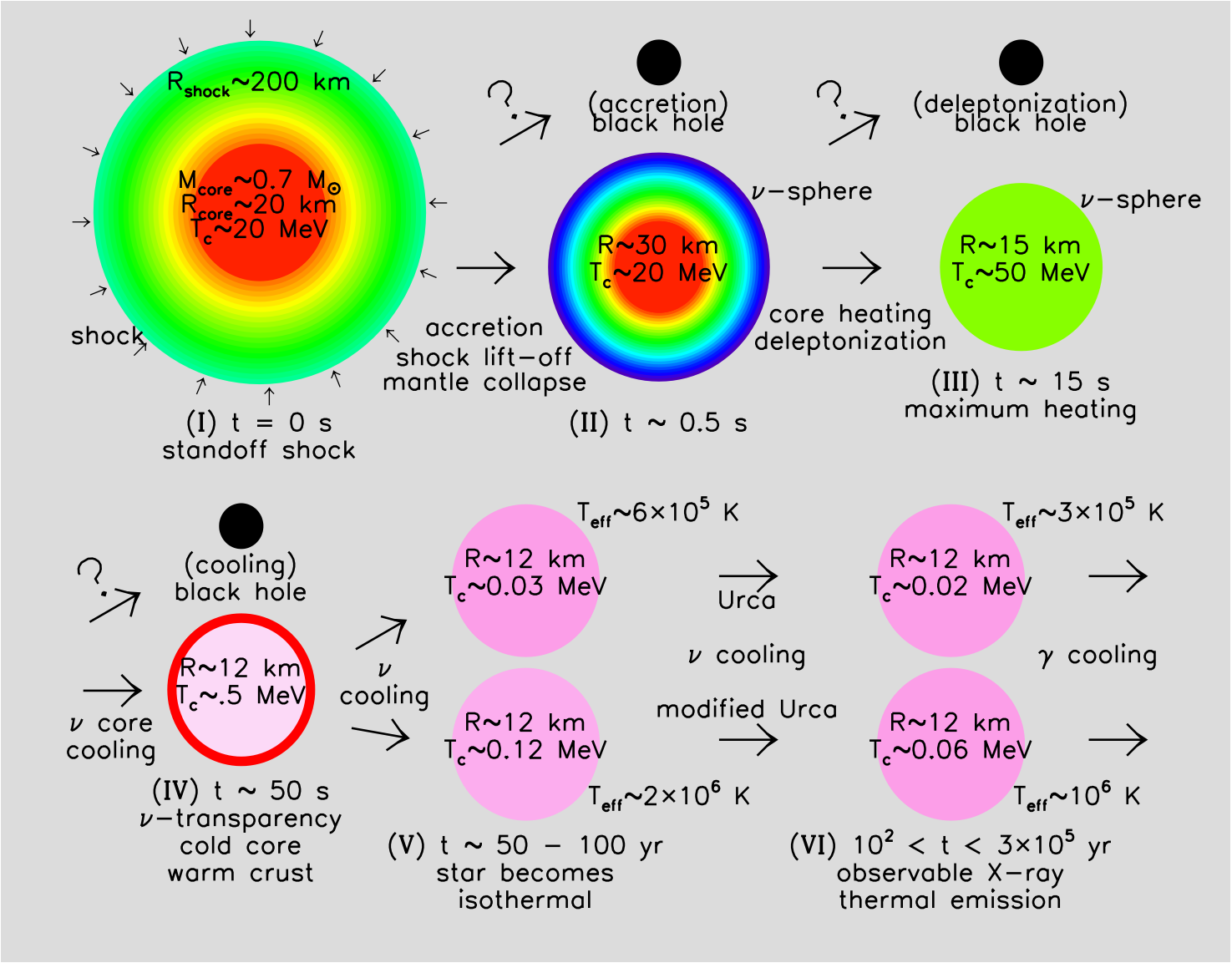
QCD at Finite Density

From the Lab to the Stars

Properties of Neutron Stars

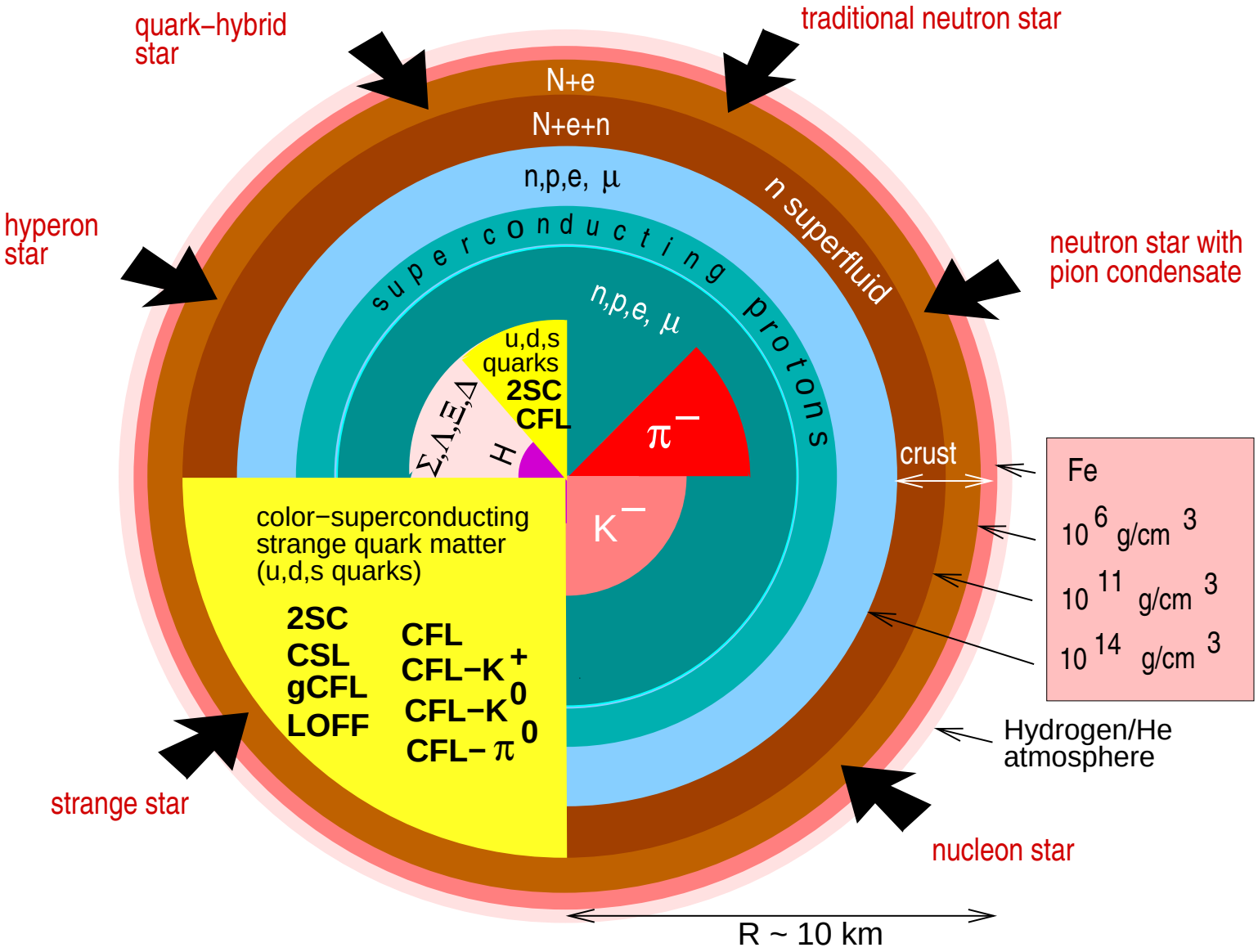
mass	$m \simeq (1-2) m_\odot$
radius	$r \simeq (10-15)$ km
spin period	$\tau \geq 1$ msec
temperature	$T = (1 \text{ keV } \ldots \text{ } 1 \text{ MeV})$
magnetic field	$B \simeq (10^{12} \ \ldots \ 10^{16}(?))$ Gauss
central density	$\rho \simeq (2.5-8)\rho_0$

Evolution of Neutron Stars



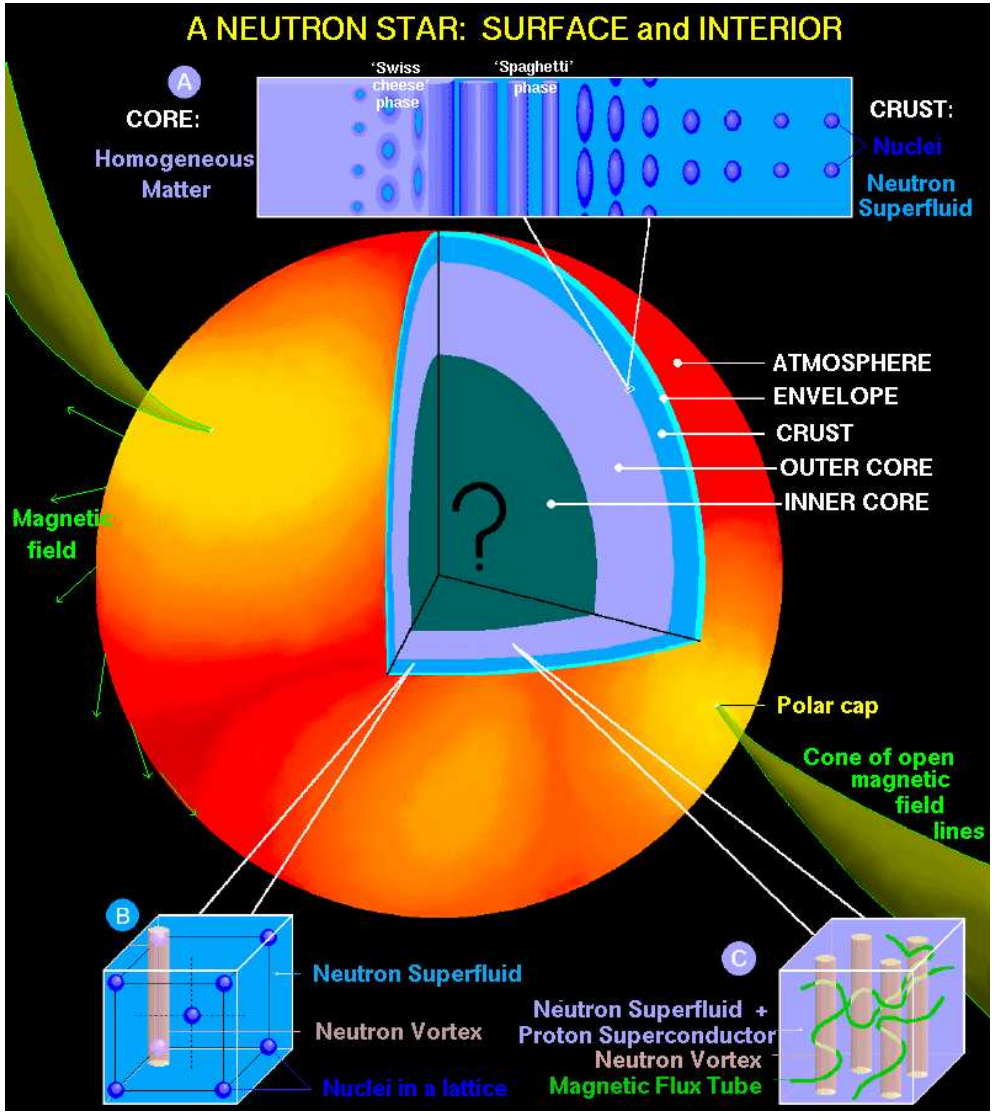
Lattimer and Prakash, Science (2005)

Composition of Neutron Stars



F. Weber (2005)

Composition of Neutron Stars II



Lattimer and Prakash, Science (2005)

Observational Constraints

Mass-radius relationship, maximum mass

Equation of state

Cooling behavior

Phase structure, low energy degrees of freedom

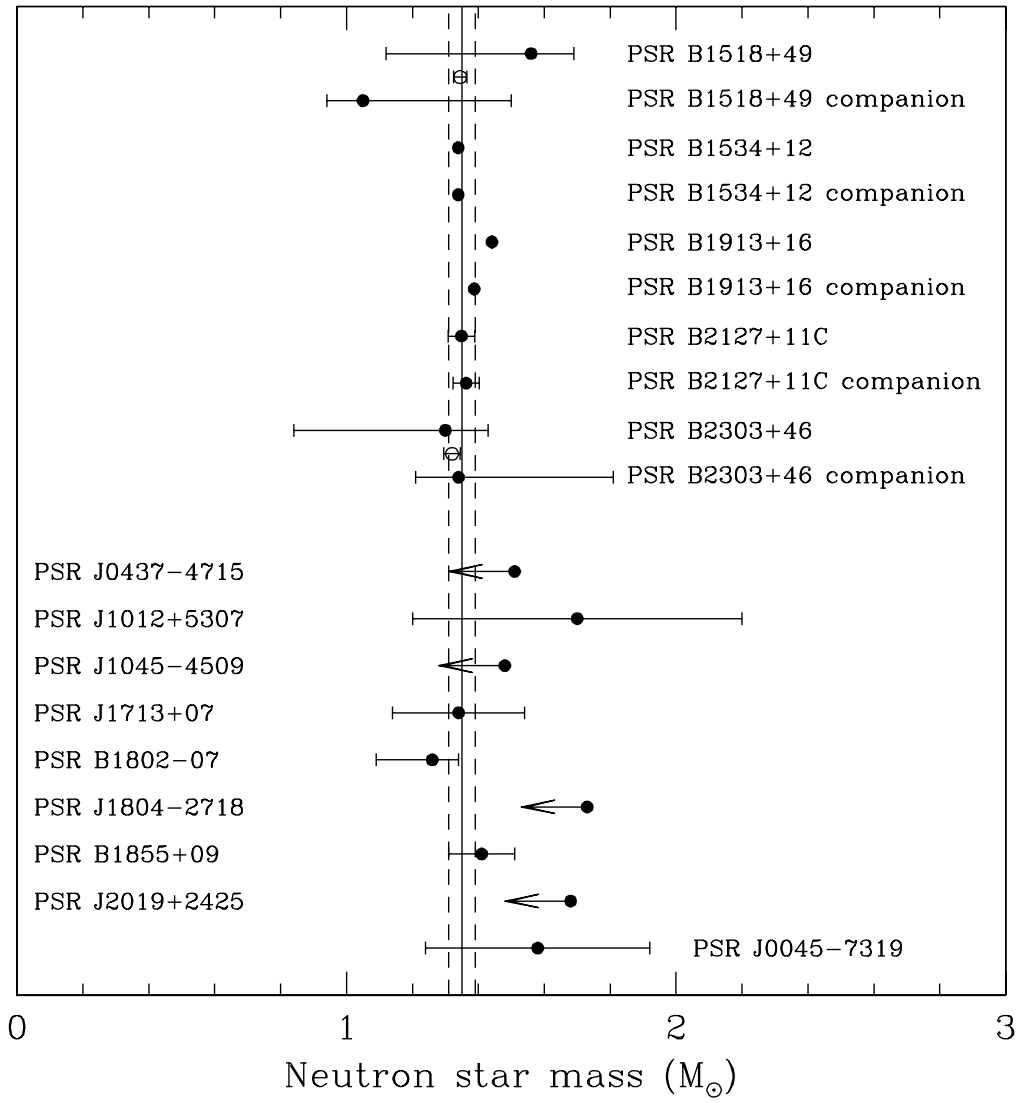
Rotation

Equation of state, Viscosity

Spin-down, glitches

Superfluidity

Masses of Neutron Stars



S. Thorsett (1998)

Tolman-Oppenheimer-Volkov Equation

Structure equation in Newtonian mechanics

$$\frac{dp}{dr} = -\frac{G\rho(r)M(r)}{r^2} = -\frac{G\epsilon(r)M(r)}{c^2 r^2}$$

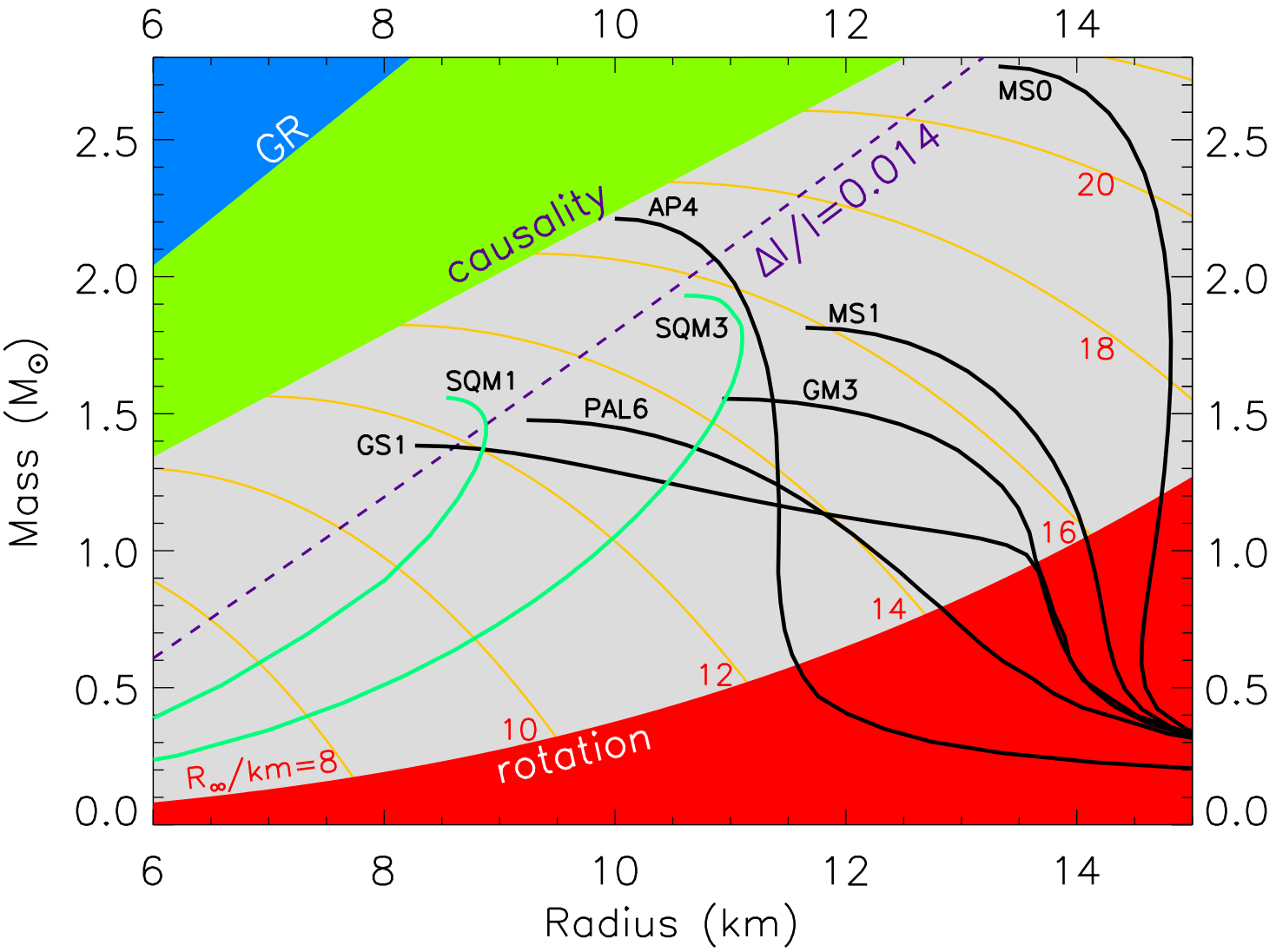
$$M(r) = 4\pi \int_0^r r'^2 dr' \rho(r')$$

Relativistic corecctions

$$\frac{dp}{dr} = -\frac{G\epsilon(r)M(r)}{c^2 r^2}\left[1+\frac{p(r)}{\epsilon(r)}\right] \times \left[1+\frac{4\pi r^3 p(r)}{M(r)c^2}\right] \times \left[1-\frac{2GM(r)}{c^2 r}\right]^{-1}$$

Note: All corrections are positive

Mass-Radius Relation



Lattimer and Prakash, Science (2005)

Cooling Processes

Direct URCA process

$$n \leftrightarrow p + e^- + \bar{\nu} \qquad \text{(fast)}$$

Indirect URCA process

$$n + n \leftrightarrow p + n + e^- + \bar{\nu} \qquad \text{(slow)}$$

Quark direct URCA process

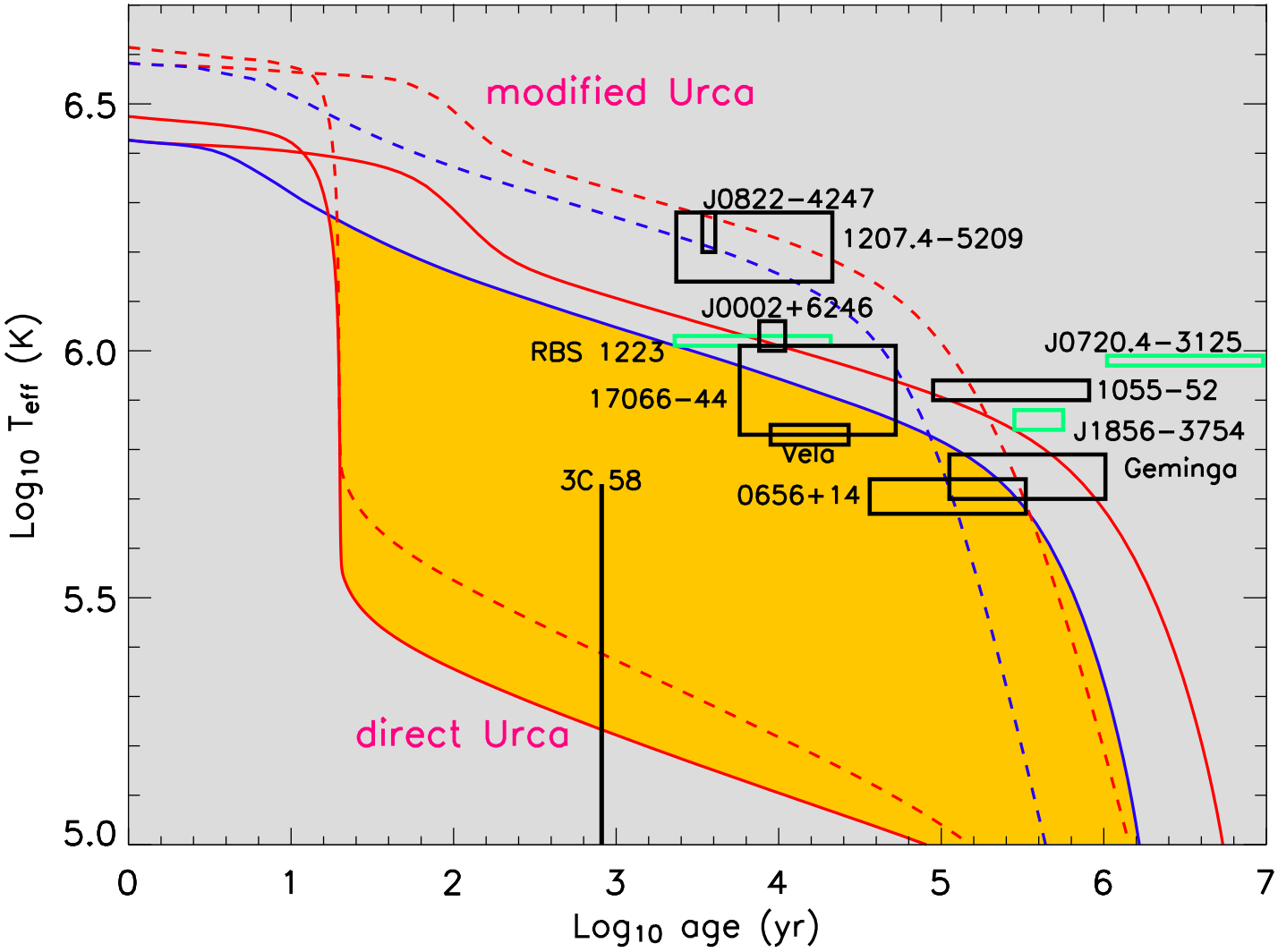
$$d \leftrightarrow u + e^- + \bar{\nu} \qquad \text{(fast)}$$

Collective modes

$$\pi^{\pm} \rightarrow e^{\pm} + \nu \qquad K^{\pm} \rightarrow e^{\pm} + \nu \qquad \text{(very fast)}$$

superfuidity suppresses URCA process

Cooling



Lattimer and Prakash, Science (2005)

Conclusion: The Many Phases of QCD