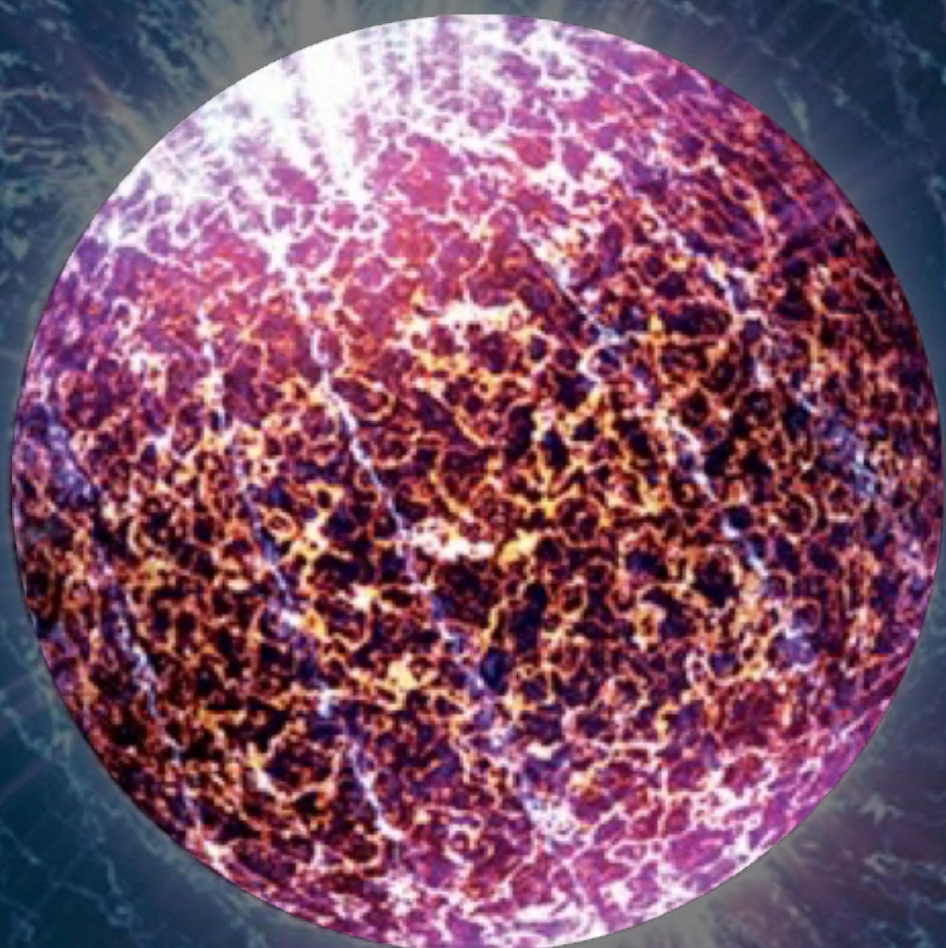
Neutron stars radius measurements: New results and future prospects,

but I'll talk about masses too…



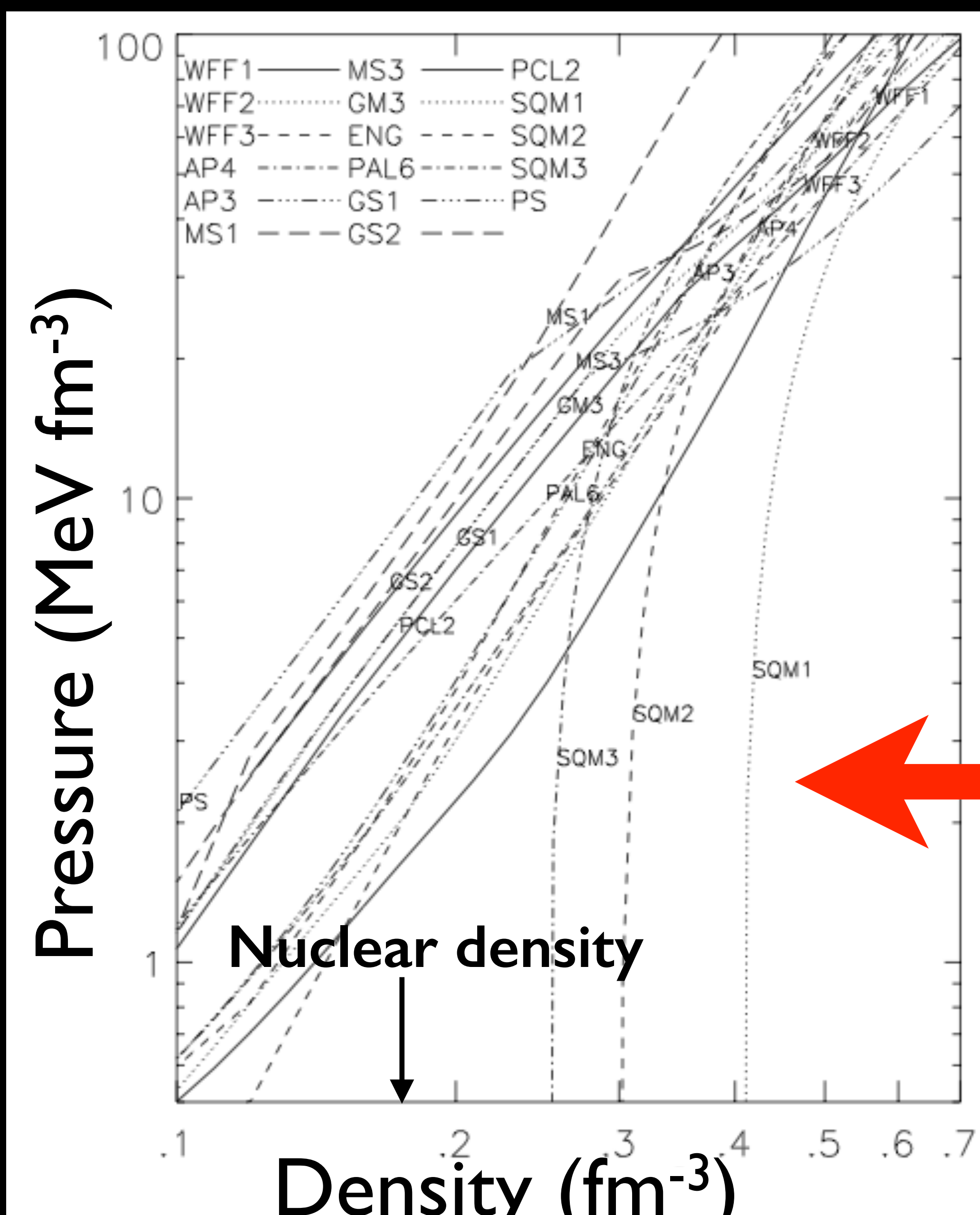
Sebastien Guillot

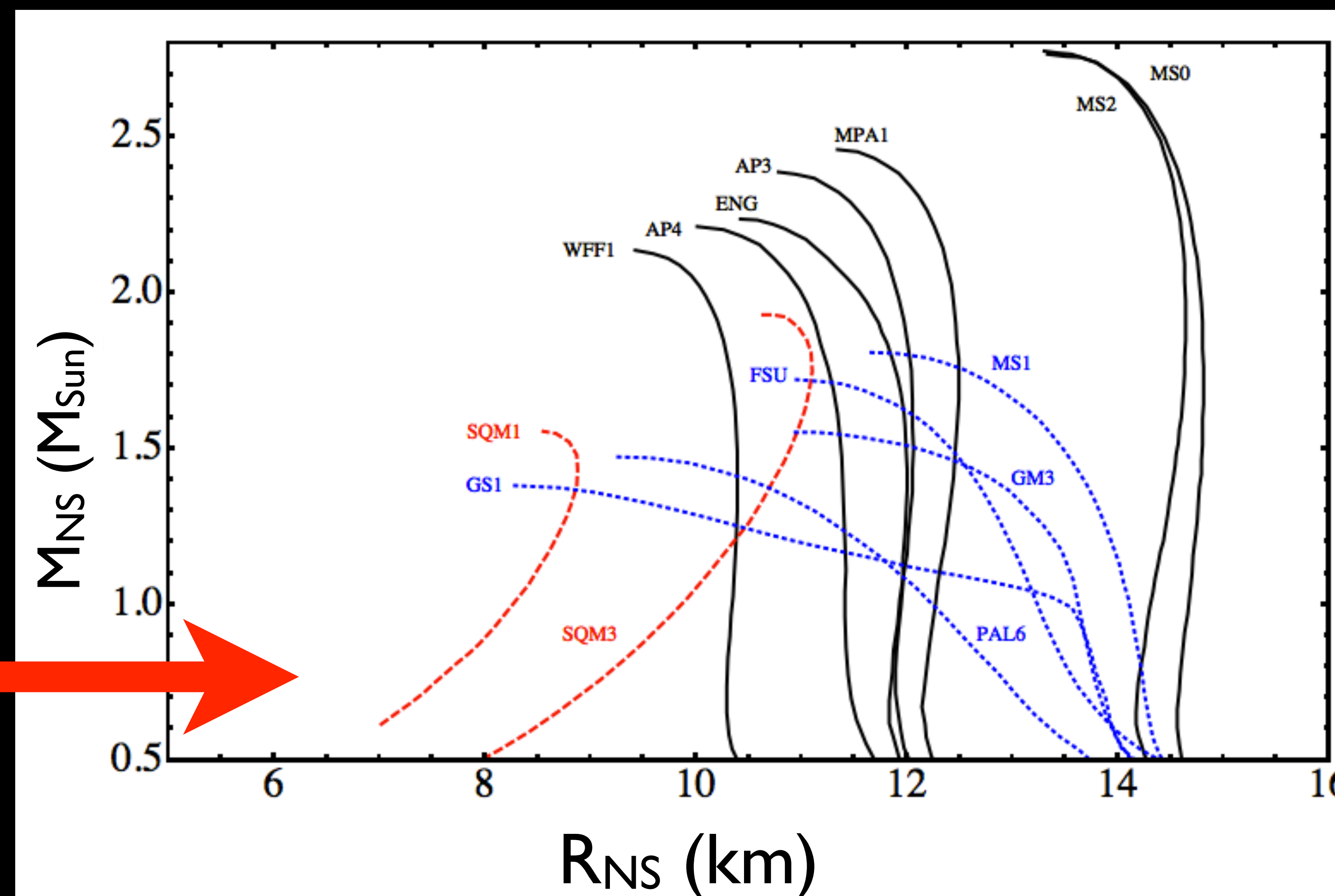
Pontificia Universidad Católica de Chile

Some collaborators

R. Rutledge, N. Webb, M. Servillat
F. Özel, C. Heinke, D. Psaltis, T. Güver
J. Margueron, N. Baillot-d'Étivaux

The nuclear matter equation of state is still unknown and many proposed theories exist.

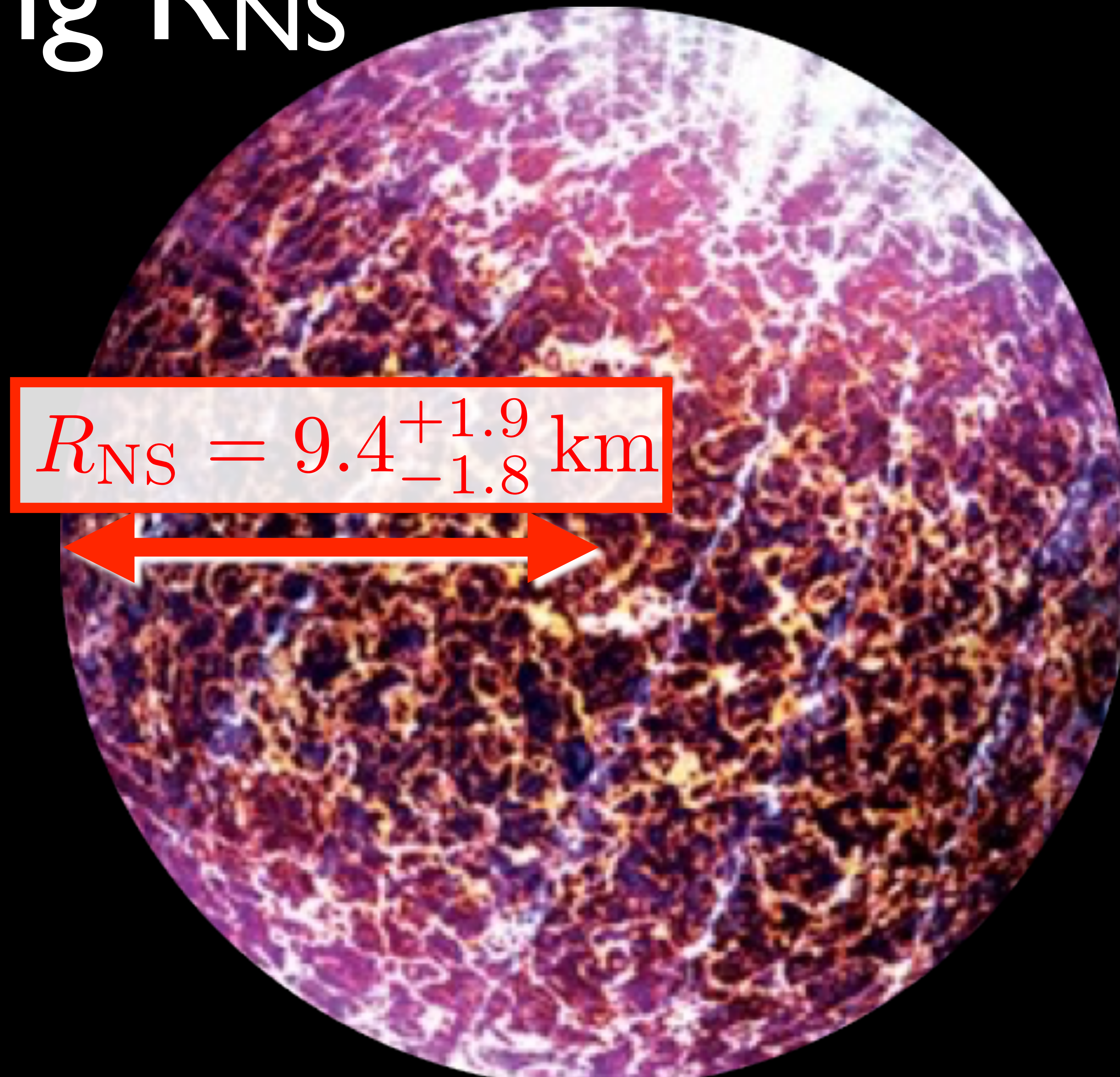




Lattimer and Prakash 2001

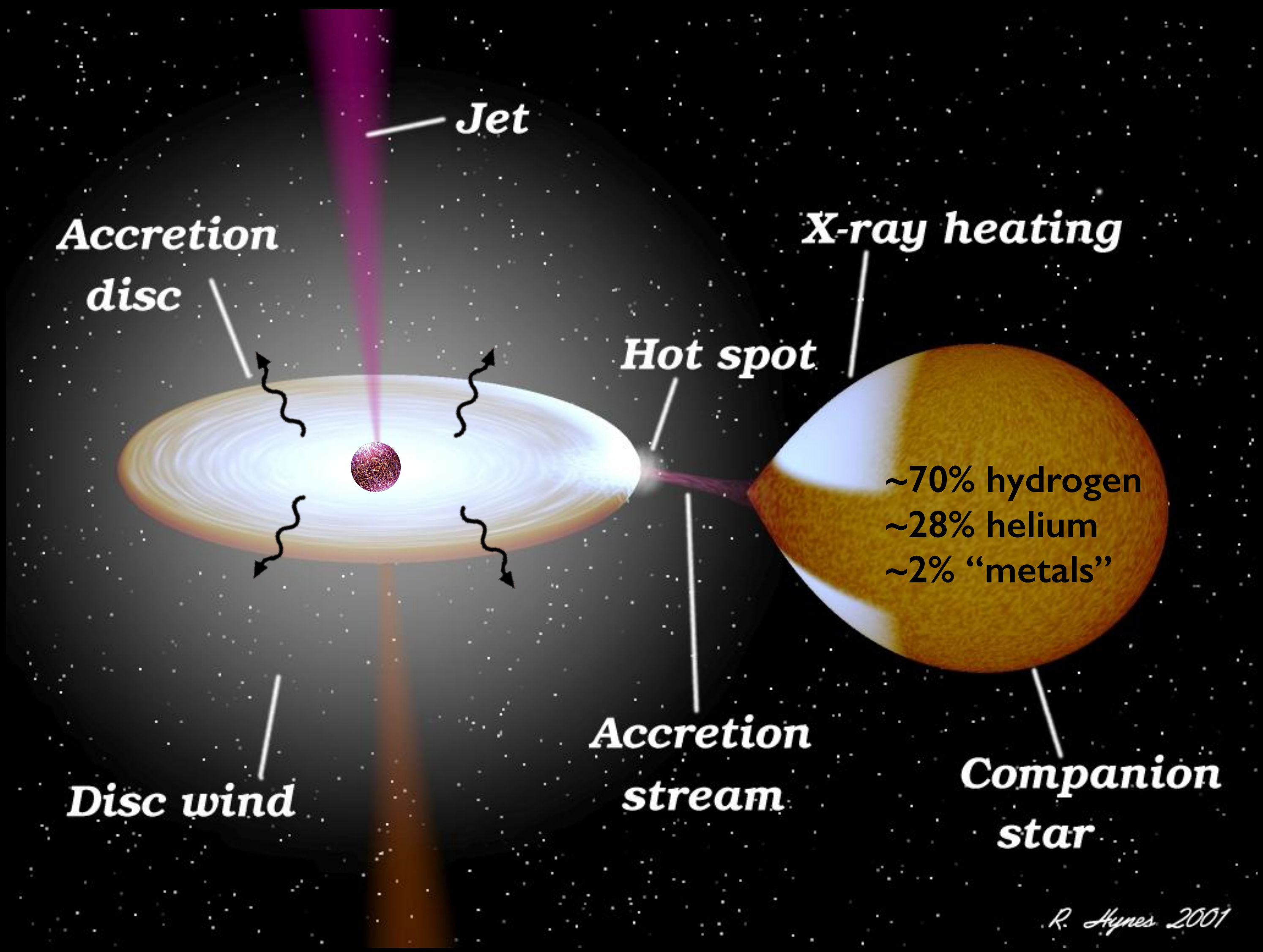
Measuring R_{NS}

Presented at NuSYM 2013



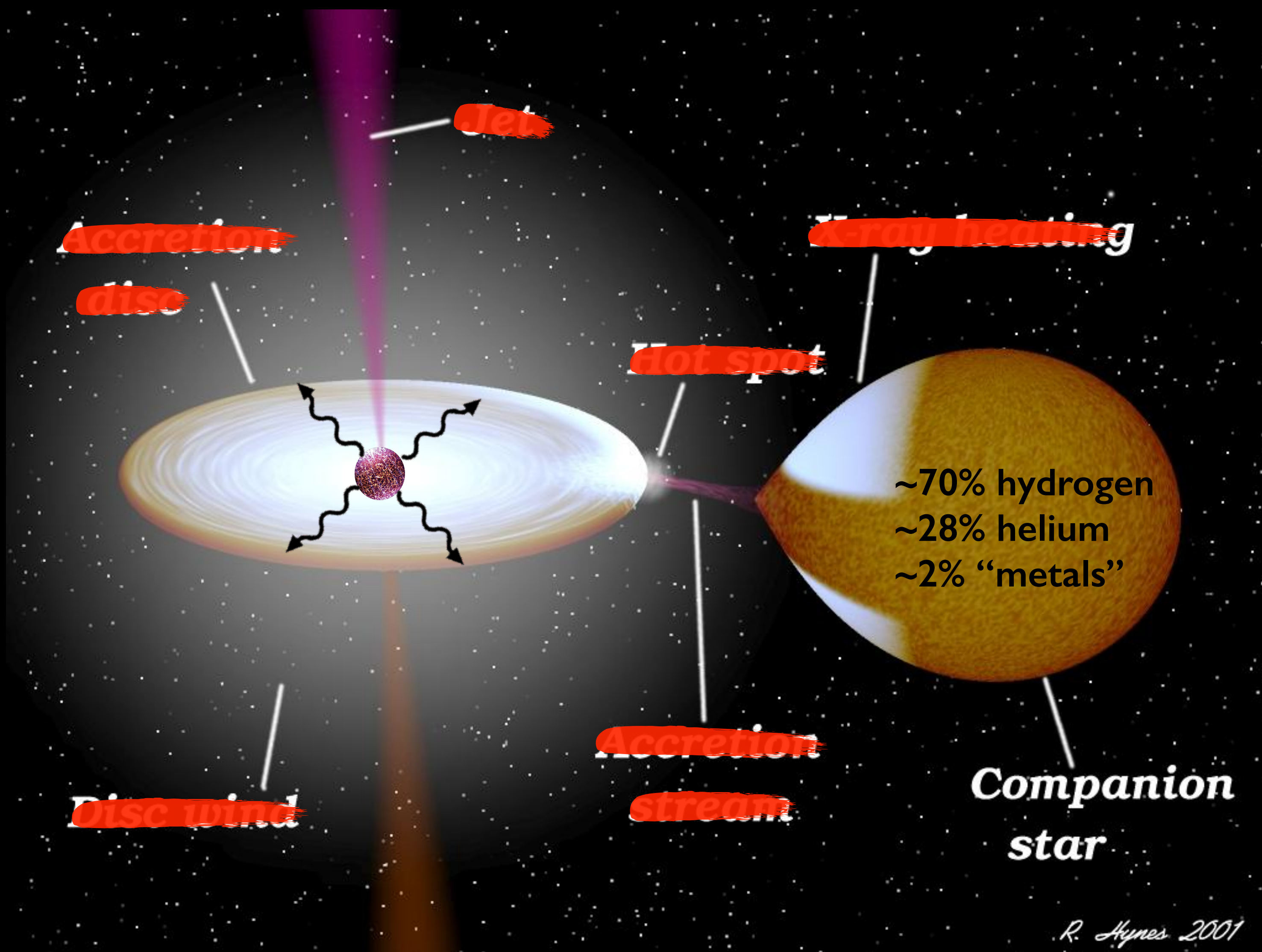
Guillot et al. 2013
Guillot & Rutledge 2014

Low-mass X-ray binaries experience high- and low-accretion states.



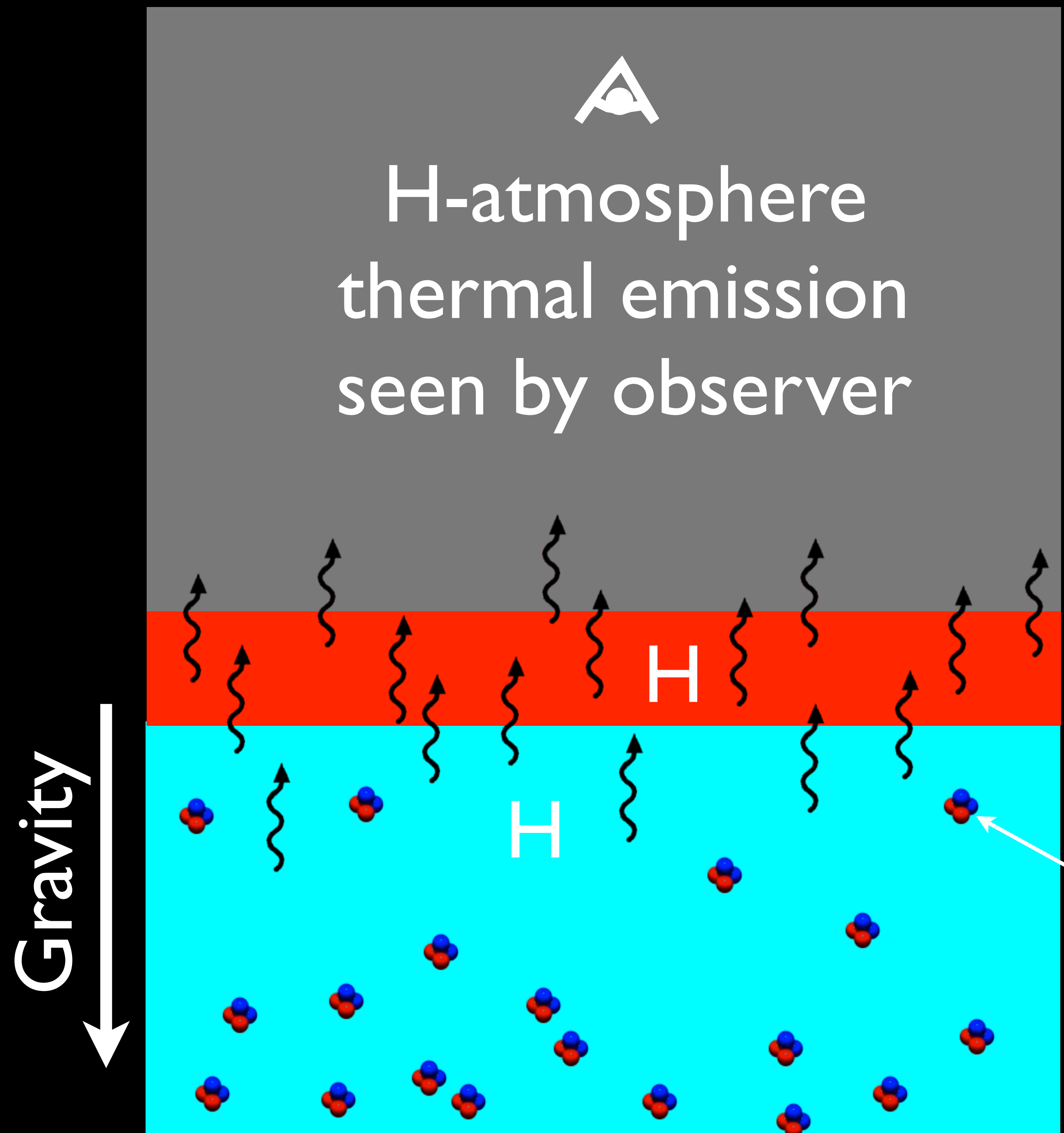
LMXB

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

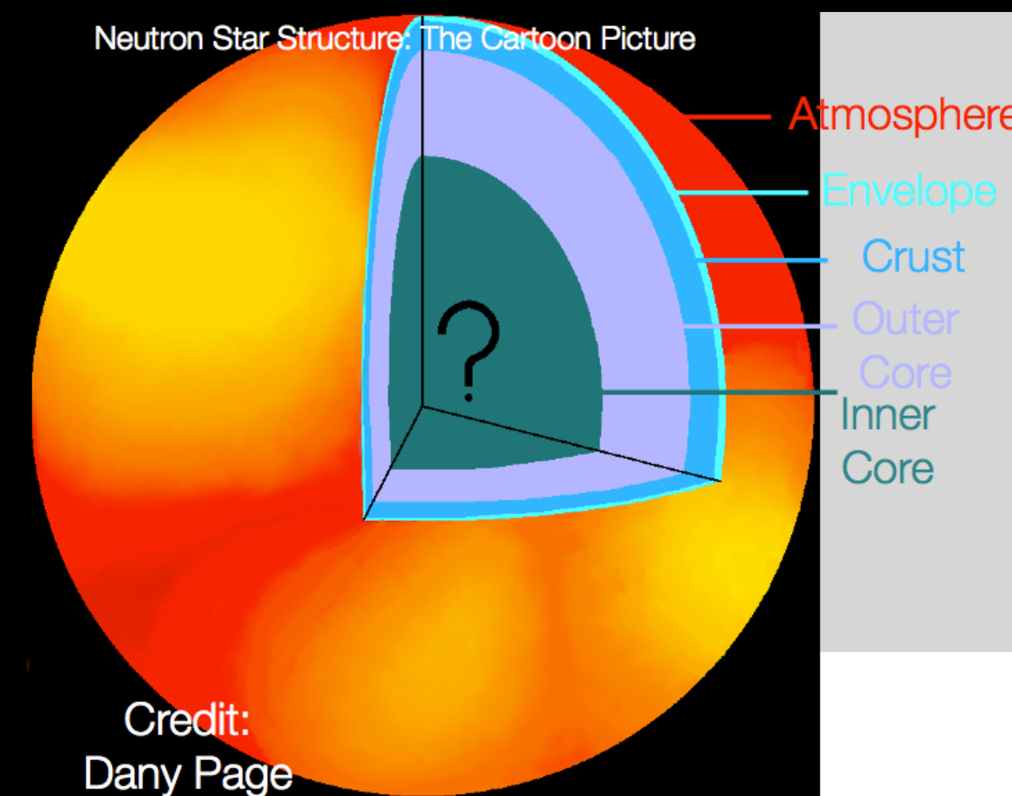


qLMXB

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



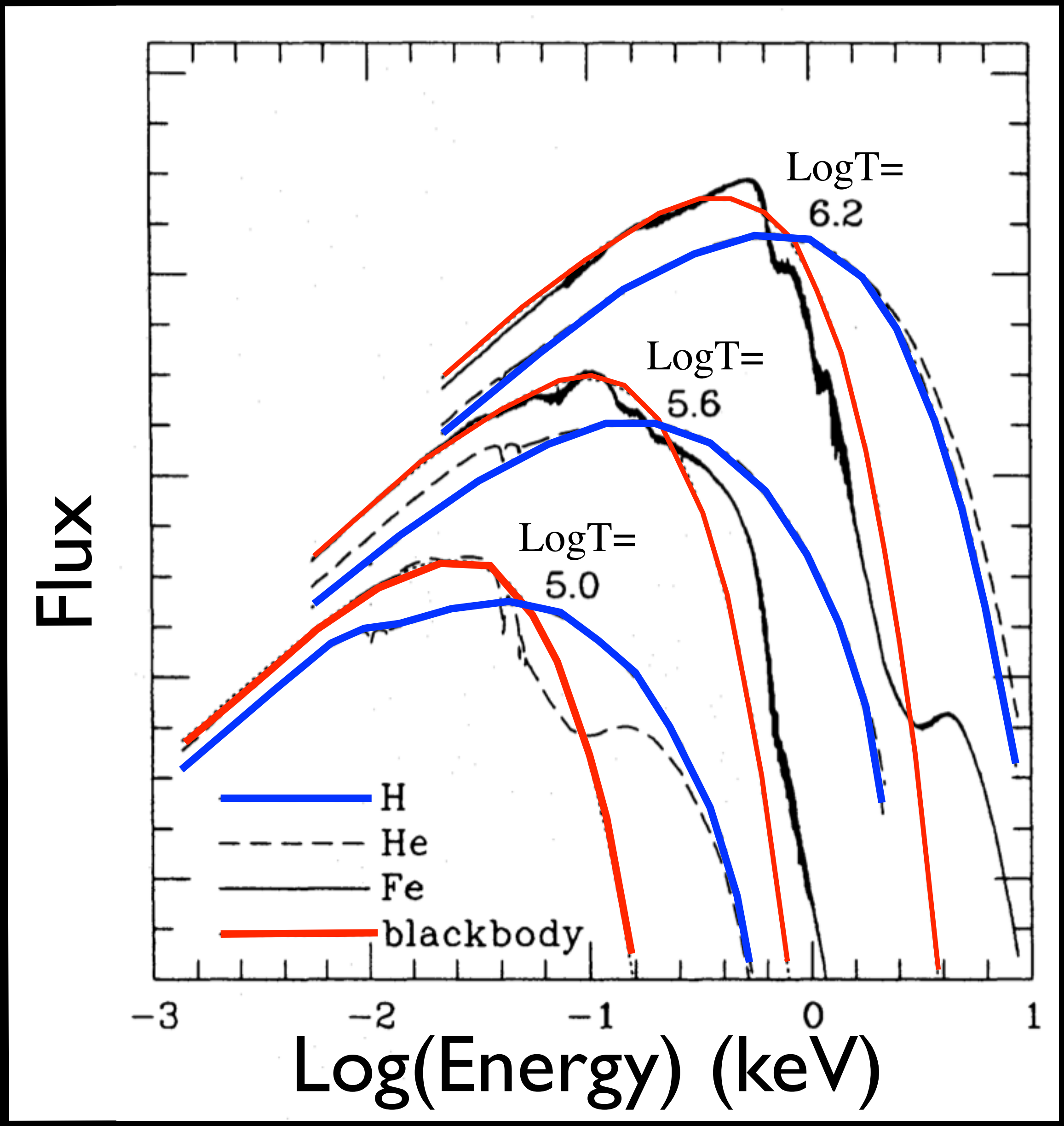
Helium



Photosphere $\lesssim 1$ cm

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

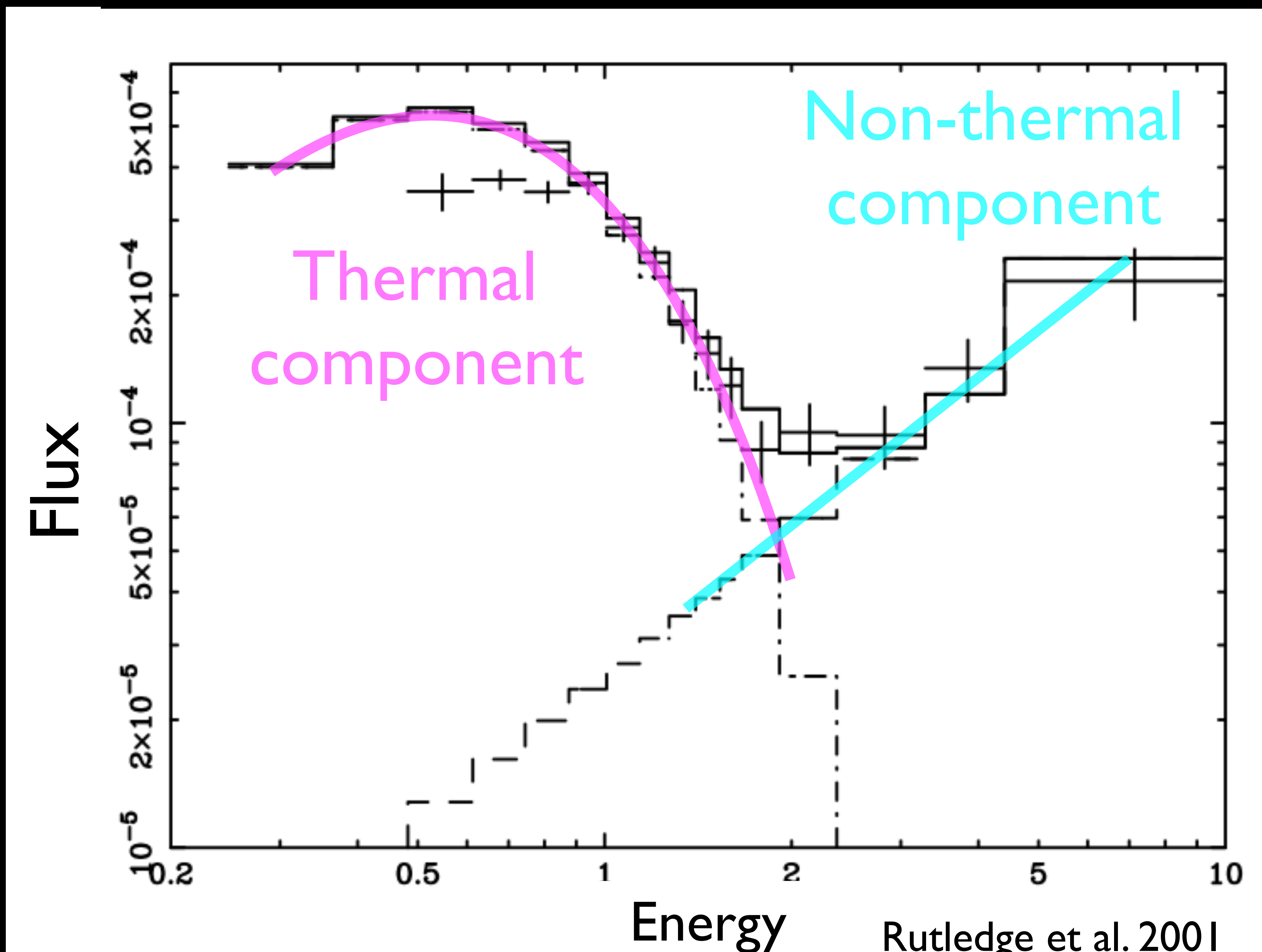
Models by Zavlin et al. (1996), Heinke et al. (2006), Haakonsen et al. (2012)



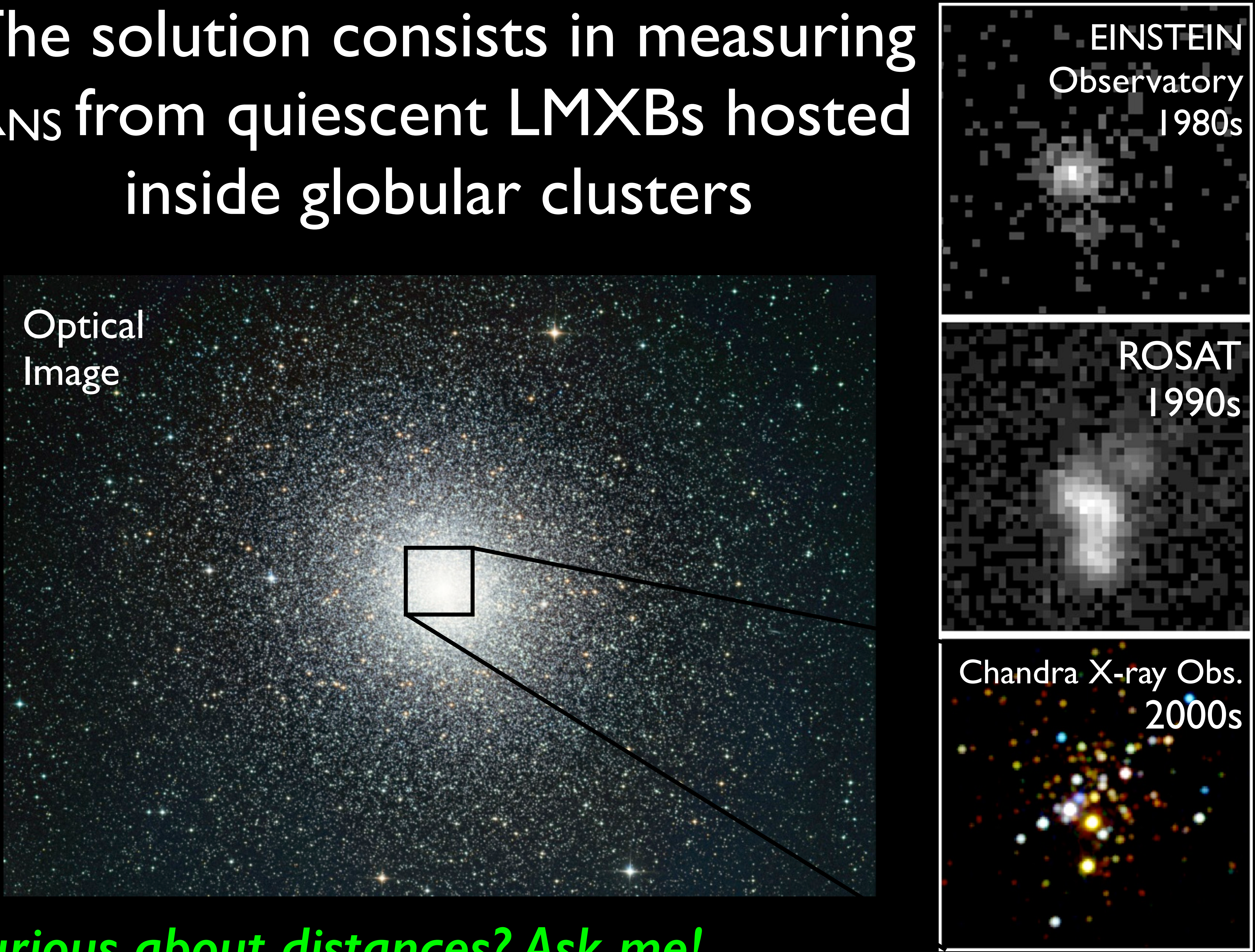
Spectral fitting of the thermal emission gives us T_{eff} and $F_X \propto (R_\infty/D)^2$

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

The first R_{NS} measurement was obtained from the known (bursting) field LMXB Cen X-4 observed during quiescence

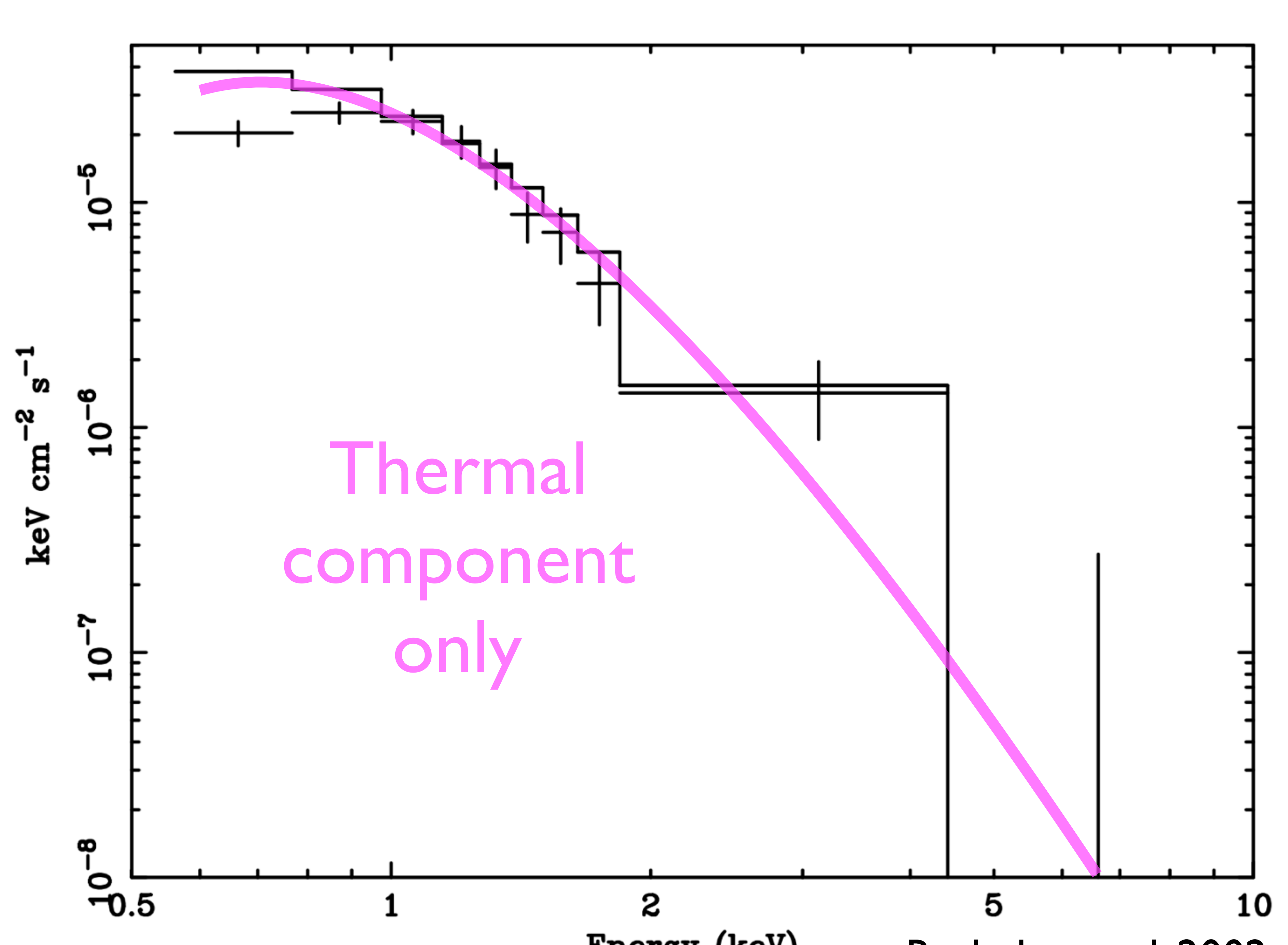


The solution consists in measuring R_{NS} from quiescent LMXBs hosted inside globular clusters



Curious about <u>distances</u>? Ask me!

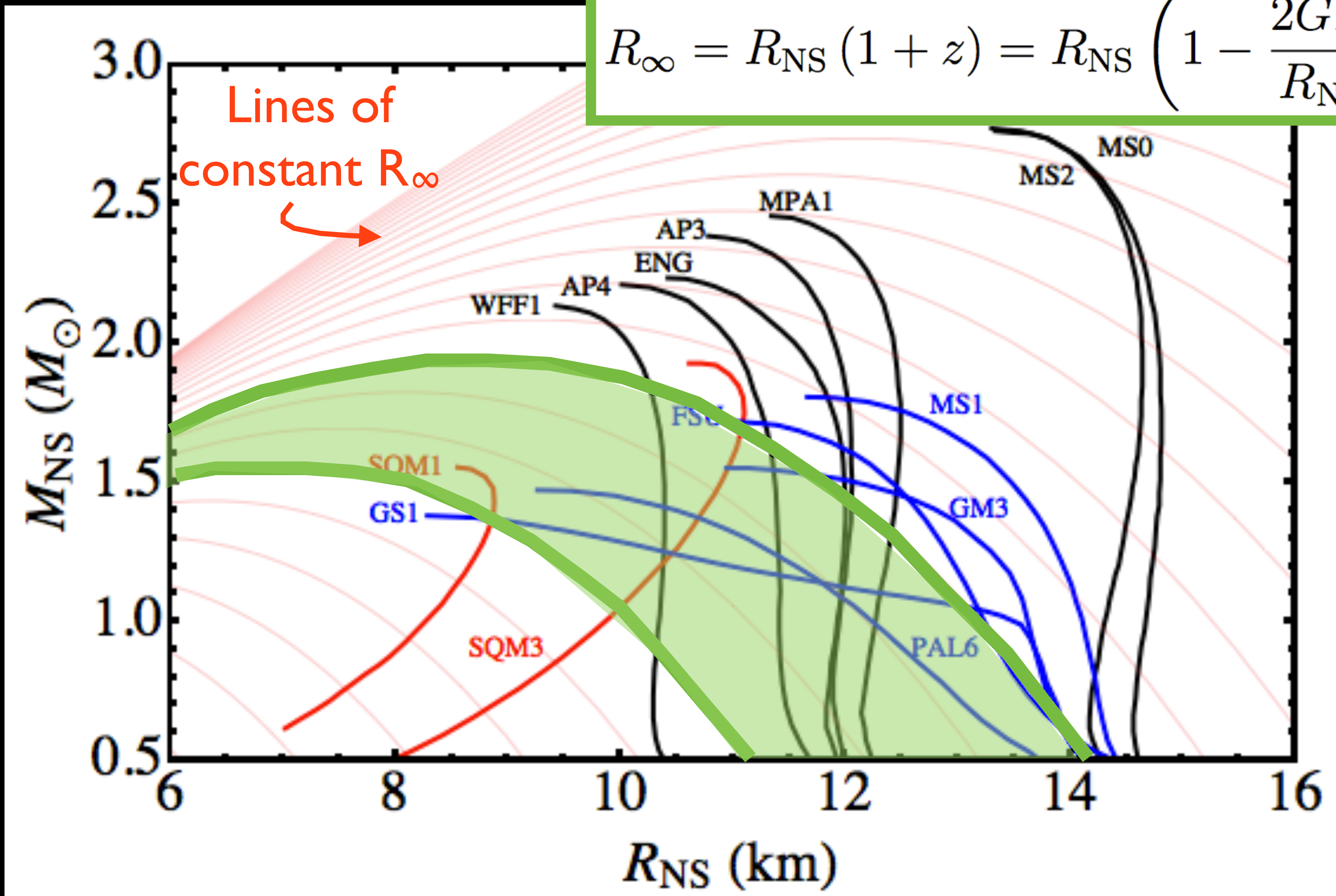
The first globular cluster qLMXB was discovered in Omega Centauri



Rutledge et al. 2002

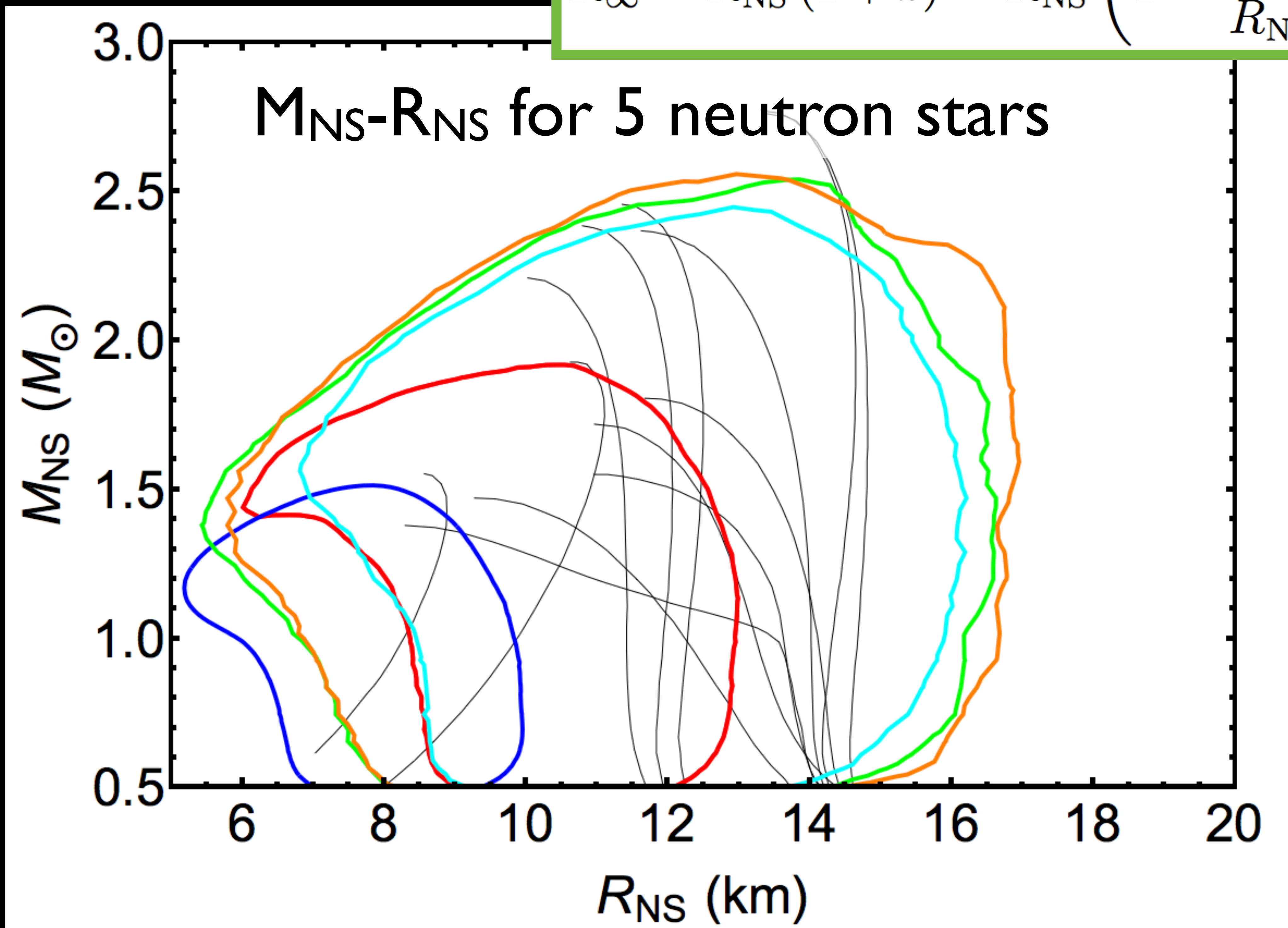
Quiescent LMXBs are routinely used for M_{NS}-R_{NS} measurements, but only place weak constraints on the dense matter EoS.

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

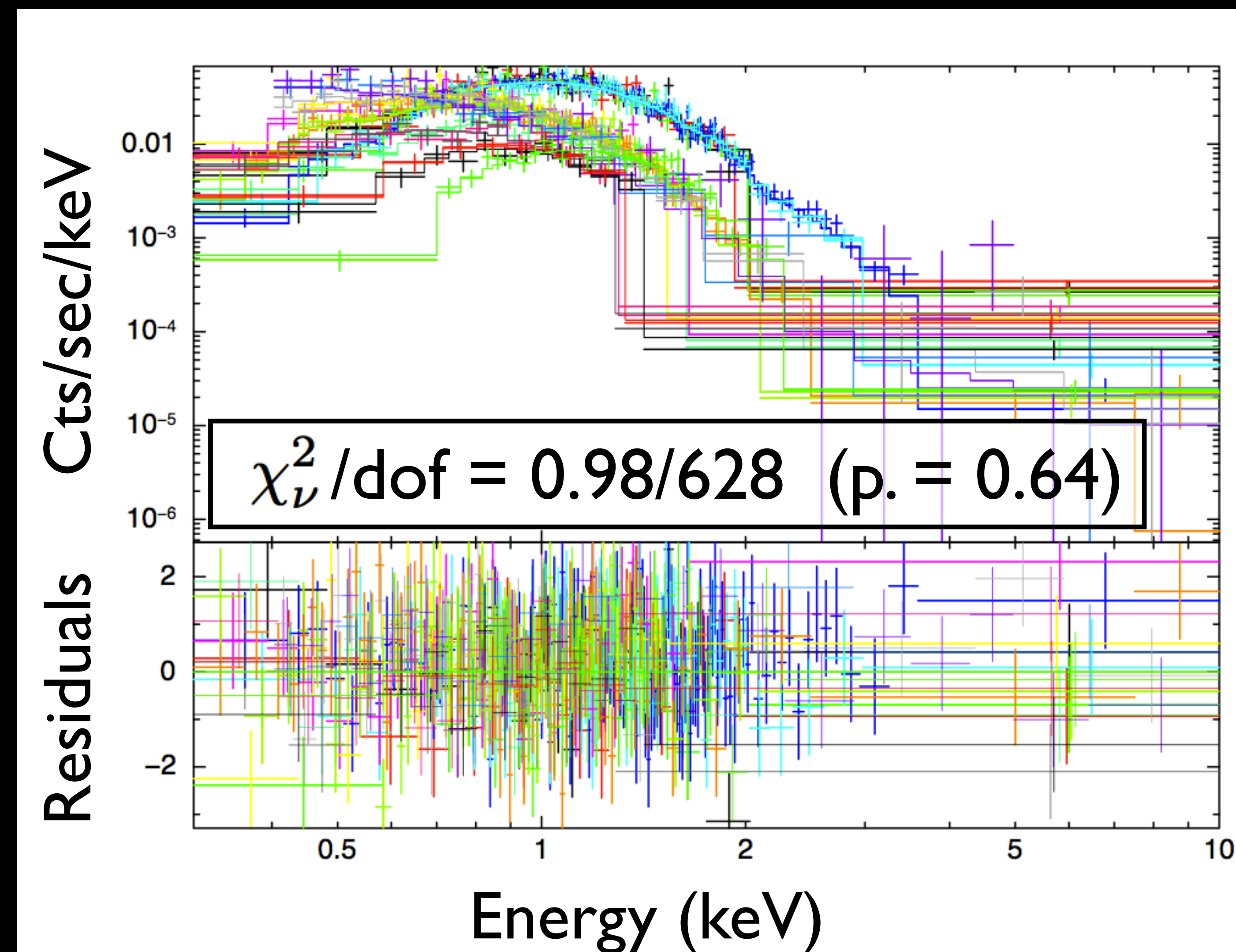


Quiescent LMXBs are routinely used for M_{NS}-R_{NS} measurements.

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



We simultaneously fitted the spectra of 6 qLMXBs with a H-atmosphere model.



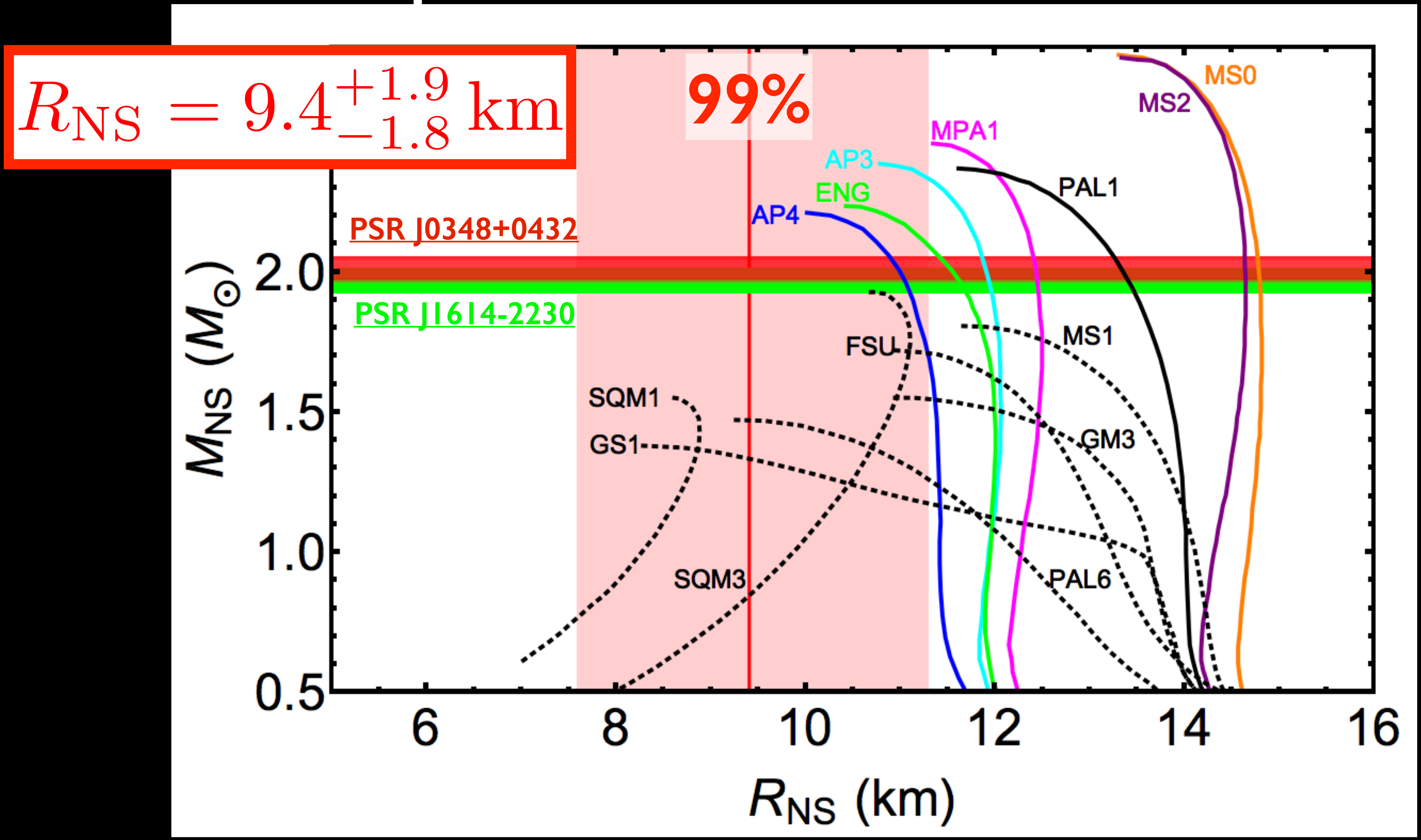
One radius to fit them all!

Five parameters per target:

Temperature T_{eff}
Mass M_{NS}
Galactic absorption
Distance of host GC
Power-law component

Spectral fitting with
Markov-Chain Monte-Carlo

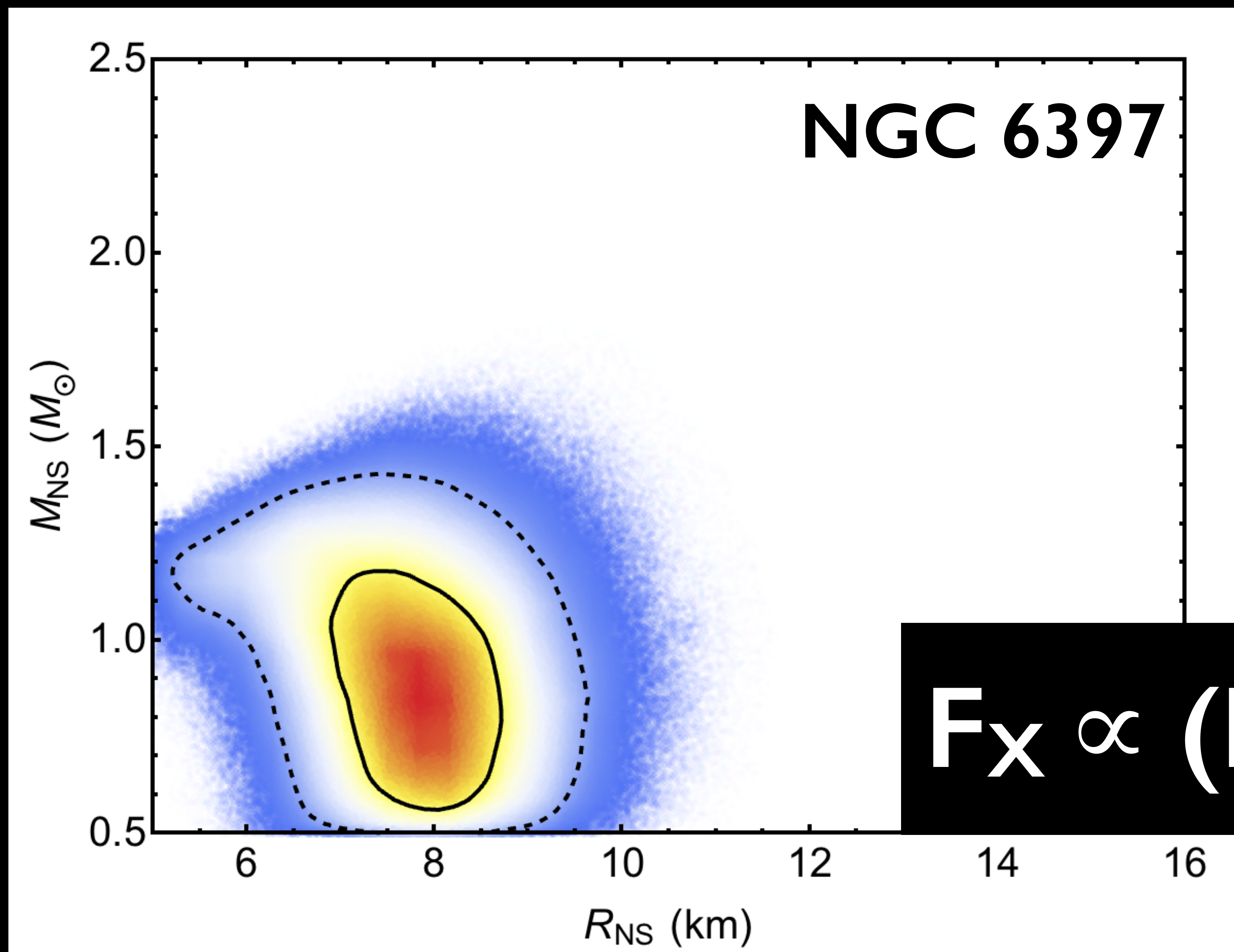
If the EoS is "quasi-vertical" in M_{NS}-R_{NS} space, our most conservative radius measurement provides constraints.



R_{NS} in the 7.6-11.3 km range at the 99%-confidence level

Guillot et al. 2013, Guillot & Rutledge 2014

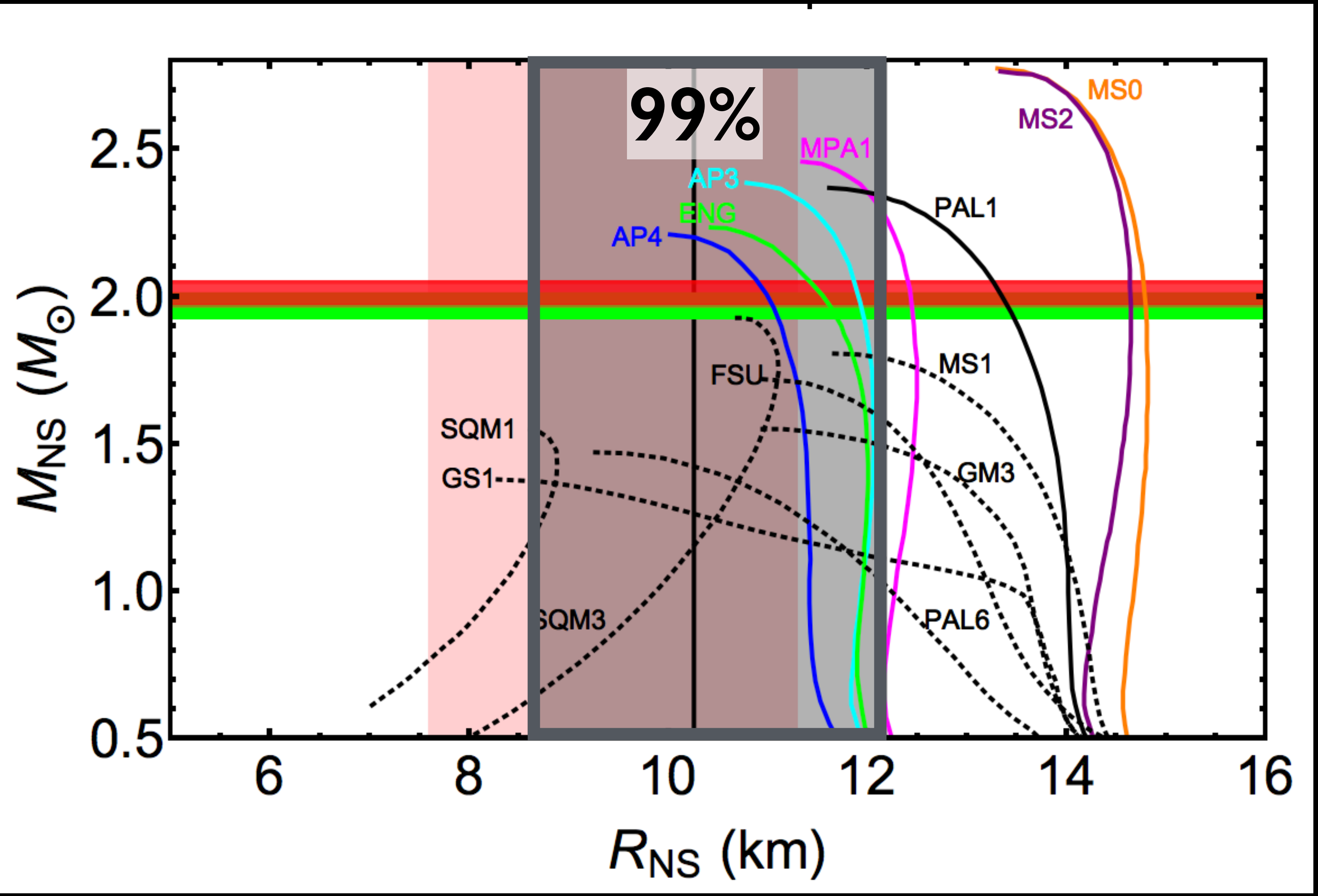
One of our 6 sources creates tension with the others.



$F_X \propto (R_\infty/D)^2$

Using recent distance measurements to the globular clusters, R_{NS} is increased by ~10%.

$$F_X \propto (R_\infty/D)^2$$



Guillot & Rutledge 2014

$$R_{\mathrm{NS}} = 9.4^{+1.9}_{-1.8}\,\mathrm{km}$$

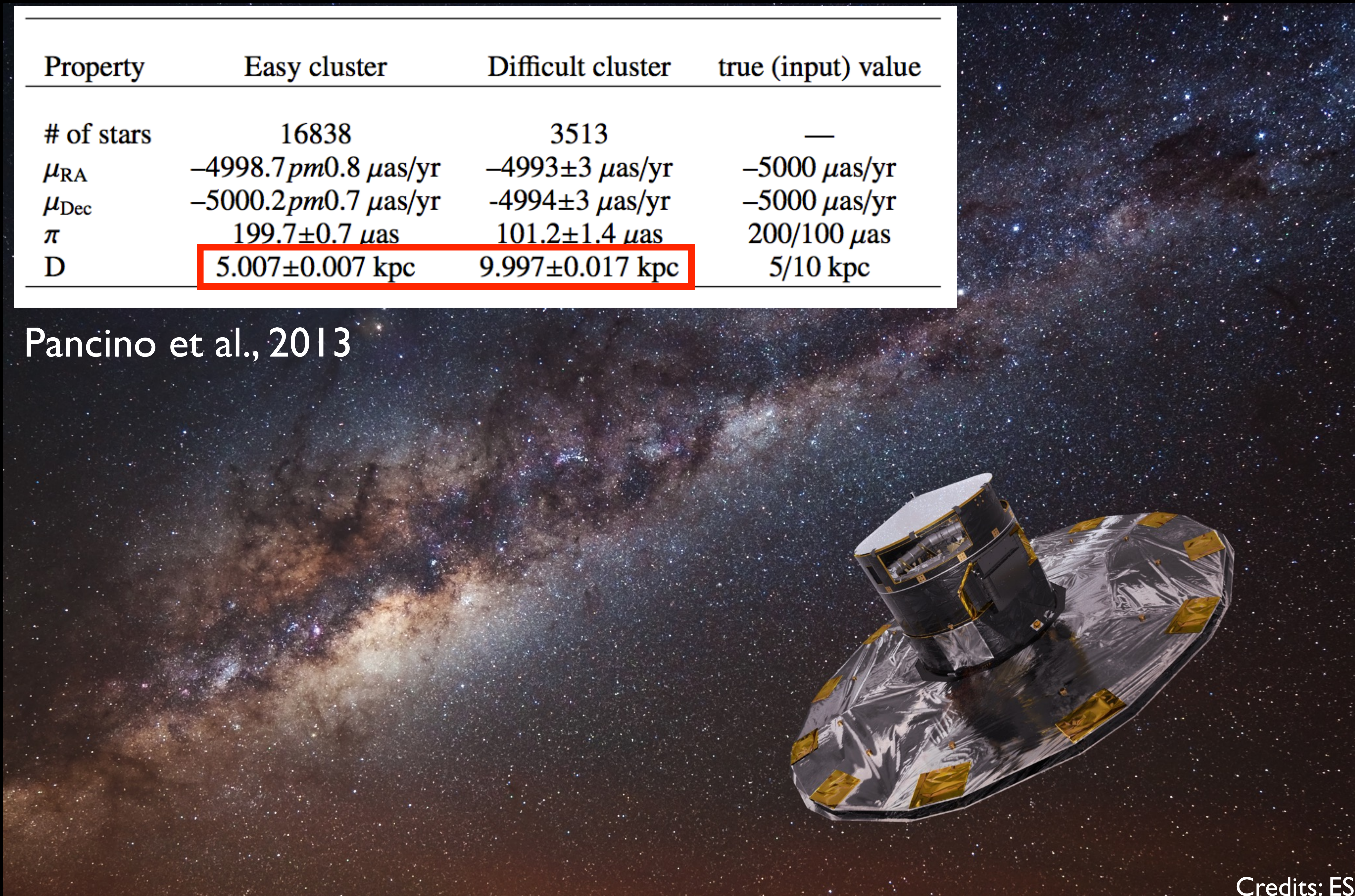
Same sources, updated distances for M13, NGC 6397 and ωCen:

$$R_{\mathrm{NS}} = 10.3^{+1.9}_{-1.7}\,\mathrm{km}$$

We are waiting for GAIA's data releases.

Property	Easy cluster	Difficult cluster	true (input) value
# of stars	16838	3513	—
μ_{RA}	–4998.7*pm*0.8 μas/yr	–4993±3 μas/yr	–5000 μas/yr
μ_{Dec}	–5000.2*pm*0.7 μas/yr	-4994±3 μas/yr	–5000 μas/yr
π	199.7±0.7 μas	101.2±1.4 μas	200/100 μas
D	5.007±0.007 kpc	9.997±0.017 kpc	5/10 kpc

Pancino et al., 2013

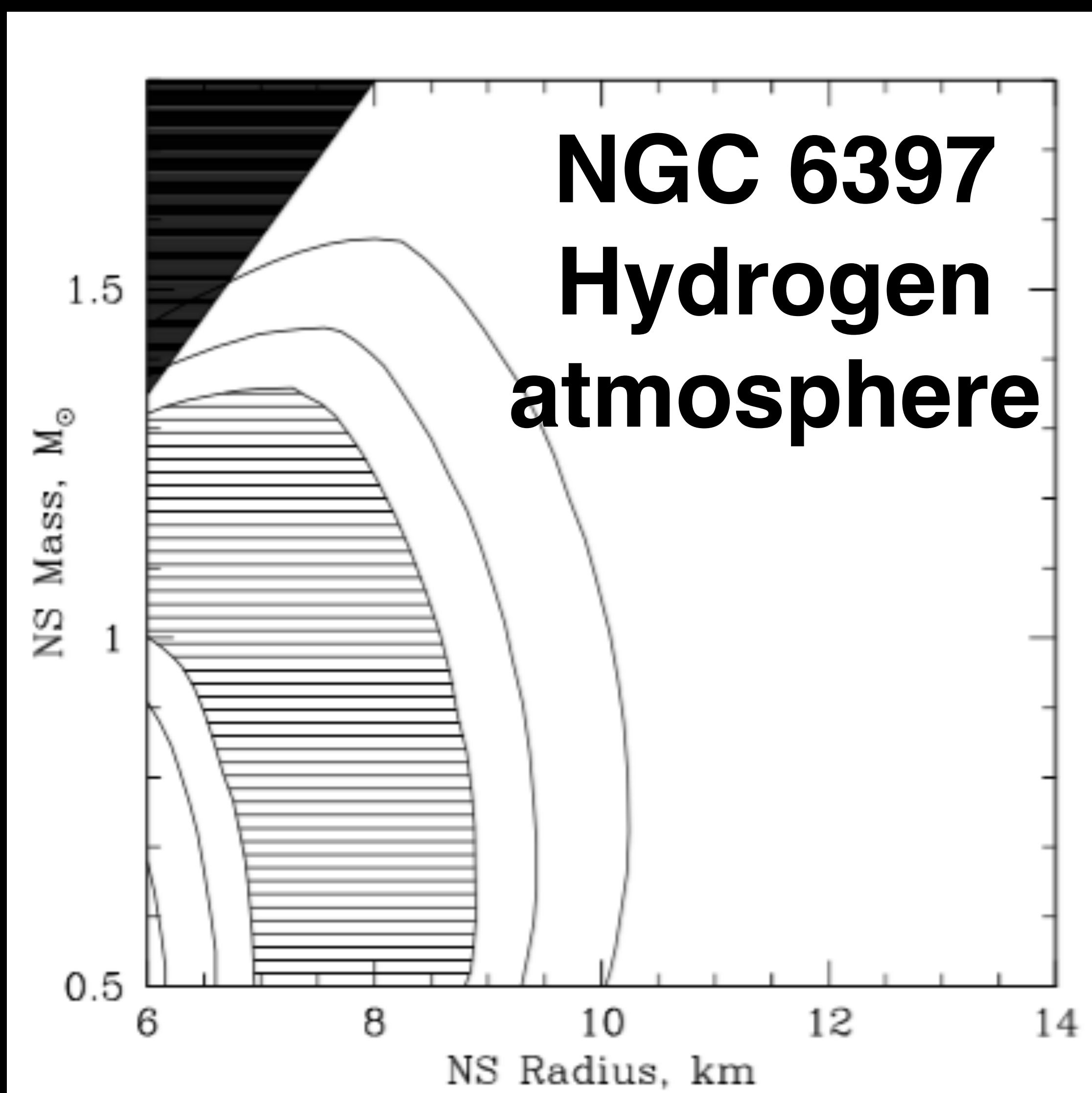


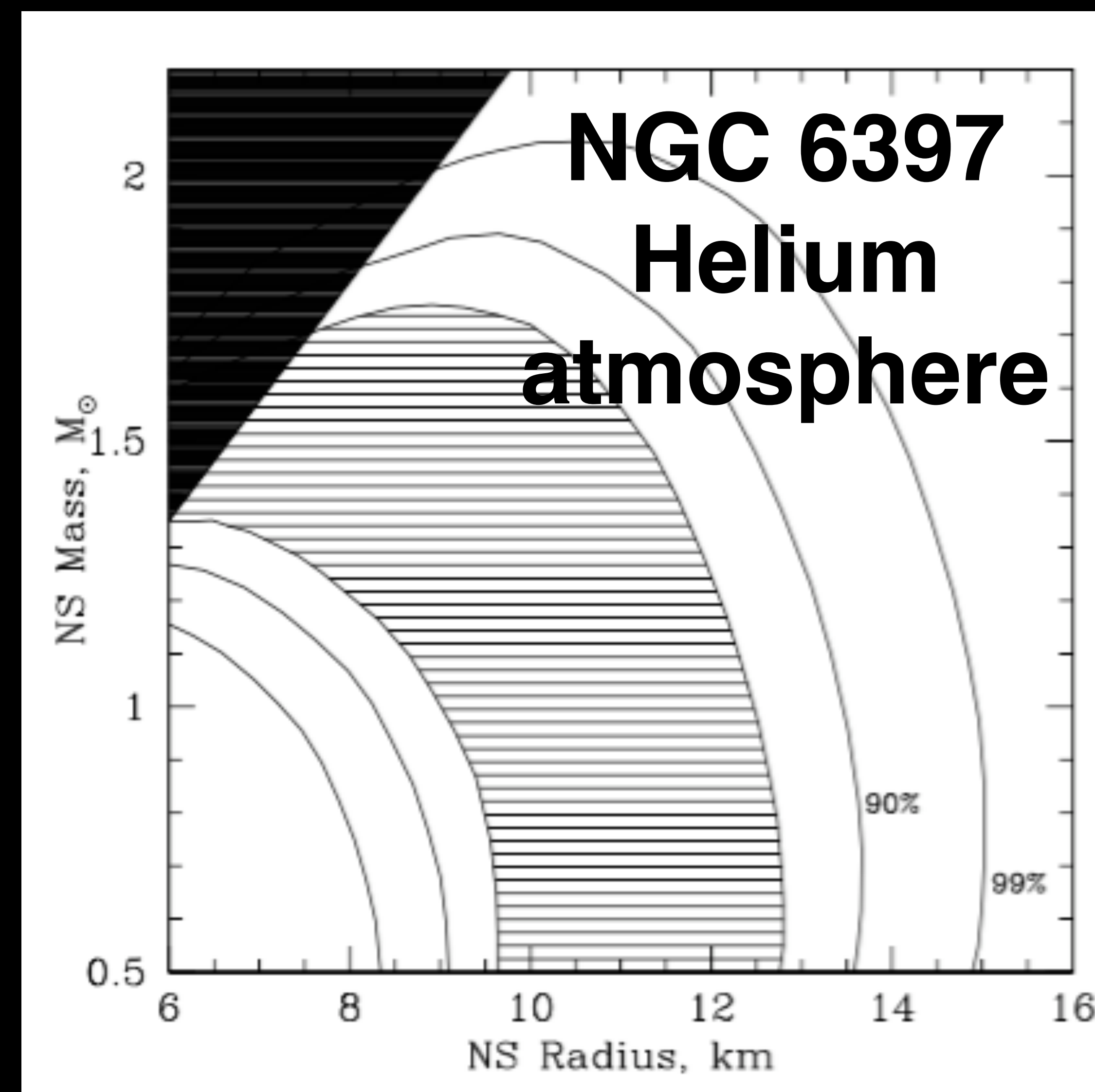
Credits: ESA

Other unknowns can bias the measurements of the neutron star radius, so we made some assumptions.

1. Negligible surface magnetic field
2. Calibration of the X-ray instruments
3. Isotropic neutron star surface emission
4. Slowly-rotating neutron stars
5. Composition of the neutron star atmosphere

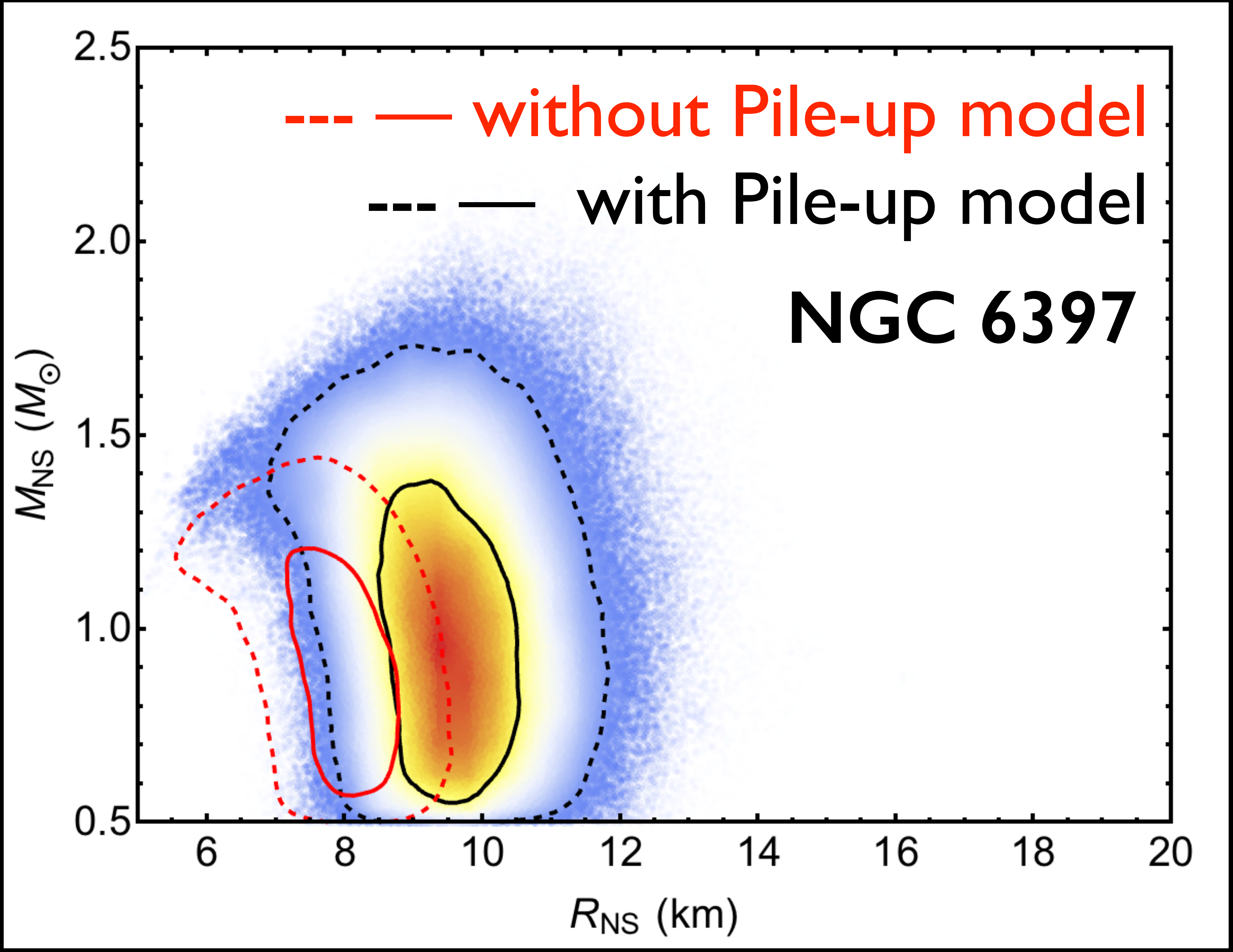
The choice of NS atmosphere composition significantly changes the measured R_∞, and therefore the M_{NS}-R_{NS} contours.





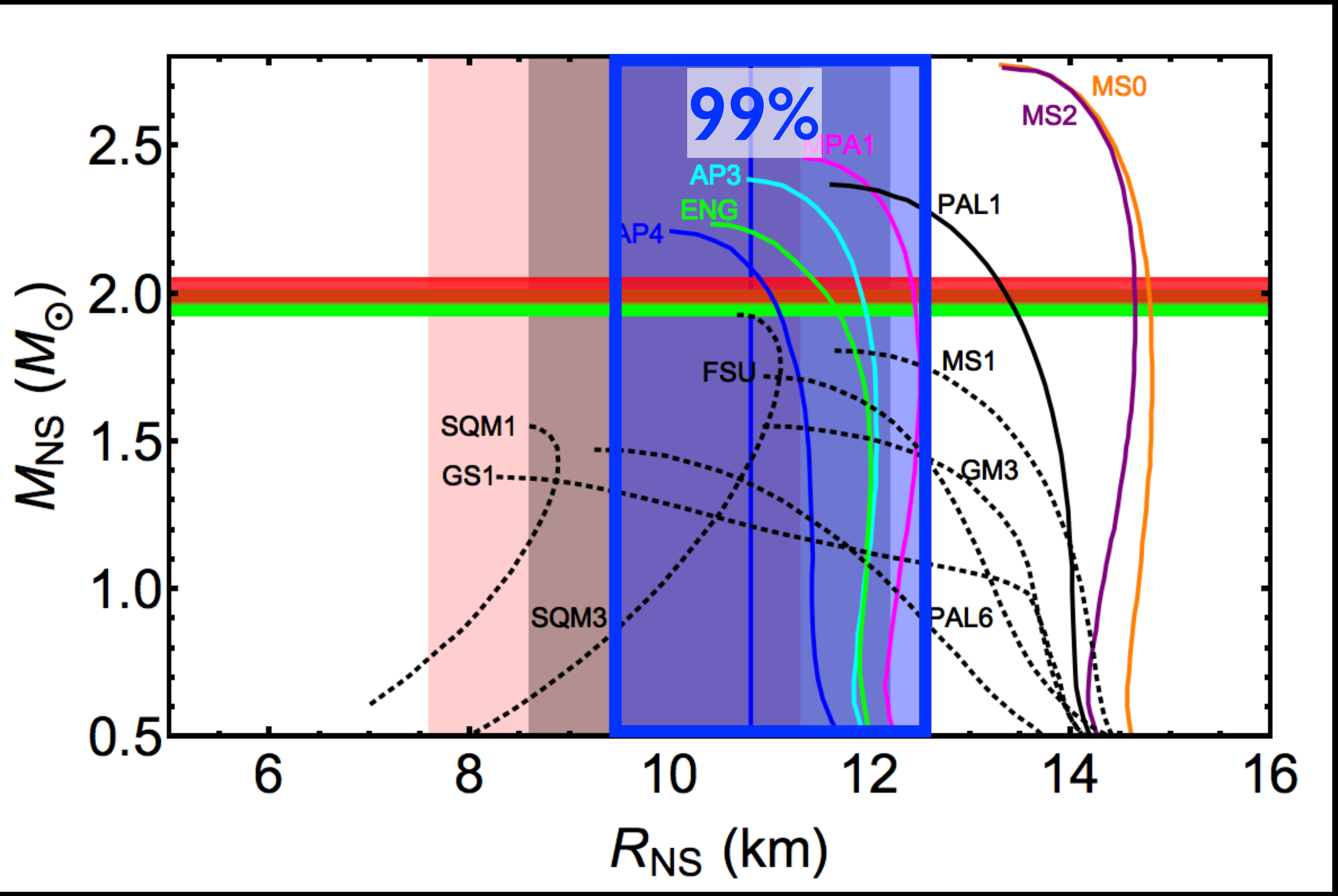
Heinke et al. 2014

An instrumental effects (pile-up) is affecting the observed spectra of NGC 6397.



Curious about pile-up? Ask me!

The constant R_{NS} solution moves up a bit more when pile-up modelling is included.



Guillot & Rutledge 2014

$$R_{NS} = 9.4^{+1.9}_{-1.8}\,\text{km}$$

Updated distances

$$R_{NS} = 10.3^{+1.9}_{-1.7}\,\text{km}$$

With Pile-up model

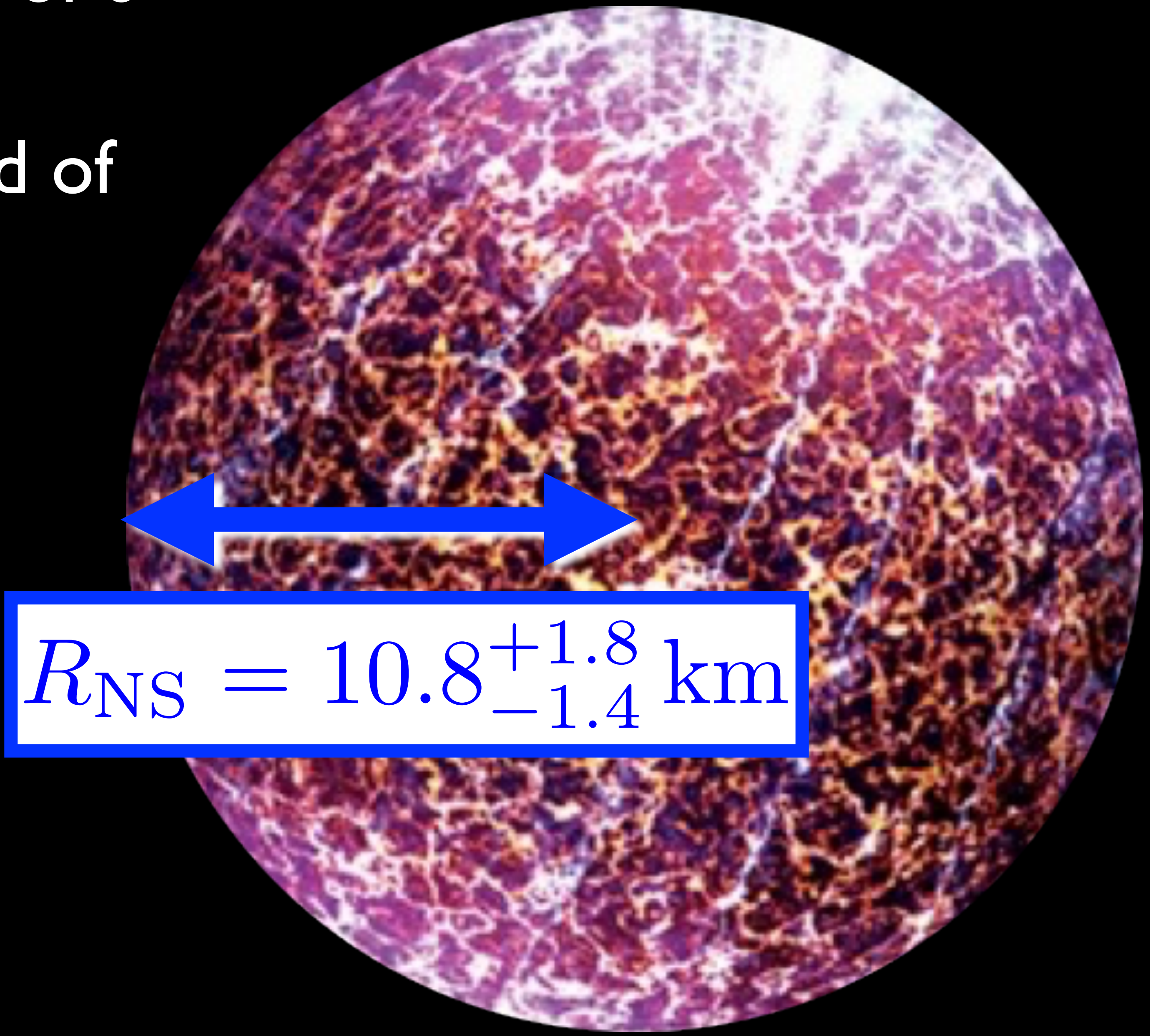
$$R_{NS} = 10.8^{+1.8}_{-1.4}\,\text{km}$$

Guillot et al., in prep.

Measuring R_{NS}

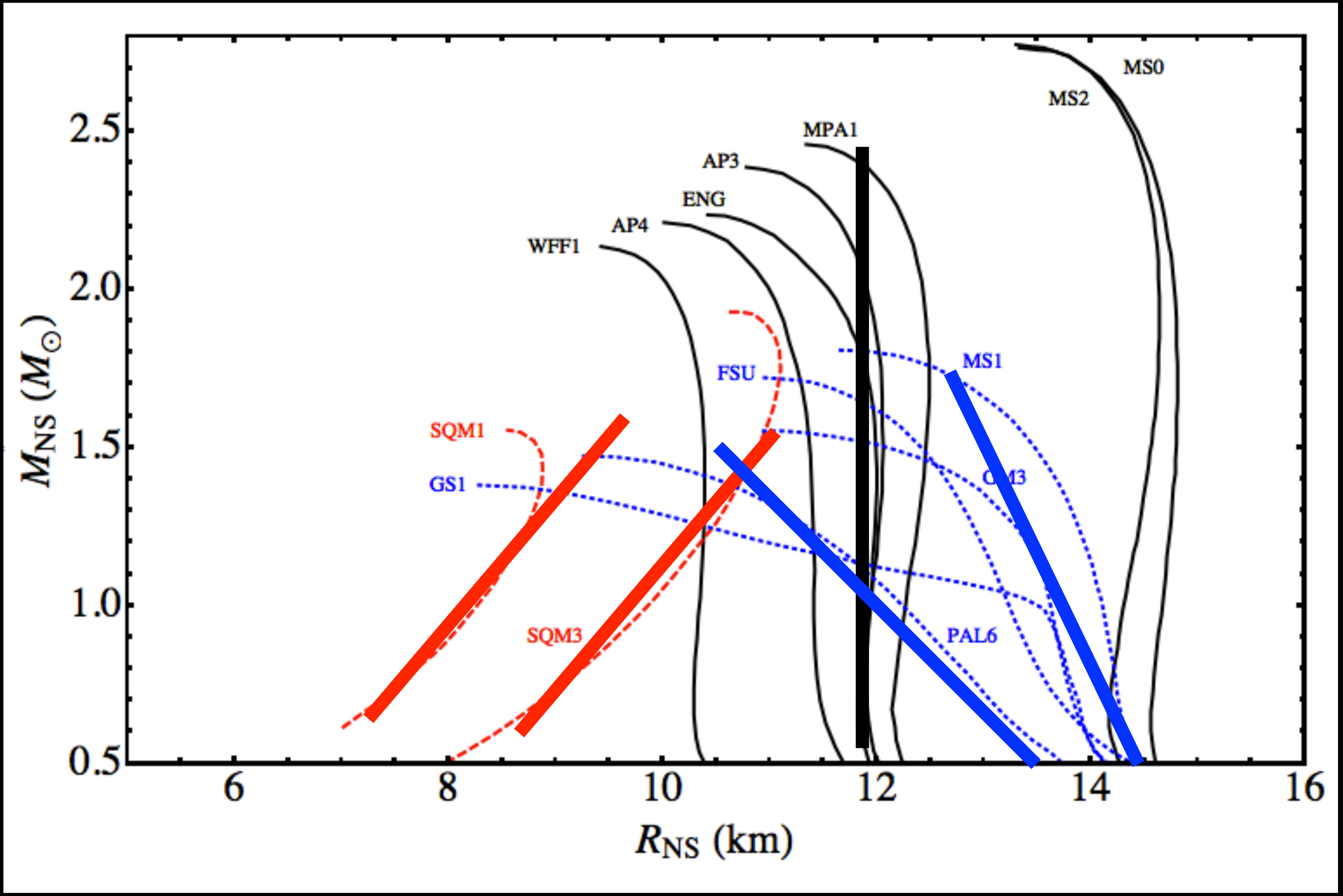
Using a Markov-Chain Monte Carlo method to fit the X-ray spectra of 6 neutron stars, assuming:

- their atmosphere is composed of pure hydrogen,
- the radius is the same for all neutron stars.

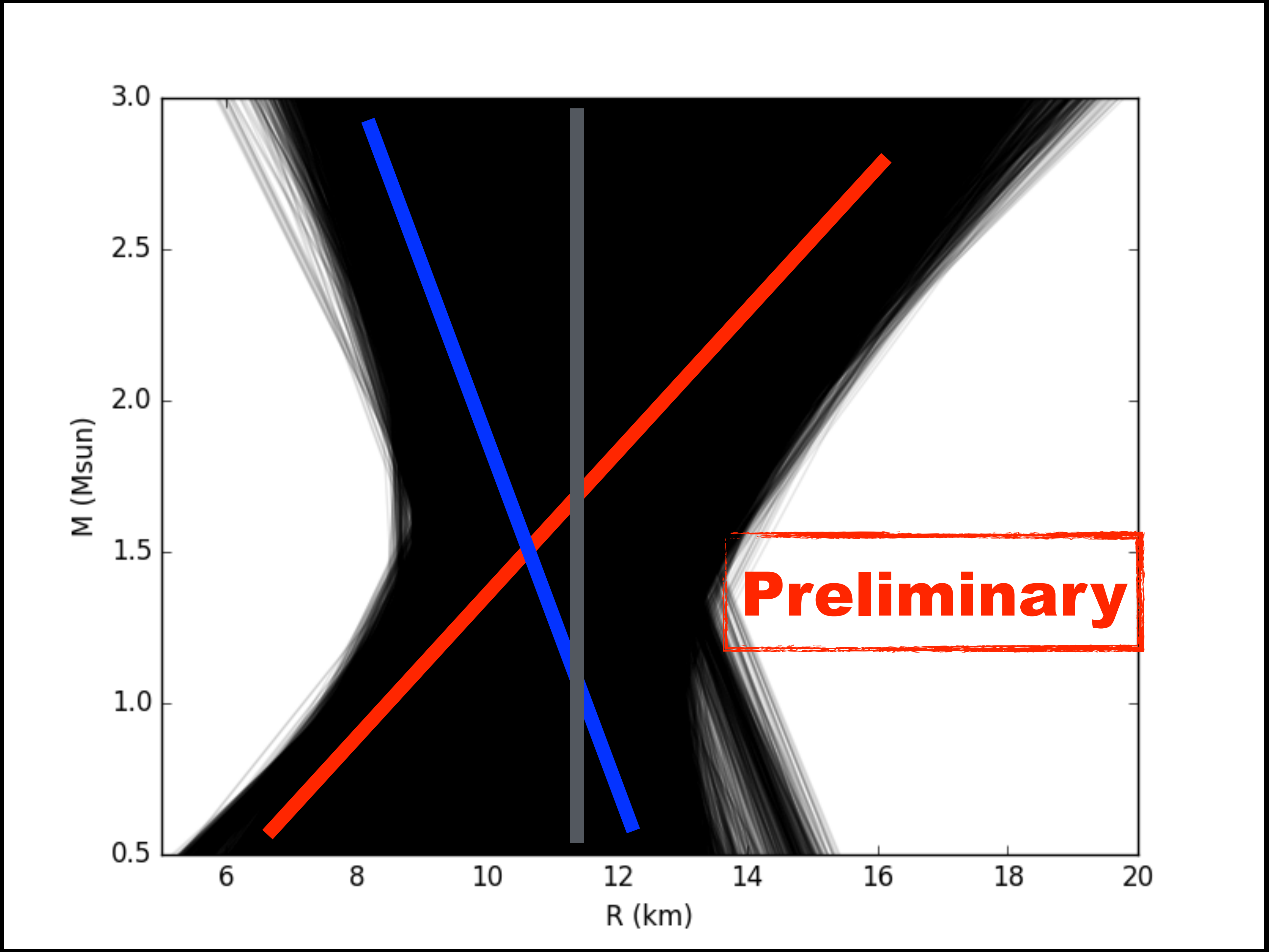


Guillot et al., in prep.

Using the same MCMC approach, I can also test a "*more advanced*" toy-model.

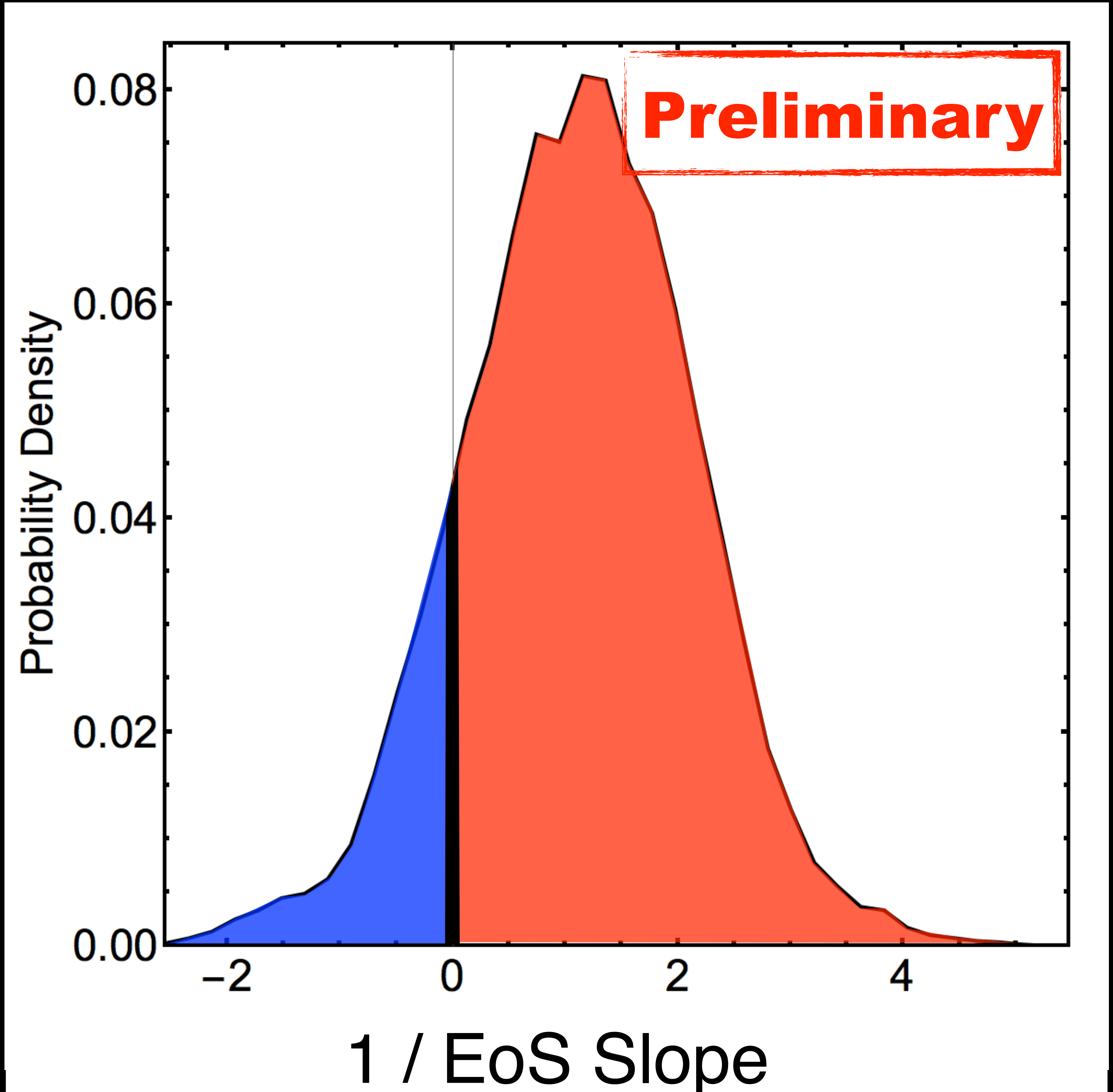


This MCMC approach is used to sample the parameter space of straight EOS.



Guillot et al., in prep.

The distribution of EoS slightly favours positive slopes, but not significantly.



Guillot et al.,
in prep.

There are several complementary ways to improve constraints on the equation of state from qLMXBs observations.

Deeper X-ray observations to increase the signal-to-noise of the X-ray spectra

More precise distance measurements of the host stellar clusters

Determine the composition of the neutron star atmosphere

Independent measurement of neutron star mass

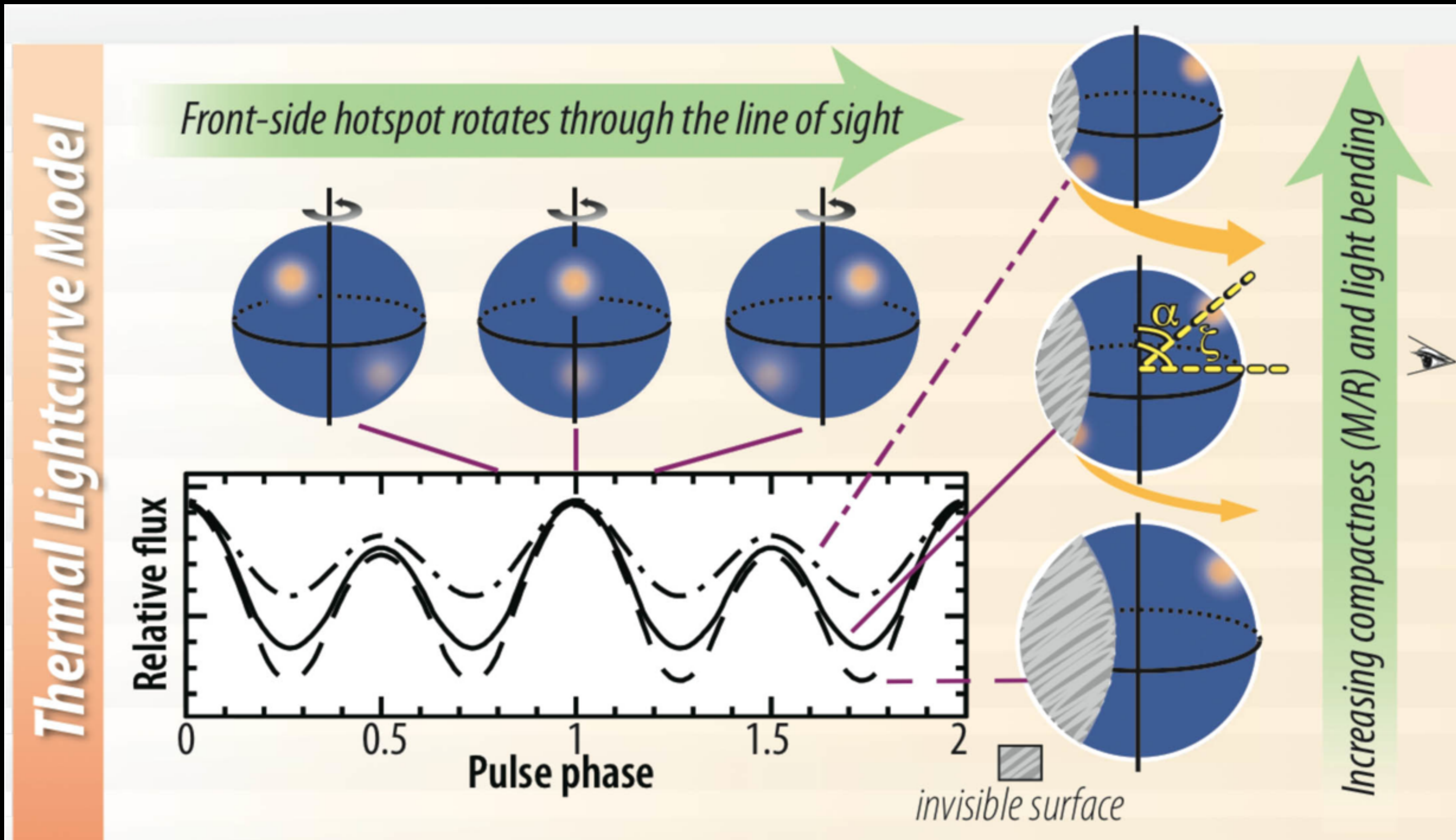
Use of realistic parameterizations of the equation of state.
See *Ozel et al. 2016*
and *Lattimer and Steiner 2014*

Curious about Lattimer and Steiner (2014)? Ask me!

Another method to measure M_{NS}/R_{NS}

with a different class of neutron stars.

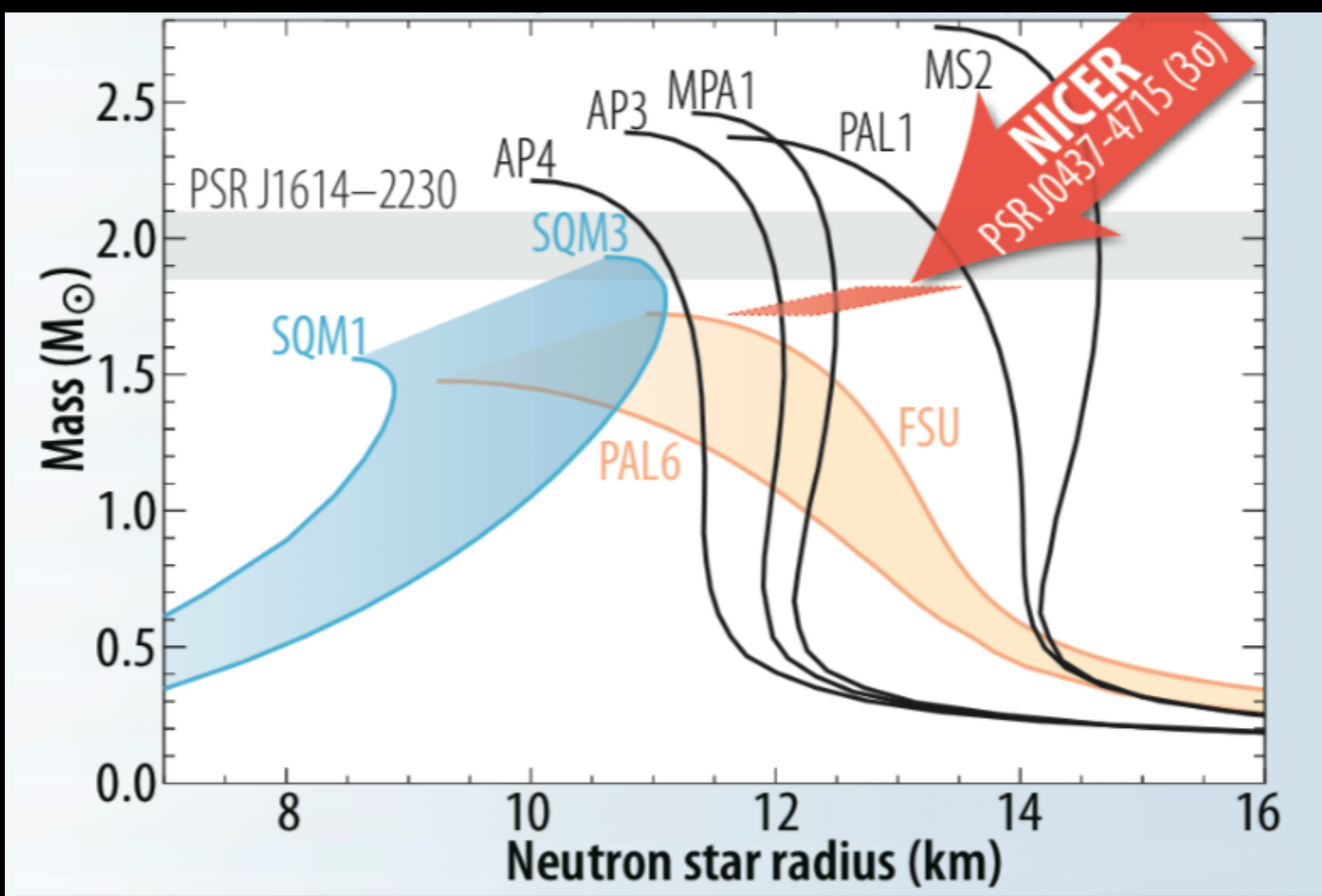
Analyzing the pulsed emission caused by hot spots on a rotating neutron star can be used to measure the compactness.

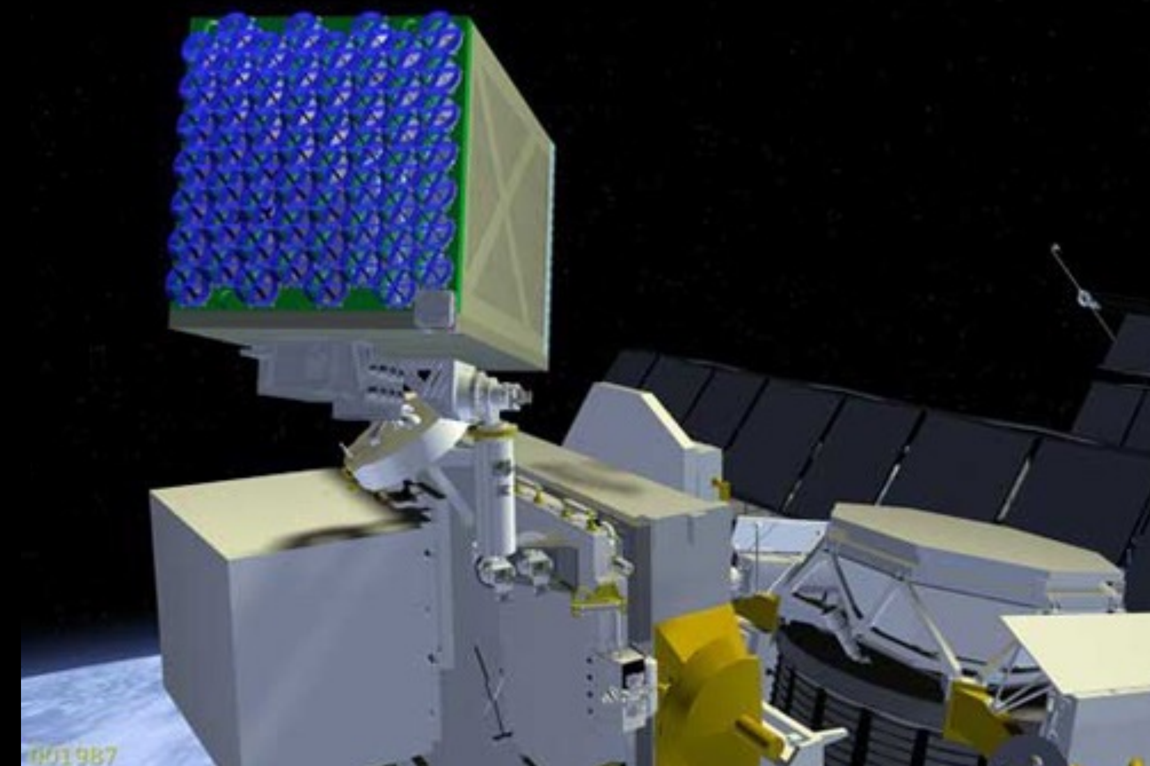


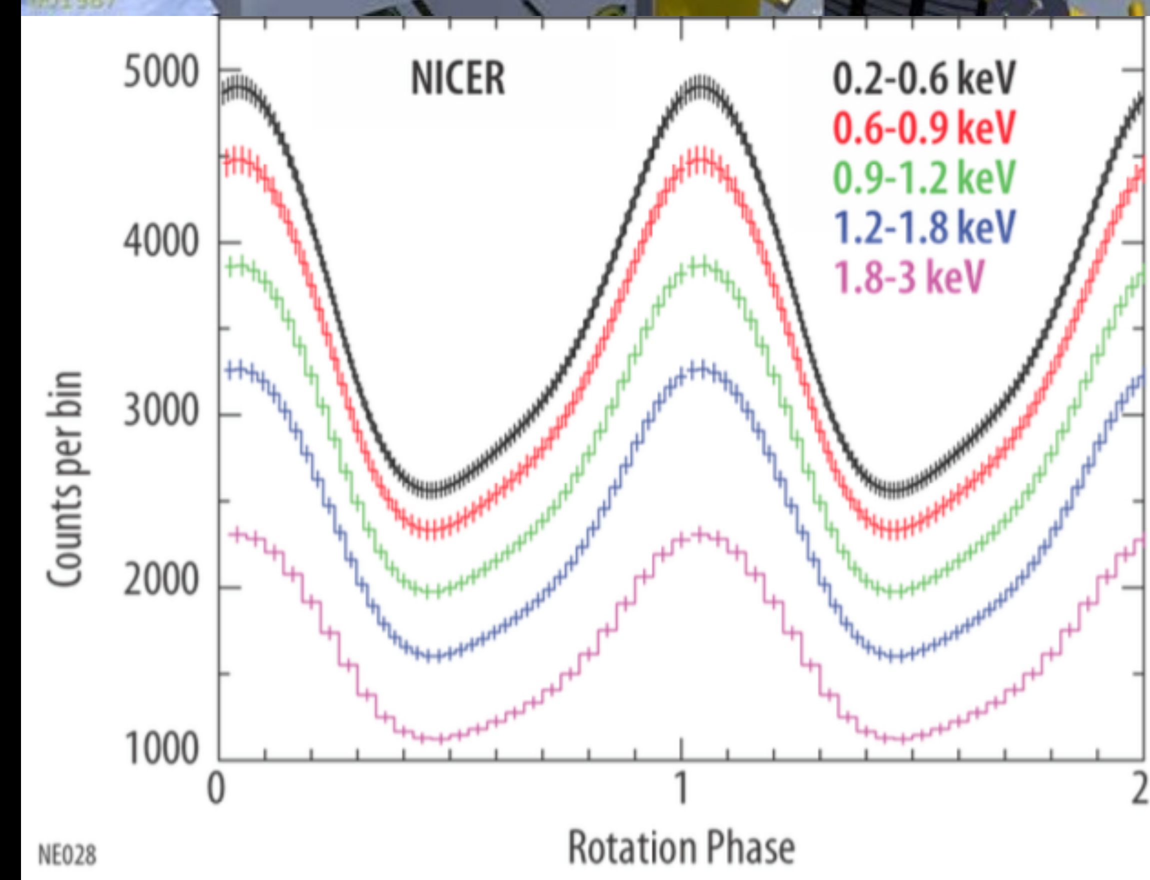
The Neutron Star Interior Composition Explorer will measure M-R very precisely.

NICER

Launch: Feb. 2017

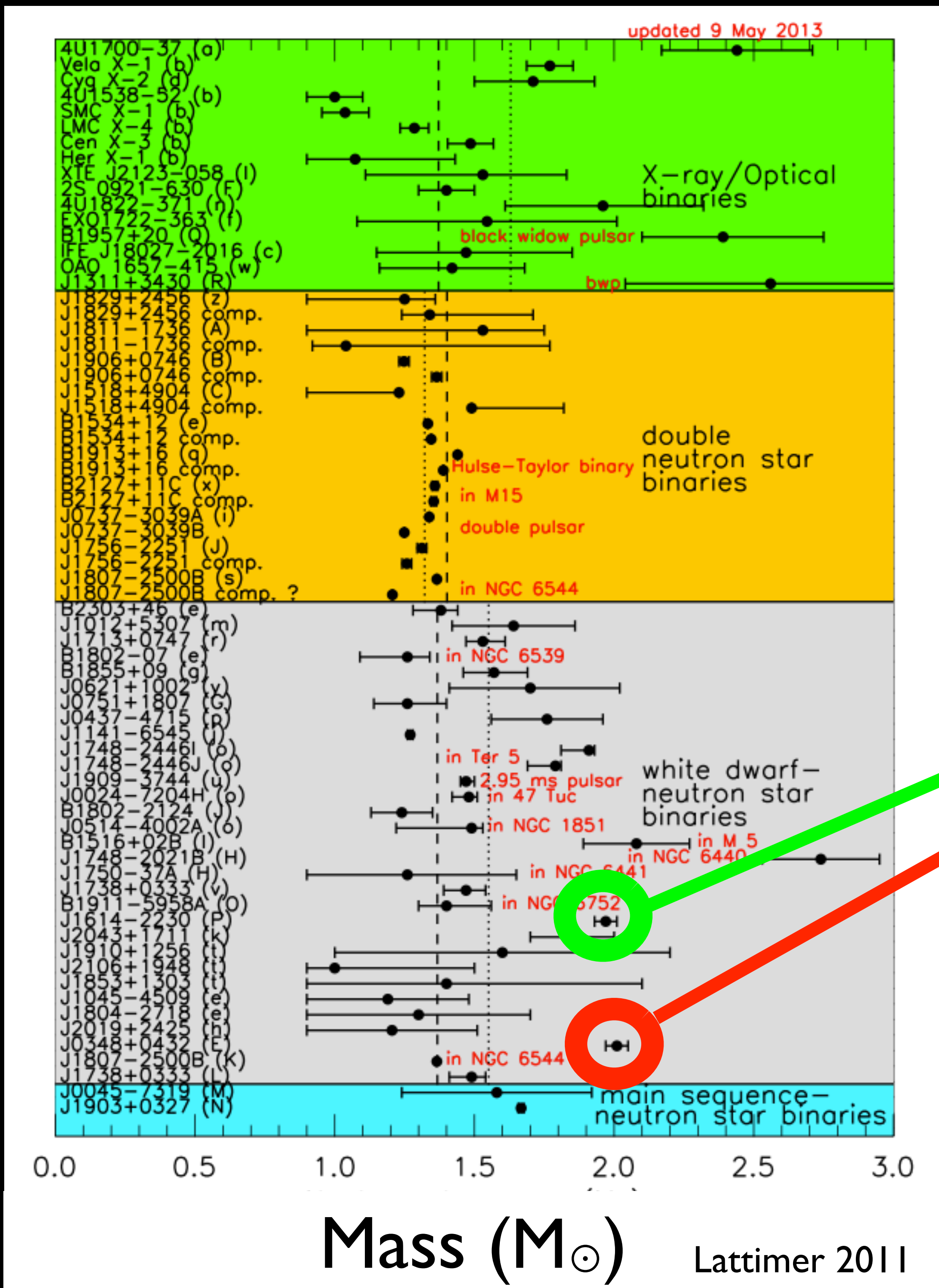






What about the largest neutron star masses?

Only new M_{NS} measurements larger than previous ones improve constraints on the dense matter equation of state



NEW MASS

PSR J1614-2230

~~M_{PSR}=1.97±0.04 M⊙~~

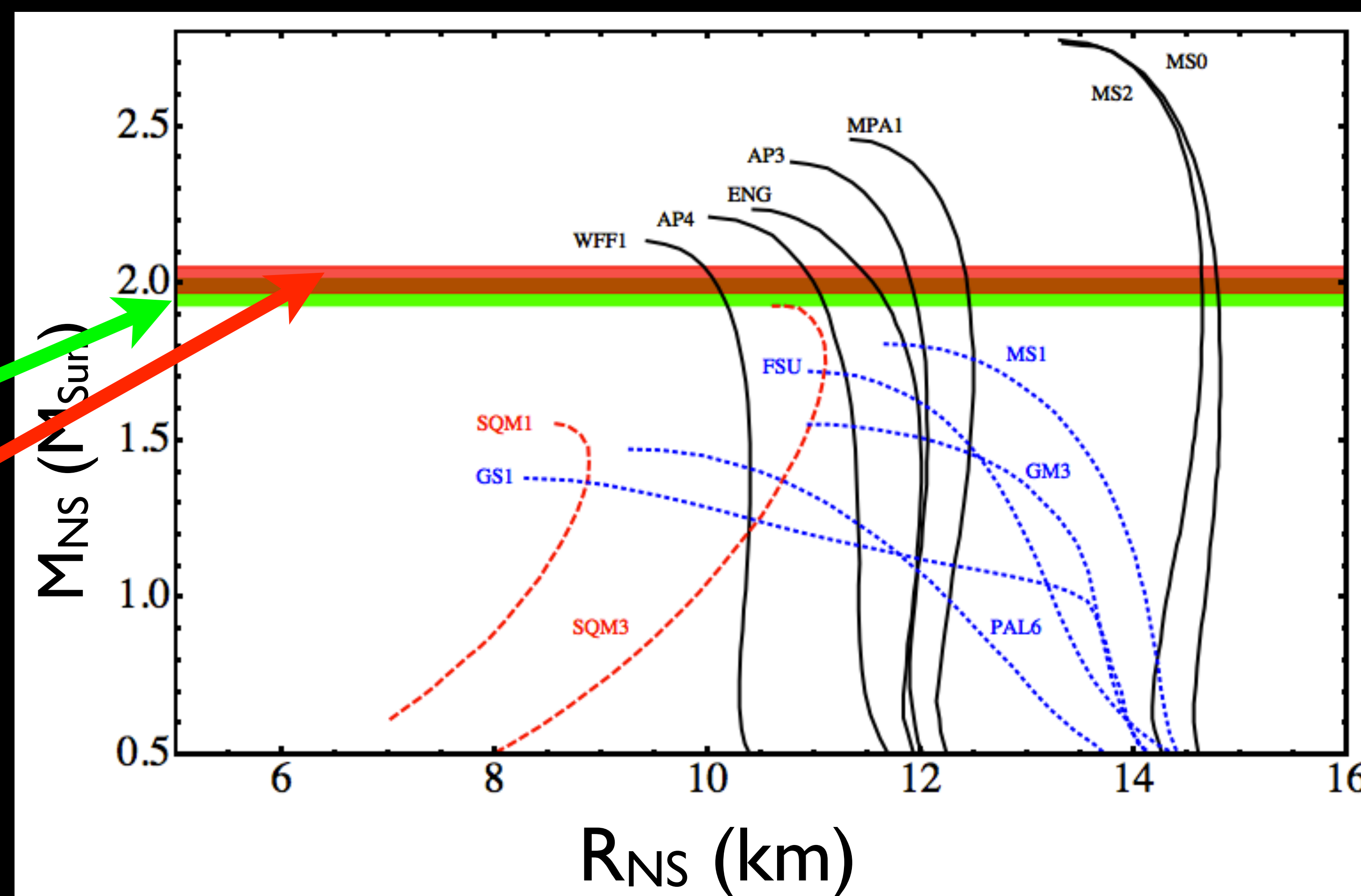
M_{PSR}=1.928±0.017 M⊙

(Fonseca et al. 2016)

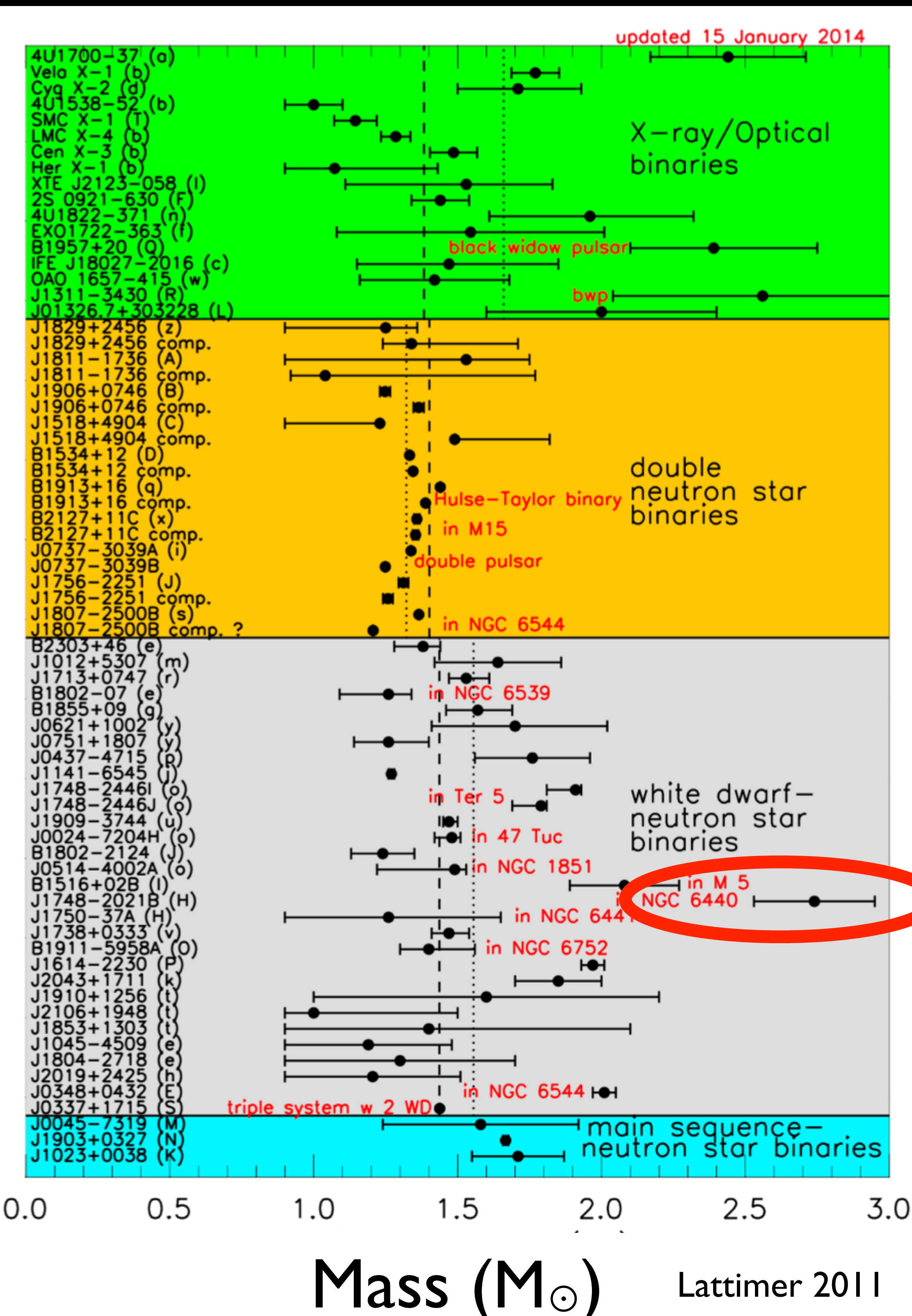
PSR J0348+0432

M_{PSR}=2.01±0.04 M⊙

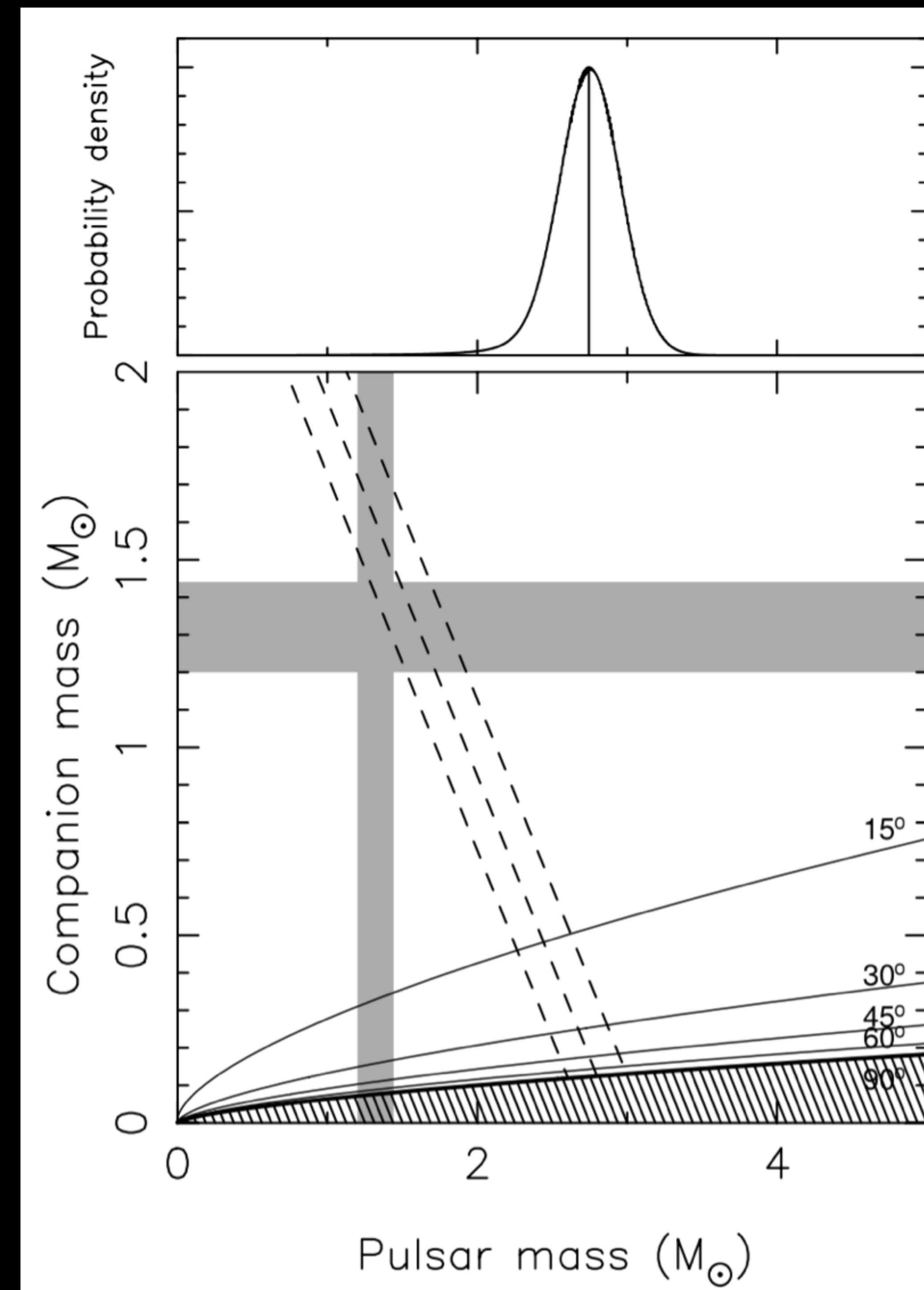
(Antoniadis et al. 2013)



Other measurements with masses over 2 $M_\odot$ suffer from systematics.

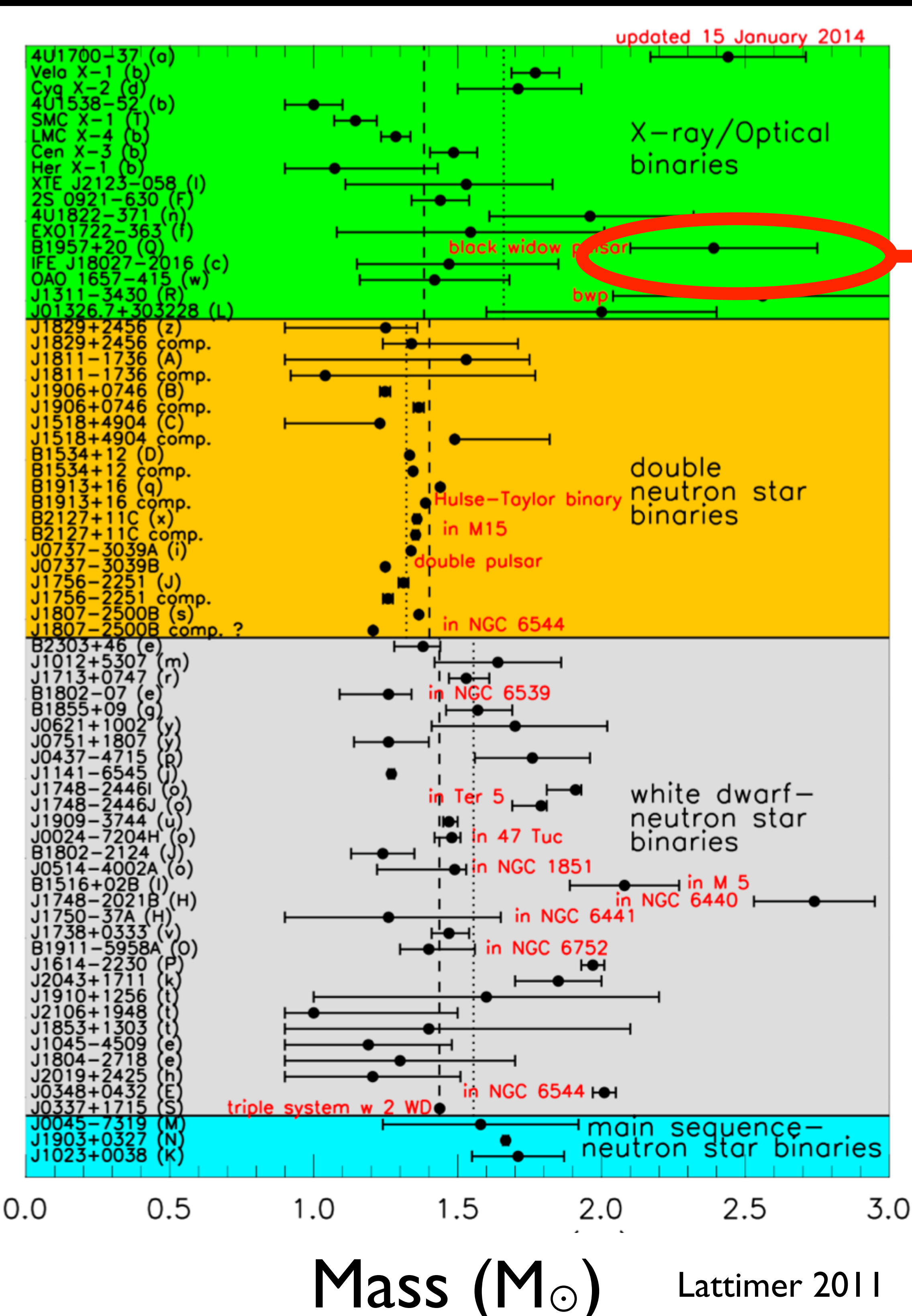


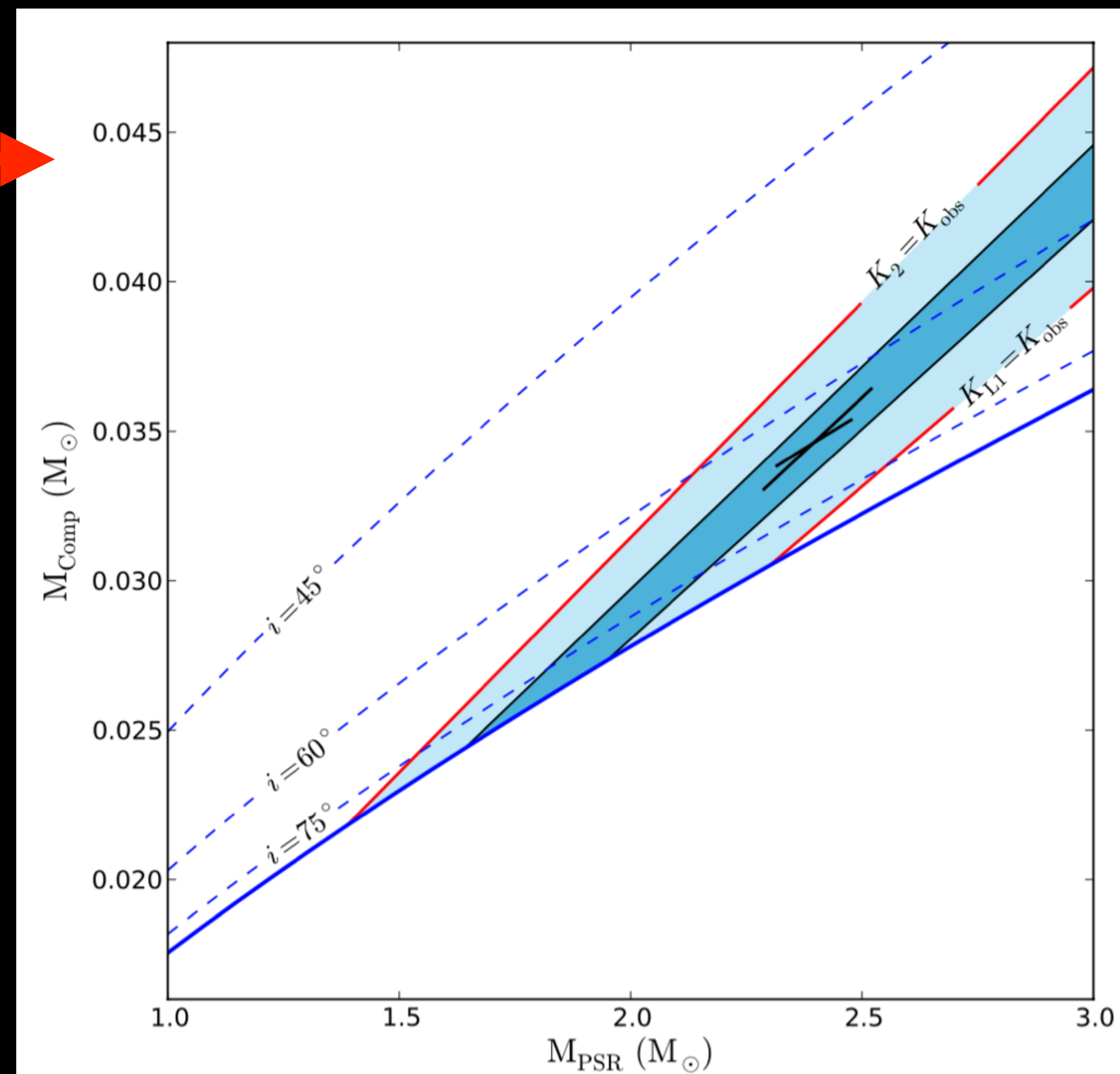
Lattimer 2011



Freire et al. 2008

Other measurements with masses over 2 M☉ suffer from systematics.





van Kerkwijk et al 2011

The Five hundred meters Aperture Spherical Telescope (FAST) will provide a leap in sensitivity for pulsar timing.

Summary

Quiescent LMXBs are stable objects from which the surface thermal emission allows us to measure the radius.

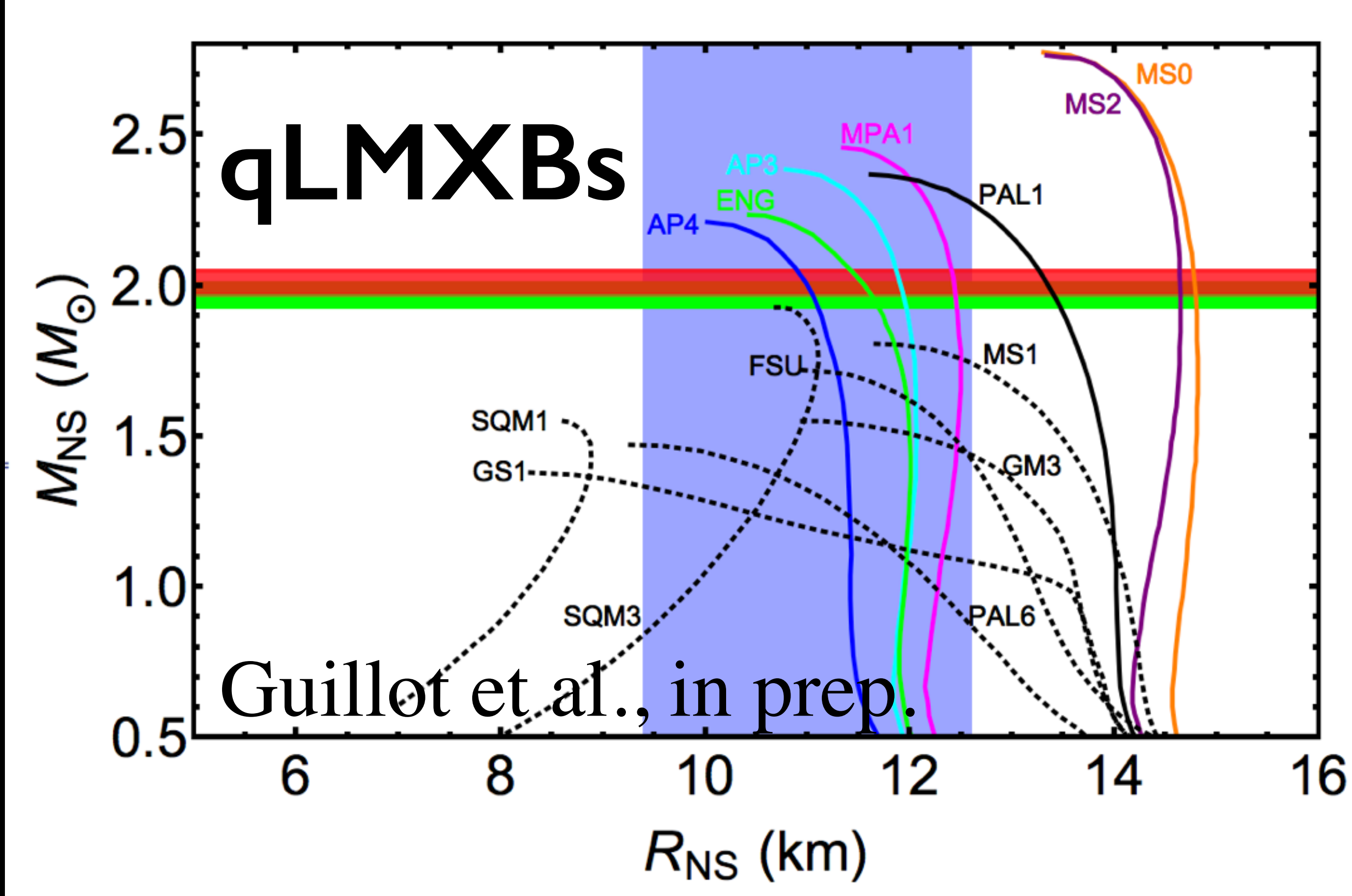
Because we actually measure R_∞, constraints on the EoS from an individual qLMXB are limited.

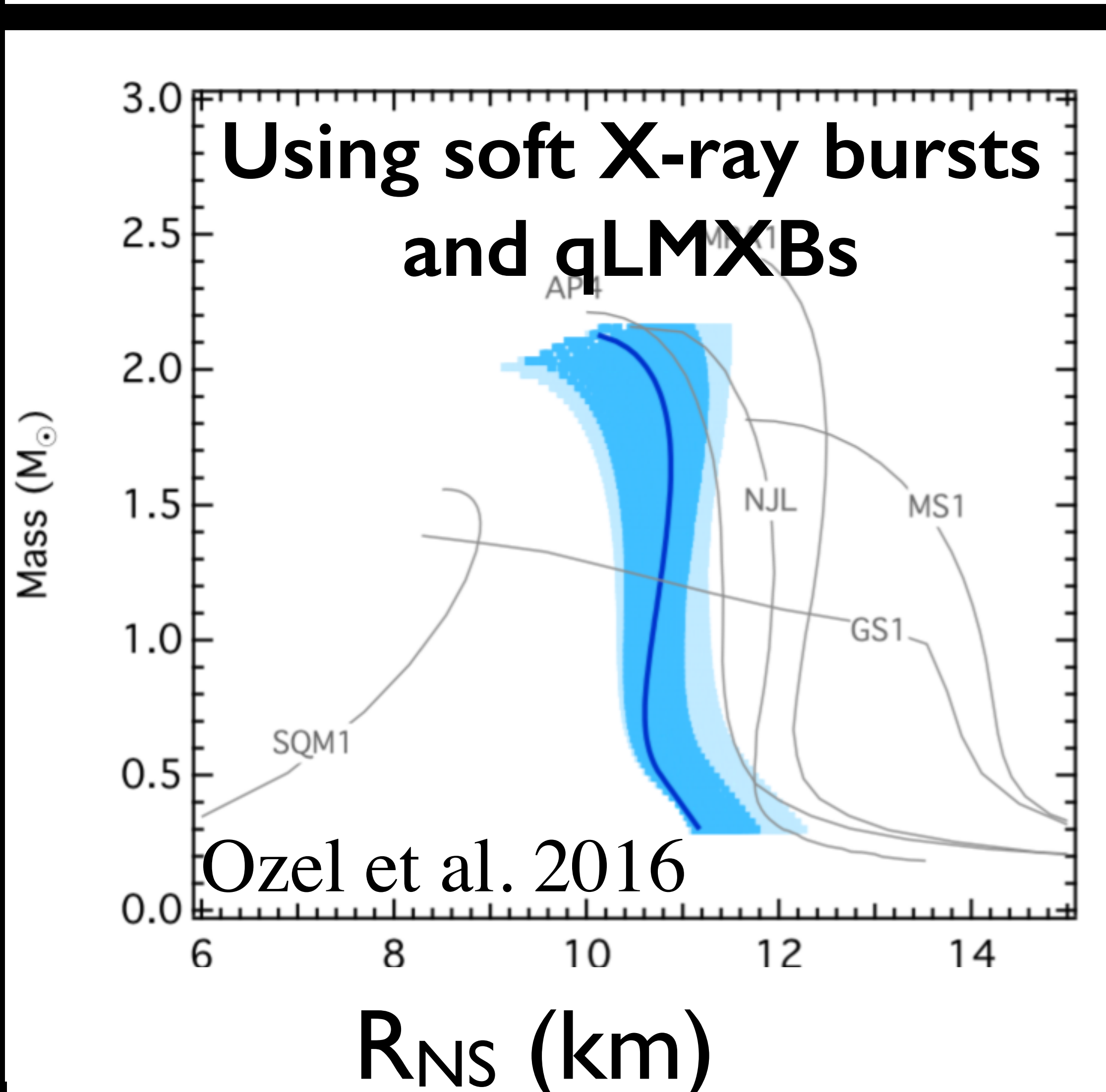
But they can be combined, with some simple or more complicated parameterization of the EoS to extract constraints

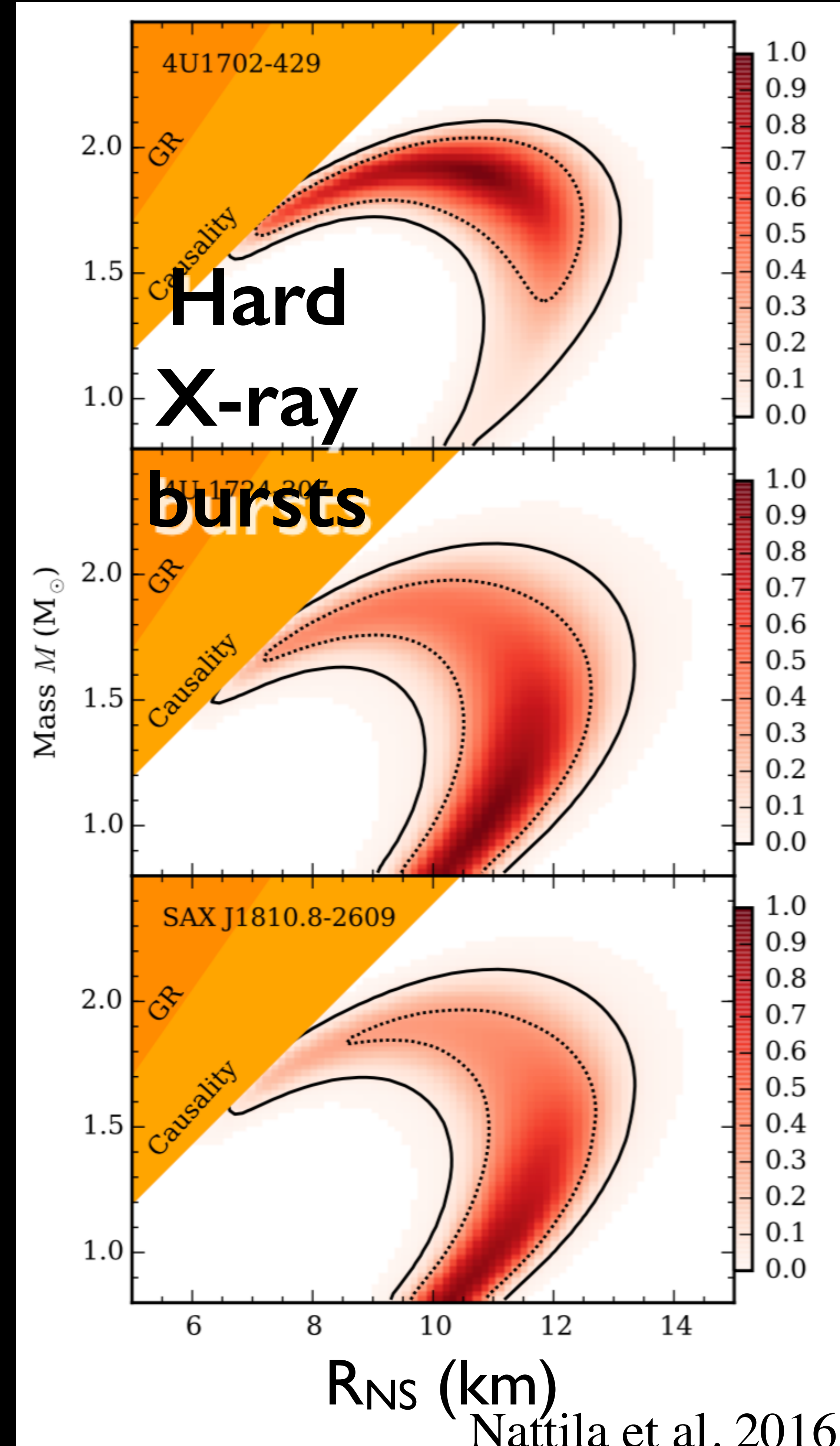
There are systematics affecting the measurements, but more observations can help us understand them.

Recent progress led to higher radii which relaxes the tension with nuclear physics and other astrophysical measurements

$$R_{\rm NS} = 10.8^{+1.8}_{-1.4}\,{\rm km}$$


qLMXBs
Guillot et al., in prep.
MS0
MS2
MPA1
AP3
ENG
AP4
PAL1
MS1
FSU
SQM1
GS1
GM3
SQM3
PAL6
M_{NS} ($M_\odot$)
R_{NS} (km)


Using soft X-ray bursts
and qLMXBs
AP4
NJL
MS1
GS1
SQM1
Ozel et al. 2016
Mass ($M_\odot$)
R_{NS} (km)

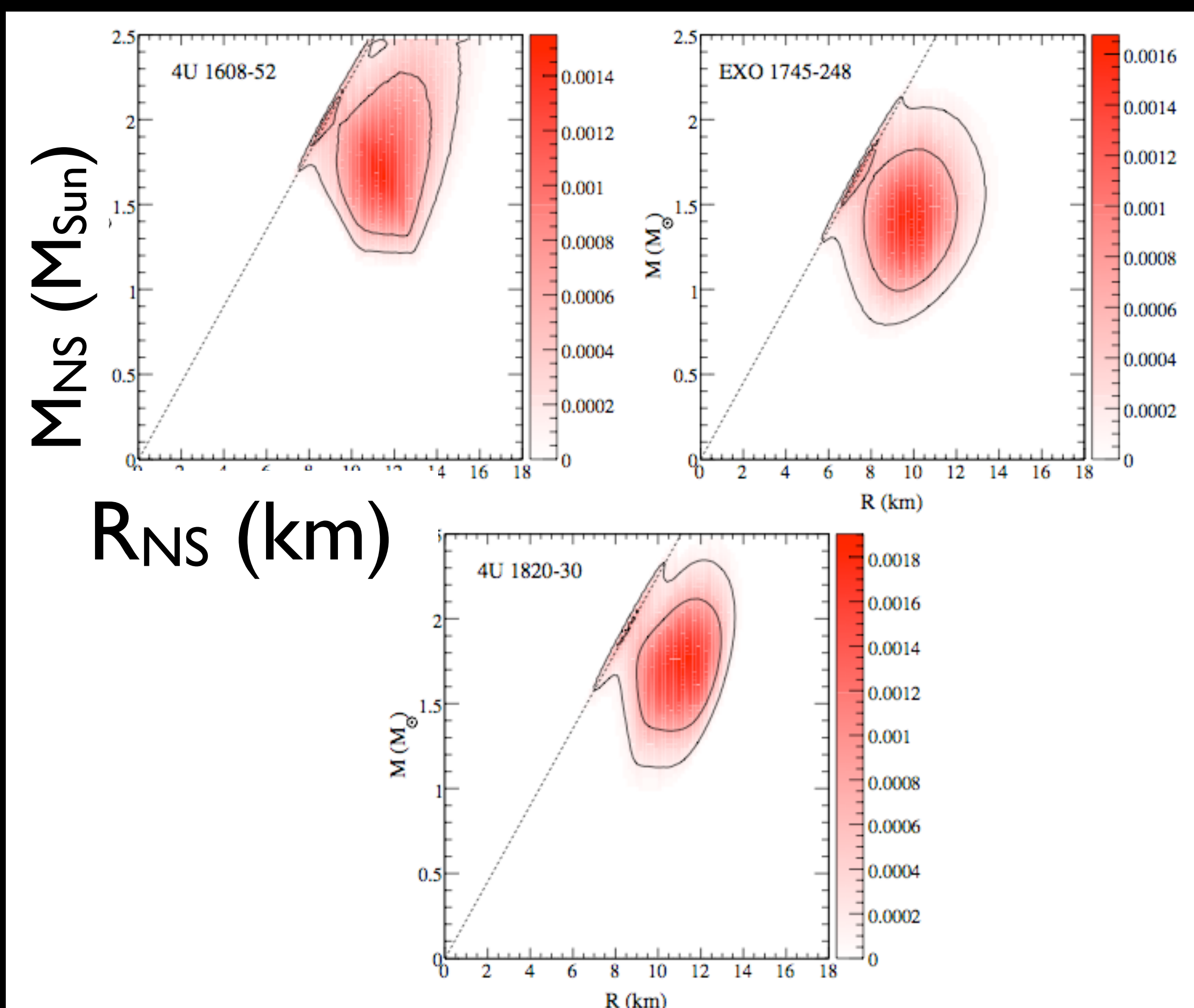

4U1702-429
Hard
X-ray
bursts
SAX J1810.8-2609
GR
Causality
Mass M ($M_\odot$)
R_{NS} (km)
Nattila et al. 2016

M_{NS}-R_{NS} contours can be combined to parametrize the EoS.

<u>Lattimer & Steiner 2014</u>

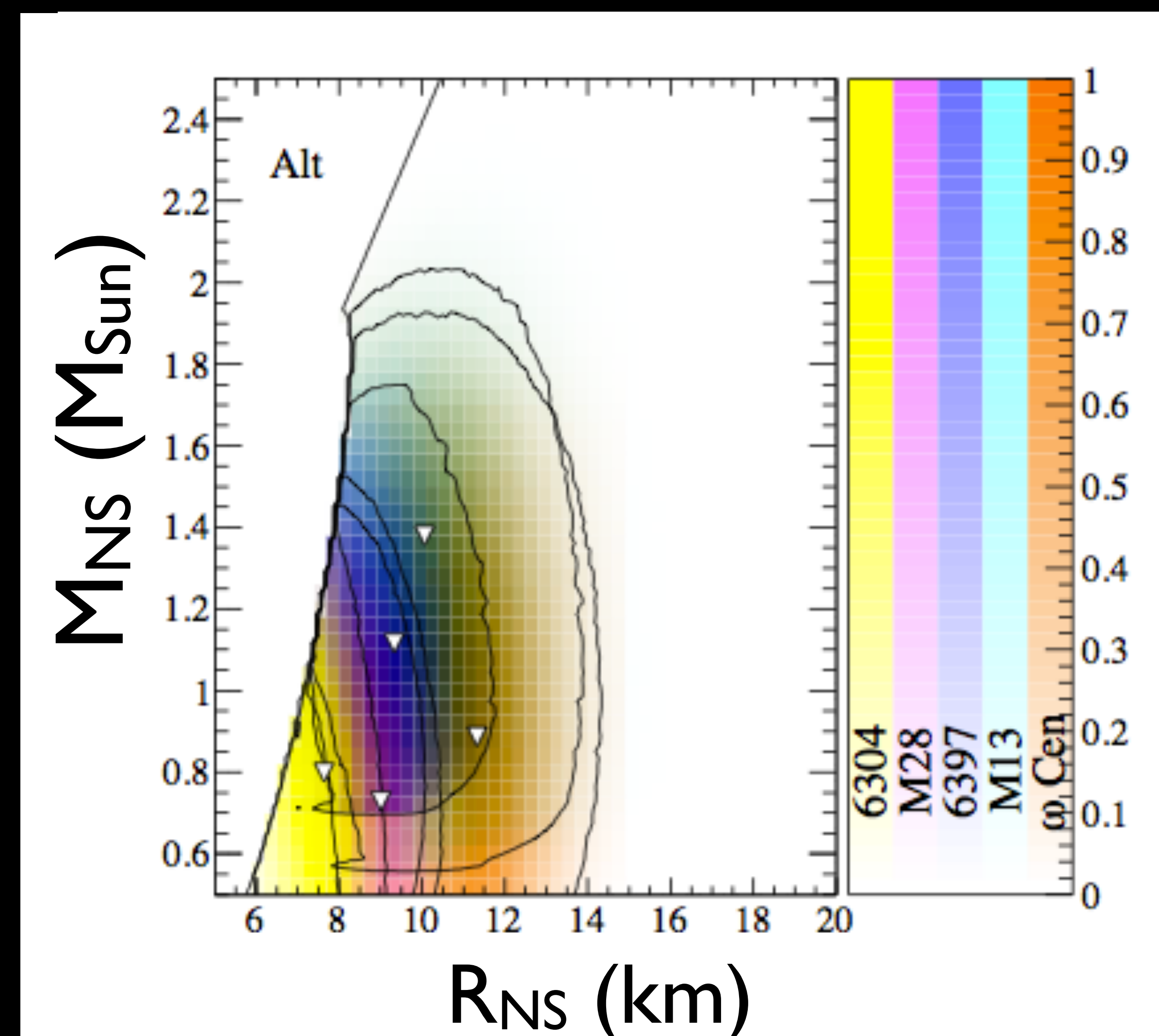
method demonstrated in Steiner et al 2010

Type I X-ray bursts



+

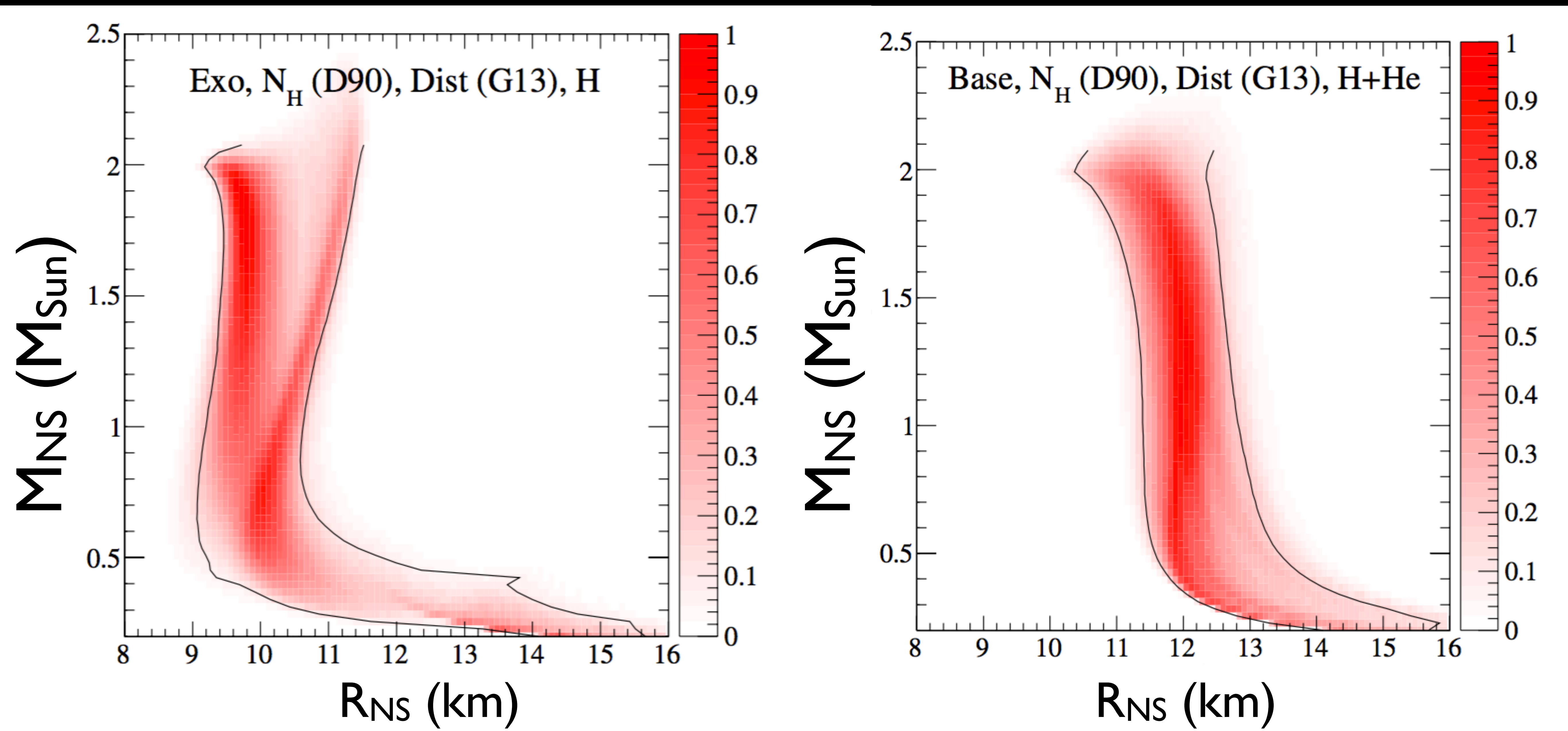
Quiescent LMXBs



Rescaled M-R contour of qLMXBs from Guillot et al. 2013

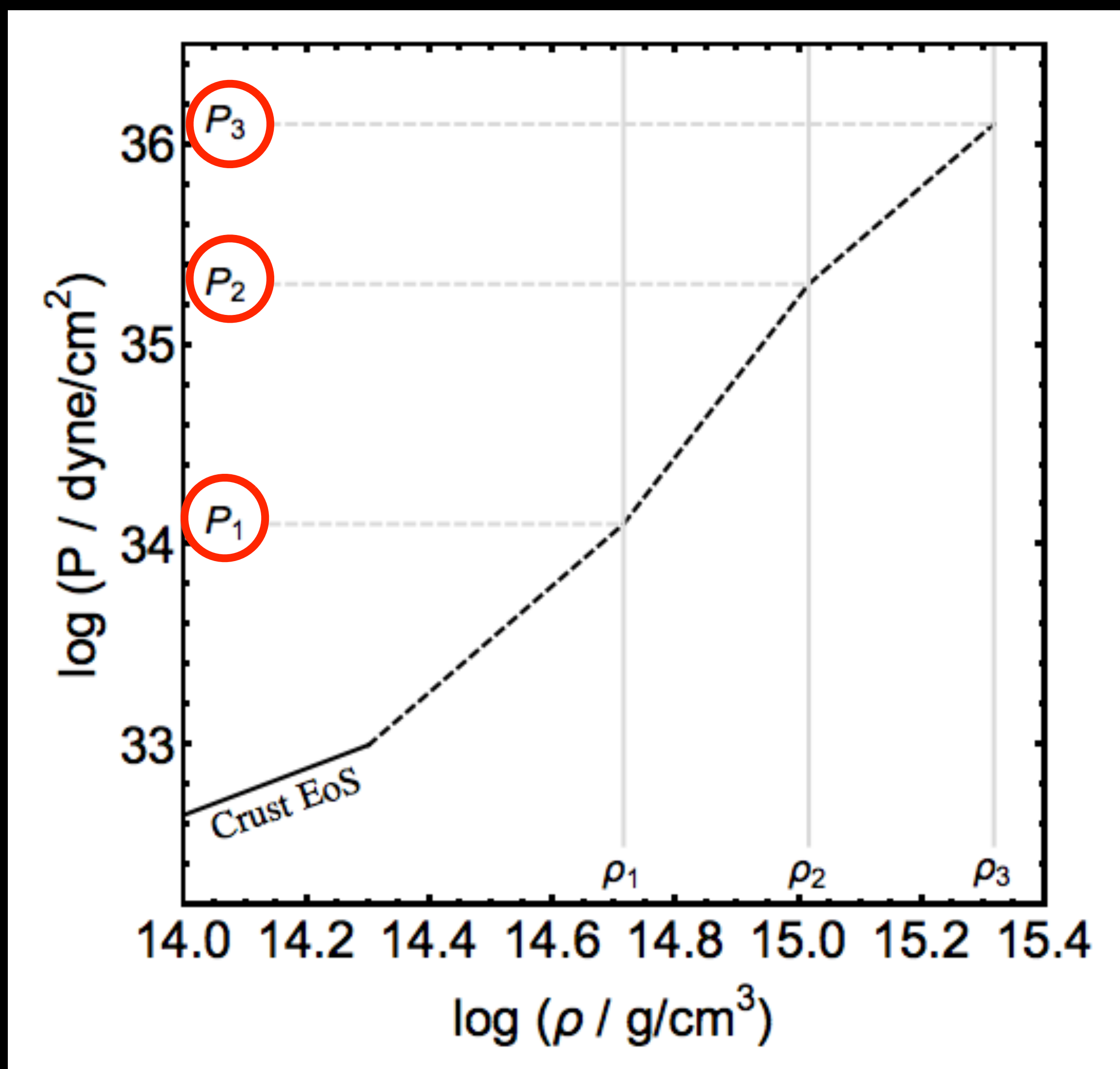
M_{NS}-R_{NS} contours can be combined to parametrize the EoS.

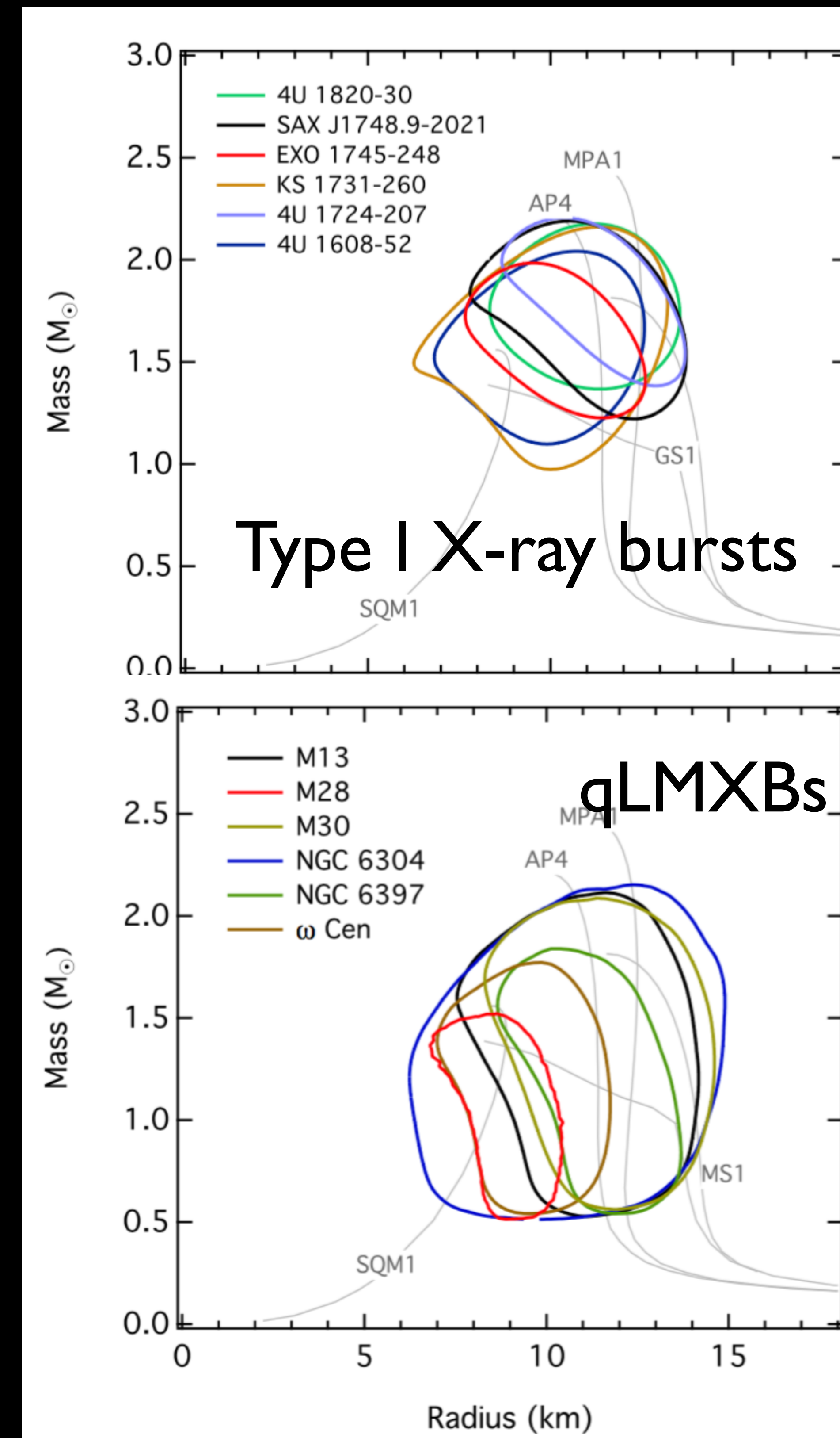
Lattimer & Steiner 2014



We combined M_{NS}-R_{NS} measurements from qLMXBs and type I X-ray bursts to place constraints on the pressure at three fiducial densities.

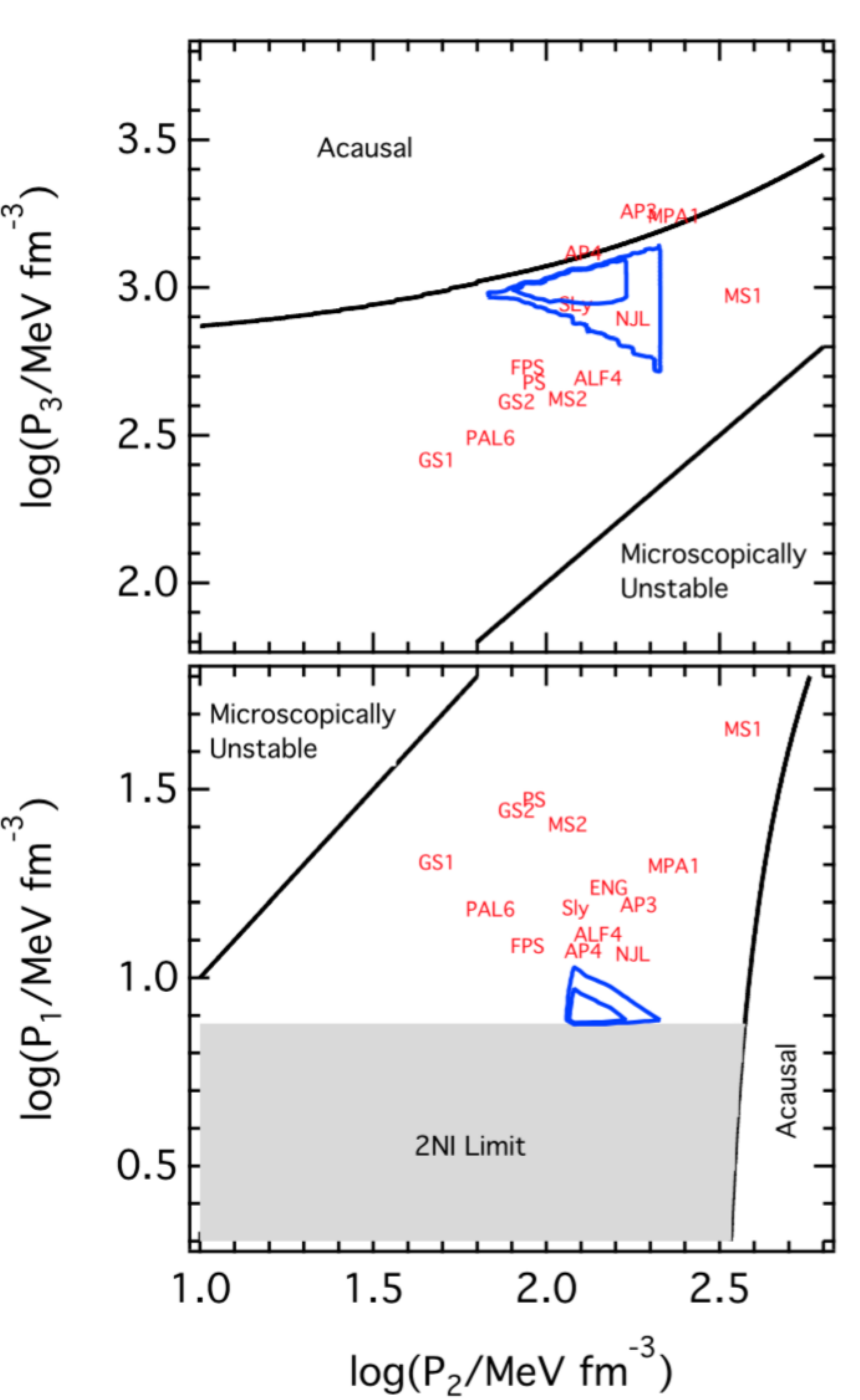
Ozel et al. 2016

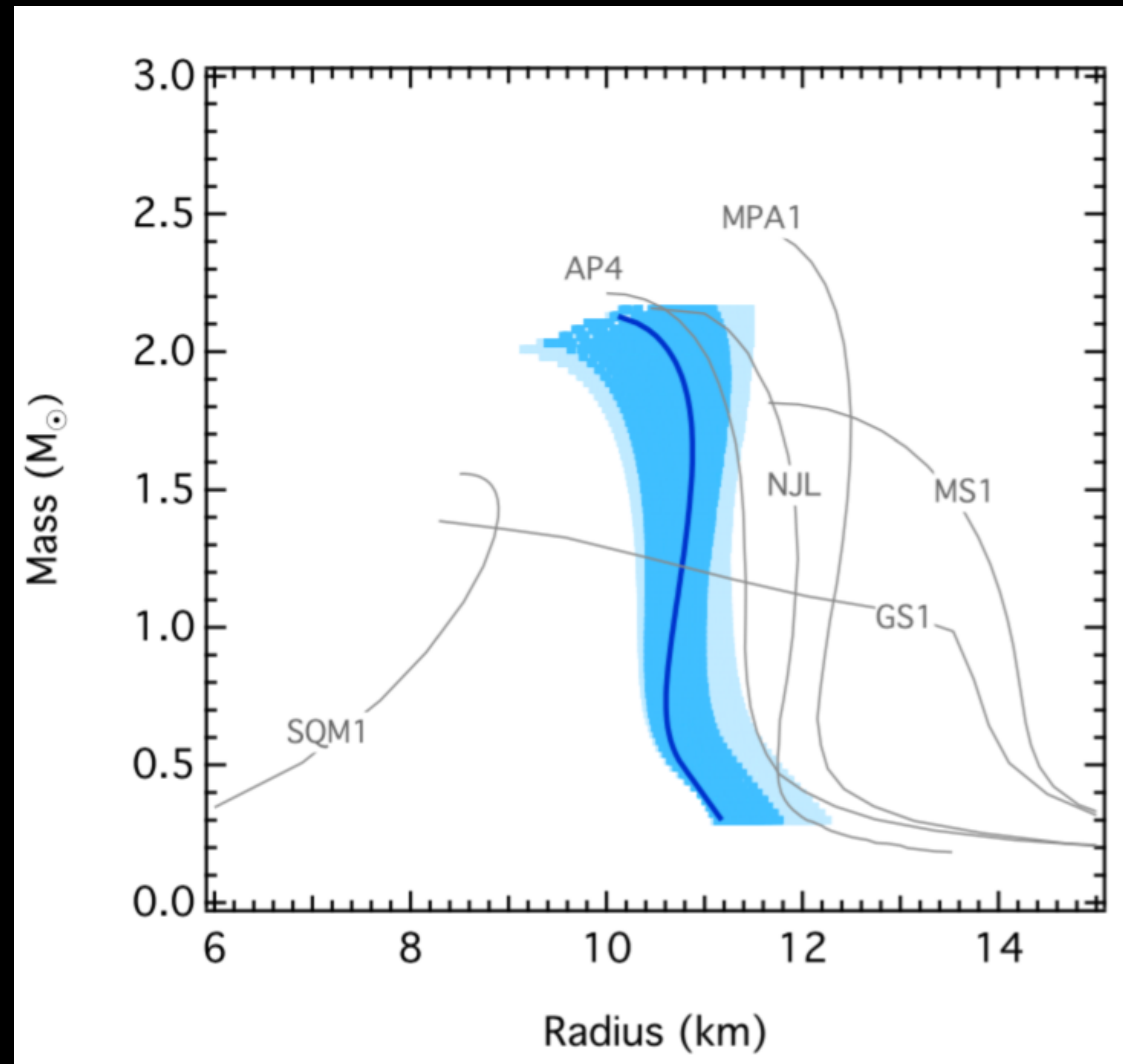




P1, P2 and P3 measured at $1.85\rho_0$, $3.7\rho_0$ and $7.4\rho_0$

We combined M_{NS}-R_{NS} measurements from qLMXBs and type I X-ray bursts to place constraints on the pressure at three fiducial densities, leading to a unique equation of state.



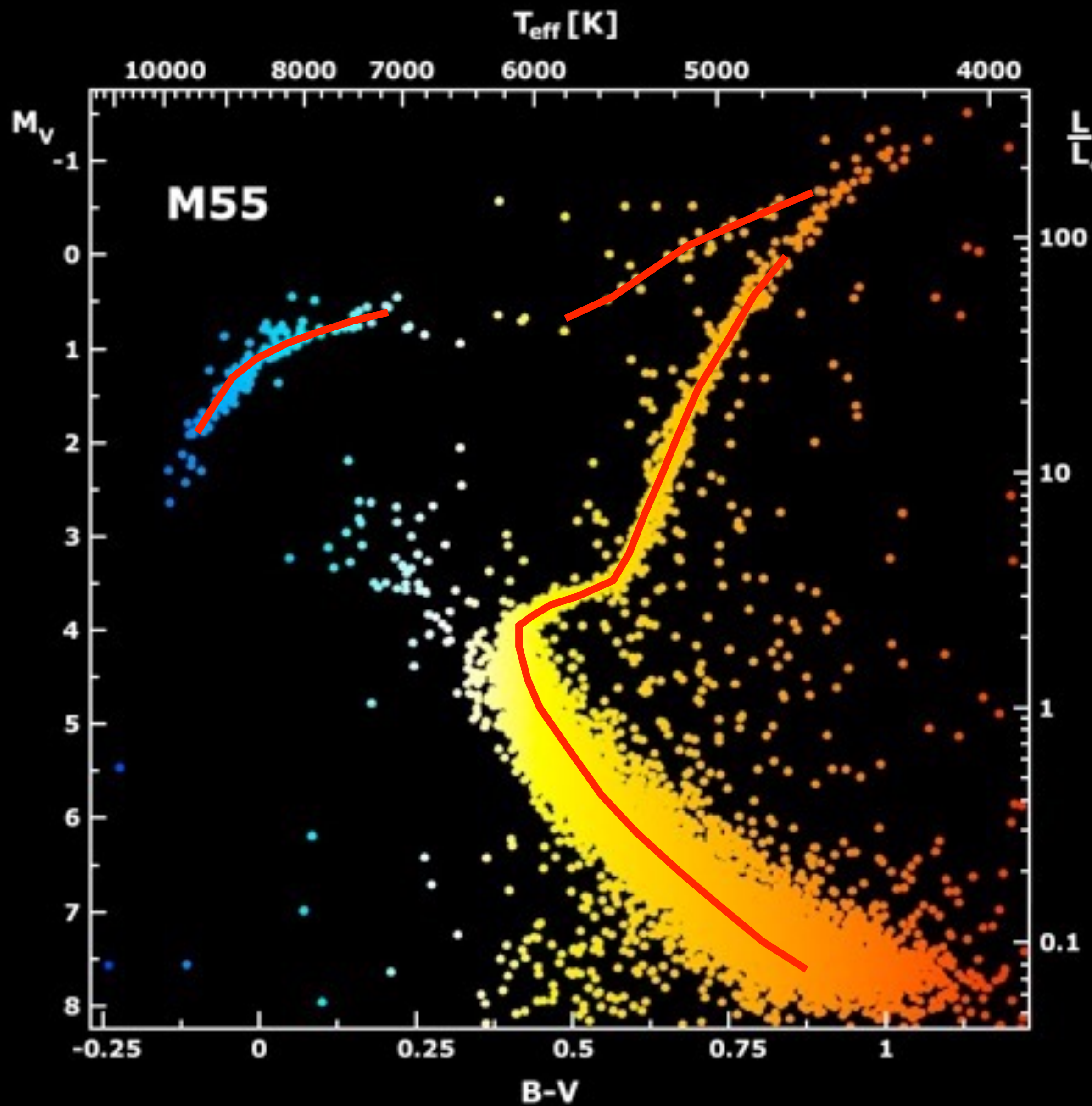


Ozel et al. 2016

Aside

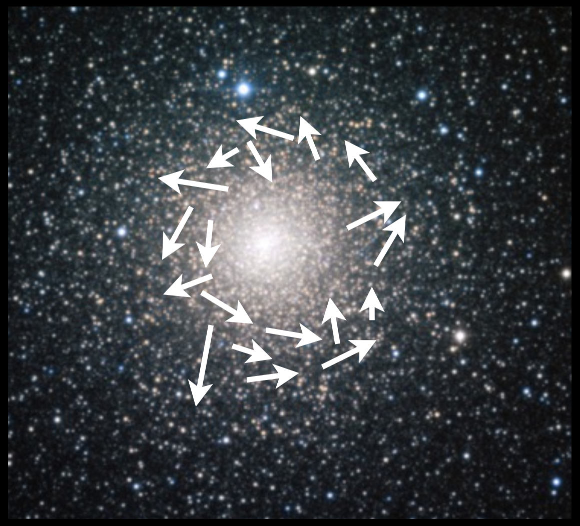
Distance to globular clusters are not trivial to obtain and can be severely affected by systematics.

Photometric distances

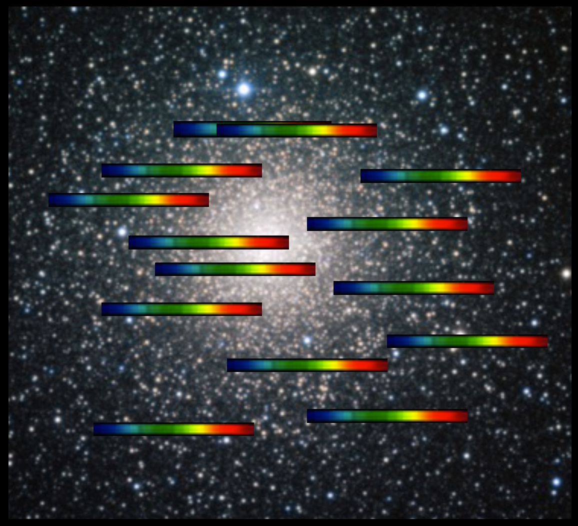


Relating apparent magnitude to absolute magnitude

Dynamical distances

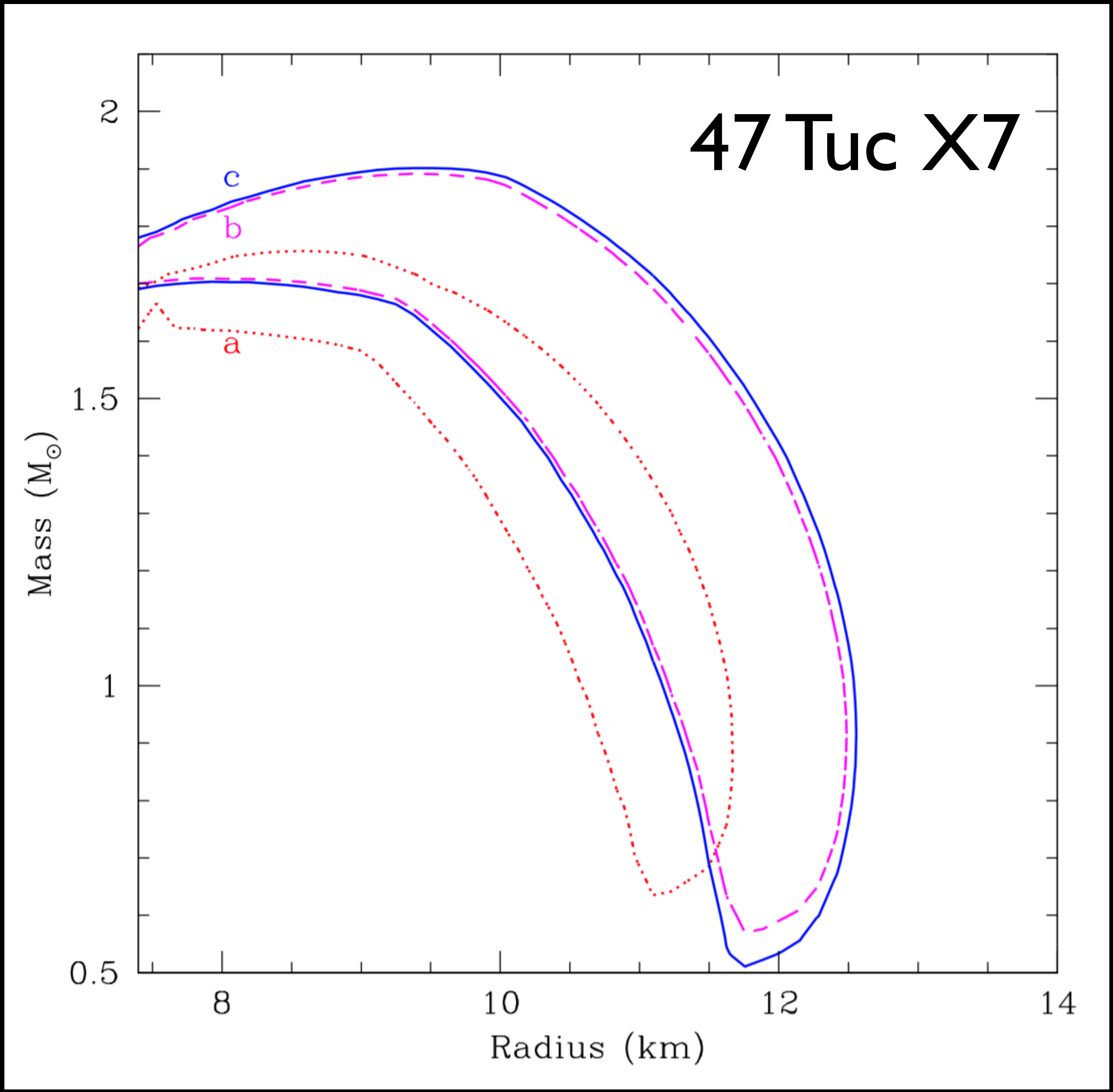


projected velocity dispersion in arcsec/year



radial velocity dispersion in km/sec

For some qLMXBs, instrumental effects may also bias the radius measurements.



Pile-up of photons on Chandra's CCD shifts the peak of the thermal spectrum, and affects the measured R_∞ by about 10%

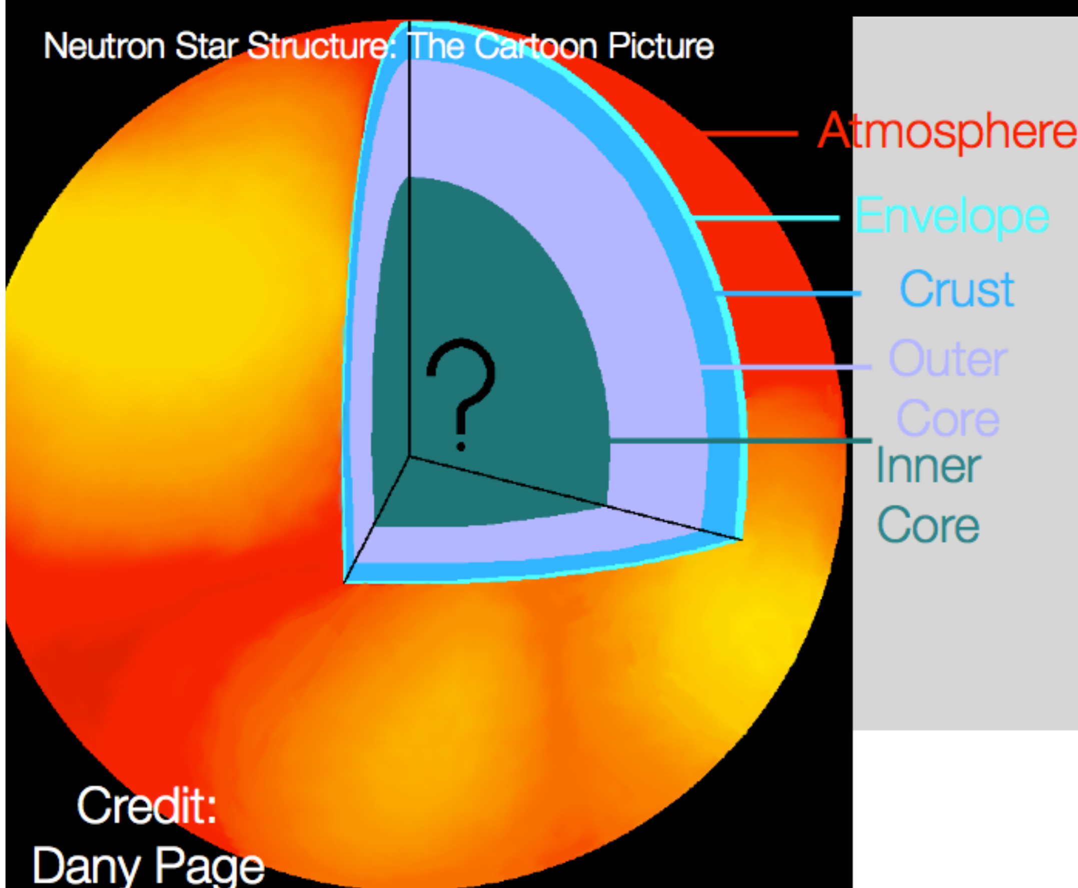
Bogdanov et al. 2016

Non-Equilibrium Processes in the Outer Crust Beginning with ^{56}Fe (Haensel &Zdunik 1990, 2003,2008)

ρ[a] ($g\,cm^{-3}$)	Process	Type of reaction	X_n[b]	Q[c] (keV)
1.49×10^{9}	$^{56}Fe \rightarrow {}^{56}Cr - 2e^- + 2\nu_e$	e^- capture	0.00	40.7
1.11×10^{10}	$^{56}Cr \rightarrow {}^{56}Ti - 2e^- + 2\nu_e$	e^- capture	0.00	35.8
7.85×10^{10}	$^{56}Ti \rightarrow {}^{56}Ca - 2e^- + 2\nu_e$	e^- capture	0.00	47.3
2.50×10^{11}	$^{56}Ca \rightarrow {}^{56}Ar - 2e^- + 2\nu_e$	e^- capture	0.00	46.1
6.11×10^{11}	$^{56}Ar \rightarrow {}^{52}S + 4n - 2e^- + 2\nu_e$	n emission	0.00	59.8
9.075×10^{11}	$^{52}S \rightarrow {}^{46}Si + 6n - 2e^- + 2\nu_e$	n emission	0.07	128.0
1.131×10^{12}	$^{46}Si \rightarrow {}^{40}Mg + 6n - 2e^- + 2\nu_e$	n emission	0.18	143.5
1.455×10^{12}	$^{40}Mg \rightarrow {}^{34}Ne + 6n - 2e^- + 2\nu_e$ $^{34}Ne + {}^{34}Ne \rightarrow {}^{68}Ca$	n emission pycnonuclear	0.39	507.9
1.766×10^{12}	$^{68}Ca \rightarrow {}^{62}Ar + 6n - 2e^- + 2\nu_e$	n emission	0.45	65.8
2.134×10^{12}	$^{62}Ar \rightarrow {}^{56}S + 6n - 2e^- + 2\nu_e$	n emission	0.45	71.6
2.634×10^{12}	$^{56}S \rightarrow {}^{50}Si + 6n - 2e^- + 2\nu_e$	n emission	0.50	77.9
3.338×10^{12}	$^{50}Si \rightarrow {}^{44}Mg + 6n - 2e^- + 2\nu_e$	n emission	0.55	84.6
4.379×10^{12}	$^{44}Mg \rightarrow {}^{36}Ne + 8n - 2e^- + 2\nu_e$ $^{36}Ne + {}^{36}Ne \rightarrow {}^{72}Ca$ $^{72}Ca \rightarrow {}^{66}Ar + 6n - 2e^- + 2\nu_e$	n emission pycnonuclear n emission	0.61	308.8
5.839×10^{12}	$^{66}Ar \rightarrow {}^{60}S + 6n - 2e^- + 2\nu_e$	n emission	0.70	29.5
7.041×10^{12}	$^{60}S \rightarrow {}^{54}Si + 6n - 2e^- + 2\nu_e$	n emission	0.73	31.0
8.980×10^{12}	$^{54}Si \rightarrow {}^{48}Mg + 6n - 2e^- + 2\nu_e$ $^{48}Mg + {}^{48}Mg \rightarrow {}^{96}Cr$ $^{96}Cr \rightarrow {}^{94}Cr + 2n$	n emission pycnonuclear n emission	0.80	135.1
1.057×10^{13}	$^{94}Cr \rightarrow {}^{88}Ti + 6n - 2e^- + 2\nu_e$	n emission	0.81	11.5
1.254×10^{13}	$^{88}Ti \rightarrow {}^{82}Ca + 6n - 2e^- + 2\nu_e$	n emission	0.82	11.3
1.506×10^{13}	$^{82}Ca \rightarrow {}^{76}Ar + 6n - 2e^- + 2\nu_e$	n emission	0.84	10.9
1.838×10^{13}	$^{76}Ar \rightarrow {}^{70}S + 6n - 2e^- + 2\nu_e$	n emission	0.85	10.0
2.287×10^{13}	$^{70}S \rightarrow {}^{64}Si + 6n - 2e^- + 2\nu_e$ $^{64}Si + {}^{64}Si \rightarrow {}^{128}Ni$ $^{128}Ni \rightarrow {}^{126}Ni + 2n$	n emission pycnonuclear n emission	0.87	67.3
2.784×10^{13}	$^{126}Ni \rightarrow {}^{124}Fe + 2n - 2e^- + 2\nu_e$	n emission	0.88	2.5
3.493×10^{13}	$^{124}Fe \rightarrow {}^{122}Cr + 2n - 2e^- + 2\nu_e$	n emission	0.89	2.4

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

Brown et al. 1998

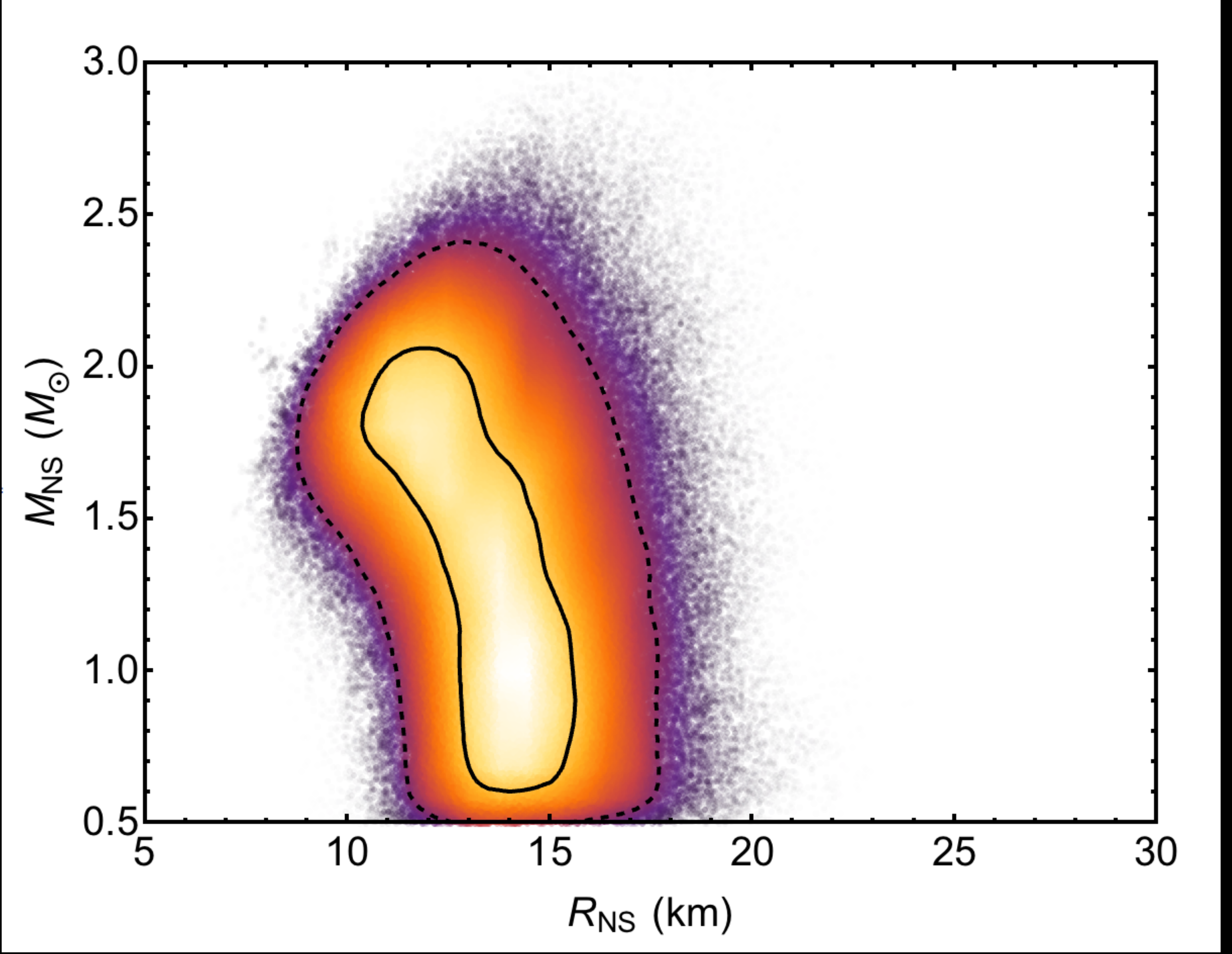


Not all globular cluster qLMXBs are useful.
This is because of large distances and/or absorption.

Globular Cluster	Distance (kpc)	Absorption (N_H in 10^{22} cm^{-2})	qLMXB	"Useful"	Difficulties	Need Chandra
ωCen	4.59	0.09	1			NO
M13	7.1	0.01	1			NO
M28	5.5	0.26	1		Moderate pile-up	YES
NGC 6304	6.2	0.27	1			YES
NGC 6397	2.3	0.14	1			YES
47 Tuc	4.5	0.03	2 (+3?)		Important pile-up	YES
M30	9	0.01	1		Large distance	YES
NGC 6553	6	0.35	1		*NEEDS TO BE CONFIRMED*	YES
M80	10.3	0.09	2		Large distance	YES
NGC 362	8.6	0.03	1		Large distance	YES
NGC 2808	9.6	0.82	1		Large distance and N_H	YES
NGC 3201	5	1.17	1		Very Large N_H	NO
NGC 6440	8.5	0.7	8		Large distance and N_H	YES
Terzan 5	8.7	1.2	4		Large distance and N_H	YES

Unconstrained R_∞ measurements

NGC 6397
with Helium and Pile-up



Straight line EoS: Radius at 1.4 Msun