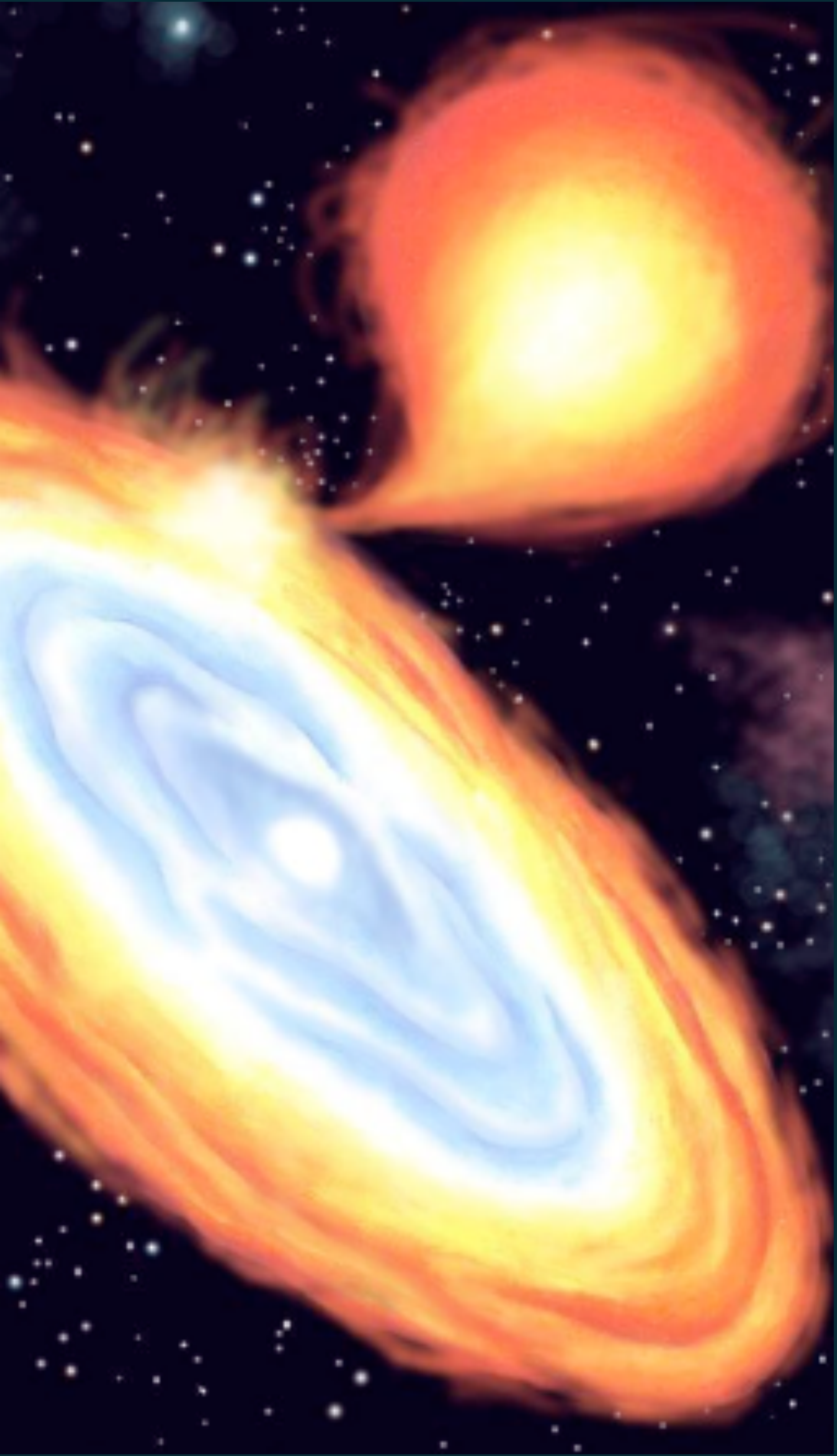

Neutron Stars and Dense Matter

Edward Brown
Michigan State University

Joint Institute for Nuclear Astrophysics

artwork courtesy T. Piro

Origin of Stellar Energy

It is well known that matter consists of nuclei and electrons. Nevertheless it can be shown that in bodies of very large mass, this usual 'electronic' state of matter can become unstable. The reason for this lies in the fact that the 'electronic' state of matter does not lead to extremely great densities, because at such densities electrons form a Fermi gas having an immense pressure. On the other hand, it is easy to see that matter can go into another state which is much more compressible—the state where all the nuclei and electrons have combined to form neutrons.[1] Even if we assume that neutrons repel each other, this repulsion can become appreciable only at densities of the order of magnitude of nuclear densities, that is, 10^{14} gm./cm.^{3}, and the pressure of a Fermi gas consisting of neutrons is much less than that of an electronic gas of the same density, because of the greater mass of the neutrons.

As regards the question of how the initial core is formed, I have already shown[2] that the formation of a core must certainly take place in a body with a mass greater than 1·5 ⊙. In stars with smaller mass the conditions which make the formation of the initial core possible have yet to be made clear.

L. Landau.

Institute for Physical Problems,
Academy of Sciences,
Moscow.

[1] Cf. Hund, F., *Erg. d. exakten Natwis.* **15**, 189 (1936).
[2] Landau, L., *Sov. Phys.*, **1**, 285 (1932).

Origin of Stellar Energy

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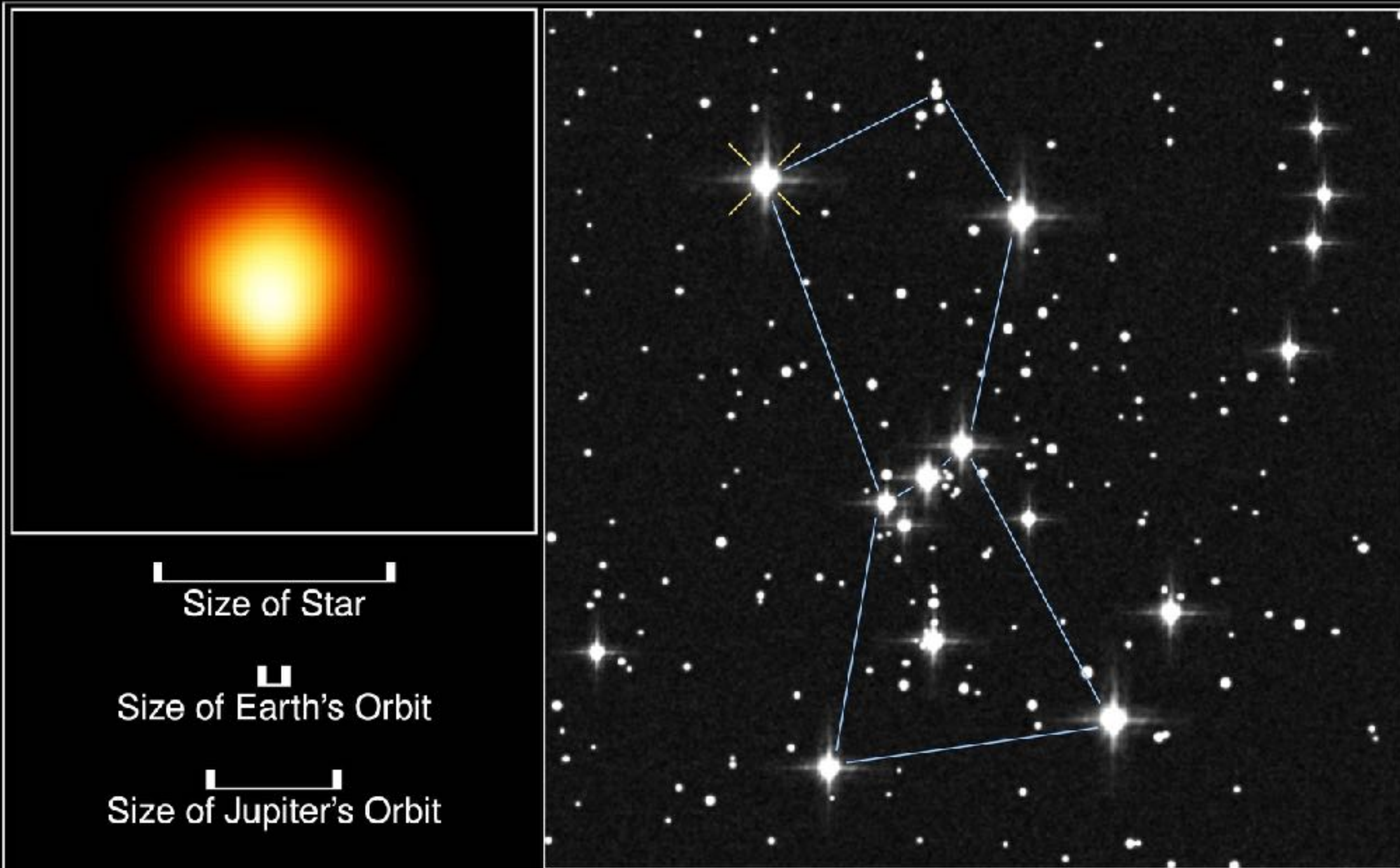
5. *The super-nova process*

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.

How are they formed?

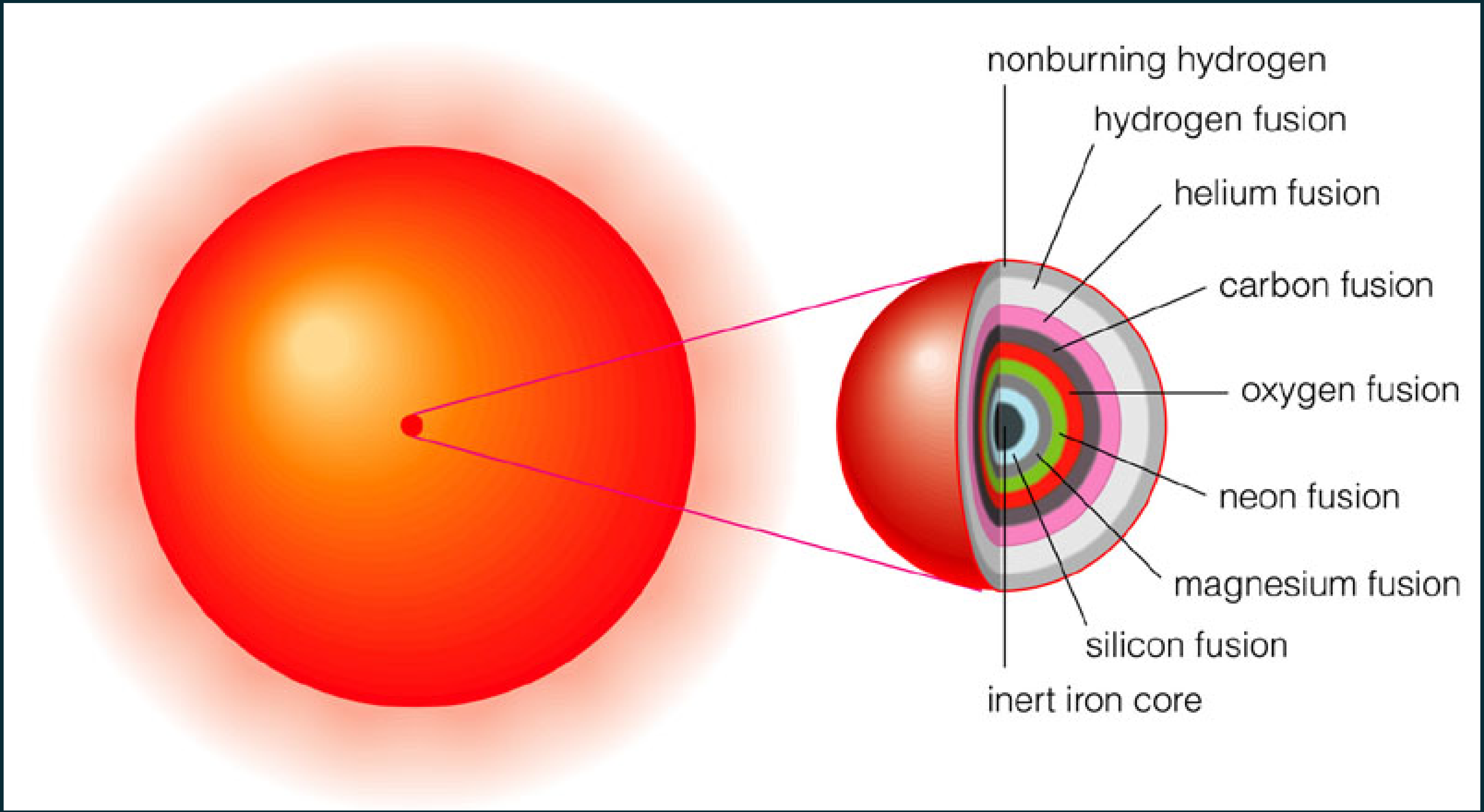


Atmosphere of Betelgeuse · Alpha Orionis

Hubble Space Telescope · Faint Object Camera

PRC96-04 · ST ScI OPO · January 15, 1996 · A. Dupree (CfA), NASA, ESA

Massive Star | Final Days



Essential Cosmic Perspective, Bennett et al.

Stellar Death

Pressure in core becomes too high, electrons capture onto protons: $e + p \to n + \bar{\nu}_e$

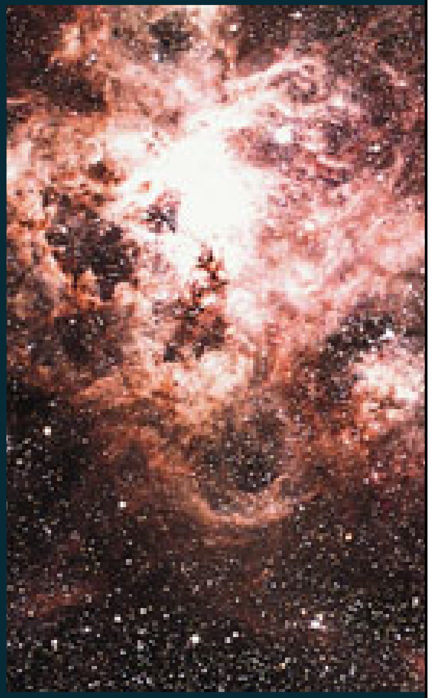
This forces core to contract, making pressure even higher…

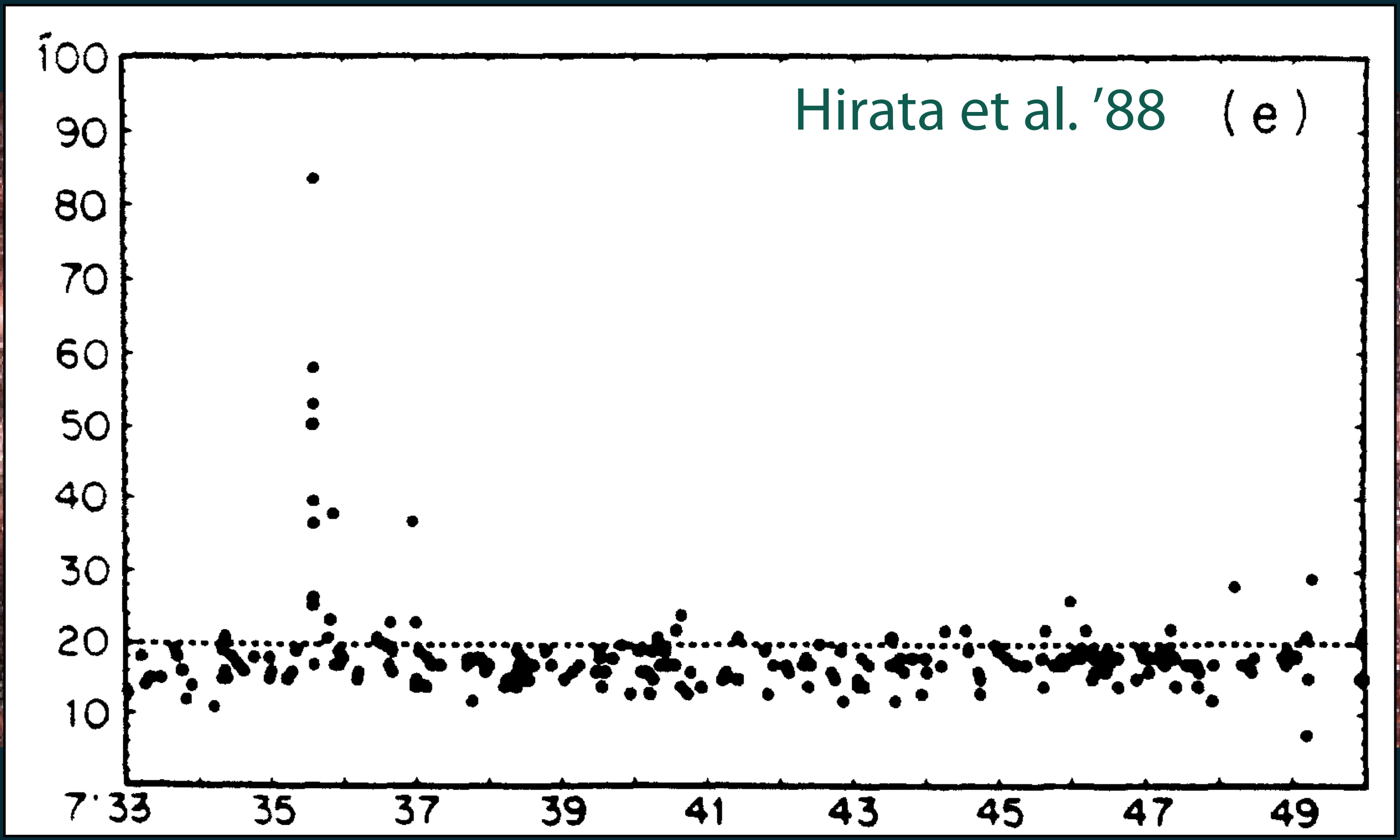
Collapse stops when nuclear density reached

1987a | neutrinos detected

Hirata et al. '88

1987a | neutrinos detected





neutron star | basics

Collapse halts when we reach nuclear density; distance between neutrons is $r_N \sim 1\,\mathrm{fm}$. A solar mass contains $N \approx 10^{57}$ nucleons, so the radius is

$$R \sim r_N N^{1/3} \approx 10\,\mathrm{km}.$$

neutron star | basics

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neutron star | basics

The gravitational potential is enormous. Dropping 1 proton (rest mass 938 MeV) liberates

$$\frac{GMm_p}{R} \approx 200\,\text{MeV} \approx 0.2 m_p c^2 .$$

General relativity is important.

neutron star | basics

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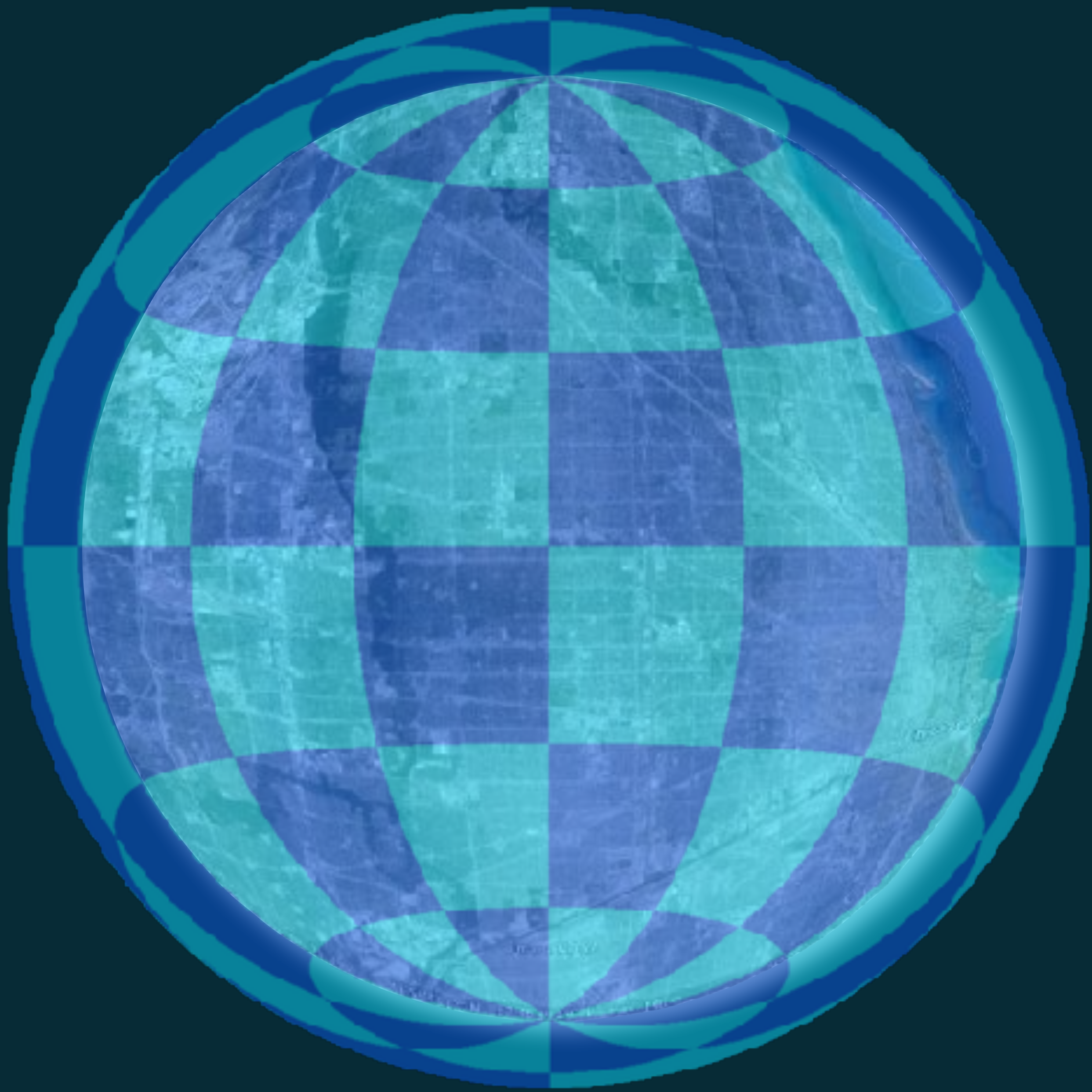

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ideal gas | $M_{max} = 0.75\ M_{sun}$

FEBRUARY 15, 1939 PHYSICAL REVIEW VOLUME 55

On Massive Neutron Cores

J. R. Oppenheimer and G. M. Volkoff
Department of Physics, University of California, Berkeley, California

(Received January 3, 1939)

It has been suggested that, when the pressure within stellar matter becomes high enough, a new phase consisting of neutrons will be formed. In this paper we study the gravitational equilibrium of masses of neutrons, using the equation of state for a cold Fermi gas, and general relativity. For masses under $\frac{1}{3}\odot$ only one equilibrium solution exists, which is approximately described by the nonrelativistic Fermi equation of state and Newtonian gravitational theory. For masses $\frac{1}{3}\odot < m < \frac{3}{4}\odot$ two solutions exist, one stable and quasi-Newtonian, one more condensed, and unstable. For masses greater than $\frac{3}{4}\odot$ there are no static equilibrium solutions.

ideal gas | $M_{max} = 0.75\ M_{sun}$

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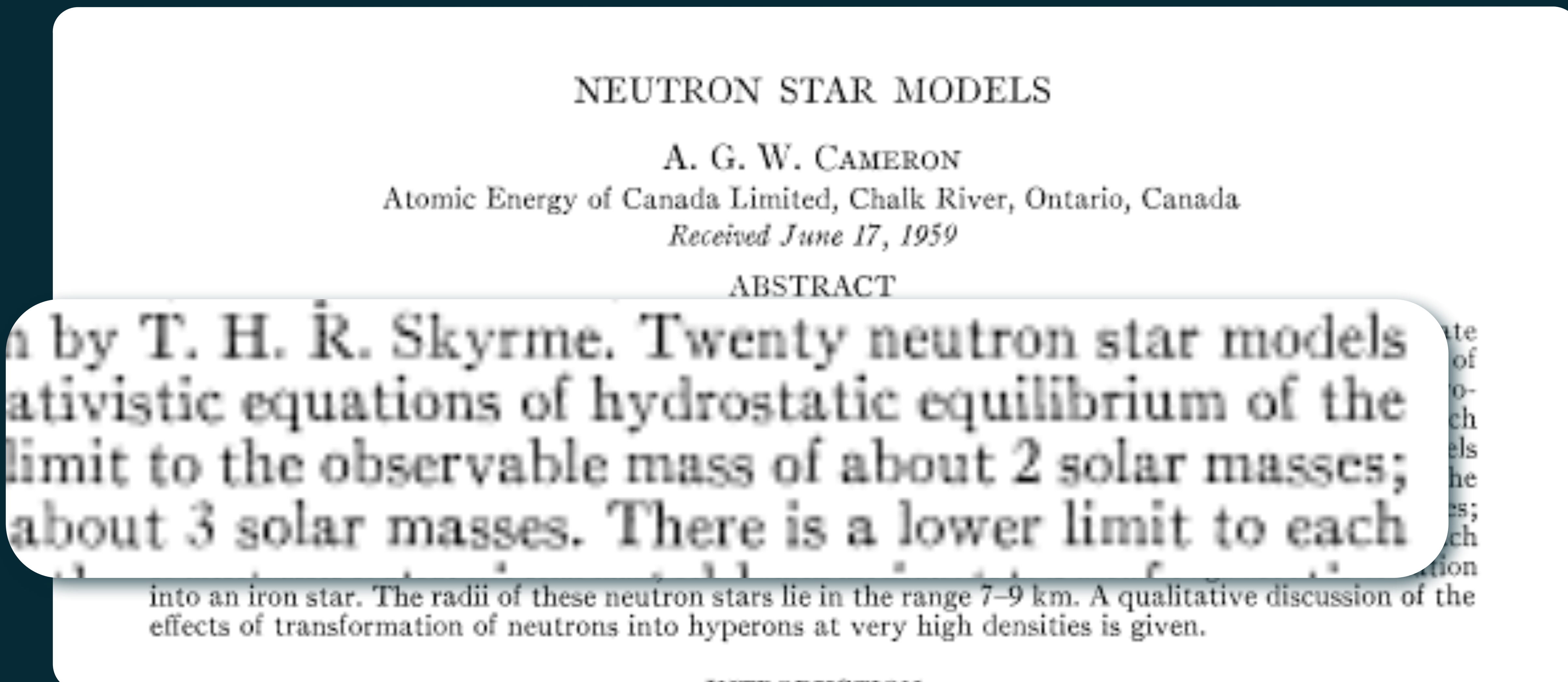
with nuclear eq. of state | $M_{max} > 2\ M_{sun}$


NEUTRON STAR MODELS

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

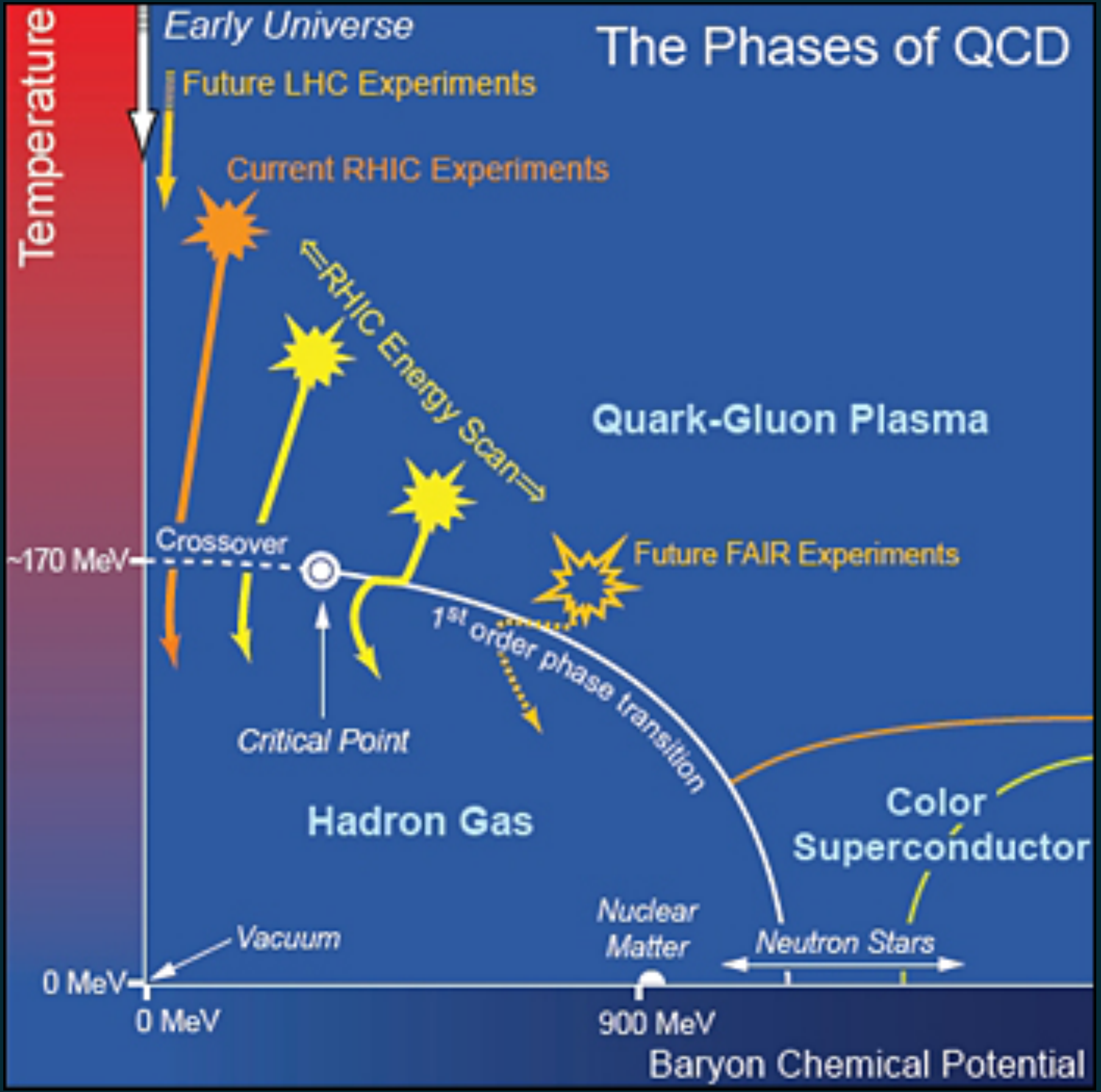
ABSTRACT

n by T. H. R. Skyrme. Twenty neutron star models
ativistic equations of hydrostatic equilibrium of the
limit to the observable mass of about 2 solar masses;
about 3 solar masses. There is a lower limit to each

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.

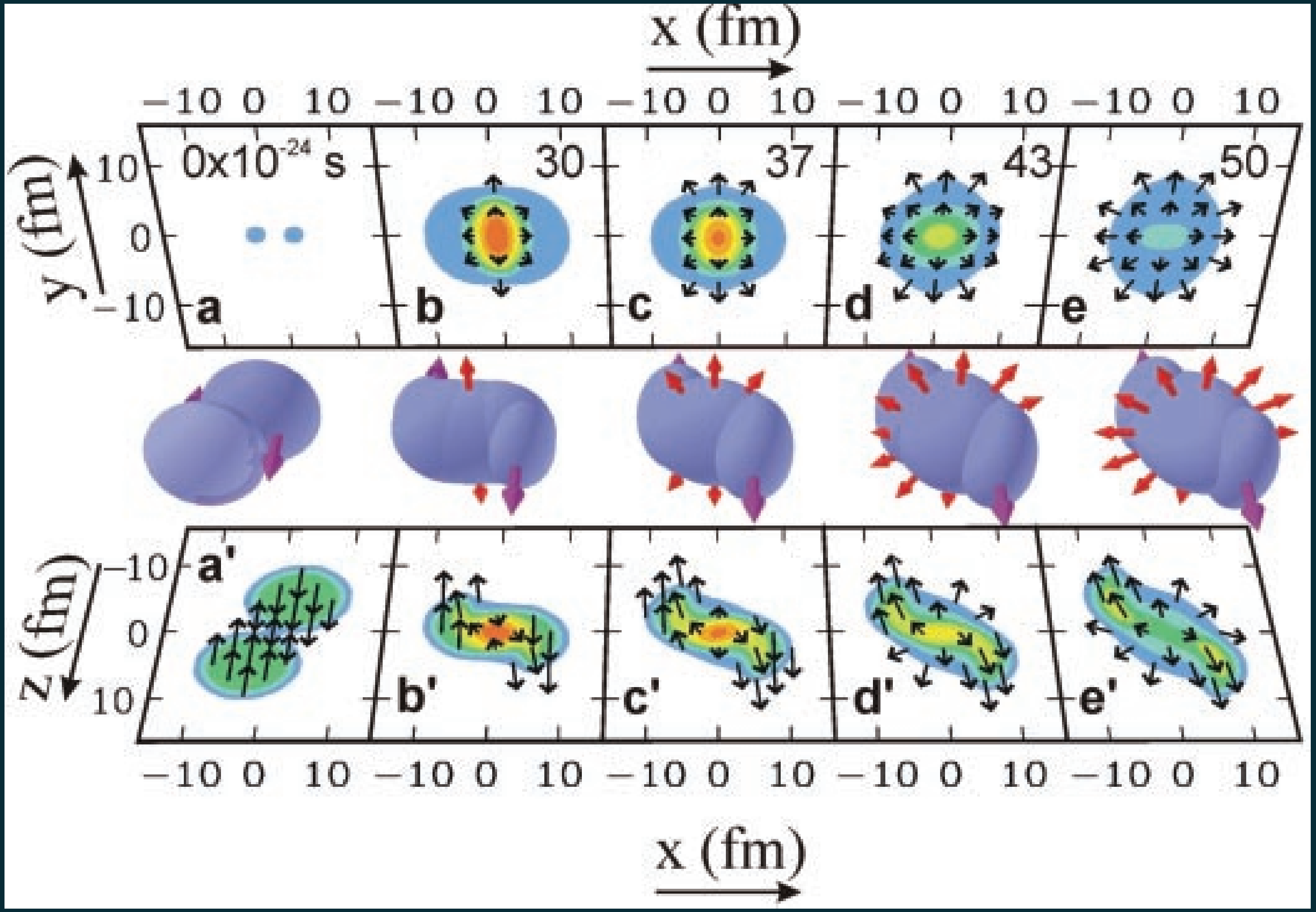
What can neutron stars teach us about dense matter?

Interest to Nuclear Physics



NSAC report '07

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



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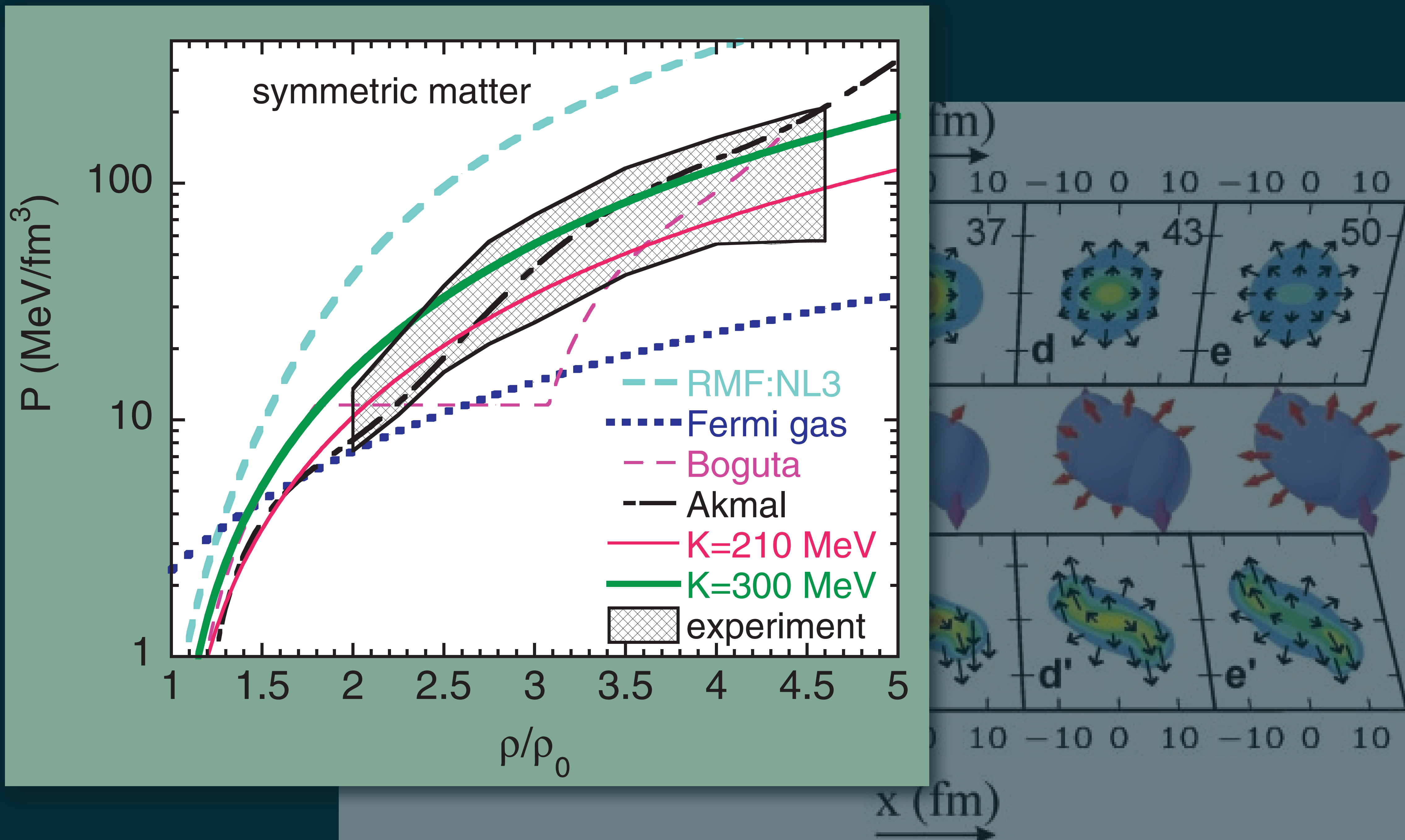
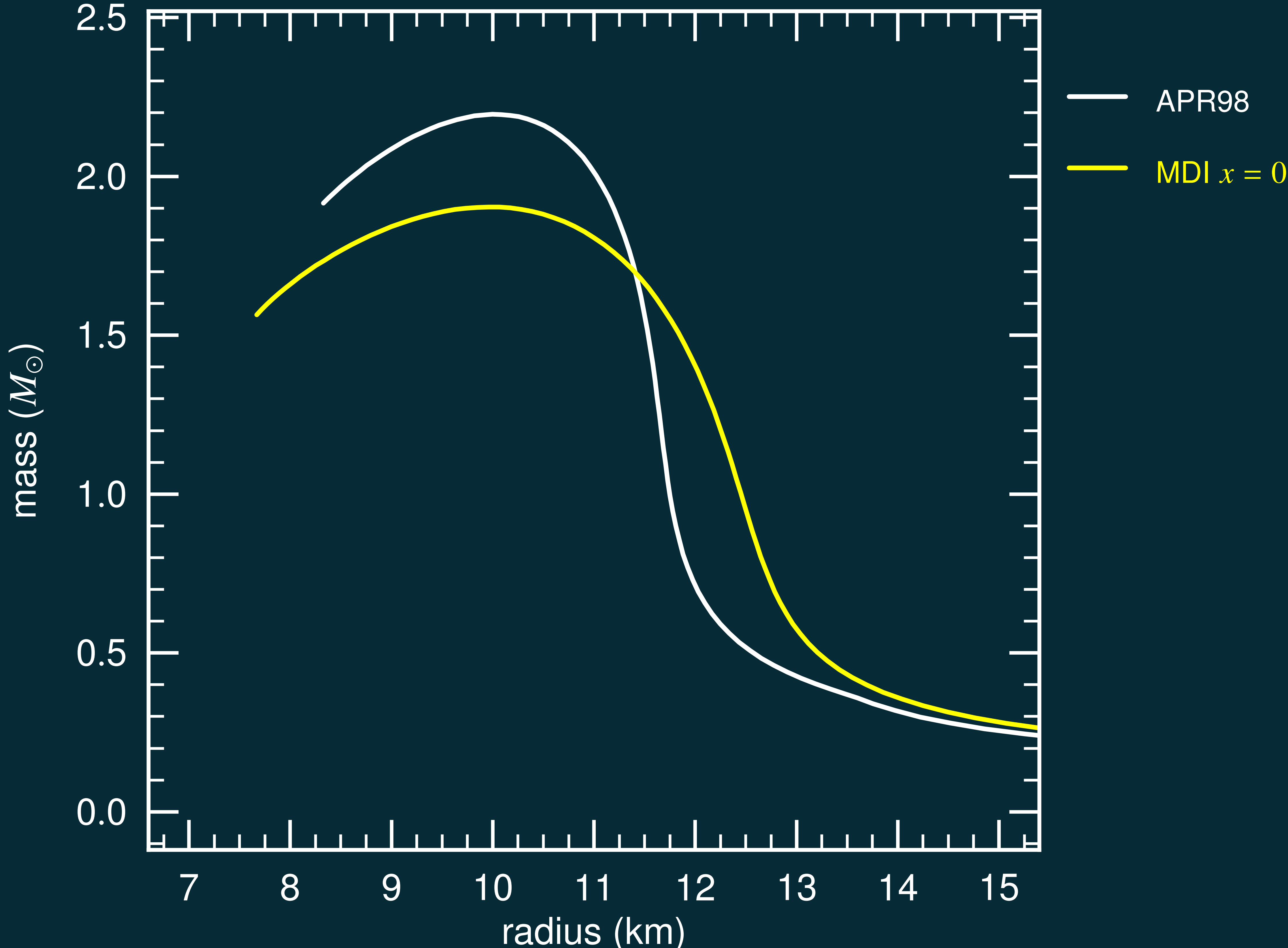
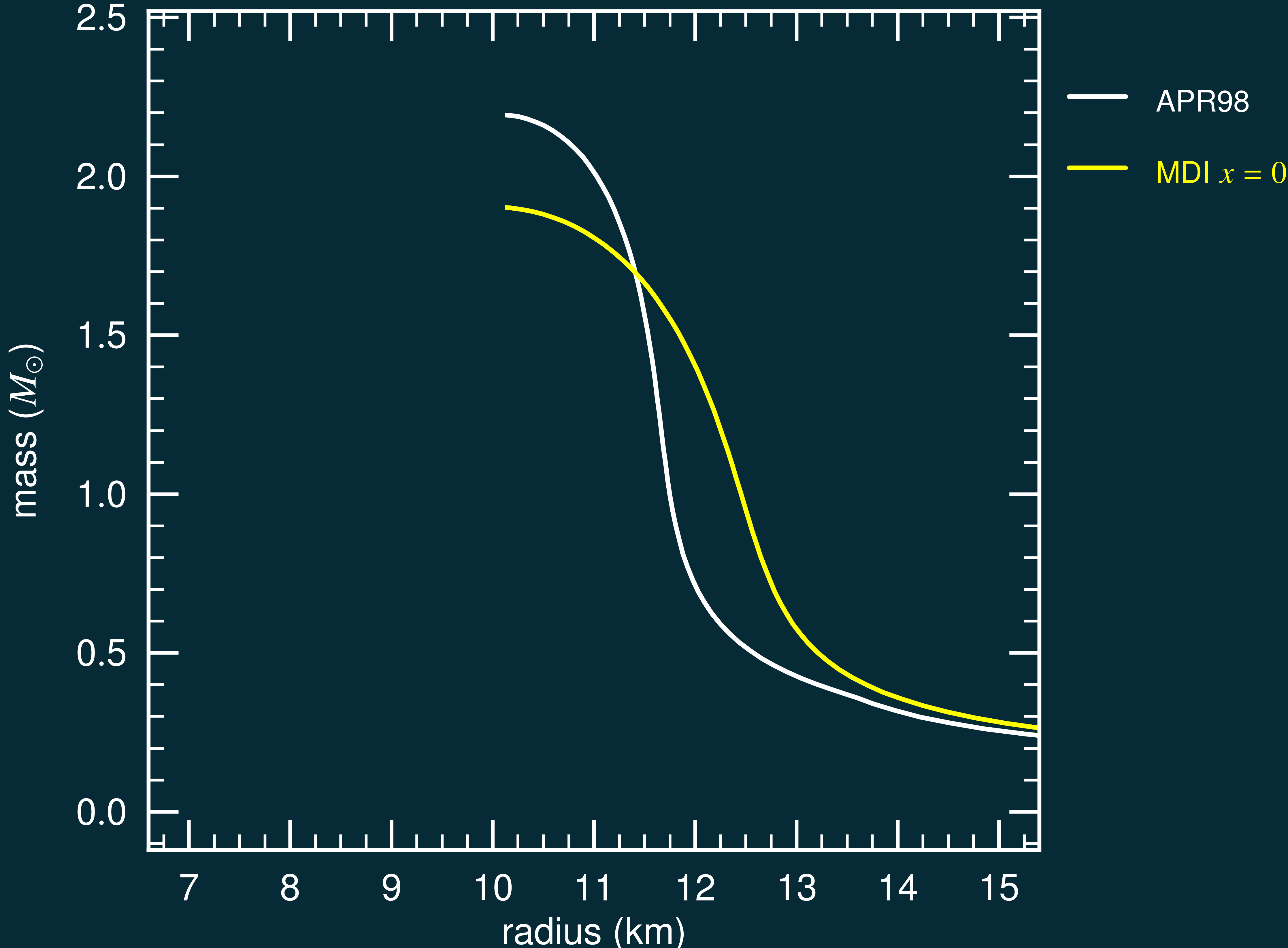


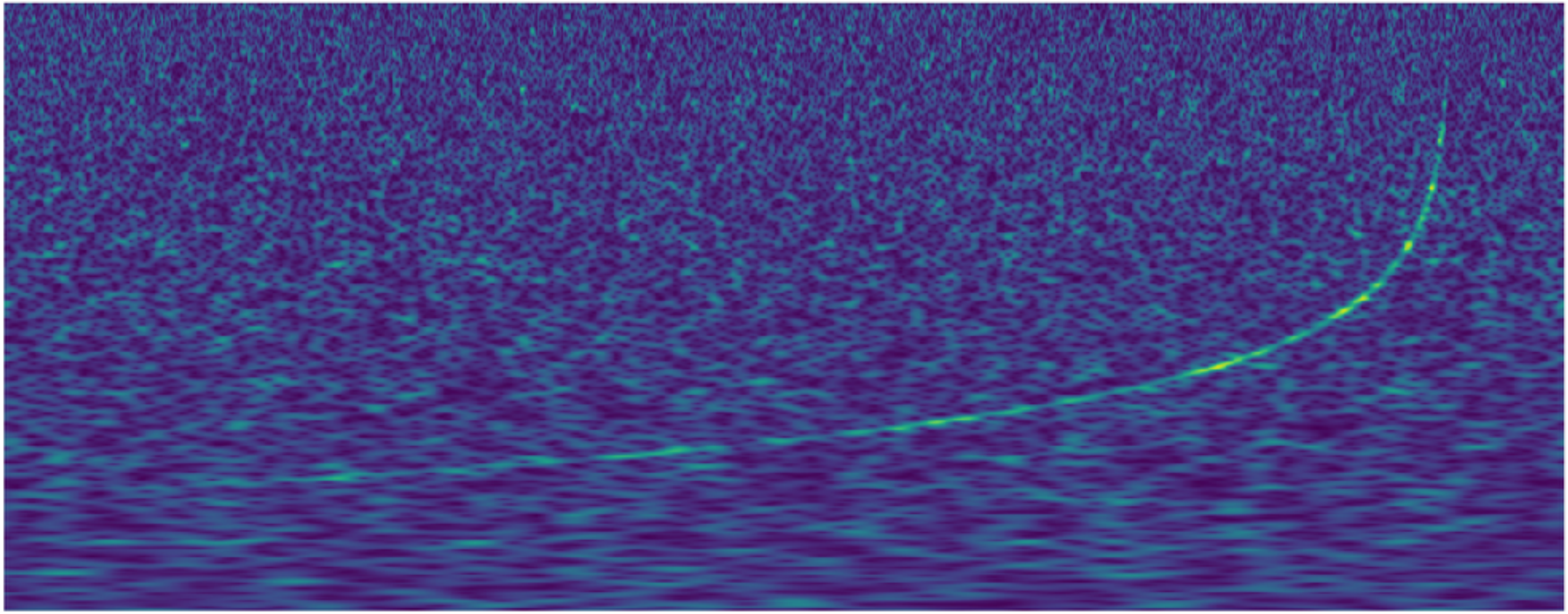
EOS | mass-radius



EOS | mass-radius

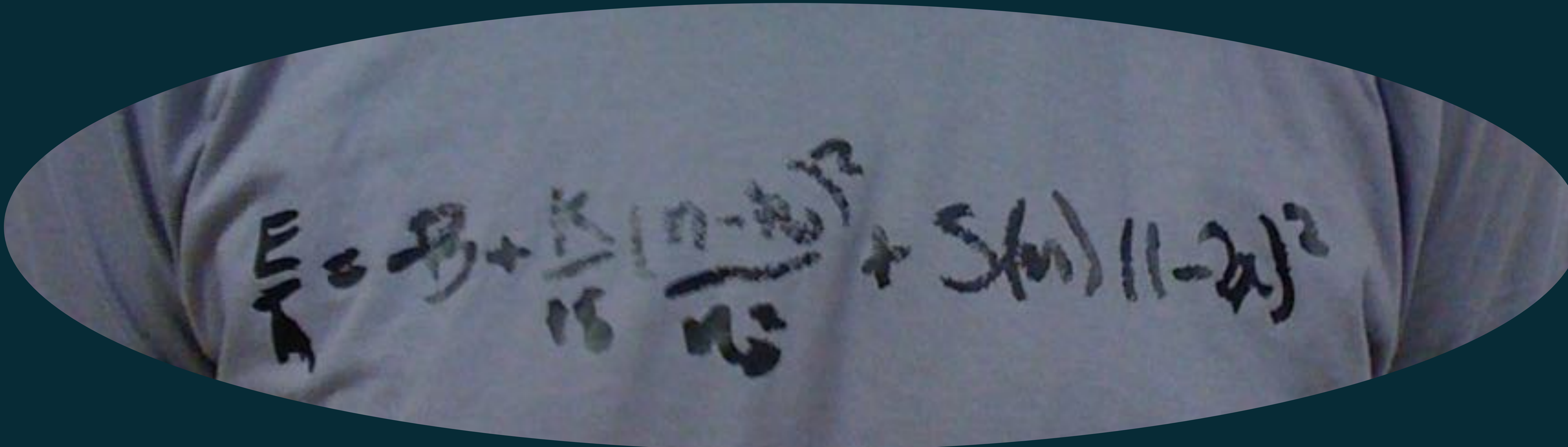


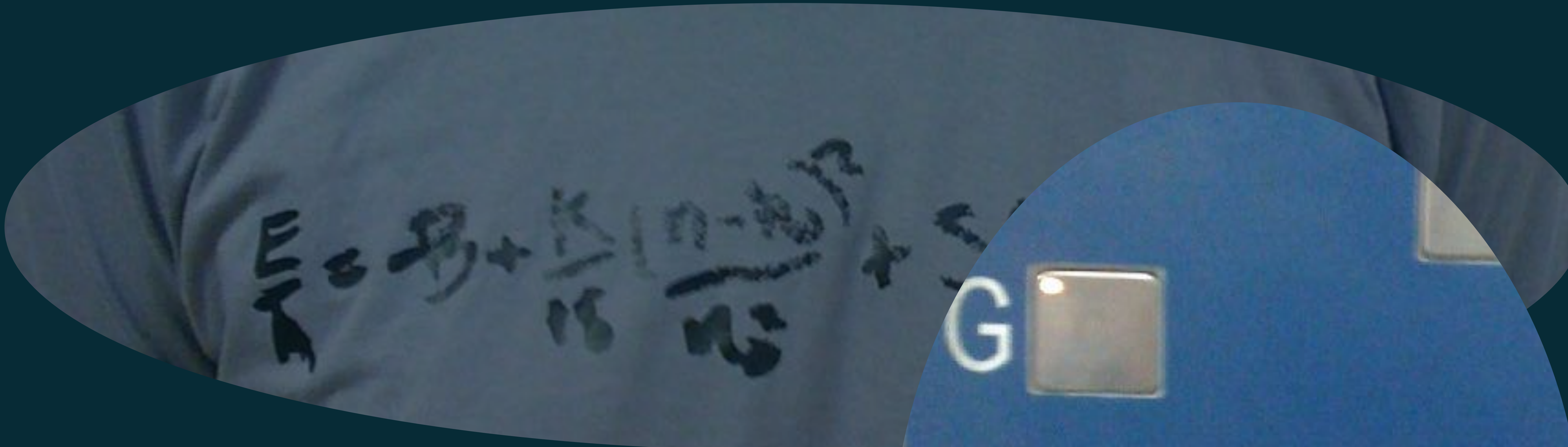
GW170817 | the multi-messenger era



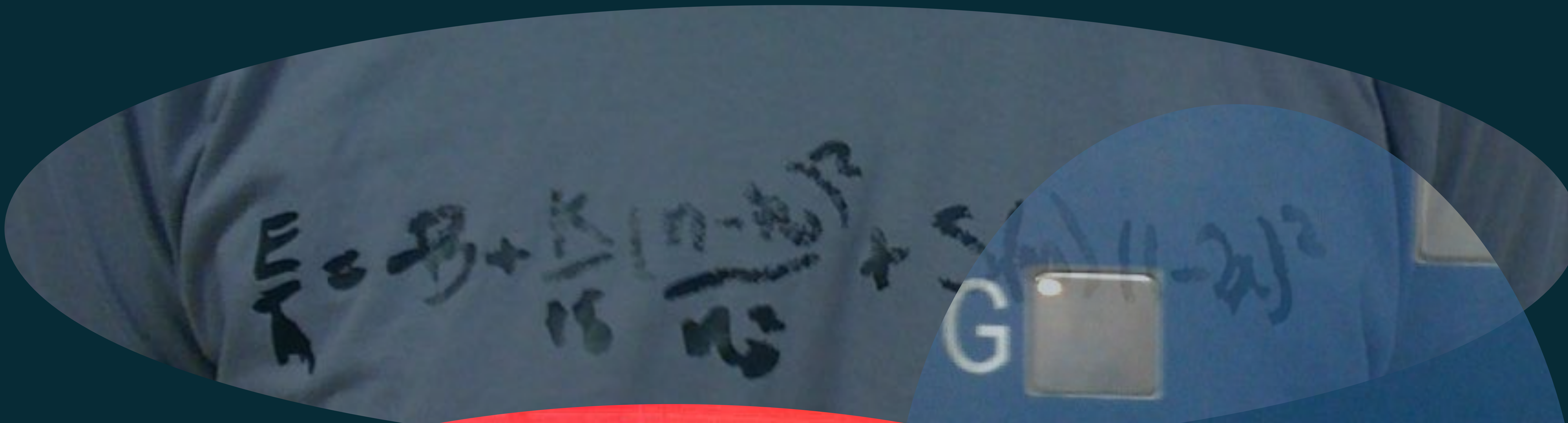
www.ligo.caltech.edu

www.ligo.caltech.edu

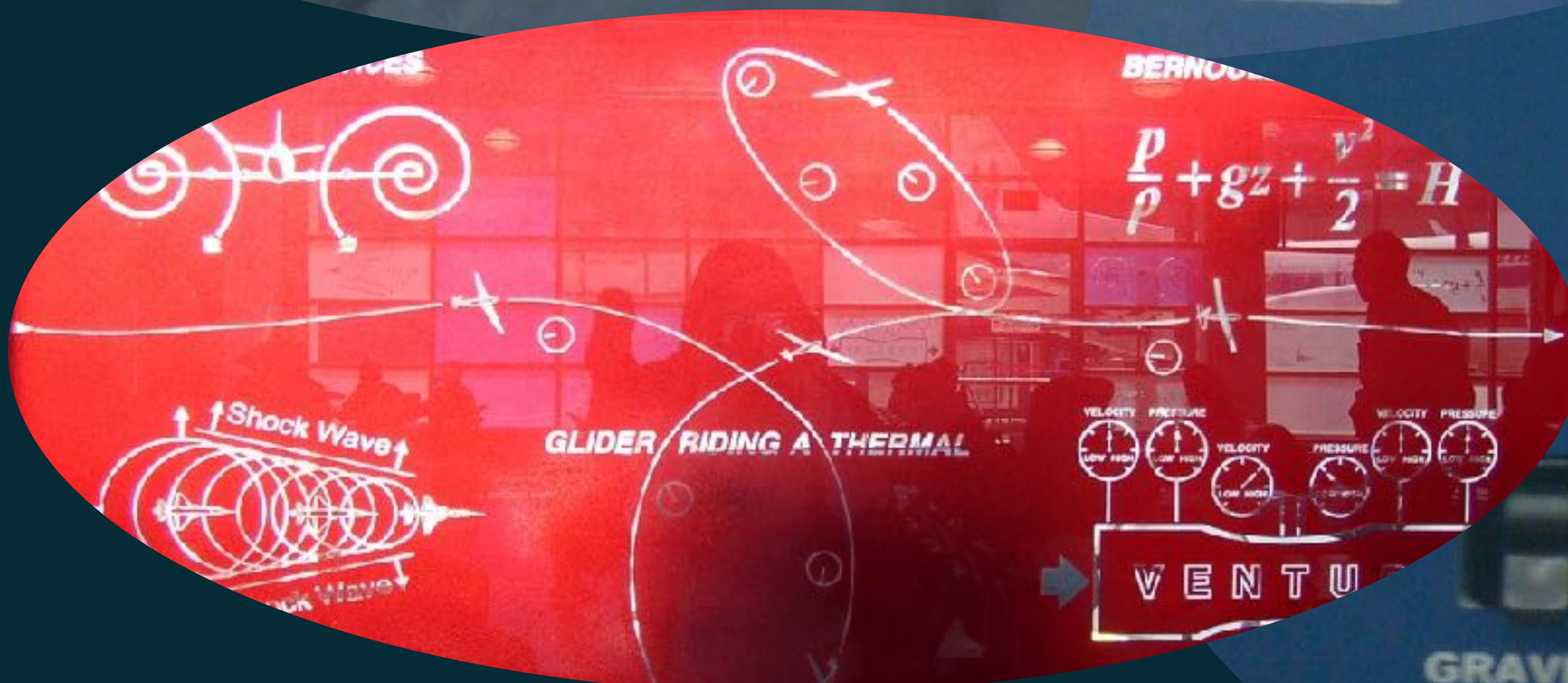





G
GRAVITY



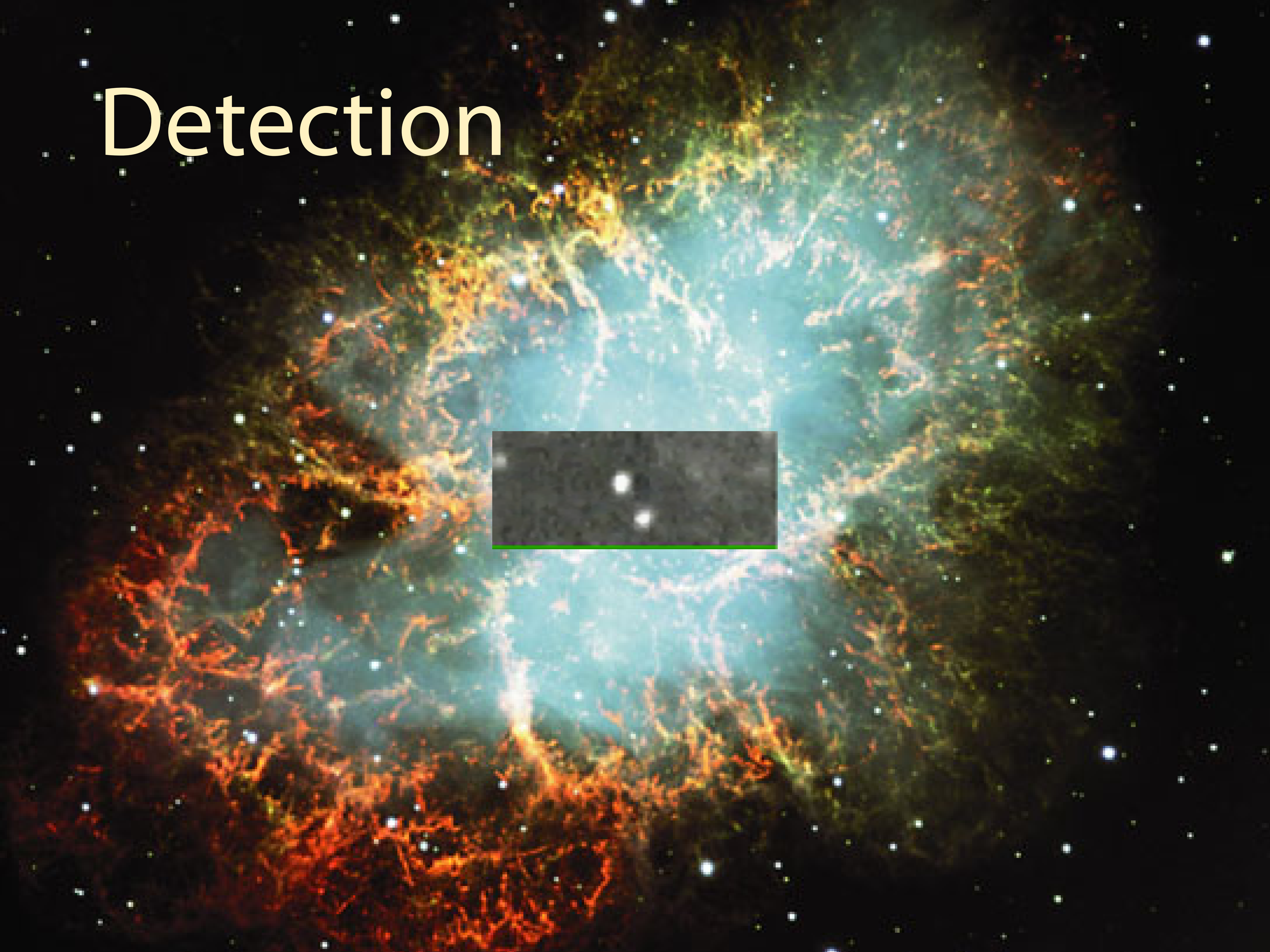

G
GRAVITY


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

How do we observe dense matter in the wild?

Detection

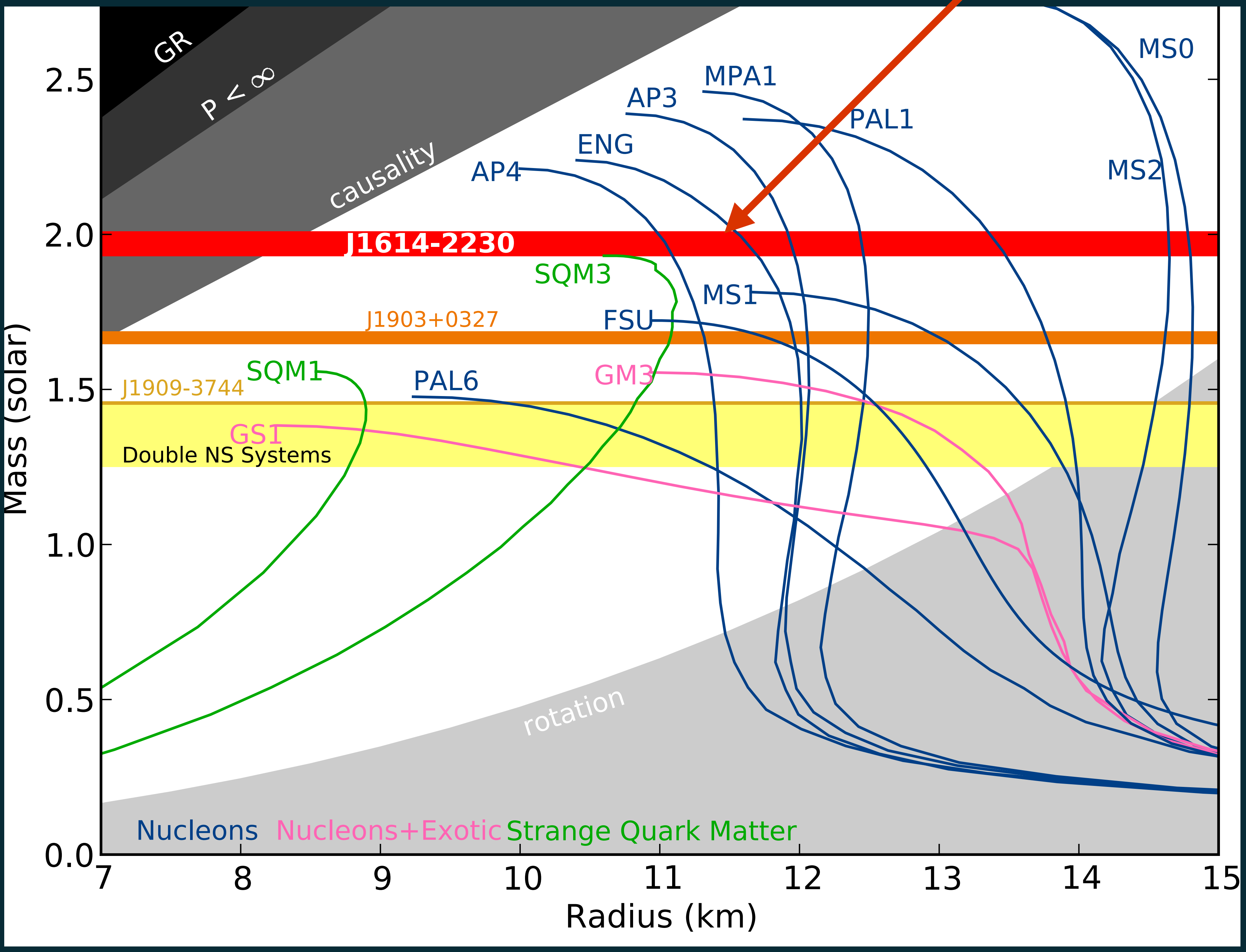
Detection



Pulsar masses

Demorest et al. 2010

no radius information



detection | X-rays

PHYSICAL REVIEW LETTERS

VOLUME 9 DECEMBER 1, 1962 NUMBER 11

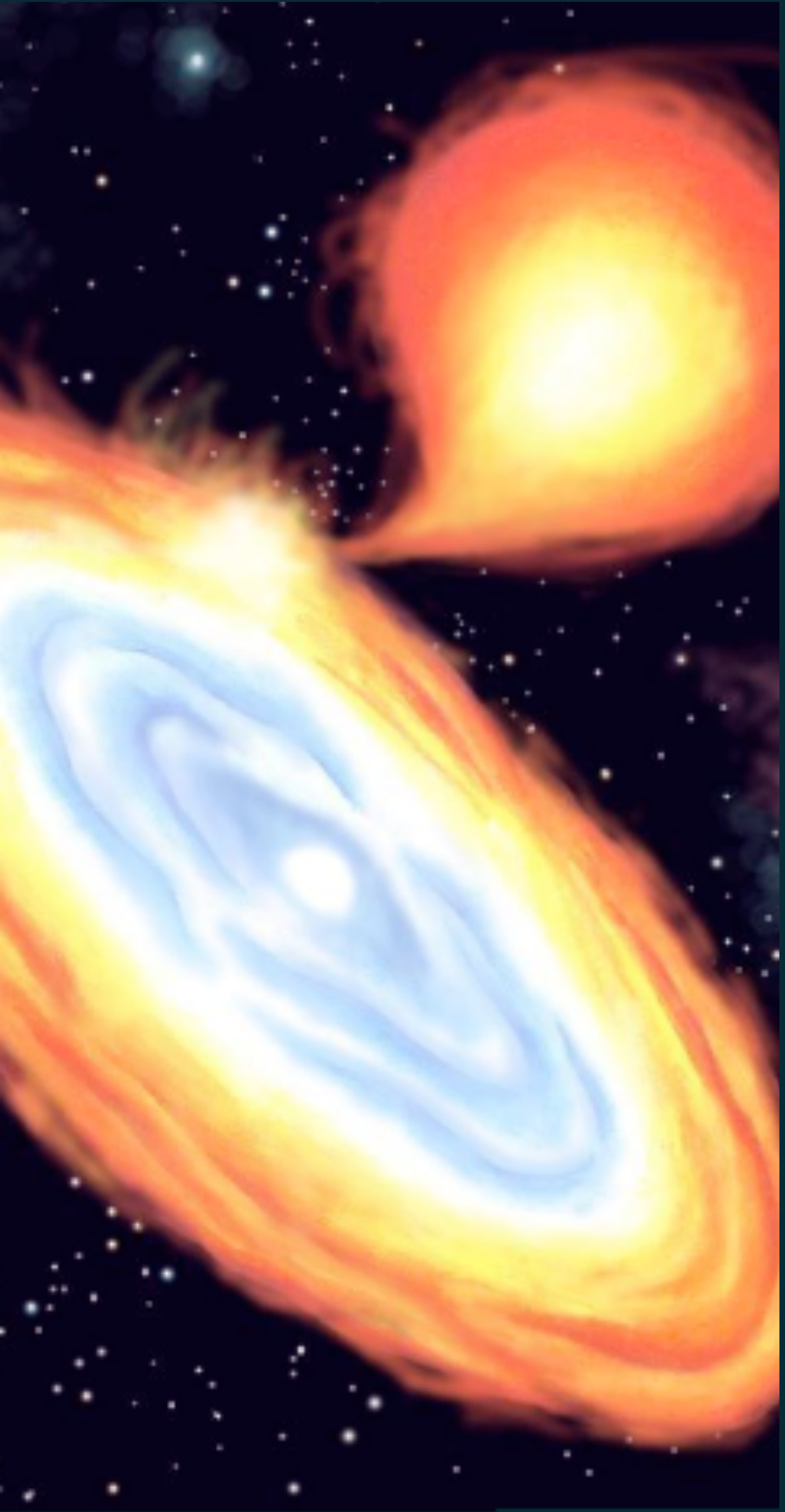
EVIDENCE FOR X RAYS FROM SOURCES OUTSIDE THE SOLAR SYSTEM*

Riccardo Giacconi, Herbert Gursky, and Frank R. Paolini
American Science and Engineering, Inc., Cambridge, Massachusetts

and

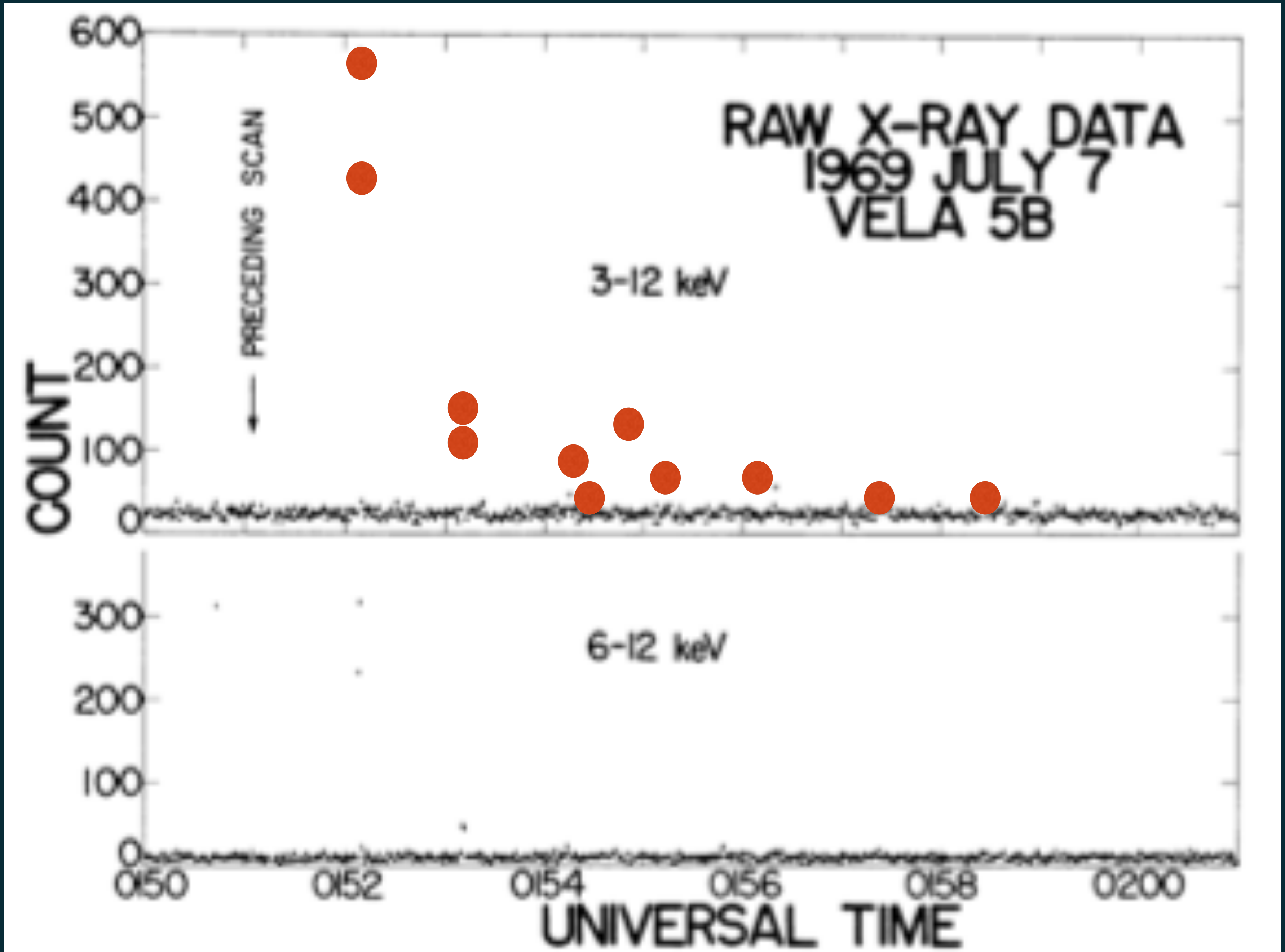
Bruno B. Rossi
Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received October 12, 1962)

accreting neutron stars

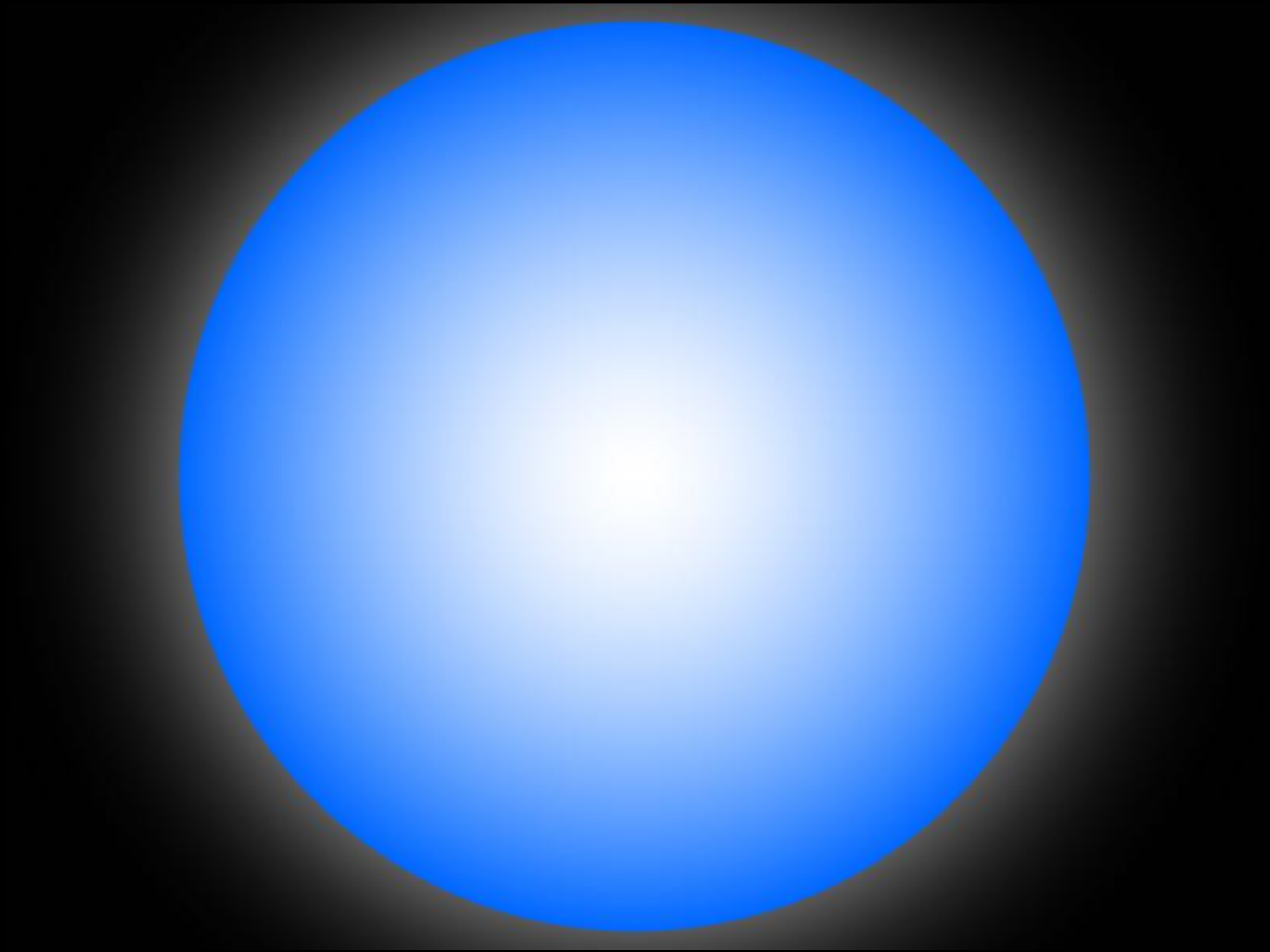


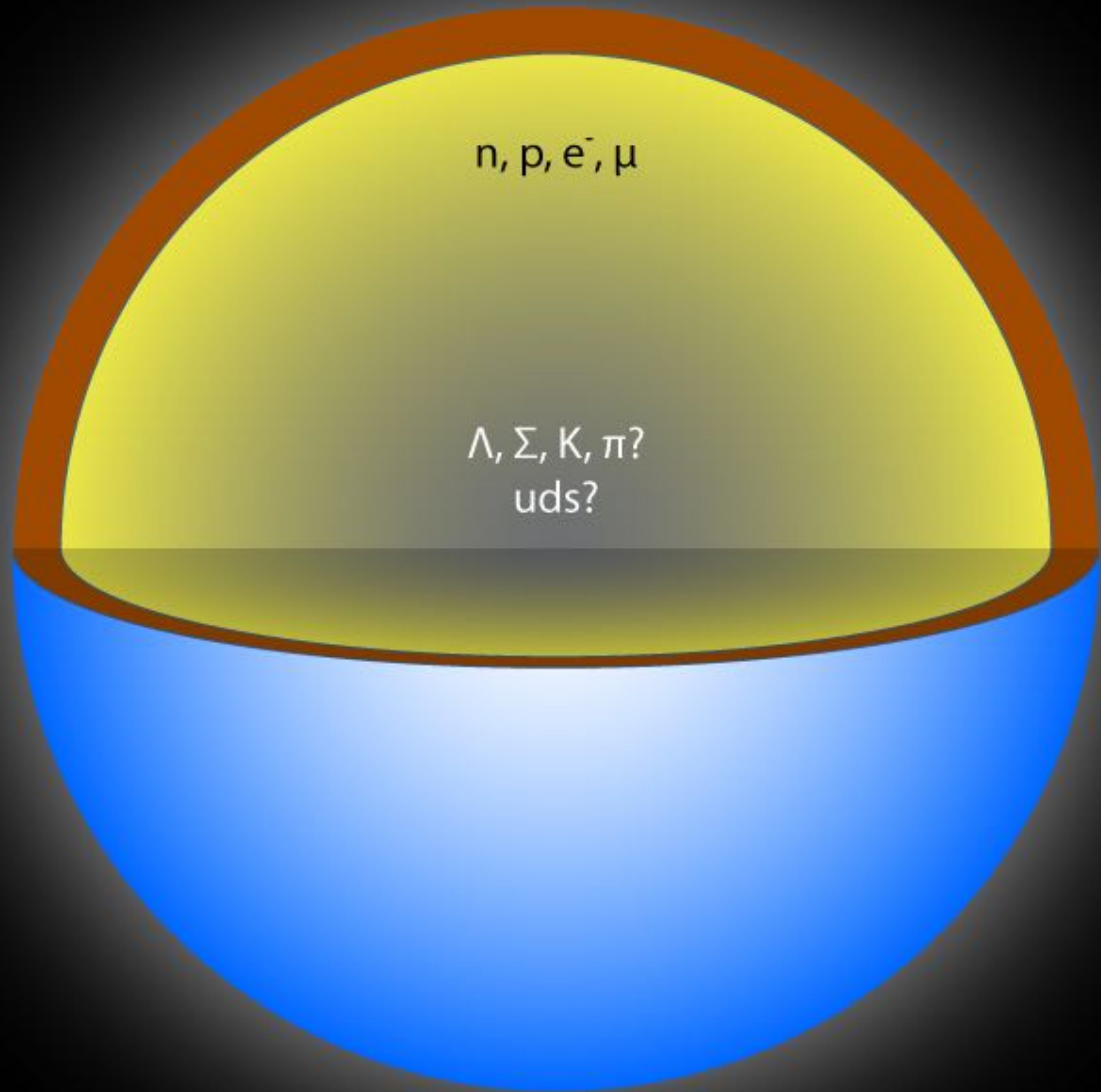
artwork courtesy T. Piro

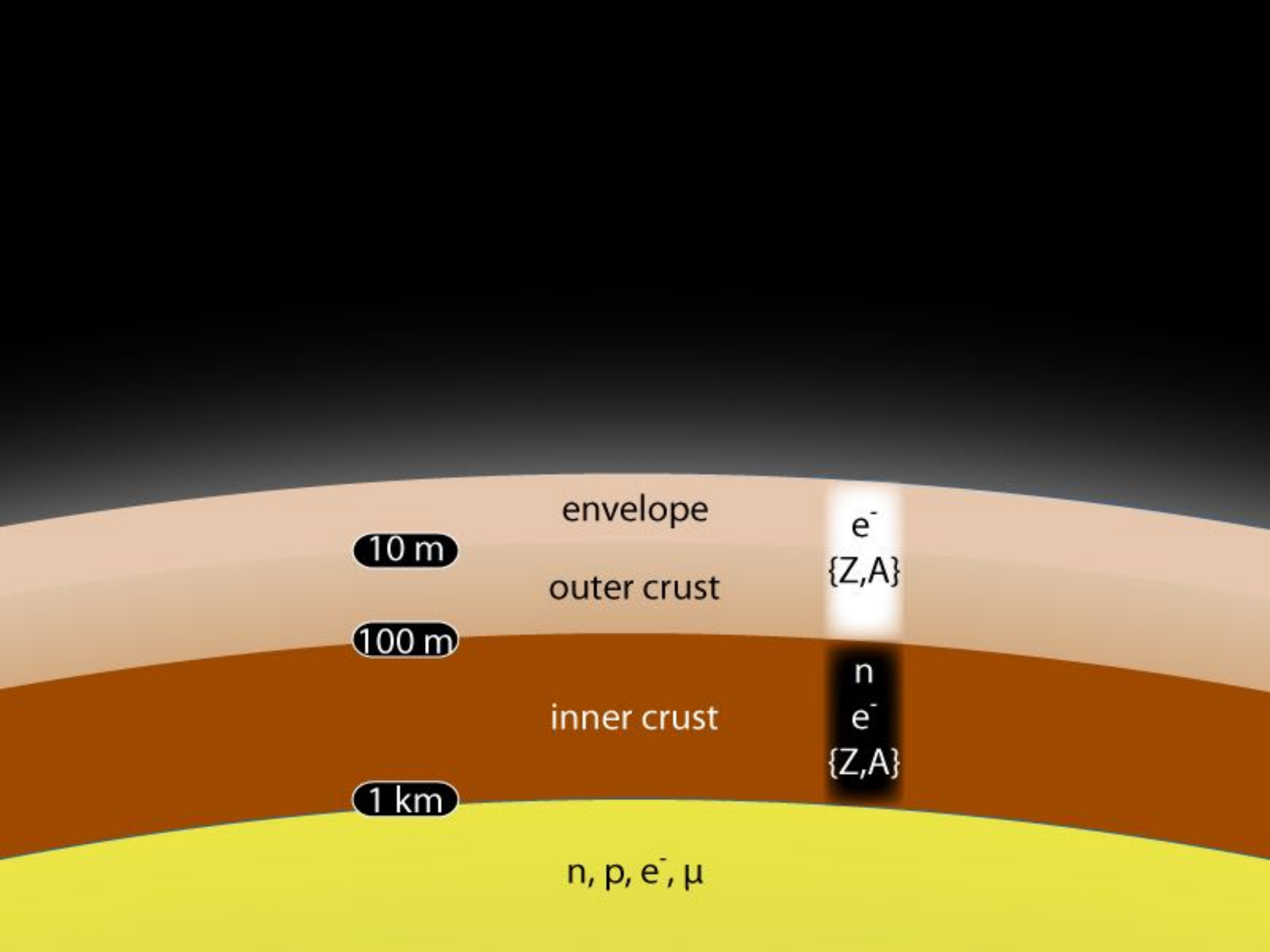
a flare detected



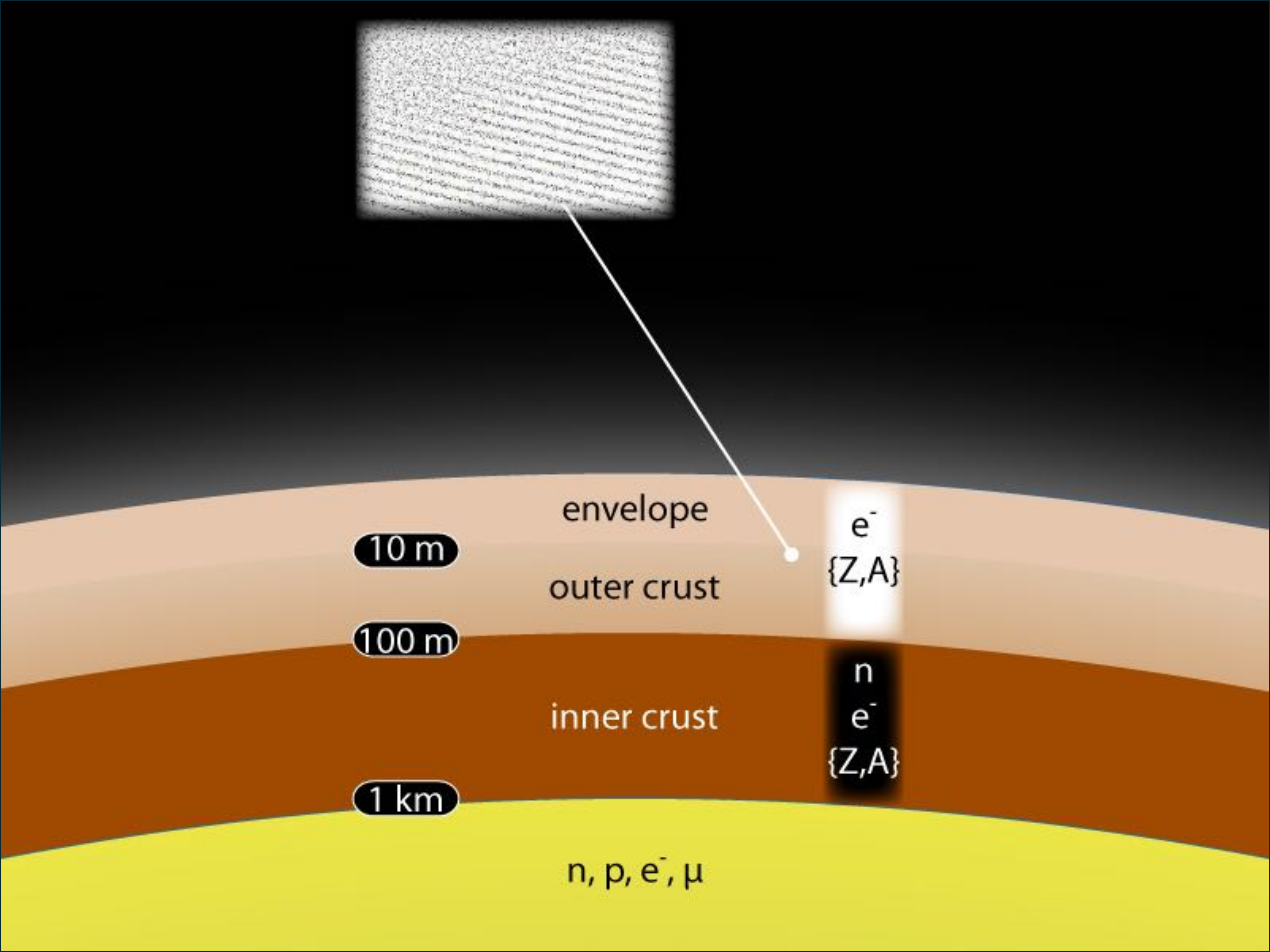
Belian et al. 1969



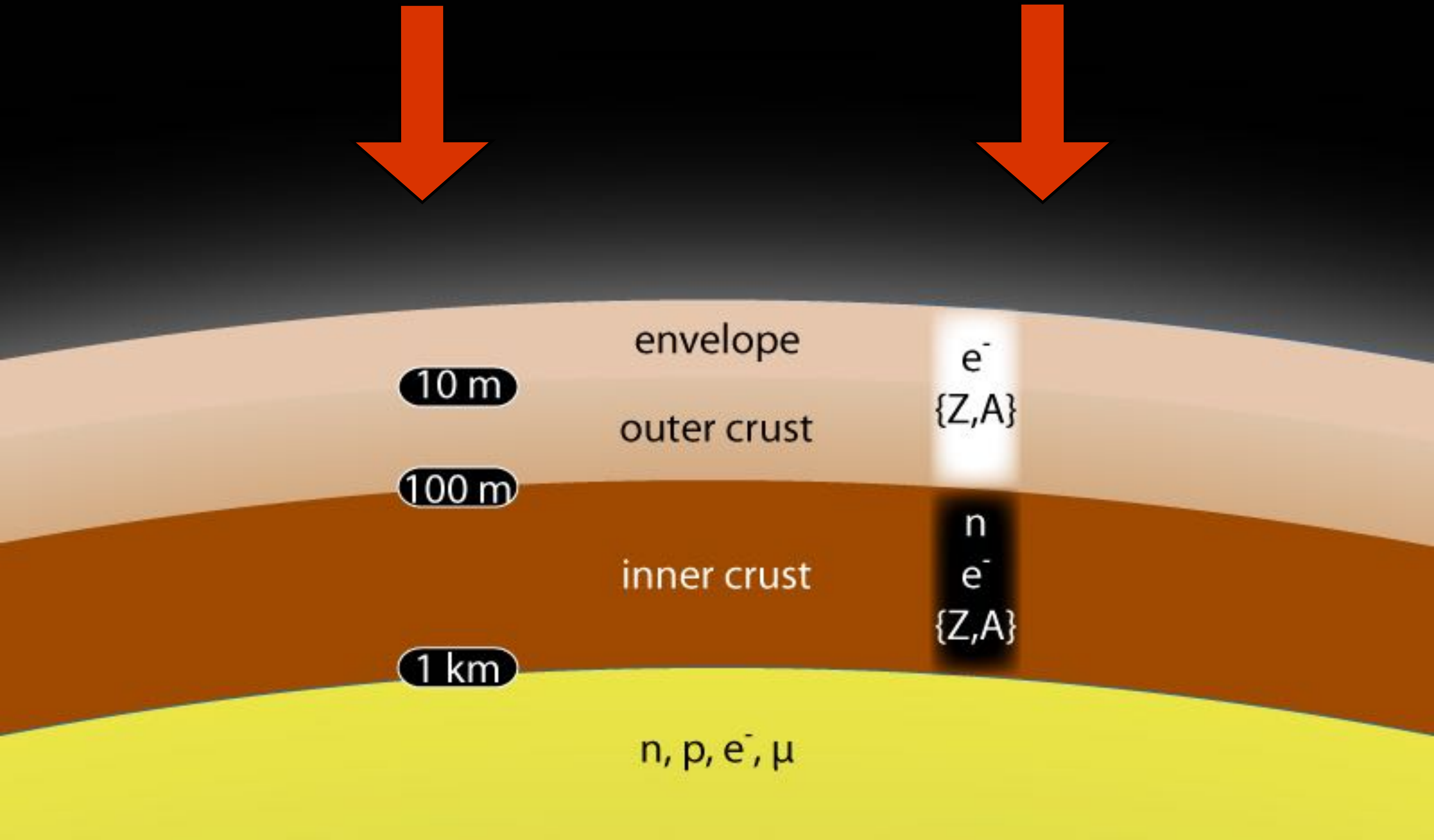

n, p, e⁻, μ
Λ, Σ, K, π?
uds?



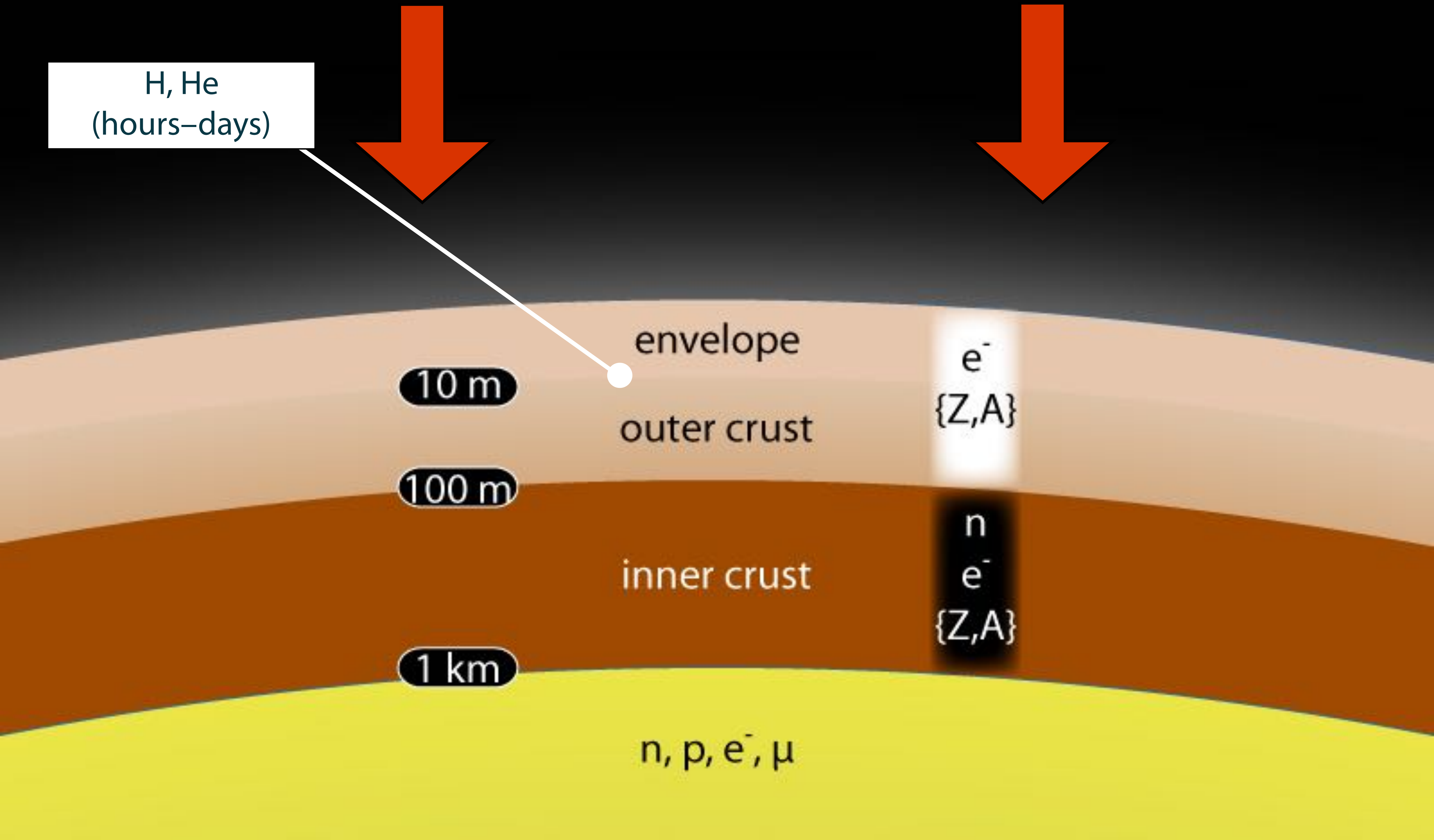
envelope
10 m
outer crust
100 m
inner crust
1 km
e-
{Z,A}
n
e-
{Z,A}
n, p, e-, μ

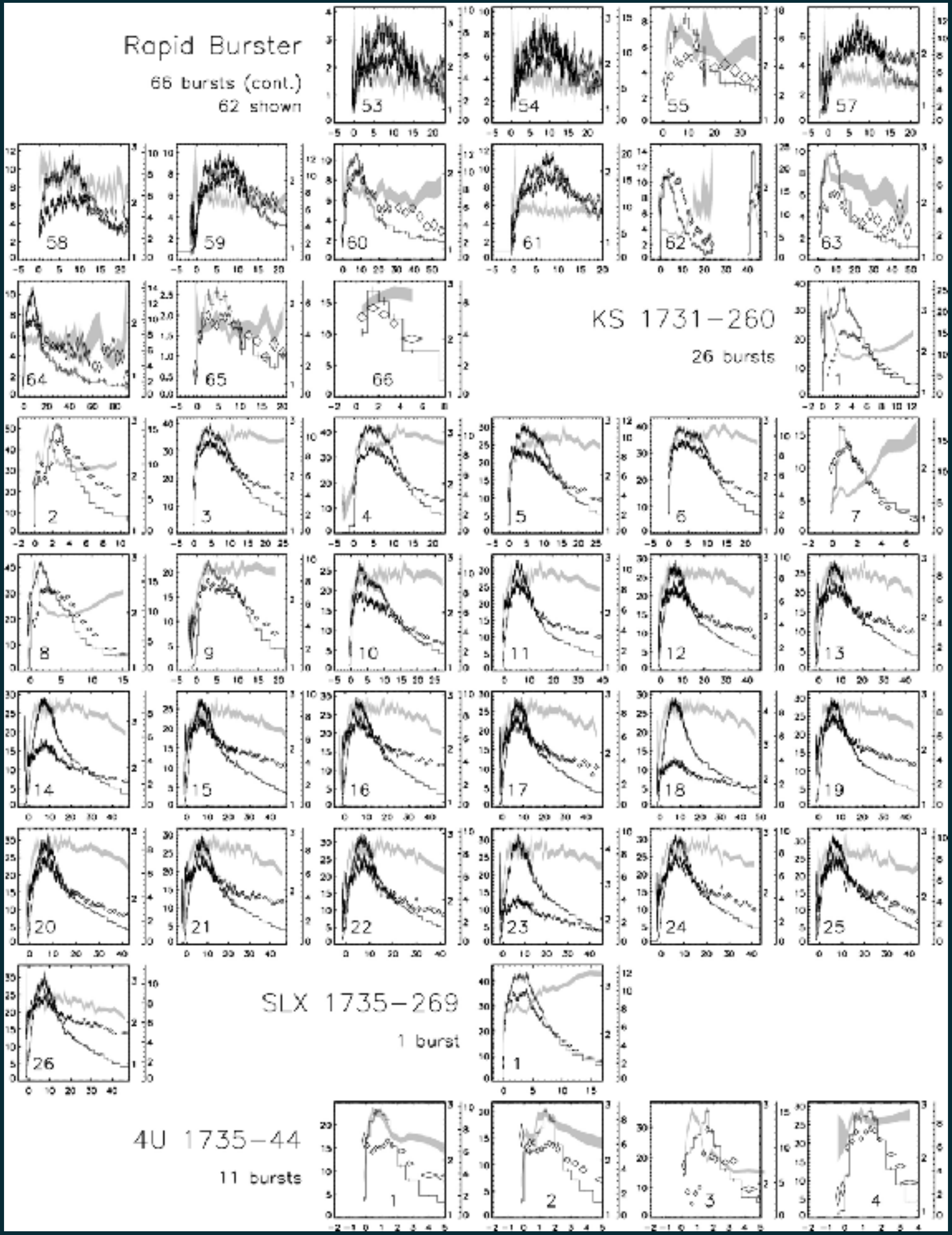

envelope
10 m
outer crust
100 m
inner crust
1 km
e-
{Z,A}
n
e-
{Z,A}
n, p, e-, μ

nuclear-powered variability



nuclear-powered variability

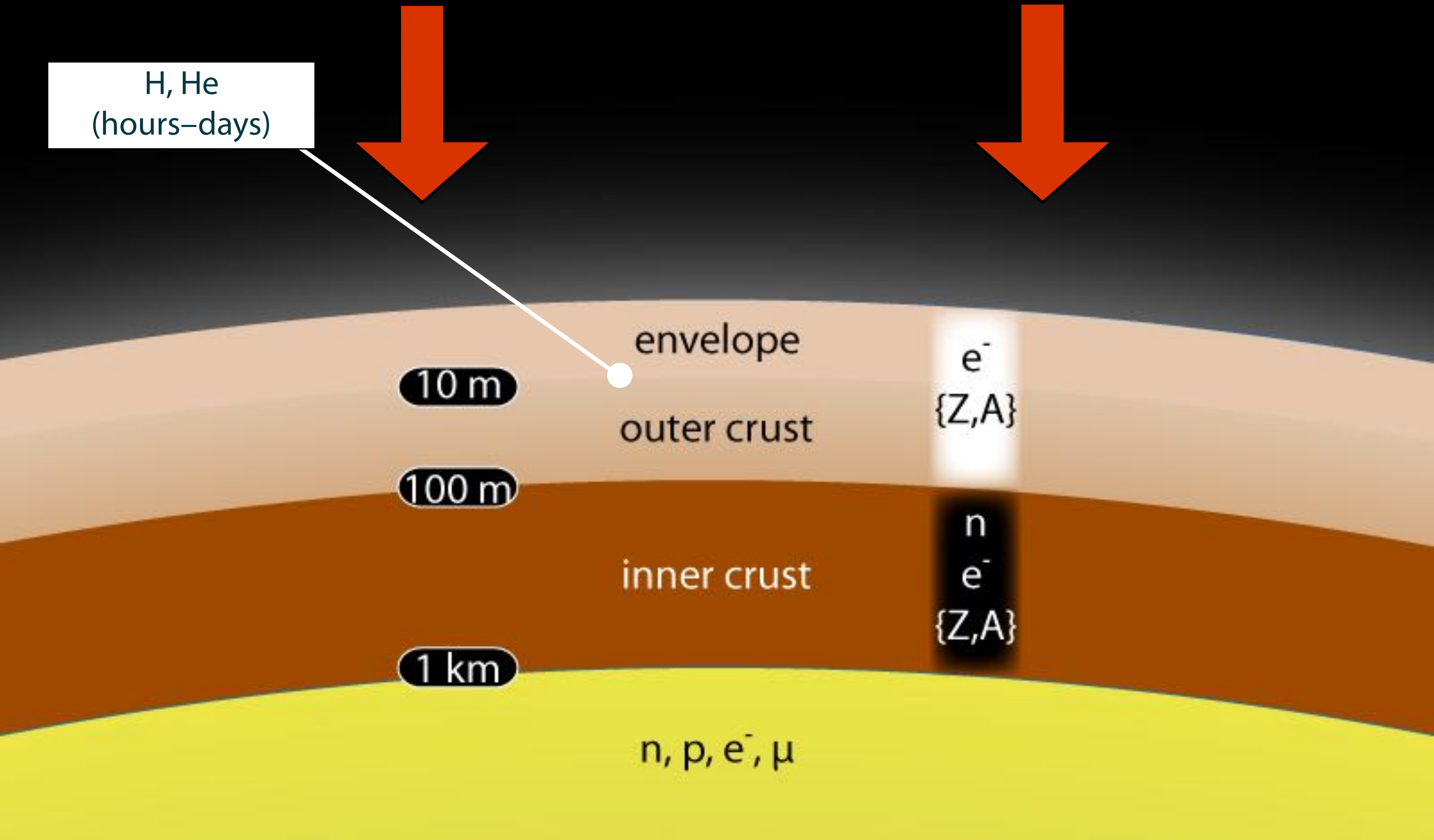




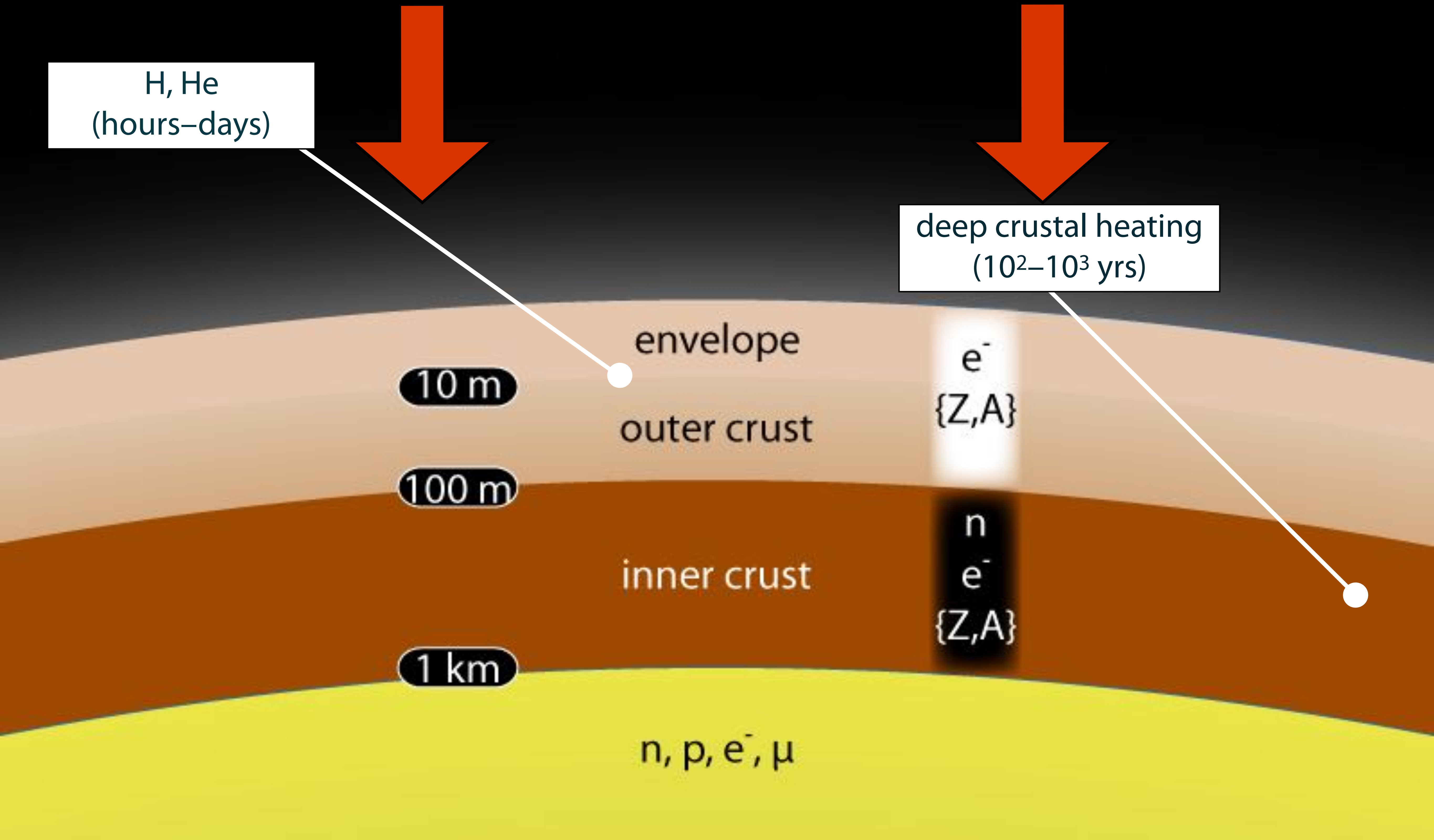
Galloway et al. 2008

MINBAR catalog: A sample of 4192 X-ray bursts from 48 sources

nuclear-powered variability

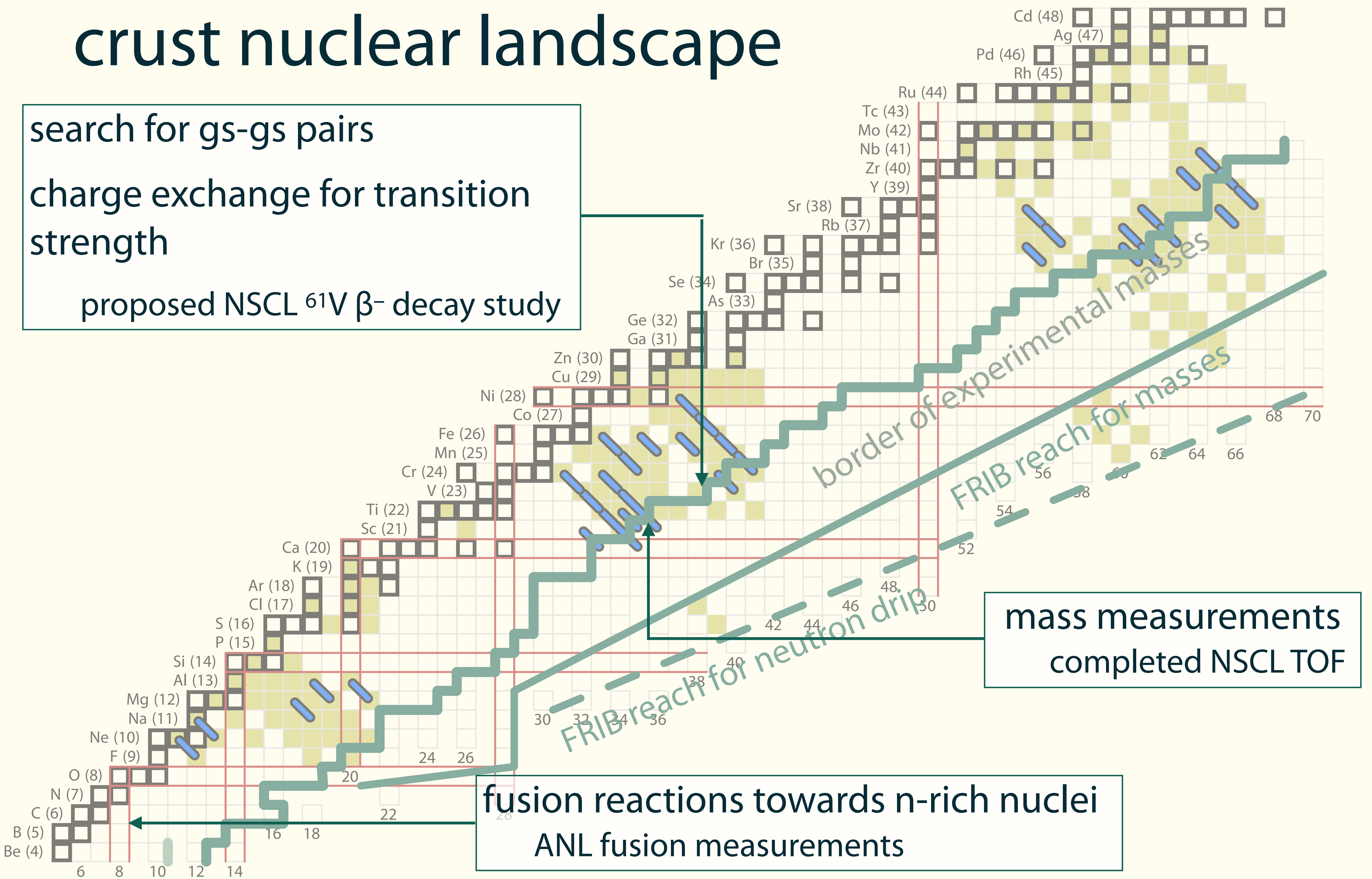


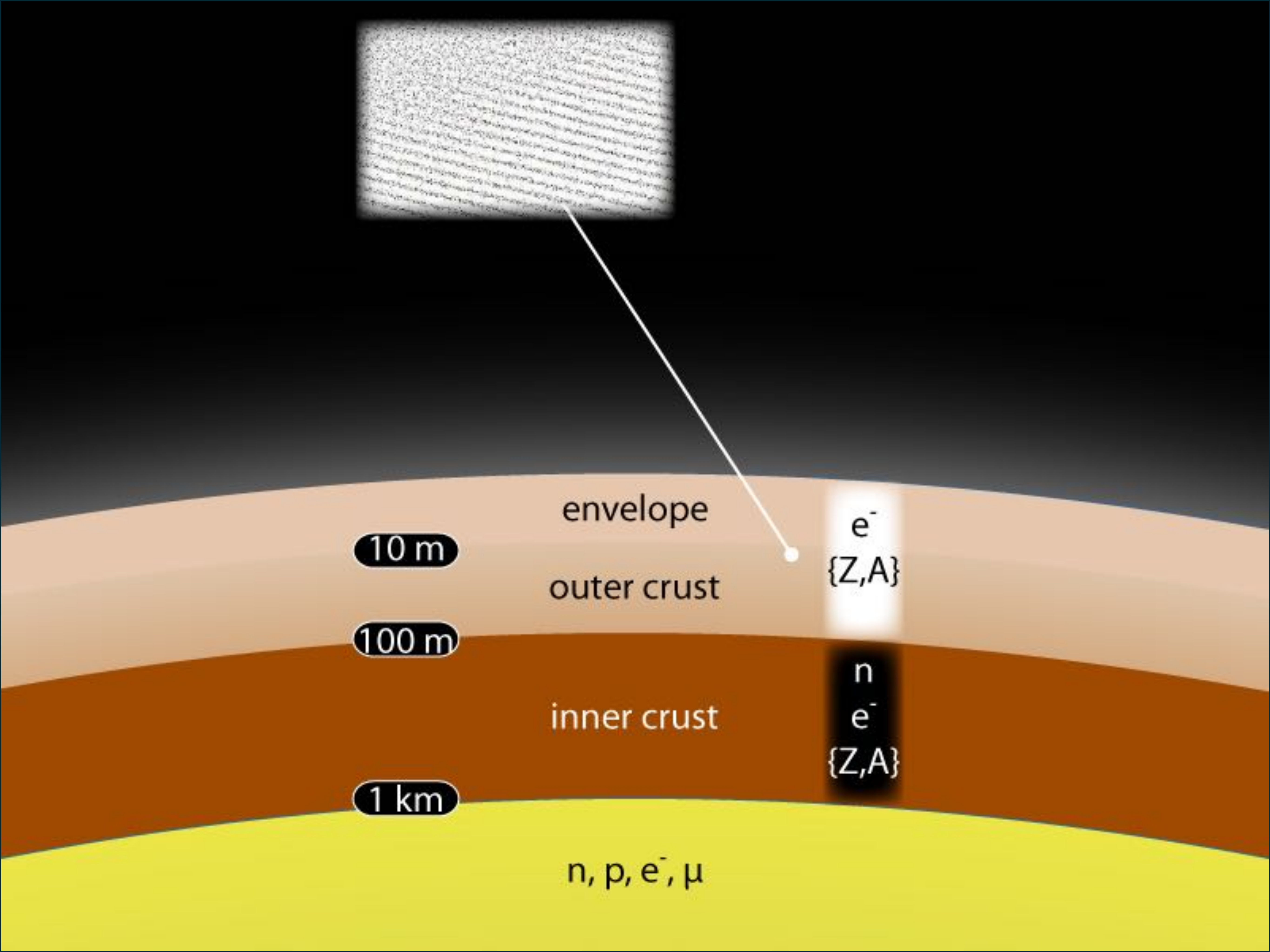
nuclear-powered variability



Crust reactions can be studied at the **F**acility for **R**are **I**sotope **B**eams at Michigan State University

JINA/JINA-CEE experiments across the crust nuclear landscape




envelope
10 m
outer crust
100 m
inner crust
1 km
e^-
$\{Z,A\}$
n
e^-
$\{Z,A\}$
n, p, e^-, μ

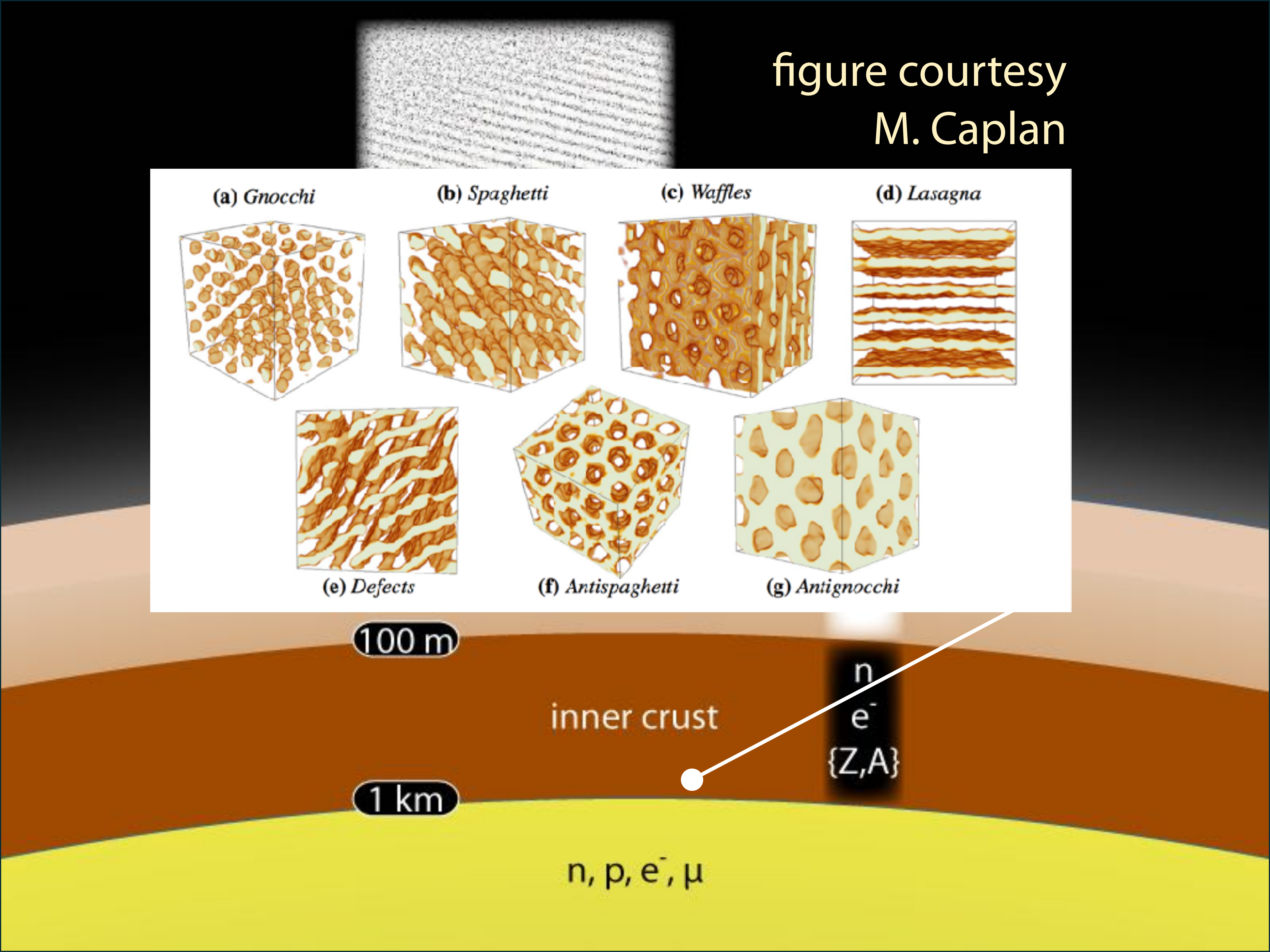


figure courtesy
M. Caplan
(a) Gnocchi
(b) Spaghetti
(c) Waffles
(d) Lasagna
(e) Defects
(f) Antispaghetti
(g) Antignocchi
100 m
inner crust
n
e-
{Z,A}
1 km
n, p, e-, μ

transient | observations

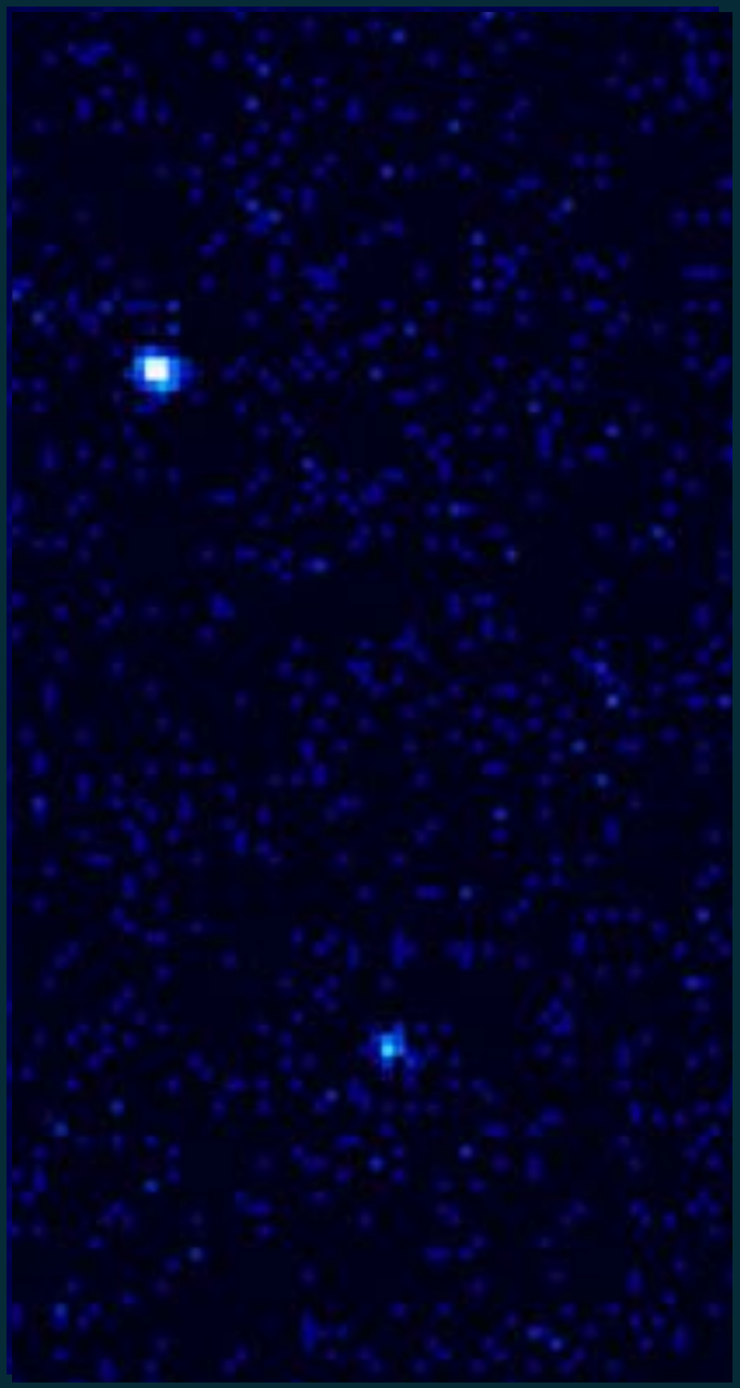


Image credit: NASA/*Chandra*/Wijnands et al.

Wijnands et al; Cackett et al; Degenaar et al; Fridriksson et al; Díaz Trigo et al; Homan et al.

transient | observations

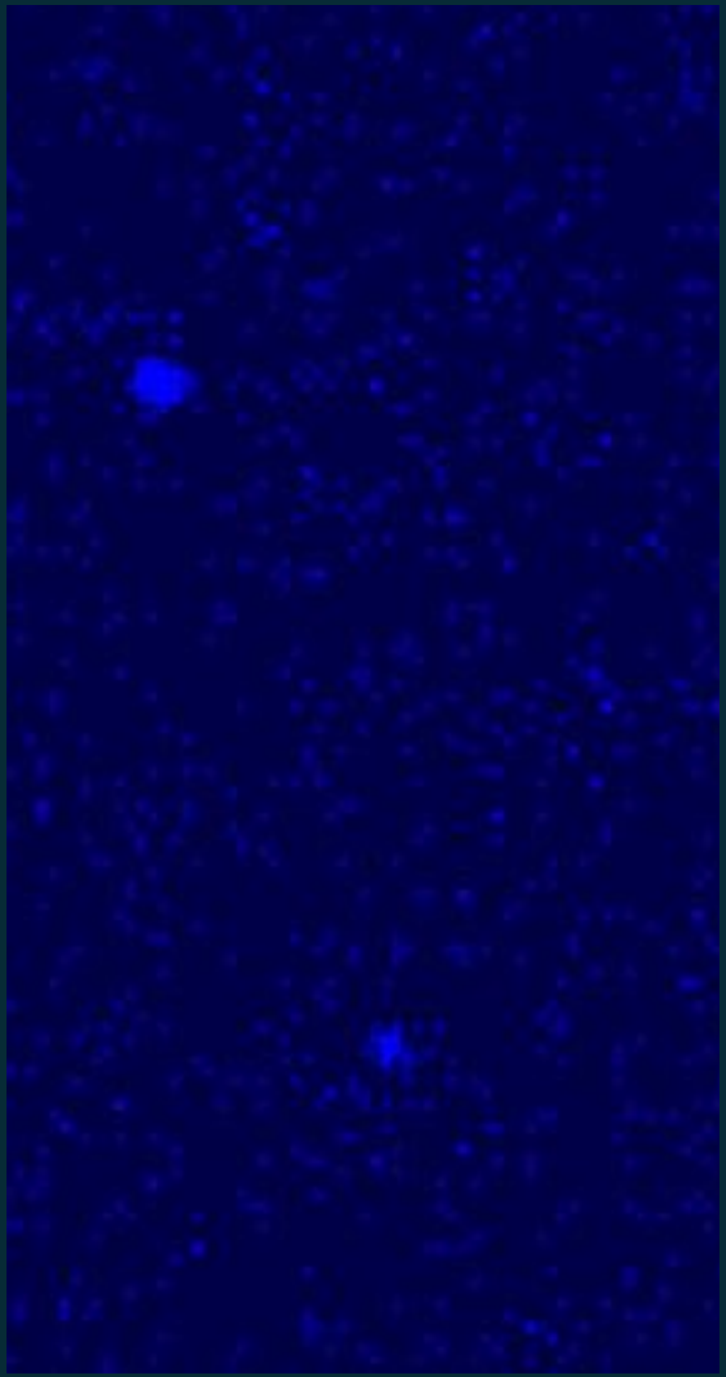


Image credit: NASA/*Chandra*/Wijnands et al.

Wijnands et al; Cackett et al; Degenaar et al; Fridriksson et al; Díaz Trigo et al; Homan et al.

transient | observations

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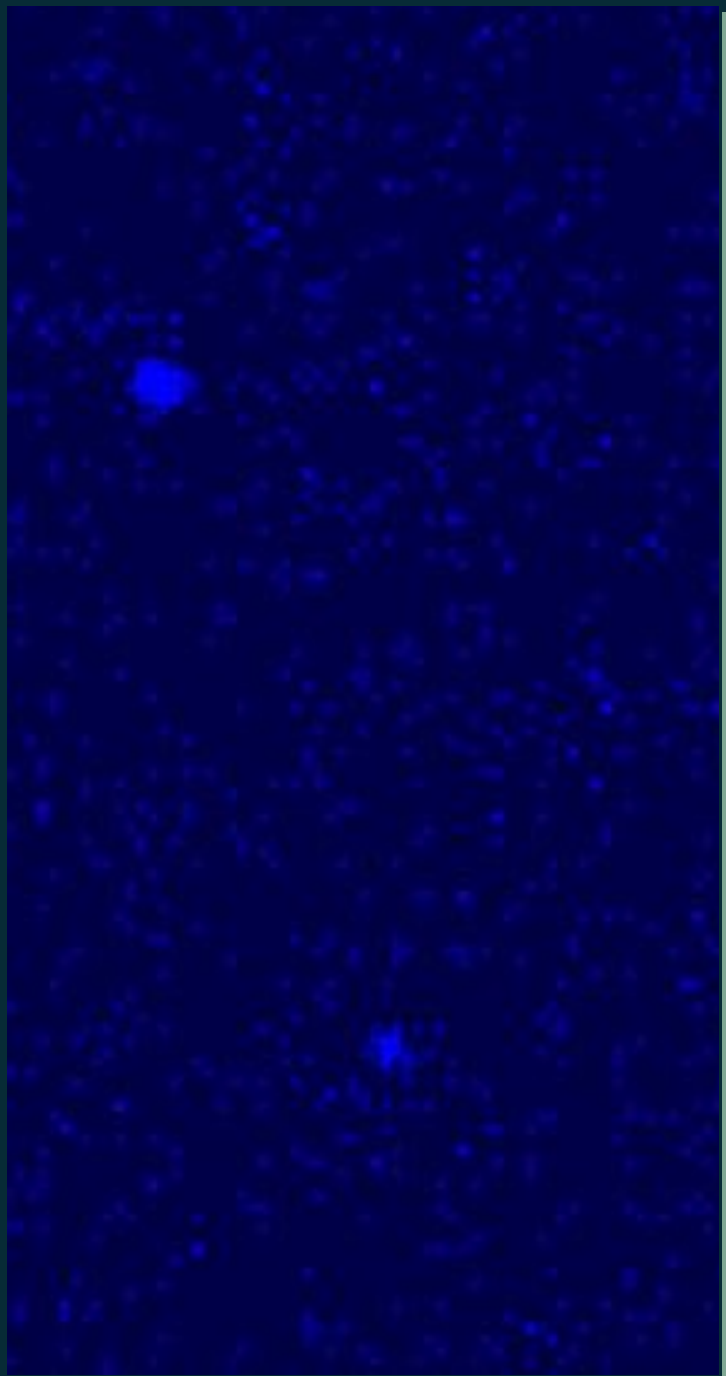
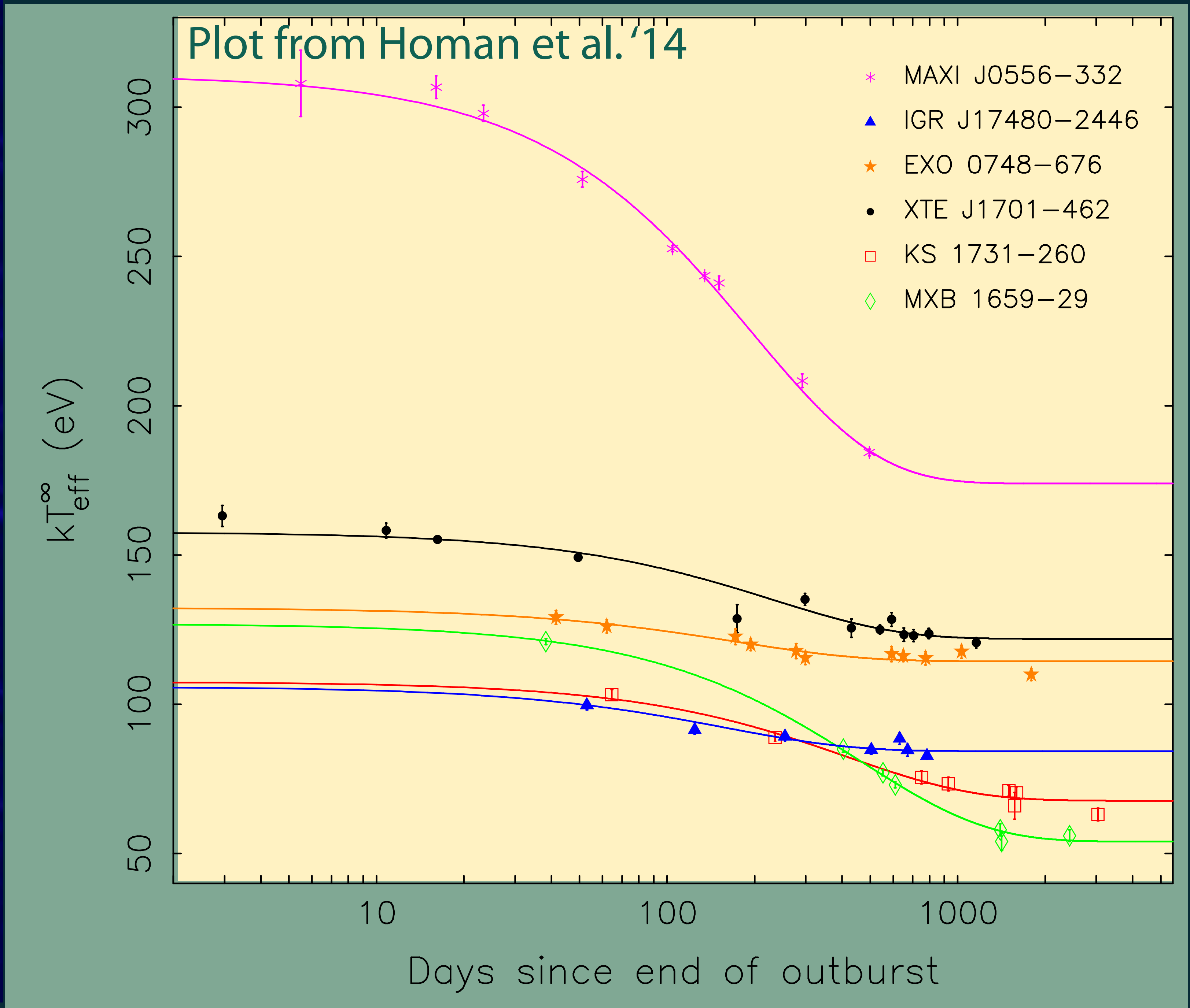
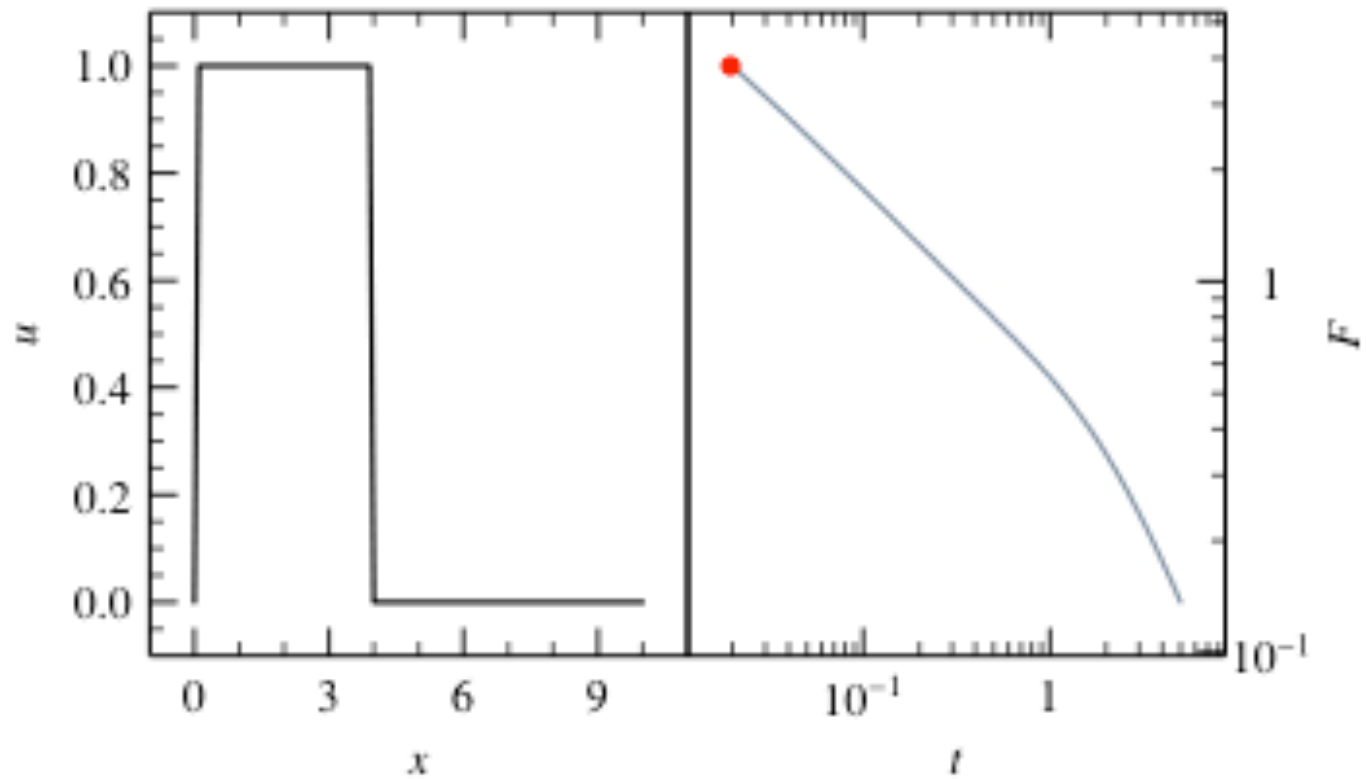




Wijnands et al; Cackett et al; Degenaar et al; Fridriksson et al; Díaz Trigo et al; Homan et al.



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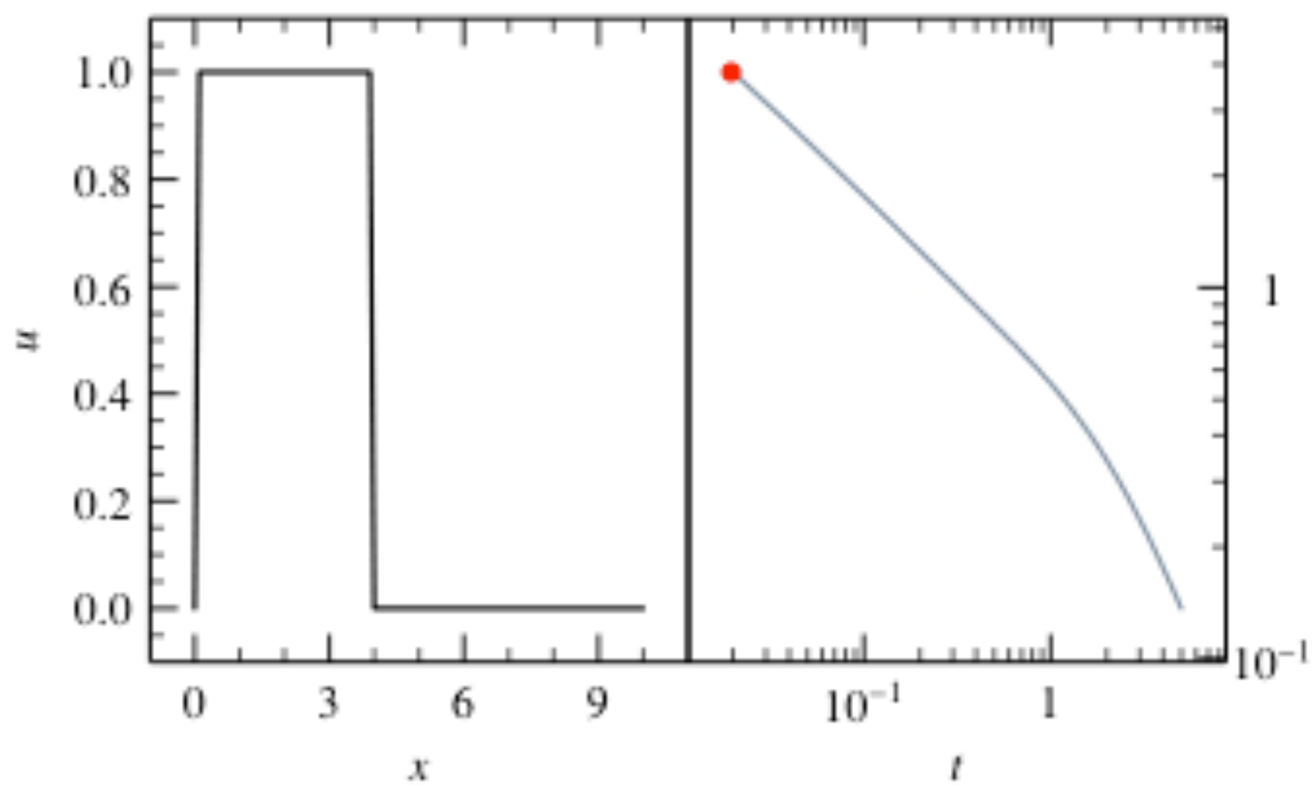

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1
10^{-1}
F

code to generate following plots is posted at https://github.com/nworbde/dStar

Branch: master ▾ dStar / README.md

Find file | Copy path

nworbde shout-out to INT talk 342383d just now

1 contributor

79 lines (50 sloc) | 4.52 KB

Raw | Blame | History

dStar

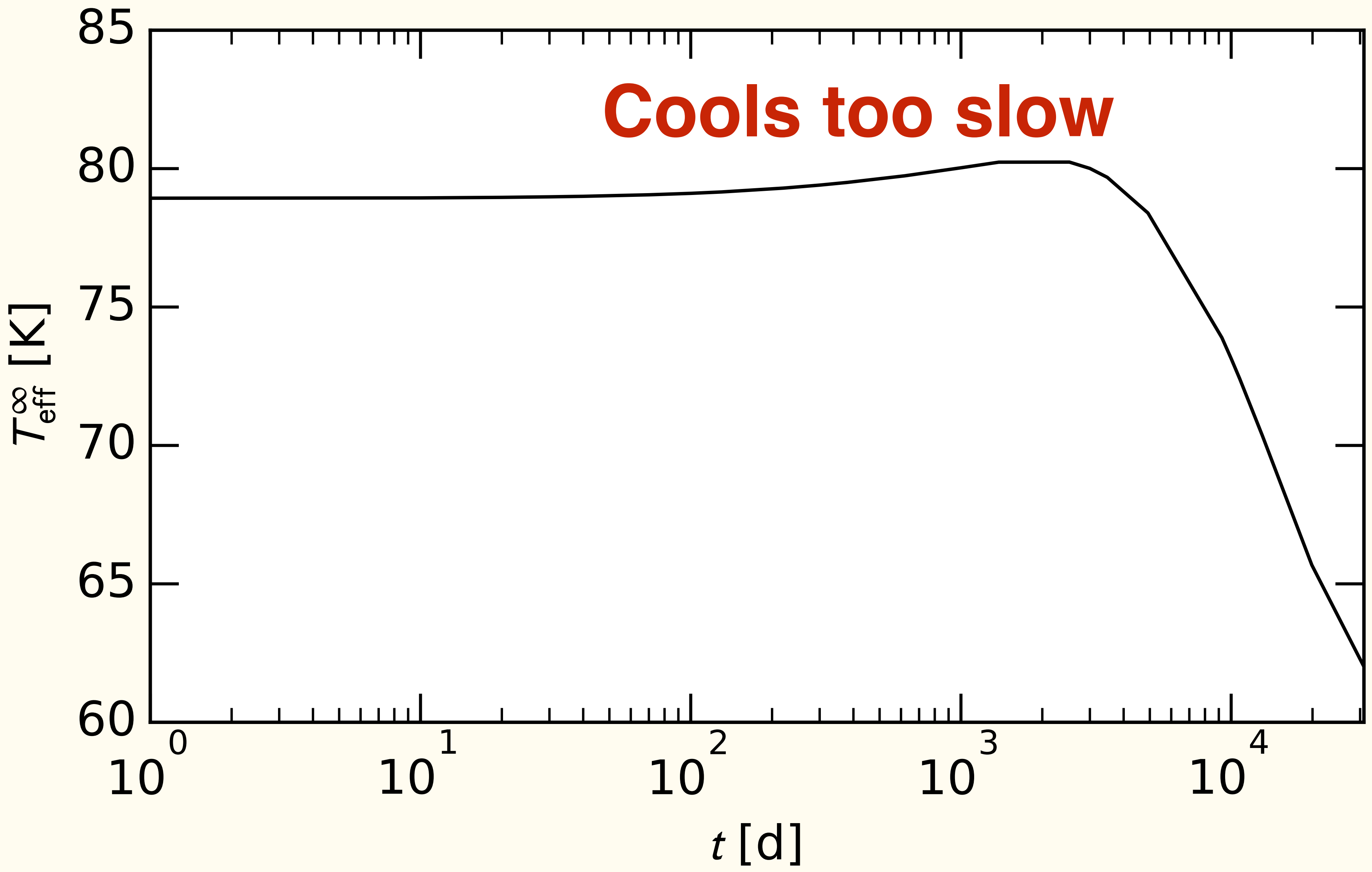
A collection of modules for computing neutron star structure and evolution.

What's new

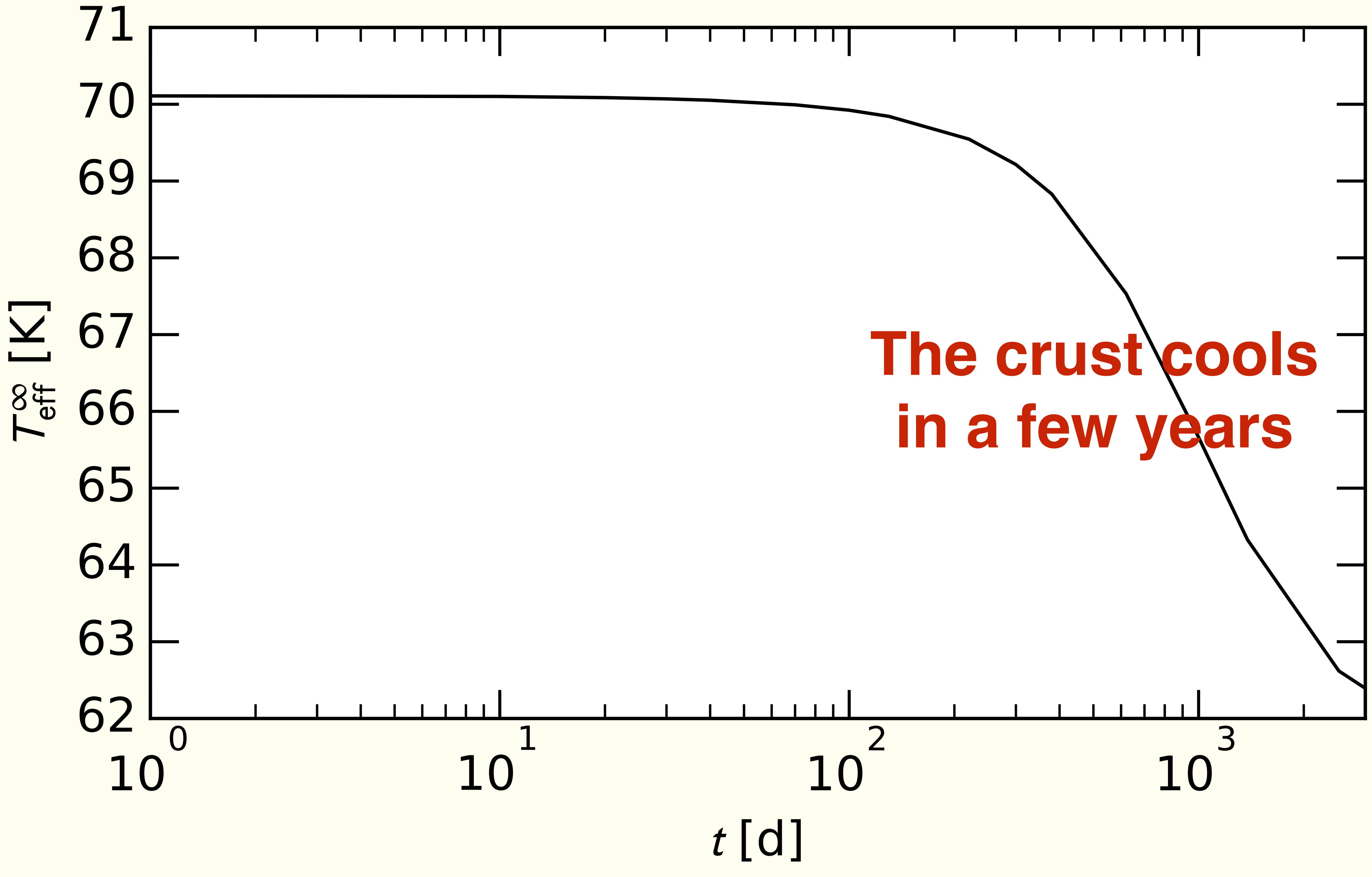
A tutorial on crust cooling

Look in the `examples/INT-16-2b-demo` directory for a demonstration of using this code that was presented in a talk given at the INT workshop 16-2b, "Phases of Dense Matter". See the `README.md` file in that directory for instructions.

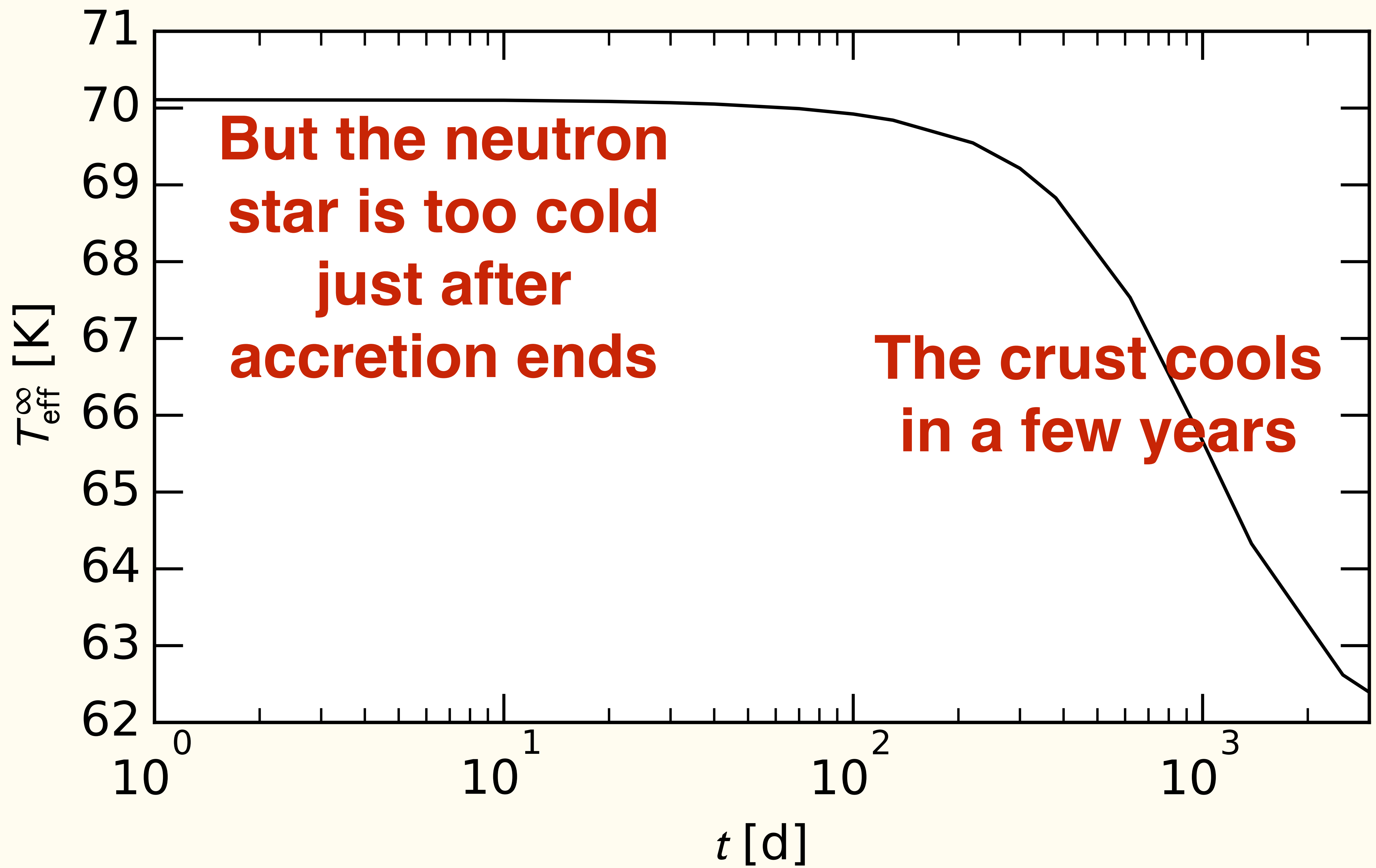
crust cooling | low conductivity



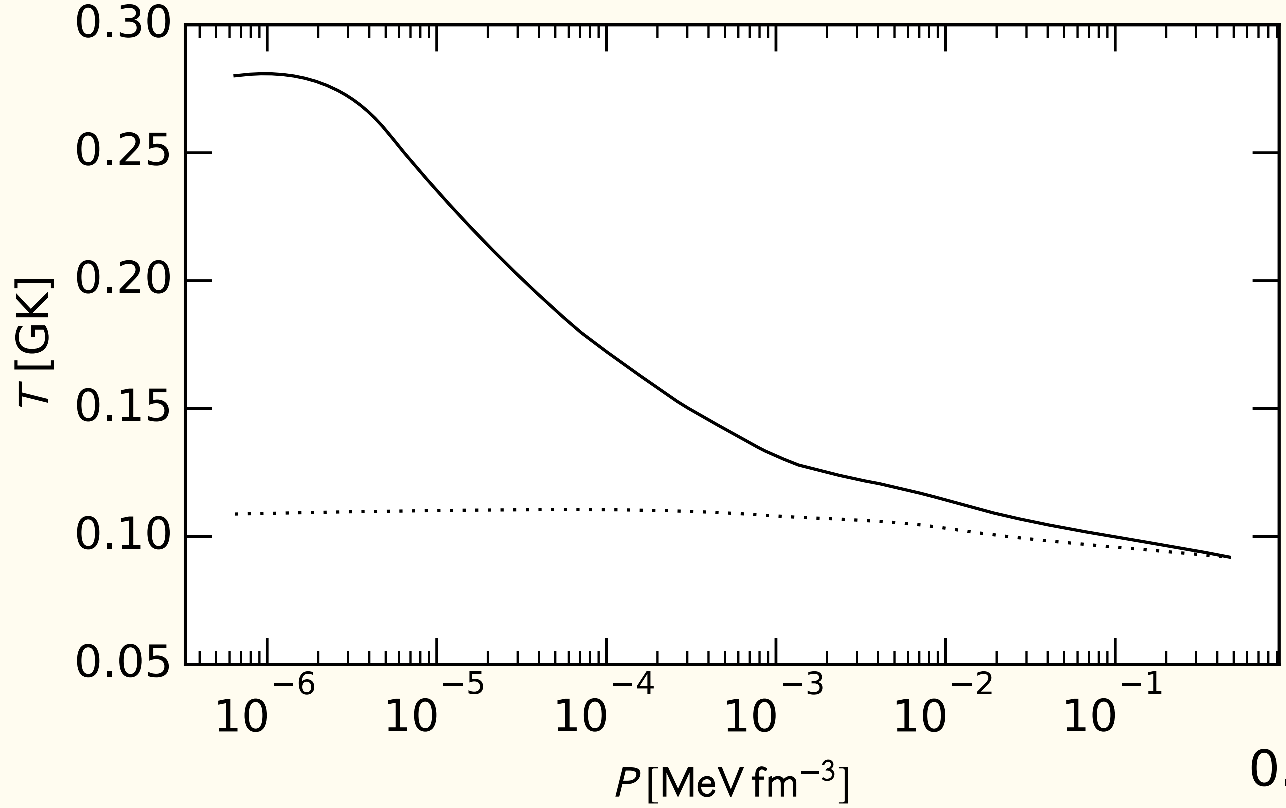
Make the crust more pure (improves heat conduction)

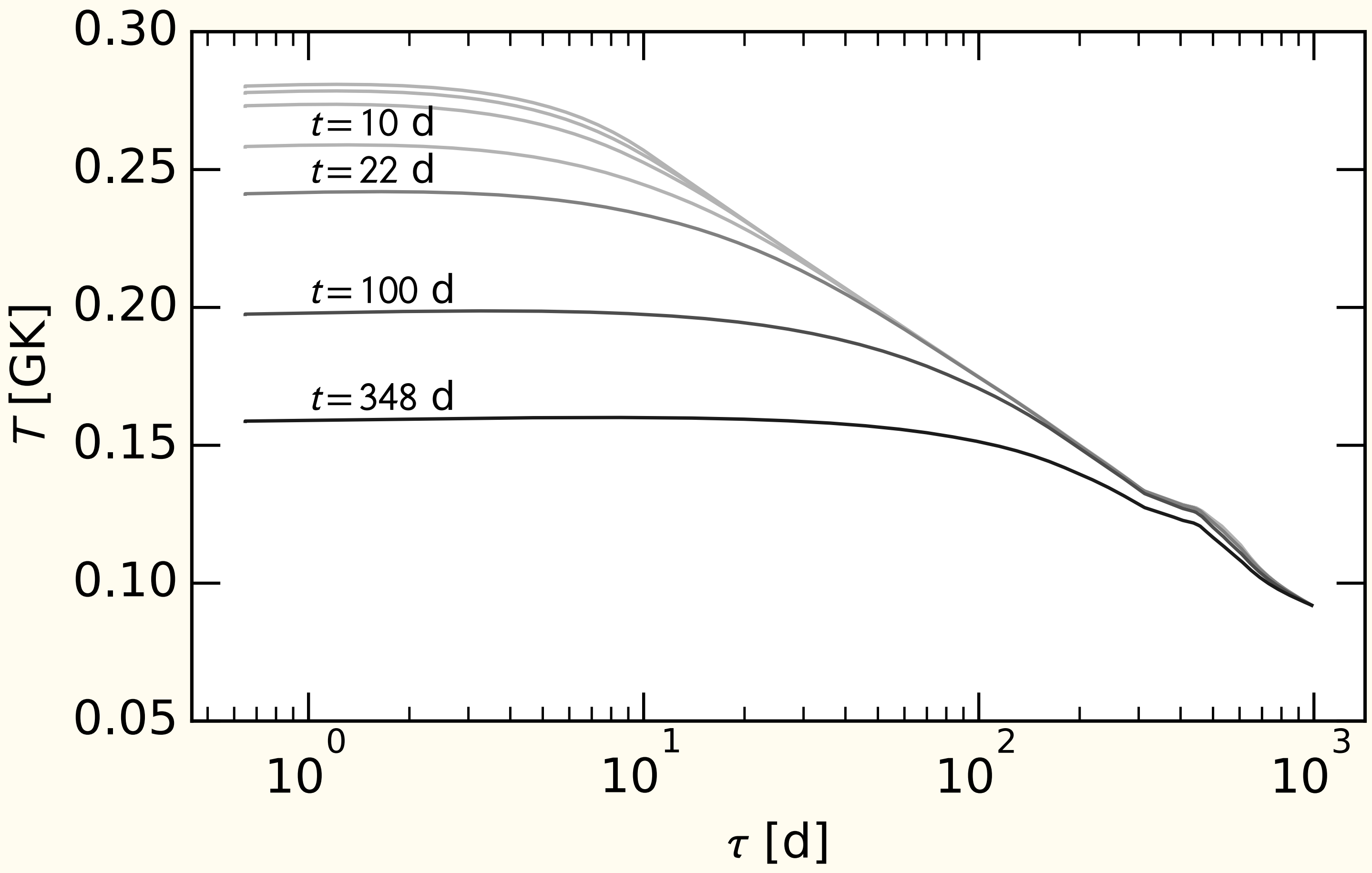


Make the crust more pure (improves heat conduction)

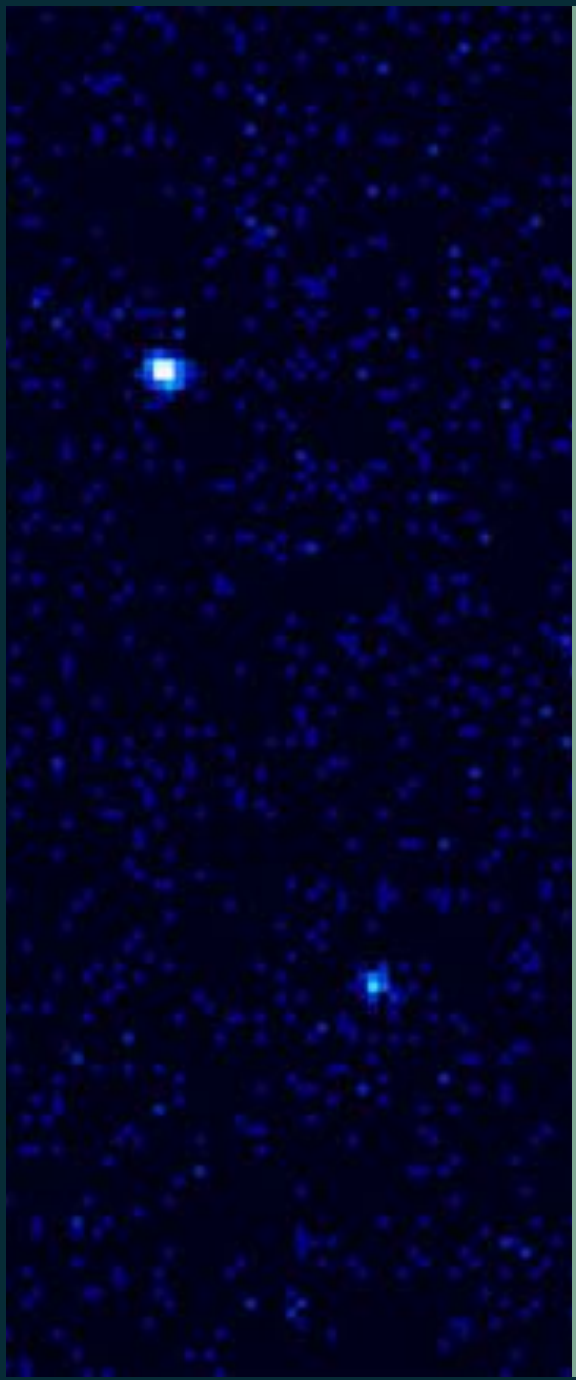


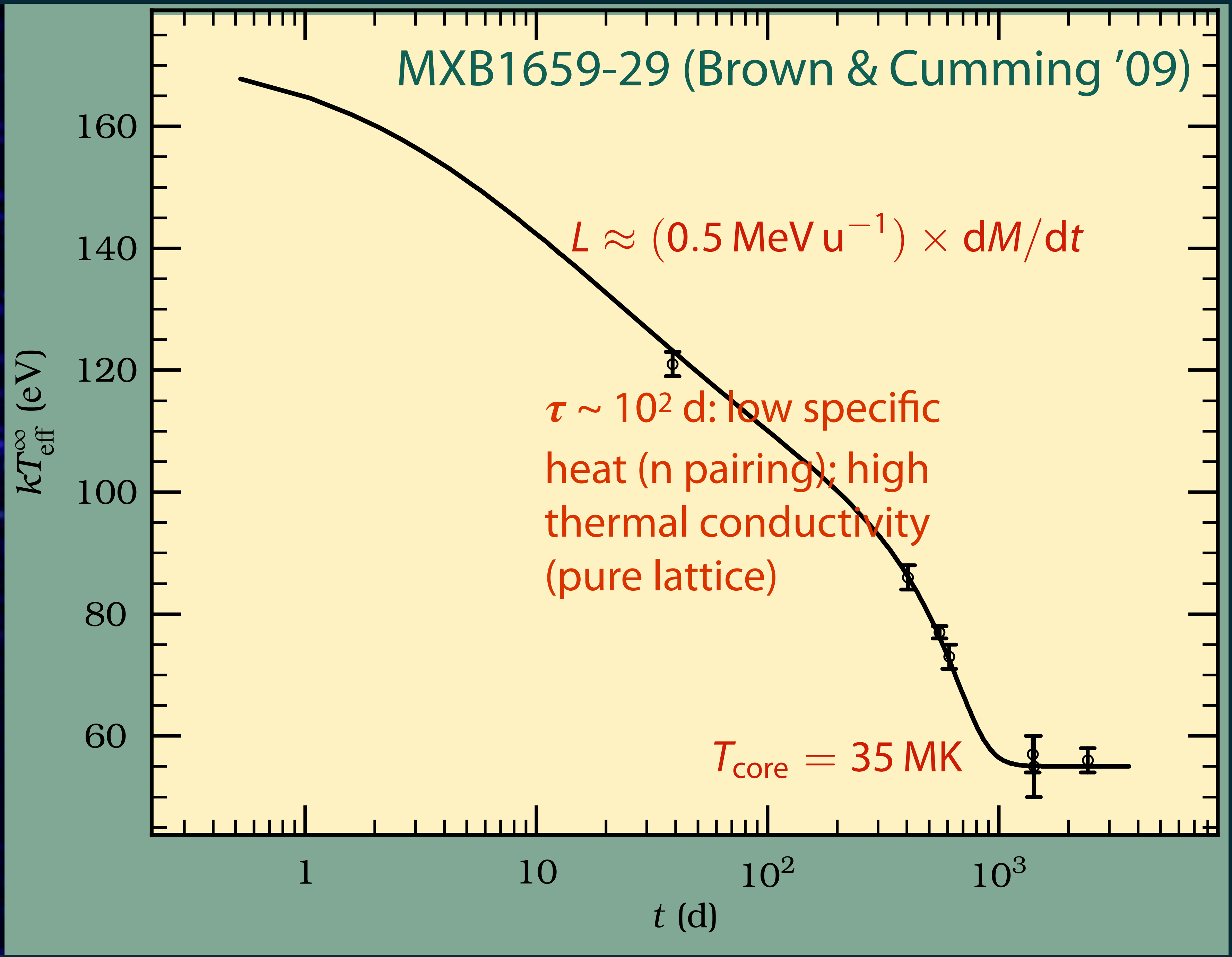
Add a heat source





crust cooling | implications





Shternin et al. '07; Brown & Cumming '09; Page & Reddy '13; Turlione '13; Deibel et al. '17; Merritt et al. '16; Waterhouse et al. '16; Parikh et al. '17

findings | questions

Neutron stars have crusts

These crusts cool quickly

Why is the crust so pure?

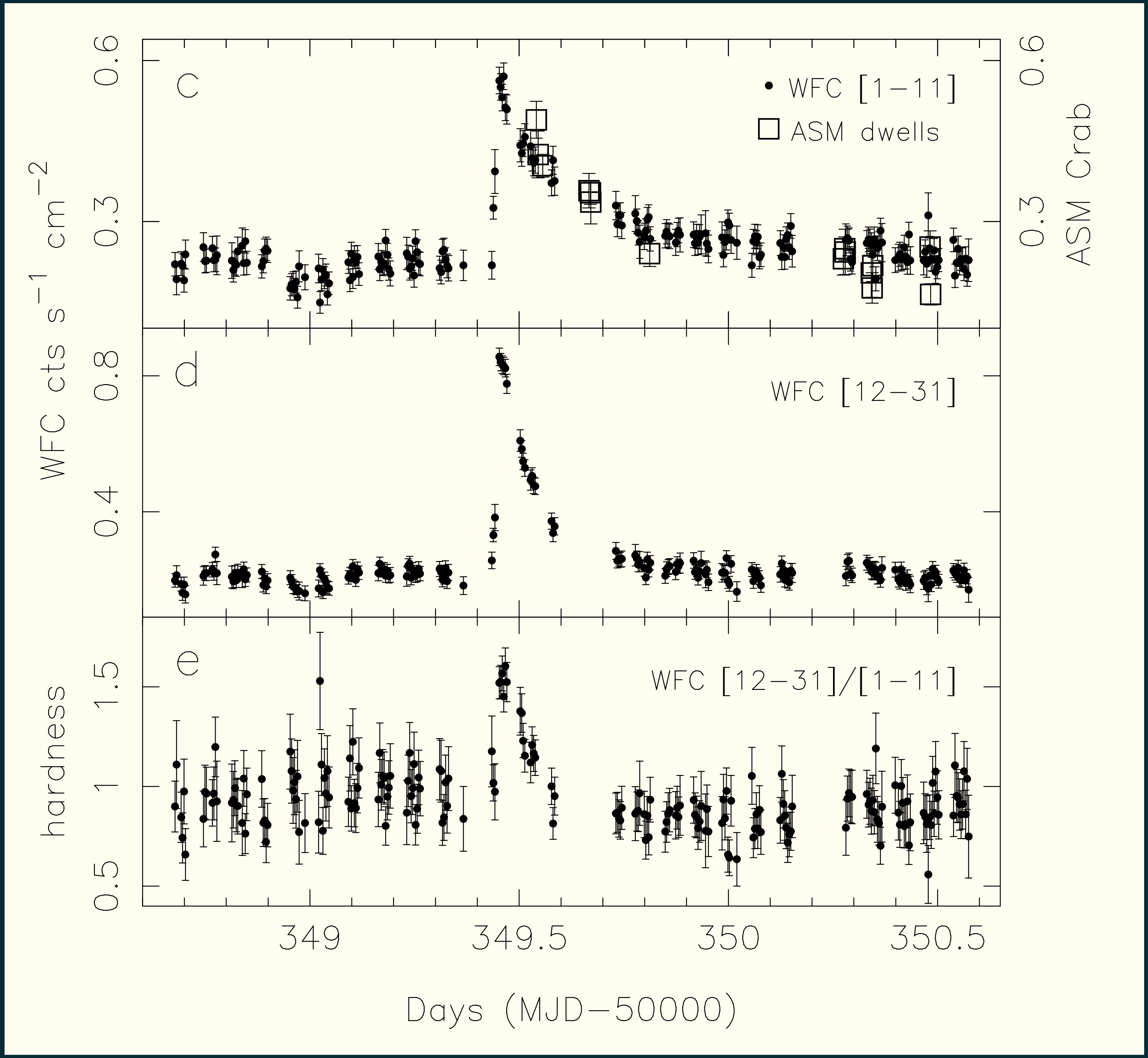
Have we found pasta?

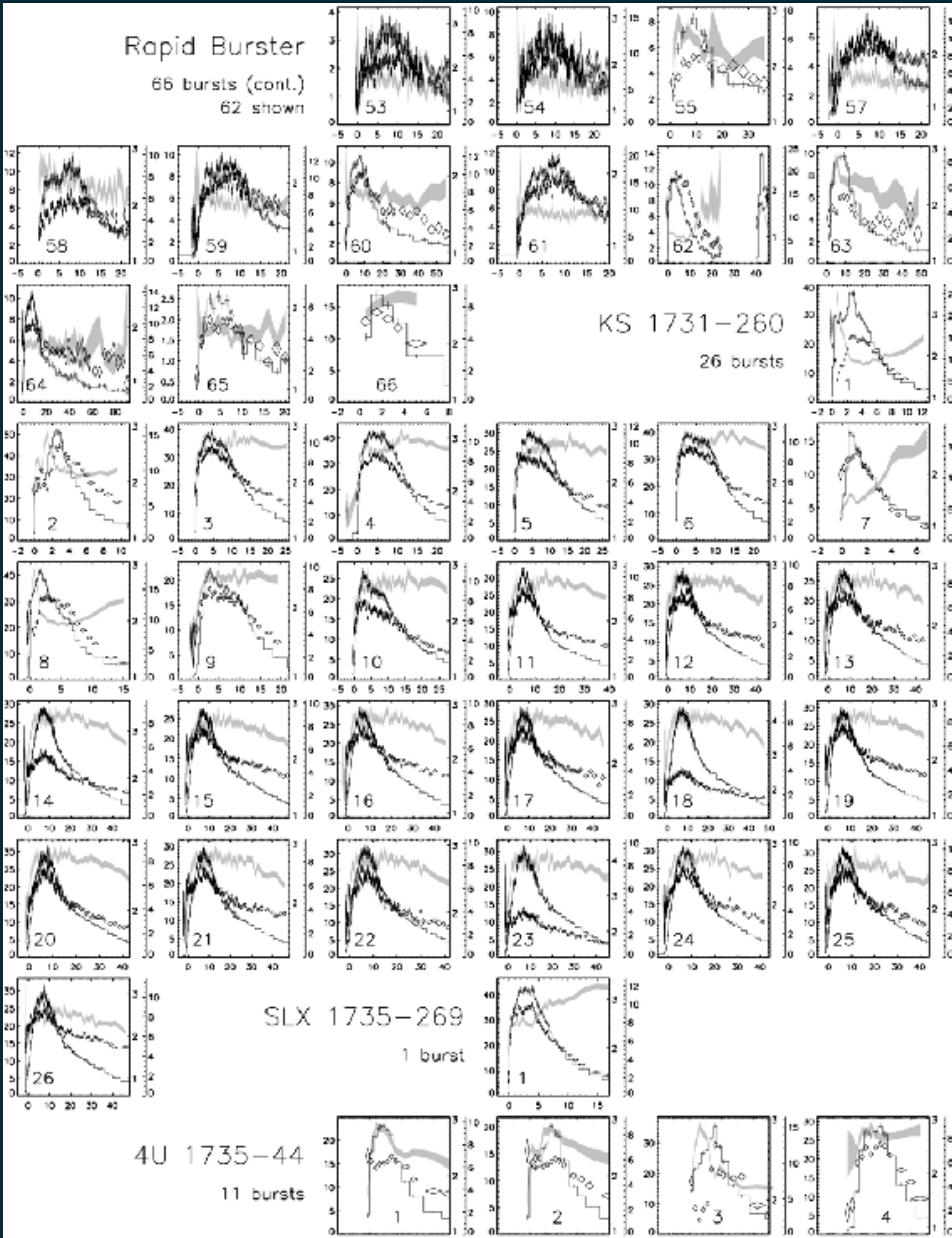
What is the source of the shallow heat?

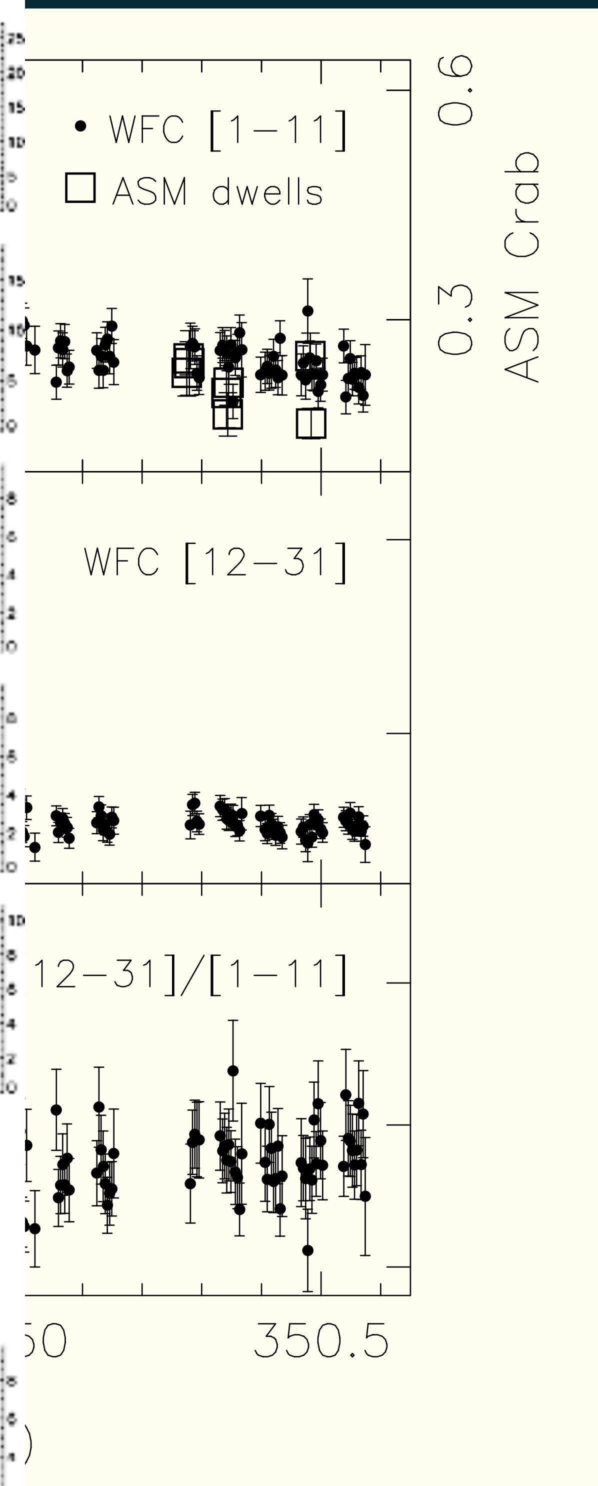
What can we infer about the neutron star core?

The Superburst Mystery

KS 1731–260 (Kuulkers 2002)




Rapid Burster
66 bursts (cont.)
62 shown
KS 1731−260
26 bursts
SLX 1735−269
1 burst
4U 1735−44
11 bursts


• WFC [1−11]
□ ASM dwells
0.6
0.3
ASM Crab
WFC [12−31]
12−31]/[1−11]
50
350.5

The Superburst Mystery

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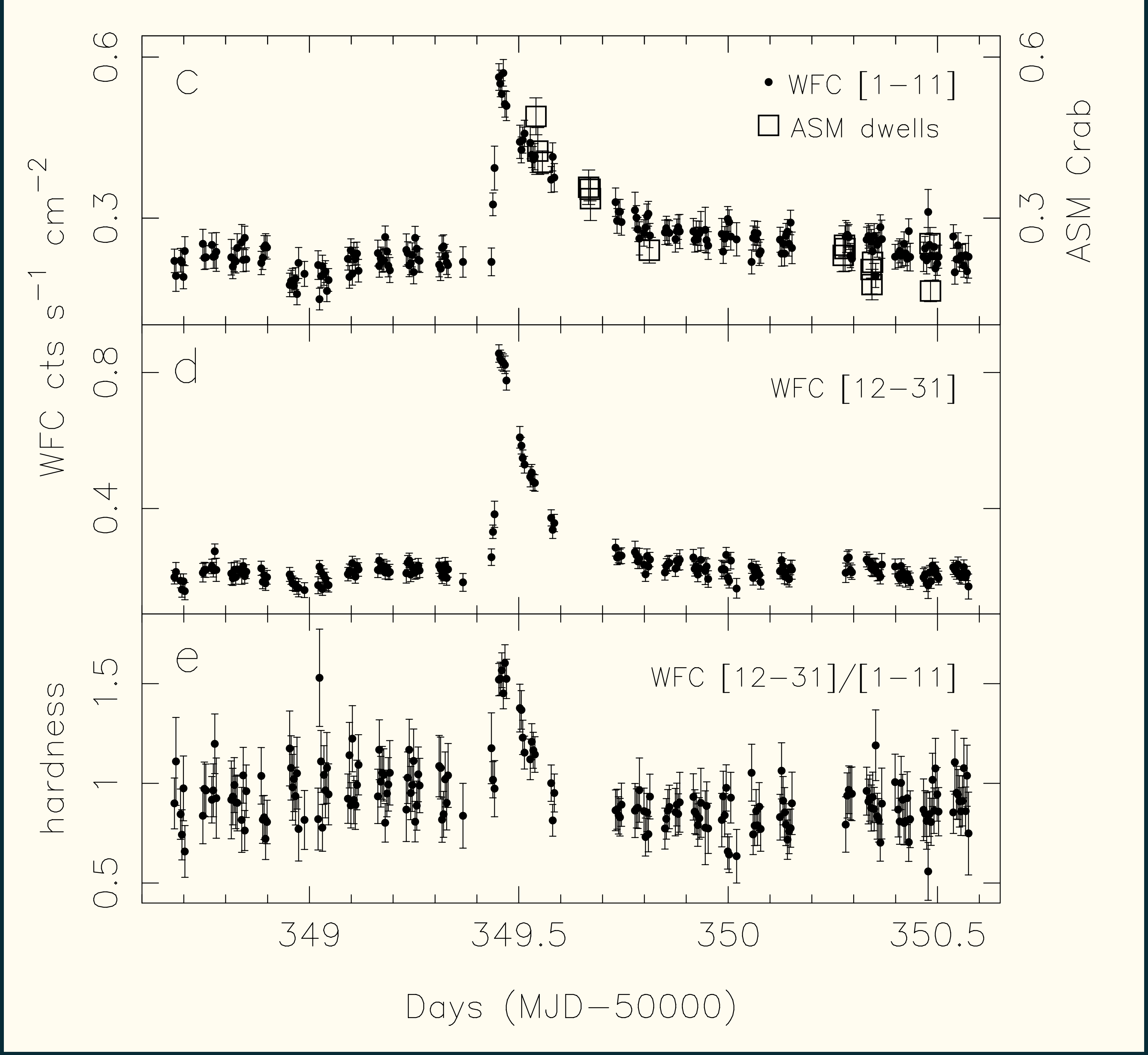

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