The Neutron Star Radius and the dense matter equation of state

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Results from Guillot et al. 2013, ApJ 772

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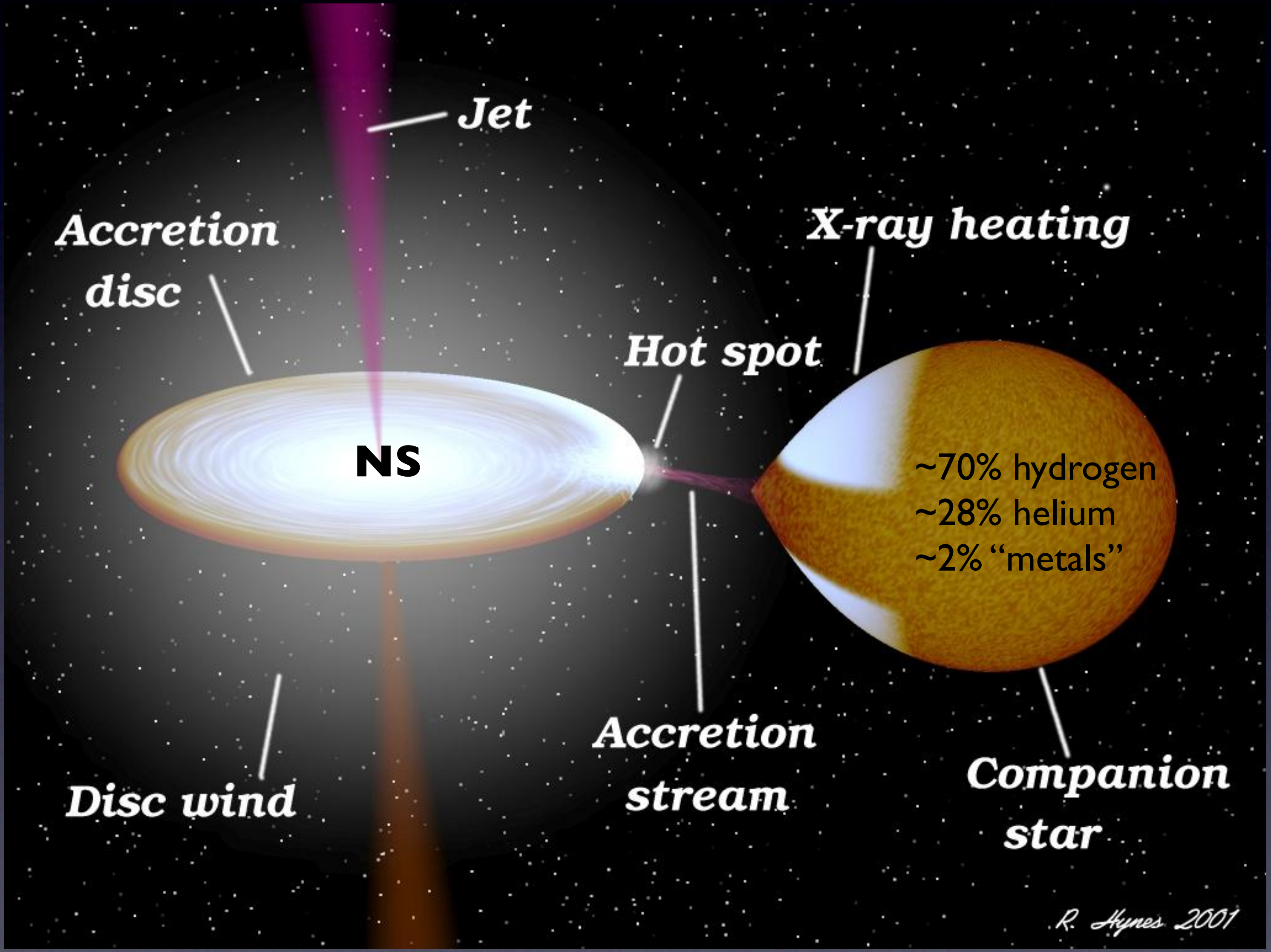
Structure and Signals from Neutron Stars
Firenze, It., March 2014

Quiescent low-mass X-ray binaries are ideal systems for Mass-Radius measurements.

- In quiescence, LMXBs have low mass accretion rate
- Thermal emission powered by deep crustal heating
- Surface thermal emission comes from a pure hydrogen atmosphere with $L_X = 10^{32-33}$ erg/sec
- Neutron star has a weak surface magnetic field



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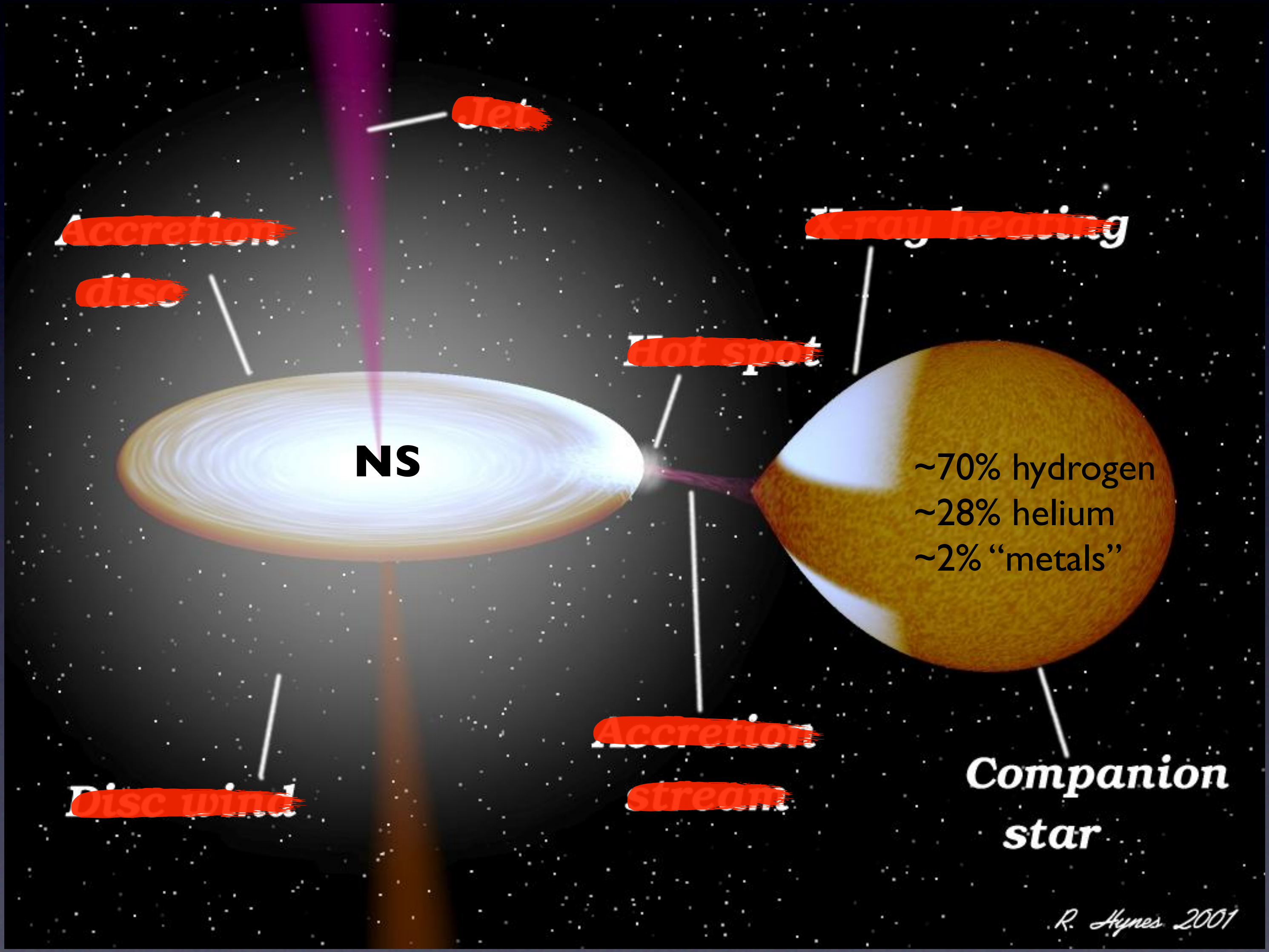
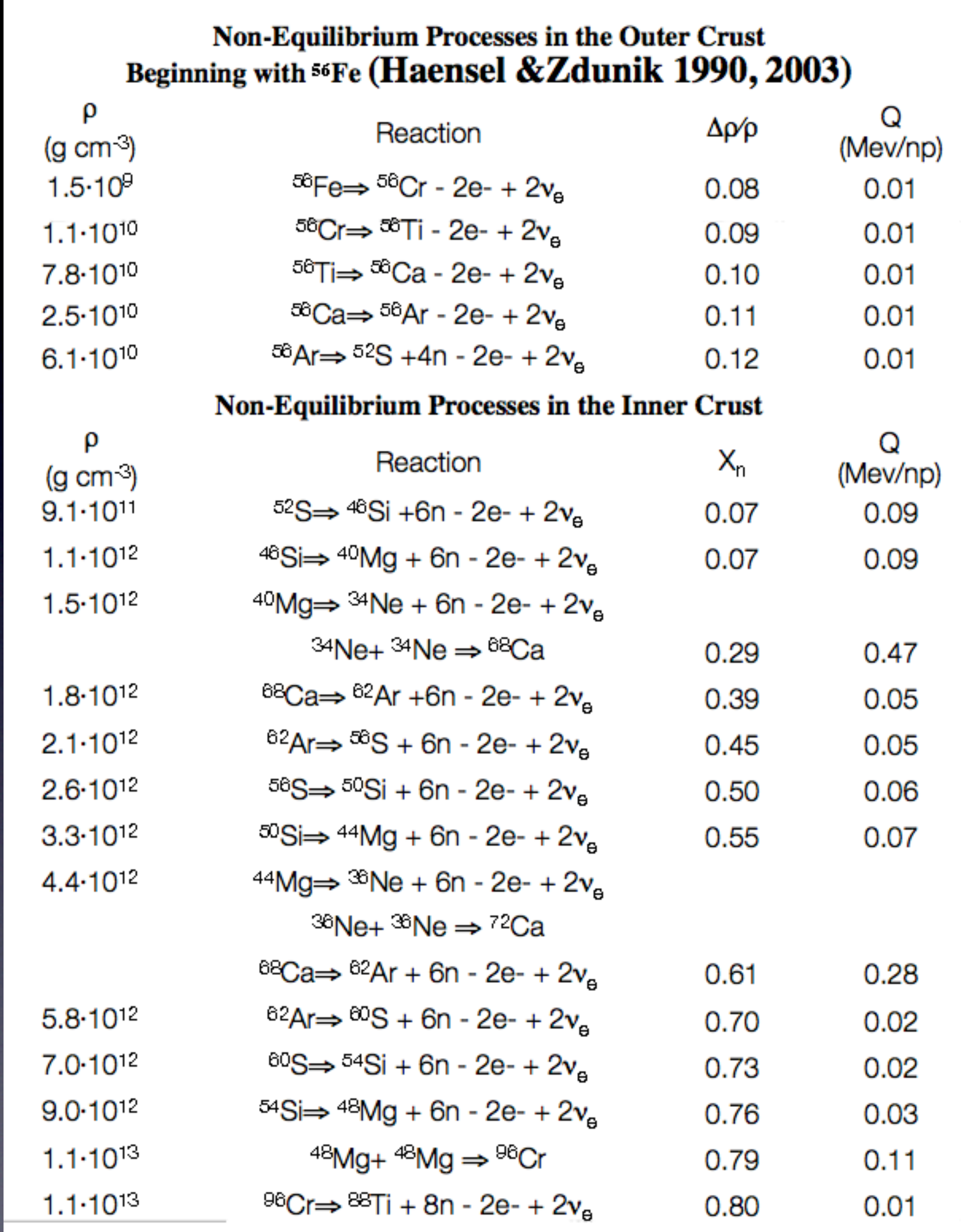


The thermal emission from qLMXB is powered by Deep Crustal Heating.

Brown et al. 1998

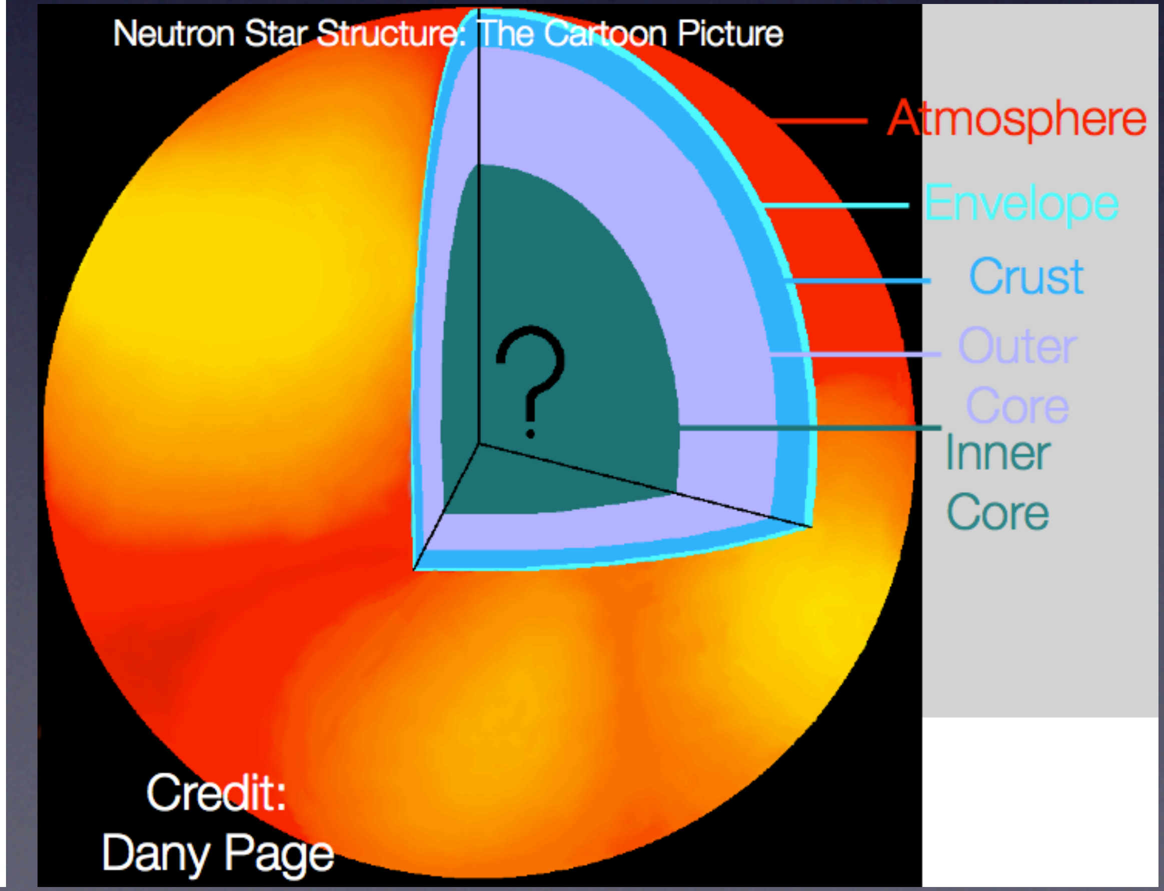


Non-Equilibrium Processes in the Outer Crust Beginning with ^{56}Fe (Haensel &Zdunik 1990, 2003)

ρ (g cm^{-3})	Reaction	Δρ/ρ	Q (Mev/np)
$1.5 \cdot 10^{9}$	$^{56}\mathrm{Fe} \Rightarrow {}^{56}\mathrm{Cr} - 2e- + 2\nu_e$	0.08	0.01
$1.1 \cdot 10^{10}$	$^{56}\mathrm{Cr} \Rightarrow {}^{56}\mathrm{Ti} - 2e- + 2\nu_e$	0.09	0.01
$7.8 \cdot 10^{10}$	$^{56}\mathrm{Ti} \Rightarrow {}^{56}\mathrm{Ca} - 2e- + 2\nu_e$	0.10	0.01
$2.5 \cdot 10^{10}$	$^{56}\mathrm{Ca} \Rightarrow {}^{56}\mathrm{Ar} - 2e- + 2\nu_e$	0.11	0.01
$6.1 \cdot 10^{10}$	$^{56}\mathrm{Ar} \Rightarrow {}^{52}\mathrm{S} + 4n - 2e- + 2\nu_e$	0.12	0.01

Non-Equilibrium Processes in the Inner Crust

ρ (g cm^{-3})	Reaction	X_n	Q (Mev/np)
$9.1 \cdot 10^{11}$	$^{52}\mathrm{S} \Rightarrow {}^{46}\mathrm{Si} + 6n - 2e- + 2\nu_e$	0.07	0.09
$1.1 \cdot 10^{12}$	$^{46}\mathrm{Si} \Rightarrow {}^{40}\mathrm{Mg} + 6n - 2e- + 2\nu_e$	0.07	0.09
$1.5 \cdot 10^{12}$	$^{40}\mathrm{Mg} \Rightarrow {}^{34}\mathrm{Ne} + 6n - 2e- + 2\nu_e$		
	$^{34}\mathrm{Ne} + {}^{34}\mathrm{Ne} \Rightarrow {}^{68}\mathrm{Ca}$	0.29	0.47
$1.8 \cdot 10^{12}$	$^{68}\mathrm{Ca} \Rightarrow {}^{62}\mathrm{Ar} + 6n - 2e- + 2\nu_e$	0.39	0.05
$2.1 \cdot 10^{12}$	$^{62}\mathrm{Ar} \Rightarrow {}^{56}\mathrm{S} + 6n - 2e- + 2\nu_e$	0.45	0.05
$2.6 \cdot 10^{12}$	$^{56}\mathrm{S} \Rightarrow {}^{50}\mathrm{Si} + 6n - 2e- + 2\nu_e$	0.50	0.06
$3.3 \cdot 10^{12}$	$^{50}\mathrm{Si} \Rightarrow {}^{44}\mathrm{Mg} + 6n - 2e- + 2\nu_e$	0.55	0.07
$4.4 \cdot 10^{12}$	$^{44}\mathrm{Mg} \Rightarrow {}^{36}\mathrm{Ne} + 6n - 2e- + 2\nu_e$		
	$^{36}\mathrm{Ne} + {}^{36}\mathrm{Ne} \Rightarrow {}^{72}\mathrm{Ca}$		
	$^{68}\mathrm{Ca} \Rightarrow {}^{62}\mathrm{Ar} + 6n - 2e- + 2\nu_e$	0.61	0.28
$5.8 \cdot 10^{12}$	$^{62}\mathrm{Ar} \Rightarrow {}^{60}\mathrm{S} + 6n - 2e- + 2\nu_e$	0.70	0.02
$7.0 \cdot 10^{12}$	$^{60}\mathrm{S} \Rightarrow {}^{54}\mathrm{Si} + 6n - 2e- + 2\nu_e$	0.73	0.02
$9.0 \cdot 10^{12}$	$^{54}\mathrm{Si} \Rightarrow {}^{48}\mathrm{Mg} + 6n - 2e- + 2\nu_e$	0.76	0.03
$1.1 \cdot 10^{13}$	$^{48}\mathrm{Mg} + {}^{48}\mathrm{Mg} \Rightarrow {}^{96}\mathrm{Cr}$	0.79	0.11
$1.1 \cdot 10^{13}$	$^{96}\mathrm{Cr} \Rightarrow {}^{88}\mathrm{Ti} + 8n - 2e- + 2\nu_e$	0.80	0.01

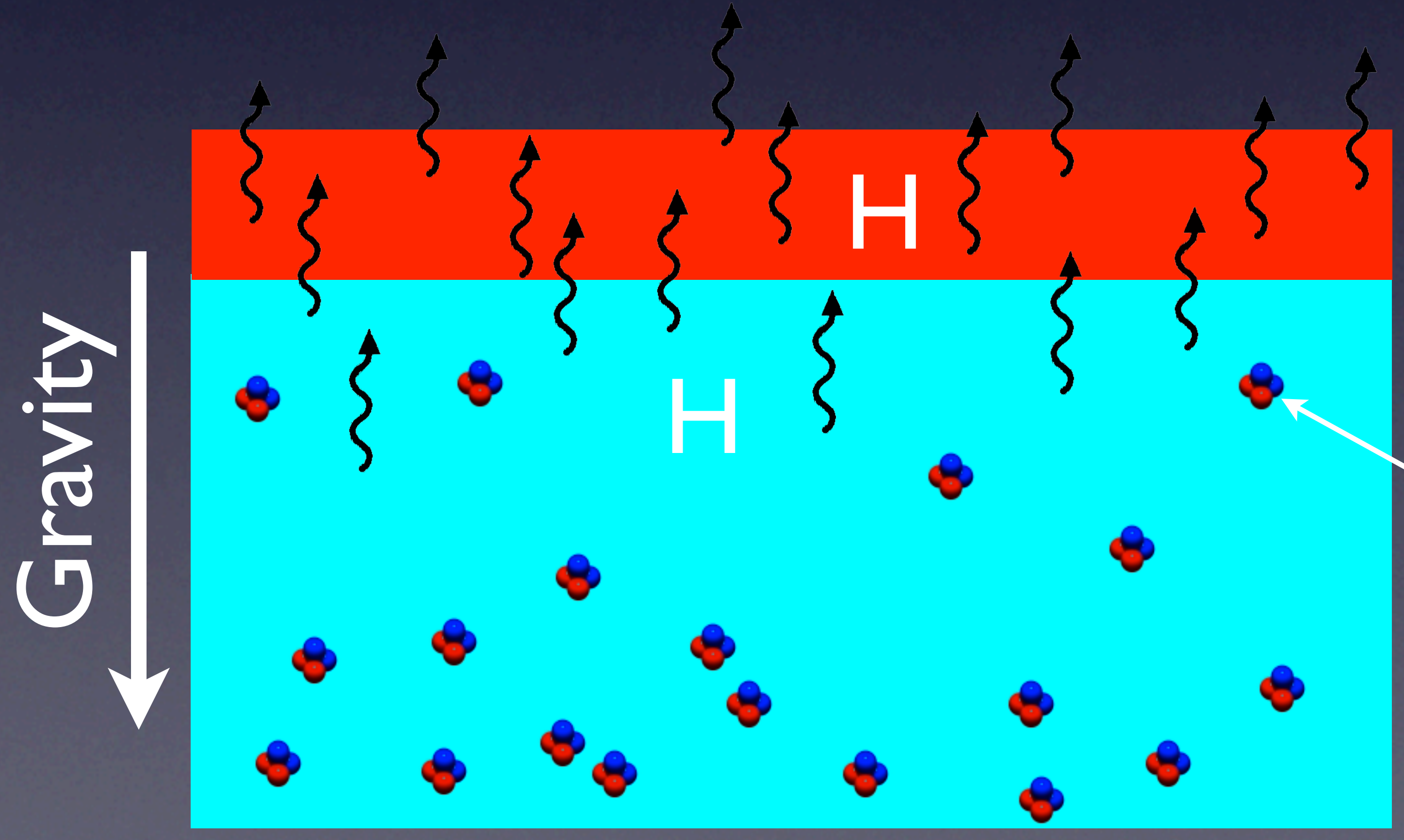


Neutron Star Structure: The Cartoon Picture

Credit: Dany Page

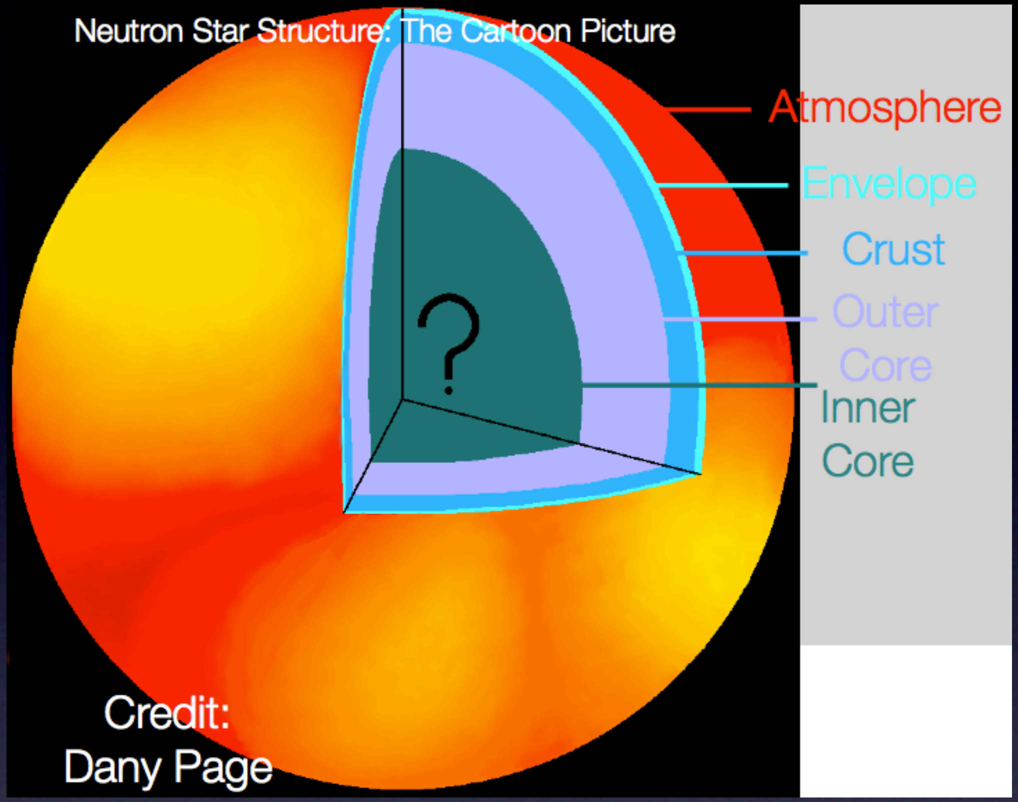
The atmosphere of the neutron star in a qLMXB is composed of pure hydrogen.

H-atmosphere
thermal spectrum
seen by observer



Photosphere ~ 10 cm

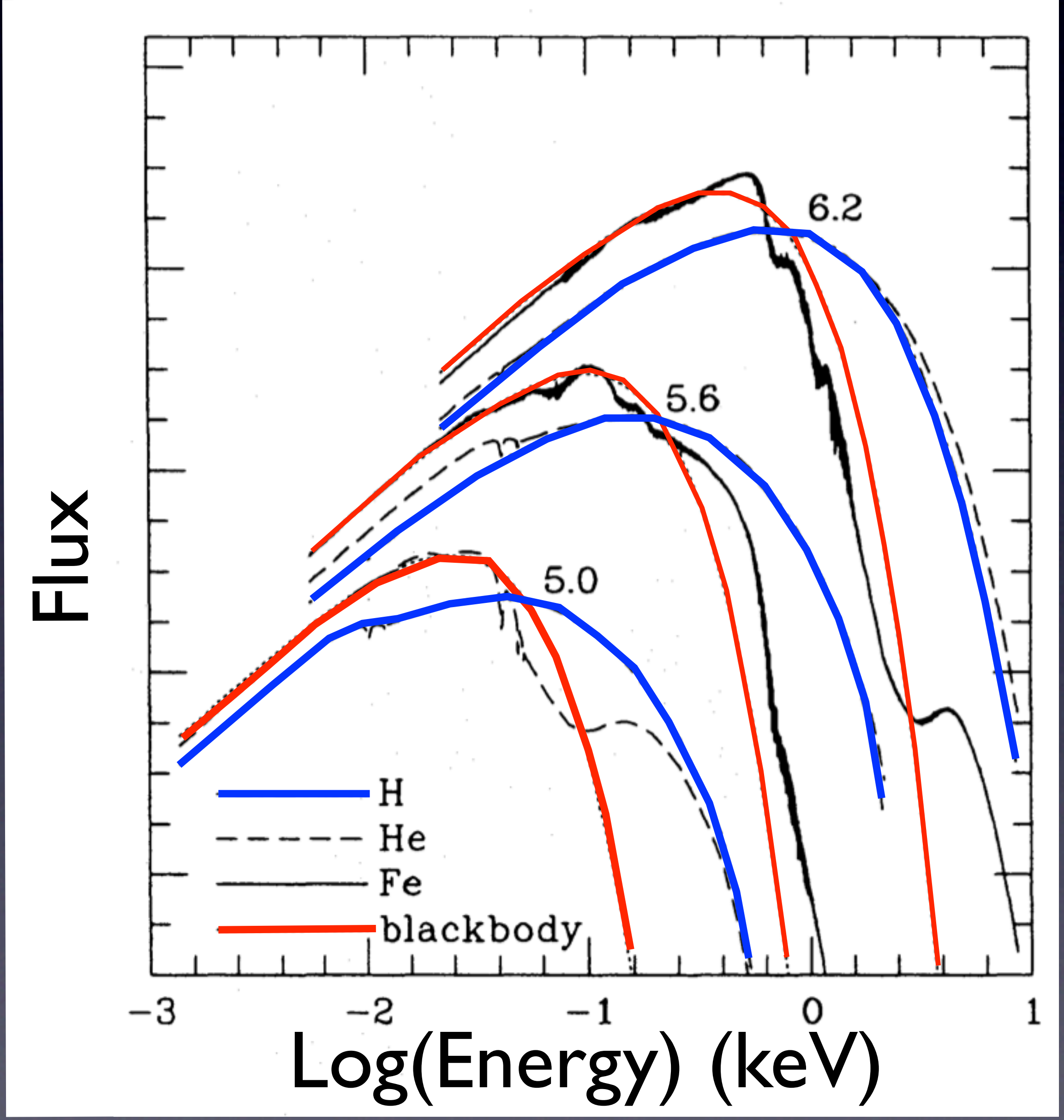
Helium



Credit:
Dany Page

The thermal emission from a NS surface is modelled with NS atmosphere models.

Models by Zavlin et al. (1996), Heinke et al. (2006), Haakonsen et al. (2012)



NSA, NSAGRAV models
Zavlin et al 1996, A&A 315

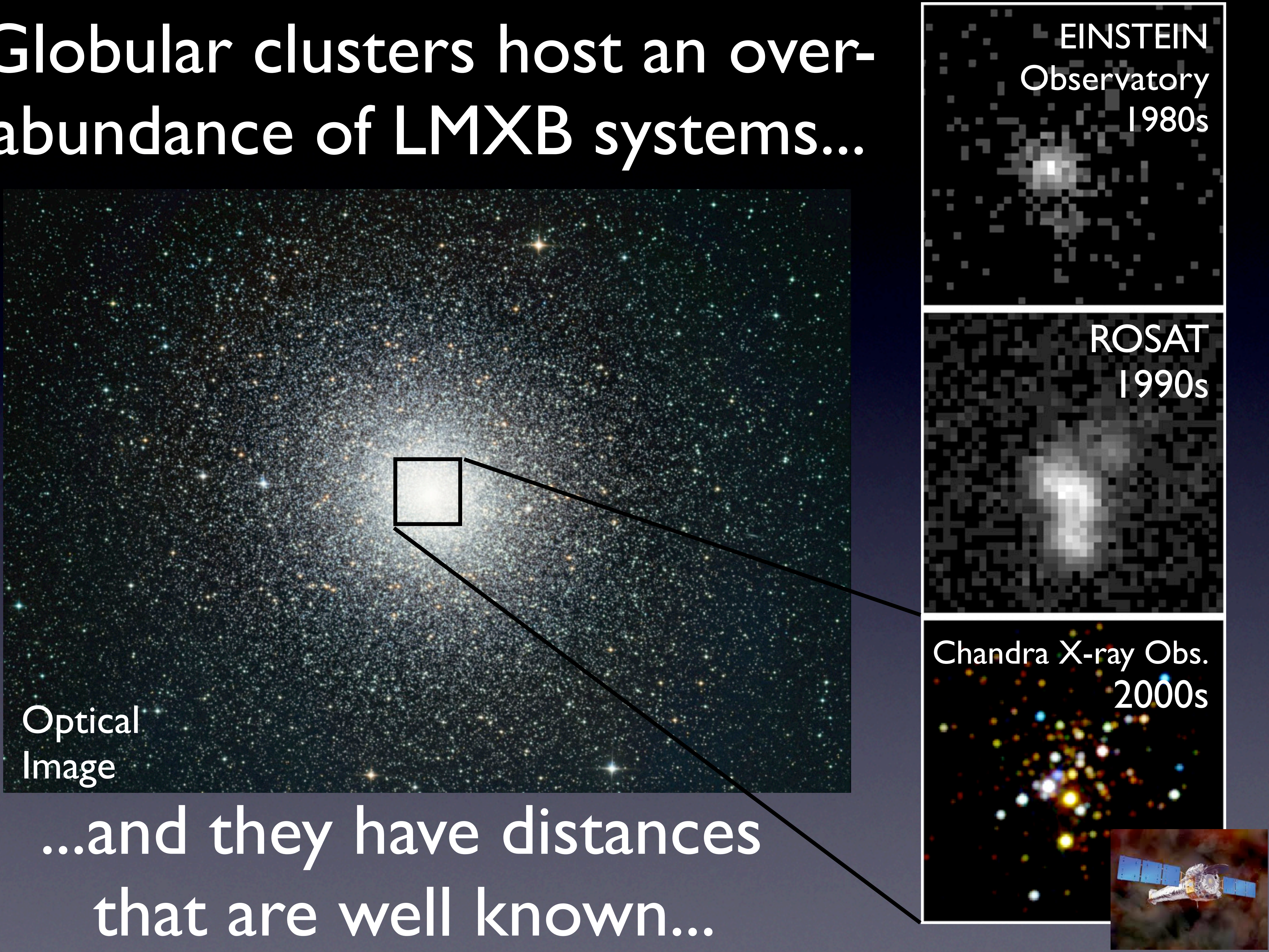
Spectral fitting of the thermal emission gives us **T_{eff}** and **$(R_\infty/D)^2$**

$$R_\infty = R_{\rm NS}\left(1 - \frac{2GM_{\rm NS}}{R_{\rm NS}\ c^2},\right)^{-1/2}$$

NS H-atmosphere model parameters are:

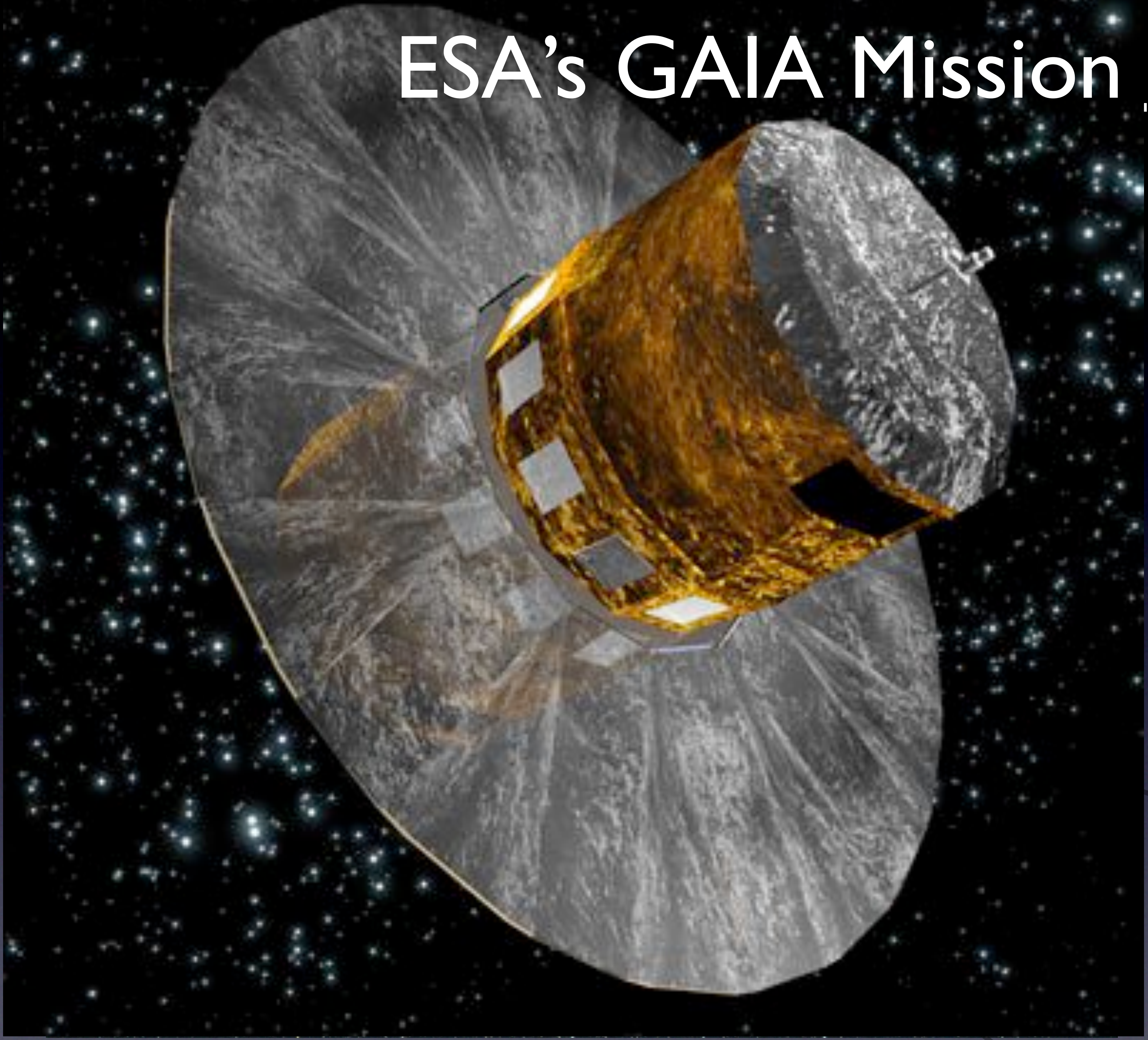
- Effective temperature kT_{eff}
- Mass M_{NS} ($M_\odot$)
- Radius R_{NS} (km)
- Distance D (kpc)

Globular clusters host an over-abundance of LMXB systems...



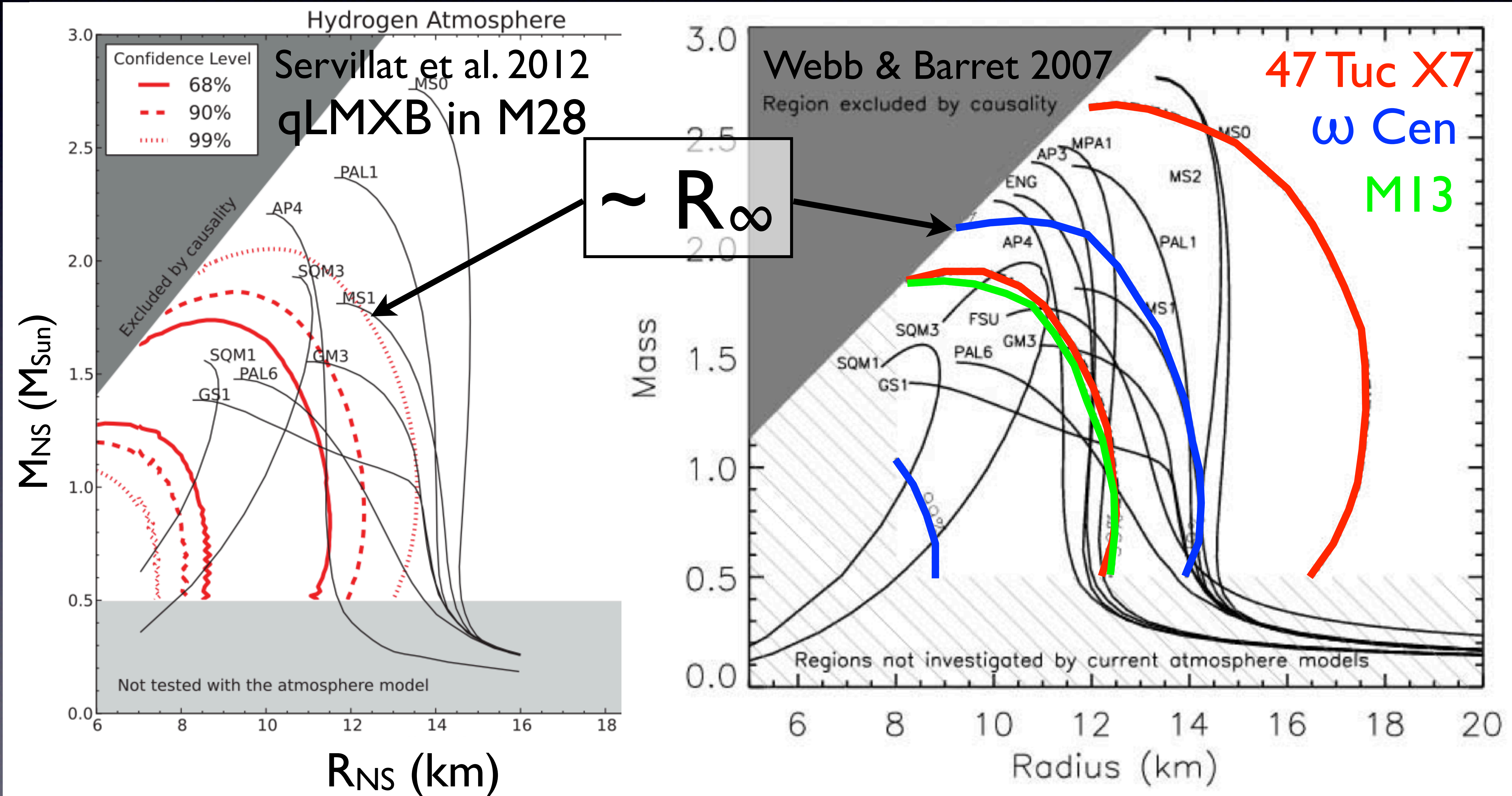
...and they have distances that are well known...

ESA's GAIA Mission



...and they have distances
that are well known...soon

Quiescent LMXBs are routinely used for M_{NS}-R_{NS} measurements, but only place weak constraints on the dense matter EoS.



Servillat et al. 2012
qLMXB in M28

Webb & Barret 2007

~ R_∞

47 Tuc X7
ω Cen
M13

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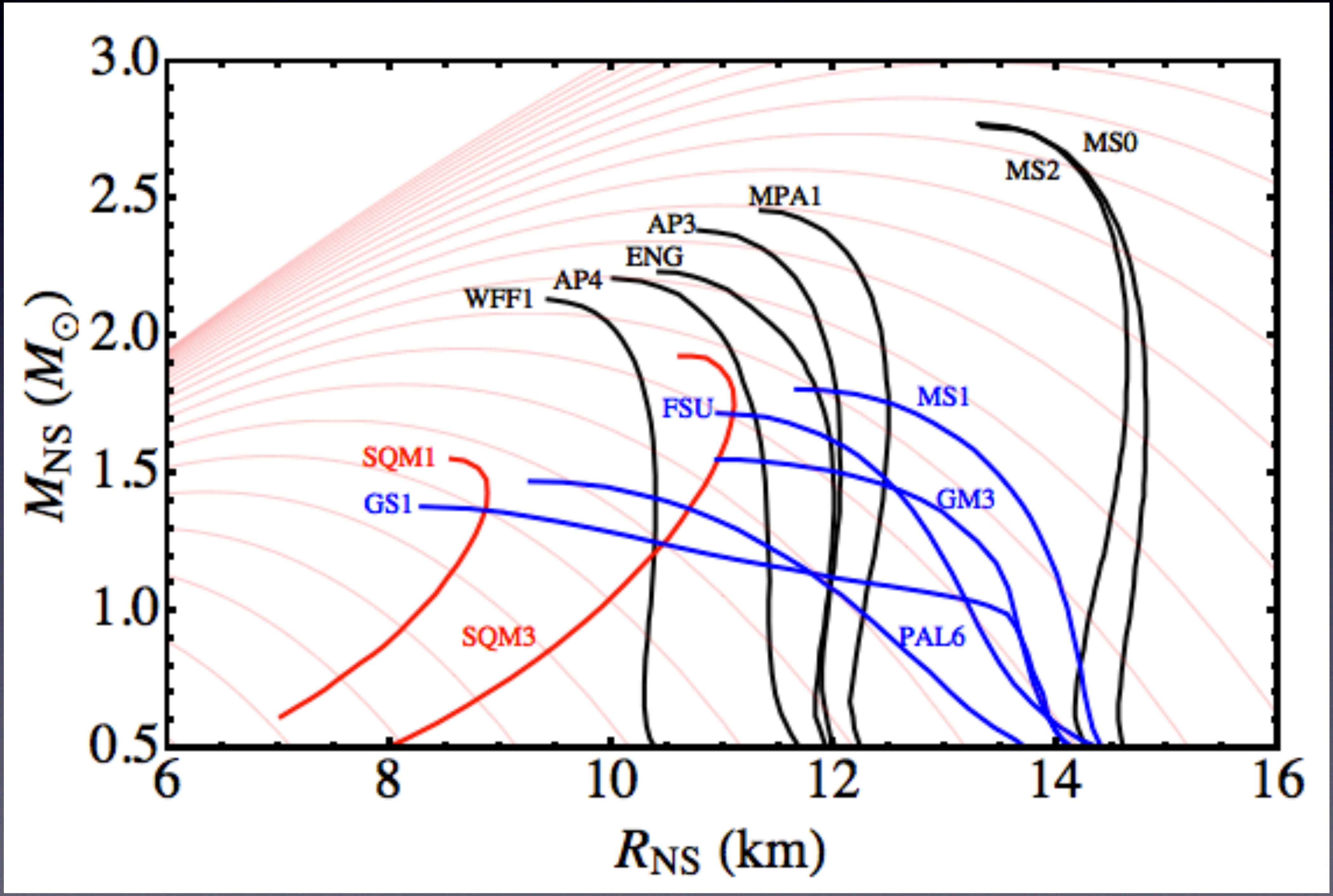
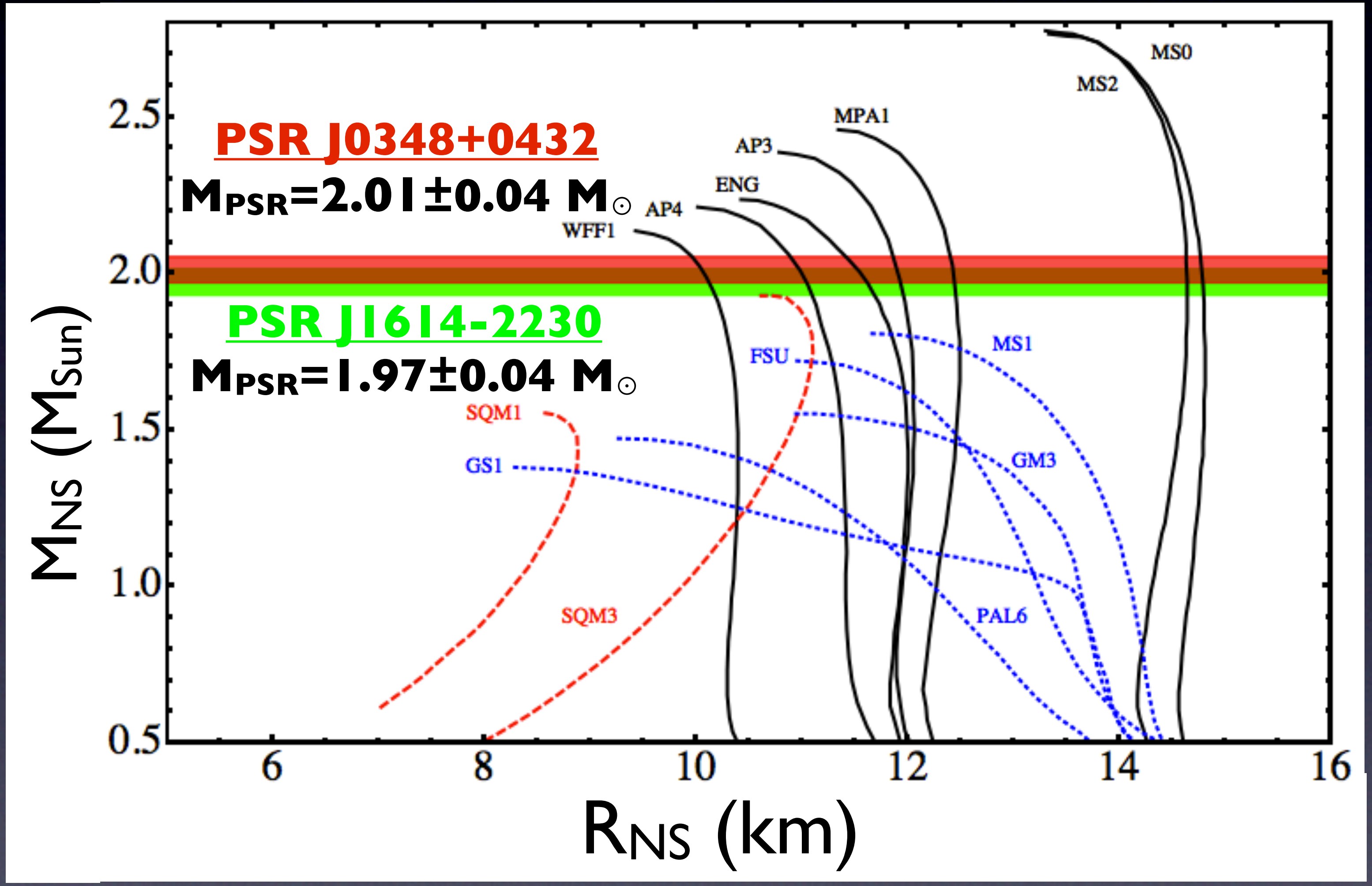


In Guillot et al (2013), we follow a simplified parametrization for the EoS.

Equations of state consistent with ~ $2M_{sun}$ are those described by a constant radius for a wide range of masses.



We assume that

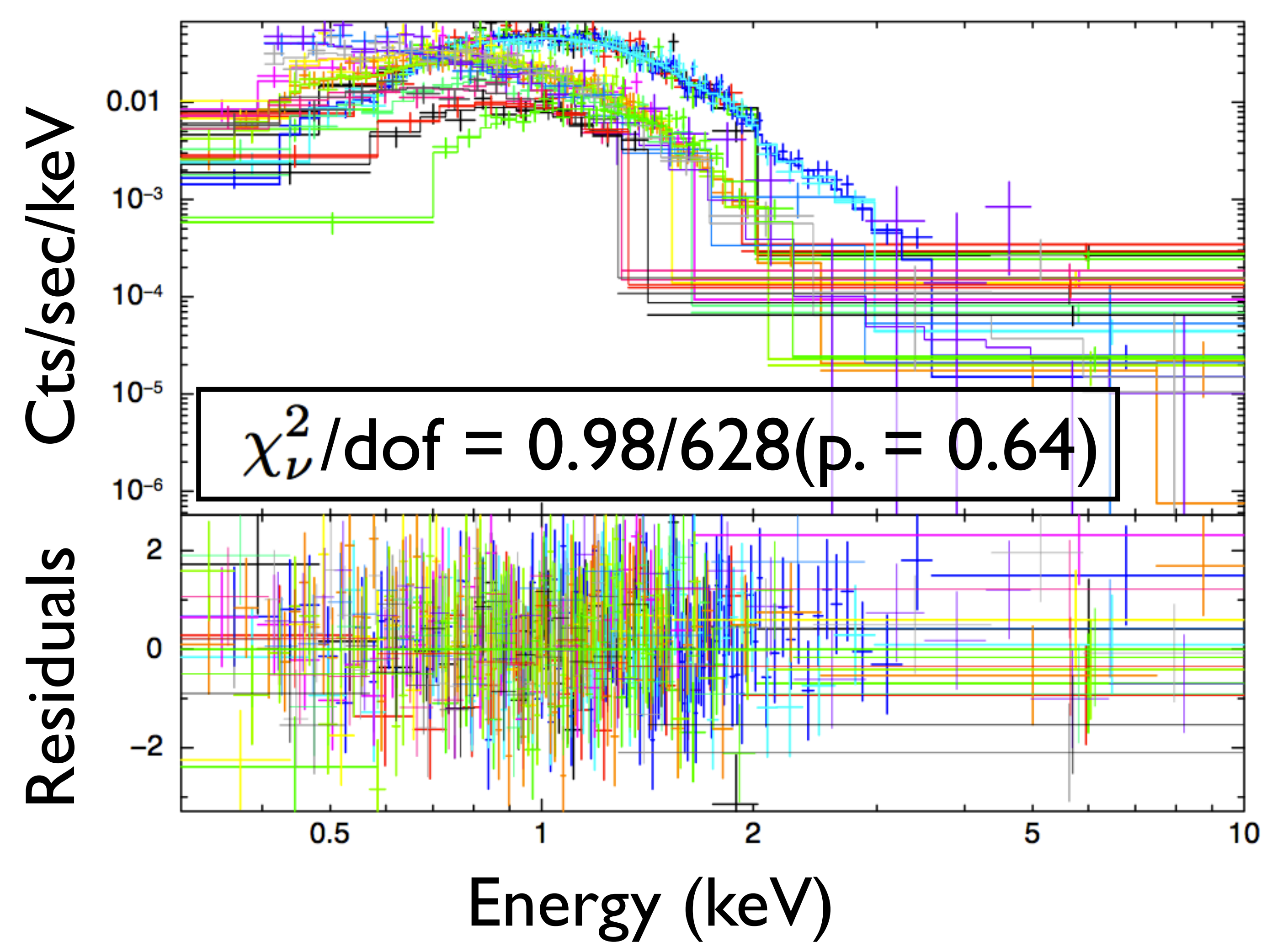
all neutron stars have the same radius

We simultaneously fit the spectra of 6 qLMXBs with H-atmosphere model

One radius to fit them all!

Five parameters per target:

T_{eff}, M_{NS}, absorption,
distance,
power-law component



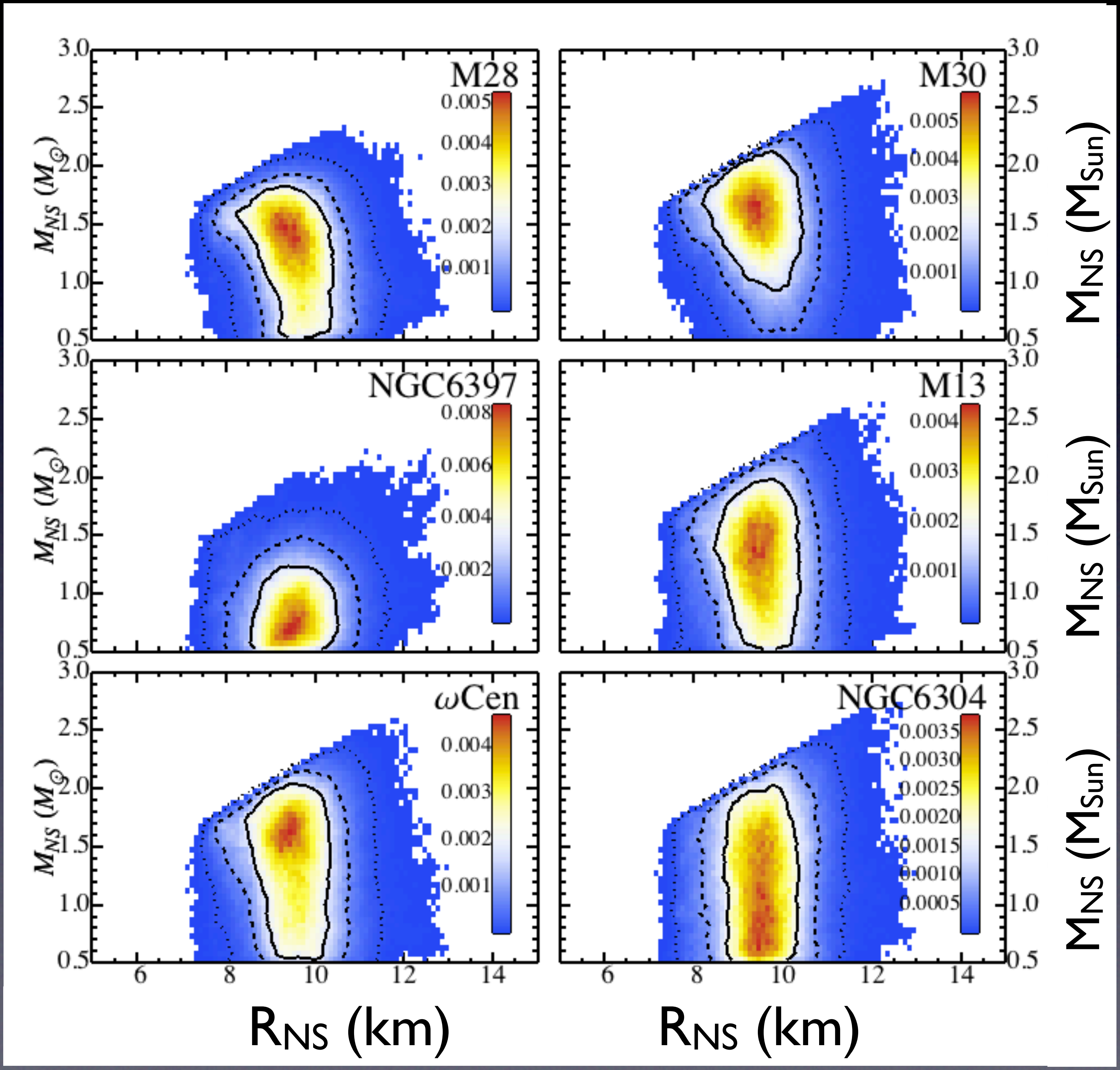
Guillot et al. 2013

Our most conservative radius measurement relies on the least number of assumptions.

Most conservative neutron star radius measurement is

$$R_{\rm NS} = 9.4^{+1.2}_{-1.2}\,{\rm km}$$

90% conf. level



Guillot et al., in prep

Our most conservative R_{NS} measurement includes most sources of uncertainty

We included the uncertainties linked to:

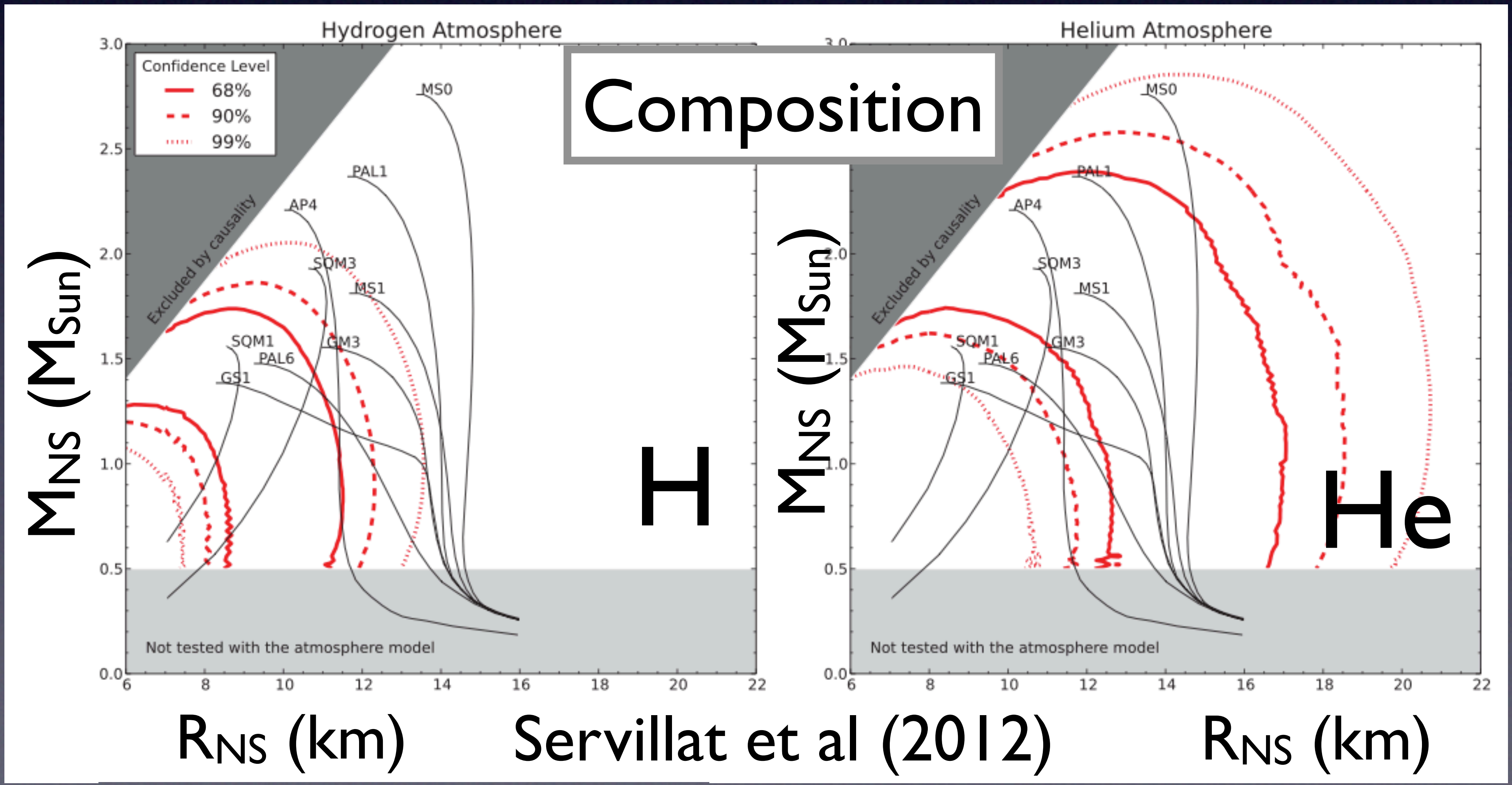
- Galactic absorption
- Distances of the host clusters
- Possible power-law component
- Calibration of x-ray detectors

There are assumptions that still remain in our analysis

NS surface emits isotropically

Negligible magnetic field

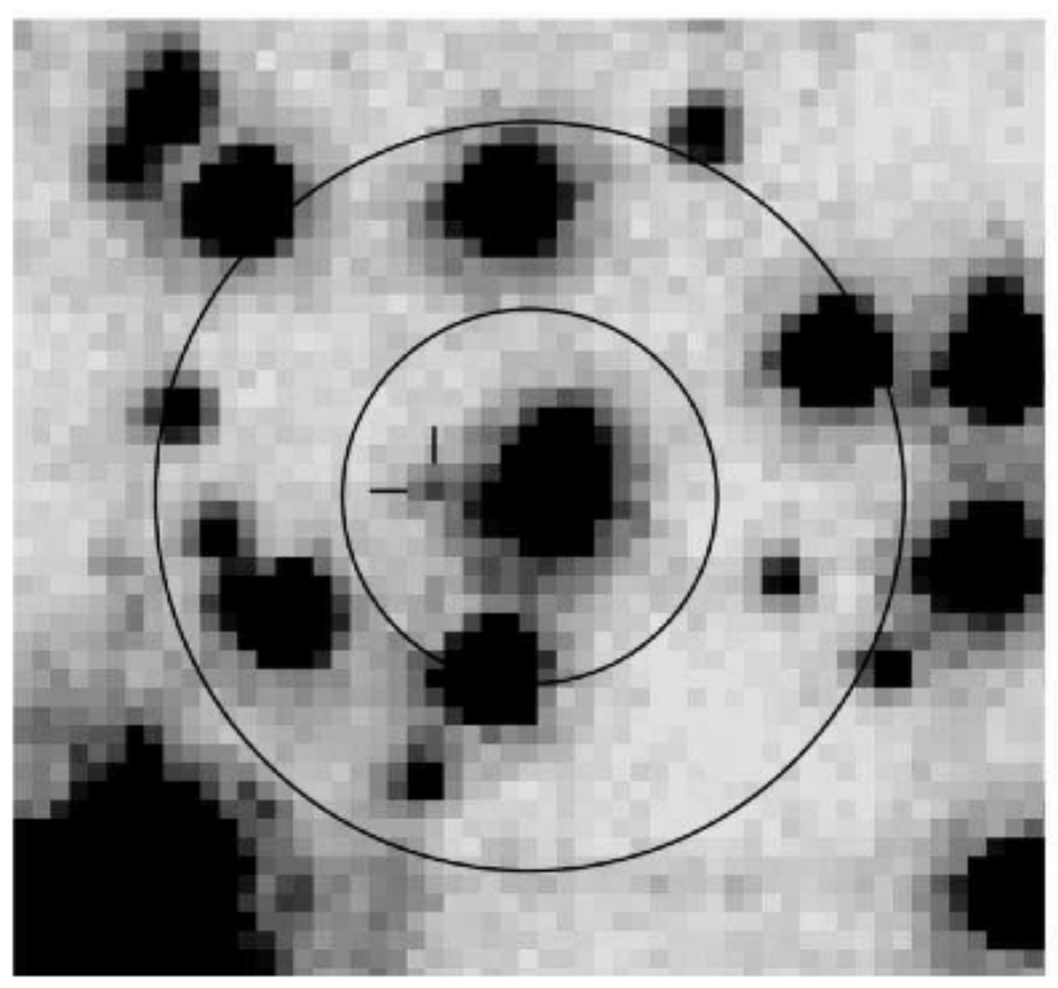
Composition



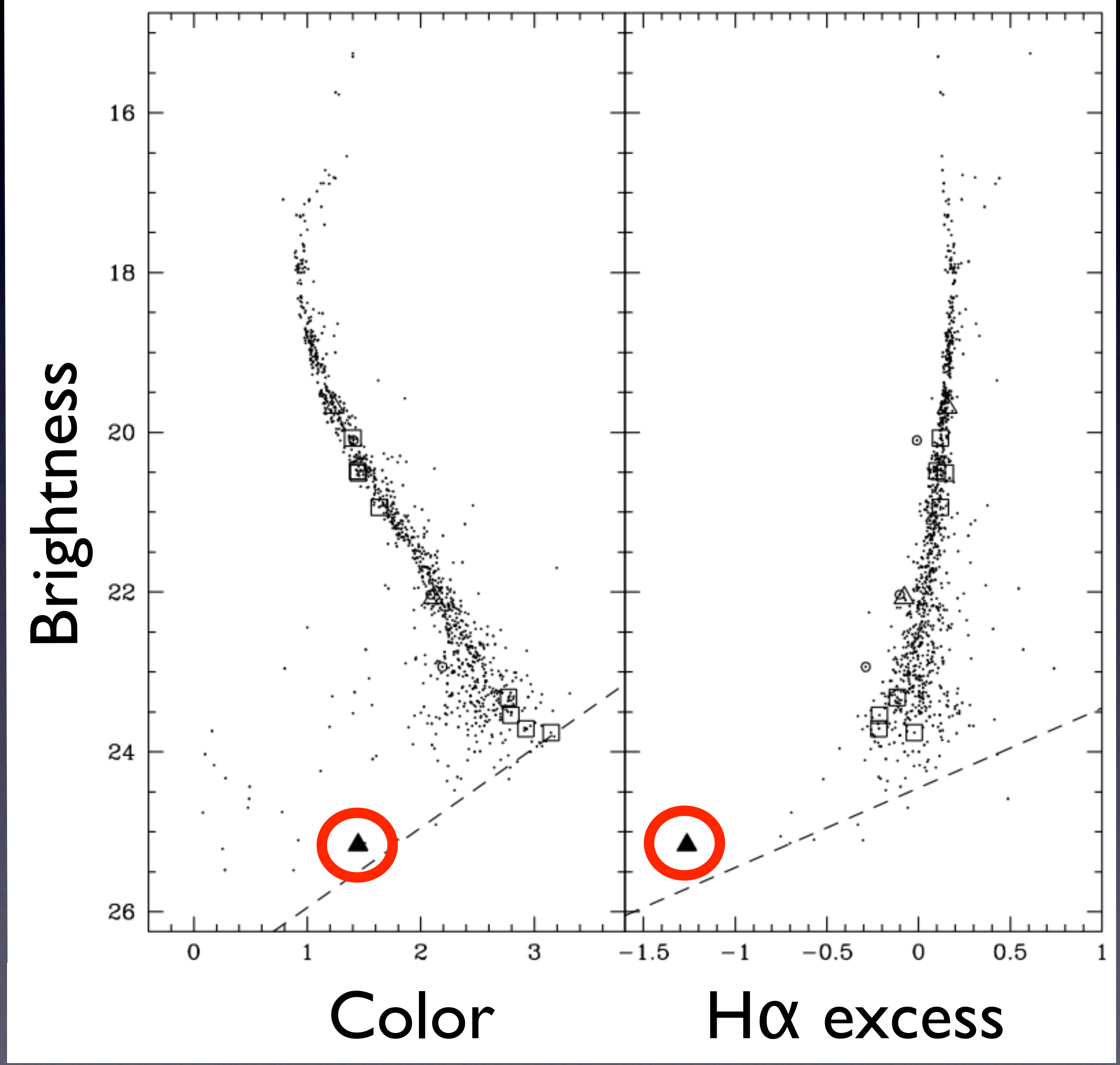
Servillat et al (2012)

Guillot et al. 2013

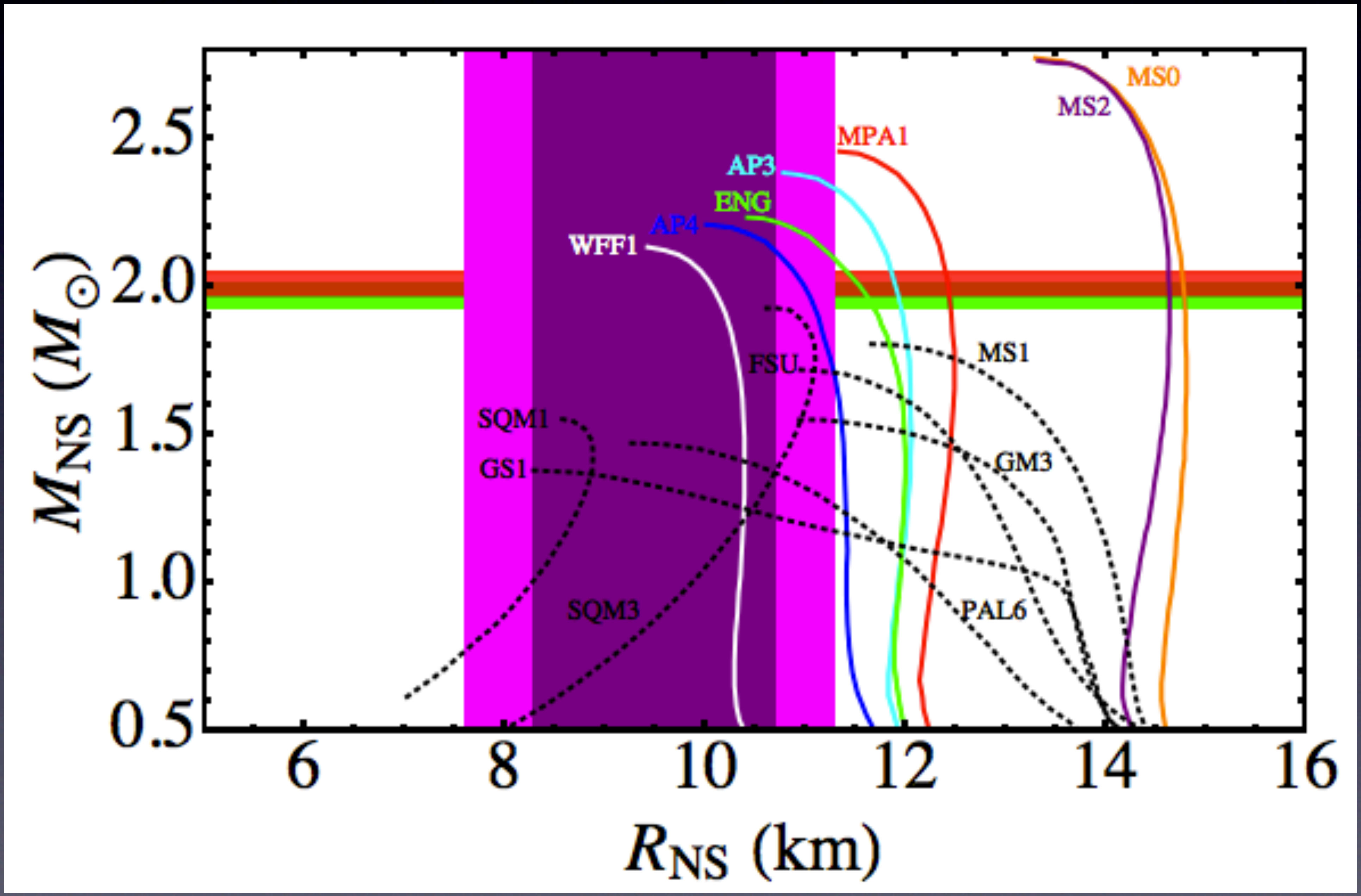
Detection of the optical counterpart can confirm the composition of the atmosphere



Detection of the counterpart to the qLMXB in the globular cluster ωCen (Haggard et al. 2004)

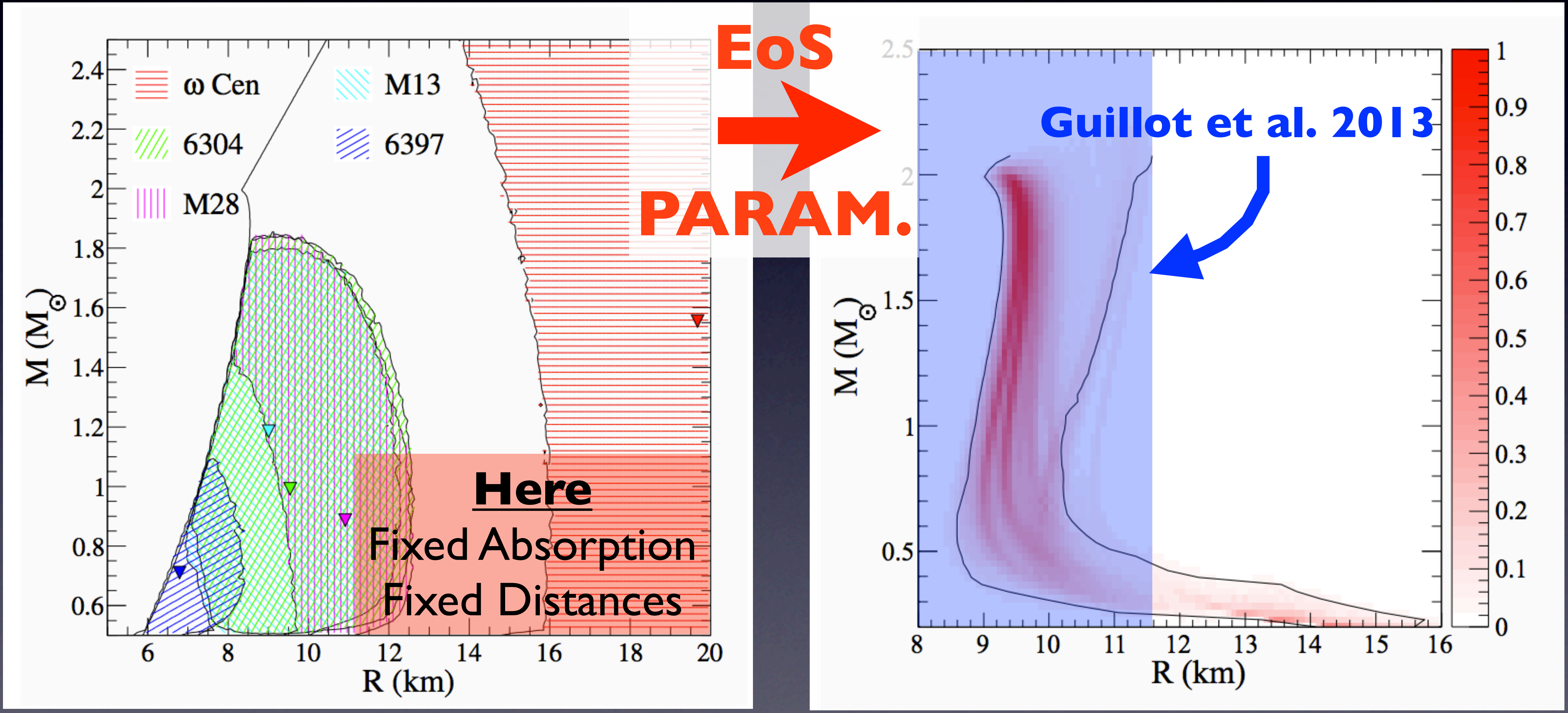


If the EoS is “quasi-vertical” in M-R space,our most conservative radius measurement provides important constraints



R_{NS} in the 7.5-11.3 km range at the 99%-confidence level

By using M_{NS}-R_{NS} contours from qLMXBs, Lattimer and Steiner (2014) obtained the most likely empirical equation of state.



Here

Fixed Absorption

Fixed Distances

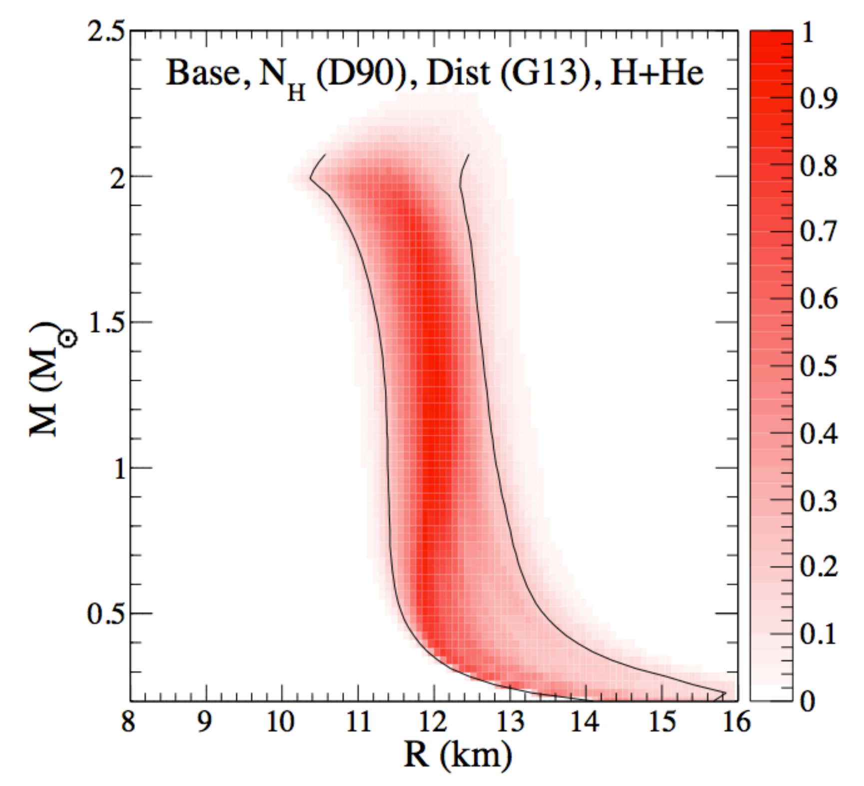
EoS

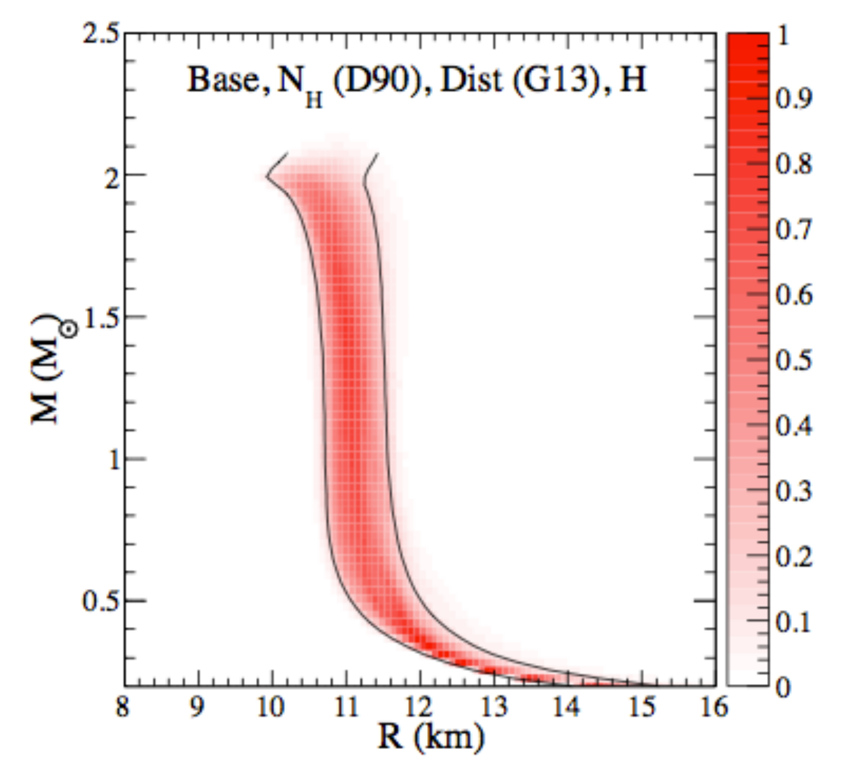
PARAM.

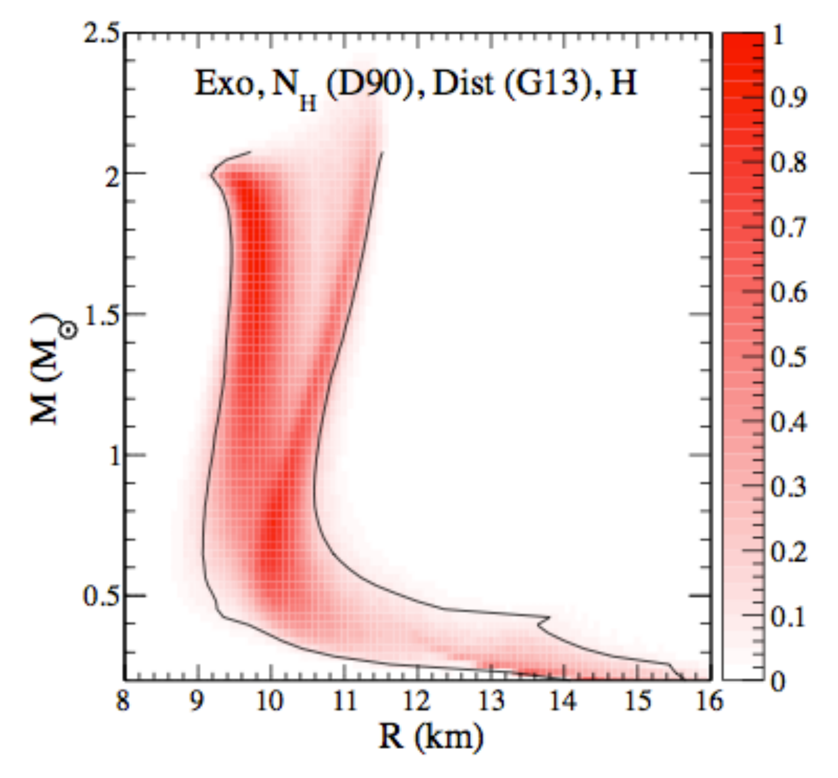
Guillot et al. 2013

Lattimer and Steiner (2014)

The different models lead to different resulting empirical EoSs







But, these models are **not** compared to the X-ray data!

This **not** *X-ray spectral analysis*.

Conclusions

- Evidence that R_{NS} is constant for a wide range of masses
- Use the assumption that R_{NS} is constant for a wide range of NS masses, we measure R_{NS} from five quiescent low-mass X-ray binaries located inside globular clusters.
- **Spectral fit** with *neutron star H-atmosphere model* using an MCMC simulation
- Measurement of $R_{\rm NS} = 9.4^{+1.9}_{-1.8}\,{\rm km}$ (99% c.l.) with the least number of assumptions, and a particular effort to control systematic uncertainties.
- Only "quasi-vertical" EoSs are tested with our assumptions!!!