Measuring the Radius of Neutron Stars

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X-Ray Binaries: Celebrating 50 Years Since the Discovery of Sco-X1
Boston, MA - July 2012

Outline

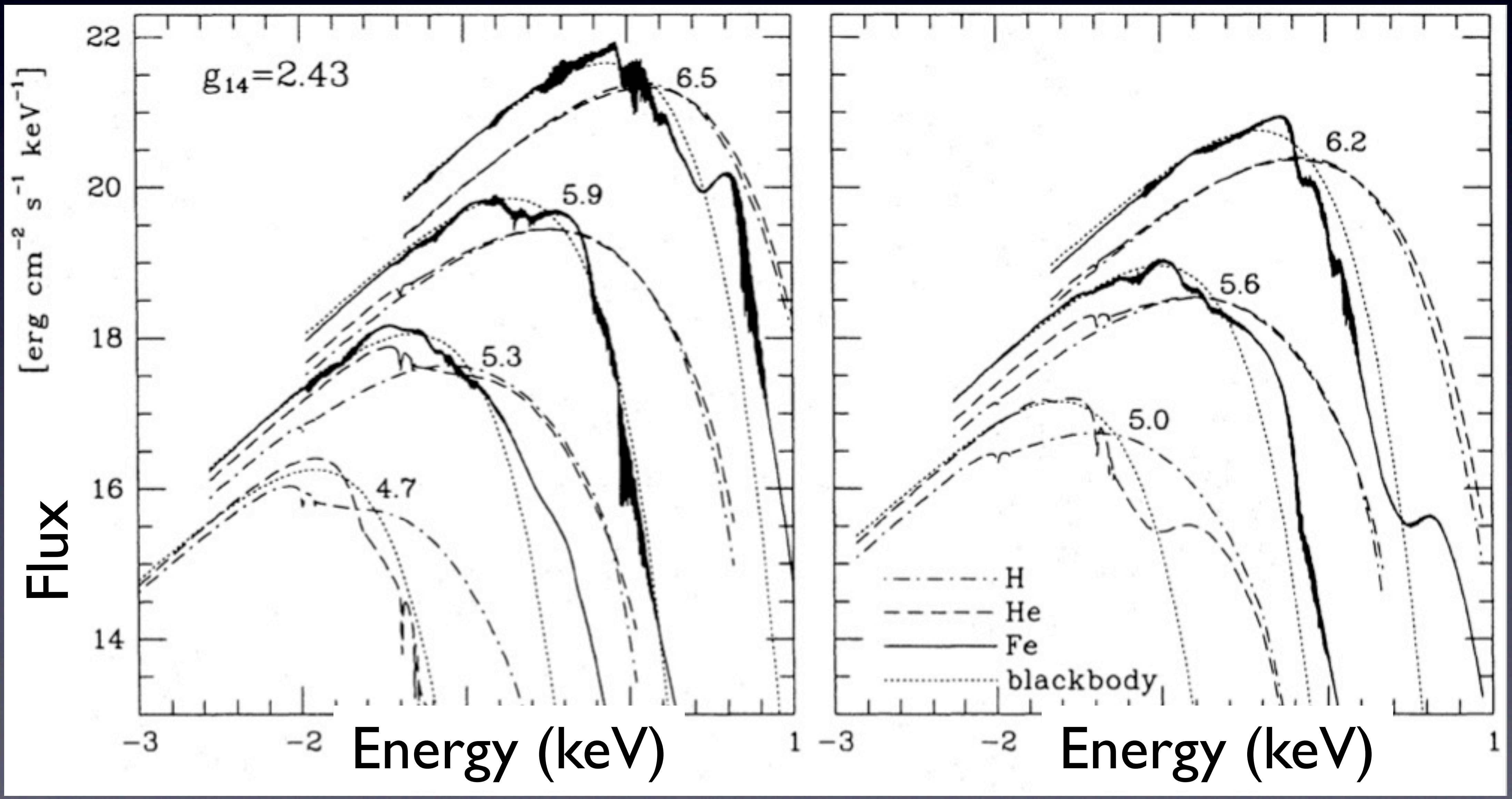
- Thermal emission of quiescent LMXBs to constrain the dense matter equation of state
- Recent measurements of masses and radii
- A new approach to measure the radius of neutron stars
- Results and constraints on the EoS

Quiescent LMXBs

- In quiescence, LMXBs have low mass accretion rate
- Thermal emission comes from the surface with $L_X=10^{32-33}$ erg/sec
- Emission powered by deep crustal heating (Brown et al. 1998)
- Thermal emission modelled with a hydrogen atmosphere model

Neutron Star Hydrogen Atmosphere Models

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



Zavlin et al 1996, A&A 315

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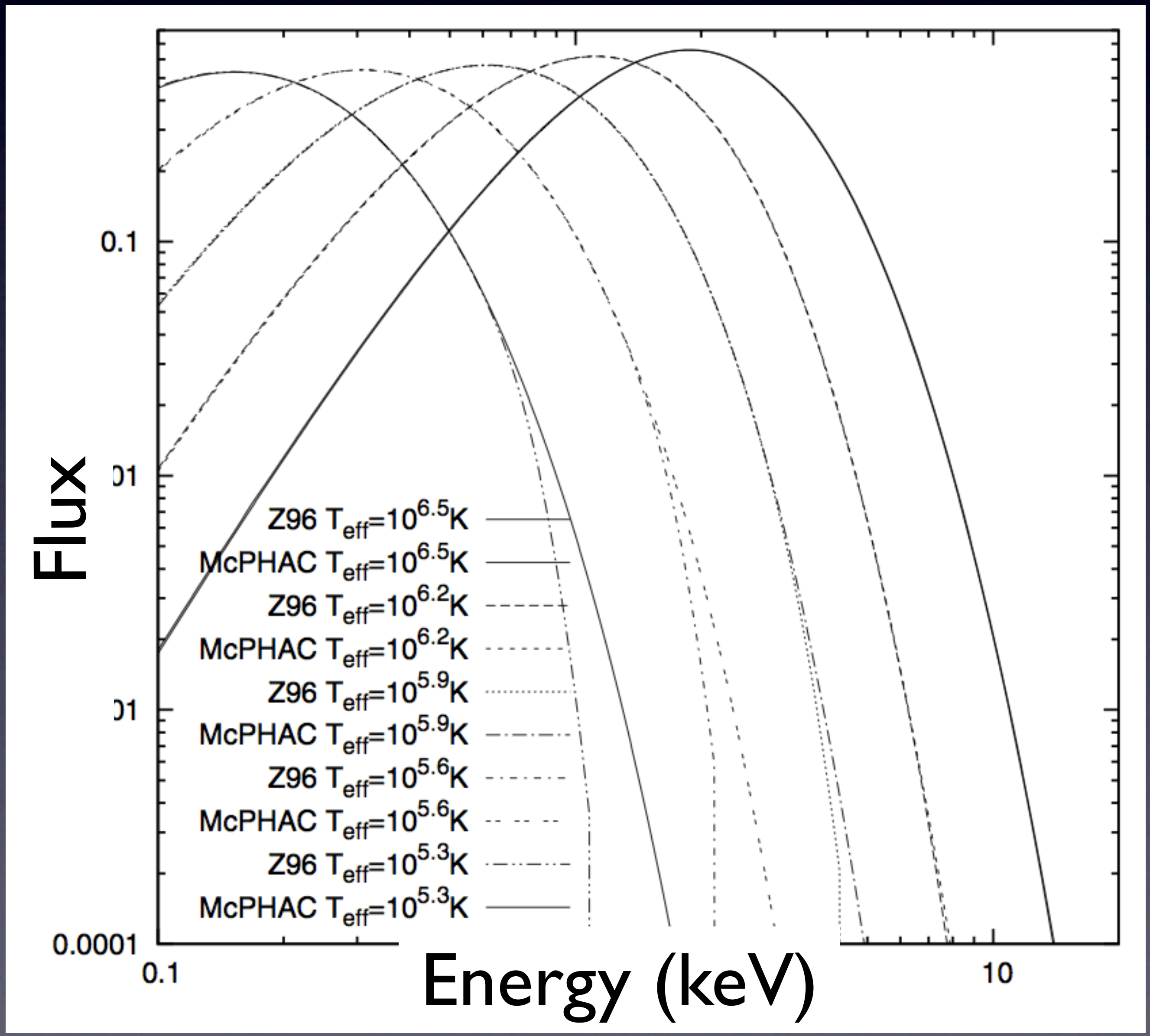
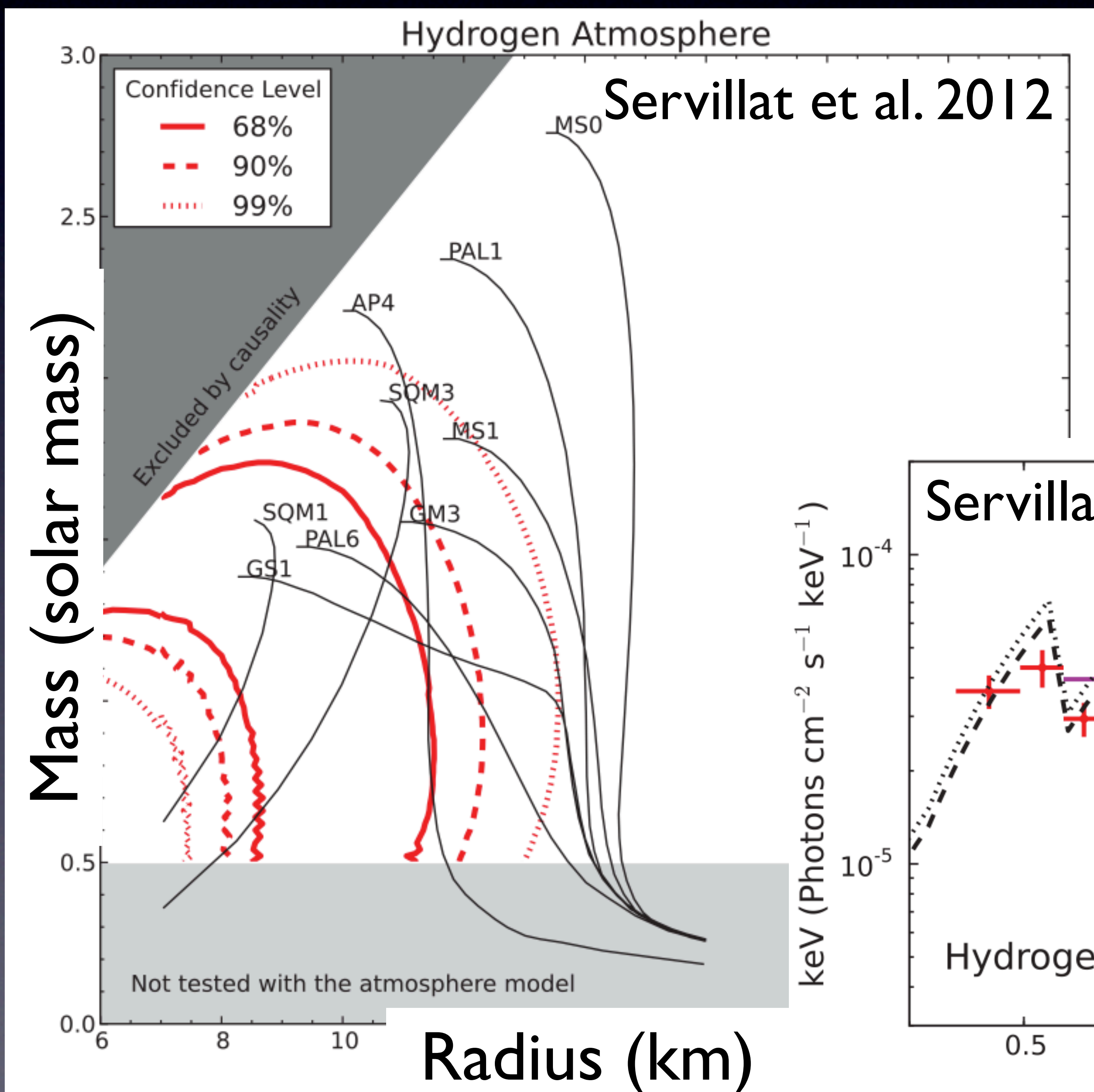
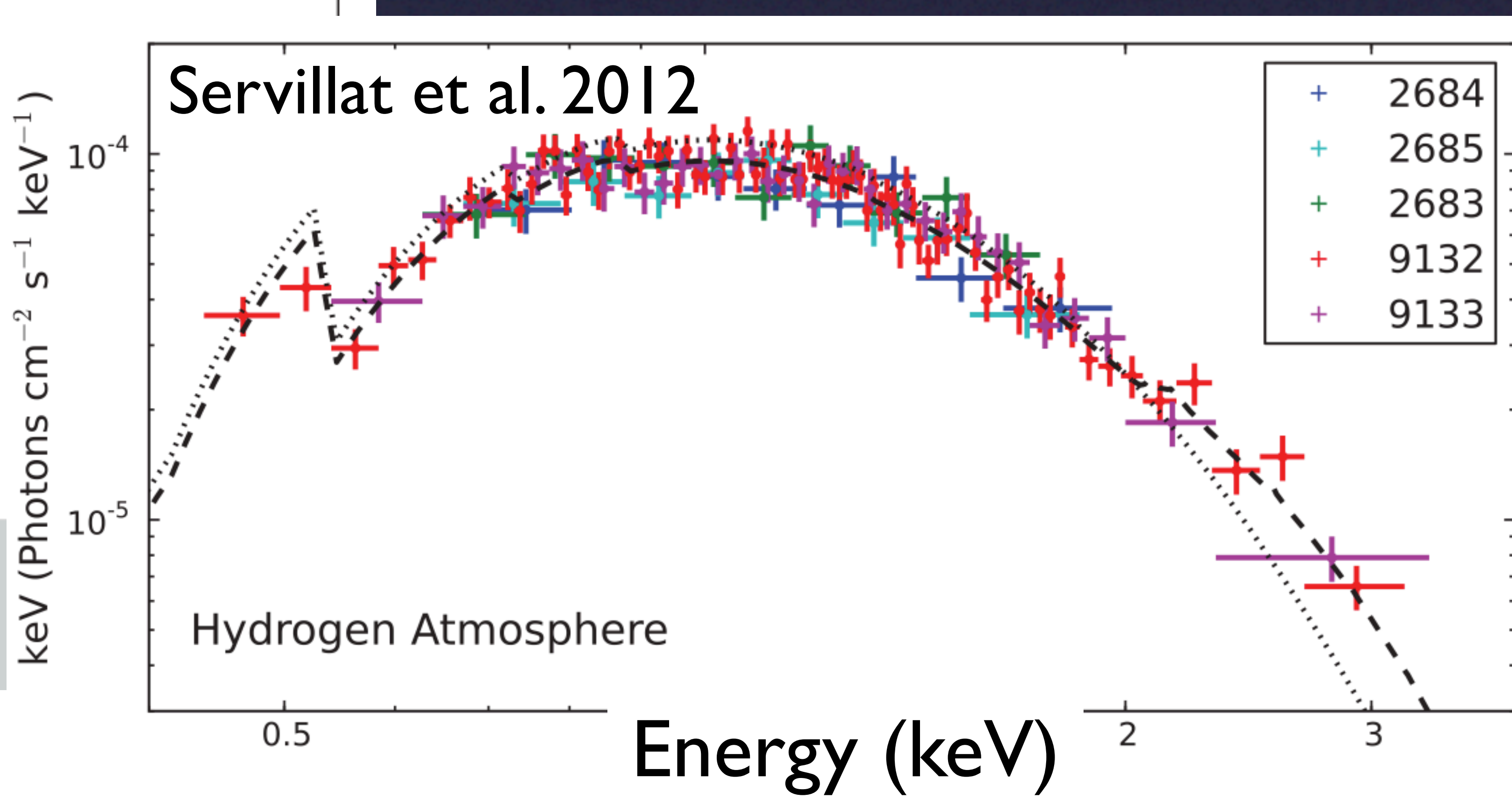


Haakonsen et al. 2012, ApJ 749

X-Ray spectral analysis of qLMXBs

NSATMOS H-atmosphere model fits for kT_{eff}, M_{NS}, and R_{NS}, for a given distance

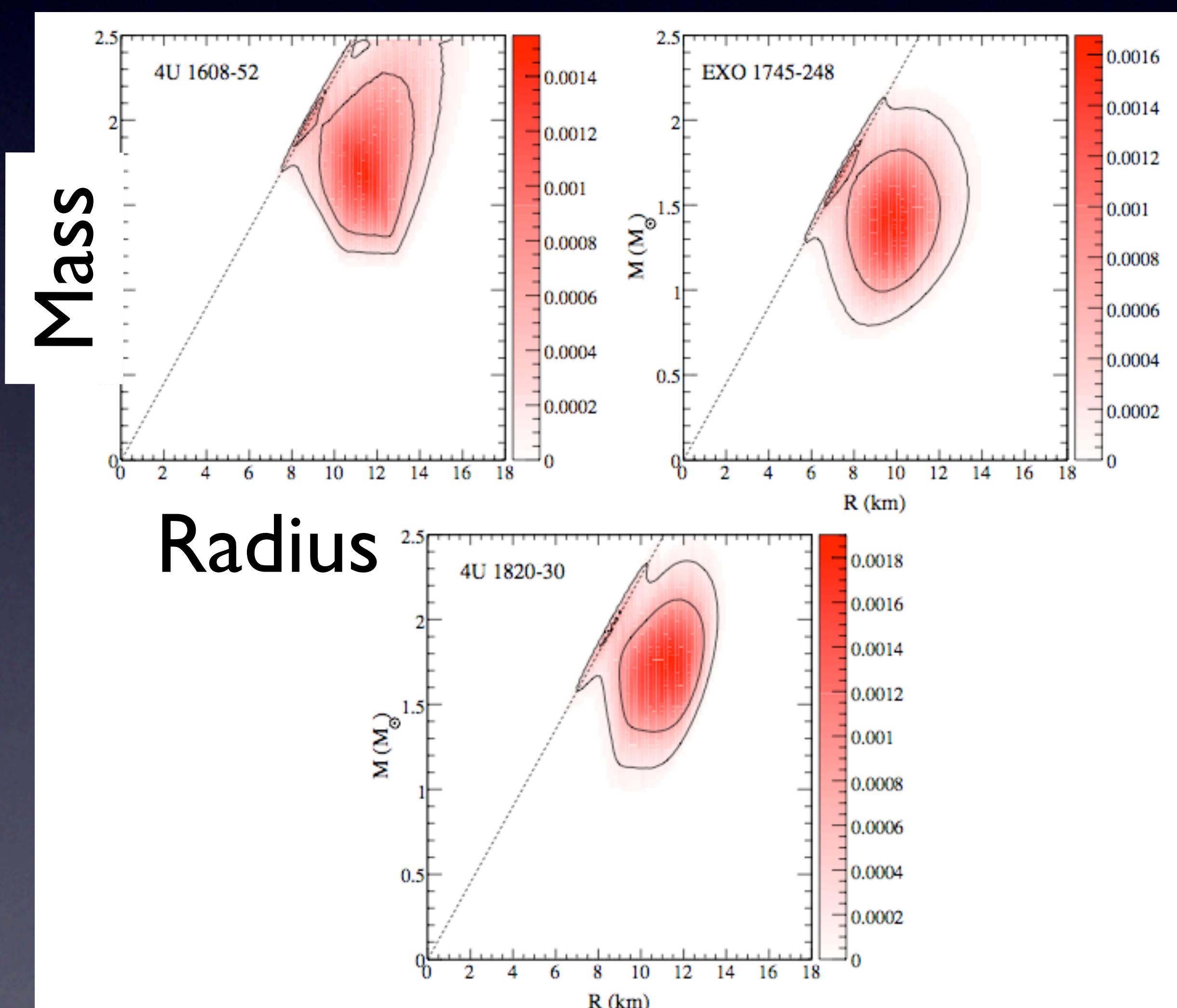




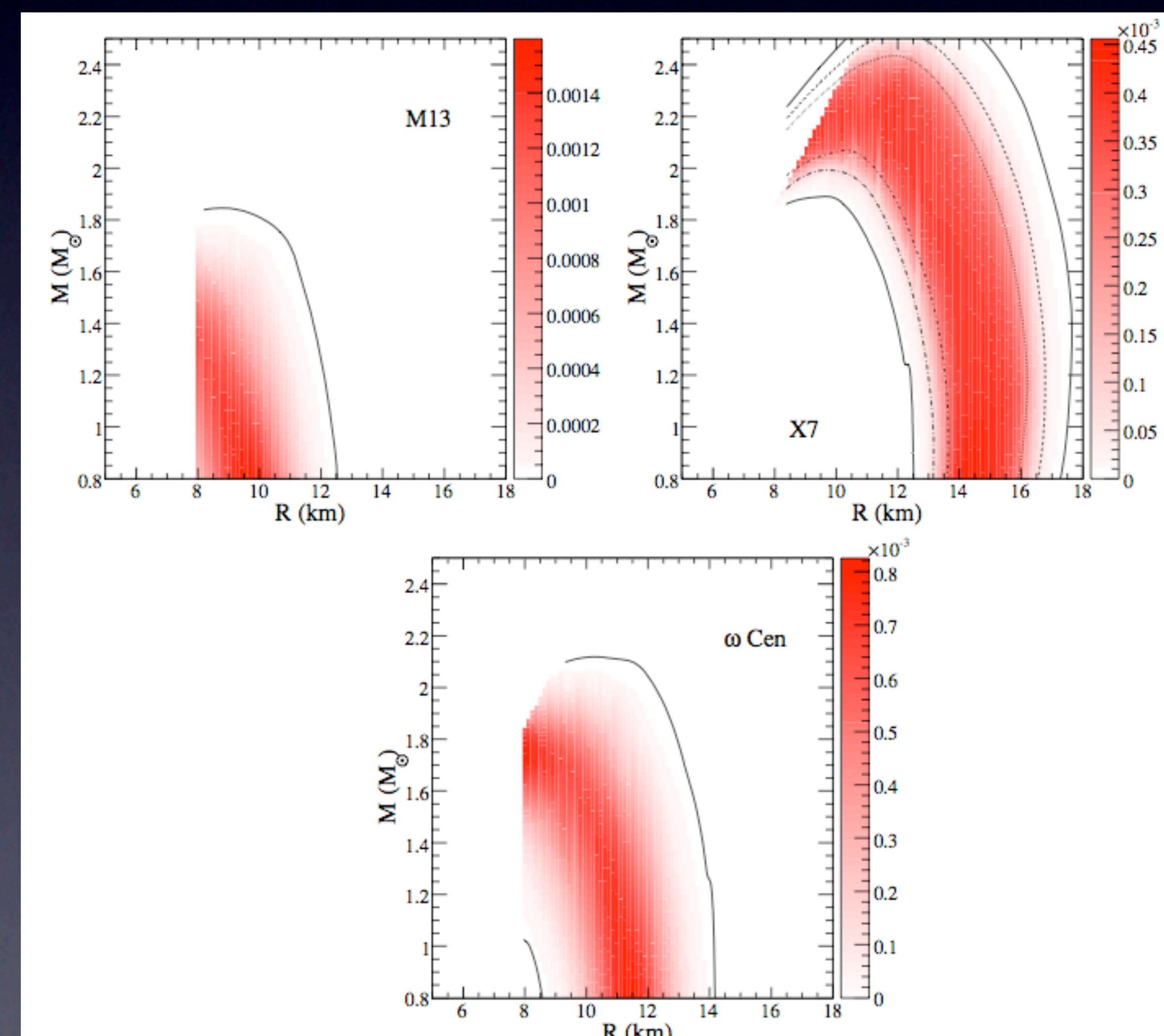
Empirical Equation of State

Steiner et al. 2010, 2012

Type I X-ray bursts



Quiescent LMXBs



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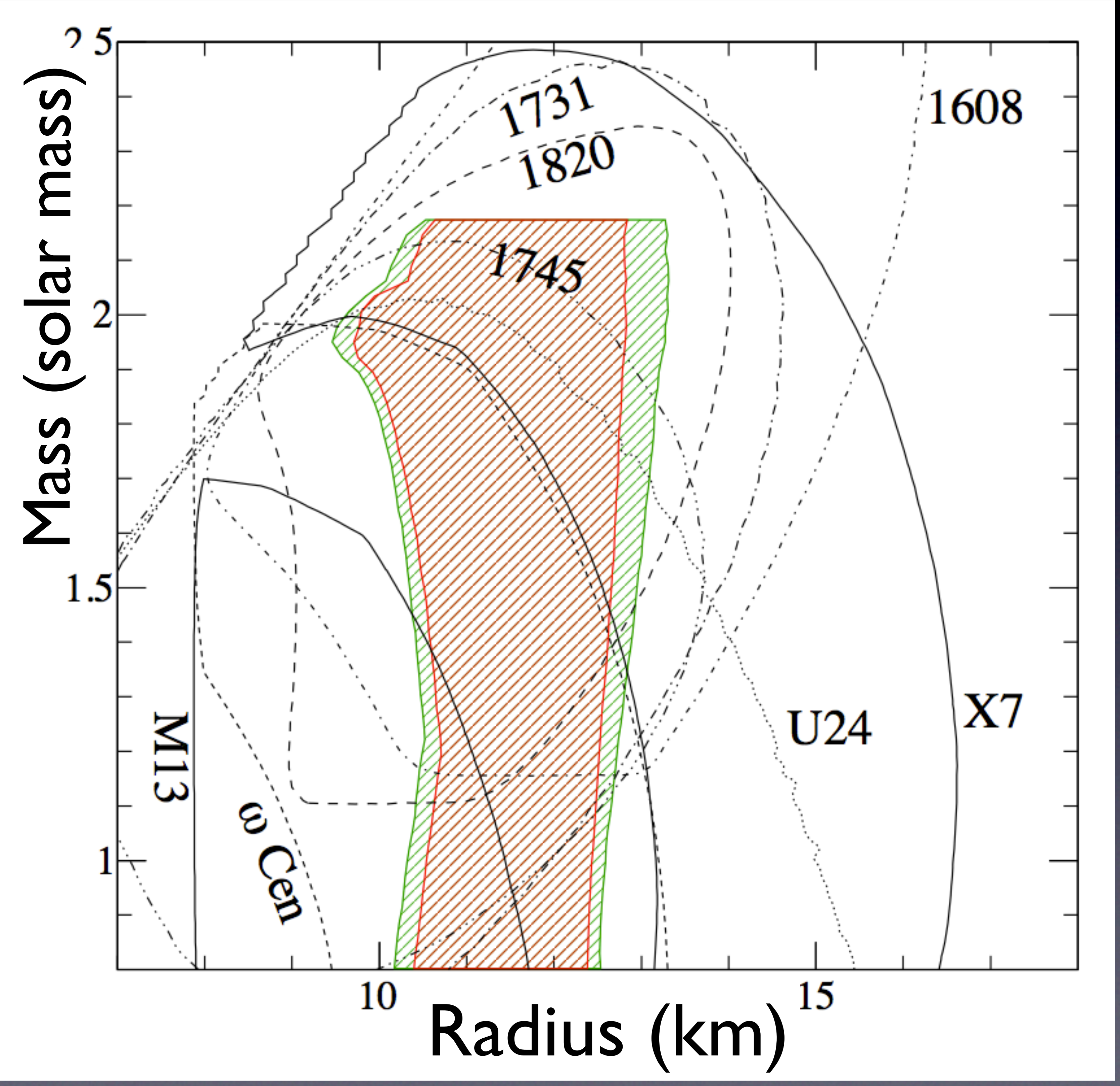
+ M-R contour of Xray burst KS1731-260
Özel et al. 2011

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

Empirical Equation of State

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



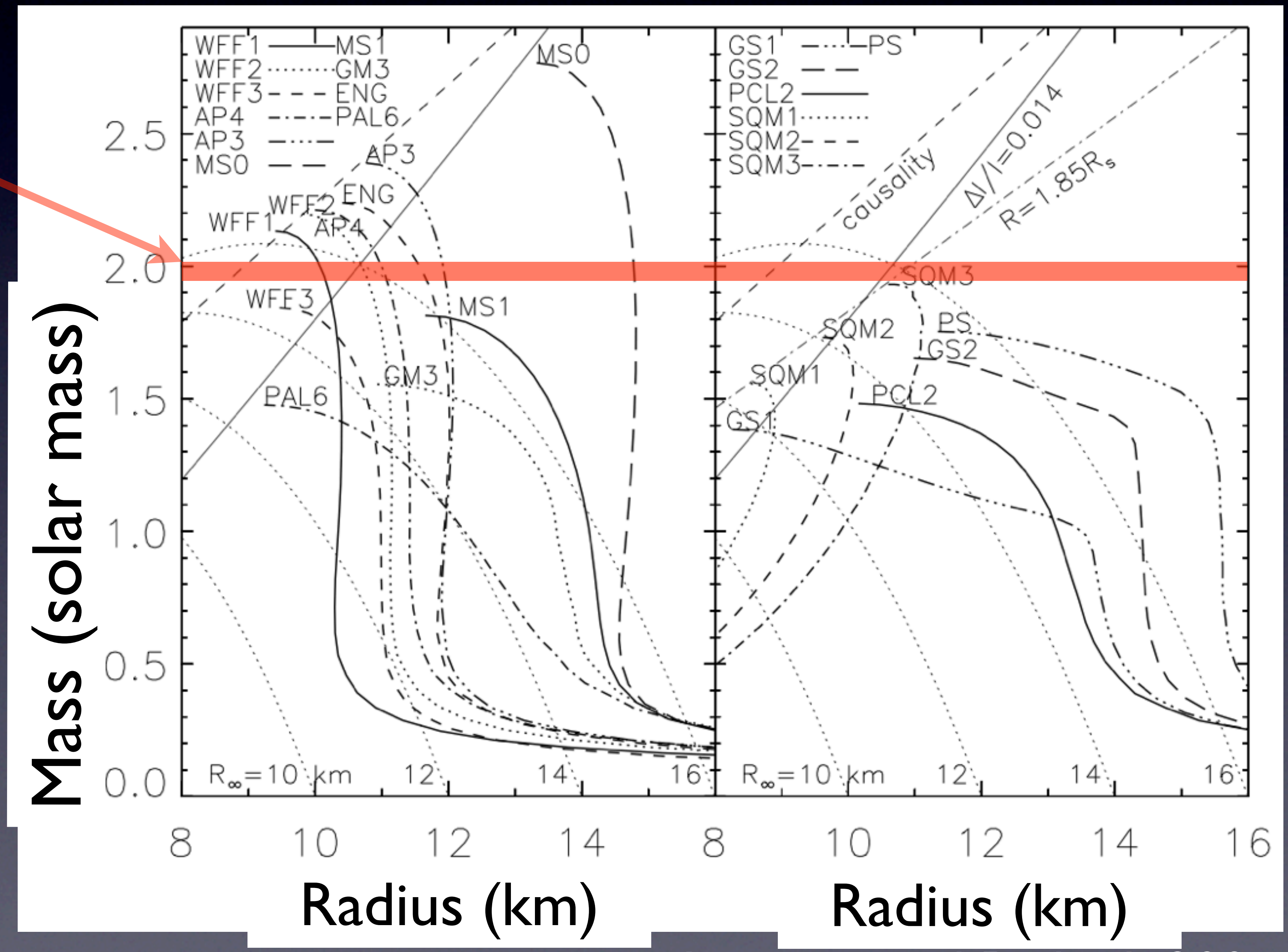
Steiner et al 2012

Dense Matter Equation of State

PSR J1614-2230

Mass measurement with Shapiro Delay: $M_{PSR}=1.97\pm0.04\ M_{\odot}$

Disfavors hybrid and quark matter equations of state

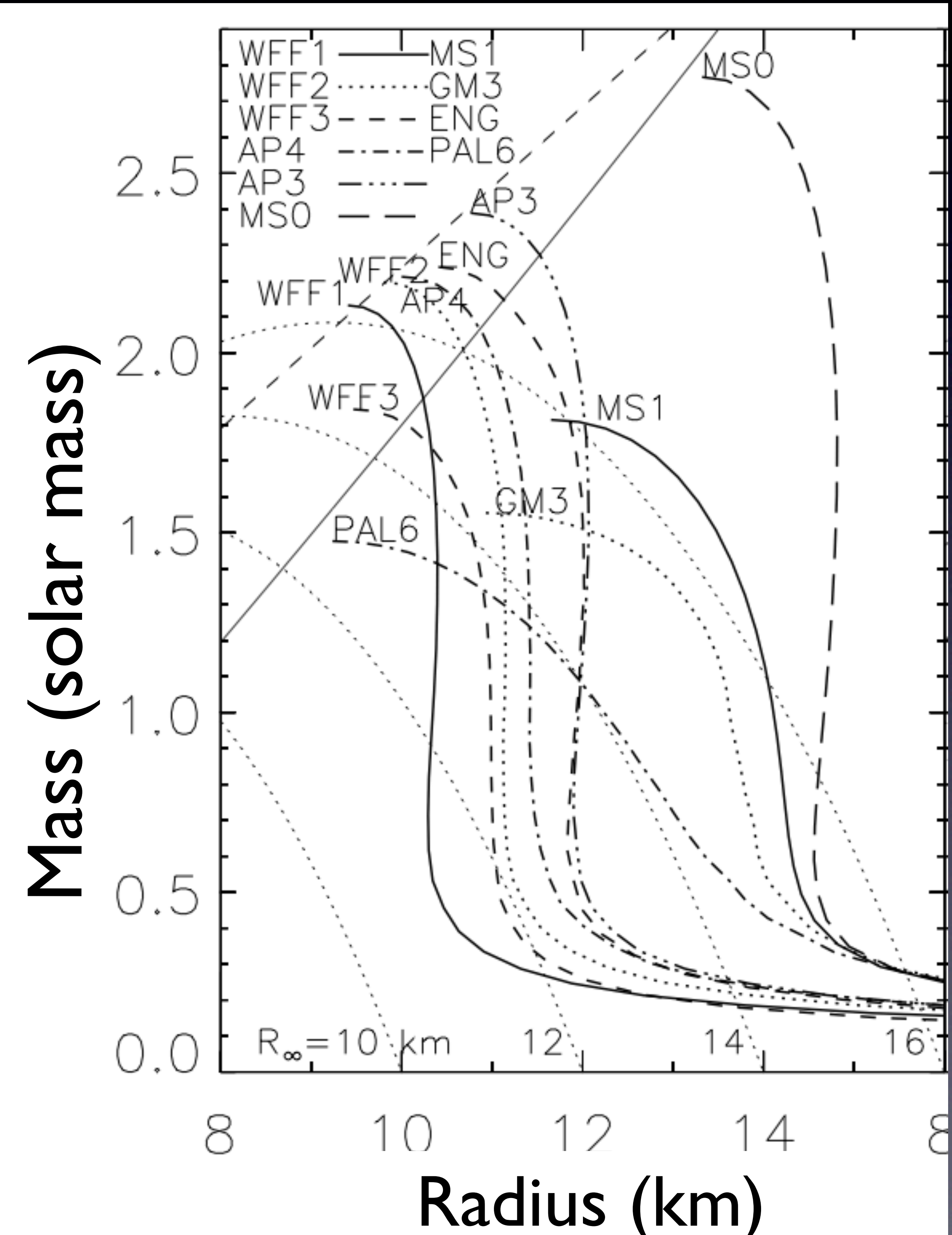


Lattimer and Prakash 2001

Assumption

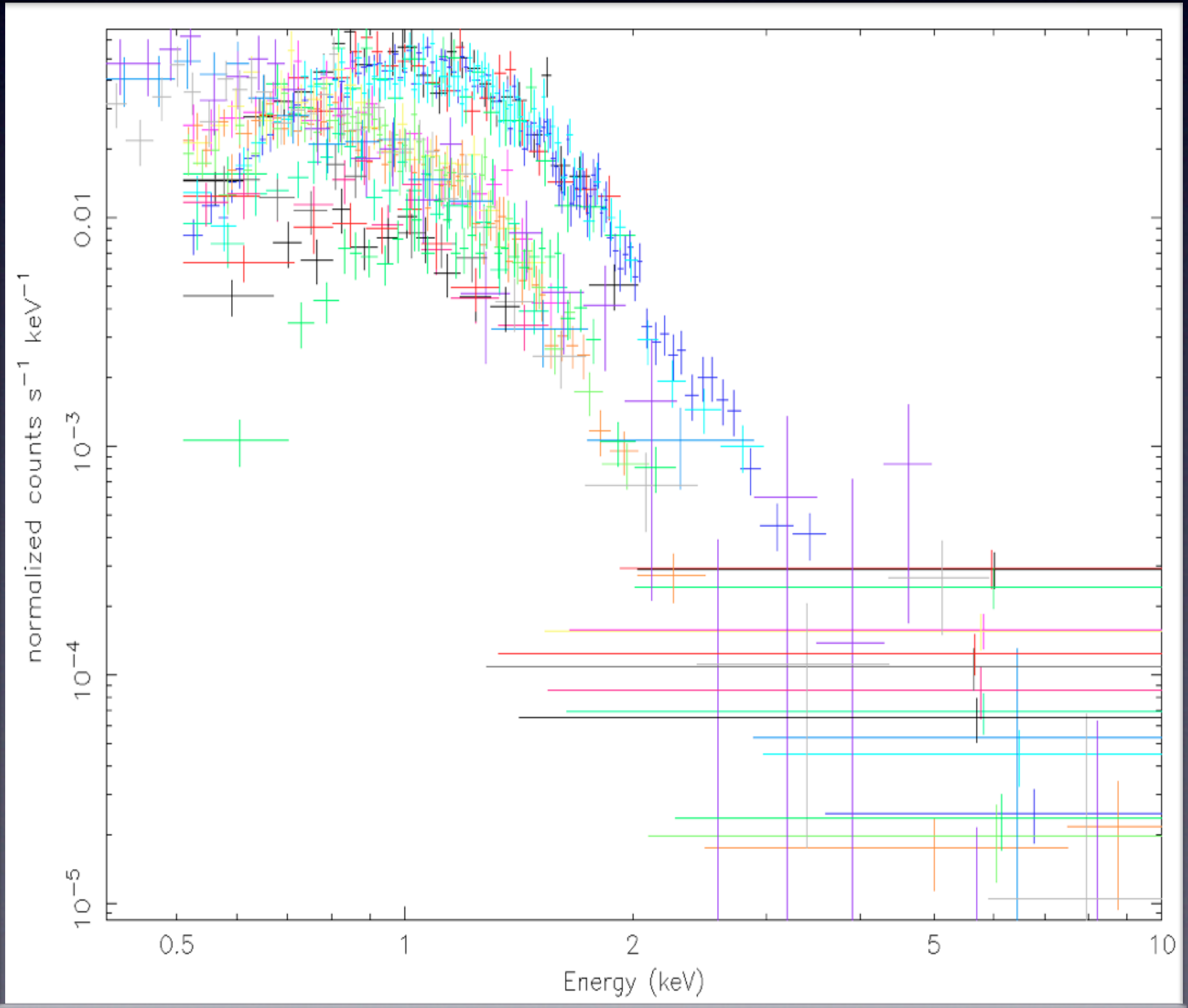
All Neutron Stars have the same radius (within ~10%) for a wide range of masses.

We apply this assumption to the spectral fitting of a group of qLMXBs with the **nsatmos** H-atmosphere model (Heinke et al. 2006), by constraining the R_{NS} to be the same for all.



Simultaneous Spectral Fit

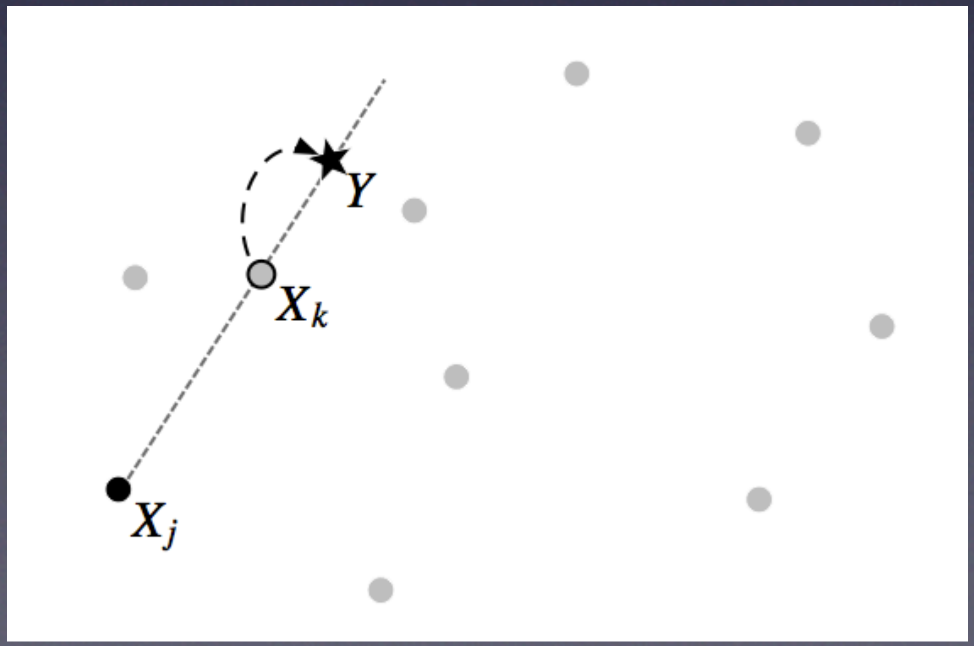
- Fit 5 qLMXBs simultaneously (M28, NGC6397, M13, ωCen and NGC6304) with one single value of R_{NS}
- Up to 5 free parameters per target: kTeff, M_{NS}, N_H, Distance, power-law component
- Up to 27 free parameters



Markov Chain Monte Carlo Simulations

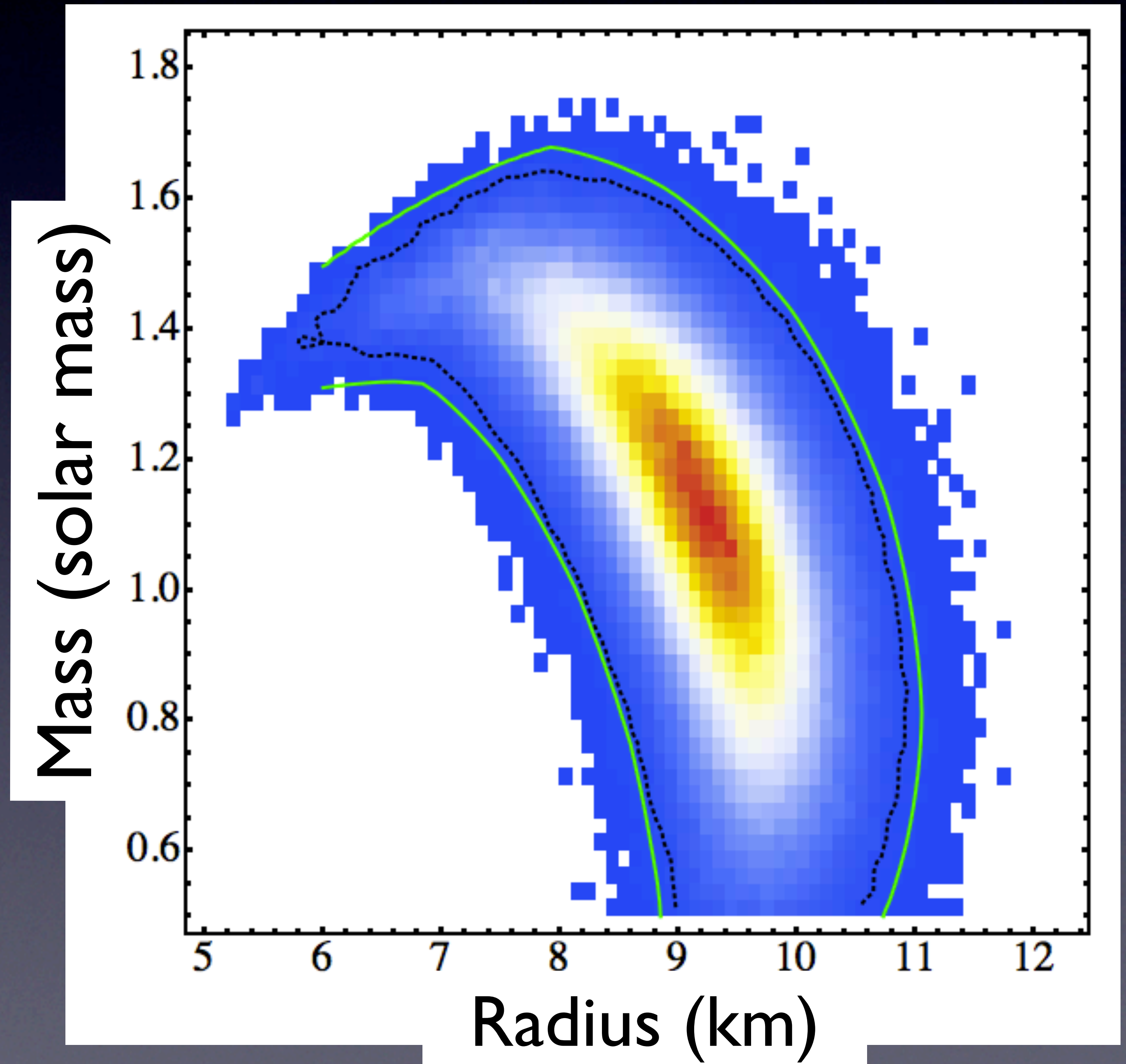
- Because the parameter space has many local minima that XSPEC struggles to identify
- Because one can include Bayesian priors for the distances
- Because one can easily obtain the marginalized posterior distribution for each parameter

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



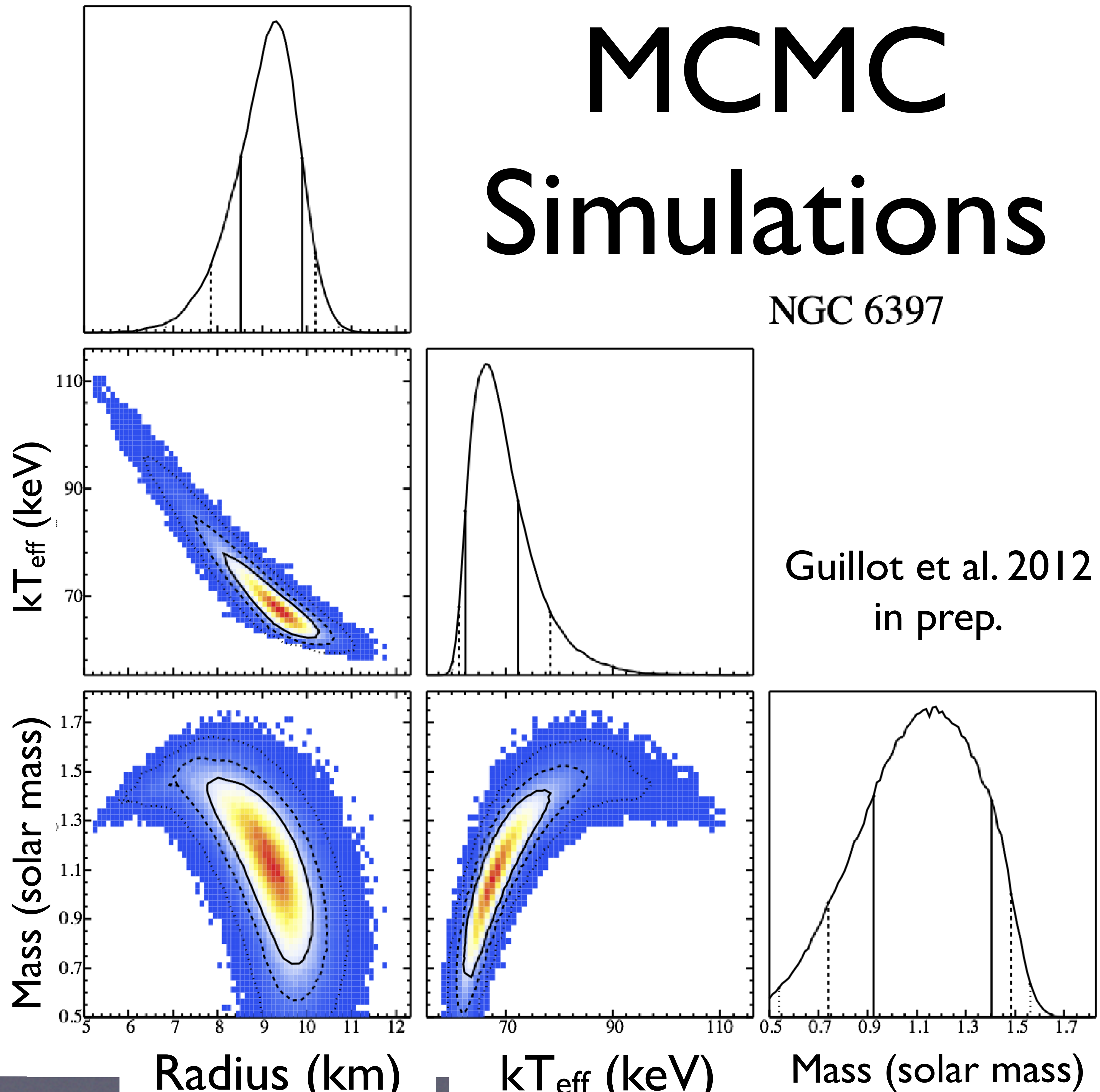
Markov Chain Monte Carlo Simulations

The MCMC approach is first tested with one single qLMXB (U24 in NGC 6397), in order to compare to XSPEC spectral analysis.



Guillot et al. 2012, in prep.

MCMC Simulations

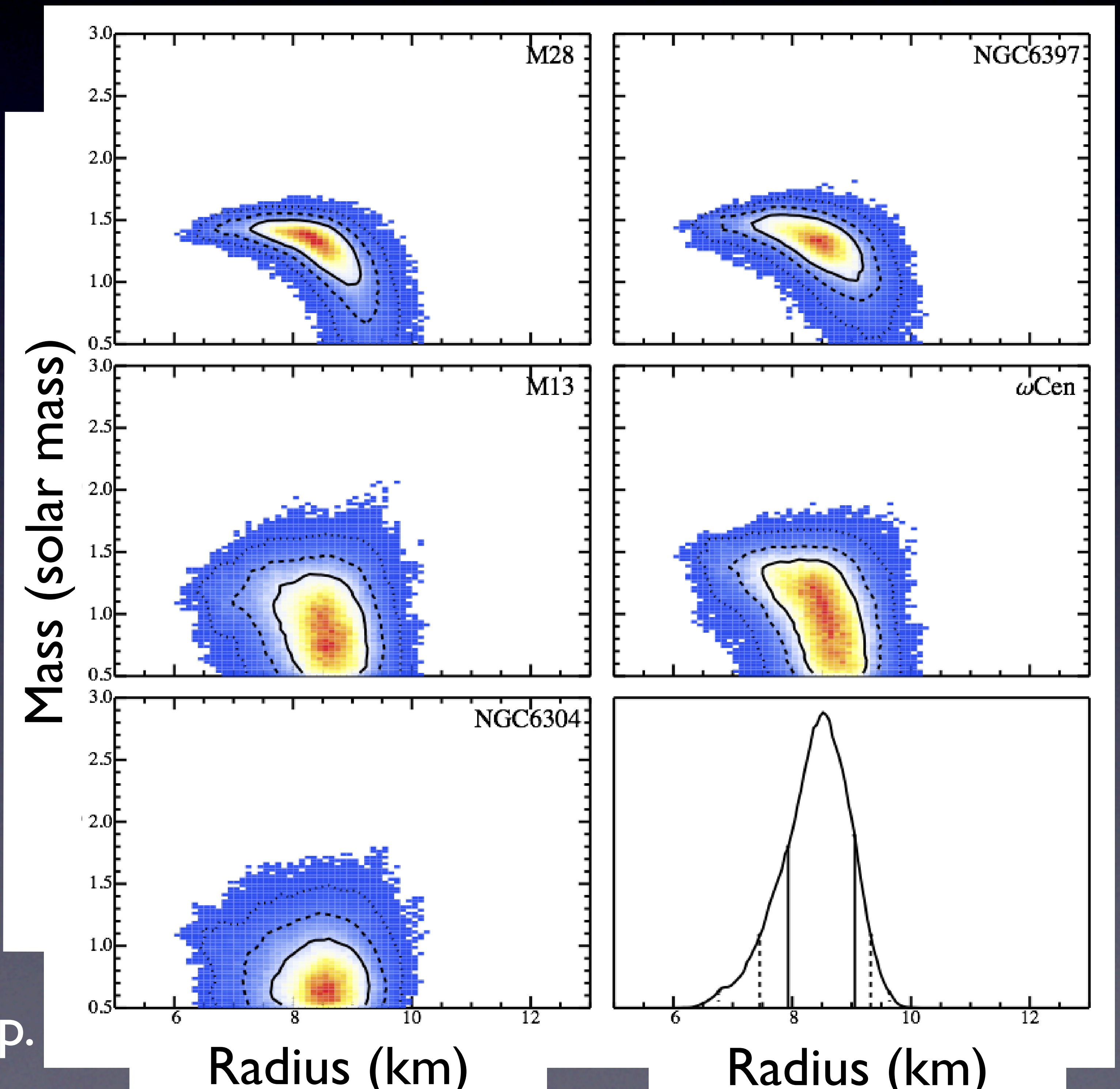


Guillot et al. 2012 in prep.

Markov Chain Monte Carlo Simulations

We run several simulations progressively relaxing all assumptions:

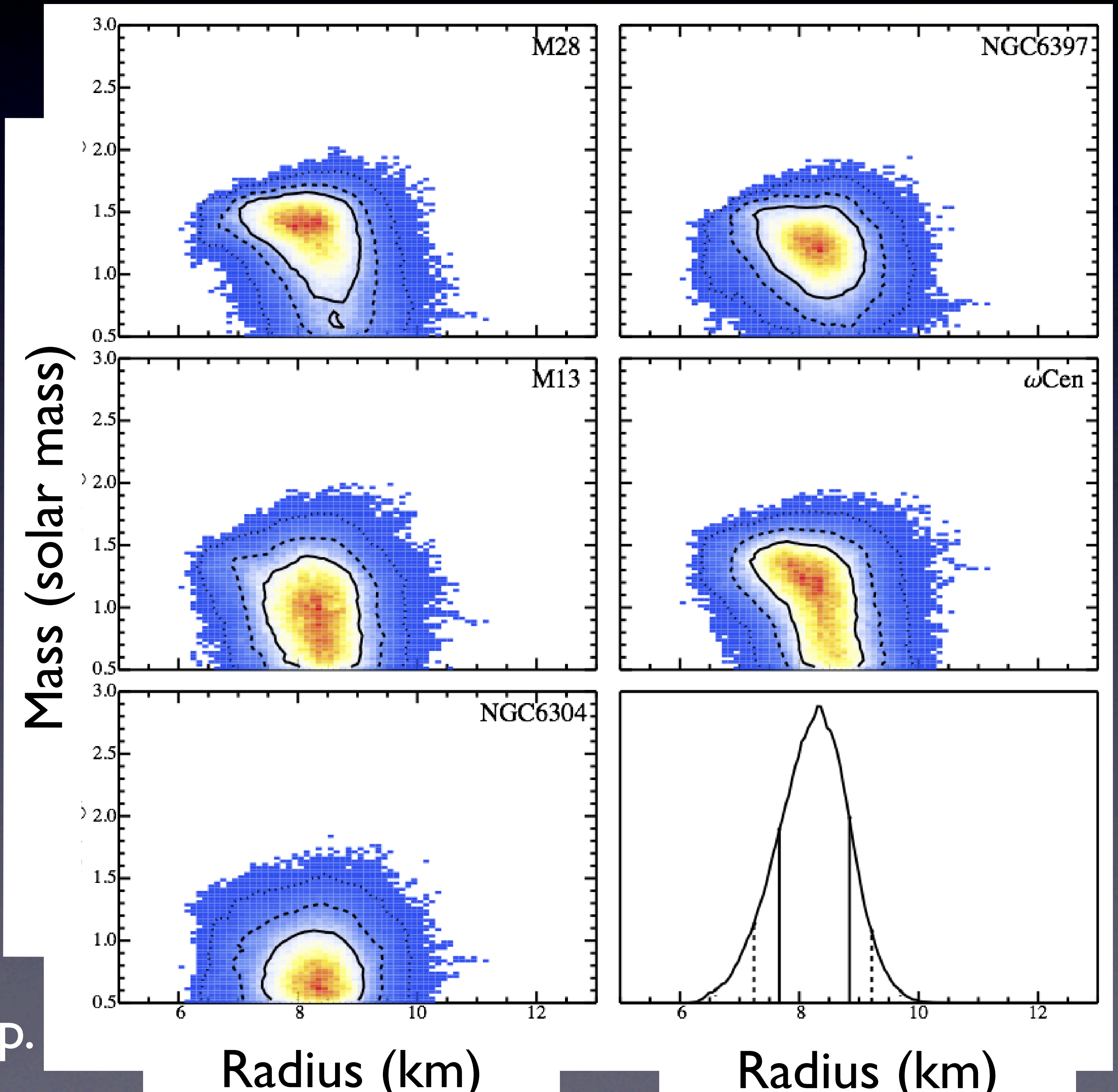
- Galactic absorption N_H
- Distances to clusters
- possible presence of a power-law component



Guillot et al. 2012, in prep.

Markov Chain Monte Carlo Simulations

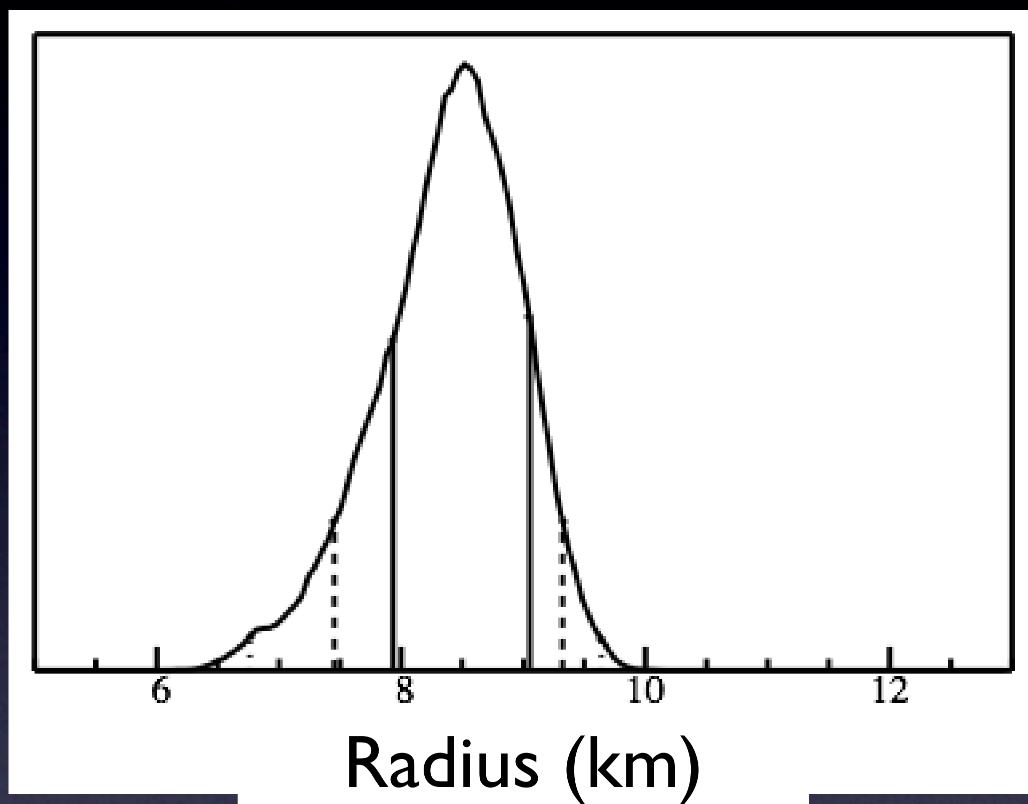
When we add distance priors (instead of keeping the distances fixed), the posterior distributions are broader in the R_∞ direction



Guillot et al. 2012, in prep.

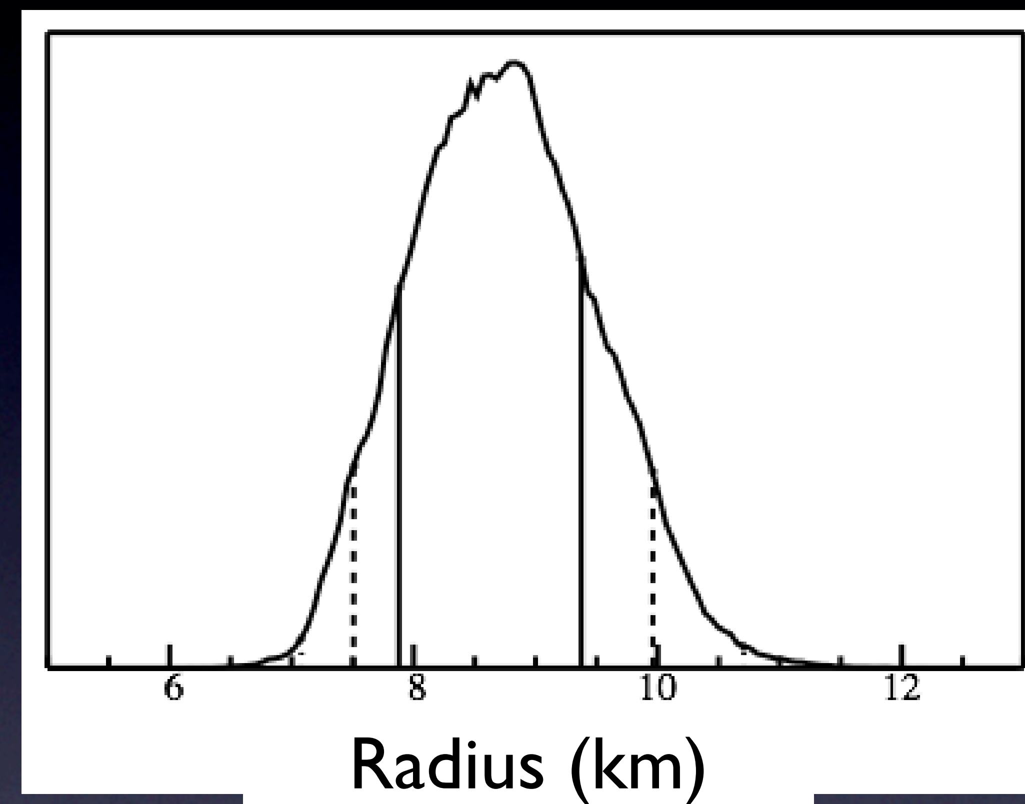
R_{NS} Measurement

Guillot et al. 2012, in prep.



Fixed N_H, Fixed distances, no power-law added

$R_{NS} = 8.5^{+0.8}_{-1.1}$ km (90%-confidence)

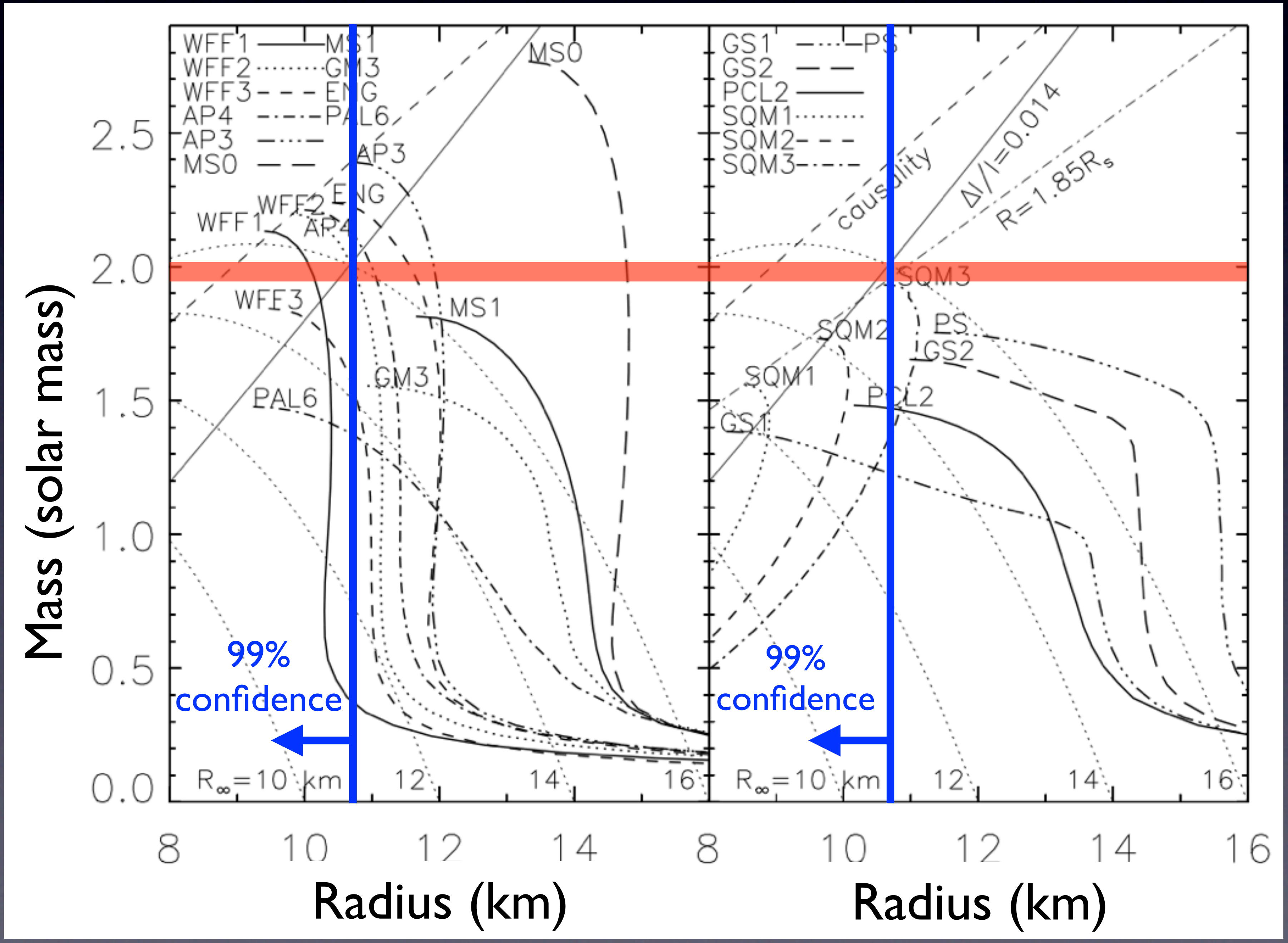


Free N_H, Bayesian priors on distances, with power-law component added

$R_{NS} = 8.8^{+1.1}_{-1.3}$ km (90%-confidence)

Constraints on Equation of State

$R_{NS} < 10.7$ km at the 99%-confidence level



Conclusion

- Evidence that R_{NS} is constant for a wide range of masses
- Use that assumption to measure R_{NS} from five quiescent low-mass X-ray binaries in globular clusters
- Spectral fit with *nsatmos* model using an MCMC simulation to obtain posterior distributions on each of the parameters (up to 27 free parameters)
- Measurement of $R_{NS} < 10.7$ km (99%-confidence) with the least number of assumptions, and a particular effort to control systematic uncertainties
- Only some EoSs are consistent with this results, for example, WFF1 (Wiringa et al 1988)