The Nuclear Symmetry Energy in Astrophysics

Edward Brown
Michigan State University
National Superconducting Cyclotron Laboratory
Joint Institute for Nuclear Astrophysics

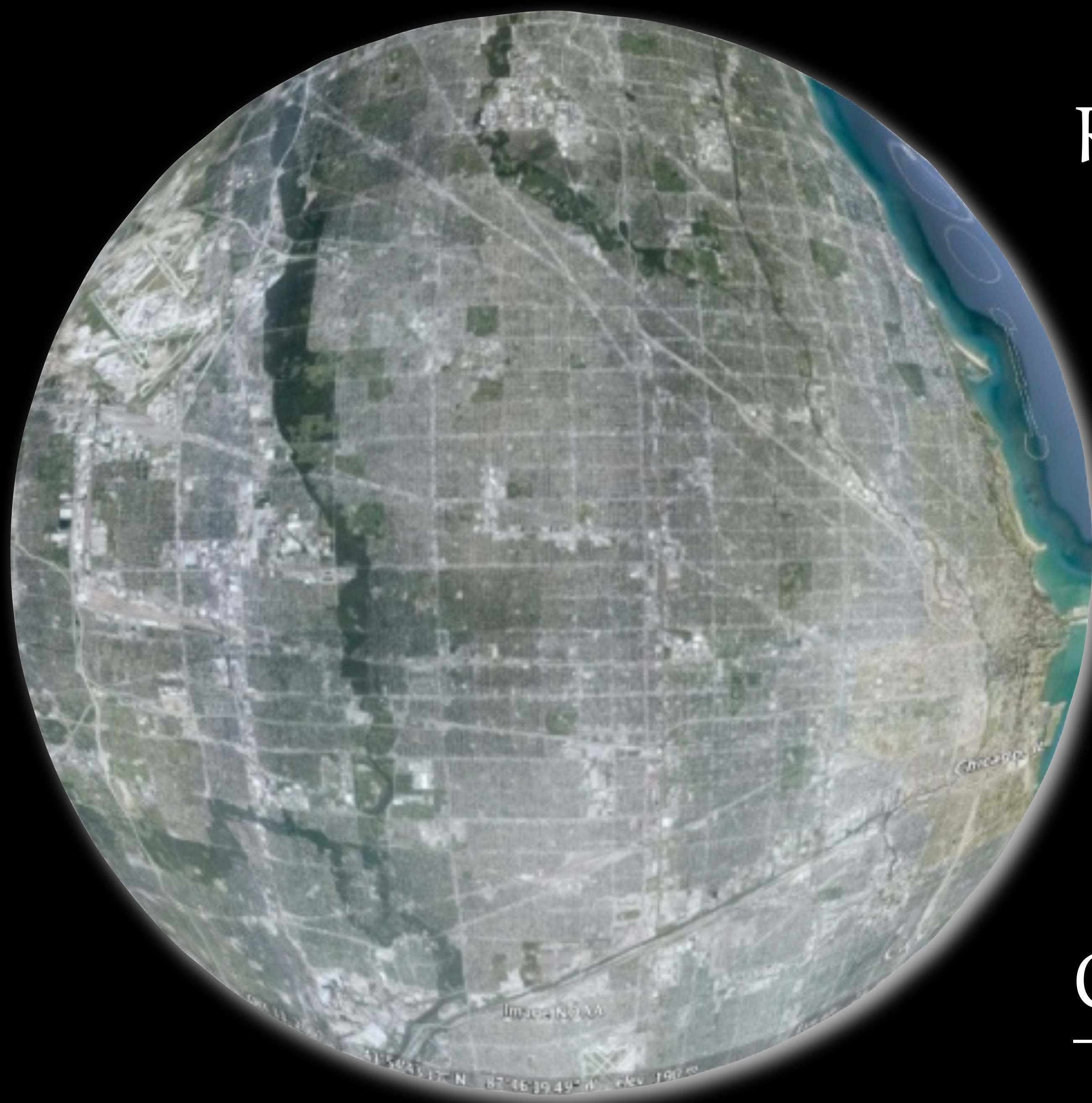
5. *The super-nova process*

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.

neutron star basics



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

$$\mathrm{redshift} \equiv \frac{\Delta\lambda}{\lambda} \approx 0.3$$

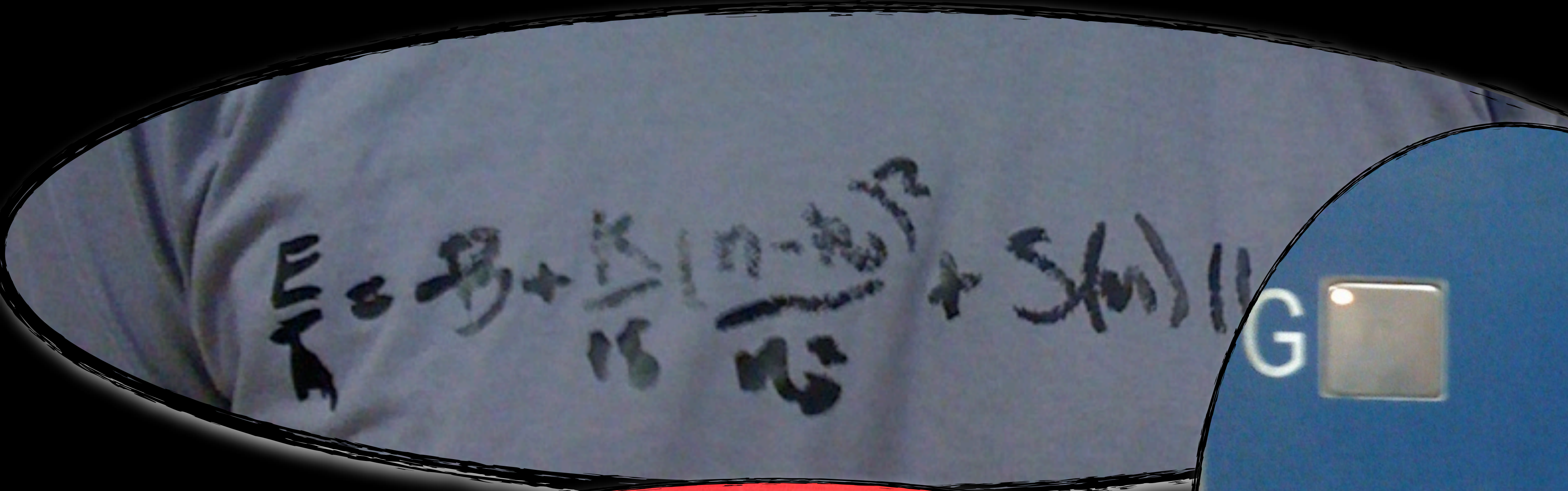
$$\frac{GMm_{\mathrm{H}}}{R} \approx 200\ \mathrm{MeV}$$

NEUTRON STAR MODELS

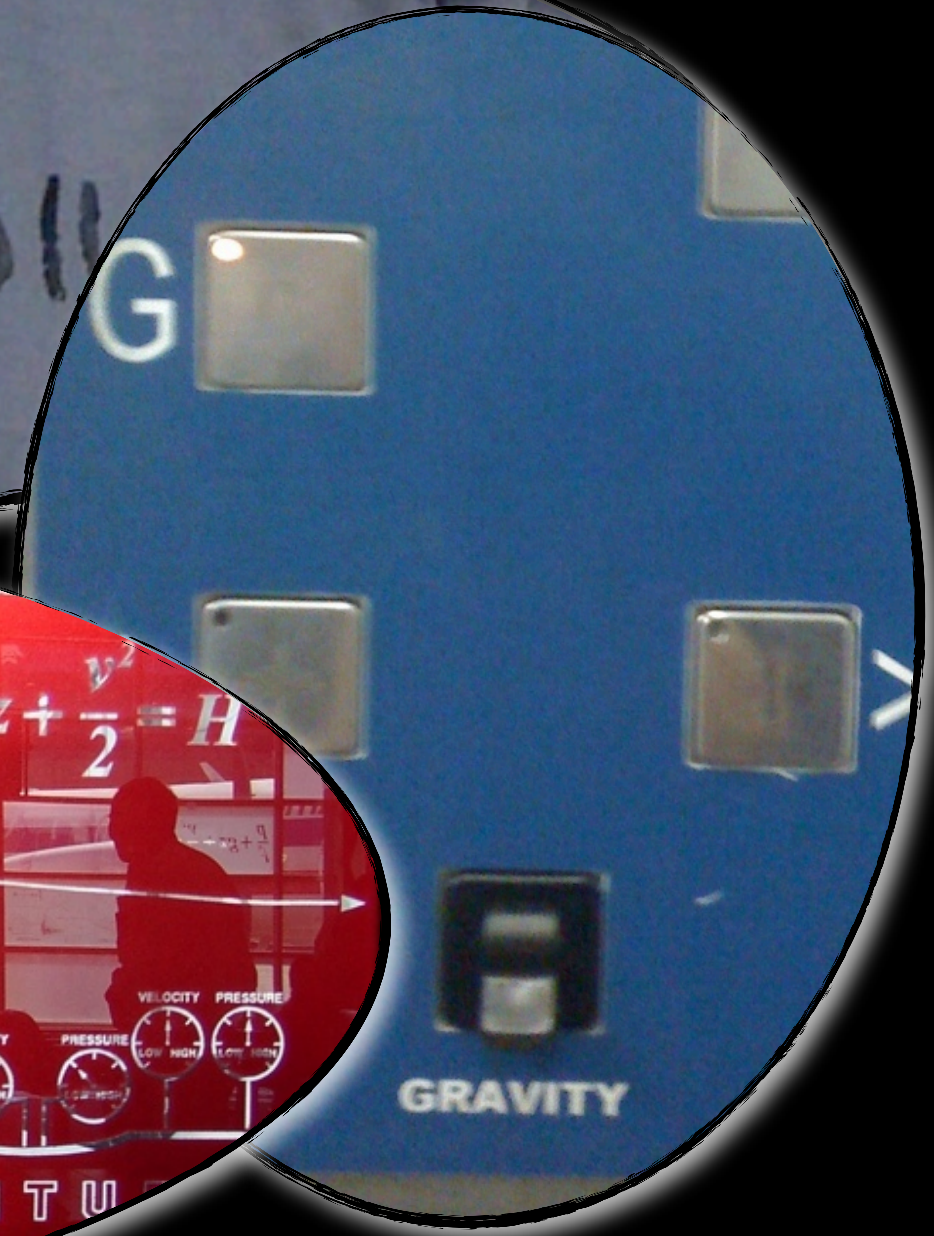
A. G. W. CAMERON
Atomic Energy of Canada Limited, Chalk River, Ontario, Canada
Received June 17, 1959

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.



$\frac{p}{\rho}+gz+\frac{v^2}{2}=H$
Shock Wave
GLIDER RIDING A THERMAL
VELOCITY
PRESSURE
LOW HIGH



G
GRAVITY

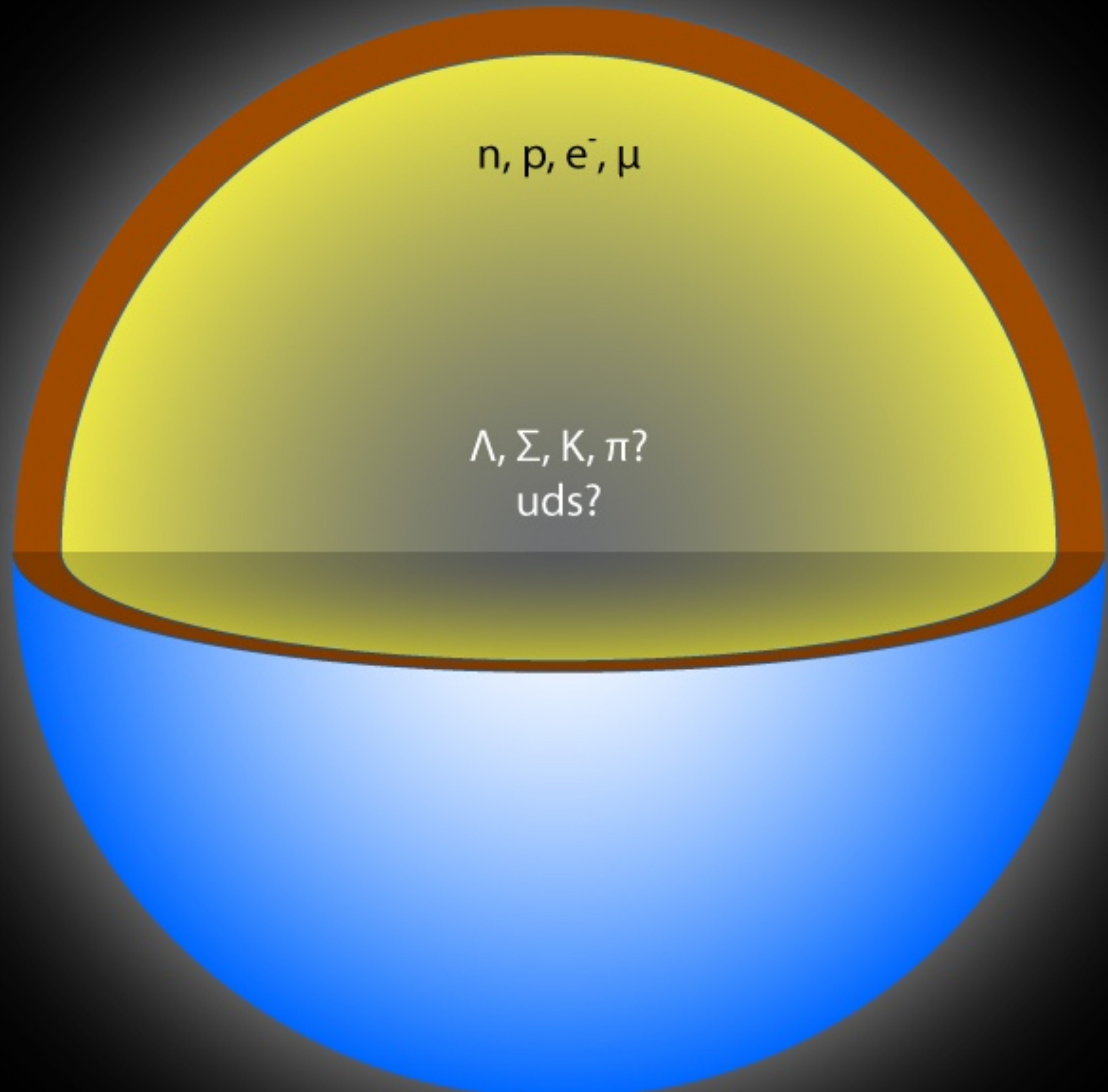
Introduction

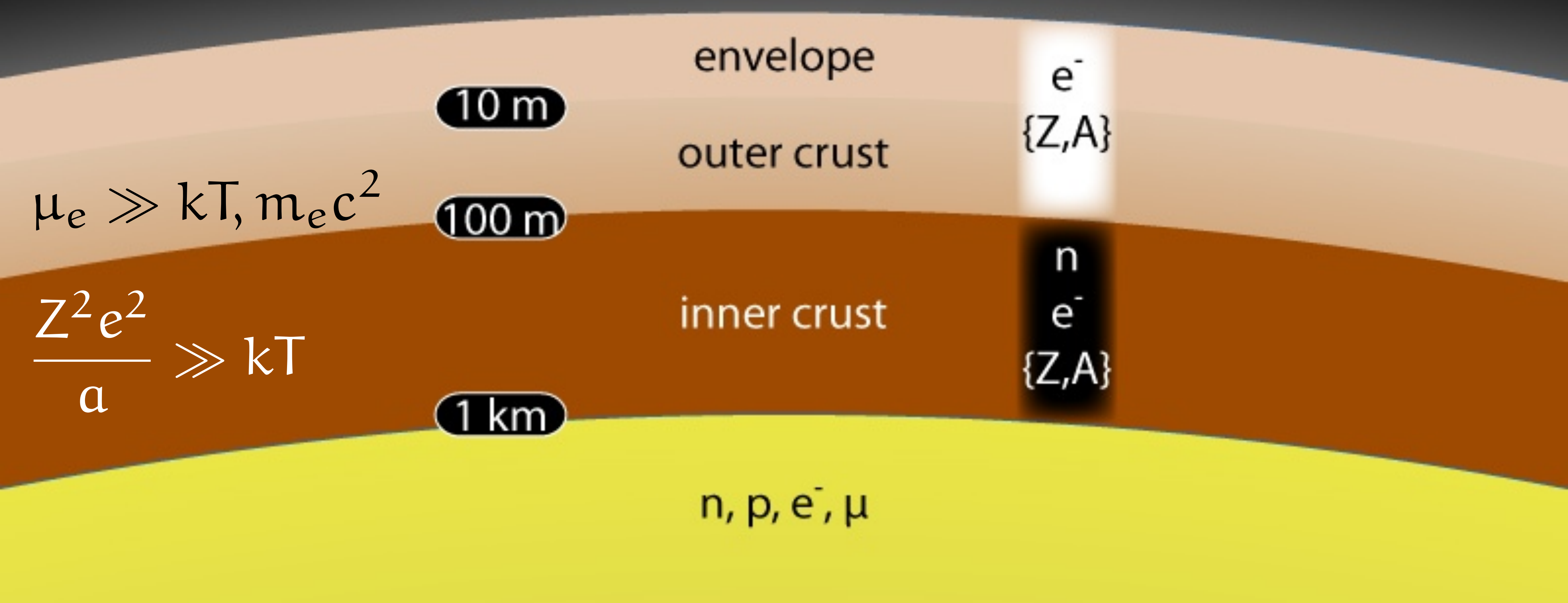
From the microscopic to the macroscopic

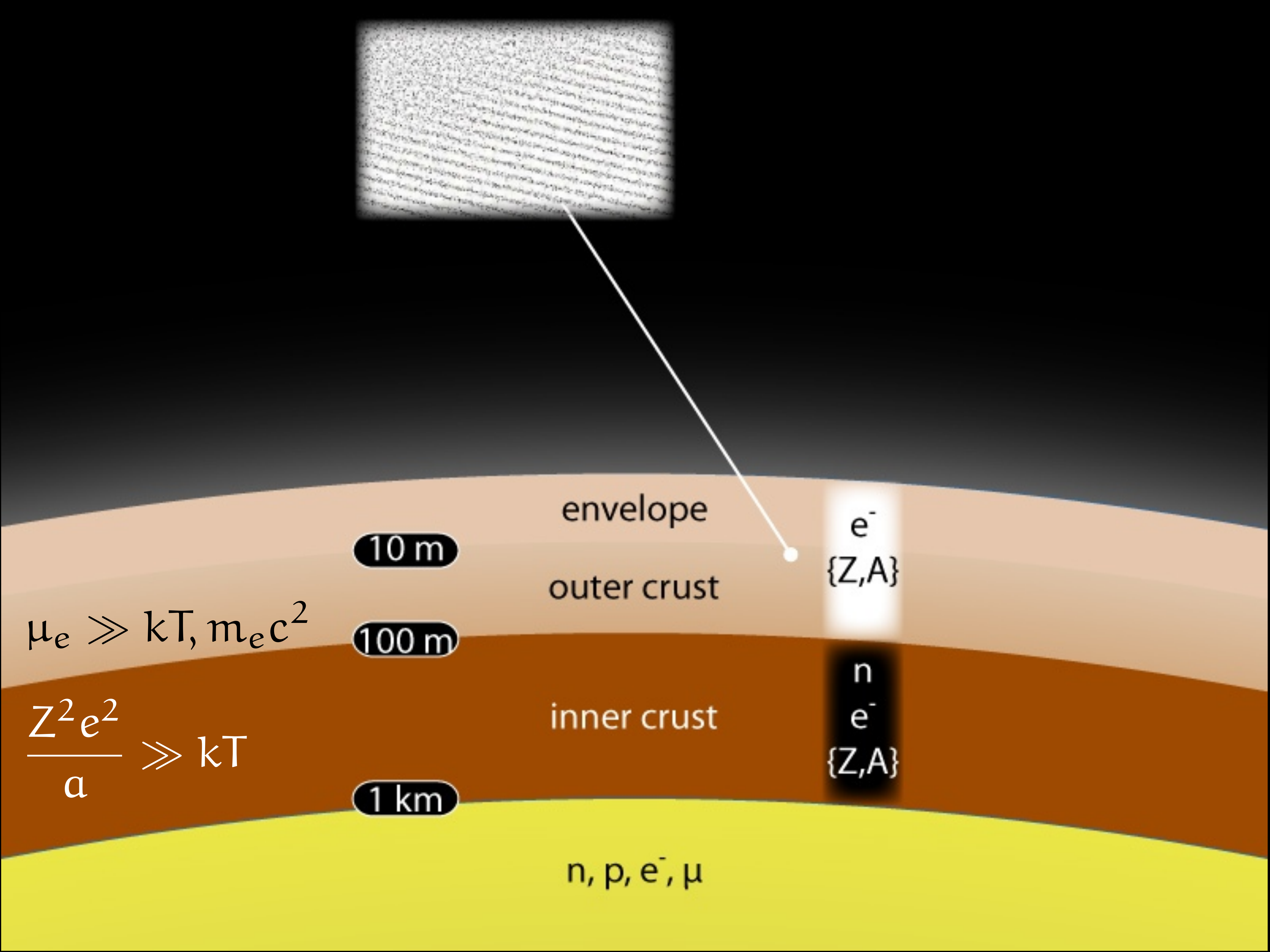
Constraints from astronomy

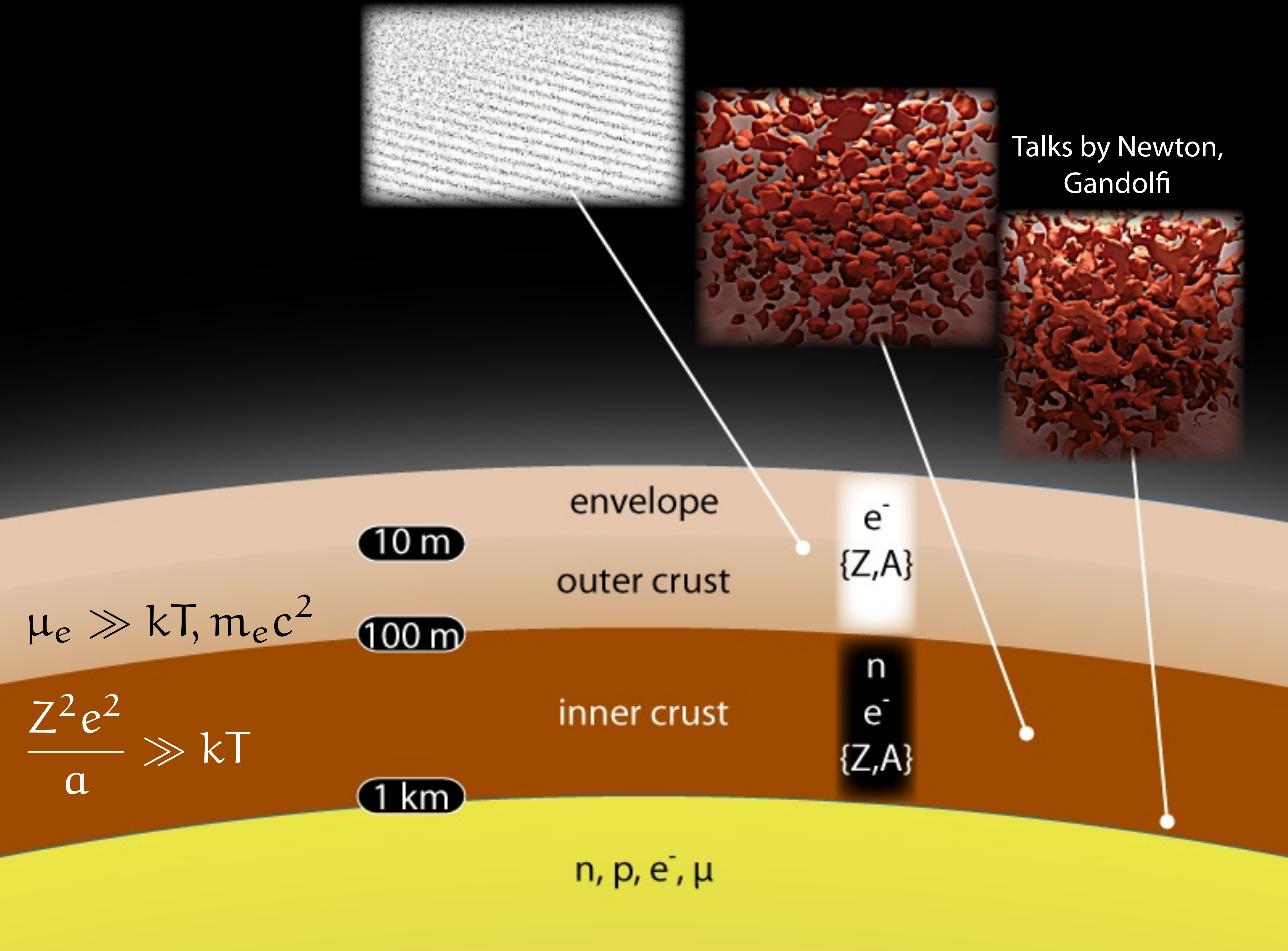
- Pulsar timing
- X-ray burst spectroscopy
- Neutron star cooling

Conclusion


n, p, e$^-$, μ
Λ, Σ, K, π?
uds?

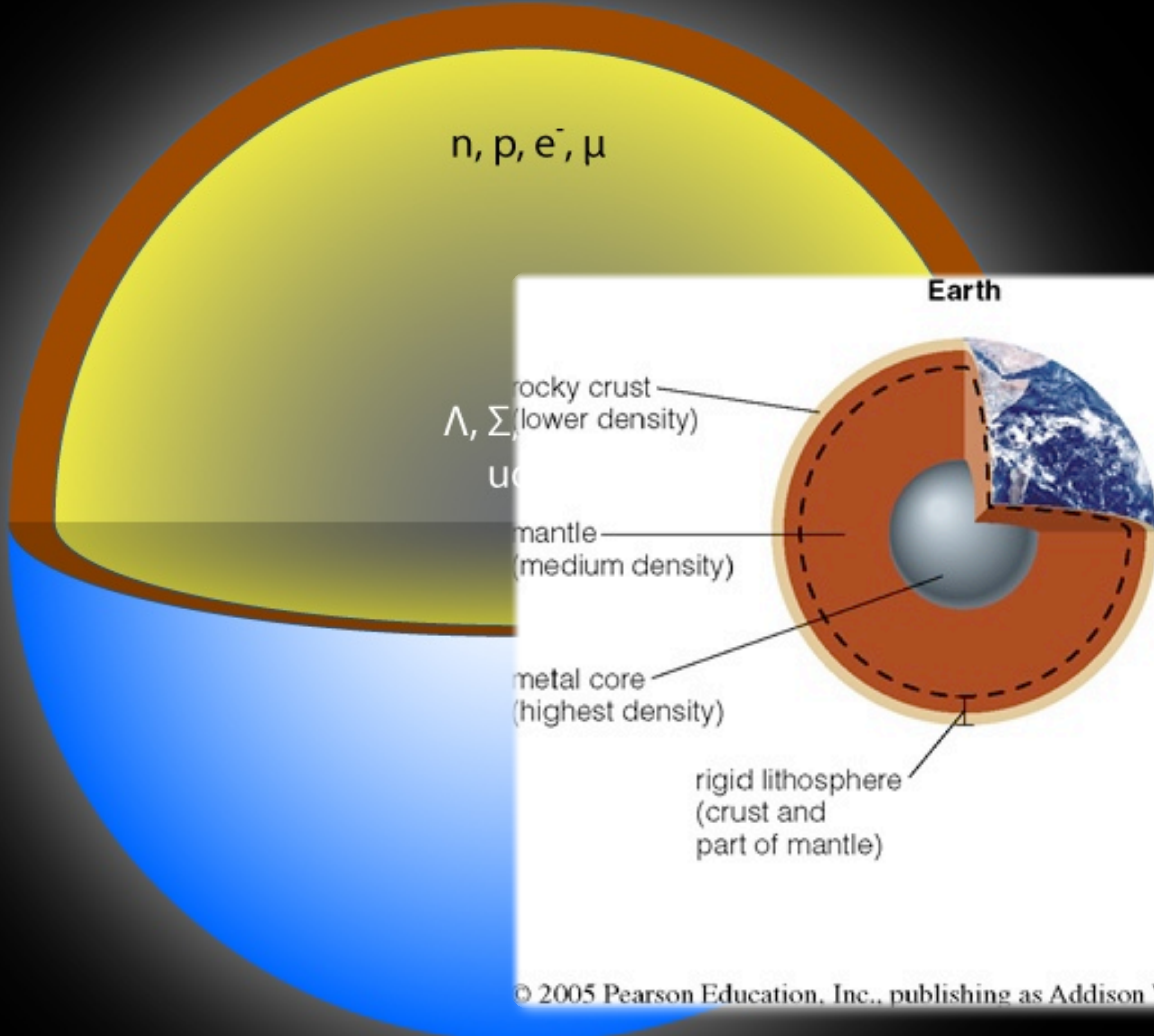

envelope
10 m
outer crust
100 m
inner crust
1 km
e-
{Z,A}
n
e-
{Z,A}
n, p, e-, μ
$\mu_e \gg kT, m_e c^2$
$\frac{Z^2 e^2}{a} \gg kT$


envelope
e$^-$
{Z,A}
10 m
outer crust
100 m
inner crust
n
e$^-$
{Z,A}
1 km
n, p, e$^-$, μ
$\mu_e \gg kT, m_e c^2$
$\frac{Z^2 e^2}{a} \gg kT$



$$\mu_e \gg kT, m_e c^2$$

$$\frac{Z^2 e^2}{a} \gg kT$$


n, p, e⁻, μ
Λ, Σ
Earth
rocky crust
(lower density)
mantle
(medium density)
metal core
(highest density)
rigid lithosphere
(crust and
part of mantle)
© 2005 Pearson Education, Inc., publishing as Addison

Thermodynamics near saturation density

see review by Lattimer & Prakash

Given npe with $x = n_p/(n_n + n_p)$, with energy per nucleon

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

- in β-equilibrium,

$$\mu_e = \mu_n - \mu_p = -\frac{\partial \varepsilon}{\partial x} = 4\varepsilon_A(1-2x);$$

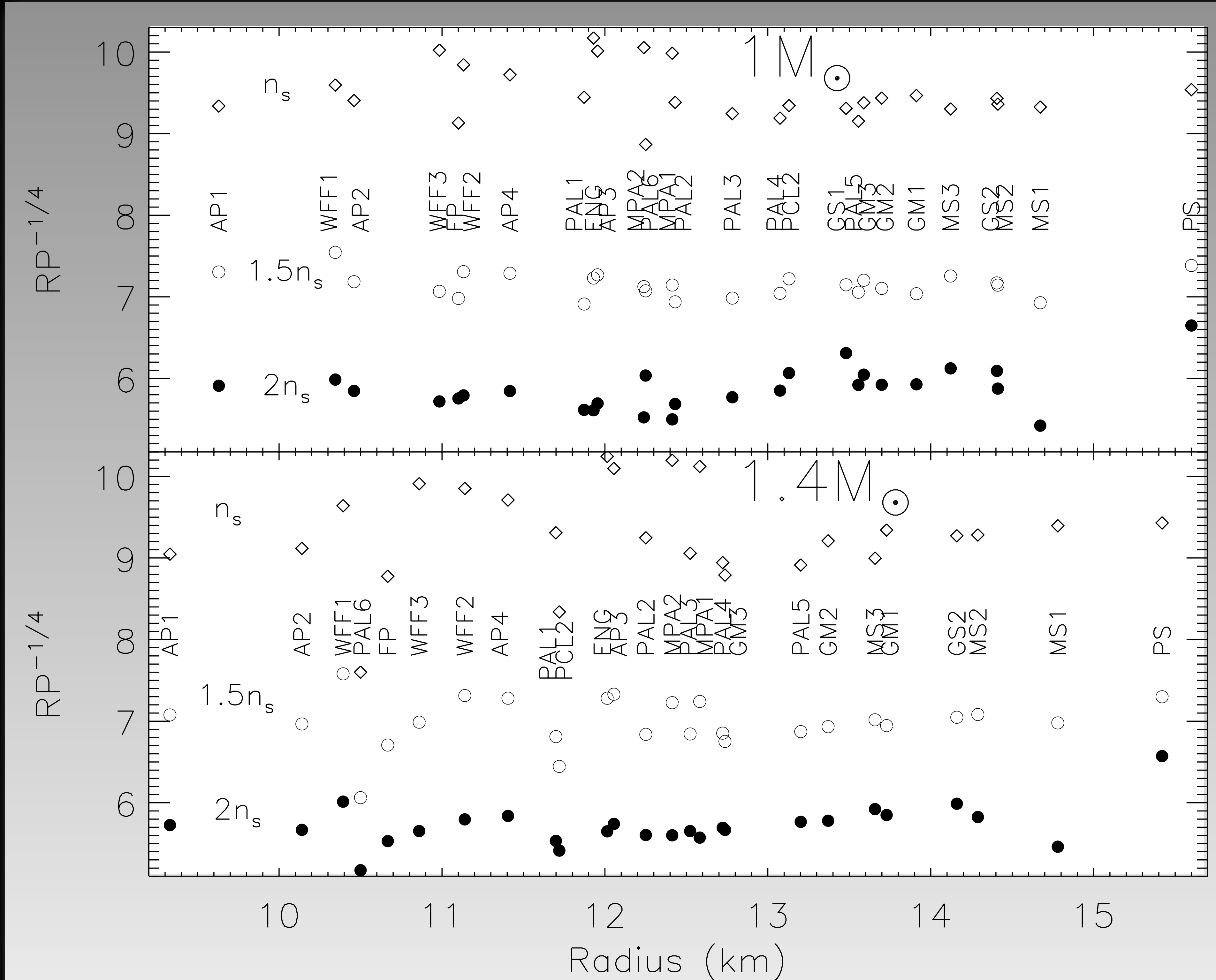
- the total pressure is

$$P = n^2 \frac{\partial \varepsilon}{\partial n} + \frac{n_e \mu_e}{4} = n(1-2x)\left[n\frac{\partial \varepsilon_A}{\partial n}(1-2x) + x\varepsilon_A\right];$$

- and upon solving $(3\pi^2 n_e)^{1/3}\hbar c = \mu_e$, the proton fraction is

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

for $\varepsilon_A = 30$ MeV.



radius correlated with pressure near saturation density

Lattimer & Prakash 2001

Introduction

From the microscopic to the macroscopic

Constraints from astronomy

- Pulsar timing
- X-ray burst spectroscopy
- Neutron star cooling

Conclusion

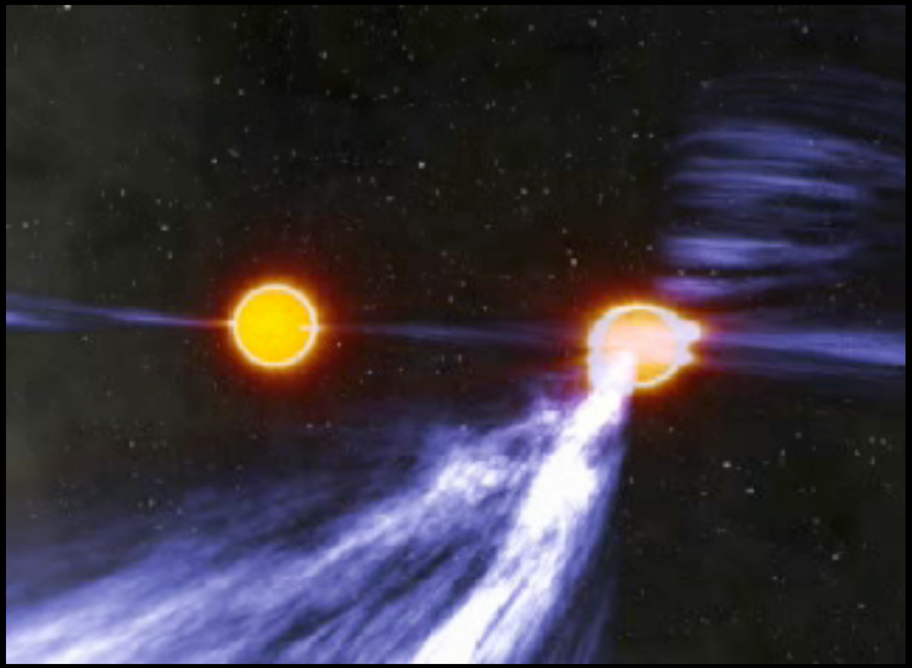
Detection: Isolated neutron stars

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

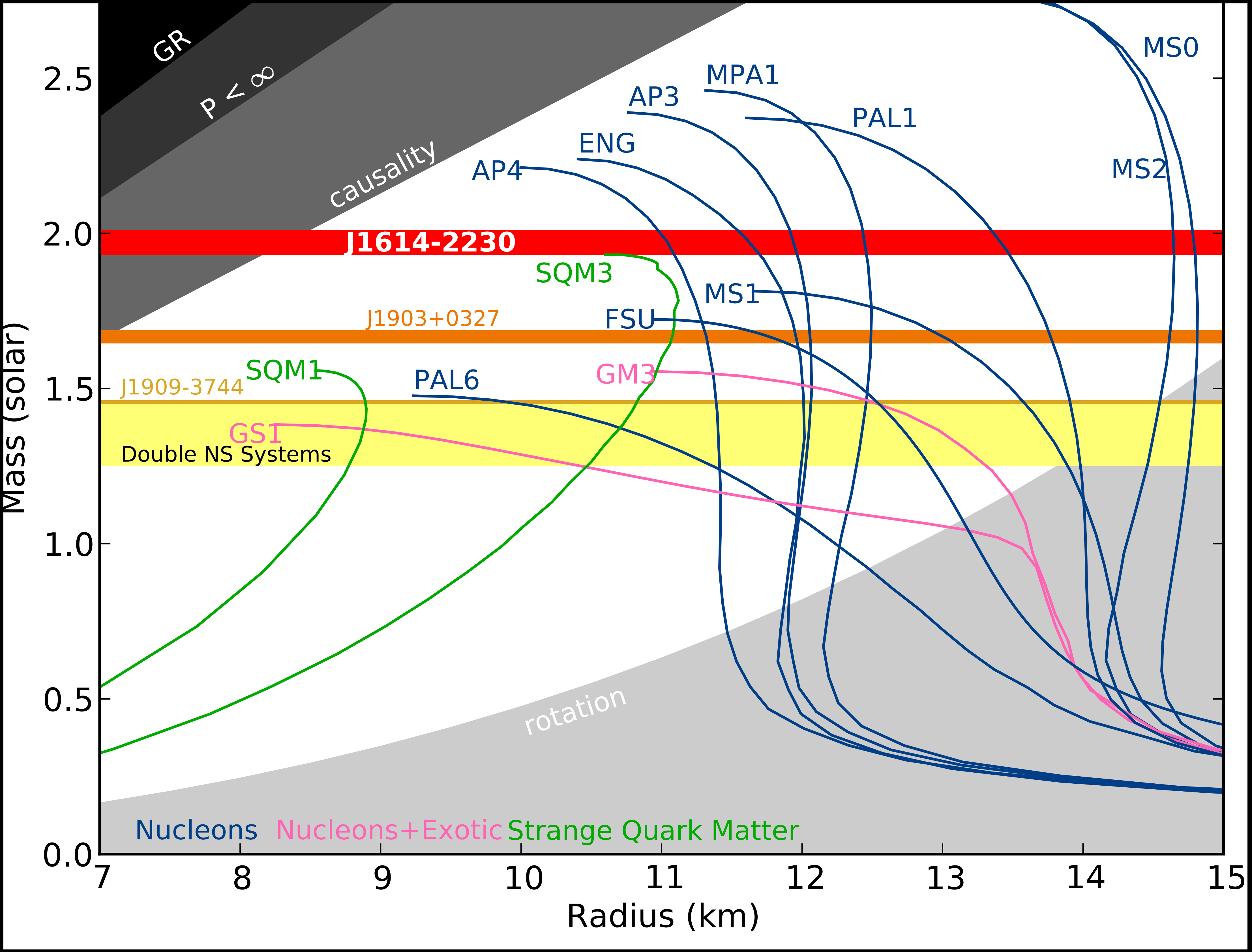
very precise mass information;

but, no radius information

PSR J0737-3039A/B

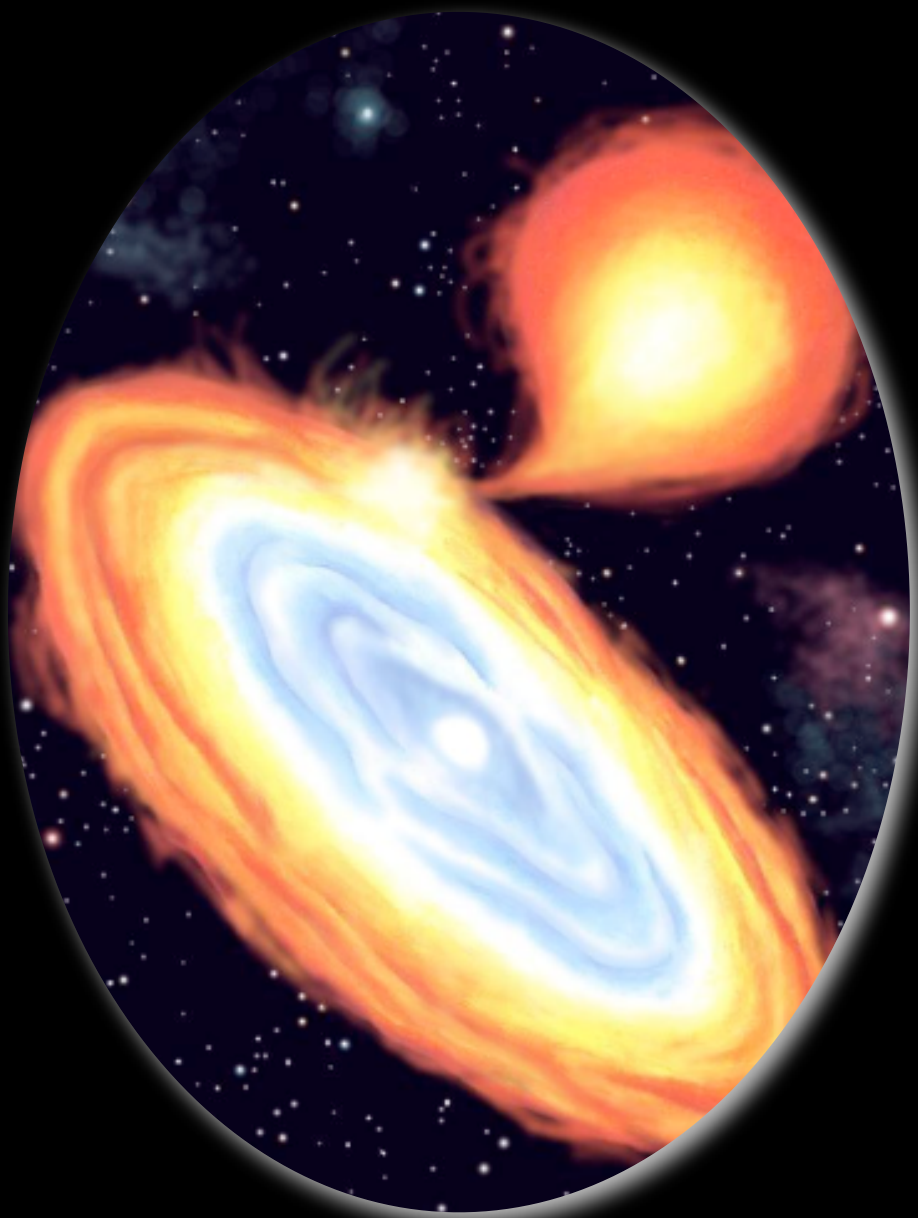


John Rowe Animation/Australia Telescope National Facility, CSIRO



Pulsar Masses, Demorest et al. 2010

Detection: Accreting neutron stars



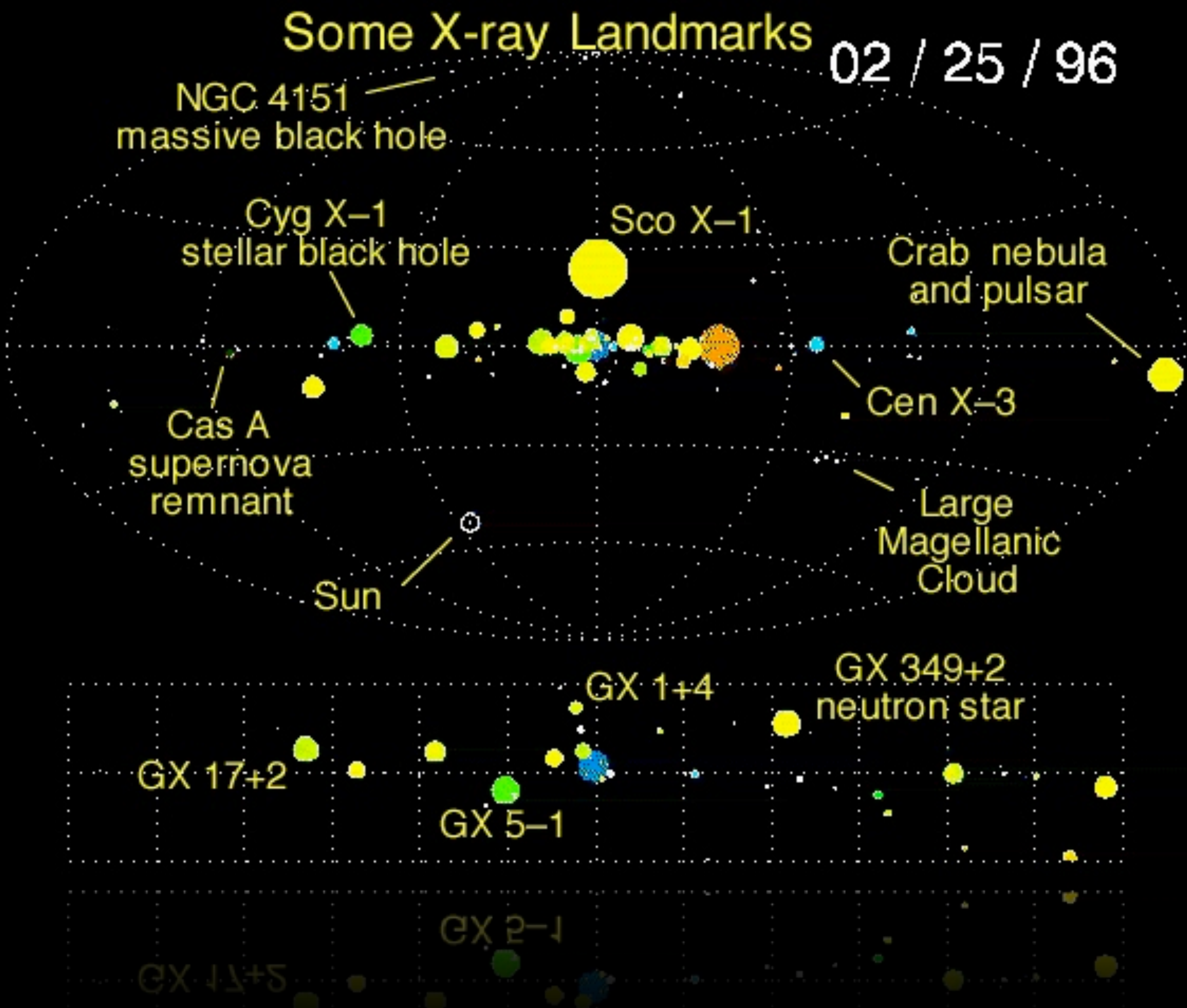
About 100 low-mass X-ray binaries known

rich phenomenology:

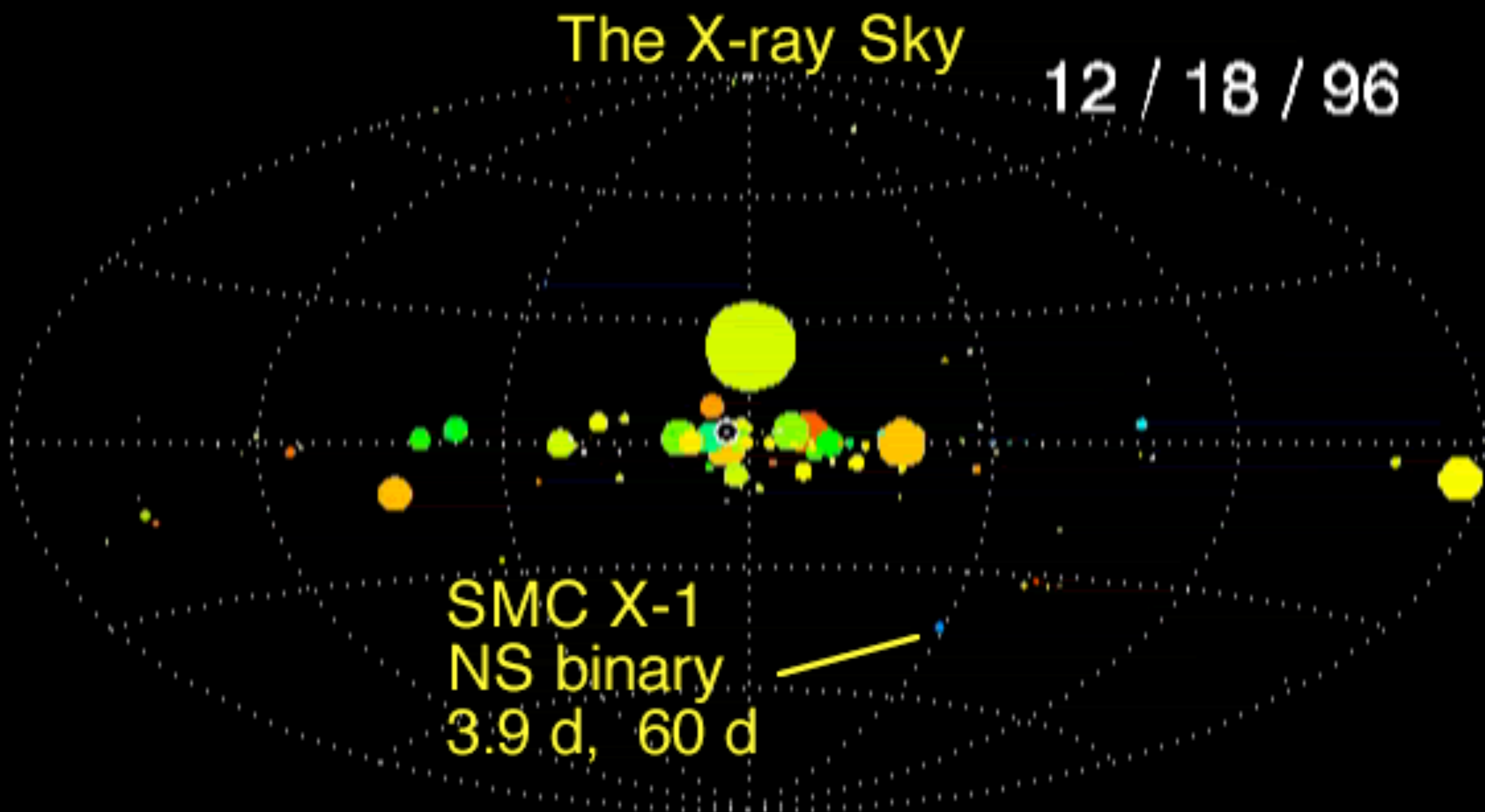
bursts, superbursts, oscillations

crust not in thermal equilibrium with core; but

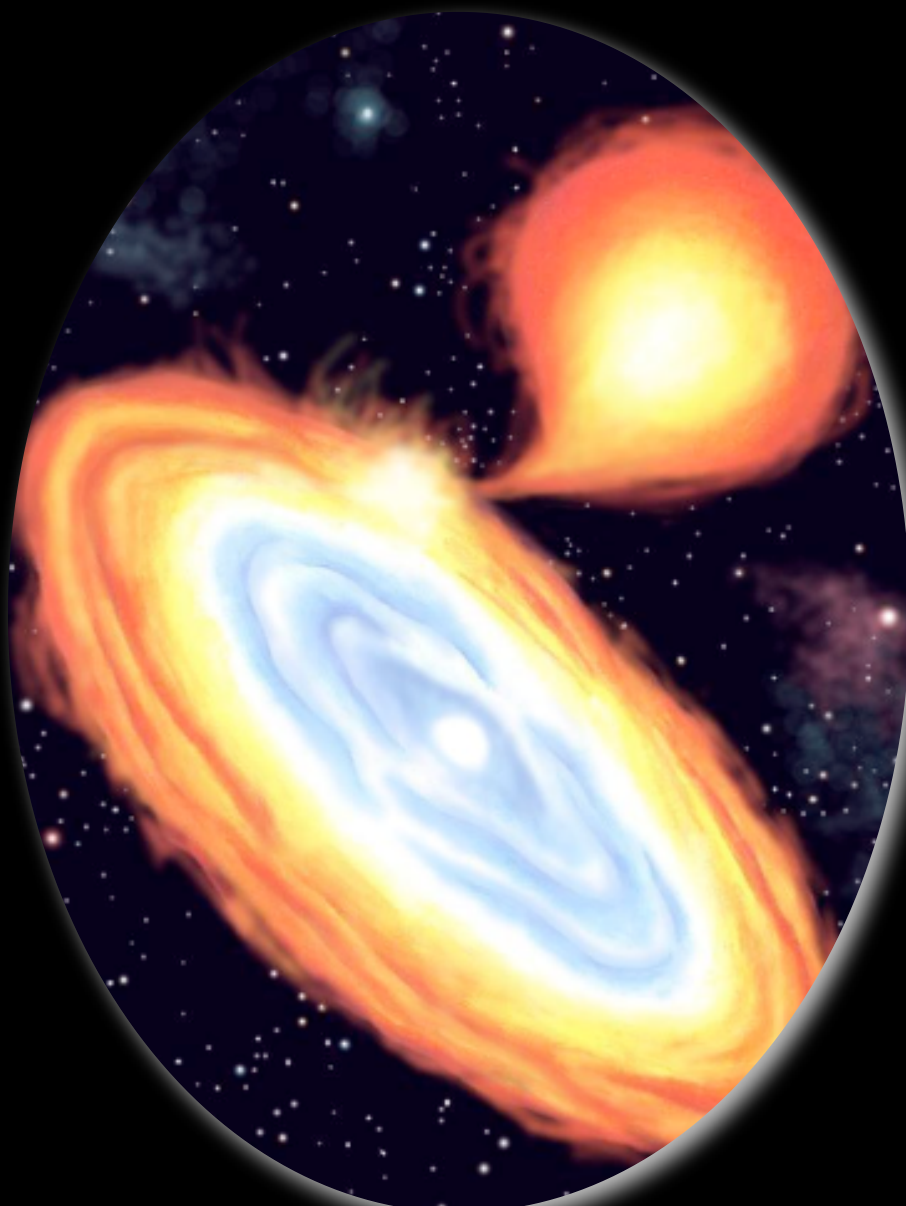
measurements not as precise



The X-ray sky, courtesy RXTE/ASM monitor team


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

Detection: Accreting neutron stars



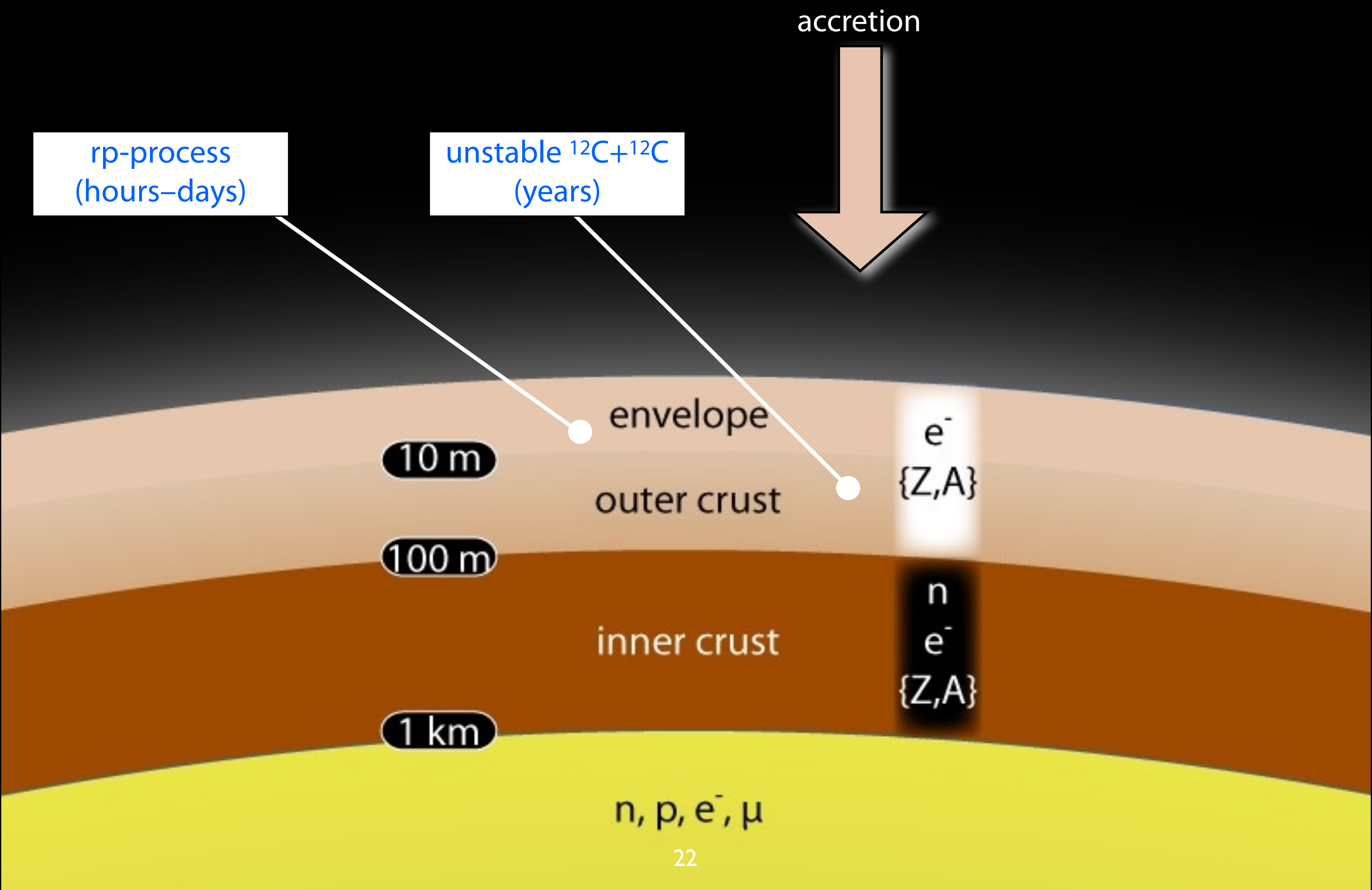
About 100 low-mass X-ray binaries known

rich phenomenology:

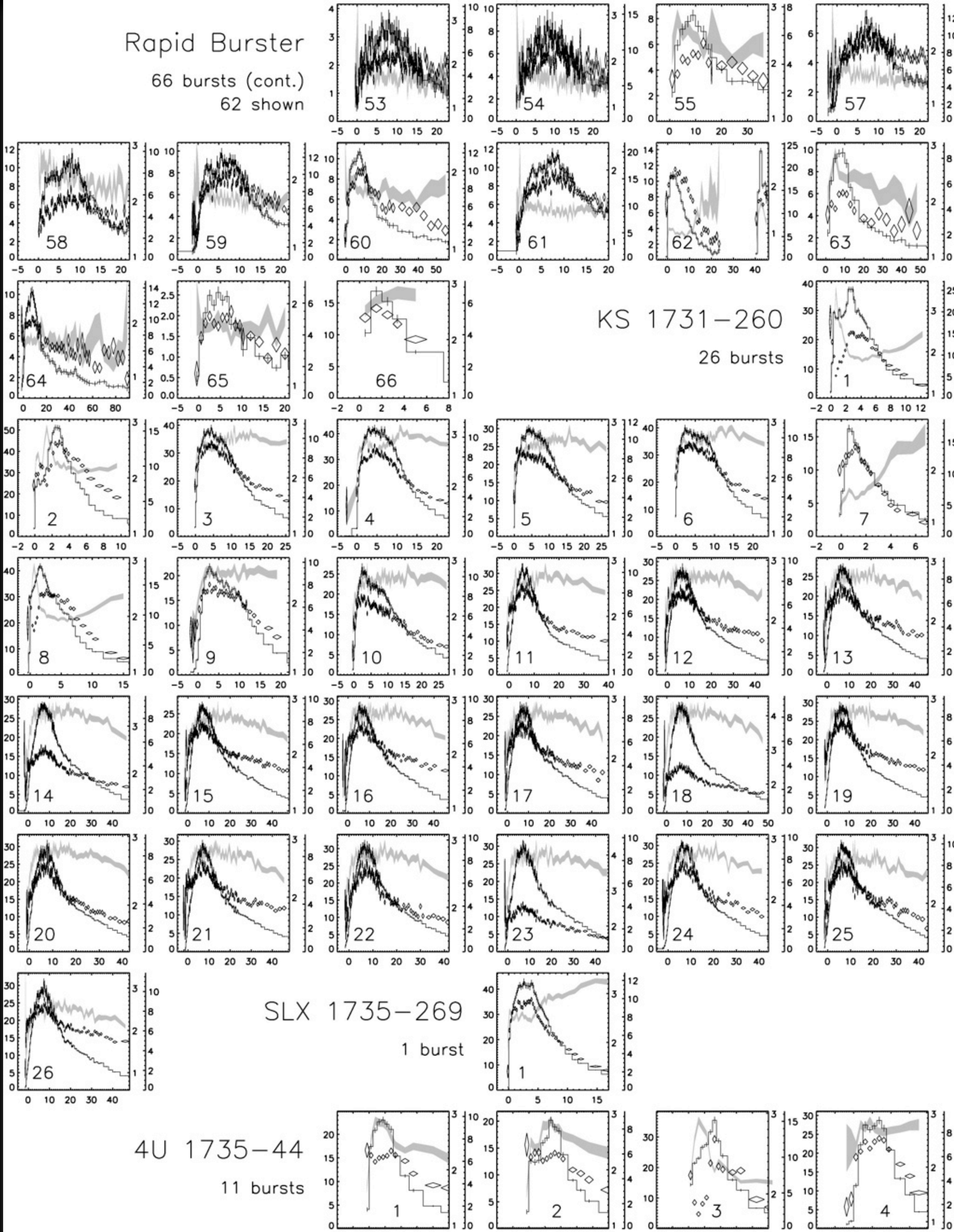
bursts, superbursts, oscillations

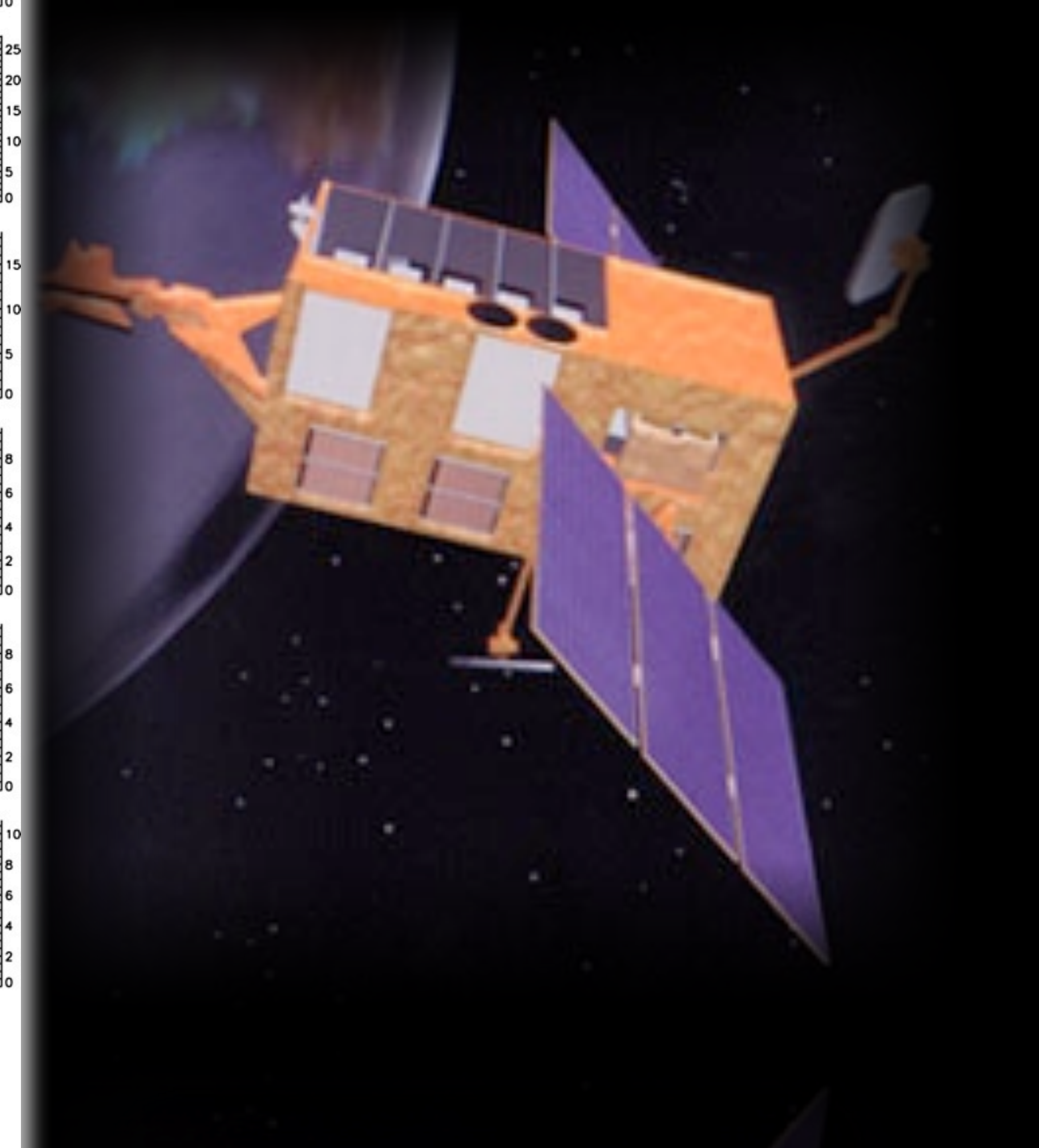
crust not in thermal equilibrium with core

measurements not as precise

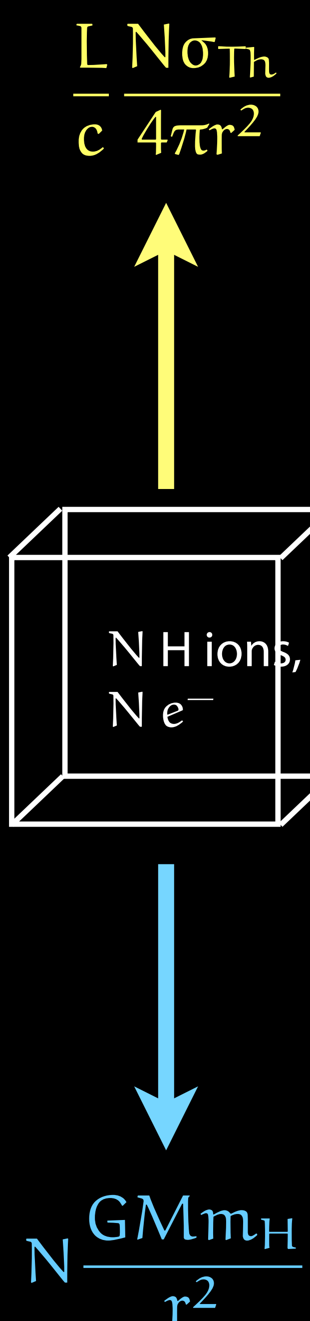

accretion
rp-process
(hours–days)
unstable $^{12}C+^{12}C$
(years)
envelope
10 m
outer crust
e^-
{Z,A}
100 m
inner crust
n
e^-
{Z,A}
1 km
n, p, e^-, μ

Galloway et al. 2008
A sample of 1187 X-ray bursts from 48 sources

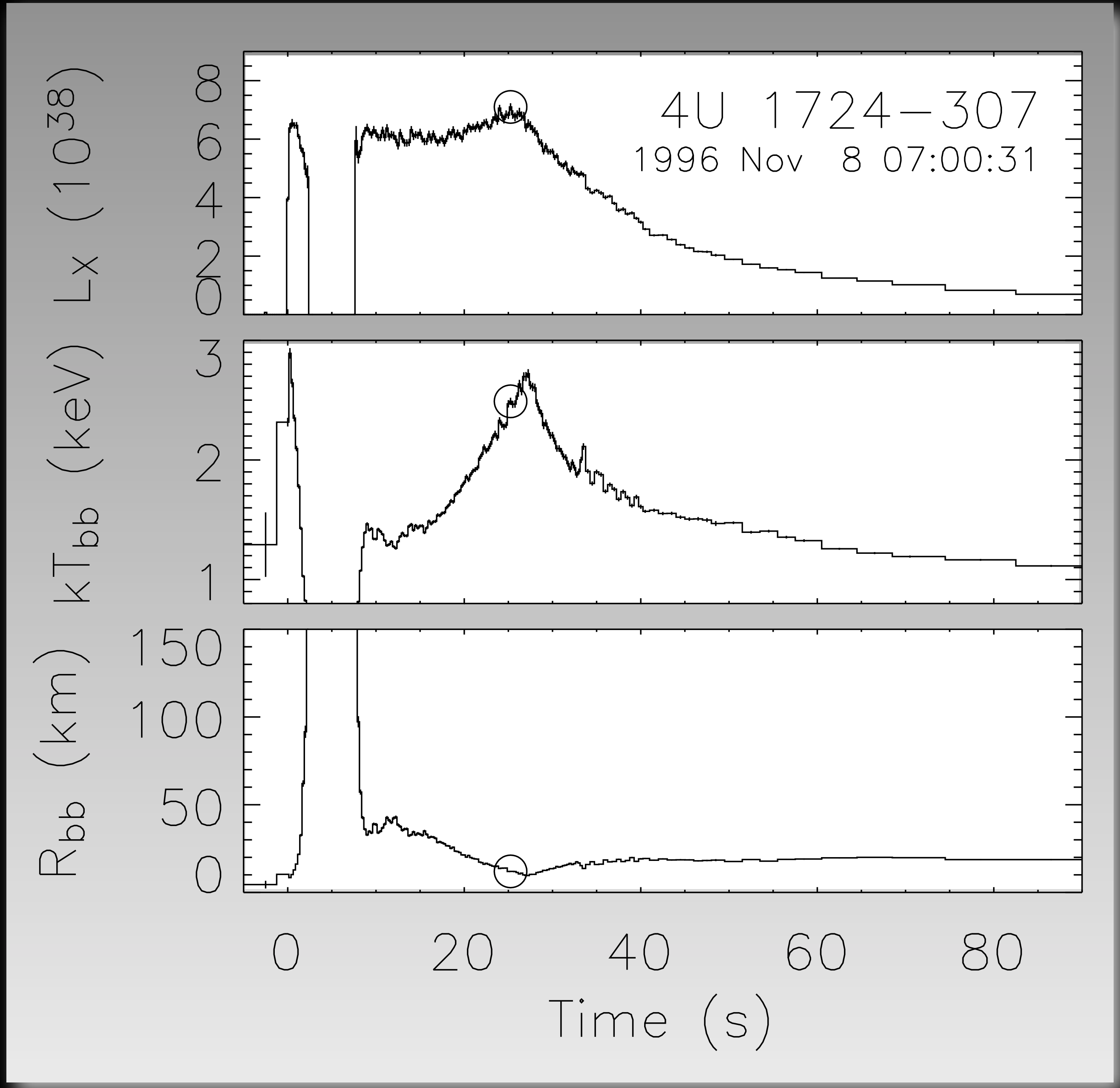




Eddington Limit



RXTE observations; Galloway et al. '08



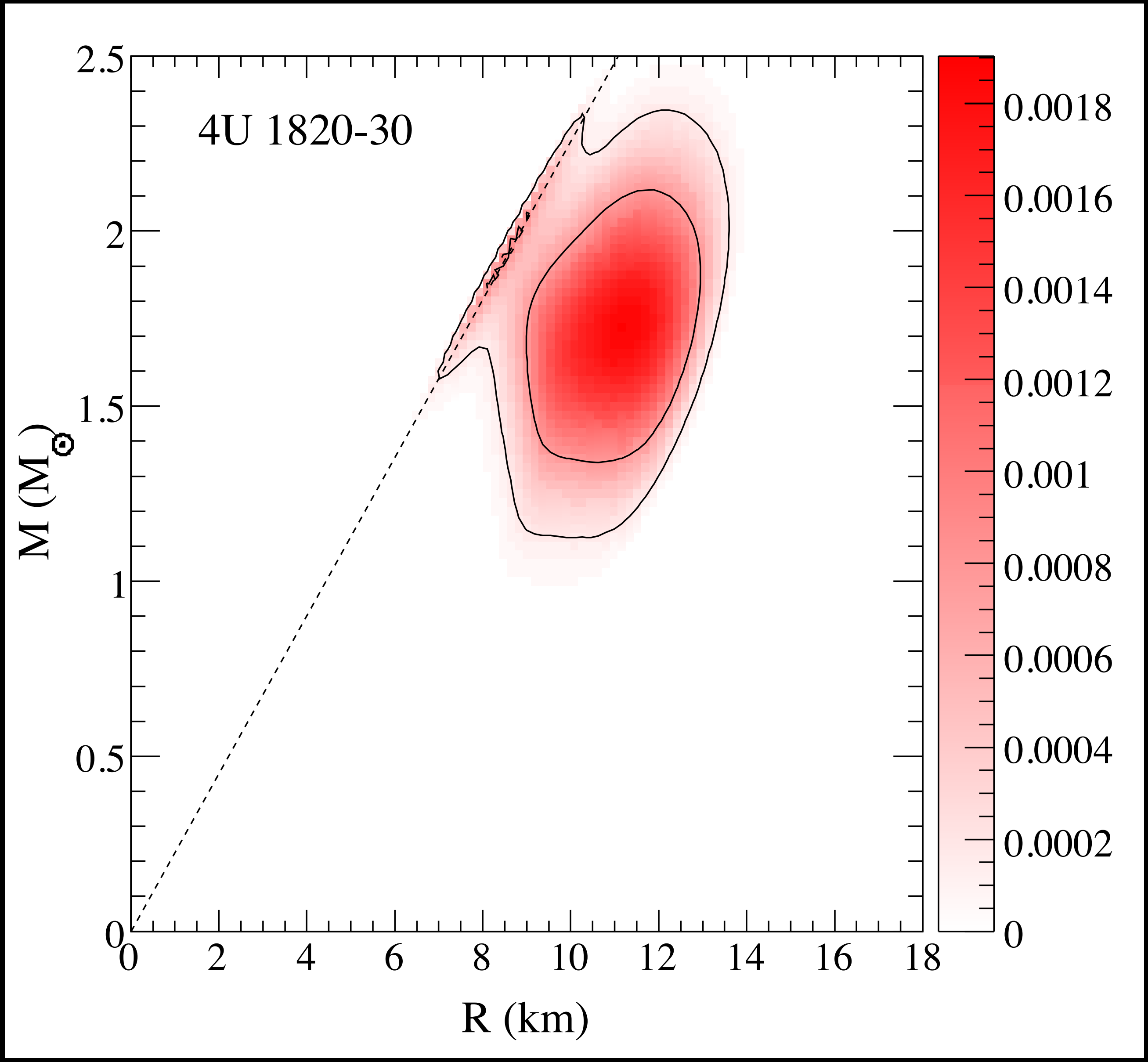
An Empirical Dense Matter Equation of State

From X-ray bursts with *photospheric radius expansion* (van Paradijs, Özel et al., Steiner et al., Suleimanov et al.)

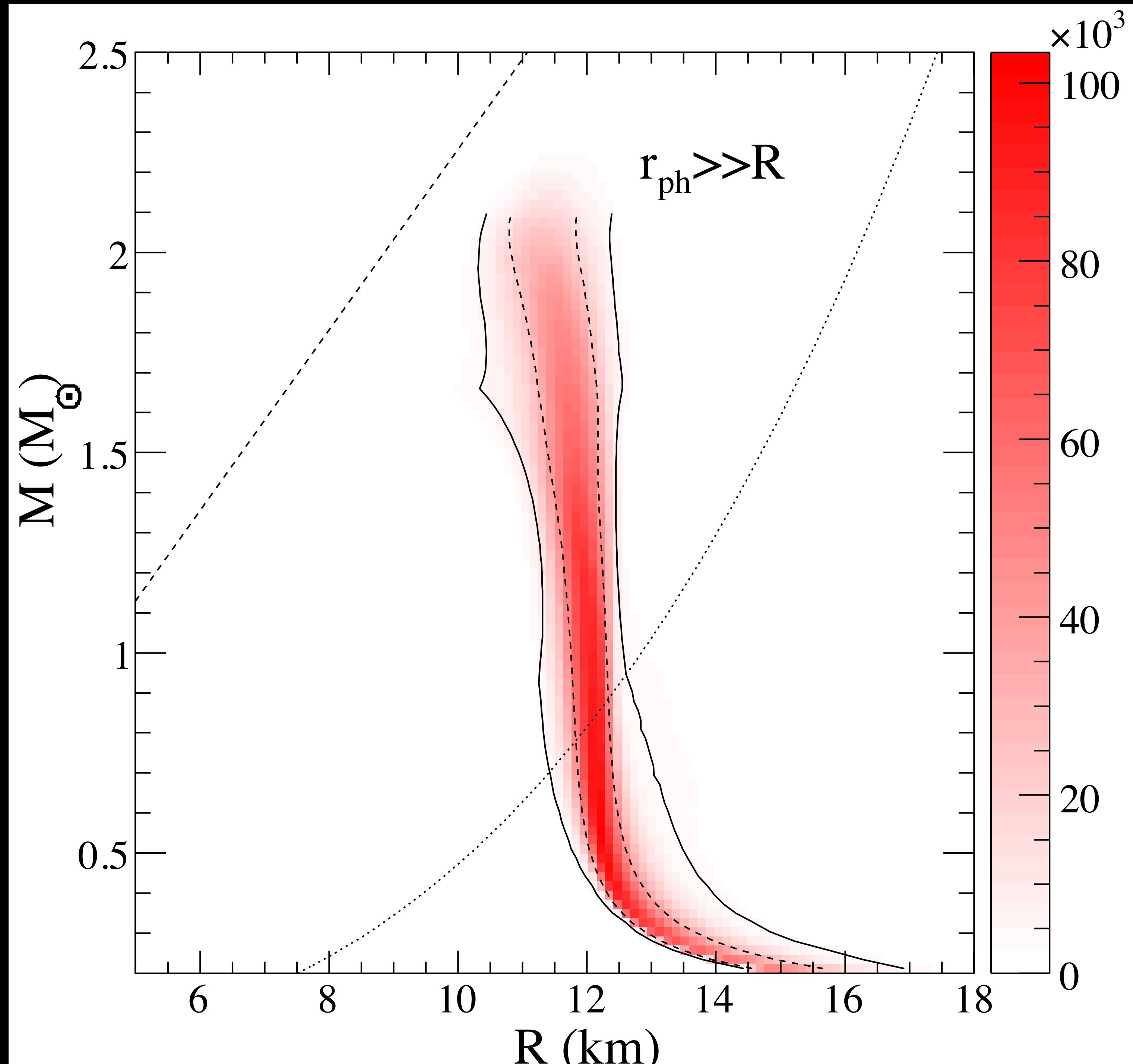
$$F_{Edd} = \frac{GMc}{\kappa D^2}\left(1 - 2\frac{GM}{r_{ph}c^2}\right)^{1/2}$$

$$\frac{F}{\sigma T_{eff}^4} = \left(\frac{R}{D}\right)^2 \left(1 - 2\frac{GM}{Rc^2}\right)^{-1}$$

Talk by A. Steiner

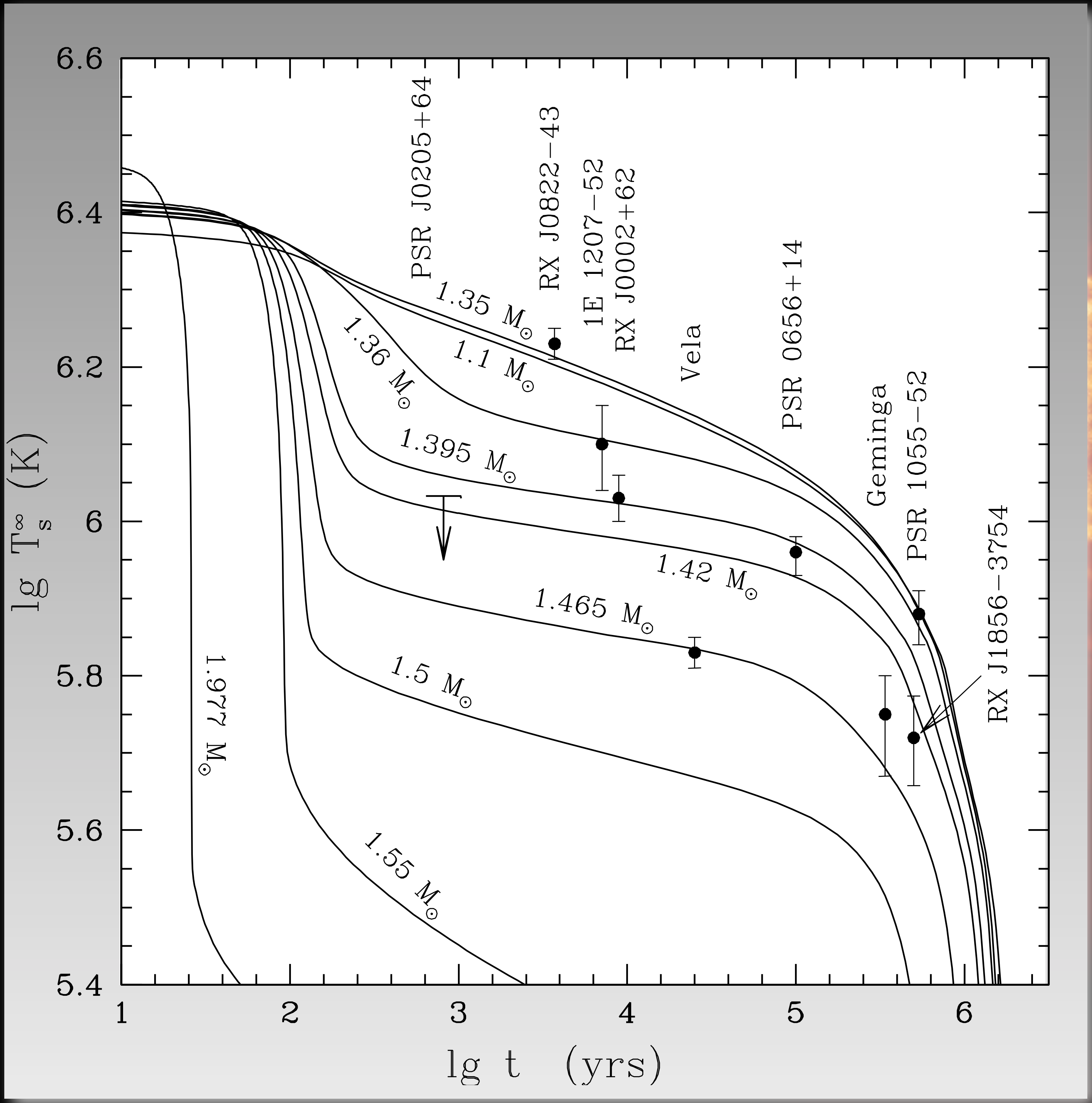


Steiner et al.; data from Guver et al. '10



An empirical *M-R* relation (Steiner et al.)

Neutron stars cooling from their fiery birth



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

cooling: the Urca process

Gamow & Schoenberg 1941

$$
\begin{aligned}
n &\rightarrow p + e + \bar{\nu} \\
p + e &\rightarrow n + \nu
\end{aligned}
$$

but this is blocked...

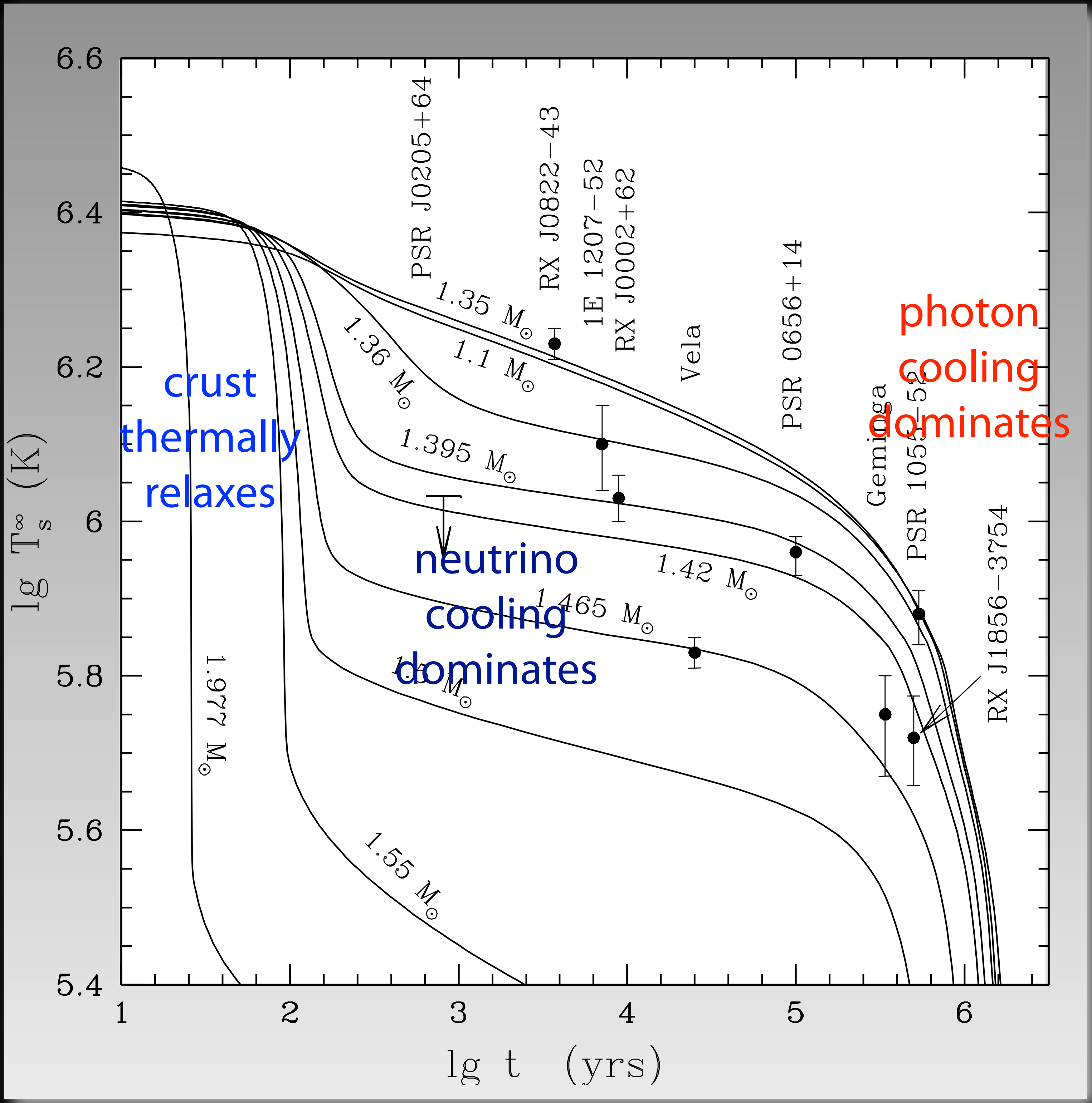
Chiu & Salpeter, Bahcall & Wolff

mom. cons.	$p_{Fn} < p_{Fe} + p_{Fp}$,
β-eq.	$\mu_e = \mu_n - \mu_p$,
charge neutrality	$n_e = n_p$

...unless $n_p/n > 0.11$

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

Neutron stars cooling from their fiery birth

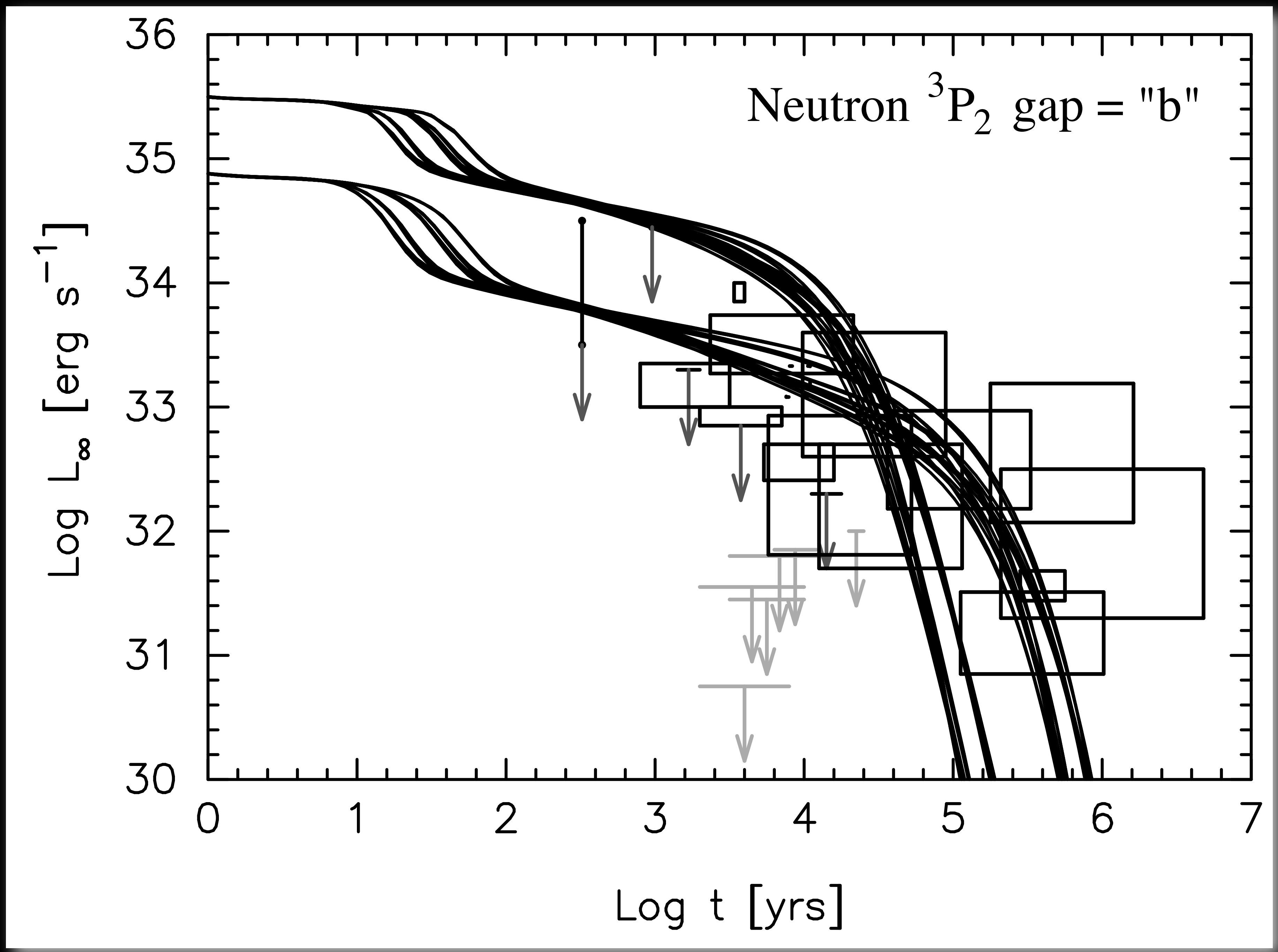


plot from Yakovlev et al. '02; see also Page et al. '04, '09

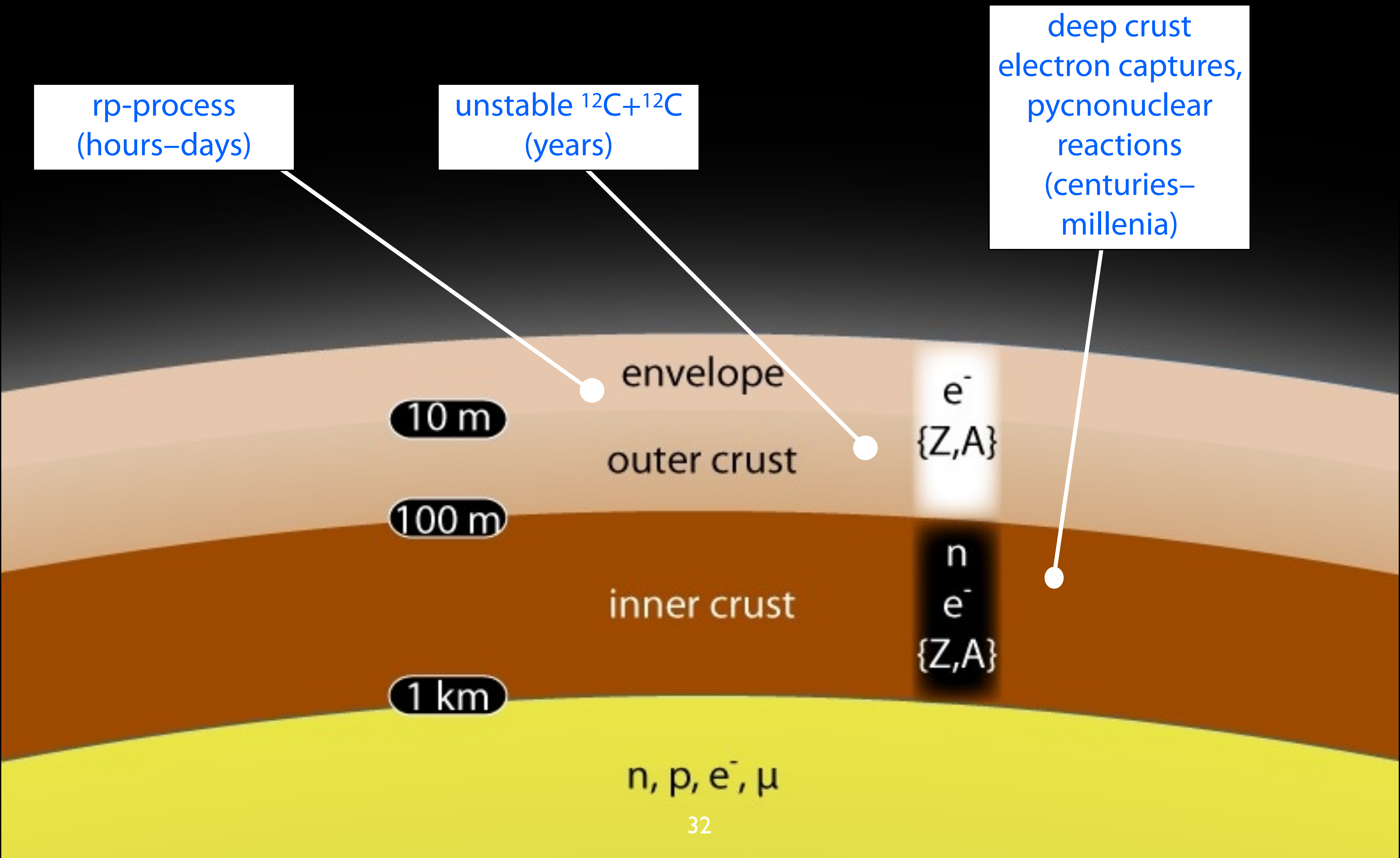
enhanced cooling (dUrca) leads to rapid drop of surface temperature after crust has relaxed

Isolated neutron stars: no enhanced cooling in models

Page, Lattimer, Prakash, & Steiner 2009



accreting neutron stars: deep crustal heating

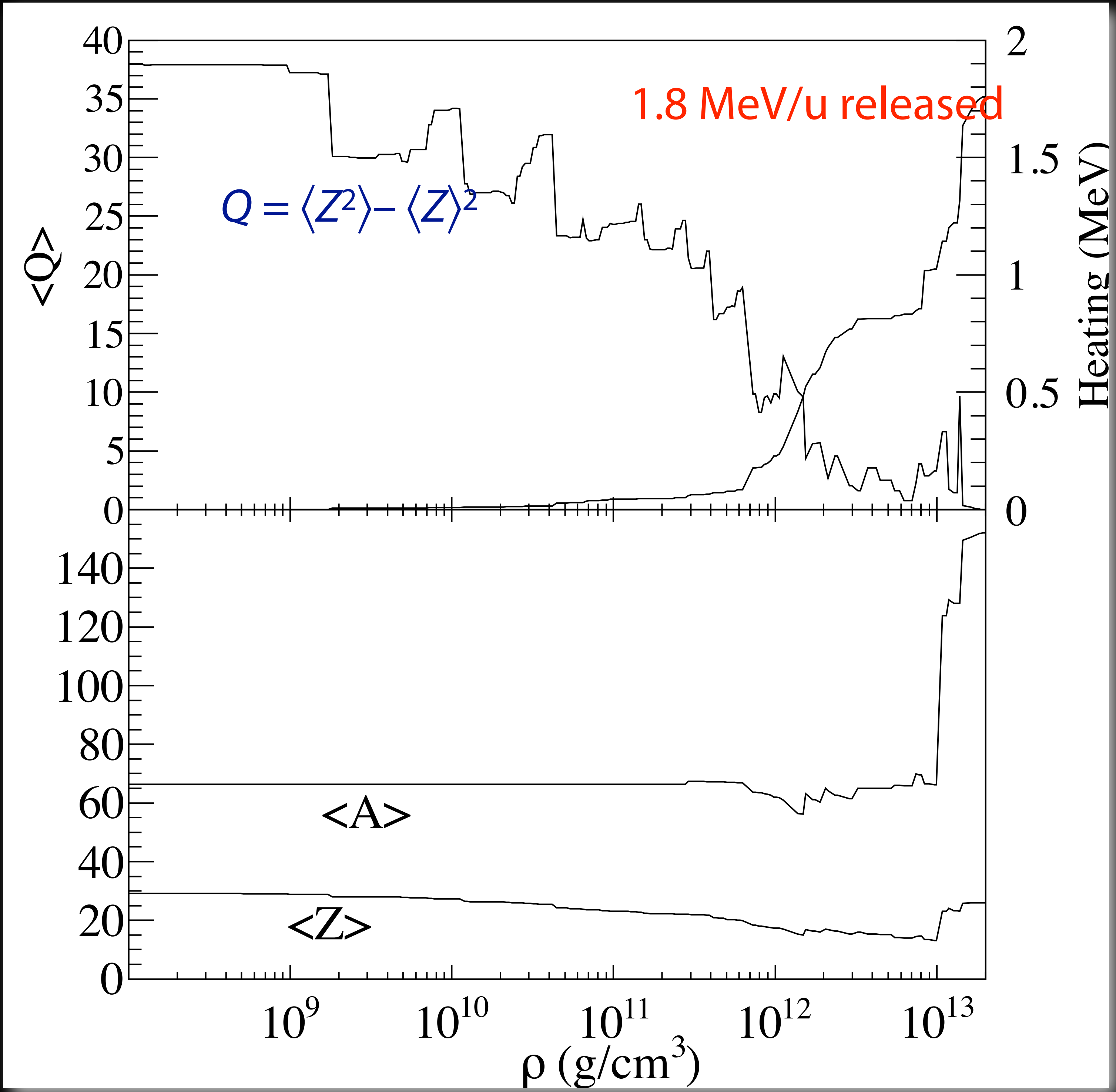


deep crustal heating

crust reactions deposit ~1.8 MeV/u in the inner crust

1. core temperature set by balance of heating, neutrino cooling
2. crust is not in thermal equilibrium with core

plot courtesy A. Steiner



transients

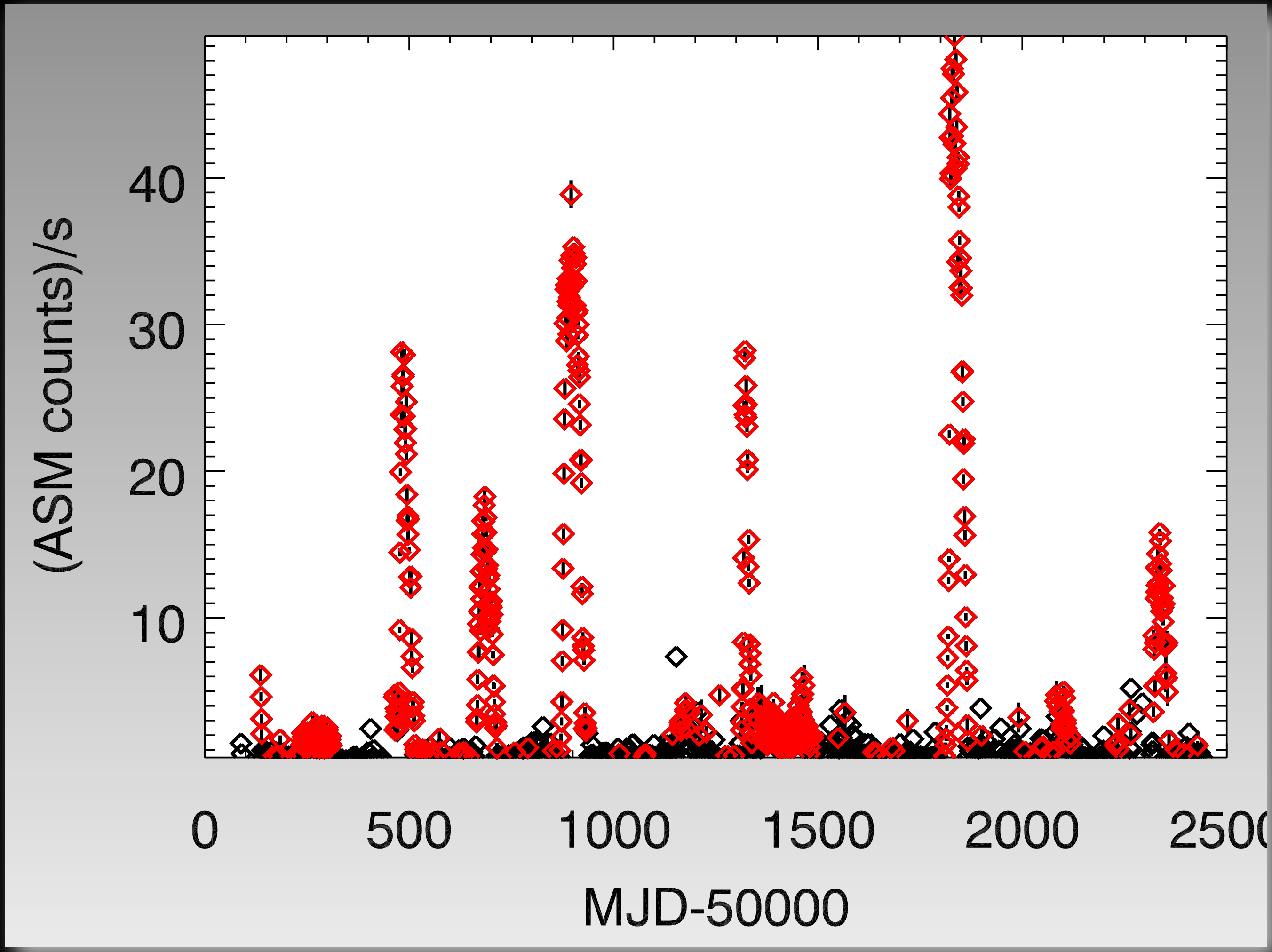
Brown, Bildsten, & Rutledge; Colpi et al.; Yakovlev et al.

Many neutron stars accrete intermittently

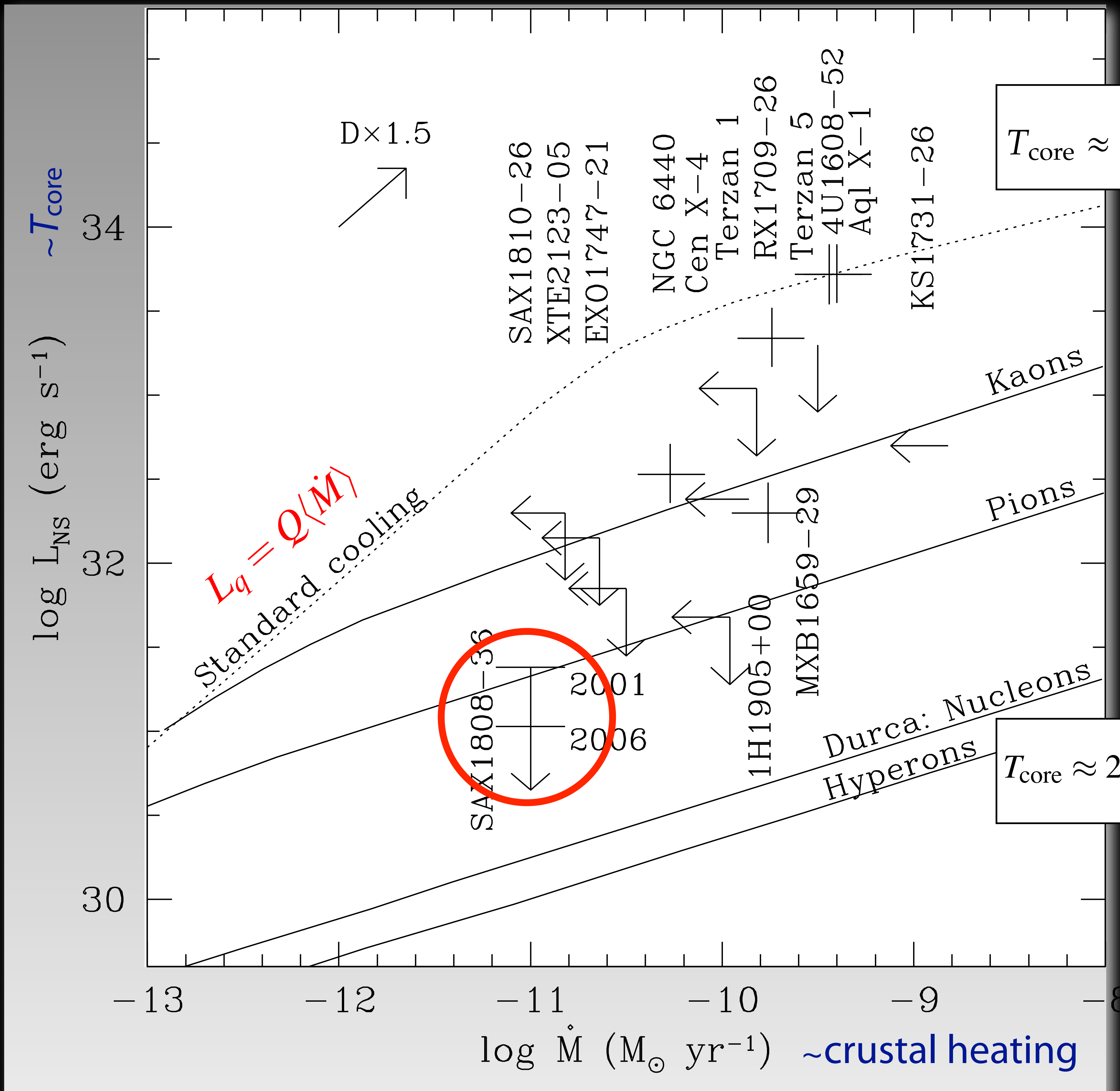
crust heats during outburst

crust cools during quiescence

Aql X-1 lightcurve. *RXTE*/ASM



Heinke et al. 2007, following Yakovlev et al. 2004

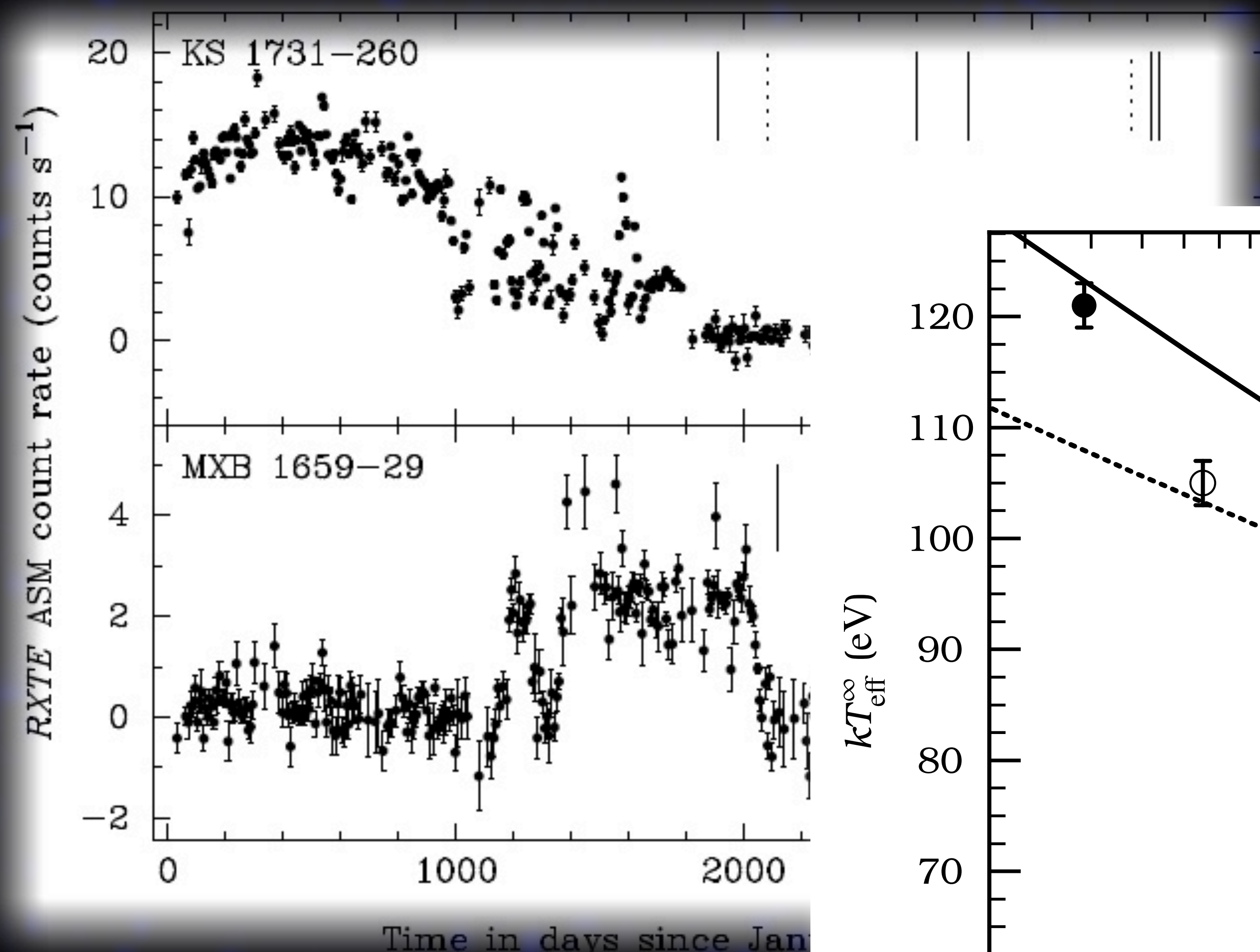


$$T_{\rm core} \approx 2\times10^8\,{\rm K}\left(\frac{\langle\dot{M}\rangle}{10^{-10}\,M_\odot\,{\rm yr}^{-1}}\right)^{1/8}$$

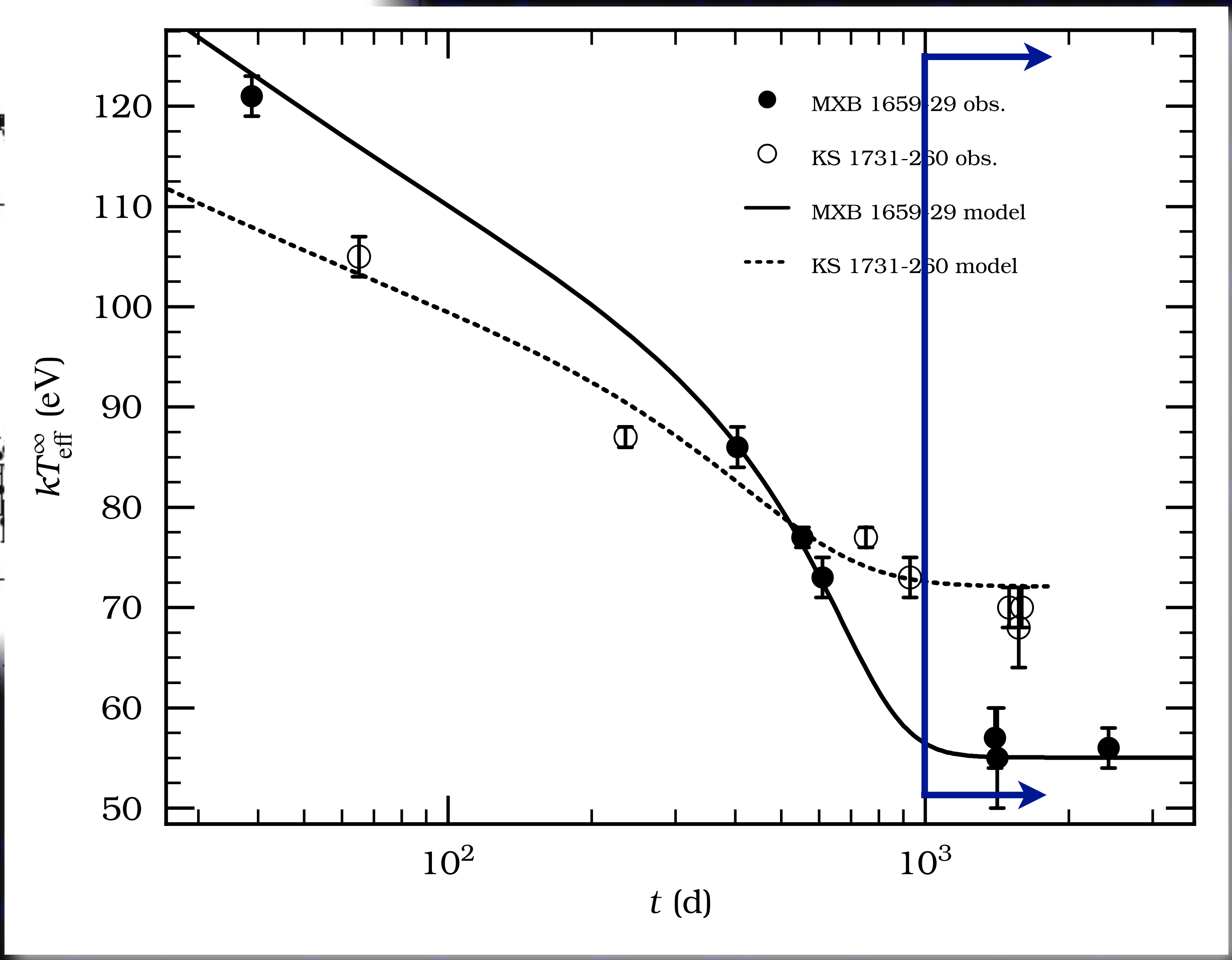
$$T_{\rm core} \approx 2\times10^7\,{\rm K}\left(\frac{\langle\dot{M}\rangle}{10^{-10}\,M_\odot\,{\rm yr}^{-1}}\right)^{1/6}$$

quasi-persistent transients

Rutledge et al. 2002, Shternin et al.2007, Brown & Cumming 2009



data from Cackett et al. 2008
fits from Brown & Cumming 2009



Summary

A number of observational probes of the nuclear EOS are available

- three examples
  - pulsar masses
  - masses and radii from X-ray bursts
  - cooling of isolated neutron stars, thermal relaxation of accreting transients
- this is not inclusive: there are others

No single observation is ideal—it's astrophysics; but

These observations, taken together, offer interesting constraints and complement theoretical and experimental efforts

The best is yet to come!