Title: Constraining neutron star interior properties with transient events from accreting neutron stars and magnetars

Date: Apr 25, 2013 01:00 PM

URL: http://pirsa.org/13040138

Abstract: The last few years have seen new opportunities for constraining the physics of neutron star interiors. I will first discuss the current state of neutron star radius measurements and then go on to discuss thermal tomography as a probe of the nuclear, magnetic, and transport properties of neutron star crusts. In each case, I will emphasize the astrophysics that must be understood to make reliable inferences about the properties of dense matter from observations of neutron stars.

Studies of neutron stars address a range of different questions

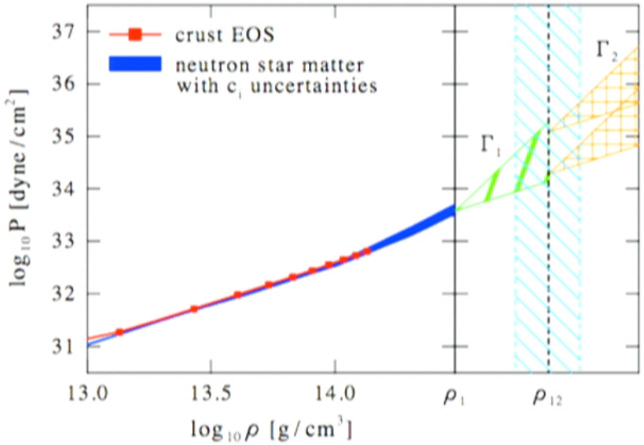
They are **extreme** objects
- dense matter, strong gravity, highly magnetized

As **endpoints** of stellar evolution
- a much more diverse population than first thought

Interesting physics!
- nuclear physics, magnetohydrodynamics, plasma physics, condensed matter physics ...

Does neutron star structure influence **gravitational wave** signatures of inspirals?

Dense matter EOS

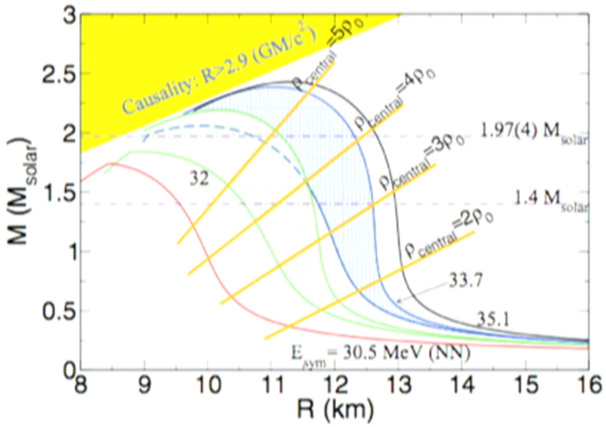


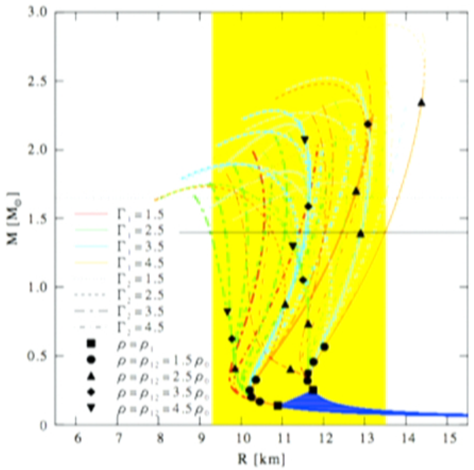
Roughly $P \propto \rho^2$

=> radius independent of mass

↔

Neutron star mass-radius relation

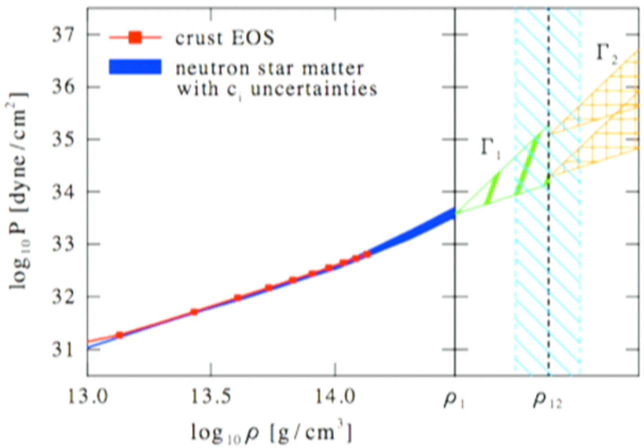




Hebeler et al. (2010)

Gandolfi, Carlson, Reddy (2012)

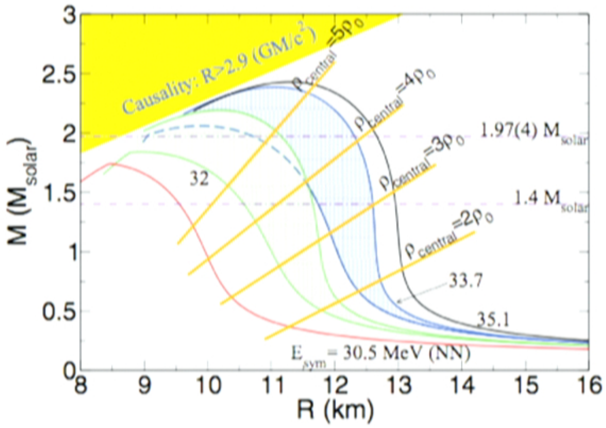
Dense matter EOS

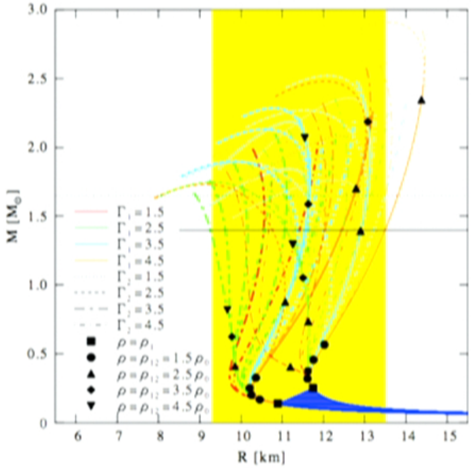


Roughly $P \propto \rho^2$

=> radius independent of mass

Neutron star mass-radius relation



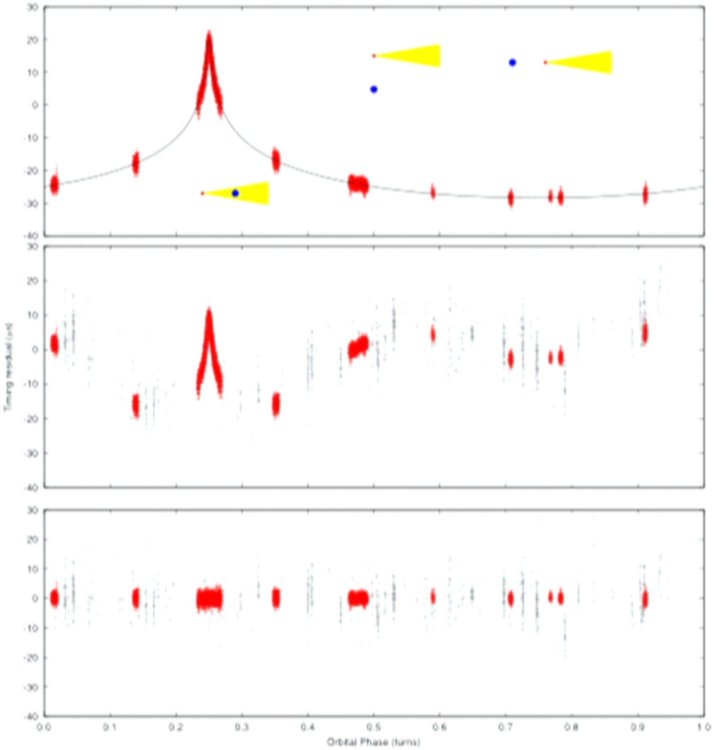


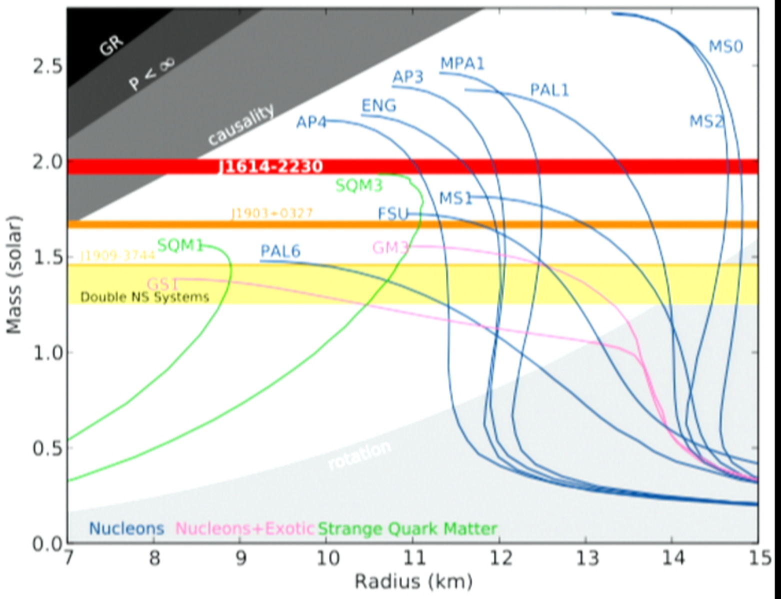
Hebeler et al. (2010)

Gandolfi, Carlson, Reddy (2012)

A 2 M_sun neutron star

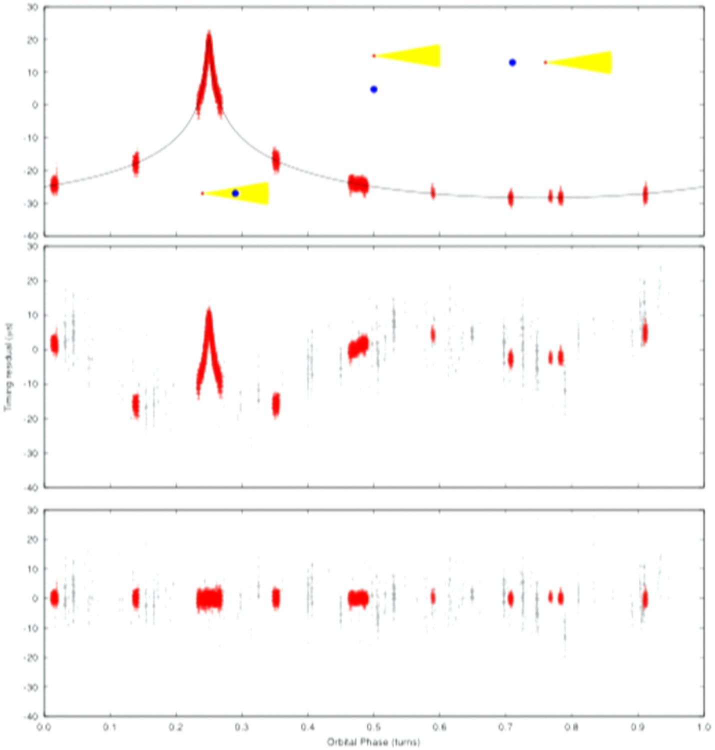
PSR 1614-2230 1.97+-0.04 M_sun Demorest et al (2010)

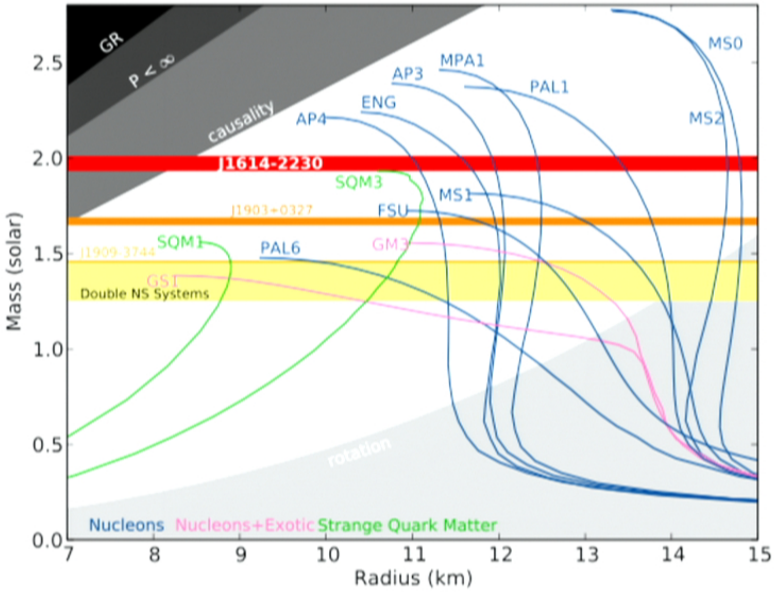




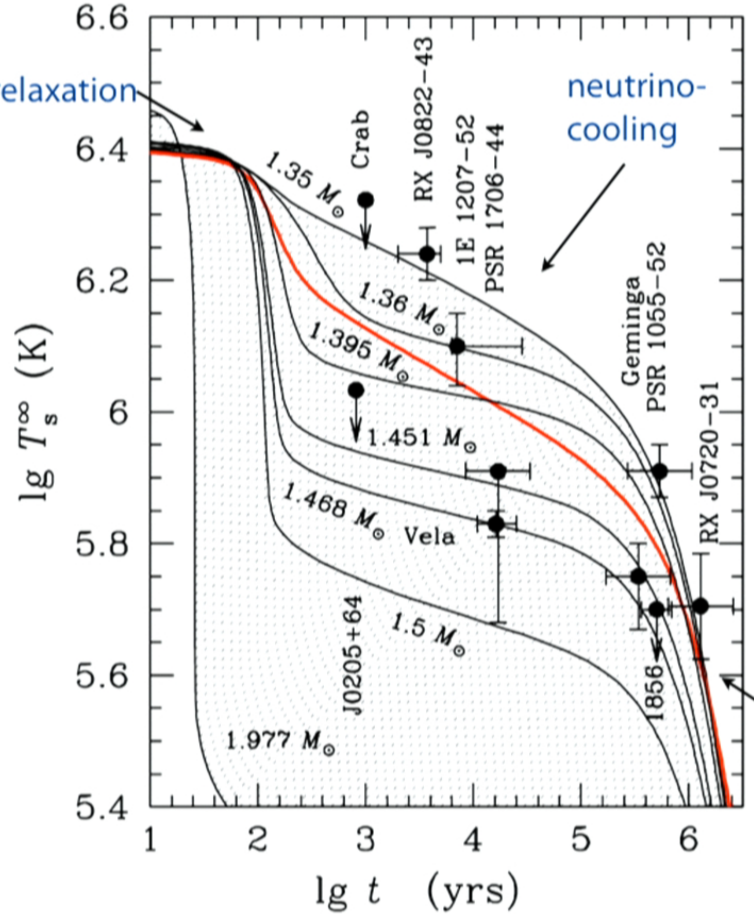
A 2 M_sun neutron star

PSR 1614-2230 1.97+-0.04 M_sun Demorest et al (2010)





Cooling curves for isolated neutron stars measure the efficiency of neutrino emission from the core



crust relaxation

neutrino-cooling

surface cooling (photons)

Fast "direct URCA"

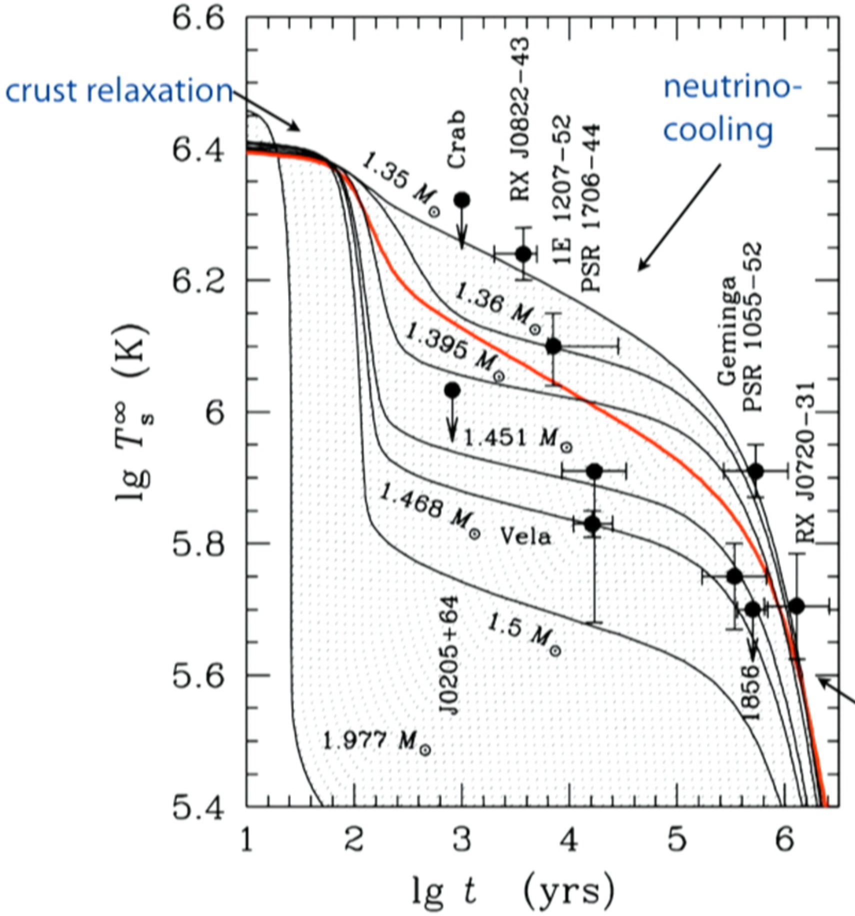
$$n \rightarrow p + e^- + \bar{\nu}$$
$$p + e^- \rightarrow n + \nu$$

Slow "modified URCA"

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

Yakovlev et al. (2004) ARAA

Cooling curves for isolated neutron stars measure the efficiency of neutrino emission from the core



crust relaxation

neutrino-cooling

surface cooling (photons)

Fast "direct URCA"

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

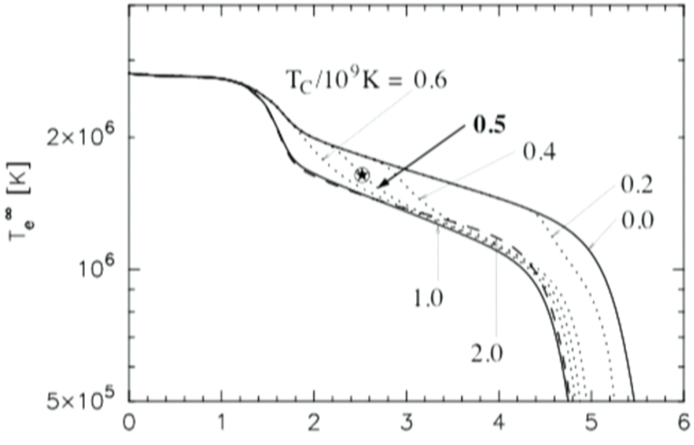
Slow "modified URCA"

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

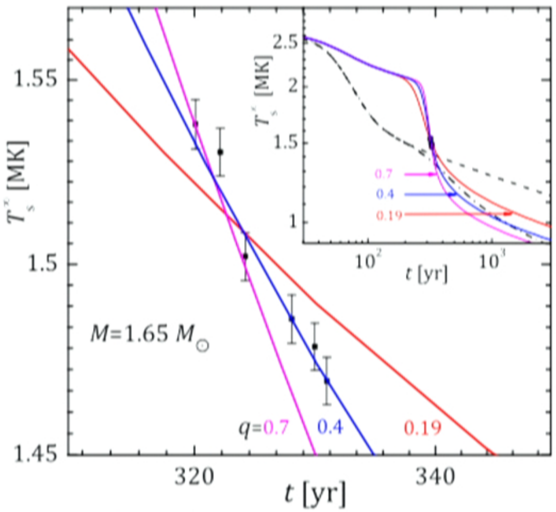
Yakovlev et al. (2004) ARAA

Studying transient behavior - thermal relaxation - of neutron stars is a powerful new probe of their internal physics

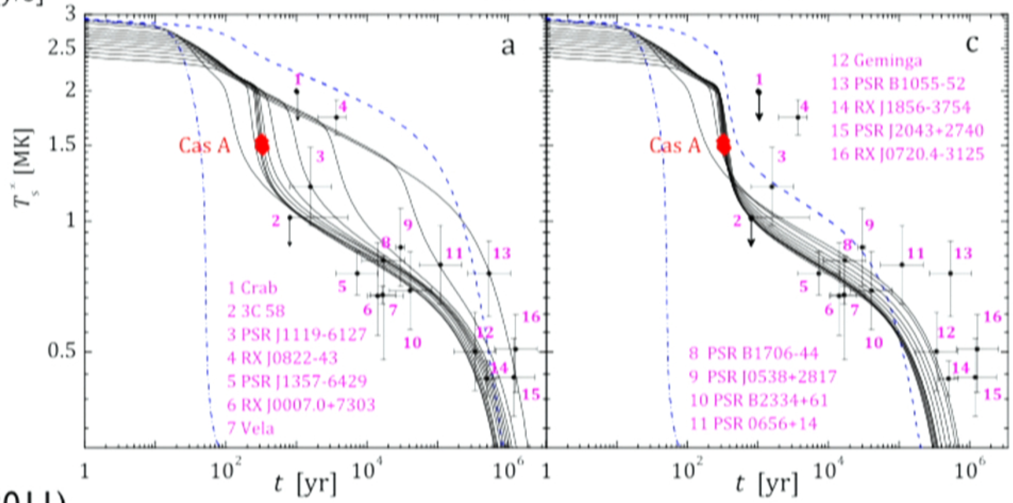
Cooling in Cas A



Page et al. (2011)

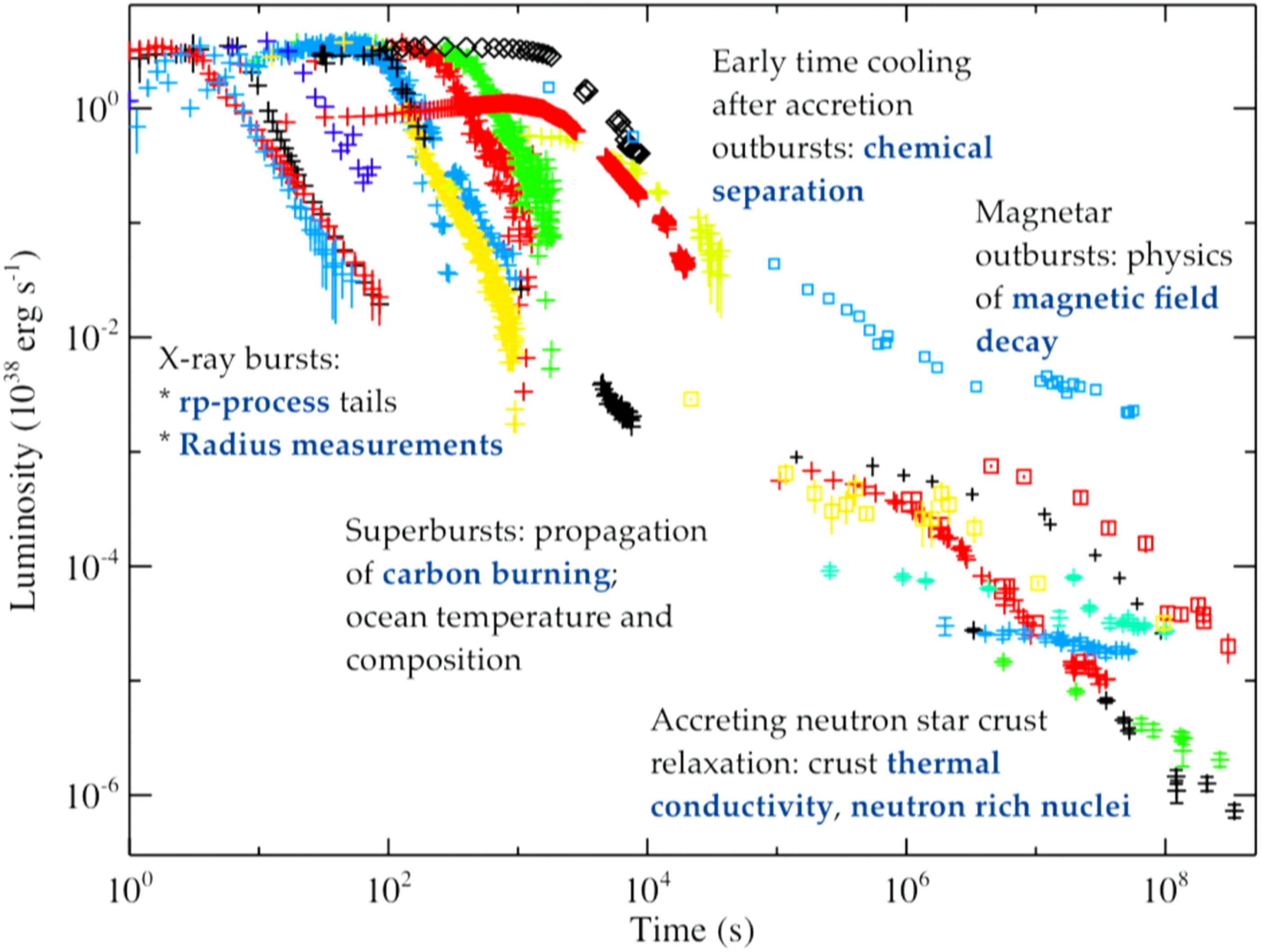


observations from Heinke et al.



Shternin et al. (2011)

Thermal tomography of neutron stars



Early time cooling after accretion outbursts: **chemical separation**

Magnetar outbursts: physics of **magnetic field decay**

X-ray bursts:
- * **rp-process** tails
- * **Radius measurements**

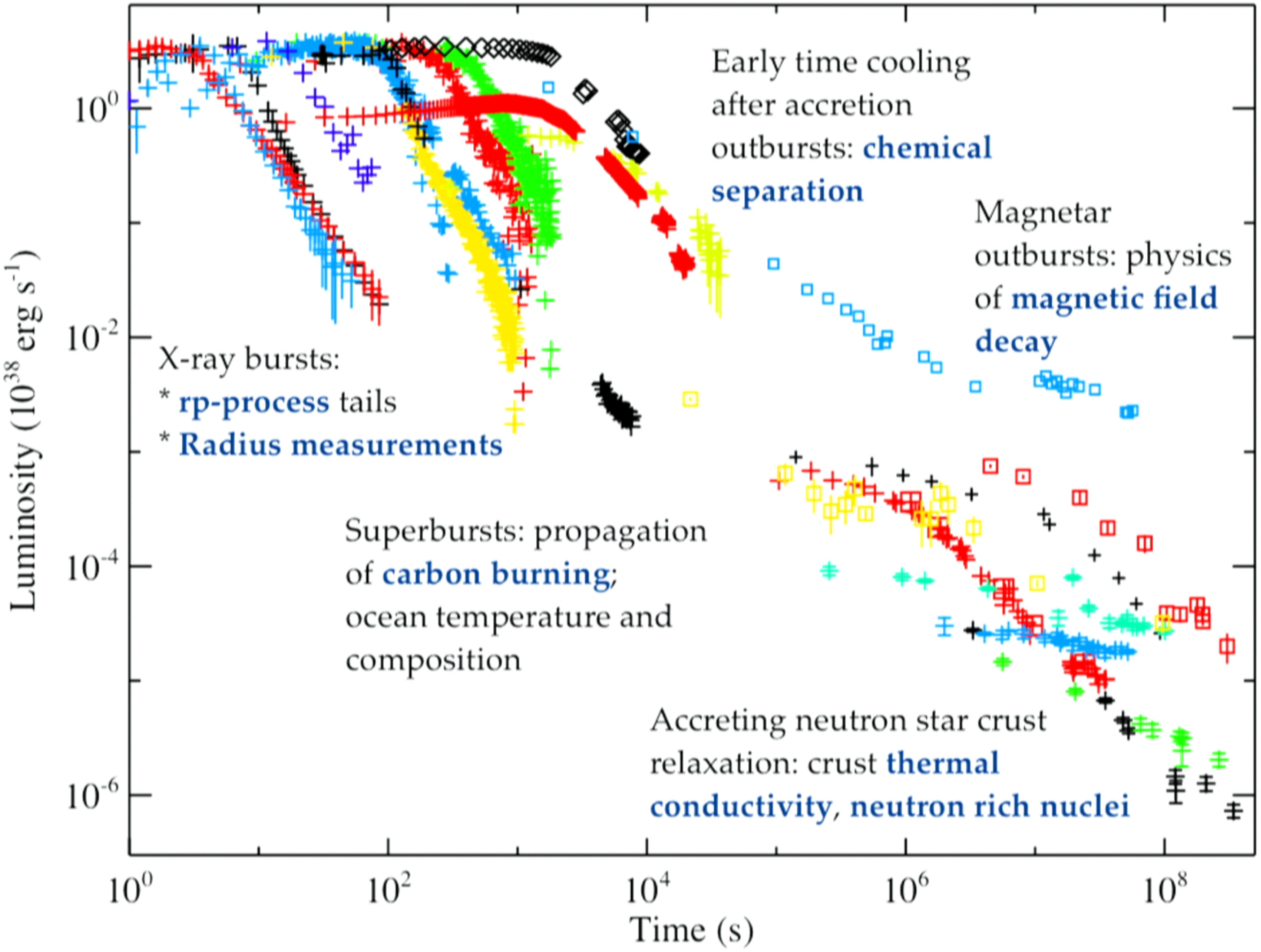
Superbursts: propagation of **carbon burning**; ocean temperature and composition

Accreting neutron star crust relaxation: crust **thermal conductivity**, **neutron rich nuclei**

Outline

- Neutron star interiors and how to constrain them
- Recent progress on radius measurements
- Thermal tomography of neutron star crusts

Thermal tomography of neutron stars



Early time cooling after accretion outbursts: **chemical separation**

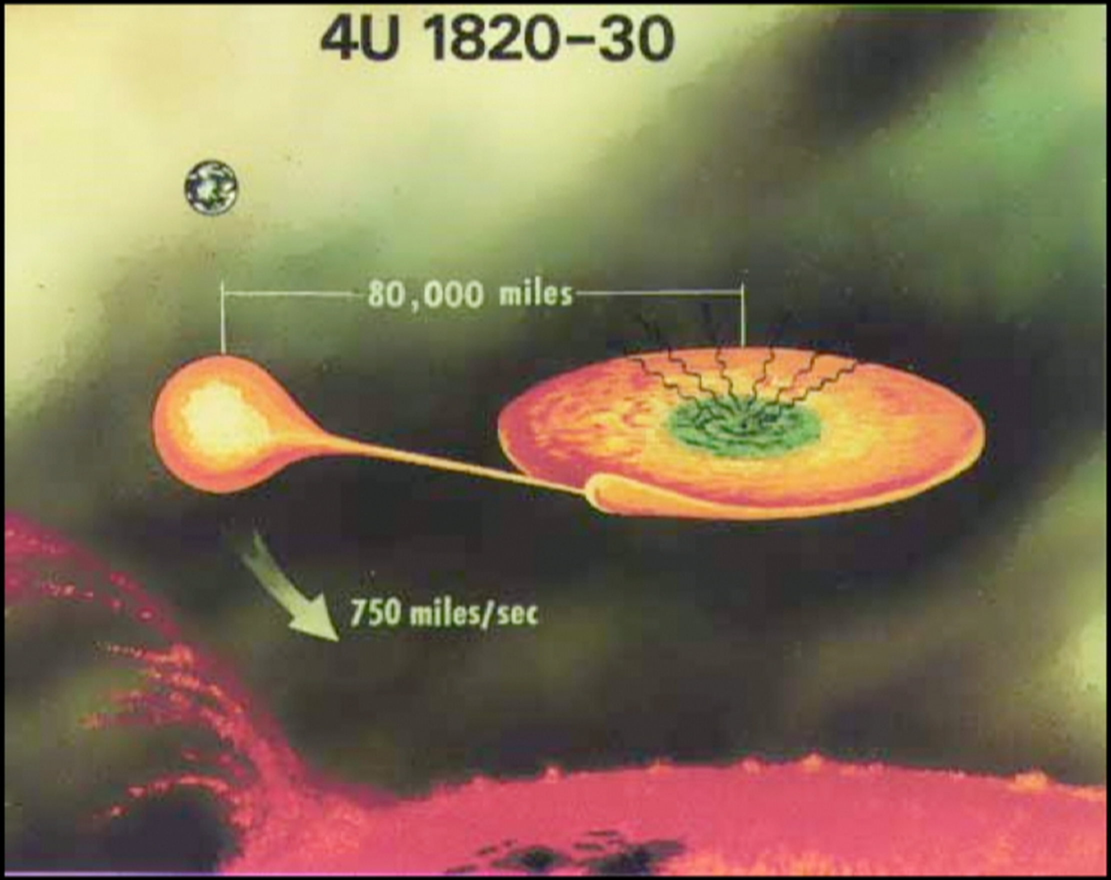
Magnetar outbursts: physics of **magnetic field decay**

X-ray bursts:
* **rp-process** tails
* **Radius measurements**

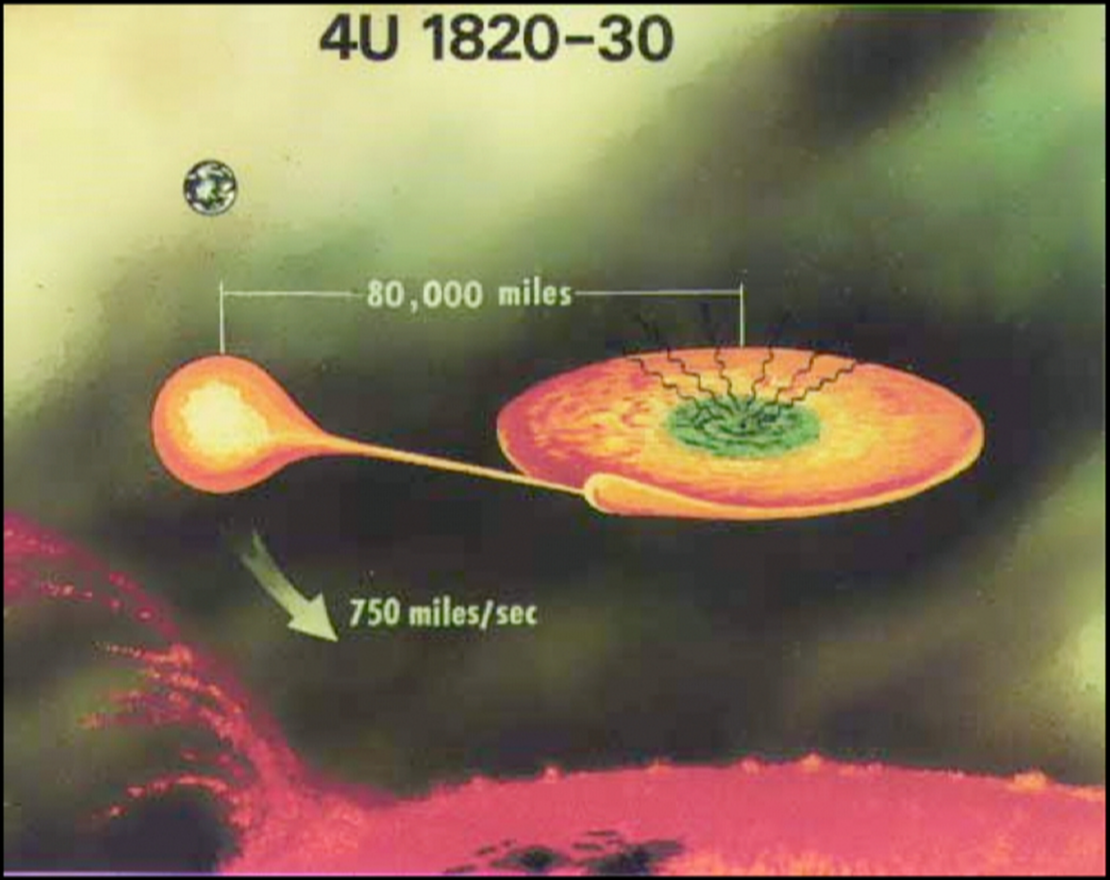
Superbursts: propagation of **carbon burning**; ocean temperature and composition

Accreting neutron star crust relaxation: crust **thermal conductivity**, **neutron rich nuclei**

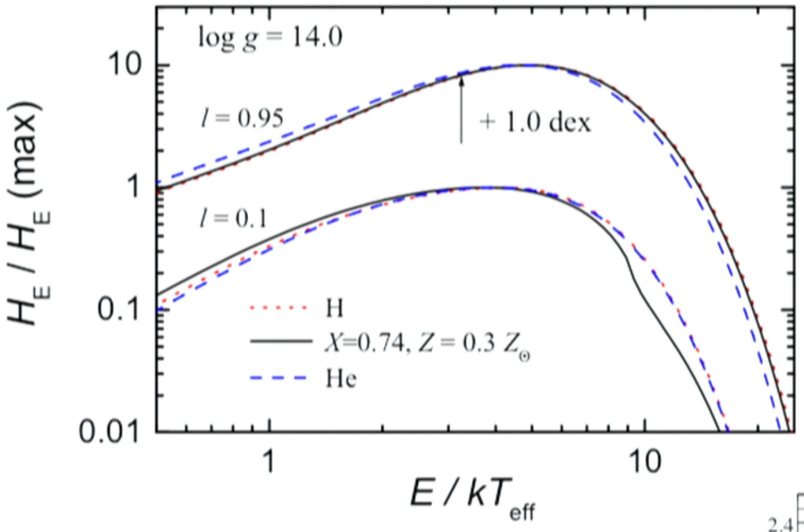
Good systems to look at are the weakly magnetized accreting neutron stars in low mass X-ray binaries - we can study the neutron star either in **quiescence** or during **thermonuclear flashes**



Good systems to look at are the weakly magnetized accreting neutron stars in low mass X-ray binaries - we can study the neutron star either in **quiescence** or during **thermonuclear flashes**



Radius measurement from thermal spectra



Model spectra for X-ray bursts from Suleimanov et al. (2010)

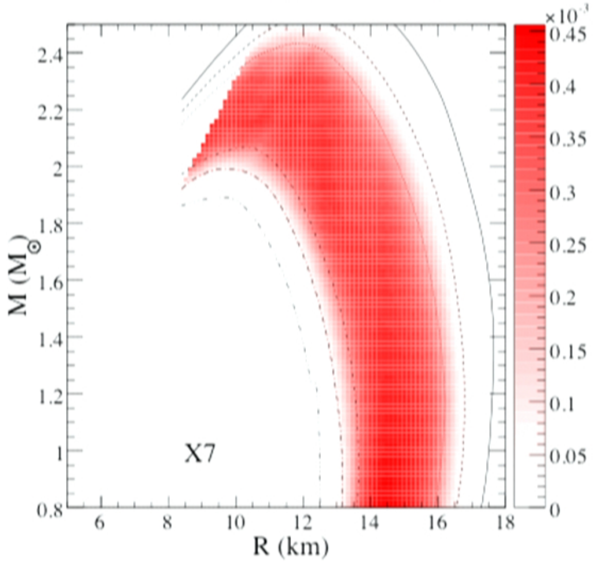
Fit thermal spectrum => peak gives the temperature

Overall luminosity

$$L = 4\pi R^2 \sigma T^4$$

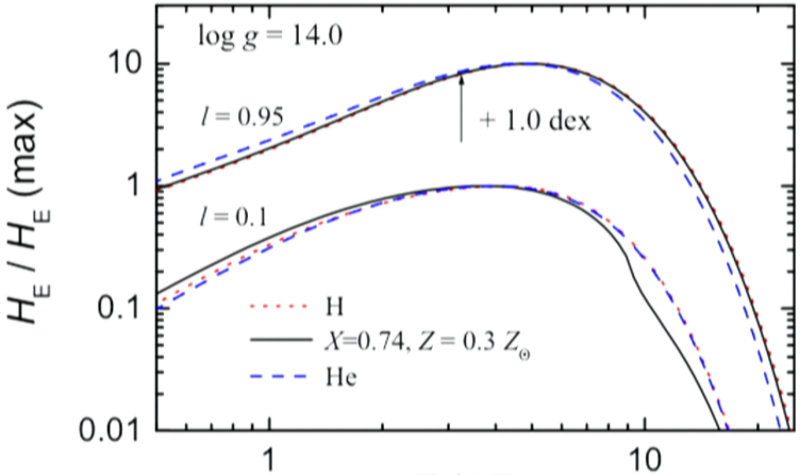
=> Normalization gives a measure of

$$R_\infty = R(1+z)$$



Example constrain for X7 from Steiner et al. (2011)

Radius measurement from thermal spectra



Model spectra for X-ray bursts from Suleimanov et al. (2010)

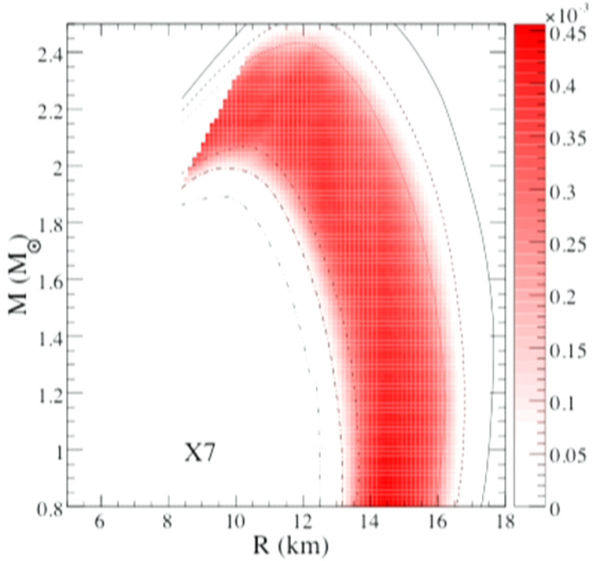
Fit thermal spectrum => peak gives the temperature

Overall luminosity

$$L = 4\pi R^2 \sigma T^4$$

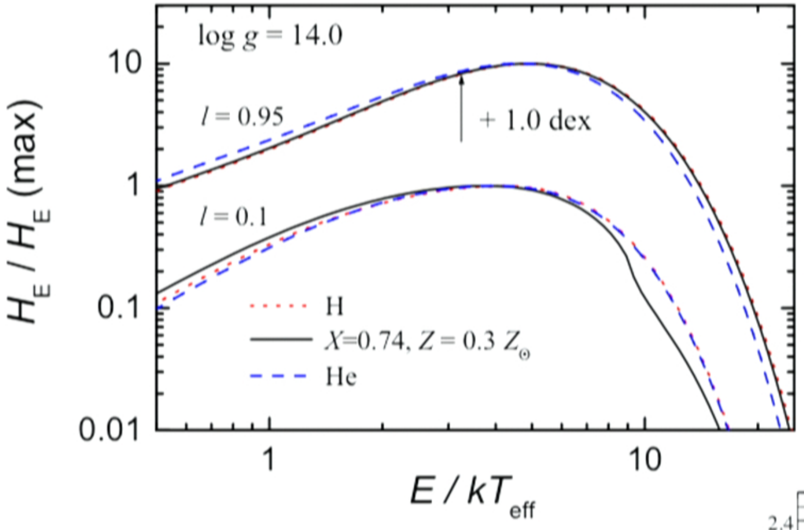
=> Normalization gives a measure of

$$R_\infty = R(1+z)$$



Example constrain for X7 from Steiner et al. (2011)

Radius measurement from thermal spectra



Model spectra for X-ray bursts from Suleimanov et al. (2010)

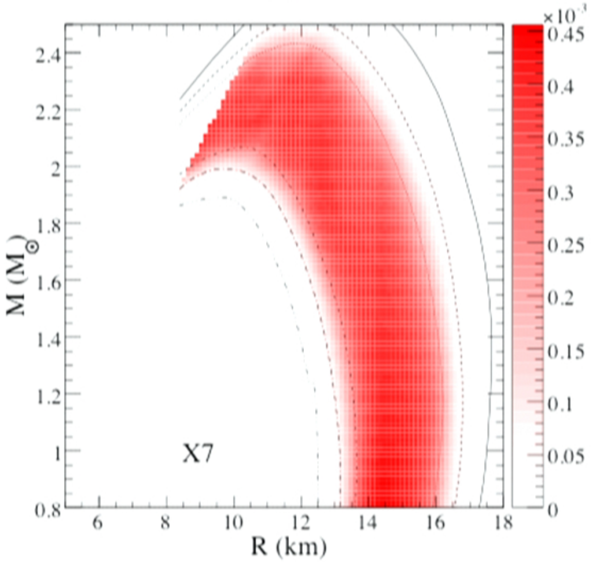
Fit thermal spectrum => peak gives the temperature

Overall luminosity

$$L = 4\pi R^2 \sigma T^4$$

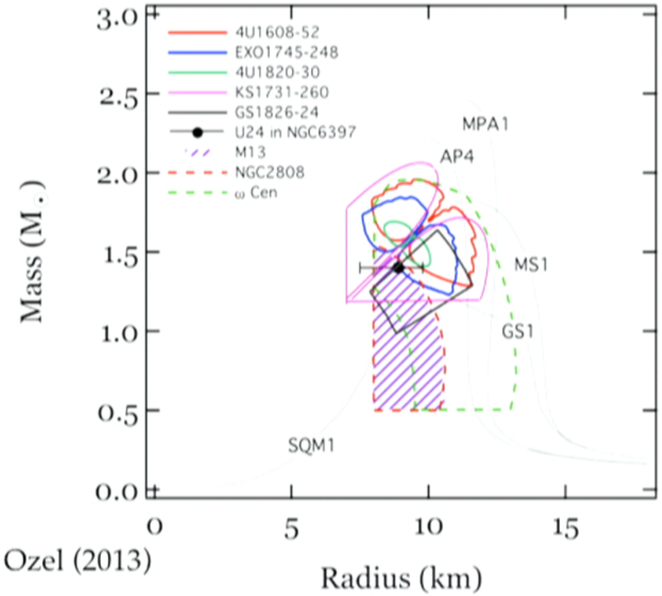
=> Normalization gives a measure of

$$R_\infty = R(1+z)$$



Example constrain for X7 from Steiner et al. (2011)

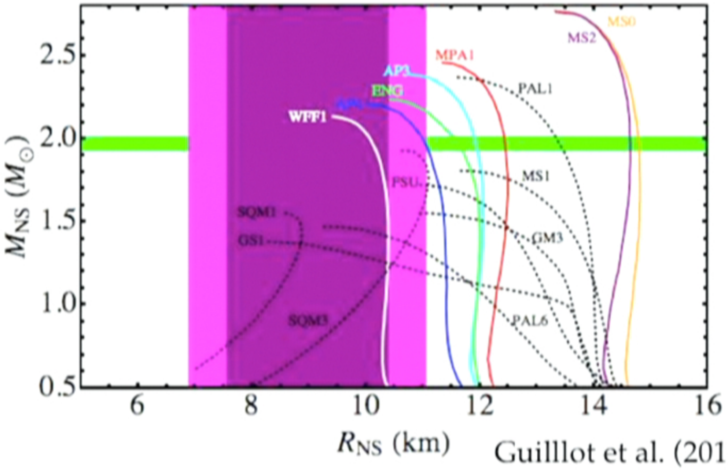
Observational constraints



Ozel (2013)

Neutron stars observed during X-ray bursts

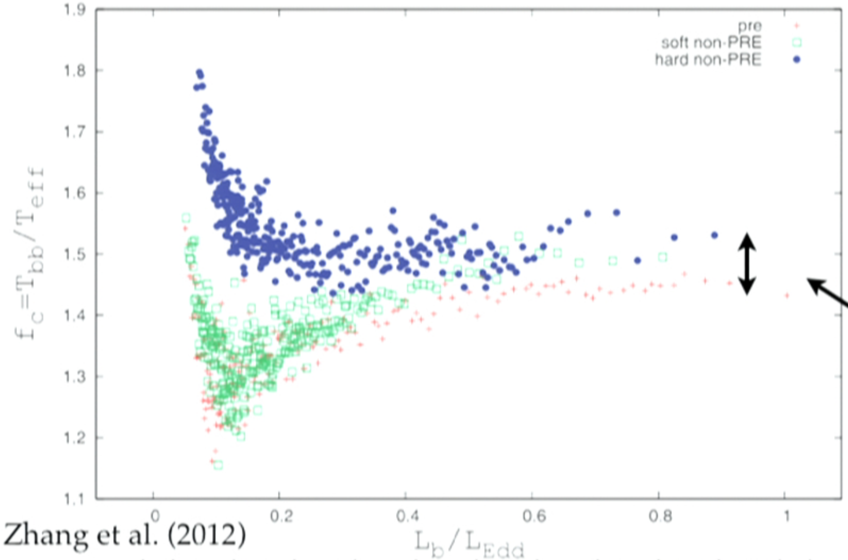
Measure Eddington luminosity L_{Edd} from photospheric radius expansion and thermal emitting area during cooling => M,R constraint



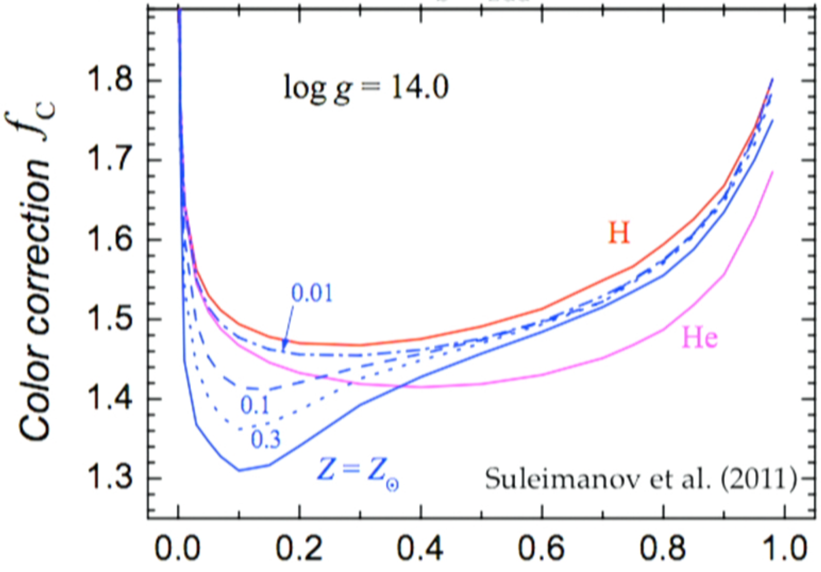
Guilllot et al. (2013)

Neutron stars observed in quiescence after an accretion outburst ends

H atmosphere fit to the thermal spectrum => R(1+z)



Zhang et al. (2012)



Suleimanov et al. (2011)

Spectral evolution changes with accretion rate

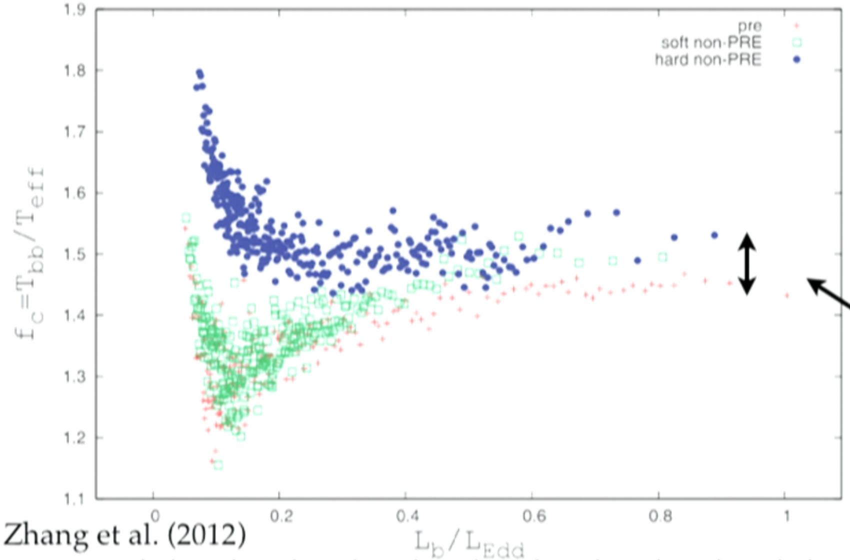
Michael Zamfir, Guobao Zhang,
Mariano Mendez, in prep

10% offset in color correction -> 20% difference in R

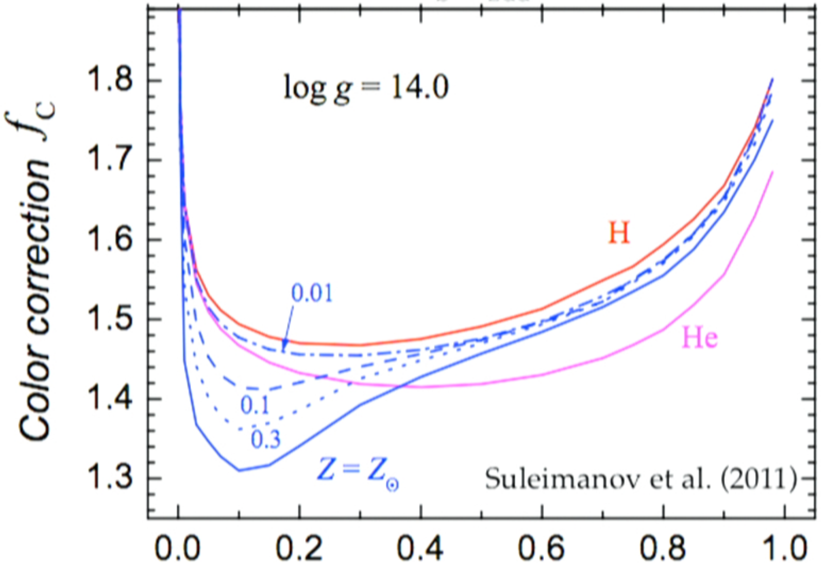
What causes the change?

Why does the "metallicity bump" go away?

Why does fc stay flat at high fluxes?



Zhang et al. (2012)



Suleimanov et al. (2011)

Spectral evolution changes with accretion rate

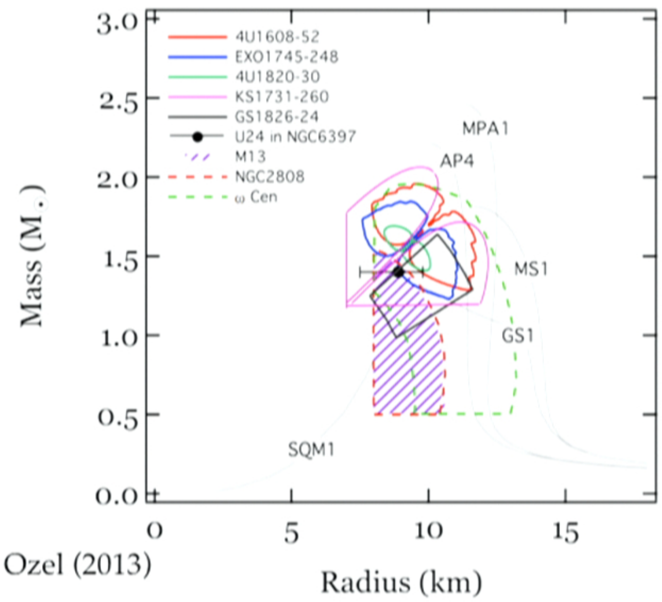
Michael Zamfir, Guobao Zhang,
Mariano Mendez, in prep

10% offset in color correction -> 20% difference in R

What causes the change?

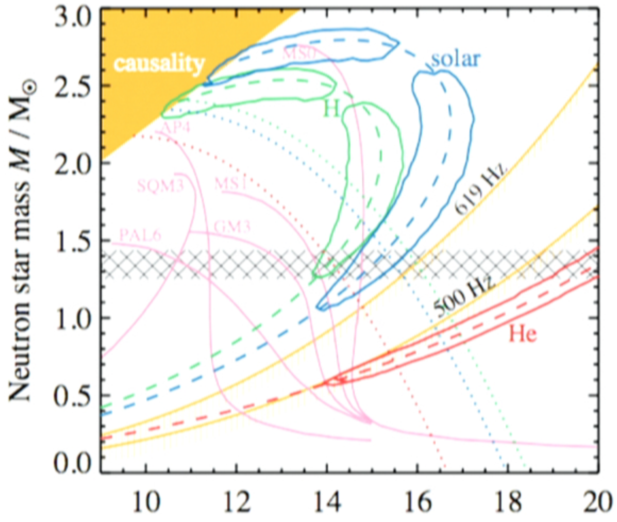
Why does the "metallicity bump" go away?

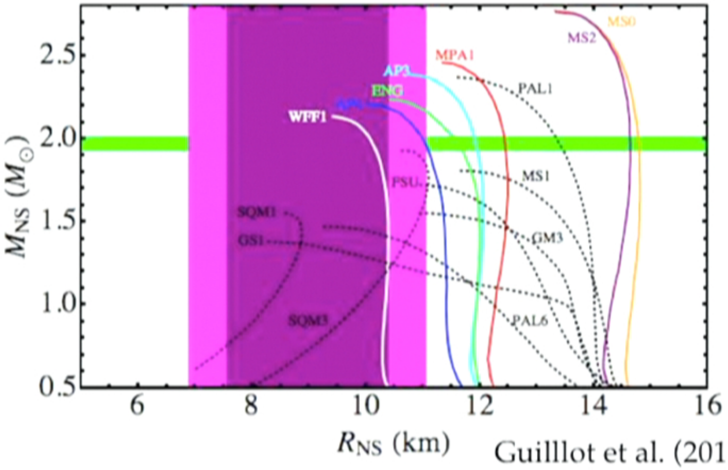
Why does fc stay flat at high fluxes?



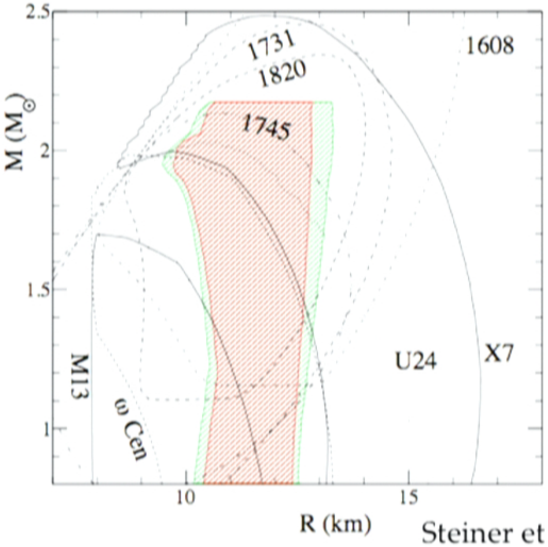
Ozel (2013)

4U 1724-307 Suleimanov et al. (2011)



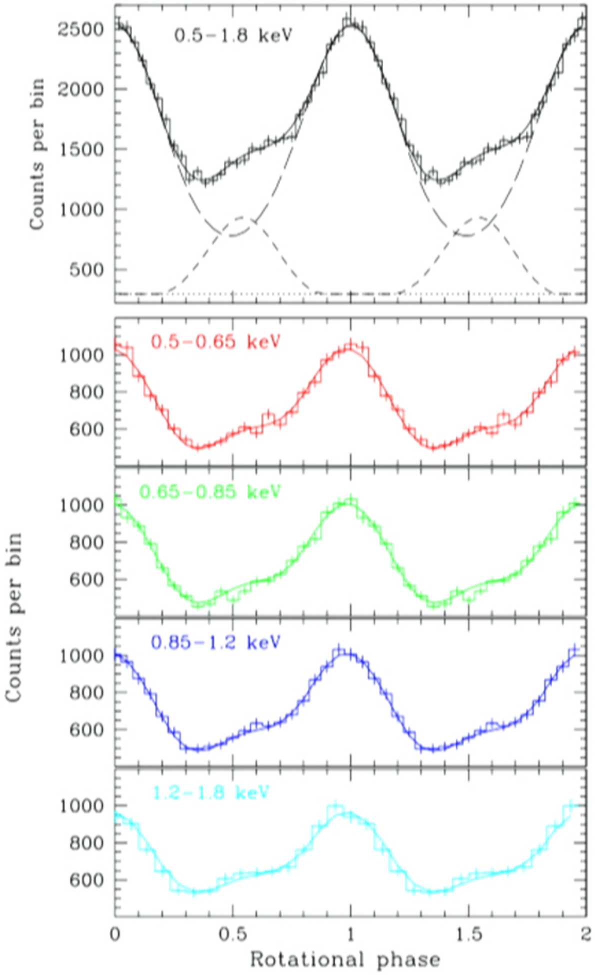


Guilllot et al. (2013)

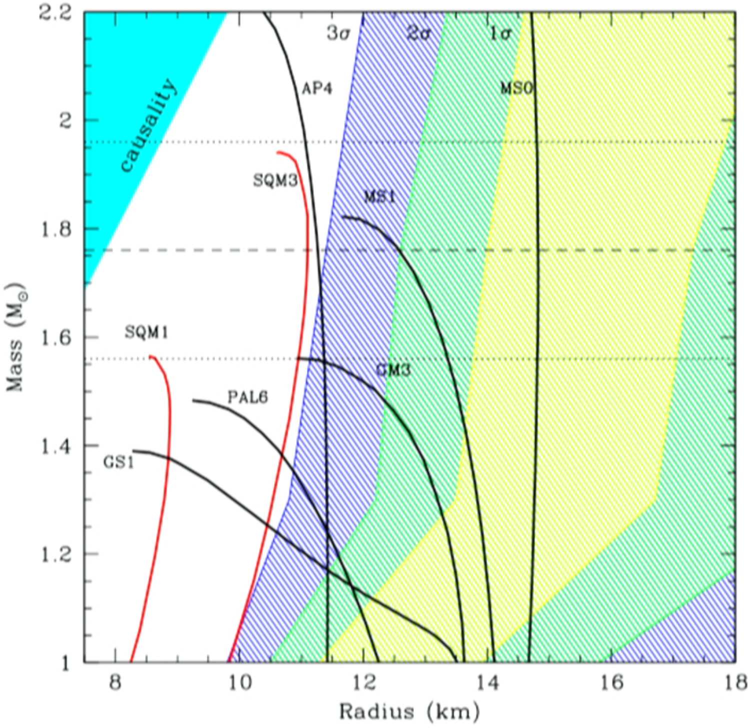


Steiner et al. (2012)

Radius determination from pulse fitting of a millisecond pulsar



Bogdanov 2012 arXiv:1211.6113



3-sigma lower limit R>11.1 km

Summary of neutron star radius measurements

Some convergence of observations and theory:

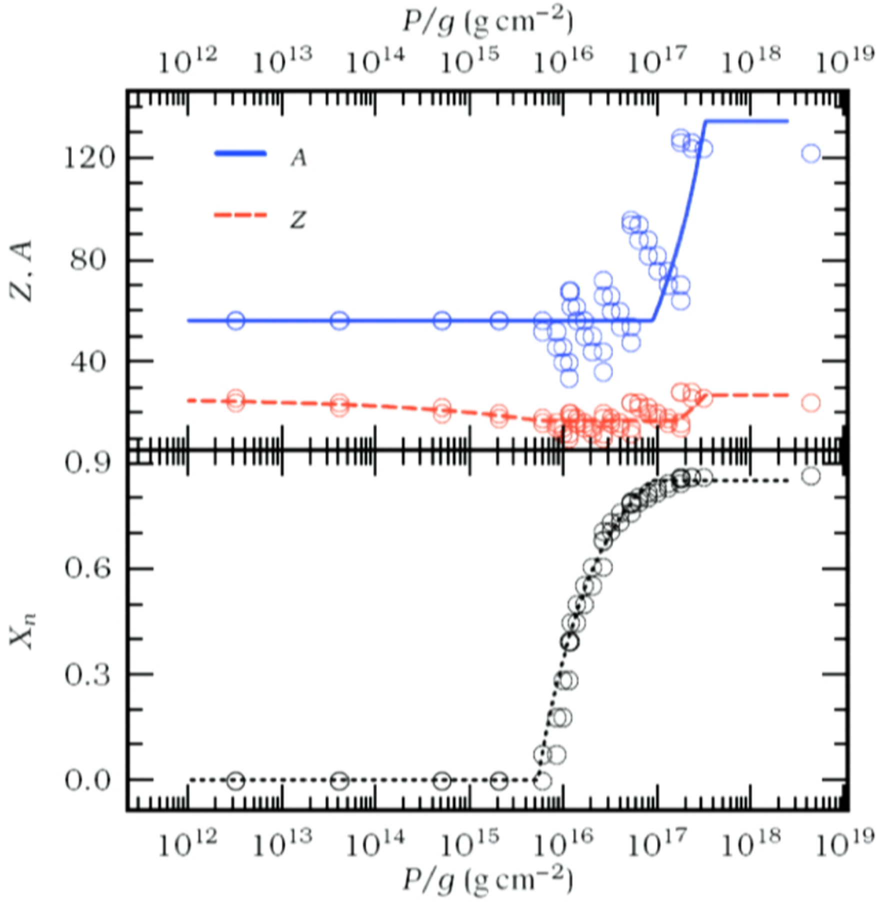
- Expectations from theory based on well-understood low density EOS => radii should be 10-13 km

- Individual observational determinations span a range, but taken together appear consistent with this range

Focus now is on understanding systematic effects:
- determination of Eddington luminosity from touchdown
- behavior of color correction: influence of surrounding accretion flow

Upcoming observatories:
- X-rays: NICER (late 2016 launch), LOFT (selection next year; launch early 2020s)
- distances: GAIA (launch late this year)

In an accreting neutron star, the composition evolves as matter is compressed to high density



Brown and Cumming (2009) following Sato (1979), Haensel & Zdunik (1990)

Example reaction sequences

Outer crust
$^{56}\mathrm{Fe} + e^- \rightarrow {}^{56}\mathrm{Mn} + \nu_e$
$^{56}\mathrm{Mn} + e^- \rightarrow {}^{56}\mathrm{Cr} + \nu_e$

Inner crust
$^{56}\mathrm{Ar} + e^- \rightarrow {}^{56}\mathrm{Cl} + \nu_e$
$^{56}\mathrm{Cl} \rightarrow {}^{55}\mathrm{Cl} + n$
$^{55}\mathrm{Cl} + e^- \rightarrow {}^{55}\mathrm{S} + \nu_e$
$^{55}\mathrm{S} \rightarrow {}^{54}\mathrm{S} + n$
$^{54}\mathrm{S} \rightarrow {}^{52}\mathrm{S} + 2n$

The associated heating is about 1 MeV/nucleon

[see Oberacker talk]

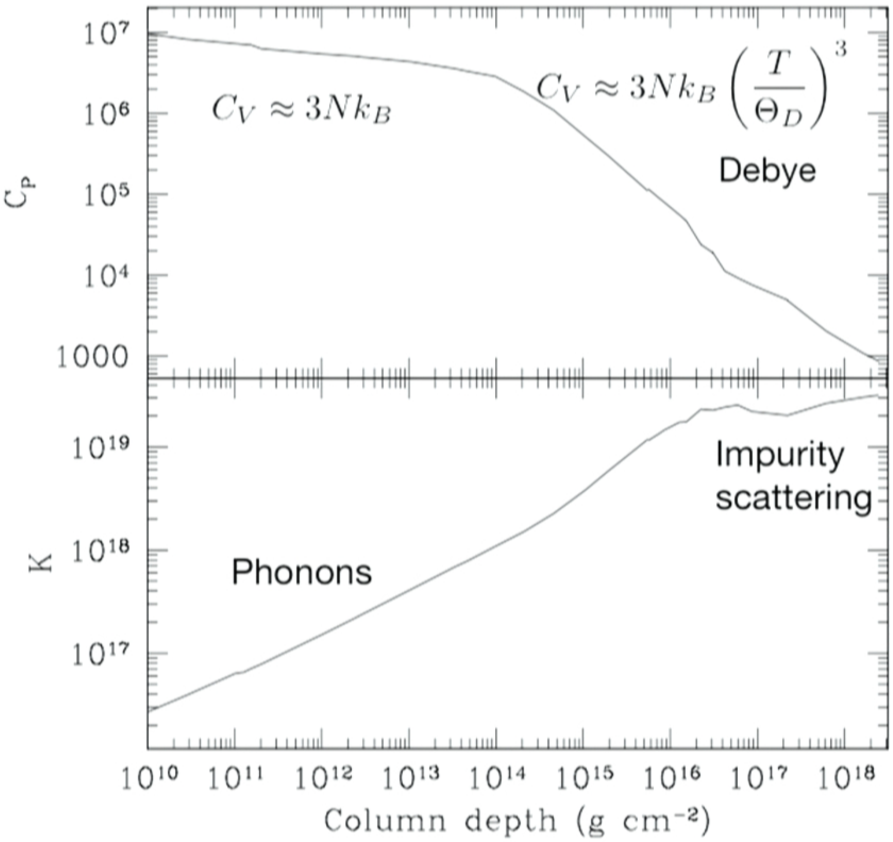
Heat capacity and thermal conductivity in the crust

thermal time

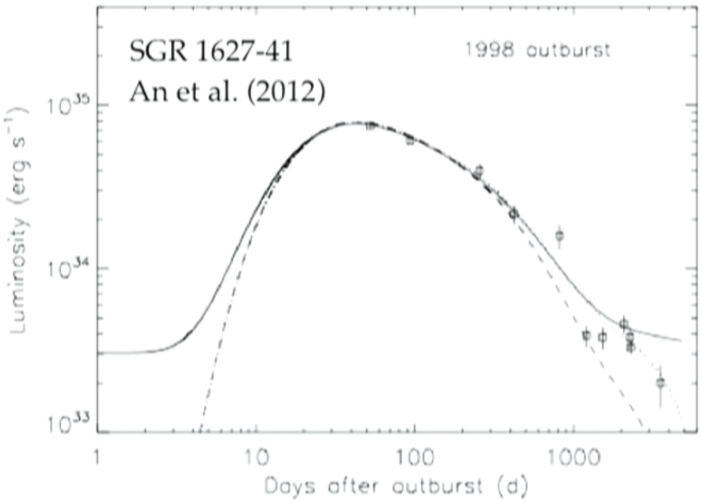
$$\tau = \left[\int_0^z \left(\frac{\rho C_P}{4K}\right)^{1/2} dz\right]^2$$

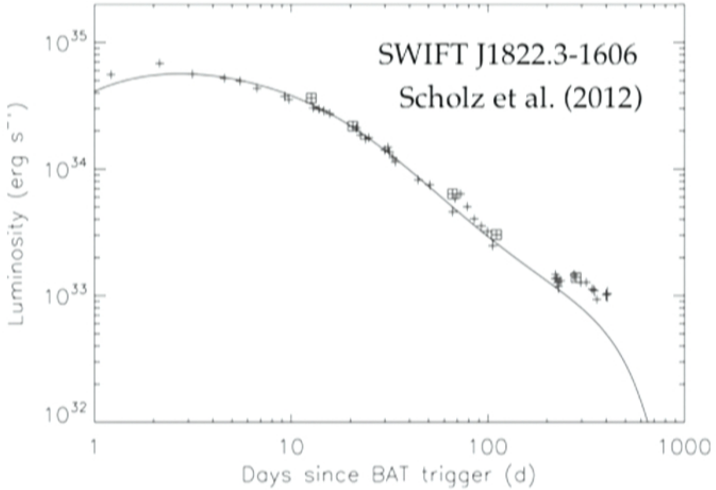
thermal conductivity

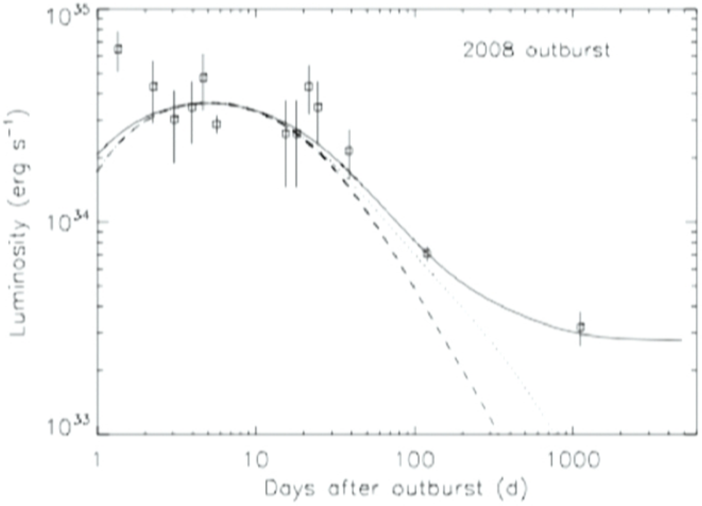
$$K = \frac{\pi^2}{3}\frac{n_e k_B^2 T \tau}{m_\star}$$

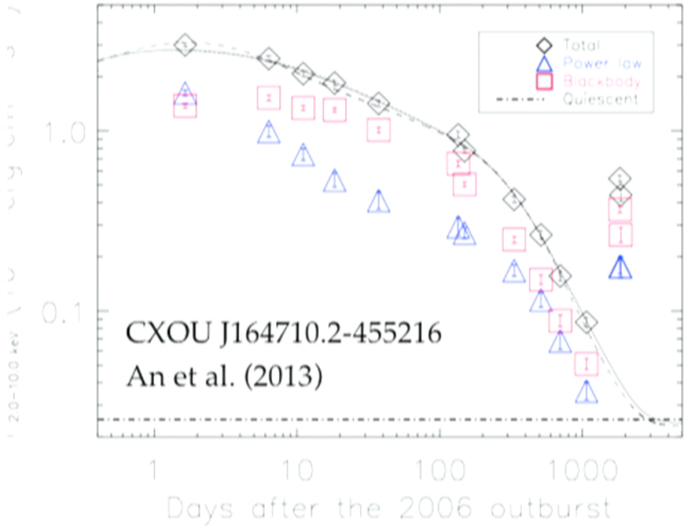


Outer crust | Inner crust


SGR 1627-41
An et al. (2012)


SWIFT J1822.3-1606
Scholz et al. (2012)




CXOU J164710.2-455216
An et al. (2013)

Conclusions

Interesting convergence on radii from theory + observations, but still significant systematic uncertainties. Progress requires work on astrophysics modelling (e.g. radius expansion events).

Thermal evolution of neutron stars on months/years timescales is a new window on crust physics

- Accreting neutron stars: measure of thermal conductivity/level of impurities in the crust; limits on neutron heat capacity
- Focused attention on multicomponent crusts: nuclear evolution at *and beyond* the neutron drip line; chemical separation and freezing of plasmas
- Magnetars: Many observed outbursts; heating appears to be in thin layers of the outer crust; a new constraint on field decay/crust yielding models