# The Neutron Star Radius and the dense matter equation of state

Sebastien Guillot
Robert Rutledge
McGill

Government of Canada | Gouvernement du Canada | Canada
Vanier Canada Graduate Scholarships | Bourses d'études supérieures du Canada Vanier

**Results from Guillot et al. 2013, ApJ 772**

Collaborators
Natalie Webb, IRAP (Toulouse, France)
Mathieu Servillat, Harvard-CfA & CEA Saclay

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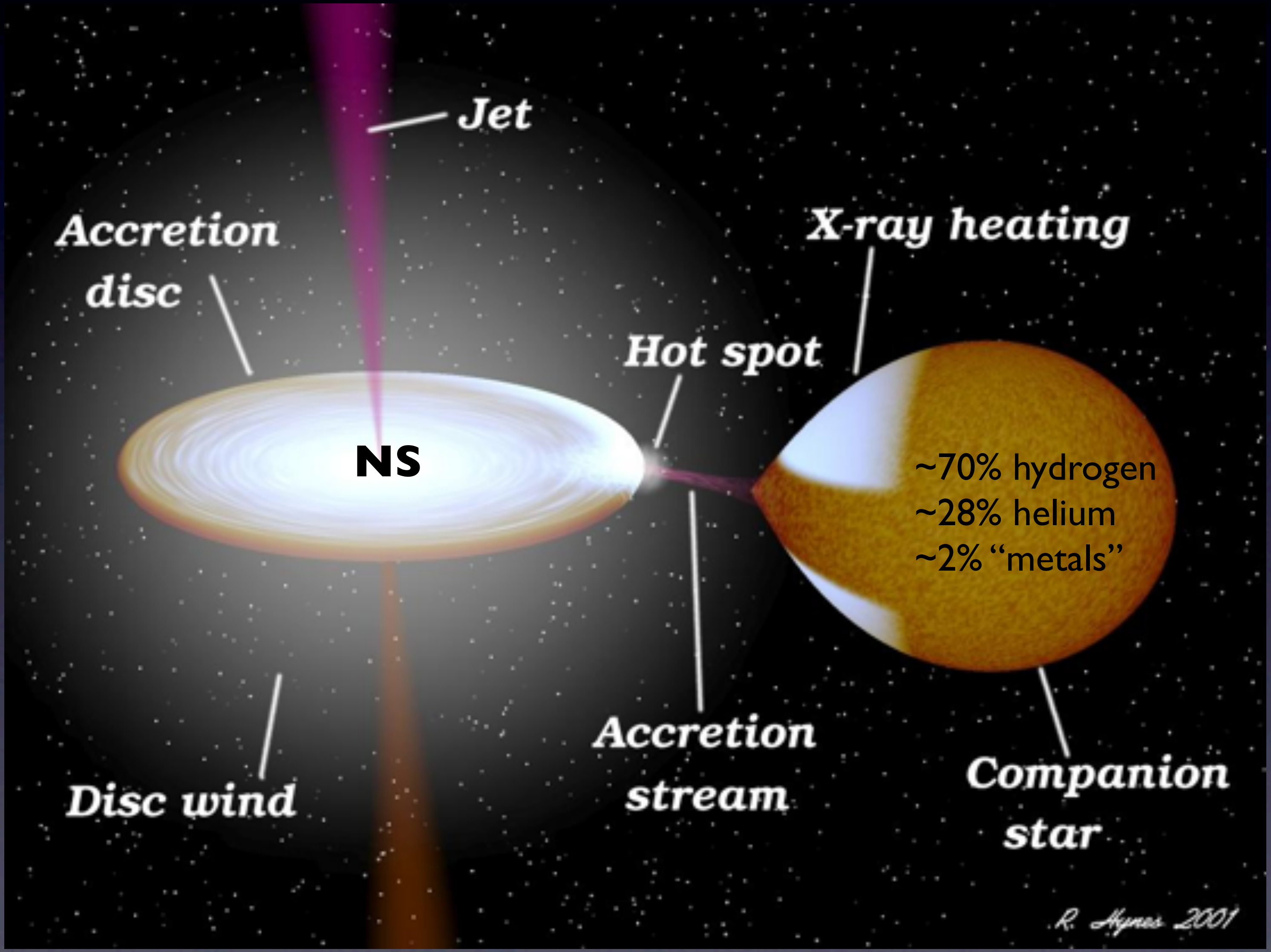
# Quiescent low-mass X-ray binaries are ideal systems for Mass-Radius measurements.

- 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 magnetic field



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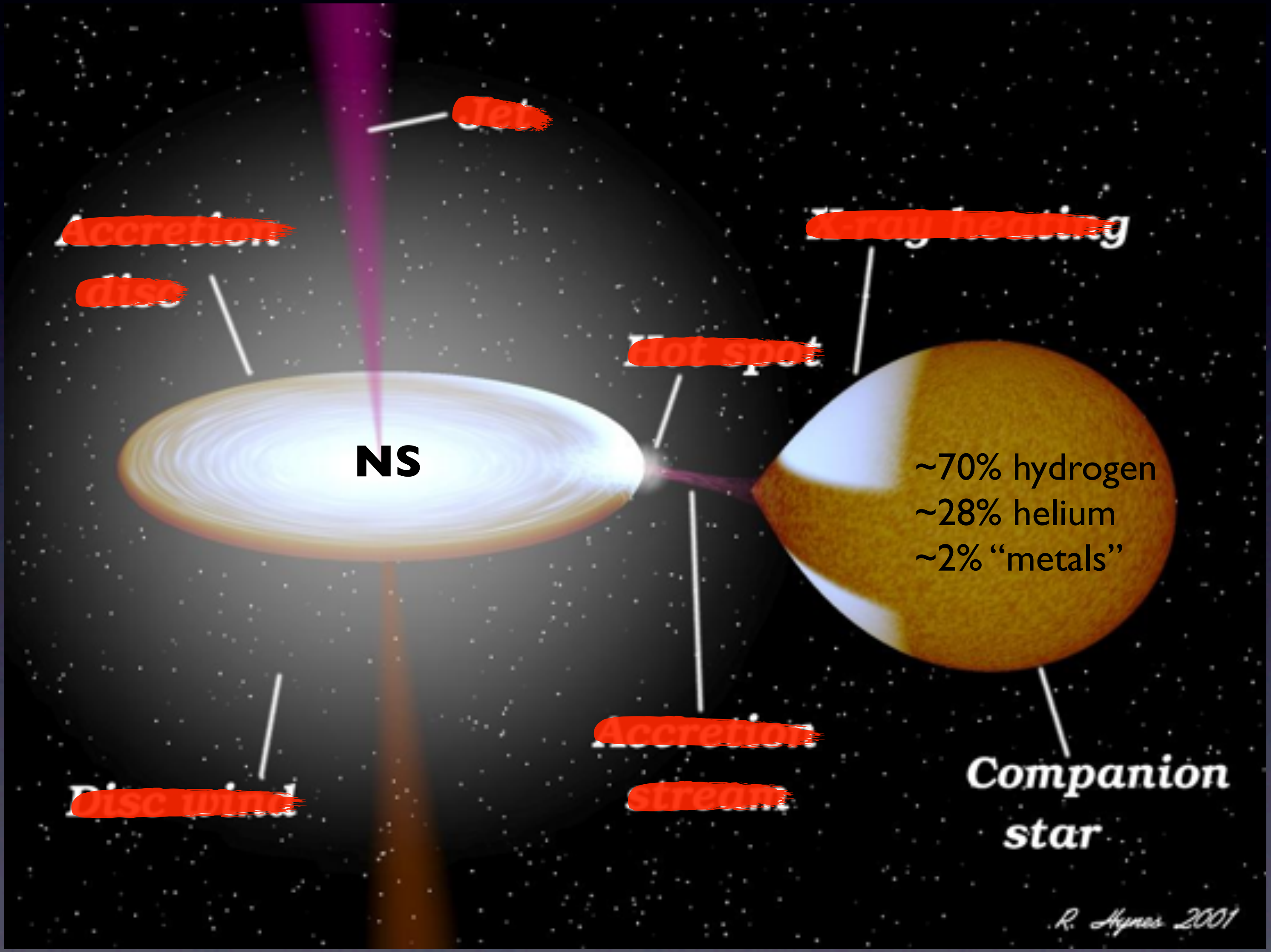
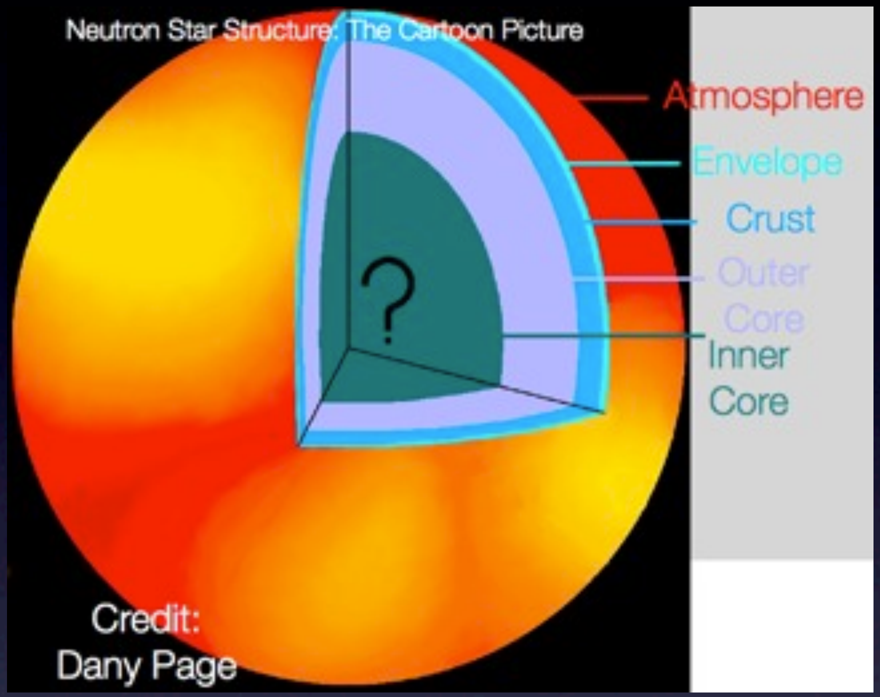
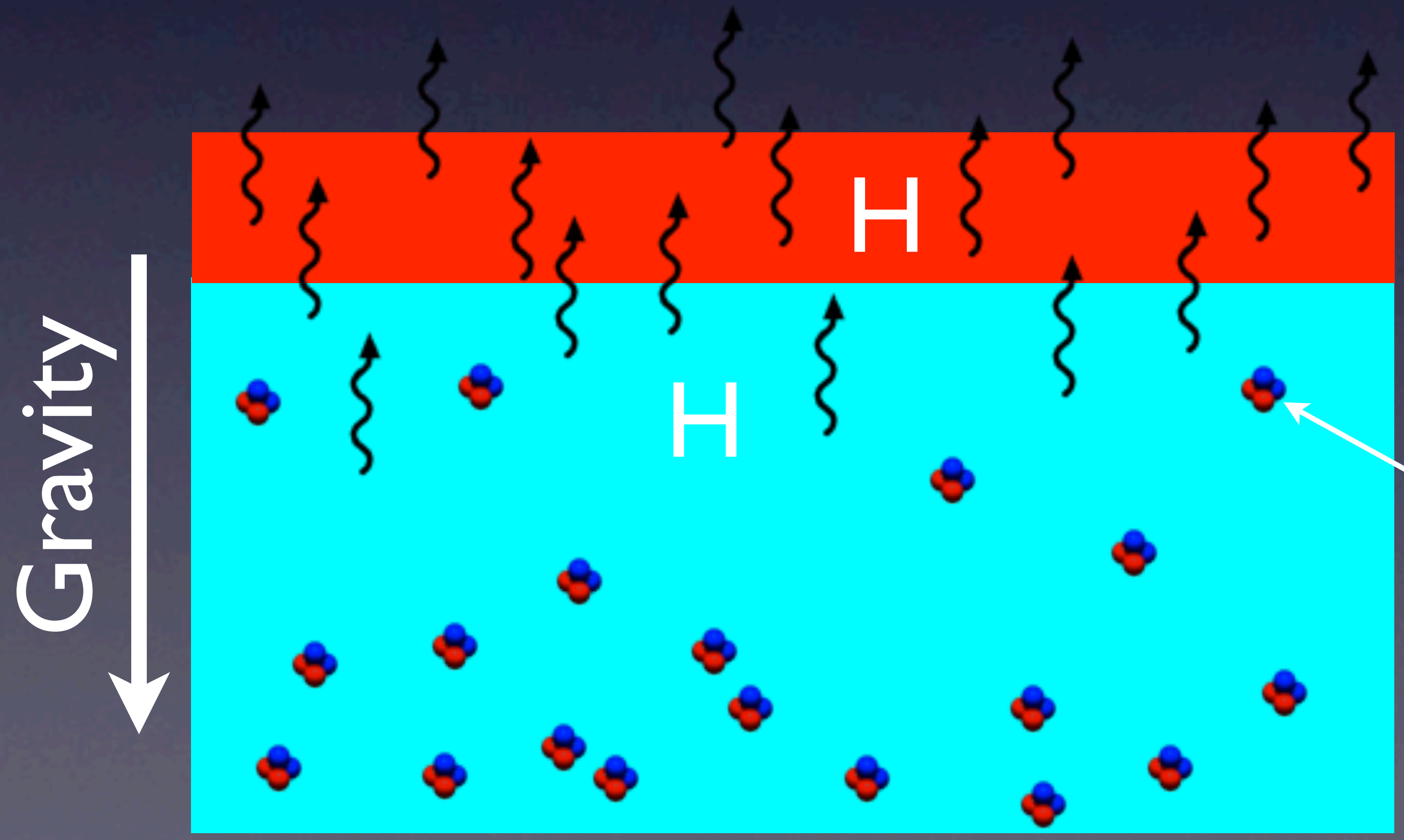


# The atmosphere of the neutron star in a qLMXB is composed of pure hydrogen.

H-atmosphere
thermal spectrum
seen by observer



Credit:
Dany Page

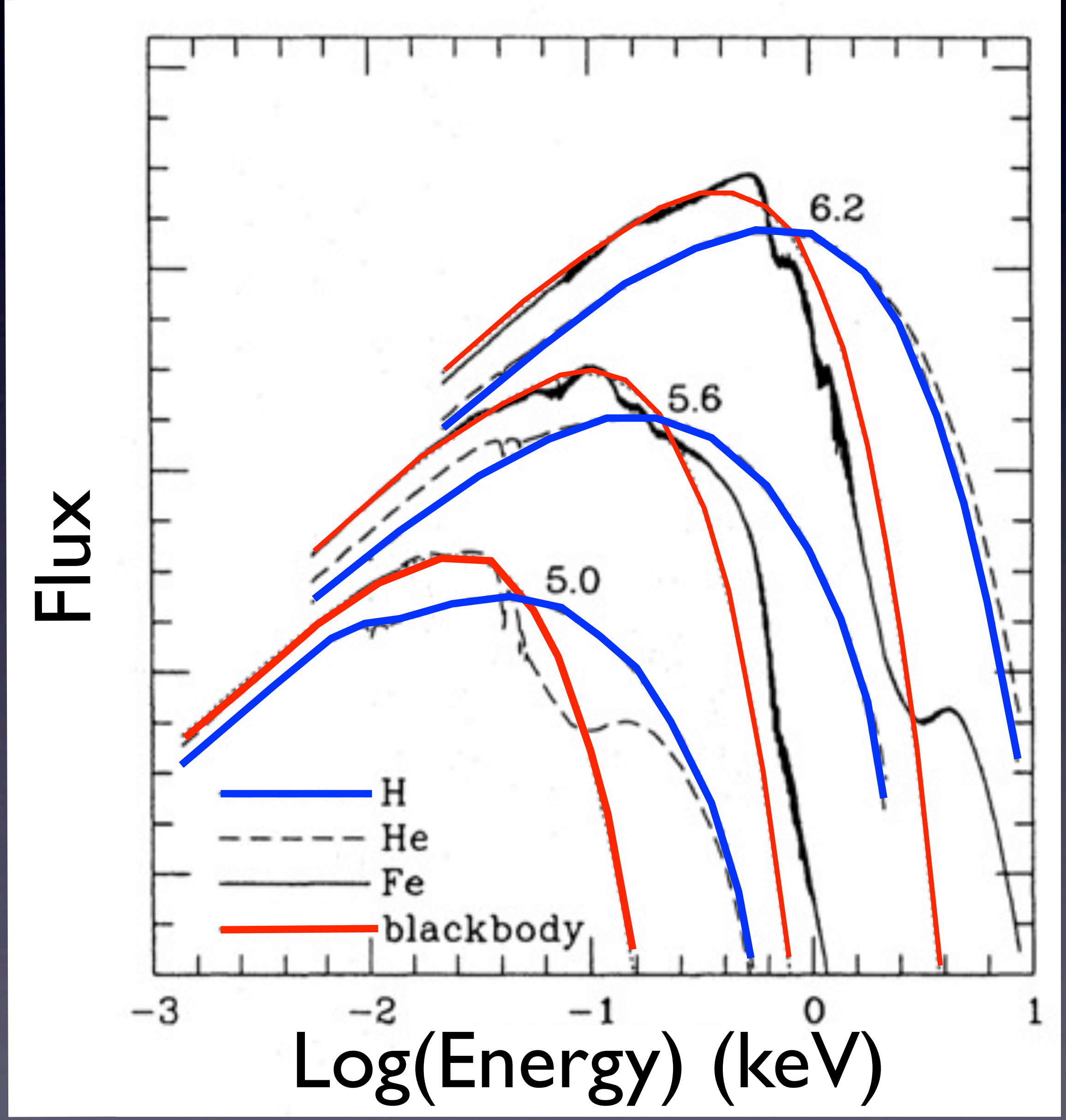


Photosphere ~ 10 cm

Helium

# 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

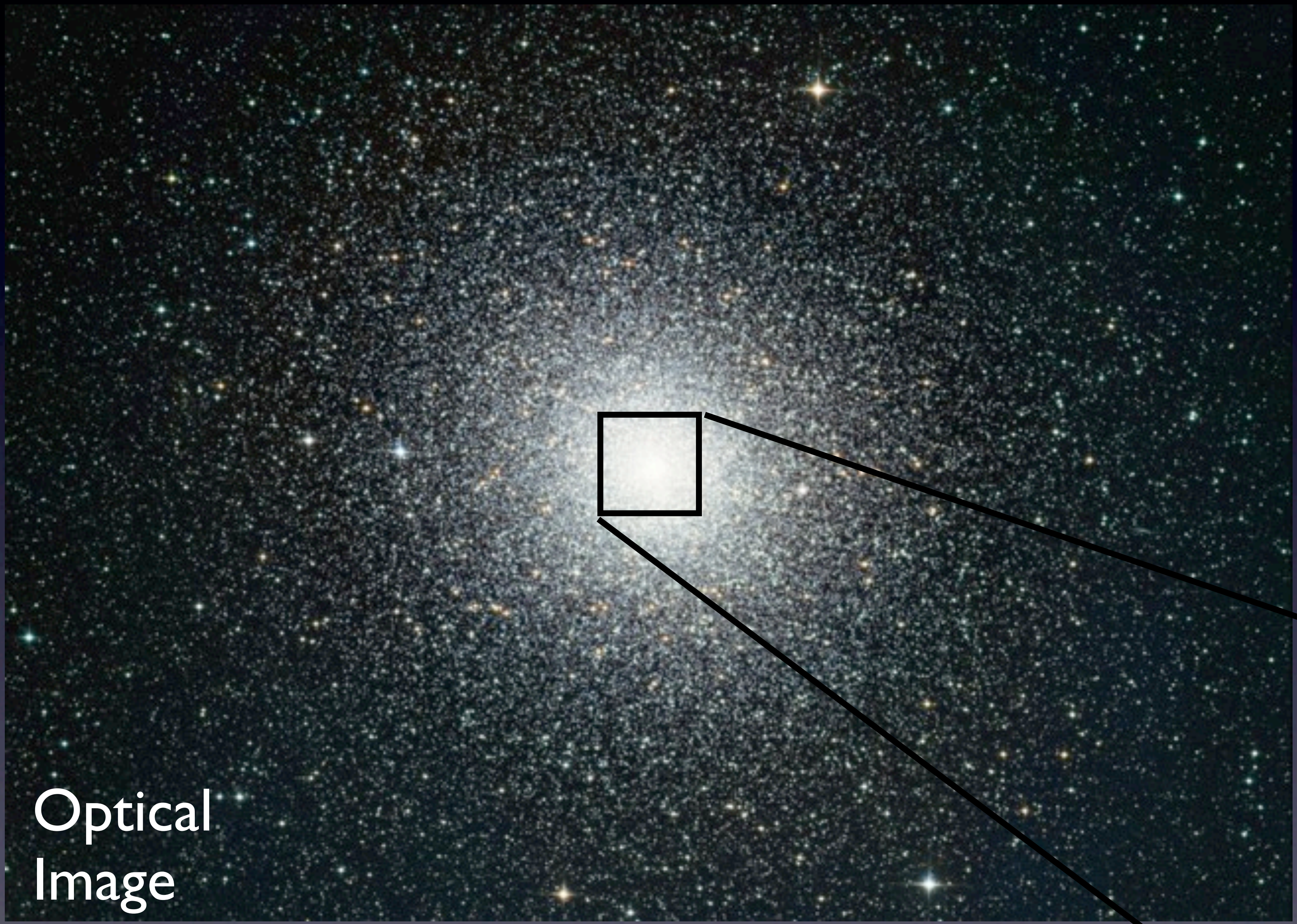
Spectral fitting of the thermal emission gives us $\mathbf{T_{eff}}$ and $\mathbf{(R_\infty/D)^2}$

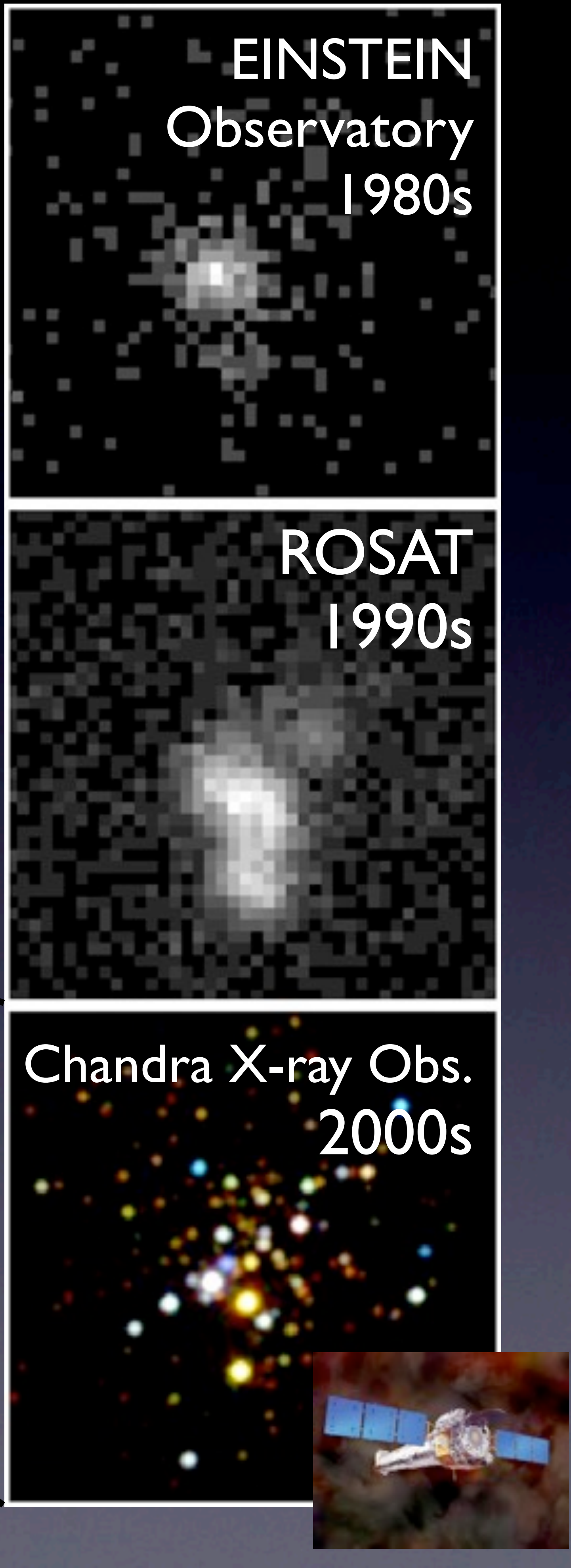
$$R_\infty = R_{\rm NS}\left(1 - \frac{2GM_{\rm NS}}{R_{\rm NS}\ c^2},\right)^{-1/2}$$

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...





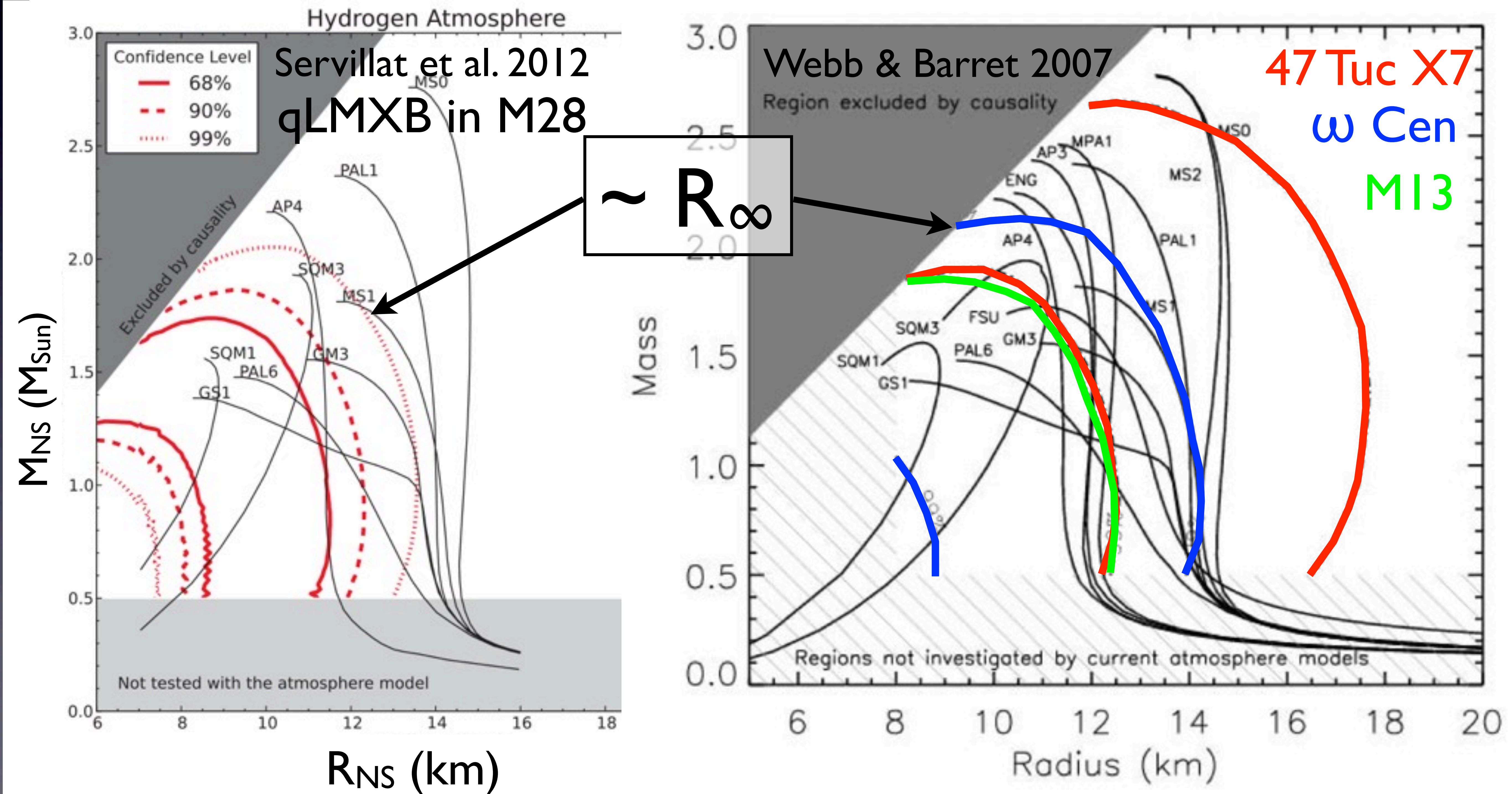
...and they have well-measured distances.

# 29 quiescent LMXBs are known within globular clusters of the Milky Way.

| Globular Cluster | Distance (kpc) | $N_H$ ($10^{22}$ cm$^{-2}$) | qLMXB | "Useful" | Difficulties | Need Chandra |
|---|---|---|---|---|---|---|
| ωCen | 5.3 | 0.09 | 1 | 🟩 | | NO |
| M13 | 7.7 | 0.01 | 1 | 🟩 | | NO |
| M28 | 5.5 | 0.26 | 1 | 🟩 | Moderate pile-up | YES |
| NGC 6304 | 6.0 | 0.27 | 1 | 🟩 | | YES |
| NGC 6397 | 2.5 | 0.14 | 1 | 🟩 | | YES |
| NGC 6553 | 6.0 | 0.35 | 1 | 🟩 | *NEEDS TO BE CONFIRMED* | YES |
| 47 Tuc | 4.5 | 0.03 | 2 (+3?) | 🟧 | Important pile-up | YES |
| M30 | 9.0 | 0.03 | 1 | 🟧 | Large distance | 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 | 5.0 | 1.17 | 1 | 🟥 | Very Large $N_H$ | NO |
| NGC 6440 | 8.5 | 0.70 | 8 | 🟥 | Large distance and $N_H$ | YES |
| Terzan 5 | 8.7 | 1.20 | 4 | 🟥 | Large distance and $N_H$ | YES |

Unconstrained measurements

# 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

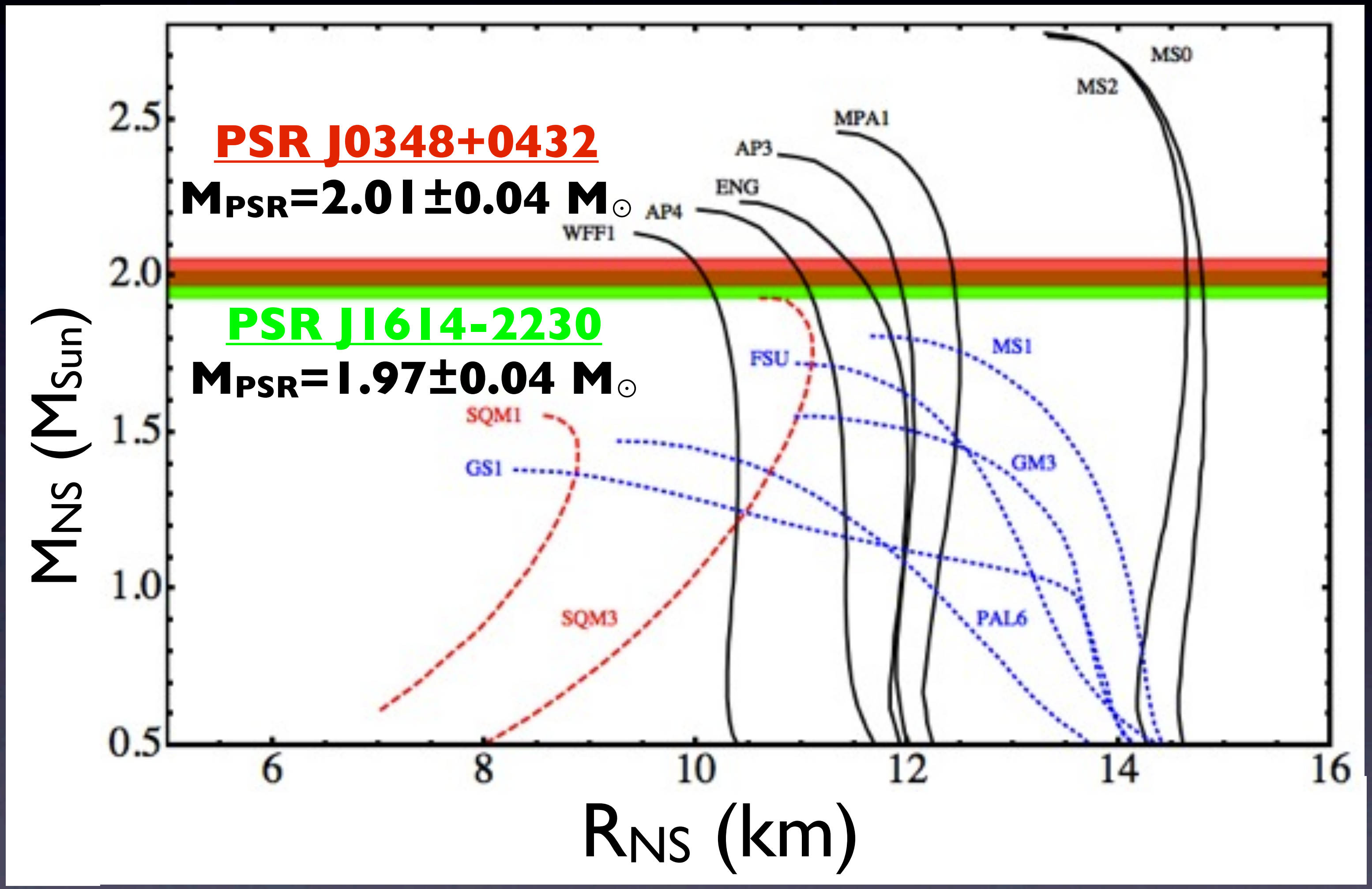
~ $R_\infty$

Webb & Barret 2007

47 Tuc X7
ω Cen
M13

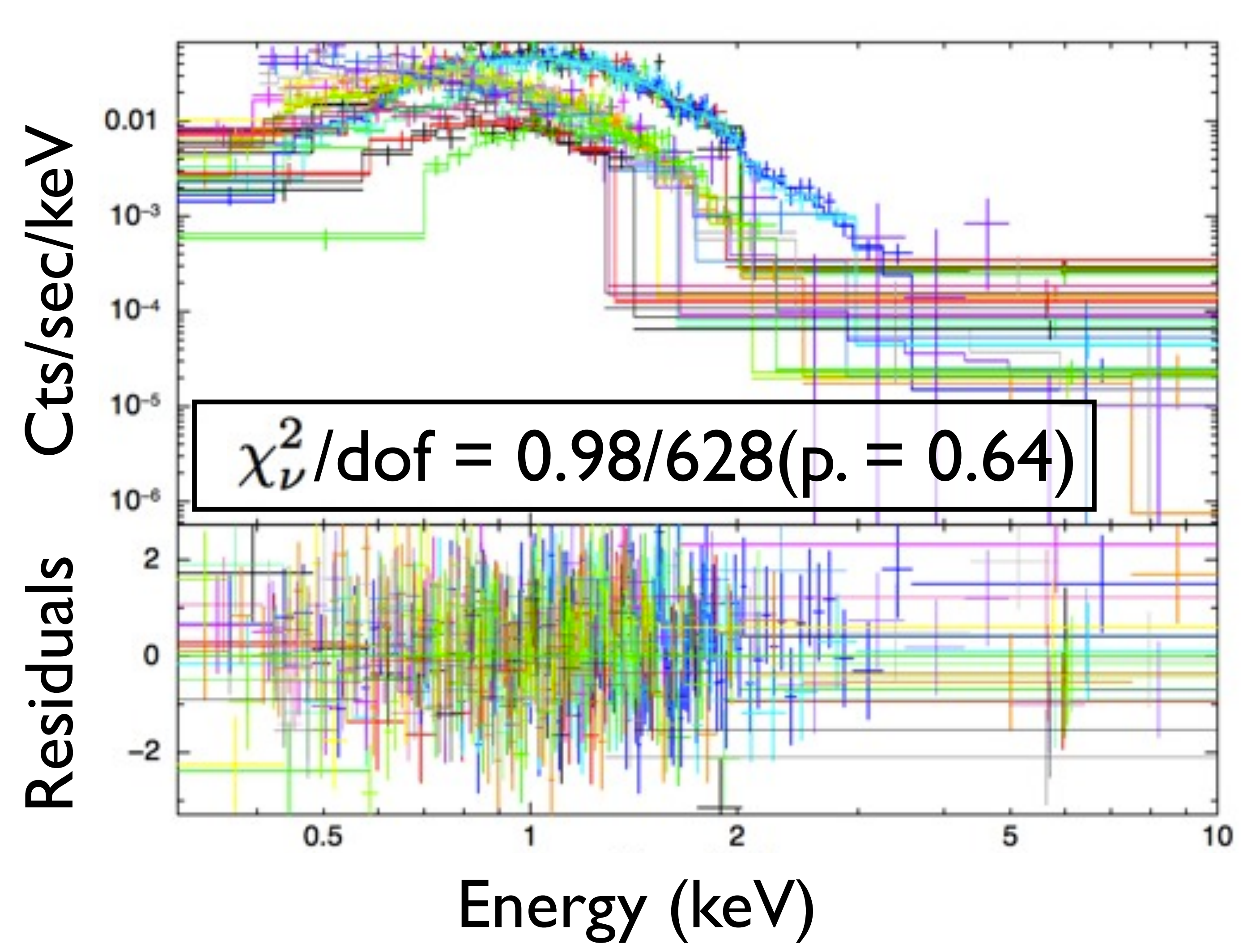
# In Guillot et al (2013), we follow a simplified parametrization for the EoS.

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 5 qLMXBs with H-atmosphere model



**One radius to fit them all!**

Five parameters per target:

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

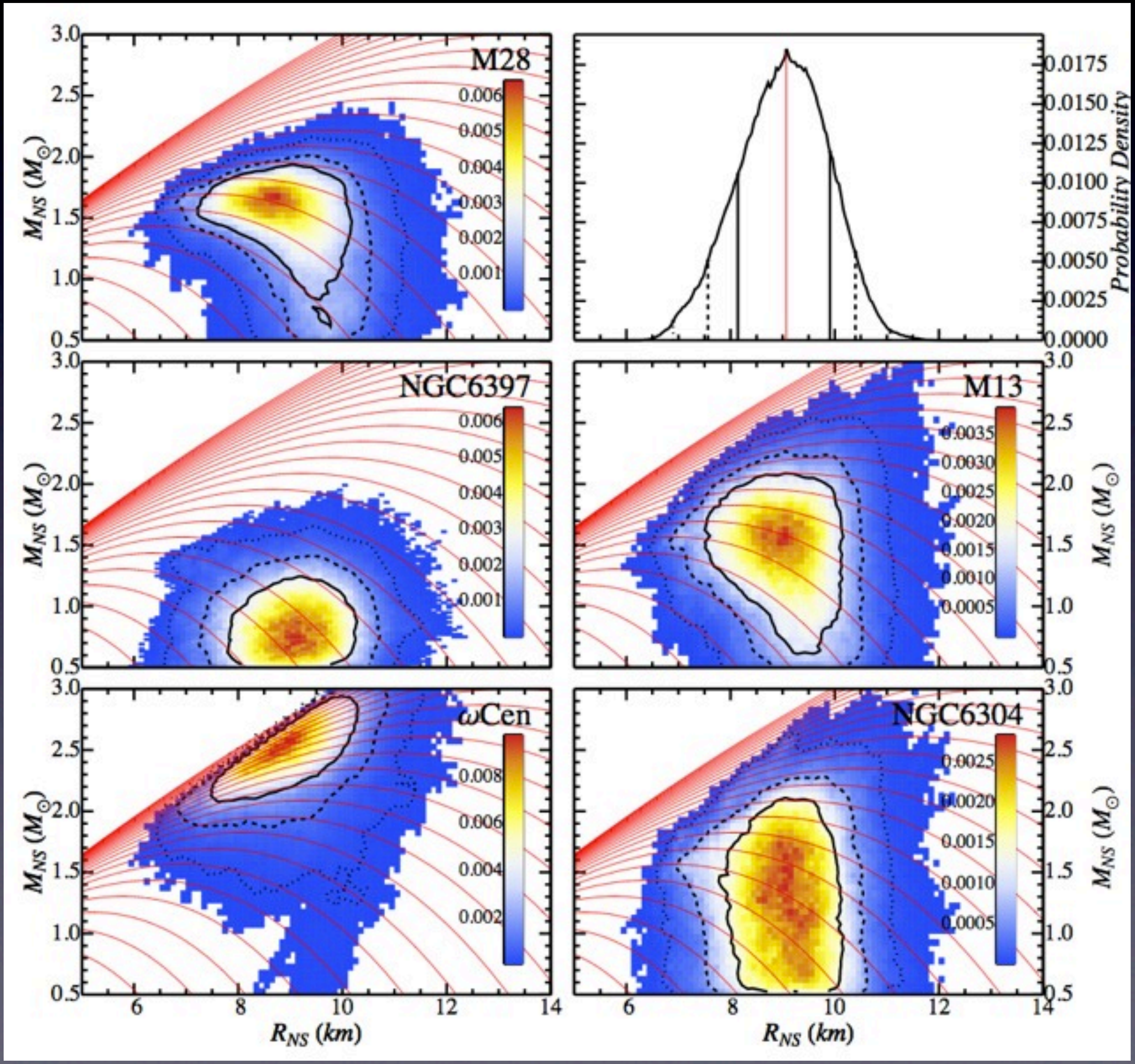
Guillot et al. 2013

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

**Most conservative NS radius measurement is**

$$R_{\rm NS} = 9.1^{+1.3}_{-1.5}\ \rm km$$

90% conf. level



Guillot et al. 2013

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

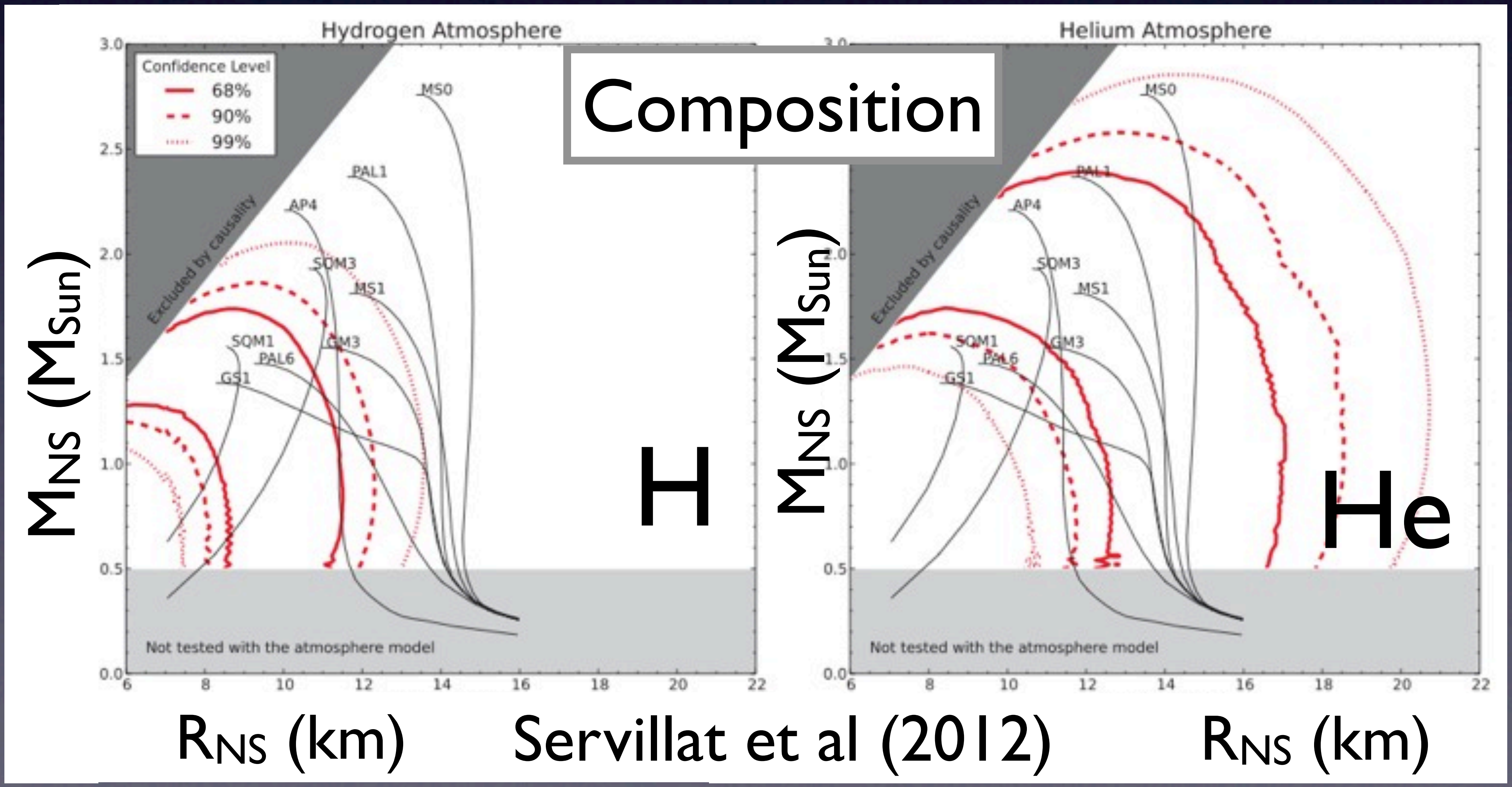
We included the uncertainties linked to:

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

# There are analysis assumptions

NS surface emits isotropically

Negligible magnetic field

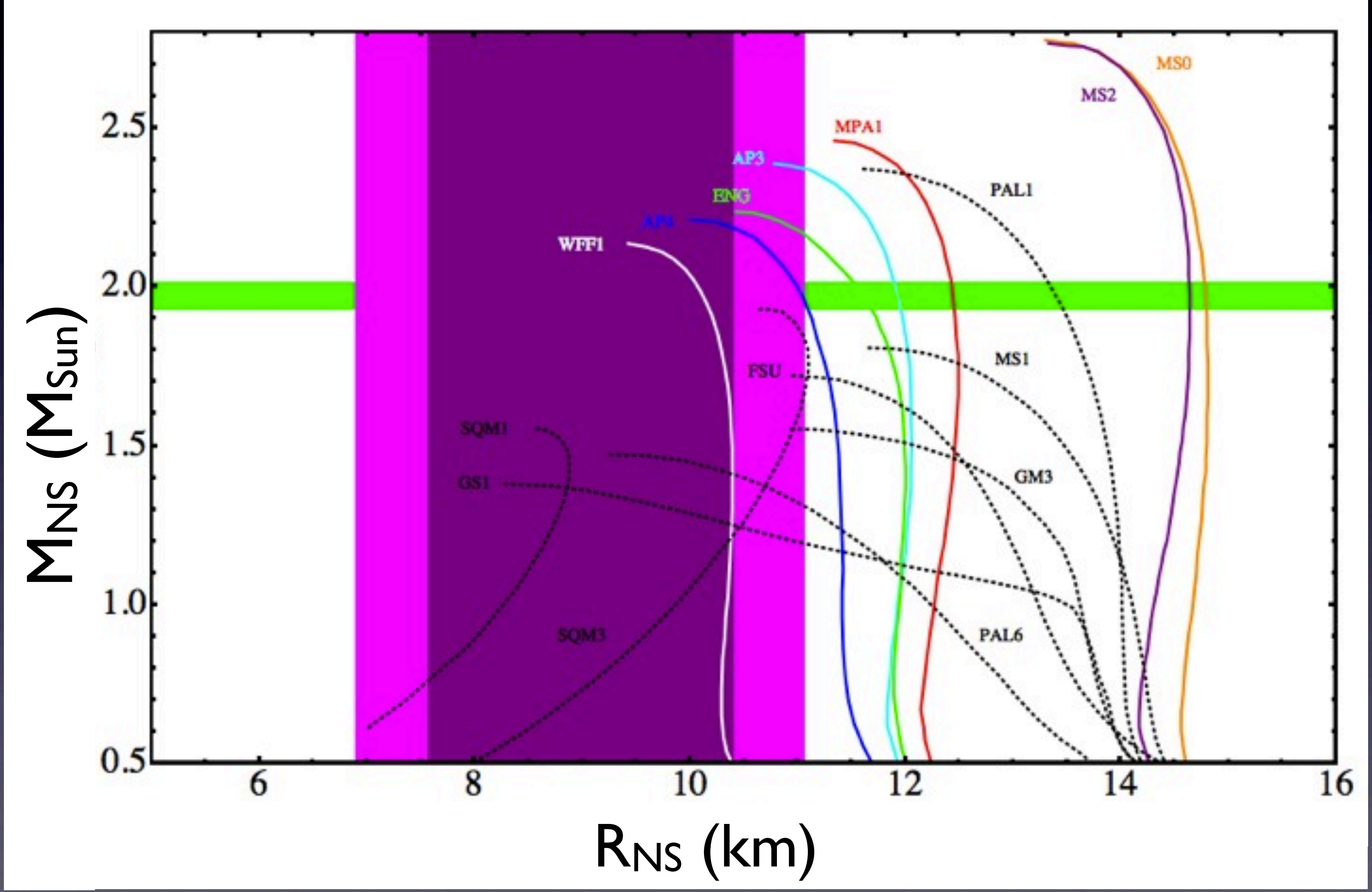


Composition

Servillat et al (2012)

Guillot et al. 2013

# Our most conservative radius measurement places important constraints on the dense matter equation of state.



$R_{NS}$ in the 7-11 km range at the 99%-confidence level

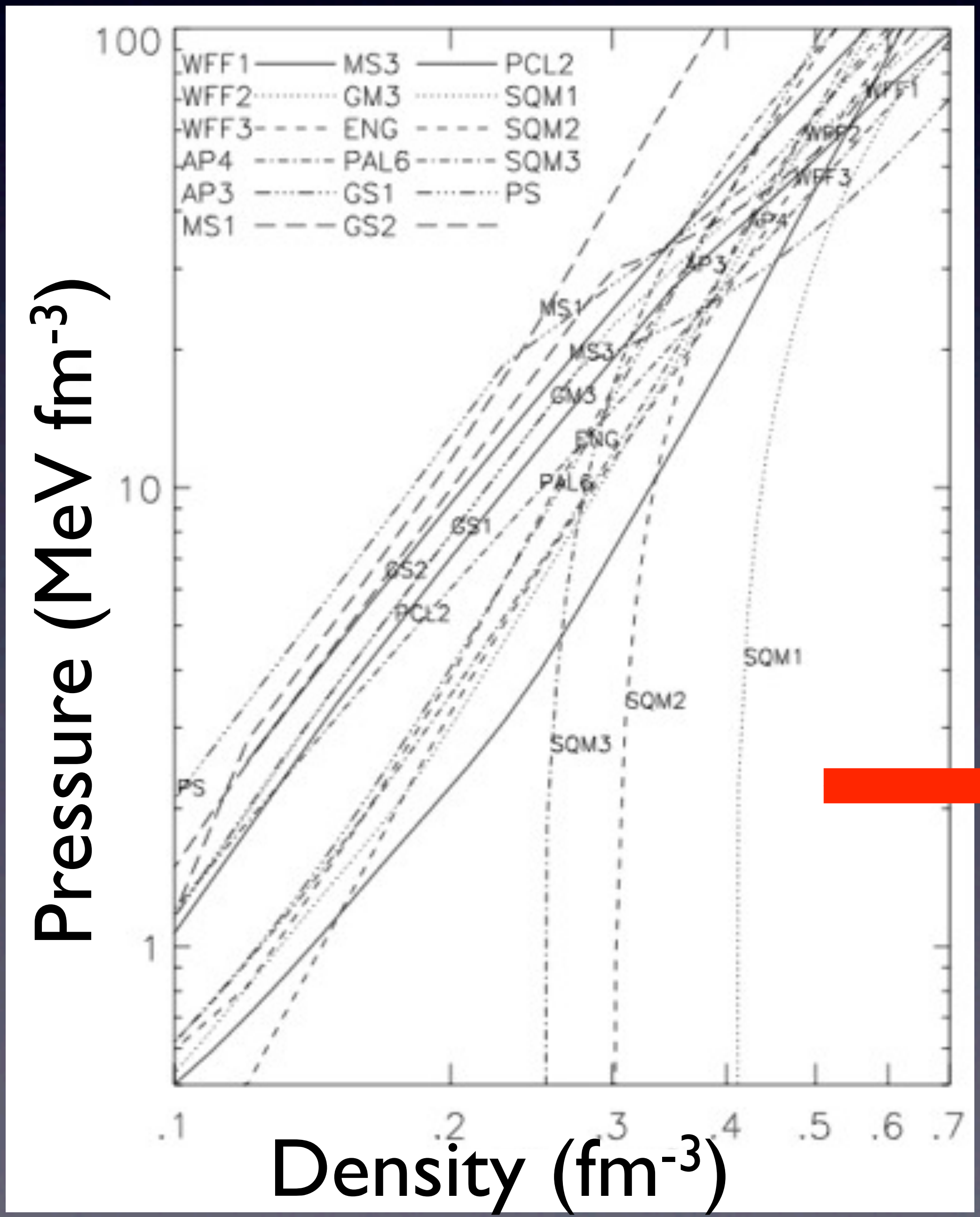
Guillot et al. 2013

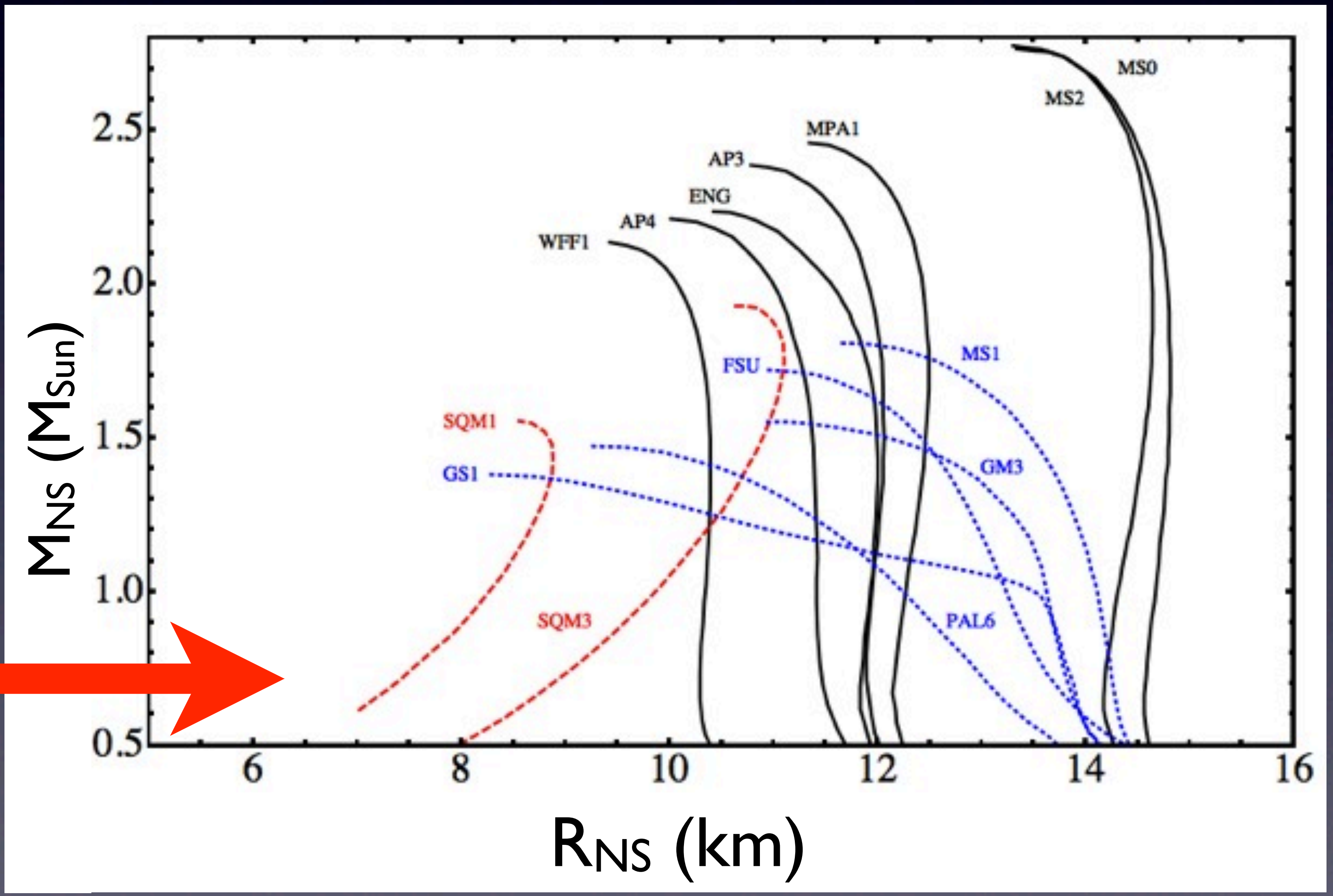
# Conclusions

- Evidence that $R_{NS}$ is constant for a wide range of masses
- Use this assumption to 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 $R_{\rm NS} = 9.1^{+2.0}_{-2.2}\,{\rm km}$ (99% c.l.) with the least number of assumptions, and a particular effort to control systematic uncertainties.
- Only some EoSs are consistent with these results, for example, WFF1 (Wiringa et al 1988)

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

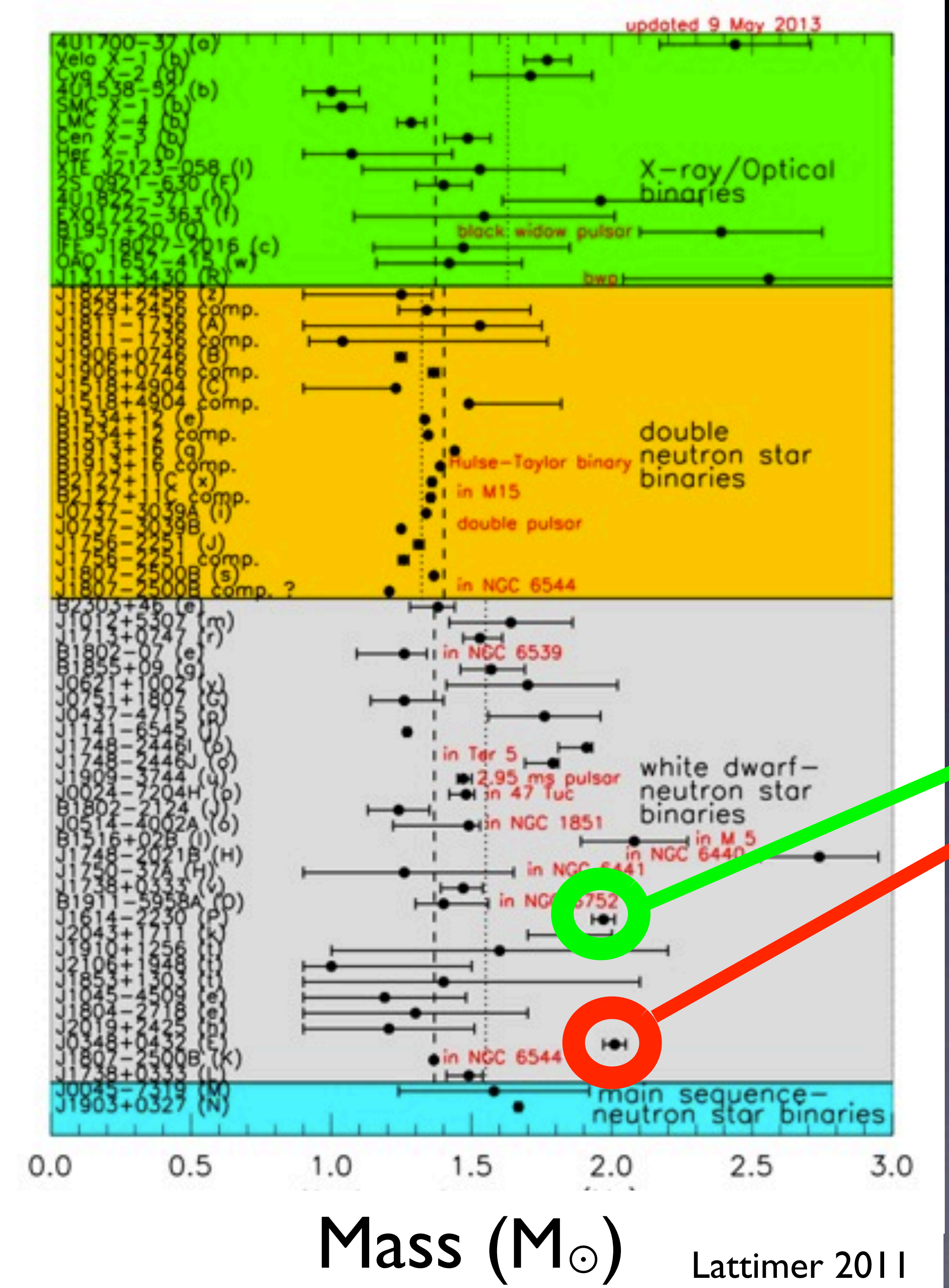
Density at and above nuclear saturation density $\rho_{nuc}=2.8\times10^{14}$ g/cm3





Lattimer and Prakash 2001

# Only new $M_{NS}$ measurements larger than previous ones improve constraints on the dense matter EoS



Lattimer 2011

**PSR J1614-2230**

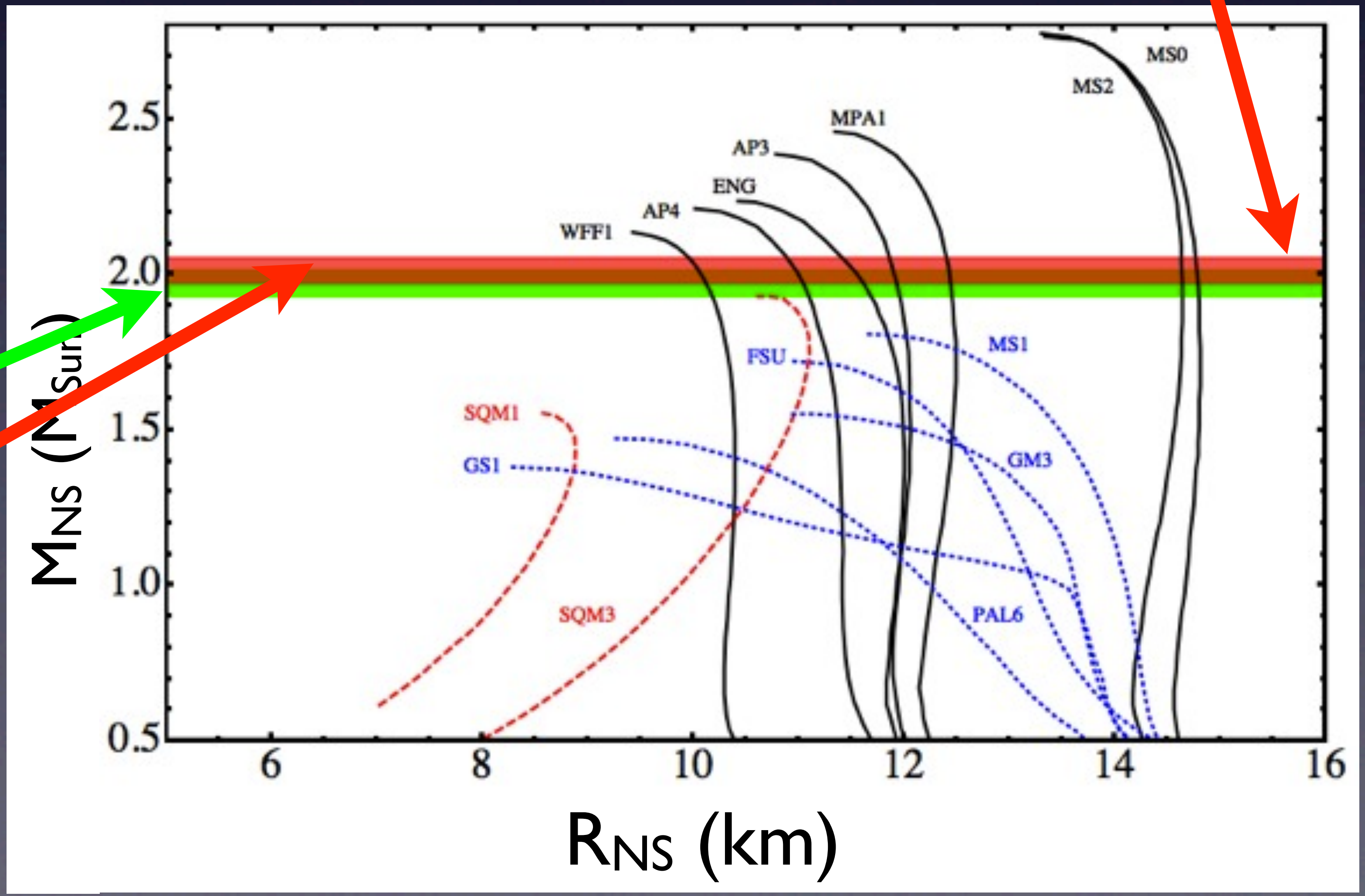
$M_{PSR}=1.97\pm0.04\ M_\odot$

(Demorest et al. 2010)

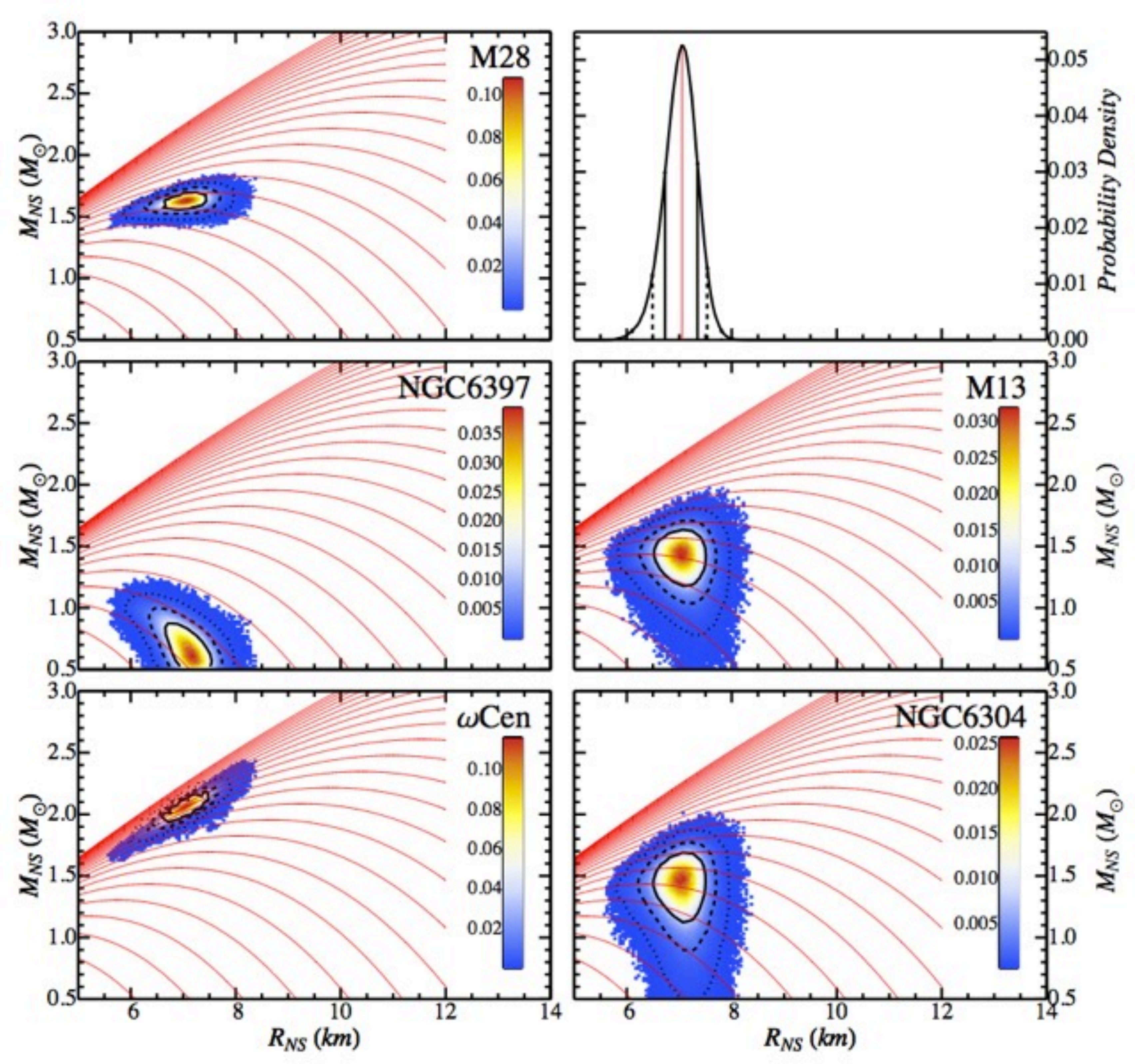
**PSR J0348+0432**

$M_{PSR}=2.01\pm0.04\ M_\odot$

(Antoniadis et al. 2013)



# Our MCMC results with the strongest assumption dependence are the most constraining



We start with an MCMC run with the following assumptions:

- fixed Galactic absorption $N_H$
- fixed distances to clusters
- no power-law component

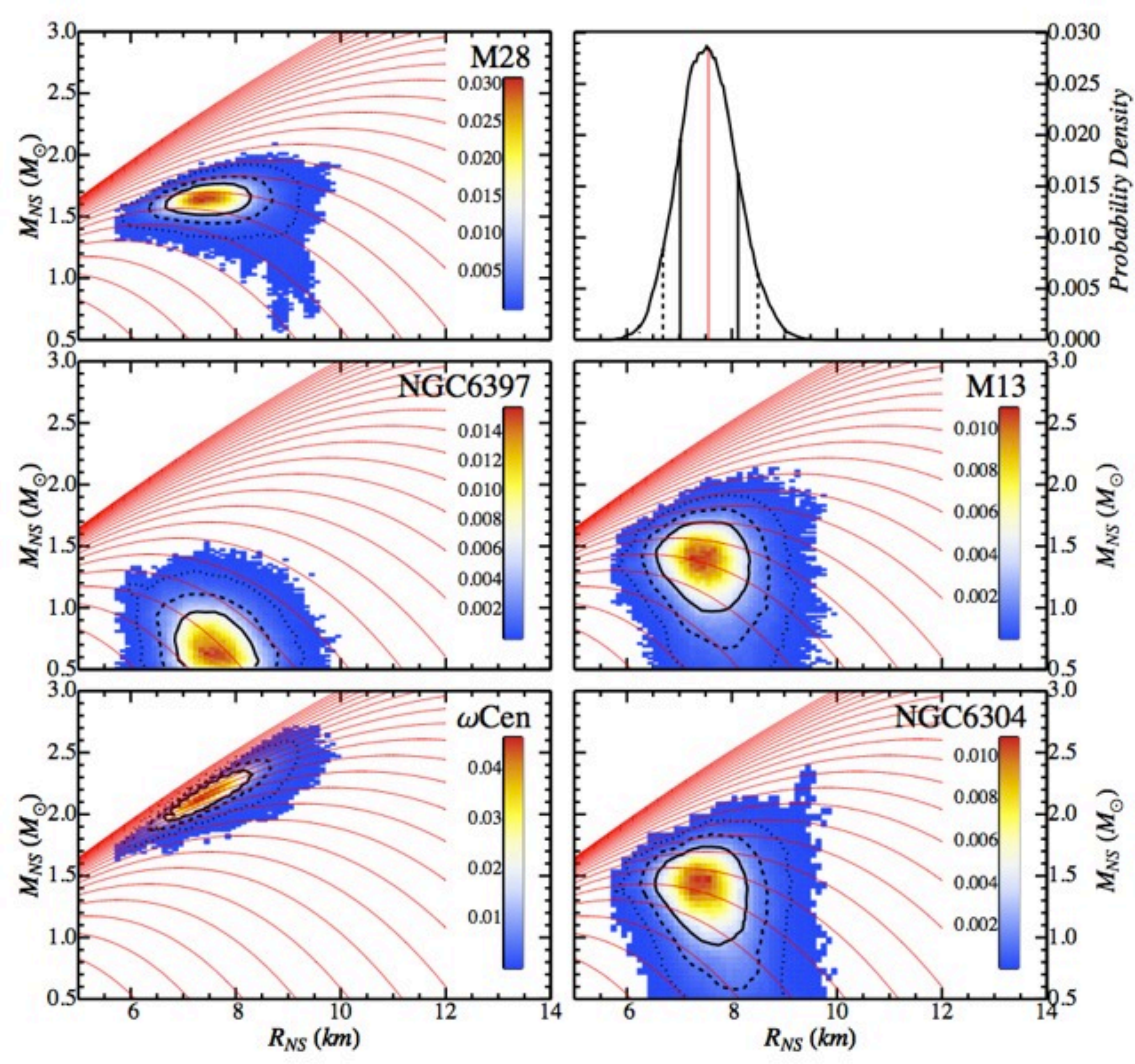
Afterwards, we progressively relax the assumptions.

Guillot et al. 2013

# As assumptions are relaxed, uncertainties increase in the $R_\infty$ direction.

Relaxing assumptions contributes to total uncertainty

For example here, the distance contributes to uncertainties in the $R_\infty$ direction



Guillot et al. 2013

# Constraints on the nuclear matter EoS can be derived from neutron star observations.

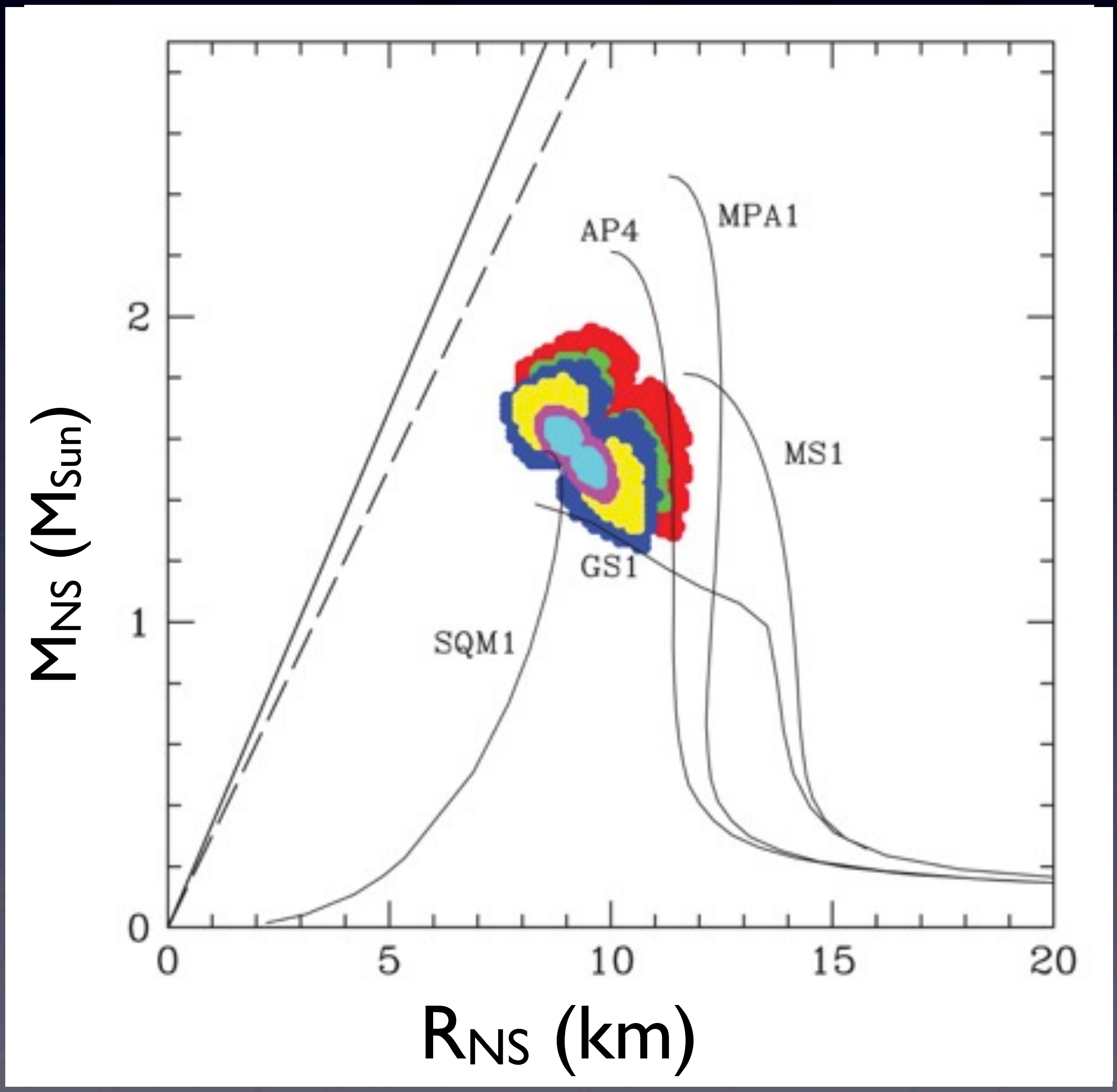
Thermonuclear X-ray burst from accreting low-mass X-ray binaries

(Özel 2006, Suleimanov et al. 2011)

<u>2 observables</u>

$$A = \frac{R^2}{D^2 f_c^4}\left(1 - \frac{2GM}{Rc^2}\right)^{-1}$$

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



Özel et al. 2010

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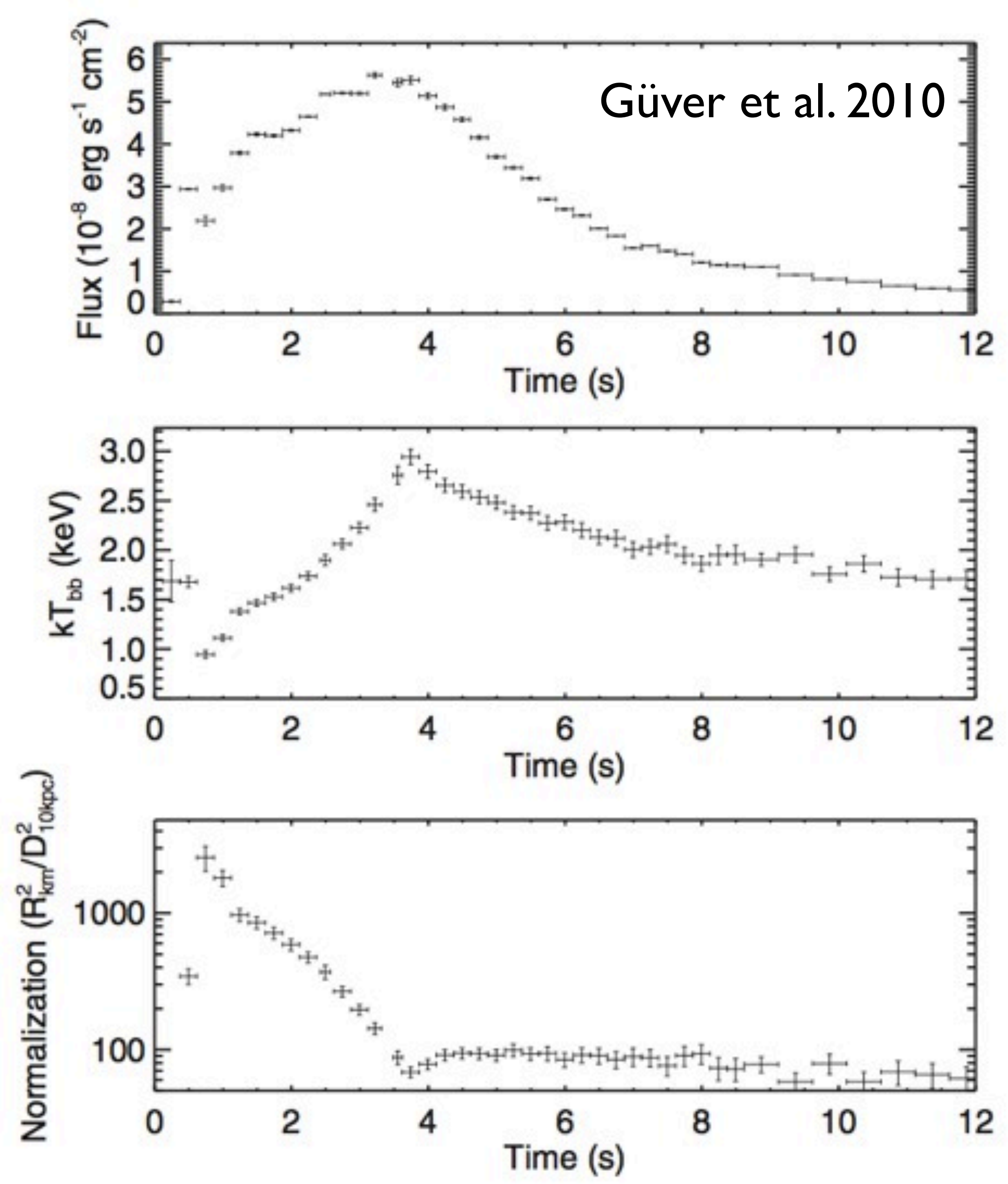

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# qLMXBs inside globular clusters are observed with Chandra, and sometimes with XMM-Newton.

Chandra X-Ray Observatory

XMM-Newton

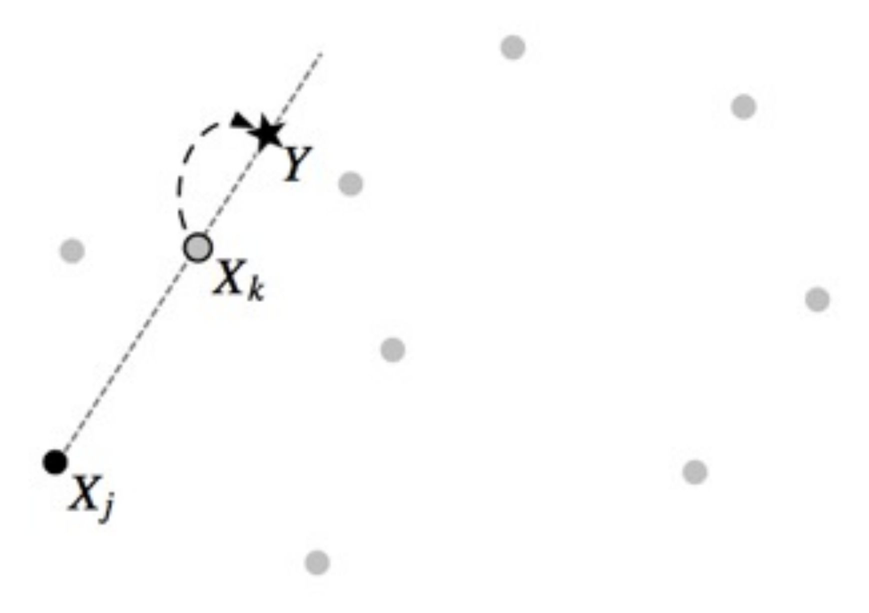
1" angular resolution

6" angular resolution
4x more effective area than Chandra

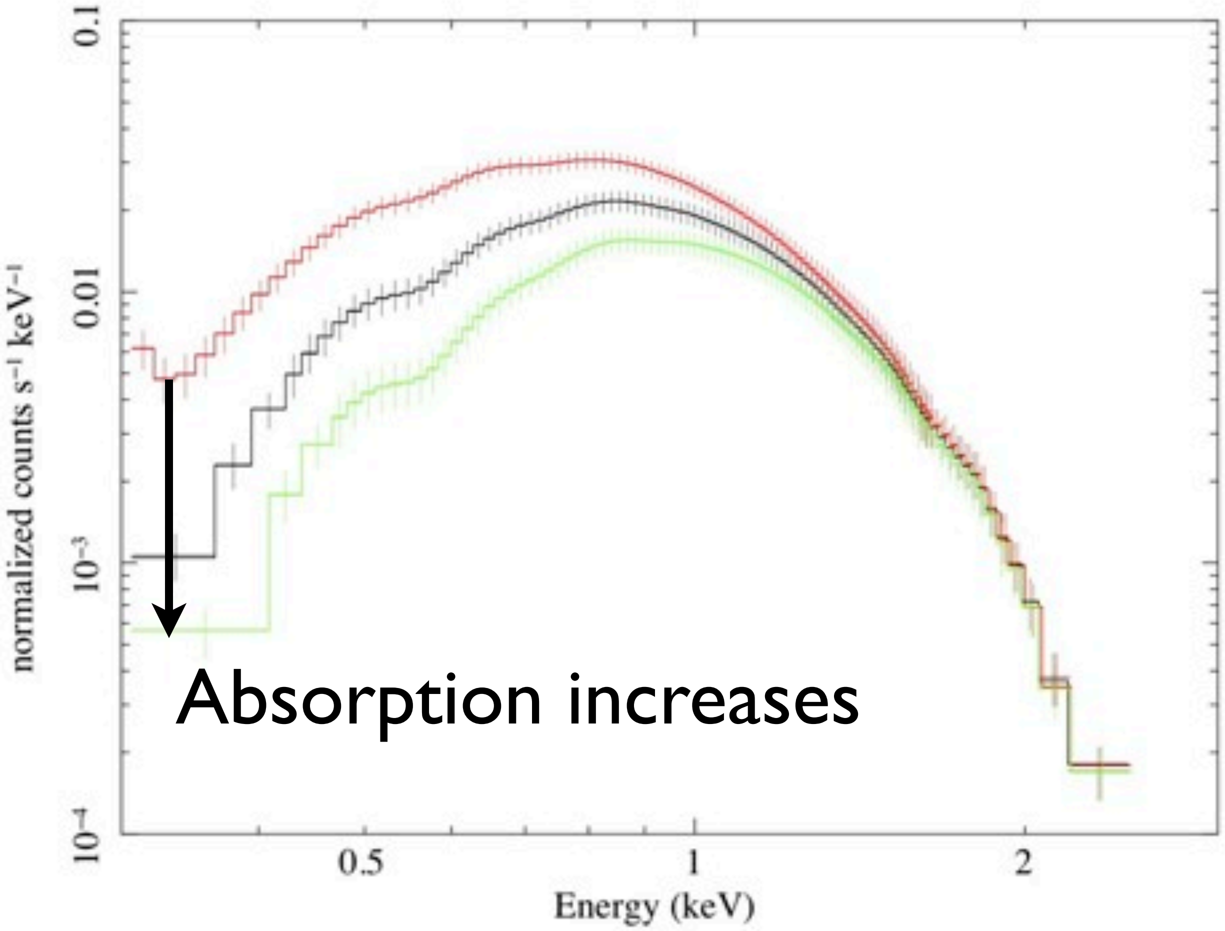
# A Markov Chain Monte Carlo approach is best for error estimation, and the addition of Bayesian priors.

- Because one cannot easily find the global minimum with standard $\chi^2$ minimization technique
- Because one can include Bayesian priors for the distances
- Because one can easily obtain the marginalized posterior distribution for each parameter

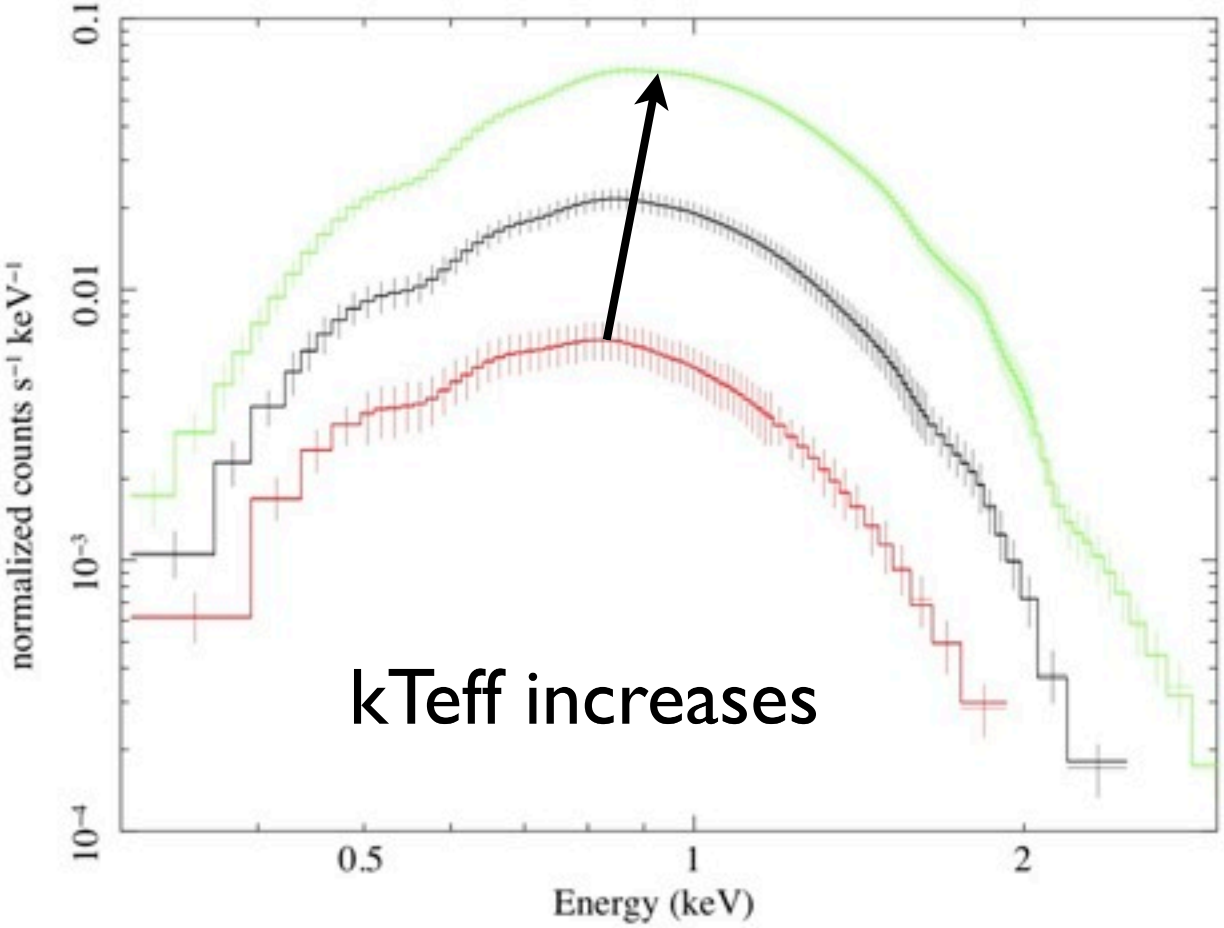
We use the "Stretch-Move" algorithm, instead of Metropolis-Hasting, because it is more appropriate (faster convergence) for elongated and curved distributions



Python implementation of "stretch-move"
MCMC algorithm by René Breton

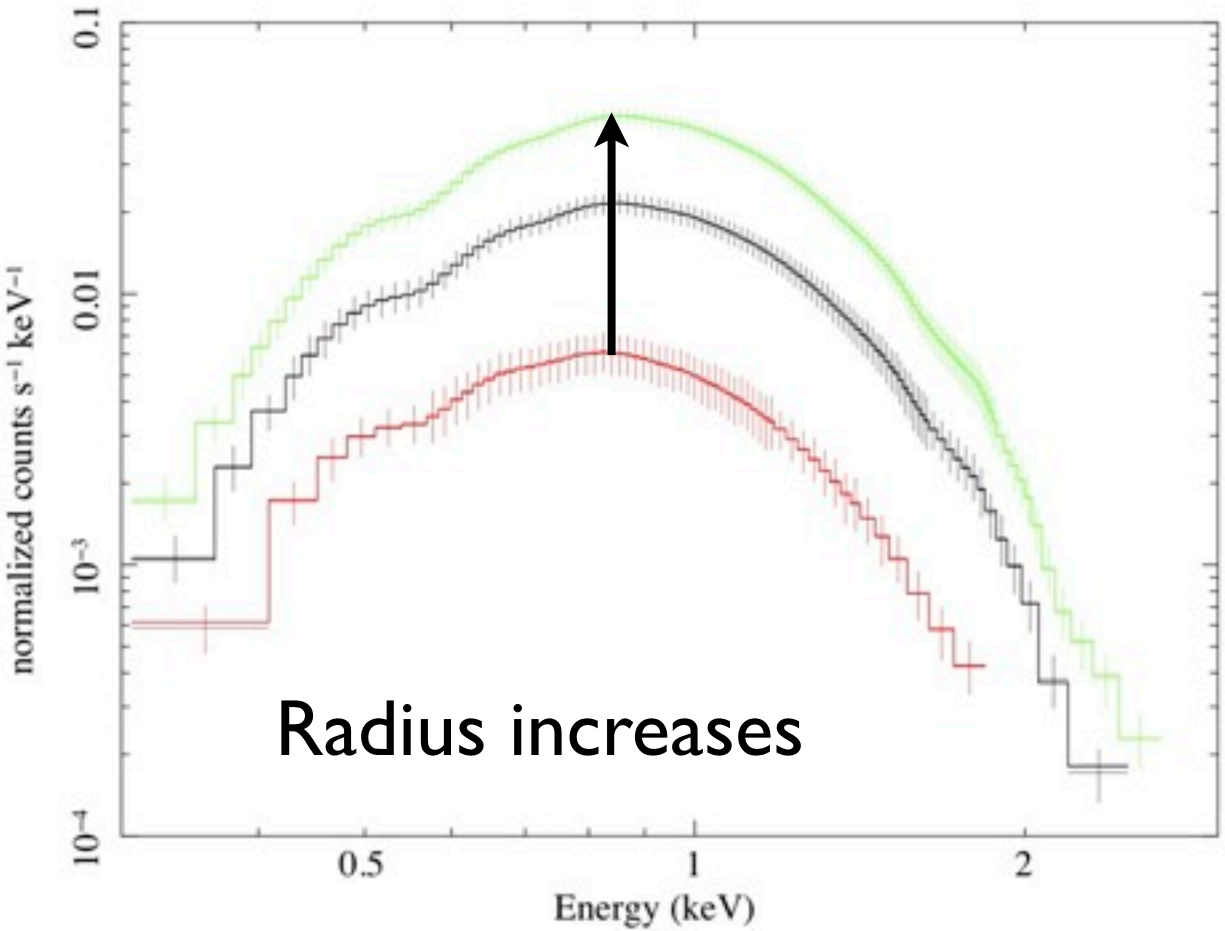


Absorption increases

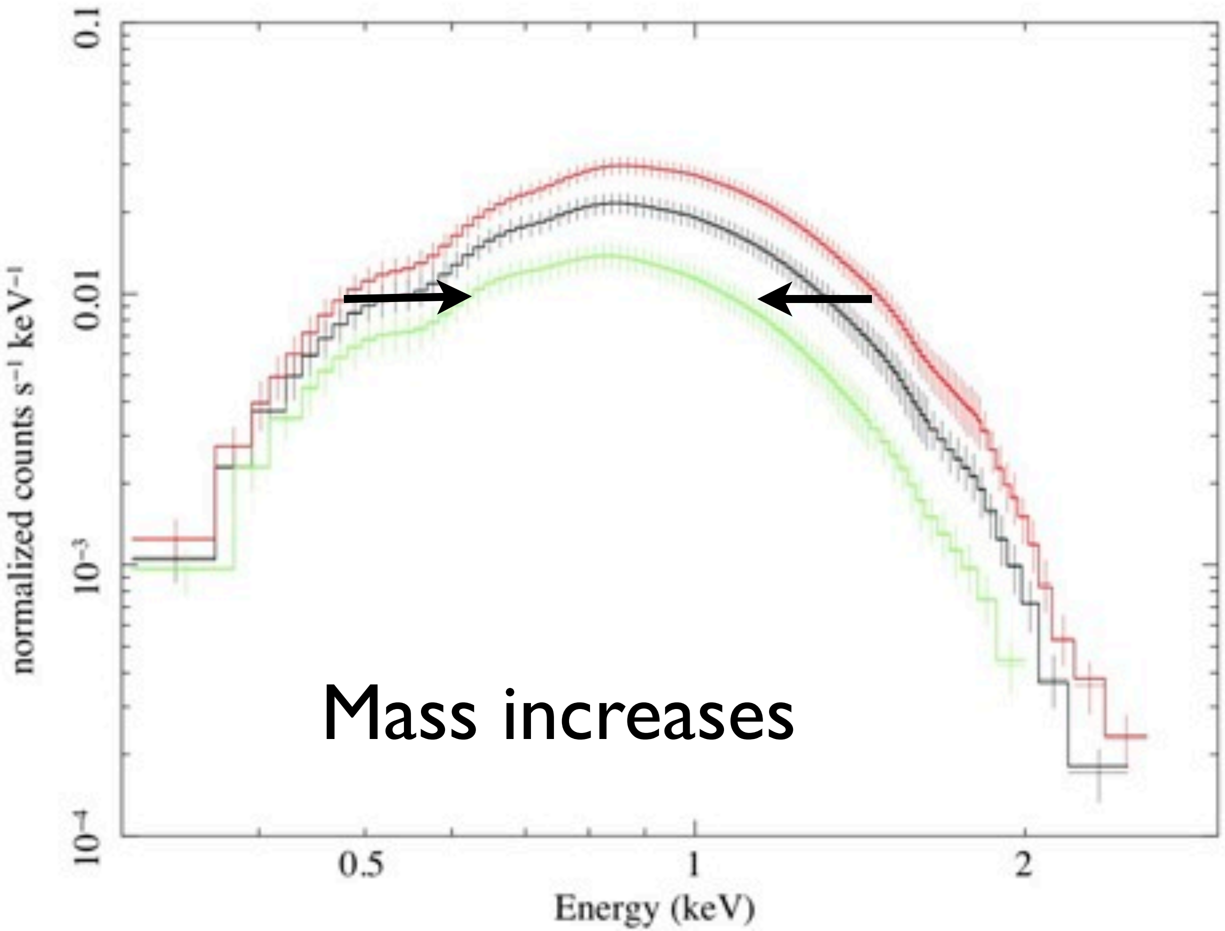


kTeff increases

**Neutron stars properties are extracted from the spectra.**



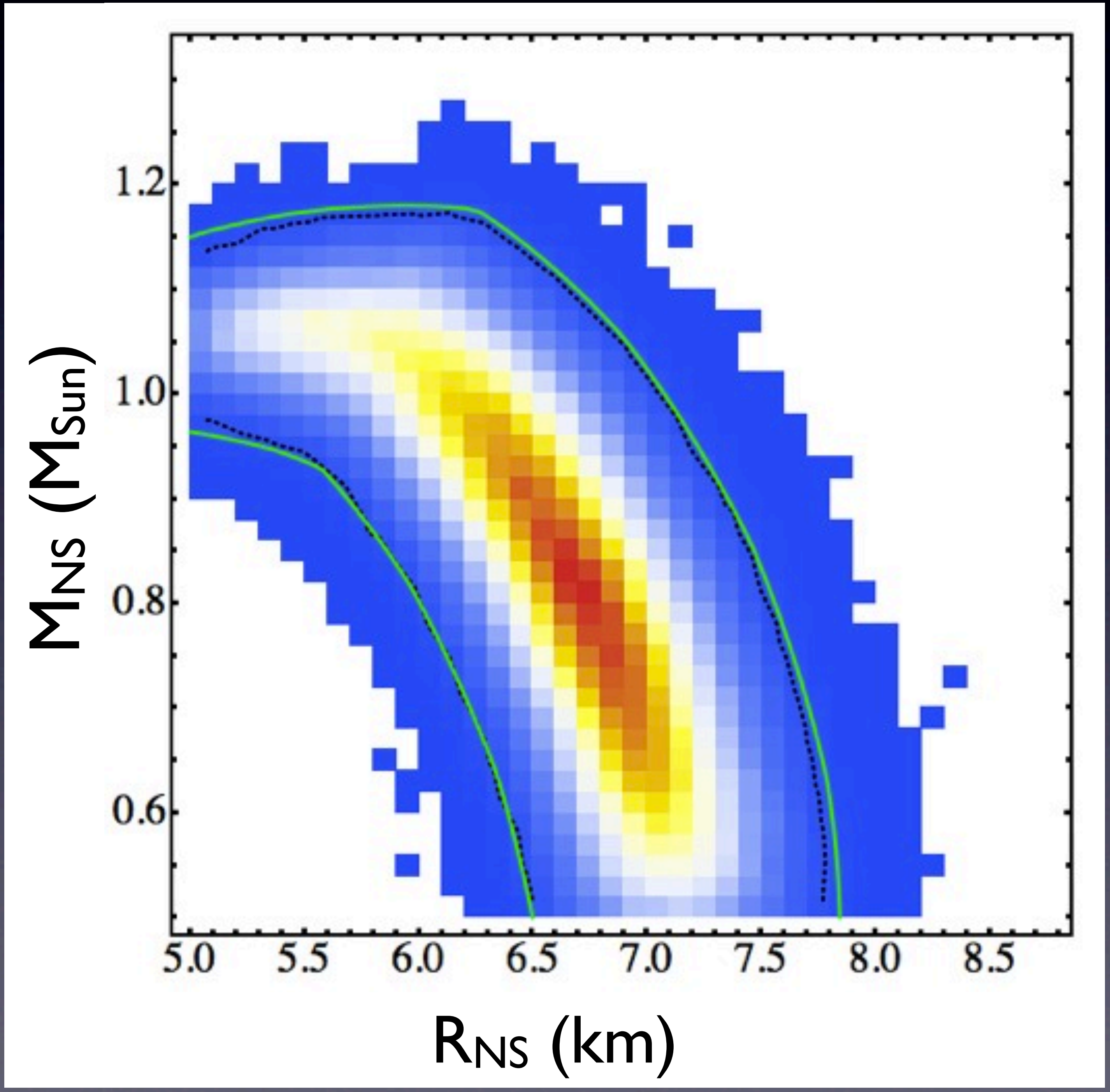
Radius increases



Mass increases

# Markov Chain Monte Carlo Simulations

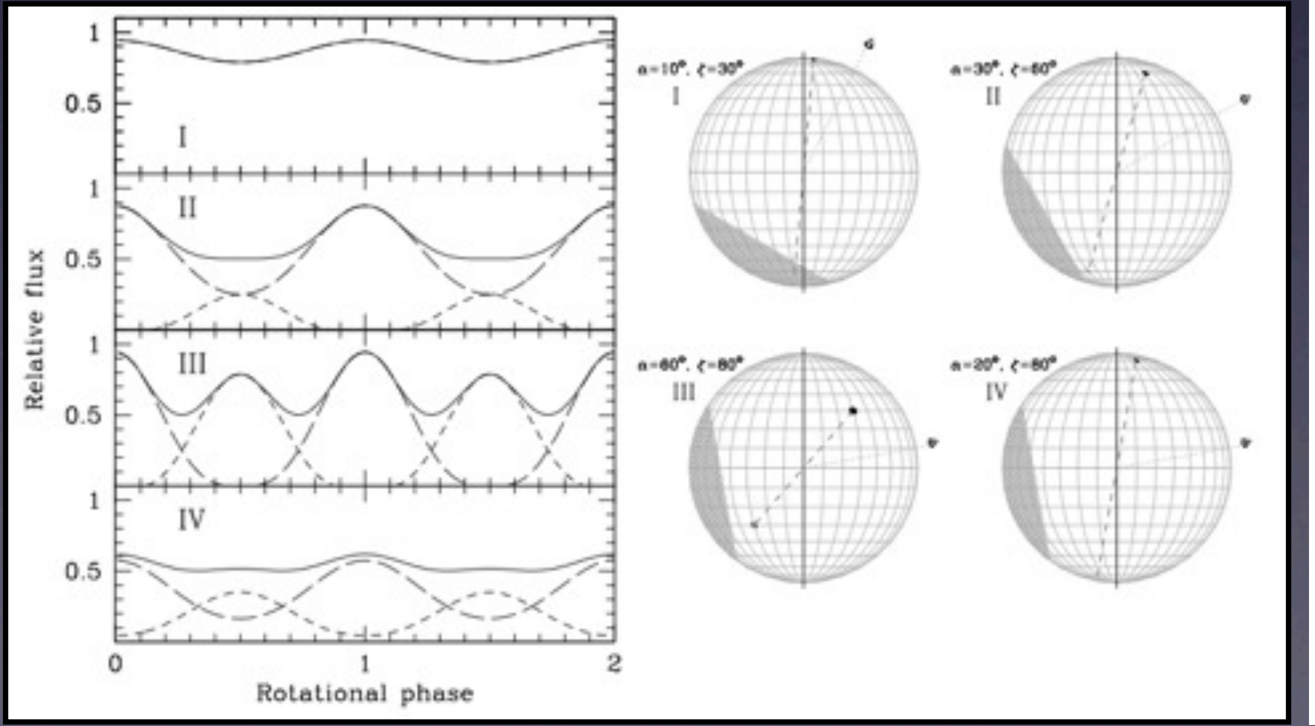
The MCMC approach is first tested with one single qLMXB, to compare the results to the standard fitting with $\chi^2$ Levenberg-Marquardt minimization

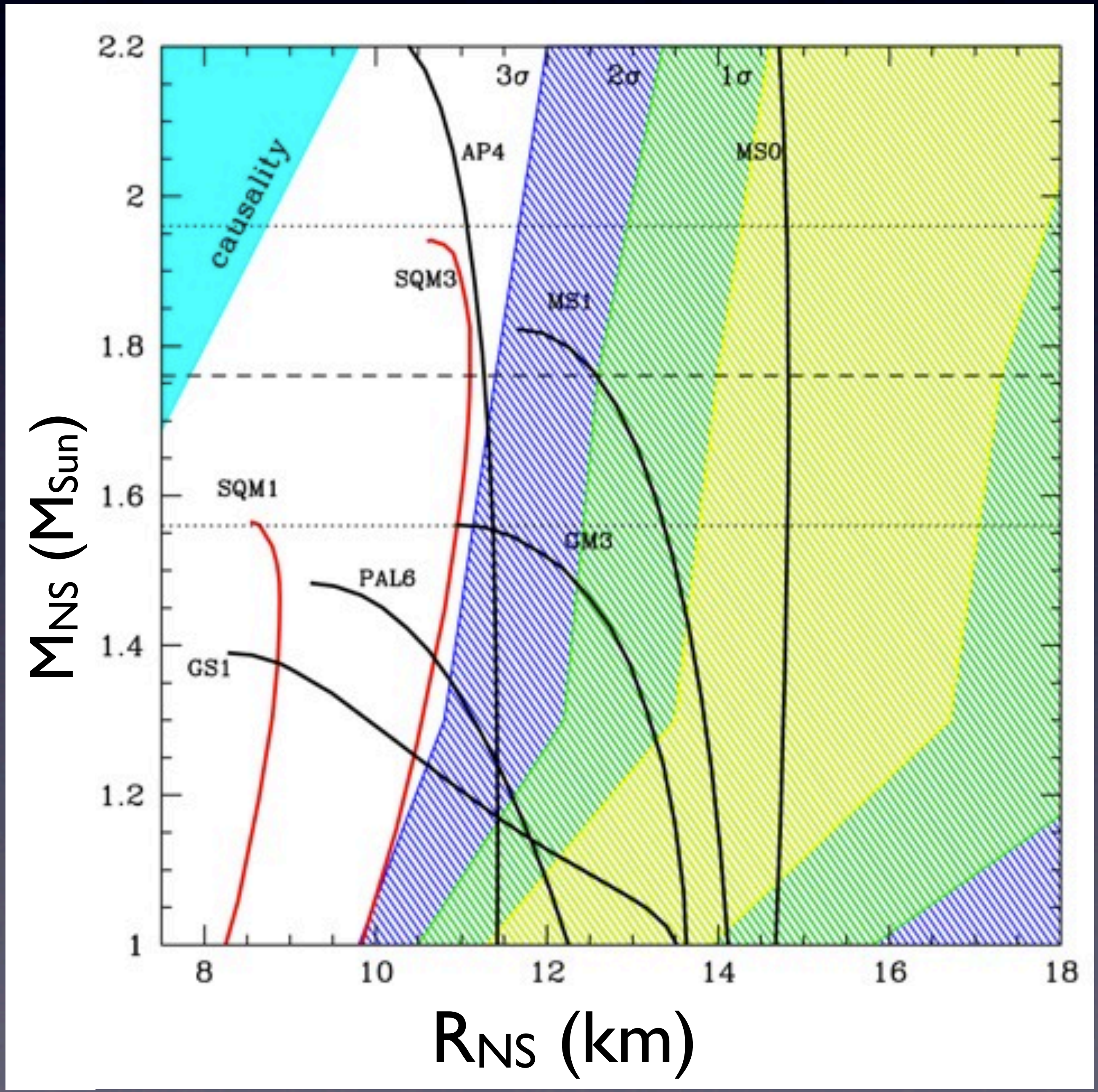


Guillot et al. 2013

# Constraints from Neutron Star Observations

- Pulse-timing analysis of millisecond pulsars (Bogdanov et al. 2008, Bogdanov 2012)





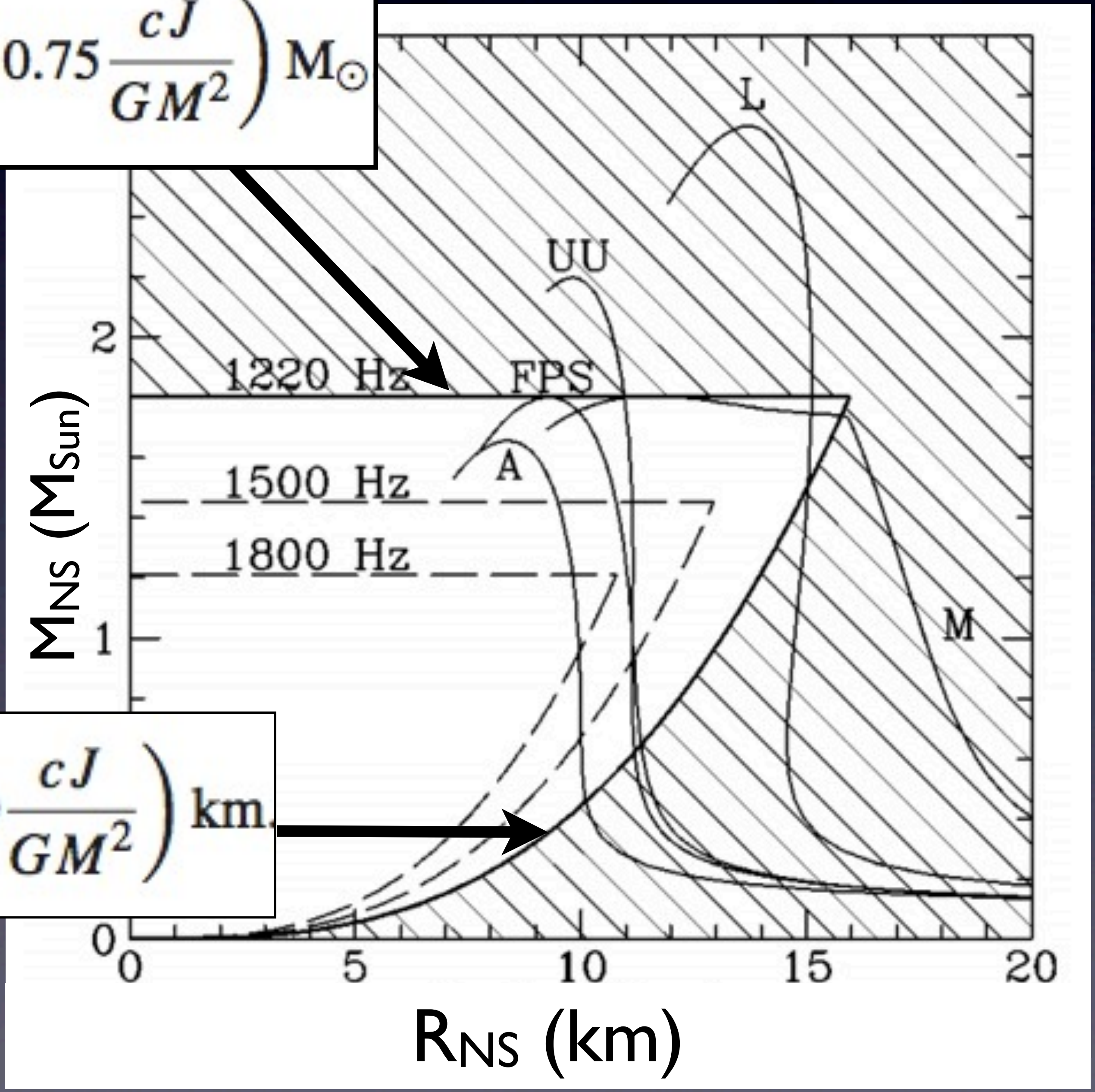
Bogdanov 2013

# Constraints from Neutron Star Observations

$$M \leqslant \left(\frac{2200\,\mathrm{Hz}}{\nu_{\mathrm{ISCO}}}\right)\left(1 + 0.75\frac{cJ}{GM^2}\right)\mathrm{M}_\odot$$

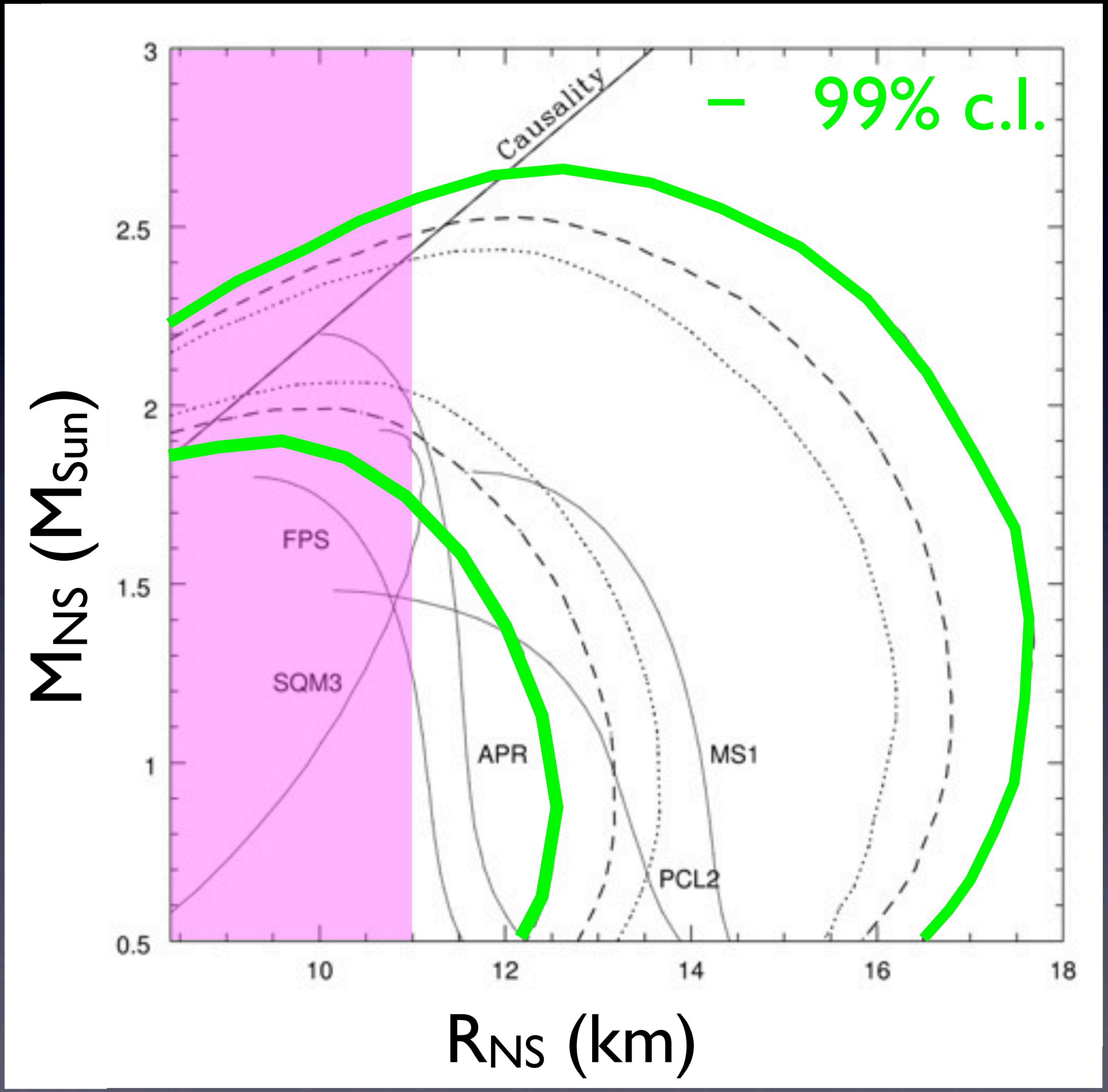
- Quasi-periodic oscillations in active binaries (Miller 1998, Méndez & Belloni 2007)

$$R \leqslant \left(\frac{1950\,\mathrm{Hz}}{\nu_{\mathrm{ISCO}}}\right)\left(1 + 0.20\frac{cJ}{GM^2}\right)\mathrm{km}$$



van der Klis 2000

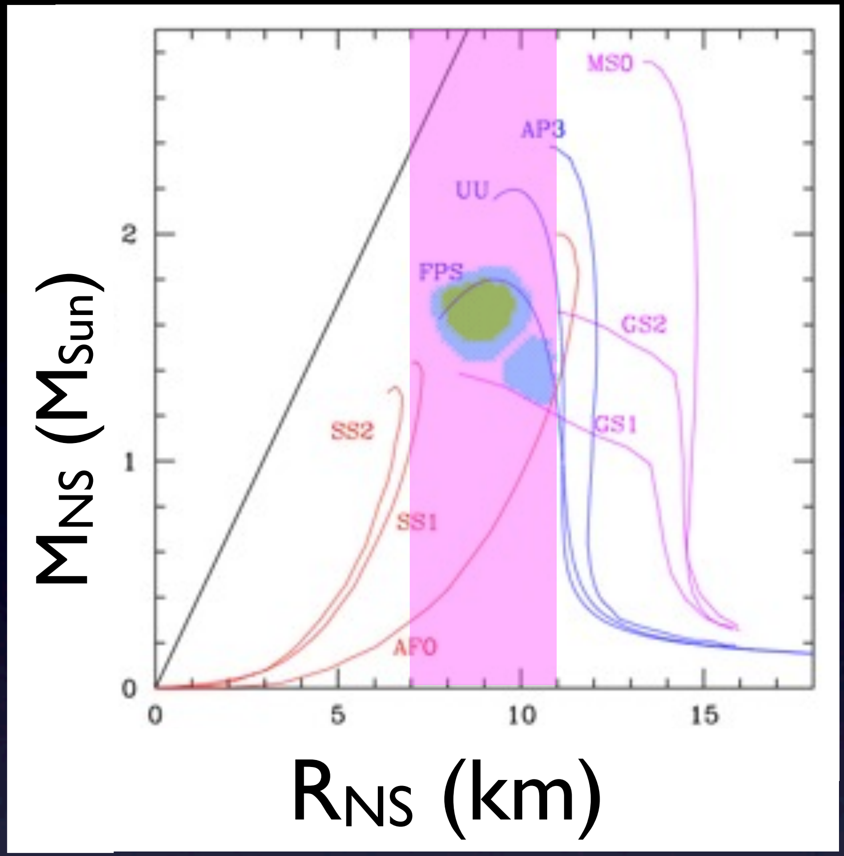
# Previous Rns measurements



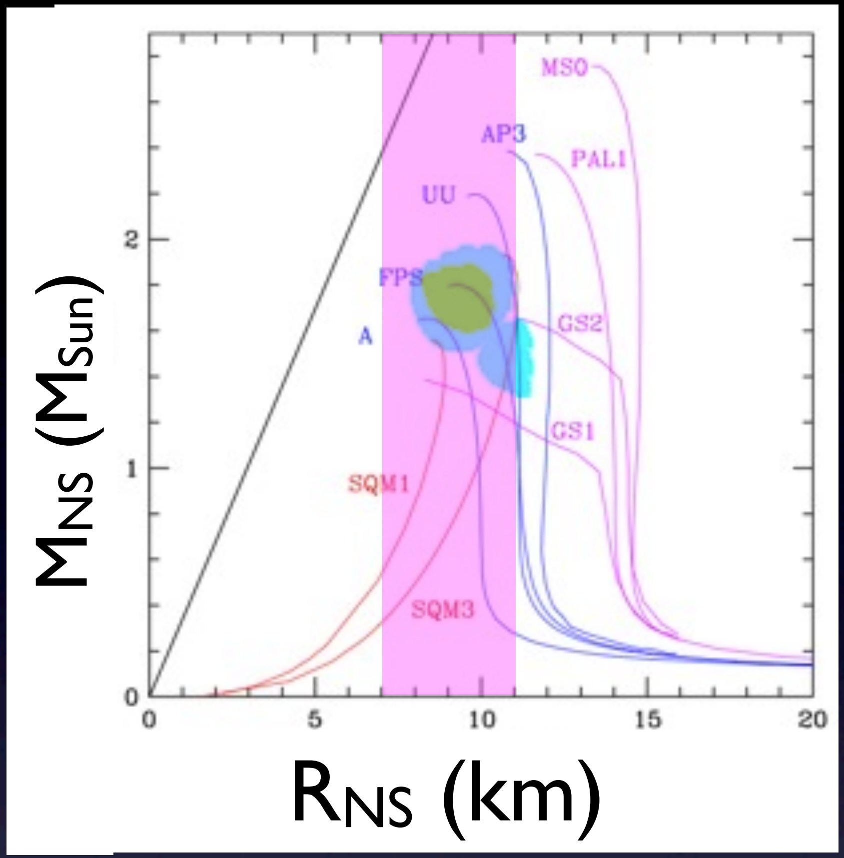
qLMXB 47Tuc X7, Heinke et al 2006

QLMXB 47Tuc X7 not used in our analysis because of a large pile-up fraction, with un-quantified uncertainties.

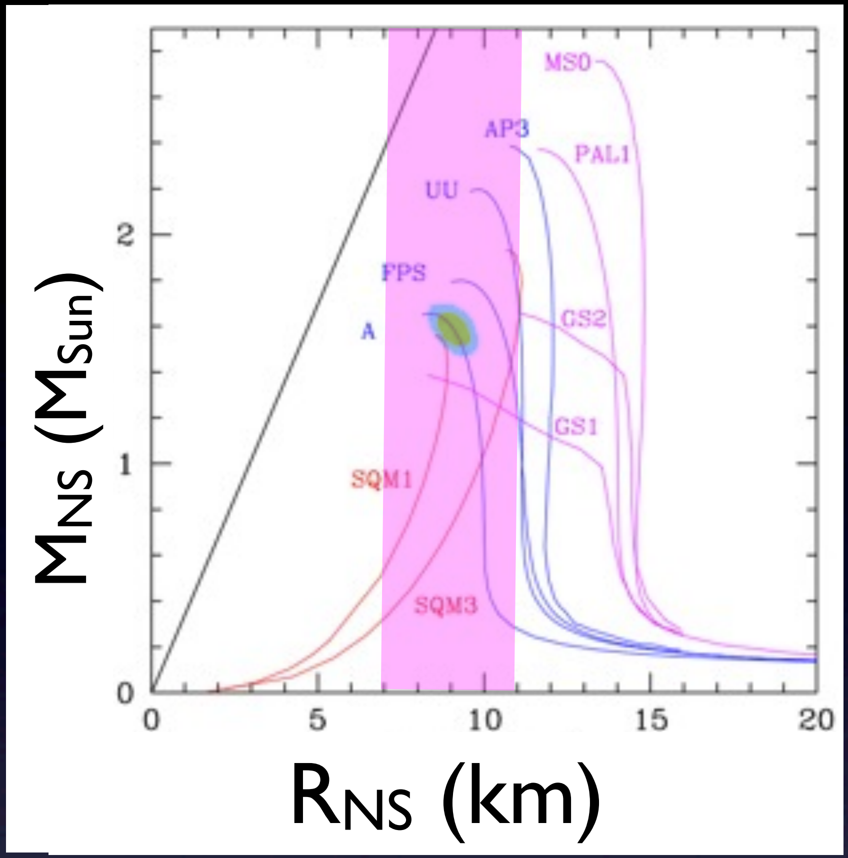
# Previous Rns measurements



EXO 1745-348
Özel et al. 2009



4U 1608-53
Güver et al. 2010a

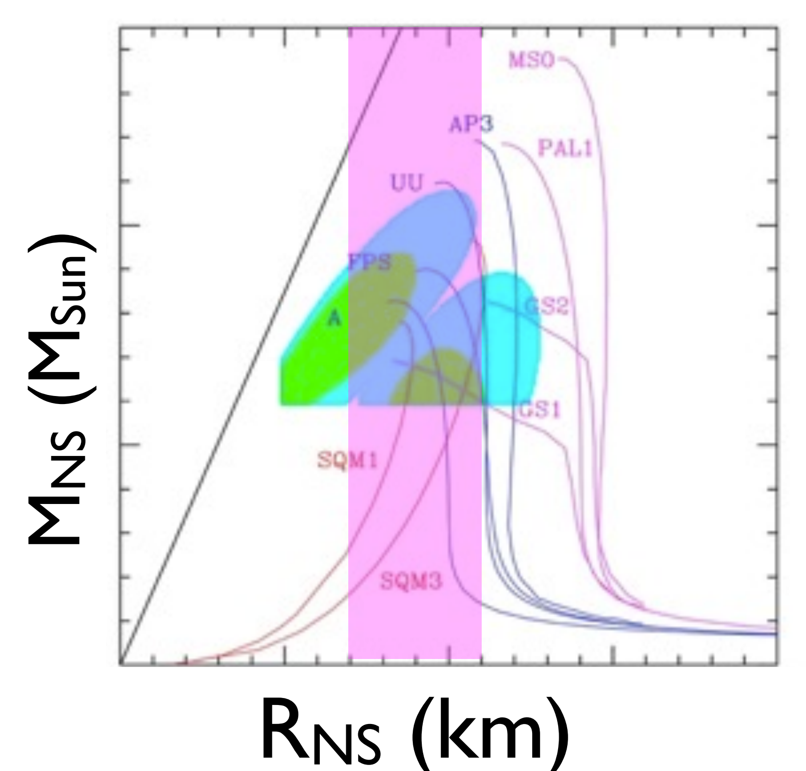


4U 1820-30
Güver et al. 2010a

Type-I X-ray bursts with photospheric radius expansion (PRE)

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

$$A = \frac{R^2}{D^2 f_c^4}\left(1 - \frac{2GM}{Rc^2}\right)^{-1}$$

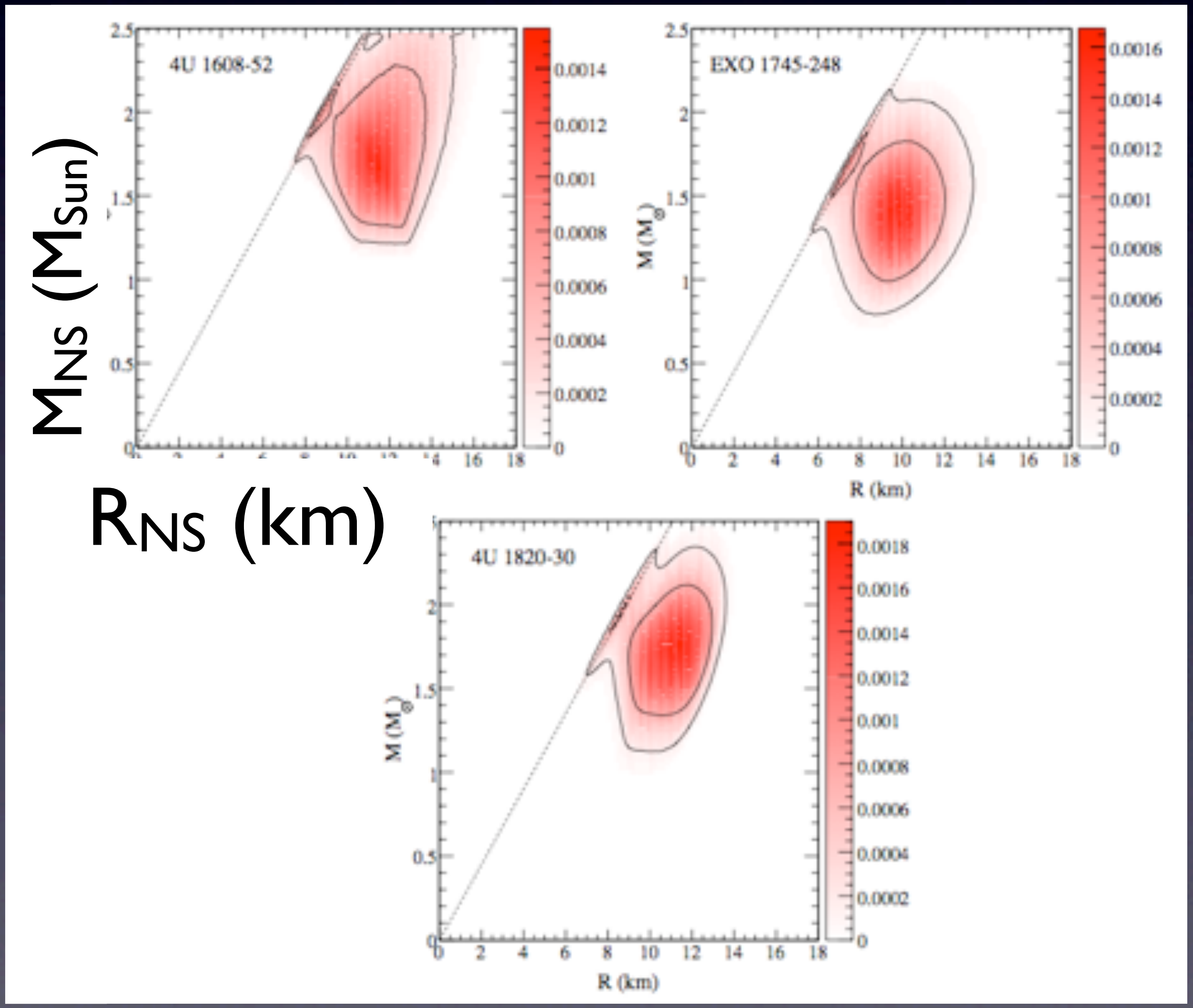


KS 1731-260
Özel et al. 2012

# Combining M-R constraints from neutron stars provides more stringent constraints.

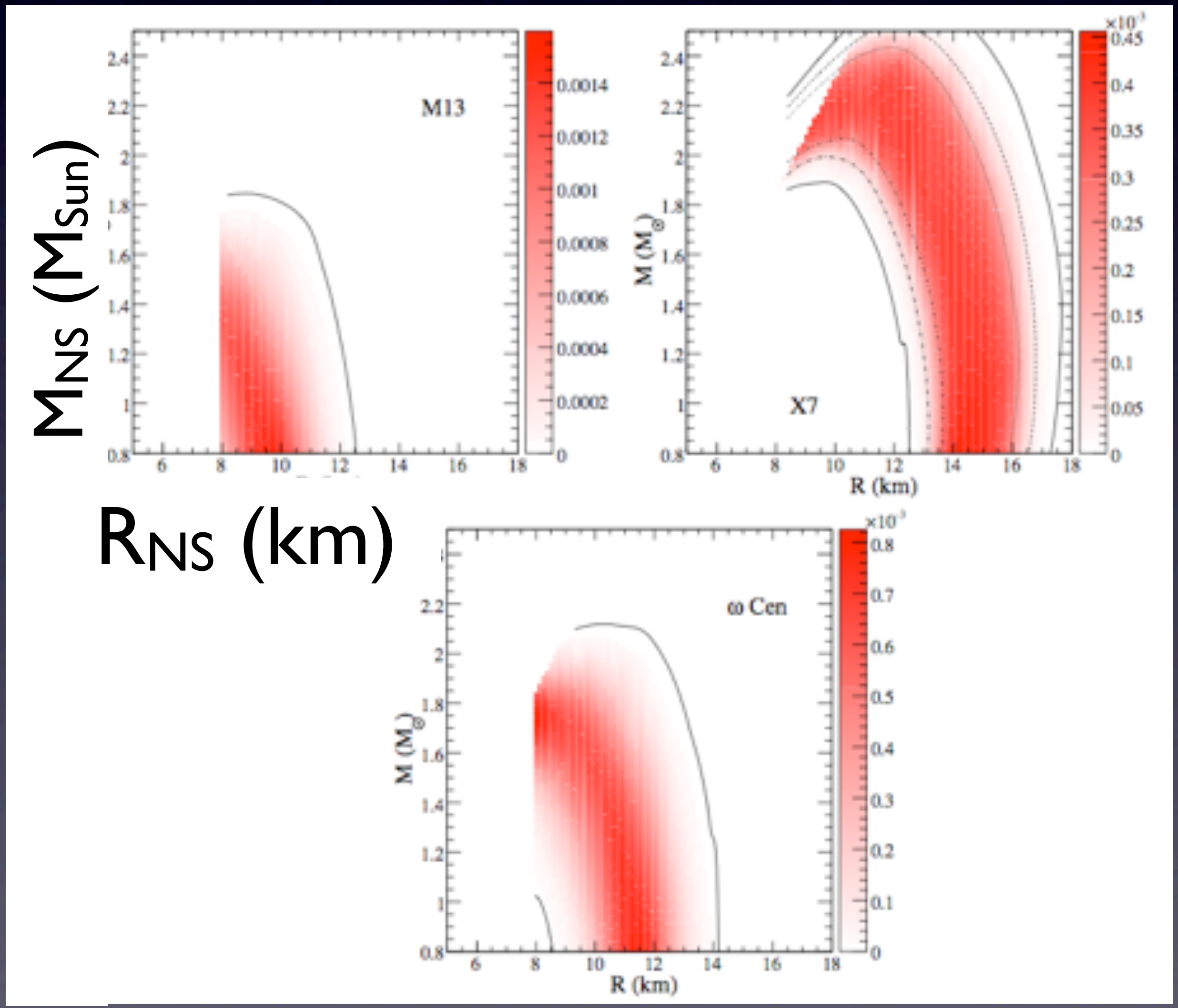
Steiner et al 2010, 2013

## Type I X-ray bursts



+

## Quiescent LMXBs



+ M-R contour of X-ray burst KS1731-260
Özel et al. 2012

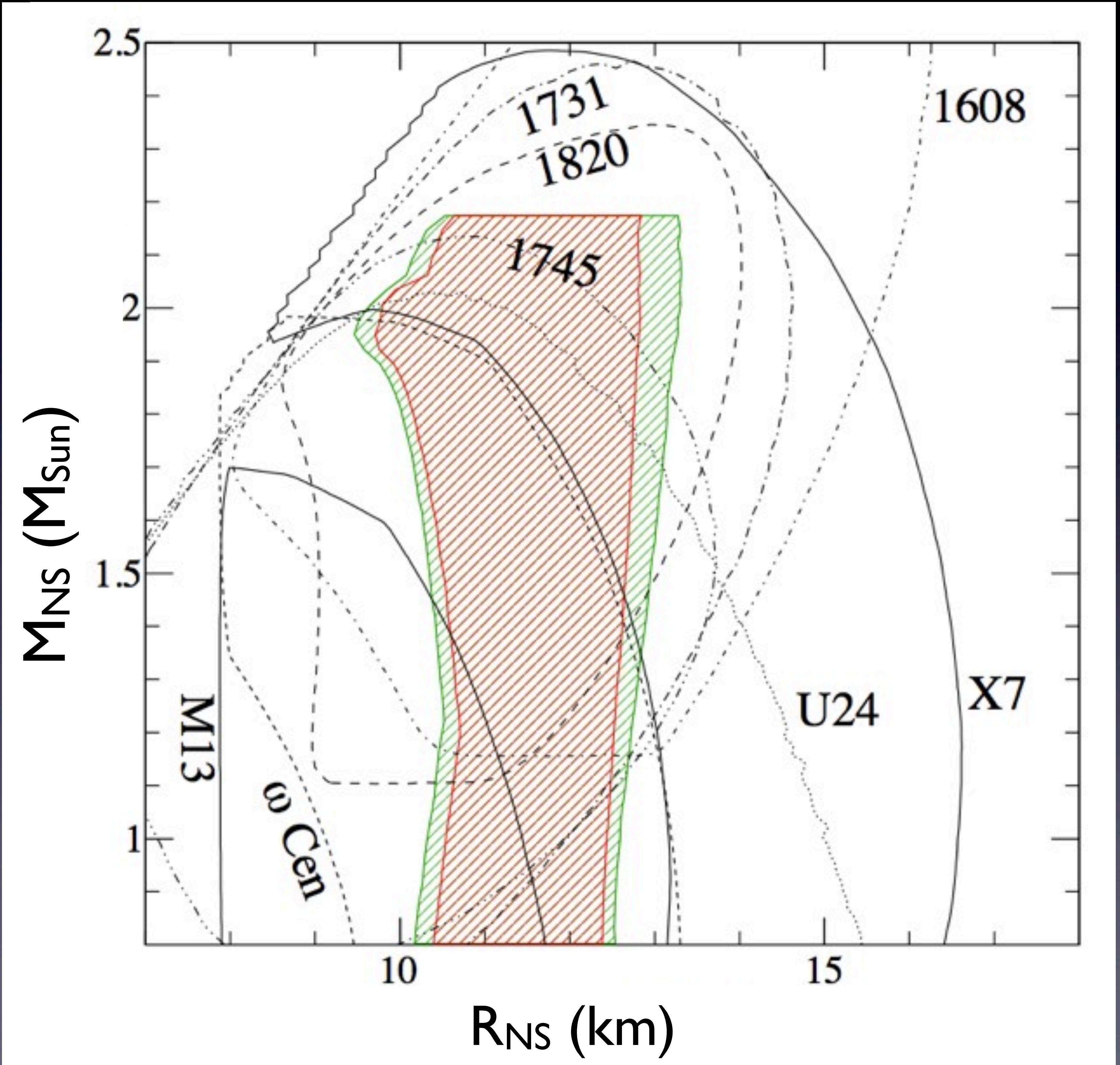
+ M-R contour of qLMXB in NGC6397
from Guillot et al. 2011

# Combining M-R constraints from neutron stars provides more stringent constraints.

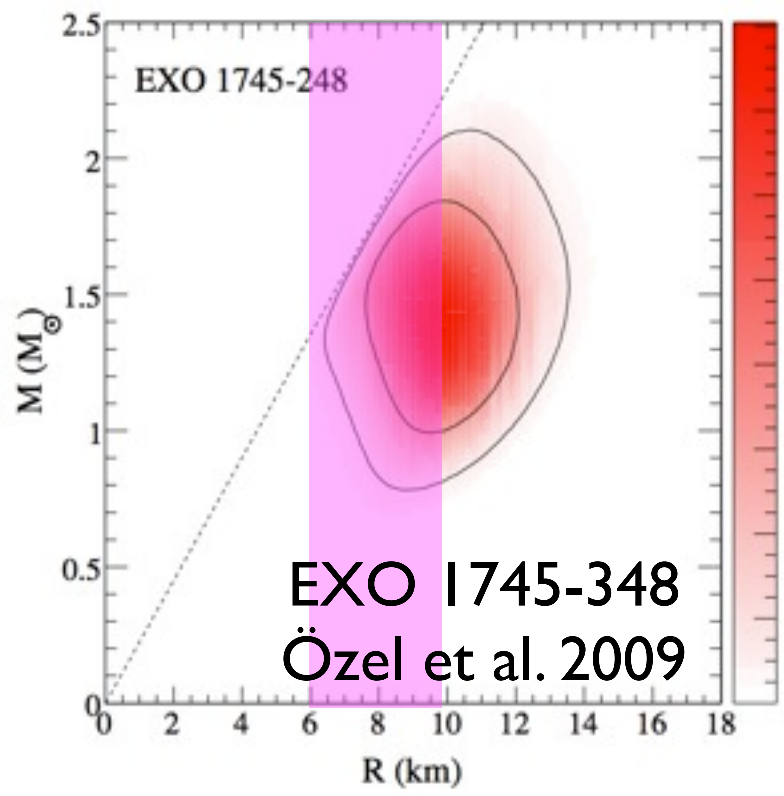
$R_{NS}$ is constrained between 10 and 13 km for a wide range of masses.

$R_{NS}$ is insensitive to the exclusion of extremum contours (like M13, or 47Tuc), or to the exclusion of type-I X-ray burst sources.

Steiner et al 2013



# Comparison with previous Rns measurements



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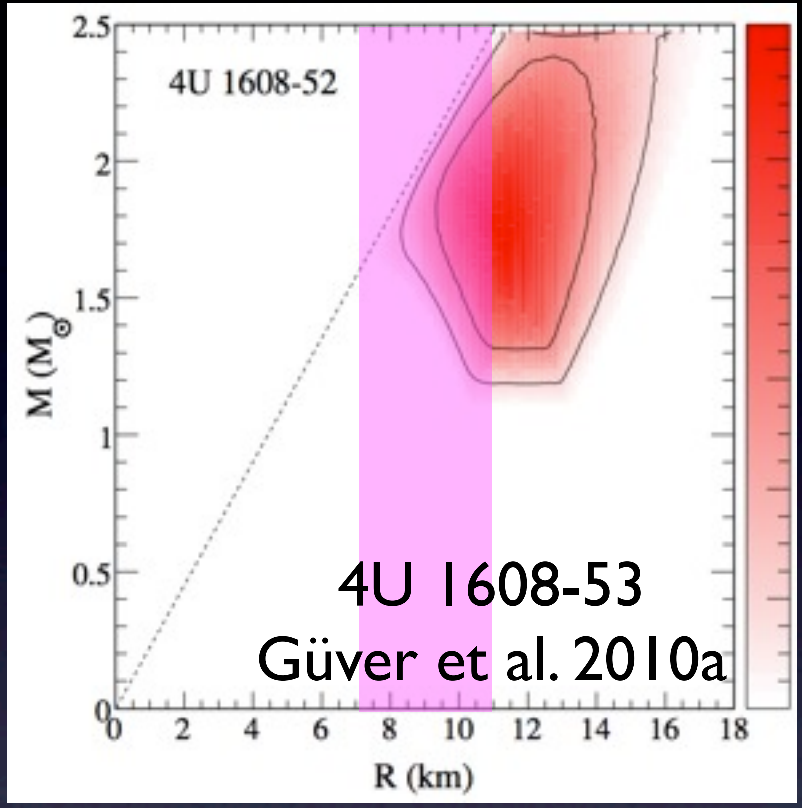

4U 1608-53
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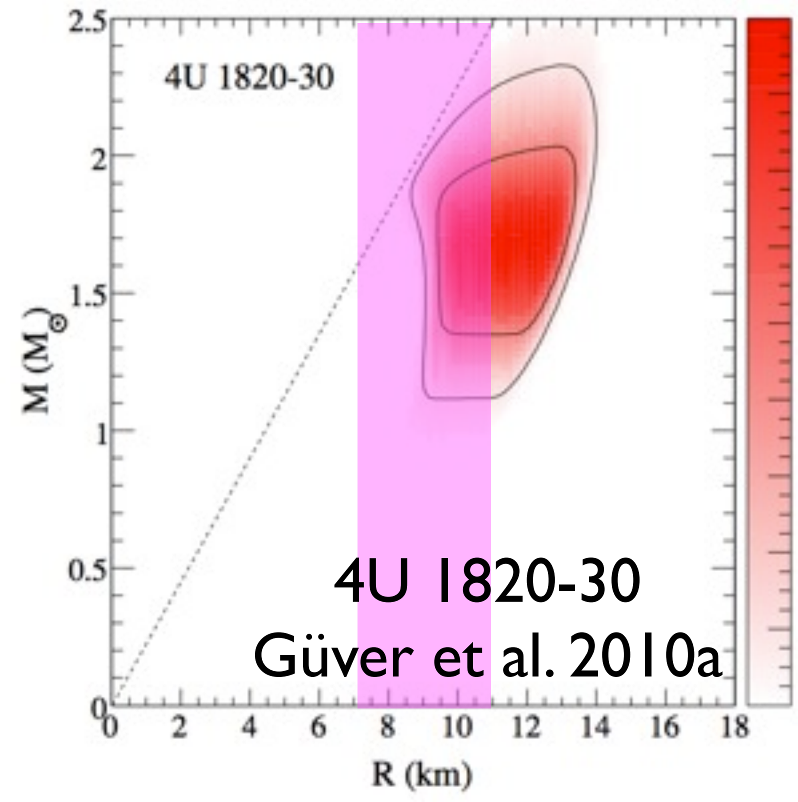


4U 1820-30
Güver et al. 2010a

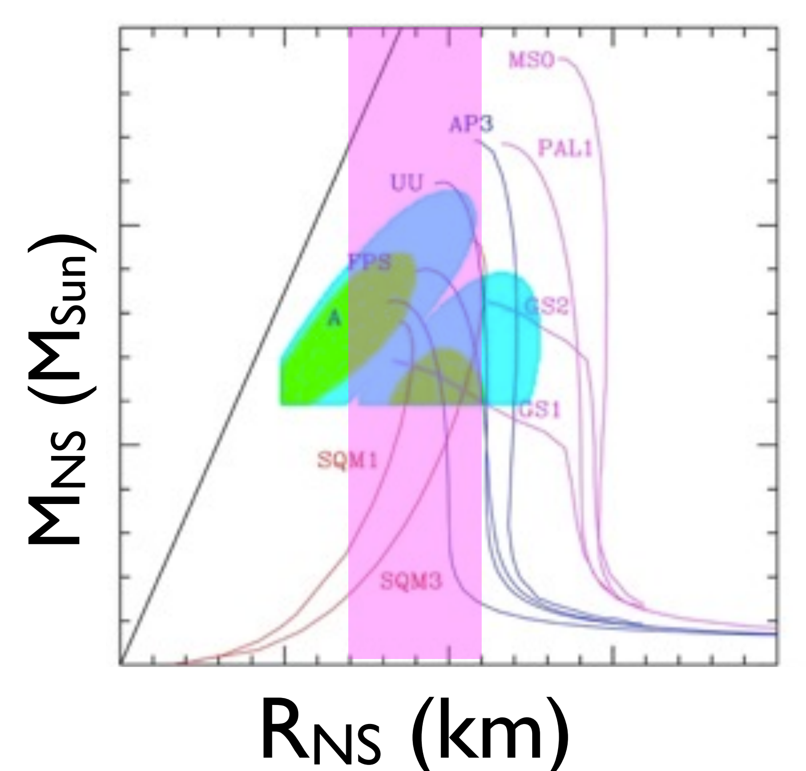
Confidence Region recalculated
by Steiner et al. 2010

Type-I X-ray bursts
with photospheric
radius expansion

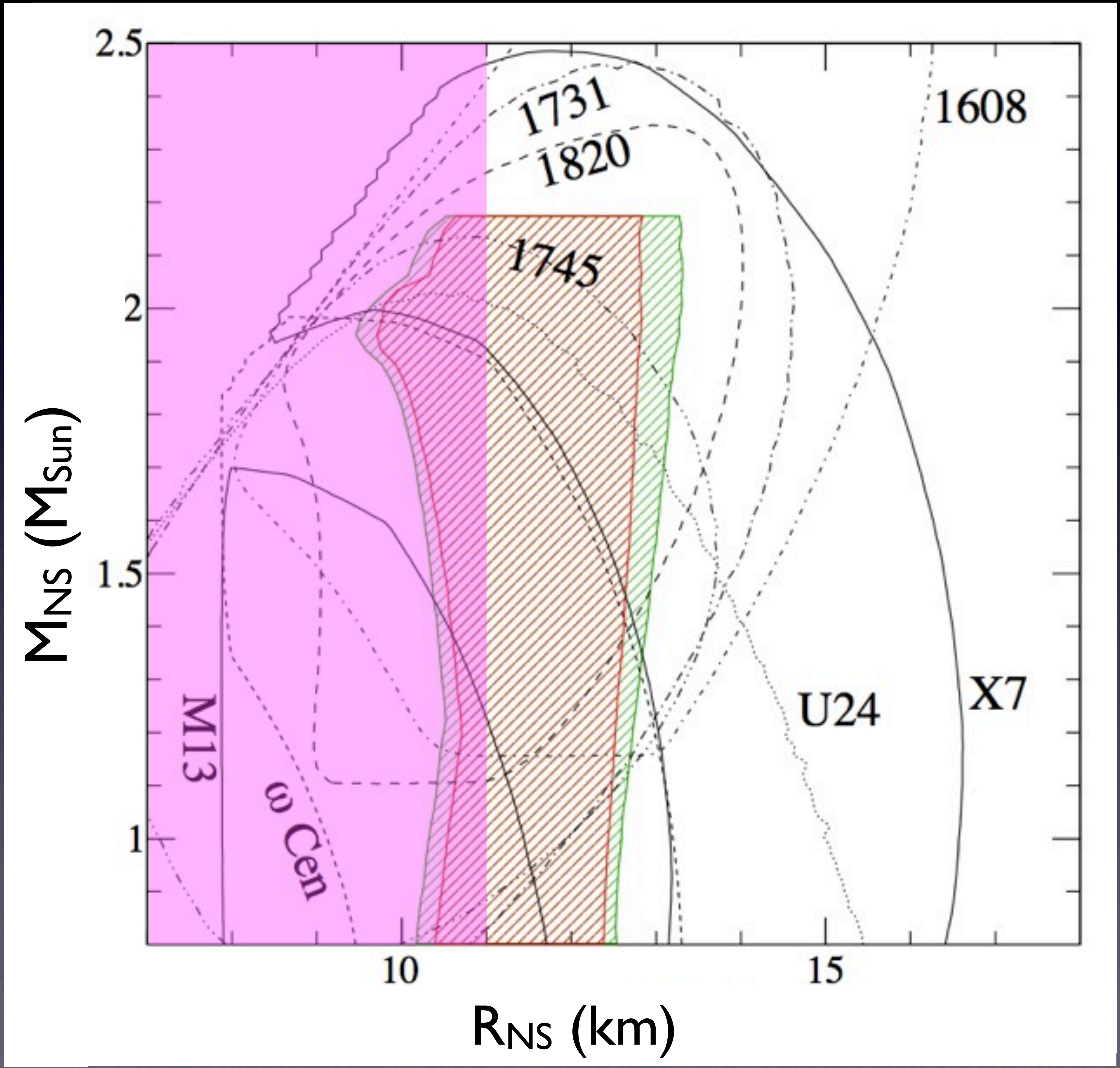
$$F_{\rm Edd} = \frac{GMc}{k_{\rm es}D^2}\left(1 - \frac{2GM}{Rc^2}\right)^{1/2}$$

$$A = \frac{R^2}{D^2 f_{\rm c}^4}\left(1 - \frac{2GM}{Rc^2}\right)^{-1}$$

KS 1731-260
Özel et al. 2012

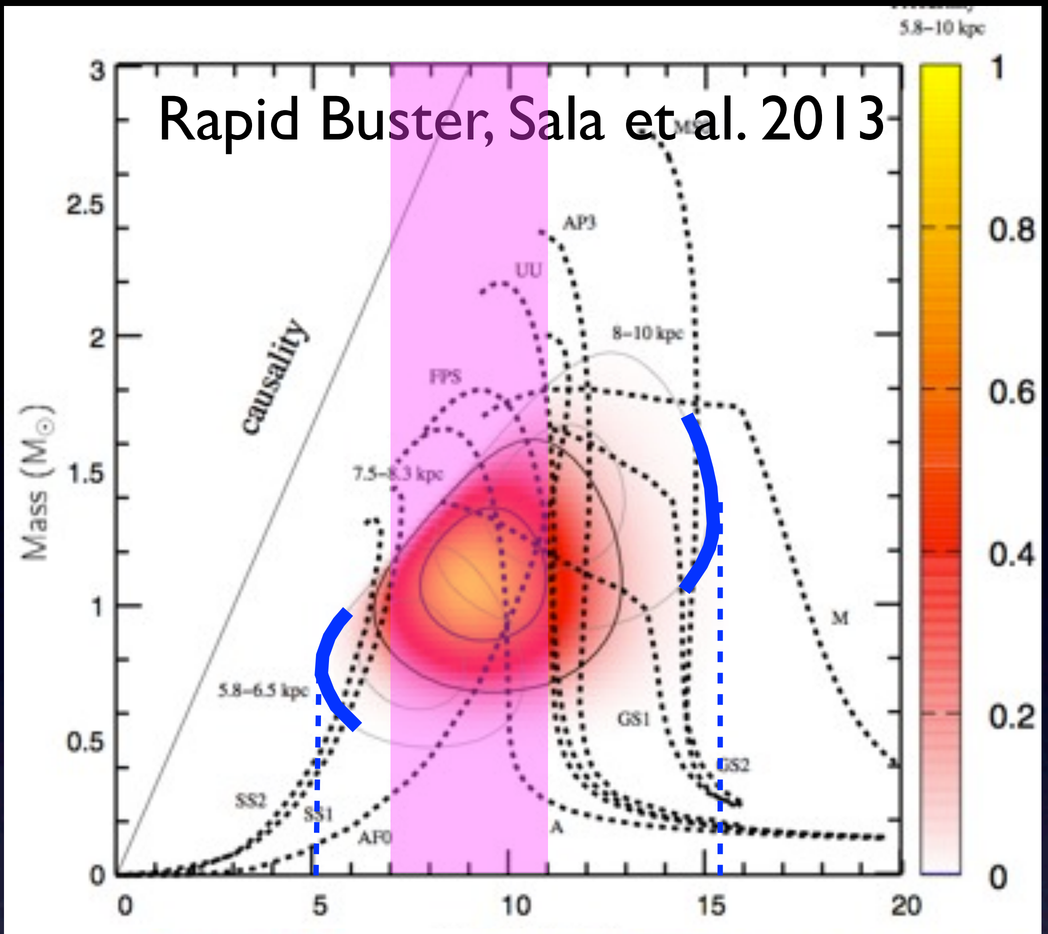


# Empirical Equation of State



Steiner
et al
2013

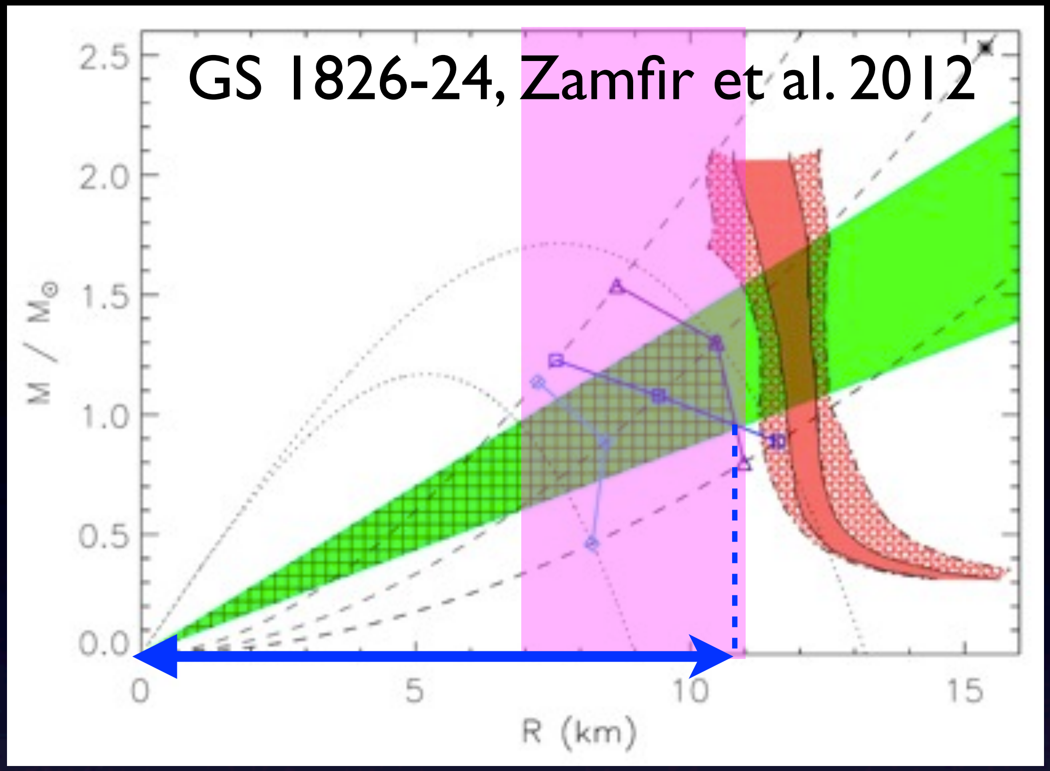
# Previous Rns measurements



Rapid Buster, Sala et al. 2013

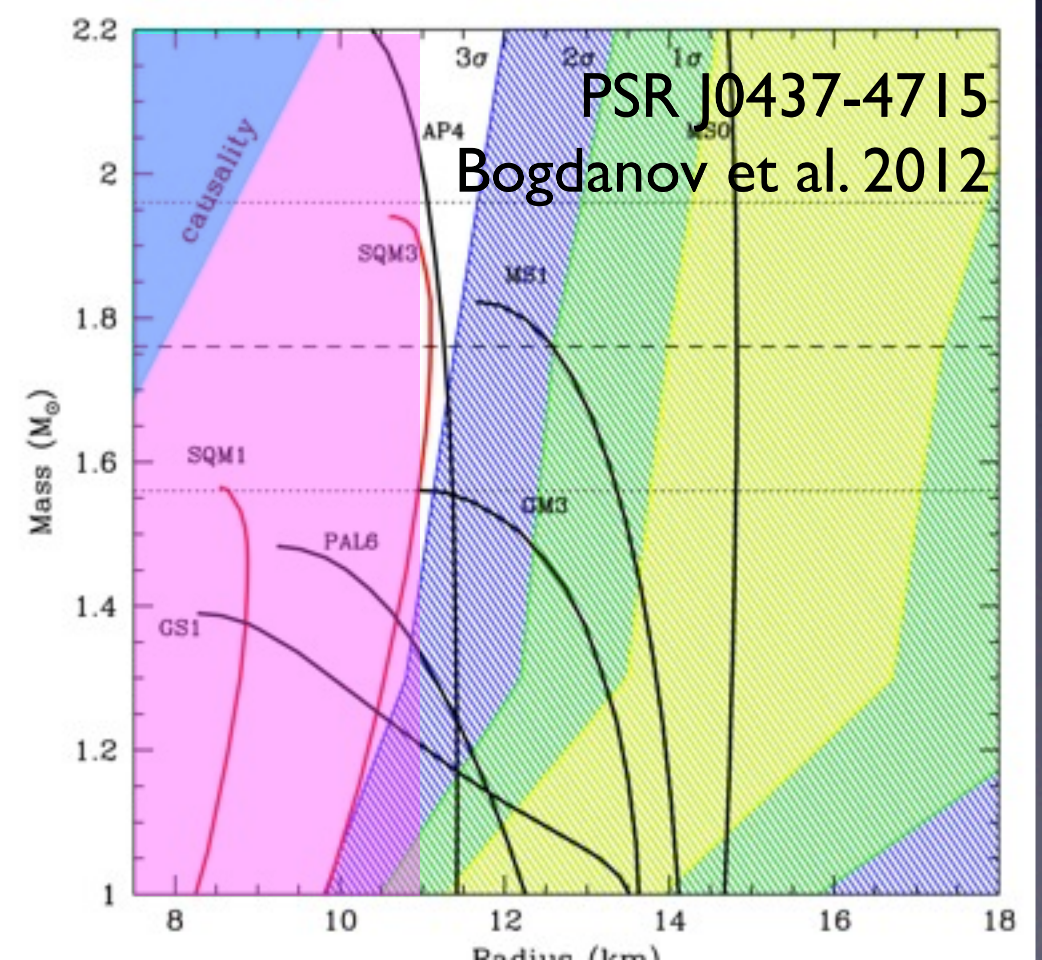
PRE type-I X-ray bursts.

Distance uncertainties seriously affect measurements



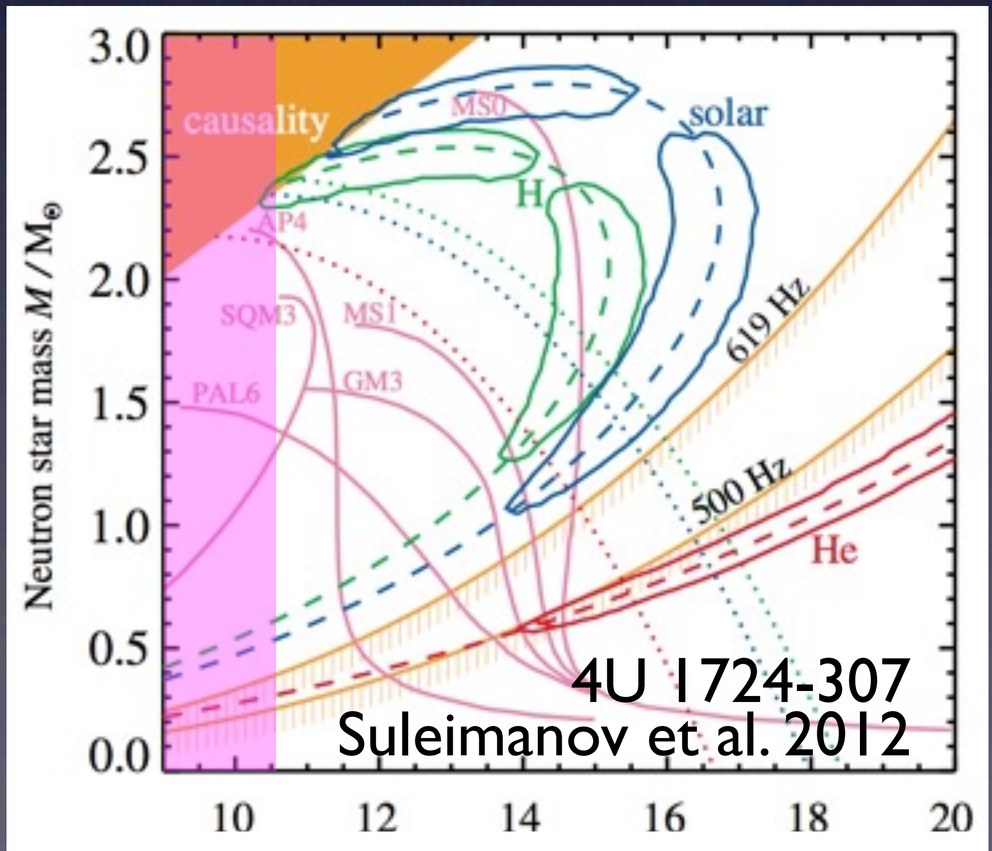
GS 1826-24, Zamfir et al. 2012

Sub-Eddington type-I X-ray bursts
Distance independent measurement



PSR J0437-4715
Bogdanov et al. 2012

Pulse timing analysis of a millisecond pulsar



4U 1724-307
Suleimanov et al. 2012

using long type-I X-ray bursts