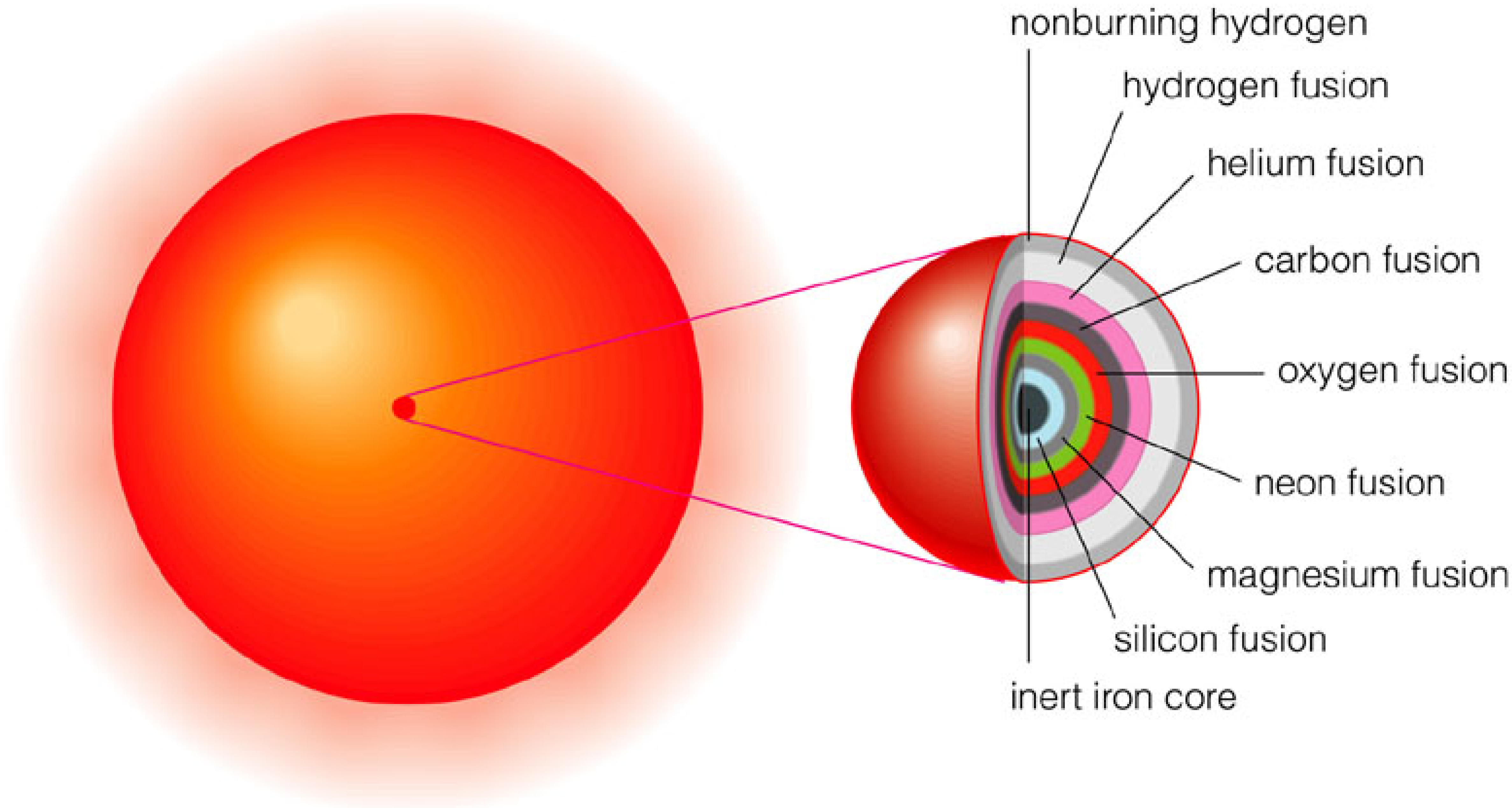
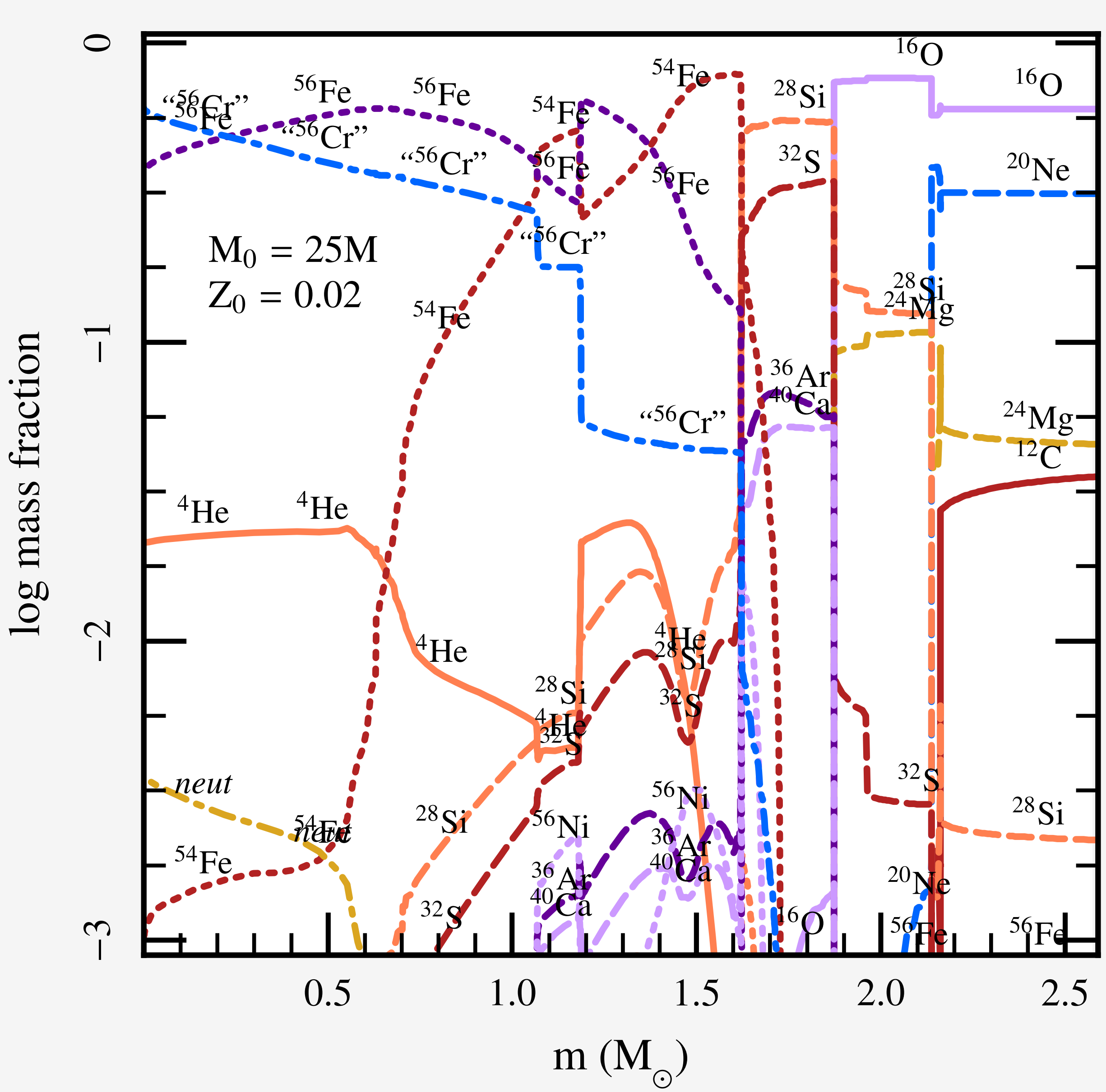
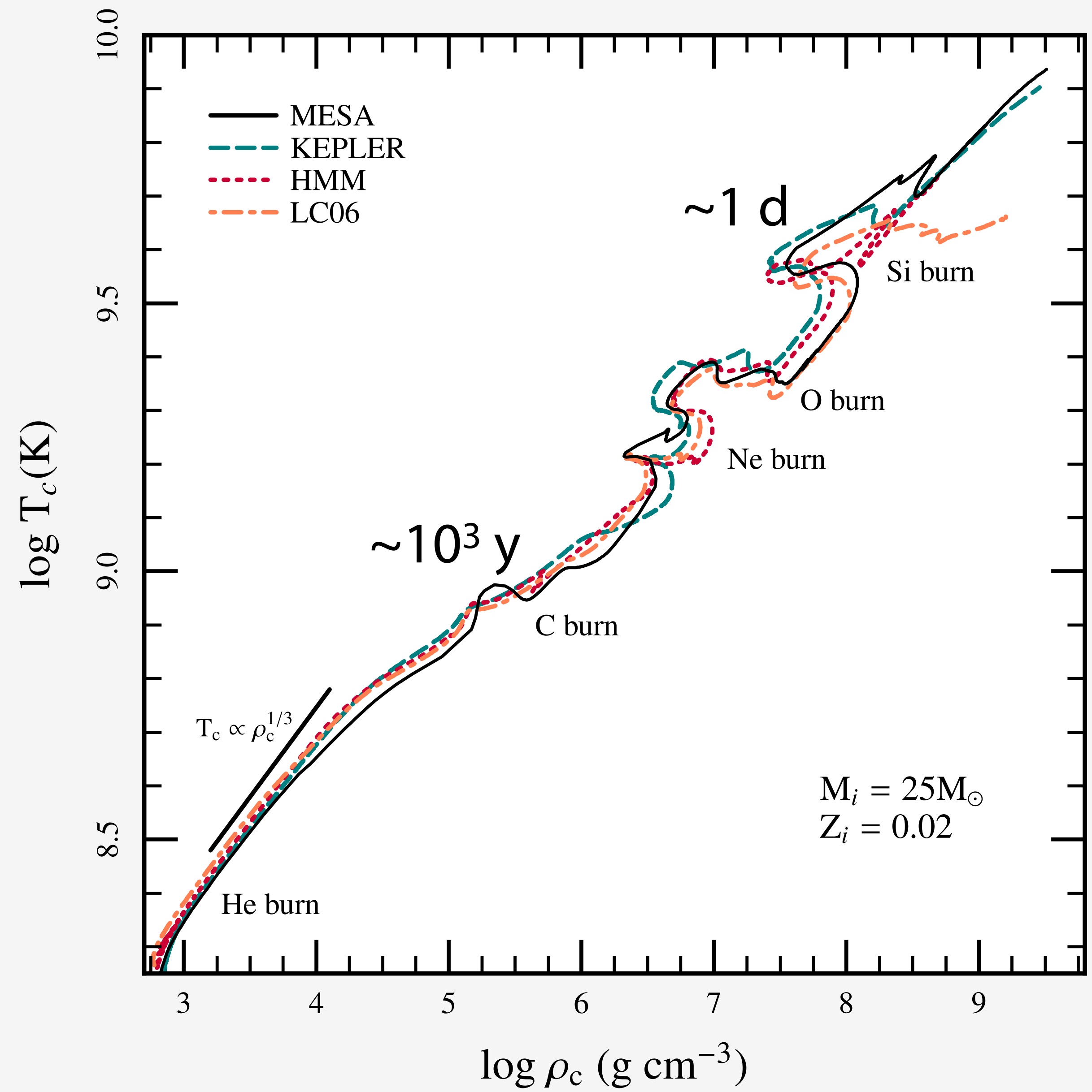
Textbook view of massive stars

Essential Cosmic Perspective, Bennett et al.



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



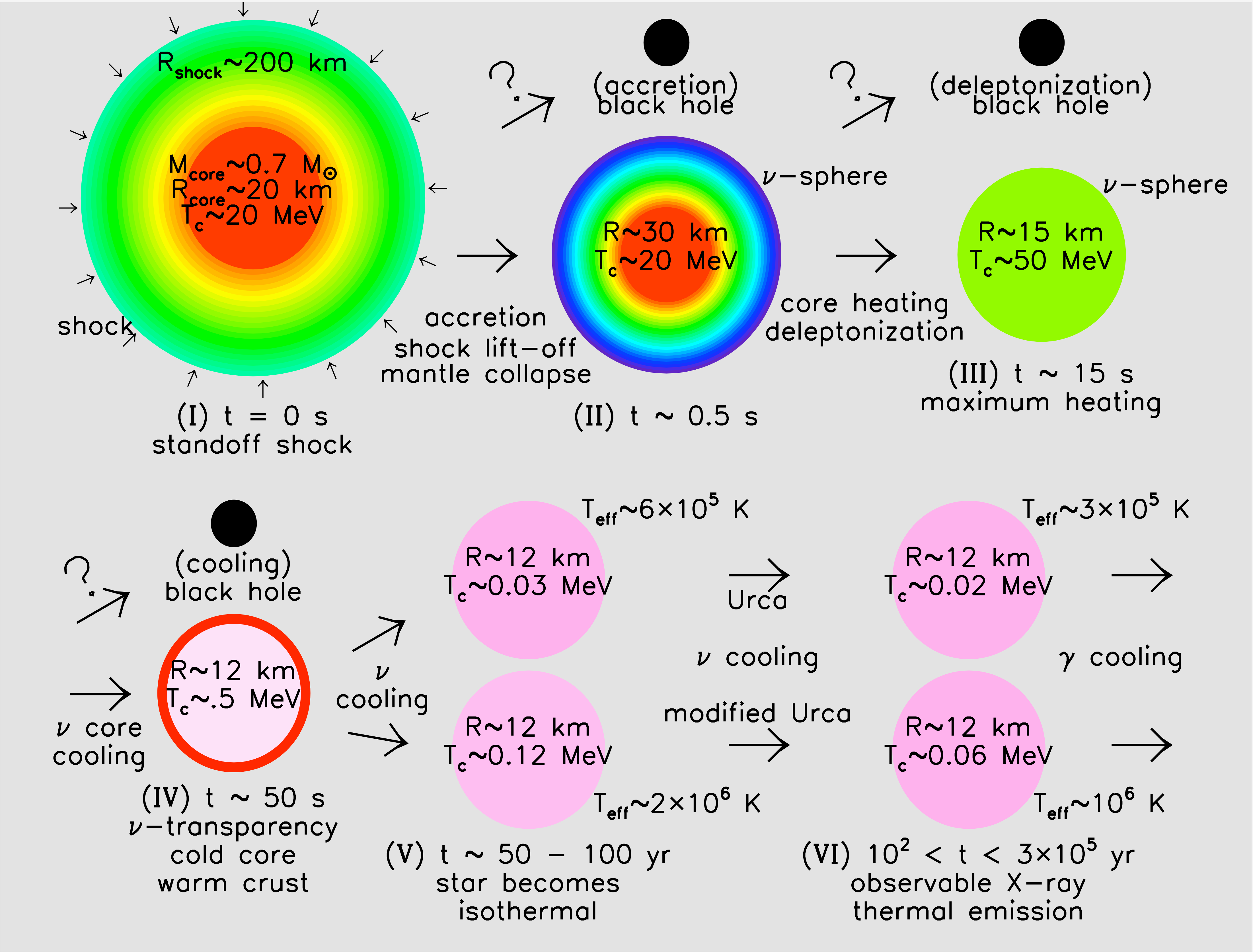


5. *The super-nova process*

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.

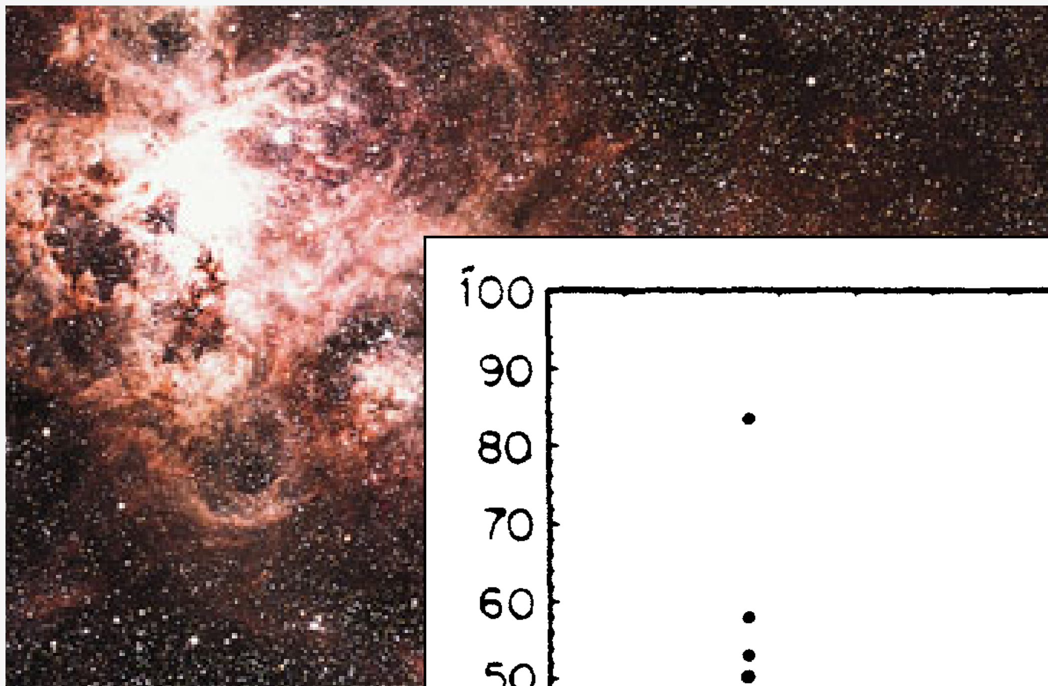
W. BAADE
F. ZWICKY

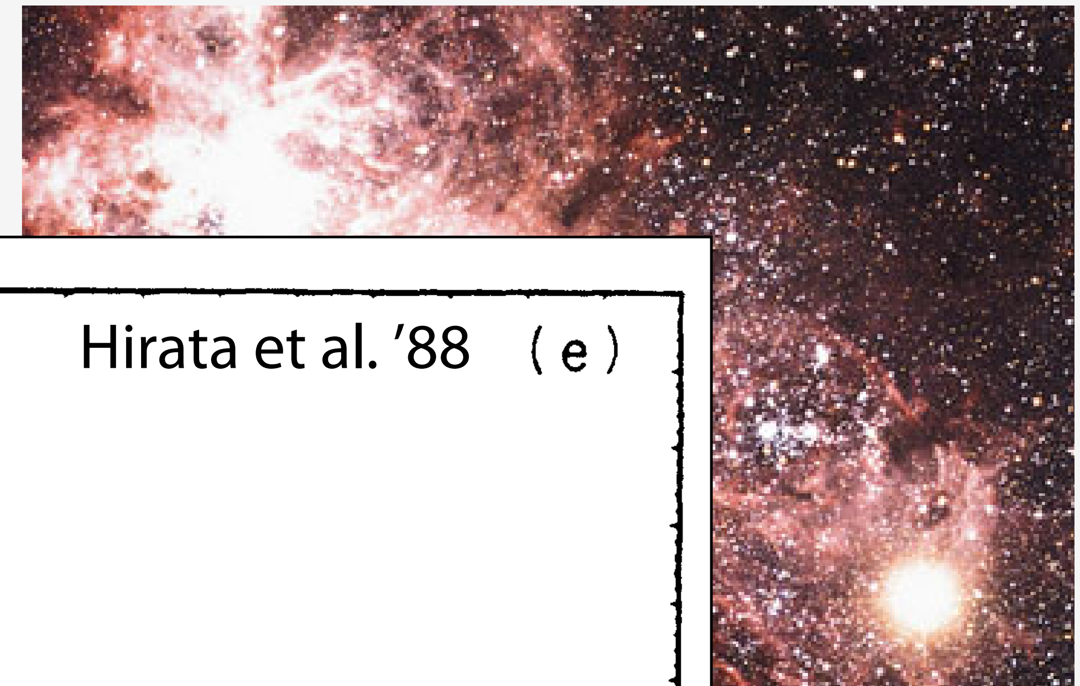
Mt. Wilson Observatory and
California Institute of Technology, Pasadena.
May 28, 1934.

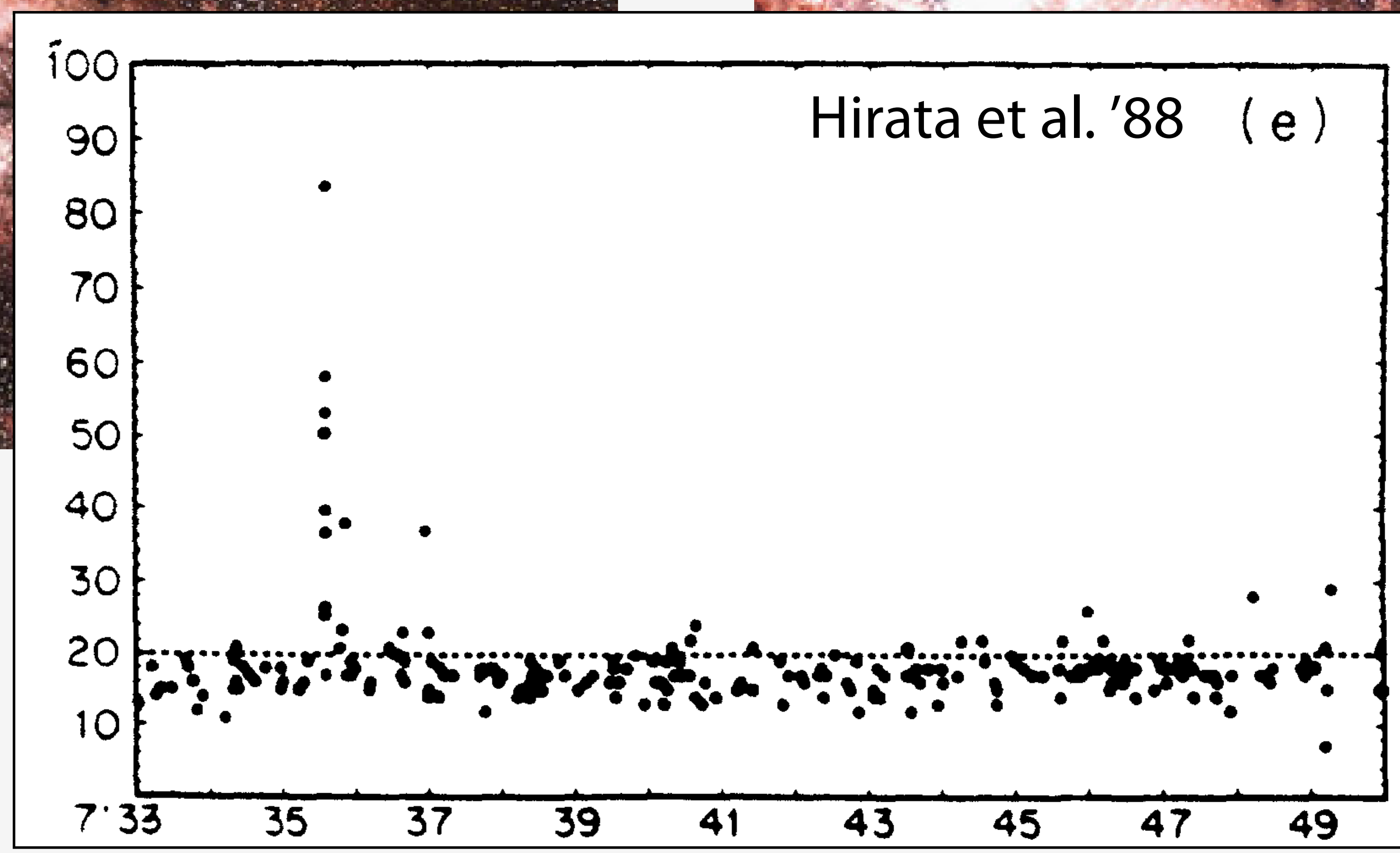


Modern view of neutron star birth

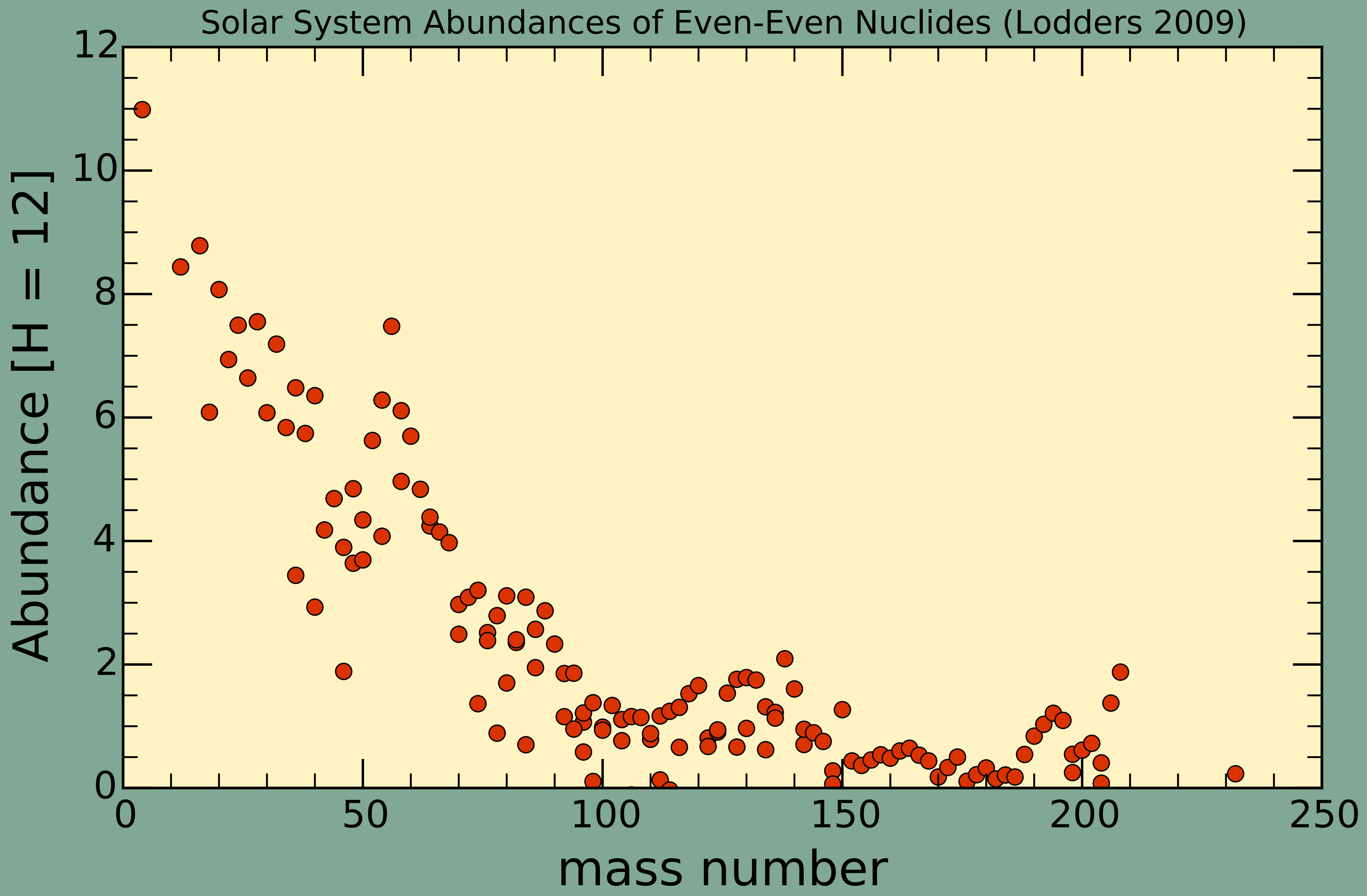
schematic from Lattimer and Prakash



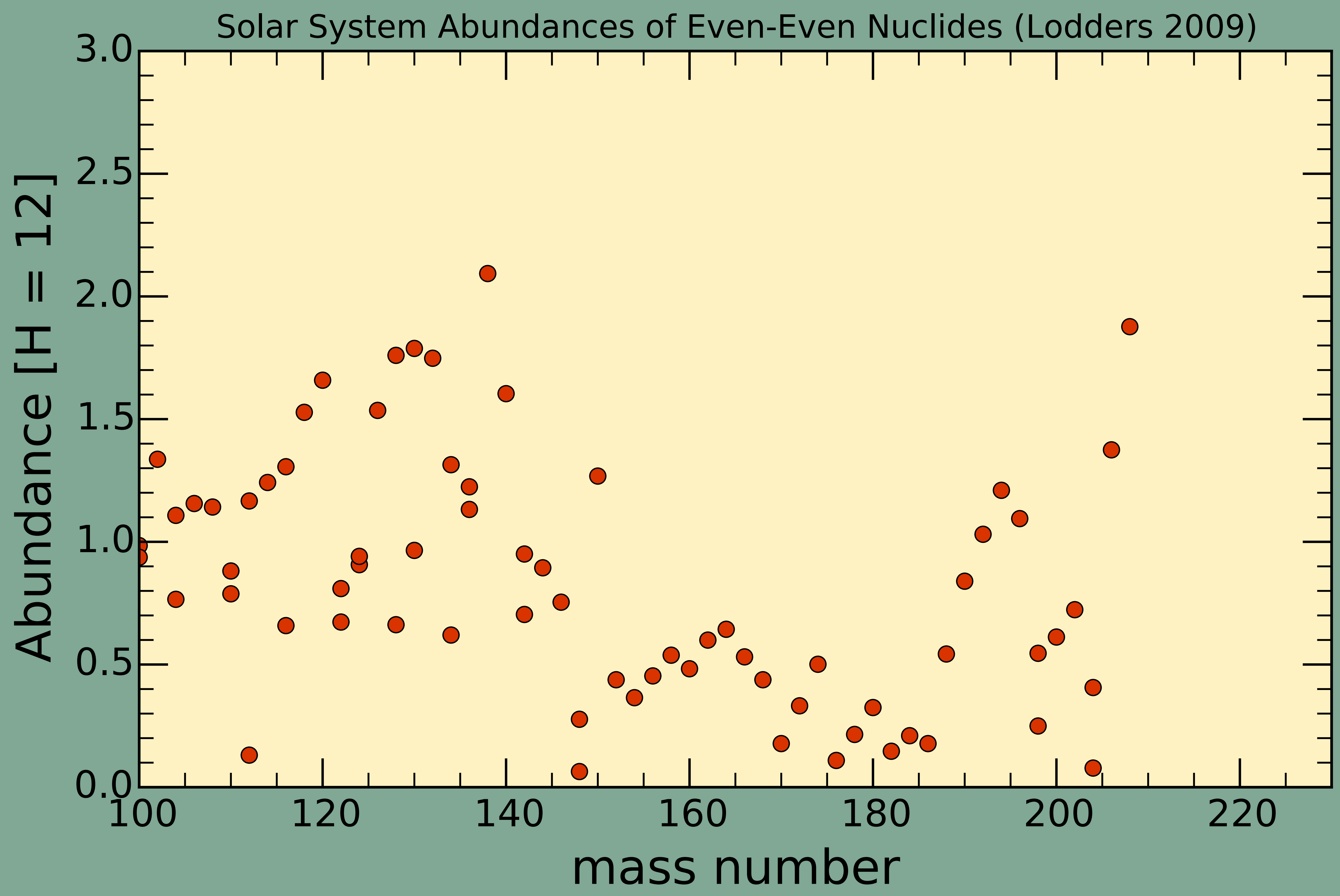




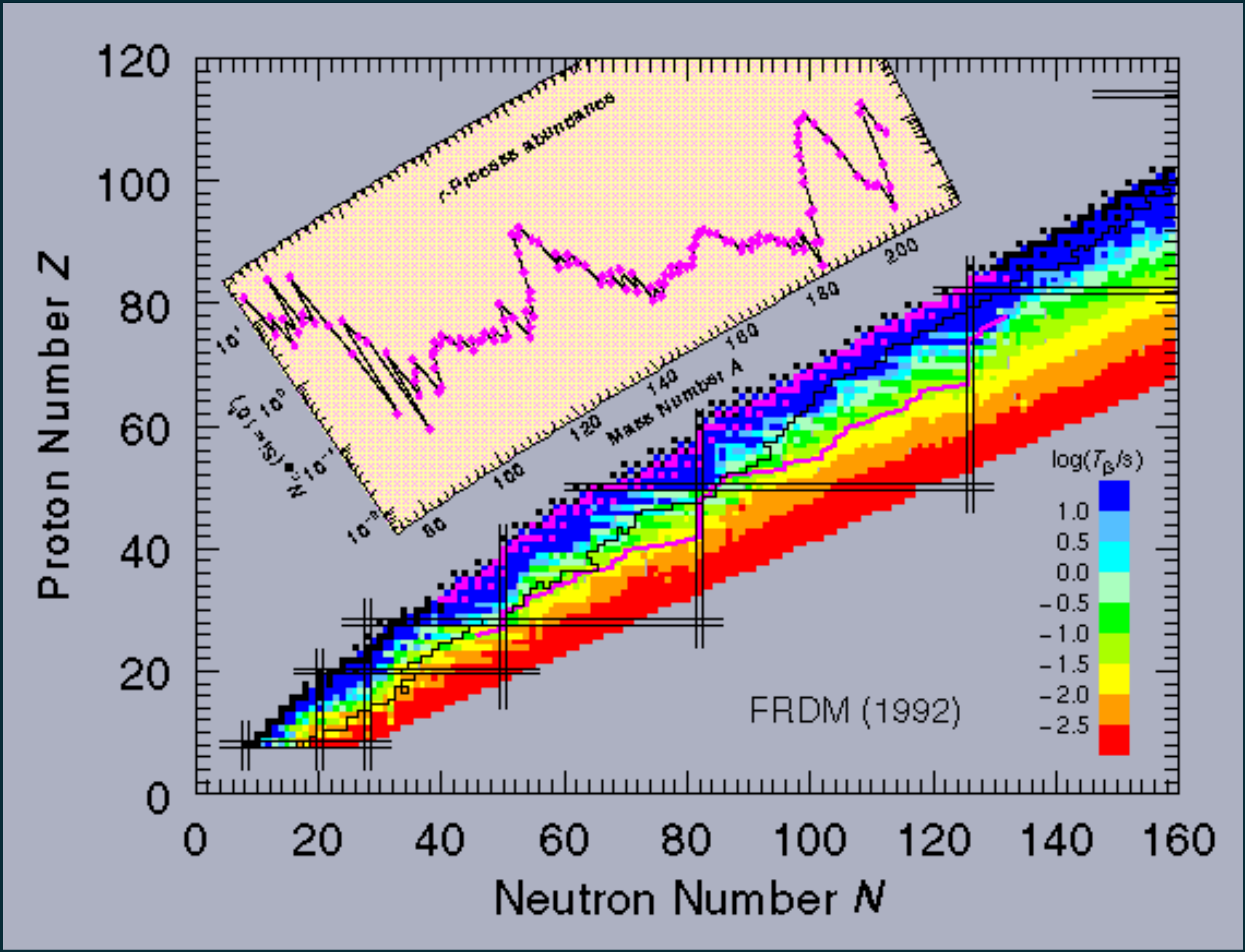
Supernova 1987a: neutrinos detected by Kamiokande!



Solar System Abundances of Even-Even Nuclides (Lodders 2009)
Abundance [H = 12]
mass number
0
2
4
6
8
10
12
0
50
100
150
200
250

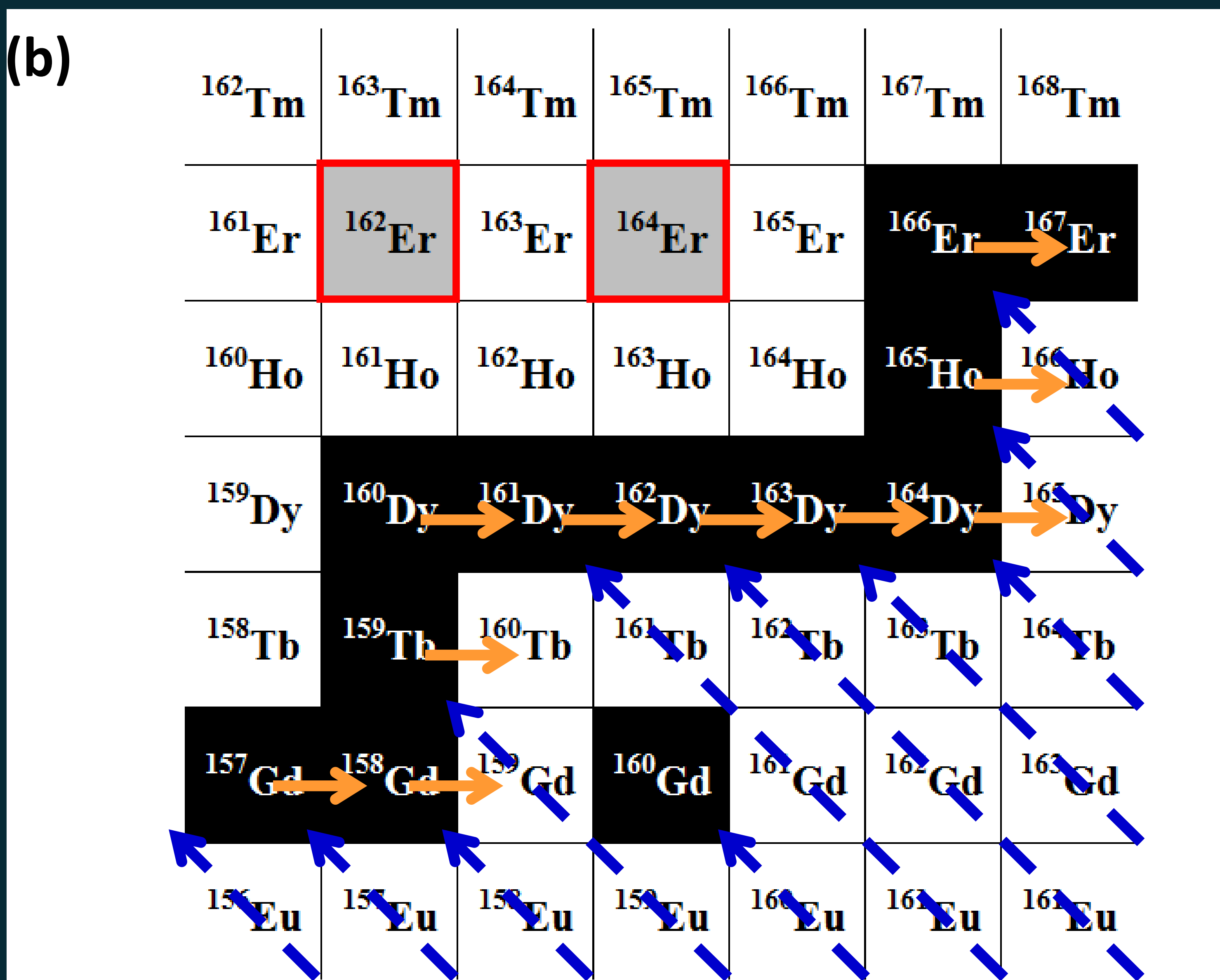


Solar System Abundances of Even-Even Nuclides (Lodders 2009)
Abundance [H = 12]
mass number
3.0
2.5
2.0
1.5
1.0
0.5
0.0
100
120
140
160
180
200
220



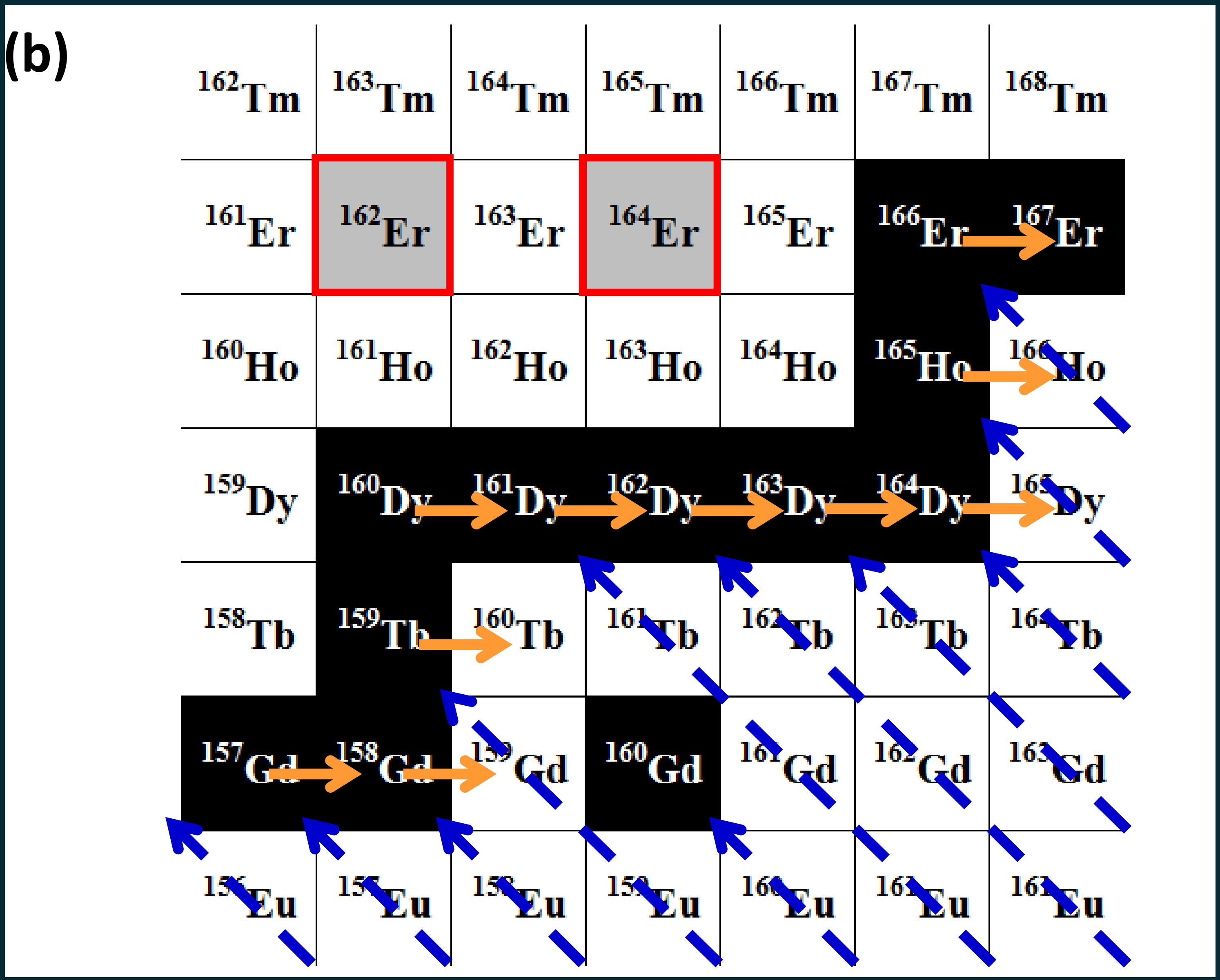
Proton Number Z
Neutron Number N
0
20
40
60
80
100
120
140
160
r-Process abundances
Mass Number A
80
100
120
140
160
180
200
log(T_β/s)
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
−2.5
FRDM (1992)

which nuclei are s-only?



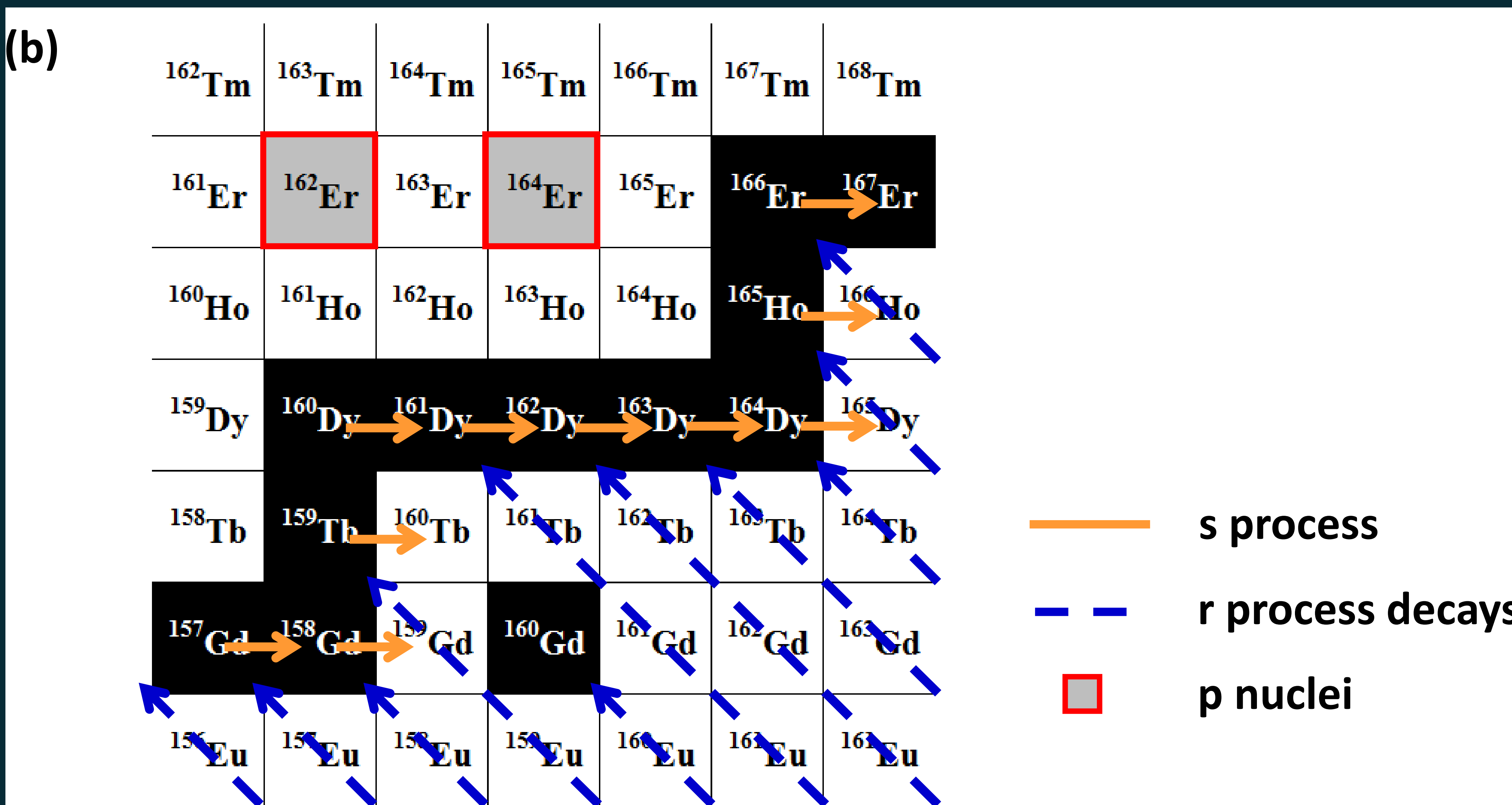
S. Quinn 2015

which nuclei are r-only?



S. Quinn 2015

which nuclei are r-only?



S. Quinn 2015

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

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

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

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

from nuclei to bulk matter

$$\frac{E}{A} \approx -a_V + a_S A^{-1/3} + a_A \left(\frac{N-Z}{N+Z}\right)^2 + a_C \frac{Z^2}{A^{4/3}}$$

Thermodynamics near saturation density

see review by Lattimer & Prakash

Let's examine properties of *npe* matter near saturation density $n = 0.16 \text{ fm}^{-3}$. 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.

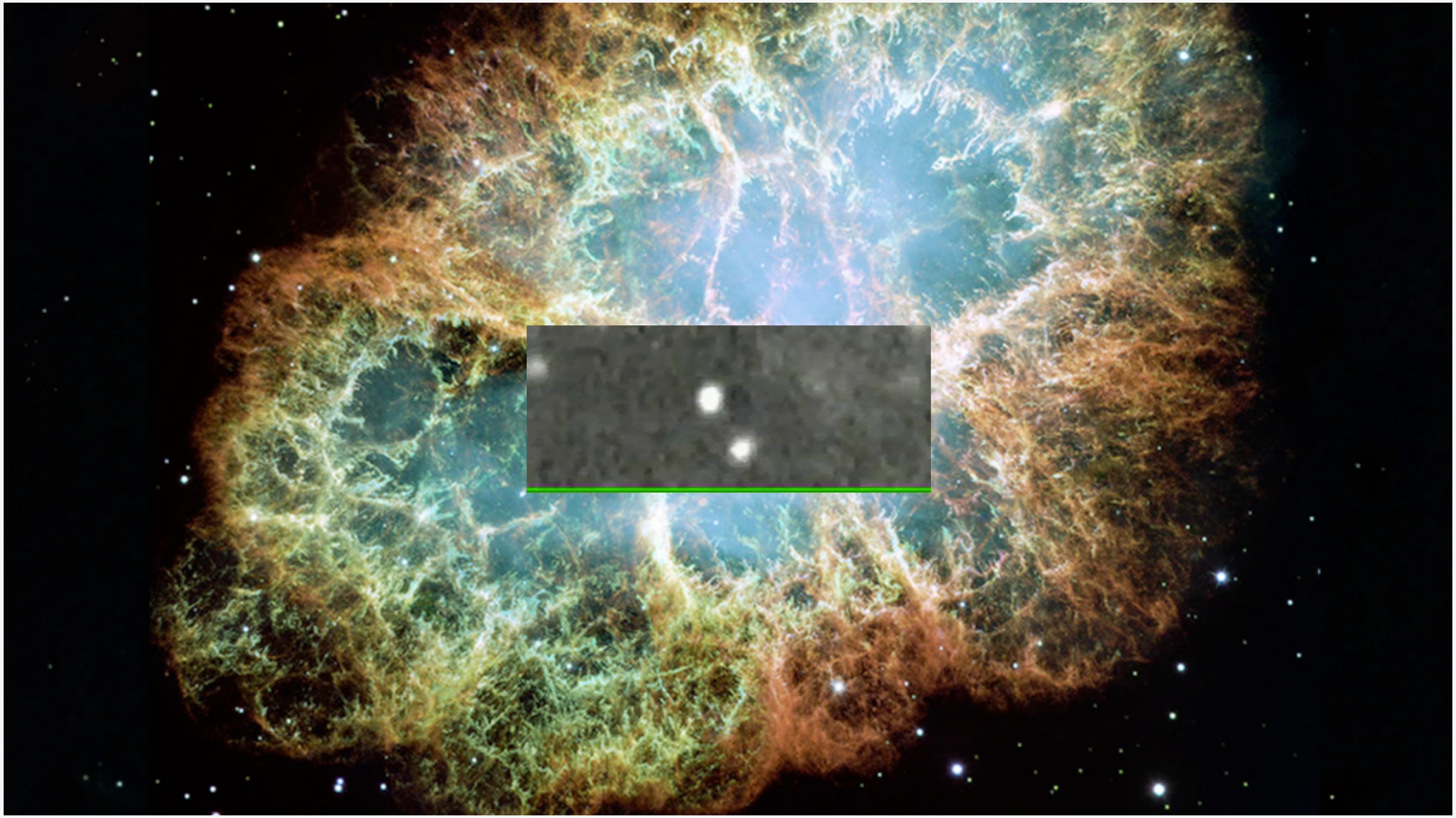
What is the pressure at saturation?

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

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

Accreting neutron stars

PHYSICAL REVIEW
LETTERS

9 DECEMBER 1, 1962 NUMBER

EVIDENCE FOR X RAYS FROM SOURCES OUTSIDE THE SOLAR SYSTEM*

Riccar
America

Massac

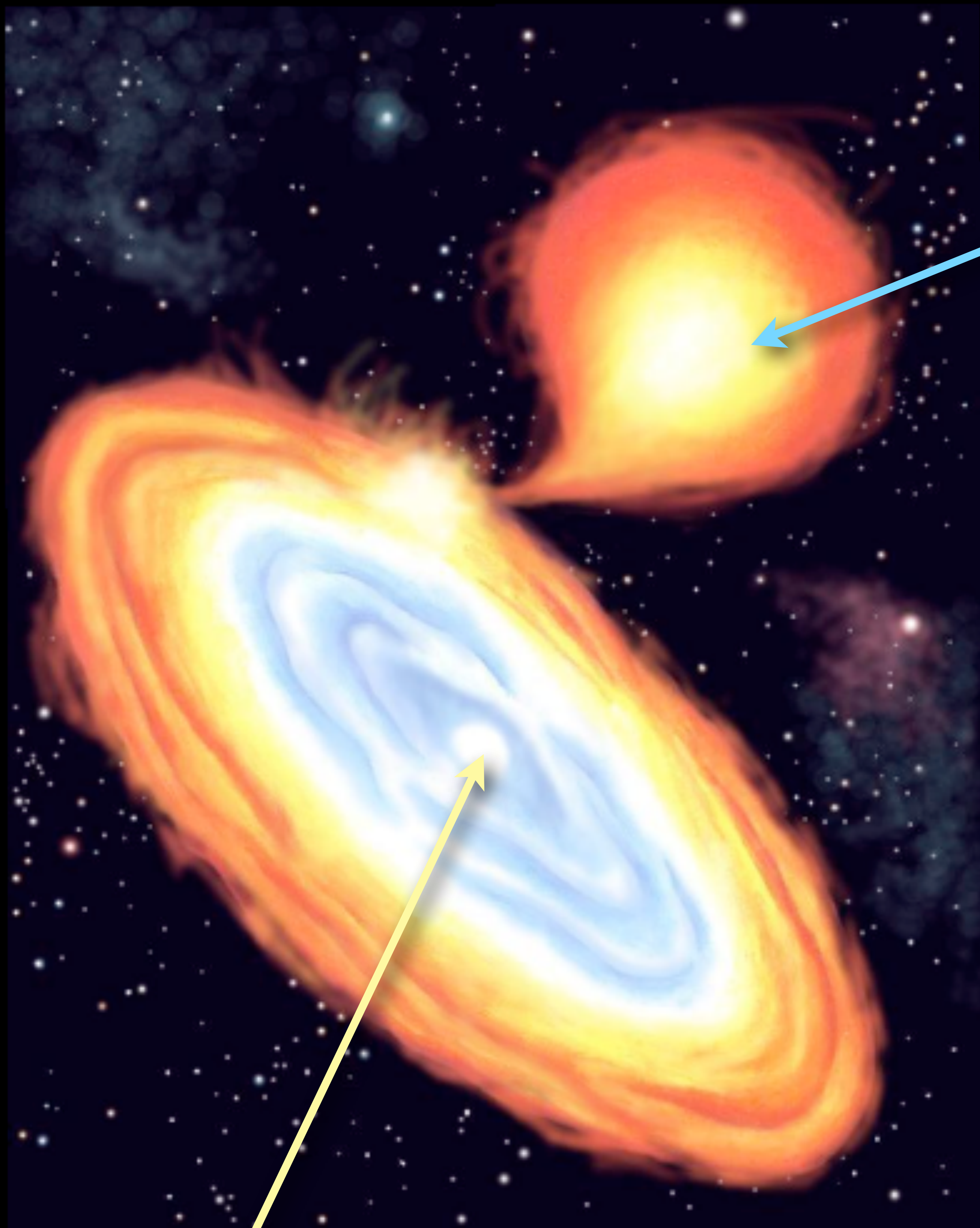
THE ASTROPHYSICAL JOURNAL

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



≈ solar mass star
P_{orb} = minutes–hours

Neutron star

Each accreted H releases

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

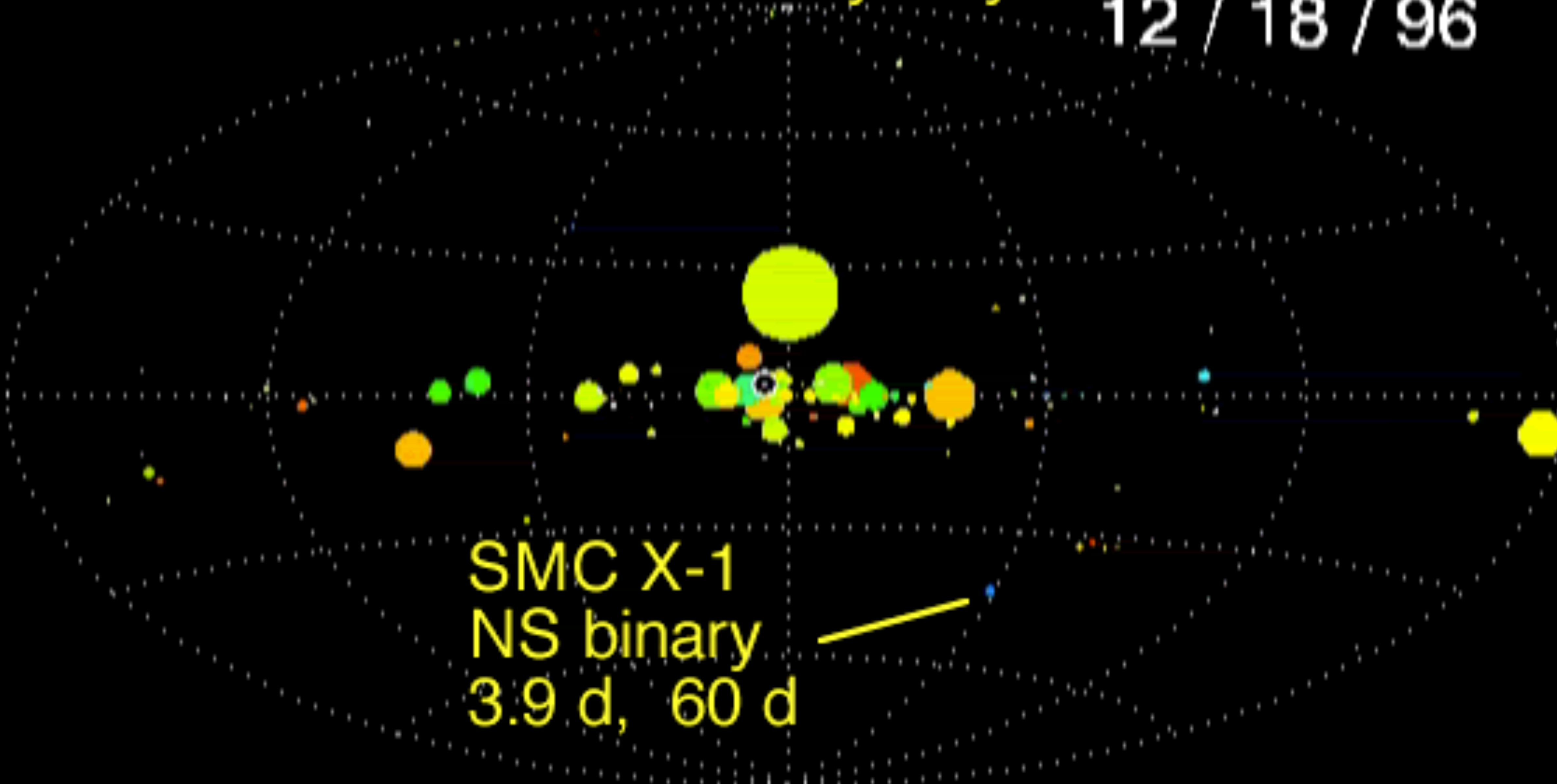
Fusing H to He releases

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

per nucleon.

The X-ray Sky

12 / 18 / 96



Detection: Isolated neutron stars

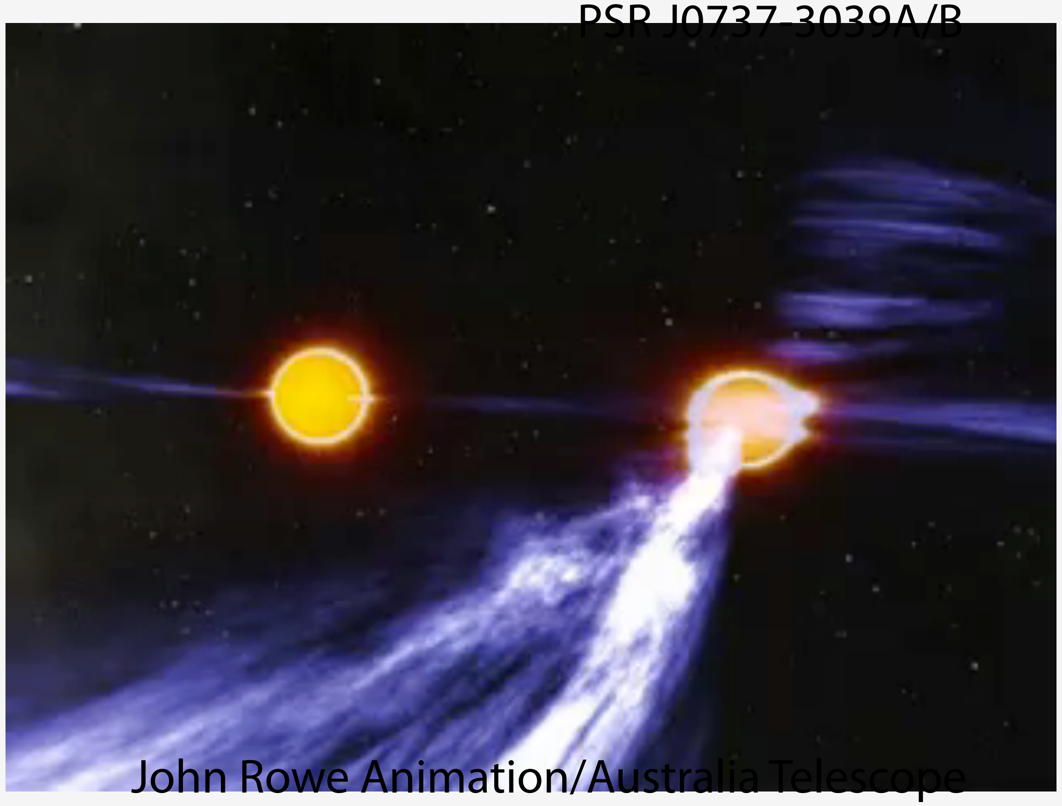
about 1700 pulsars detected; about 50 are in binary systems with some mass information

very precise mass information;

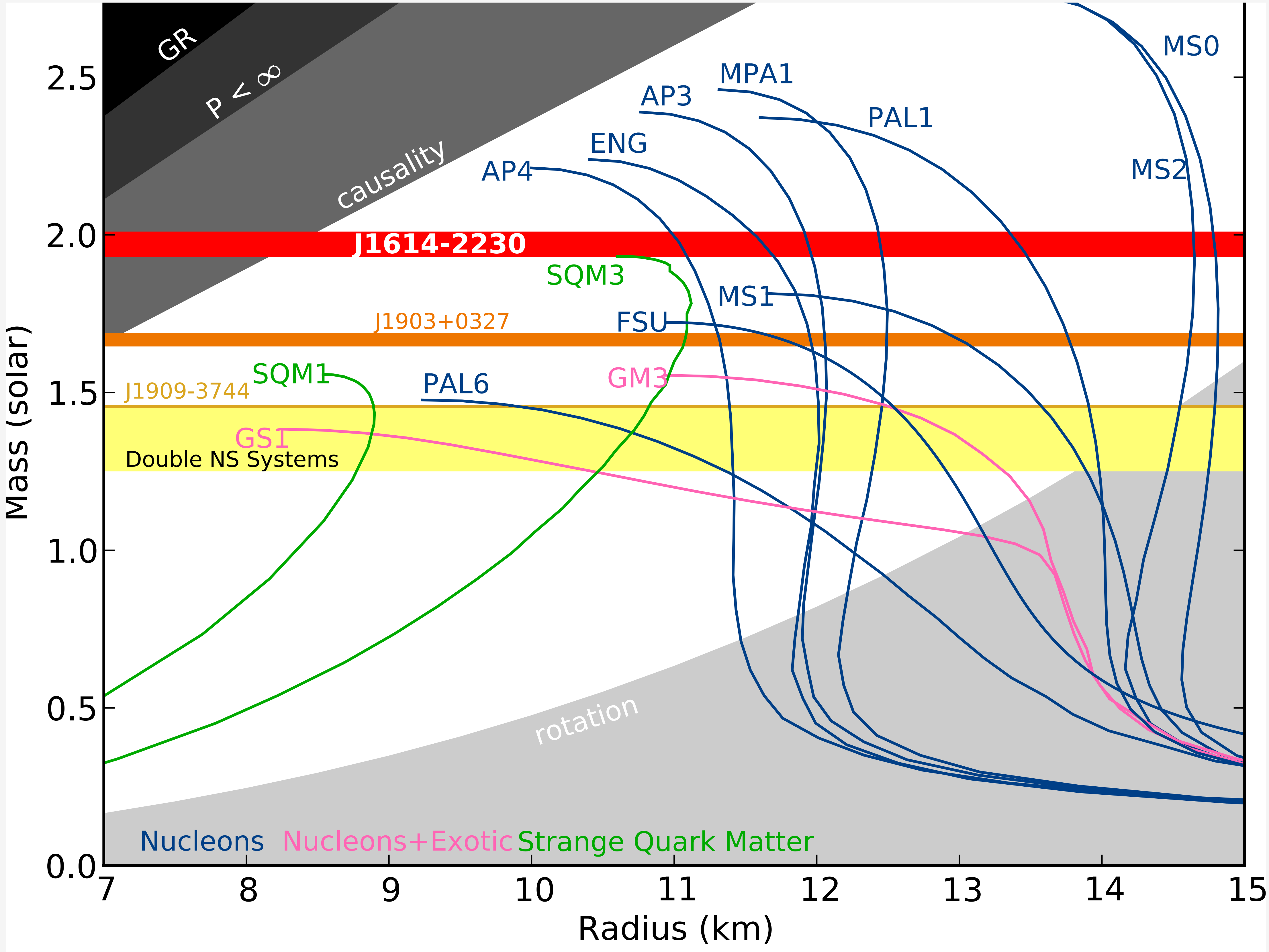
but, no radius information

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

PSR J0737-3039A/B

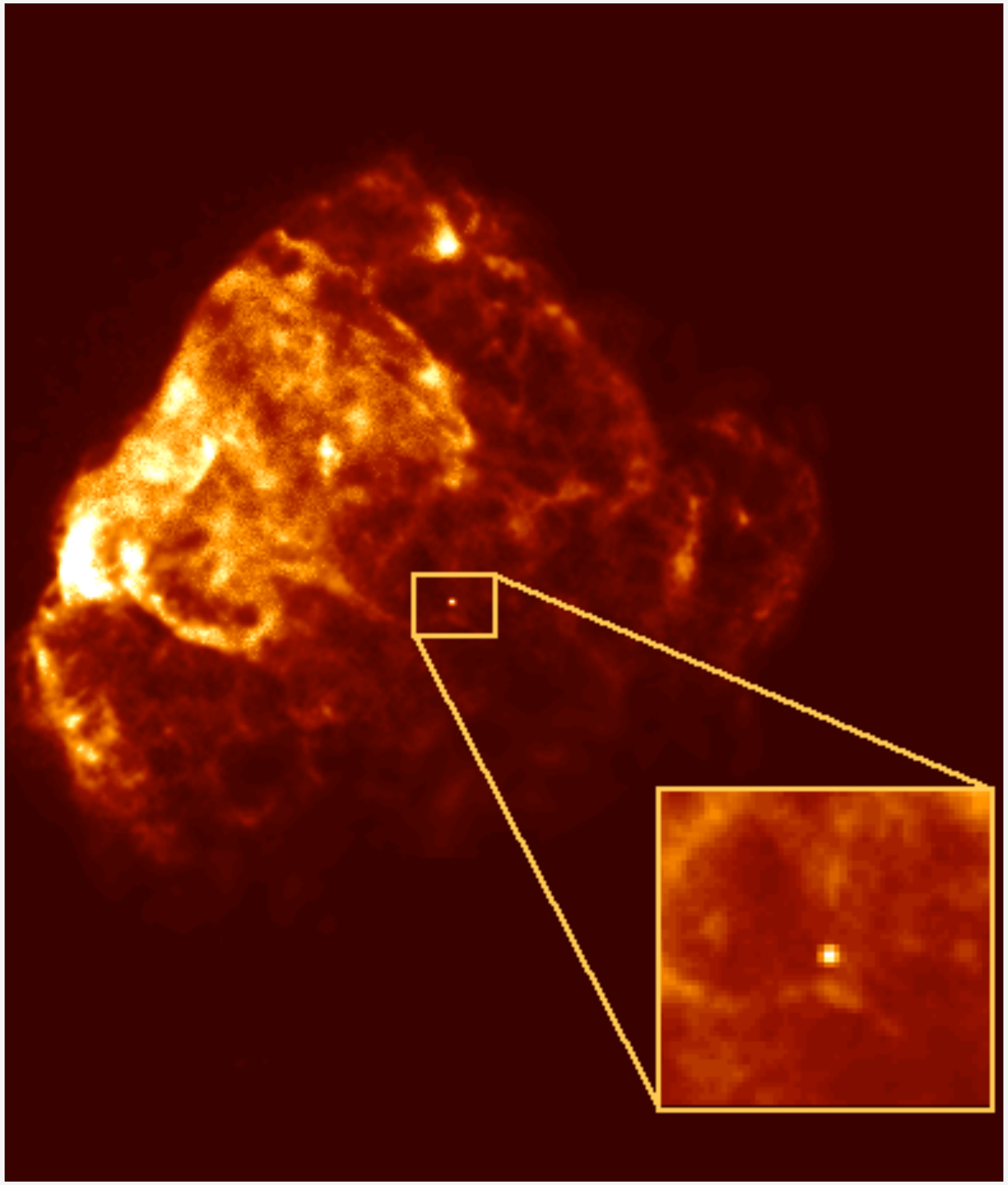


John Rowe Animation/Australia Telescope National Facility, CSIRO



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., $n+n \rightarrow n+p+e^{-}+\bar{\nu}_e$.

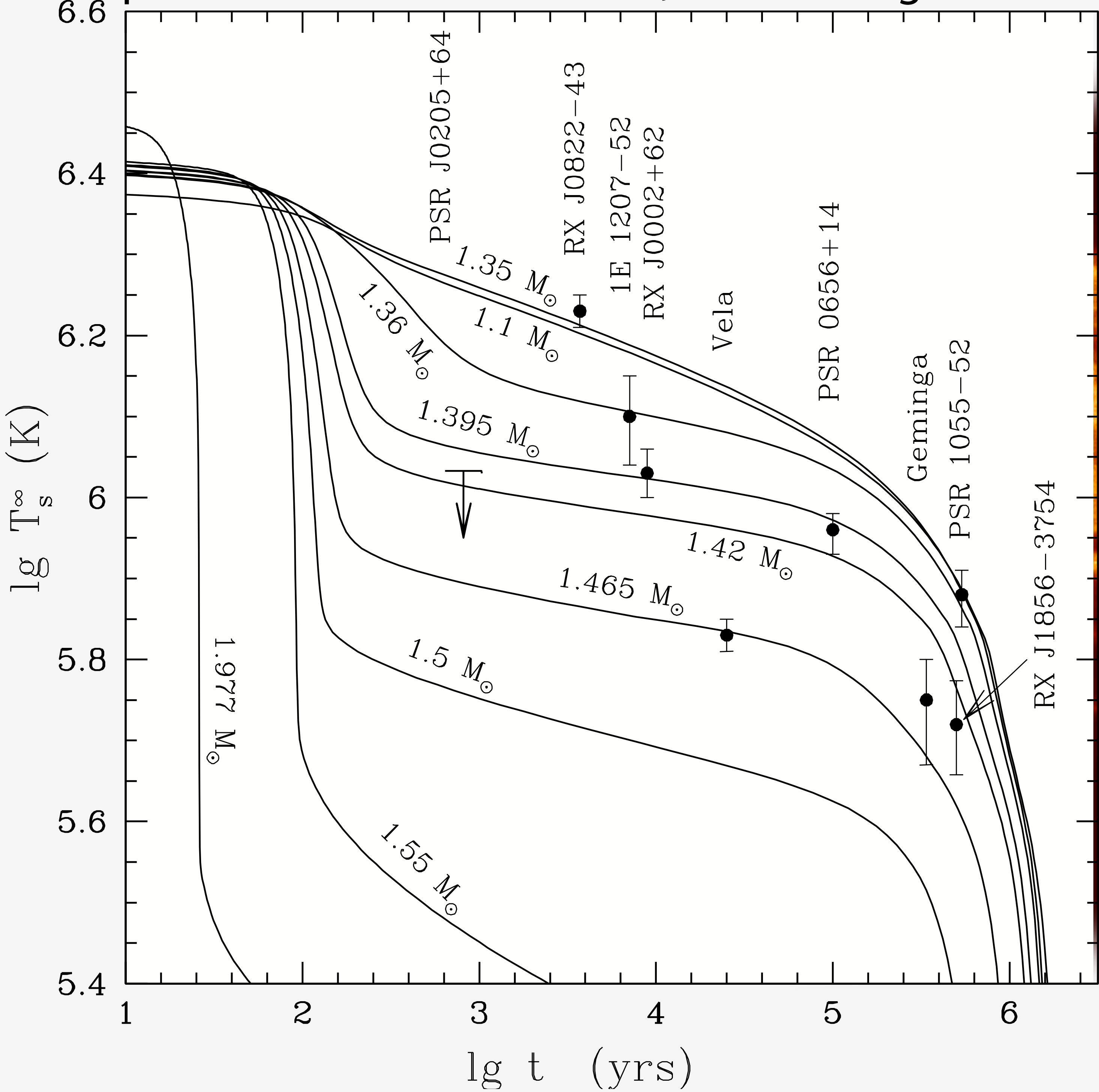
This rate is > 10^6 times slower at typical $T < 10^8$ K.

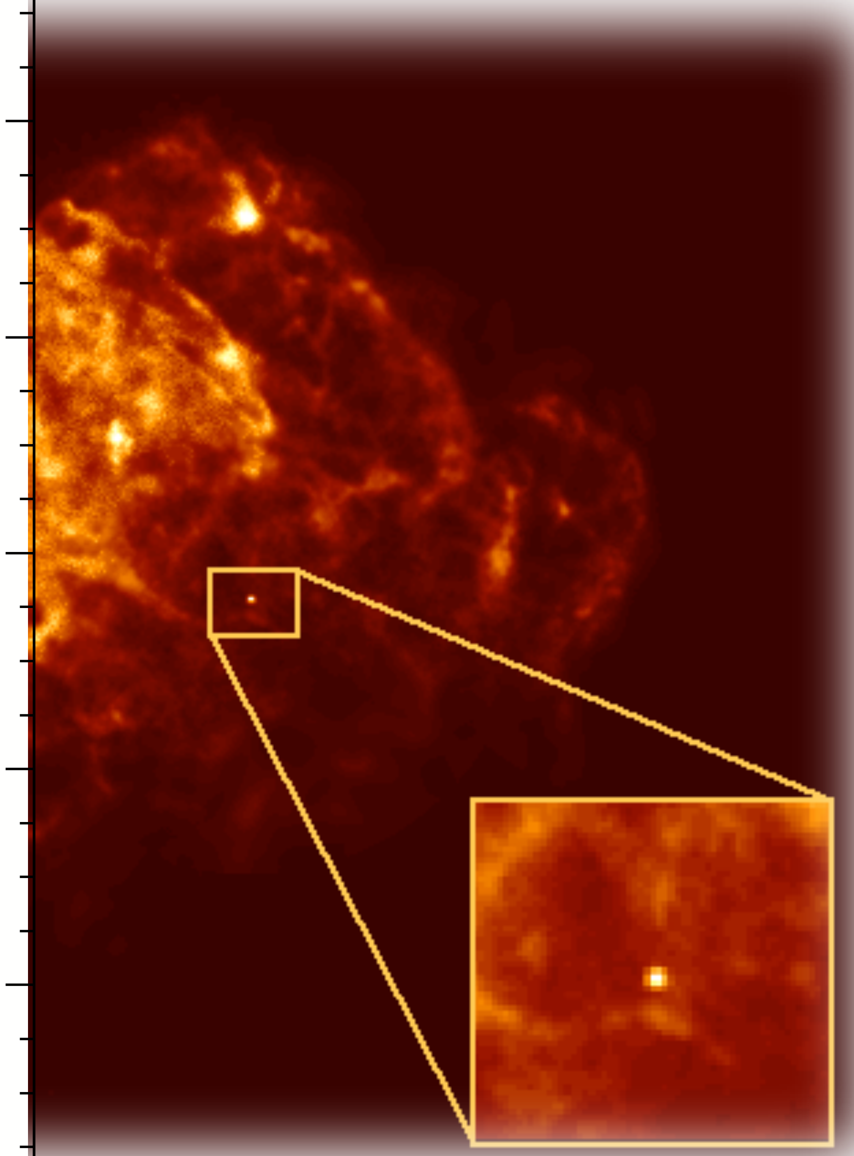
If $n_{\mathrm{p}}/n > 0.11$, direct process can go. Also if other channels, e.g. hyperons, are available.

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

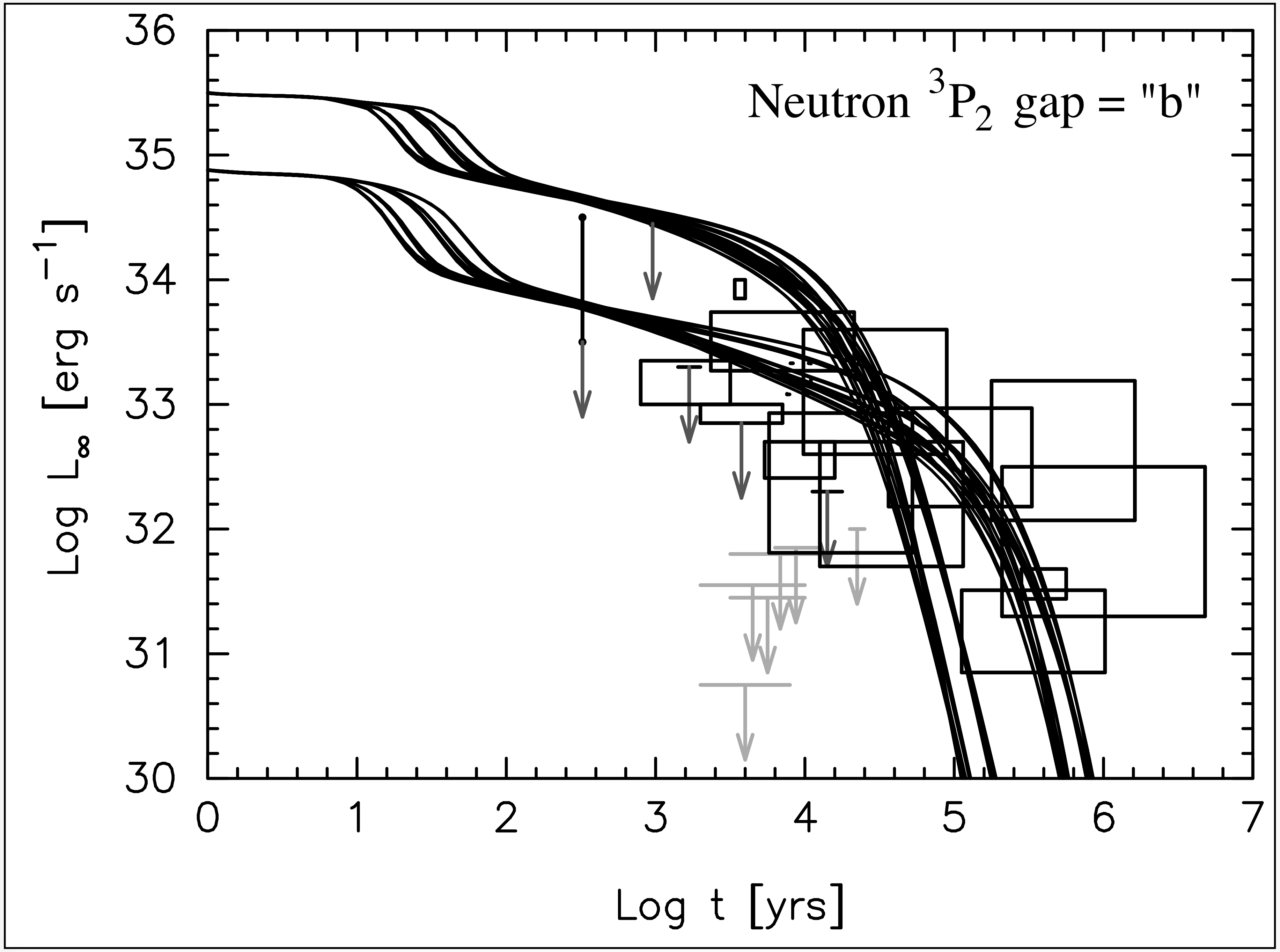
plot from Yakovlev et al. ‘02; see also Page et al. ’04, ’09

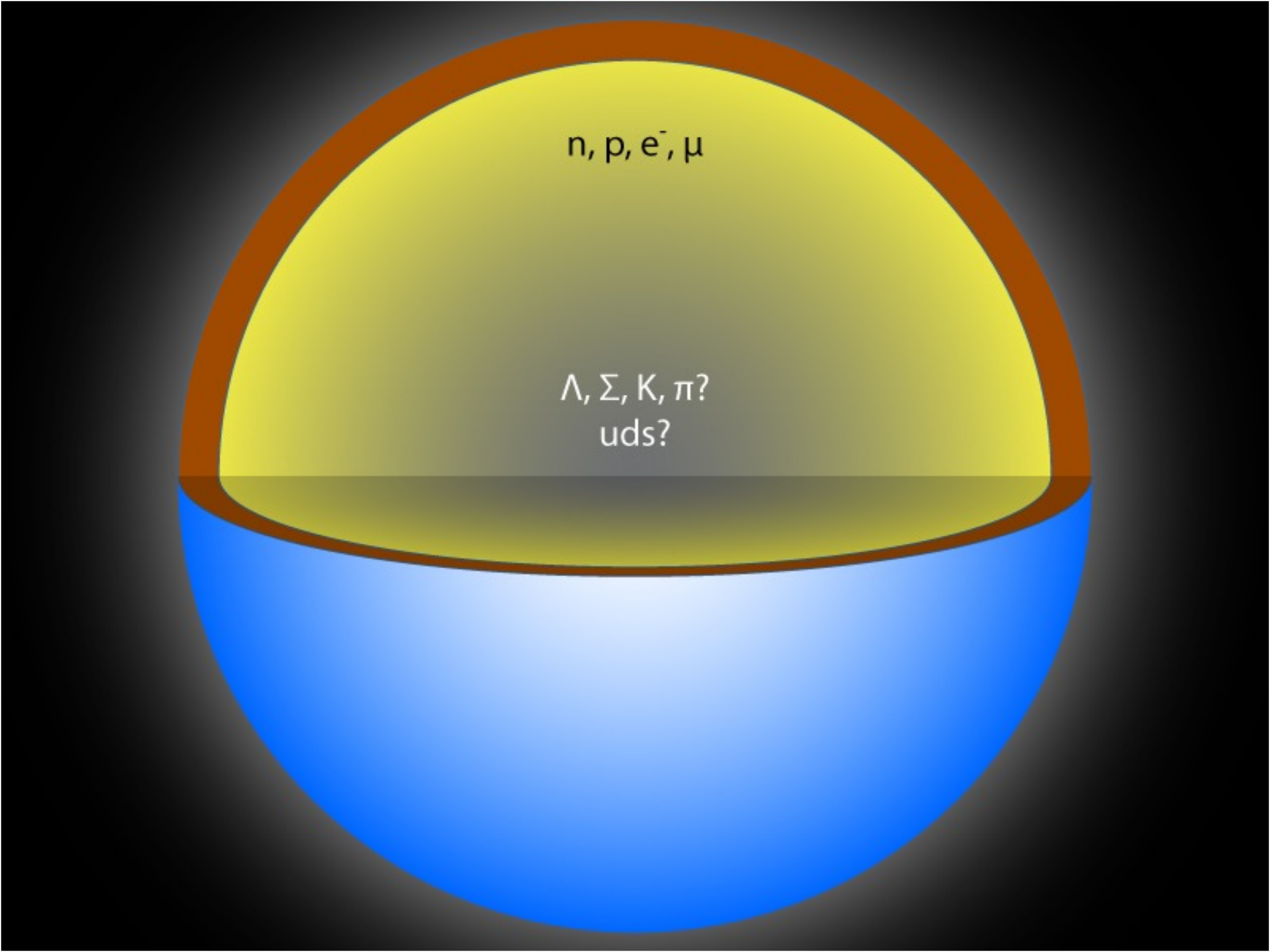




Models with no enhanced cooling

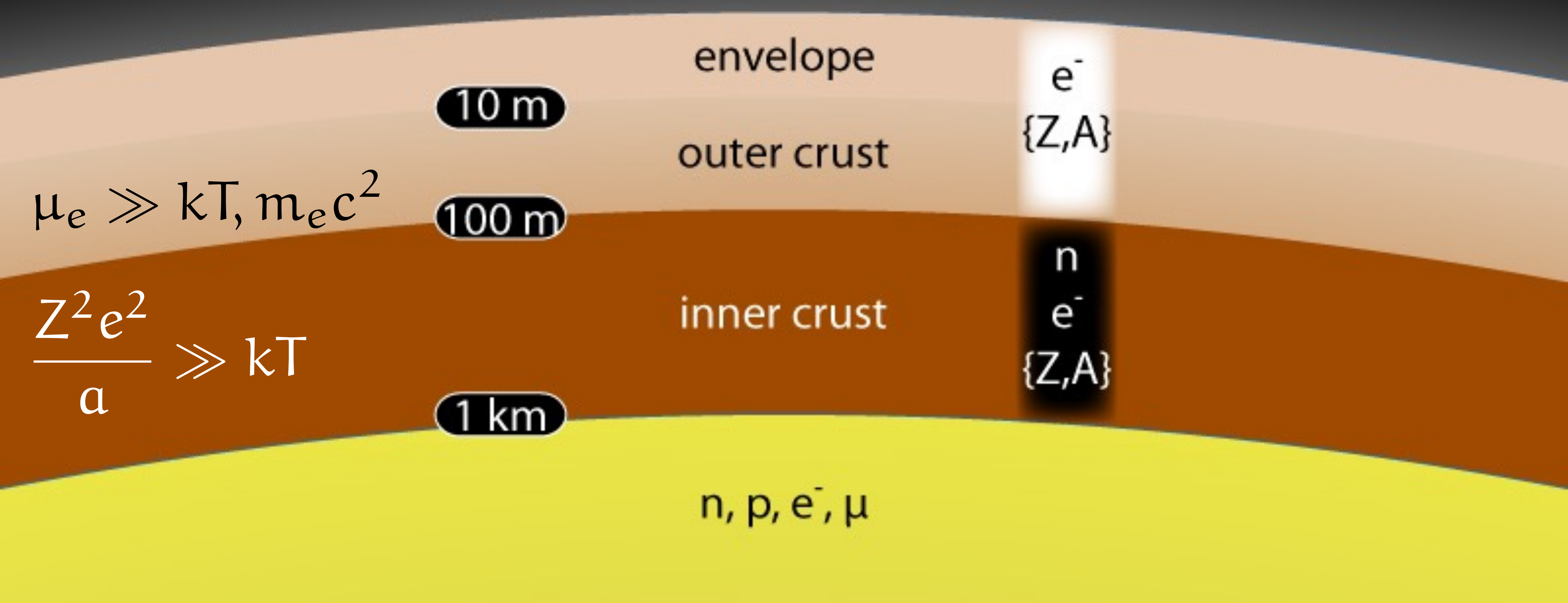
Page, Lattimer, Prakash, & Steiner 2009

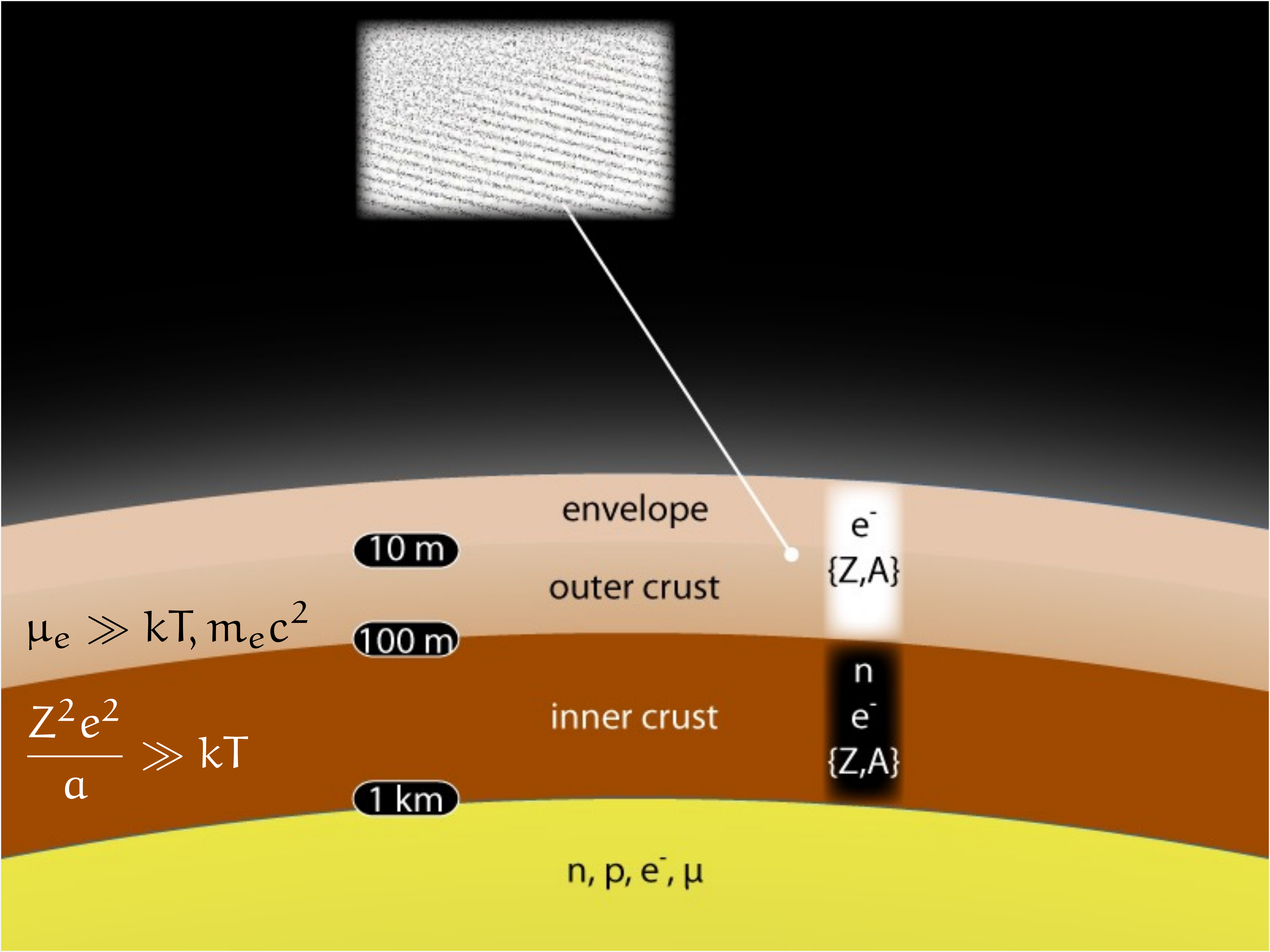


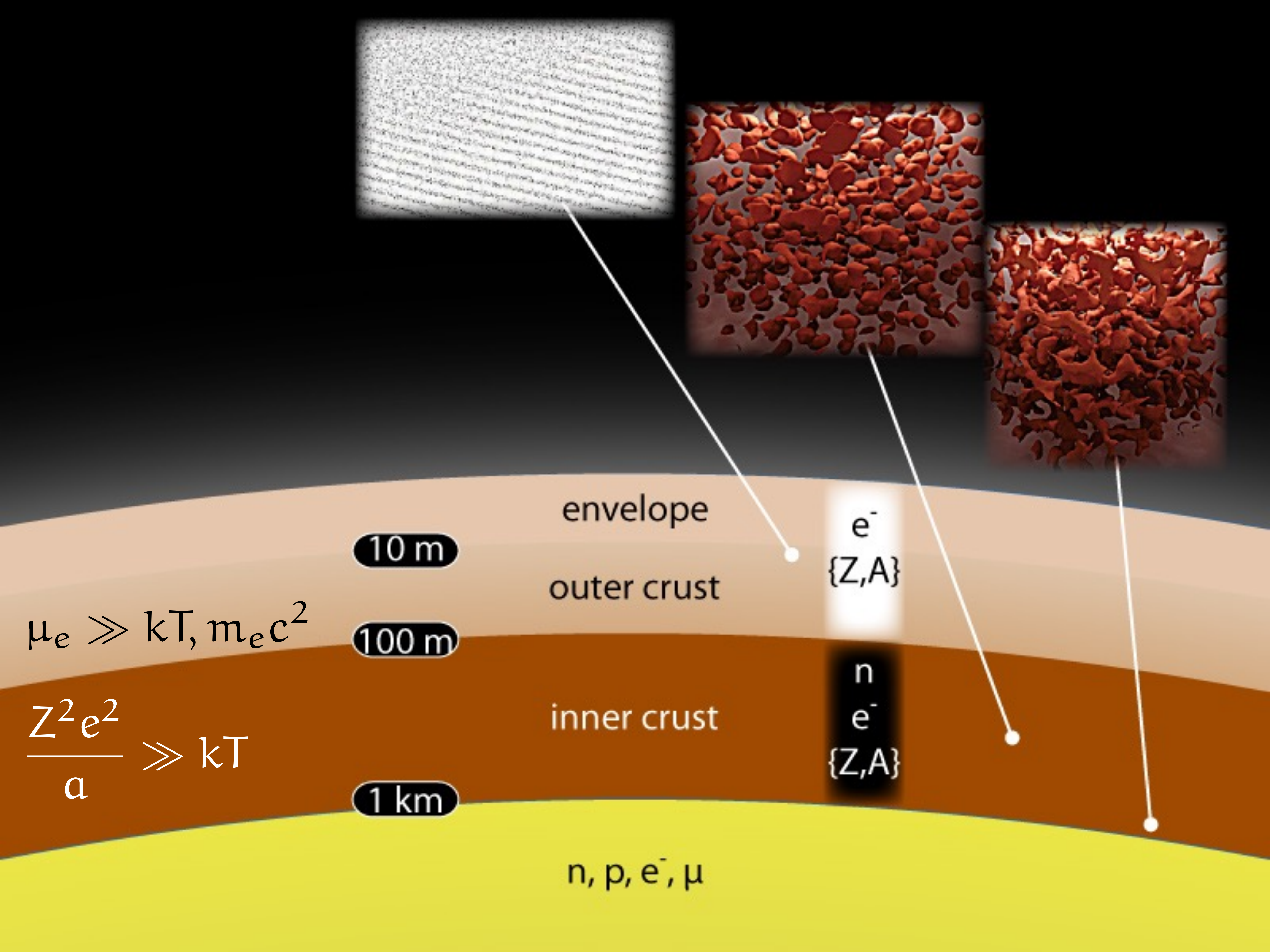

n, p, e⁻, μ
Λ, Σ, K, π?
uds?

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

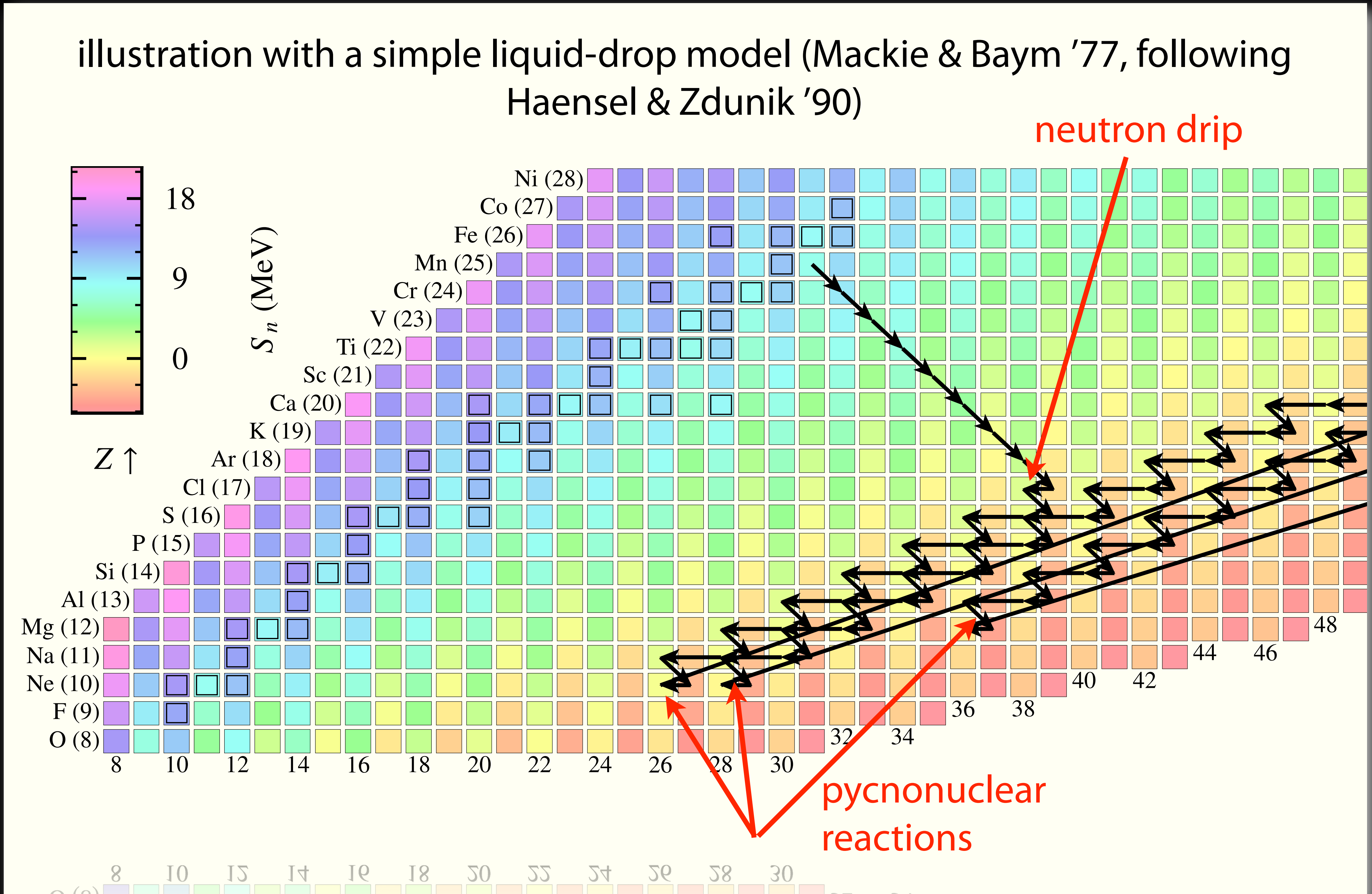
$$\frac{Z^2 e^2}{a} \gg kT$$




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

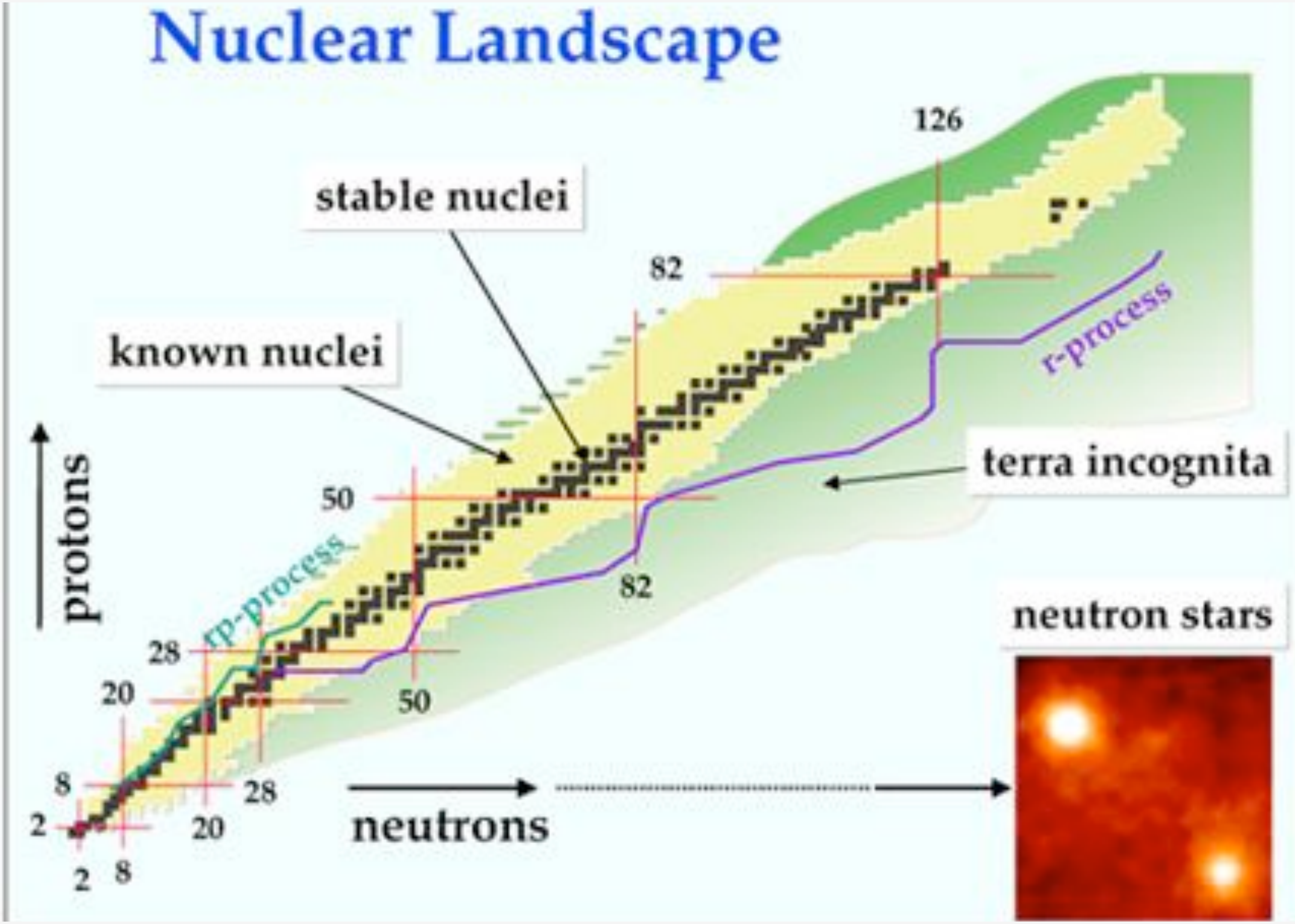


envelope
10 m
outer crust
100 m
inner crust
1 km
e⁻
{Z,A}
n
e⁻
{Z,A}
n, p, e⁻, μ
$\mu_e \gg kT, m_e c^2$
$\frac{Z^2 e^2}{a} \gg kT$



crust reactions

Sato '79; Haensel & Zdunk '90; Gupta et al. '07; Steiner '12; Schatz et al. '13; Lau et al. (in prep)



Many of these reactions are within reach of FRIB

Disordered nuclear pasta, magnetic field decay, and crust cooling in neutron stars

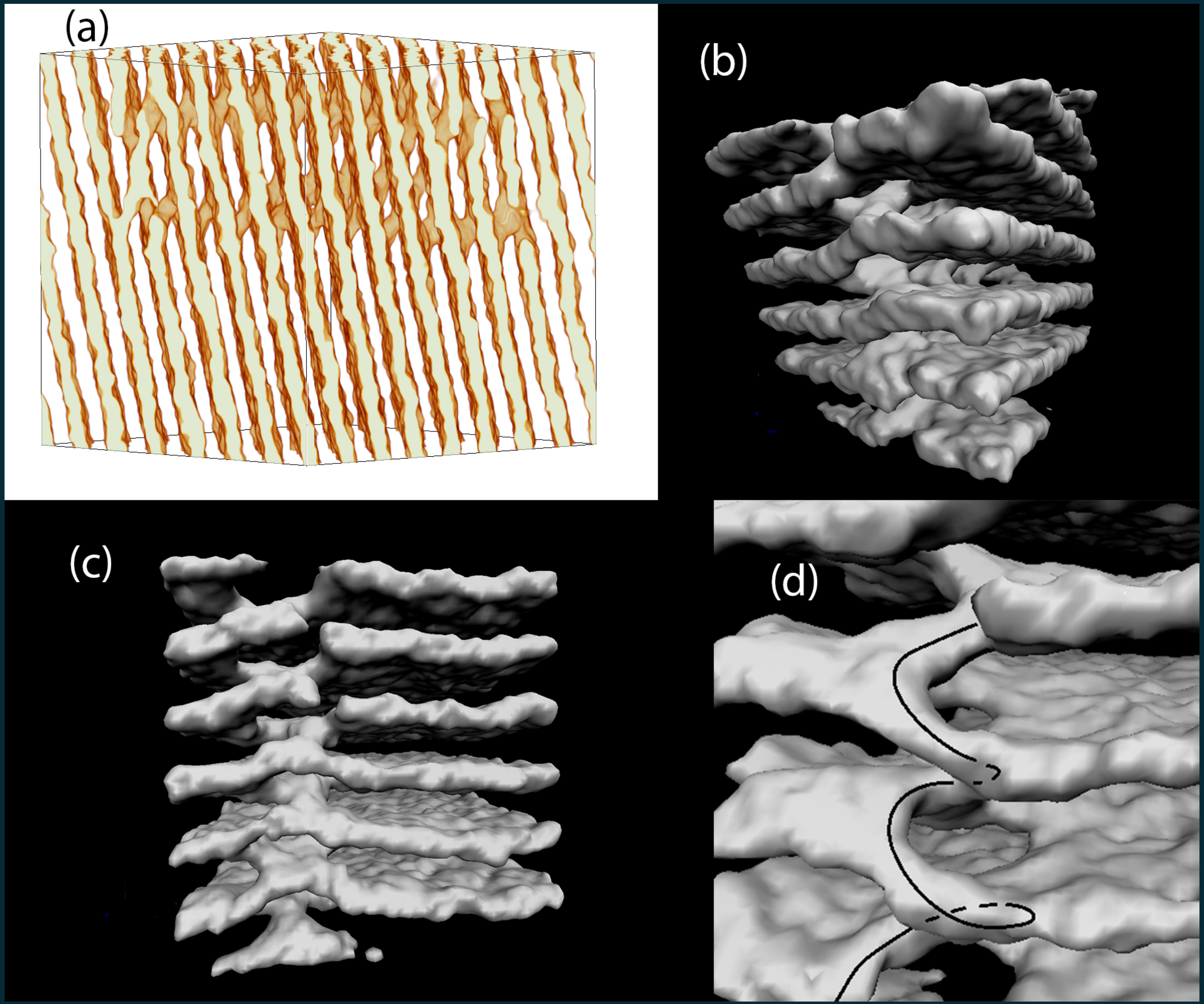
C. J. Horowitz,[1,*] D. K. Berry,[2] C. M. Briggs,[1] M. E. Caplan,[1] A. Cumming,[3] and A. S. Schneider[1]

[1] *Department of Physics and Center for the Exploration of Energy and Matter, Indiana University, Bloomington, IN 47405, USA*

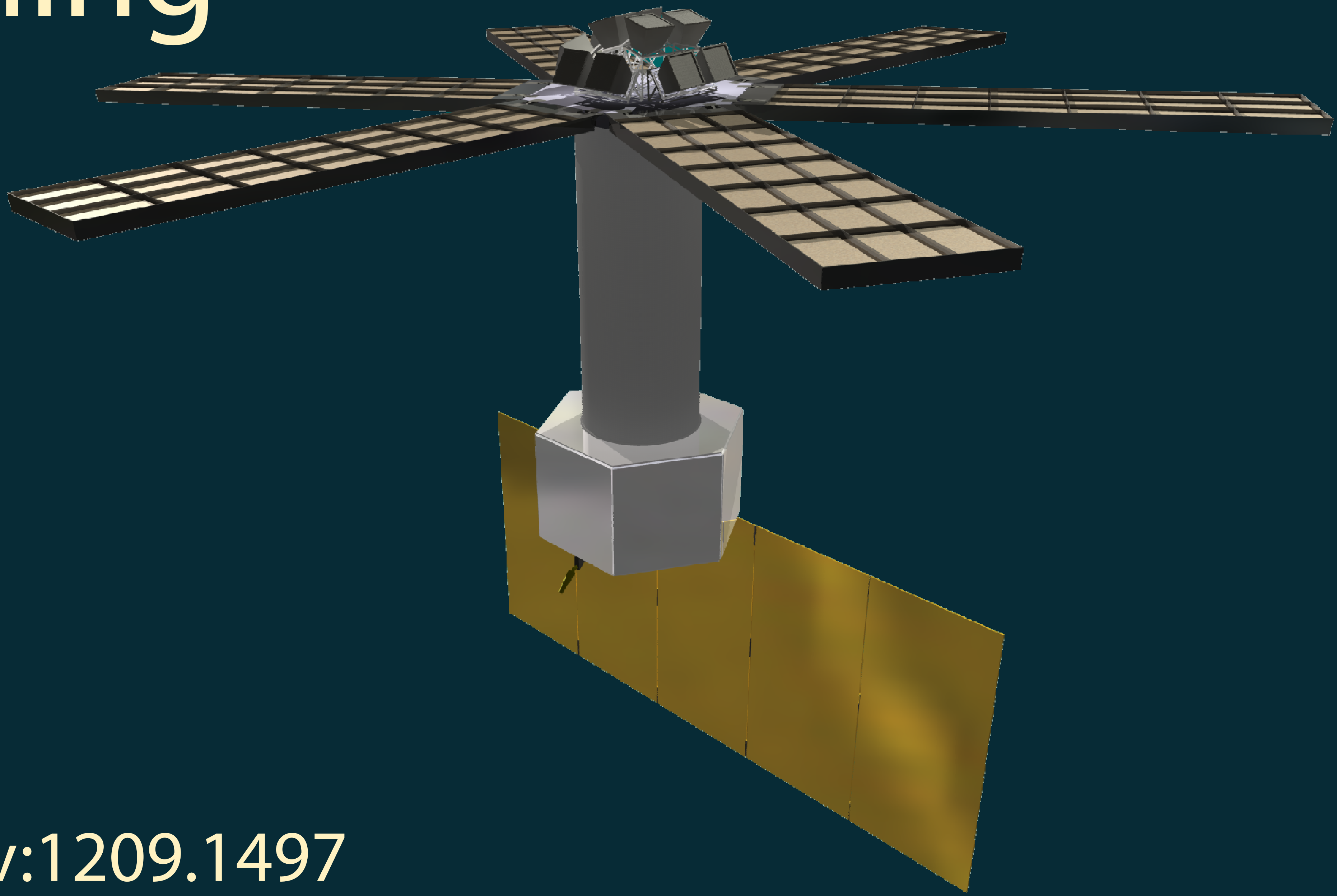
[2] *University Information Technology Services, Indiana University, Bloomington, IN 47408, USA*

[3] *Department of Physics, McGill University, 3600 rue University, Montreal QC, H3A 2T8 Canada*

(Dated: October 9, 2014)



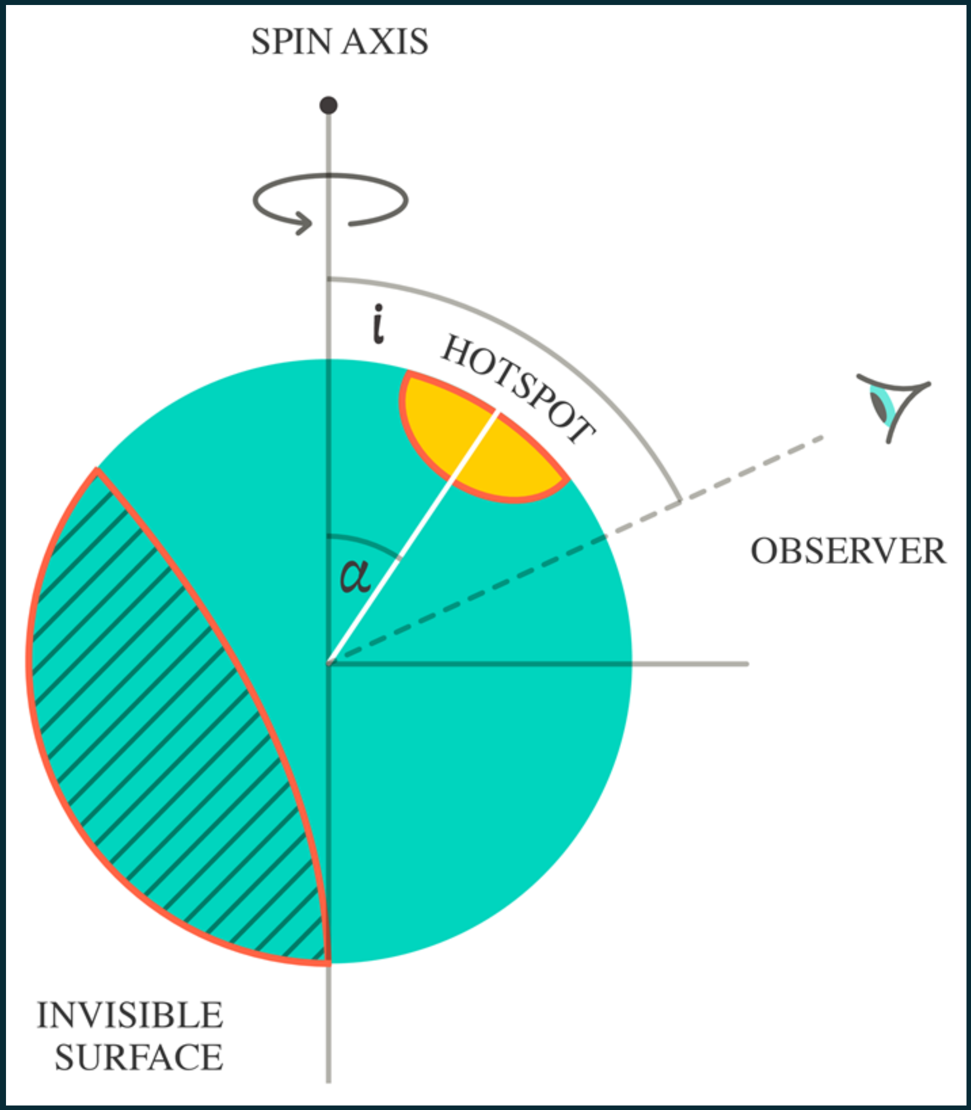
Large Observatory For x-ray Timing

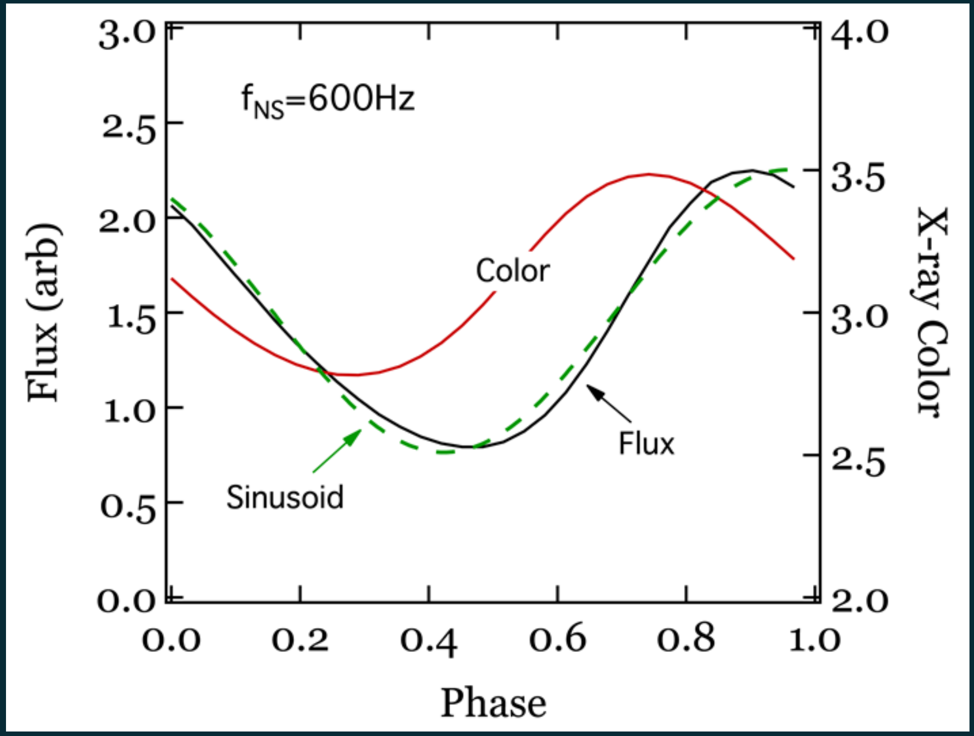


arxiv:1209.1497

Figure 2. A pictorial view of the LOFT mission currently being studied by the LOFT Consortium, showing the deployed LAD panels, including the detector modules, as well as the 10 cameras comprising the 5 units of the WFM. The structure of 21 Modules in each Panel is shown, although the individual detector tiles are not visible. A structural tower supports the optical bench, with the service module supporting the solar panel array.

EOS from pulse phase spectroscopy





LOFT yellow book

LIGO. Hanford, WA site: will it observe neutron stars?

Summary

- A number of observational probes of the nuclear EOS are available
  - pulsar masses
  - masses and radii from X-ray bursts, seismology
  - cooling of isolated neutron stars, thermal relaxation of accreting transients
  - gravitational wave emission
- No single observation is ideal and there are substantial systematic uncertainties—it's astrophysics; but
- These observations, taken together, offer interesting constraints and complement theoretical and experimental efforts in nuclear physics
- *Stay tuned! There are lots of opportunities to make advances in the next few years.*