Model Composition of a M=1.7 M_{sun} Neutron Star

Equatorial direction

$\varepsilon_c/\varepsilon_0=3$ @ $v=v_K$

Polar direction

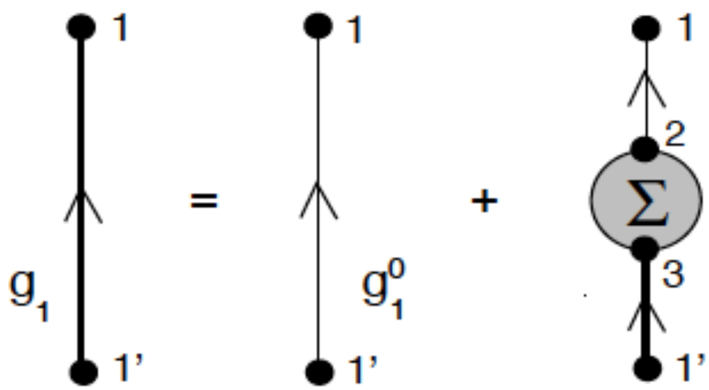




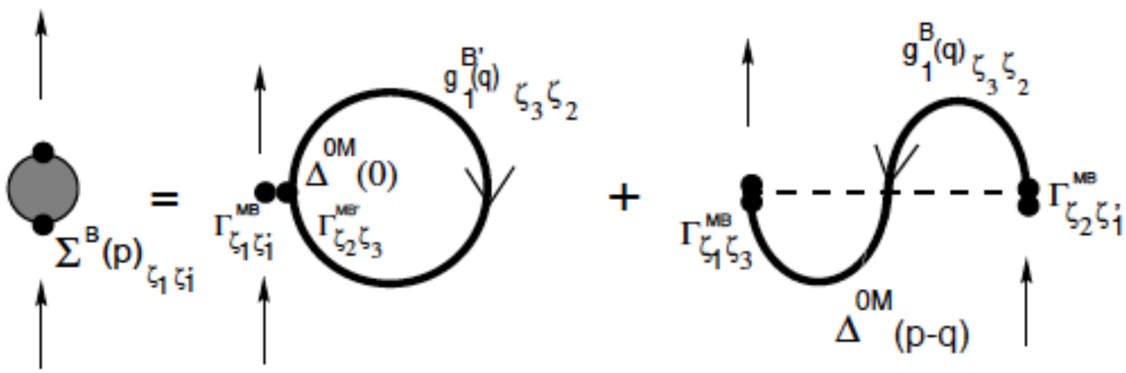
$\varepsilon_c/\varepsilon_0=7$ @ $v=0$

Rosenfield, (SDSU, 2008); Equation of state: DDRMF, Hofmann, Keil, Lenske.

A word of caution seems appropriate



Dyson equation



Self-energy

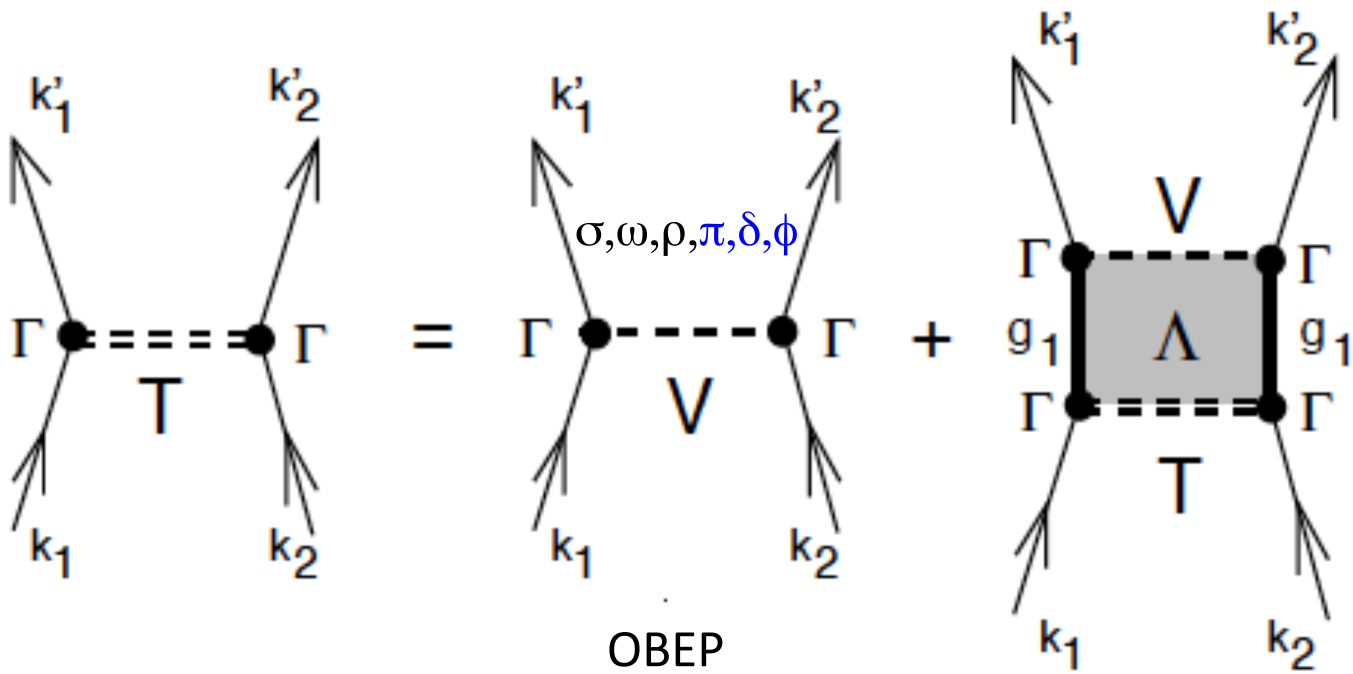
Direct term

Exchange term

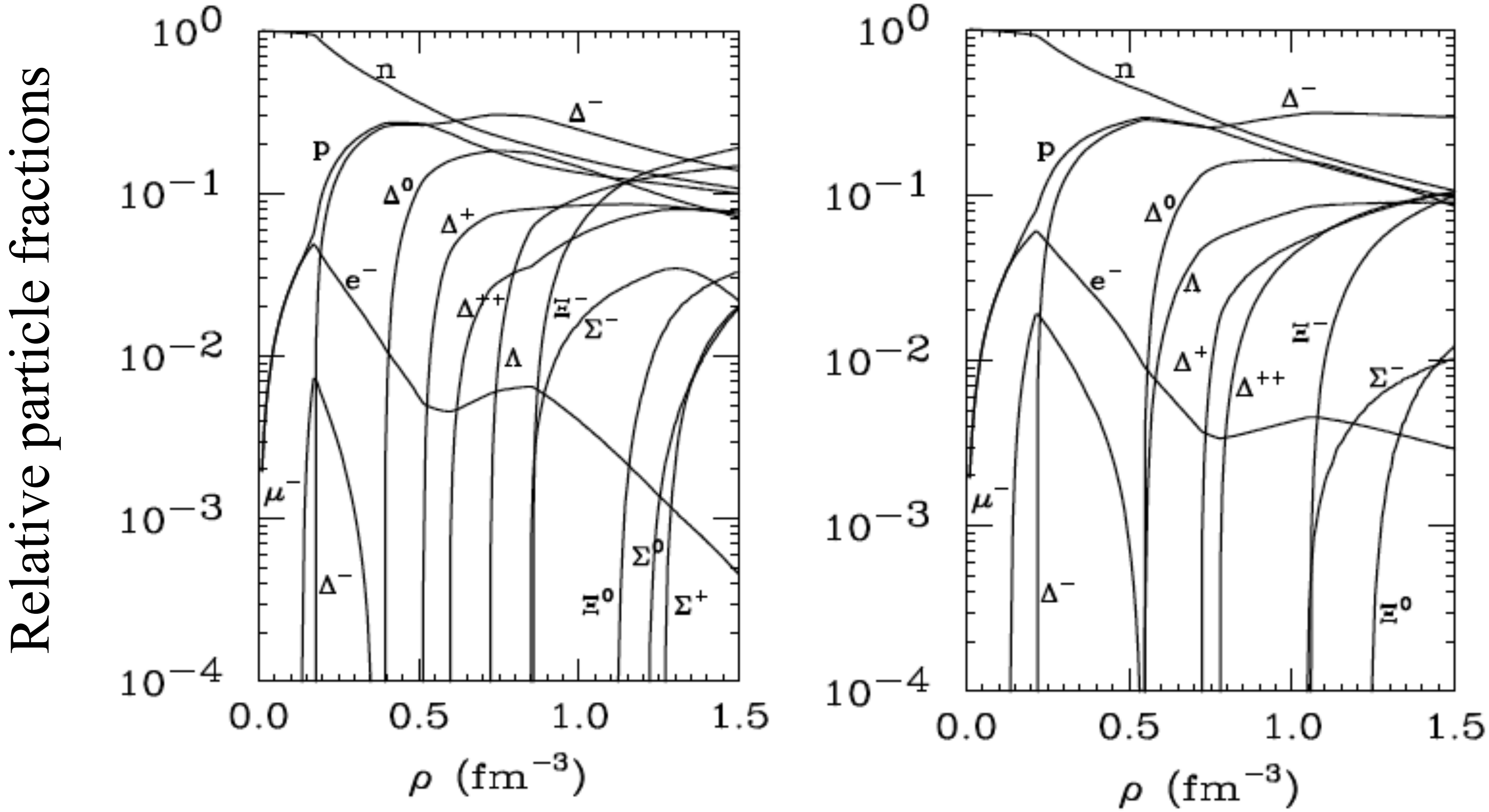
Hartree (Walecka)

Hartree-Fock

T-matrix approximation

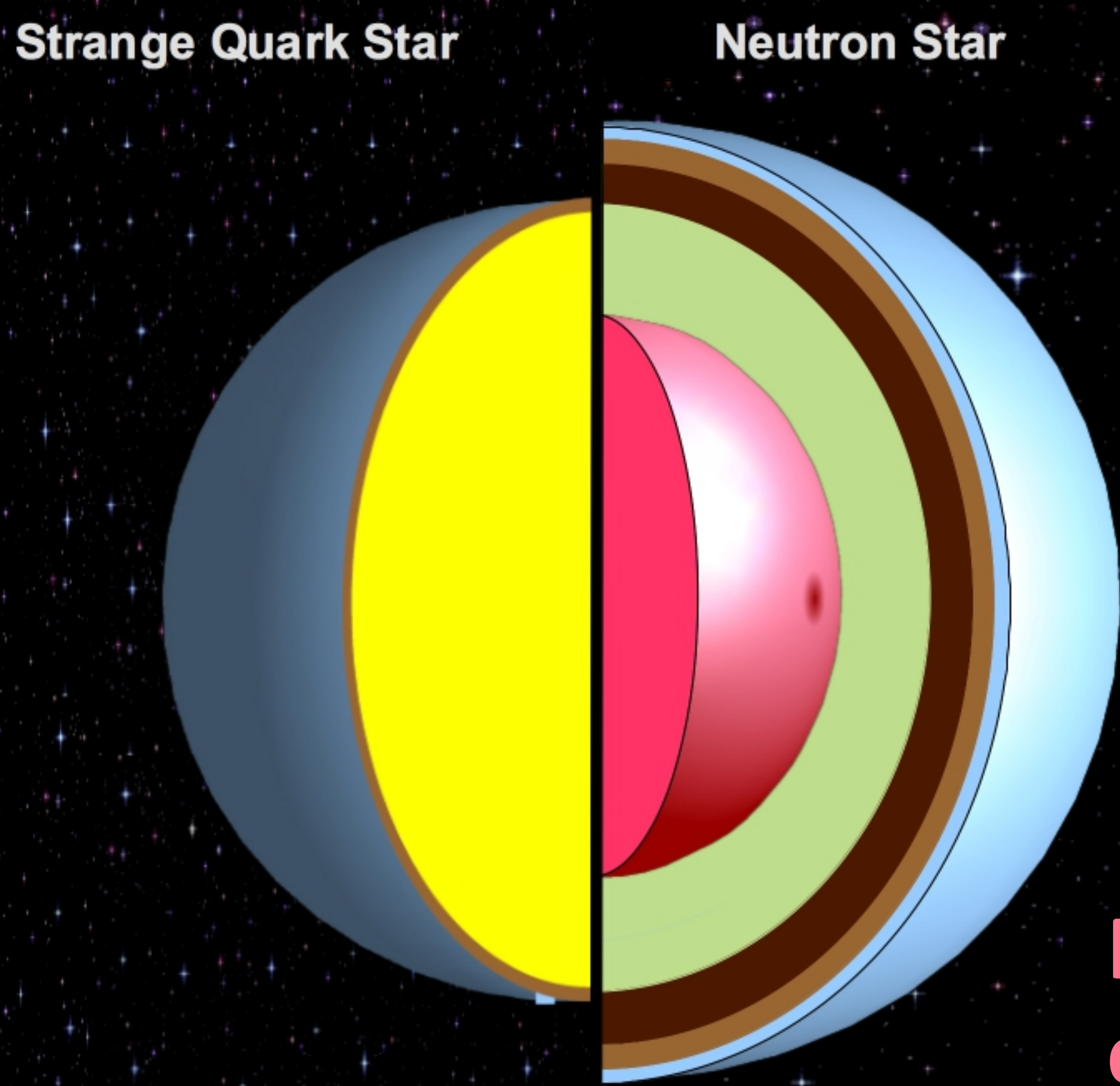


Composition computed for RBHF approximation



universal coupling

non-universal coupling



Rotation-driven changes in quark matter content

Modeling the Quark-Hadron Phase Transition in the Cores of Neutron Stars

- Phenomenological model for confined hadronic matter (RMF, RHF, RBHF)
- Phenomenological model for quark matter (MIT bag, NJL)

$$P_h(\mu, \mu^e, \chi) = P_q(\mu, \mu^e, \chi)\,, \quad \chi \equiv V_q/(V_q + V_h)$$

- Impose global electric charge neutrality (Glendenning 1992)
- Impose chemical equilibrium

$$\mathcal{L} = \sum_{B=n,p,\Lambda,\Sigma,\Xi} \bar{\psi}_B \big[\gamma_\mu (i\partial^\mu - g_\omega \omega^\mu - g_\rho \vec{\rho}^\mu) - (m_N - g_\sigma \sigma)\big] \psi_B + \frac{1}{2}(\partial_\mu \sigma \partial^\mu \sigma - m_\sigma^2 \sigma^2) - \frac{1}{3} b_\sigma m_N (g_\sigma \sigma)^3 - \frac{1}{4} c_\sigma (g_\sigma \sigma)^4 - \frac{1}{4}\omega_{\mu\nu}\omega^{\mu\nu} + \frac{1}{2} m_\omega^2 \omega_\mu \omega^\mu + \frac{1}{2} m_\rho^2 \vec{\rho}_\mu \cdot \vec{\rho}^\mu - \frac{1}{4}\vec{\rho}_{\mu\nu}\vec{\rho}^{\mu\nu} + \sum_{\lambda=e^-,\mu^-} \bar{\psi}_\lambda (i\gamma_\mu \partial^\mu - m_\lambda)\psi_\lambda \,,$$

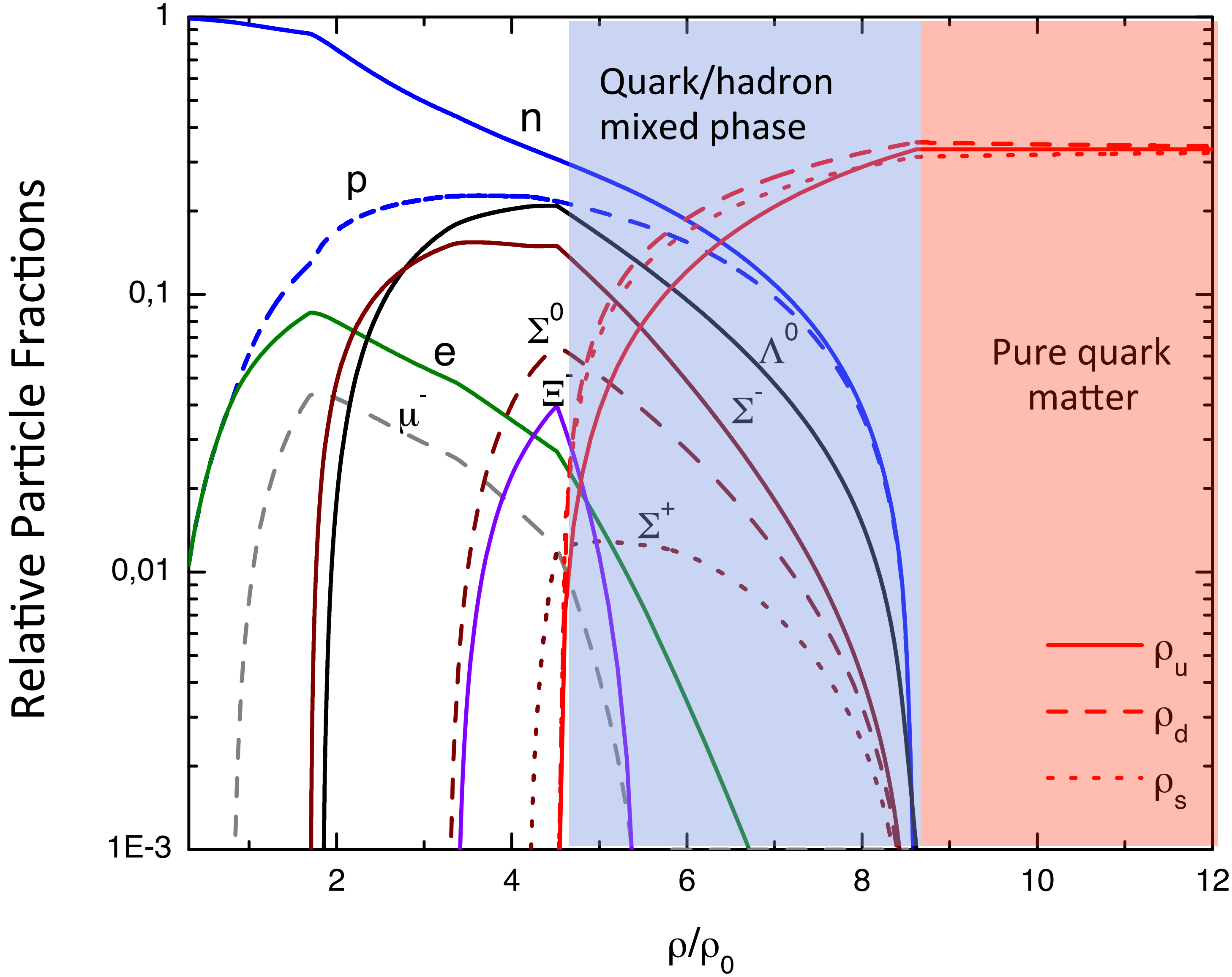
RMF

$$S_E = \int d^4x \, \{\bar{\psi}(x) \left[-i\gamma_\mu \partial_\mu + \hat{m}\right] \psi(x) - \frac{G_s}{2} \left[j_a^S(x)\; j_a^S(x) + j_a^P(x)\; j_a^P(x)\right] - \frac{H}{4}\, T_{abc} \left[j_a^S(x) j_b^S(x) j_c^S(x) - 3\; j_a^S(x) j_b^P(x) j_c^P(x)\right] - \frac{G_V}{2} j_{V,f}^\mu(x) j_{V,f}^\mu(x),$$

n3fNJL

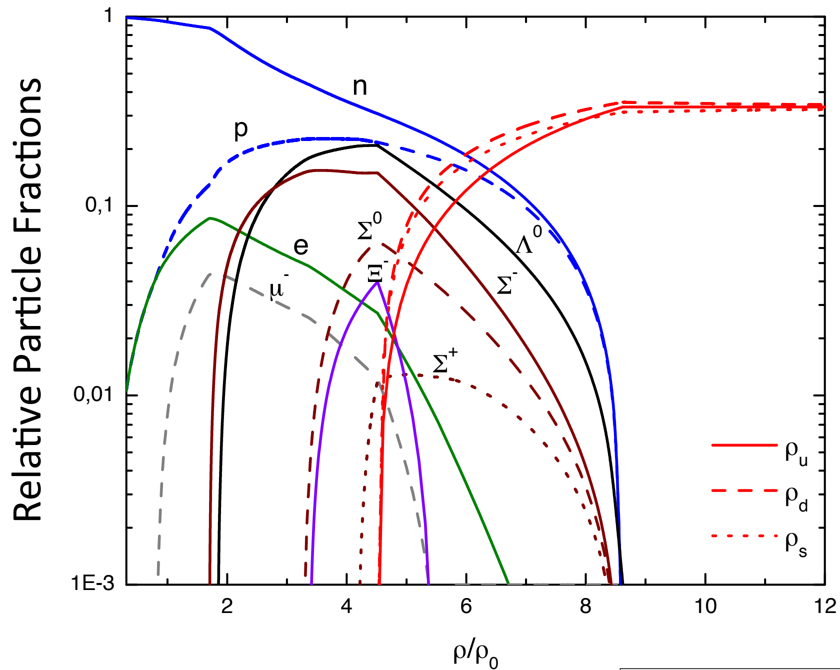
M. Orsaria, H. Rodrigues, FW, G. A. Contrera (October, 2012)

Model Neutron Star Matter Composition

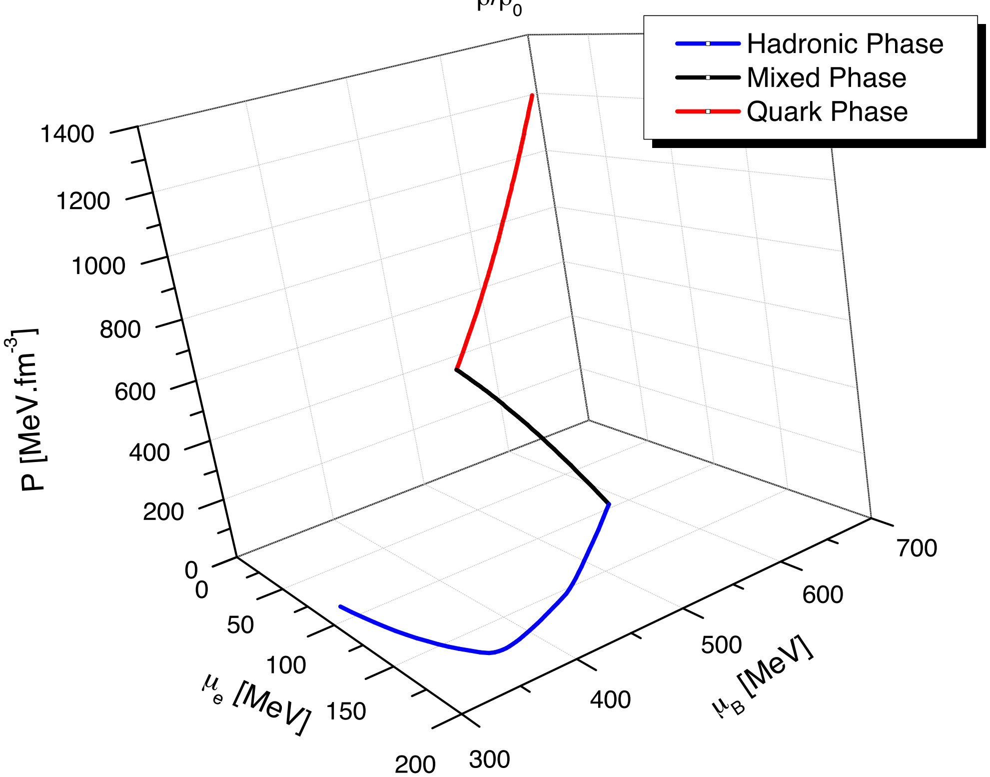


Milva Orsaria & Hilario Rodrigues (June 2012)

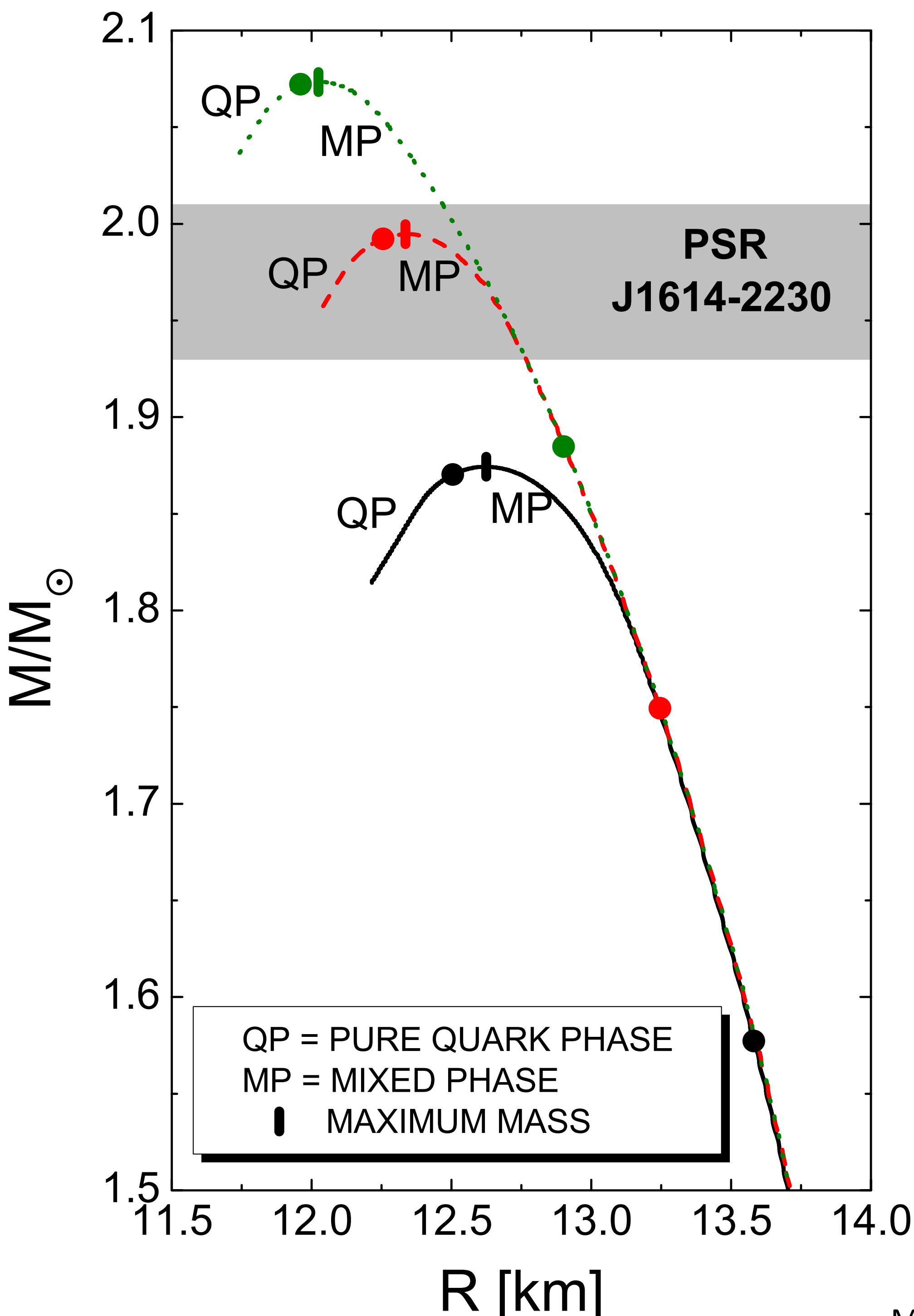
Model neutron star matter composition



Associated equation of state



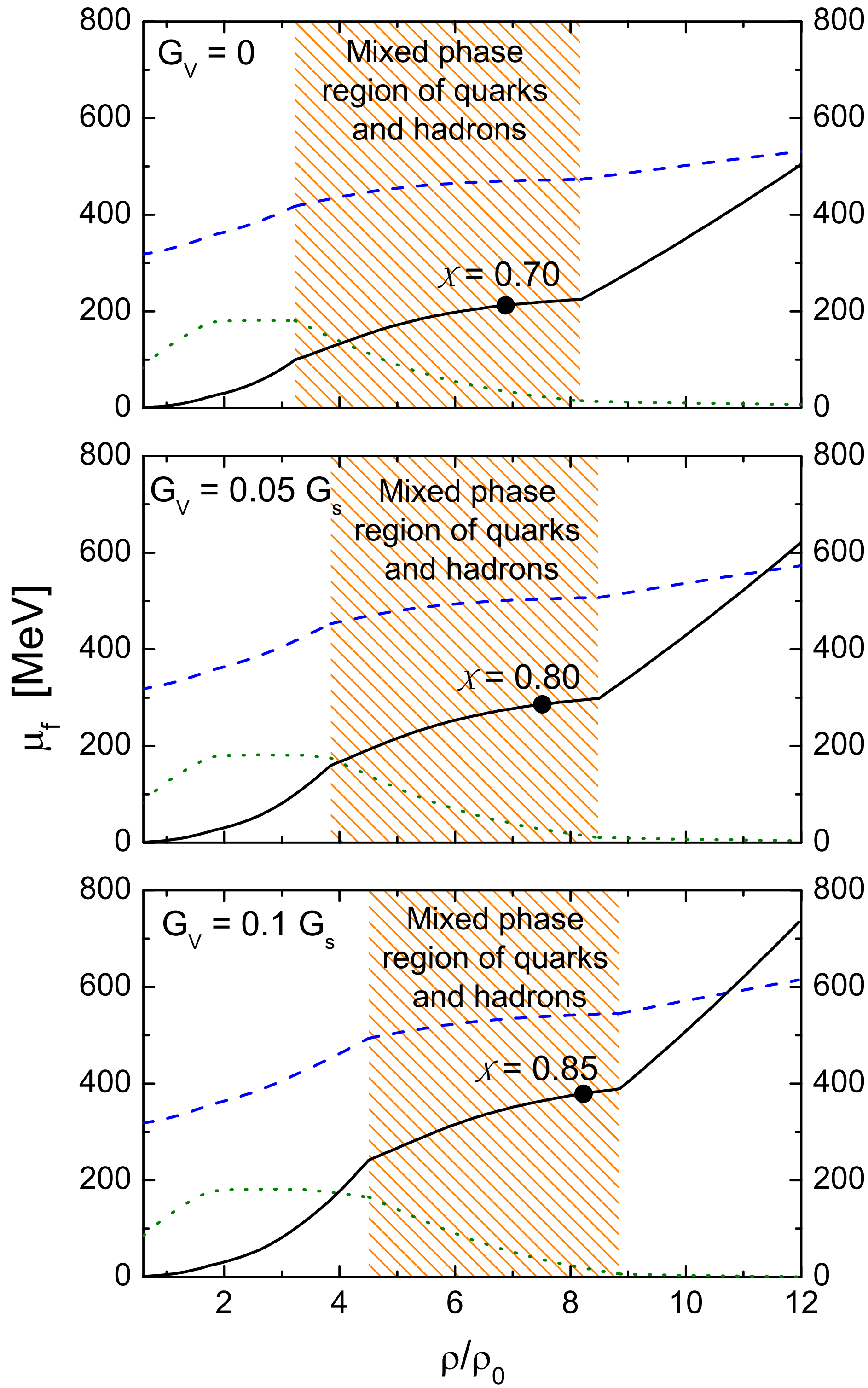
Milva Orsaria & Hilario Rodrigues (June 2012)



Mass-Radius Relationship

Non-local SU(3) NJL model
with vector coupling

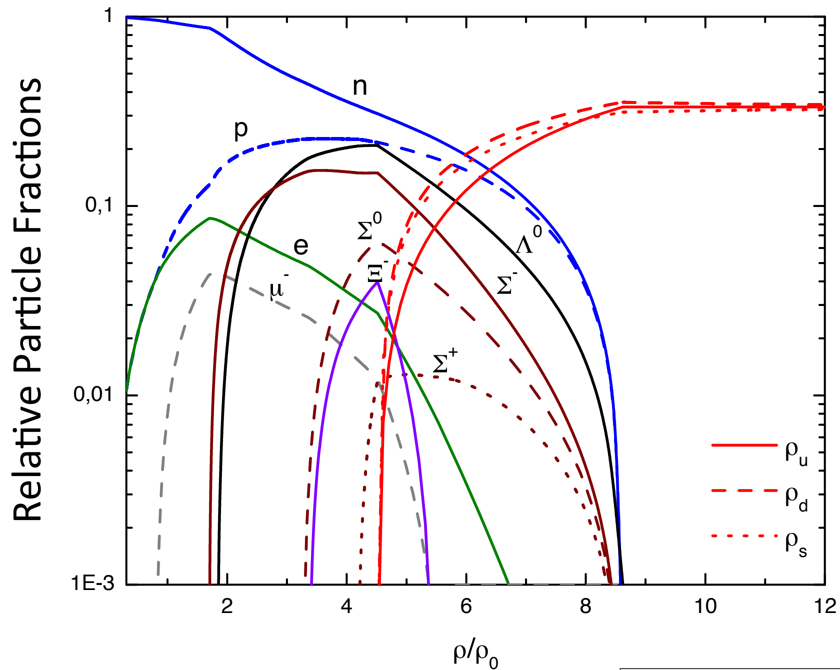
M. Orsaria, H. Rodrigues, FW, G. A. Contrera (October, 2012)



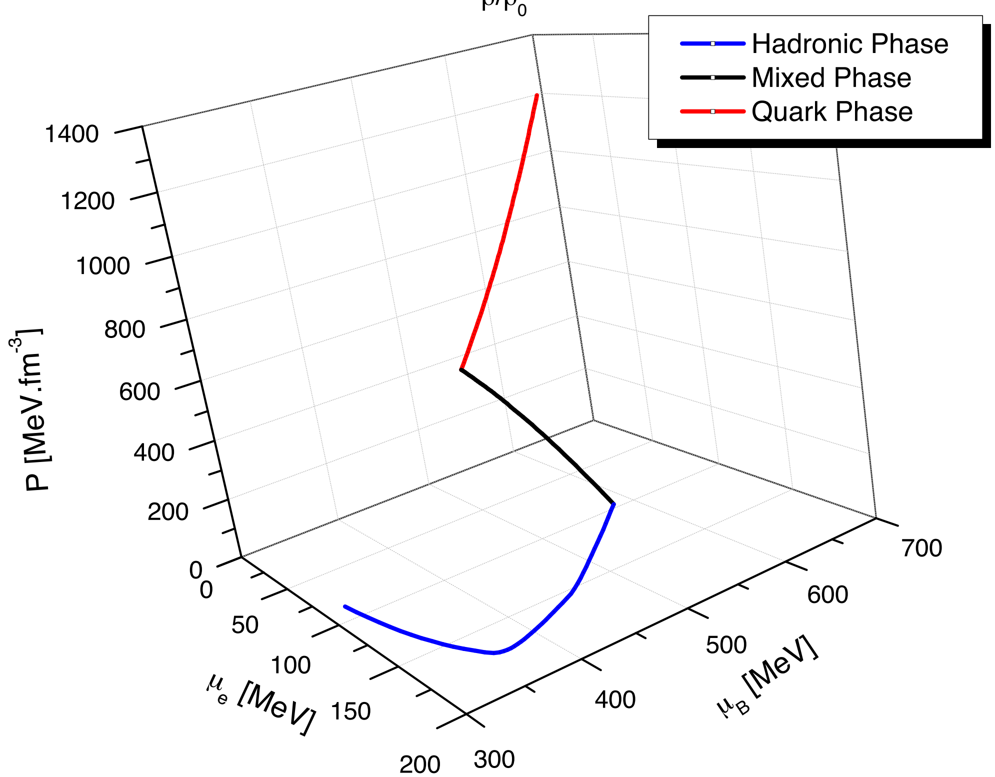
Non-local SU(3) NJL model with vector coupling

M. Orsaria, H. Rodrigues, FW, G. A. Contrera (October, 2012)

Model neutron star matter composition



Associated equation of state



Milva Orsaria & Hilario Rodrigues (June 2012)

Moment of inertia

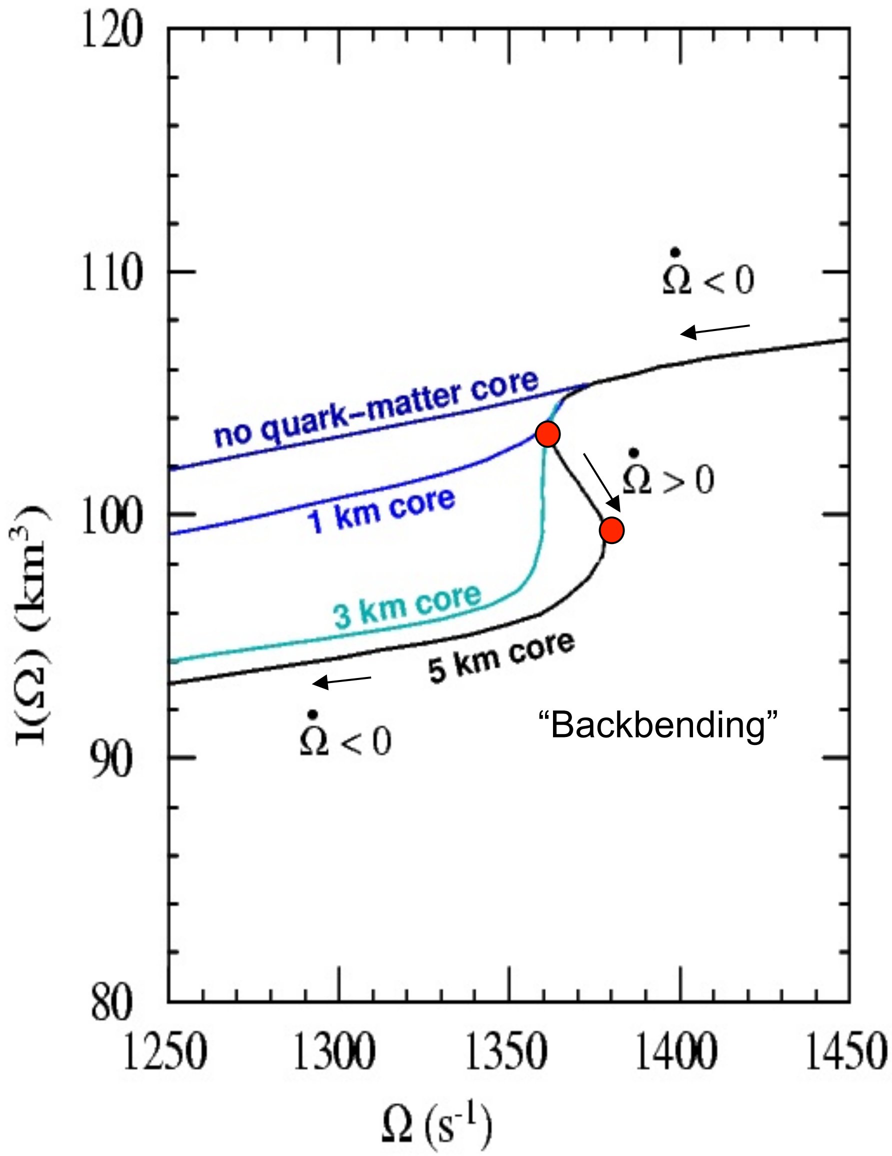
$$I = \frac{1}{\Omega} \int dr\, d\theta\, d\phi\, T_\phi{}^t \sqrt{-g}$$

Braking index (n) of a pulsar:

$$n = 3 - \frac{I''\Omega^2 + 3I'\Omega}{I'\Omega + 2I}$$

Signals of quark deconfinment:

- Braking indices of pulsars $-\infty < n < +\infty$
- Spin-up of isolated rotating neutron stars



Glendenning, Pei, FW, PRL 79 (1997) 1603
Chubarian, Grigorian, Poghosyan, Blaschke A&A 357 (2000)
FW, Prog. Nucl. Part. Phys. 54 (2005) 193

Geometrical Structures in Quark-Hadron Phase

…. N. K. Glendenning, PRD 46 (1992) 1274

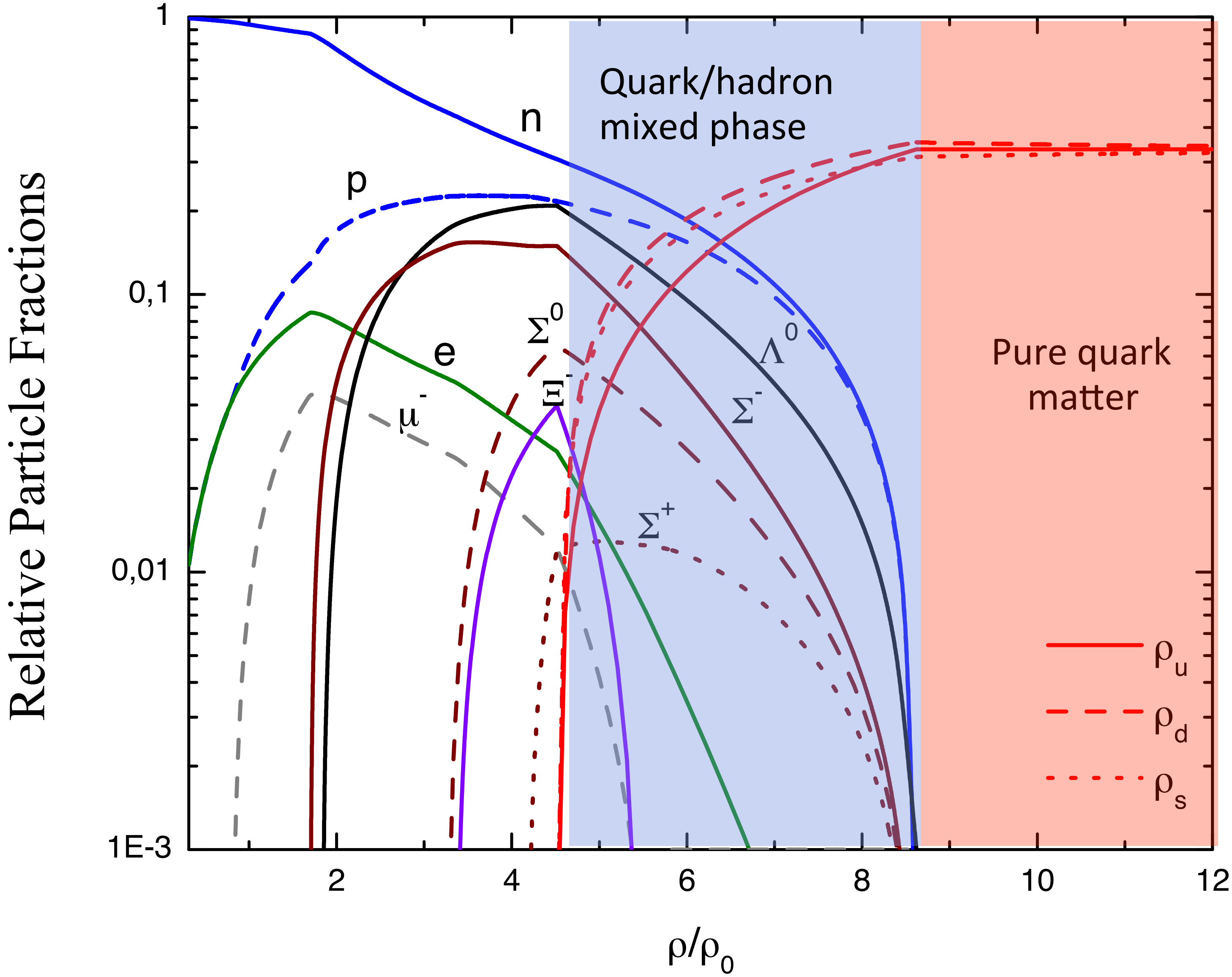
- Impose **global** (rather than local) electric charge neutrality

- Relaxes the extreme isospin asymmetry of neutron star matter
  - Allows for re-arrangement of electric charges
  - **Positively** charged regions of nuclear matter
  - **Negatively** charged regions of quark matter

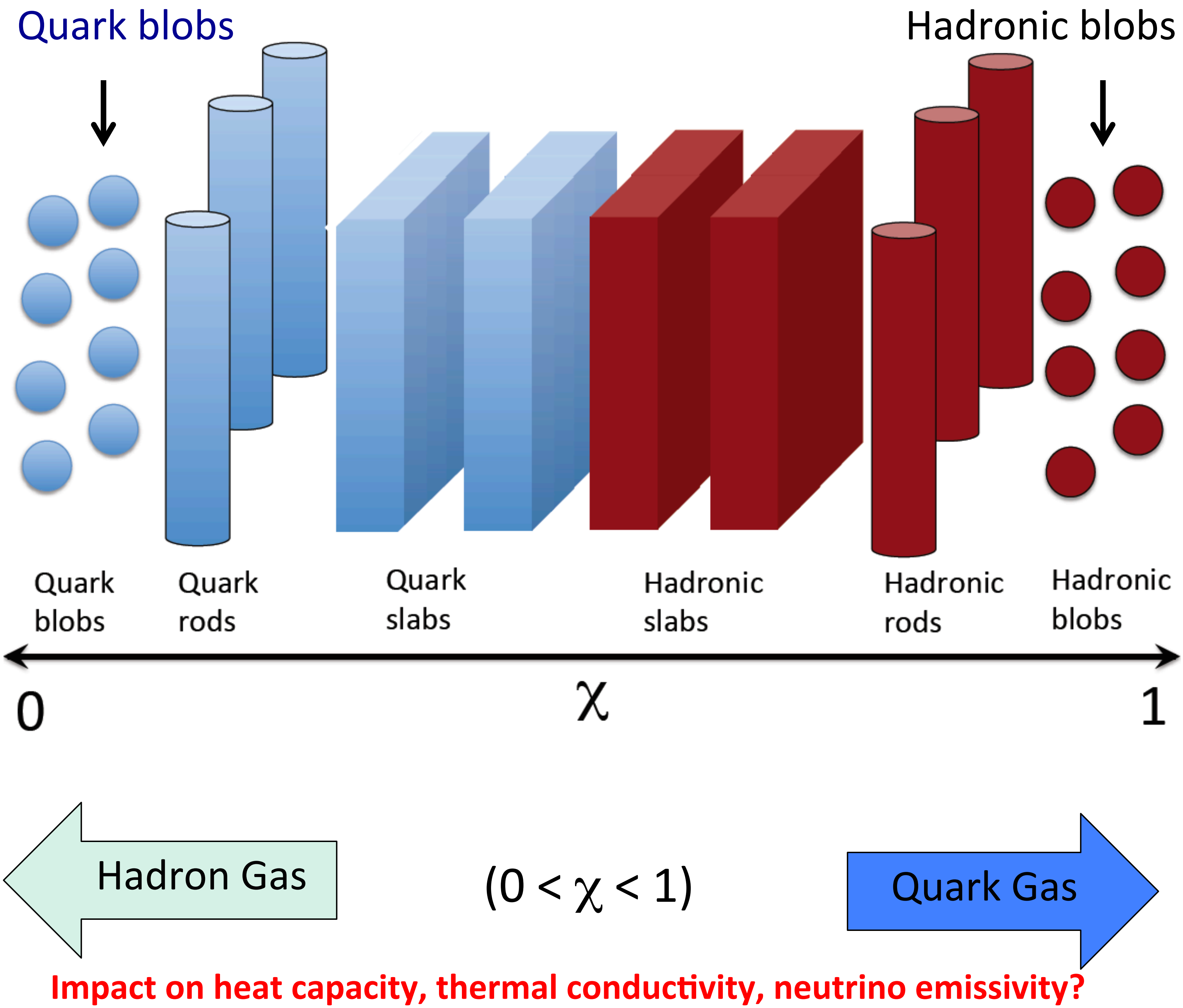
- Competition between Coulomb and surface energies in the mixed phase

- Mixed quark-hadron phase may develop geometrical structures

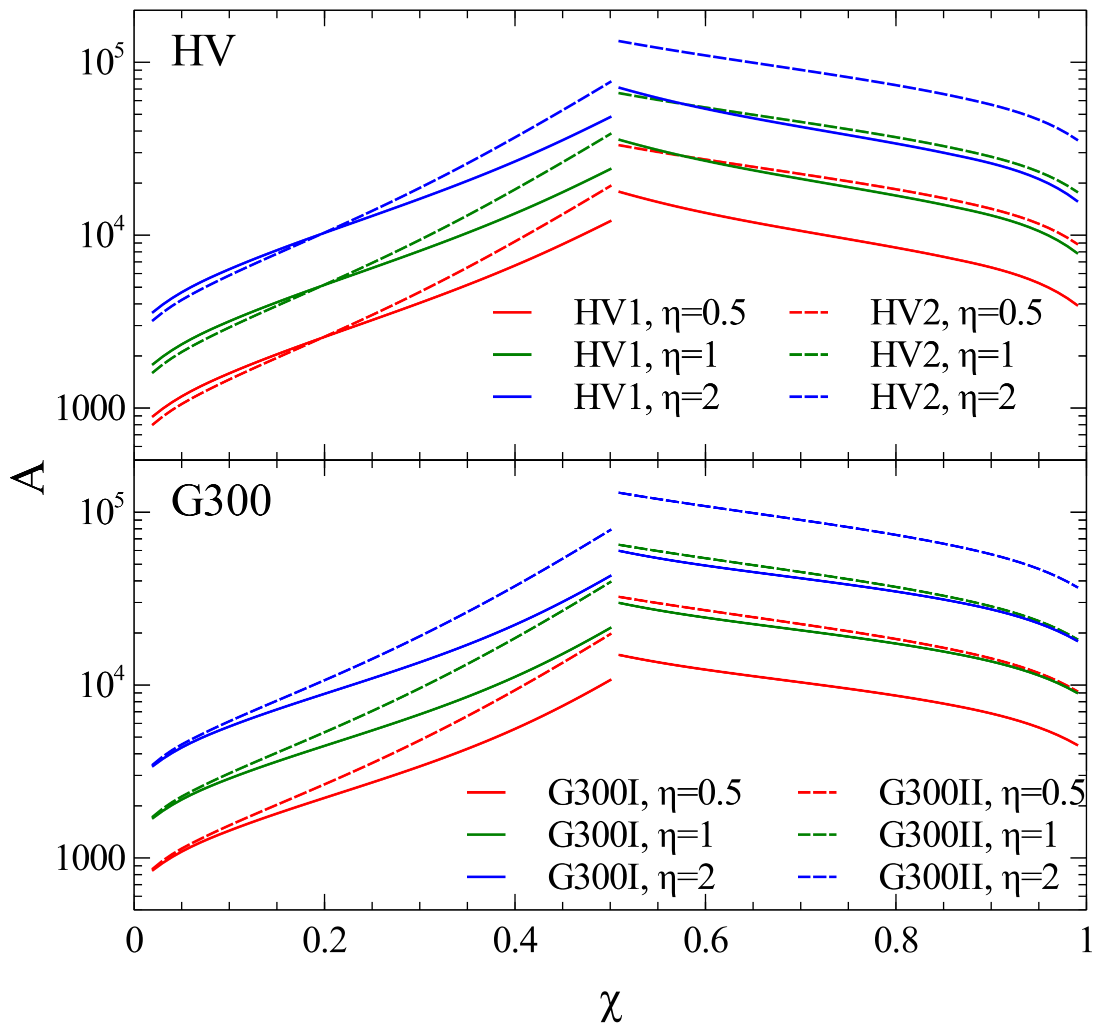
Model Neutron Star Matter Composition



Milva Orsaria & Hilario Rodrigues (June 2012)

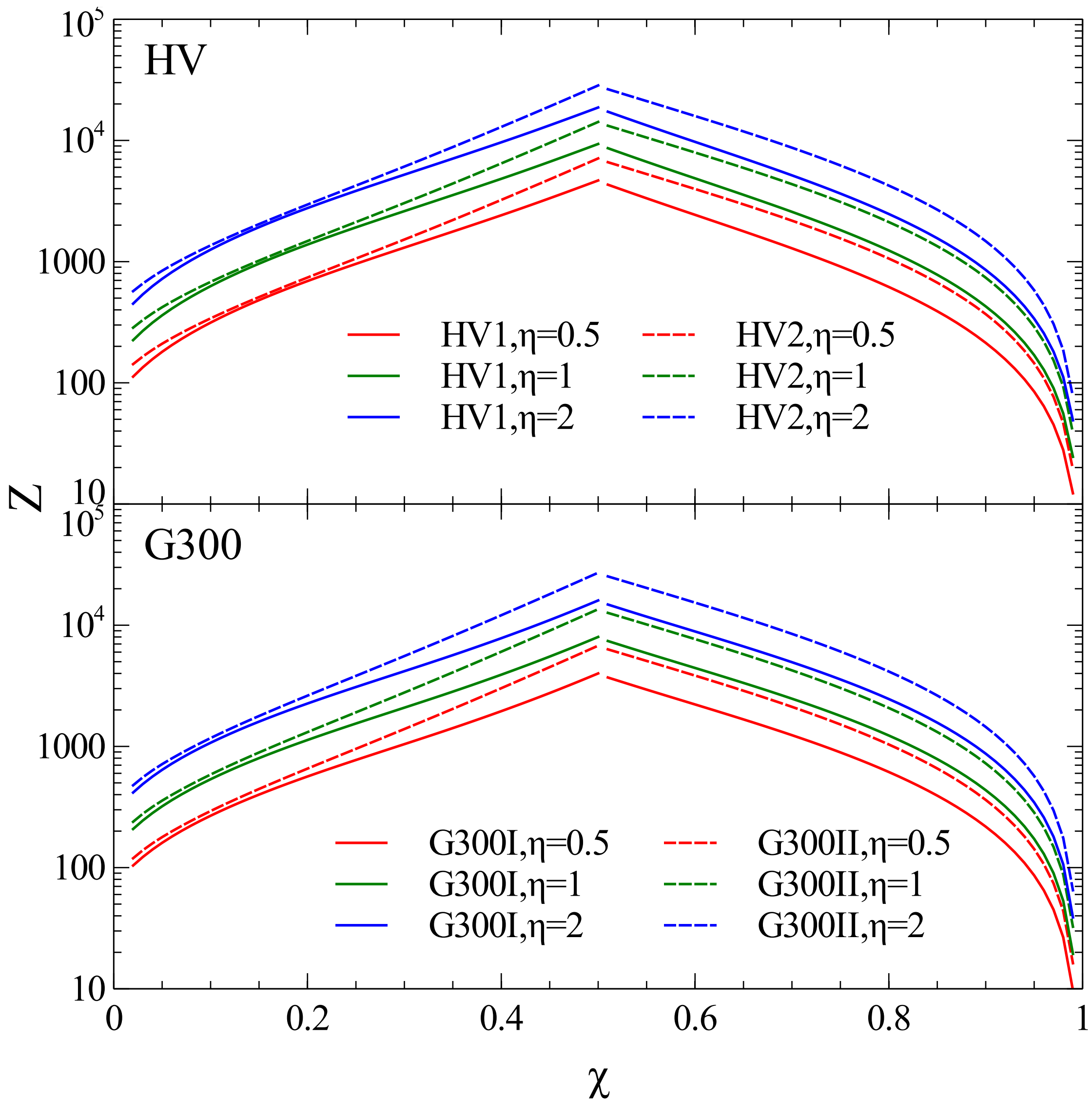

Quark blobs
Hadronic blobs
Quark blobs
Quark rods
Quark slabs
Hadronic slabs
Hadronic rods
Hadronic blobs
0
χ
1
Hadron Gas
(0 < χ < 1)
Quark Gas
Impact on heat capacity, thermal conductivity, neutrino emissivity?

Mass number, A, of spherical blobs as a function of quark volume fraction, χ

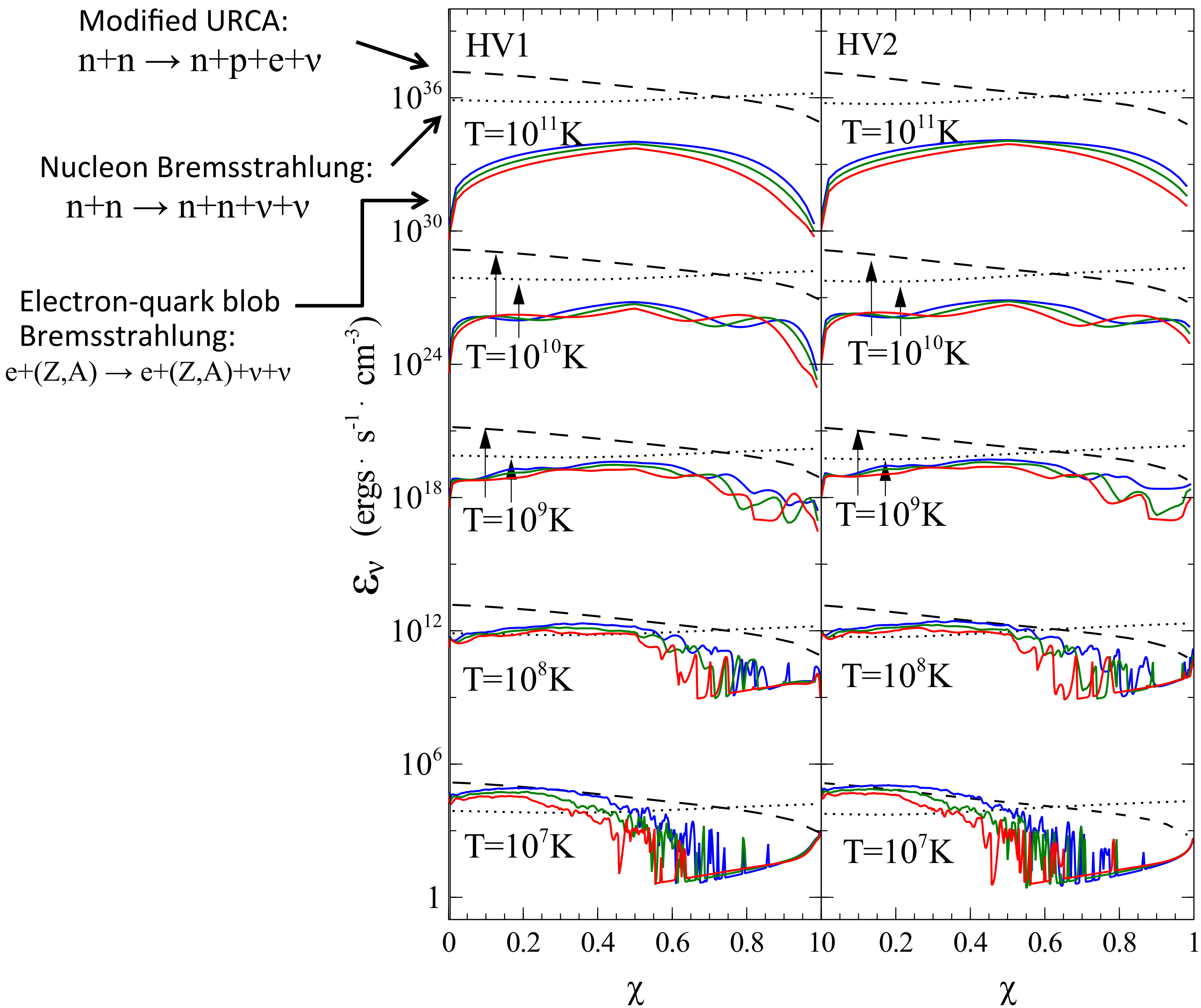


Xuesen Na, R. X. Xu & FW, arXiv:1208.5022v1 astro-ph.SR (to appear in PRD)

Electric charge, Z, of spherical blobs as a function of quark volume fraction, χ

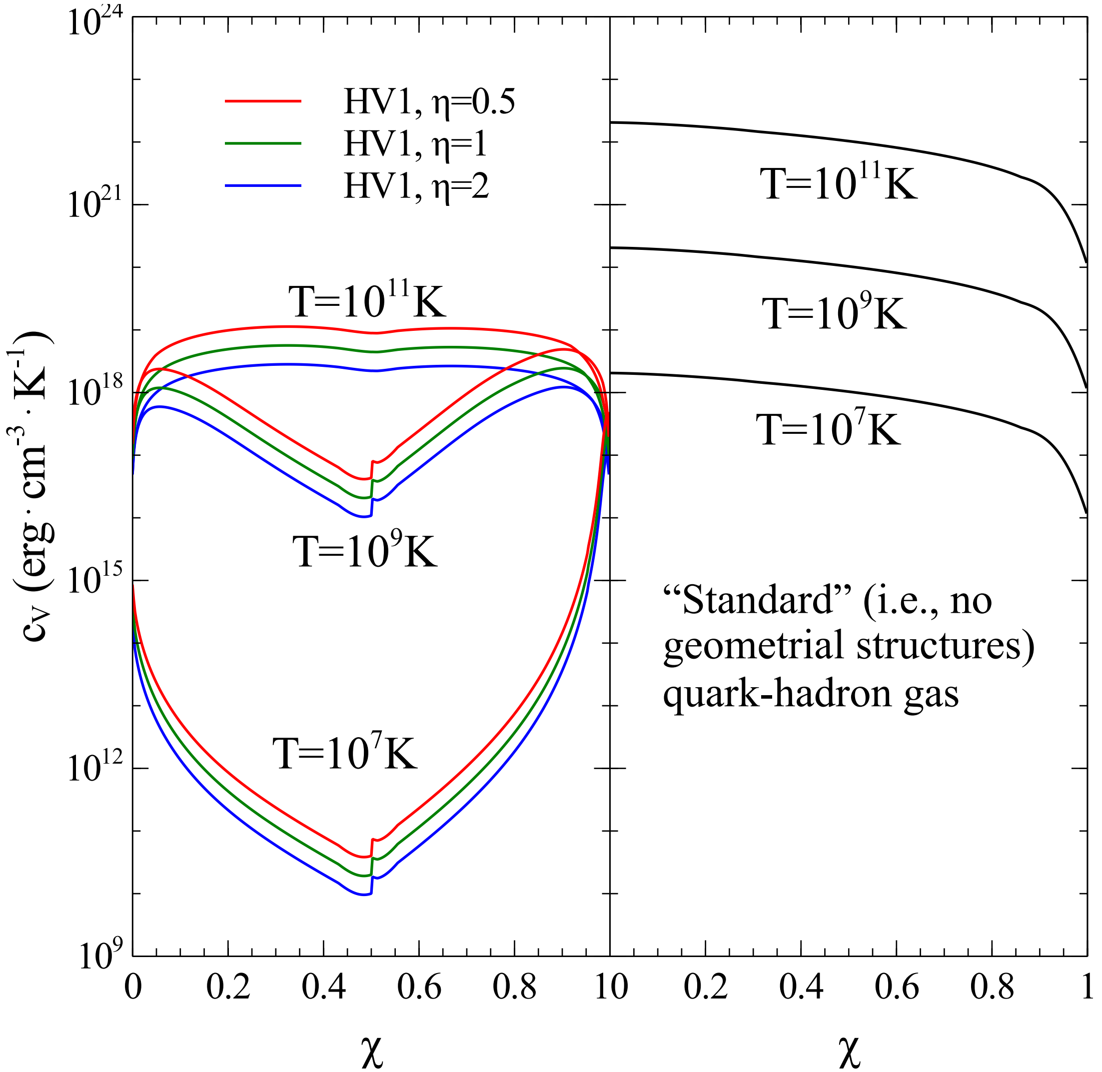


Xuesen Na, R. X. Xu & FW, arXiv:1208.5022v1 astro-ph.SR (to appear in PRD)



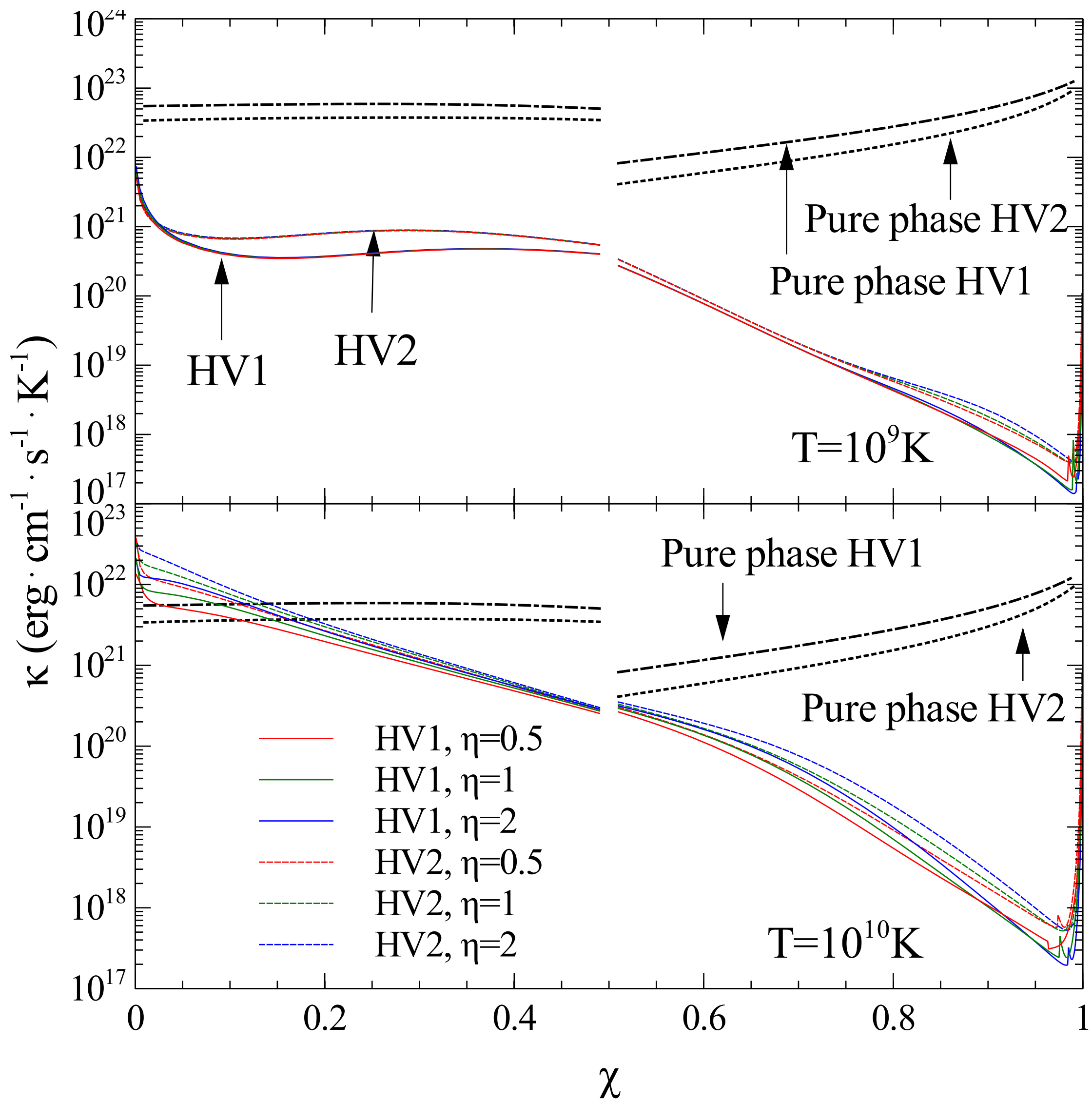
Xuesen Na, R. X. Xu & FW, arXiv:1208.5022v2 (to appear in PRD)

Specific heat, c_v, of quark-hadron phase as a function of quark volume fraction, χ



Xuesen Na, R. X. Xu & FW, arXiv:1208.5022v1 astro-ph.SR (to appear in PRD)

Thermal Conductivity



Xuesen Na, R. X. Xu & FW, arXiv:1208.5022v1 astro-ph.SR (to appear in PRD)

FACTS TO TAKE HOME

Particle composition in rotating (proto-) neutron stars is not frozen in:

- Neutron-to-proton ratio
- Hyperon population
- Boson condensates
- Quark matter fraction

all change with frequency.

Hyperons, boson condensates, quark matter may be removed/produced during spin-up/spin-down

FACTS TO TAKE HOME

Particle composition in rotating (proto-) neutron stars is not frozen in:

- Neutron-to-proton ratio
- Hyperon population
- Boson condensates
- Quark matter fraction

all change with frequency.

Observable signals

- Enhanced cooling turned on/off
- Spin-up of isolated NSs
- Backbending
- Braking index

Hyperons, boson condensates, quark matter may be removed/produced during spin-up/spin-down