Entr'acte

Neutron stars are a unique probe of matter at super-saturation density

Masses and radii provide information about the EOS (pressure-density relation) of nuclear matter

Cooling tests the behavior of nuclear matter at high density; rapid cooling indicates presence of exotic particles or a high proton fraction (large symmetry energy)

Neutron stars accreting from a companion provide other probes of dense matter.

This lecture

Follow a fluid element from its deposition into the atmosphere to its assimilation into the core

- thermally unstable light-element reactions: X-ray bursts and superbursts
- deep crustal heating: electron captures and neutron emissions

Implications for studying dense matter

Thought question

Suppose you could send a probe to the surface of a neutron star. What is a likely value for the density?

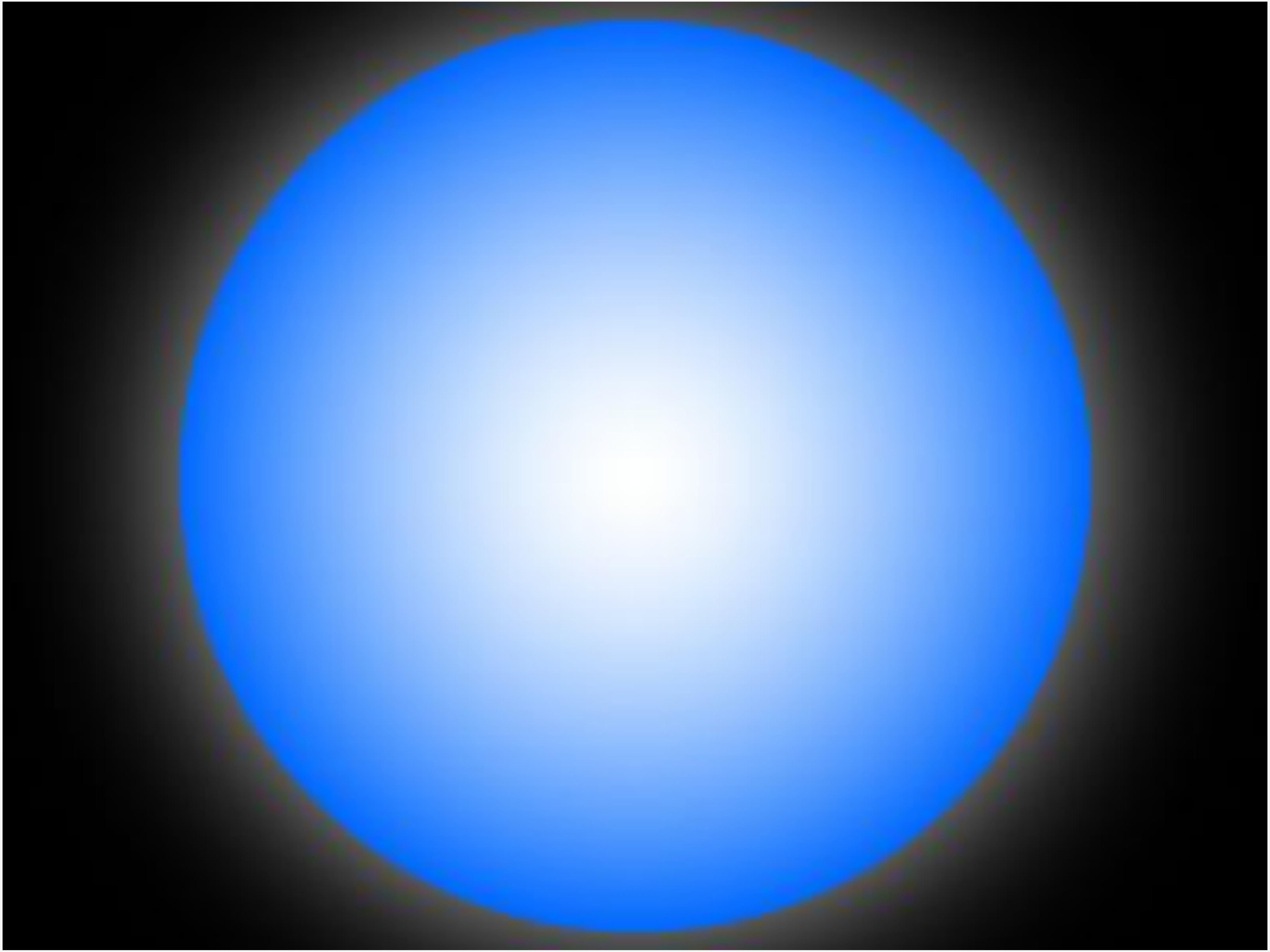
Recall that

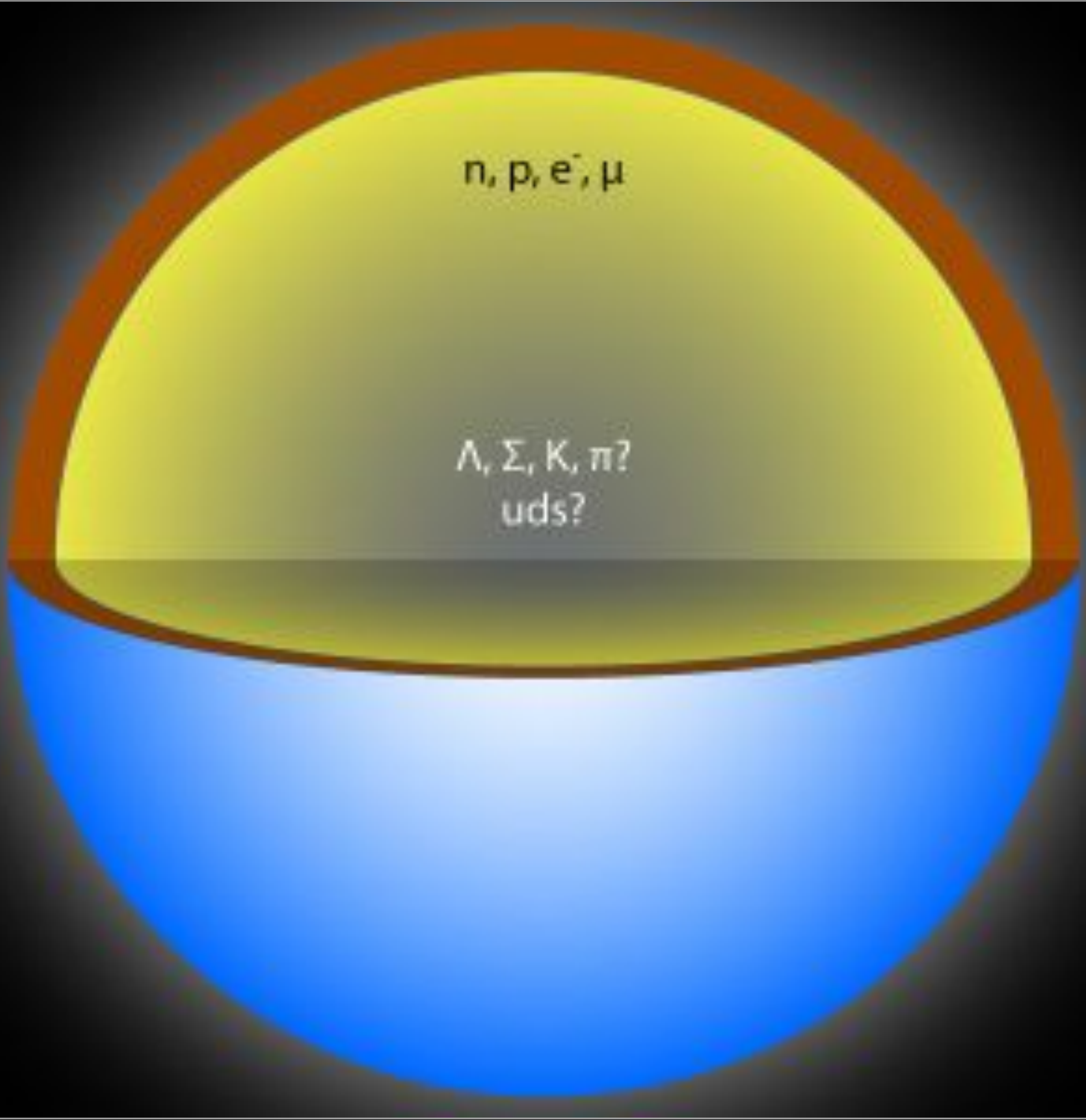
$$\frac{\mathrm{d}P}{\mathrm{d}r} = -\rho\frac{GM}{R^2}.$$

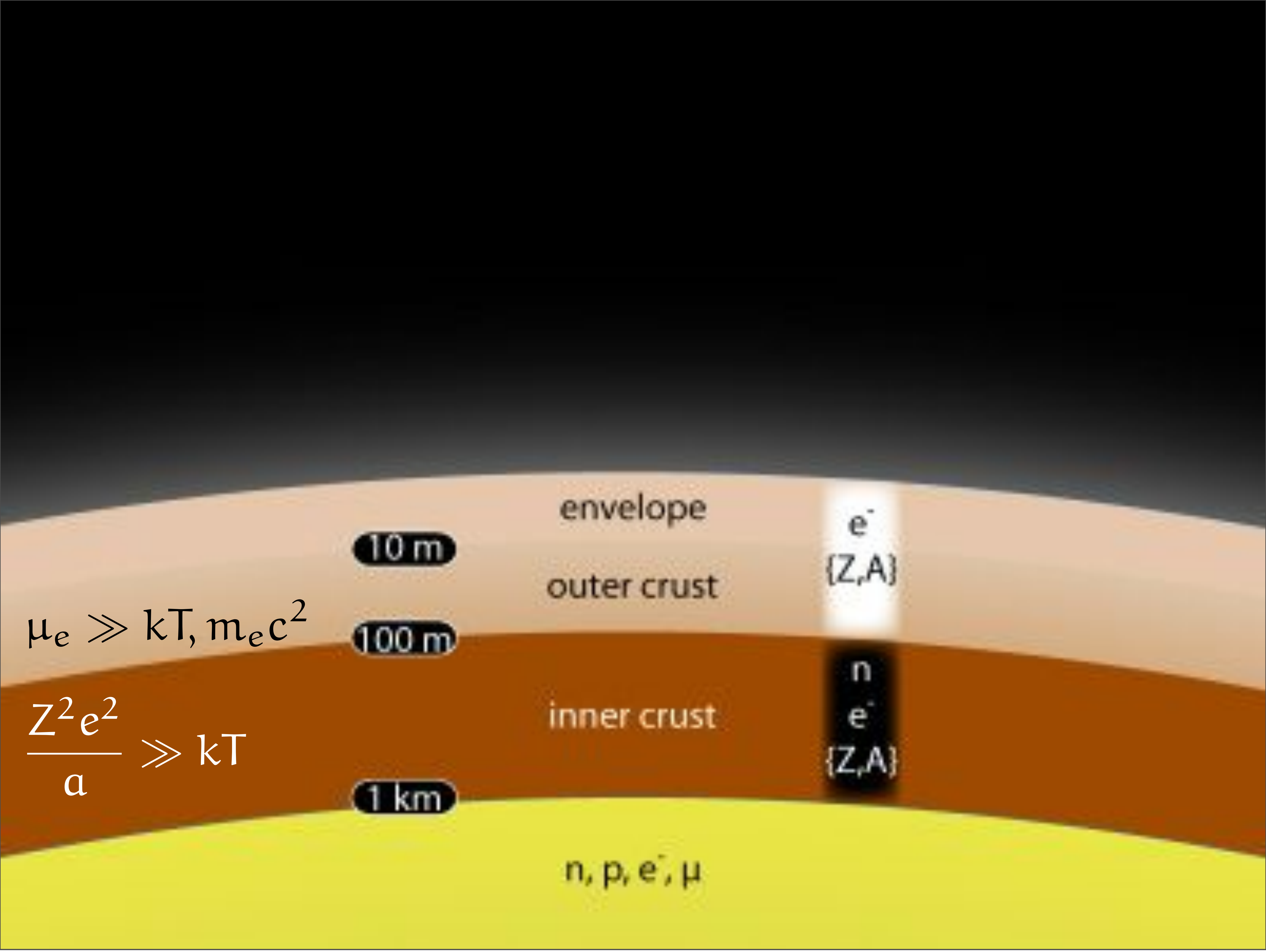
The characteristic length over which the pressure changes is

$$H_P = -\left(\frac{\mathrm{d}\ln P}{\mathrm{d}r}\right)^{-1} = \frac{P}{\rho g}$$

and is $\sim$ cm at the neutron star surface.

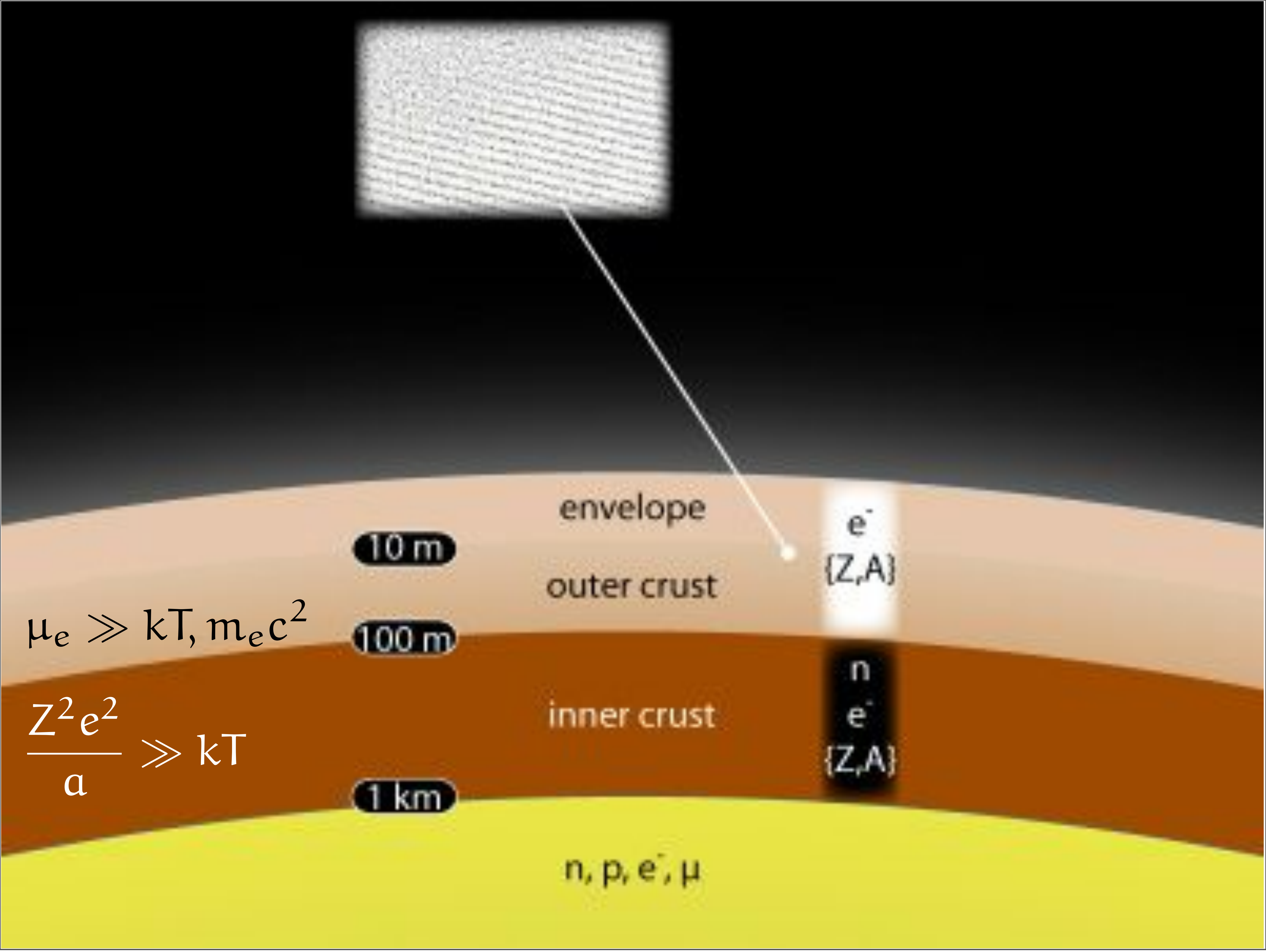



n, p, e^-, μ
Λ, Σ, K, π?
uds?



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

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



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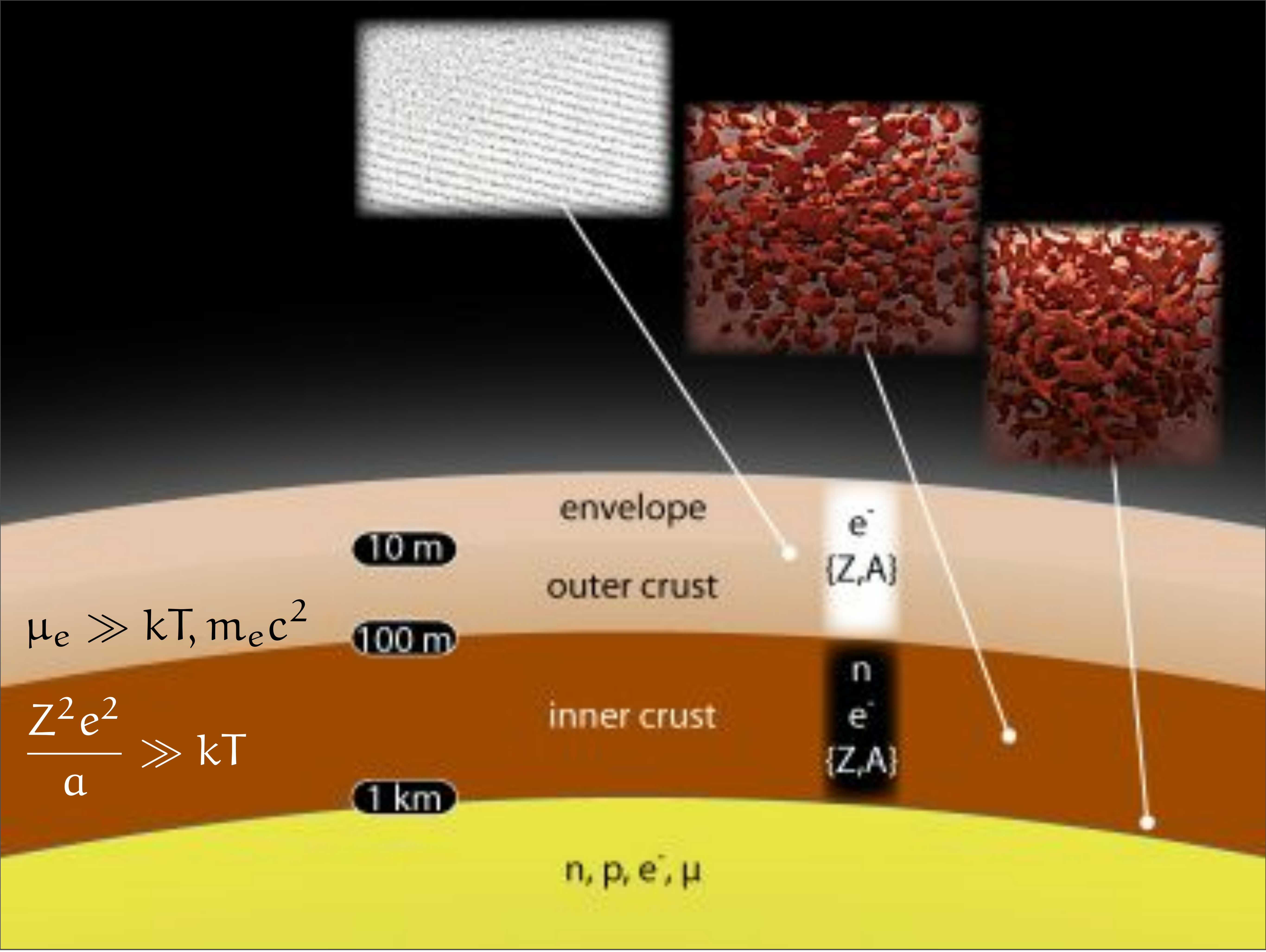

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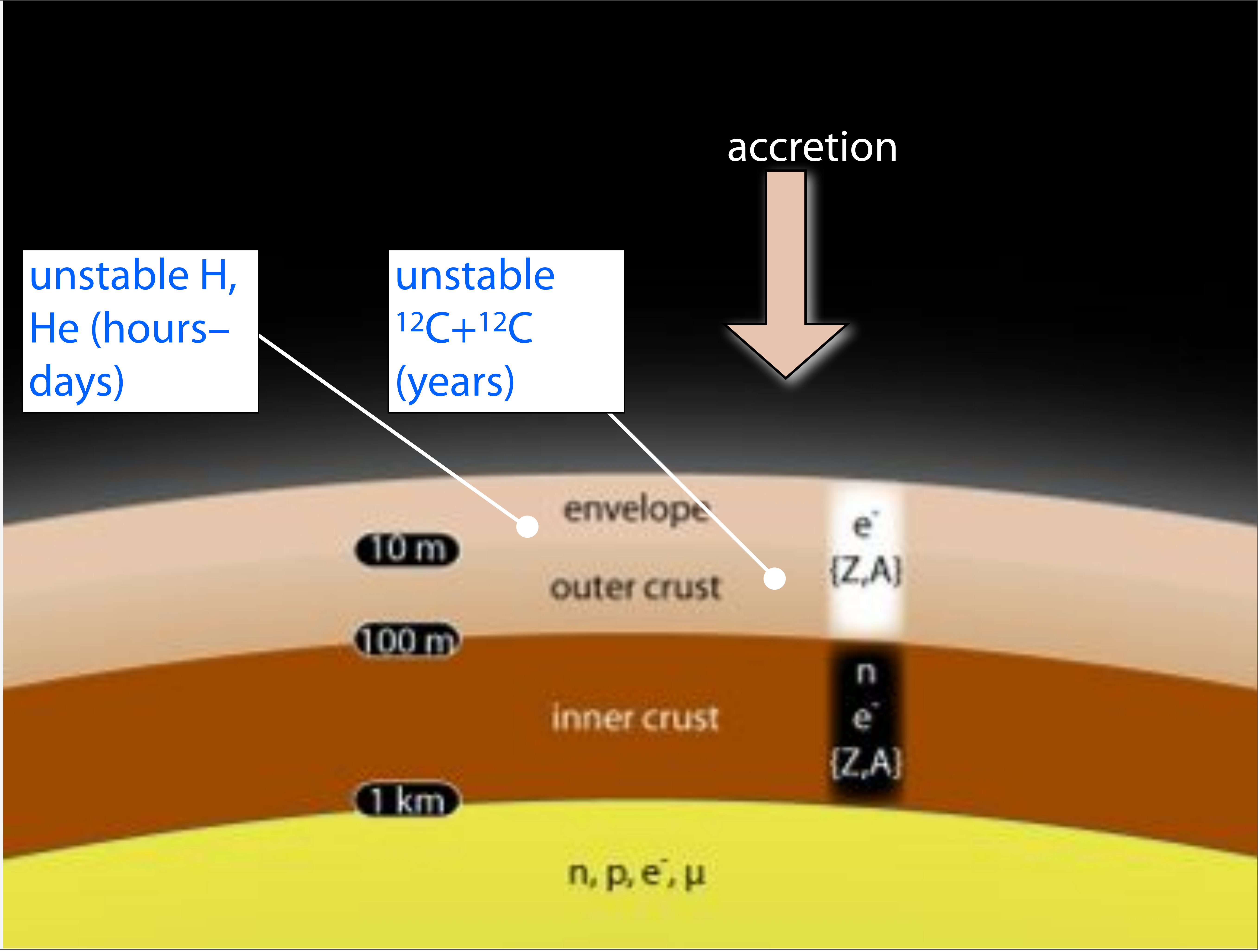


accretion

unstable H, He (hours–days)

unstable $^{12}C+^{12}C$ (years)

unstable ignition of H/He

Hansen & van Horn; Fujimoto et al.; Narayan & Heyl; Cooper & Narayan

Start with

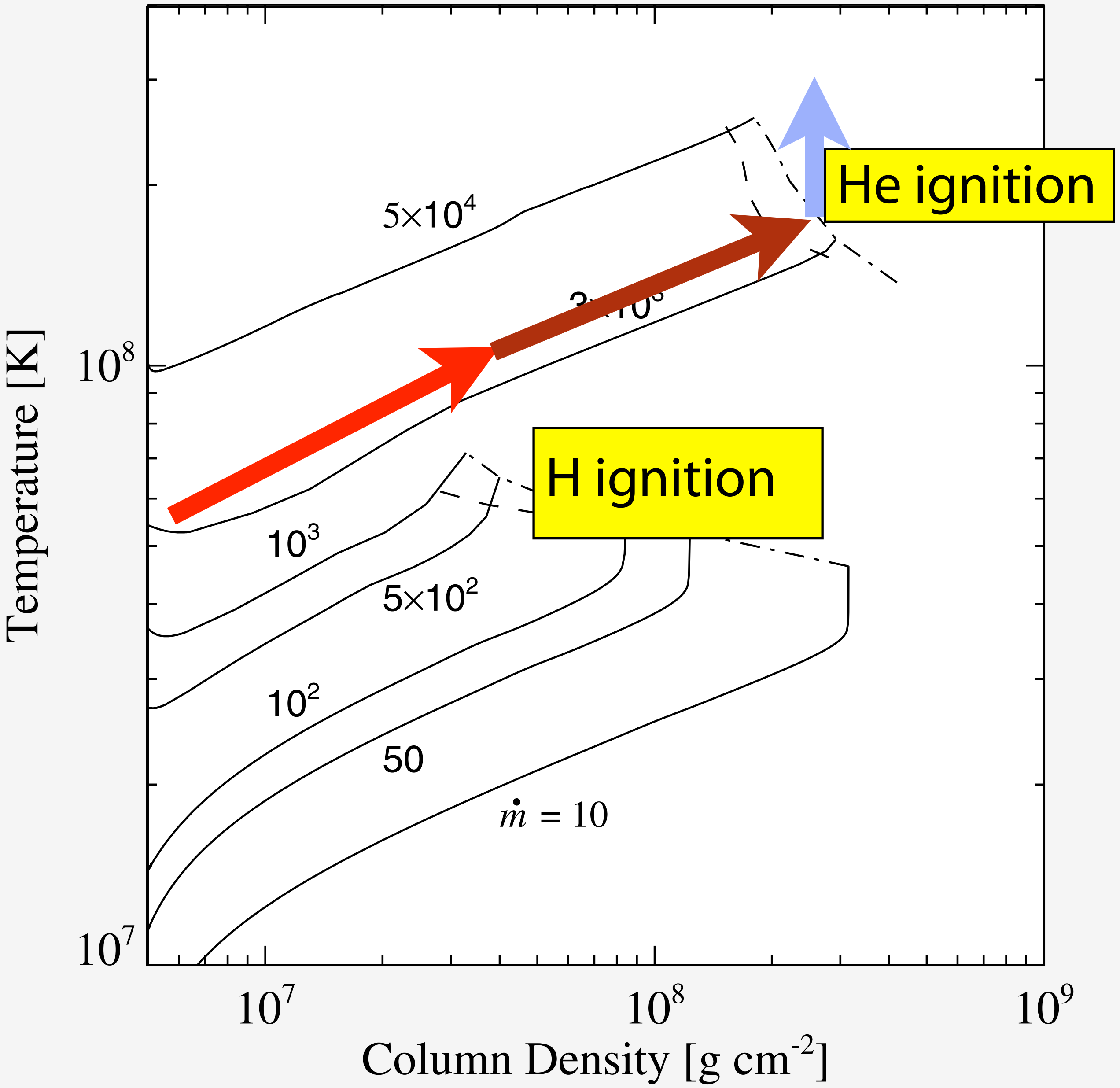
$$T\frac{\mathrm{d}s}{\mathrm{d}t} = \varepsilon + \frac{1}{\rho}\frac{\partial}{\partial r}\left(K\frac{\partial T}{\partial r}\right).$$

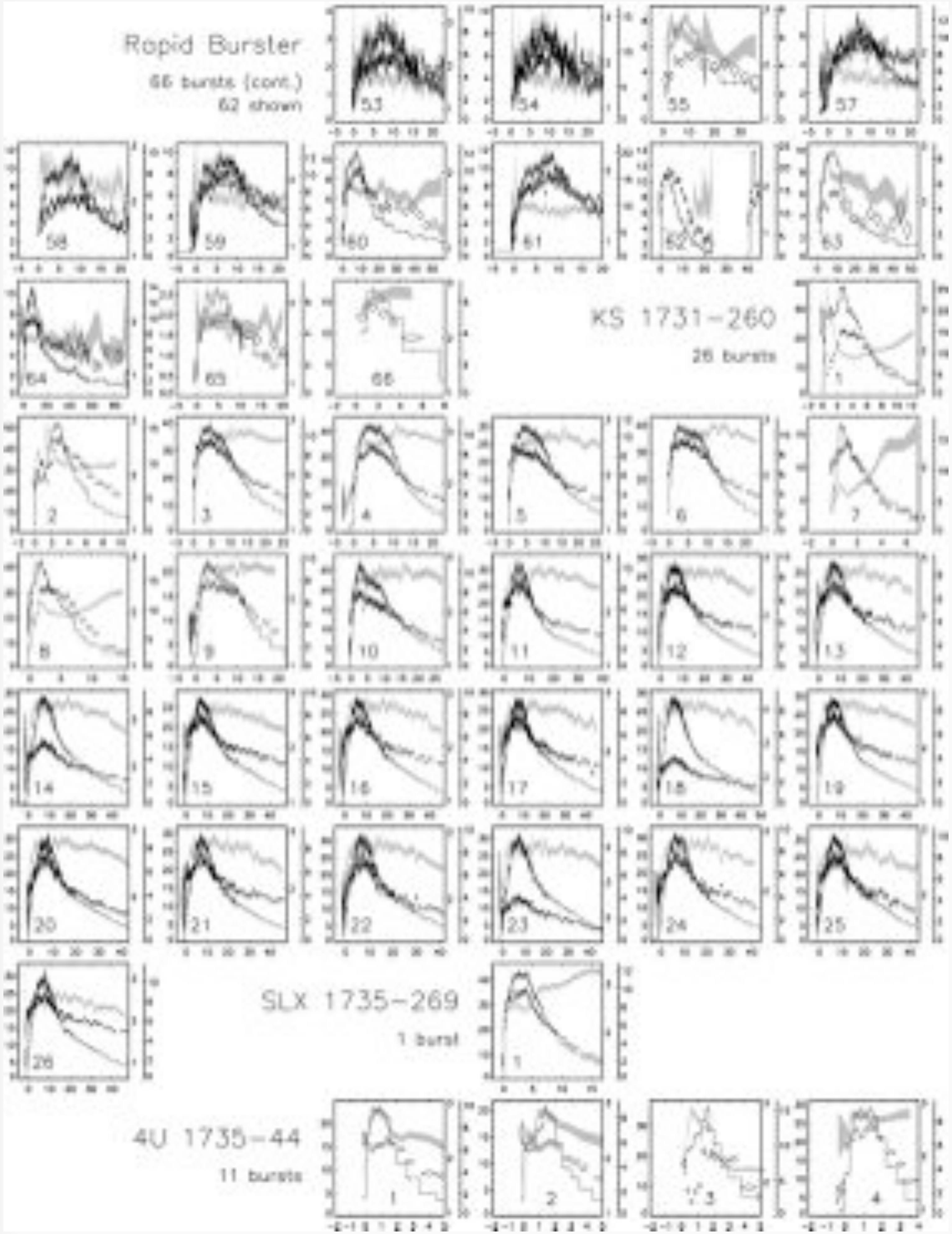
Since the accreted layer is thin, find steady-state solution and perturb *T* about the solution; look for unstable modes.

$$\frac{\partial \ln \varepsilon}{\partial \ln T} > \frac{\partial \ln \varepsilon_{\mathrm{cool}}}{\partial \ln T}$$

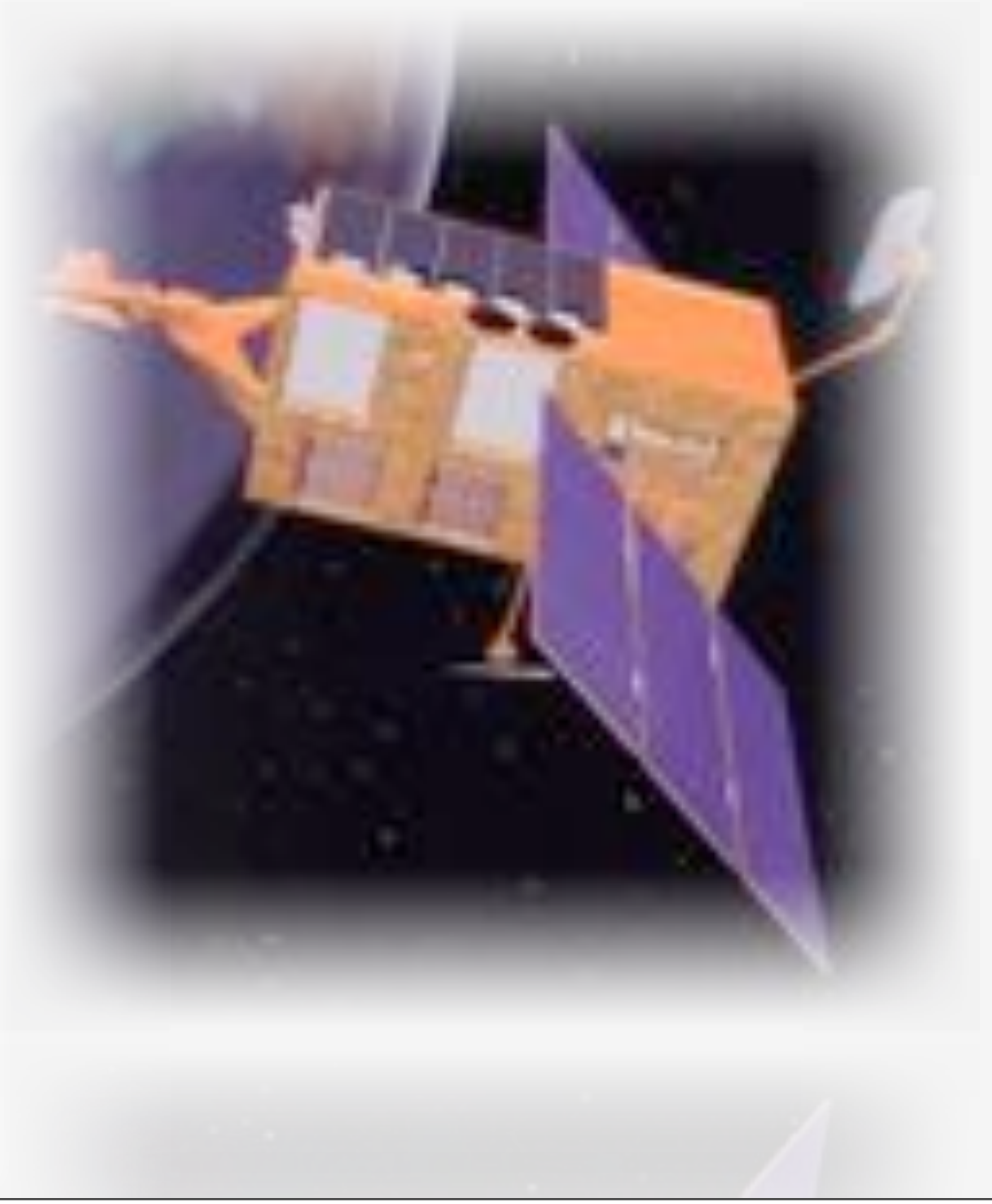
$$\varepsilon_{\mathrm{cool}} \approx \frac{K\Delta T}{\rho(\Delta r)^2}$$

Peng et al. 2007

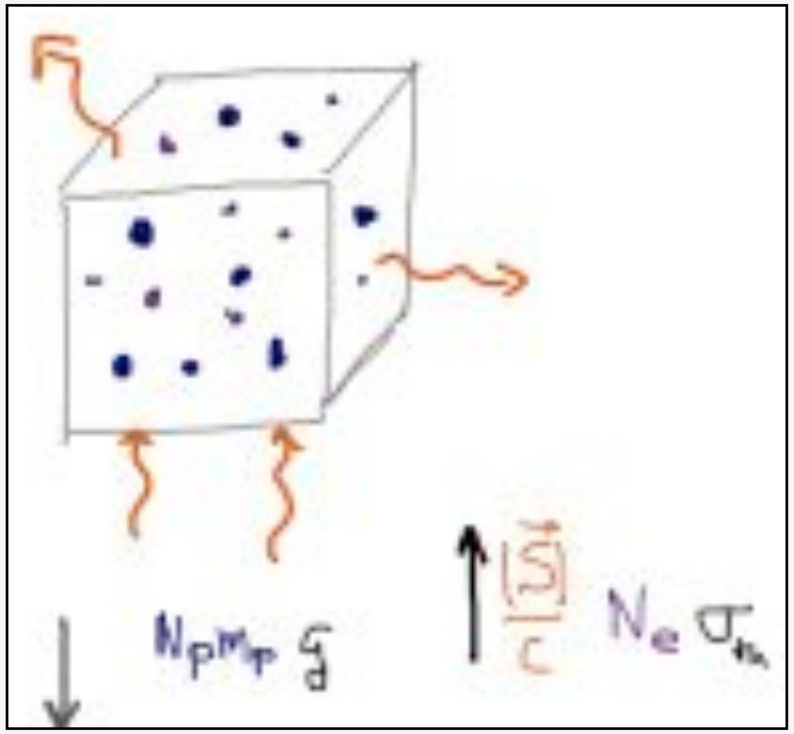




MINBAR catalog (Galloway et al.): A sample of >1200 X-ray bursts from ≈50 sources



Eddington limit: balance radiative force, gravitation



$$\begin{aligned} \text{force from radiation} &= \frac{L}{4\pi r^2 c} N_e \sigma_{\mathrm{Th}} \\ \text{gravitation force} &= N_p m_p \frac{GM}{r^2} \end{aligned}$$

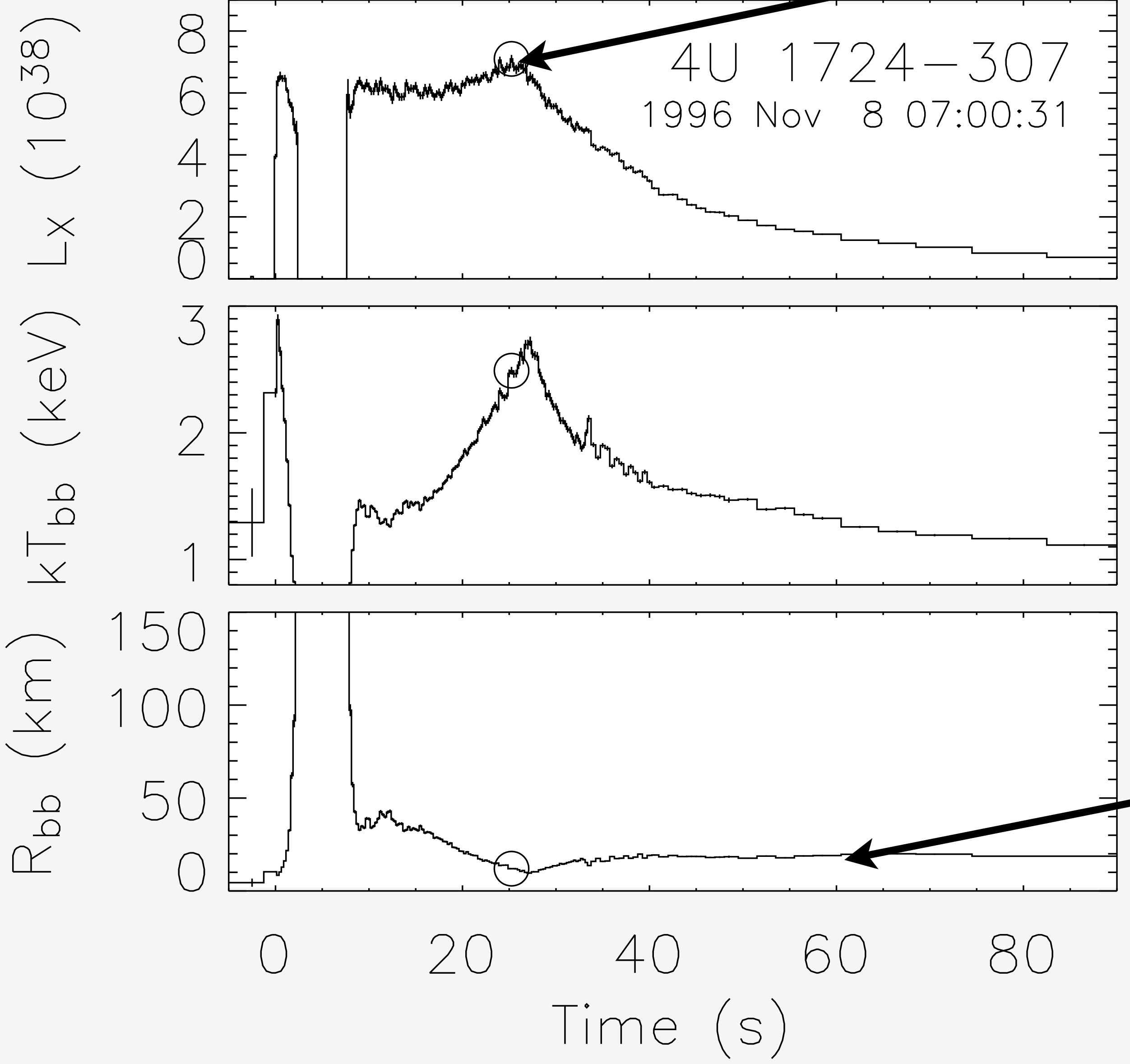
This defines the *Eddington limit*,

$$L_{\mathrm{Edd}} = \frac{4\pi GMc}{Y_e \sigma_{\mathrm{Th}}/m_p}.$$

For a solar mass, $L_{\mathrm{Edd}} \approx 10^{38}\ \mathrm{erg\,s}^{-1} \approx 10^5\ L_\odot$.

Some bursts show strong expansion of the photosphere

$$F_{\mathrm{Edd}} = \frac{L_{\mathrm{Edd}}}{4\pi D^2} = \frac{GMc}{\kappa D^2}$$



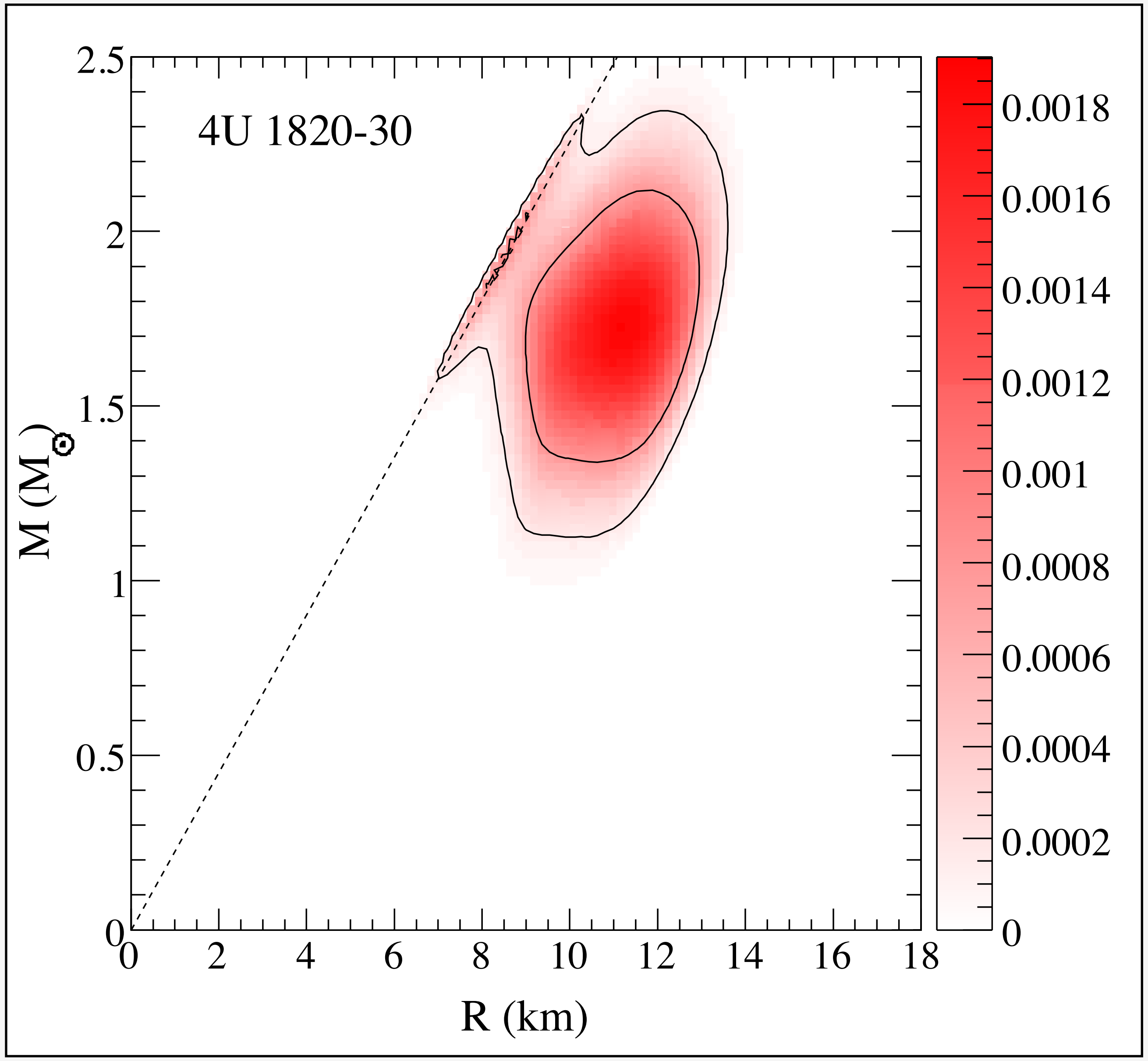
$$\frac{F}{\sigma T_{\mathrm{eff}}} = \left(\frac{R}{D}\right)^2$$

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.)

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

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



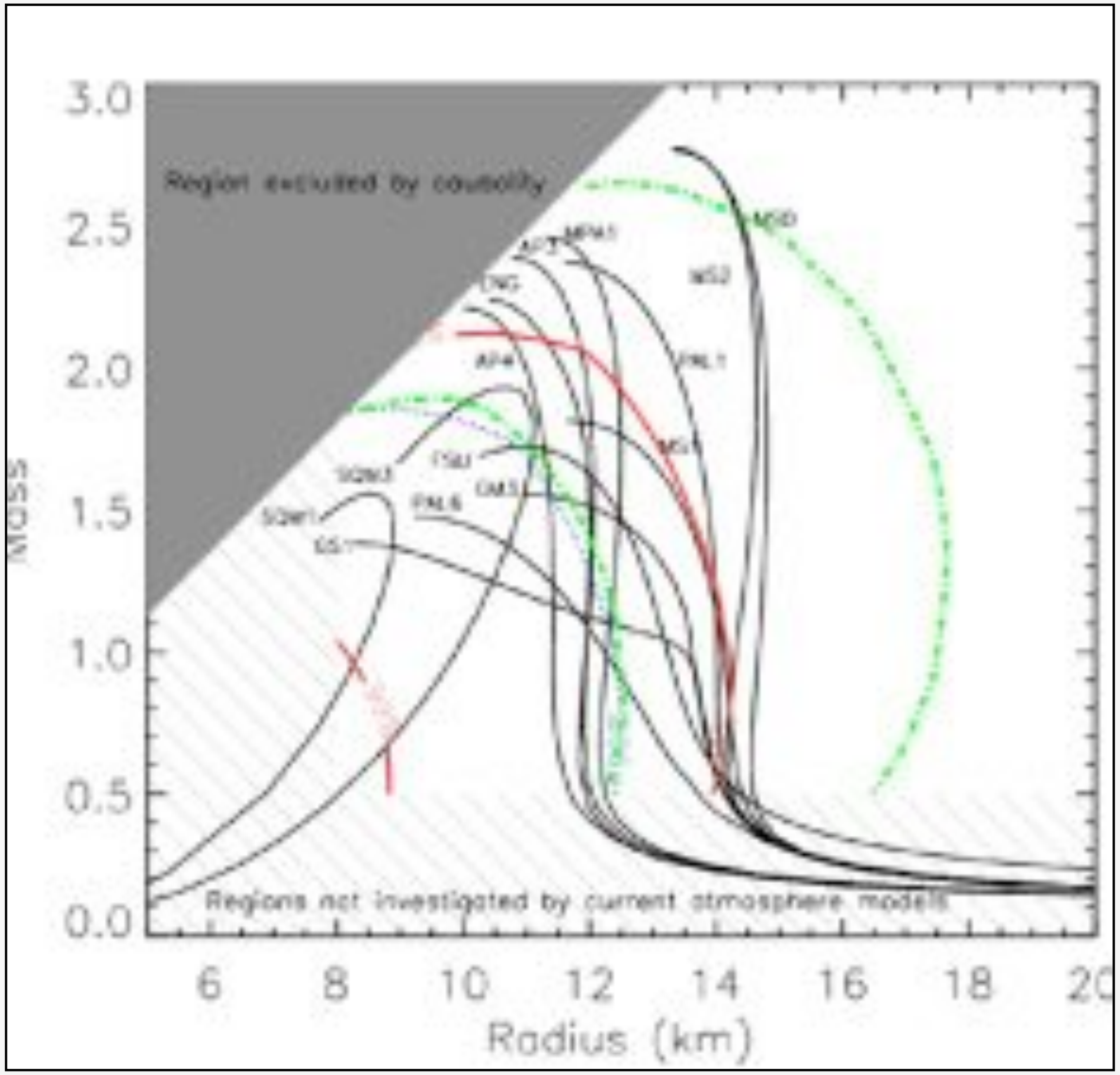
Steiner et al.; data from Guver et al. '10

An Empirical Dense Matter Equation of State

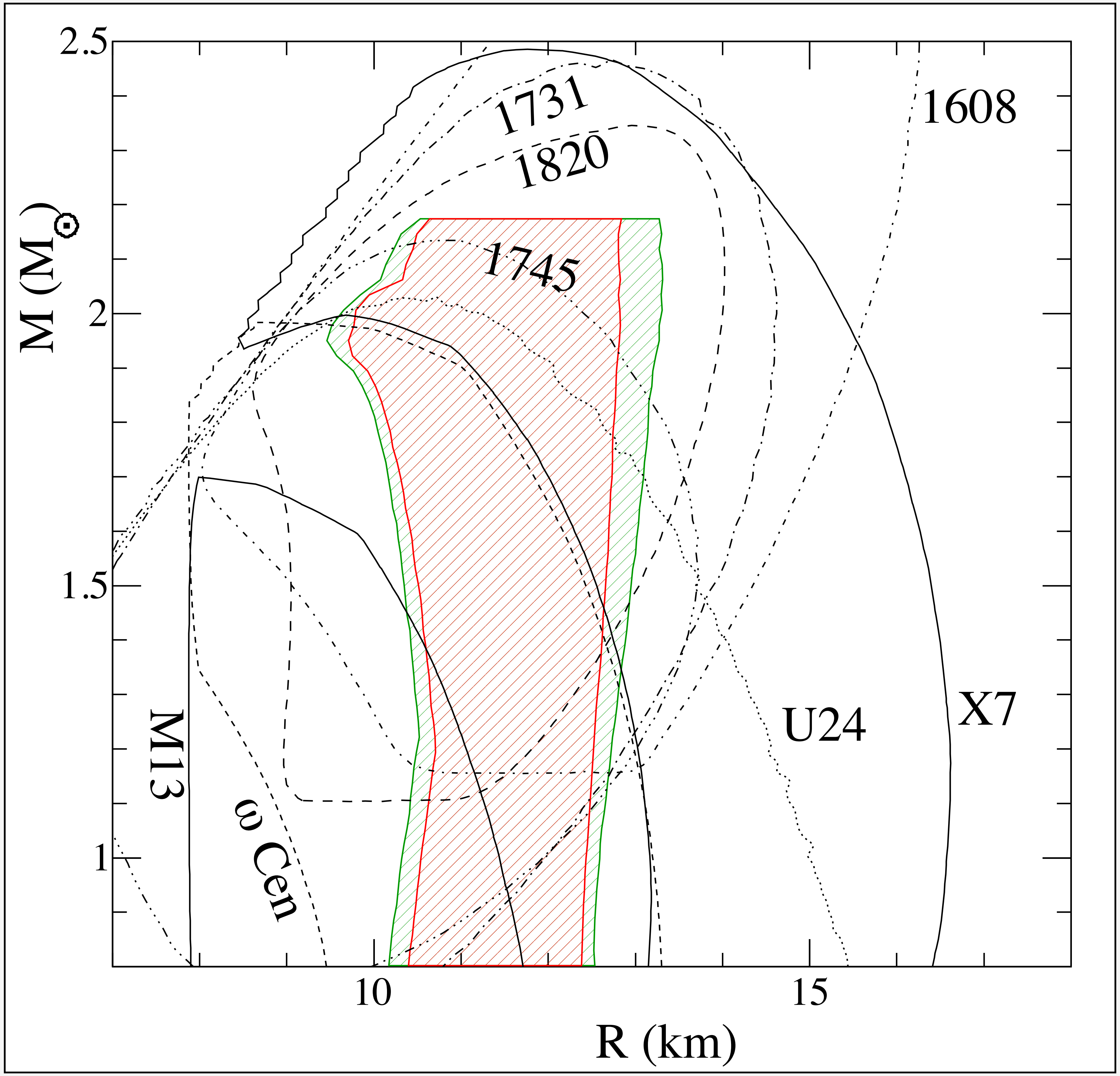
Transients

From observations of quiescent neutron stars with pure hydrogen atmospheres one gets emitting area (with redshift correction; Marshall ’82)

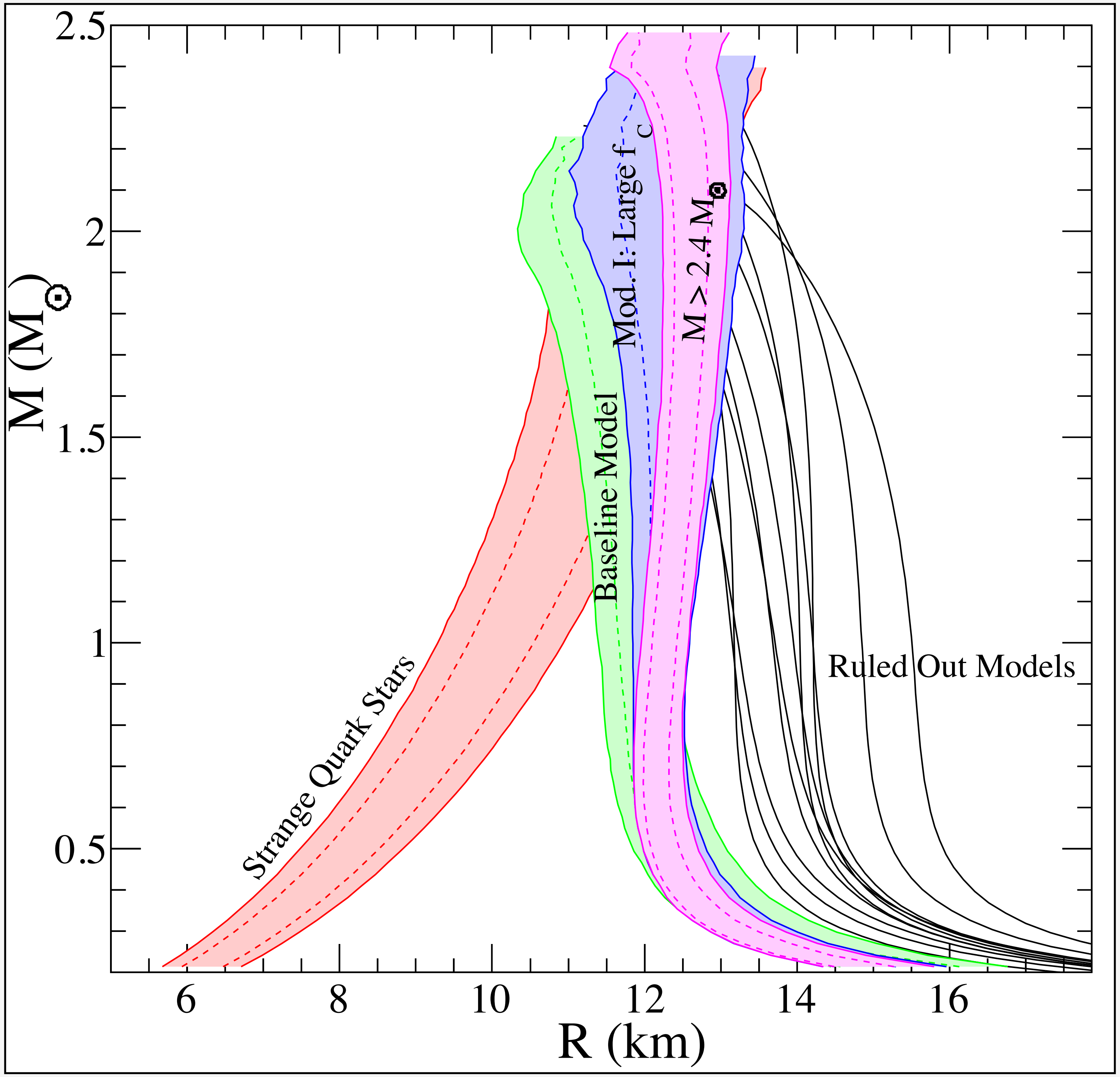
$$\frac{F}{\sigma T_{\mathrm{eff}}^4} = \left(\frac{R}{D}\right)^2 \left(1 - \frac{2GM}{Rc^2}\right)^{-1}$$



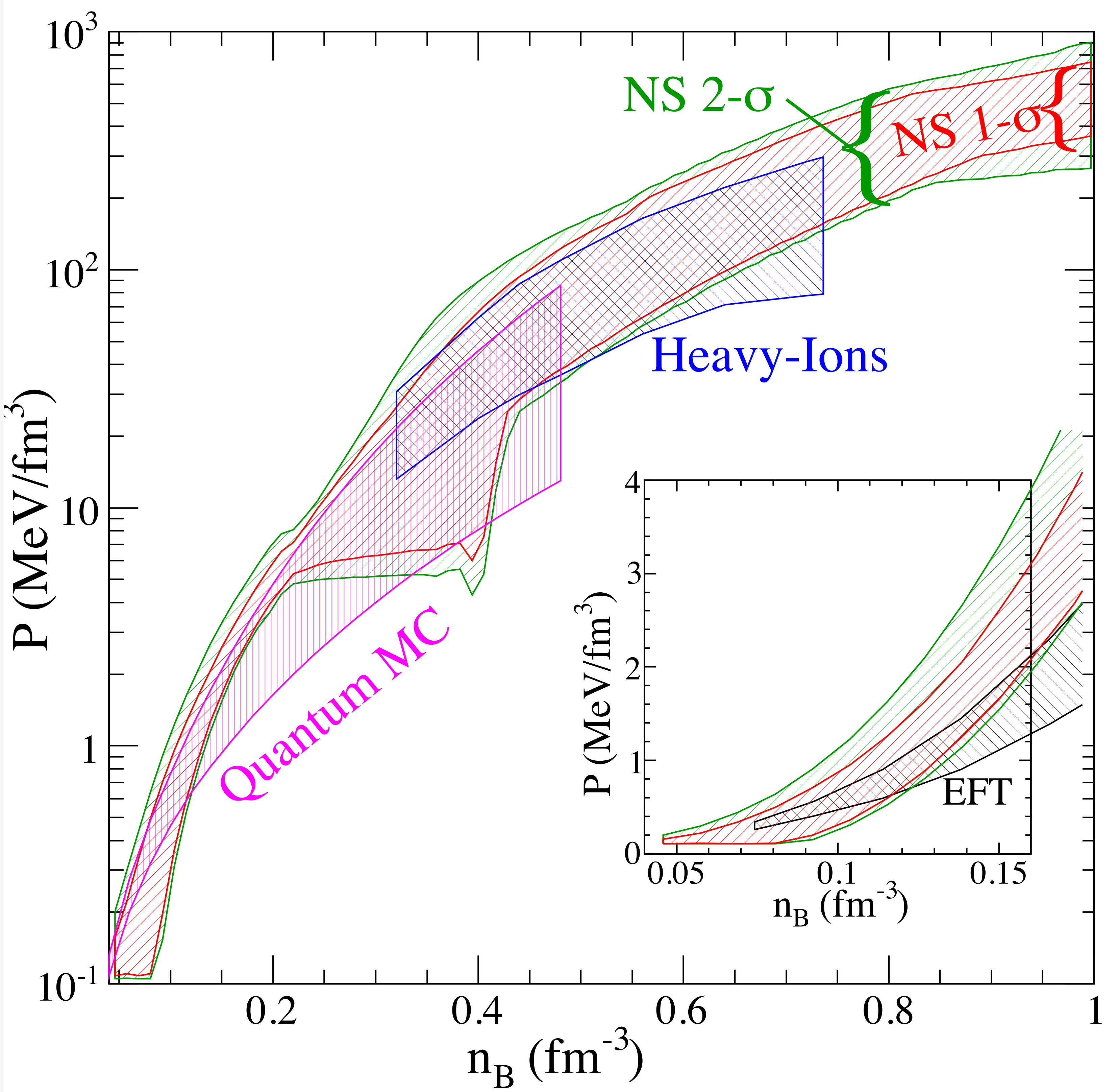
Plot from Webb & Barrett ’07



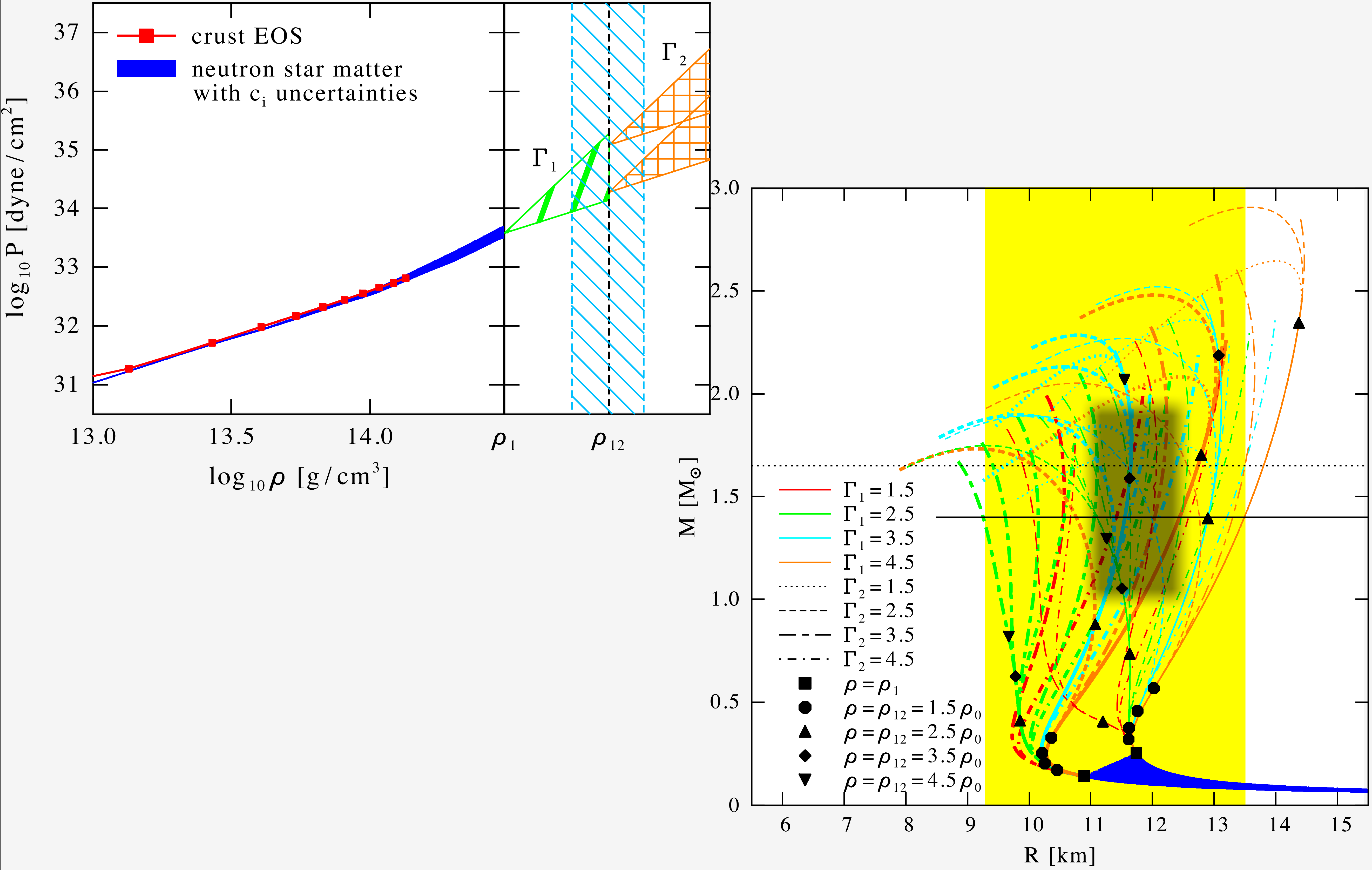
several neutron stars, one equation of state



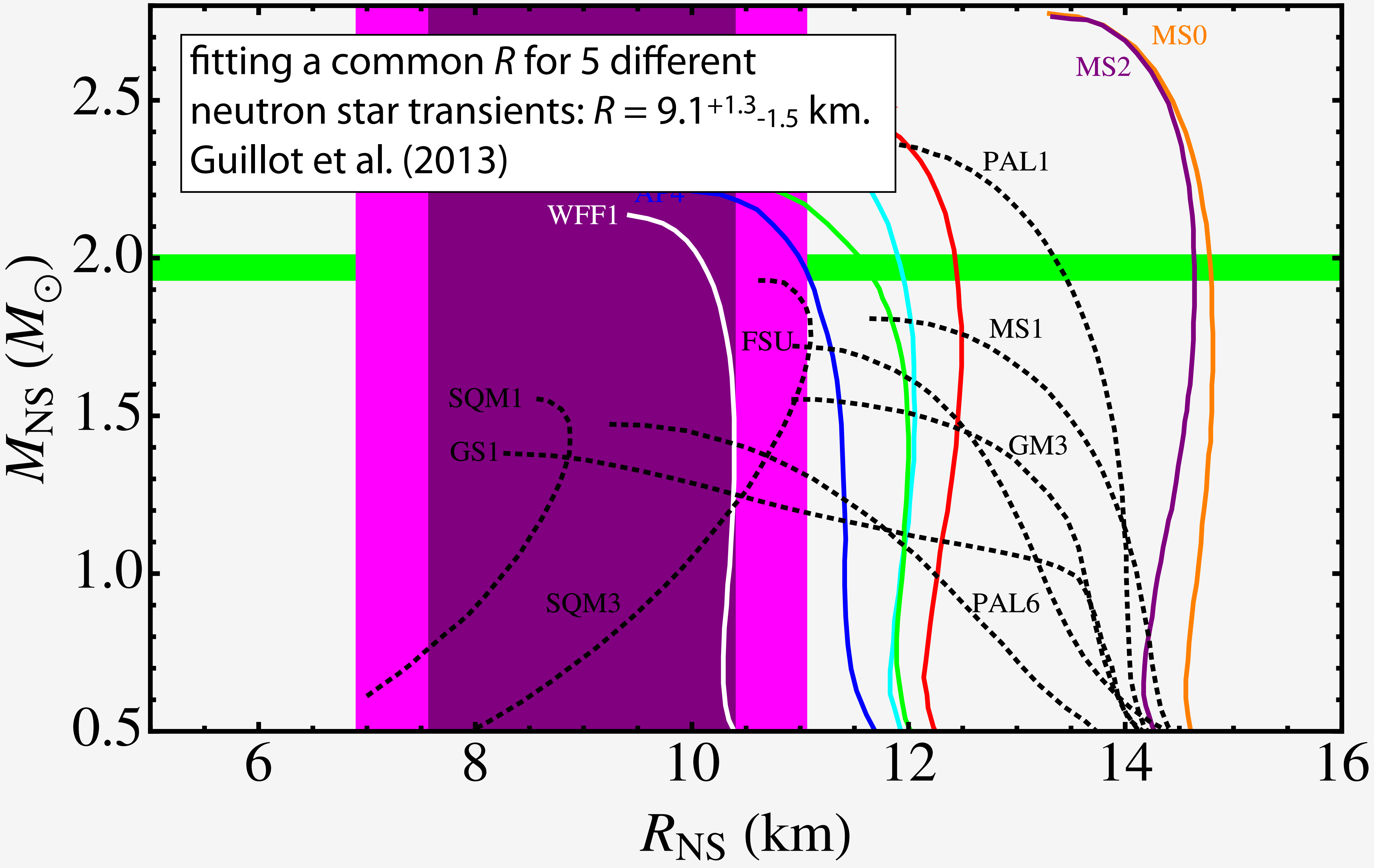
An empirical *M-R* relation (Steiner et al. '10, '13)



comparison with theory, experiment (Steiner et al., 2013)

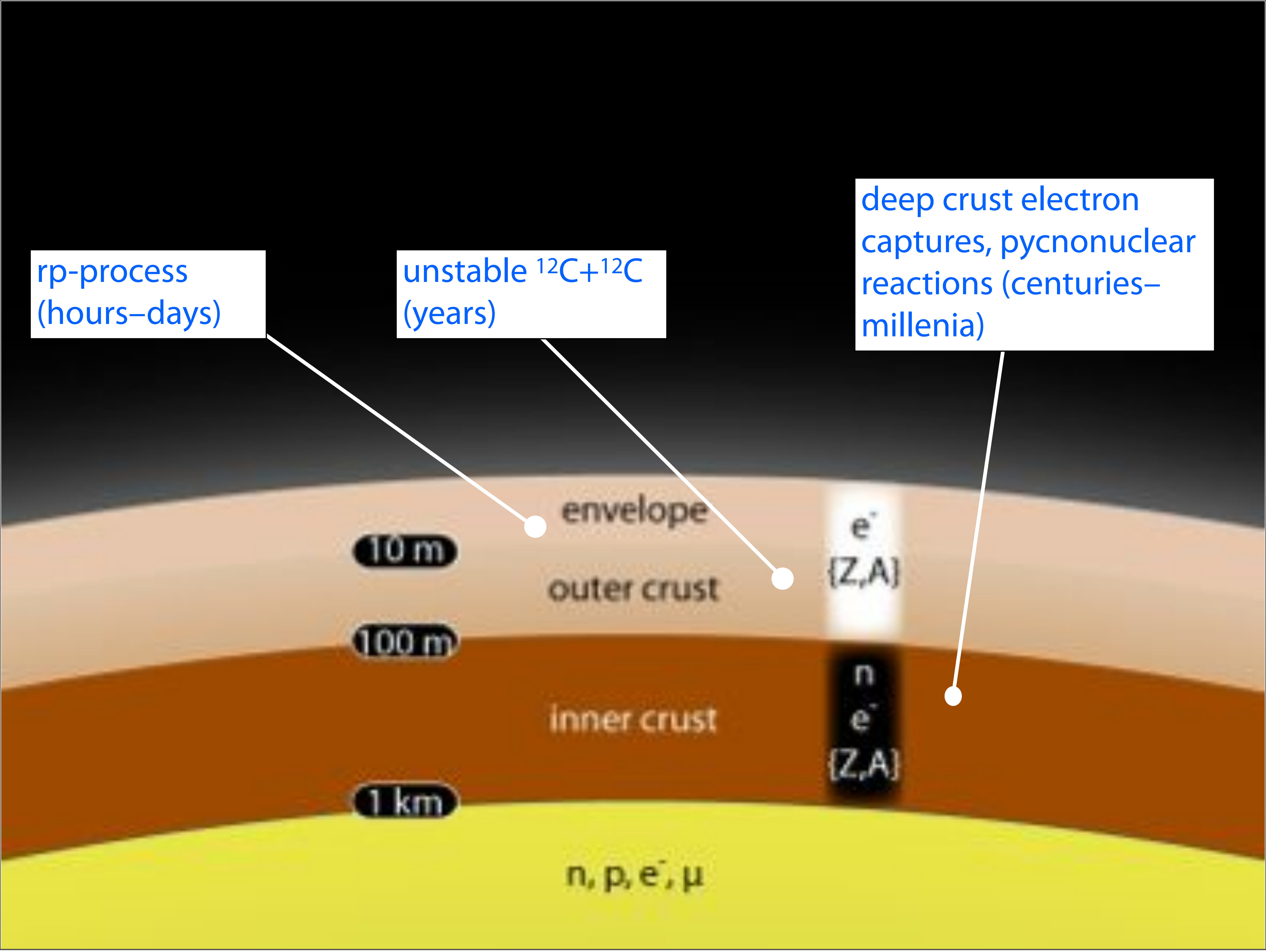


consistent with Hebeler et al. (2010, PRL)



fitting a common R for 5 different neutron star transients: $R = 9.1^{+1.3}_{-1.5}$ km.
Guillot et al. (2013)

But not everything is settled…



rp-process (hours–days)

unstable $^{12}C+^{12}C$ (years)

deep crust electron captures, pycnonuclear reactions (centuries–millenia)

neutronization

$$E \approx -a_V(N+Z) + a_A \frac{(N-Z)^2}{N+Z}$$

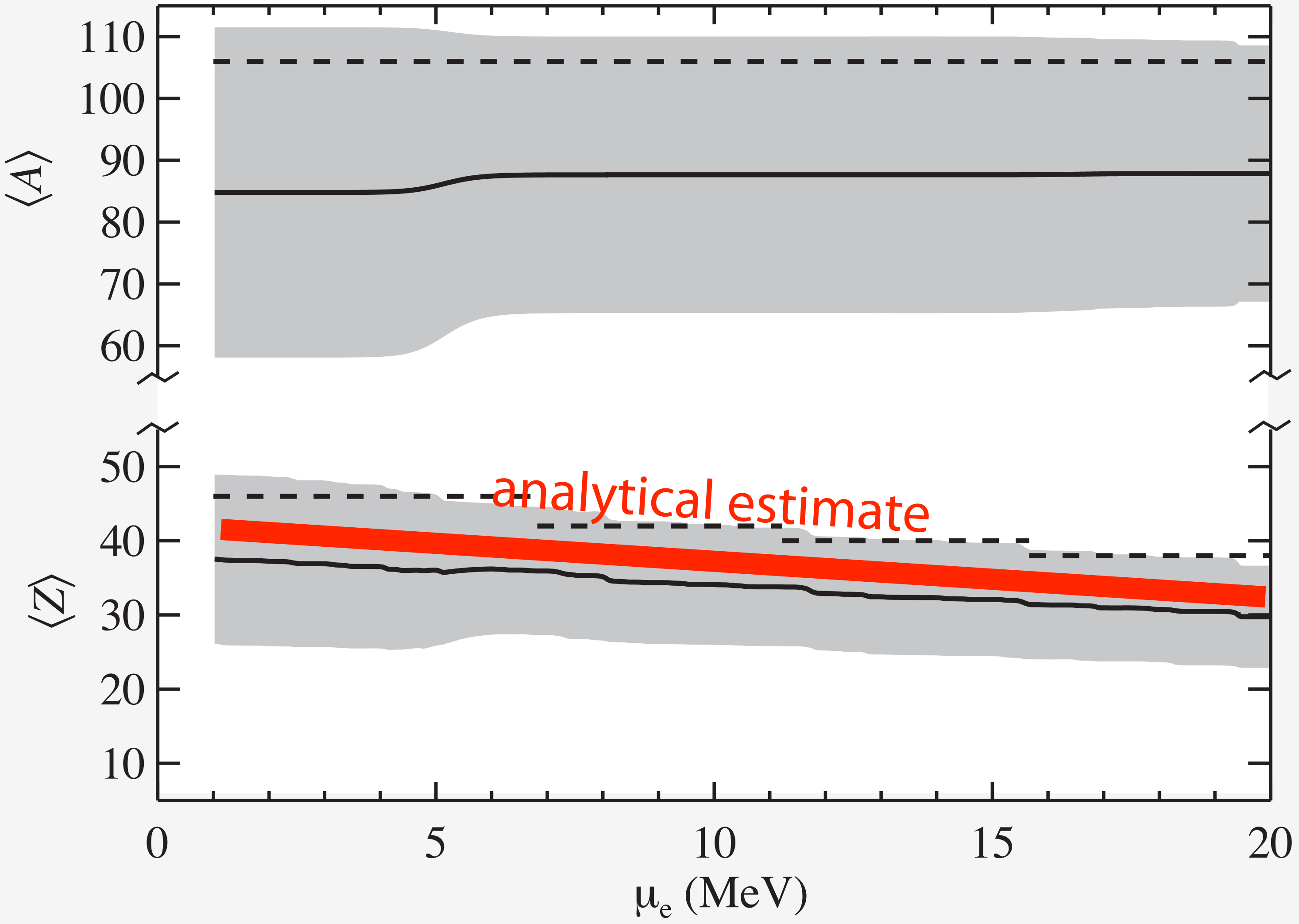
In β-equilibrium, $\mu_e = \mu_n - \mu_p$, with

$$\mu_n = \left(\frac{\partial E}{\partial N}\right)_Z, \quad \mu_p = \left(\frac{\partial E}{\partial Z}\right)_N.$$

$$\frac{Z}{A} \approx \frac{1}{2} - \frac{\mu_e}{8a_A}$$

Comparison with reaction network calculation

Gupta et al. ’07



Reaction network run with pressure increasing in time (compression of fluid element).

neutronization

$$E \approx -a_V(N+Z) + a_A \frac{(N-Z)^2}{N+Z}$$

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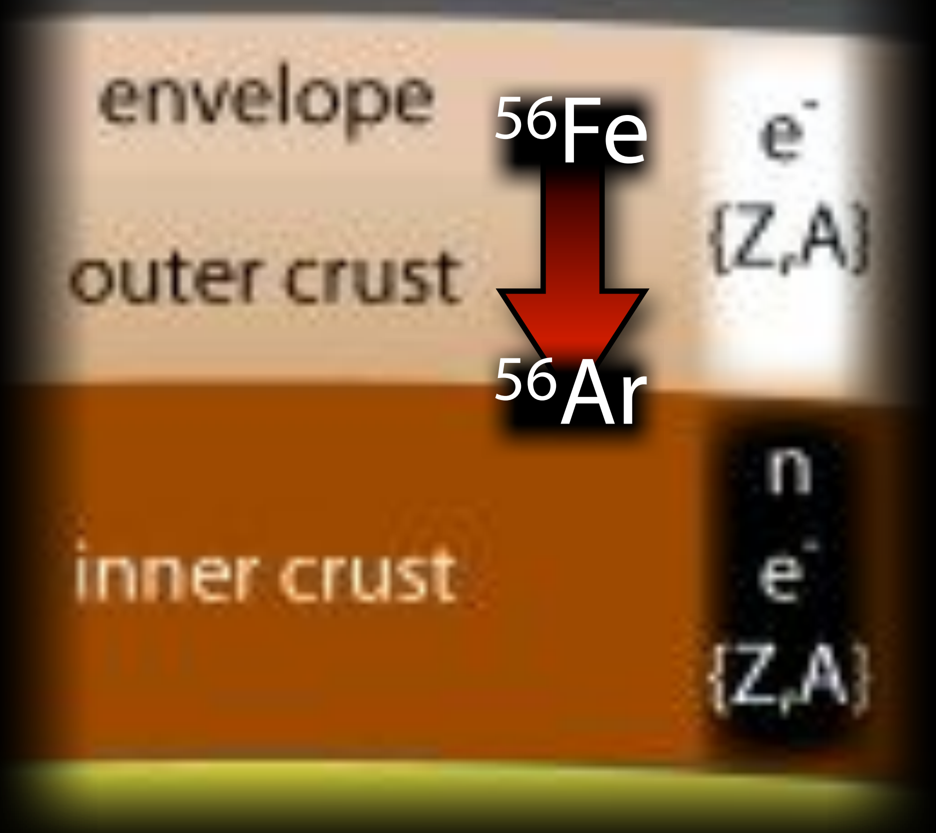


neutron drip

$$E \approx -a_V(N+Z) + a_A \frac{(N-Z)^2}{N+Z}$$

At neutron drip,

$$\mu_n = \left(\frac{\partial E}{\partial N}\right)_Z \to 0$$

$$\mu_e \approx 2a_V \approx 30\ \mathrm{MeV}$$

This is about 10^{-3} of saturation density

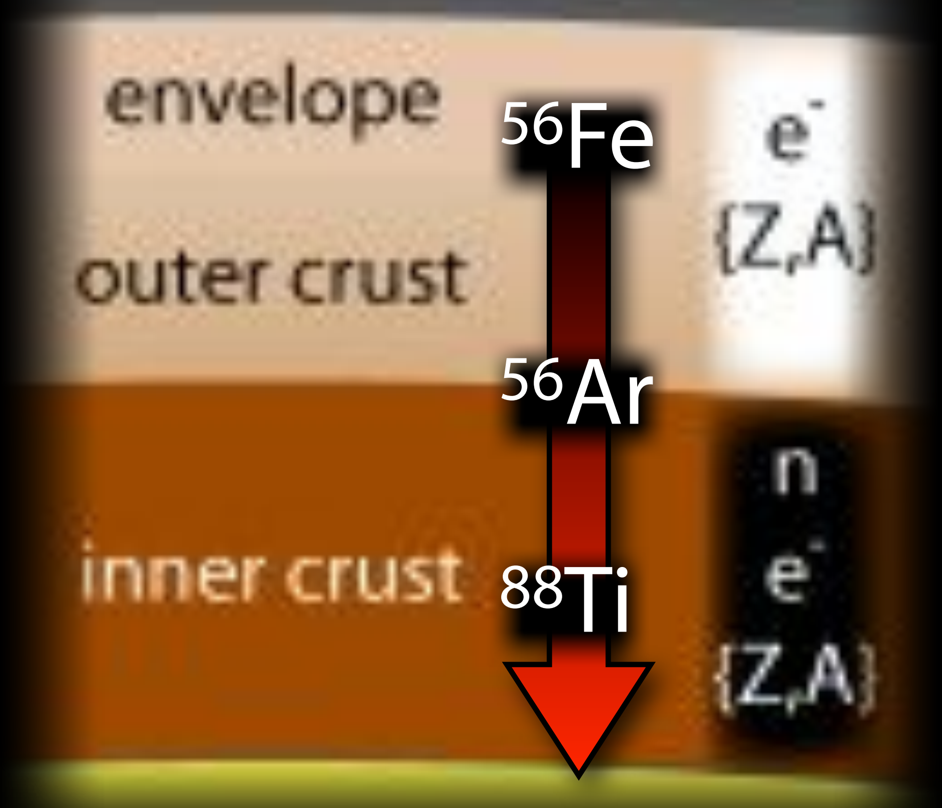
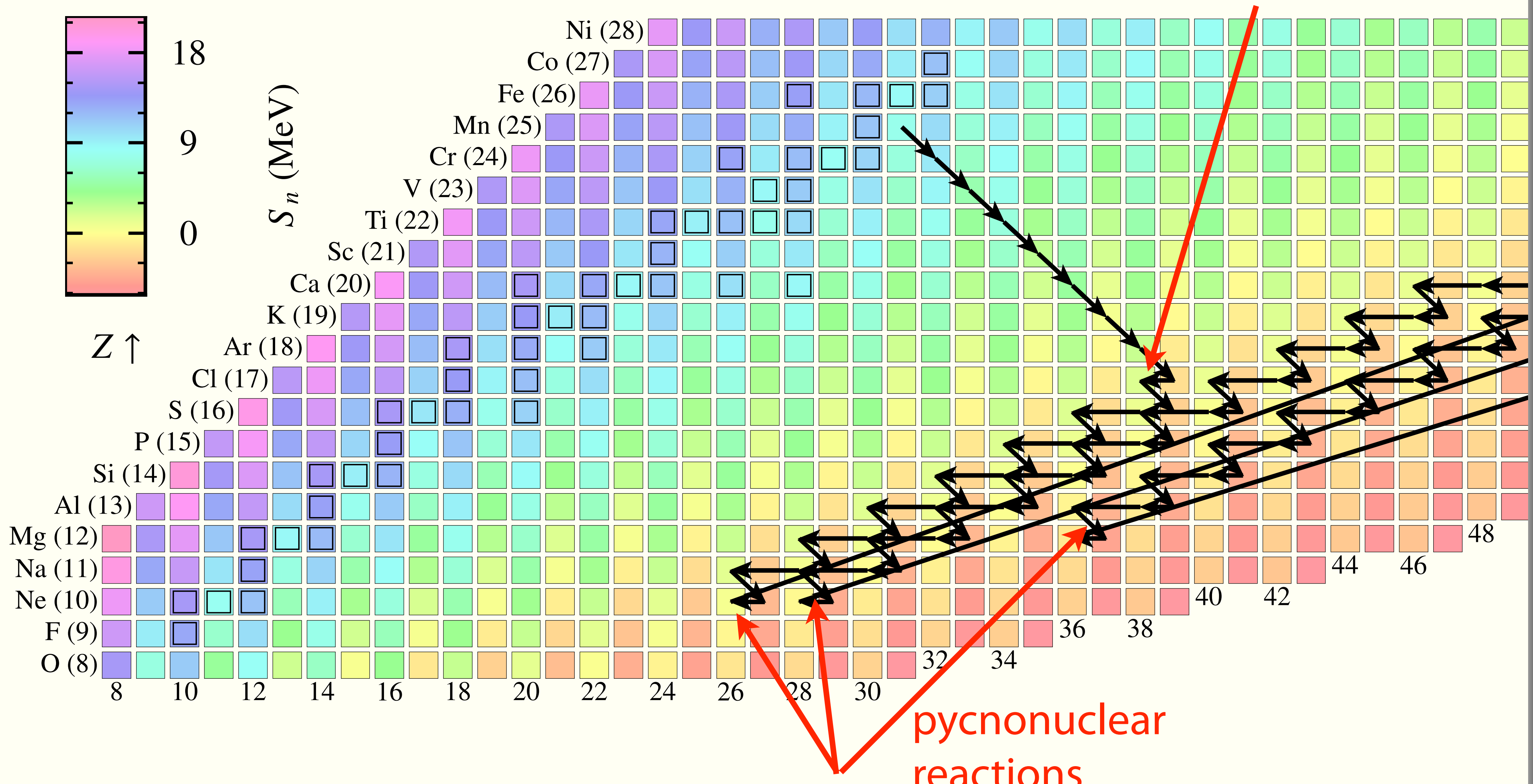


illustration with a simple liquid-drop model (Mackie & Baym '77, following Haensel & Zdunik '90)

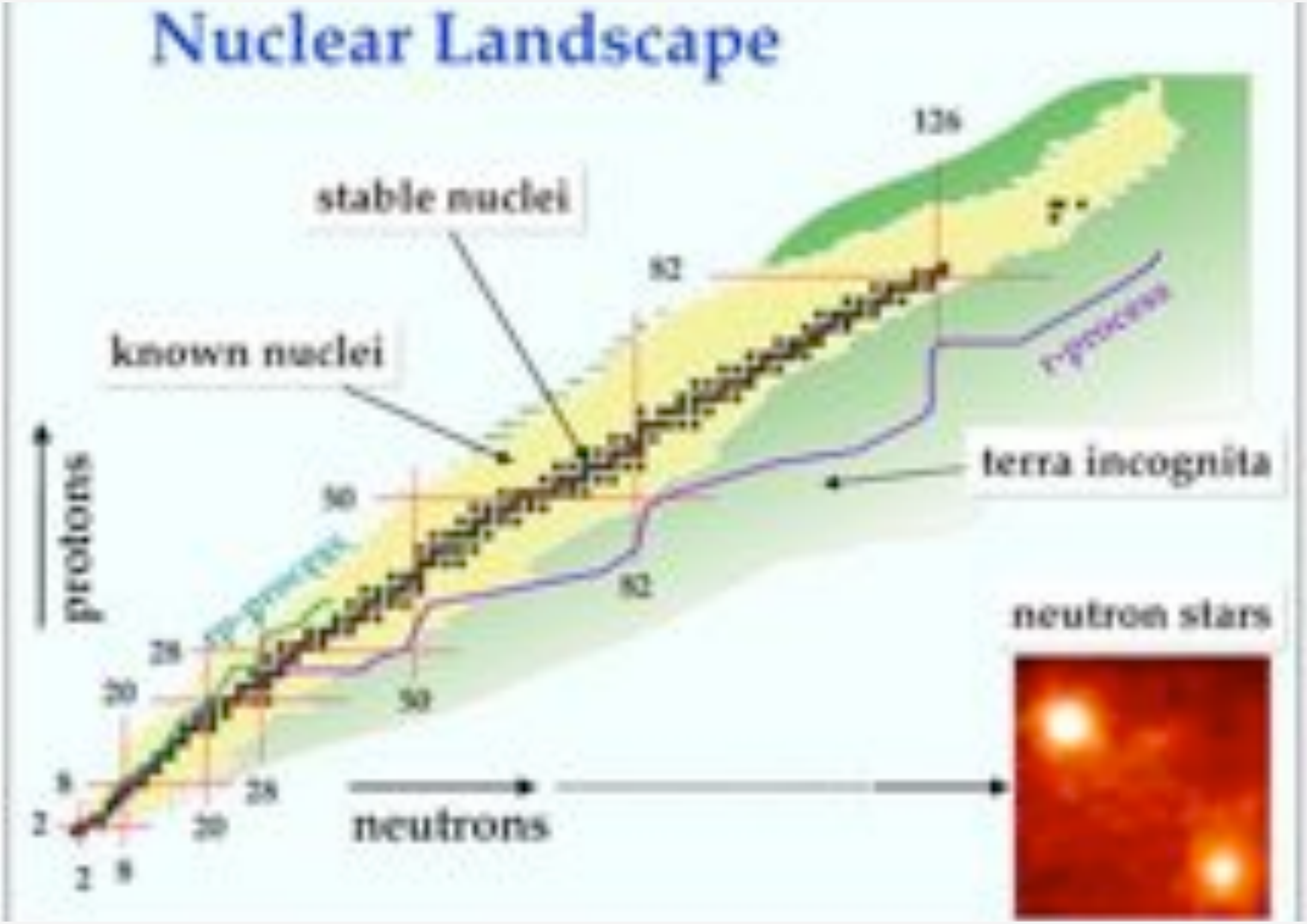


neutron drip

pycnonuclear reactions

crust reactions

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

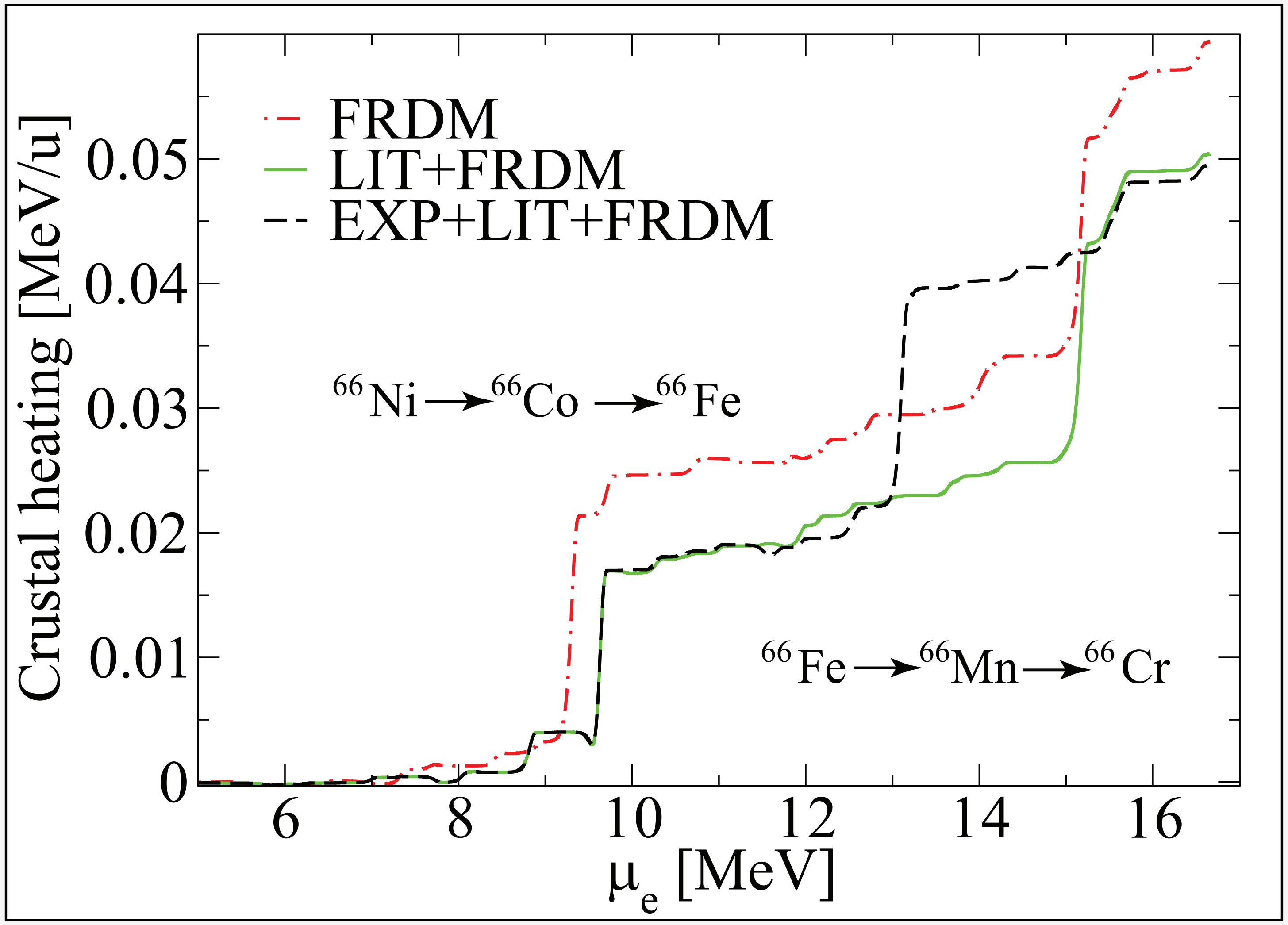


Many of these reactions are within reach of FRIB

Time-of-flight mass measurements for nuclear processes in neutron star crusts

A. Estradé,[1,2,3,*] M. Matoš,[1,3,4] H. Schatz,[1,2,3] A. M. Amthor,[1,2,3] D. Bazin,[1] M. Beard,[5,3]
A. Becerril,[1,2,3] E. F. Brown,[1,2,3] R. Cyburt,[1,3] T. Elliot,[1,2,3] A. Gade,[1,2] D. Galaviz,[1,3]
S. George,[1,3] S. S. Gupta,[6,3] W. R. Hix,[7] R. Lau,[1,2,3] G. Lorusso,[1,2,3] P. Möller,[8] J. Pereira,[1,3]
M. Portillo,[1] A. M. Rogers,[1,2,3] D. Shapira,[7] E. Smith,[9,3] A. Stolz,[1] M. Wallace,[8] and M. Wiescher[5,3]

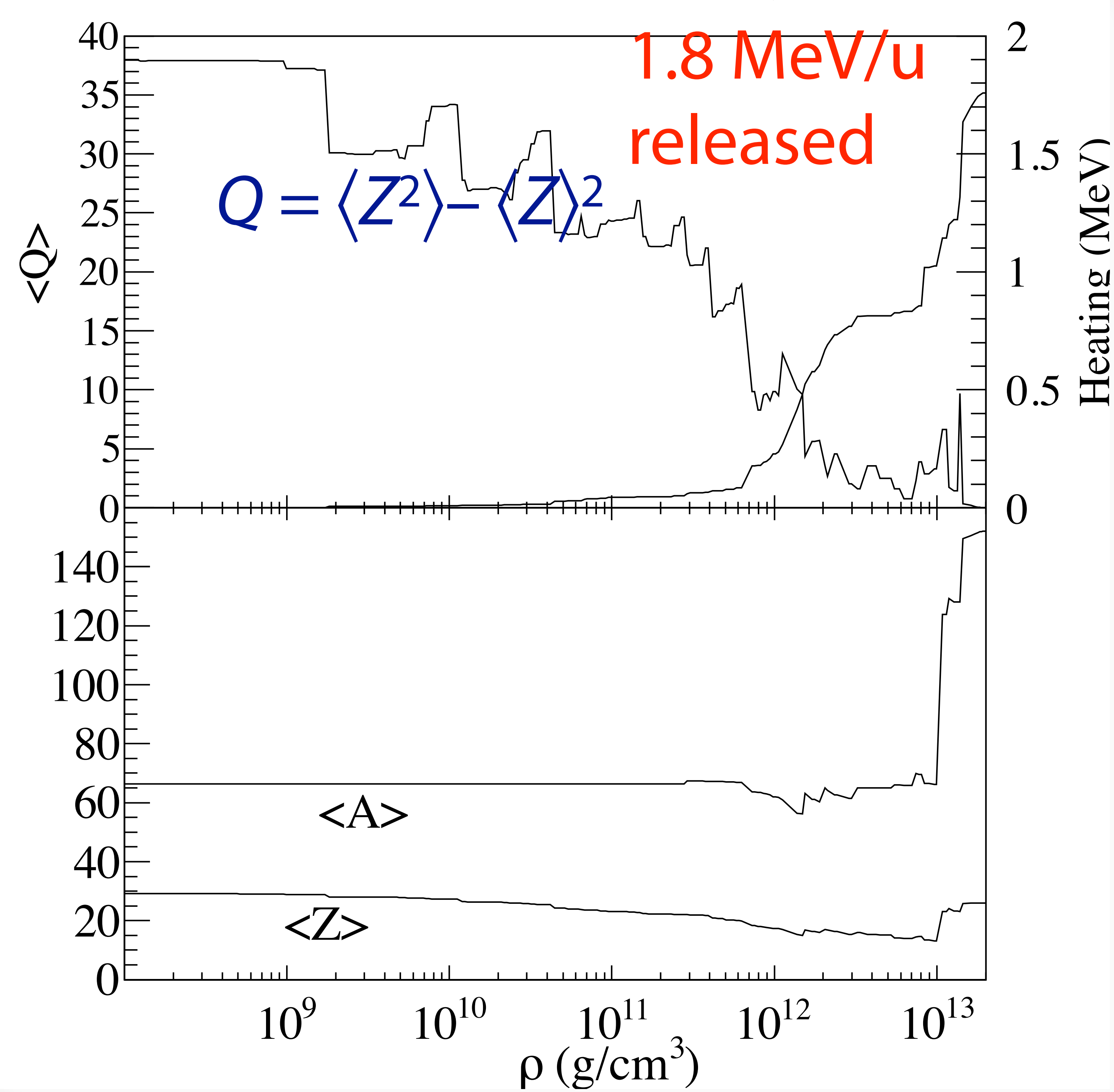
2011, *PRL*



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



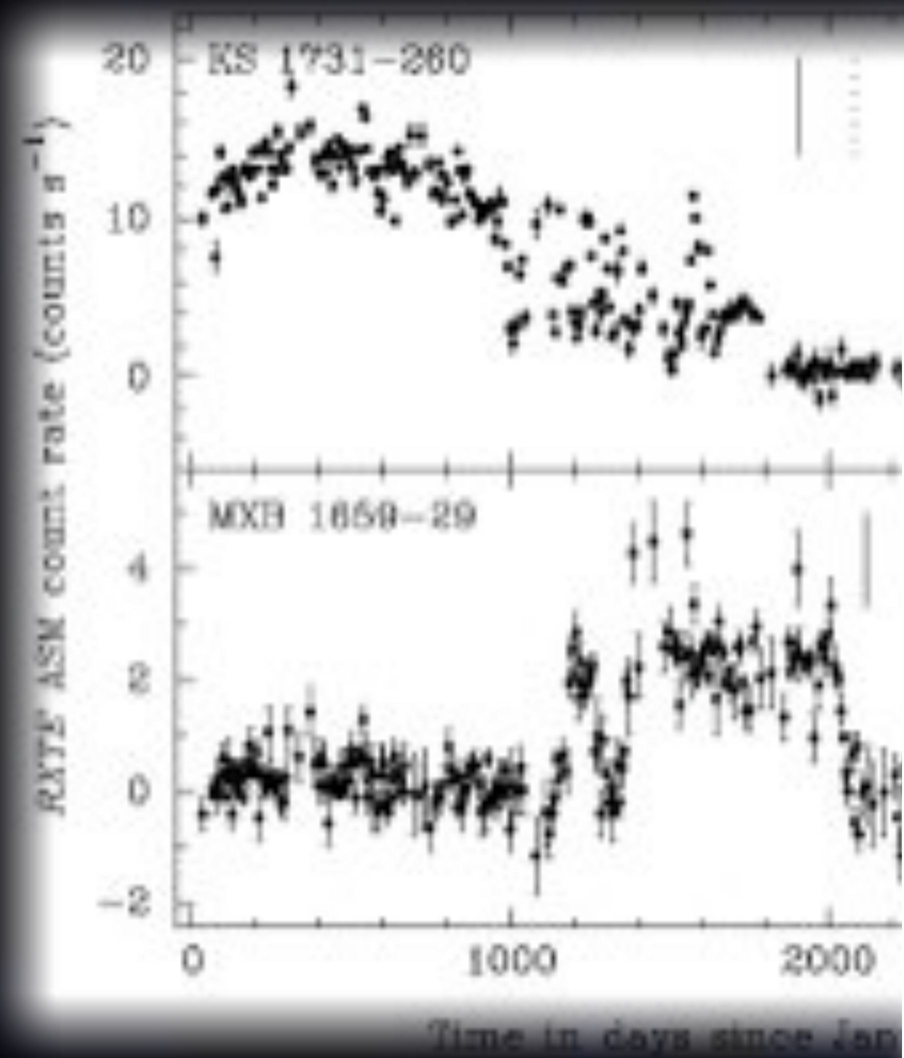
plot courtesy A. Steiner

1.8 MeV/u released

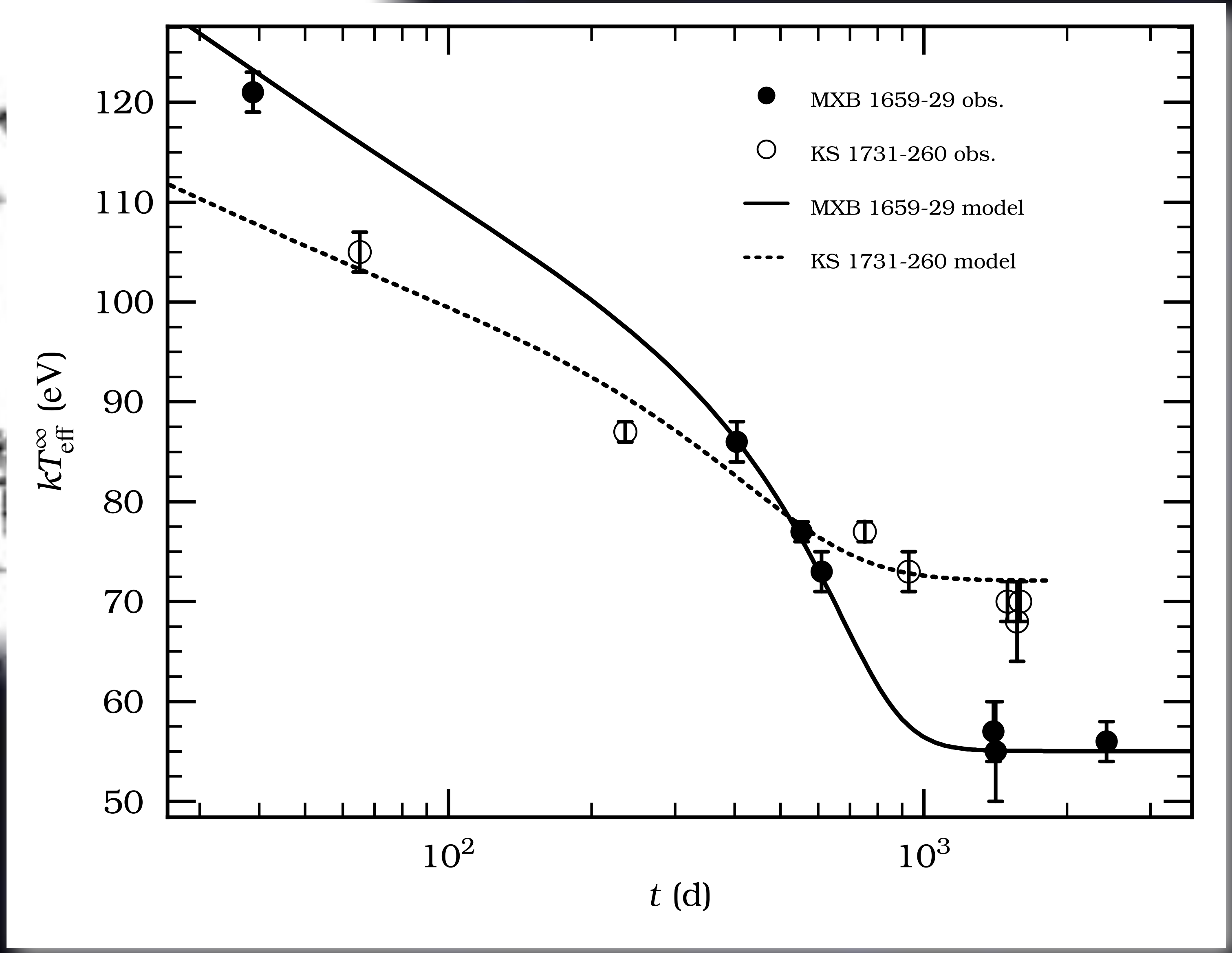
$$Q = \langle Z^2\rangle - \langle Z\rangle^2$$

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



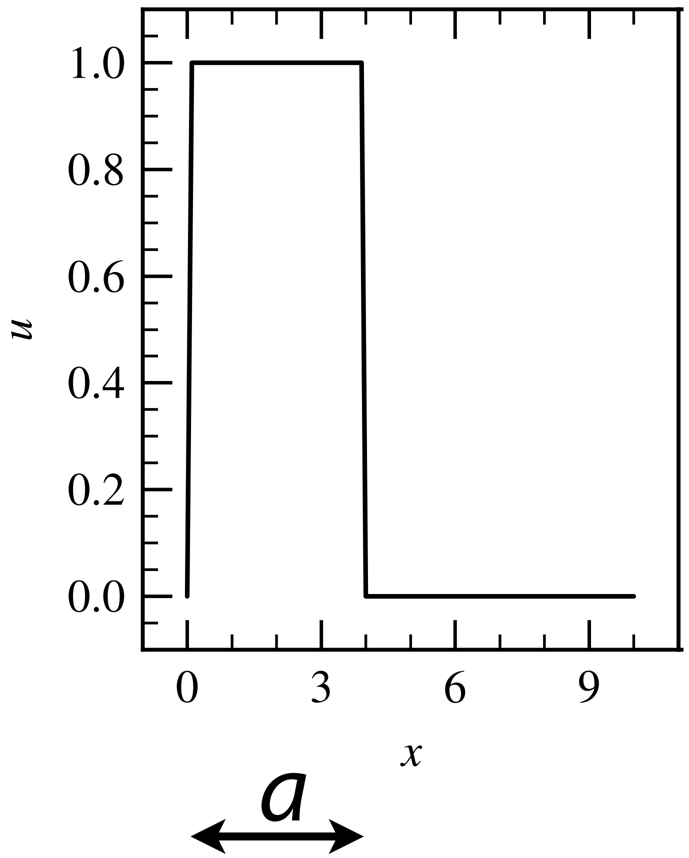
a cooling slab

For

$$\frac{\partial T}{\partial t} = D\frac{\partial^2 T}{\partial x^2},$$

the flux at $x = 0$ is

$$D\ \frac{\partial T}{\partial x}\bigg|_{x=0} \sim ?$$



a cooling slab

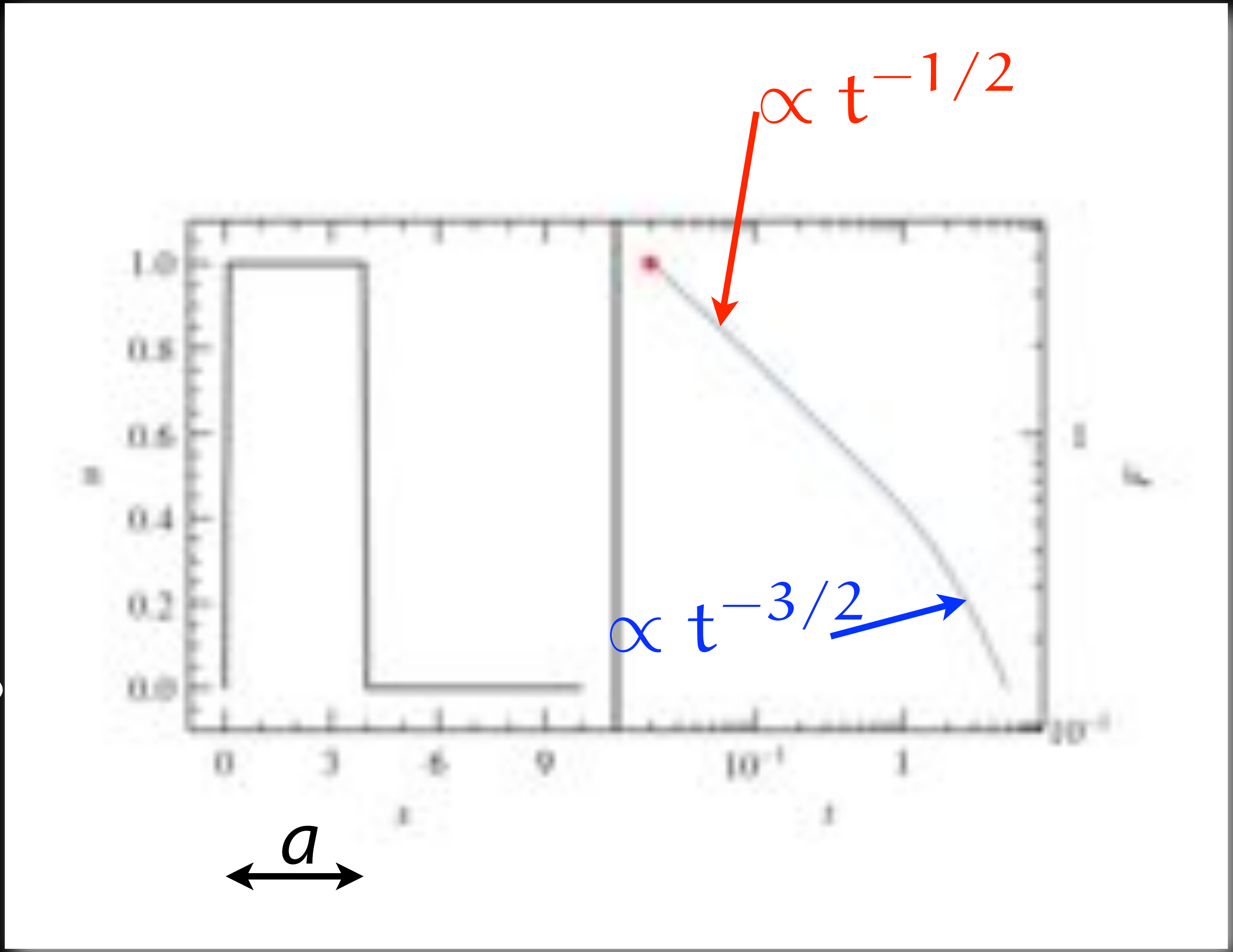
For

$$\frac{\partial T}{\partial t} = D\frac{\partial^2 T}{\partial x^2},$$

the flux at $x = 0$ is

$$\propto \left(\frac{\tau}{t}\right)^{1/2}\left[1 - \exp\left(-\frac{\tau}{t}\right)\right],$$

where $\tau = a^2/(4D)$.



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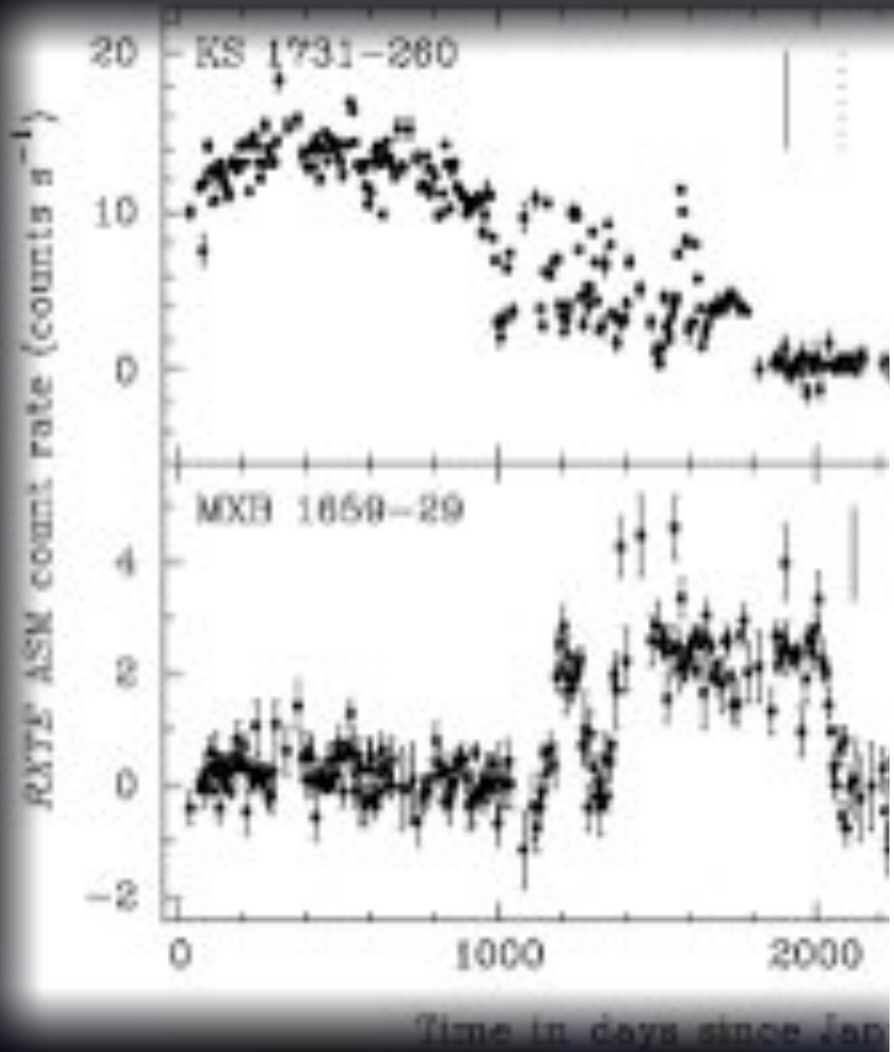

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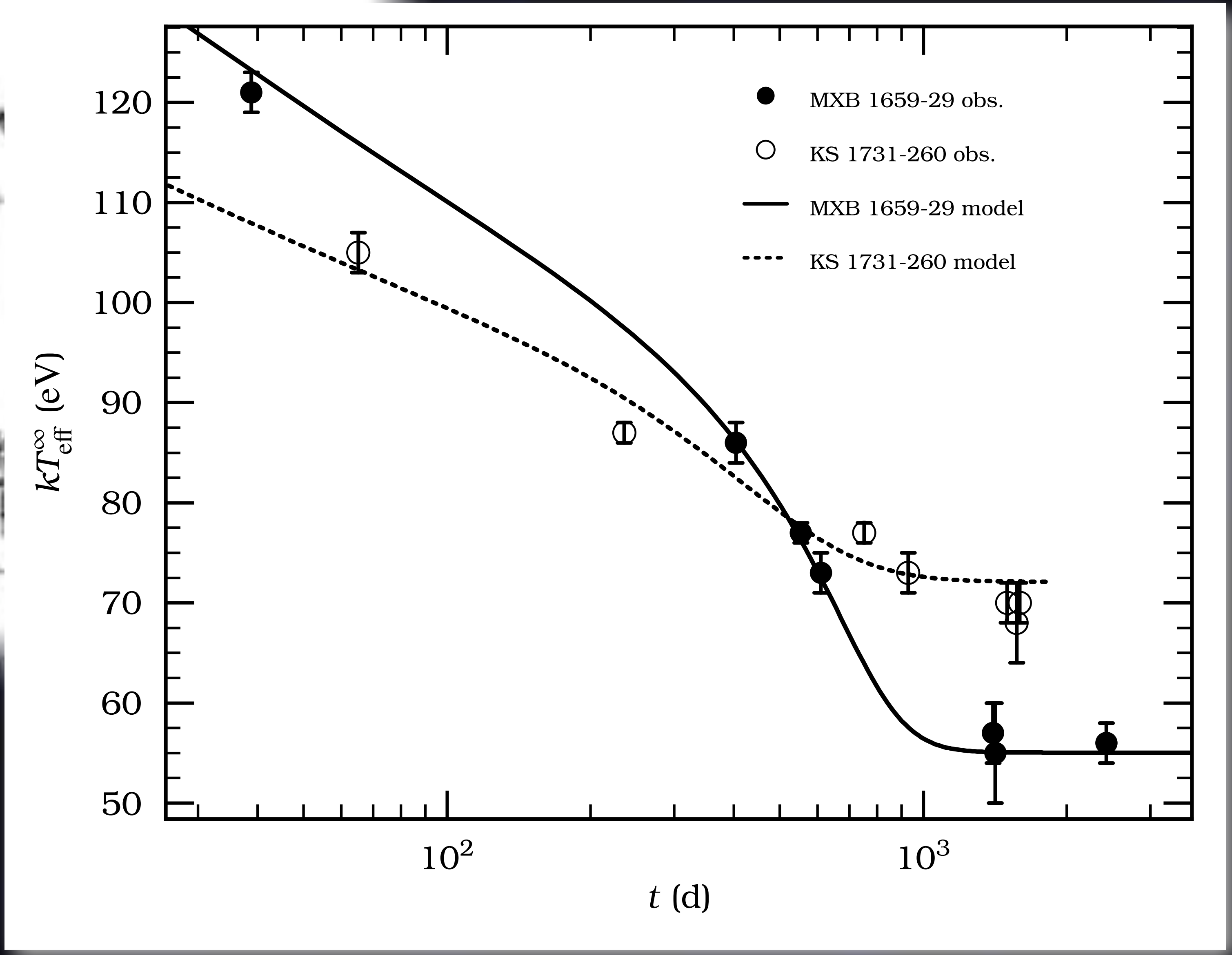


Summary

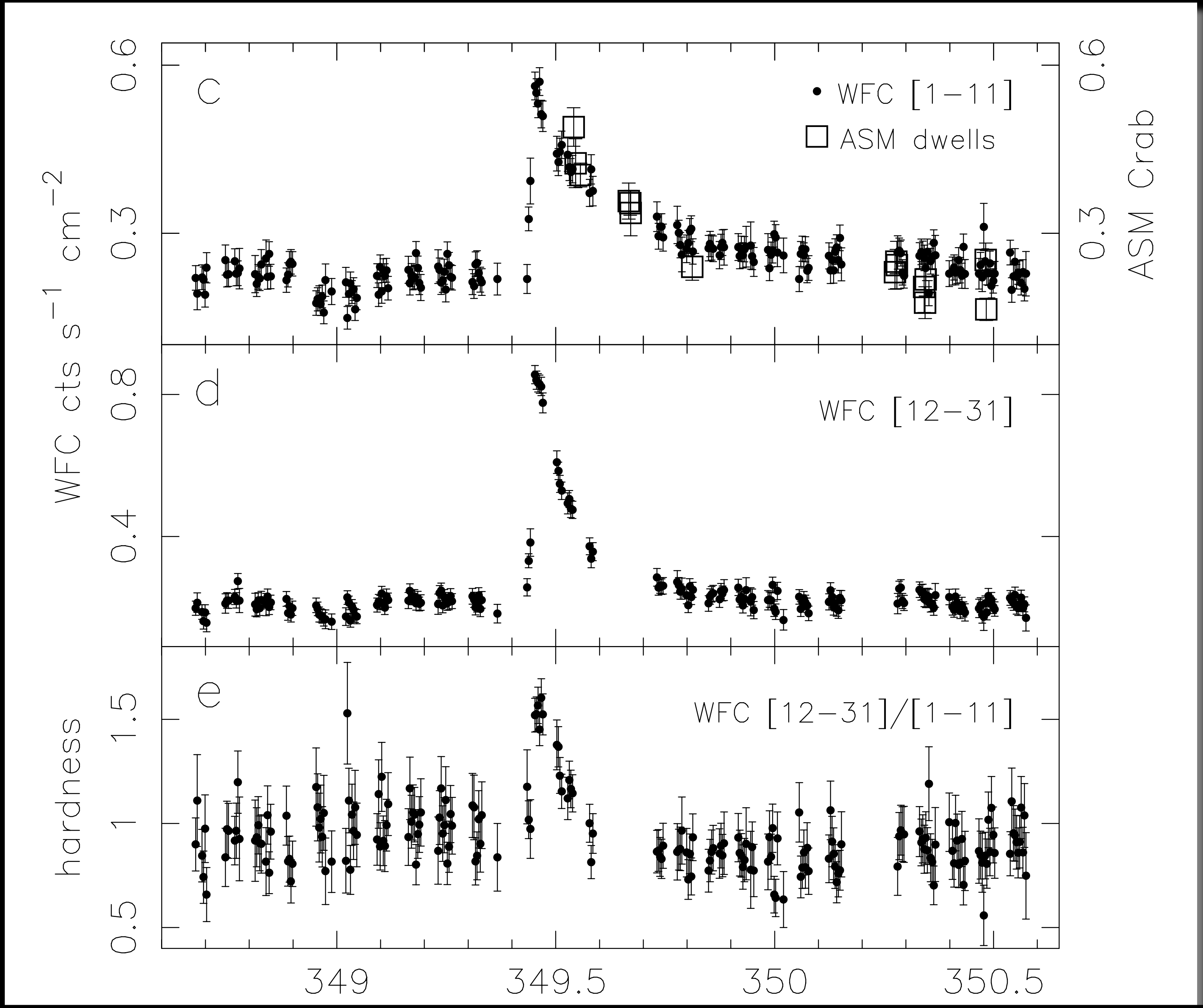
A number of observational probes of the nuclear EOS are available

- 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 and there are substantial systematic uncertainties—it’s astrophysics

Superbursts!

KS 1731–260; Kuulkers 2002



superbursts are ≈1000 times more...

energetic, longer-lasting, and infrequent...

than regular X-ray bursts

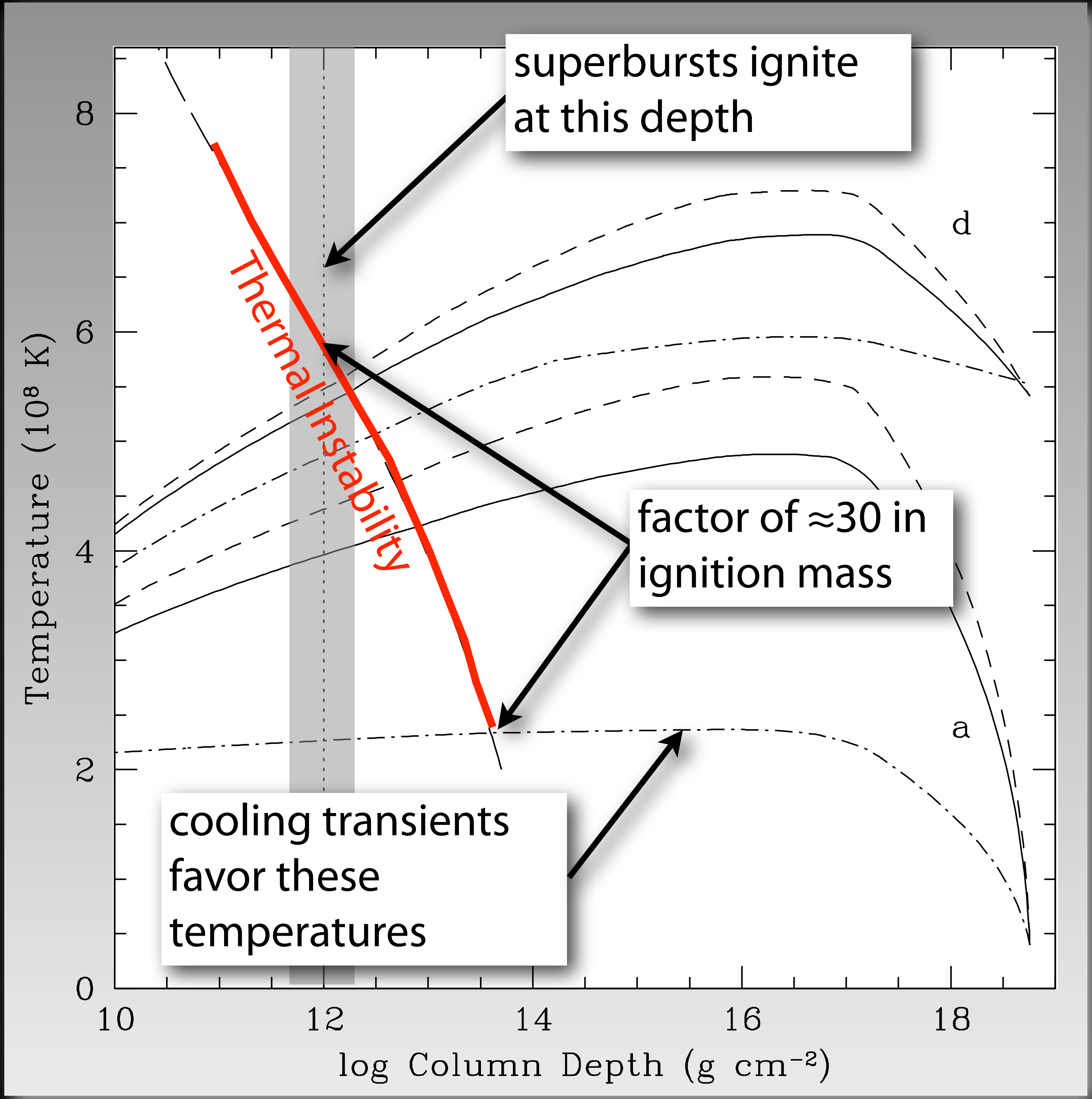
Why weren’t these predicted?

They were! Sort of...

Taam & Picklum 1978, Brown & Bildsten 1998

superbursts like it hot—perhaps too hot?

Brown 2004, Cooper & Narayan 2005, Cumming et al. 2006



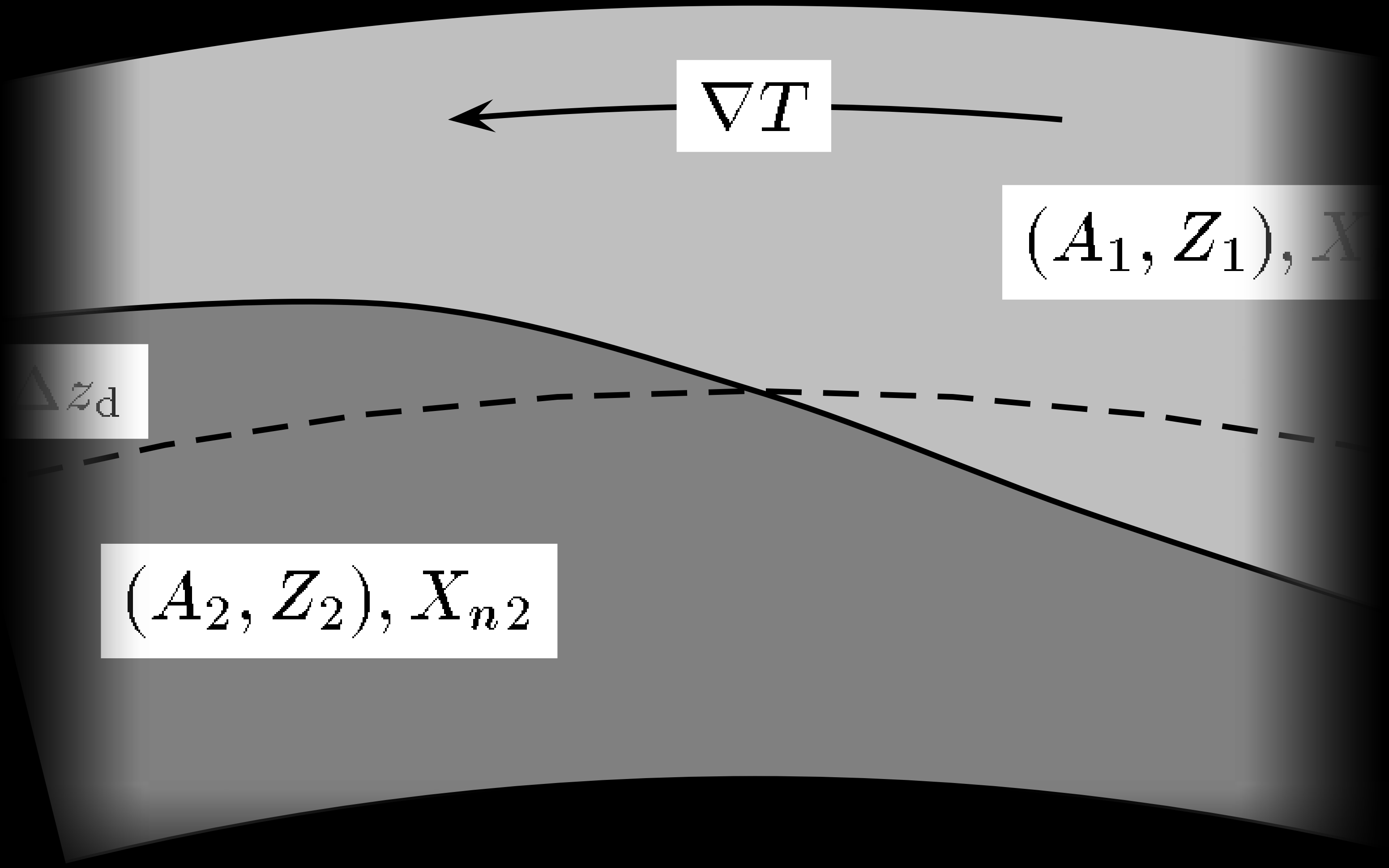
superbursts ignite at this depth

factor of ≈30 in ignition mass

cooling transients favor these temperatures

Plot from Cumming et al. 2006

Going beyond 1-d
Could there be crust "mountains"?



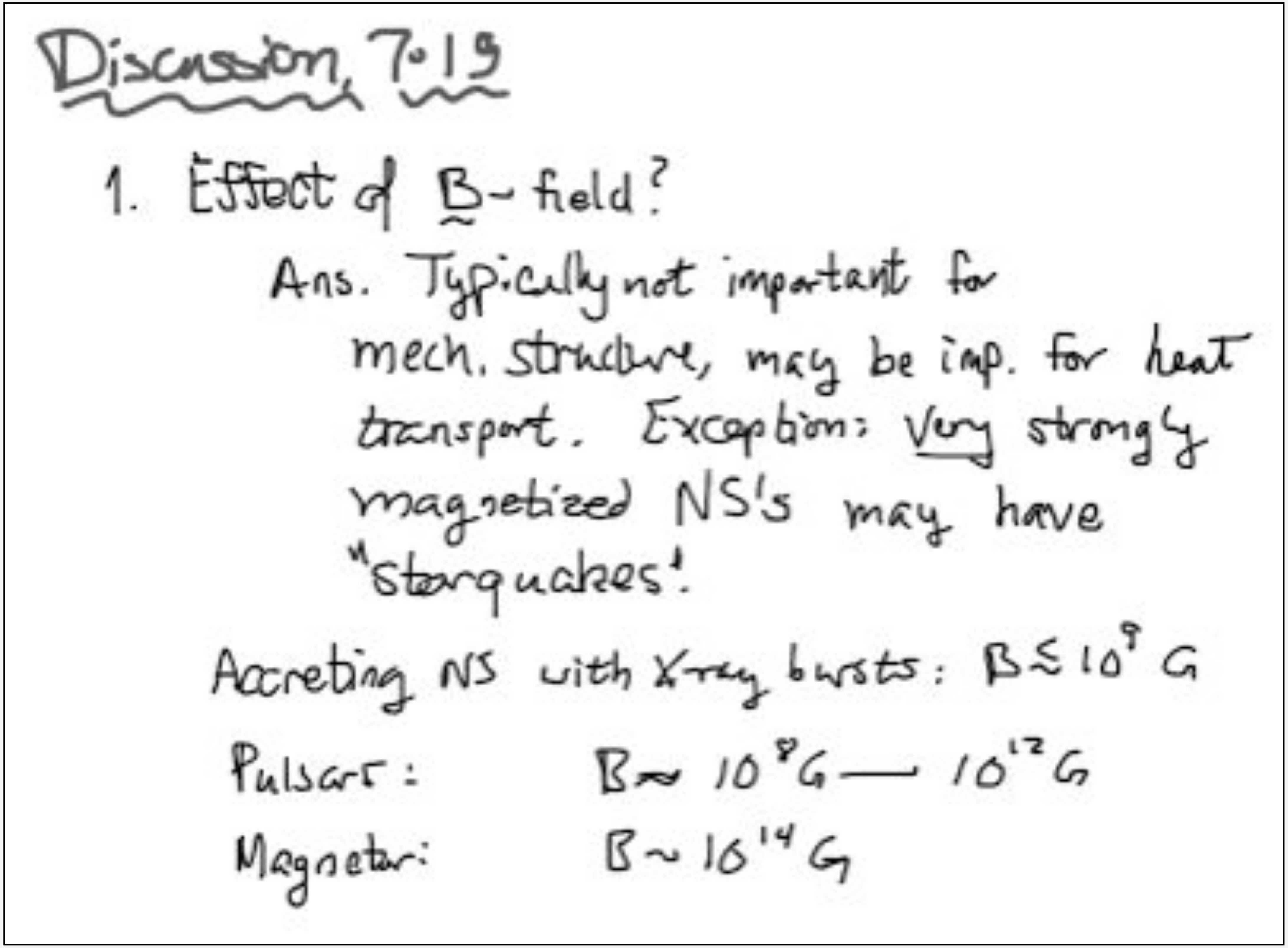
Bildsten 1998
Ushomirsky et al. 2000
Haskell et al. 2006

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

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 several others
- 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.*

From discussion section



Discussion, 7.19

1. Effect of $\underset{\sim}{B}$-field?

Ans. Typically not important for mech. structure, may be imp. for heat transport. Exception: Very strongly magnetized NS's may have "starquakes".

Accreting NS with X-ray bursts: $B \lesssim 10^9$ G

Pulsars: $B \sim 10^8 G — 10^{12} G$

Magnetar: $B \sim 10^{14} G$