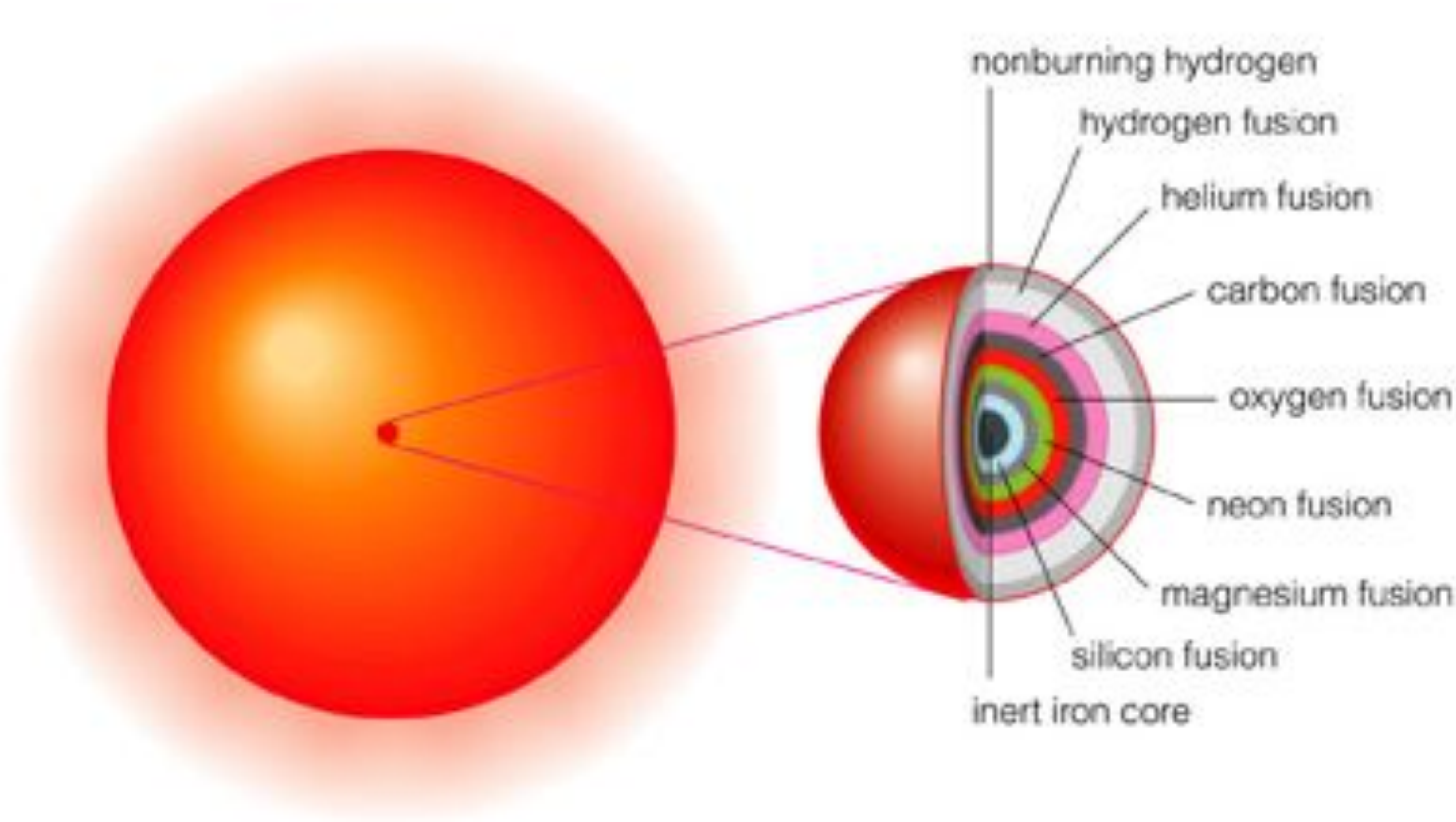
Neutron Stars

Birth, Structure, Cooling

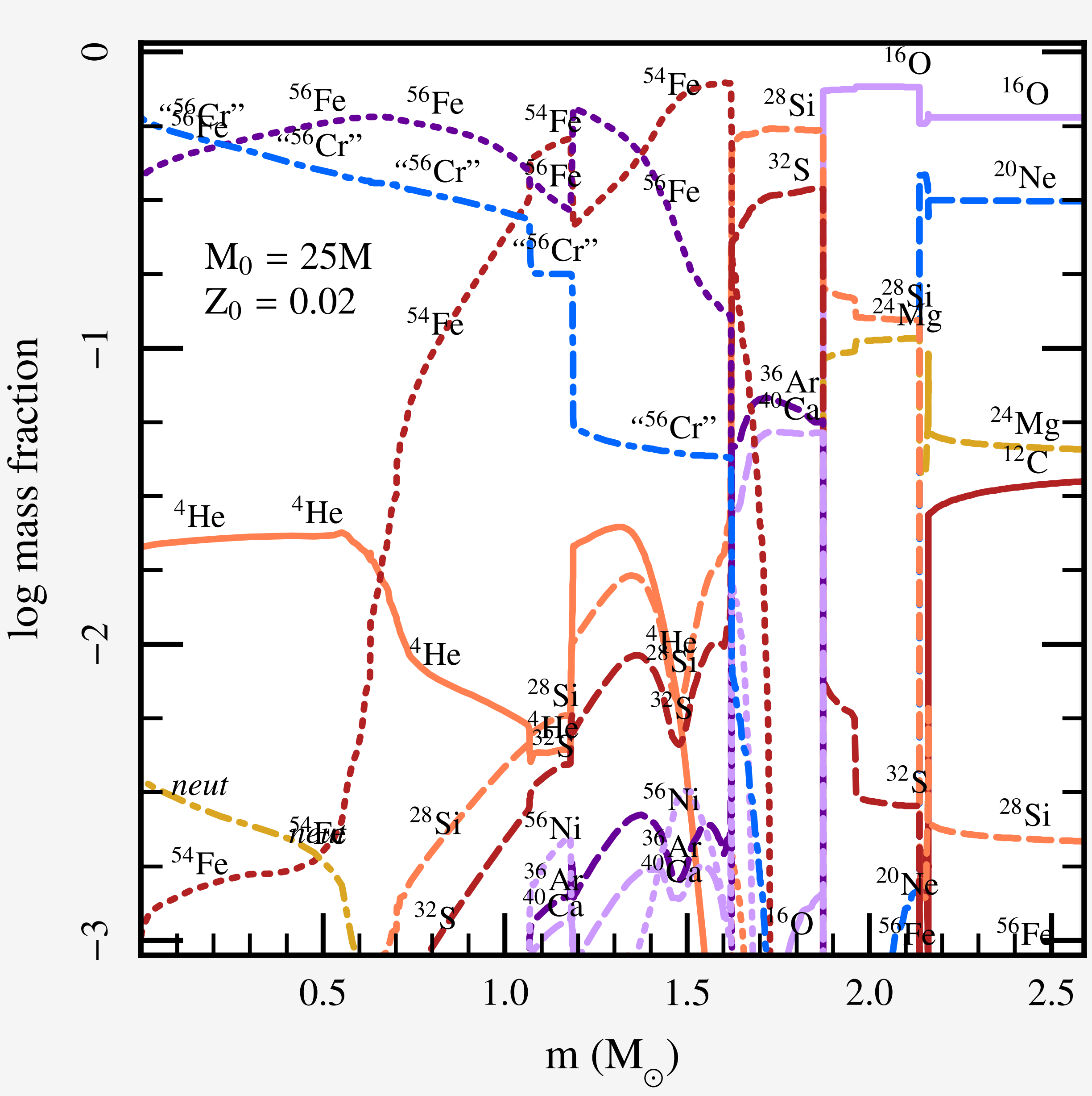
Edward Brown

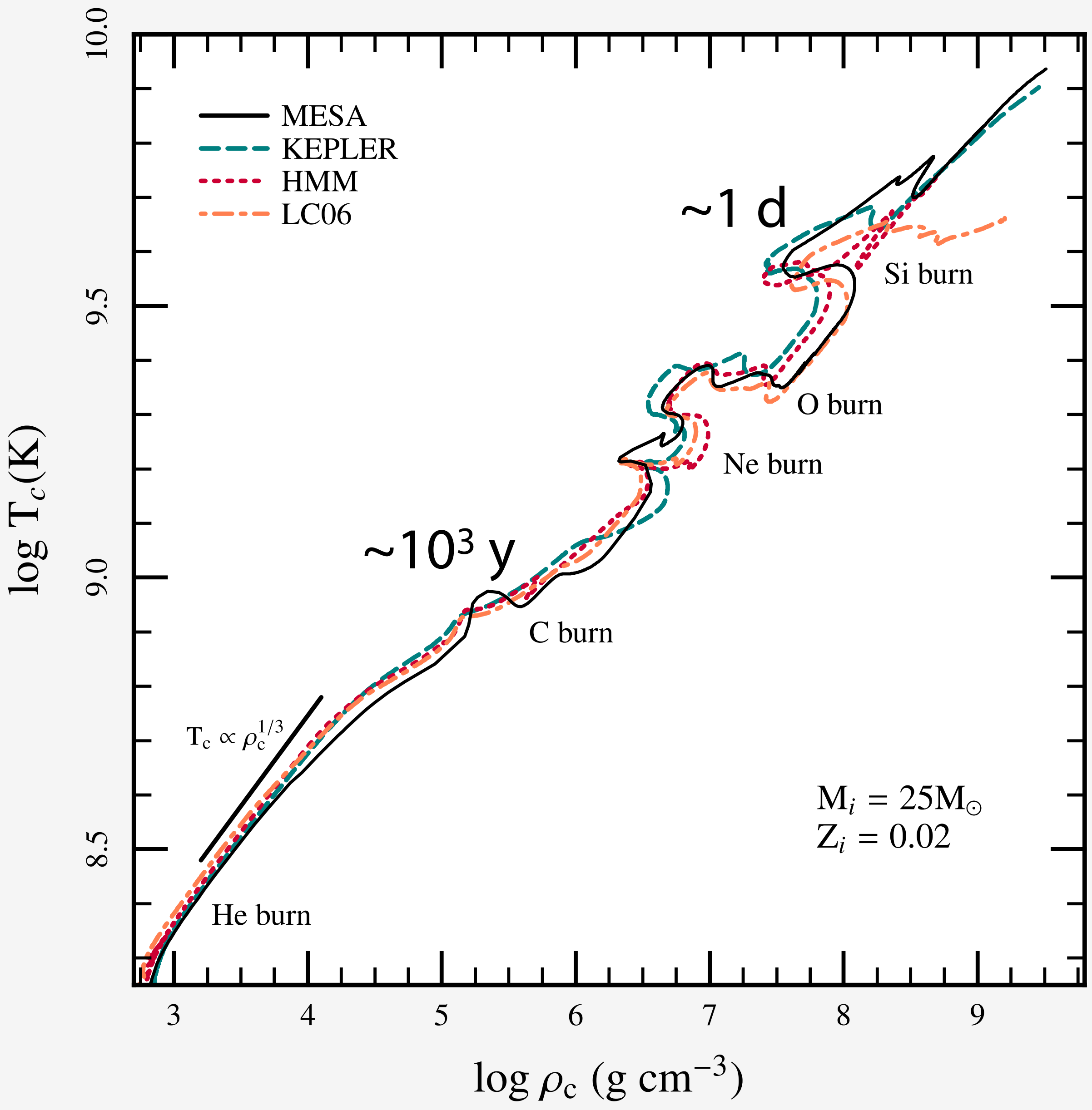
Textbook view of massive stars

Essential Cosmic Perspective, Bennett et al.



Massive stars: advanced stages of burning with *MESA*, Paxton et al. 2010





A note about silicon "burning"

For $T \gtrsim 10^9$ K, photodissociation reactions such as

$$(\gamma, n), \quad (\gamma, p)$$

become possible. Forward and inverse reaction flows come into balance, and material relaxes to Nuclear Statistical Equilibrium. Most bound nuclei around Fe-peak.

Collapse

For a relativistic ideal gas,

$$P = \frac{1}{4} n\mu = \frac{1}{4} \left(3\pi^2\right)^{1/3} \hbar c \left(\frac{Y_e \rho}{m_\mathrm{u}}\right)^{4/3} .$$

How does radius scale with mass for $P \sim M^2 R^{-4}$, $\rho \sim MR^{-3}$?

A relativistic gas has a characteristic mass scale, the *Chandrasekhar* mass

$$M_\mathrm{Ch} = 1.4(2Y_e)^2 \, M_\odot .$$

Energy considerations

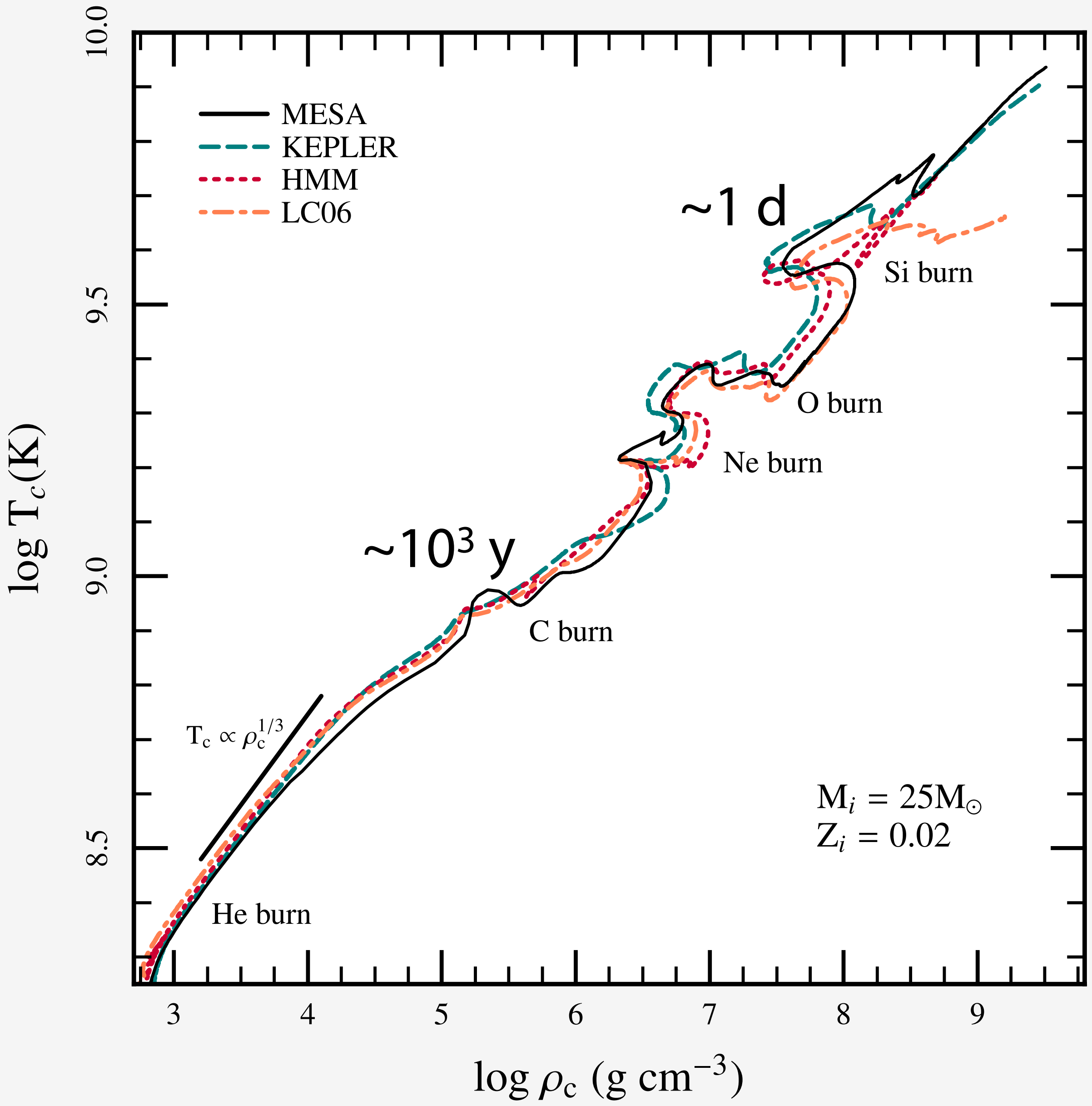
One can use the virial system to show that if $P \sim \rho^\gamma$, then the total (gravitational and thermal) energy of the star is

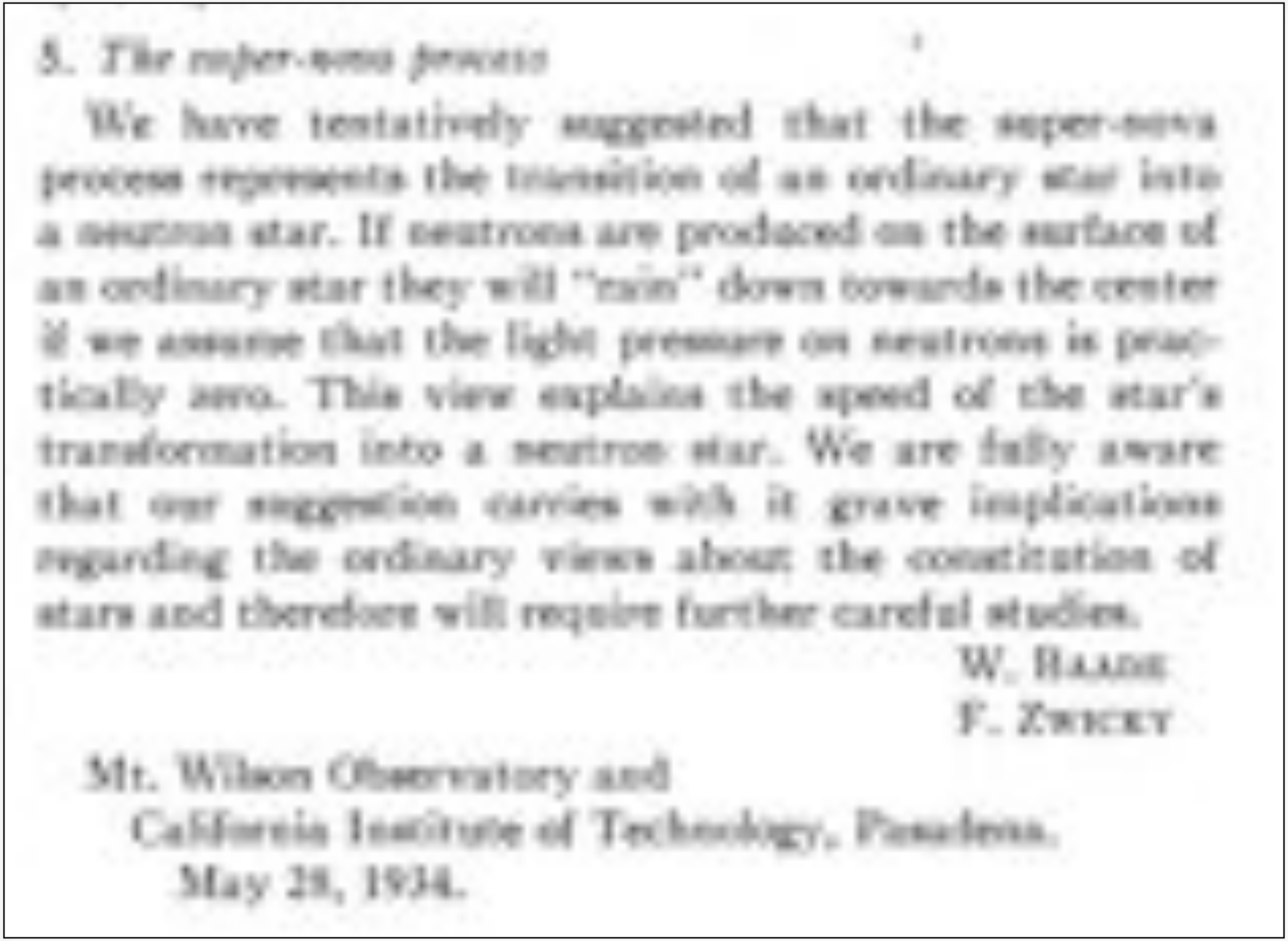
$$E = -\frac{3(\gamma - 1) - 1}{5\gamma - 6}\frac{GM^2}{R}.$$

Core (~1 M_{sun}) becomes unstable, dynamically collapses

What is the timescale for collapse?
Construct an estimate.

MESA calculations; Paxton et al. 2010



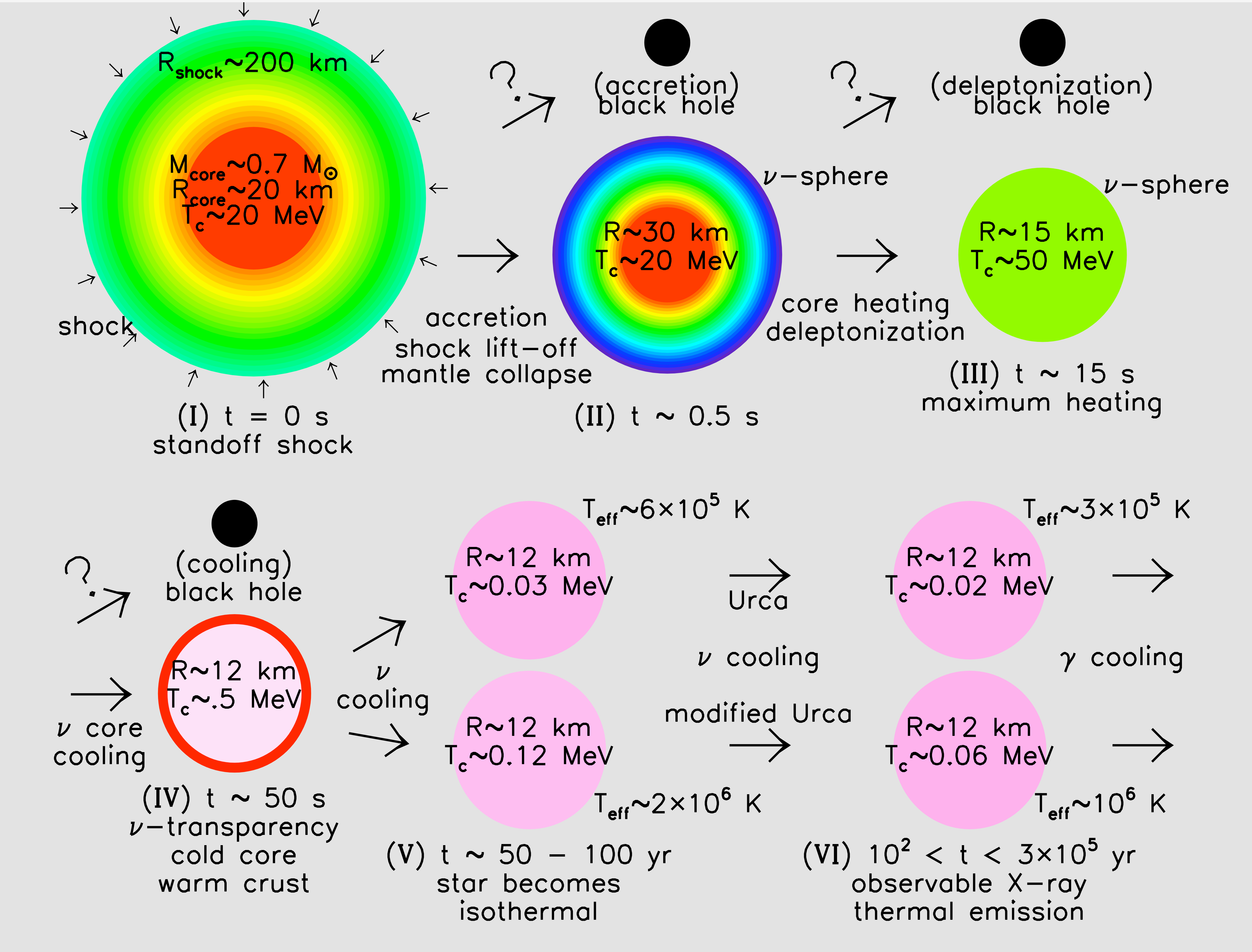


5. *The super-nova process*

We have tentatively suggested that the super-nova process represents the transition of an ordinary star into a neutron star. If neutrons are produced on the surface of an ordinary star they will "rain" down towards the center if we assume that the light pressure on neutrons is practically zero. This view explains the speed of the star's transformation into a neutron star. We are fully aware that our suggestion carries with it grave implications regarding the ordinary views about the constitution of stars and therefore will require further careful studies.

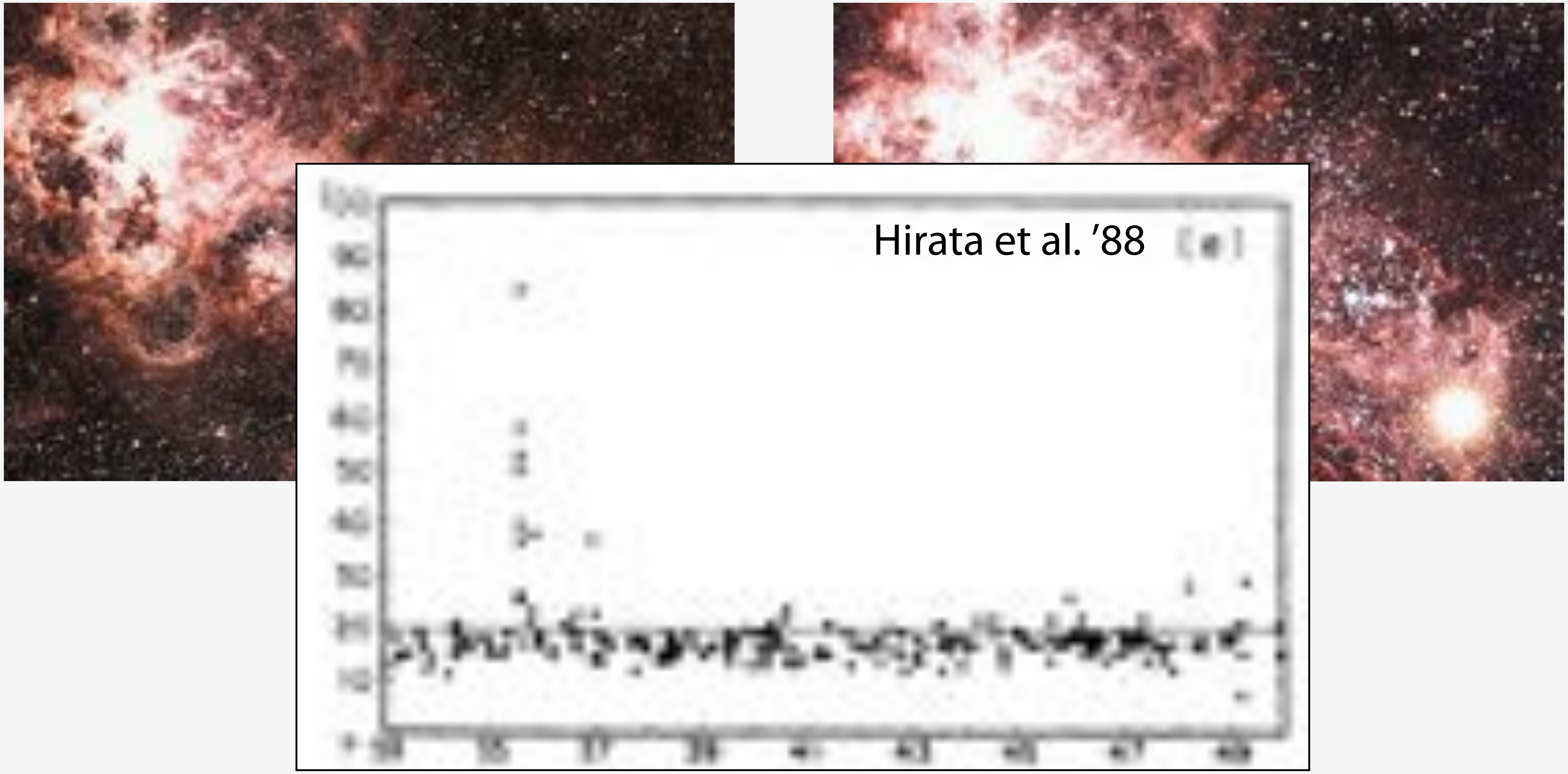
W. BAADE
F. ZWICKY

Mt. Wilson Observatory and
California Institute of Technology, Pasadena.
May 28, 1934.



Modern view of neutron star birth

schematic from Lattimer and Prakash



Hirata et al. '88

Supernova 1987a: neutrinos detected by Kamiokande!

neutron star basics

A solar mass consists of ~ 10^{57} nucleons. If they are separated by typical inter-nucleon distances, what would the radius of the volume containing them be?

neutron star basics

$$R \sim 1\ \mathrm{fm} \cdot \left(10^{57}\right)^{1/3} \sim 10\ \mathrm{km}$$

$$\frac{GM}{Rc^2} \approx 0.2 \approx \frac{\Delta\lambda}{\lambda}$$

$$\frac{GMm_{\mathrm{H}}}{R} \approx 200\ \mathrm{MeV}$$

Exercise

What is the dynamical time of a solar-mass neutron star (density is ≈$2 \cdot 10^{14}$ g/cm^3; density of sun is ≈1 g/cm^3)?

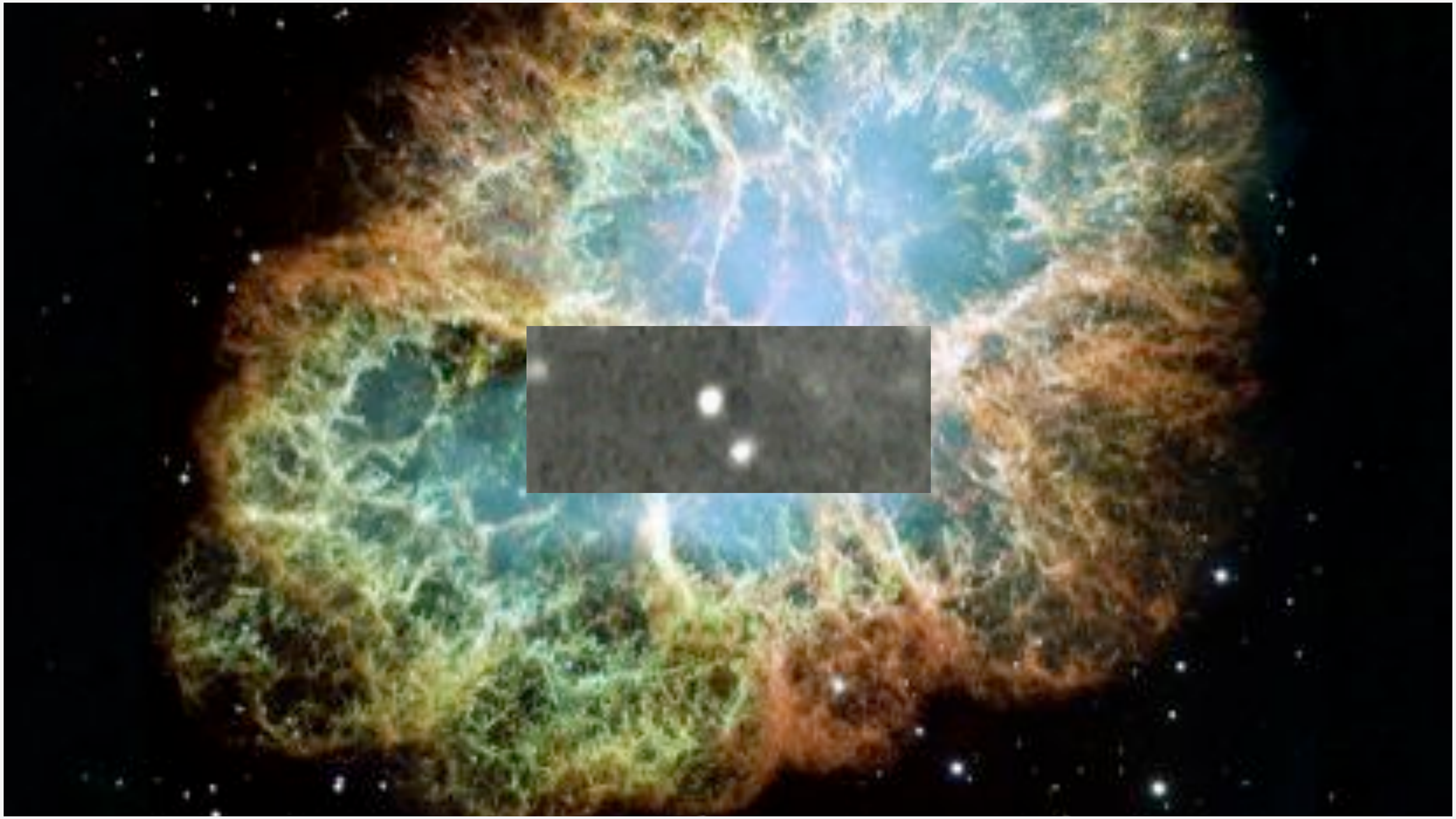
Recall that we defined a dynamical time

$$\tau_{\mathrm{dyn}} = \left(G\bar{\rho}\right)^{-1/2}$$

Discovery!

radio pulsations discovered (Hewish, Bell, et al. 1968)

Gold (1968): explained as due to rotation of a neutron star (WHY?)



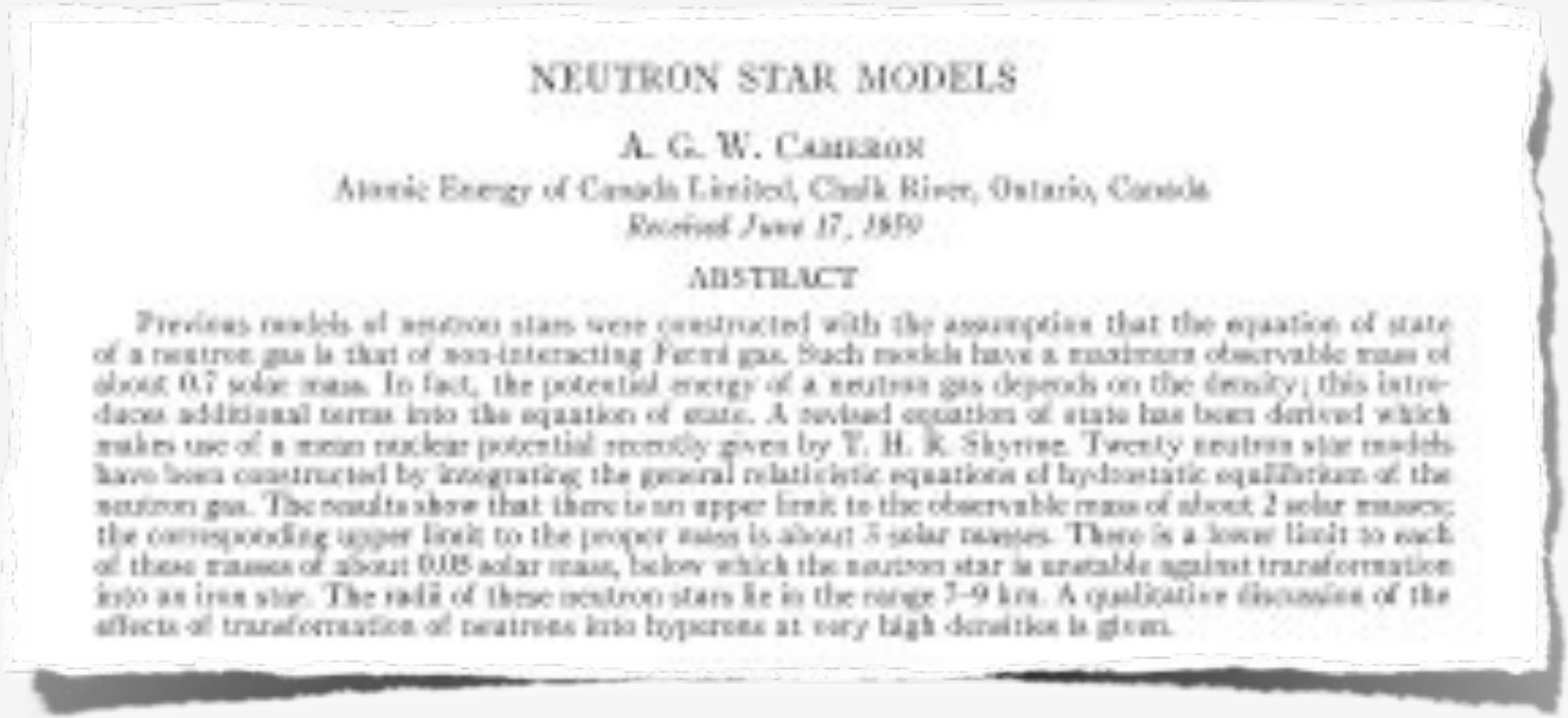
Crab Nebula: Remnant of supernova in 1054

Discovery!

radio pulsations discovered (Hewish, Bell, et al. 1968)

Gold (1968): explained pulsations as being due to rotation of a magnetized neutron star (WHY?)

Unlike white dwarfs, can’t assume ideal Fermi gas EOS



NEUTRON STAR MODELS

A. G. W. Cameron
Atomic Energy of Canada Limited, Chalk River, Ontario, Canada

Received June 17, 1959

ABSTRACT

Previous models of neutron stars were constructed with the assumption that the equation of state of a neutron gas is that of non-interacting Fermi gas. Such models have a maximum observable mass of about 0.7 solar mass. In fact, the potential energy of a neutron gas depends on the density; this introduces additional terms into the equation of state. A revised equation of state has been derived which makes use of a mean nuclear potential recently given by T. H. R. Skyrme. Twenty neutron star models have been constructed by integrating the general relativistic equations of hydrostatic equilibrium of the neutron gas. The results show that there is an upper limit to the observable mass of about 2 solar masses; the corresponding upper limit to the proper mass is about 3 solar masses. There is a lower limit to each of these masses of about 0.05 solar mass, below which the neutron star is unstable against transformation into an iron star. The radii of these neutron stars lie in the range 7–9 km. A qualitative discussion of the effects of transformation of neutrons into hyperons at very high densities is given.

neutron stars and nuclear physics

Nuclear Astrophysics

- **The Origin of the Elements**
- **Explosive Nucleosynthesis**
- **Composition of Neutron Stars**—There are roughly one billion neutron stars in our galaxy, yet their internal structure and the composition of their crusts are poorly understood. ... a FRIB can study the central questions concerning the composition and energetics of their upper mantles.—*Scientific Opportunities with a Rare-Isotope Facility in the United States,* National Research Council (2006)

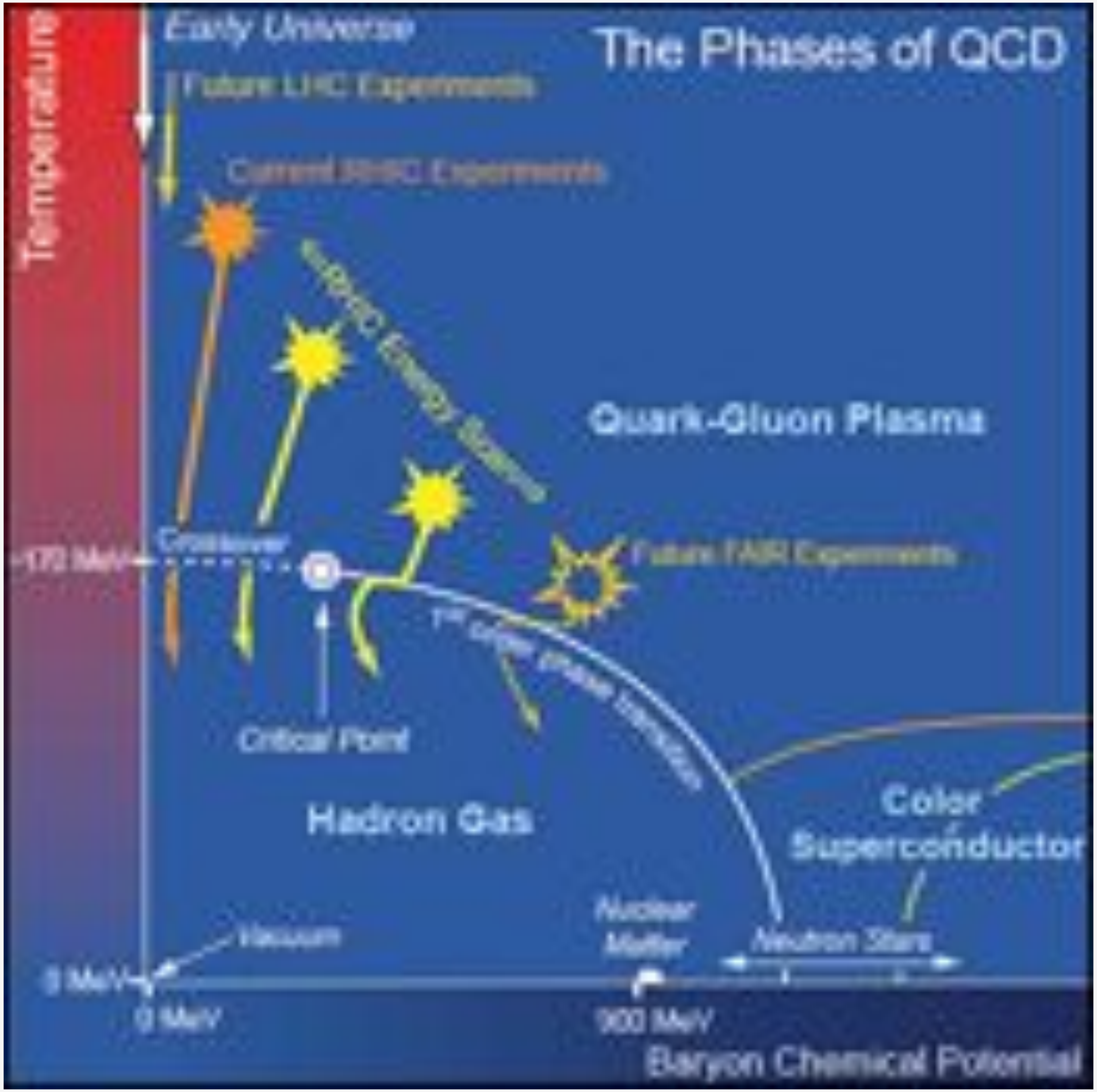
neutron stars and astrophysics

“What is the nature of dense matter?” is one of the top unanswered questions for the 21st century

-*Connecting Quarks with the Cosmos,* Nat’l Academies Press

“Measuring neutron star masses and radii yields direct information about the interior composition [of neutron stars] that can be compared with theoretical predictions.”

-*New Worlds, New Horizons in Astronomy and Astrophysics* (Decadal survey of astronomy)



graphic from RHIC new article 7-22-2010

Neutron stars are a unique probe of dense matter

Thermodynamics near saturation density

see review by Lattimer & Prakash

Let’s examine properties of *npe* matter near saturation density $n = 0.16\ \mathrm{fm}^{-3}$. The proton fraction is

$$x = n_p/(n_n + n_p),$$

and charge neutrality requires that

$$n_e = n_p = xn.$$

We write the energy per nucleon as

$$\varepsilon(n, x) = \varepsilon_S(n) + \varepsilon_A(n)(1 - 2x)^2.$$

Why so neutron-rich?

In β-equilibrium,

$$\begin{aligned}\mu_e &= \mu_n - \mu_p = \left(\frac{\partial\varepsilon}{\partial n_n}\right)_{n_p} - \left(\frac{\partial\varepsilon}{\partial n_p}\right)_{n_n} \\ &= -\frac{\partial\varepsilon}{\partial x} = 4\varepsilon_A(1-2x).\end{aligned}$$

For relativistic electrons, $\mu_e = (3\pi^2 n_e)^{1/3}\hbar c$, so we can solve for the proton fraction

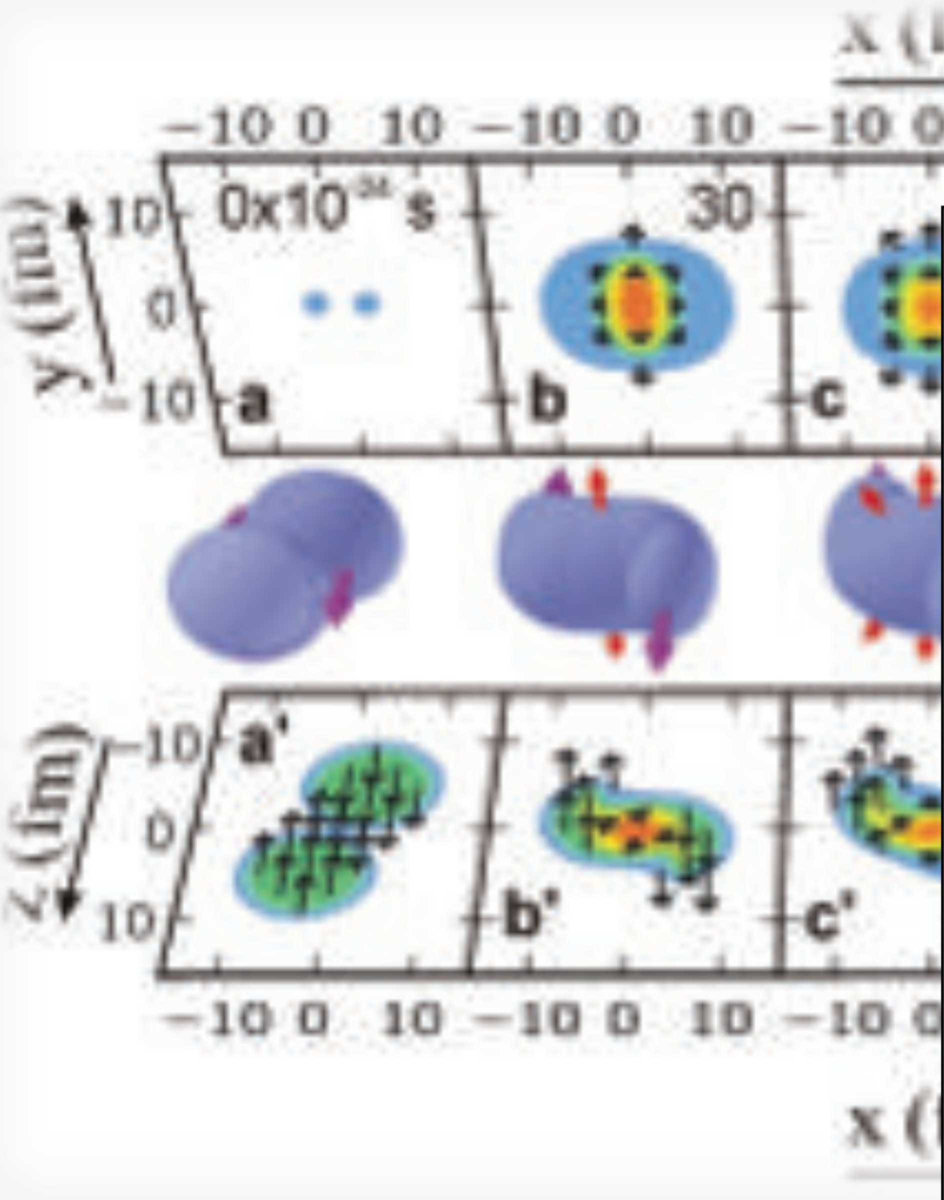
$$x = \left[6 + \frac{3\pi^2}{64}\left(\frac{\hbar c}{\varepsilon_A}\right)^3 n\right]^{-1} \approx 0.04$$

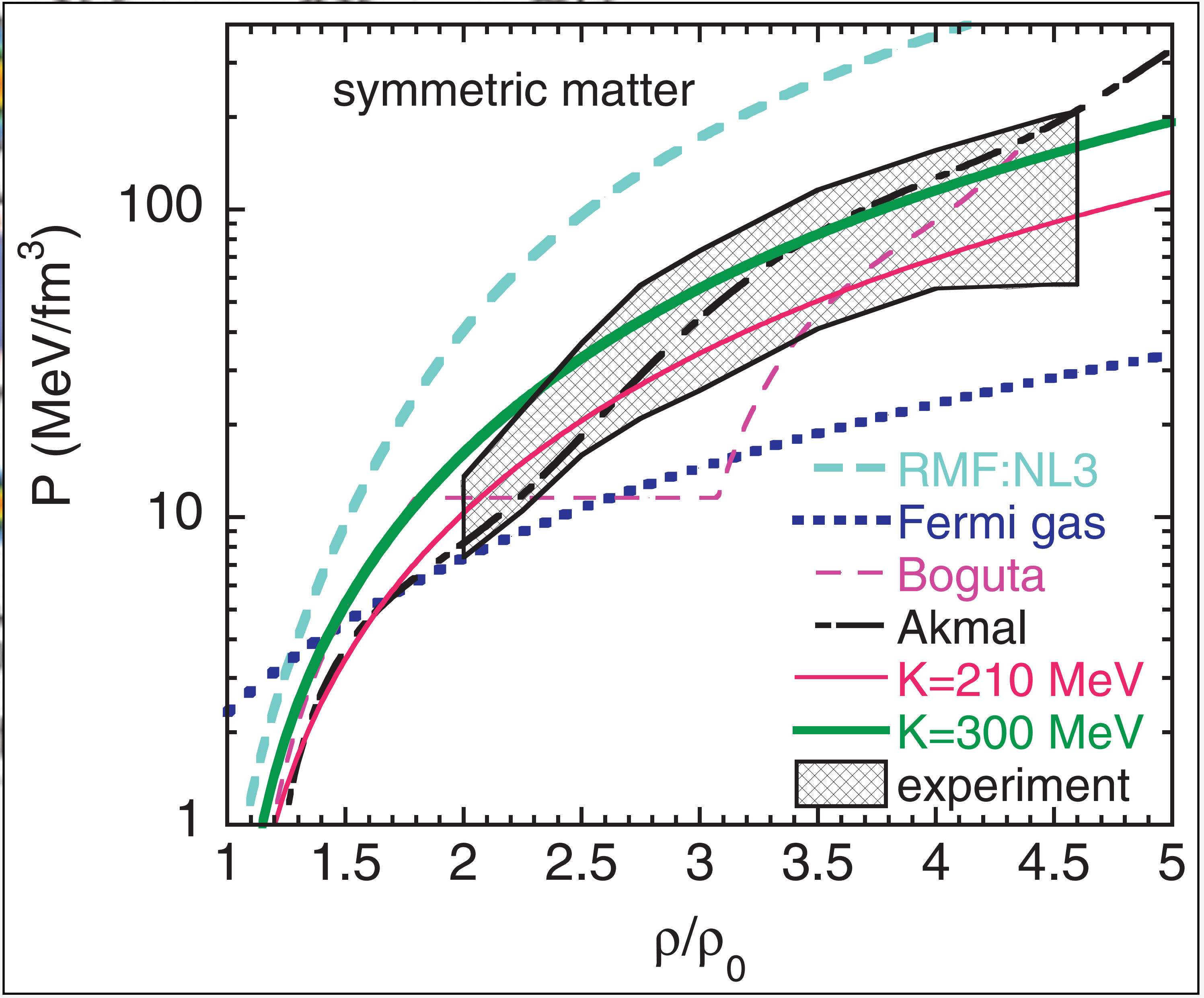
for $\varepsilon_A = 30$ MeV.

What is the pressure at saturation?

$$
\begin{aligned}
P &= n^2\frac{\partial \varepsilon}{\partial n} + \frac{n_e\mu_e}{4} \\
&= \cancel{n^2\frac{\partial \varepsilon_S}{\partial n}} + n^2\frac{\partial \varepsilon_A}{\partial n}(1-2x)^2 + \varepsilon_A(1-2x)xn \\
&= n(1-2x)\left[n\frac{\partial \varepsilon_A}{\partial n}(1-2x) + x\cancel{\varepsilon_A}\right].
\end{aligned}
$$

equation of state from heavy nucleus collisions
Danielewicz et al. (2002) *Science*





ongoing projects at NSCL,
RIKEN (SAMURAI/TPC)

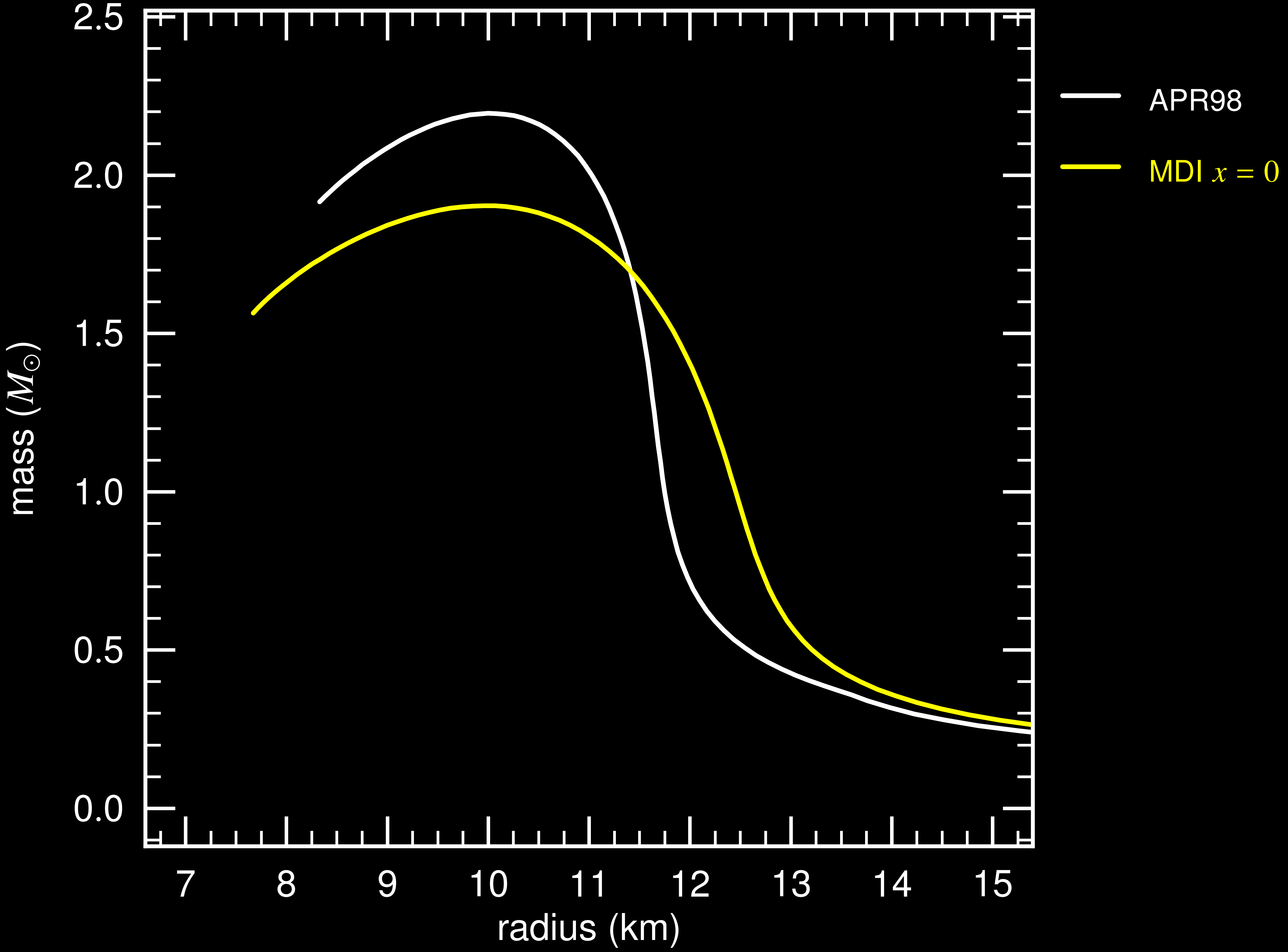
Relativistic stellar structure equations (non-rotating)

Tolman; Oppenheimer & Volkoff 1939; Thorne 1967

$$\longrightarrow$$

$$\begin{aligned}\frac{\mathrm{d}m}{\mathrm{d}r} &= 4\pi r^2 \rho\\ \frac{\mathrm{d}P}{\mathrm{d}r} &= -\rho\frac{Gm(r)}{r^2}\end{aligned}$$

$$\begin{aligned}\frac{\mathrm{d}m}{\mathrm{d}r} &= 4\pi r^2 \rho\\ \frac{\mathrm{d}P}{\mathrm{d}r} &= -\rho\frac{Gm}{r^2}\left\{\frac{\left(1+4\pi r^3 P/mc^2\right)\left(1+P/\rho c^2\right)}{\left(1-2Gm/rc^2\right)}\right\}\end{aligned}$$



2.5
2.0
1.5
1.0
0.5
0.0
mass ($M_\odot$)
7
8
9
10
11
12
13
14
15
radius (km)
APR98
MDI $x = 0$

Detection: Isolated neutron stars

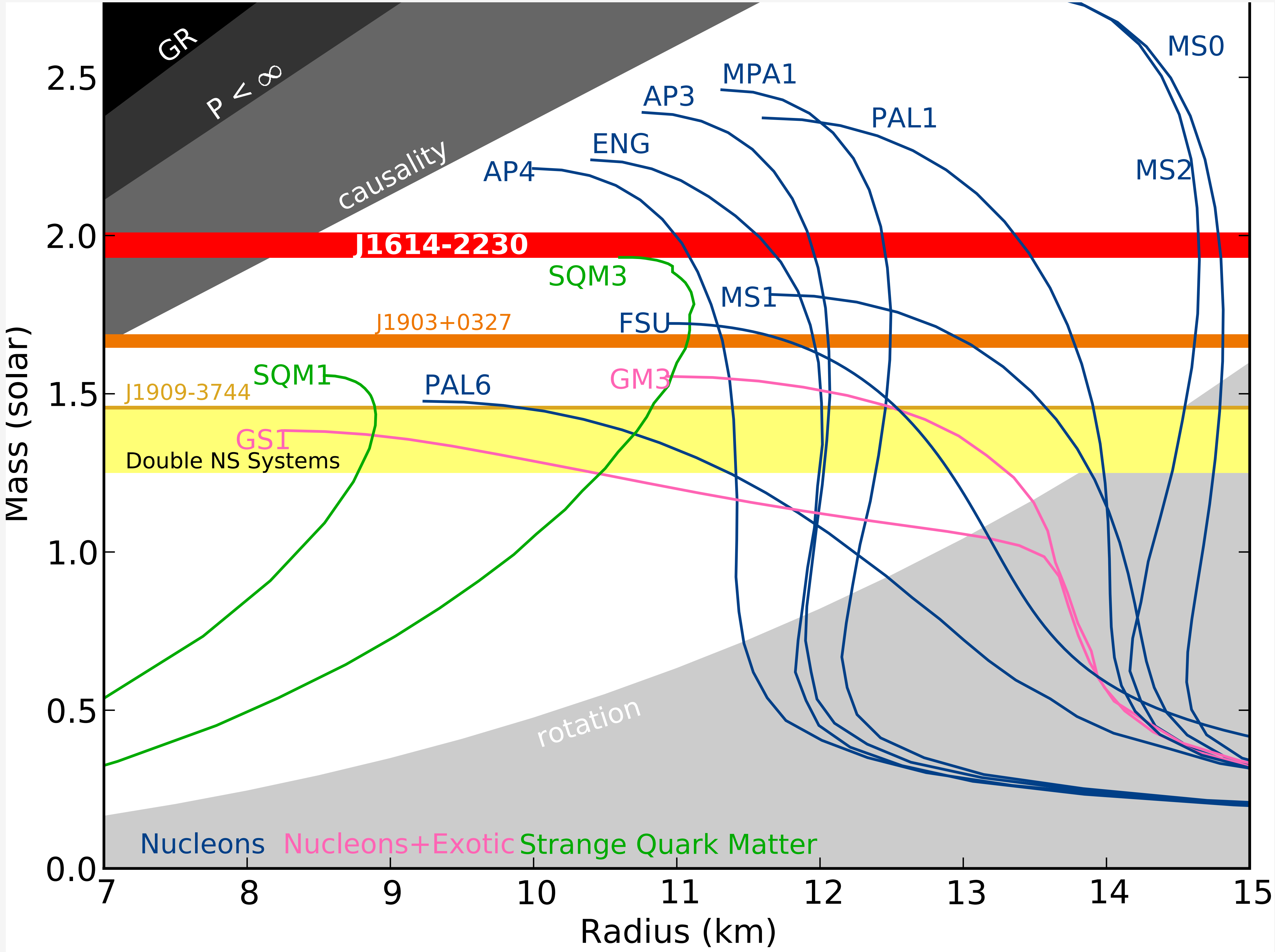
about 1700 pulsars detected; about 50 are in binary systems with some mass information

- very precise mass information;
- but, no radius information

fastest spin is 716 Hz (Hessels et al. 2006; faster than household blender!)

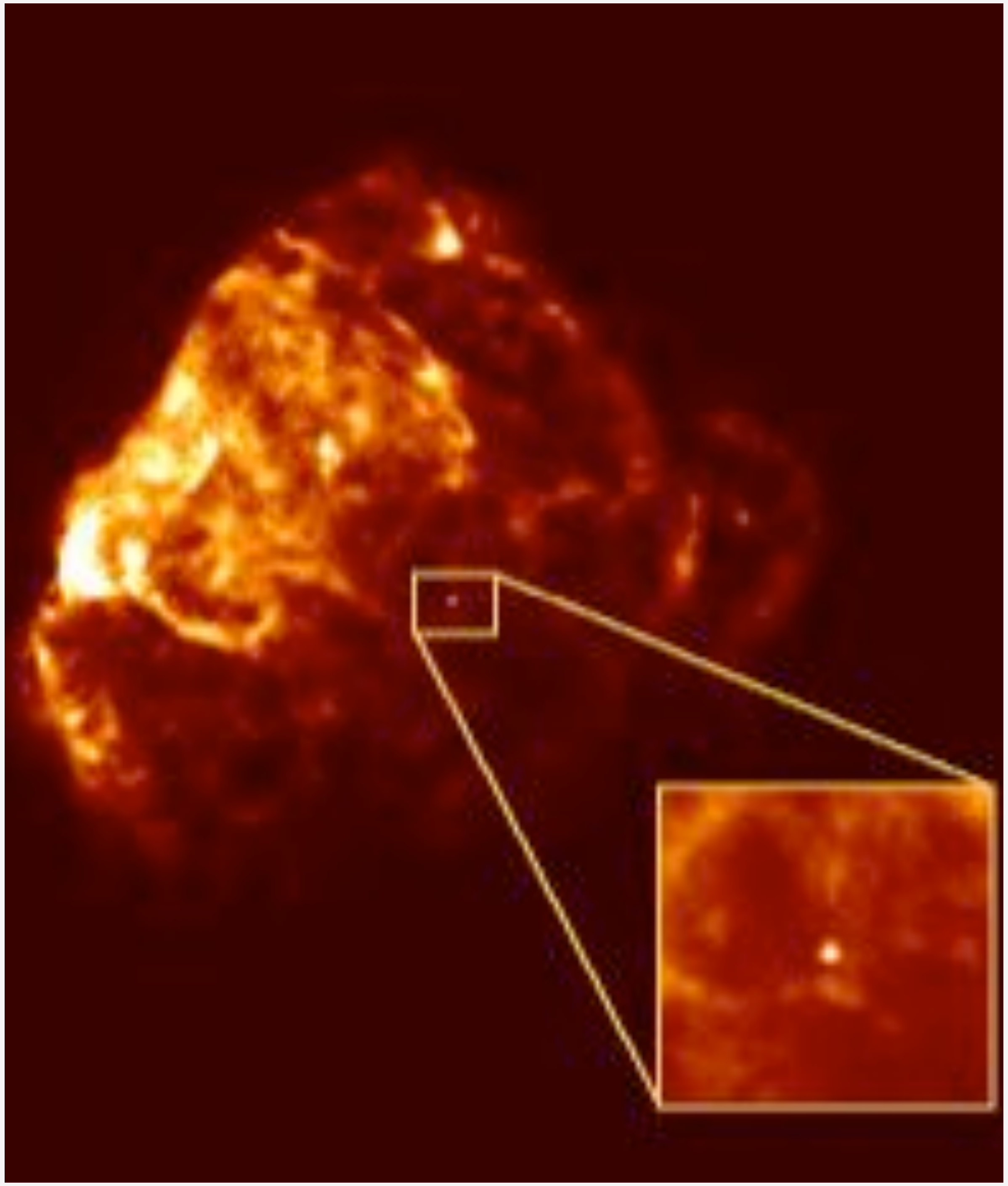
PSR J0737-3039A/B

John Rowe Animation/Australia Telescope National Facility, CSIRO



Neutron stars can reach 2 M_{sun}! Demorest et al. 2010

A neutron star cooling from its fiery birth



ROSAT Image of thermal emission from neutron star in Puppis A supernova remnant

cooling: the Urca process

Gamow & Schoenberg 1941

In npe-matter, maintain β-equilibrium via

$$\begin{aligned} n &\rightarrow p + e^{-} + \bar{\nu}_e \\ p + e^{-} &\rightarrow n + \nu_e \end{aligned}$$

Integration of the rate over phase space gives a T^6 dependence of the cooling rate.

but this is blocked...

Chiu & Salpeter, Bahcall & Wolff

mom. cons.	$p_{\mathrm{F},n} < p_{\mathrm{F},e} + p_{\mathrm{F},p}$
β-equil.	$\mu_e = \mu_n - \mu_p$
charge neut.	$n_e = n_p$

Need a “bystander” particle, e.g., $n + n \to n + p + e^- + \bar{\nu}_e$.

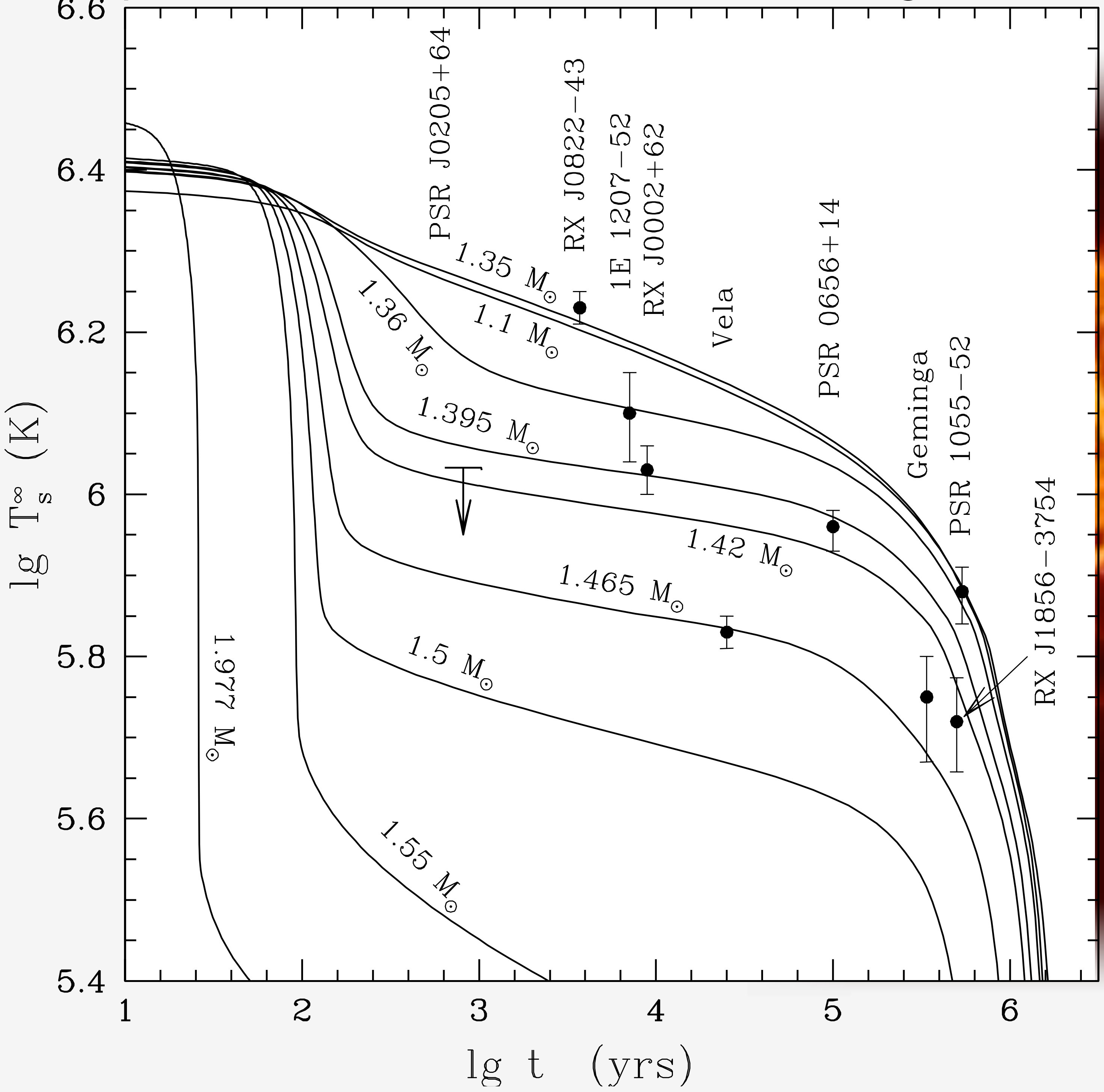
This rate is > 10^6 times slower at typical $T < 10^8$ K.

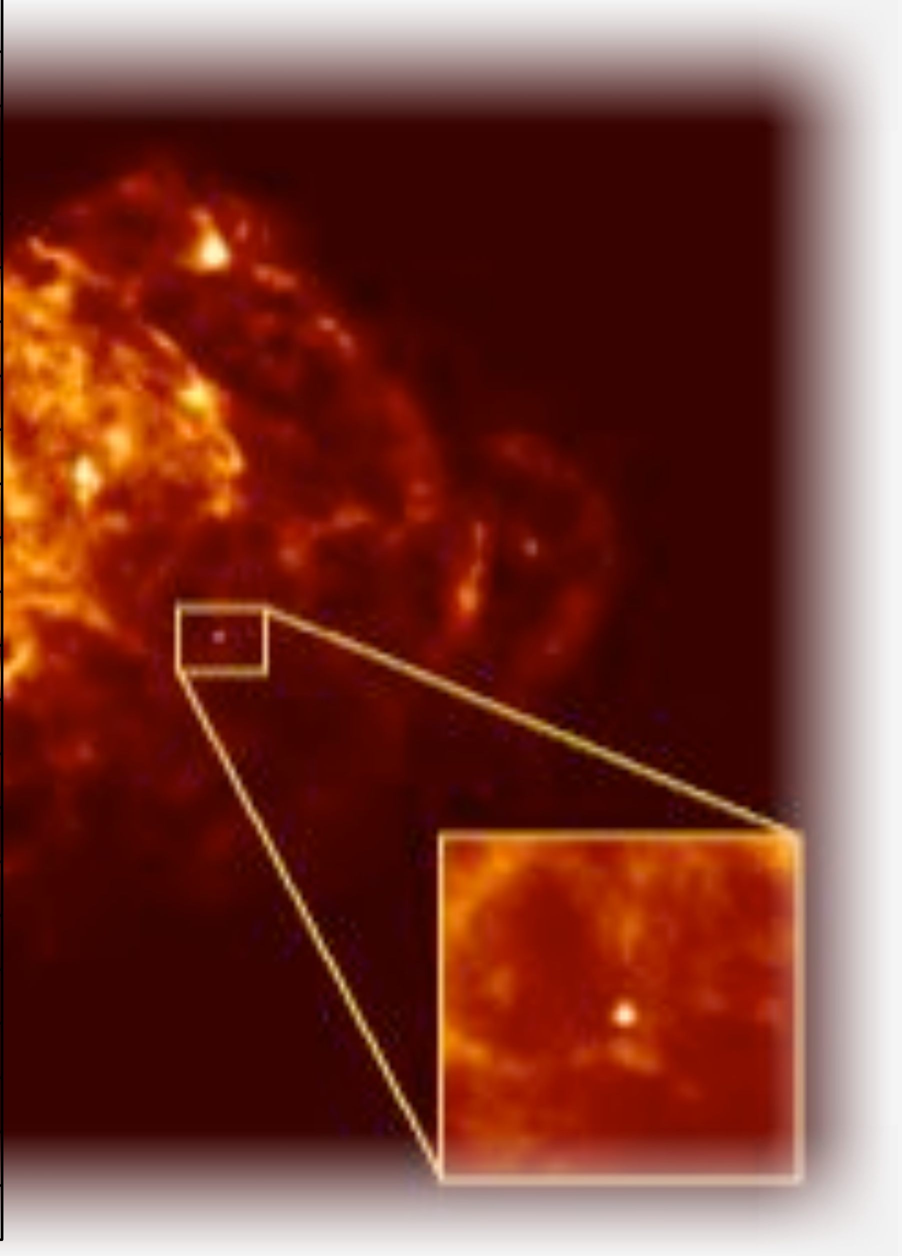
If $n_\mathrm{p}/n > 0.11$, direct process can go. Also if other channels, e.g. hyperons, are available.

A high symmetry energy implies that neutron stars should cool rapidly!
—Lattimer & Prakash 2007

Neutron stars cooling from their fiery birth: “fast” and “slow” neutrino emissivities

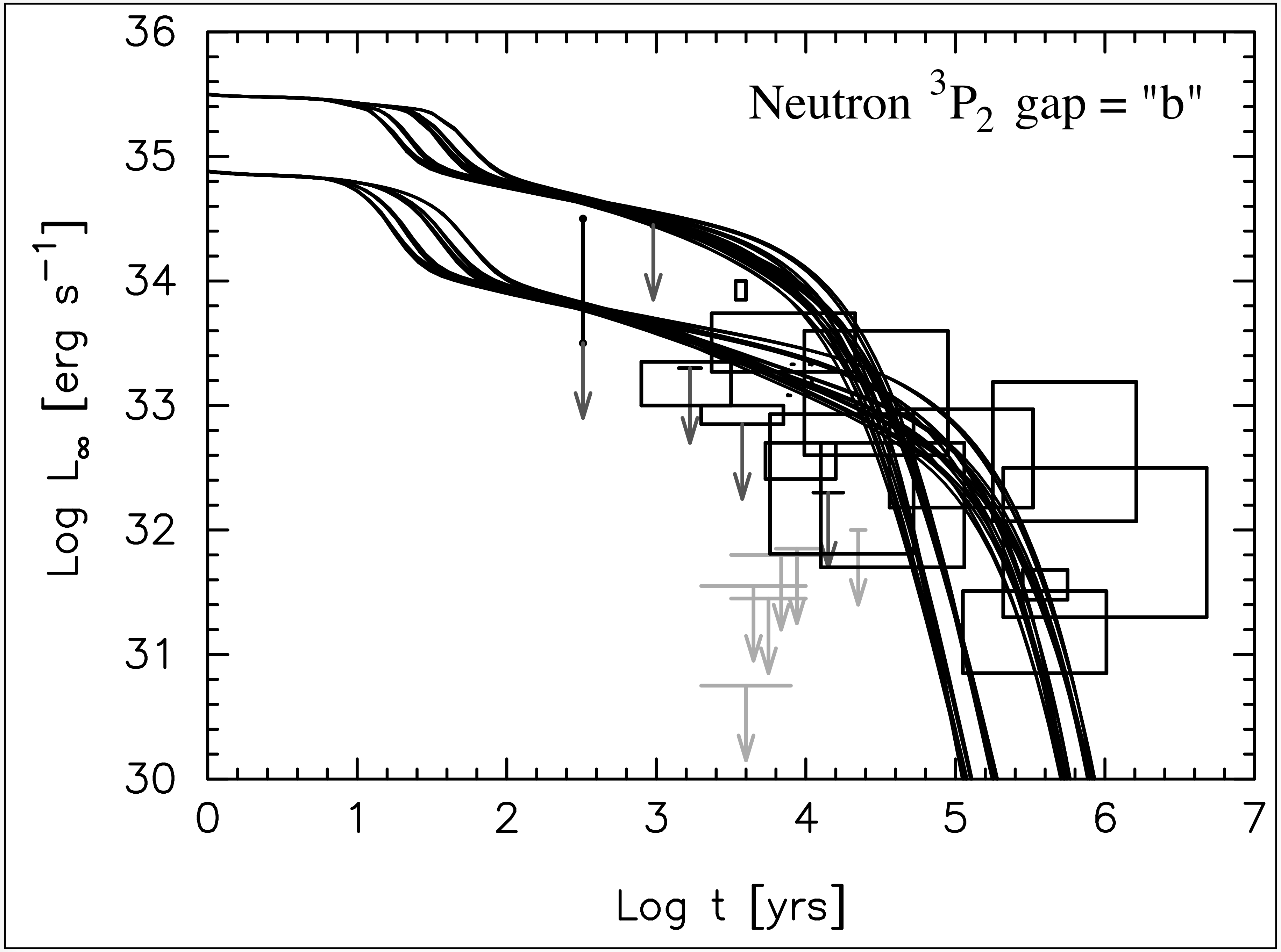
plot from Yakovlev et al. ‘02; see also Page et al. ’04, ’09



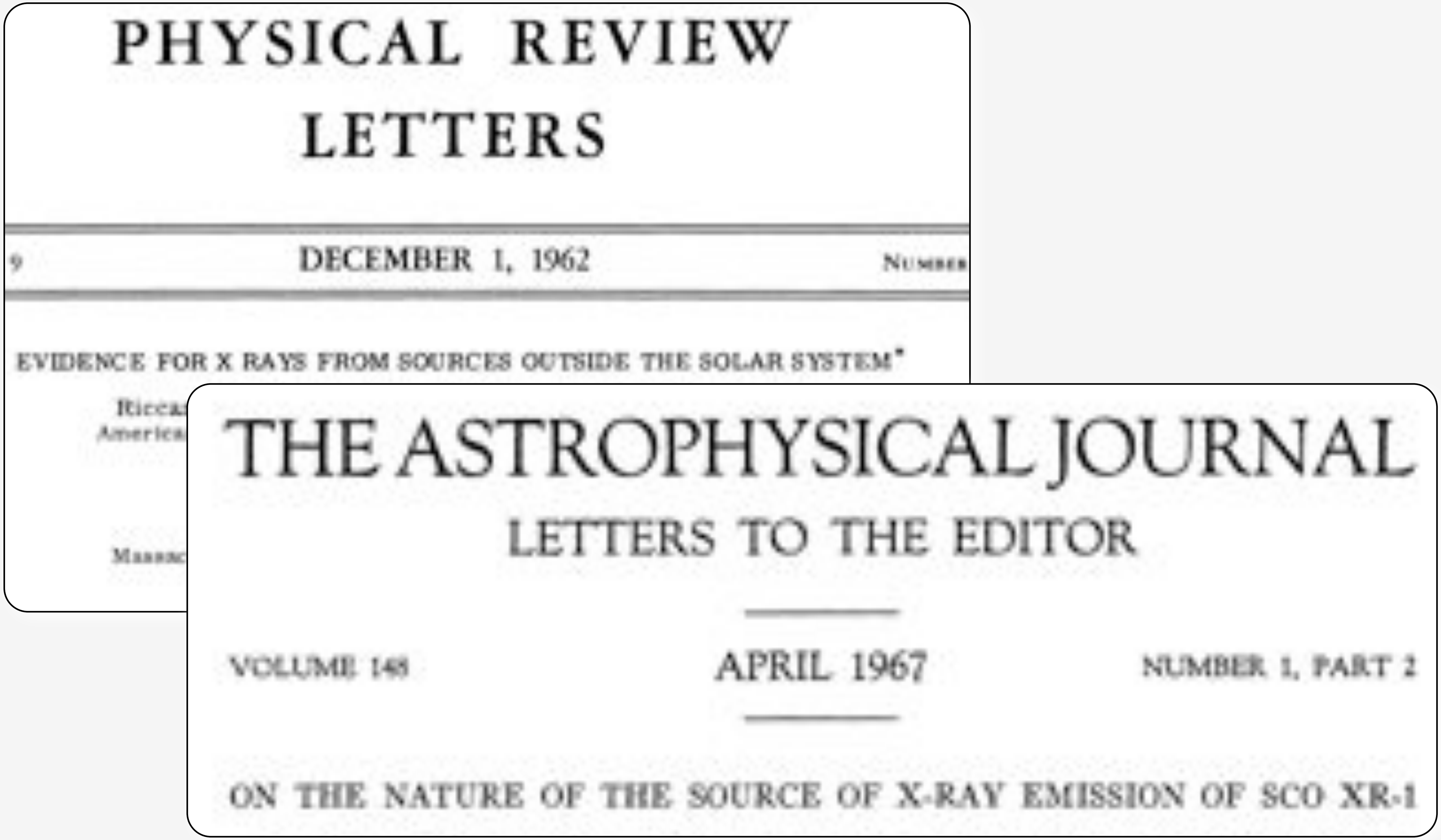


Models with no enhanced cooling

Page, Lattimer, Prakash, & Steiner 2009



Accreting neutron stars



PHYSICAL REVIEW
LETTERS

9 DECEMBER 1, 1962 NUMBER

EVIDENCE FOR X RAYS FROM SOURCES OUTSIDE THE SOLAR SYSTEM*

Ricca
America

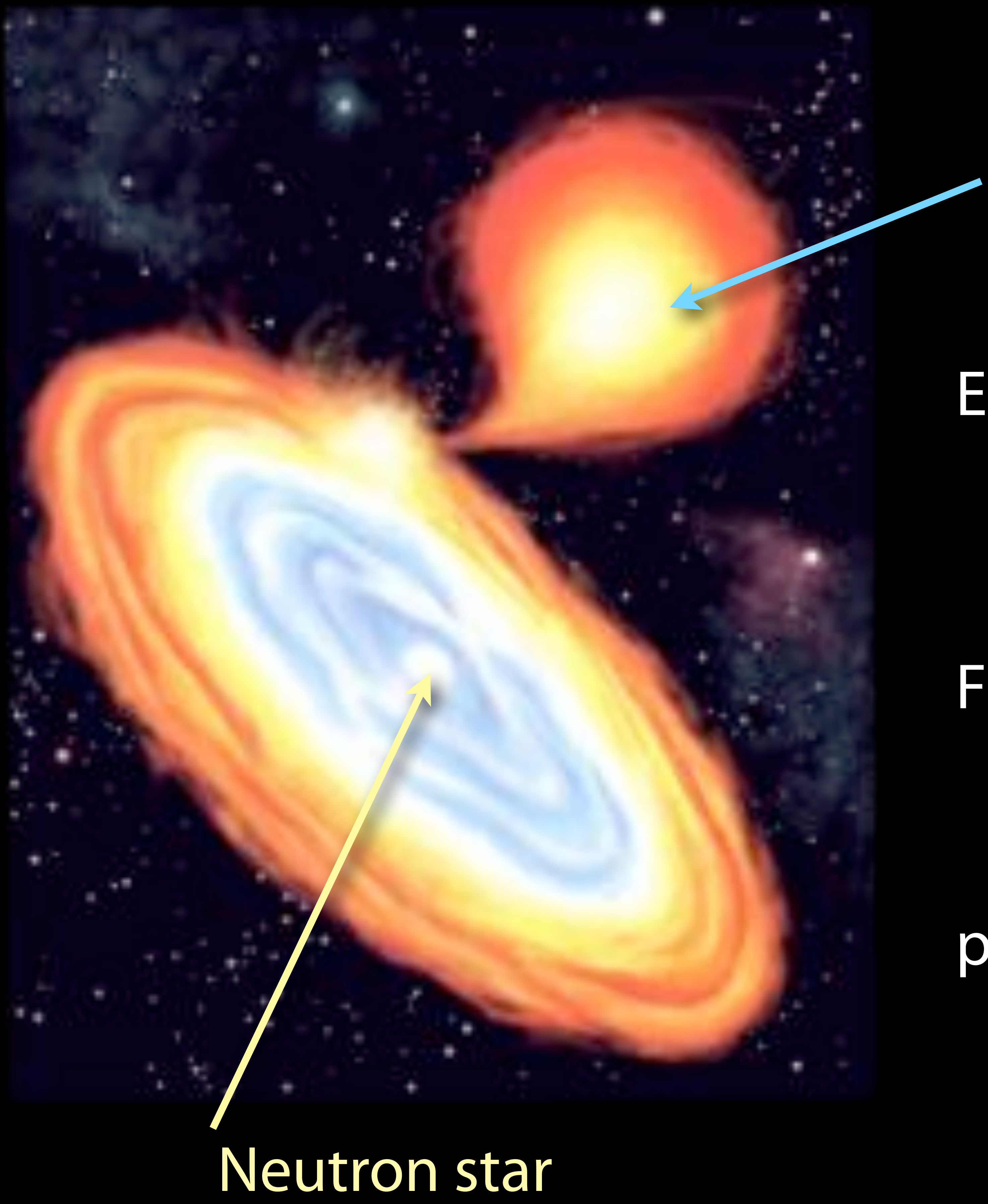
Massac

THE ASTROPHYSICAL JOURNAL
LETTERS TO THE EDITOR

VOLUME 148 APRIL 1967 NUMBER 1, PART 2

ON THE NATURE OF THE SOURCE OF X-RAY EMISSION OF SCO XR-1

Artwork courtesy T. Piro



$\approx$ solar mass star
$P_{\rm orb}$ = minutes–hours

Each accreted H releases

$$\approx \frac{GMm_H}{R} \approx 200\ \mathrm{MeV}.$$

Fusing H to He releases

$$\approx 7\ \mathrm{MeV}$$

per nucleon.


The X-ray Sky
12 / 18 / 96
SMC X-1
NS binary
3.9 d, 60 d