QUARK DECONFINEMENT IN NEUTRON STARS

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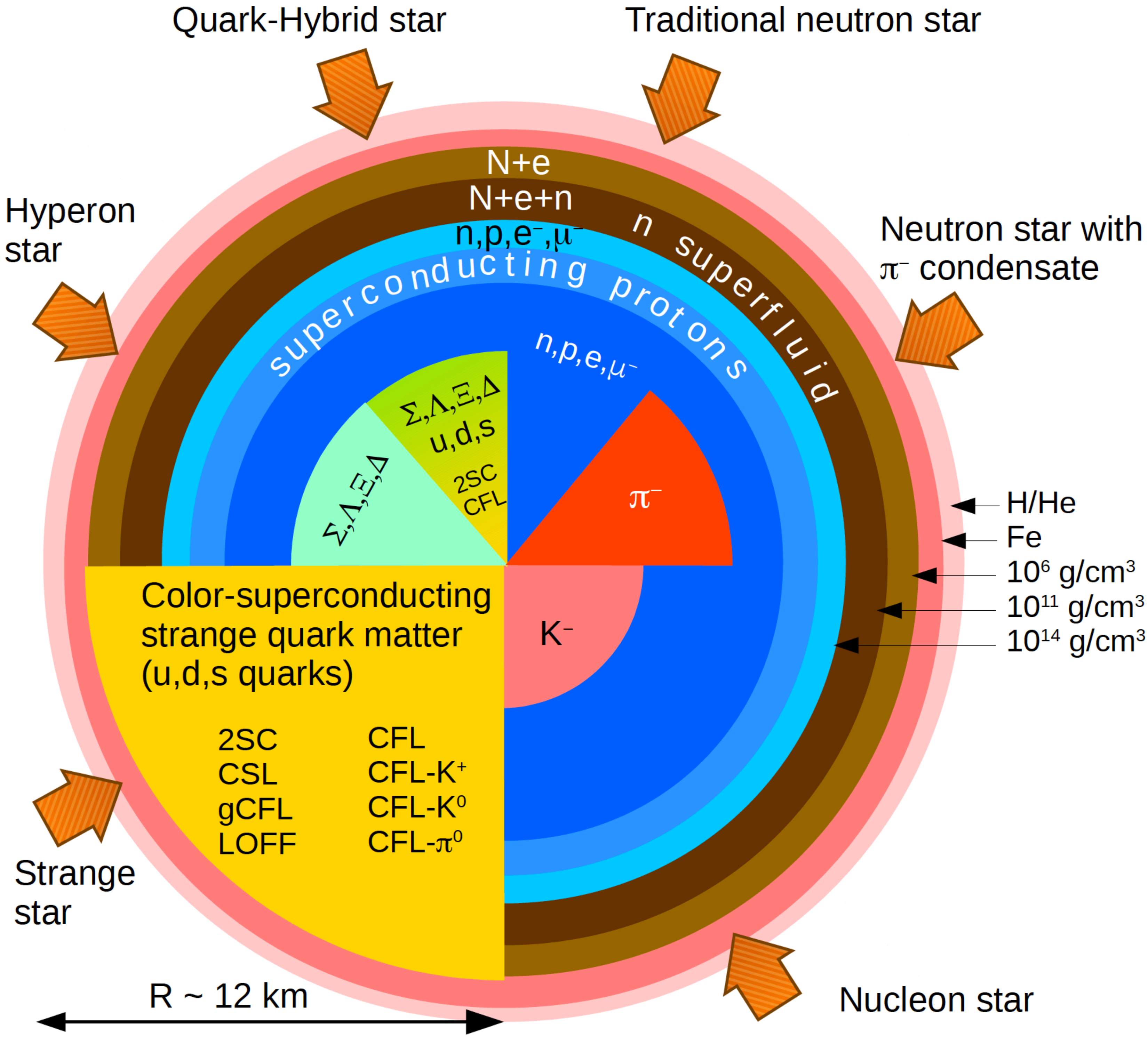
INT Program INT-16-2b
The Phases of Dense Matter, July 11 — August 12, 2016


Quark-Hybrid star
Traditional neutron star
Hyperon star
Neutron star with π^- condensate
N+e
N+e+n
n,p,e$^-$,μ^-
n superfluid
superconducting protons
n,p,e,μ^-
Σ,Λ,Ξ,Δ
u,d,s
2SC
CFL
Σ,Λ,Ξ,Δ
π^-
H/He
Fe
10^6 g/cm^3
10^{11} g/cm^3
10^{14} g/cm^3
Color-superconducting strange quark matter (u,d,s quarks)
K$^-$
2SC
CSL
gCFL
LOFF
CFL
CFL-K$^+$
CFL-K^0
CFL-π^0
Strange star
Nucleon star
R ~ 12 km

OUTLINE

- **Strange Stars versus Neutron Stars**

  Distinguishing features

- **Quark-Hadron Phase Transition inside Pulsars**

  Current status

  Possible signal of quark deconfinement

- **Δ populations**

- **Rotating Neutron Stars**

  Rotation in GR

  Rotation-driven compositional changes

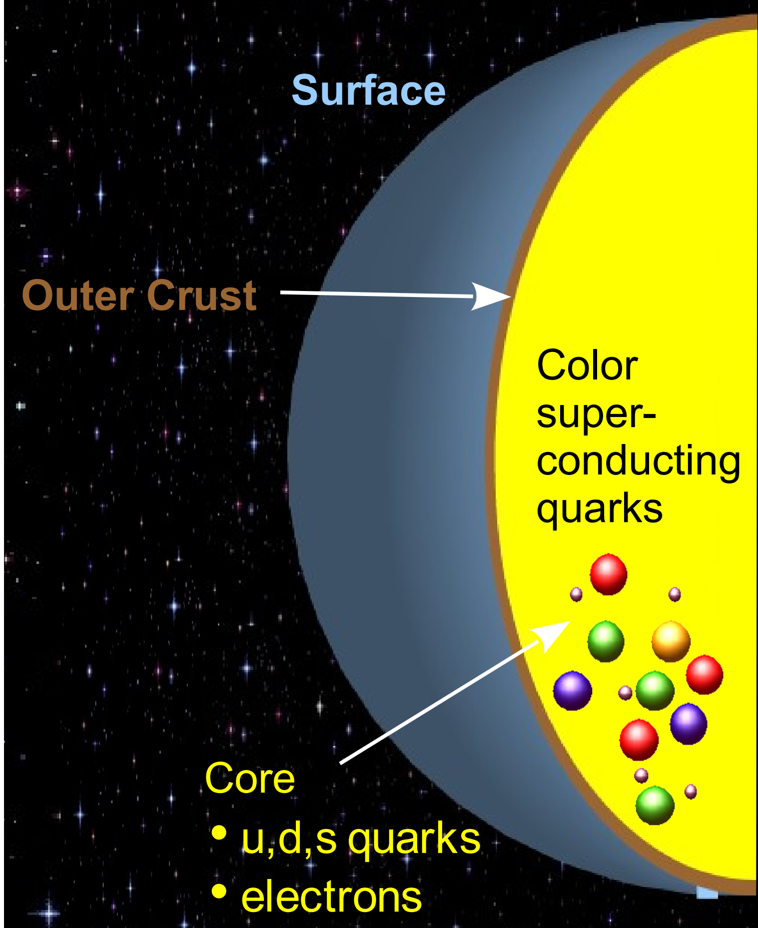
- **Quark-hadron Lattices**

- **Non-rotating but nevertheless deformed?**

- **Summary**

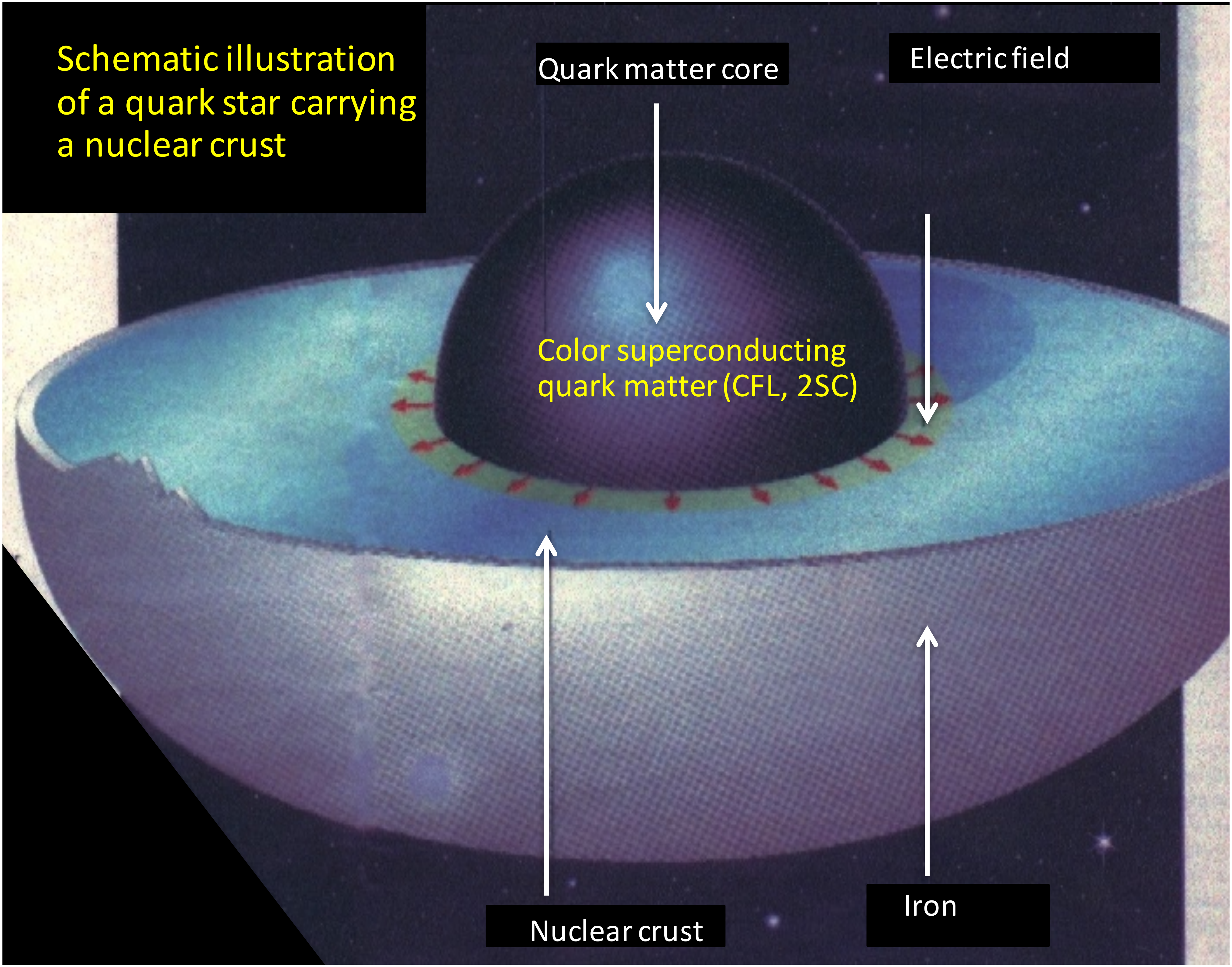
Strange Quark Stars

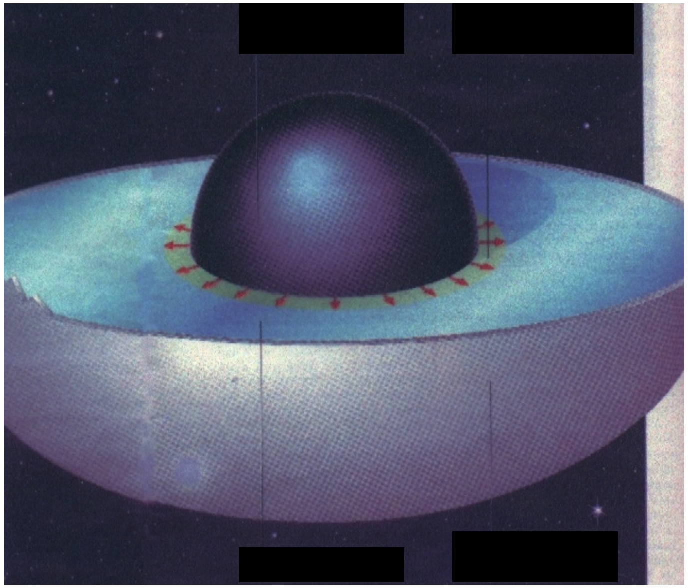
Strange Quark Star



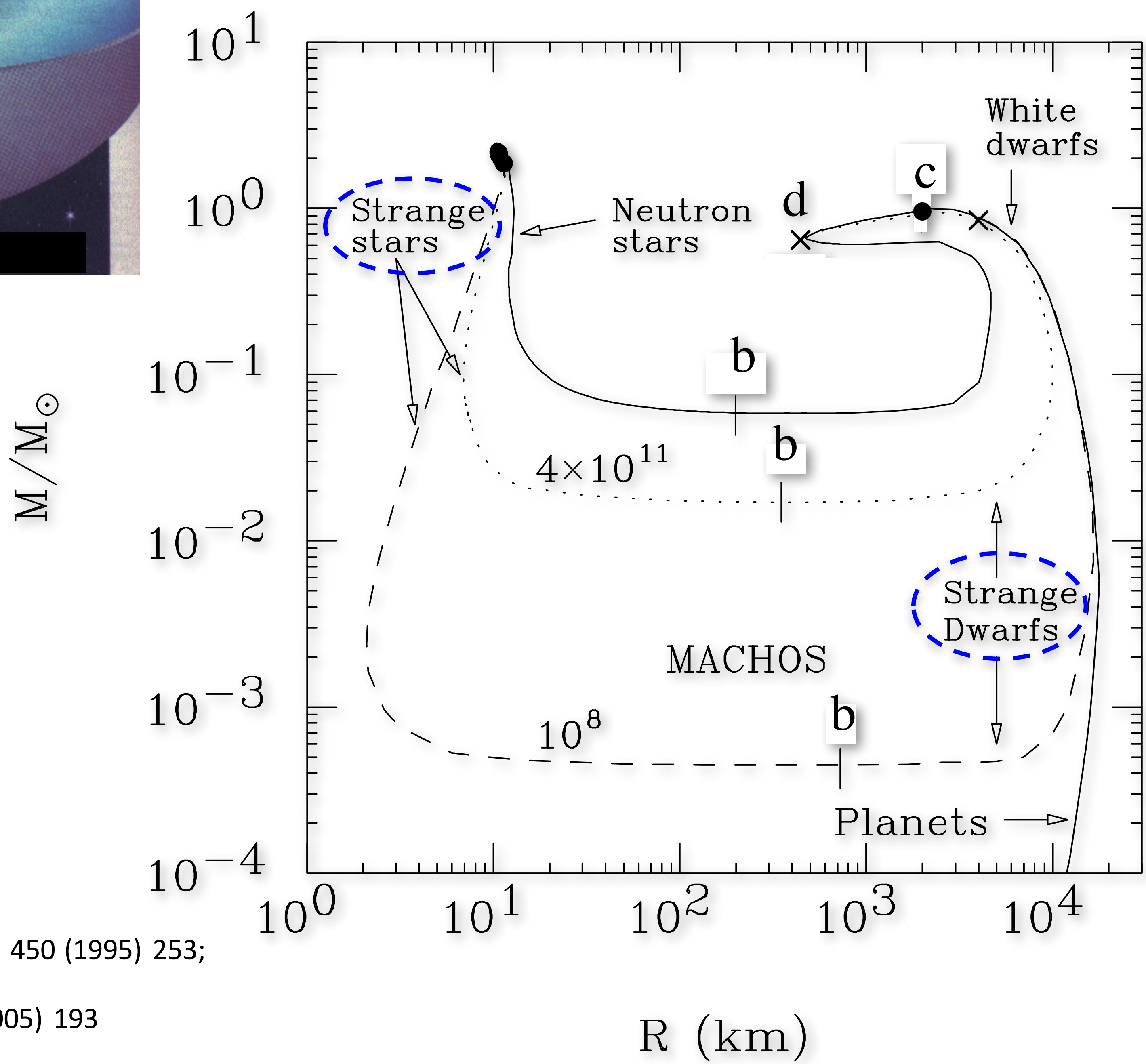
- **Made entirely of deconfined quarks**
- Self-bound ($M \sim R^3$)
- Electron dipole layer at surface (ultra-strong electric fields)
- Either bare or “dressed”
- Only outer crusts
- No inner crusts
- Two-parameter stellar sequence

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);
V. Usov, ApJ 559 (2001), 550 (2001)


Schematic illustration of a quark star carrying a nuclear crust
Quark matter core
Electric field
Color superconducting quark matter (CFL, 2SC)
Nuclear crust
Iron

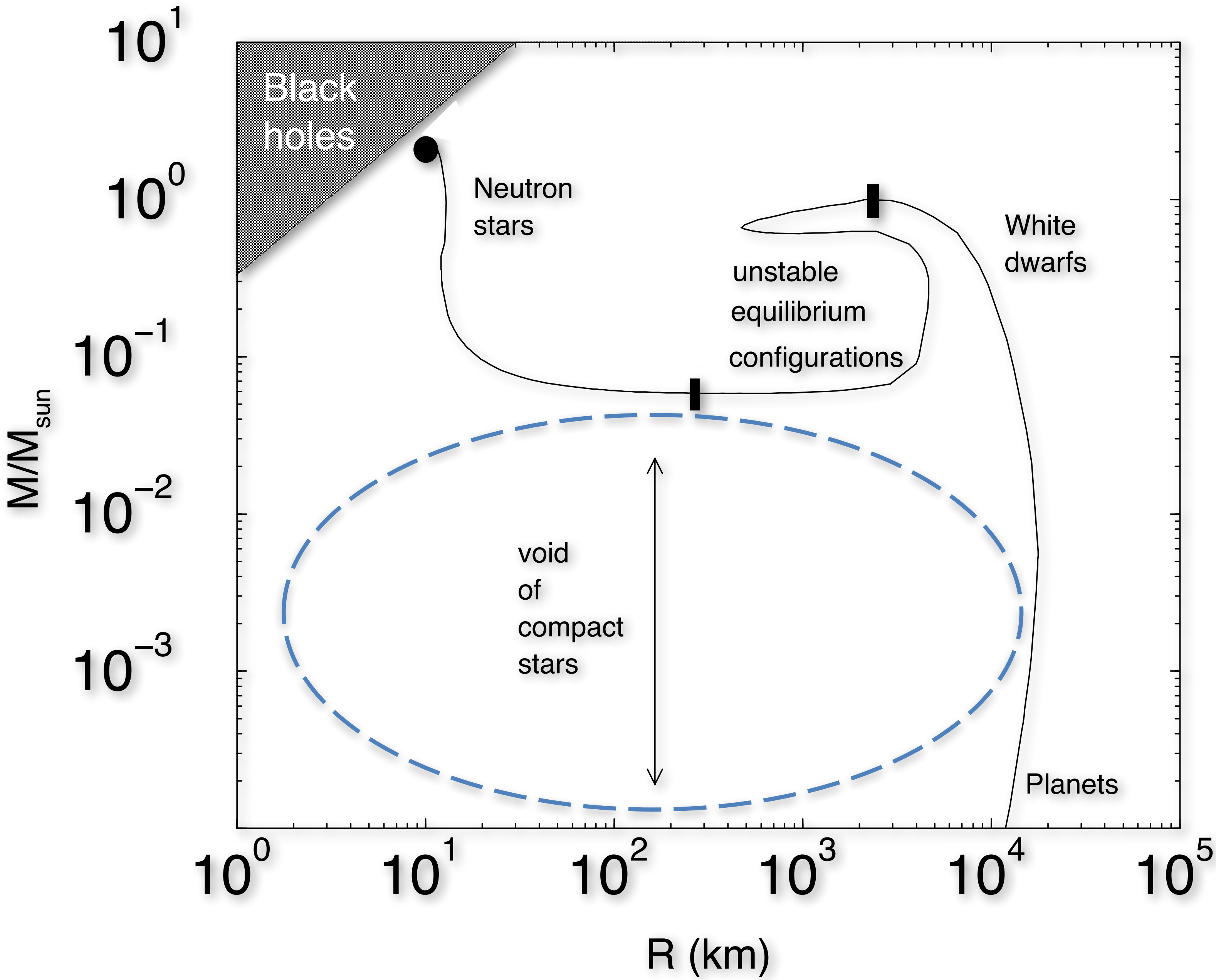


Mass-radius relationship of neutron stars and **strange quark stars**

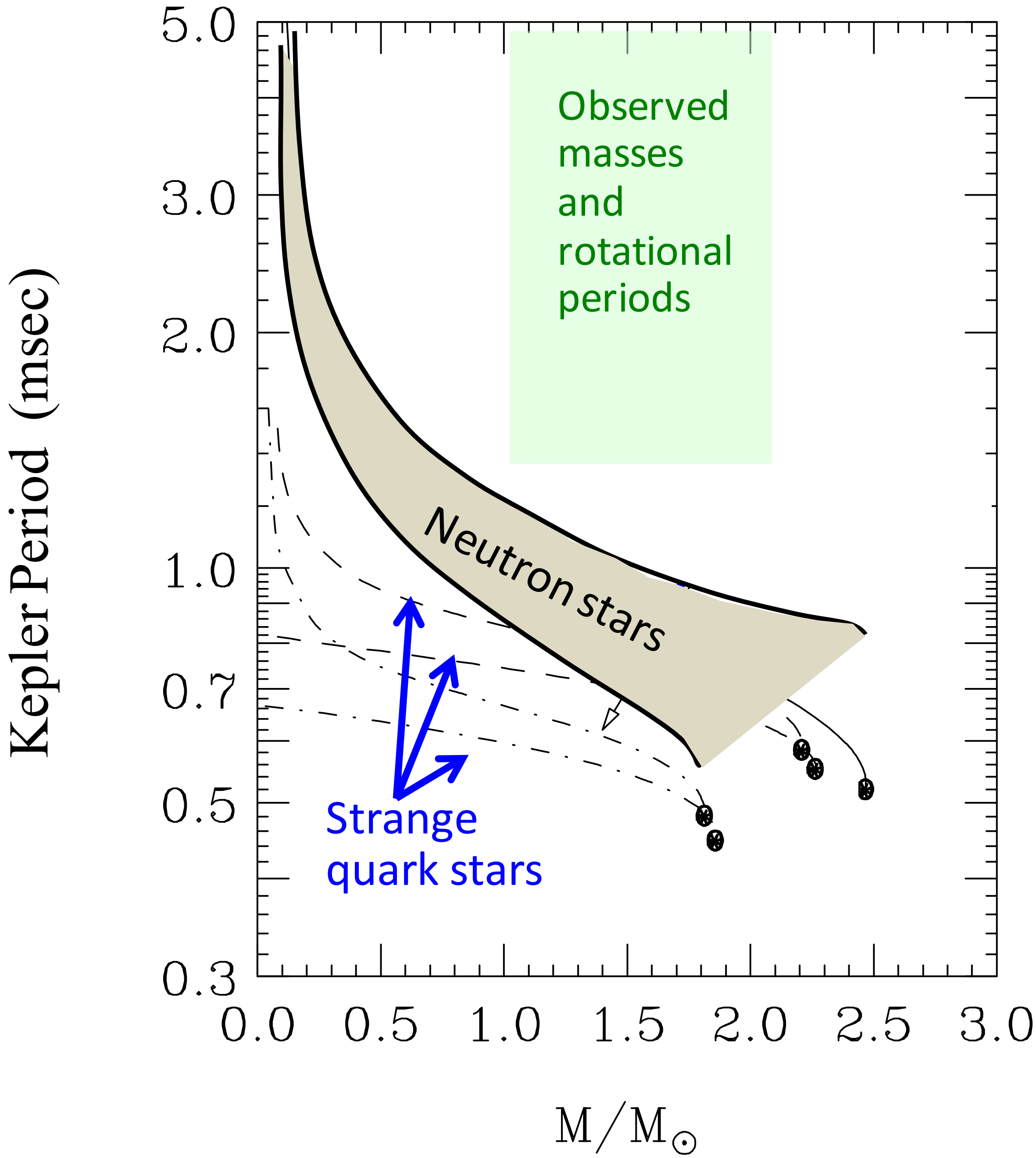


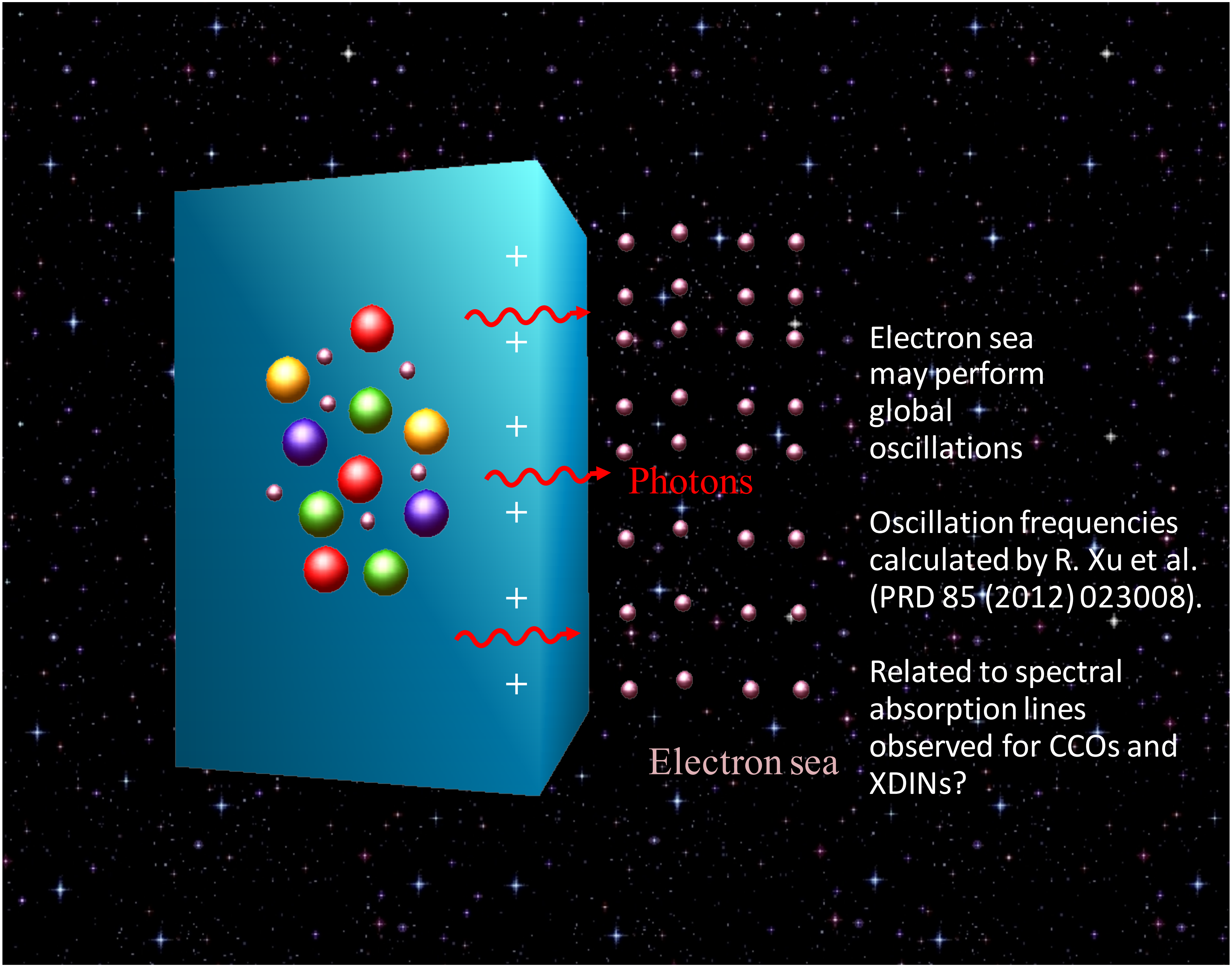
Glendenning, Kettner, FW, ApJ 450 (1995) 253;
PRL 74 (1995) 3519
FW, Prog Part Nucl Phys 54 (2005) 193

Mass-radius relationship of **neutron stars**



Rotation at Sub-Millisecond Periods





Electron sea may perform global oscillations
Photons
Oscillation frequencies calculated by R. Xu et al. (PRD 85 (2012) 023008).
Related to spectral absorption lines observed for CCOs and XDINs?
Electron sea

CCOs and XDINs with observed spectral absorption lines

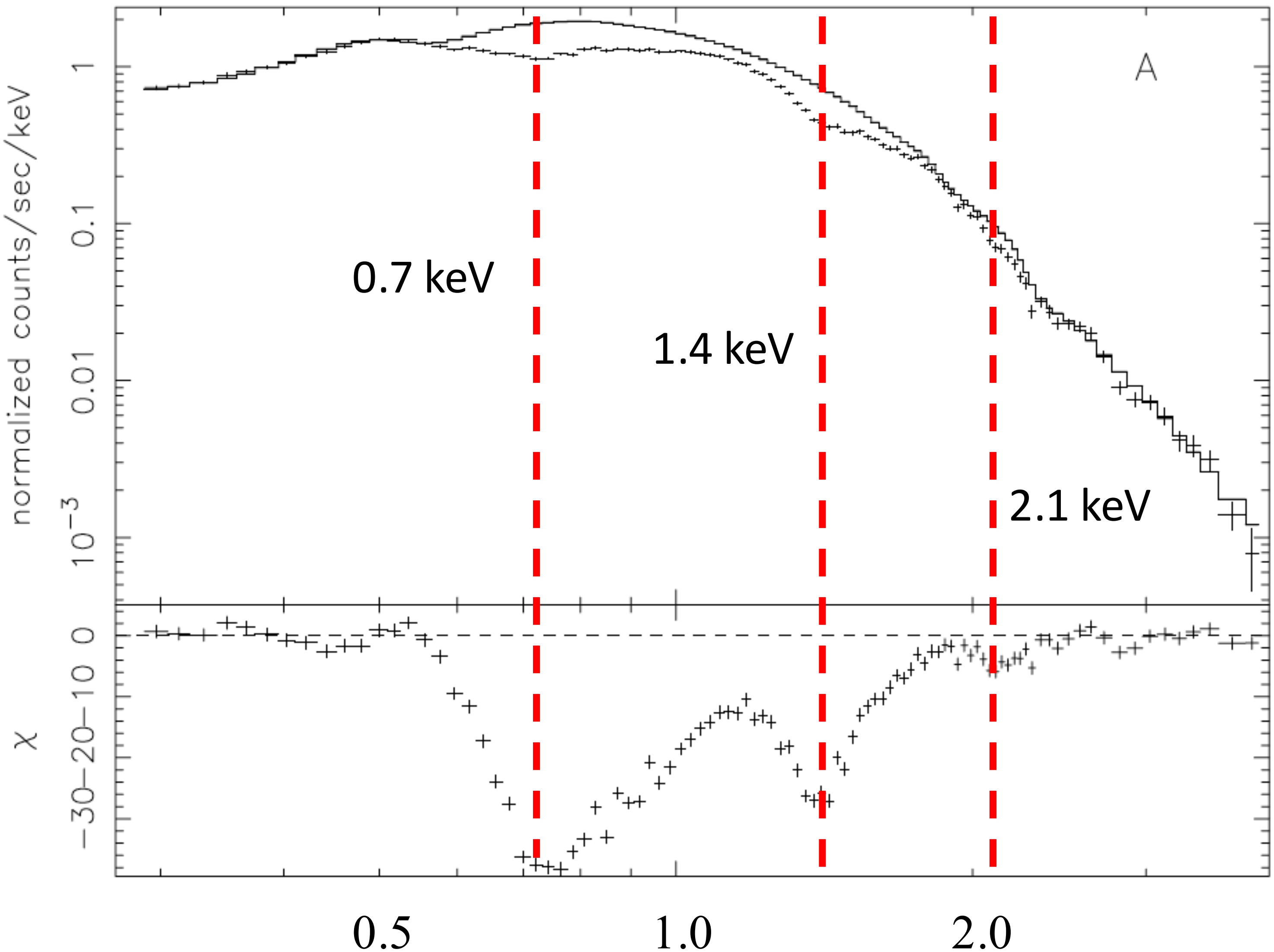
Source	P/s	B_{10}	kT/keV	E_a/keV
RX $J0822.0-4300$	0.112	<98	0.4	···
1E $1207.4-5209$	0.424	<33	0.22	0.7, 1.4
CXOU $J185238.6+004020$	0.105	3.1	0.3	···
RX $J0720.4-3125$	8.39		0.085	0.27
RX $J0806.4-4123$	11.37		0.096	0.46
RX $J0420.0-5022$	3.45		0.045	0.33
RX $J1308.6+2127$	10.31		0.086	0.3
RX $J1605.3+3249$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

Pavlov, Sanwal & Teter (2004); Halpern & Gotthelf (2010)

Oscillation frequencies (R. Xu et al. (2012))

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

Absorption features detected in the thermal X-ray 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

Quark-Hadron
Phase Transition

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

- ❑ Baryonic matter (Schroedinger-based, RMF, RHF, RBHF, . . .)
- ❑ Quark matter (MIT bag model, NJL)

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

Gibbs or Maxwell?

- ❑ Electric charge neutrality (global versus local)
- ❑ Chemical equilibrium

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

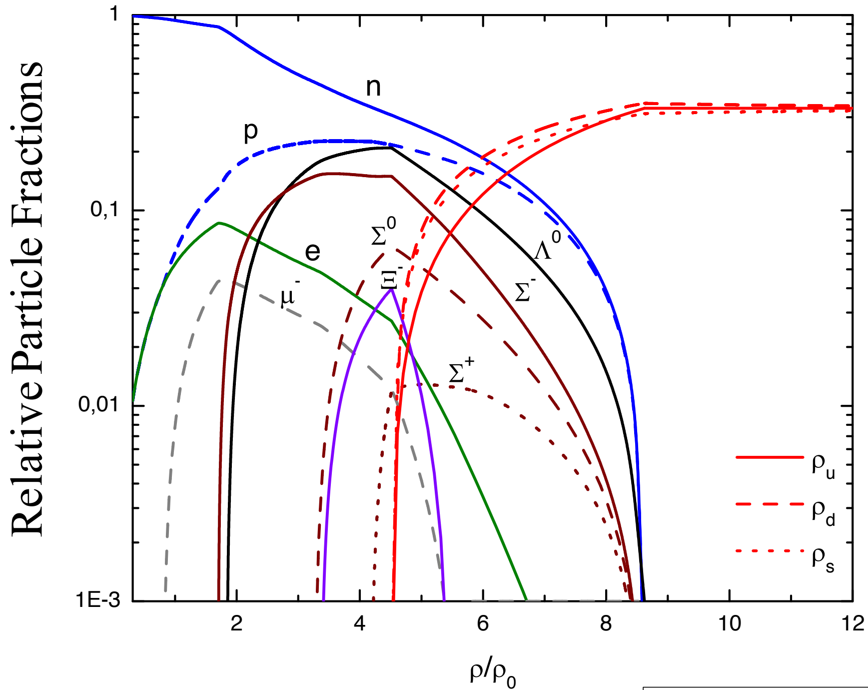
RMF

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

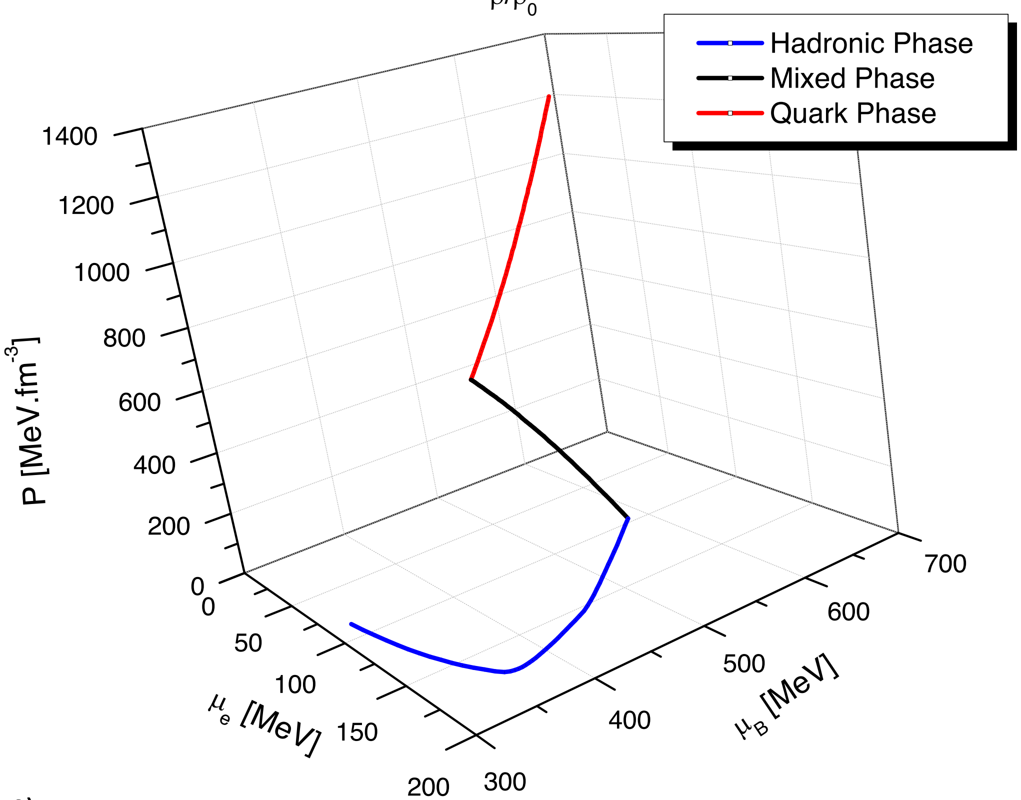
Local/
non-local
NJL models

M. Orsario et al; Blaschke et al., Sedrakian et al., Lugones et al., Kashiwa, Hell & Weise, …

Model neutron star matter composition



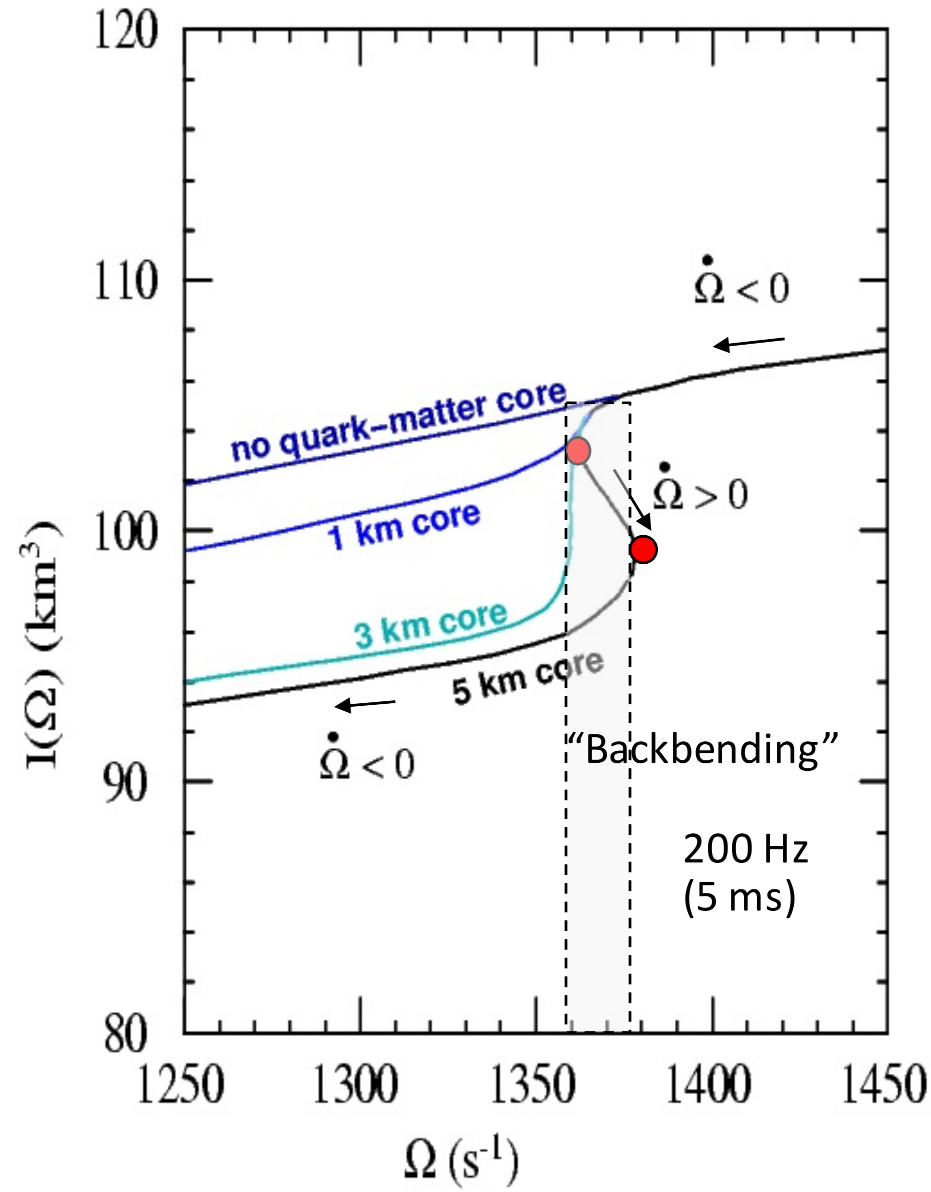
Associated equation of state



Milva Orsaria et al. (2012, 2014)

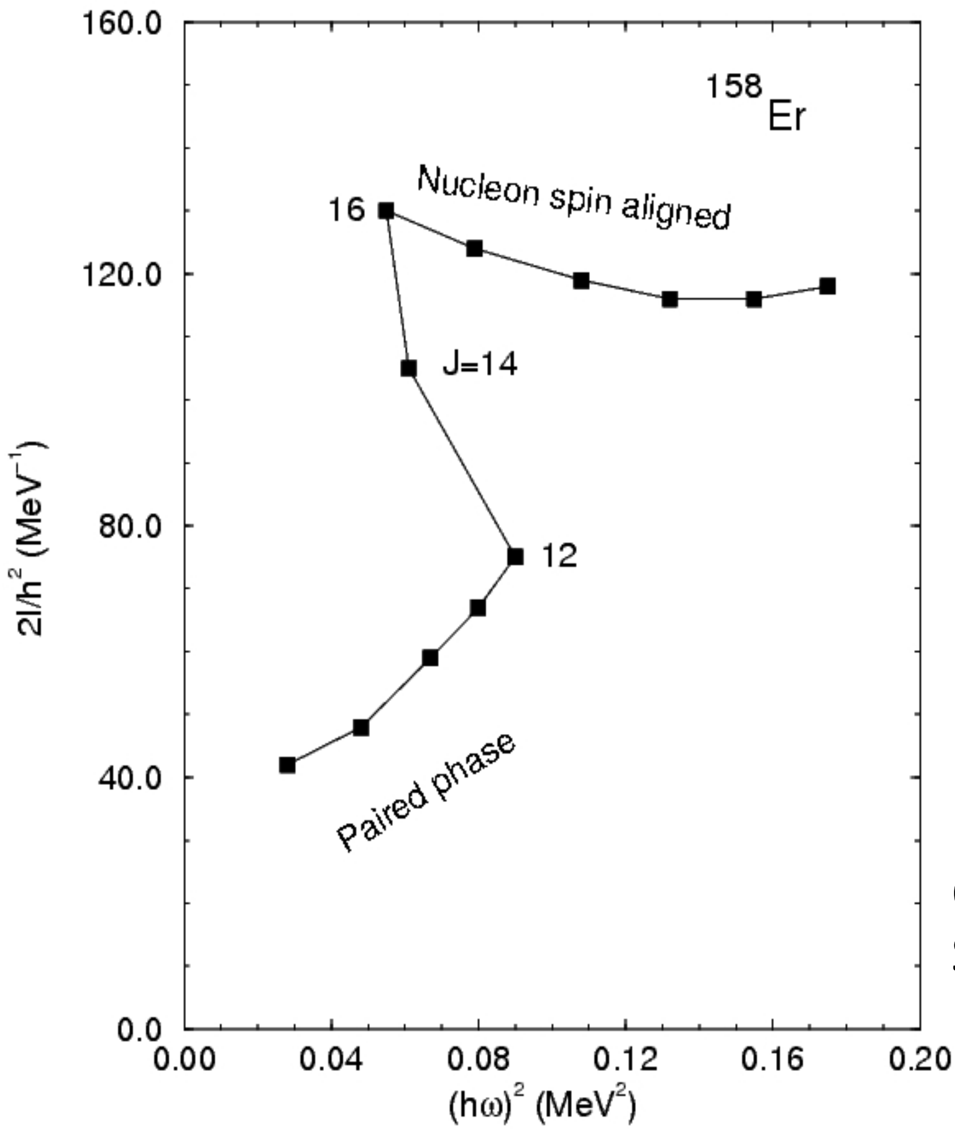
A Possible Signal of Quark Deconfinement in isolated Pulsars during spin-down

$$J = \int d^3x \; T_3{}^0 \; \sqrt{-g}$$



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

Backbending - well known in Nuclear Physics ...



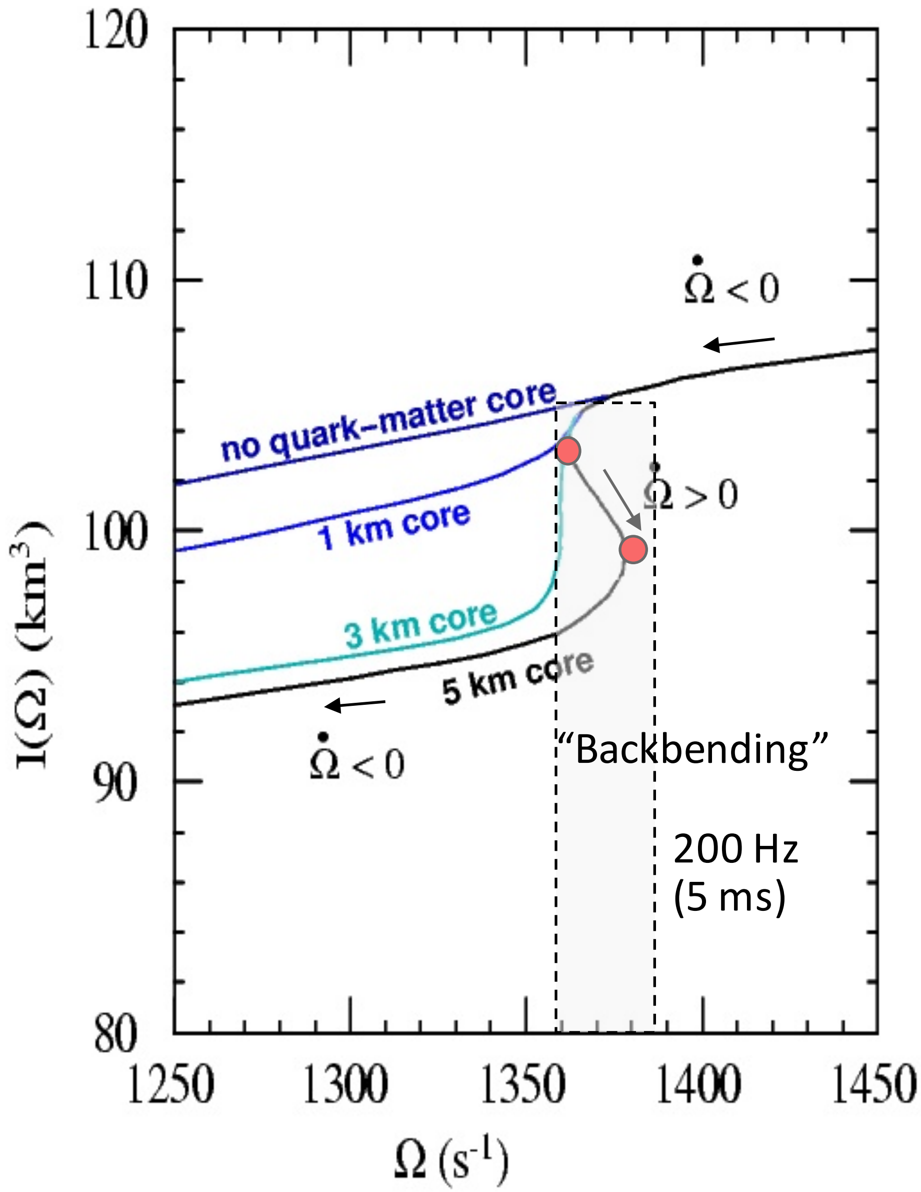
and from the Olympics

Backbending predicted in 1960 by Mottelson & Valatin

Observed in 1972 by Stephens & Simon

Braking index of a pulsar

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



Glendenning, Pei, FW, PRL 79 (1997) 1603
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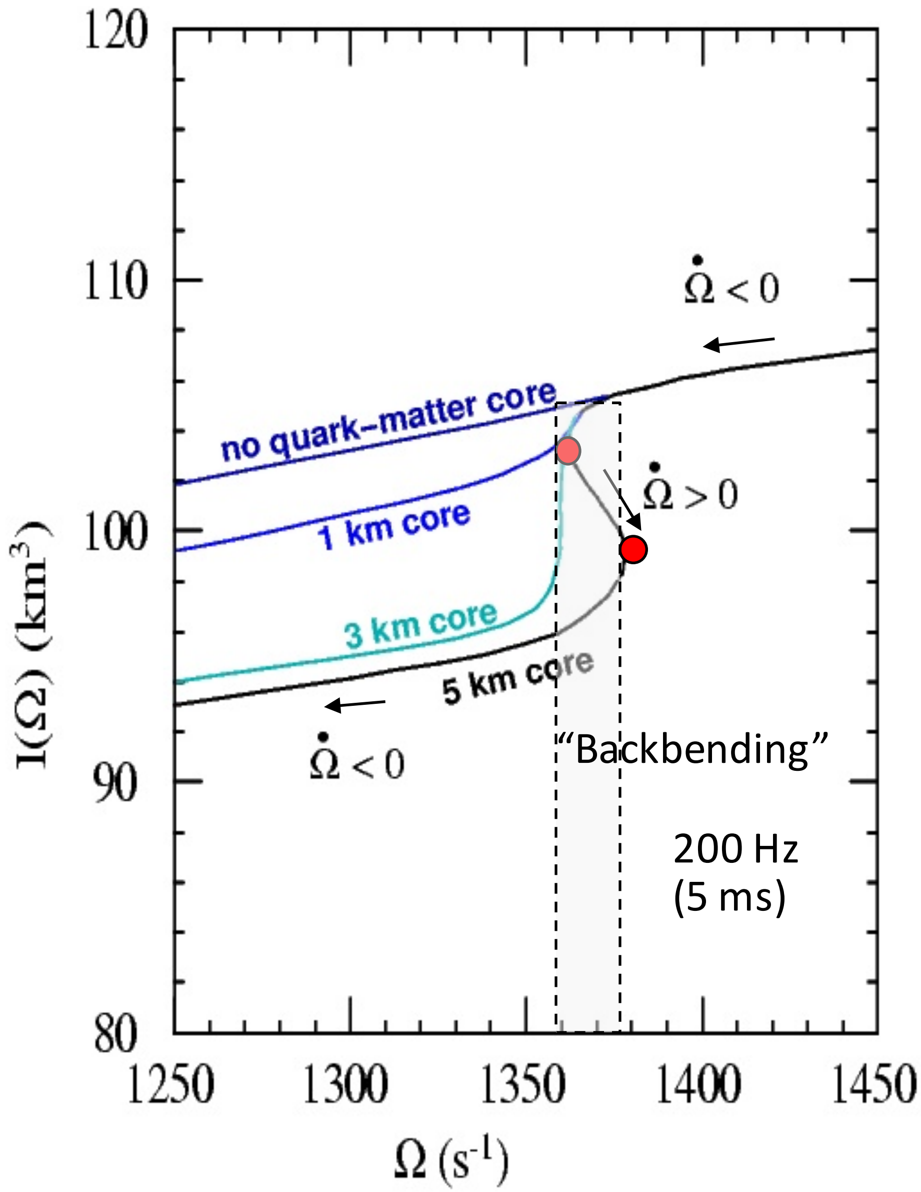
Braking index of a pulsar

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

Signals of quark deconfinement

- Braking indices of pulsars **$-\infty < n < +\infty$**
- Spin-up of isolated MSPs



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

Δ’s populations

M-R relationship of non-rotating neutron stars

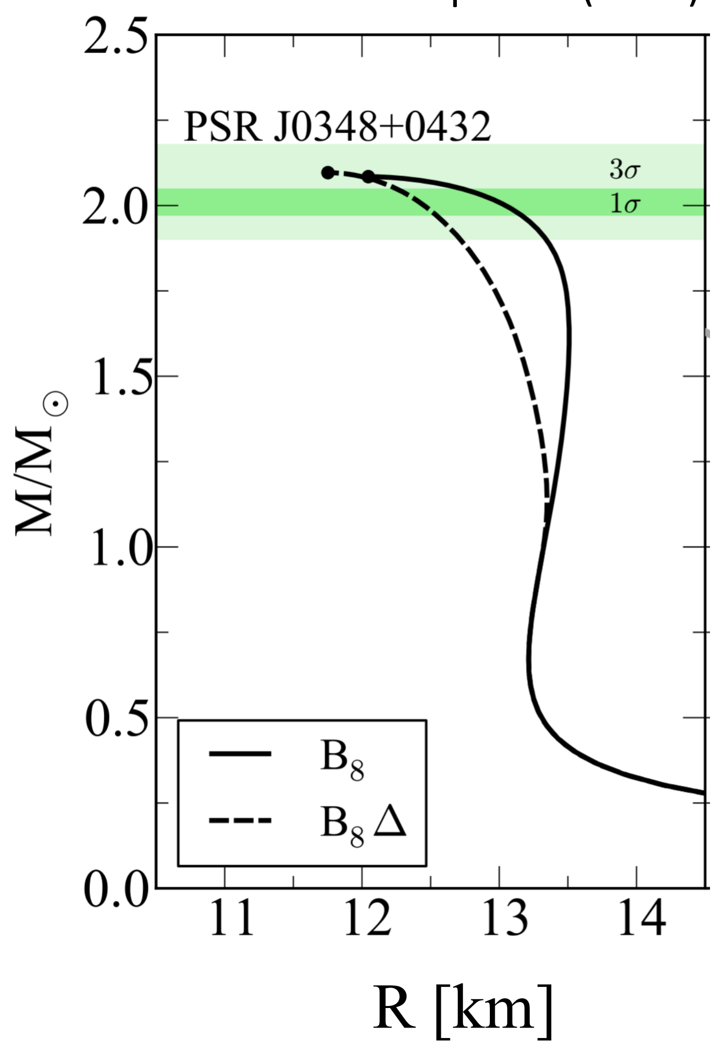
EOS: DD2 (Typel, 2010)

Saturation parameters: $n_0 = 0.149\ fm^{-3}$:
E/A = -16.03 MeV, $K_0 = 242.7$ MeV,
$a_{sym} = 31.64$ MeV, $L_0 = 56.7$ MeV, $m^* = 0.56$

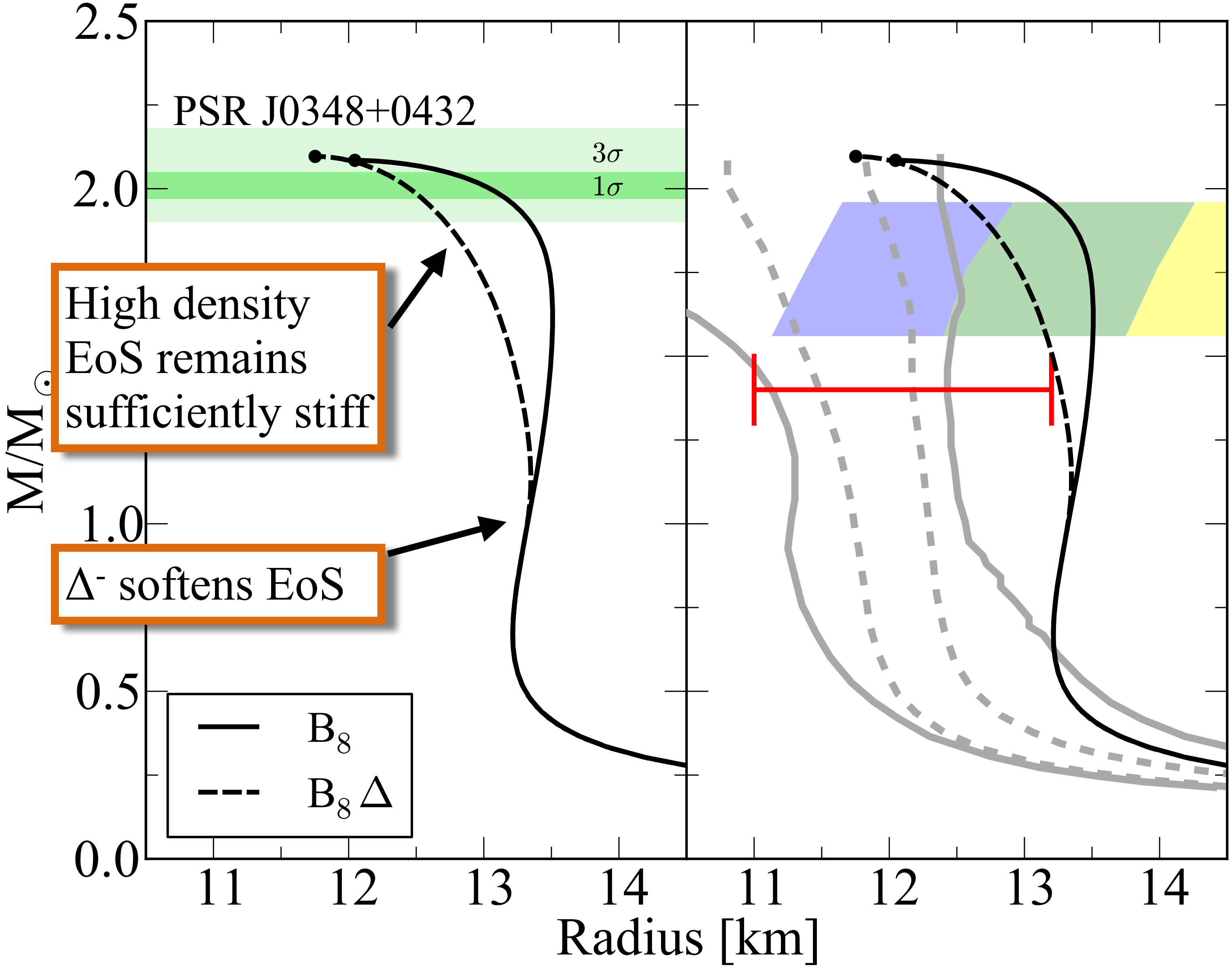
Couplin constants:
$g_{\sigma Y}$ fixed to hypernuclear potentials at n_0:
$U_\Lambda^{(N)} = -28$ MeV, $U_\Sigma^{(N)} = +30$ MeV, $U_\Xi^{(N)} = -18$ MeV

$g_{\omega Y}$ at n_0: $x_{\omega\Lambda} = x_{\omega\Sigma} = 0.79$, $x_{\omega\Xi} = 0.59$
(Rijken et al., 2010, Mayatsu et al., 2013)

W. Spinella (2016)

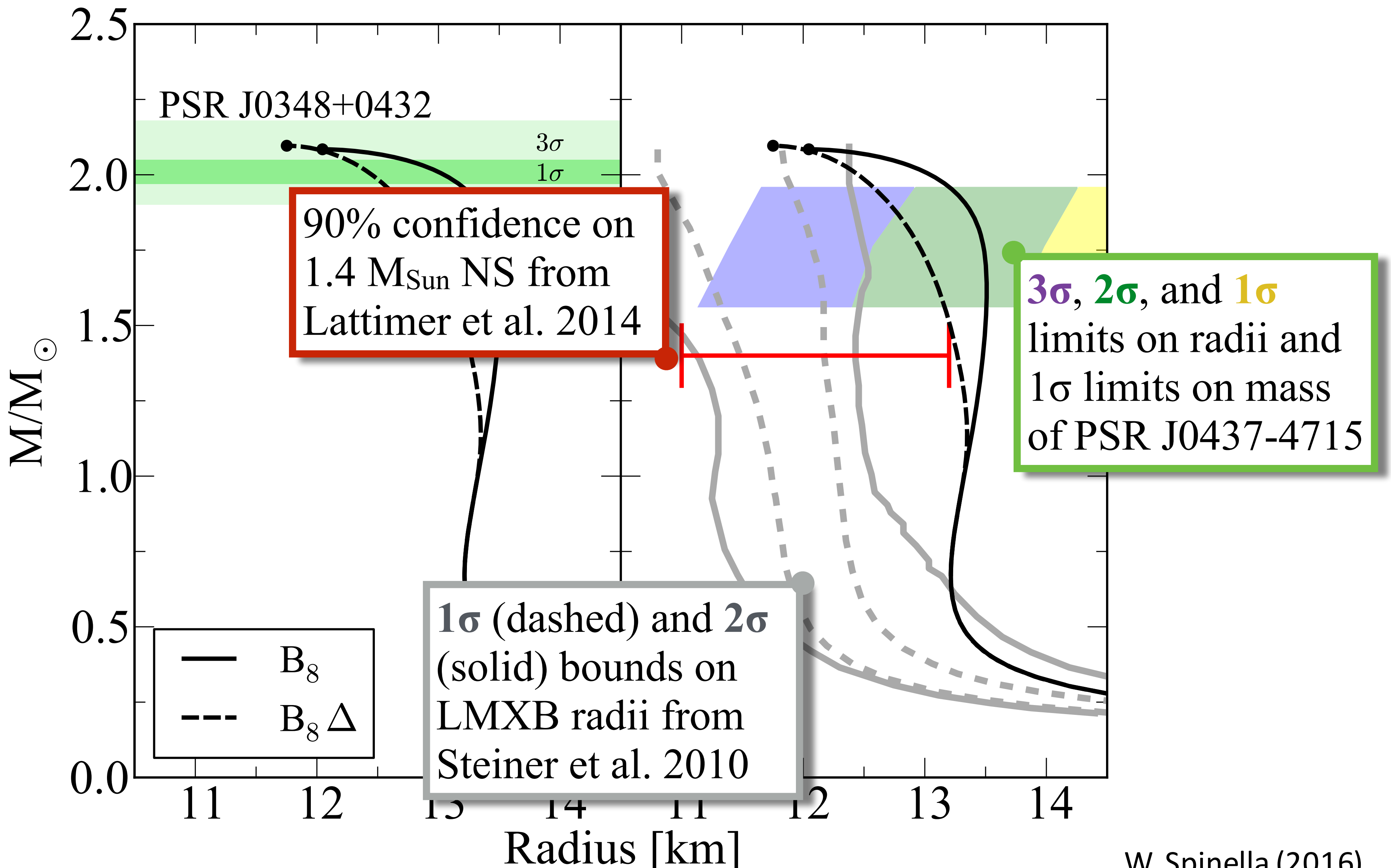


Mass-Radius+Constraints with Hyperons+Deltas



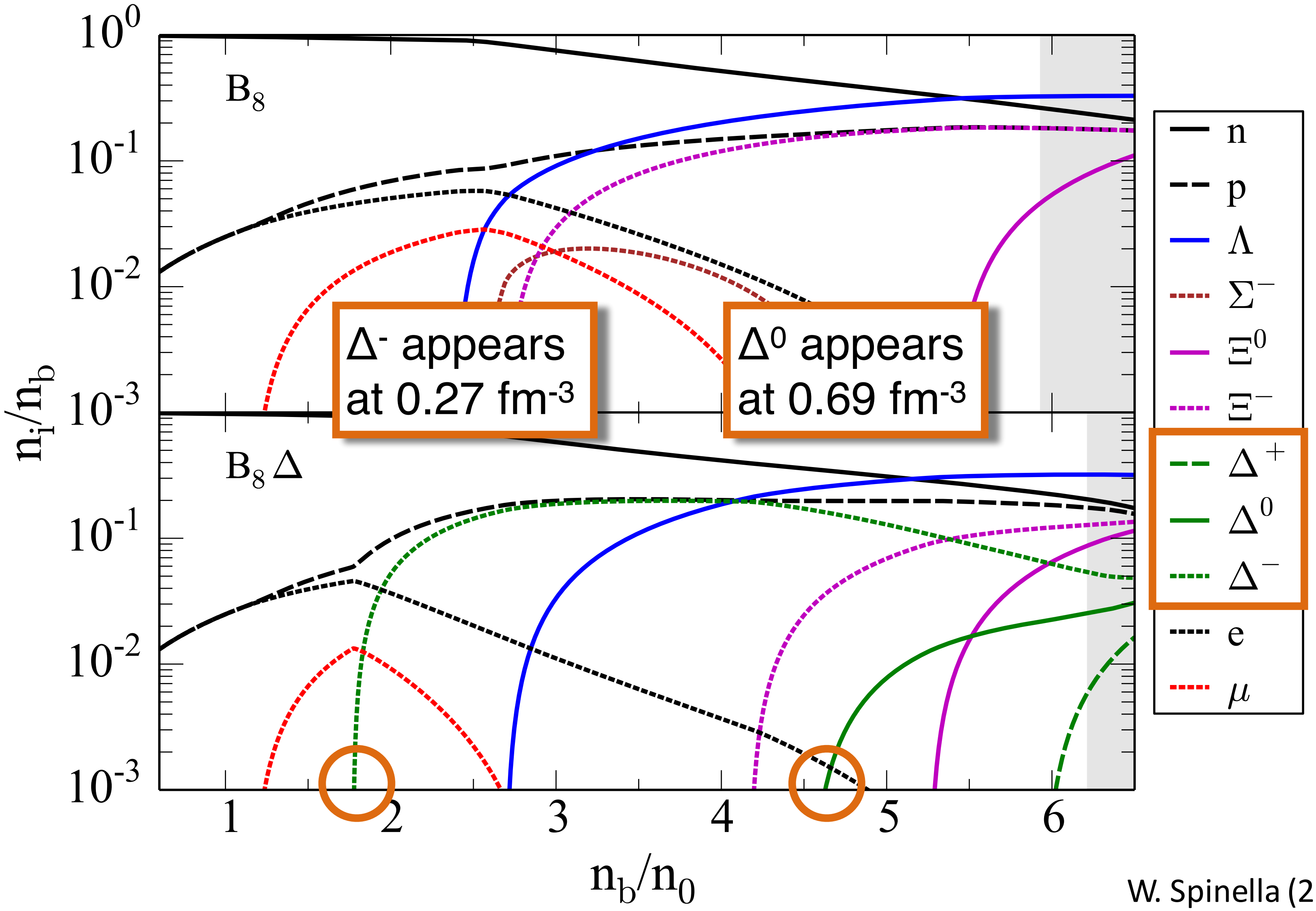
W. Spinella (2016)

Mass-Radius+Constraints with Hyperons+Deltas



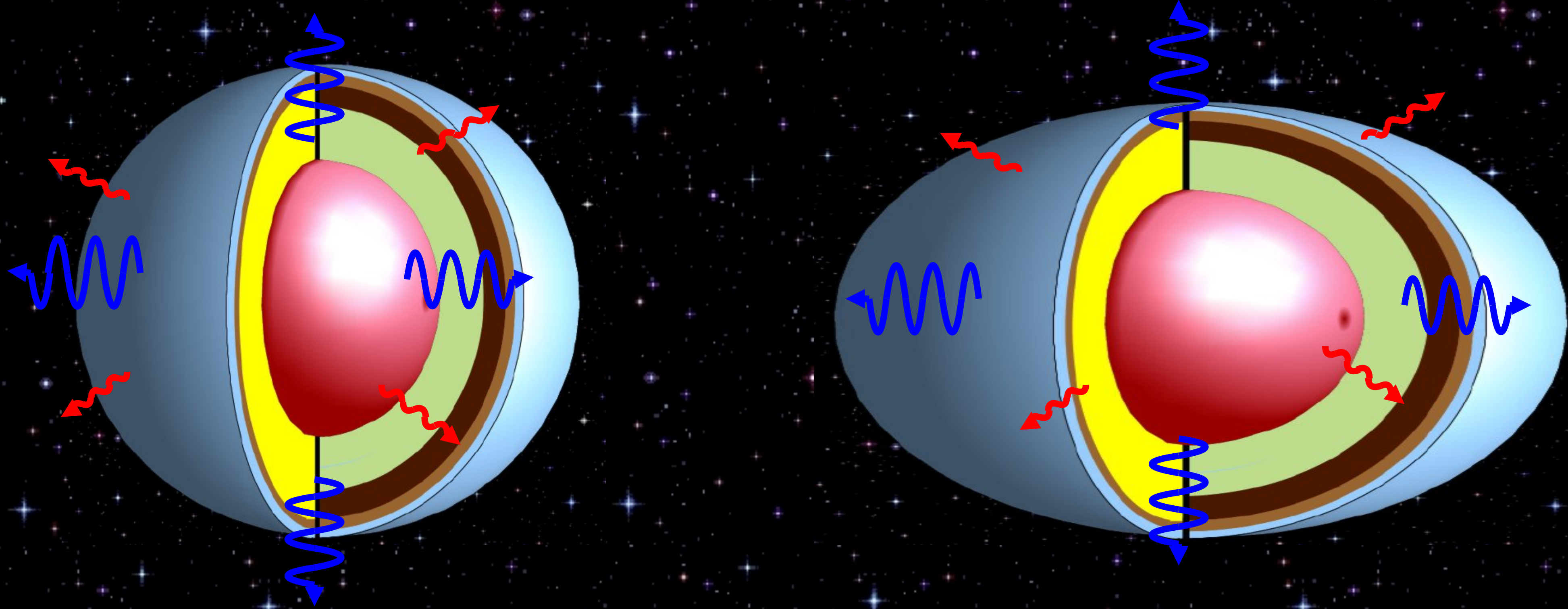
W. Spinella (2016)

Δ's in Neutron Star Matter



W. Spinella (2016)

Rotating Neutron Stars



R. Mellinger (2016)

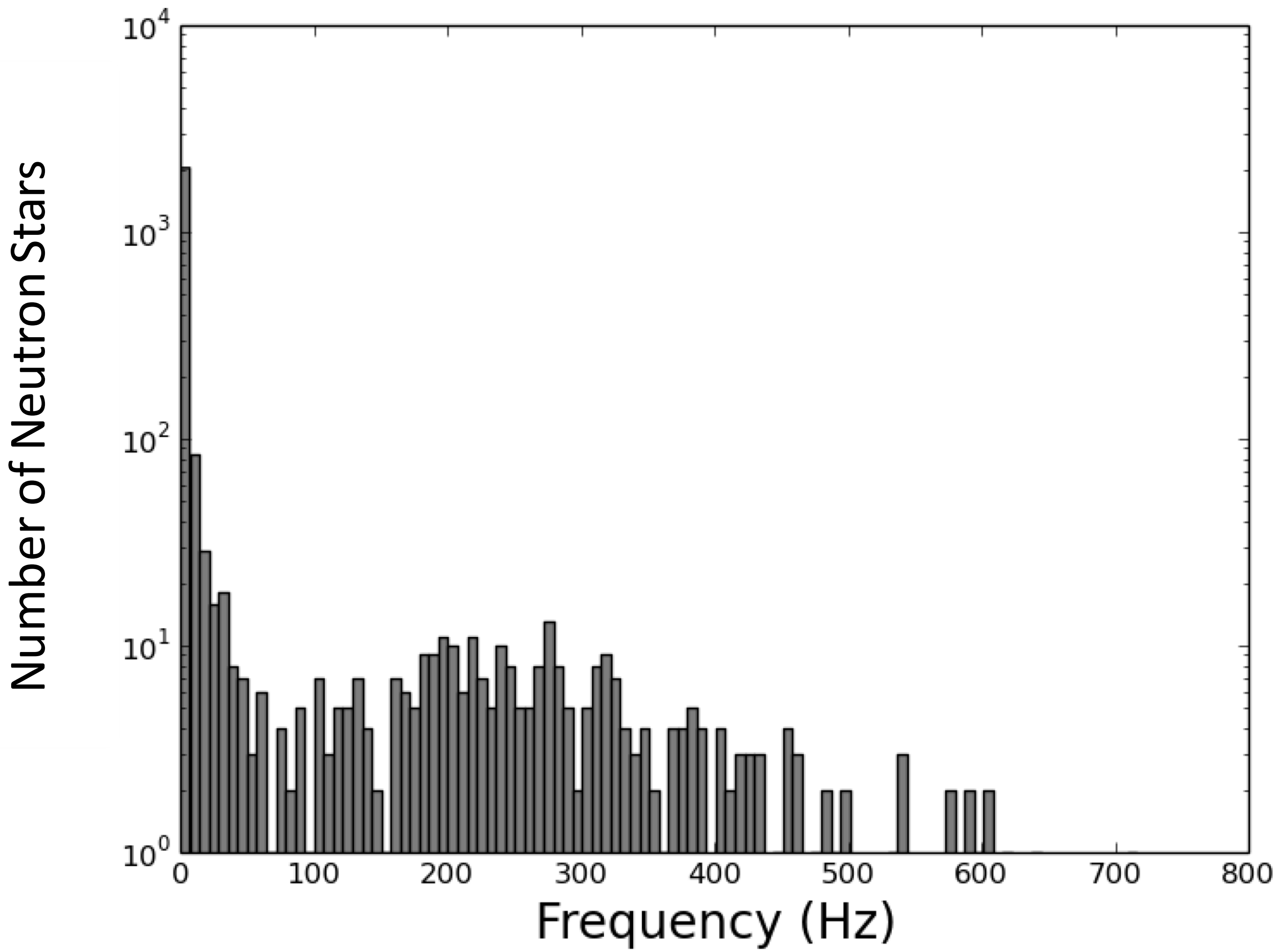
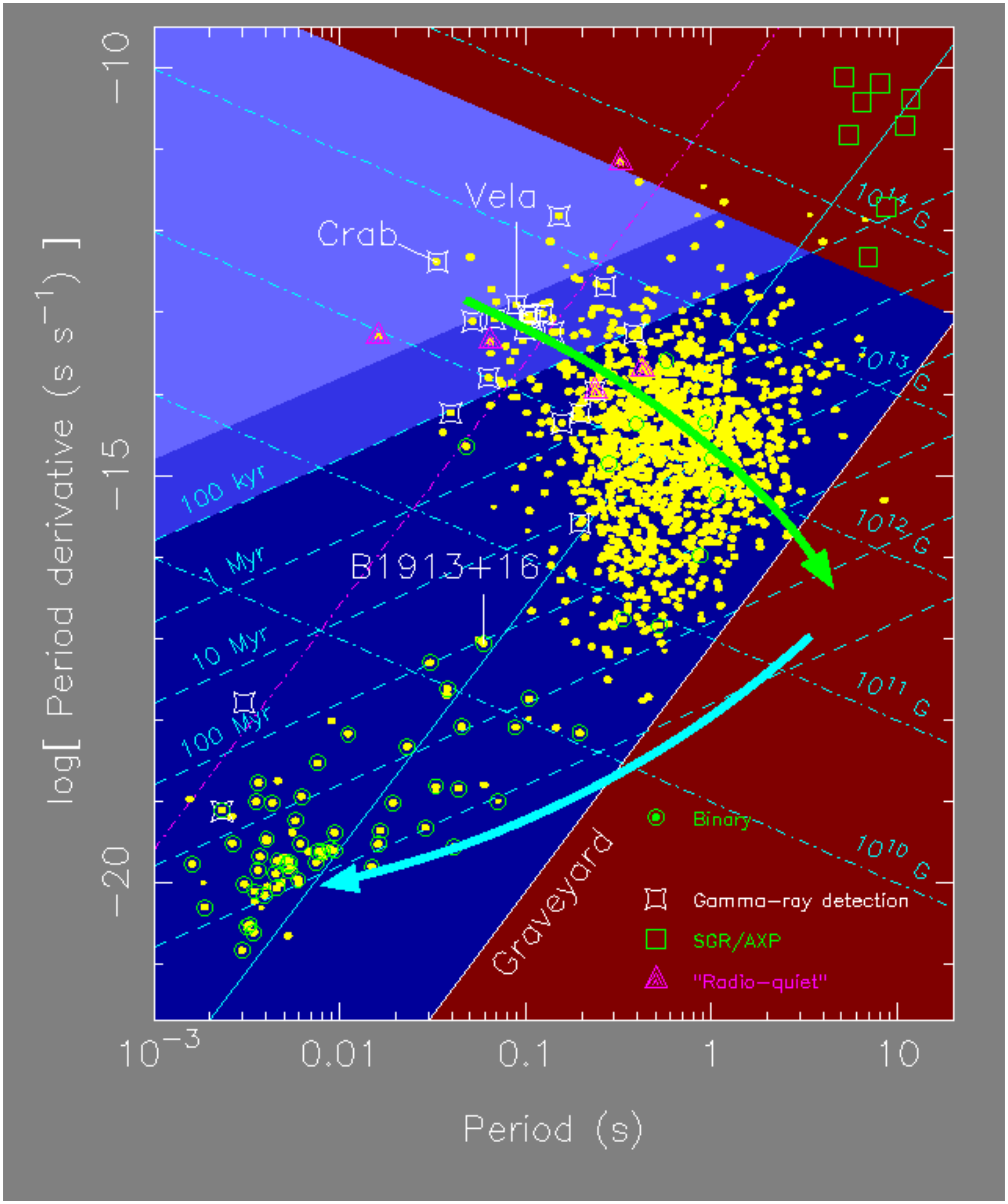


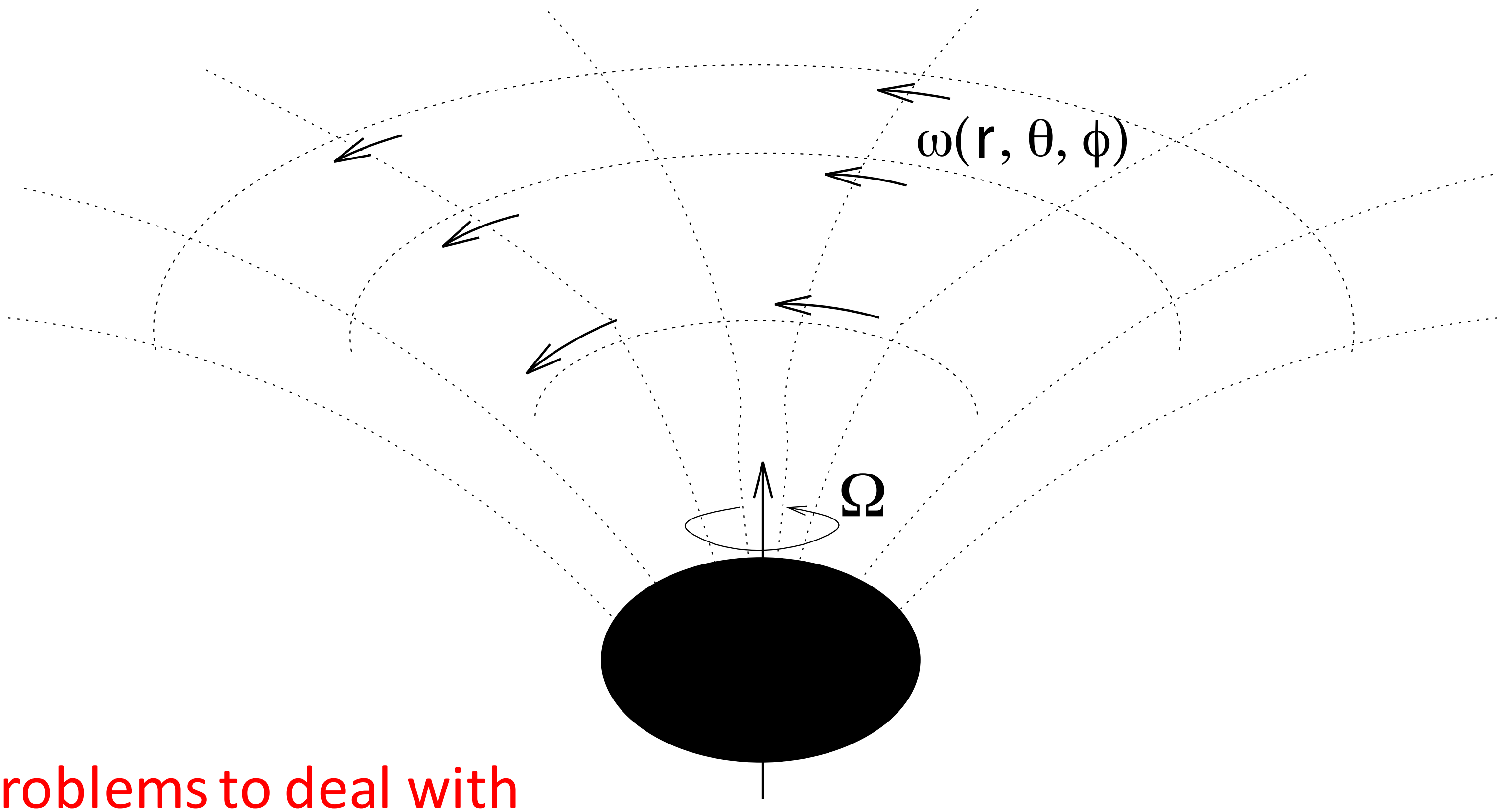
Figure 1. Histogram for the frequencies of all 2,510 pulsars which have frequency data in version 1.53 of The Australia Telescope National Facility Pulsar Catalogue.



Source:
Jodrell Bank Centre
for Astrophysics

http://www.jb.man.ac.uk

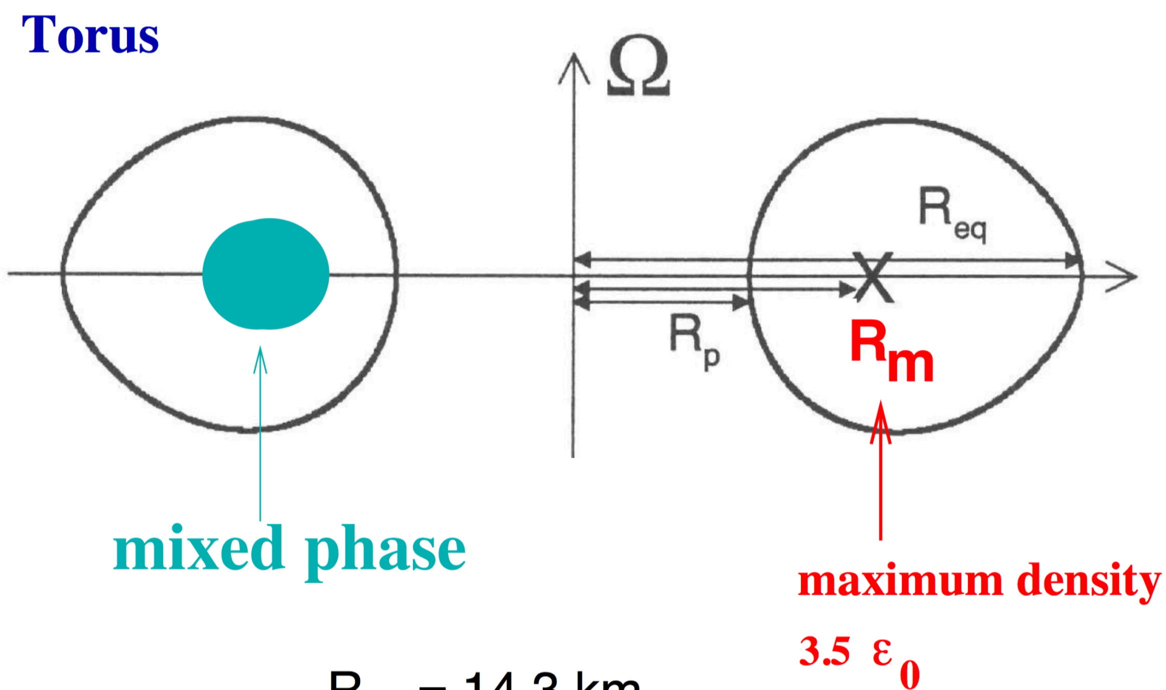
Rotation in General Relativity



Problems to deal with

- 2-D system
- Dragging of local inertial frames (Lense-Thirring effect)
- Maximum rotational frequency

Differential rotation



R_{eq} = 14.3 km

R_p = 1.9 km

R_m = 5.5 km

Einstein's Field Equations for Rotating Compact Objects

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

Friedman, Ipser & Parker (1986)

- 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: $R_{\mu\nu} = R^{\tau}{}_{\mu\tau\nu}$

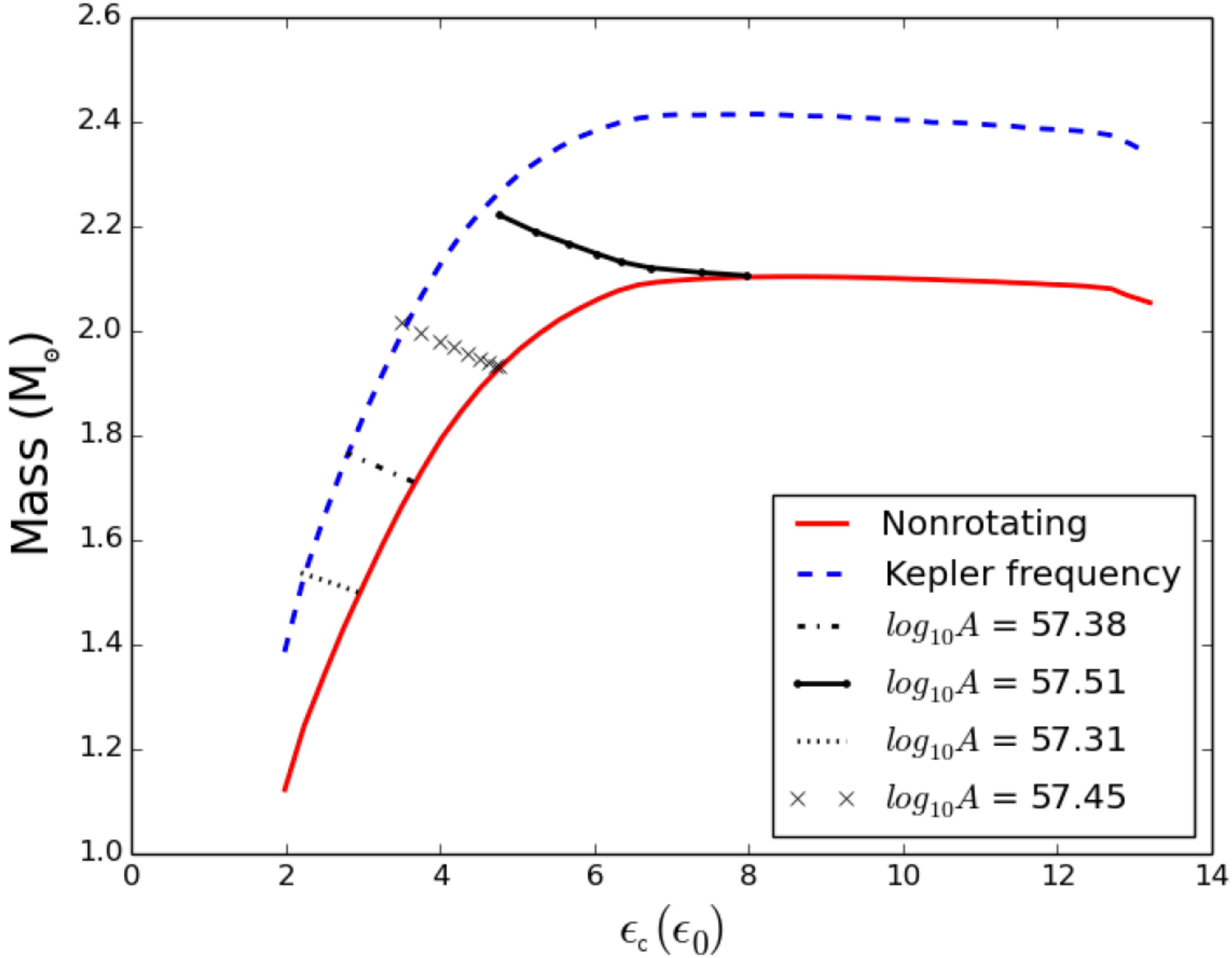
- Scalar curvature: $R = R_{\mu\nu}\,g^{\mu\nu}$

- Kepler frequency: $\Omega_K = r^{-1}\,e^{\nu-\alpha-\beta}\,U_K + N^{\varphi} \xrightarrow{\text{Newtonian limit}} \sqrt{M/R^3}$

- Differential rotation/uniform rotation at $0 < \Omega < \Omega_K$

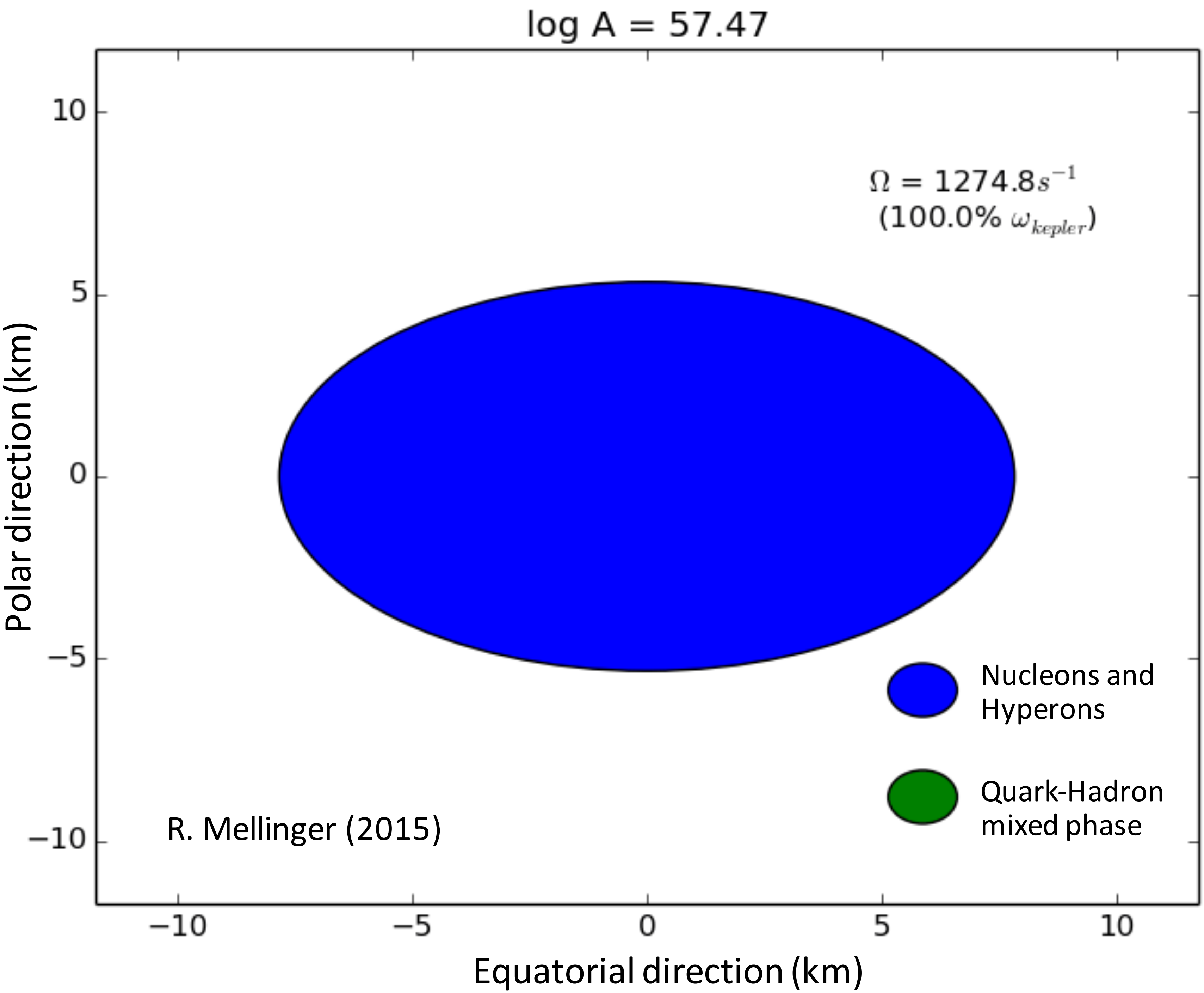
Stellar properties: $\mathbf{M, R_p, R_{eq}, I, z, \Omega_K, \omega, P(r), \varepsilon(r), \rho(r)}$

R. Mellinger (2016)



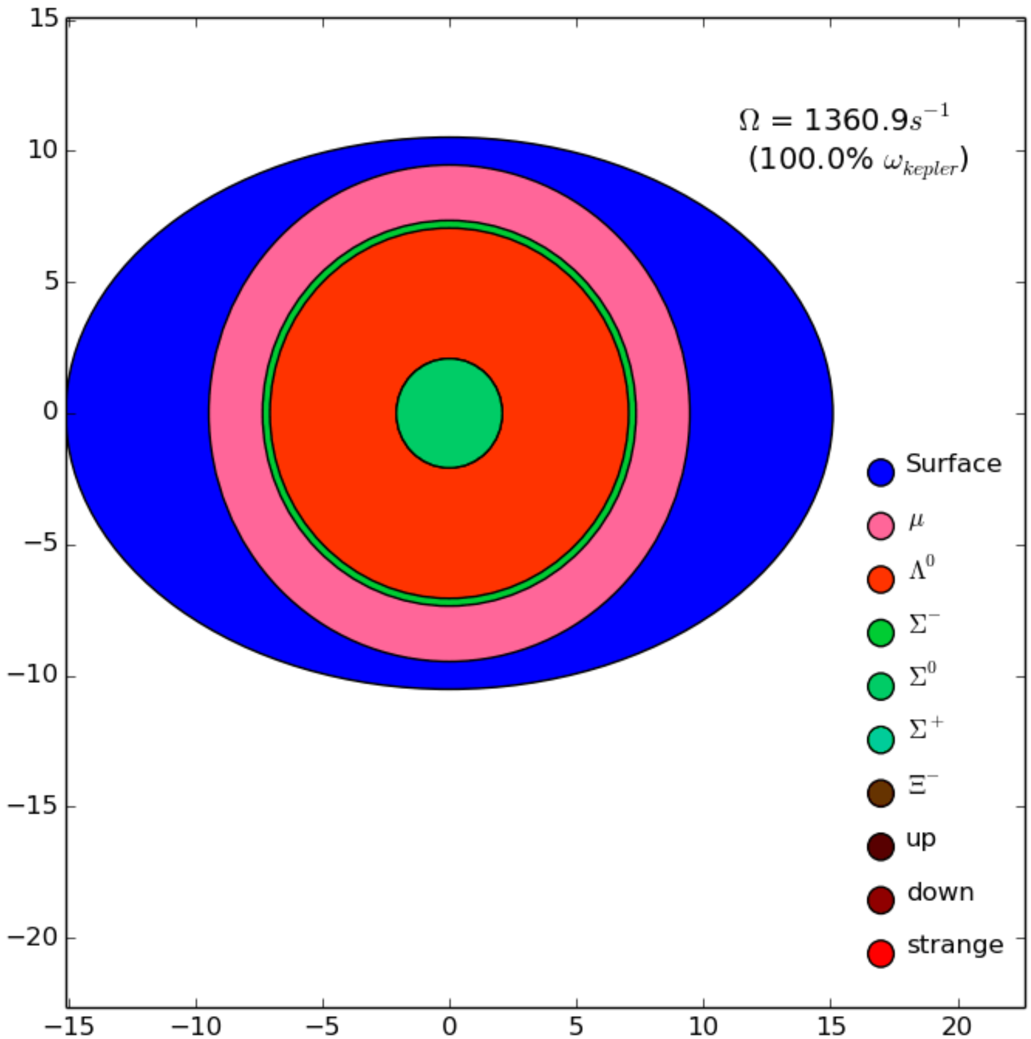
Central stellar density

Rotation-driven compositional changes inside of neutron stars



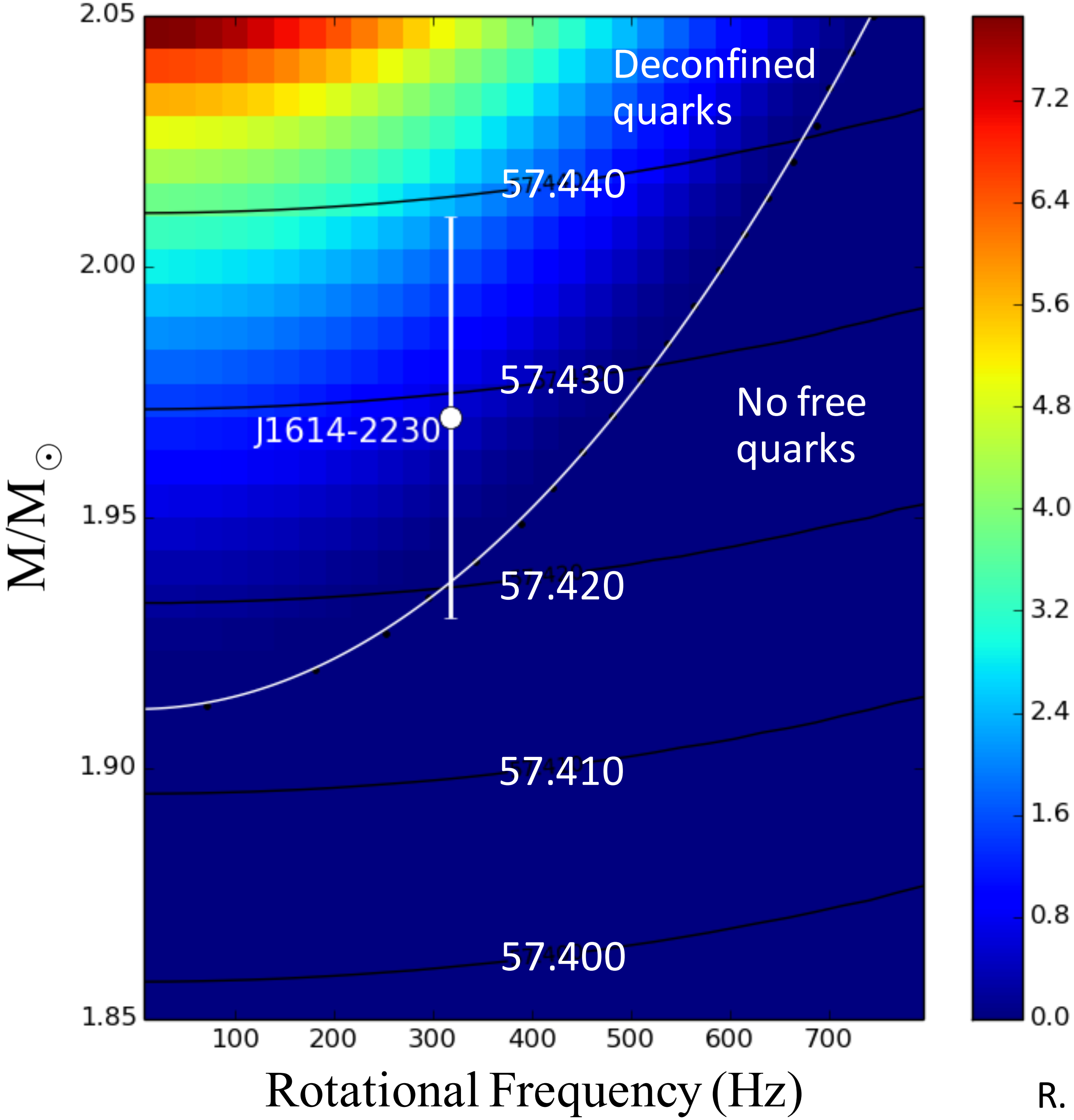
Rotation-driven compositional changes inside of neutron stars

Polar direction (km)



Equatorial deformation (km)

Rotation-driven compositional changes inside of neutron stars

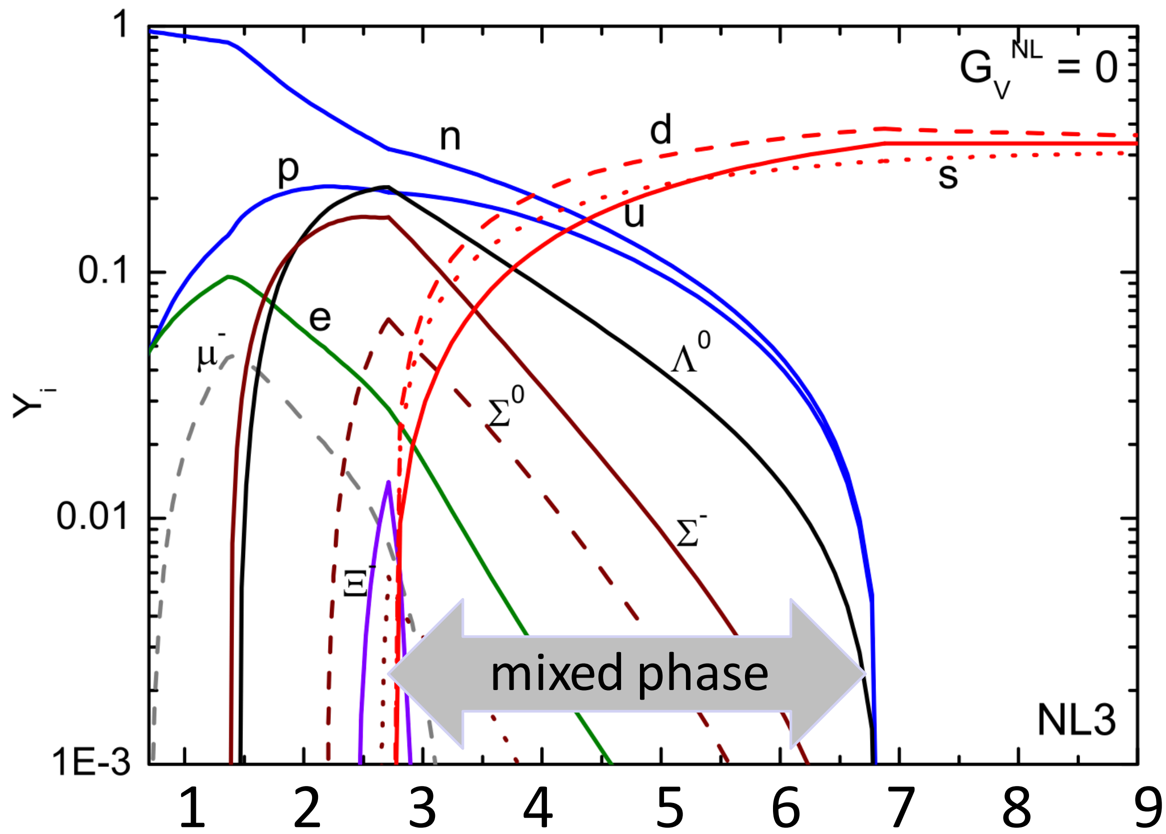


R. Mellinger (2016)

Quark-Hadron Lattices

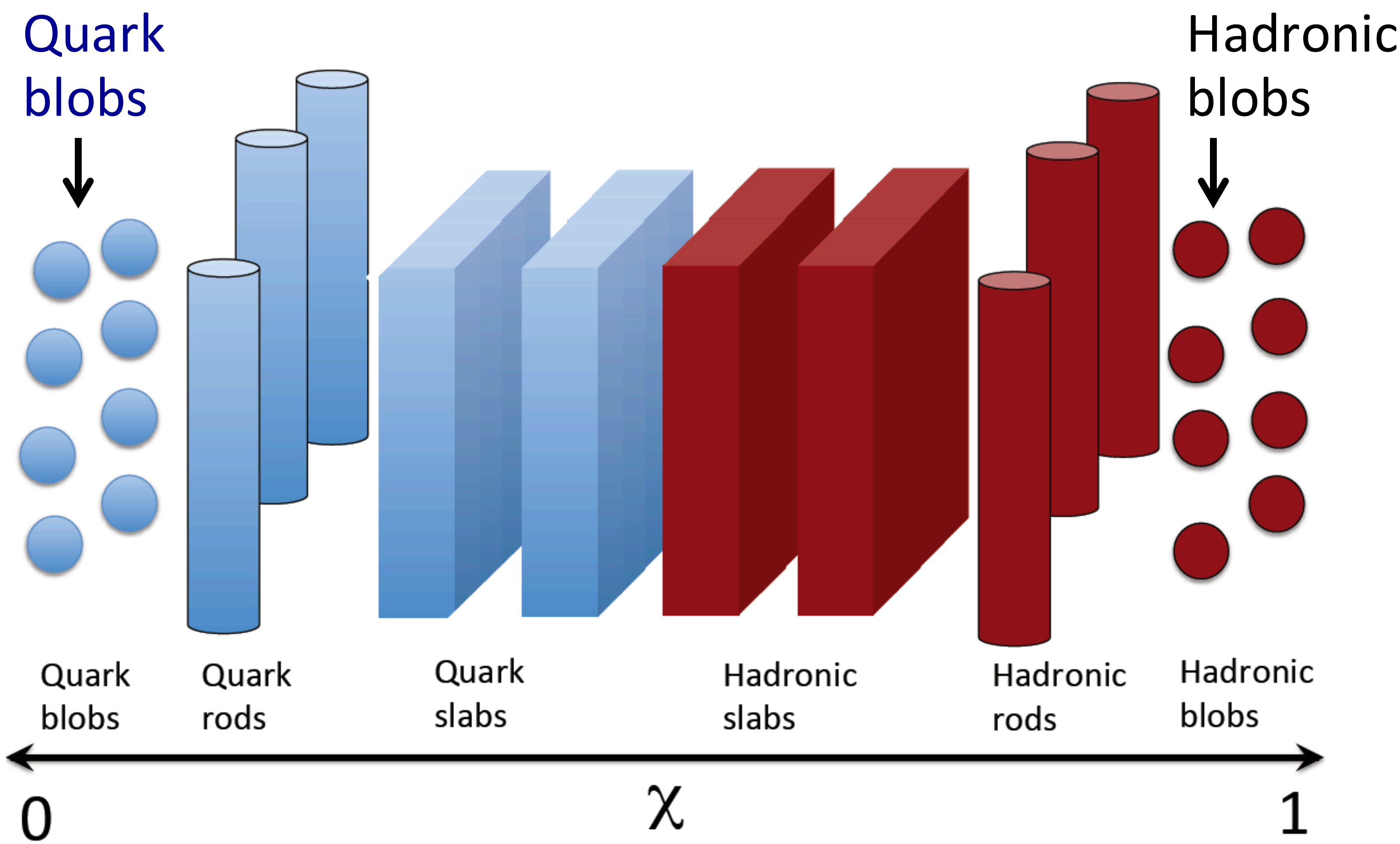
Geometrical Structures in the mixed Quark-Hadron Phase

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

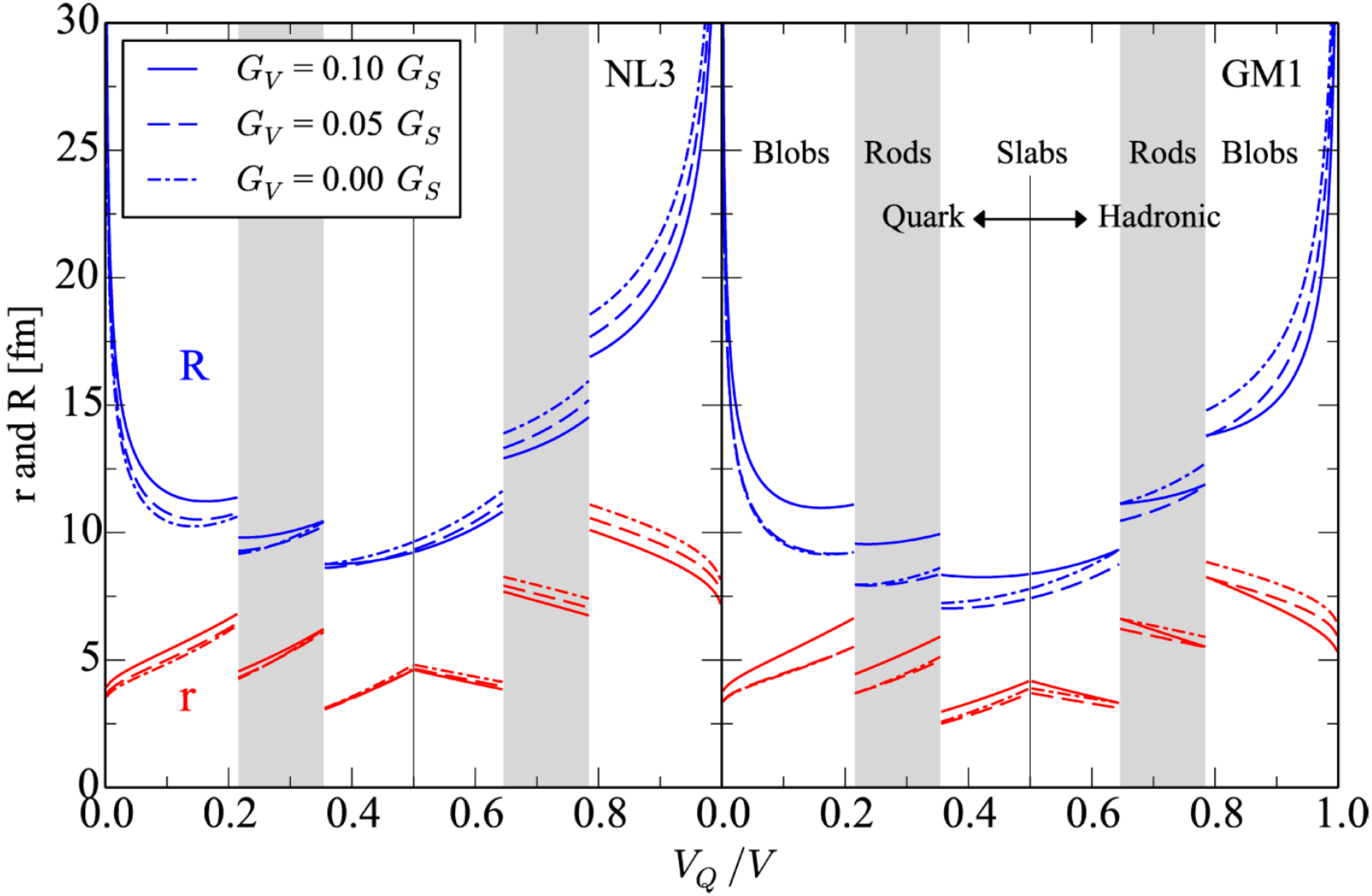


- Competition between Coulomb and surface energies in the mixed phase
- Mixed quark-hadron phase may develop geometrical structures

Quark-Hadron Mixed Phase in Cores of Neutron Stars?



Leads to changes the heat capacity, thermal conductivity, neutrino emissivity!



W. Spinella et al. (EPJA 52 (2016) 61)
See also Glendenning Phys Rep 342 (2001) 393; X. Na et al., PRD 86 (2012) 123016

Electron-Quark Scattering leads to Bremsstrahlung

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

↑

Quark blobs/rods/slabs

For the scattering of neutrinos from quark droplets, see S. Reddy, G. Bertsch, M. Prakash, PLB 475 (2000) 1

Electron-Quark Scattering leads to Bremsstrahlung

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

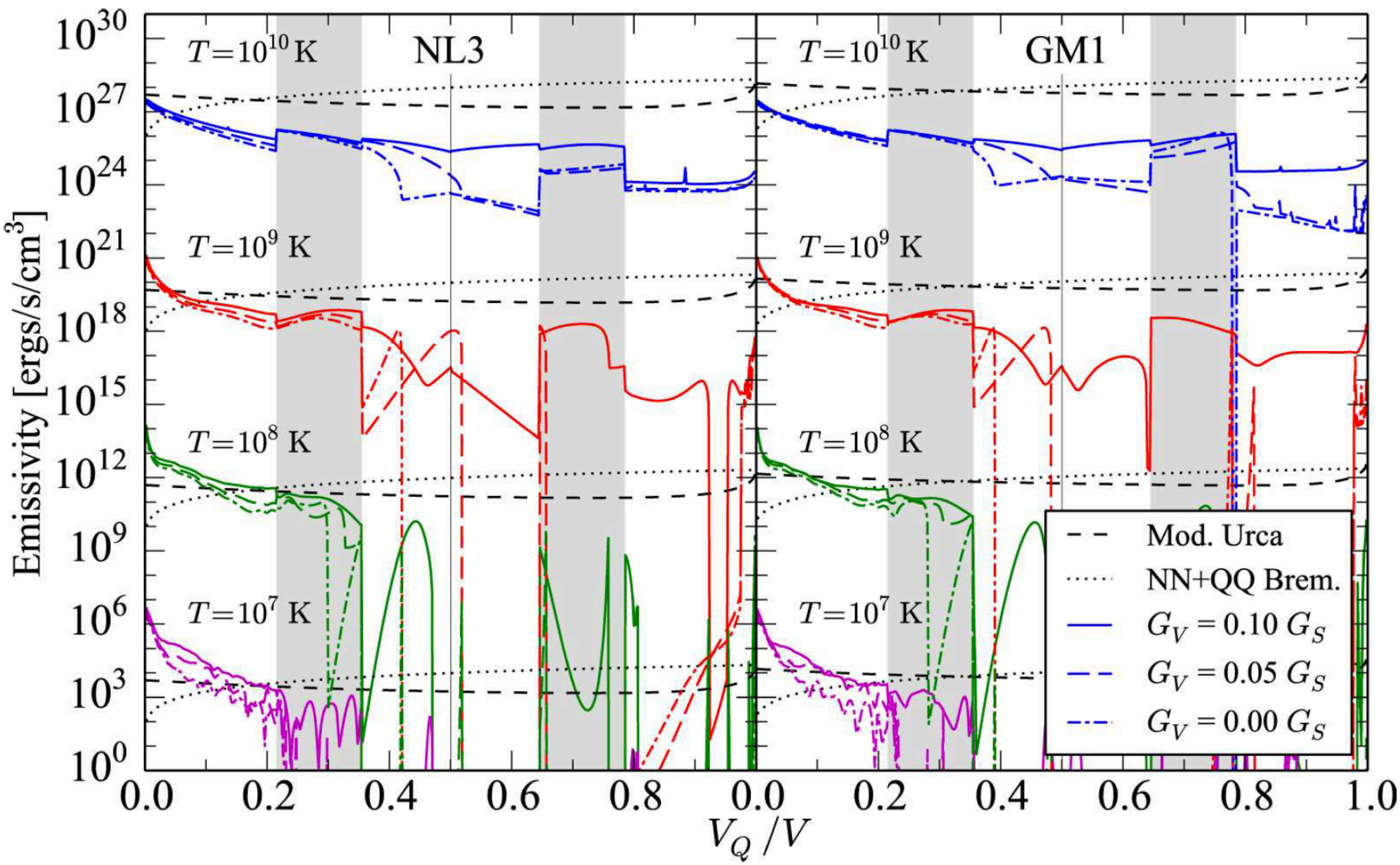
Sub-nuclear NS matter (electrons + heavy atomic nuclei):

- Haensel Kaminker, Yakovlev (1996)
- Yakovlev, Kaminker (1996)
- Kaminker, Pethick, Potekhin, Thorsson, Yakovlev (1999)

Modified URCA: $n+n \rightarrow n+p+e+\bar{\nu}$

Nucleon Bremsstrahlung: $n+n \rightarrow n+n+\nu+\bar{\nu}$

Electron-quark blob Bremsstrahlung: $e+(Z,A) \rightarrow e+(Z,A)+\nu+\bar{\nu}$



W. Spinella (2015); see also X. Na et al., PRD 86 (2012) 123016

Non-rotating
but
nevertheless Deformed?

Anisotropic equations of state (see E. J. Ferrer et al., PRC 82 (2010) 065802)

Metric of spherically symmetric mass distributions

(Schwarzschild metric)

$$ds^2 = -e^{2\Phi}dt^2 + e^{2\Lambda}dr^2 + r^2 d\theta^2 + r^2 \sin^2\theta d\phi^2$$

isotropic case

$$(T^{\mu\nu}) = \begin{pmatrix} \epsilon & 0 & 0 & 0 \\ 0 & P_{xx} & P_{xy} & P_{xz} \\ 0 & P_{yx} & P_{yy} & P_{yz} \\ 0 & P_{zx} & P_{zy} & P_{zz} \end{pmatrix} = \begin{pmatrix} \epsilon & 0 & 0 & 0 \\ 0 & P & 0 & 0 \\ 0 & 0 & P & 0 \\ 0 & 0 & 0 & P \end{pmatrix}$$

More on the isotropic case

$$(T^{\mu\nu}) = \begin{pmatrix} \epsilon & 0 & 0 & 0 \\ 0 & P_{xx} & P_{xy} & P_{xz} \\ 0 & P_{yx} & P_{yy} & P_{yz} \\ 0 & P_{zx} & P_{zy} & P_{zz} \end{pmatrix} = \begin{pmatrix} \epsilon & 0 & 0 & 0 \\ 0 & P & 0 & 0 \\ 0 & 0 & P & 0 \\ 0 & 0 & 0 & P \end{pmatrix}$$

↓ Rank-2 tensor transformation

$$T^{\mu\nu} = (\epsilon + P)u^\mu u^\nu + g^{\mu\nu} P$$

Tolman-**O**ppenheimer-**V**olkoff equation

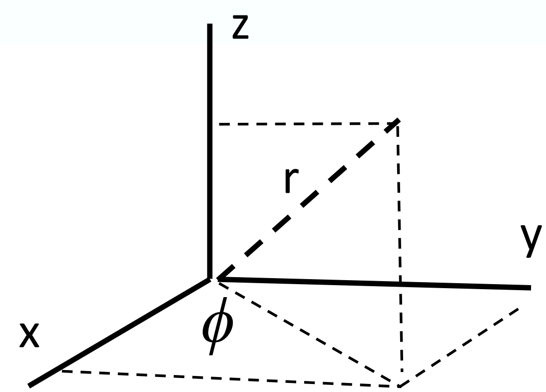
$$\frac{dP}{dr} = -\frac{\epsilon\left(1+\frac{P}{\epsilon}\right) m \left(1+\frac{4\pi P r^3}{m}\right)}{r^2\left(1-\frac{2m}{r}\right)}$$

$$m(r) = 4\pi \int_0^r \; r'^2 \epsilon(r') \; dr'$$

Energy-momentum tensor of non-isotropic matter

$$T^{\mu}{}_{\nu} = \begin{array}{c} \\ t \\ r \\ z \\ \phi \end{array} \begin{array}{c} \begin{array}{cccc} t & r & z & \phi \end{array} \\ \begin{pmatrix} \epsilon & 0 & 0 & 0 \\ 0 & P_{rr} & P_{rz} & 0 \\ 0 & P_{zr} & P_{zz} & 0 \\ 0 & 0 & 0 & P_{\phi\phi} \end{pmatrix} \end{array}$$

$$T^{t}{}_{t} = \epsilon$$
$$T^{r}{}_{r} = P_{\parallel}$$
$$T^{z}{}_{r} = \tilde{P}$$
$$T^{r}{}_{z} = \tilde{P}$$
$$T^{z}{}_{z} = P_{\perp}$$
$$T^{\phi}{}_{\phi} = \tilde{P}$$



Energy-momentum tensor of non-isotropic matter

$$T^{\mu}{}_{\nu} = \begin{array}{c|cccc} & t & r & z & \phi \\ \hline t & \epsilon & 0 & 0 & 0 \\ r & 0 & P_{rr} & P_{rz} & 0 \\ z & 0 & P_{zr} & P_{zz} & 0 \\ \phi & 0 & 0 & 0 & P_{\phi\phi} \end{array}$$

$$T^{t}{}_{t} = \epsilon$$

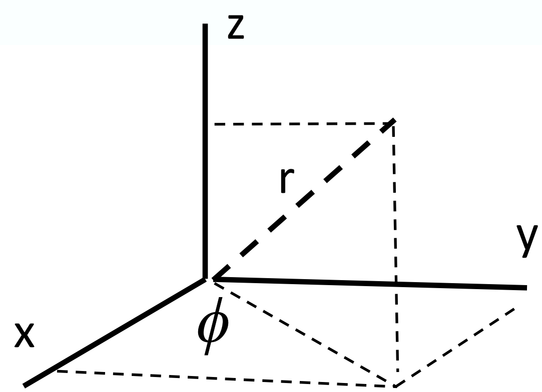
$$T^{r}{}_{r} = P_{\parallel}$$

~~$T^{z}{}_{r} = \tilde{P}$~~

~~$T^{r}{}_{z} = \tilde{P}$~~

$$T^{z}{}_{z} = P_{\perp}$$

~~$T^{\phi}{}_{\phi} = \tilde{P}$~~



Full Stellar Structure Equations of Deformed NSs

$$\frac{\partial P_{\parallel}}{\partial r} = -\frac{(\epsilon + P_{\parallel})\left[\frac{1}{2}r + 4\pi r^3 P_{\parallel} - \frac{1}{2}r\left(1 - \frac{2\mathcal{M}(r,z)}{r}\right)\right]}{r^2\left(1 - \frac{2\mathcal{M}(r,z)}{r}\right)} \,,$$

$$\frac{dP_{\perp}}{dz} = -\frac{(\epsilon + P_{\perp})\left[\frac{z}{2} + 4\pi z^3 P_{\perp} - \frac{z}{2}\left(1 - \frac{2\mathcal{M}(r,z)}{z}\right)\right]}{z^2\left(1 - \frac{2\mathcal{M}(r,z)}{z}\right)}$$

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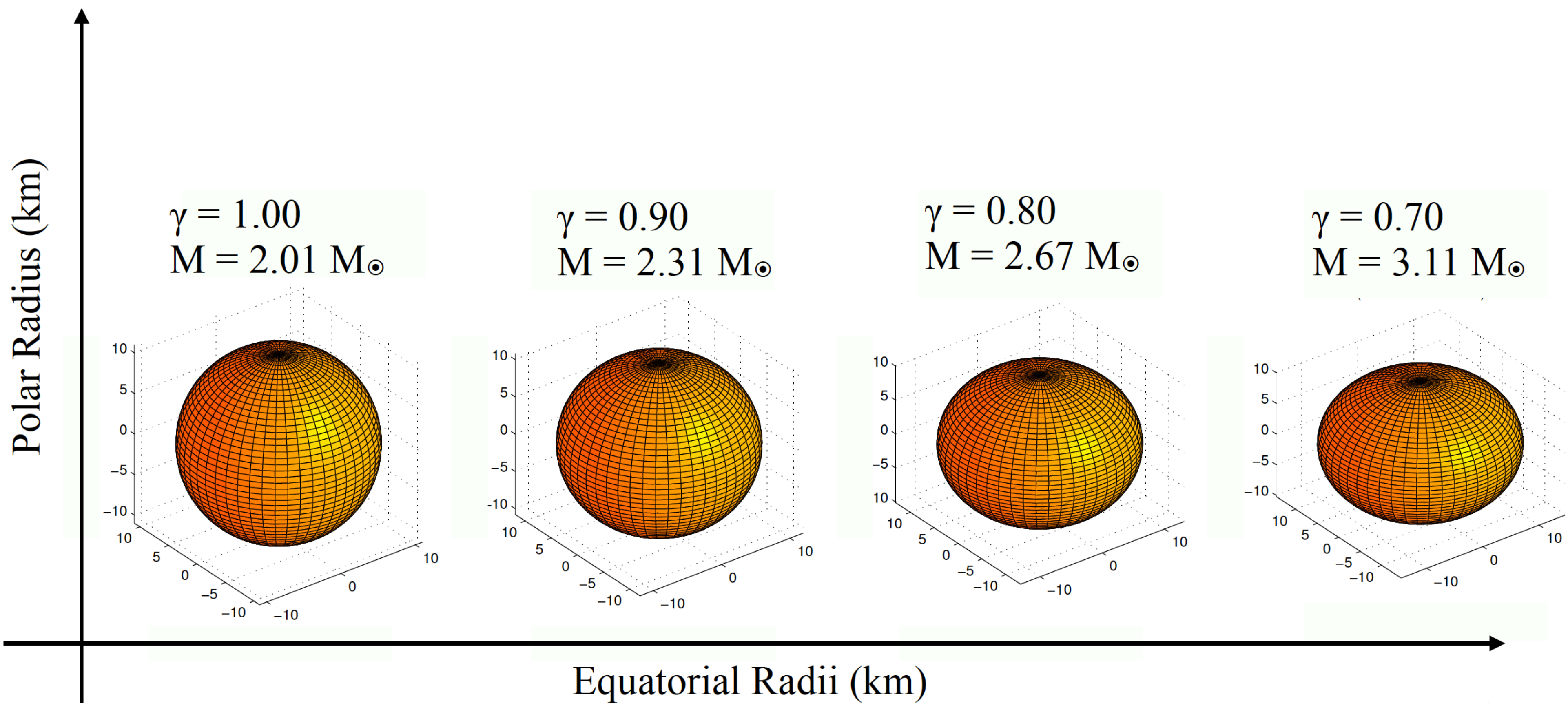
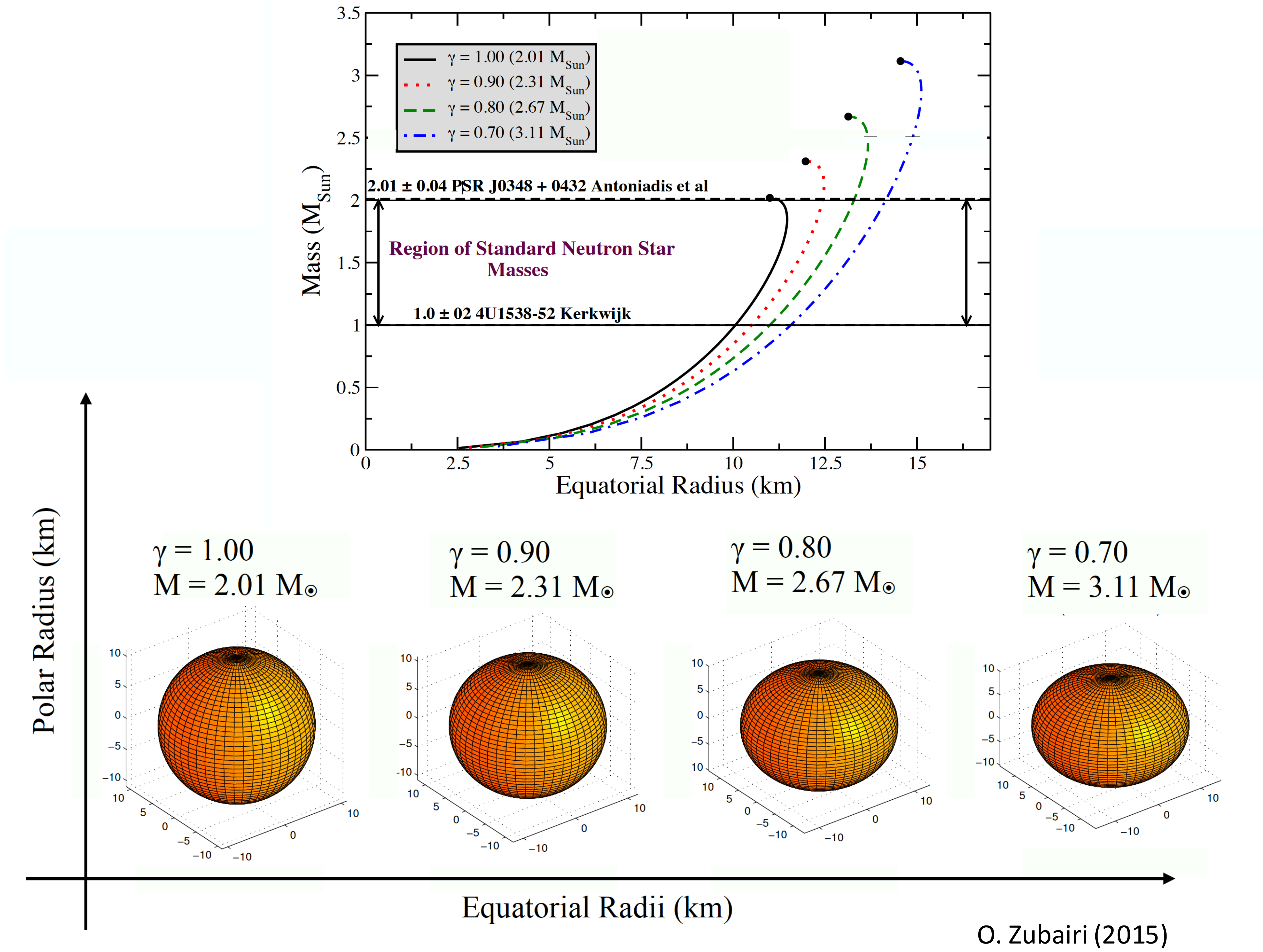
$$M(r,z) = \frac{\partial m(r,z)}{\partial r} + \frac{\partial m(r,z)}{\partial z} - \frac{1}{3}\pi\,\epsilon(r,z)\,r^2\,z$$

$$P_{\parallel}(r = R) = 0$$
$$P_{\perp}(r = Z) = 0$$

Oblate deformation



O. Zubairi (2015)



γ = 1.00 (2.01 M_Sun)
γ = 0.90 (2.31 M_Sun)
γ = 0.80 (2.67 M_Sun)
γ = 0.70 (3.11 M_Sun)
2.01 ± 0.04 PSR J0348 + 0432 Antoniadis et al
Region of Standard Neutron Star Masses
1.0 ± 02 4U1538-52 Kerkwijk
Mass (M_Sun)
Equatorial Radius (km)
γ = 1.00
M = 2.01 M⊙
γ = 0.90
M = 2.31 M⊙
γ = 0.80
M = 2.67 M⊙
γ = 0.70
M = 3.11 M⊙
Polar Radius (km)
Equatorial Radii (km)
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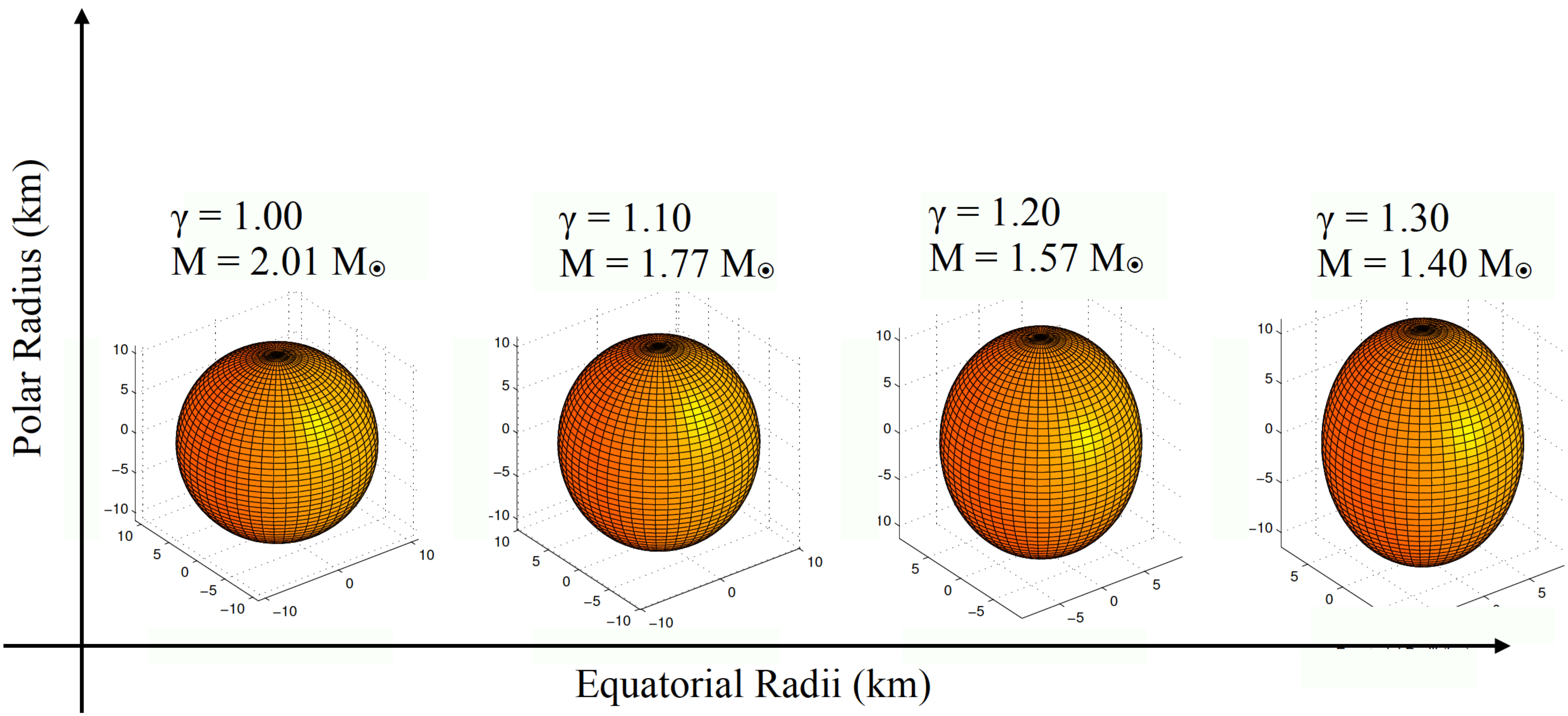
Prolate deformation



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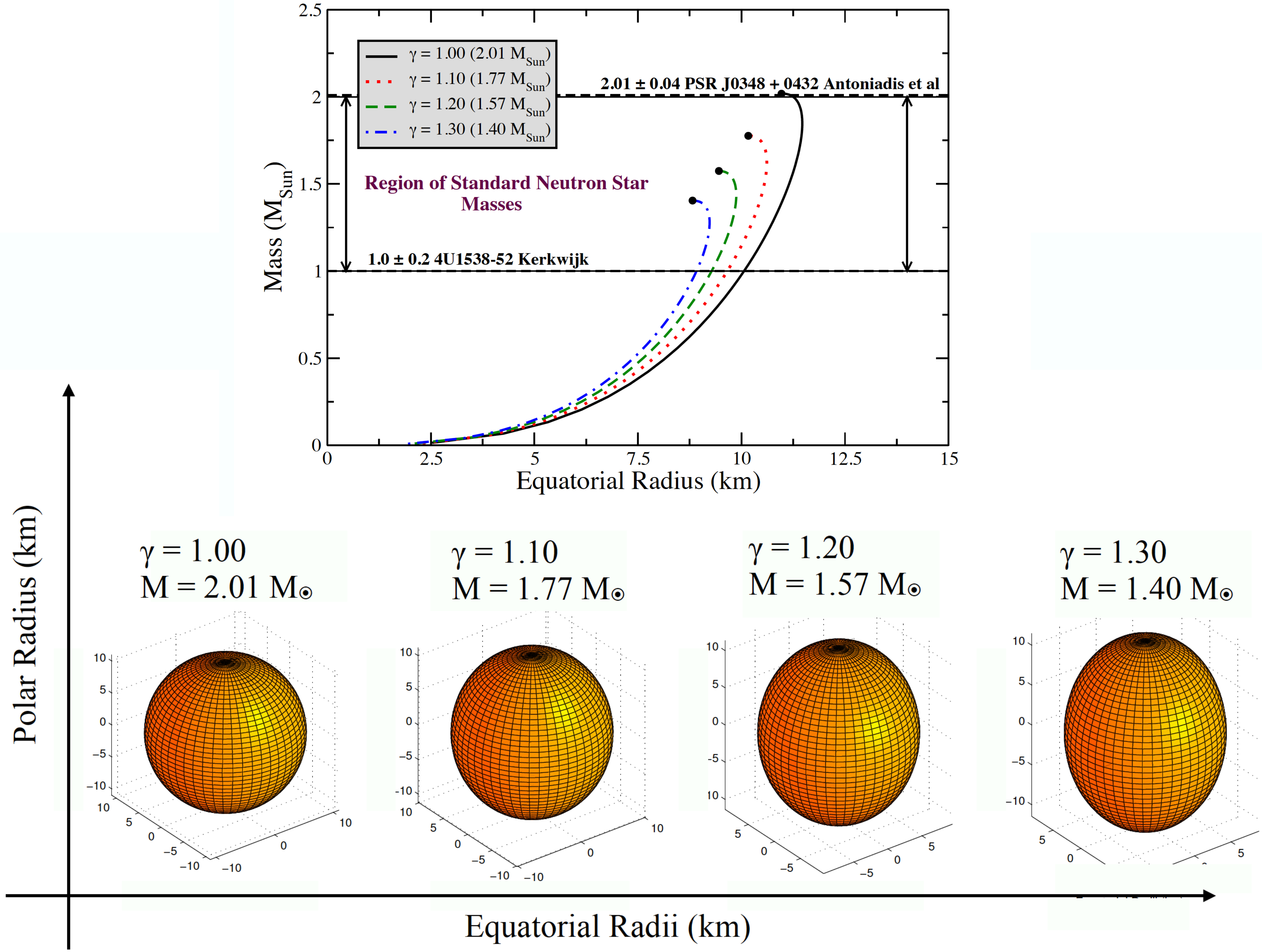

O. Zubairi (2015)

SUMMARY

- Composition and structure of rotating neutron stars depend on rotational frequency (neutron-to-proton ratio, hyperon population, boson condensates, quark-hadron composition)
- MSPs & NSs in LMXBs may be ideal objects to look for phase transitions (e.g., stellar backbending)
- Δ's in NS matter? (open issue)
- Broad collection of quark-hybrid EOSs -> all predict a mixed phase
- Quark-hadron lattices in NSs may lead to enhanced cooling of older NSs
- Anisotropic EOSs may impact maximum mass.