VIJAY

- Scientist
- Colleague
- Friend
- Human being

His science

- Hard problems
- Good sense of what could be calculated
- Rock solid calculations
- Took into account all data
- Diversity of systems (nuclear matter, neutron matter, liquid helium, nuclei, droplets, atomic gases …)
- Increasing scope:

  (energy, excitations, pairing, …)
- Did things his way

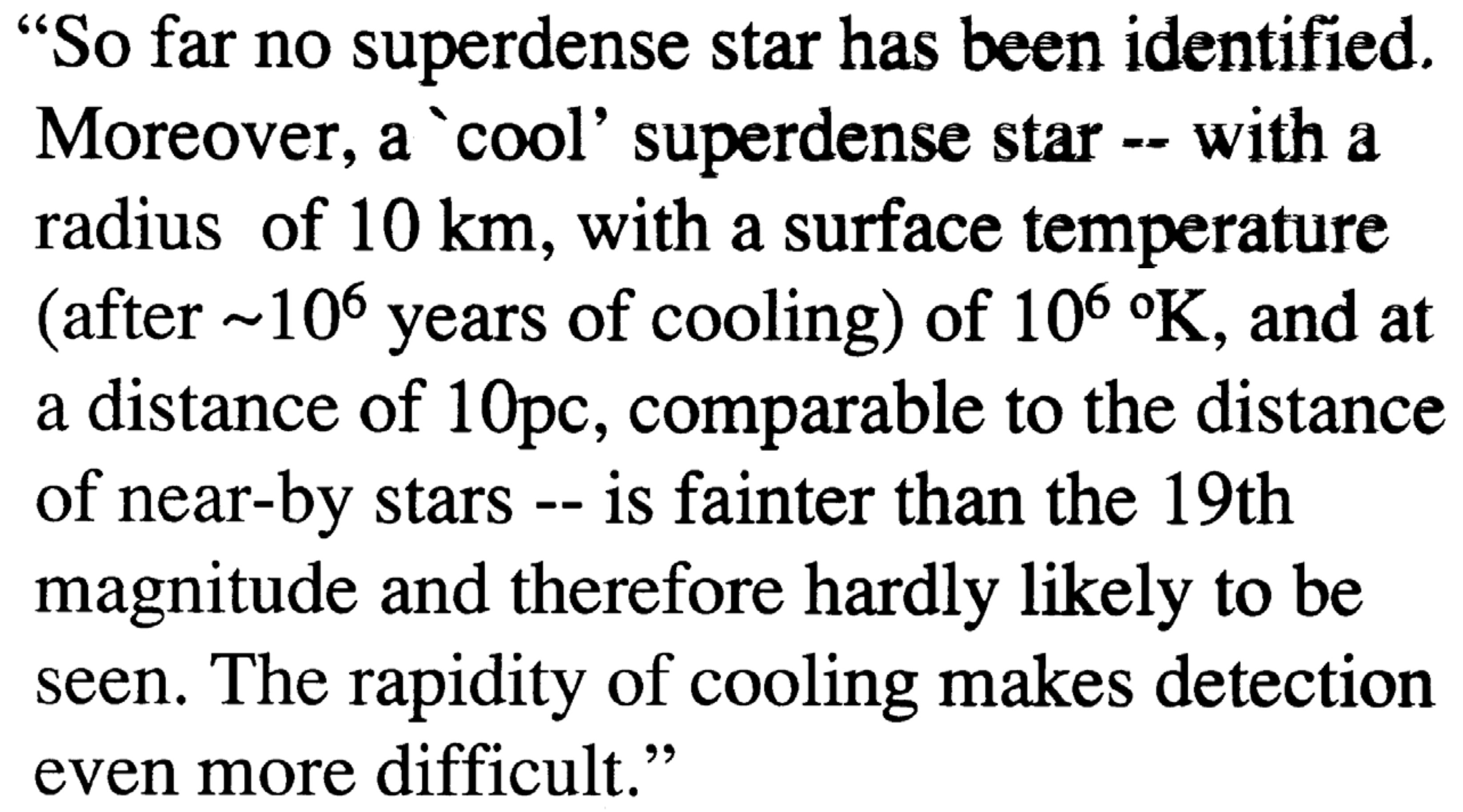
Neutron Stars

- Early history
  - Baade, Zwicky (1932)
  - Oppenheimer, Volkoff (1939)
  - Wheeler, Thorne
  - Salpeter, Chiu
  - Zeldovich, Novikov, Ambartsumian
  - Cameron, Tsuruta
  - Detection proposed:

    -- Cooling of neutron stars

    -- Accretion

J. Wheeler
Ann. Rev. Astronomy and Astrophysics, 1966



“So far no superdense star has been identified. Moreover, a `cool’ superdense star -- with a radius of 10 km, with a surface temperature (after ~10^6 years of cooling) of 10^6 °K, and at a distance of 10pc, comparable to the distance of near-by stars -- is fainter than the 19th magnitude and therefore hardly likely to be seen. The rapidity of cooling makes detection even more difficult.”

Radio pulsars

- Discovery of rotation-powered pulsars (1967). Hewish’s telescope. Cheap, low tech, unfashionable frequency, designed for other purposes, but good time resolution.
- Good graduate student

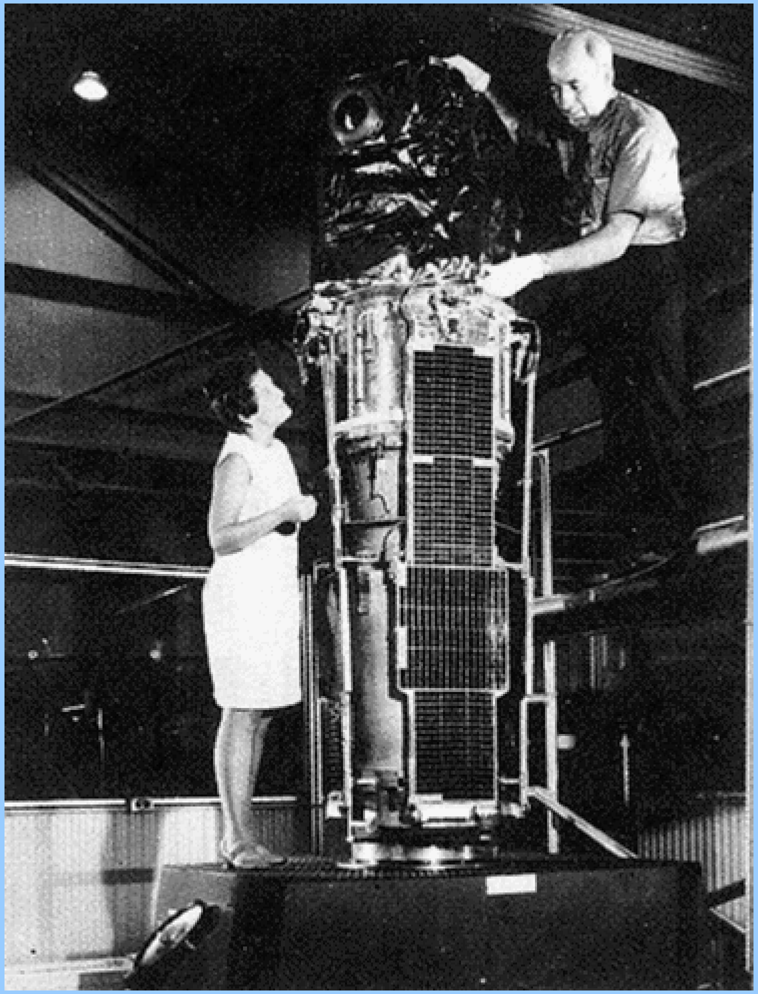
Accretion-powered pulsars

- UHURU X-ray satellite (1971).

Proportional counters. (Not imaging)

Not designed for high time resolution

UHURU (Freedom)



Bruno Rossi (MIT) and Marjorie Townsend (NASA)

The challenge of high densities

- Neutron stars exist! Not just hypothetical.

  The subject becomes “respectable”.
- Extend range of densities and compositions of nucleon matter.

  The need for a deeper understanding.

H. A. Bethe
Ann. Rev. Nucl. Sci. 21, 93-244 (1971)

Theory of Nuclear Matter

“The only theoretical method which has so far proved adequate and successful in getting results is that of Brueckner (1) and Goldstone (2) which will be described in Sec. 3.’’

"I made a straightforward proposal, Moira, and all I ask is a linear response."

Lowest order constrained variational (LOVC, LOCV) method

- Startling simplicity

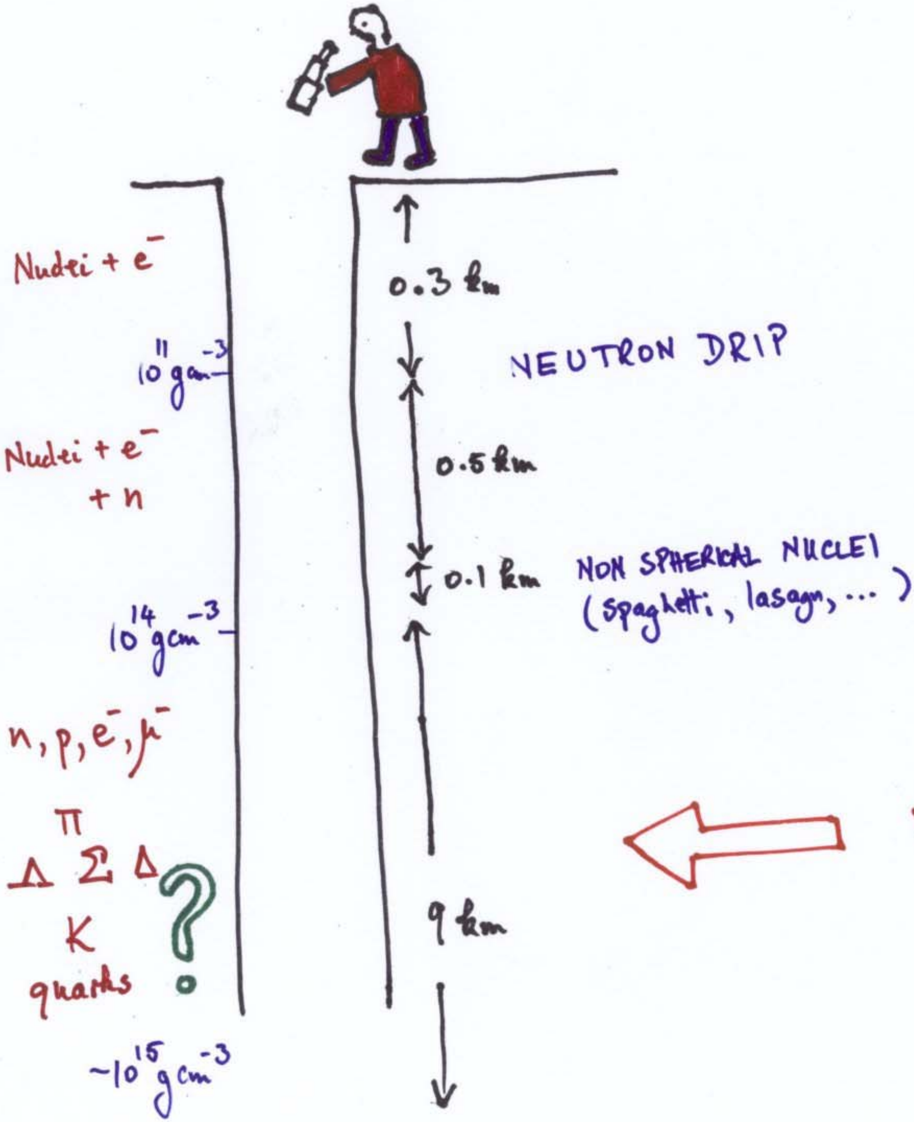
-- Variational approach. Jastrow wave function

$$\Psi = \prod_{ij} f(r_{ij}) \Psi_{\text{free}}$$

-- Short distances. Solve two-body problem

-- Take many-body effects into account via a boundary condition

(Vijay’s love of TLA and MLNA)



bulk binding energy

$$\frac{n_{drip}}{n_s} \simeq \left(-\frac{b_{bulk}}{E_F}\,\frac{v_n}{c}\right)^3$$

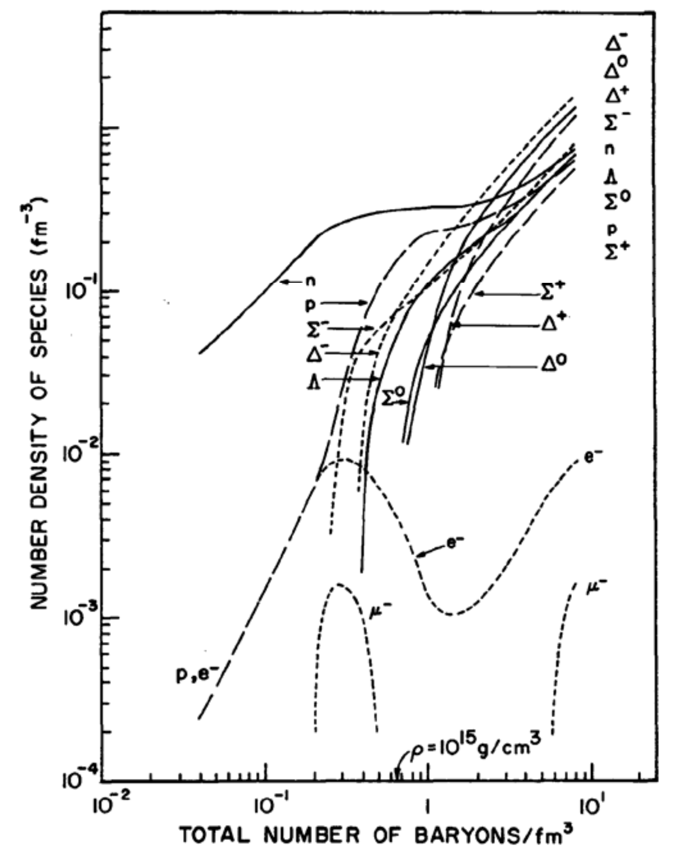
symmetry energy   Fermi velocity

$$\frac{n_p}{n} \simeq \left(\frac{2S}{E_F}\,\frac{v_n}{c}\right)^3$$

MOST OF MASS OF STAR!

Hyperons in dense matter

Hyperon X, with baryon no. A and charge eQ appears when $A\mu_n - Q\mu_e > m_X$ (plus interaction corrections)



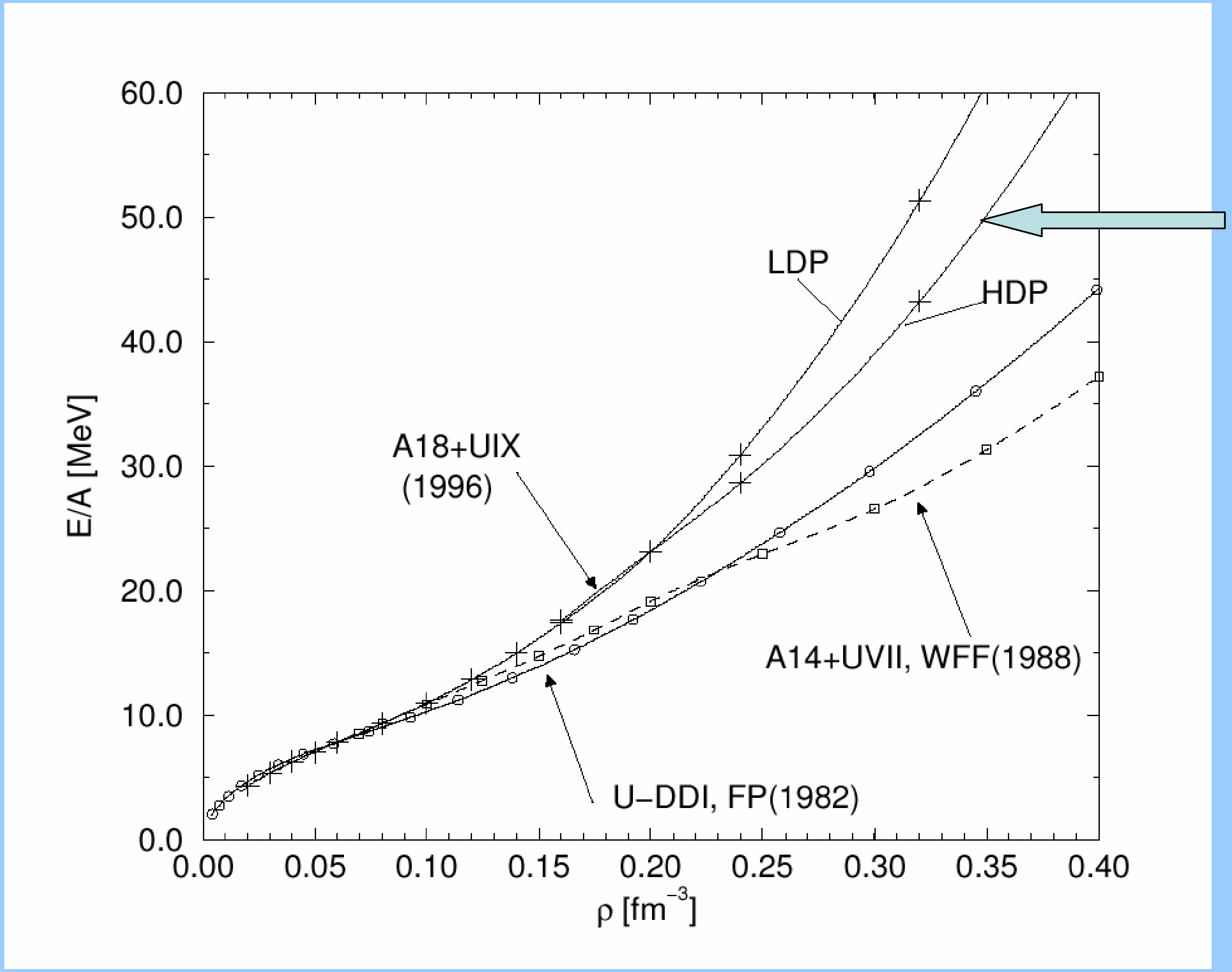
*V. R. Pandharipande, Nucl. Phys. A**178**, 123 (1971)*

Equation of state

- Friedman and Pandharipande, Nucl. Phys. A, 361 (1981). (Lagaris)
- Wiringa, Fiks, and Fabrocini, Phys. Rev. C 38, 1010 (1988).
- Akmal and Pandharipande, Phys. Rev. C 56, 2261 (1997) .
- Akmal, Pandharipande, and Ravenhall, Phys. Rev. C 58, 1804 (1998).

Energy per nucleon in pure neutron matter

Akmal, Pandharipande and Ravenhall, Phys. Rev. C58 (1998) 1804

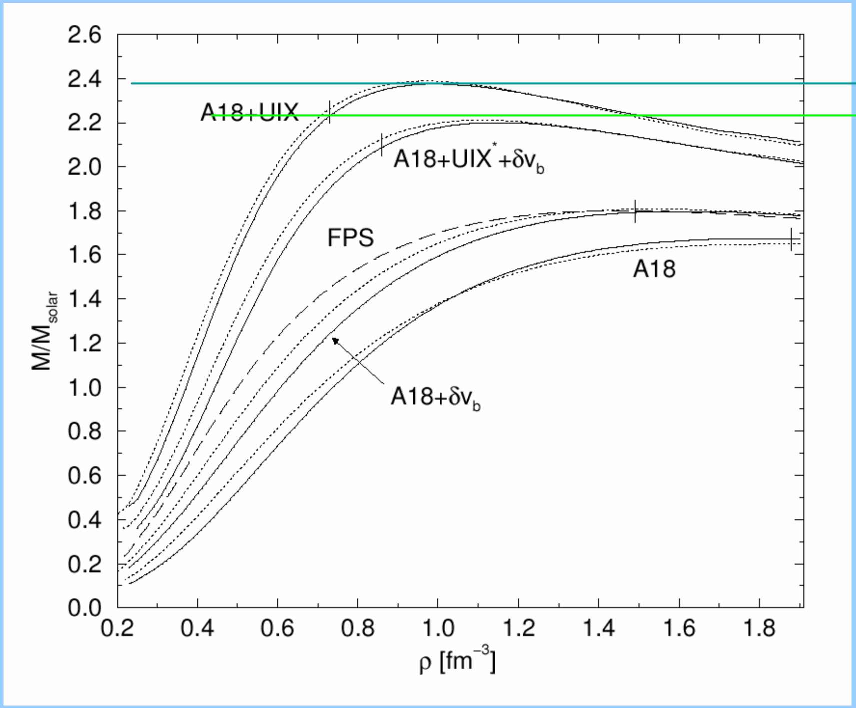


$\langle \pi^0 \rangle$

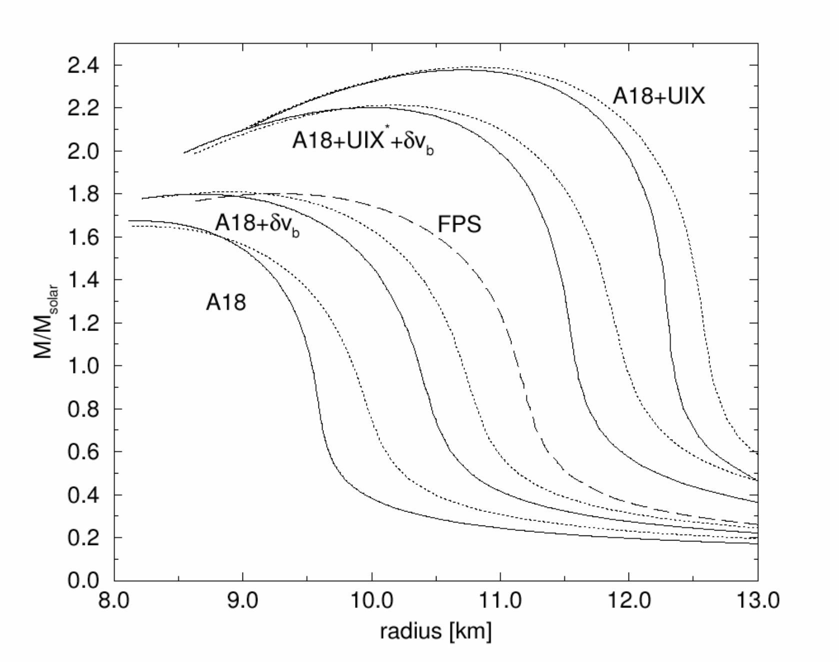
condensate

Maximum neutron star mass

$2.2M_{\odot}$



Mass vs. central density

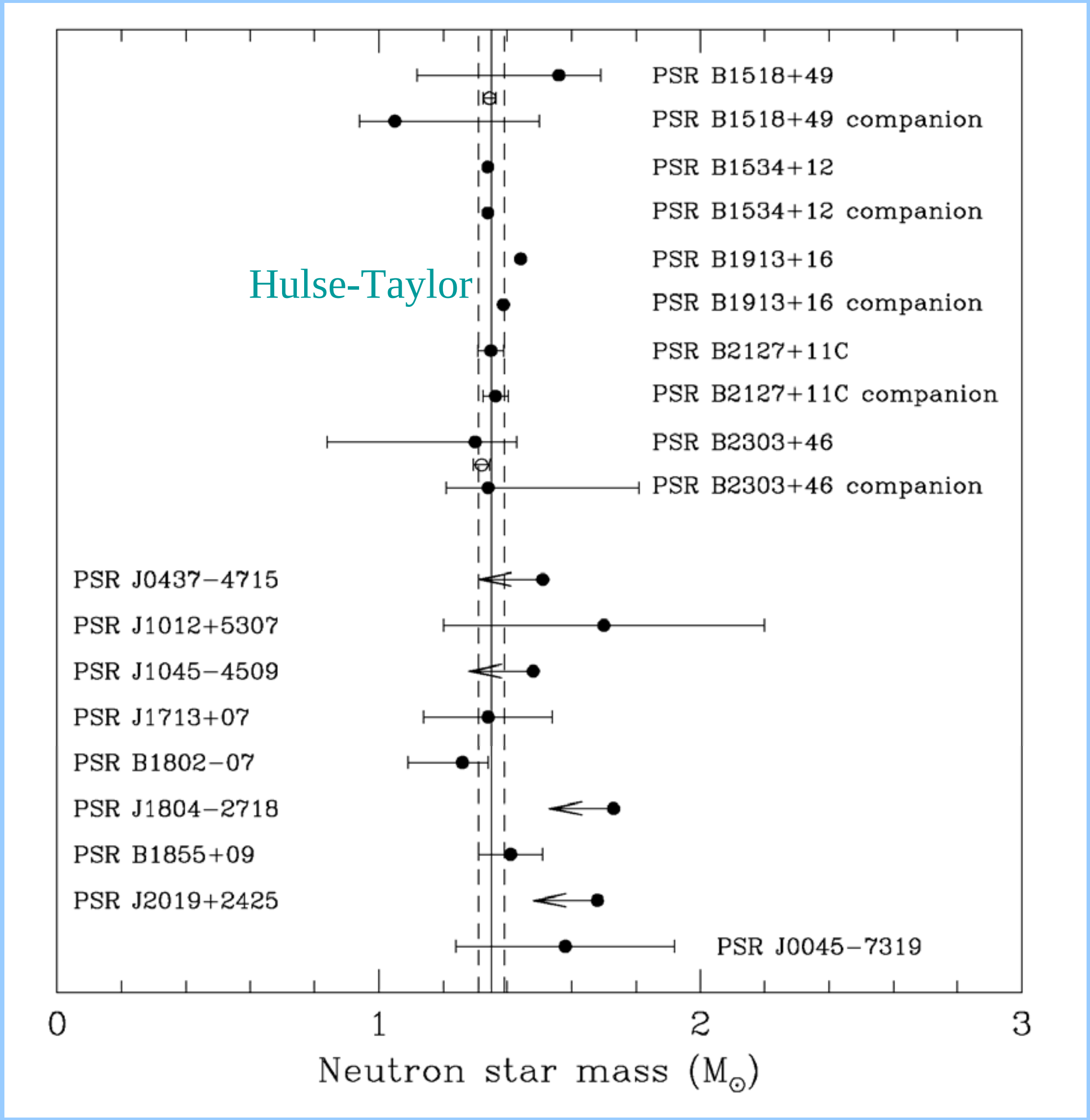


Mass vs. radius

Akmal, Pandharipande and Ravenhall, 1998

Measured neutron star masses in radio pulsars

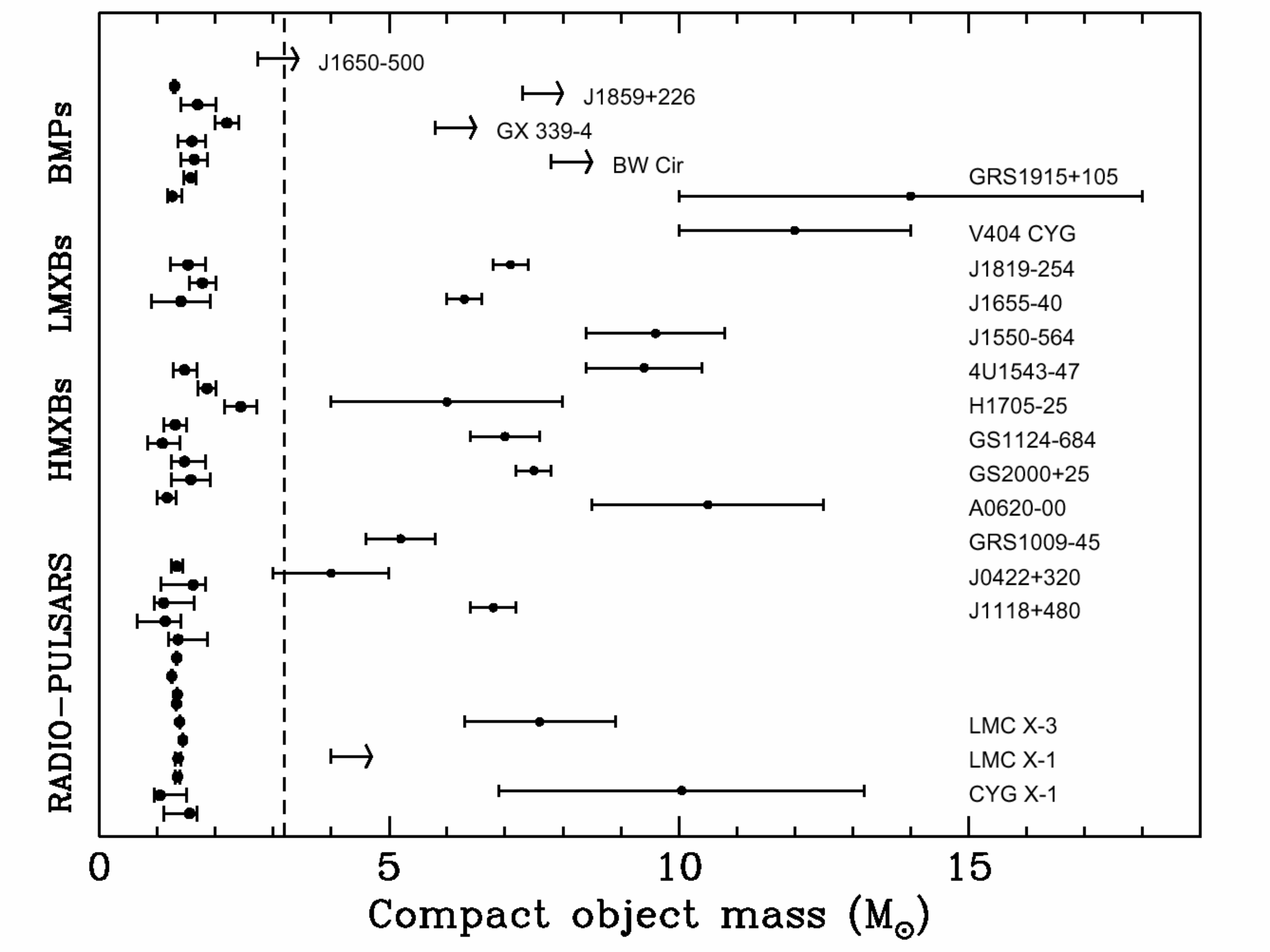
Thorsett and Chakrabarty, Ap. J. 1998



neutron star
- neutron star
binaries

$M=1.35\pm0.04M_\odot$

Masses of compact objects in X-ray binaries



J. Caceres, astro-ph/0503071

Maximum mass of a neutron star

- Assume equation of state known up to density ρ_0
- Assume $dP/d\rho = c^2$ at higher densities

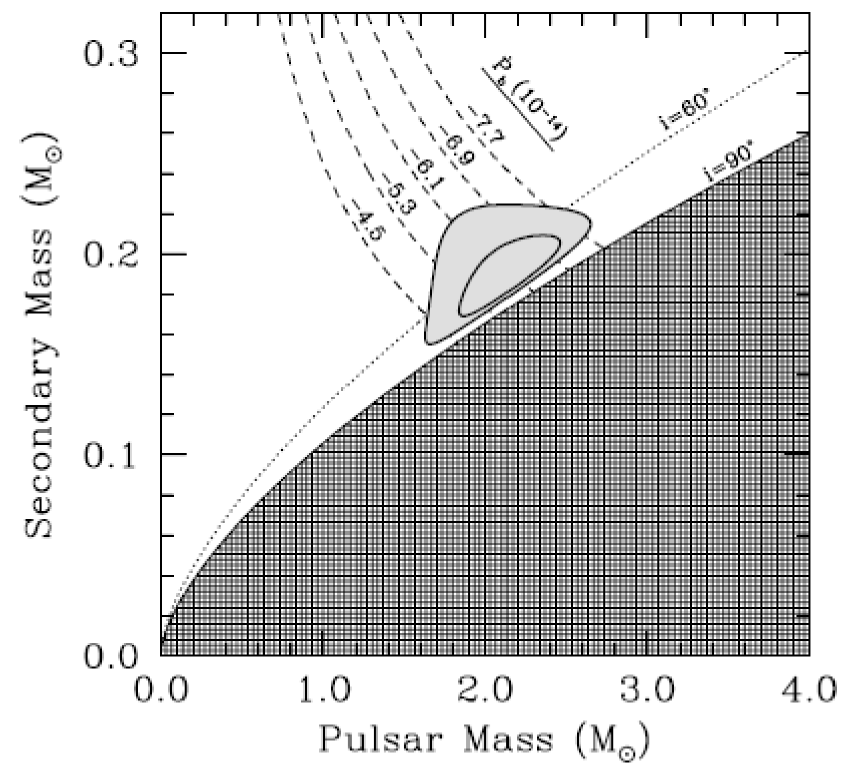
$$M_{\mathrm{max}} = 3.2 M_\odot \quad (\rho_0 = \rho_{\mathrm{s}})$$

$$M_{\mathrm{max}} = 2.9 M_\odot \quad (\rho_0 = 2\rho_{\mathrm{s}})$$

$$M_{\mathrm{max}} = 2.2 M_\odot \quad (\rho_0 = 4\rho_{\mathrm{s}})$$

Rhodes and Ruffini (1974),
Kalogera and Baym (1996) for WWF eos

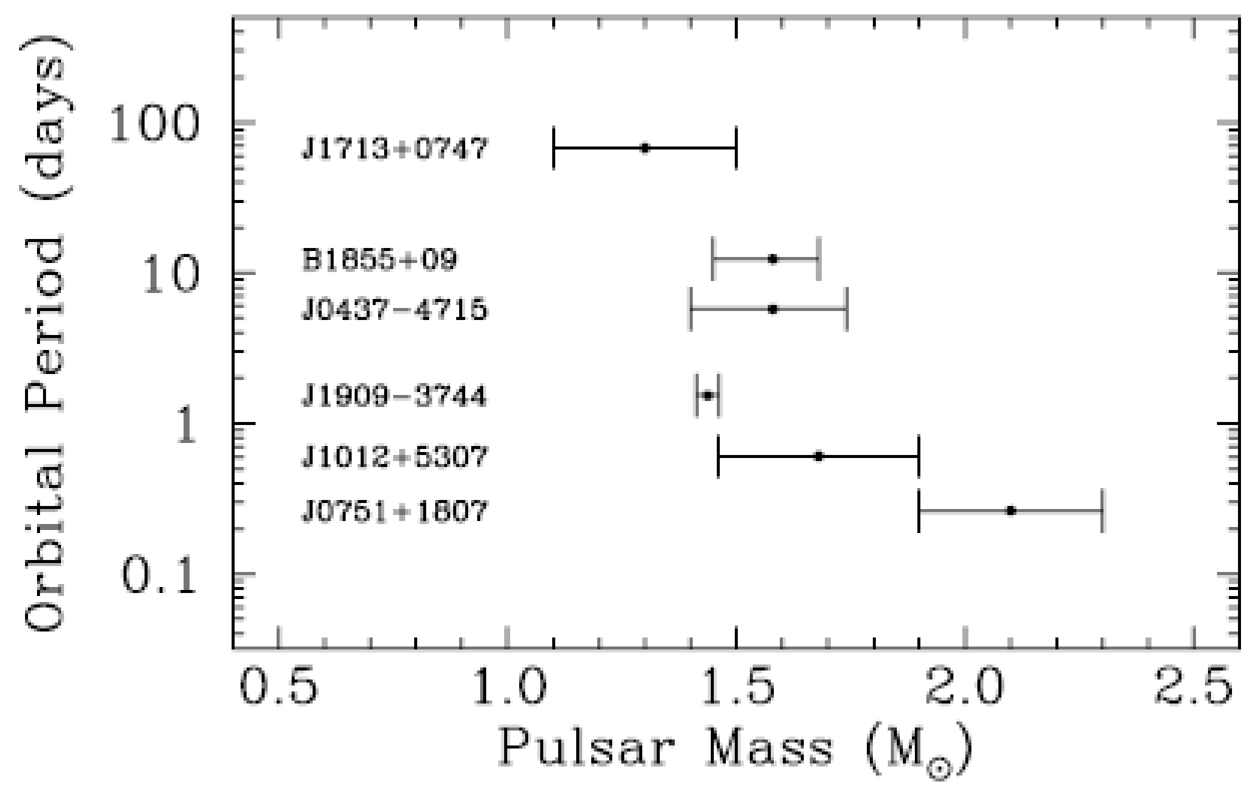
Pulsar—white-dwarf binaries



PSR J0751+1807 $M = 2.1 \pm 0.2 M_\odot$

Nice *et al., Ap. J. 634, 1242 (2005)*

Masses of neutron stars in pulsar—white-dwarf binaries



Nice *et al., Ap. J. 634, 1242 (2005)*

Quasiperiodic oscillations

- Accretion onto neutron star
- Strong peak in power spectrum, but not perfectly periodic
- Beat frequency model
- Last stable circular orbit at radius

$$R_{\mathrm{min}} = \frac{6GM}{c^2}$$

QPO 4U1820-30 (RXTE)

Lamb, Miller, Psaltis

innermost circular stable orbit

=> $M \sim 2.2\text{-}2.3\ M_{\odot}$

Implies stiff equation of state
No exotica likely
Central density ~ $1.0\ \mathrm{fm}^{-3} \sim 6\rho_{nm}$

Summary on masses

- Heavier neutron stars are being found

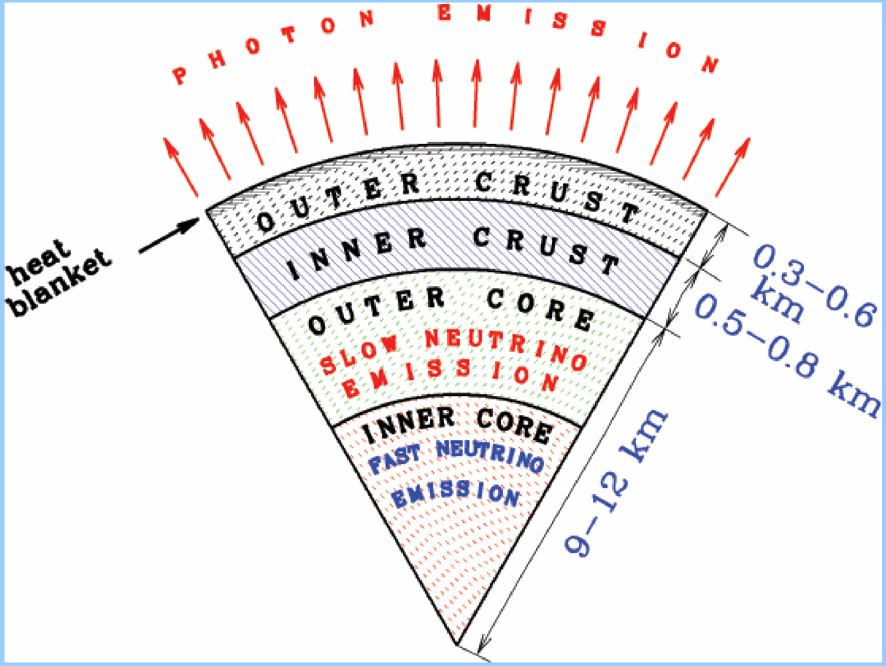
- Information on neutron star masses points to a relatively stiff equation of states like that for models based on nucleon degrees of freedom

Cooling of neutron stars

Thermal balance:

$$C(T)\frac{dT}{dt} = -L_\nu(T) - L_\gamma(T_s)$$

Photon luminosity: $L_\gamma = 4\pi\sigma R^2 T_s^4$



Heat blanketing envelope: $T_s = T_s(T)$

Heat content: $U_T \sim 10^{48}\ T_9^2\ \ ergs$

Neutrino emission: slow and/or fast?

Main cooling regulators:

1. Equation of state
2. Neutrino emission
3. Superfluidity
4. Magnetic fields
5. Light elements on the surface

Neutrino emission processes

- Direct Urca

$$\mathsf{n} \rightarrow \mathsf{p} + \mathsf{e}^- + \bar{\nu}_\mathsf{e}$$

$$\mathsf{p} + \mathsf{e}^- \rightarrow \mathsf{n} + \nu_\mathsf{e}$$

Energy emission rate $\propto$ T^6

Fast process $\tau \sim \dfrac{1\mathsf{min}}{T_9^4}$

Requires proton concentration greater than ~ 10%

- Modified Urca process (Chiu and Salpeter)

$$\mathrm{n} + \mathrm{N} \rightarrow \mathrm{p} + \mathrm{e}^- + \bar{\nu}_\mathrm{e} + \mathrm{N}$$

$$\mathrm{p} + \mathrm{e}^- + \mathrm{N} \rightarrow \mathrm{n} + \nu_\mathrm{e} + \mathrm{N}$$

Energy emission rate $\propto$ T^8

Slow process $$\tau \sim \frac{1\mathrm{yr}}{T_9^6}$$

Other fast processes

- Pion condensate. Excitations are superpositions of neutrons and protons
- Kaon condensate
- Quark matter
- Hyperons

Kinematics similar to direct Urca

Matrix elements generally smaller

(Influence of Vijay and collaborators)

Other slow process

- Bremsstrahlung of neutrino pairs

$$\mathrm{N} + \mathrm{N} \rightarrow \mathrm{N} + \mathrm{N} + \nu + \bar{\nu}$$

Energy emission rate $\propto T^8$,

but smaller than modified Urca

Inner cores of massive neutron stars(?)

Nucleons, hyperons	$n \to p + e + \bar{\nu}_e$ $p + e \to n + \nu_e$	$Q \sim 3 \times 10^{27} T_9^6 \ \frac{erg}{cm^3 \ s}$	$L_\nu \sim 10^{46} T_9^6 \ \frac{erg}{s}$
Pion condensates	$\tilde{n} \to \tilde{p} + e + \bar{\nu}_e$ $\tilde{p} + e \to \tilde{n} + \nu_e$	$Q \sim 10^{24-26} T_9^6 \ \frac{erg}{cm^3 \ s}$	$L_\nu \sim 10^{42-44} T_9^6 \ \frac{erg}{s}$
Kaon condensates	$\tilde{q} \to \tilde{q} + e + \bar{\nu}_e$ $\tilde{q} + e \to \tilde{q} + \nu_e$	$Q \sim 10^{23-24} T_9^6 \ \frac{erg}{cm^3 \ s}$	$L_\nu \sim 10^{41-42} T_9^6 \ \frac{erg}{s}$
Quark matter	$d \to u + e + \bar{\nu}_e$ $u + e \to d + \nu_e$	$Q \sim 10^{23-24} T_9^6 \ \frac{erg}{cm^3 \ s}$	$L_\nu \sim 10^{41-42} T_9^6 \ \frac{erg}{s}$

Everywhere in neutron star cores

Modified Urca (Murca)	$n + N \to p + e + N + \bar{\nu}_e$ $p + e + N \to n + N + \nu_e$	$Q \sim 10^{20-22} T_9^8 \ \frac{erg}{cm^3 \ s}$	$L_\nu \sim 10^{38-40} T_9^8 \ \frac{erg}{s}$
Brems-strahlung	$N + N \to N + N + \nu + \bar{\nu}$ $\Downarrow$ $\nu_e, \ \nu_\mu, \ \nu_\tau$	$Q \sim 10^{18-20} T_9^8 \ \frac{erg}{cm^3 \ s}$	$L_\nu \sim 10^{36-38} T_9^8 \ \frac{erg}{s}$

Pairing

- Gaps appear and suppress neutrino processes at low temperatures
- ${}^1S_0$ at low density, ${}^3P_2 - {}^3F_2$ at high
- New neutrino emission process:

Neutrino pair production by annihilation of pairs of excitations

Rate very high just below T_c, up to 100 times the modified Urca rate

X-ray observatories

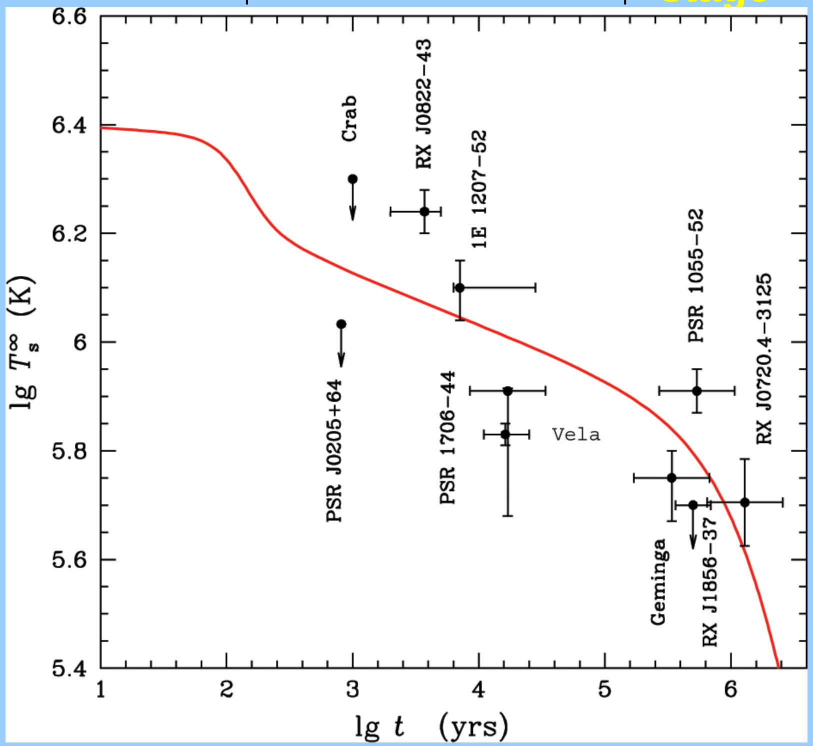
- Einstein (1978-1981)
- EXOSAT (1983-1986)
- ROSAT (1990-1998)
- Chandra (1999-)
- XMM-Newton (1999-)

(Also ground-based telescopes for low frequencies)

OBSERVATIONS AND BASIC COOLING CURVE

Nonsuperfluid star
Modified Urca
neutrino emission:
slow cooling

Surface temperature



Relaxa-tion

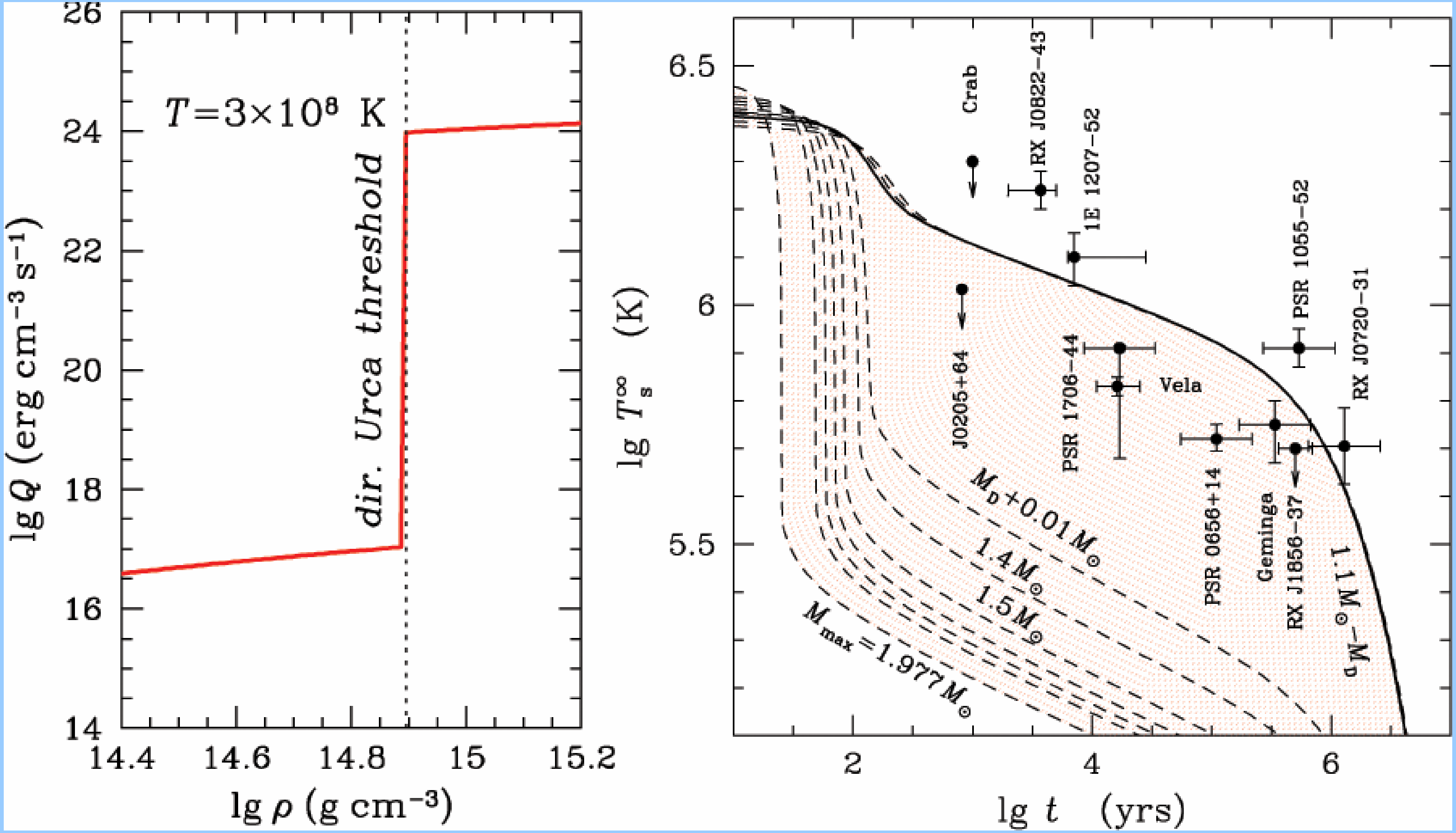
Neutrino cooling stage

Photon stage

Age

Yakovlev & Pethick, ARAA (2004)

Modified Urca versus Direct Urca: No pairing



Yakovlev & Pethick 2004

Salient points

- Cooling curves similar to modified Urca
- Magnetic fields and different compositions not enough to account for differences
- Cooling neutron stars not homogeneous sample

Possible interpretation

- Slower than modified Urca cooling

  Low mass stars with emission suppressed by pairing

- Faster cooling

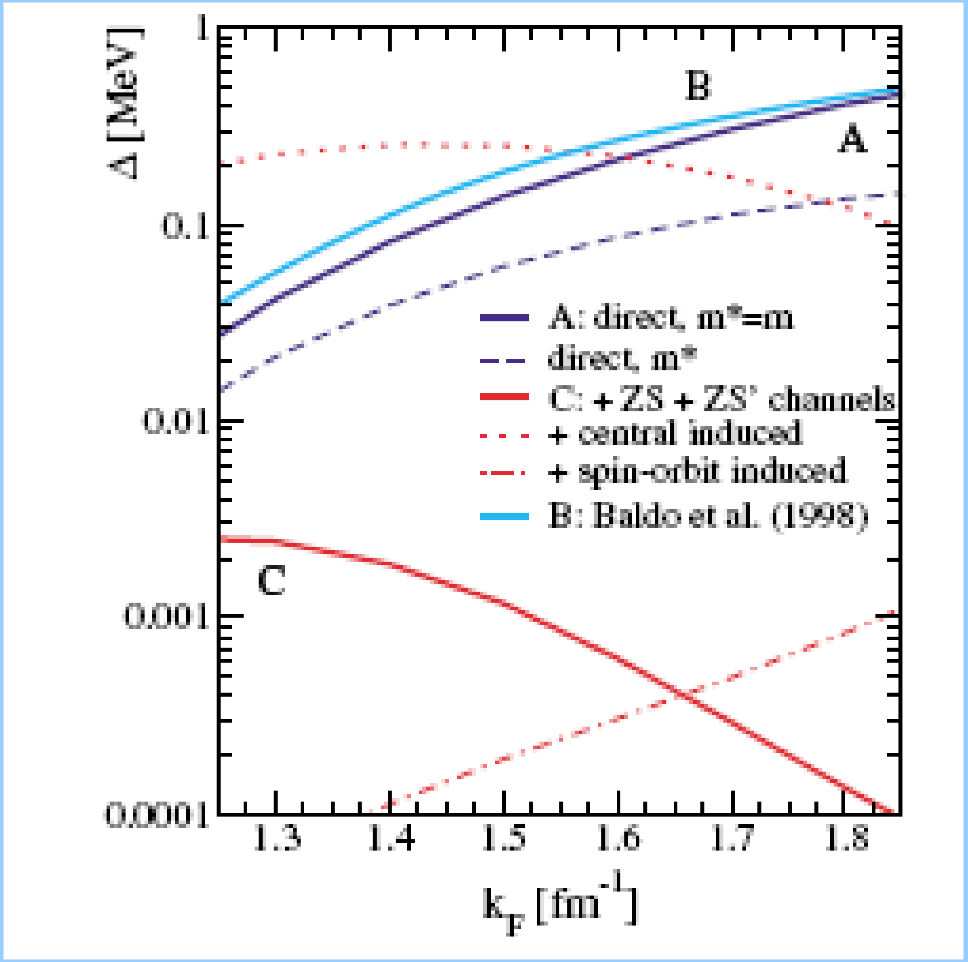
  High mass stars with some sort of direct Urca process in core

  Little pairing in the inner core

(Yakovlev and collaborators)

$^3P_2 - {}^3F_2$ pairing at high density

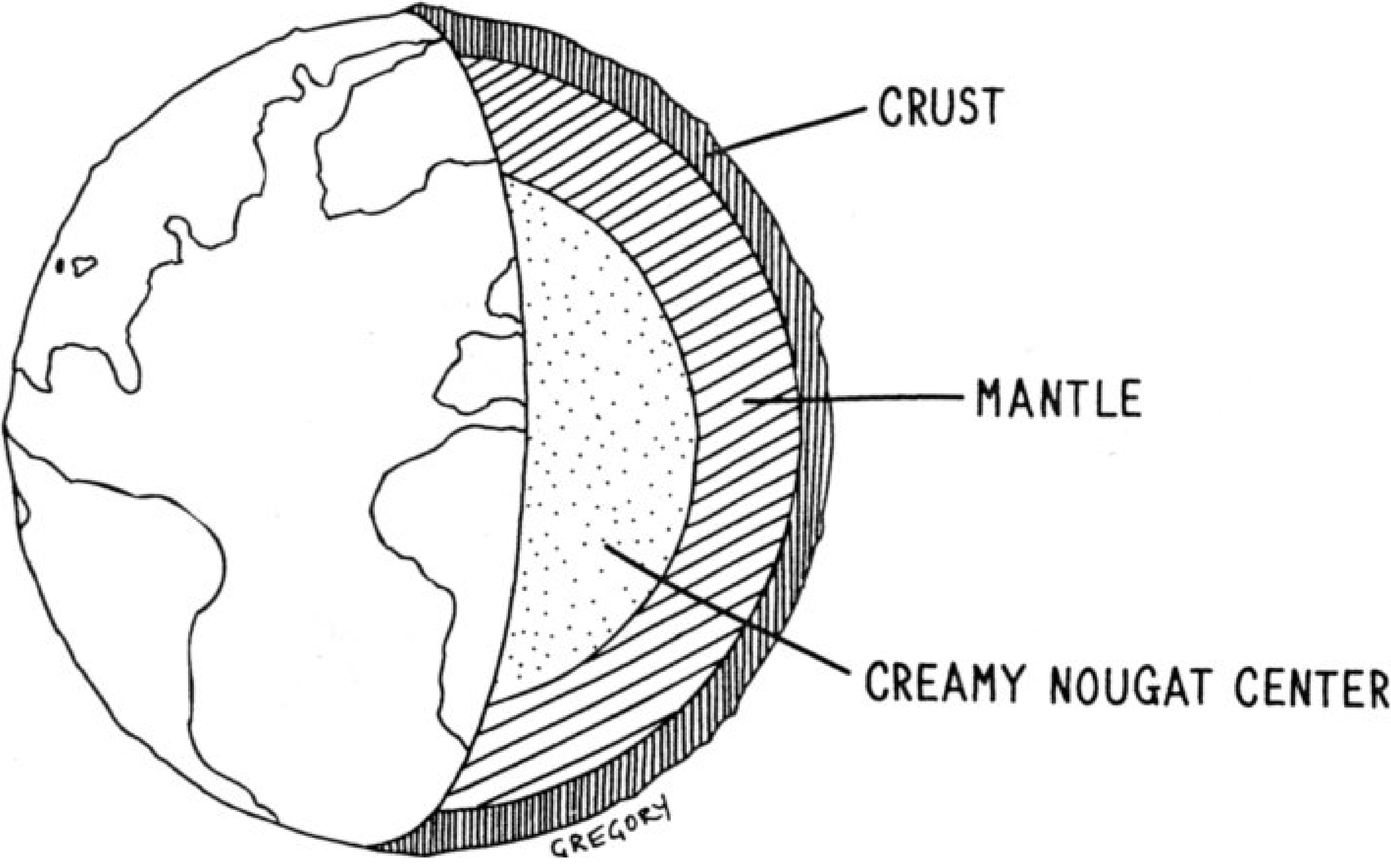
Induced interaction due to tensor force reduces gap



Schwenk and Friman, PRL 92, 082501 (2004)

Bottom line

- Progress is being made, both in theory and observation
- Neutron star masses and neutron star cooling point to properties of matter like a nucleon liquid. WHY?
- Influence of Vijay and his collaborators on neutron star research is unparalleled
- Questions remain …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