SIGNALS OF QUARK MATTER IN COMPACT STARS

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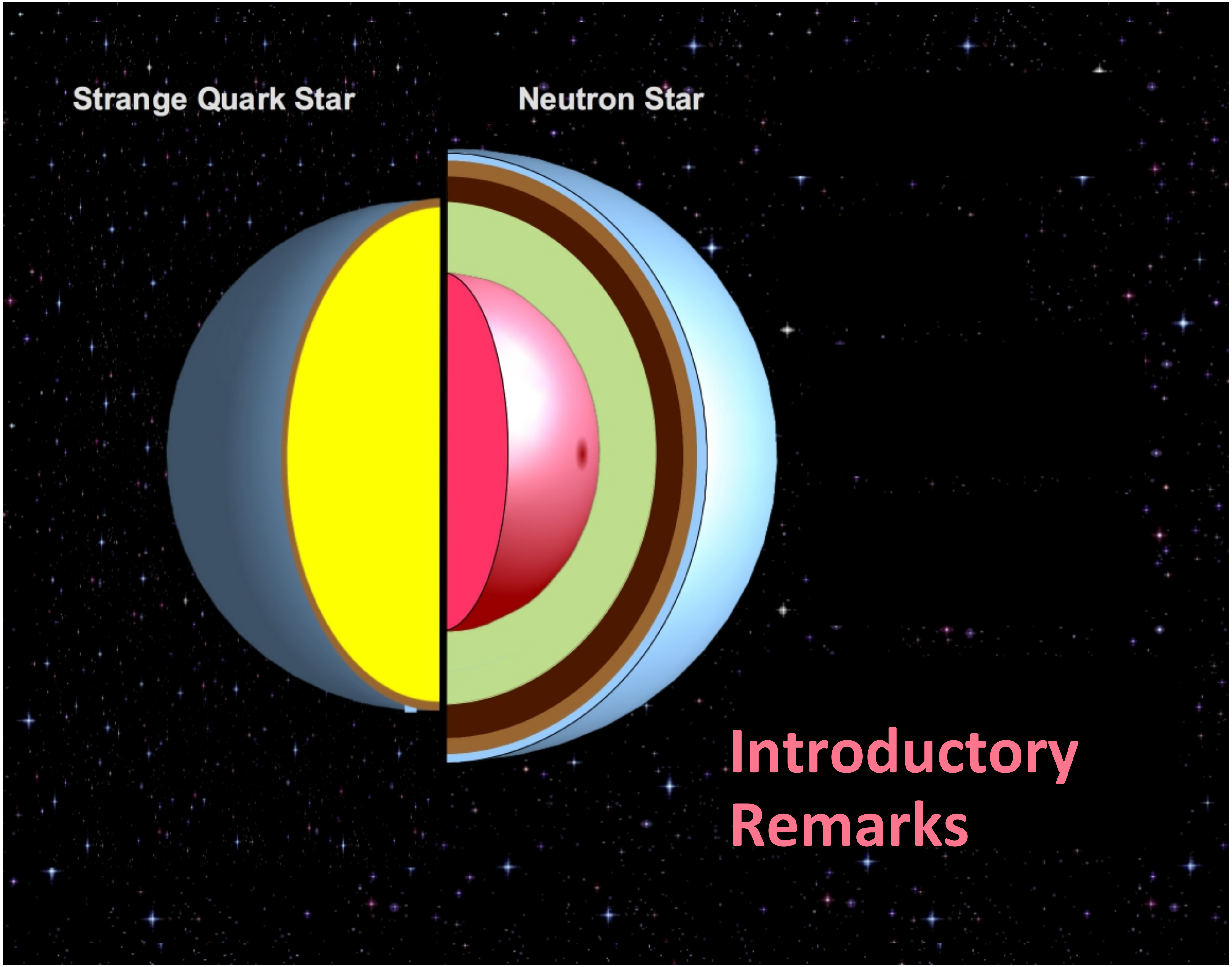
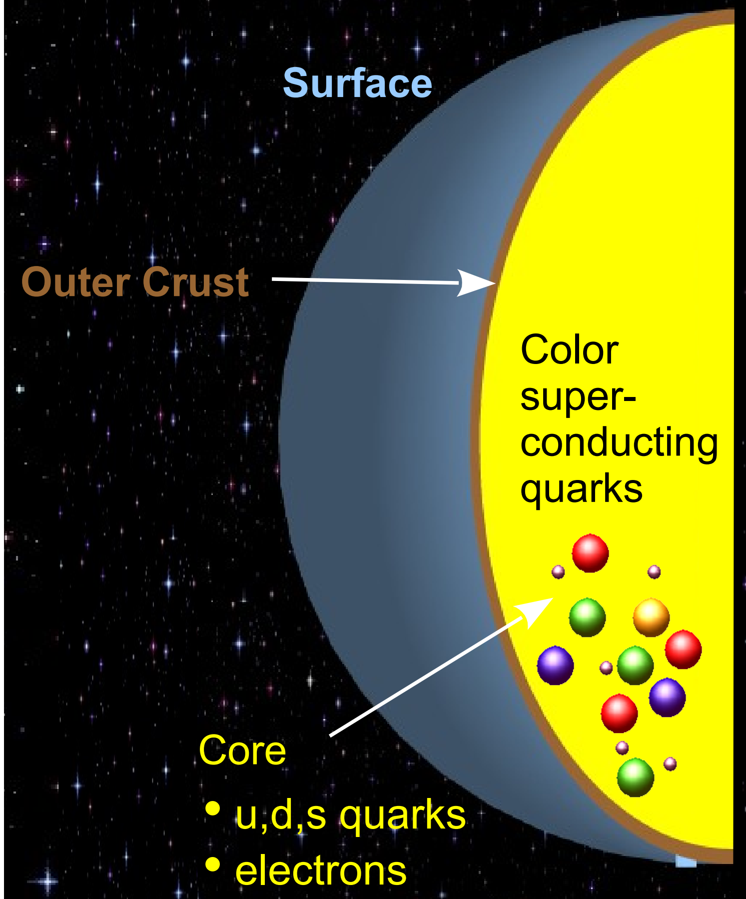
OUTLINE

- **Strange Quark Stars**
  - Mass-Radius relationship
  - Rapid rotation
  - Ultra-high electric fields
  - Oscillations of electron sea
  - Meissner effect (vortex expulsion)
- **"Neutron" Stars**
  - Rotation-driven particle repopulation
  - Mixed quark-hadron phase
  - Pure quark matter
  - Backbending
  - Quark-hadron lattice
  - Pycnonuclear reaction rates
- **Summary**

Introductory Remarks



Strange Quark Star



Radii < 10 km

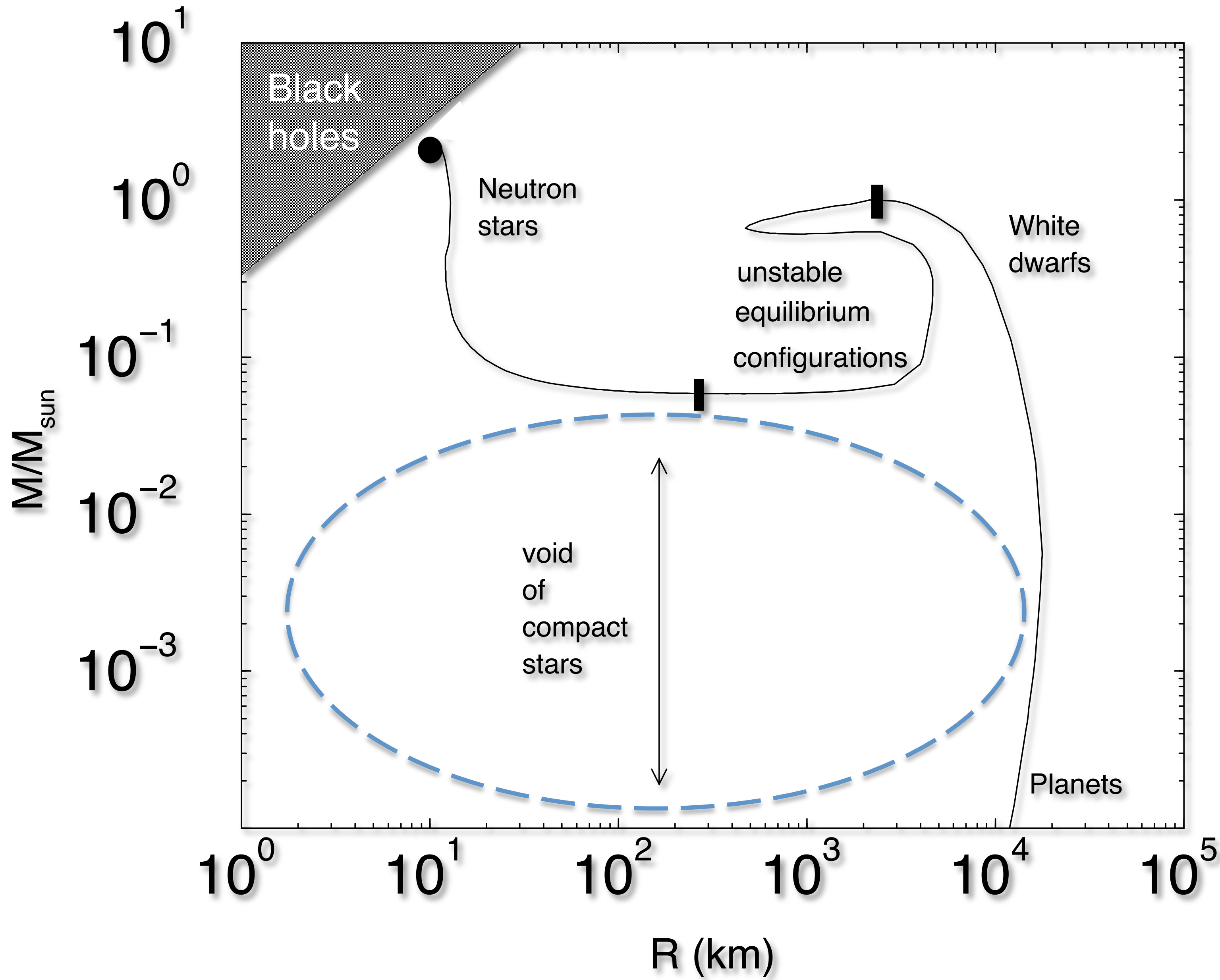
Masses ~1

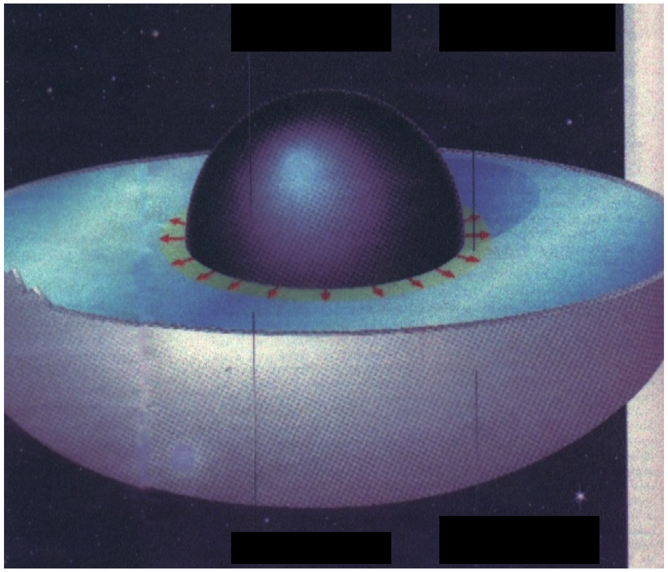
- **Made entirely of deconfined quarks**
- Self-bound ($M \sim R^3$)
- Electron dipole layer at surface (super-high electric fields)
- Either bare or “dressed” (i.e. may posses outer crusts)
- No inner crusts
- Two-parameter stellar sequence

Alcock, Farhi, Olinto, ApJ 310 (1986) 261;
Alcock & Olinto, Ann. Rev. Nucl. Part. Sci. 38 (1988) 161;
Madsen, Lecture Notes Phys. 516 (1999) 162.
Proc. Of Strange Quark Matter in Physics and Astrophysics, J. Madsen & P. Haensel, NPB (Proc. Suppl. 24B (1991)

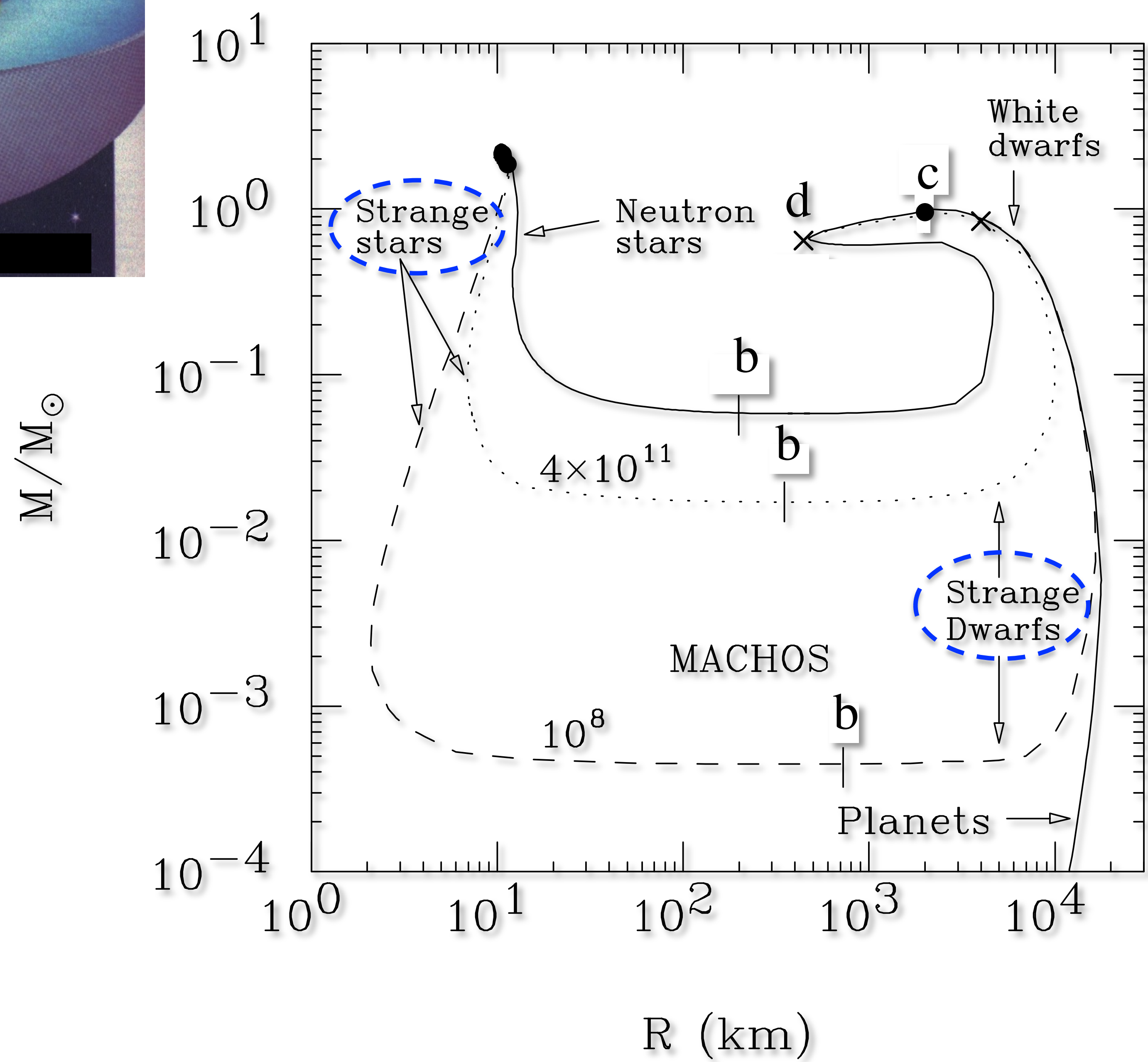
F. Weber (SDSU, 2012)

Mass-radius relationship of **neutron stars**

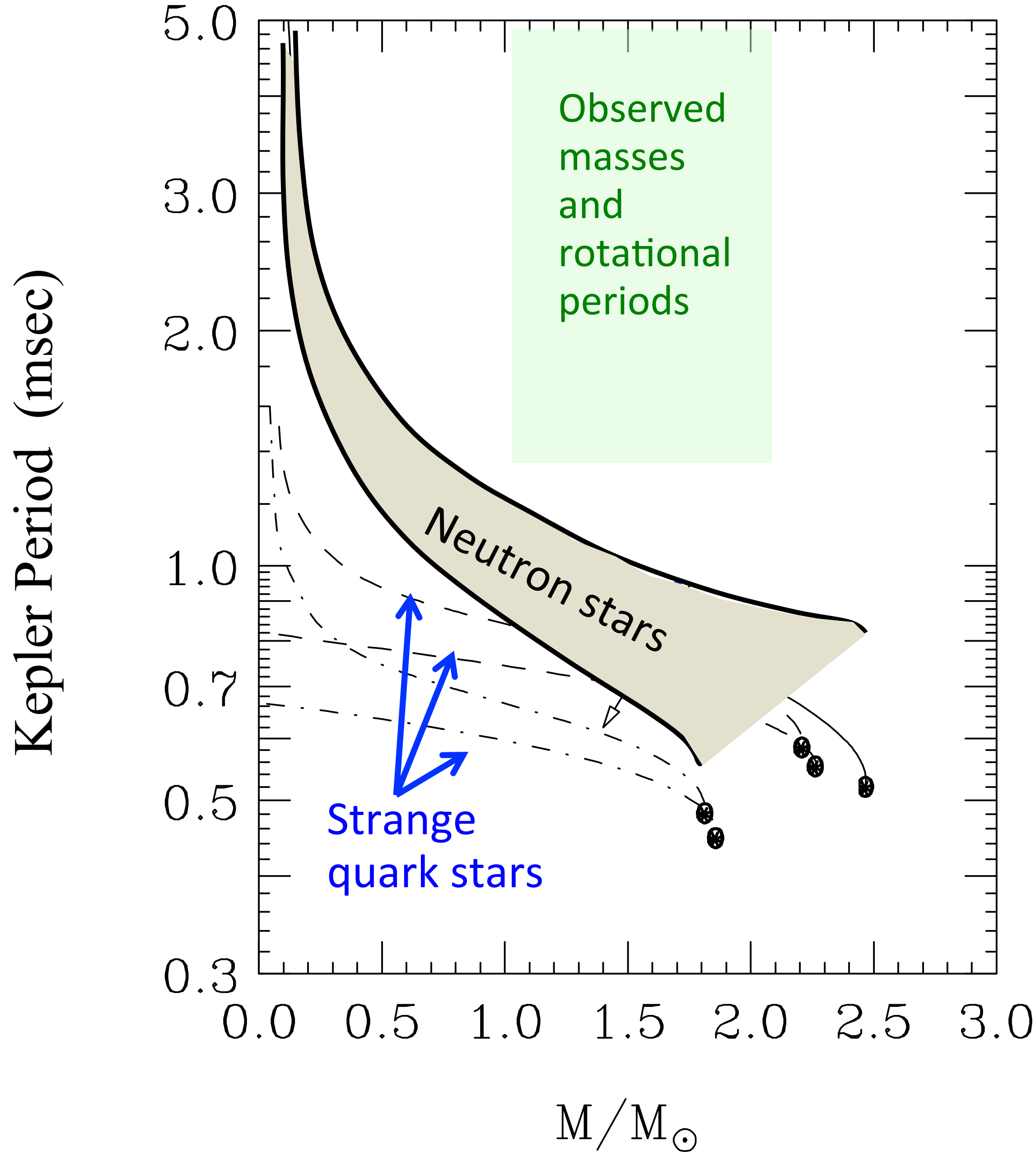




Mass-radius relationship of neutron stars and **strange quark stars**



Rotation at Sub-Millisecond Periods



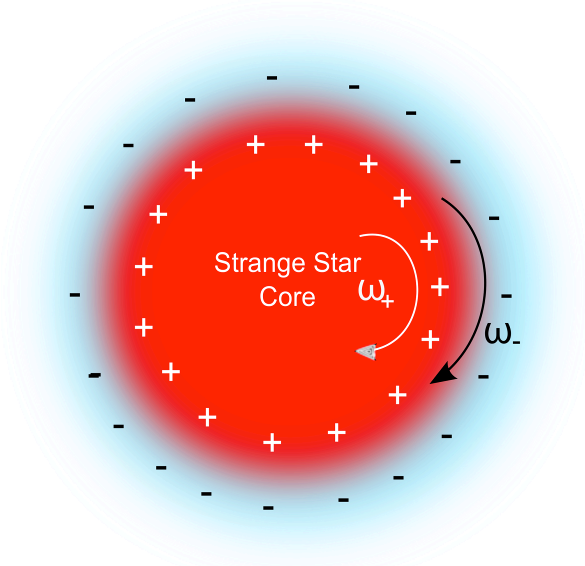
Electrically Charged Strange Quark Stars

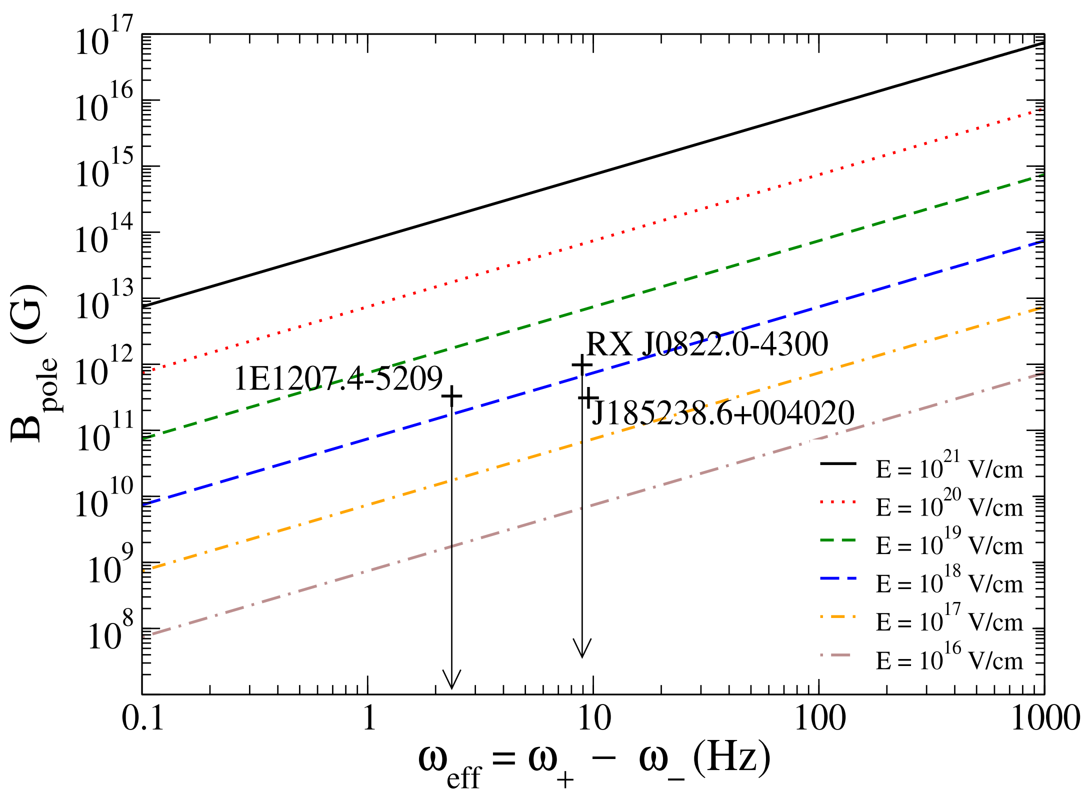
Electron sphere and quark core may rotate at different frequencies

Electric surface current: $I = \sigma(\omega_+ - \omega_-)$

Magnetic dipole field:

$$B = \text{const}\ E\,(\omega_+ - \omega_-)\,R$$





Could explain observed magnetic fields of 3 CCOs, whose rotation rate is known

R. Negreiros, I. Mishustin, S. Schramm, FW, PRD 82 (2010) 103010

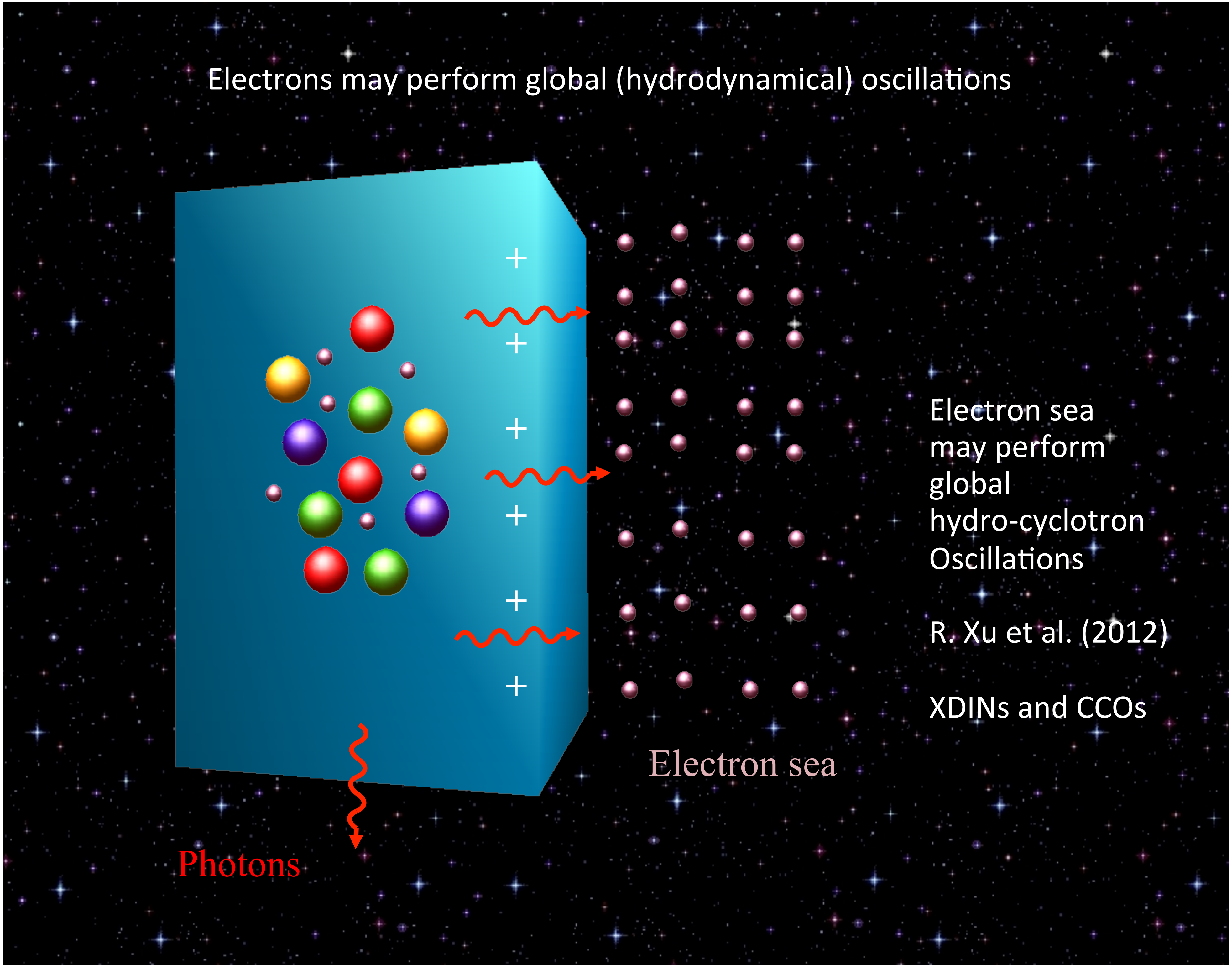
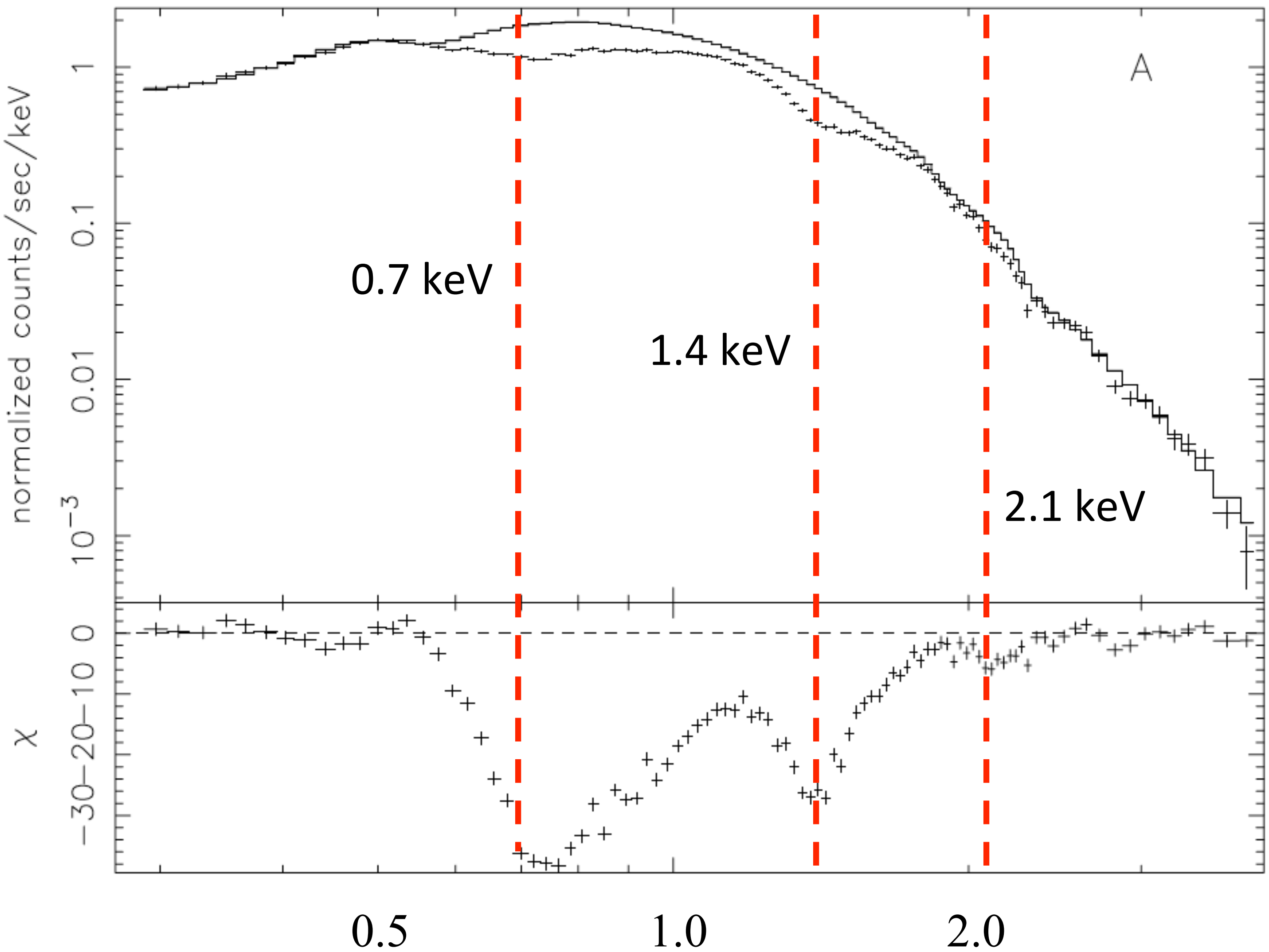

Electrons may perform global (hydrodynamical) oscillations
Electron sea
may perform
global
hydro-cyclotron
Oscillations
R. Xu et al. (2012)
XDINs and CCOs
Electron sea
Photons

TABLE I. Dead pulsars (CCOs and XDINSs) with observed spectral absorption lines [13–15], with P as the spin period, B the magnetic field ($B_{10} = B/10^{10}$ G) derived by magnetodipole braking, T the effective thermal temperature detected at infinity, and E_a the absorption energy. We do not list the B fields of XDINSs for which the propeller braking could be significant because of their long periods.

Source	P/s	B_{10}	kT/keV	E_a/keV
RX $J0822.0 - 4300$	0.112	$\lesssim$98	0.4	···
1E $1207.4 - 5209$	0.424	<33	0.22	0.7, 1.4
CXOU $J185238.6 + 004020$	0.105	3.1	0.3	···
RX $J0720.4 - 3125$	8.39		0.085	0.27
RX $J0806.4 - 4123$	11.37		0.096	0.46
RX $J0420.0 - 5022$	3.45		0.045	0.33
RX $J1308.6 + 2127$	10.31		0.086	0.3
RX $J1605.3 + 3249$	···		0.096	0.45
RX $J2143.0 + 0654$	9.43		0.104	0.7

Broad absoption lines observed

Absorption features in spectrum of 1E 1207.4-5209 at 0.7, 1.4 and 2.1 keV*



*G. F. Bignami, P. A. Caraveo, A. De Luca, & S. Mereghetti, Nature 423 (2003) 725

Absorption features in spectrum of 1E 1207.4-5209 at 0.7, 1.4 and 2.1 keV*

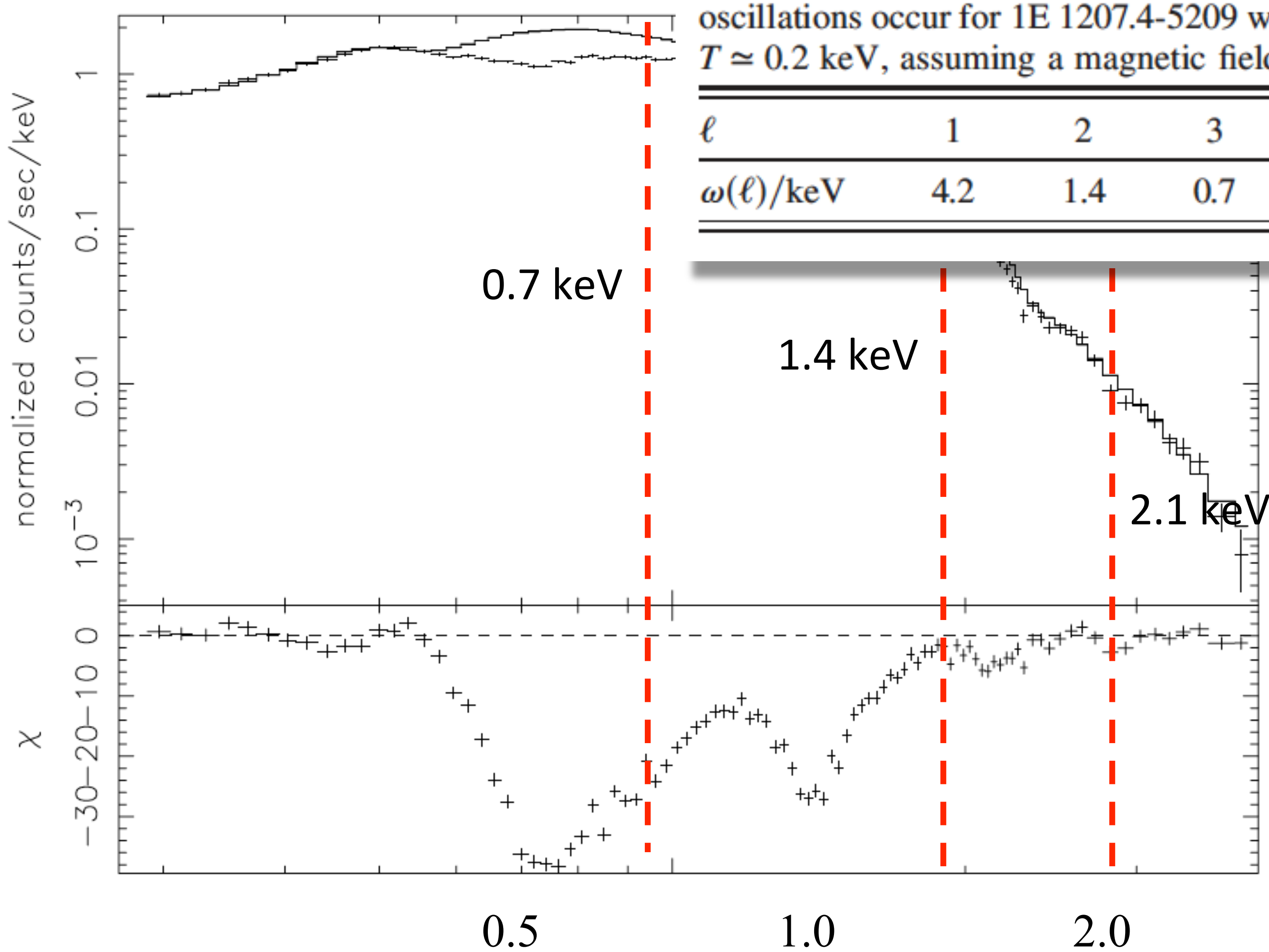


TABLE III. The frequencies, $\omega(\ell)$, at which hydrocyclotron oscillations occur for 1E 1207.4-5209 with effective temperature $T \simeq 0.2$ keV, assuming a magnetic field of $B \simeq 7 \times 10^{11}$ G.

ℓ	1	2	3	4	5	6
$\omega(\ell)$/keV	4.2	1.4	0.7	0.4	0.3	0.2

$$\frac{\omega(l)}{\omega_c} = \frac{1}{l(l+1)}$$

R. X. Xu at al.
PRD 85 (2012)
023008

*G. F. Bignami, P. A. Caraveo, A. De Luca, & S. Mereghetti, Nature 423 (2003) 725

Reheating of CFL Quark Stars via Vortex Expulsion

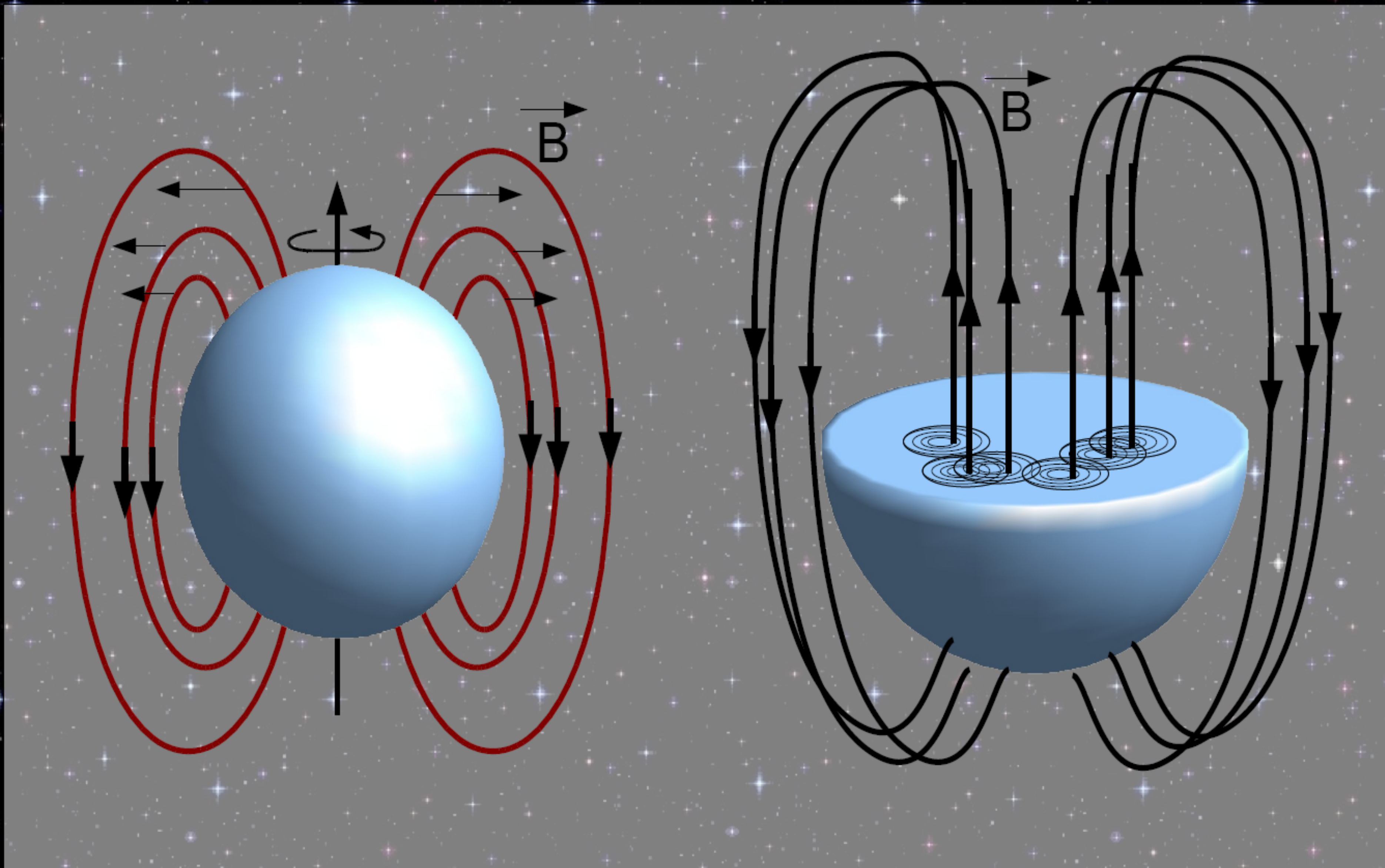
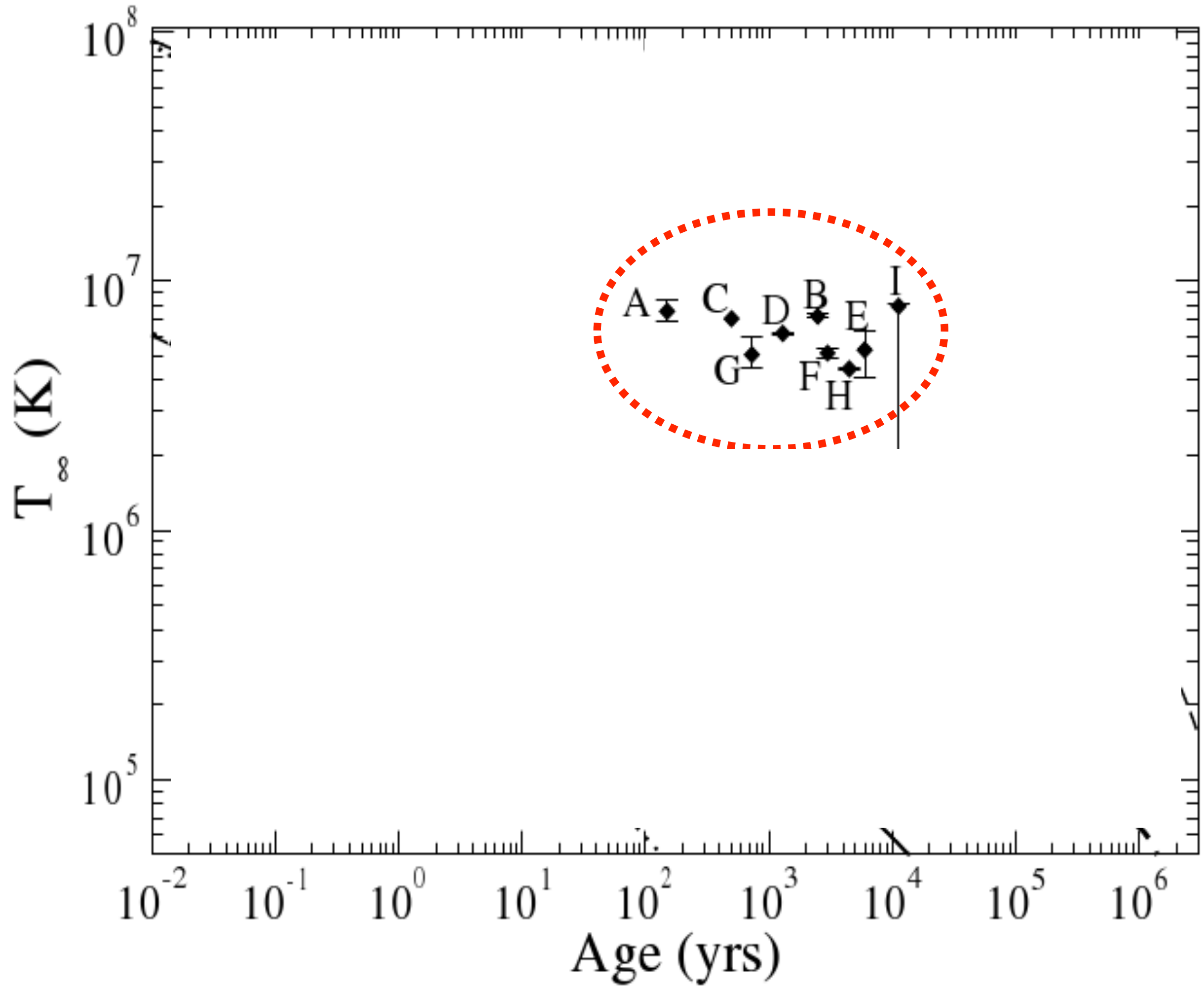
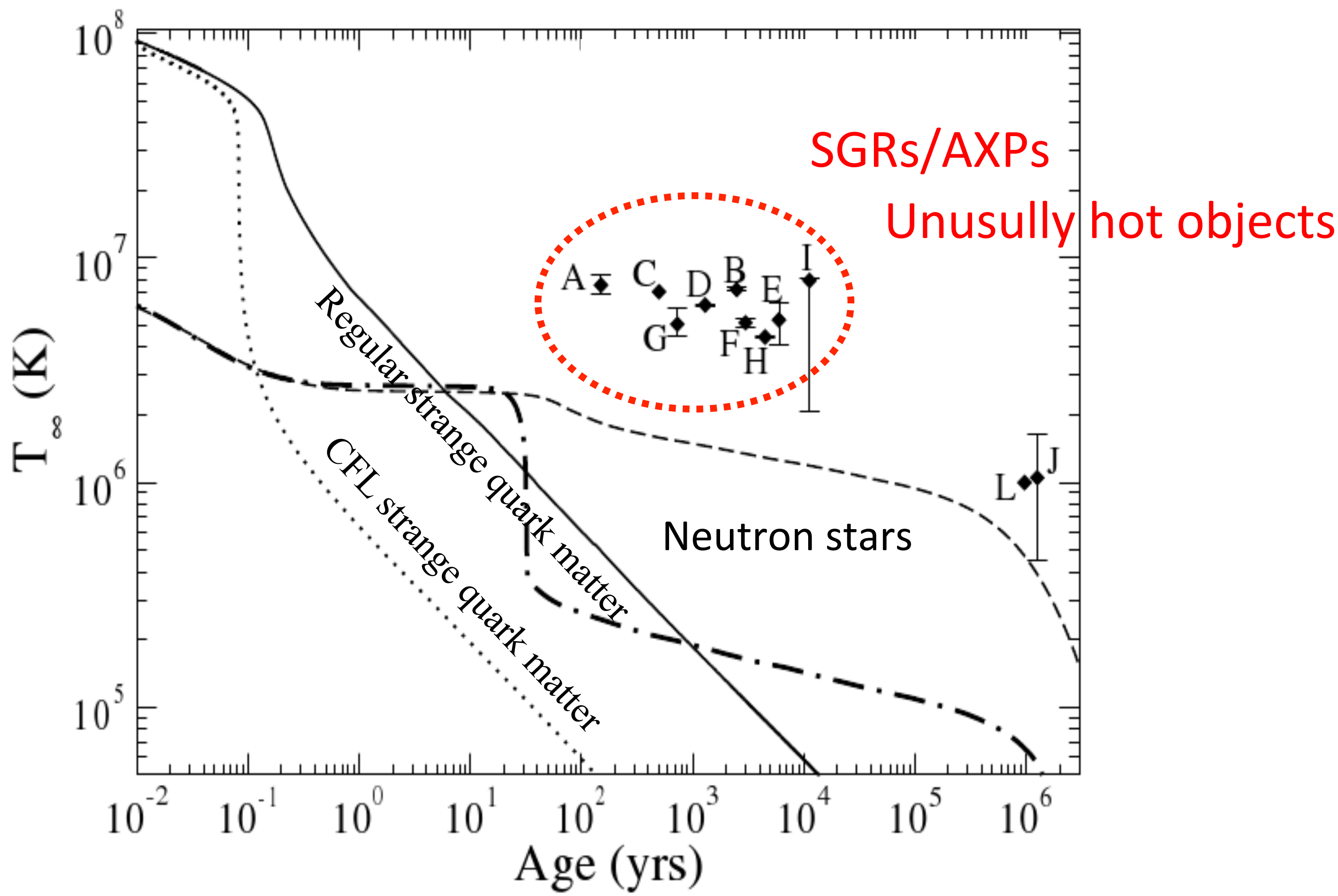


Image Credit: Rodrigo Negreiros

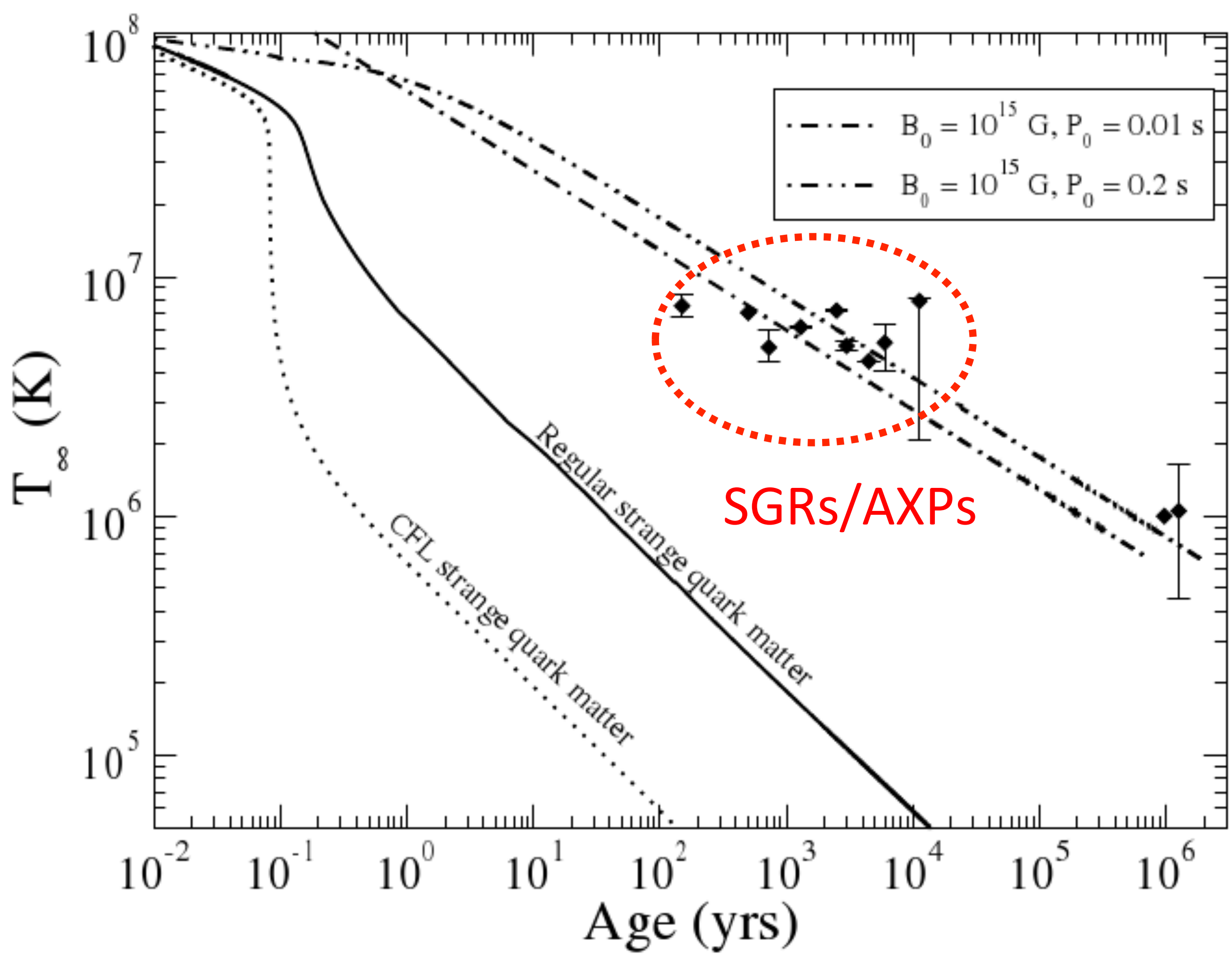


Negreiros, Niebergal, Ouyed, FW, PRD 81 (2010) 043005



Negreiros, Niebergal, Ouyed, FW, PRD 81 (2010) 043005

Cooling of CFL Quark Stars via Vortex Expulsion



Negreiros, Niebergal, Ouyed, FW, PRD 81 (2010) 043005

Equations of energy balance and thermal energy transport

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

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

Input: observed values for B_0 , P_0

Output: $P(t)$, $dP(t)/dt$, $B(t)$, $T(t)$, $l(t)$

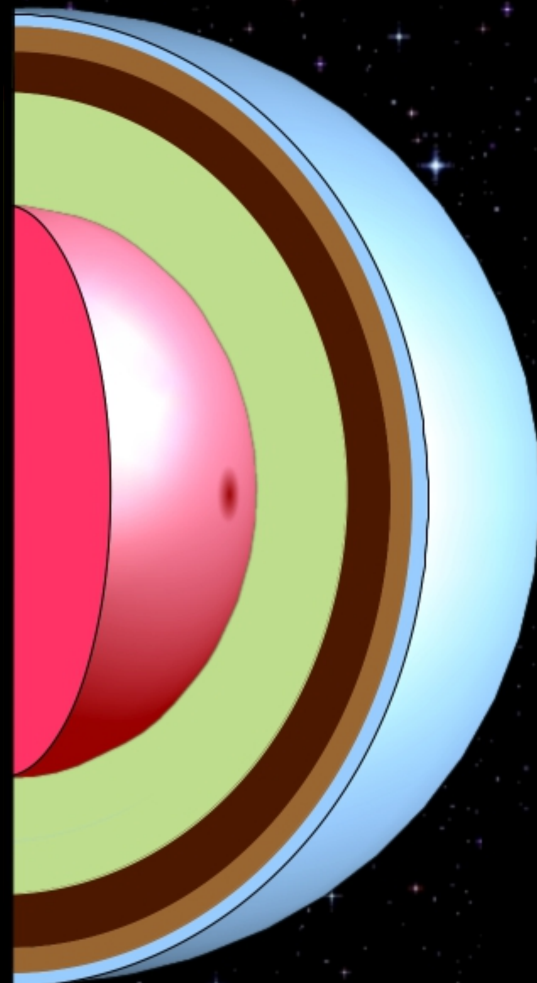
SUMMARY – STRANGE QUARK STARS

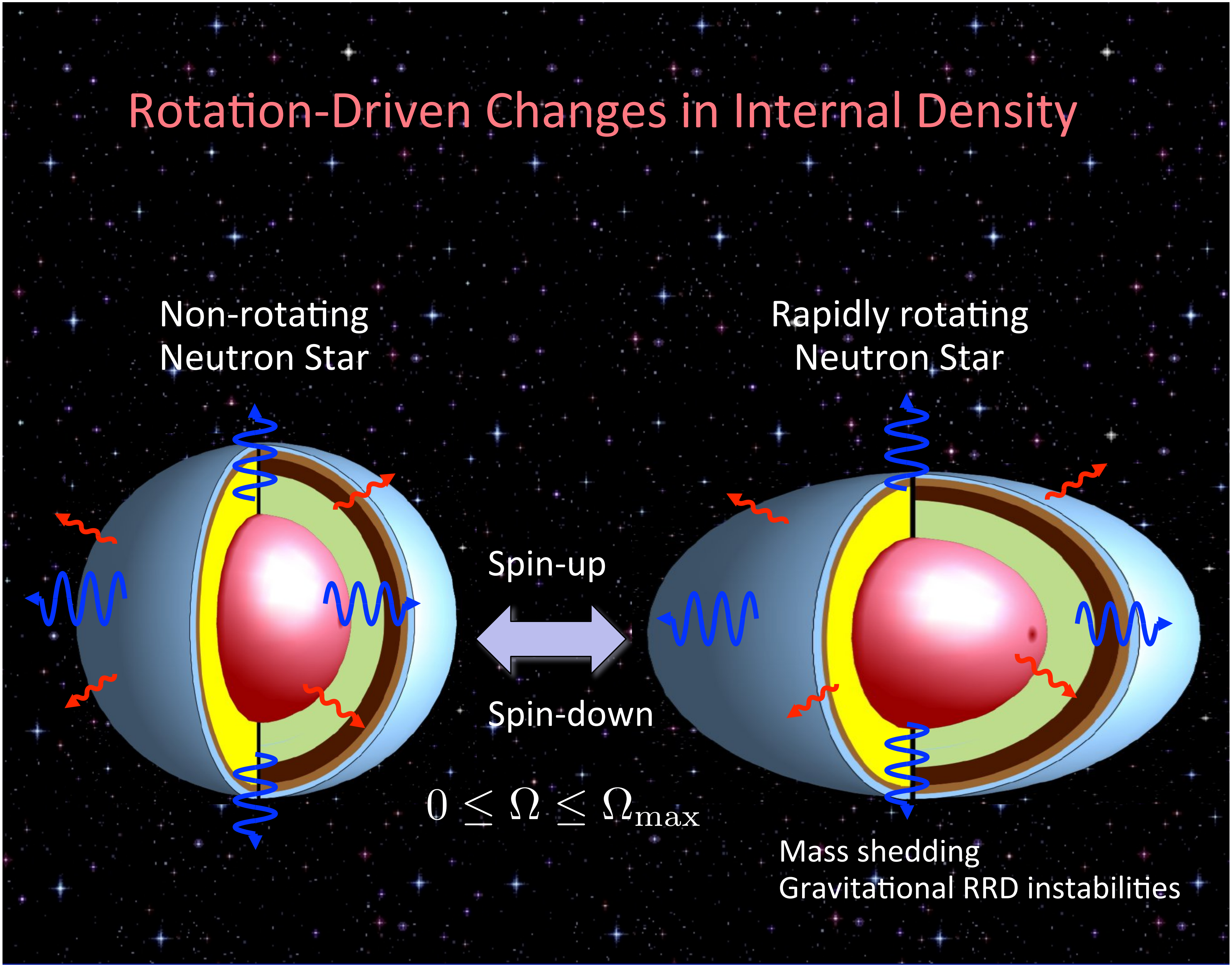
- Key differences between neutron stars and quark stars emerge from the fact that quark stars are **self-bound, form 2-paramter sequences,** and possess **electron seas** at their surfaces.

- Stellar properties/phenomena to watch out for:
  - Superfast rotation of light compact objects
  - Strange quark matter objects enveloped in thick nuclear crusts (strange dwarfs)
  - Rotating electron sea (could explain magnetic fields of CCOs)
  - Global oscillations of electron sea (absorption features of CCOs, XDINs)
  - Meissner effect could reheat quark stars (hot objects SGRs, AXPs)
  - Superbursts from strange stars (D. Page & A. Cumming)
  - Quark-Nova model (R. Ouyed et al.)

Neutron Star

- Bound by gravity
- 10^{56} to 10^{57} baryons
- Outer crust
- Inner crust
- **Deconfined quarks only in stellar core (if at all)**
- One-parameter stellar sequence

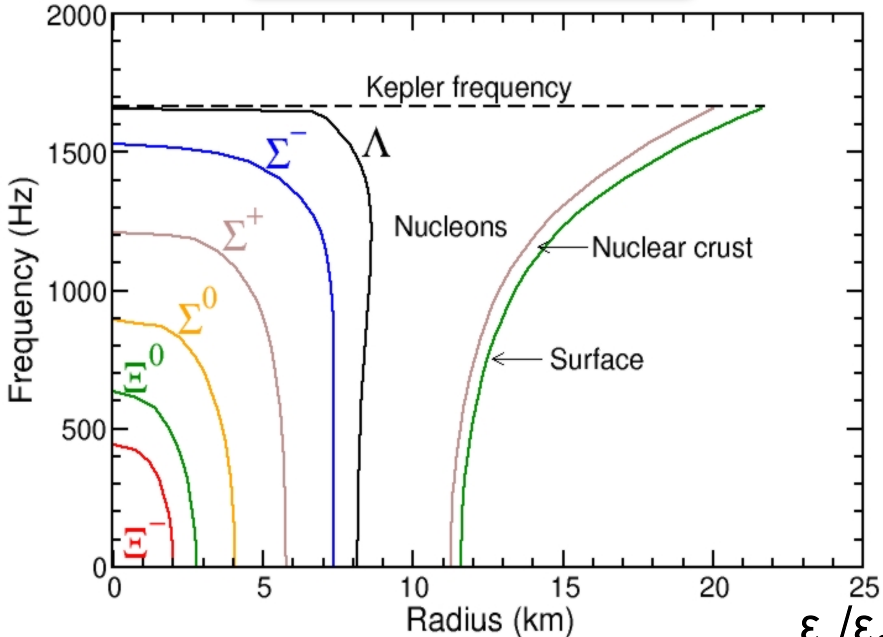



Rotation-Driven Changes in Internal Density
Non-rotating
Neutron Star
Rapidly rotating
Neutron Star
Spin-up
Spin-down
$0 \leq \Omega \leq \Omega_{\mathrm{max}}$
Mass shedding
Gravitational RRD instabilities

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

Equatorial direction

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



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

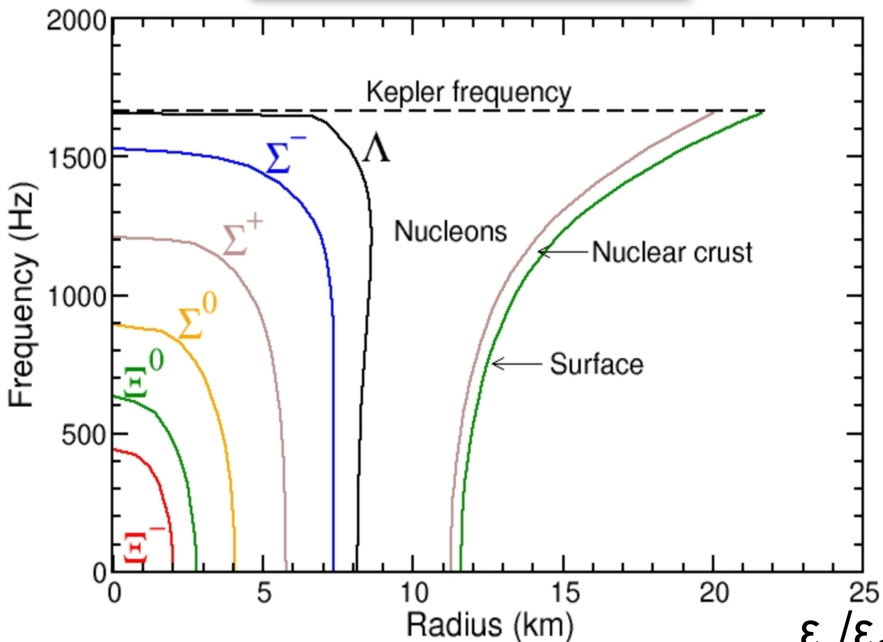
Rosenfield, (SDSU, 2008); Equation of state: DDRMF, Hofmann, Keil, Lenske.

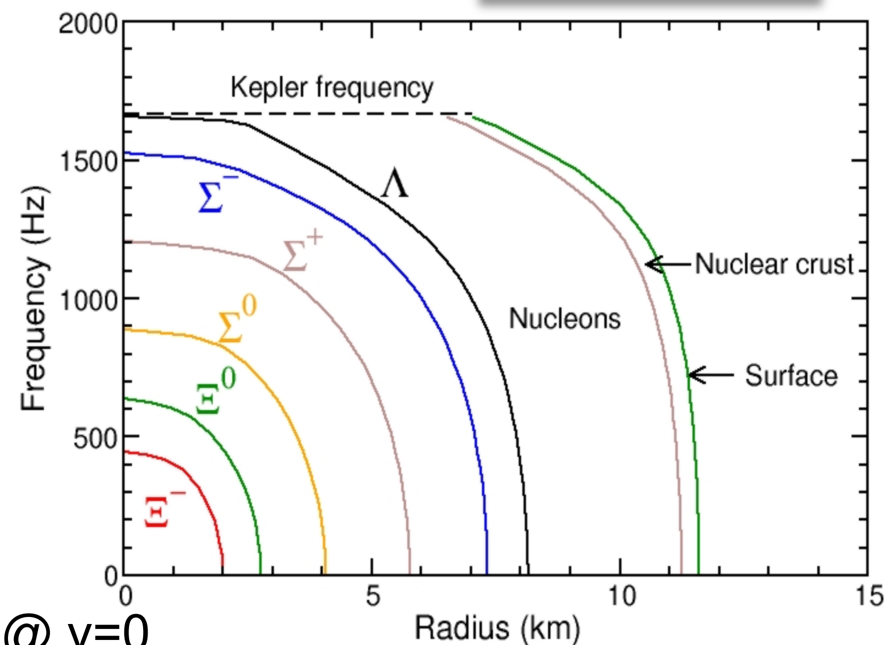
Model Composition of a M=1.7 M_{sun} Neutron Star

Equatorial direction

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

Polar direction

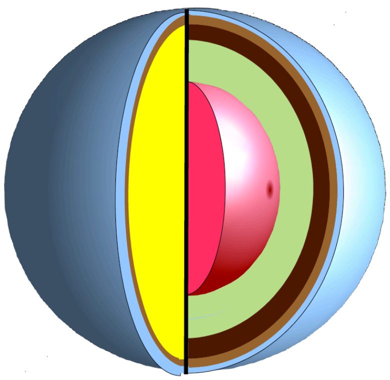


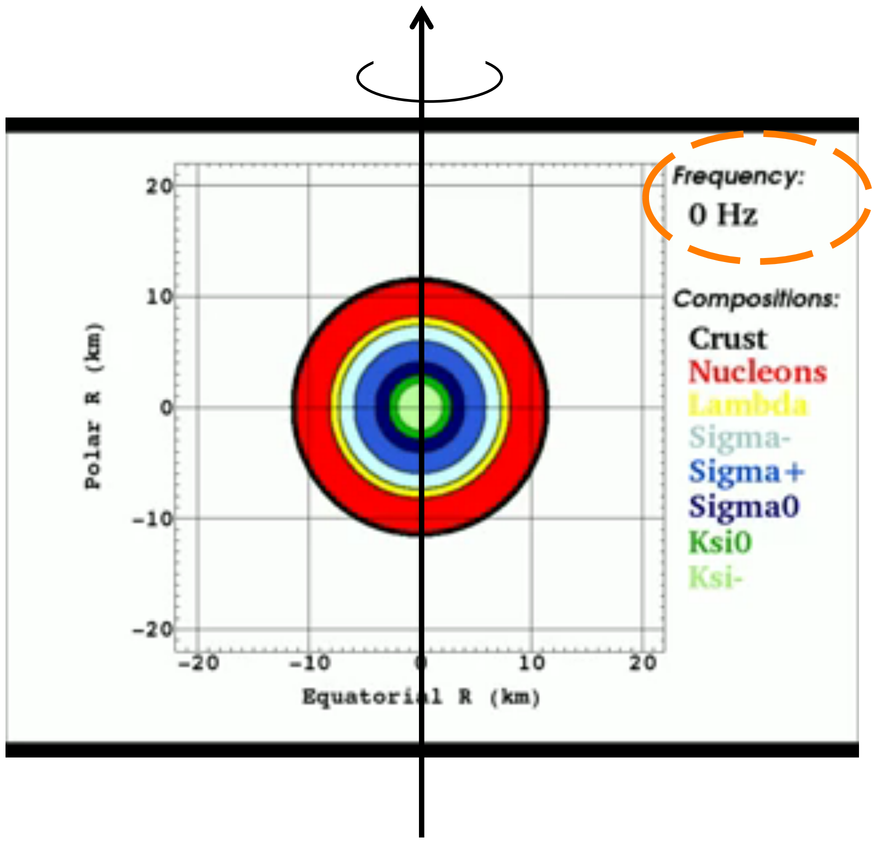


$\varepsilon_c/\varepsilon_0=7$ @ $v=0$

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

Rotation-driven compositional changes inside of neutron stars





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

Jirina Stone (ORNL) & FW, 2012

EoS: DDRMF (Hofmann, Keil, Lenske)

Quark-Hadron Matter In Cores of Neutron Stars?

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

- Model for confined hadronic matter (Schroedinger-based, RMF, RHF, RBHF)

- Phenomenological model for quark matter (MIT bag model, NJL)

$$P_h(\mu, \mu^e, \chi) = P_q(\mu, \mu^e, \chi) \,,$$

- Global/local electric charge neutrality

- Chemical equilibrium

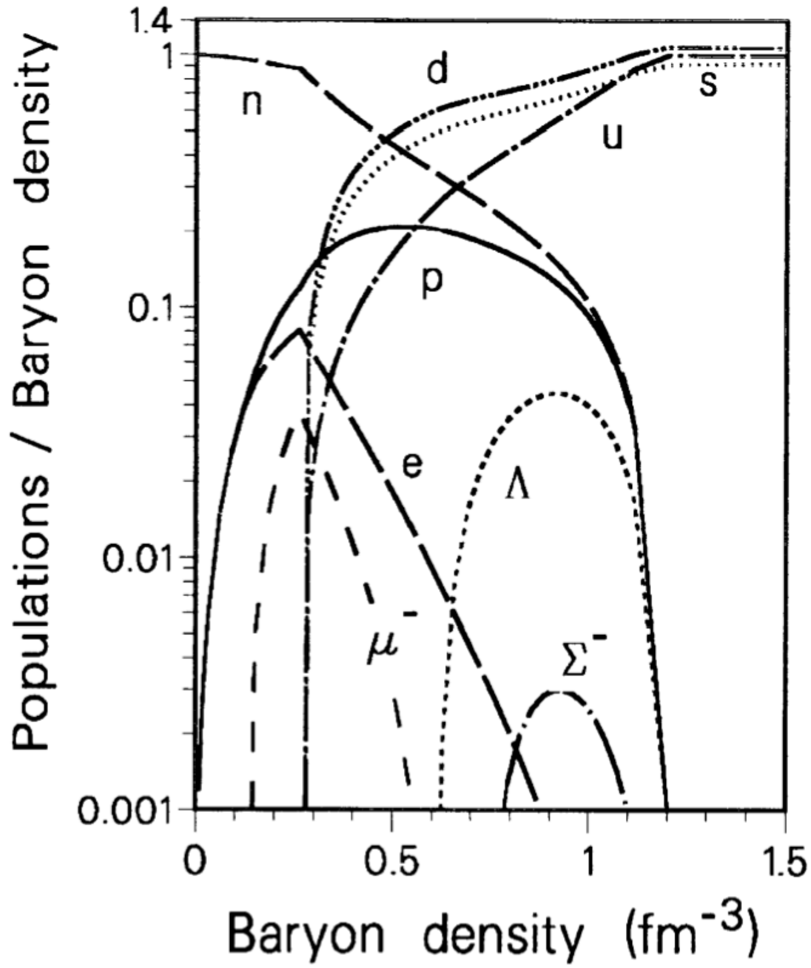
$$\mathcal{L} = \sum_{B=n,p,\Lambda,\Sigma,\Xi} \bar{\psi}_B \big[\gamma_\mu (i\partial^\mu - g_\omega \omega^\mu - g_\rho \vec{\rho}^\mu)$$
$$- (m_N - g_\sigma \sigma)\big]\psi_B + \frac{1}{2}(\partial_\mu \sigma \partial^\mu \sigma - m_\sigma^2 \sigma^2)$$
$$- \frac{1}{3} b_\sigma m_N (g_\sigma \sigma)^3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

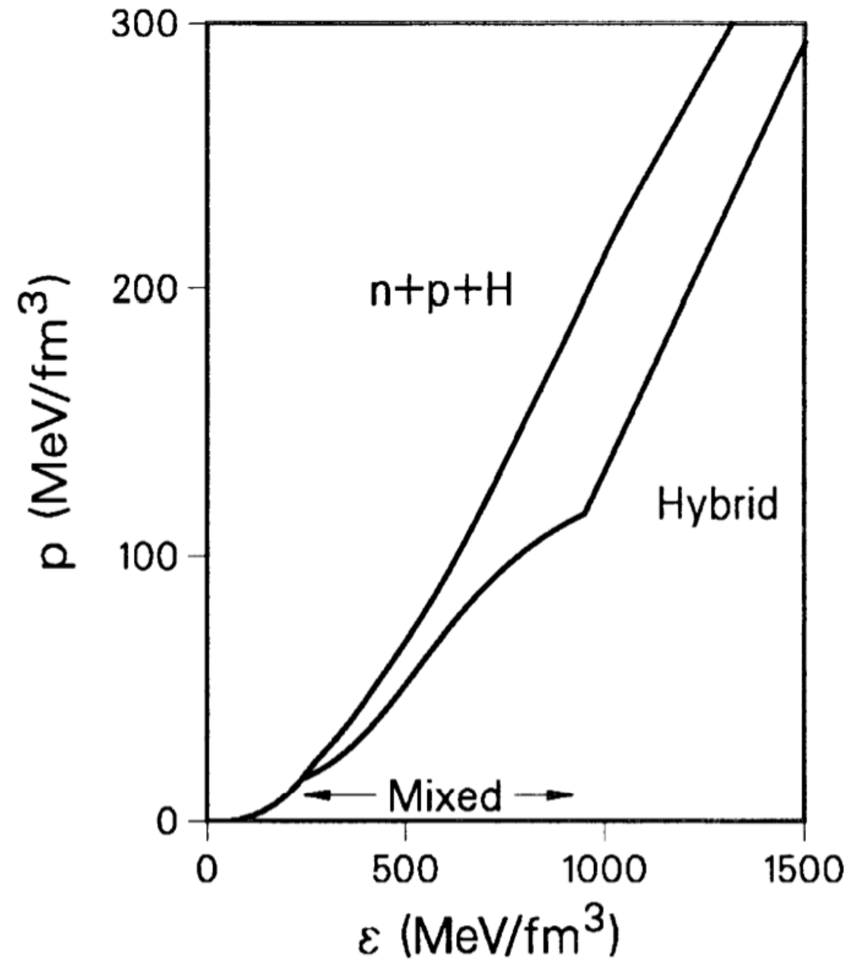
RMF

$$p = -B + \sum_f \frac{1}{4\pi^2} \left[\mu_f (\mu_f^2 - m_f^2)^{1/2} (\mu_f^2 - \tfrac{5}{2} m_f^2) + \tfrac{3}{2} m_f^4 \ln \left(\frac{\mu_f + (\mu_f^2 - m_f^2)^{1/2}}{m_f} \right) \right]$$

$$\epsilon = B + \sum_f \frac{3}{4\pi^2} \left[\mu_f (\mu_f^2 - m_f^2)^{1/2} (\mu_f^2 - \tfrac{1}{2} m_f^2) - \tfrac{1}{2} m_f^4 \ln \left(\frac{\mu_f + (\mu_f^2 - m_f^2)^{1/2}}{m_f} \right) \right]$$

MIT Bag model



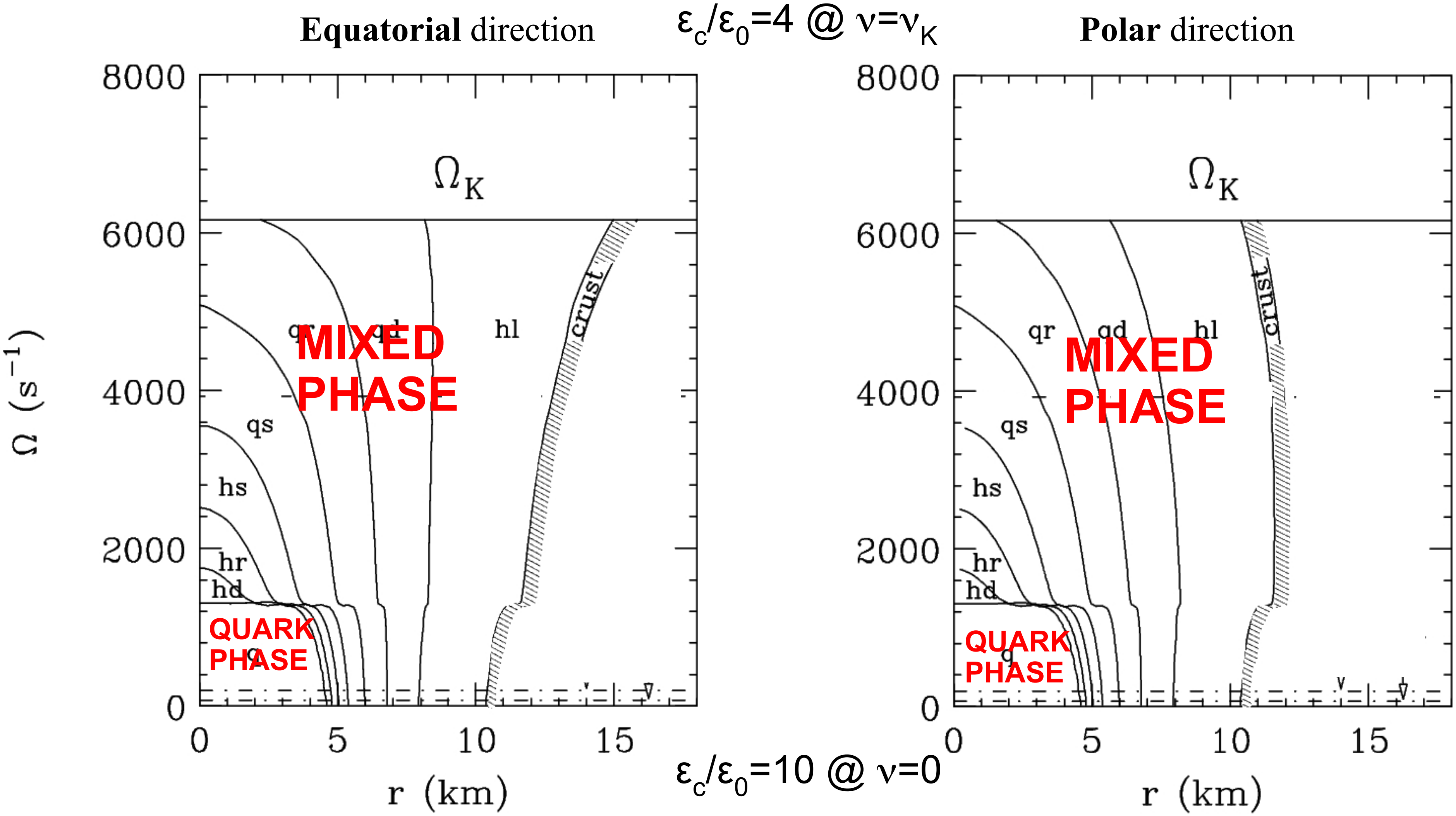


Glendenning, Phys. Rep. 342 (2001) 393

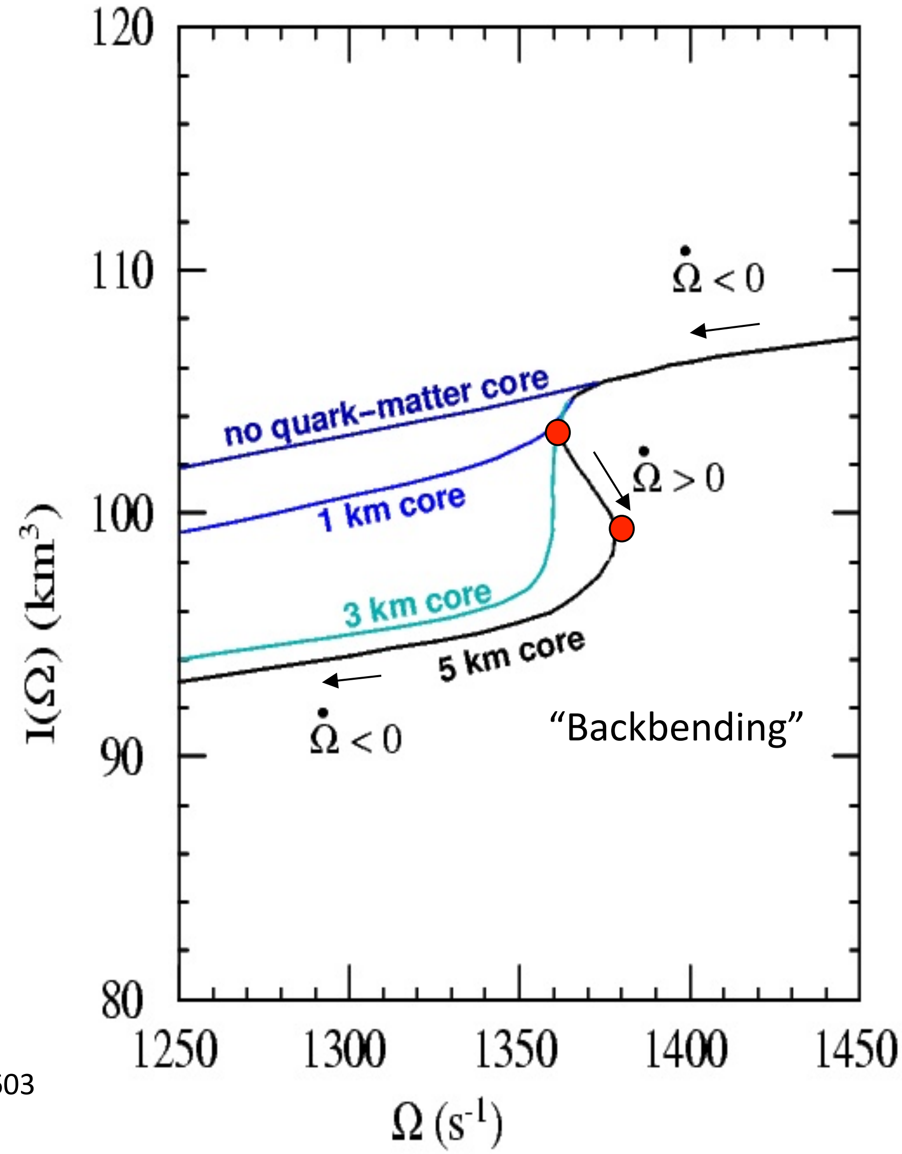
Characteristic features:

1. Broad mixed phase
2. $M_{max} < 1.5\ M_{sun}$

Model Quark-Hadron Composition of 1.45 M_{sun} Neutron Star



Moment of inertia of rotating quark-hybrid star



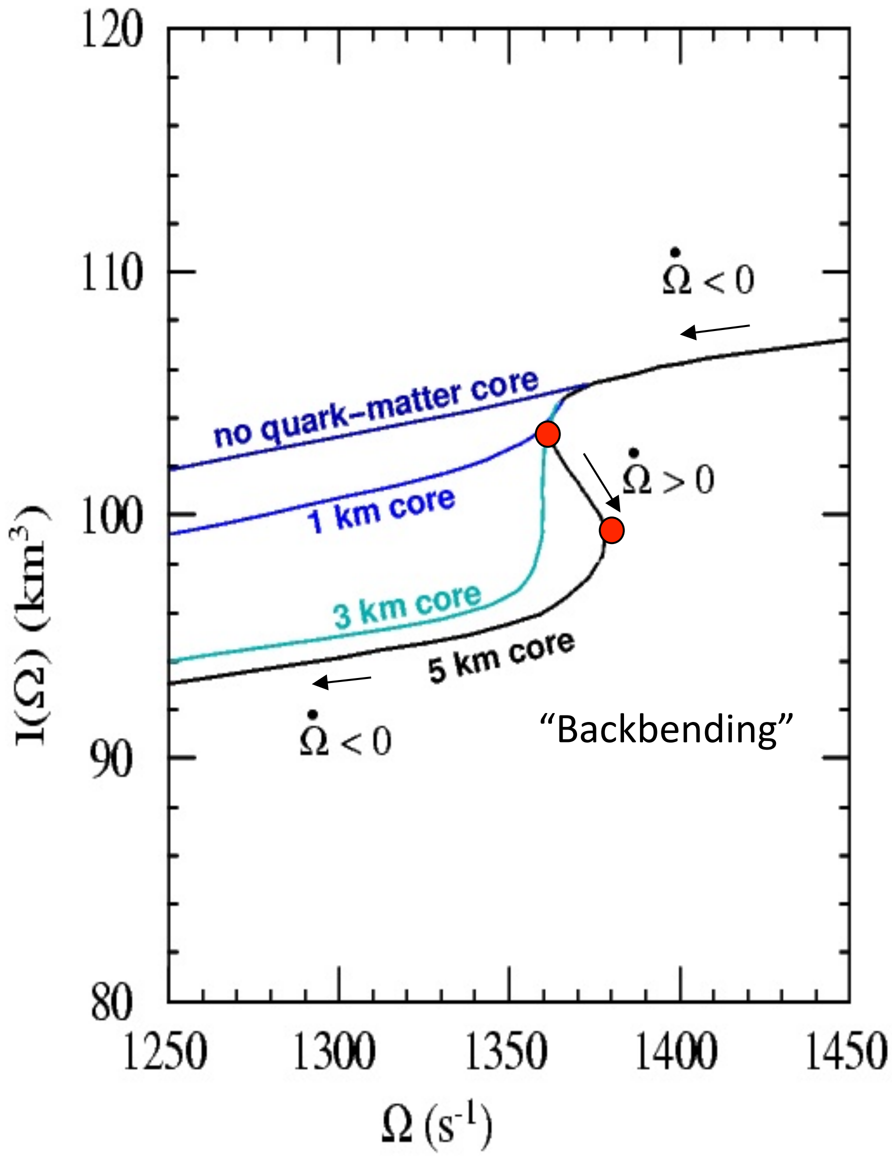
Glendenning, Pei, FW, PRL 79 (1997) 1603
Chubarian, Grigorian, Poghosyan, Blaschke A&A 357 (2000)
FW, Prog. Nucl. Part. Phys. 54 (2005) 193

Braking index of a pulsar

$$n(\Omega) \equiv \frac{\Omega\,\ddot{\Omega}}{\dot{\Omega}^2} = 3 - \frac{3I'\Omega + I''\Omega^2}{2I + I'\Omega}$$

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

Going beyond the bag model …

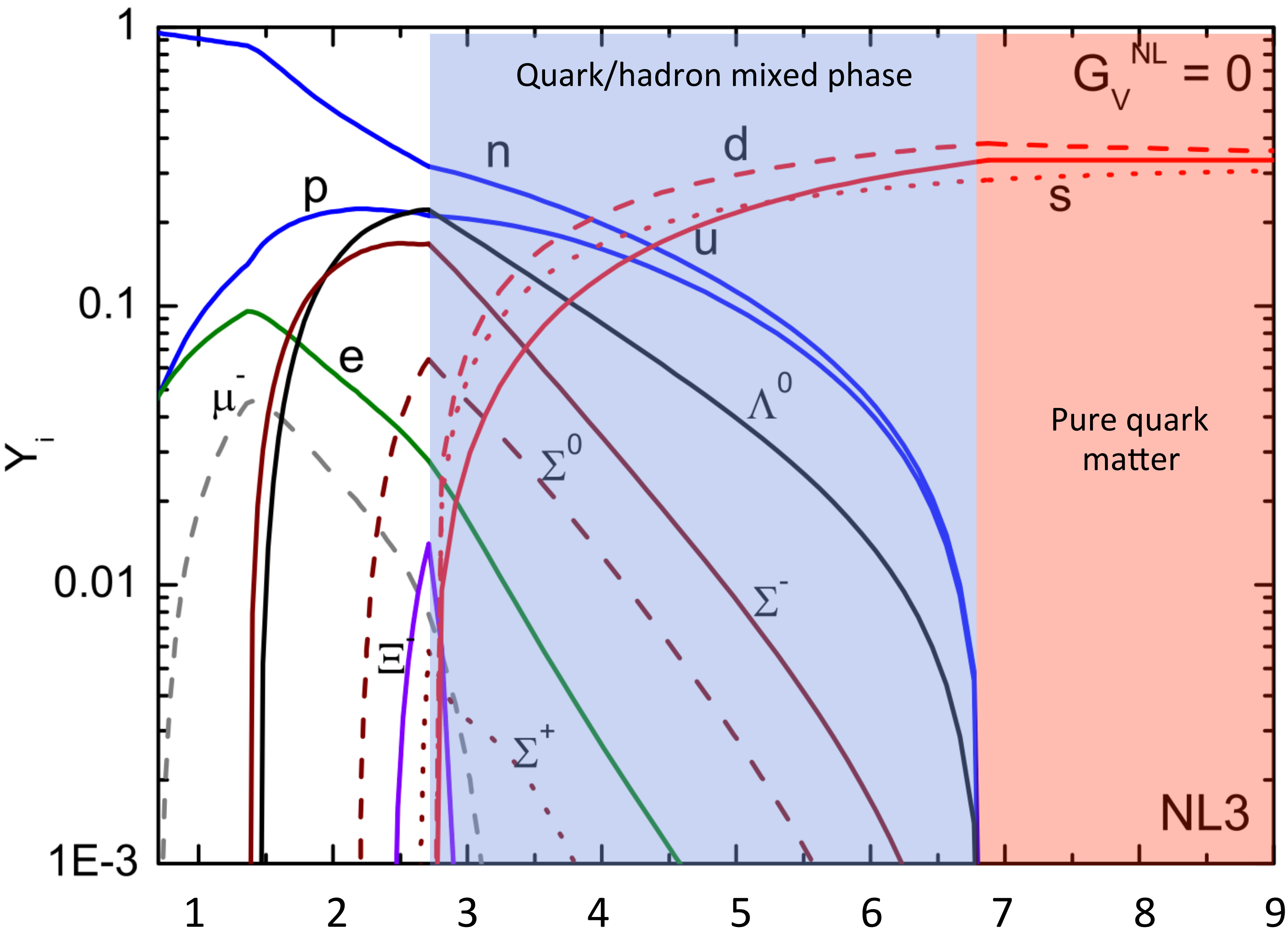
$$\mathcal{L} = \sum_{B=n,p,\Lambda,\Sigma,\Xi} \bar{\psi}_B \big[\gamma_\mu (i\partial^\mu - g_\omega \omega^\mu - g_\rho \vec{\rho}^\mu) - (m_N - g_\sigma \sigma)\big]\psi_B + \frac{1}{2}(\partial_\mu \sigma \partial^\mu \sigma - m_\sigma^2 \sigma^2) - \frac{1}{3} b_\sigma m_N (g_\sigma \sigma)^3 -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

RMF

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

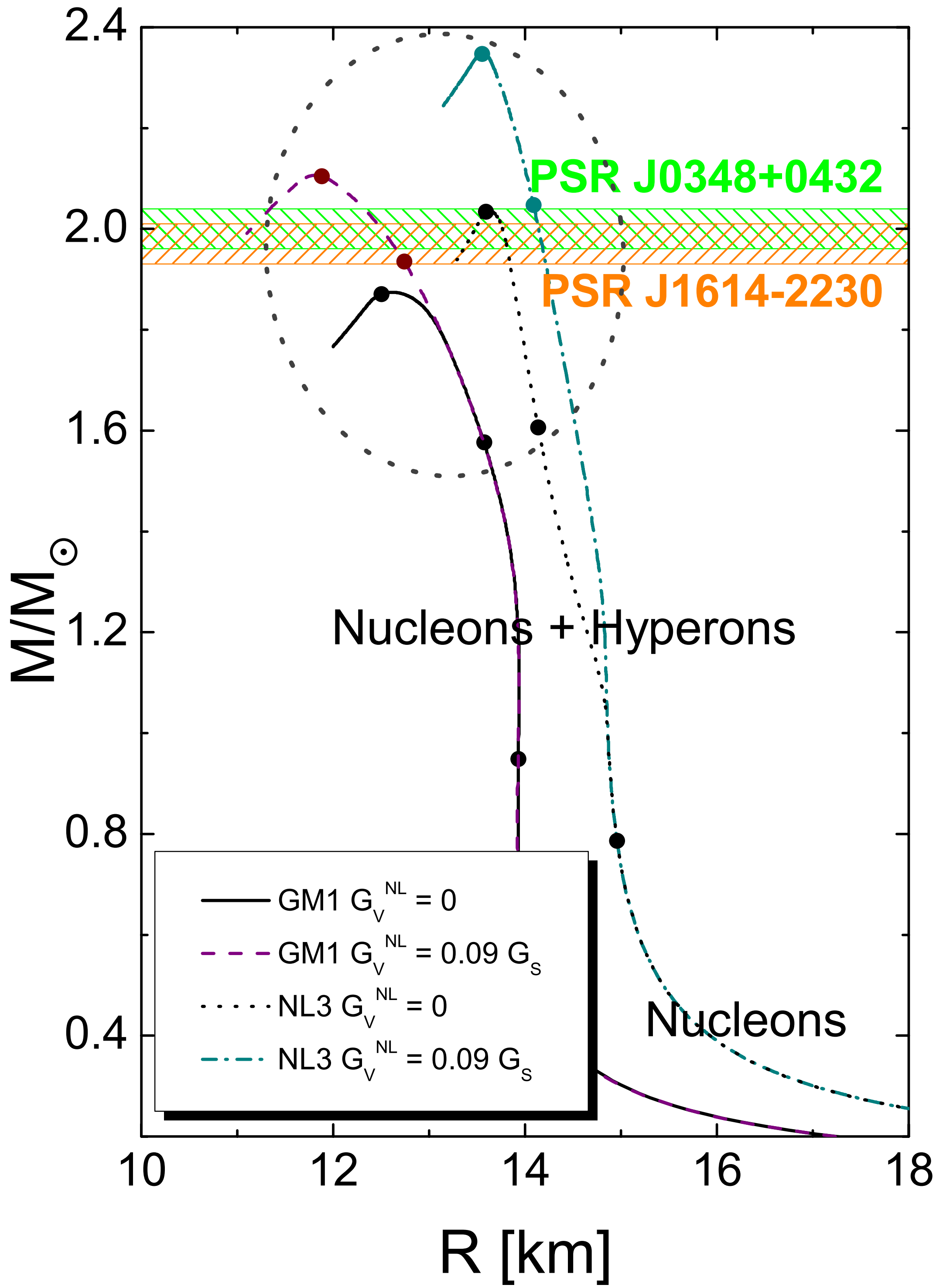
Local/
non-local
NJL models

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



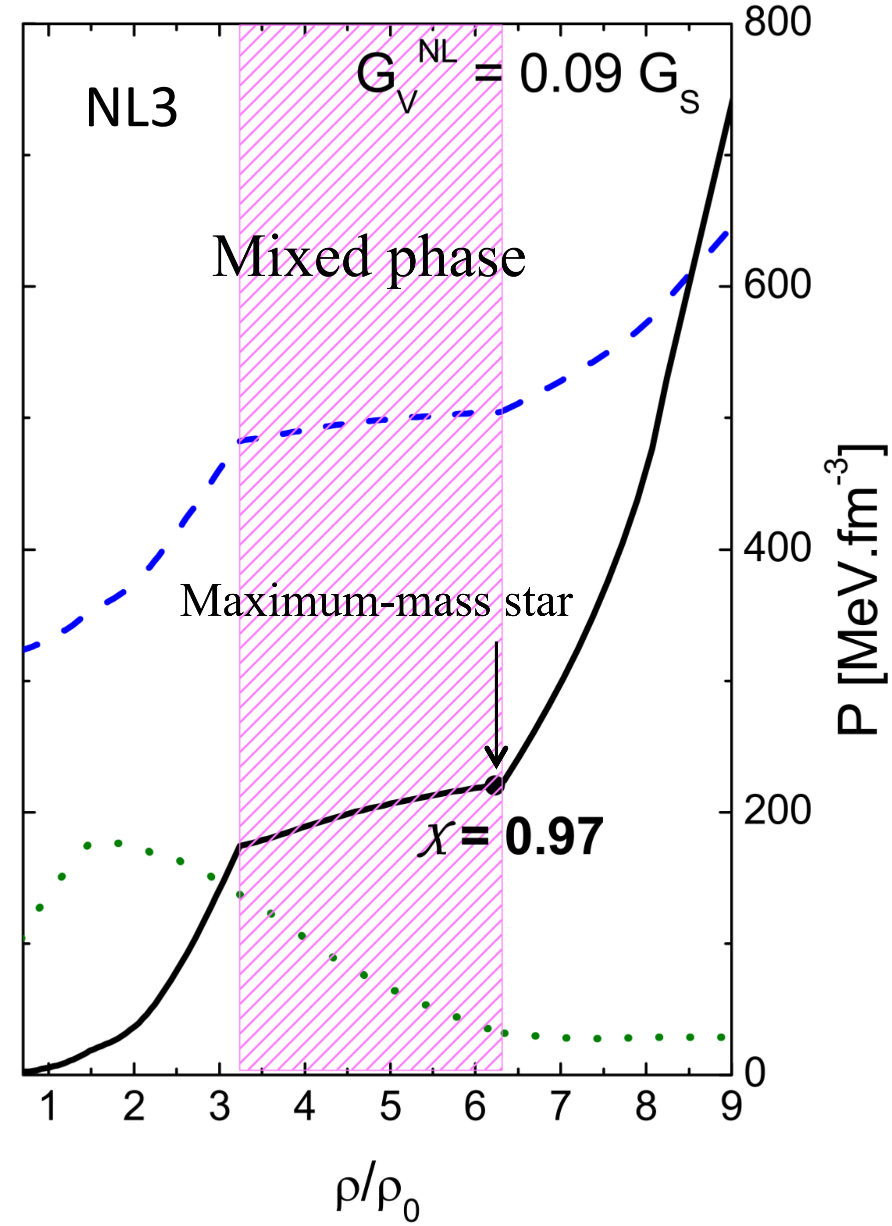
M. Orsario et al; see also Blaschke et al., Sedrakian et al., Lugones et al., . . .

non-local NJL



No pure quark matter cores but still a mixed phase of quarks and hadrons

non-local NJL



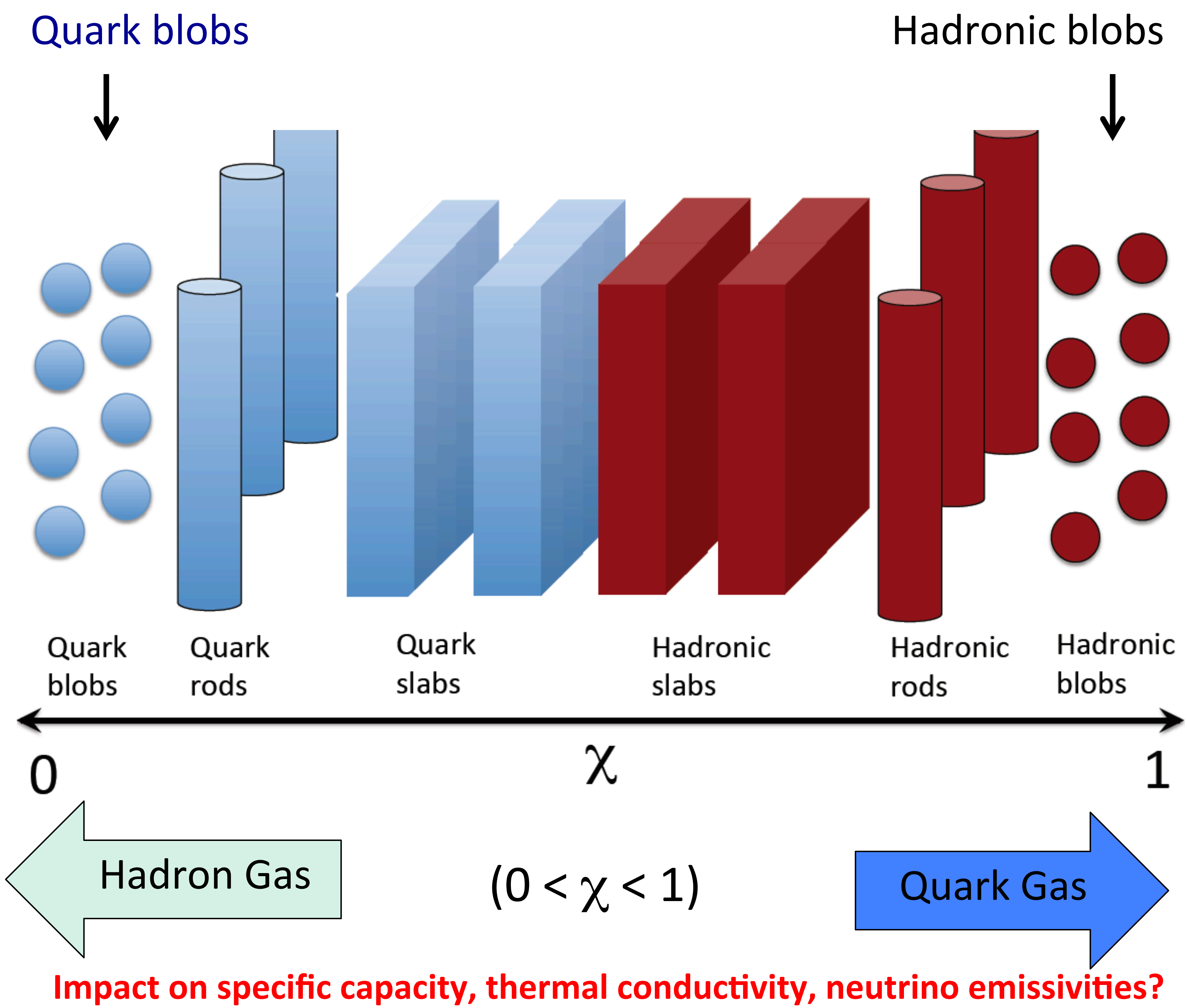
non-local NJL

Geometrical Structures in Quark-Hadron Phase

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

Imposing **global** electric charge neutrality:

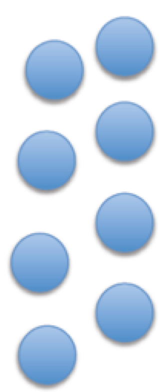
- Relaxes the extreme isospin asymmetry of neutron star matter
    - Allows for re-arrangement of electric charges
    - **Positively** charged regions of nuclear matter
    - **Negatively** charged regions of quark matter
- Competition between Coulomb and surface energies in the mixed phase
- Mixed quark-hadron phase may develop geometrical structures

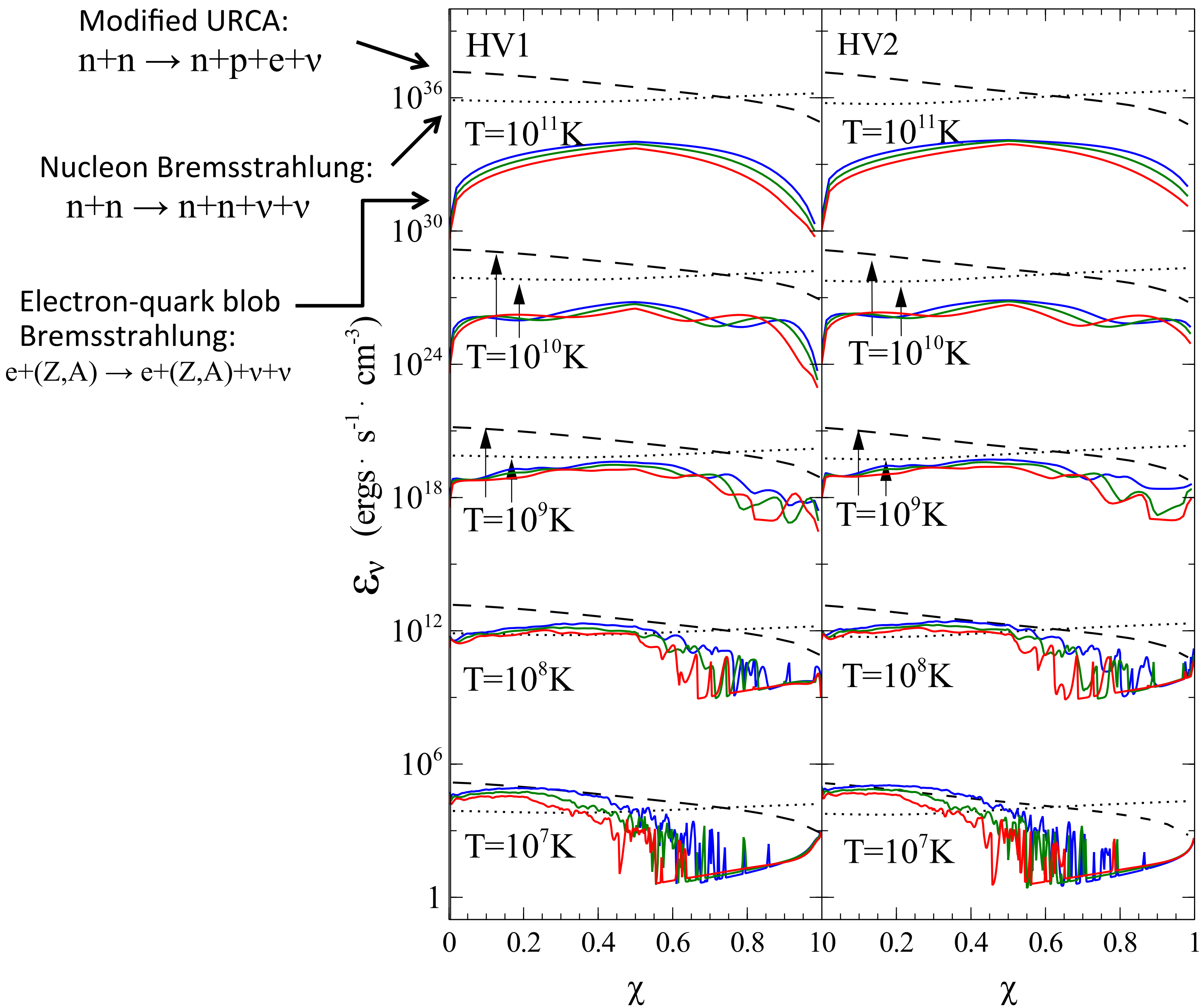

Quark blobs
Hadronic blobs
Quark blobs
Quark rods
Quark slabs
Hadronic slabs
Hadronic rods
Hadronic blobs
0
χ
1
Hadron Gas
(0 < χ < 1)
Quark Gas
Impact on specific capacity, thermal conductivity, neutrino emissivities?

Electron-Quark blob Scattering gives rise to Bremsstrahlung

$$e + (Z,A) \rightarrow e + (Z,A) + \nu + \bar{\nu}$$

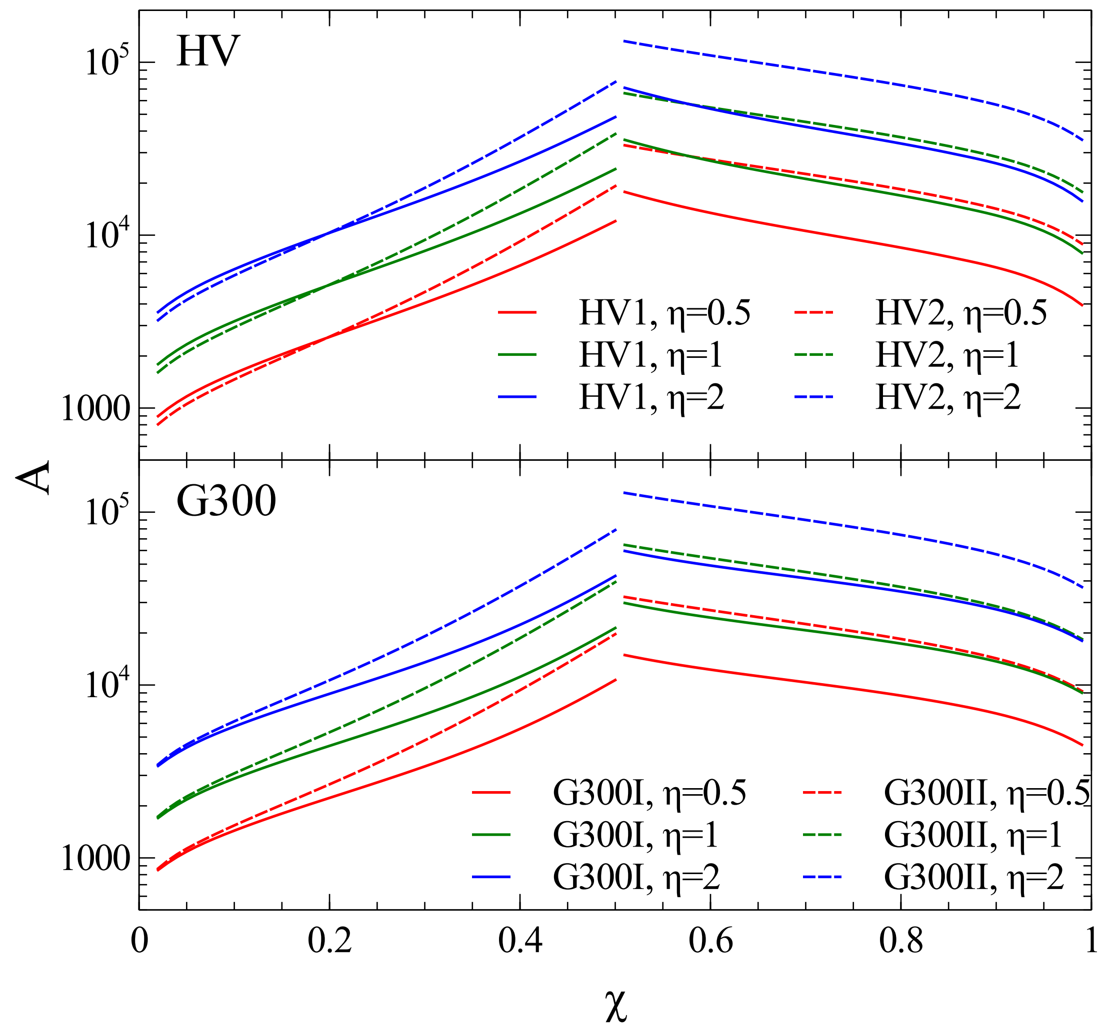
Quark blob





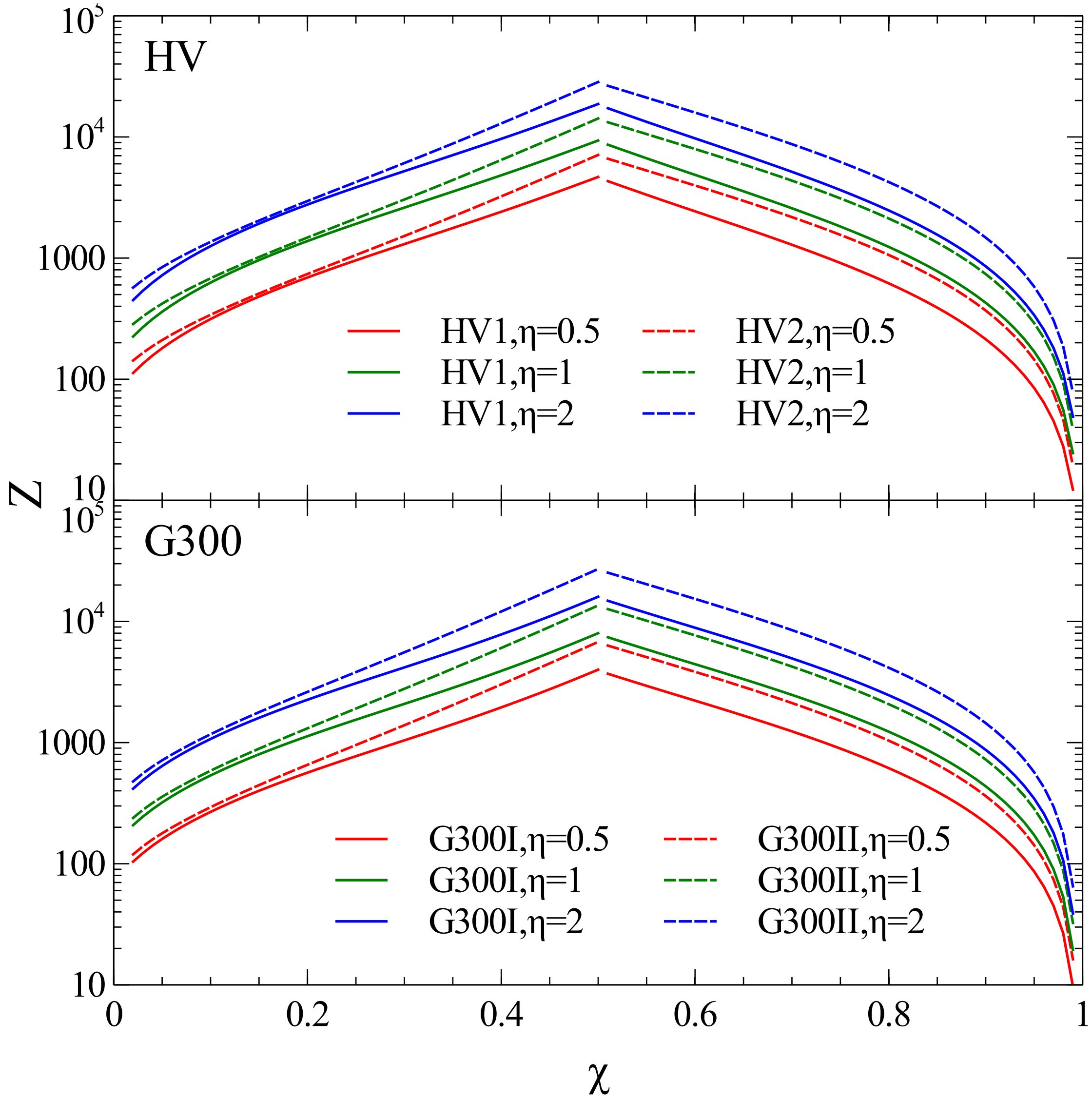
X. Na, R. X. Xu & FW, PRD 86 (2012) 123016

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



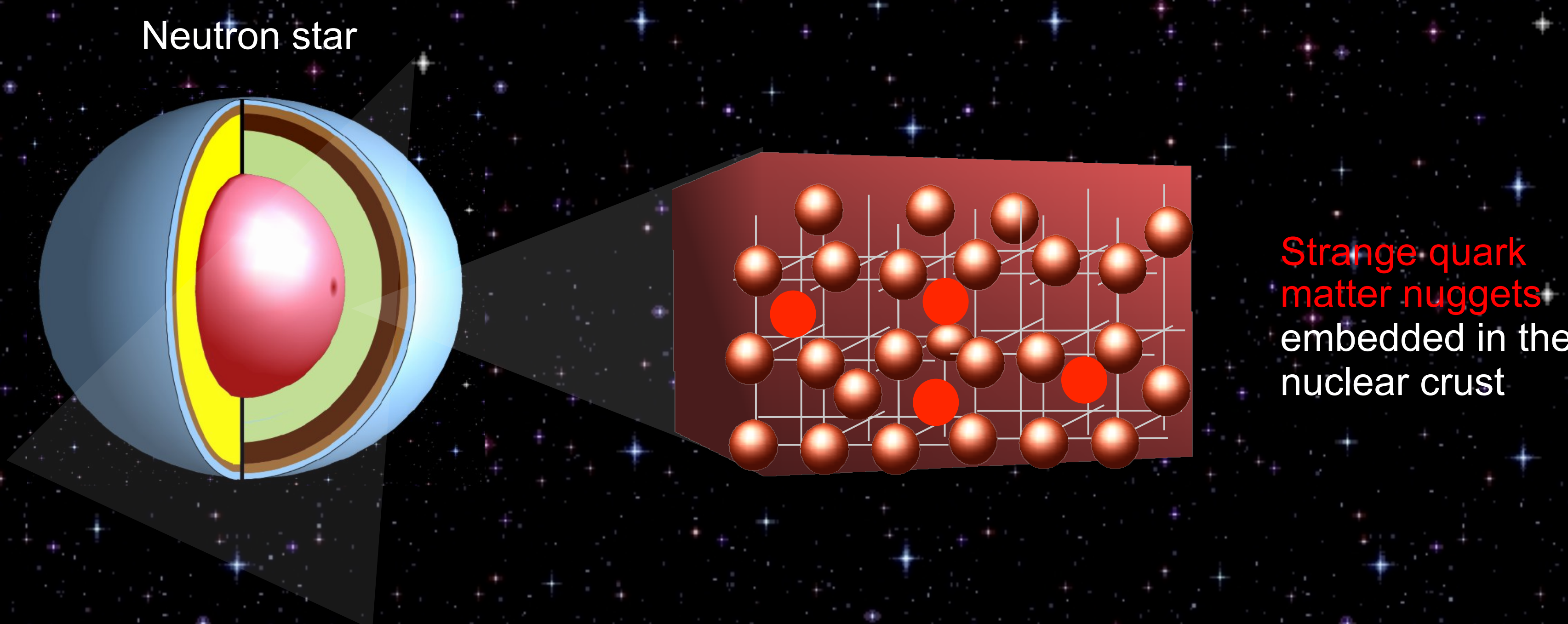
Xuesen Na, R. X. Xu & FW

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

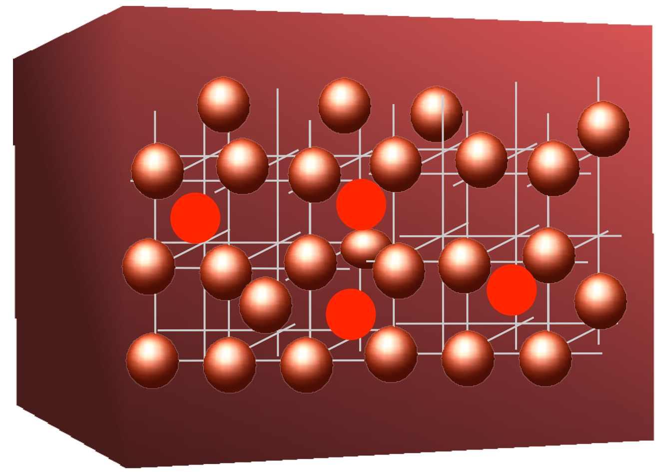


Xuesen Na, R. X. Xu & FW, arXiv:1208.5022v1 astro-ph.SR (to appear in PRD)

Pycnonuclear Reactions in the Crusts of Neutron Stars



Strange Quark Matter Nuggets



- $N_u \sim N_d \sim N_s$
- $A > A_{min}$ (~10 to 100)
- Charge-to-baryon number ratio depends on whether SQM is made of
  - "ordinary" quark matter, $Z \approx 0.1\,(m_{150})^2 A$, or
  - color superconducting quark matter, $Z \approx 0.3\, m_{150}\, A^{2/3}$

Farhi & Jaffe, PRD 30 (1984) 2379; Berger & Jaffe, PRC 35 (1987) 213; Alcock, Farhi, Olinto, ApJ 310 (1986) 261; Madsen, PRL 87 (2001) 172003

Madsen, PRL 87 (2001) 172003; Rajagopal & Wilczek, PRL 86 (2001) 3492; Oertel & Urban PRD 77 (2008) 074015

$$R = (\text{lattice pairs}) \times T_{\text{Coulomb barrier}} \times S \times E^{-1}$$

$$R = 3.90 \, x \, 10^{46} \; \frac{8\,\rho\, A_1 A_2 Z_1^2 Z_2^2}{A_1 + A_2} \; S(E) \; \lambda^{7/4} \; e^{-2.636/\sqrt{\lambda}} \; s^{-1}$$

S: S-factor

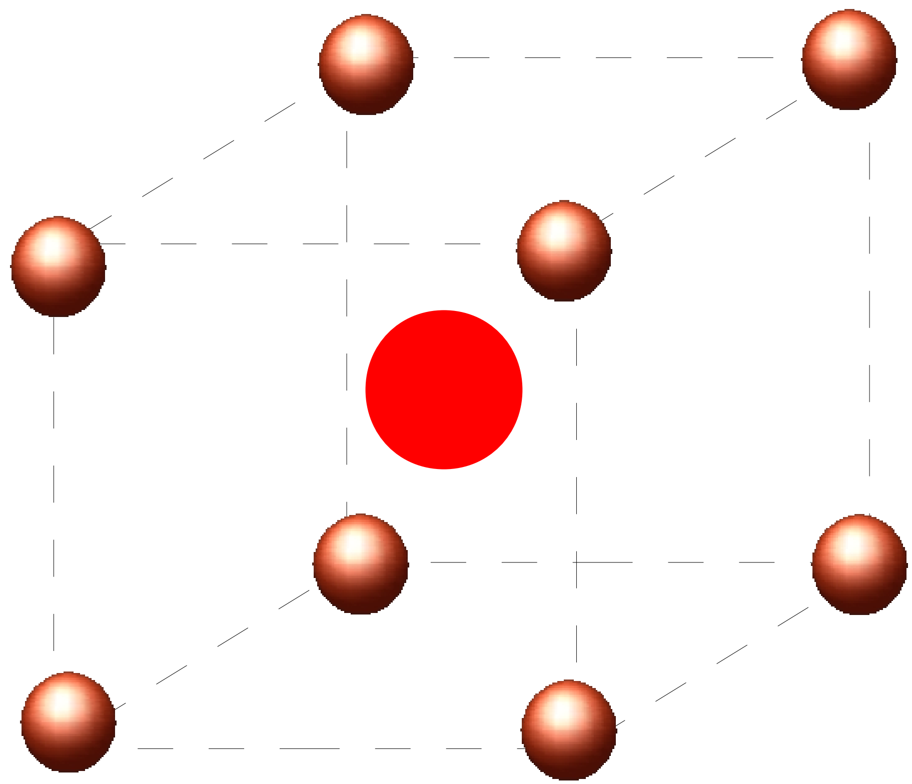
Z: electric charge

A: mass number

ρ: mass density

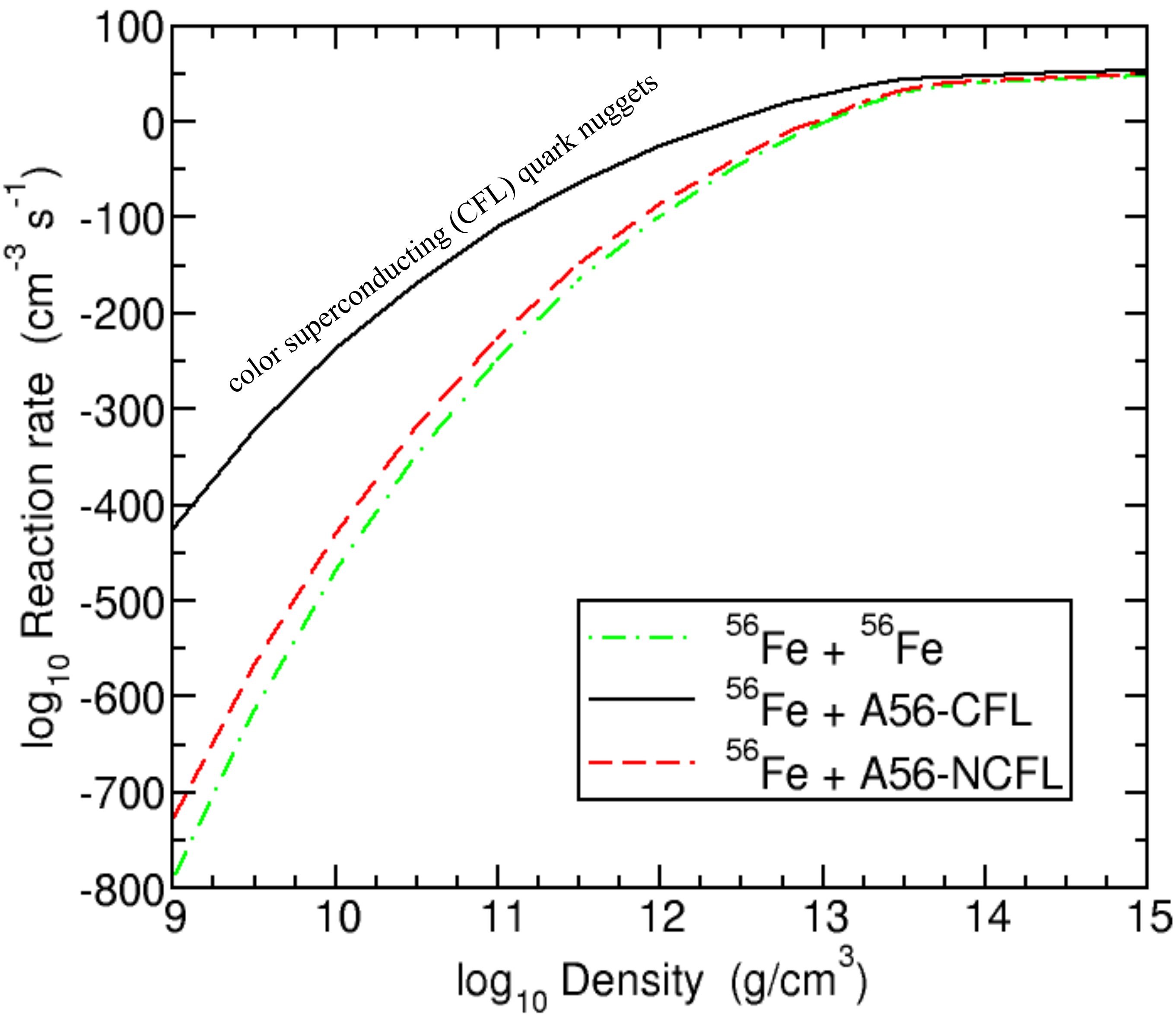
λ: inverse length parameter

Gasques et al. PRC 72 (2005) 025806
Yakovlev et al. PRC 74 (2006) 035803



body centered cubic (bcc) lattice

Impact of quark matter nuggets on pycnonuclear reaction rates



B. Golf, J. Hellmers, F. Weber, PRC 80 (2009) 015804

FACTS TO TAKE HOME

Particle compositions in rotating neutron stars are not frozen in as it is the case for static (non-rotating) neutron stars. Therefore,

- Neutron-to-proton ratio
- Hyperon populations
- Boson condensates
- Quark matter fractions

all change with stellar frequency.

Quark-hadron matter may be removed/produced during spin-up/spin-down!

FACTS TO TAKE HOME

Particle compositions in rotating neutron stars are not frozen in as it is the case for static (non-rotating) neutron stars. Therefore,

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Observable signals

- Enhanced cooling turned on/off
- Spin-up of isolated NSs (Backbending)
- Braking index vastly different from 3

iMSPs & NSs in LMXBs appear as ideal objects to look for phase transitions