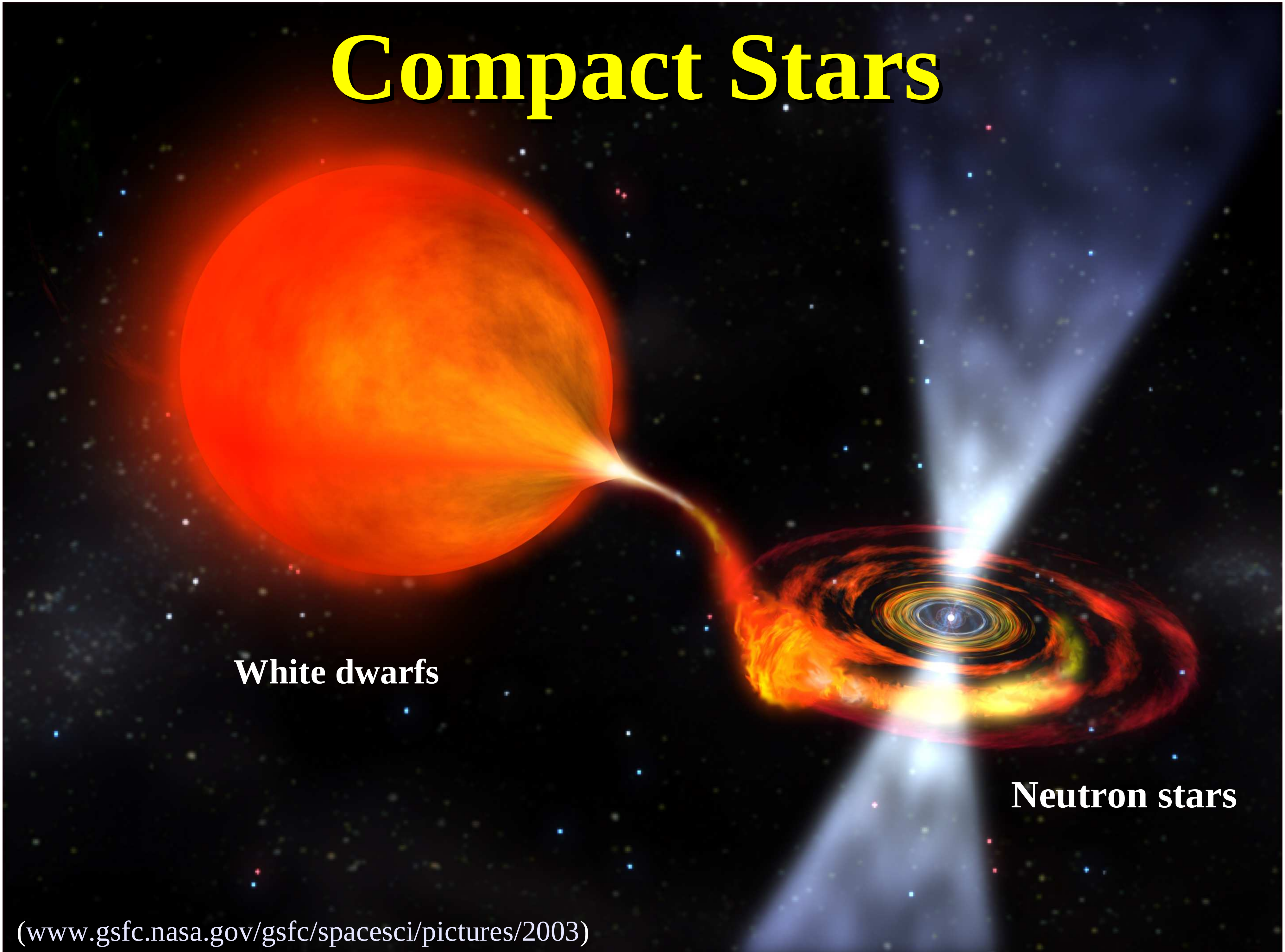
09/01/2004

The Nuclear Equation of State of Compact Stars

Fridolin Weber
San Diego State University
San Diego, CA, USA

228th ACS National Meeting, Philadelphia, PA, August 22-26, 2004

Compact Stars

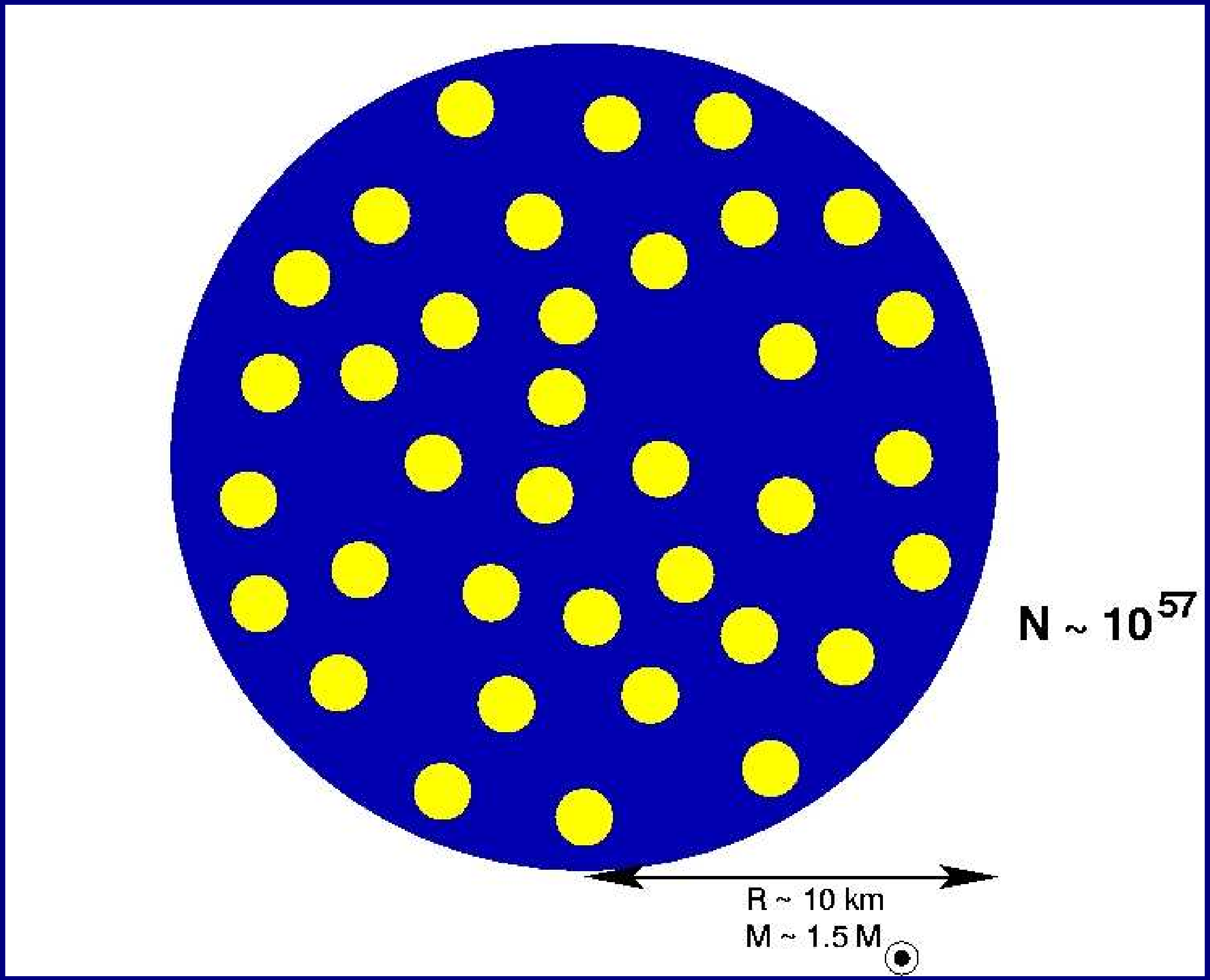


(www.gsfc.nasa.gov/gsfc/spacesci/pictures/2003)

09/01/2004

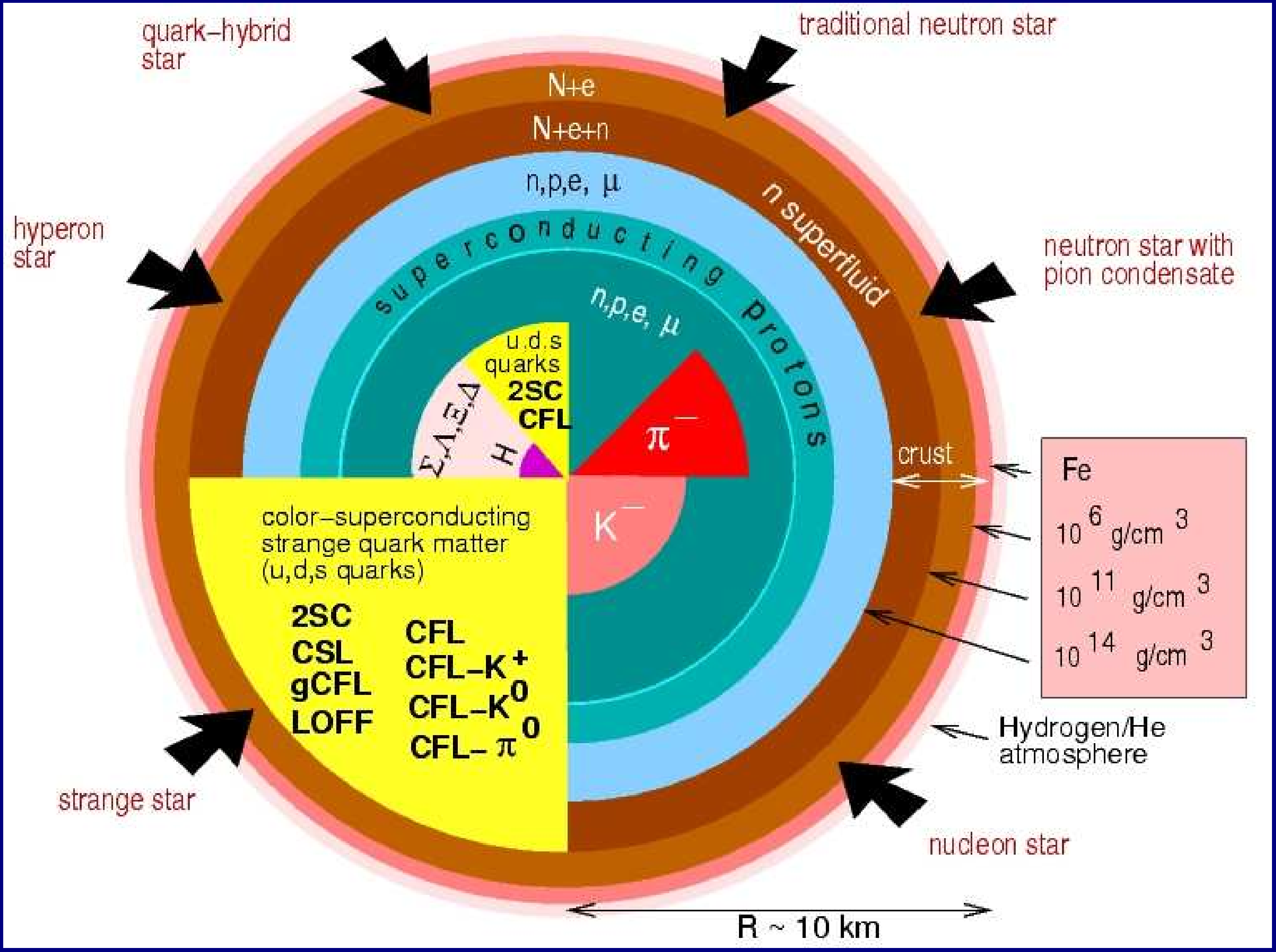
Classical Neutron Star Composition ~ 1930's

Neutrons only

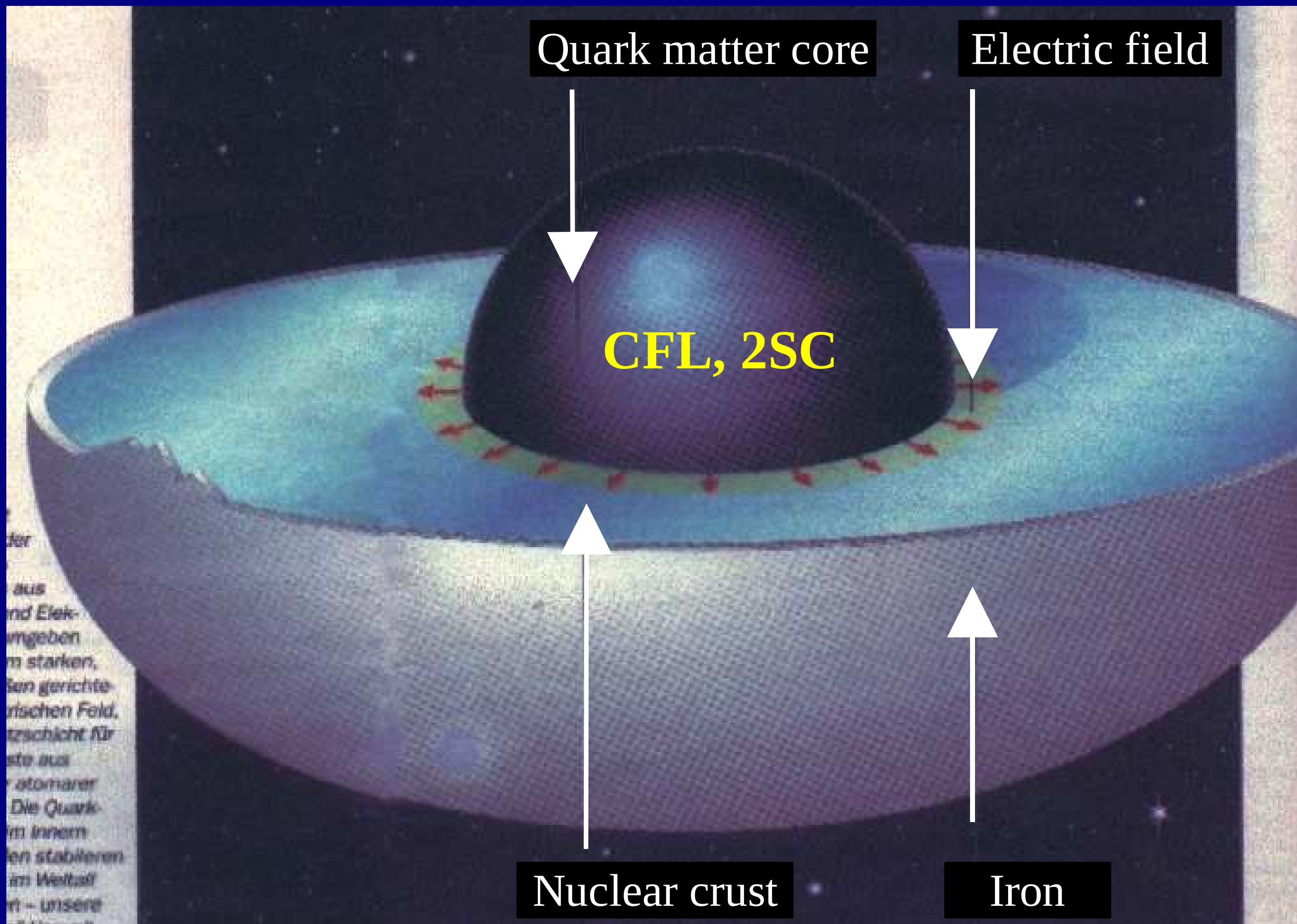


09/01/2004

Neutron Star Composition in 2004

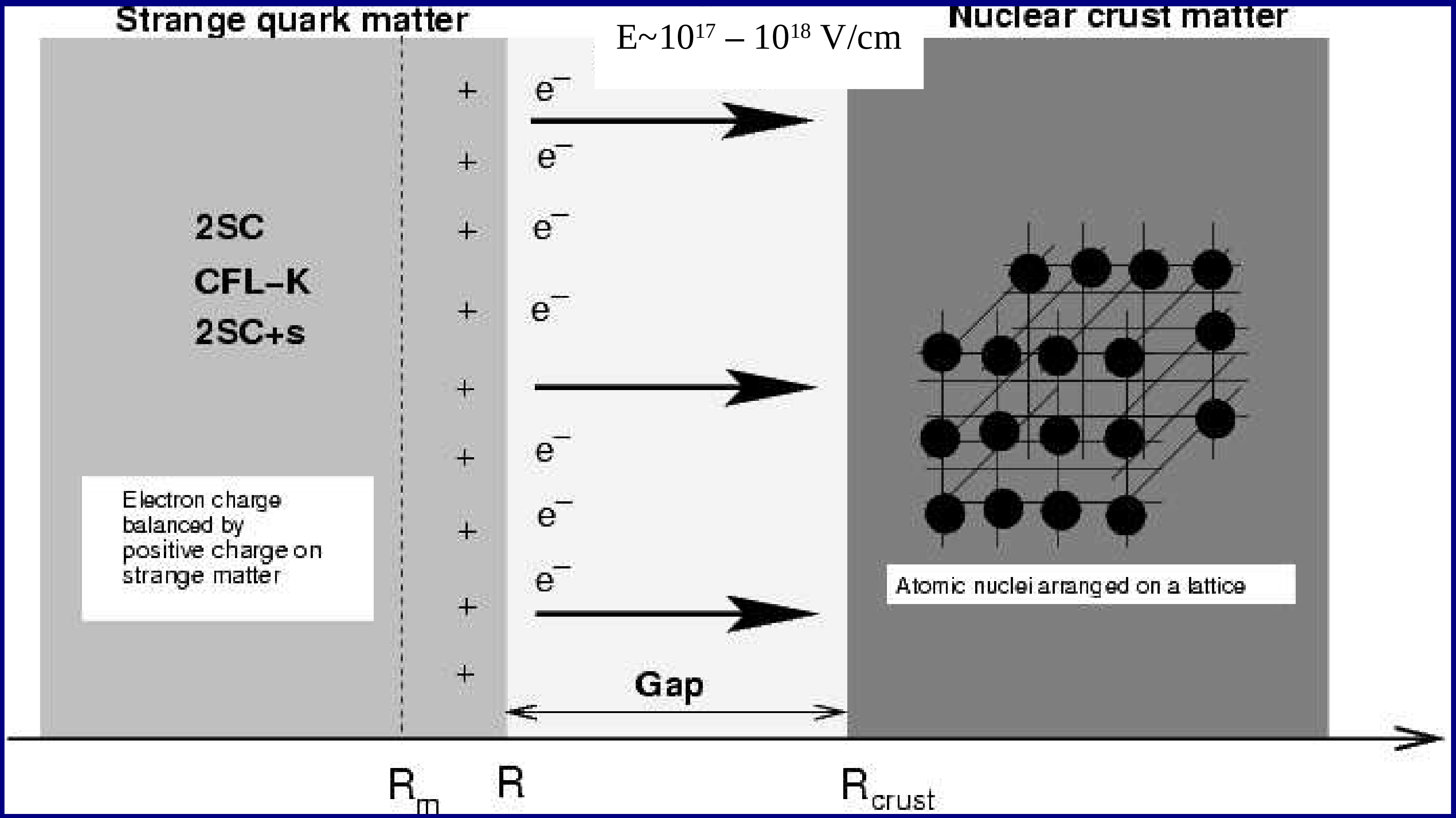


Structure and EoS of Strange Stars

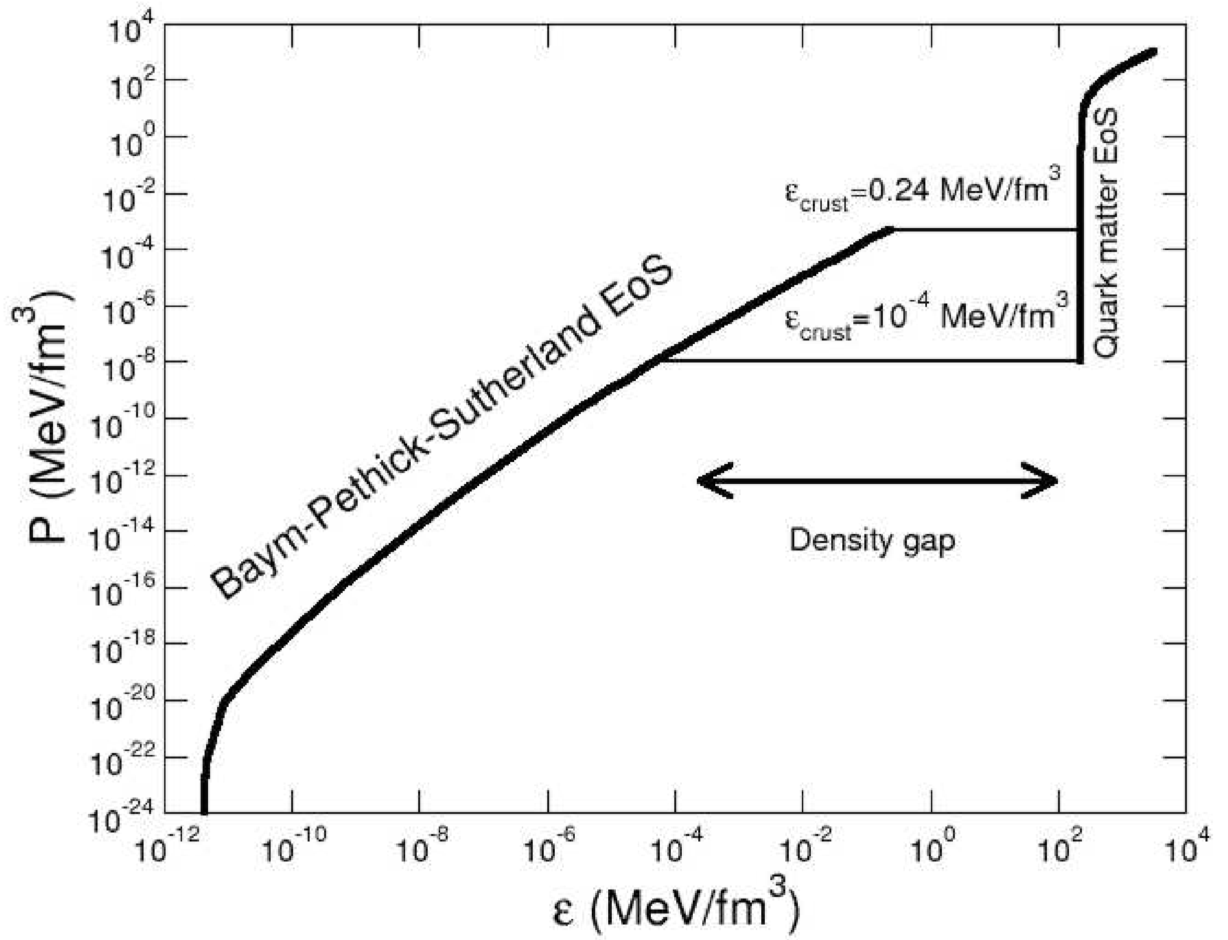


Strange Dwarfs: PRL 74 (1995) 3519; surface properties: see V. Usov, astro-ph/0408217

Surface Properties of Strange Matter

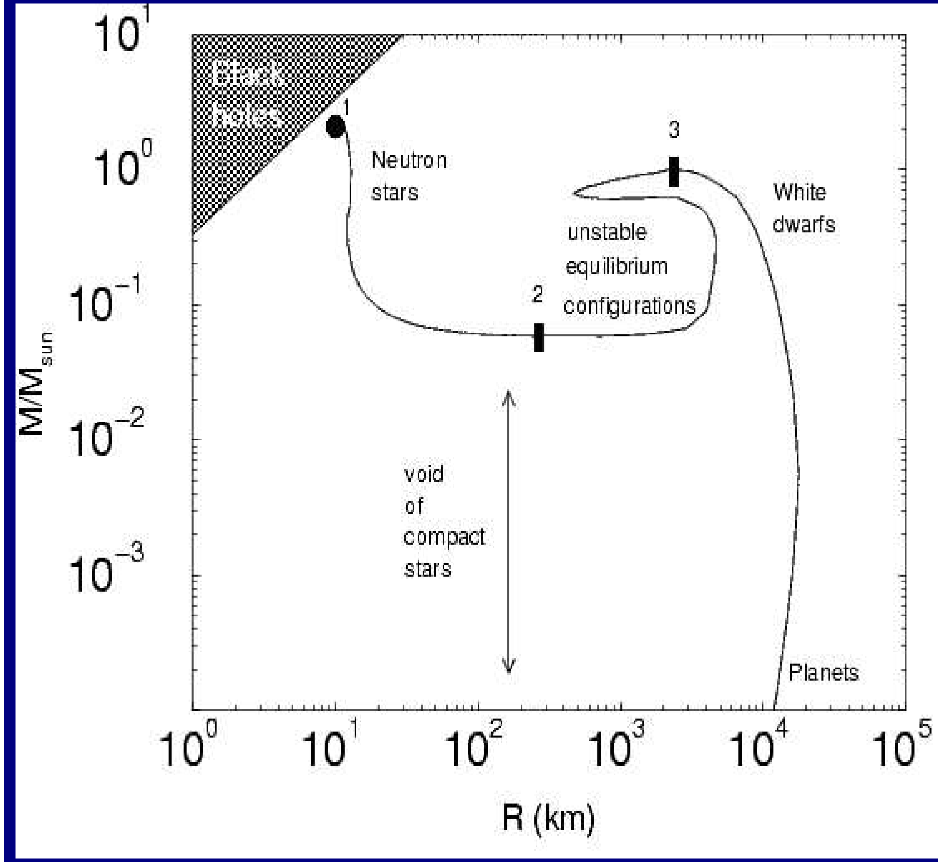


Equation of State of Strange Stars with Nuclear Crusts

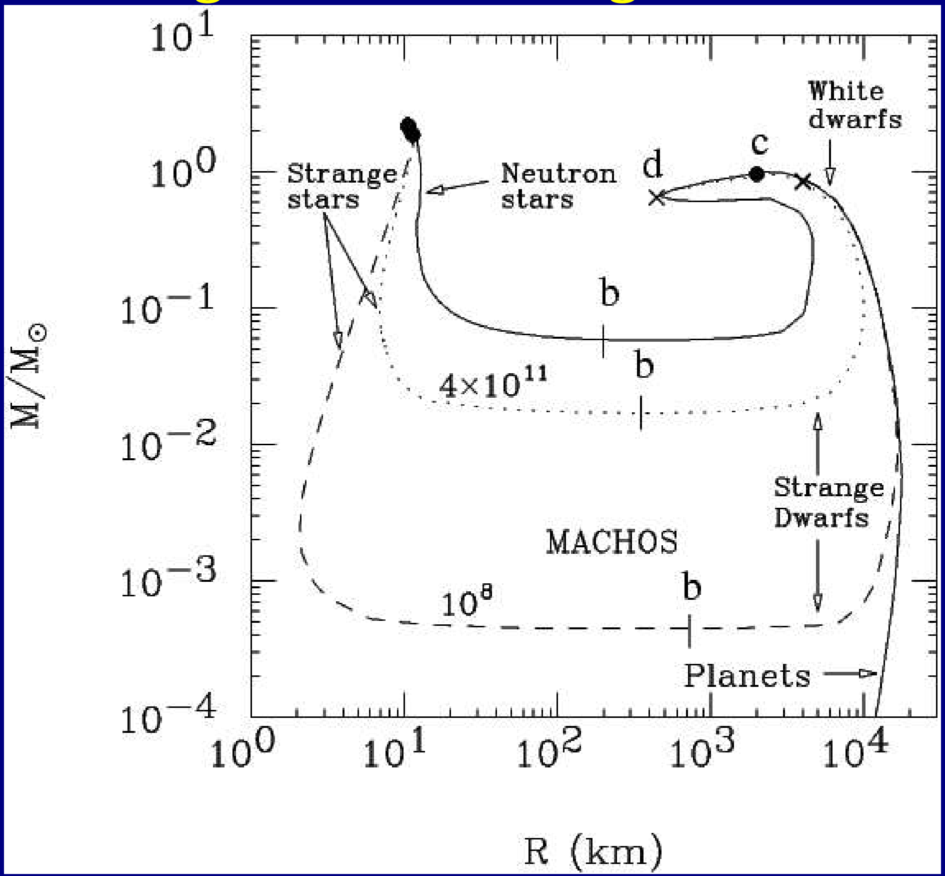


Complete Sequences of Compact Stars

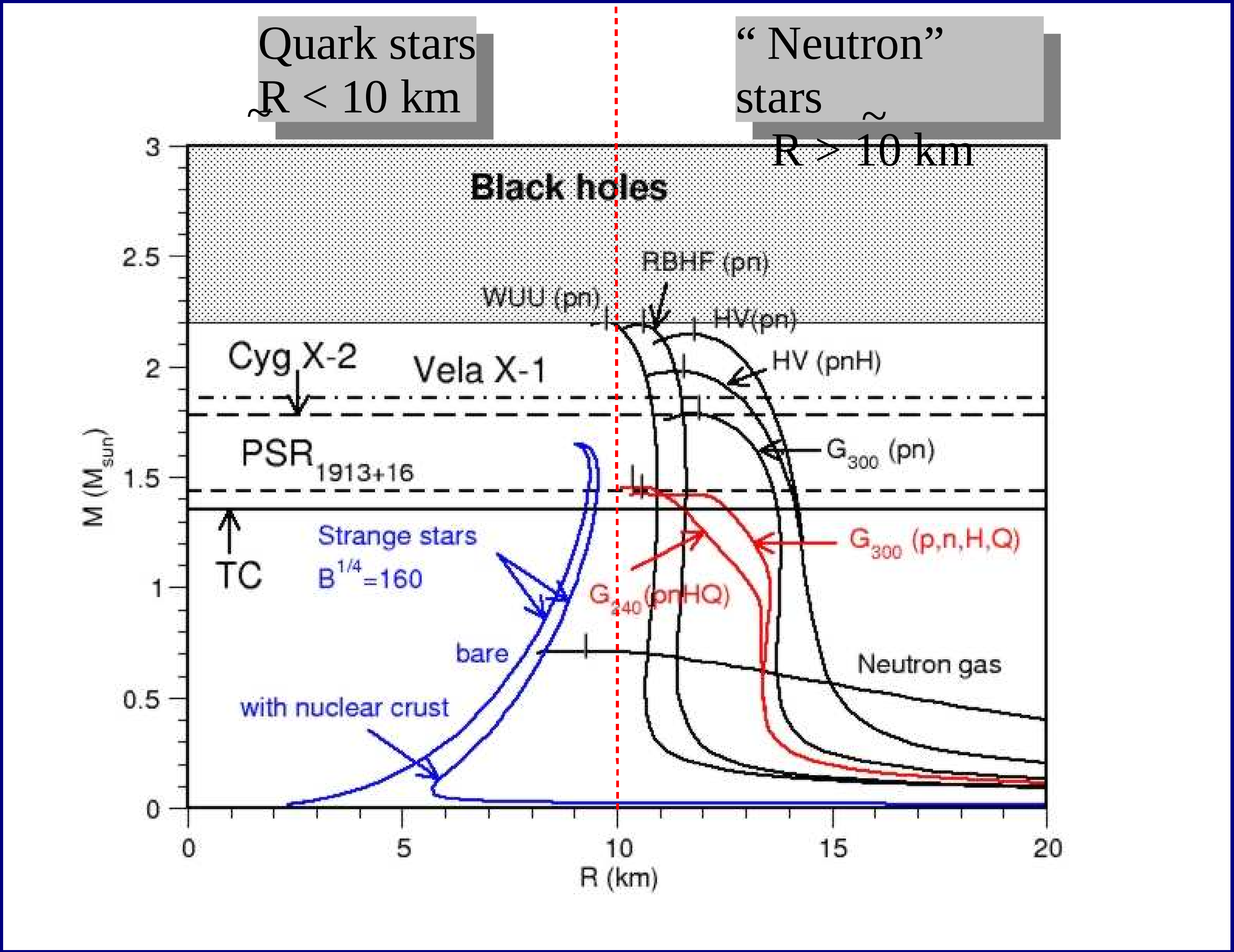
Neutron Stars – White Dwarfs



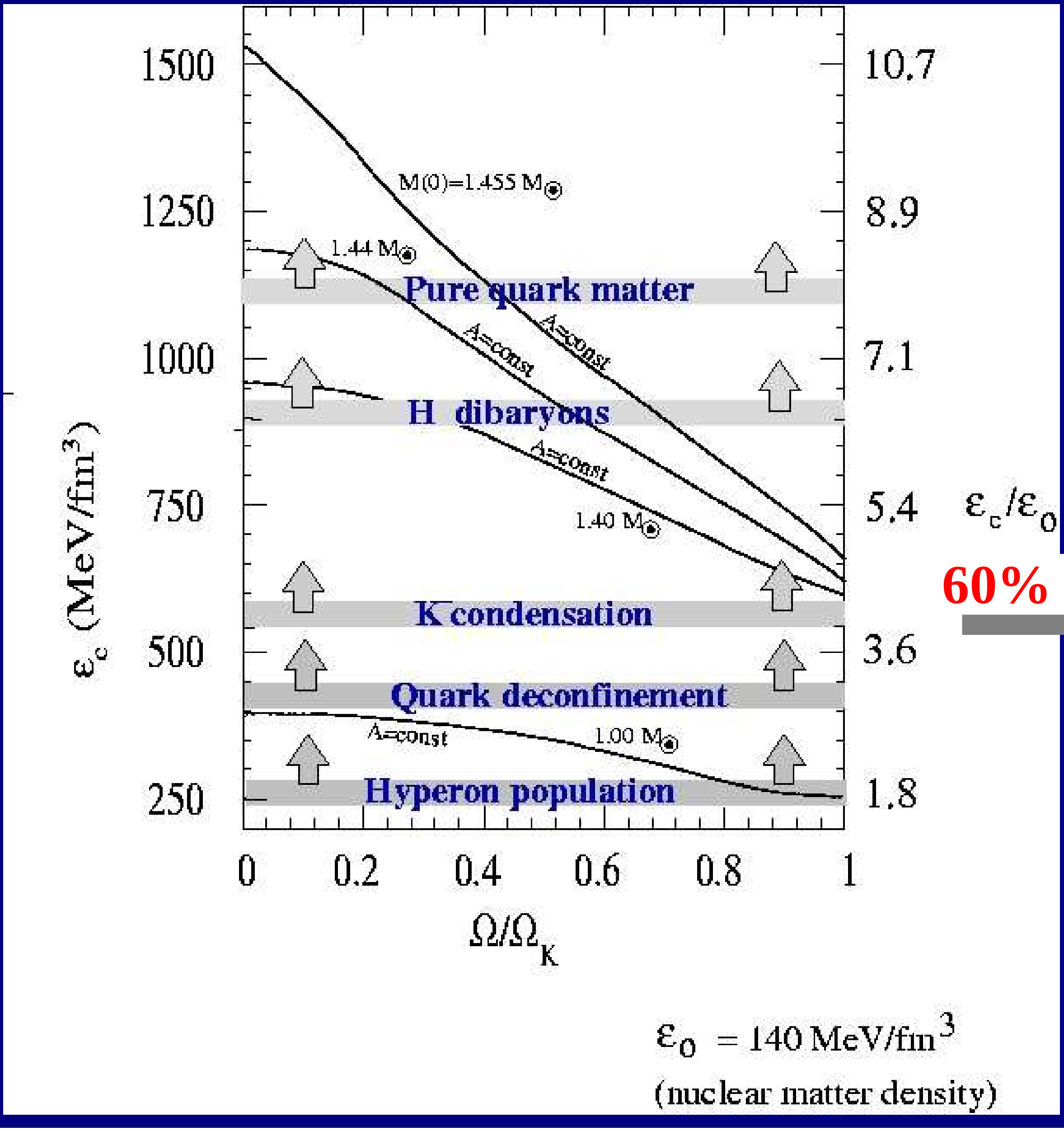
Strange Stars – Strange Dwarfs



Mass-Radius Relationship of Neutron and Quark Stars



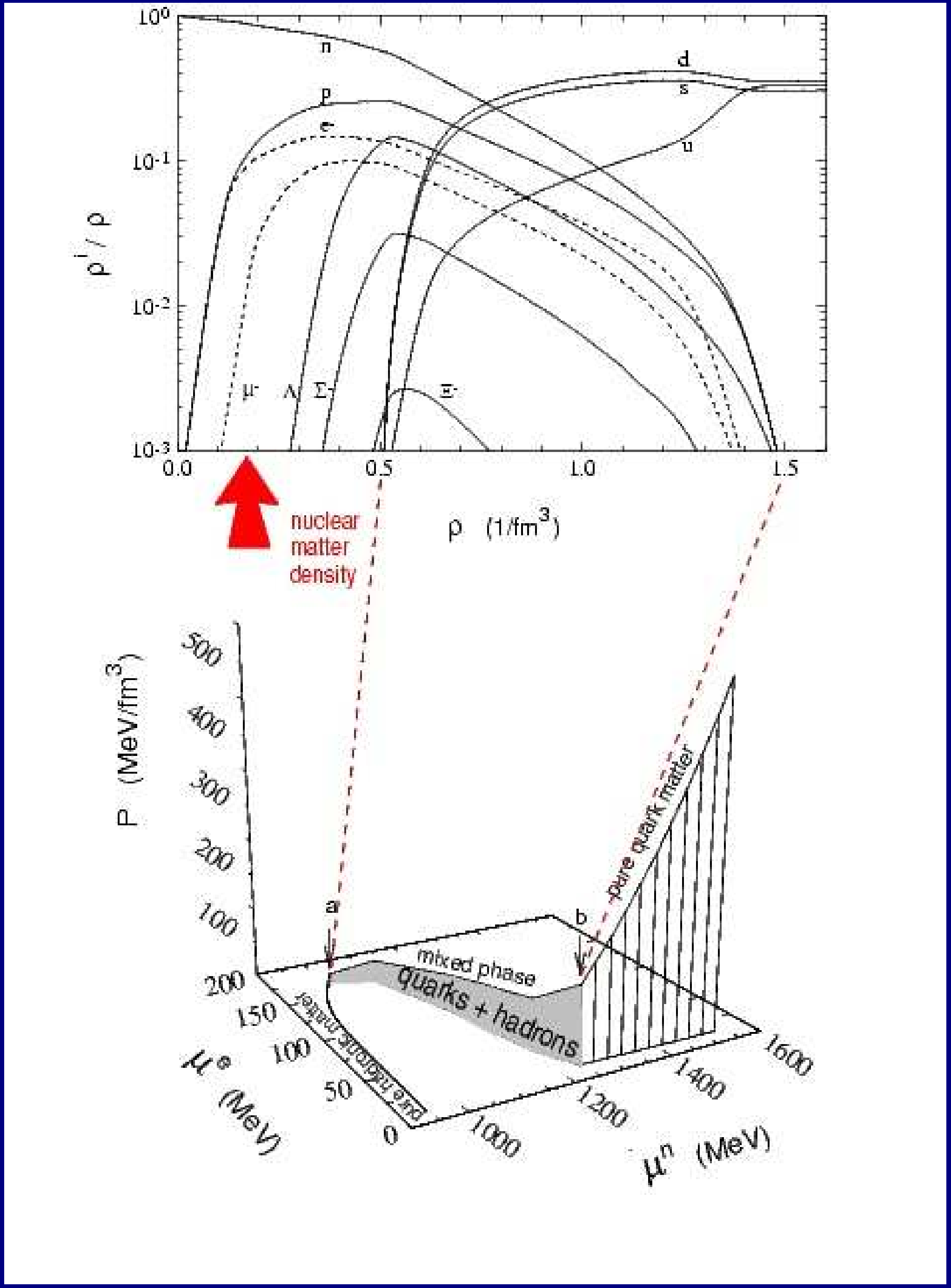
Dependence of Particle Thresholds on Spin Frequency of a Neutron Star



60% change!!

F. Weber, J. Phys. G: Nucl. Part. Phys. 25 (1999) R195

Model Quark-Hadron Composition



Einstein's field equation:

$$R^{\mu\nu} - 1/2\, g^{\mu\nu} R = 8\pi T^{\mu\nu}(\varepsilon, P)$$

Energy-momentum tensor:

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

Line element of a non-rotating star:

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

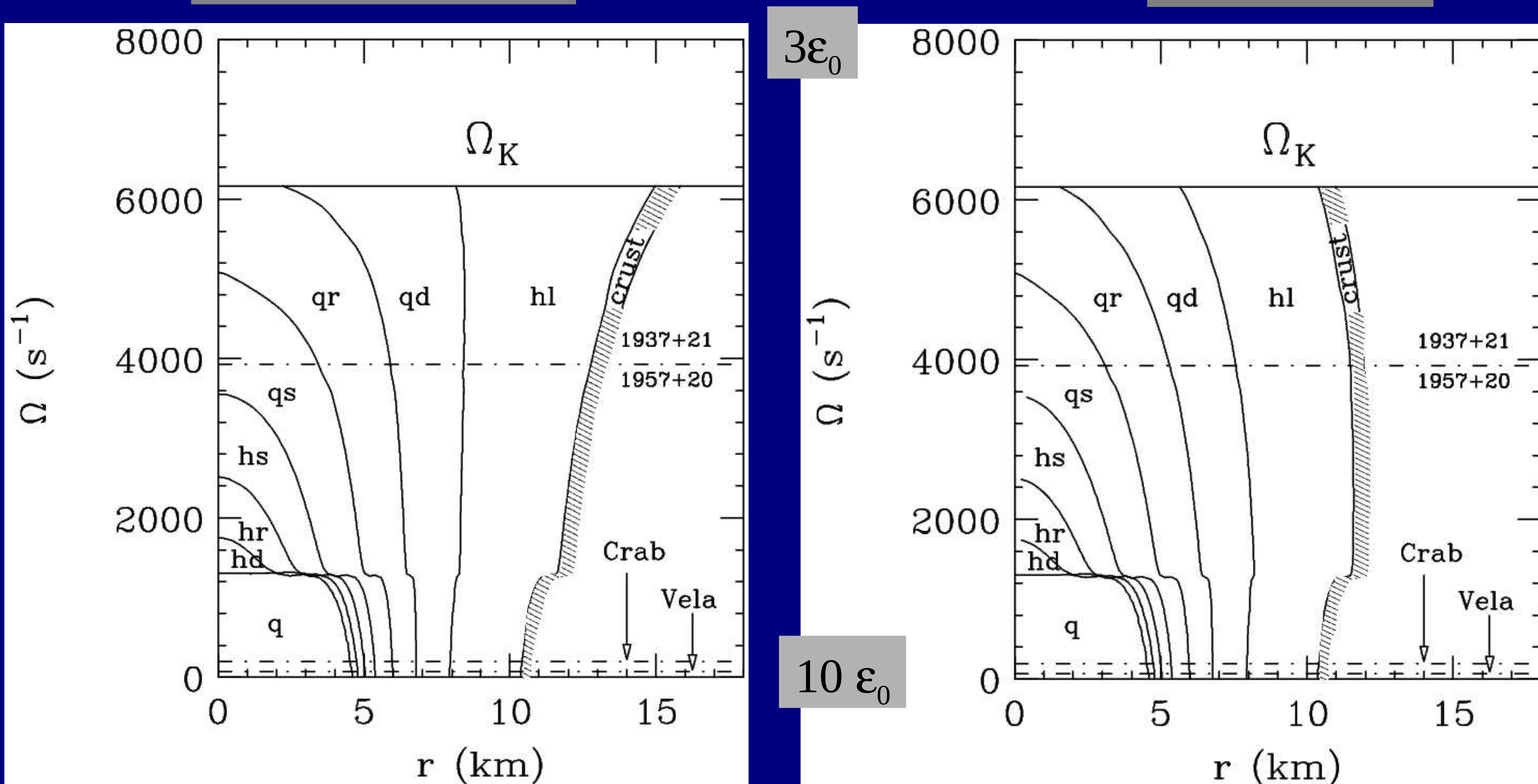
Line element of a rotating star:

$$ds^2 = -e^{2\Phi(r,\theta,\phi,\Omega)} dt^2 + e^{2\Lambda(r,\theta,\phi,\Omega)} dr^2 + e^{2\mu(r,\theta,\phi,\Omega)} d\theta^2 + e^{2\psi(r,\theta,\phi,\Omega)} (d\phi - \omega\, dt)^2$$

Quark-Hadron Composition in Rotating " Neutron" Stars

Equatorial direction

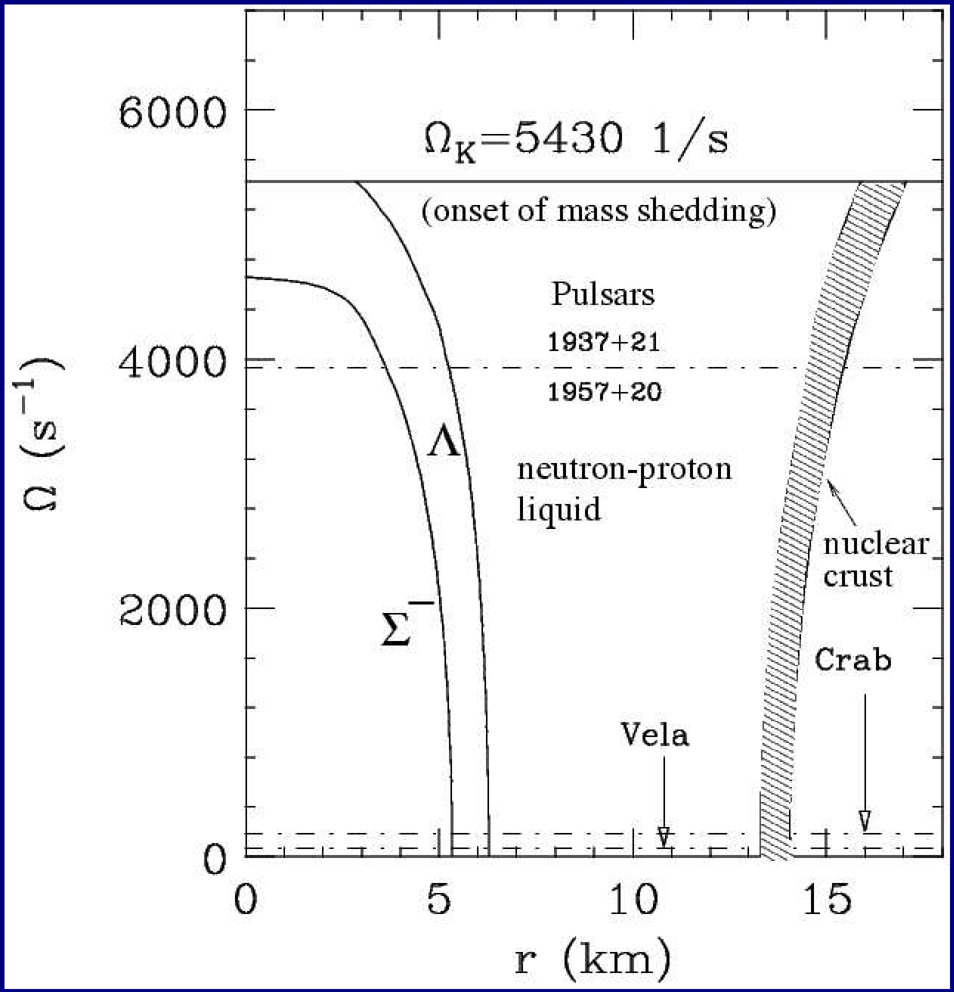
Polar direction



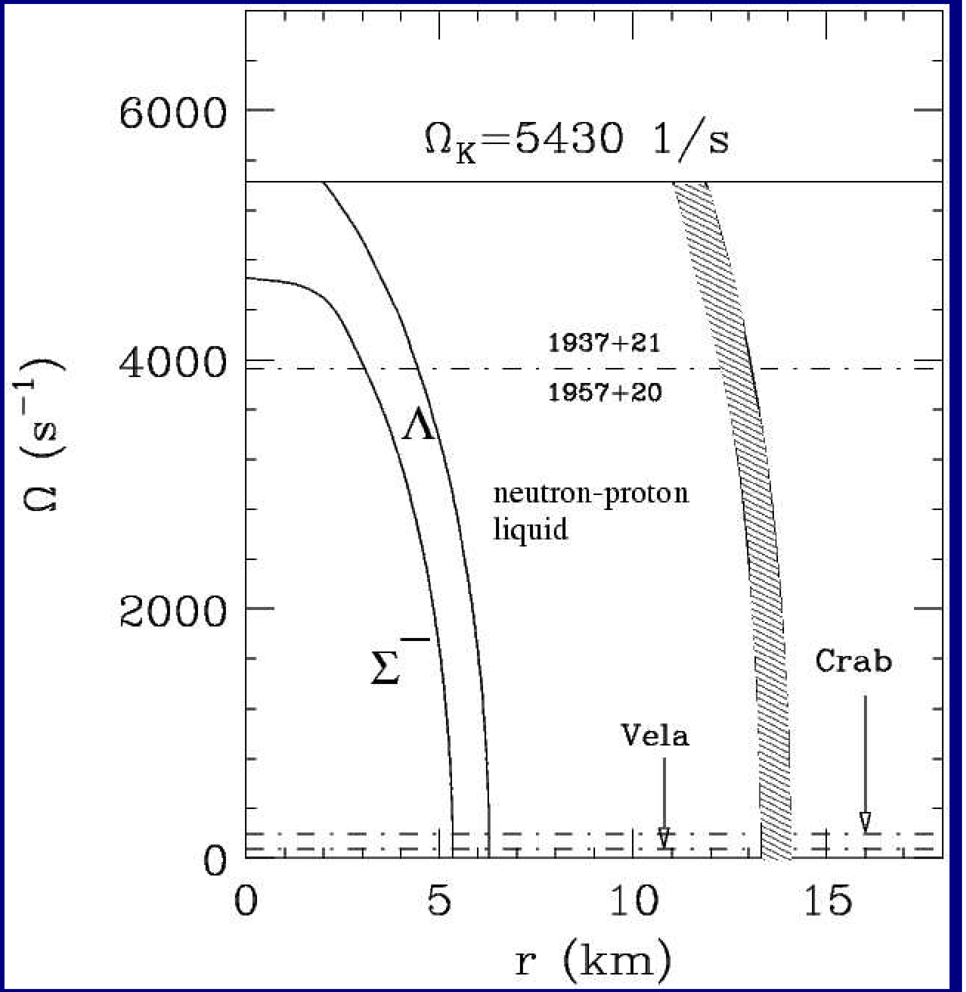
09/01/2004

Hyperon Population in Rotating Neutron Stars

Equatorial direction



Polar direction



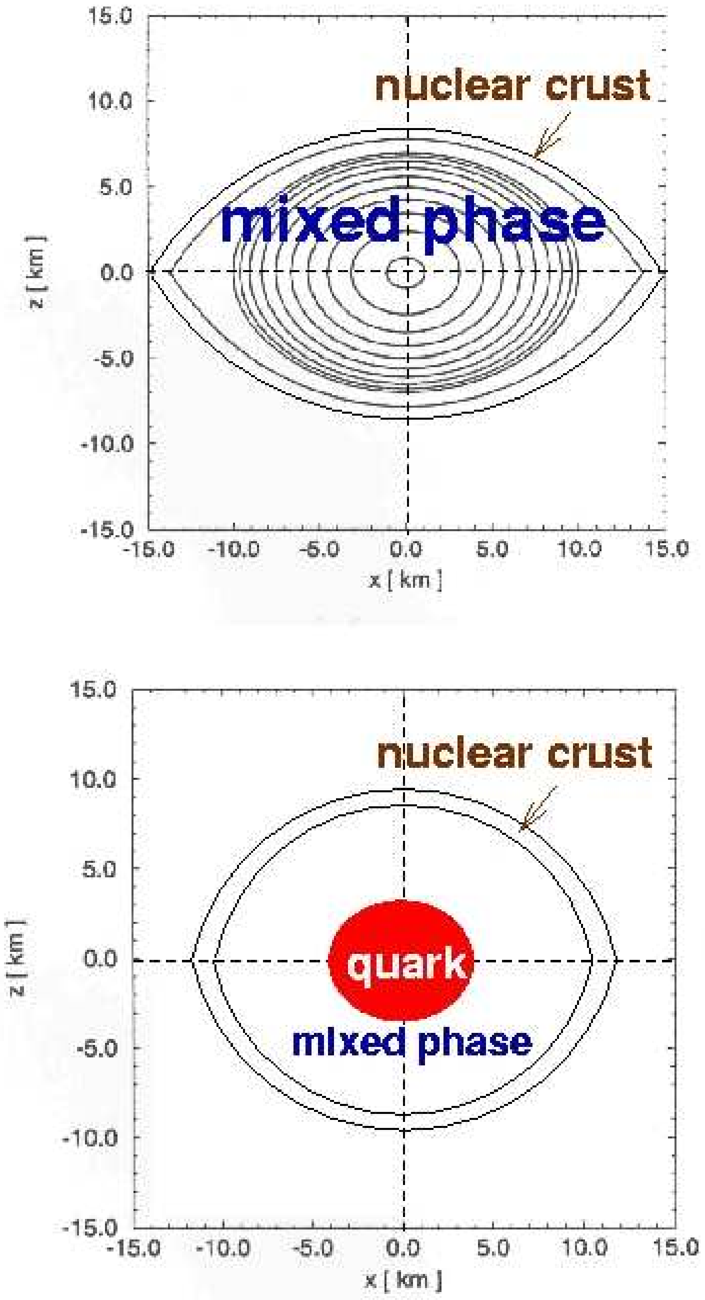
But ...

Zdunik, Haensel, Gourgoulhon, and Bejger (A&A 416 (2004) 1013):

Find backbending due to hyperon softening for some models of the EOS based on Lattimer-Swesty equation.

Not found for relativistic mean-field EOSs.

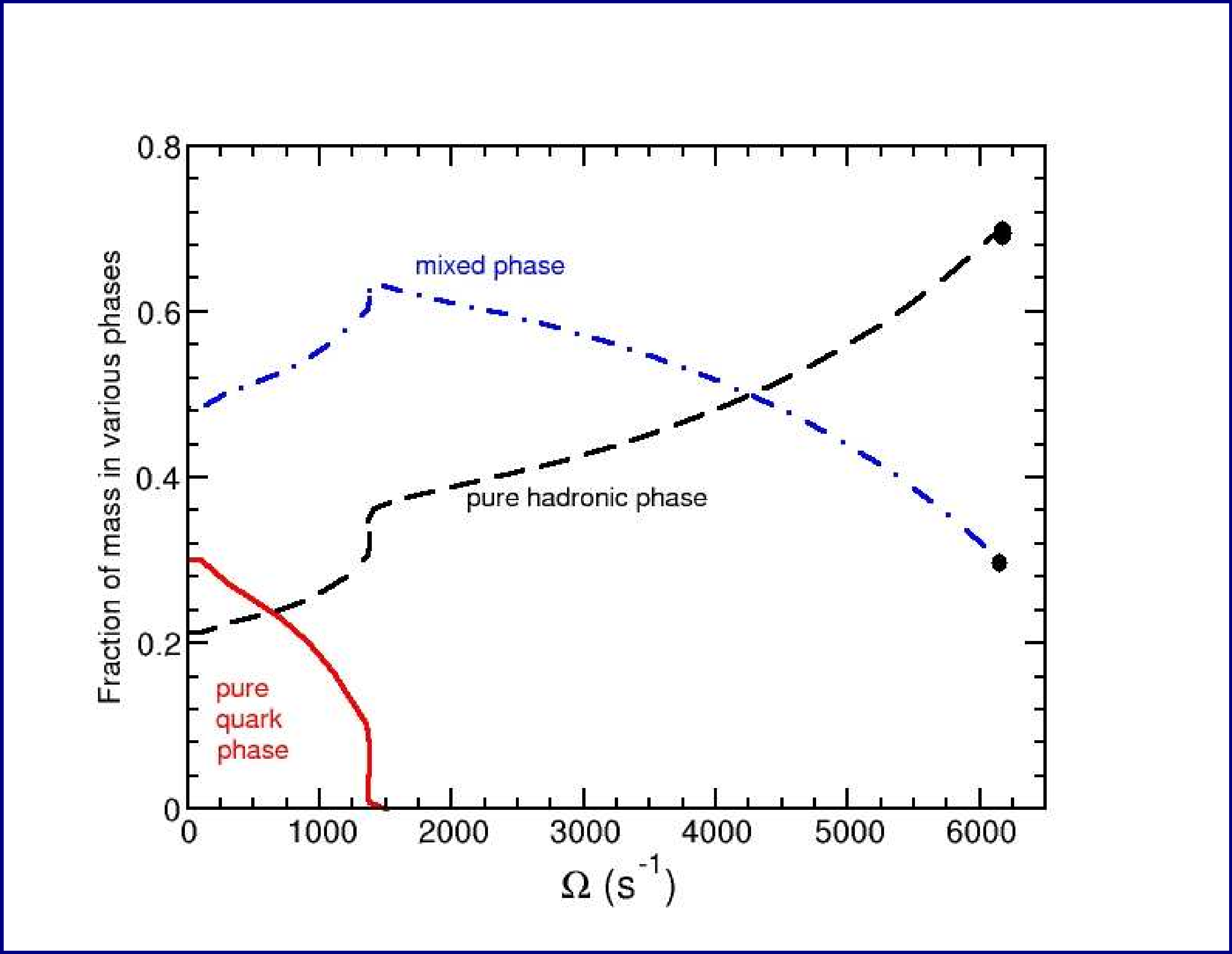
Density Profiles of Rotating Quark-Hybrid Stars



ν_K = 990 Hz
(P = 1 ms)

ν = 200 Hz
(P = 5 ms)

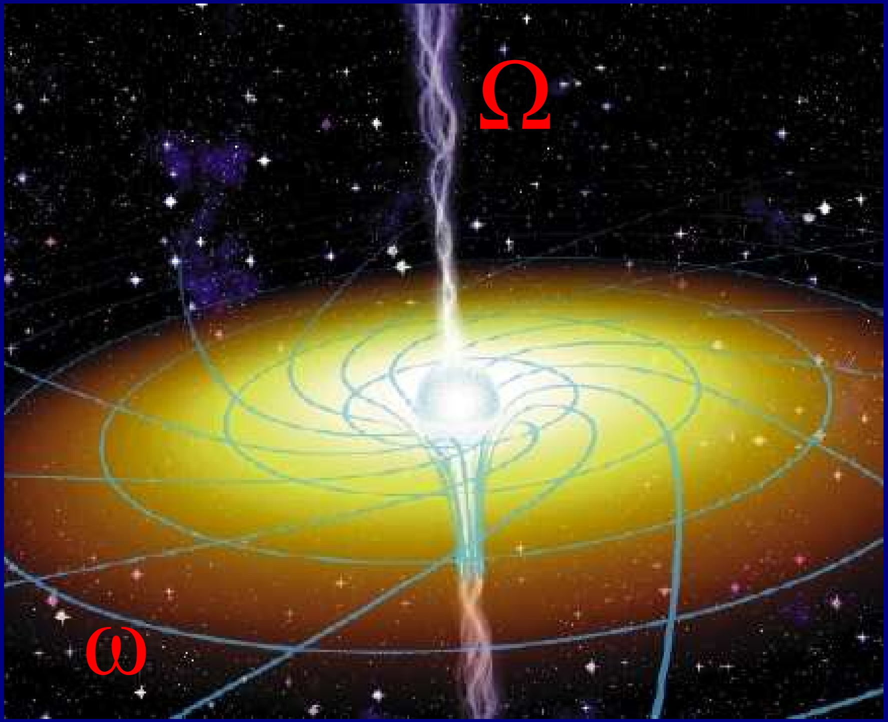
Quark-Hadron Composition of Rotating " Neutron" Stars



Moment of Inertia in General Relativity Theory

Newtonian theory: $I = \int r^2\, dm = \int r^2\, \varepsilon\, dV$

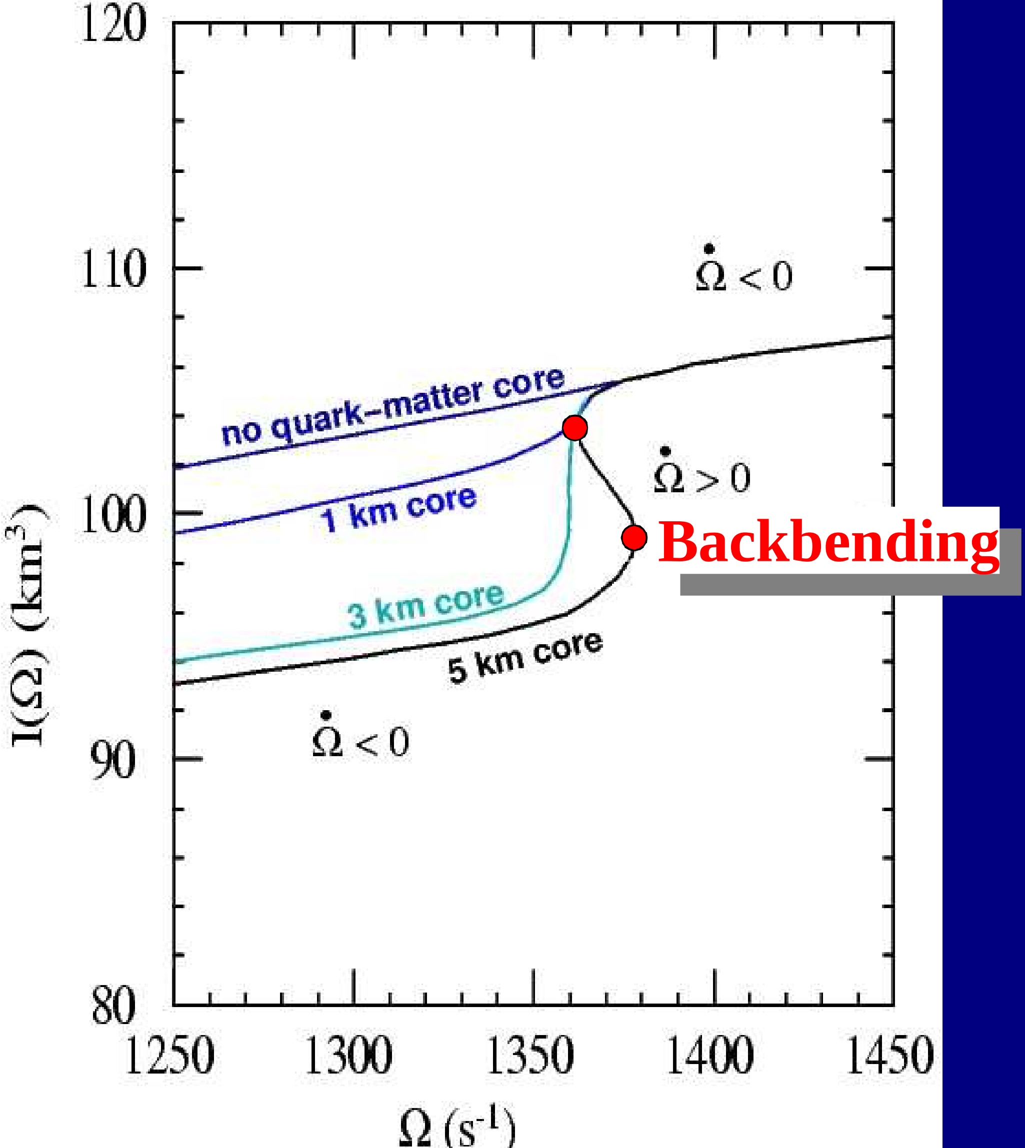
Einstein:



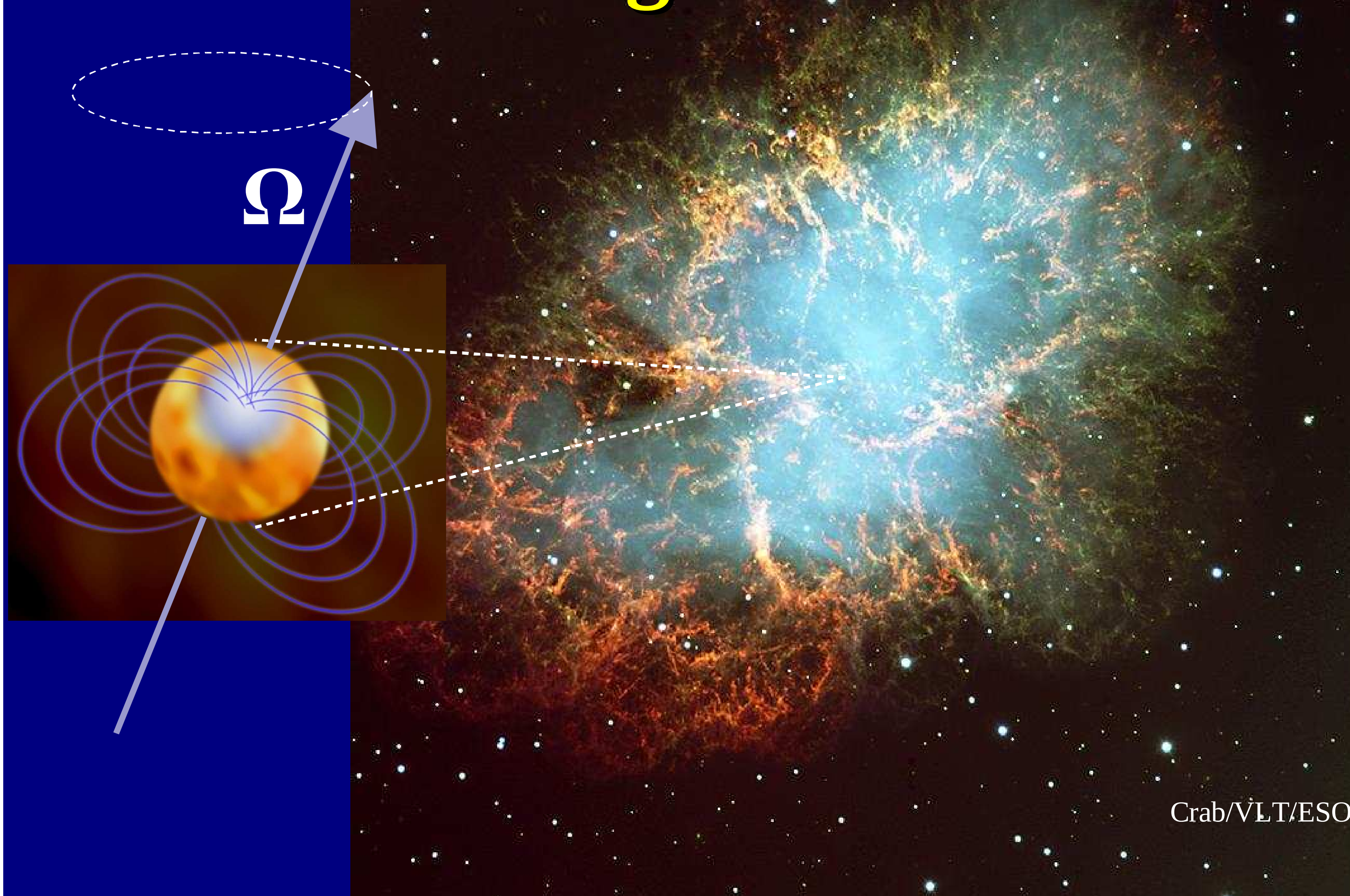
$$I = \Omega^{-1} \int \{[(\varepsilon+P)(\Omega-\omega)\, e^{2\psi}]\, [e^{2\Phi} - (\Omega-\omega)^2\, e^{2\Psi}]^{-1}\, e^{\Phi+\Lambda+\mu+\Psi}\, dV\}$$

09/01/2004

Moment of Inertia



Braking Index of a Pulsar



$$n = (\Omega \ \ d^2\Omega/dt^2)\ (d\Omega/dt)^{-2}$$

Braking Index

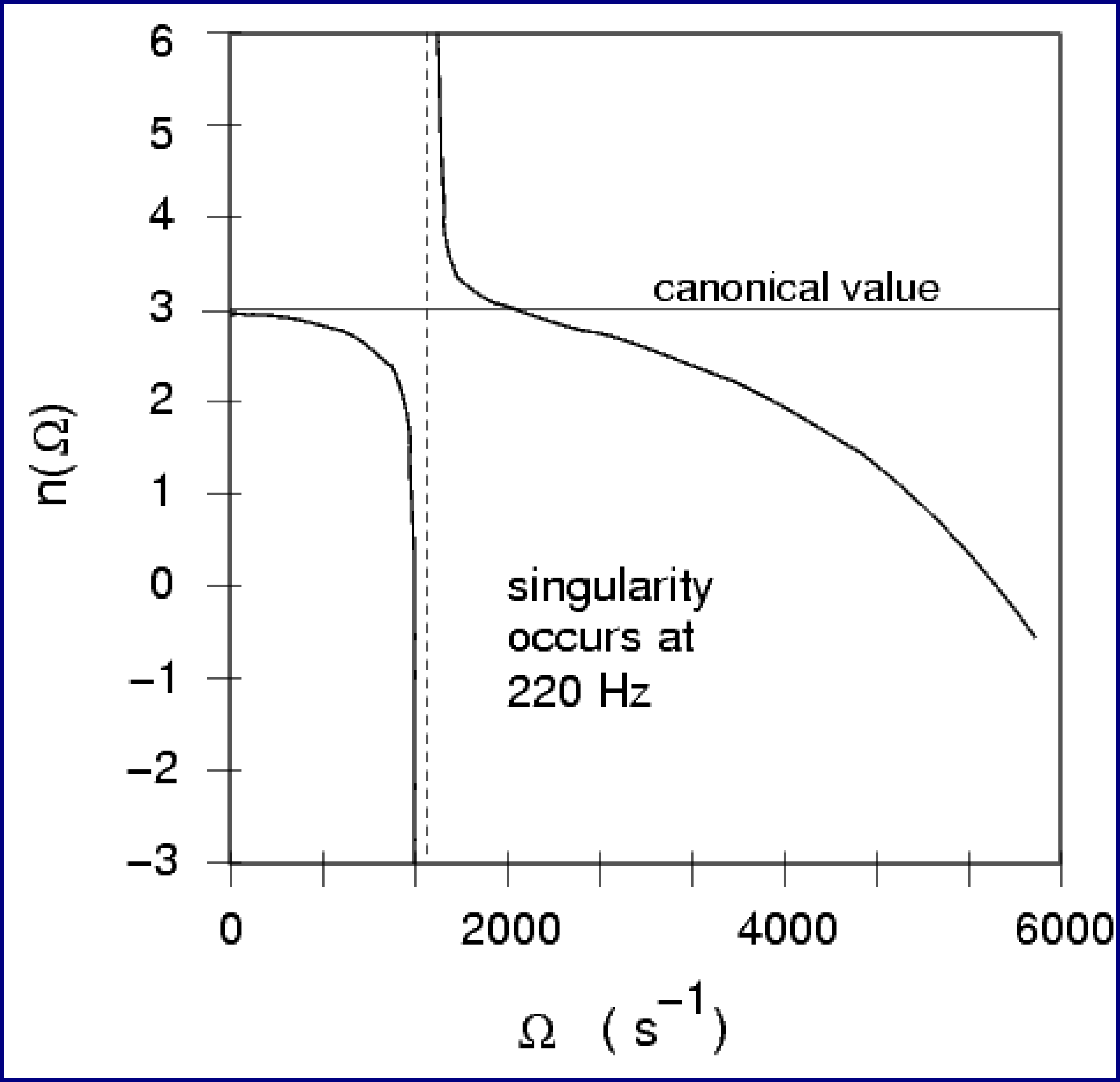
$$n(\Omega) = \Omega\ (d^2\Omega/dt^2)\ /\ (d\Omega/dt)^2$$

$d\mathbf{E}/dt = -\ C\ \Omega^{n+1}$

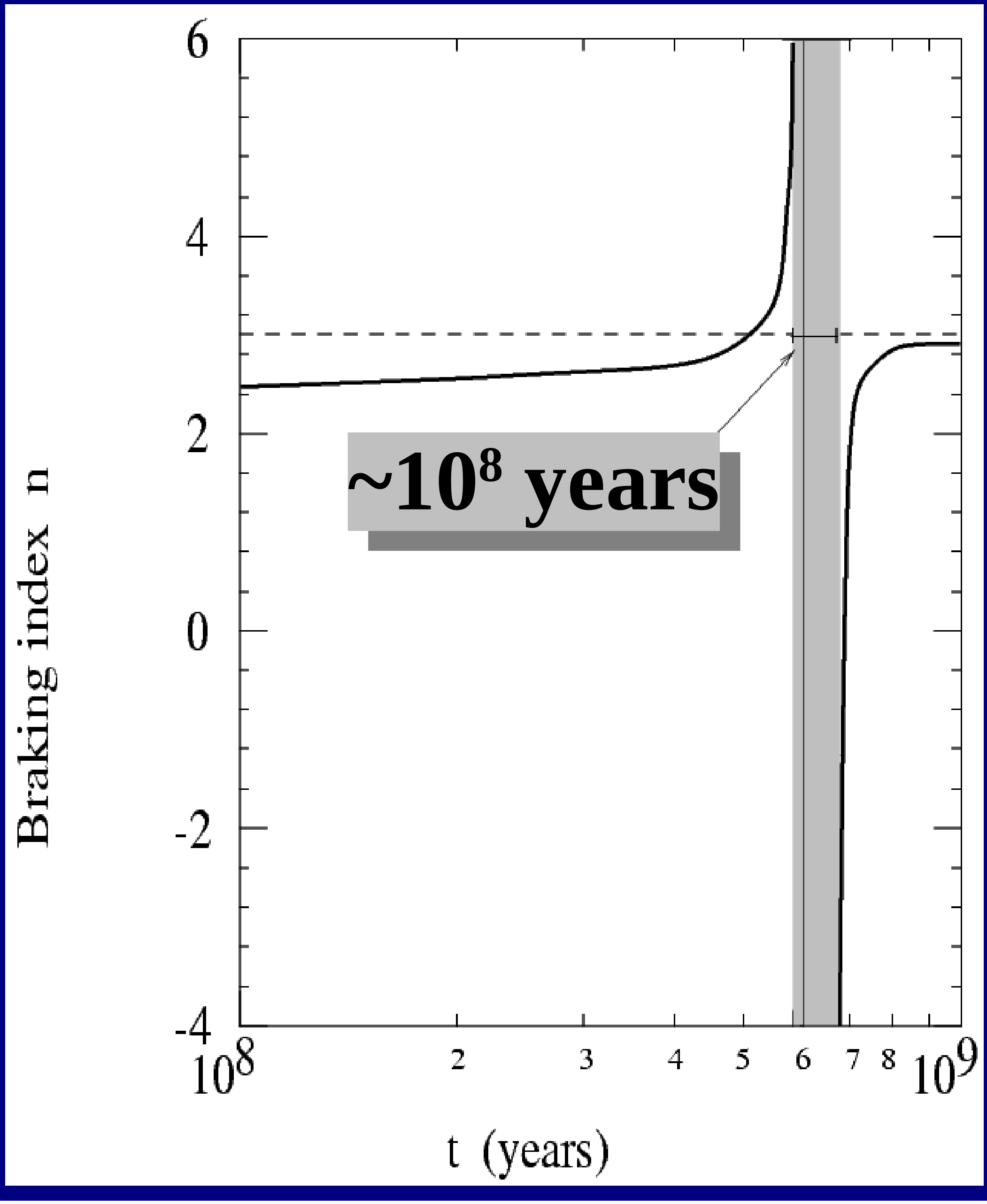
Star's total energy: $\mathbf{E} = M_0\ c^2 + U + \mathbf{T} + W$

$$n(\Omega) = 3 - (I''\ \Omega^2 + 3I'\ \Omega)\ (I'\ \Omega + 2I)^{-1}$$

Possible Astrophysical Signal of Quark Deconfinement



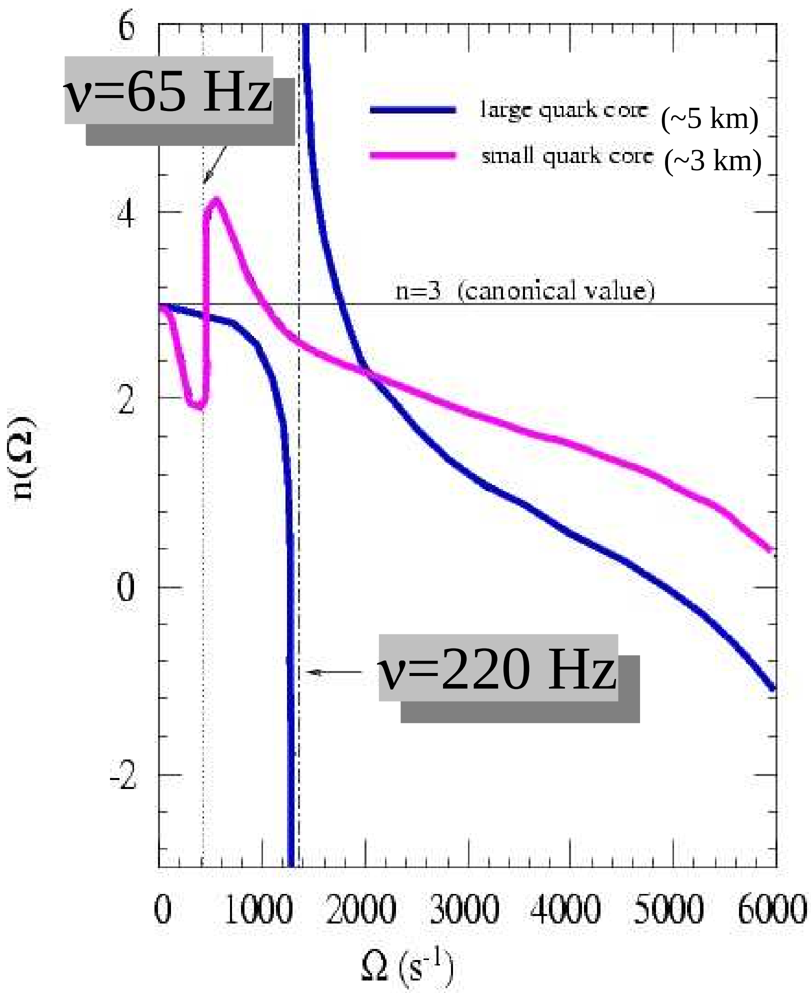
Epoch over which "n" is anomalous



Signal of Quark Matter in NSs

Braking index

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



Glendenning, Pei, Weber, PRL 79 (1997) 1603

Weber, J. Phys. G: Nucl. Part. Phys. 25 (1999) R195

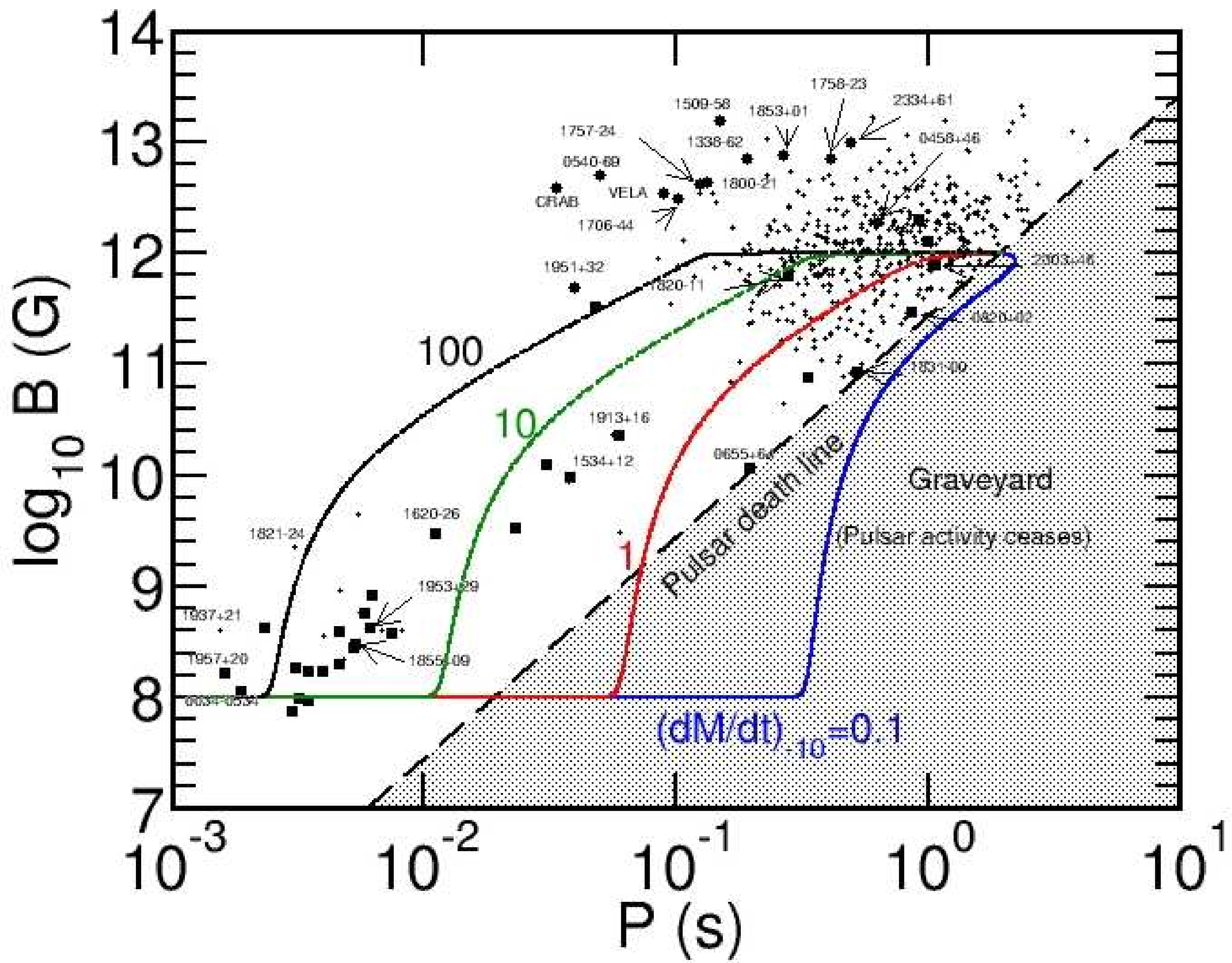
Weber, Prog. Part. Nucl. Phys. (in print)

Open Issues

Is signal restricted to stellar masses that are within a few percent of M_{max} ?

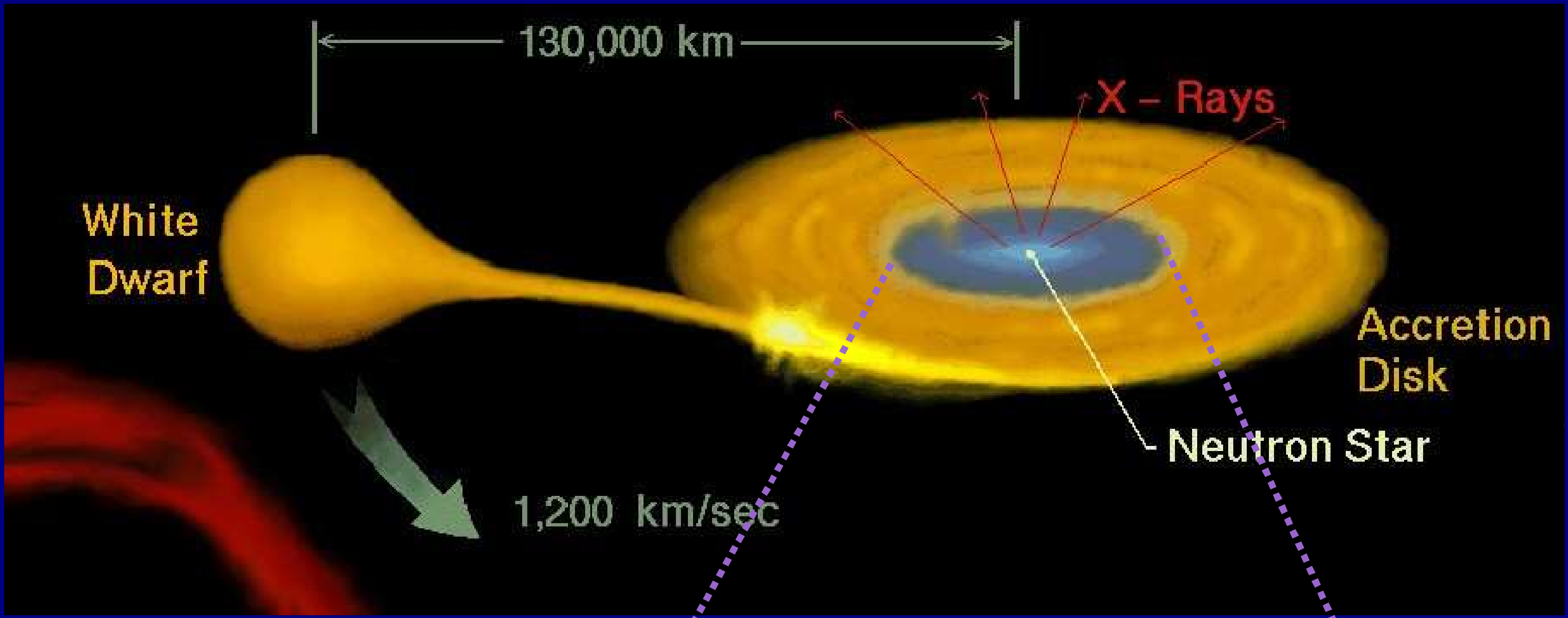
Is signal restricted to millisecond pulsars ?

Spin Evolution of Accreting Neutron Stars

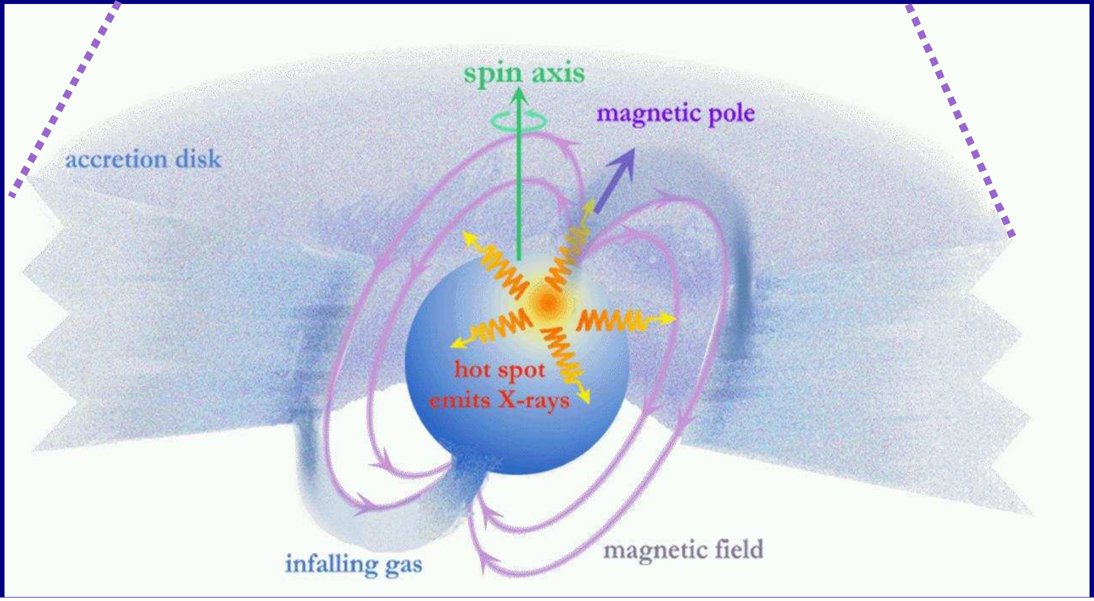


09/01/2004

Neutron Stars in Binary Systems (LMXBs)

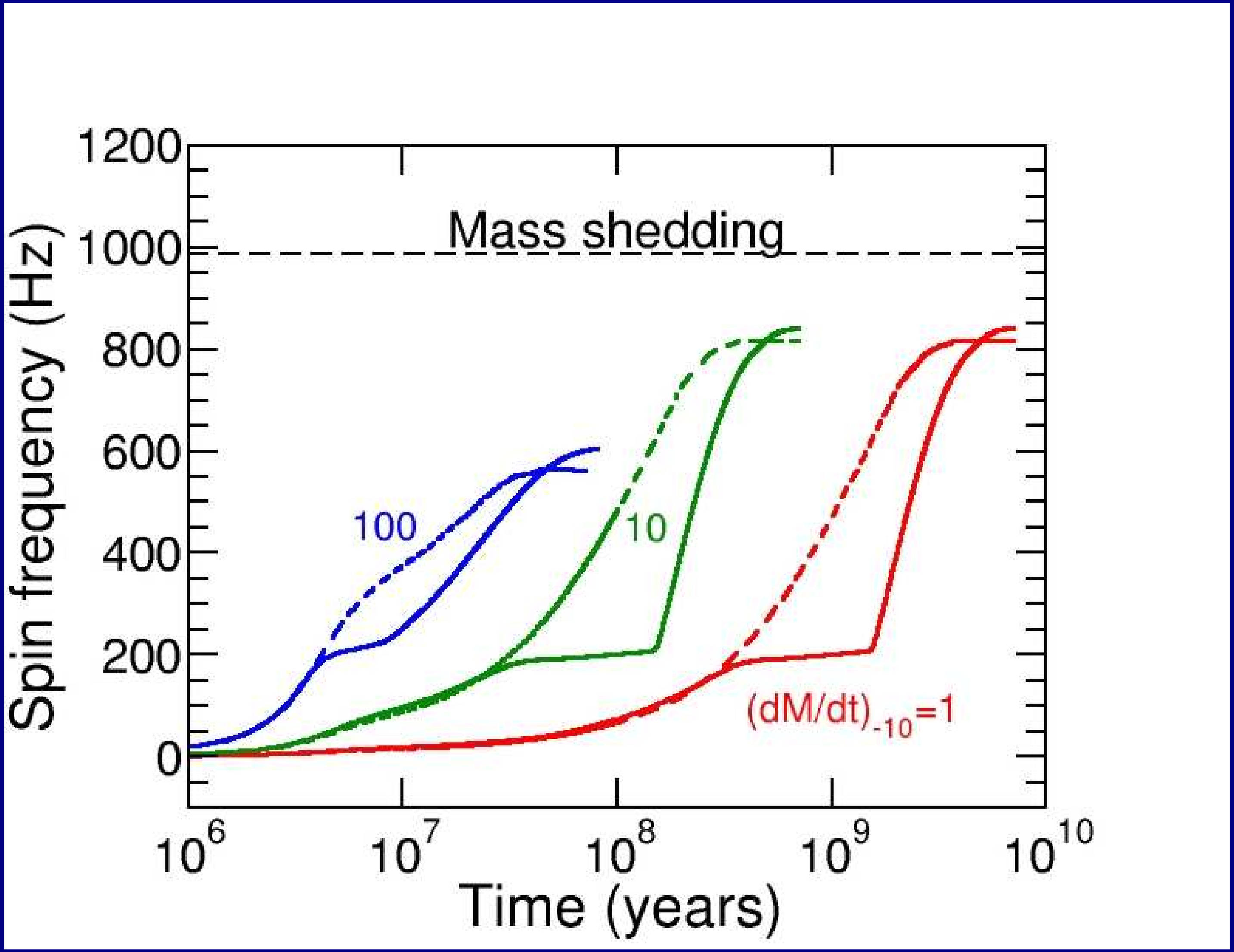


Accretion rates:
$dM/dt \sim 10^{-10}\ M_{sun}/year$

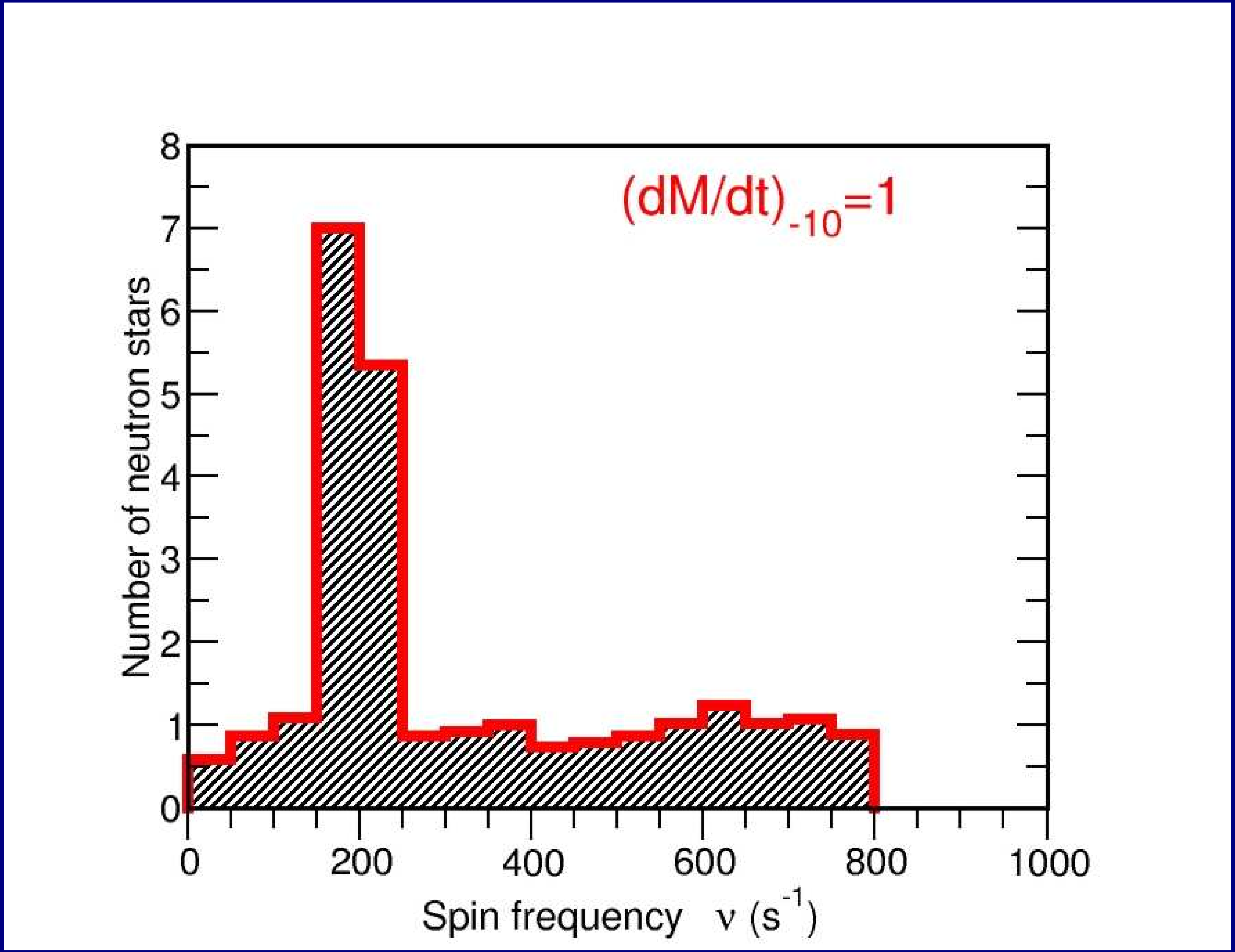


Mathematically:
$dJ/dt = dM/dt\ L - N$

Spin Frequency Evolution of Neutron Stars in LMXB's



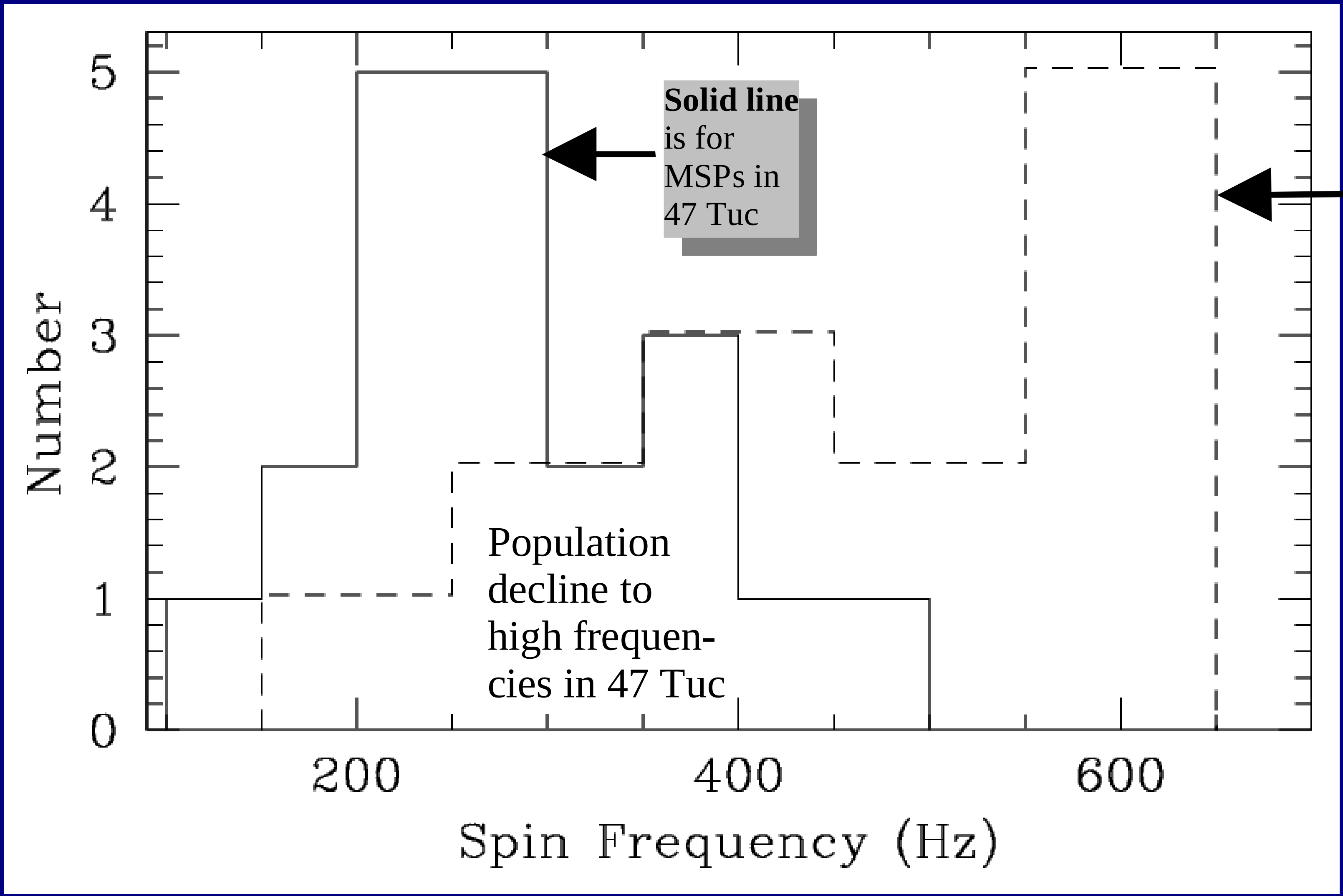
Frequency Distribution of X-Ray Neutron Stars



Glendenning & Weber, ApJ 559 (2001) L119

Histogram of Neutron Stars Spin Frequencies

(from L. Bildsten, astro-ph/0212004)



Dashed line is for
4U 1916-053
4U 1702-429
4U 1728-34
KS 1731-260
Aql X-1
MXB 1658-298
4U 1636-53
MXB 1743-29
SAX J1750.8-2980
4U 1608-52
Sax J1808.4-3658
XTE J1751-305
XTE J0929-314

Summary

Physical properties of matter at super-nuclear densities are highly uncertain and associated **EoS is only very poorly known.**

Major open issues: strangeness, meson condensates, quark-hadron
phase transition.

Possible astrophysical signals of **quark deconfinement** inside neutron stars may be:

1. Spin-up of isolated pulsars (backbending).
2. Dramatic anomaly in braking indices of pulsars.
3. Anomalous spin distribution of accreting neutron stars.

Open issues: Unambiguousness of these signals?
r-modes or mass quadrupole moment could explain NS pile-up as well.

Model dependences: B(t=0), dB/dt, μ, dM/dt, M_{max}, M_{donor}, ...
Signal limited to MSPs?
Limited to pulsar masses ~M_{max}?