Measuring M_{NS}, R_{NS}, M_{NS}/R_{NS} or R_∞

Sebastien Guillot

Advisor: Robert Rutledge

Galileo Galilei Institute, Firenze
March 2014

McGill

Government of Canada
Vanier Canada Graduate Scholarships

Gouvernement du Canada
Bourses d'études supérieures du Canada Vanier

Canada

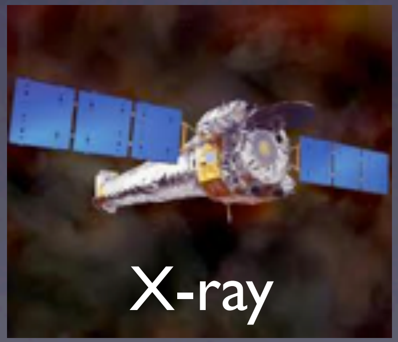
Some Reviews

Lattimer and Prakash, 2007

Miller C., 2013

Heinke et al., 2013

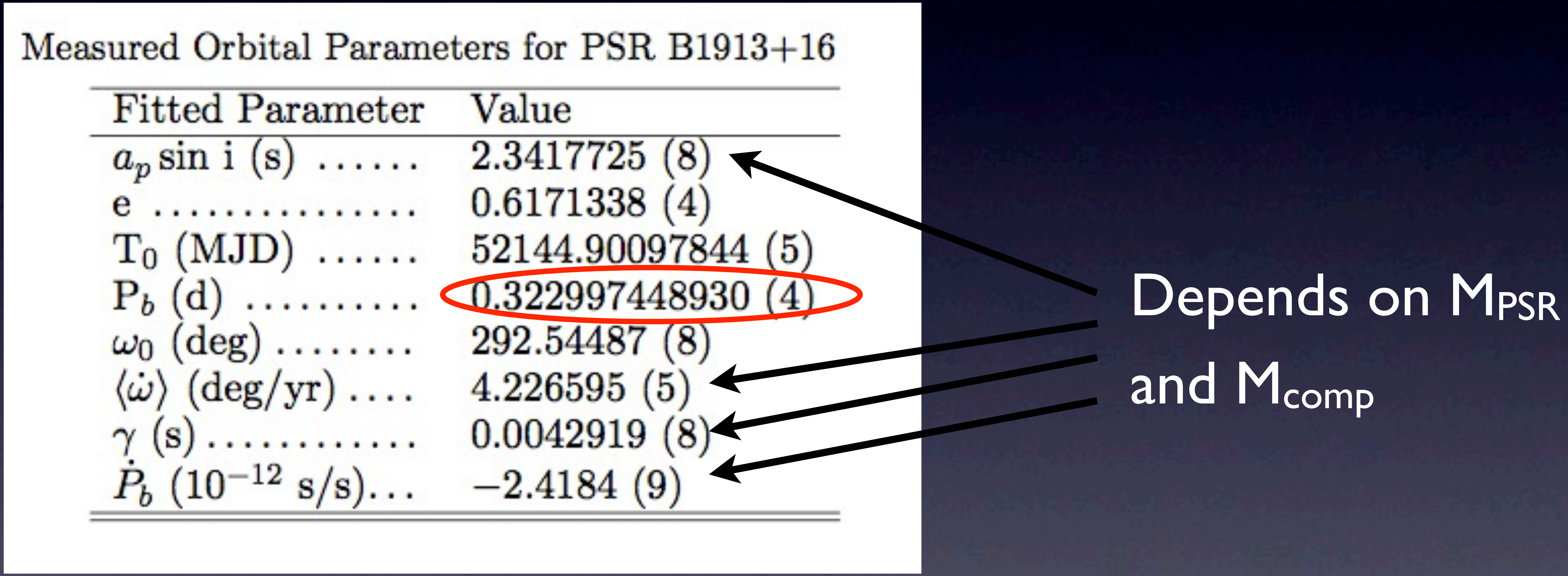
Reminder Labels



Measuring M_{NS}

Double neutron stars binary systems lead to precise M_{NS} measurements

Double NS system PSR B1913+16



Measured Orbital Parameters for PSR B1913+16

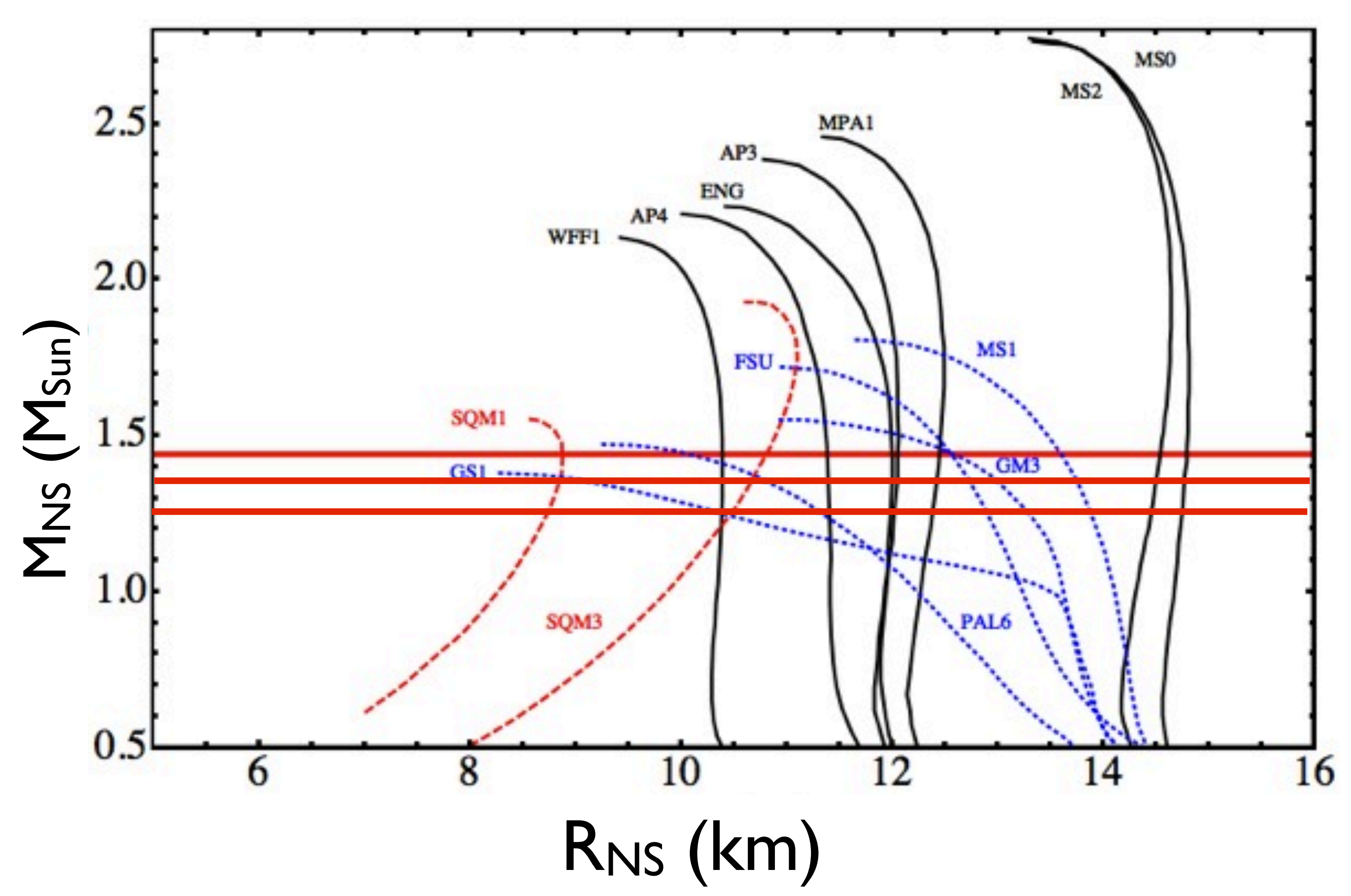
Fitted Parameter	Value
a_p sin i (s) ……	2.3417725 (8)
e ……………	0.6171338 (4)
T_0 (MJD) ……	52144.90097844 (5)
P_b (d) ………	0.322997448930 (4)
ω_0 (deg) ……	292.54487 (8)
$\langle\dot{\omega}\rangle$ (deg/yr) ….	4.226595 (5)
γ (s) …………	0.0042919 (8)
$\dot{P}_b$ (10^{-12} s/s)…	−2.4184 (9)

Depends on M_{PSR} and M_{comp}

Double-NS system PSR B1913+16
Best M_{NS} measurement
$M_{PSR} = 1.4414 \pm 0.0002\ M_\odot$
(Weisberg et al. 2005)

Double-Pulsar system PSRJ0737−3039
$M_{PSRA} = 1.3381 \pm 0.0007\ M_\odot$
$M_{PSRB} = 1.2489 \pm 0.0007\ M_\odot$
(Kramer et al. 2006)

Double neutron stars binary systems lead to precise M_{NS} measurements

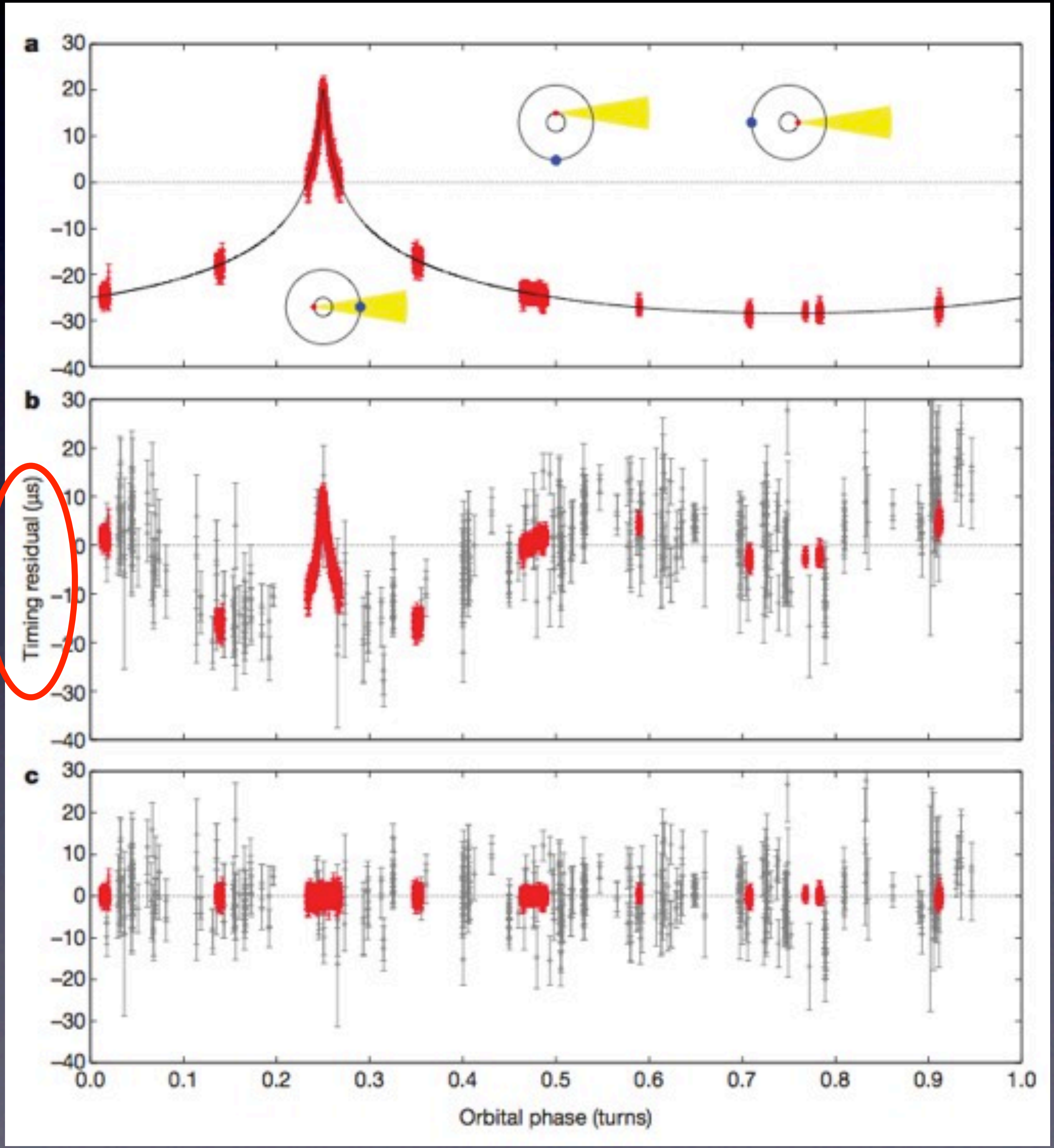


Not constraining enough!!

Neutron stars in binary systems need additional input to get M_{NS}

Additional post-Keplerian parameters, e.g. Shapiro delay, to break the degeneracies between mass ratio and inclination

$M_{PSR} = 1.97 \pm 0.04\ M_\odot$
(Demorest et al. 2010)

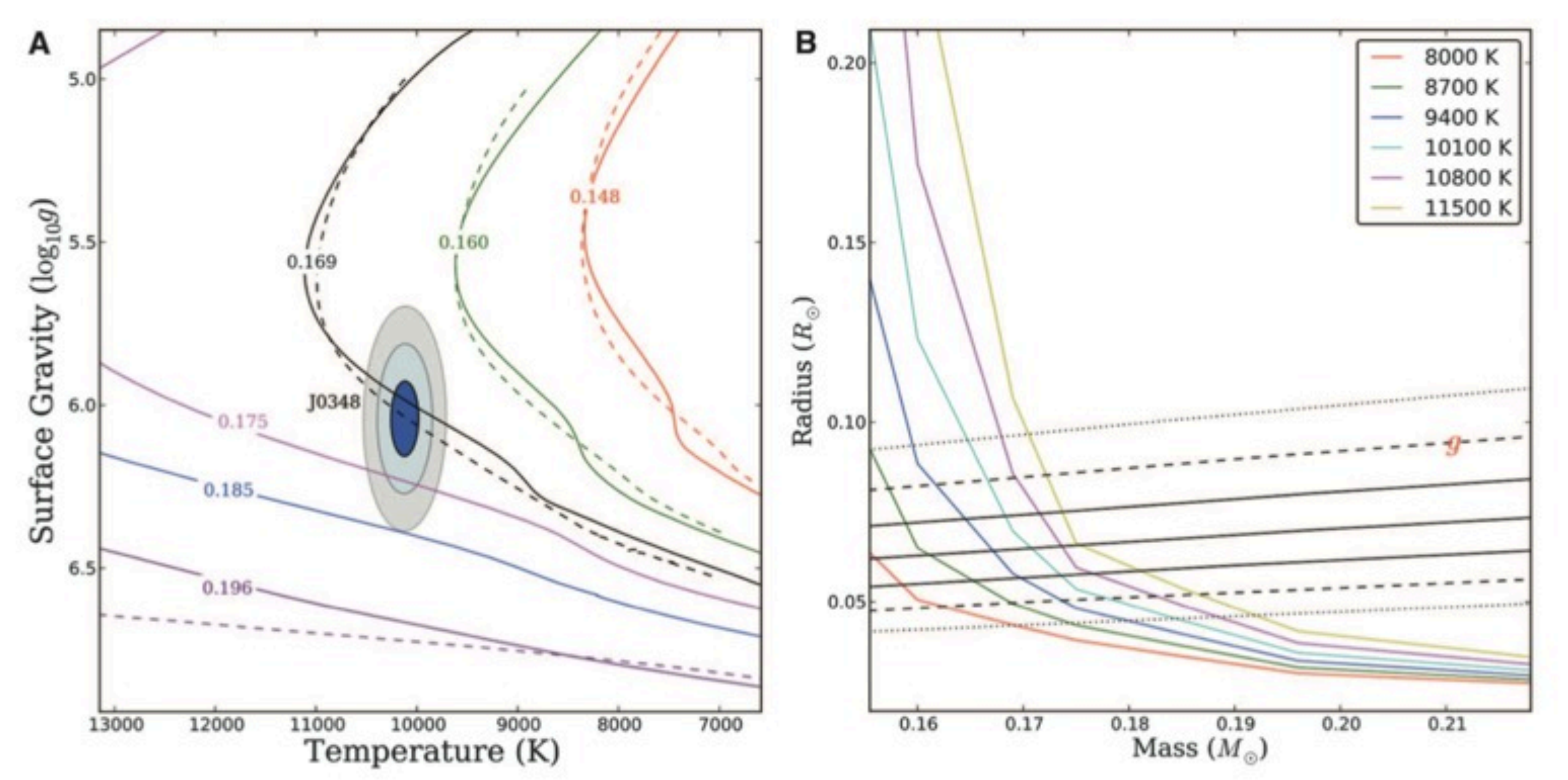


Neutron stars in binary systems need additional input to get M_{NS}

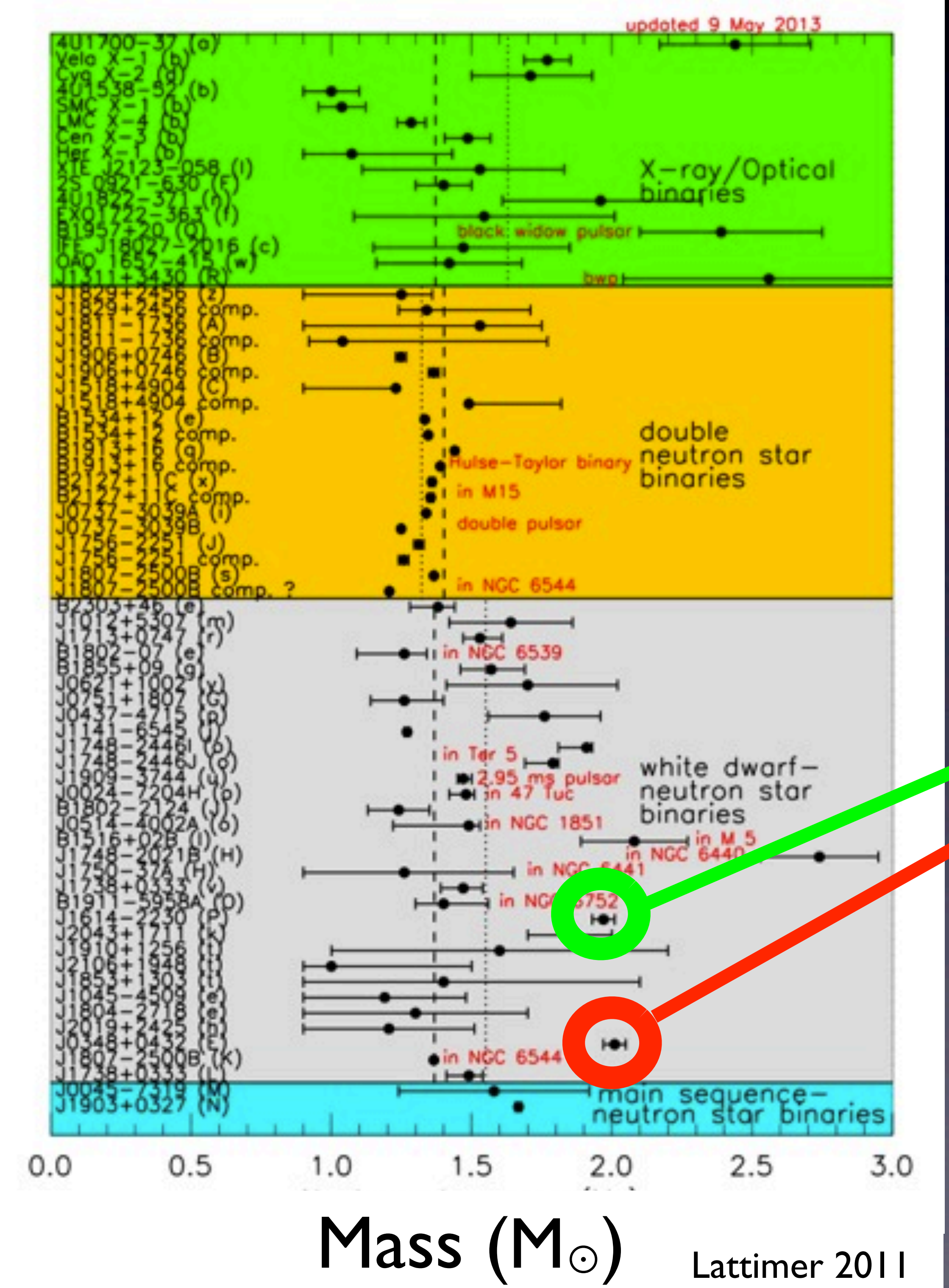
Independent measure of M_{comp}

e.g., for WD companion to PSR J0348+0432

$M_{PSR} = 2.01 \pm 0.04\ M_\odot$ (Antoniadis et al. 2013)



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



Lattimer 2011

PSR J1614-2230

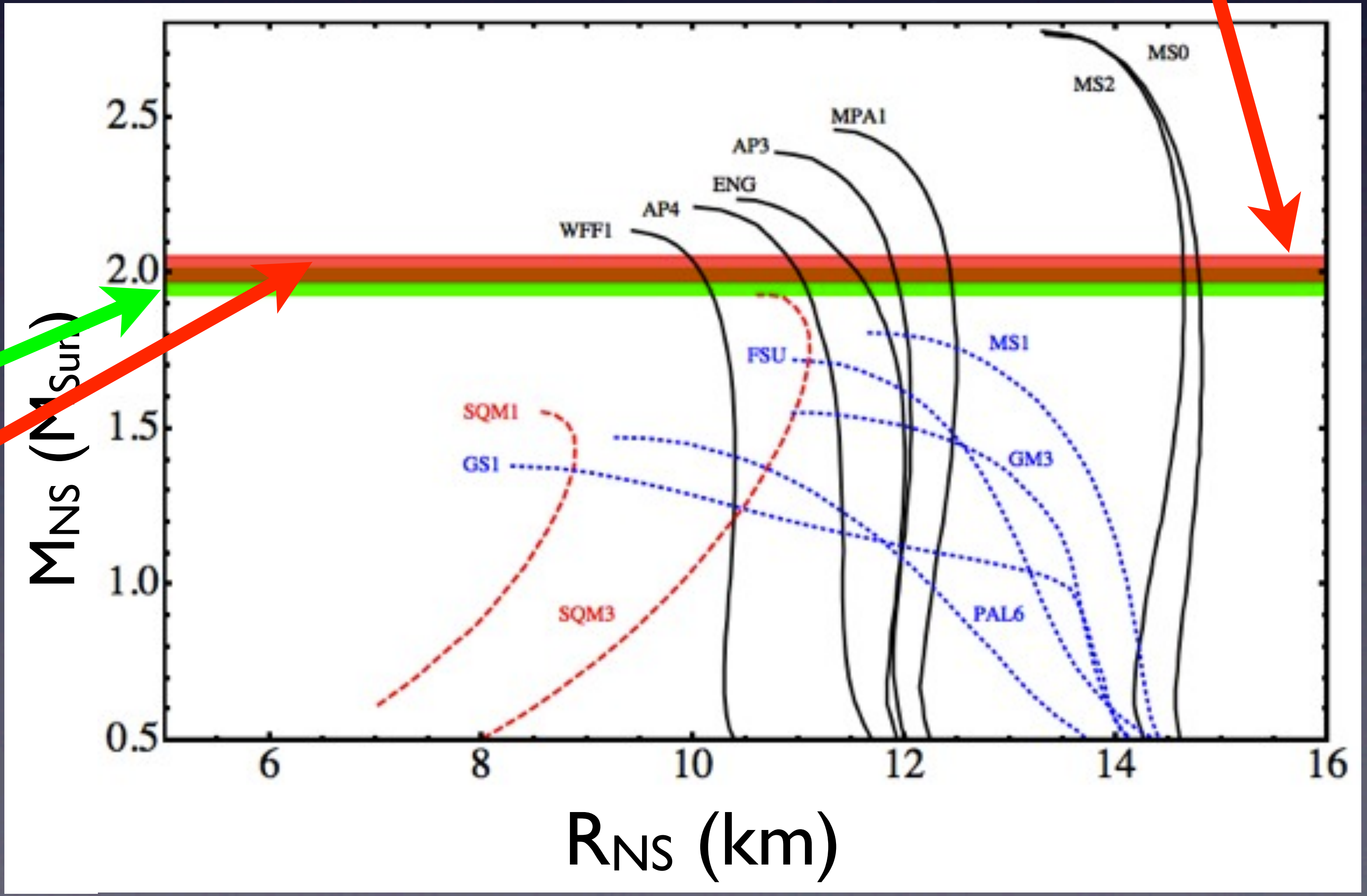
$M_{PSR}=1.97\pm0.04\ M_\odot$

(Demorest et al. 2010)

PSR J0348+0432

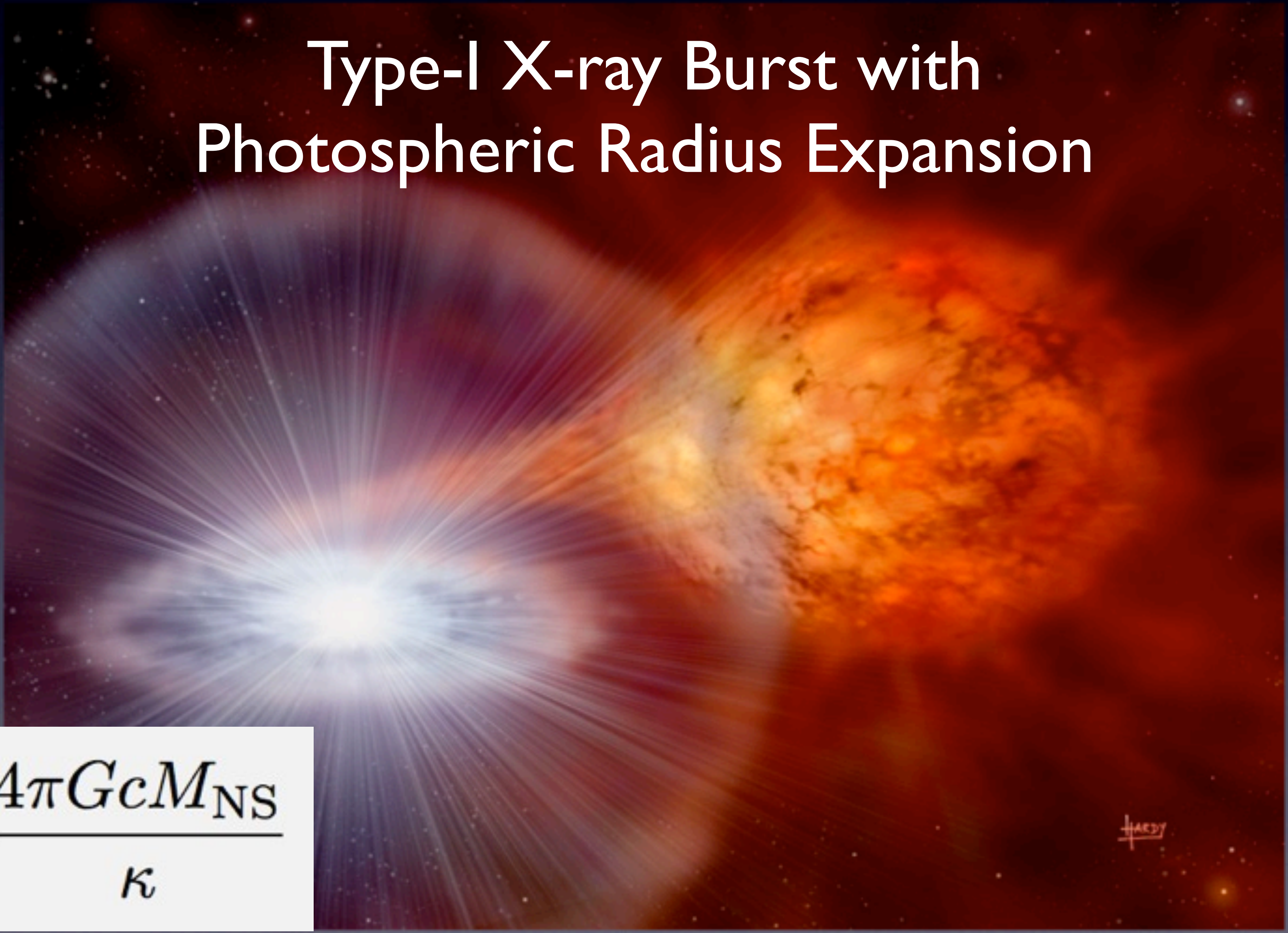
$M_{PSR}=2.01\pm0.04\ M_\odot$

(Antoniadis et al. 2013)



Enough with M_{NS},
Let's measure M_{NS} and R_{NS}

Two observables are necessary to measure both M_{NS} and R_{NS} from Type-I X-ray bursts with PRE


Type-I X-ray Burst with
Photospheric Radius Expansion

$$L_{\mathrm{Edd}} = \frac{4\pi G c M_{\mathrm{NS}}}{\kappa}$$

Two observables are necessary to measure both M_{NS} and R_{NS} from Type-I X-ray bursts

Two observables

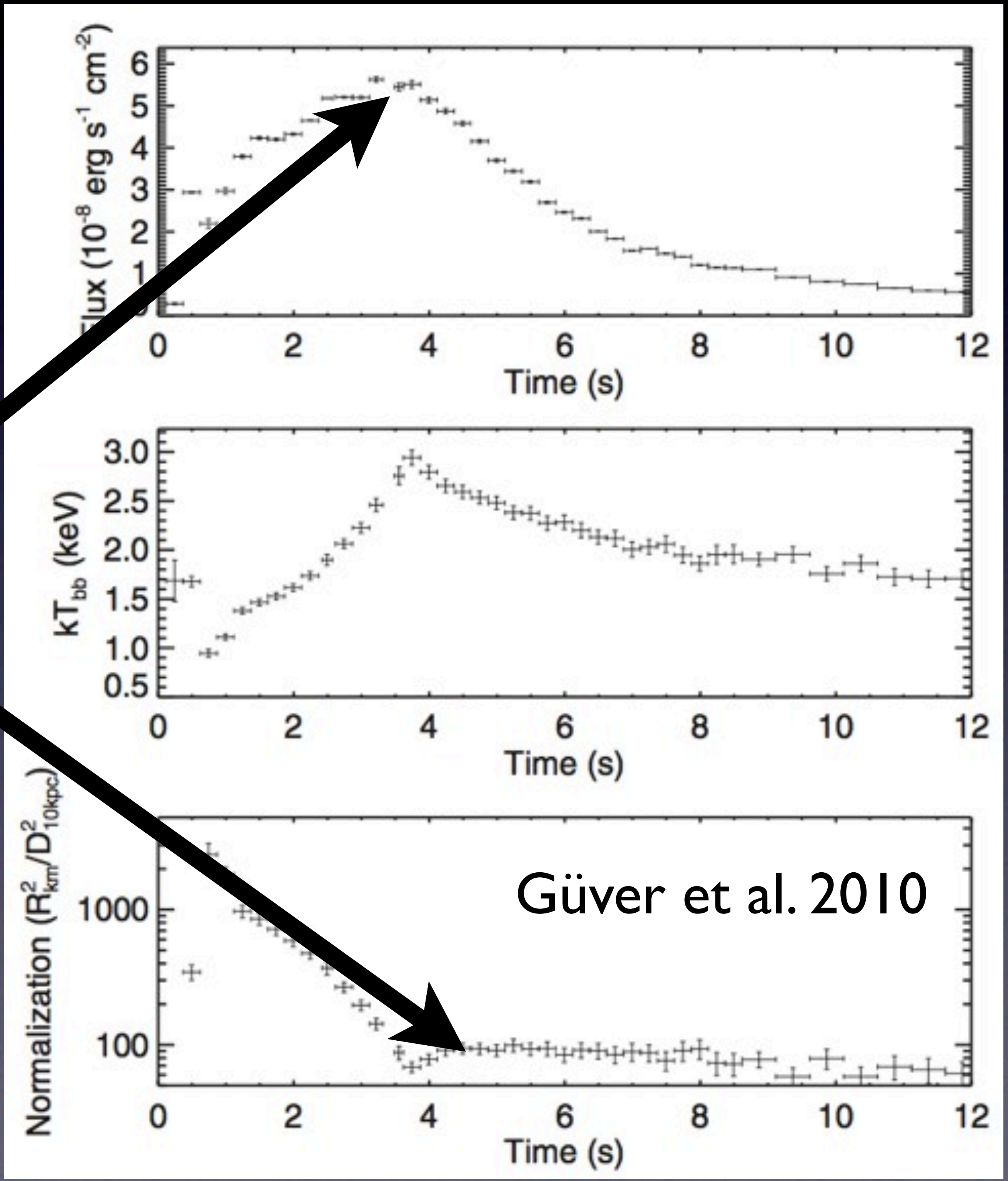
$$F_{\mathrm{Edd},\infty} = \frac{GcM_{\mathrm{NS}}}{\kappa D^2}\frac{1}{(1+z)}$$

$$A_\infty = \frac{R^2}{f_c^4 D^2}(1+z)^2$$

model dependent

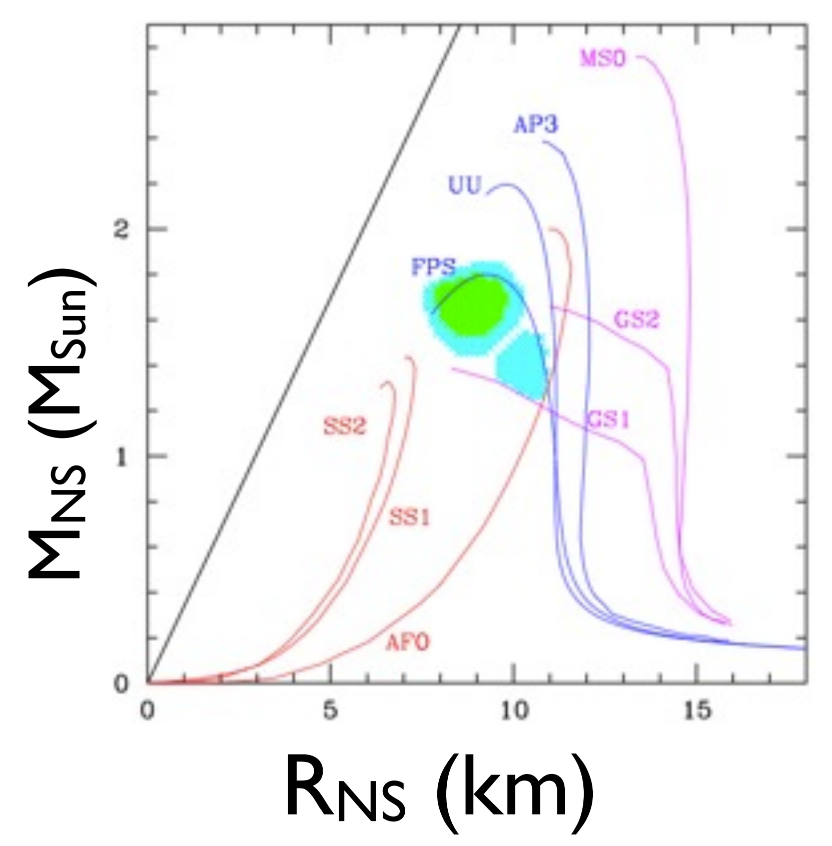
with

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

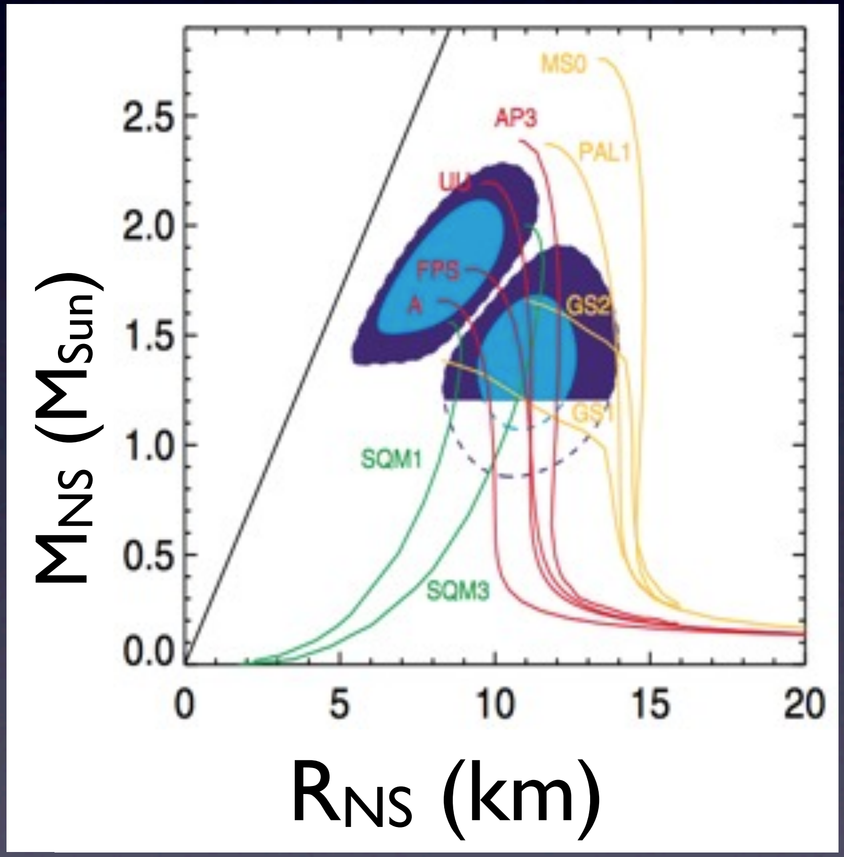


Güver et al. 2010

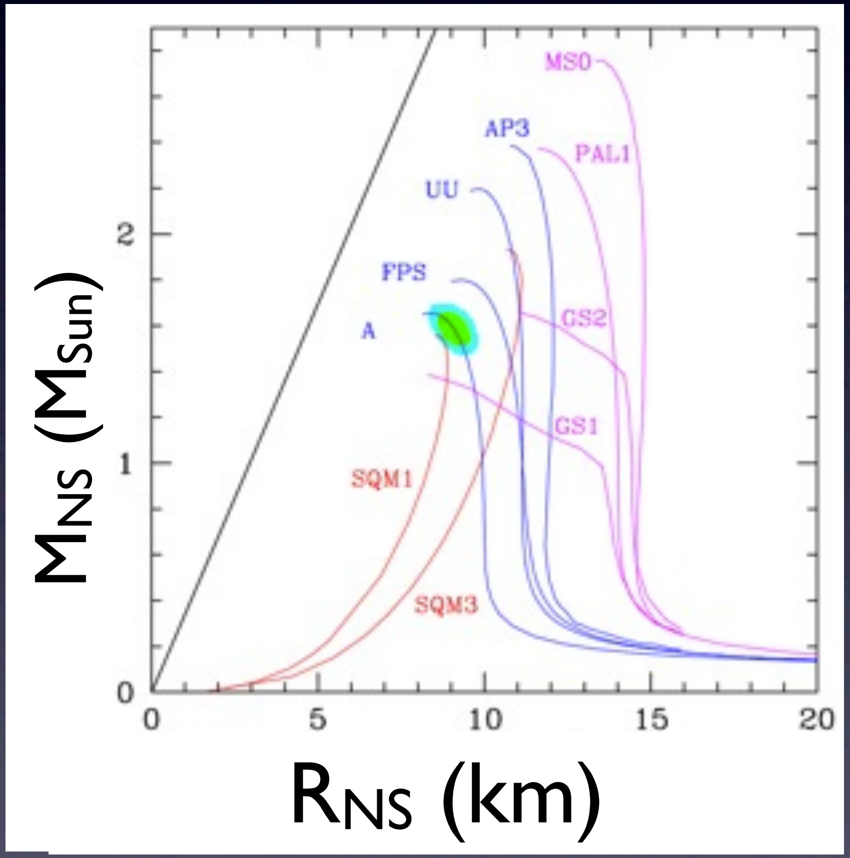
M_{NS} and R_{NS} measurements with “*known distances*” are very constraining... Or are they?



EXO 1745−348
in globular cluster
Terzan 5
(Özel et al. 2009)

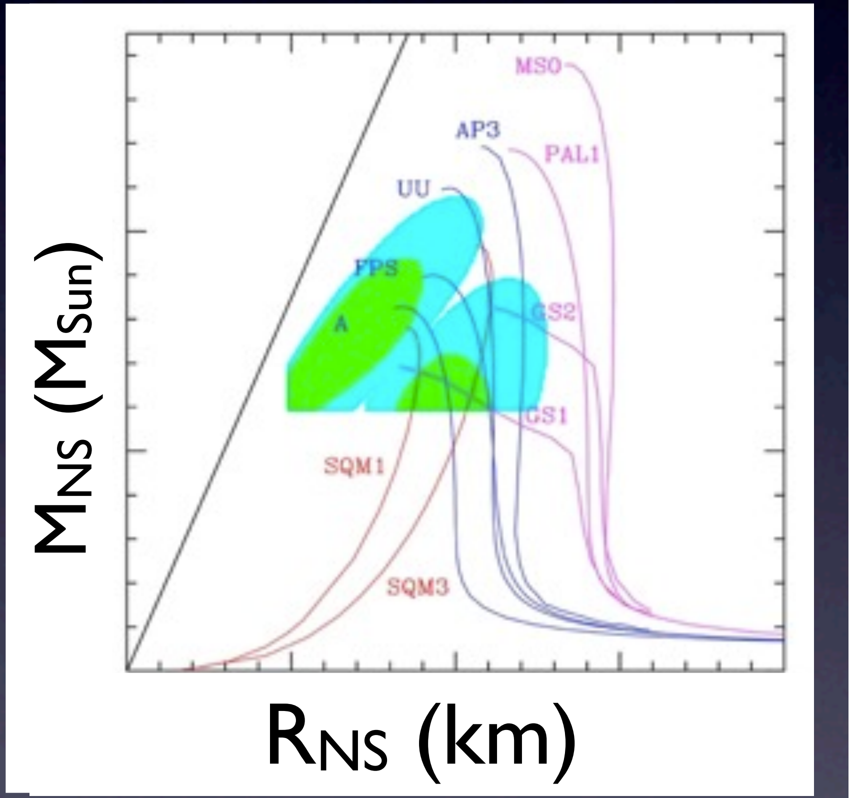


SAX J1748.9−2021
in globular cluster
NGC 6440
(Güver & Özel, 2013)

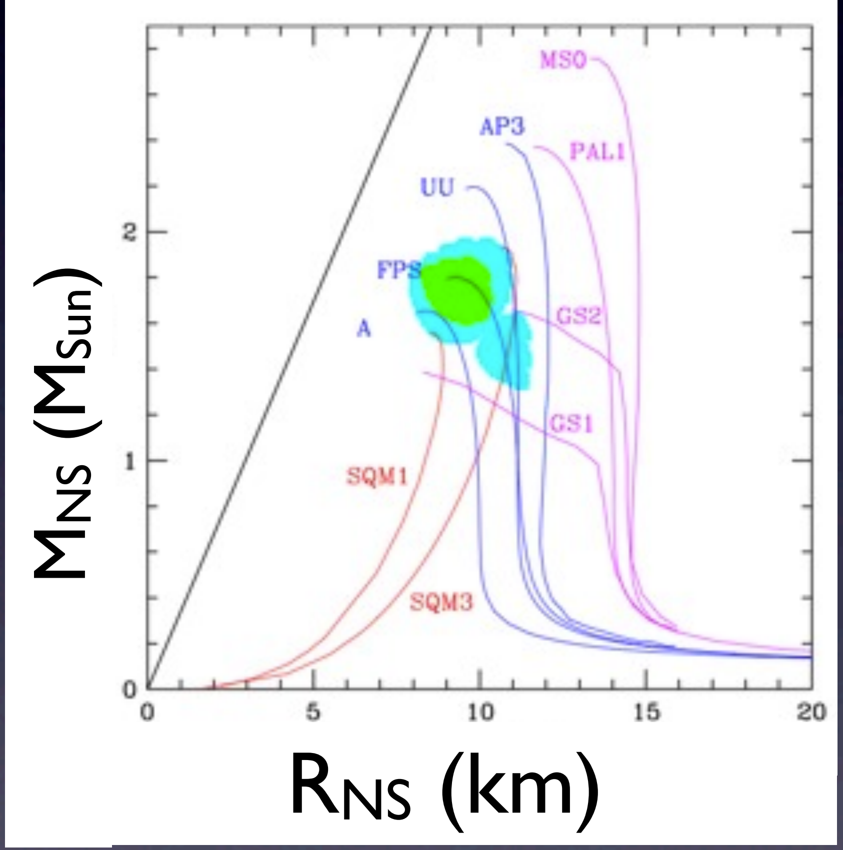


4U 1820−30
in globular cluster
NGC 6624
(Güver et al. 2010a)

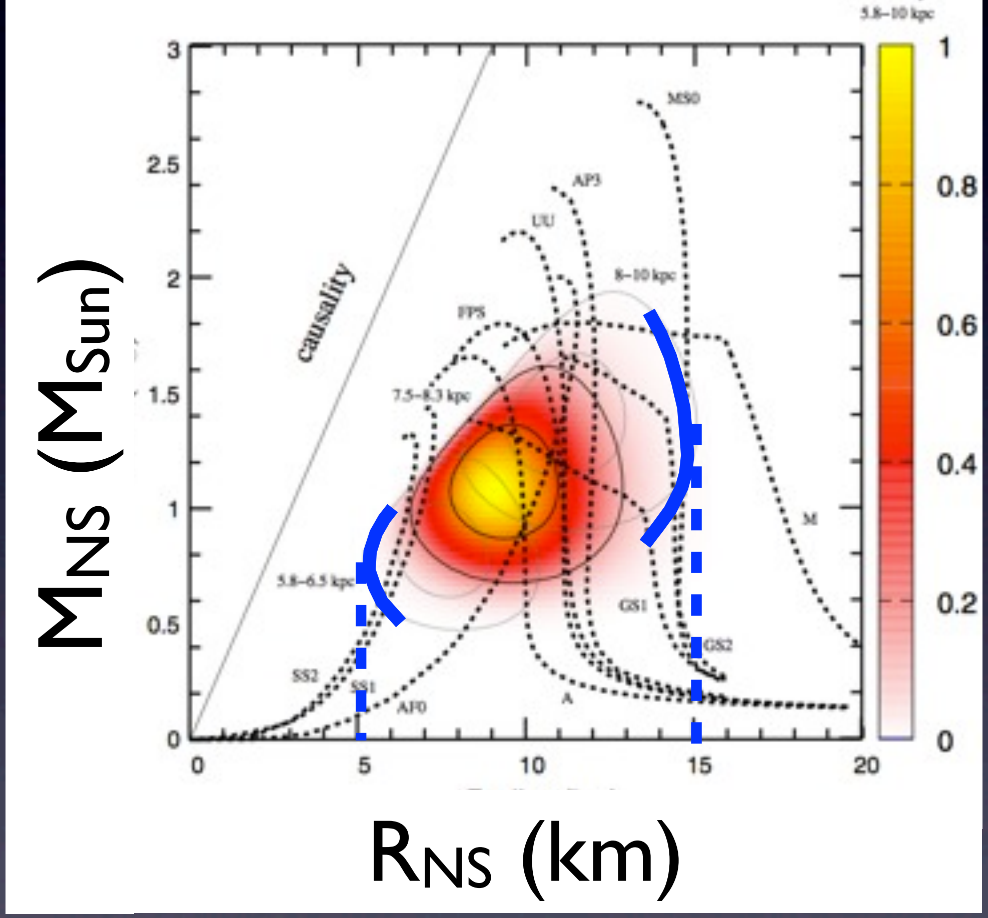
M_{NS} and R_{NS} measurements with "*known distances*" are very constraining... Or are they?



KS 1731−260
Distance estimated from distribution of surrounding stars
(Özel et al. 2012)



4U 1608−53
Using surrounding red clump stars
(Güver et al. 2010a)



Rapid Buster
Assuming a wide range of distances
(Sala et al. 2013)

When the distance is unknown, an additional observable is necessary!

$$M = \frac{c^5}{4G\kappa}\left(\frac{R_\infty}{d}\right)^2 \frac{1}{F_{\mathrm{Edd},\infty}} \frac{1}{(1+z)^3}\left[1-(1+z)^{-2}\right]^2$$

$$R = \frac{c^3}{2\kappa}\left(\frac{R_\infty}{d}\right)^2 \frac{1}{F_{\mathrm{Edd},\infty}} \frac{1}{(1+z)^3}\left[1-(1+z)^{-2}\right]^2$$

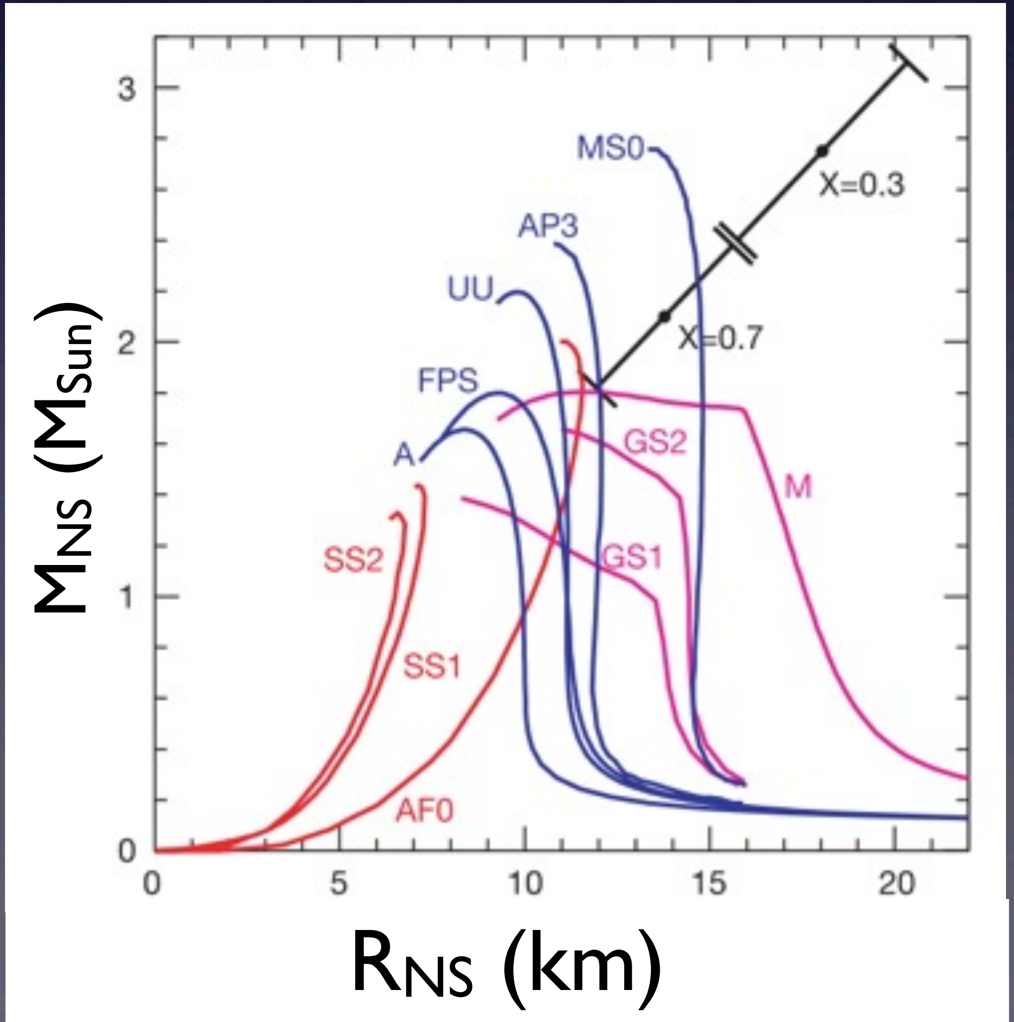
$$d = \frac{c^3}{2G\kappa}\left(\frac{R_\infty}{d}\right) \frac{1}{F_{\mathrm{Edd},\infty}} \frac{1}{(1+z)^2}\left[1-(1+z)^{-2}\right]$$

Gravitational redshift measured from spectral lines in EXO 0748−676
z = 0.35 (Cottam et al. 2002)

used to measure M_{NS}-R_{NS}
(Ozel et al. 2006)

However, those lines were not confirmed later on (Cottam et al. 2008)

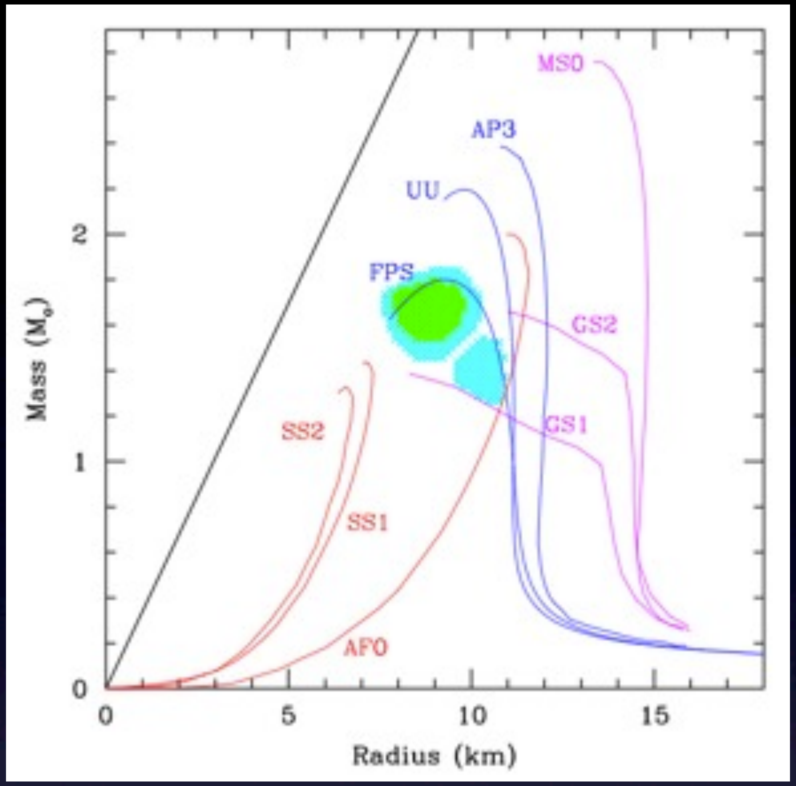
opacities κ still depends on unknown composition



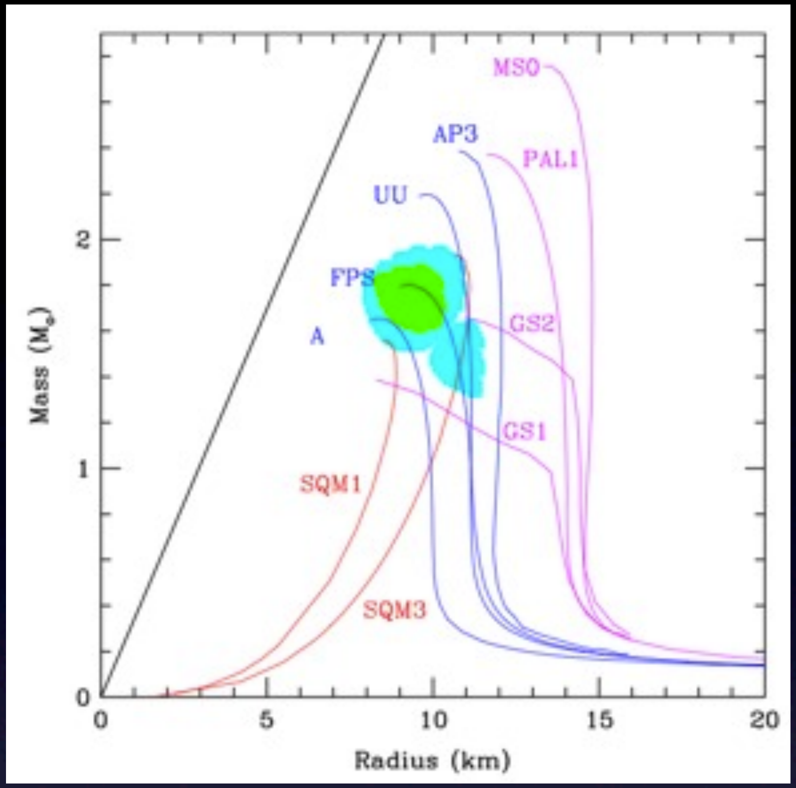
Type-I X-ray bursts are controversial for M_{NS} and R_{NS} measurements!

- Composition of the atmosphere
- Color correction factor f_c (constant or not)?
- Distance measurement used (and uncertainties)
- Analysis not self-consistent (Steiner et al. 2010)
- Short bursts do not match passive cooling theory (Suleimanov et al. 2011)

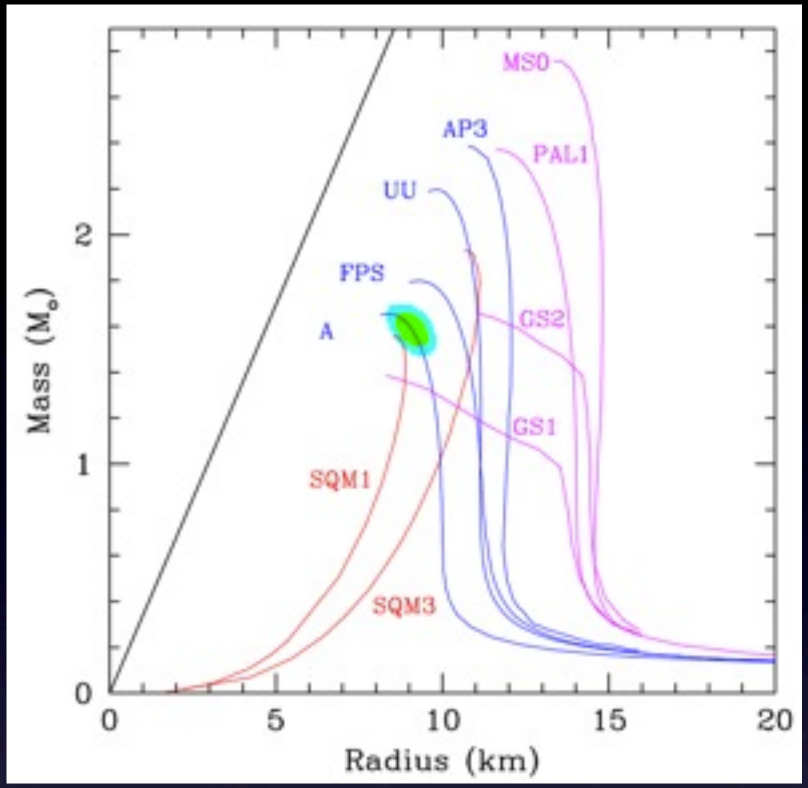
M_{NS}-R_{NS} contours are fixed by relaxing $R_{touchdown} = R_{NS}$



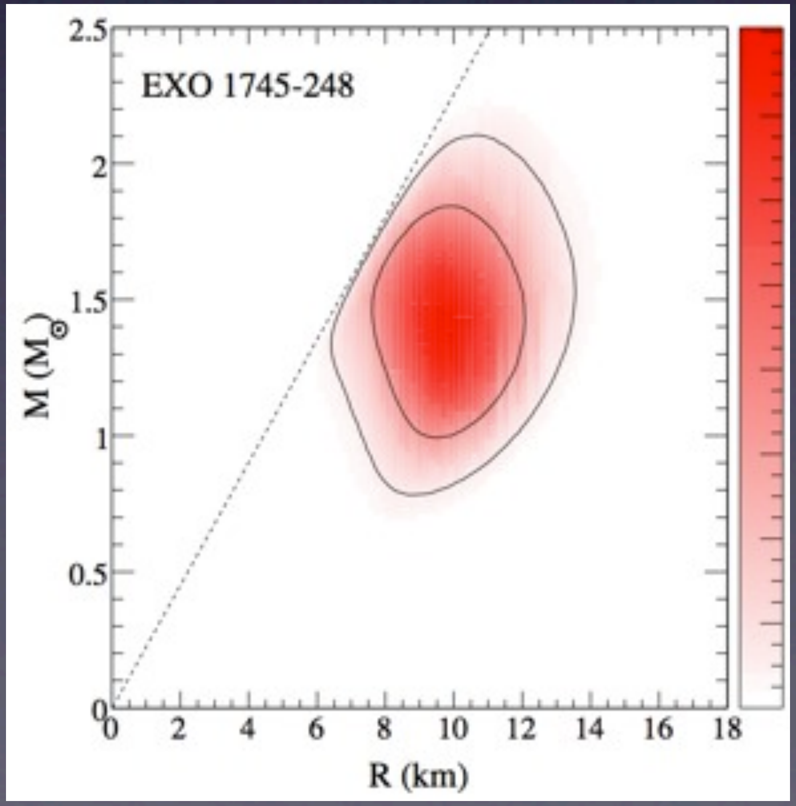
EXO 1745−348
Özel et al. 2009

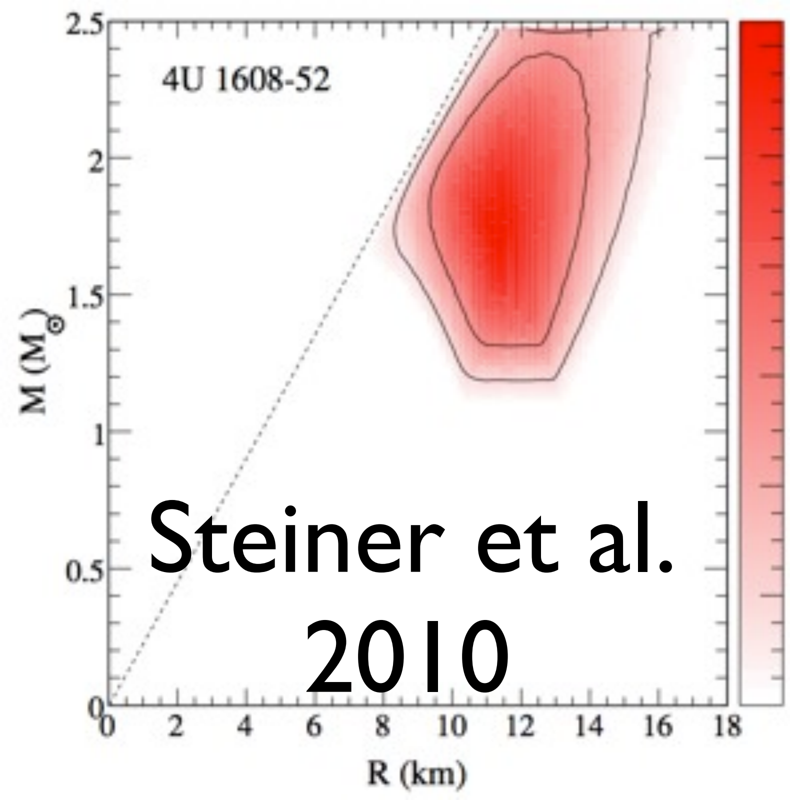


4U 1608−53
Güver et al. 2010a

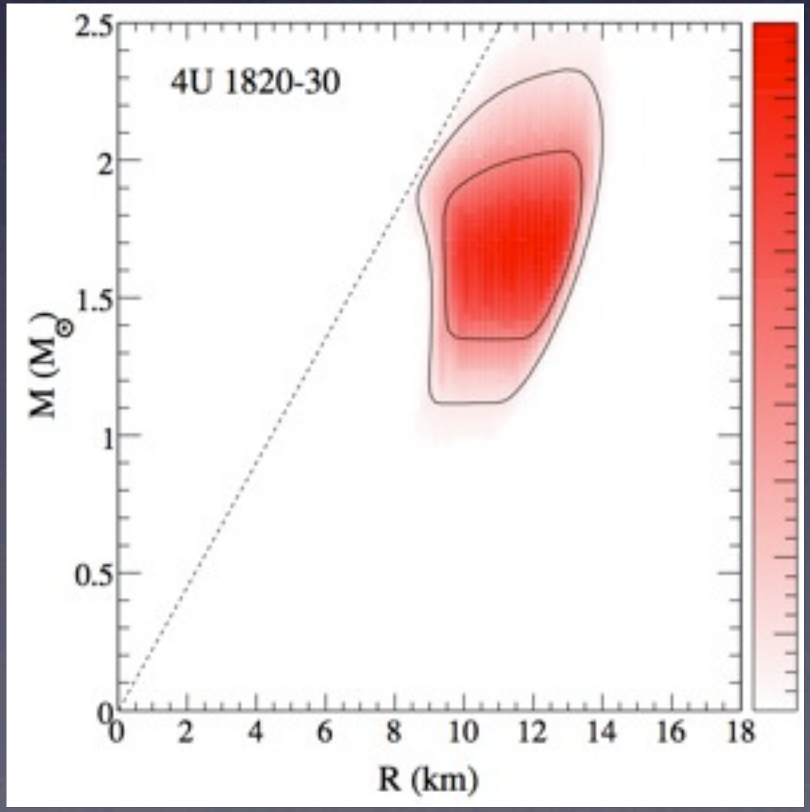


4U 1820−30
Güver et al. 2010a

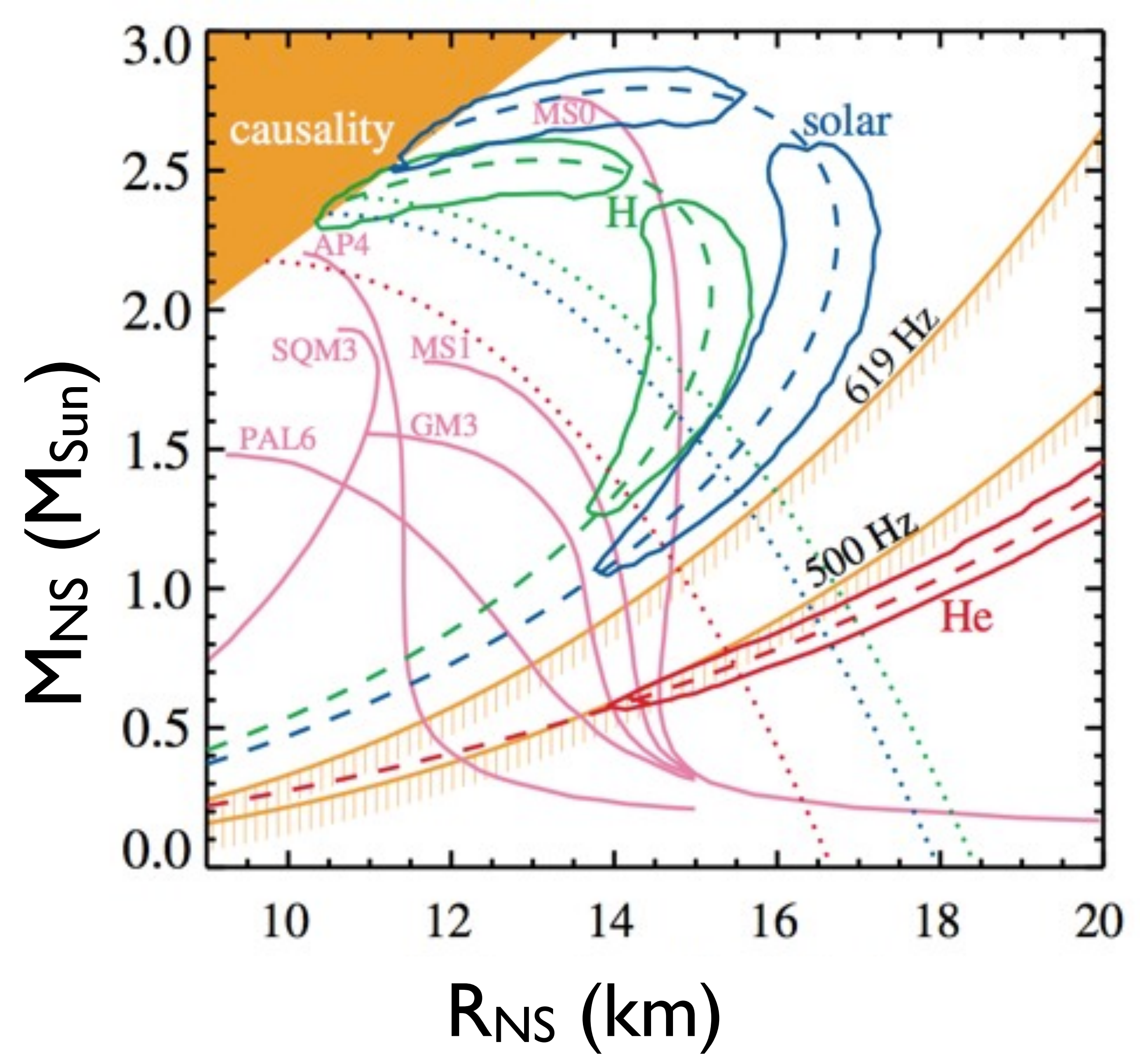




Steiner et al. 2010



Different constraints are obtained when using long X-ray bursts instead of short X-ray bursts, and by fitting the entire cooling tail

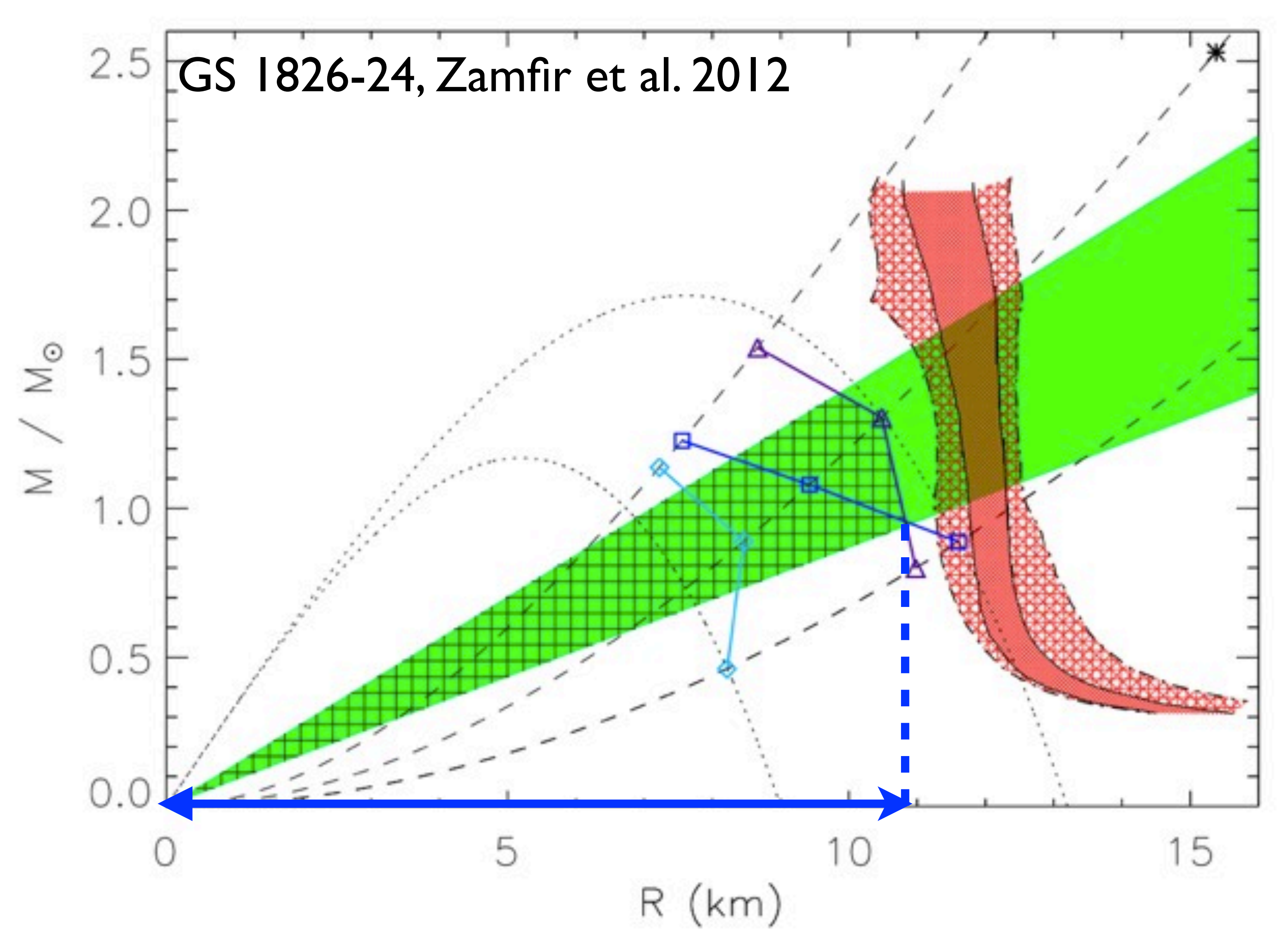


4U 1724-307
(Suleimanov et al. 2012)

Sub-Eddington bursts can also be used to provide distance independent measurements

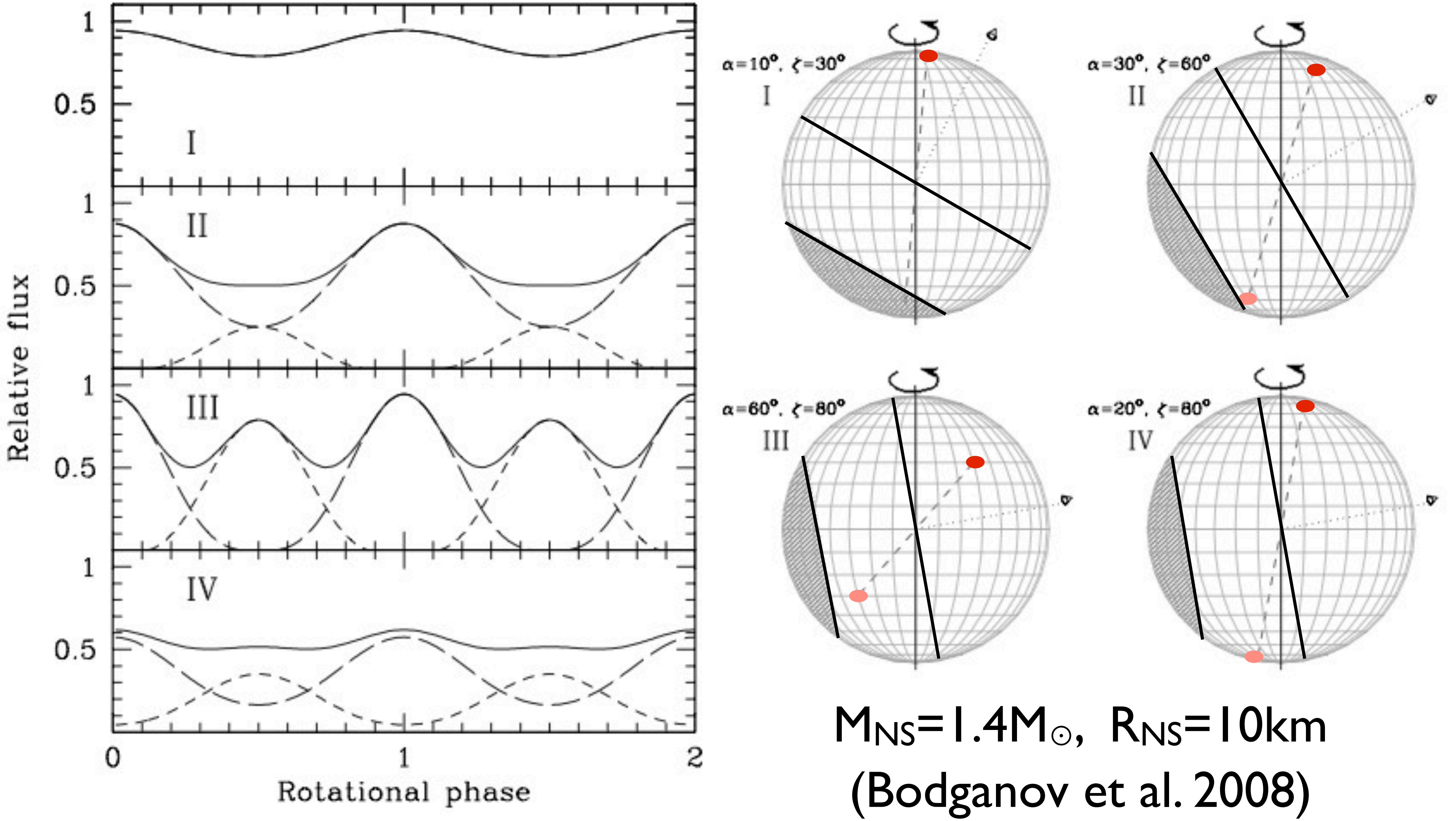
X-ray

X-ray burster GS 1826−24



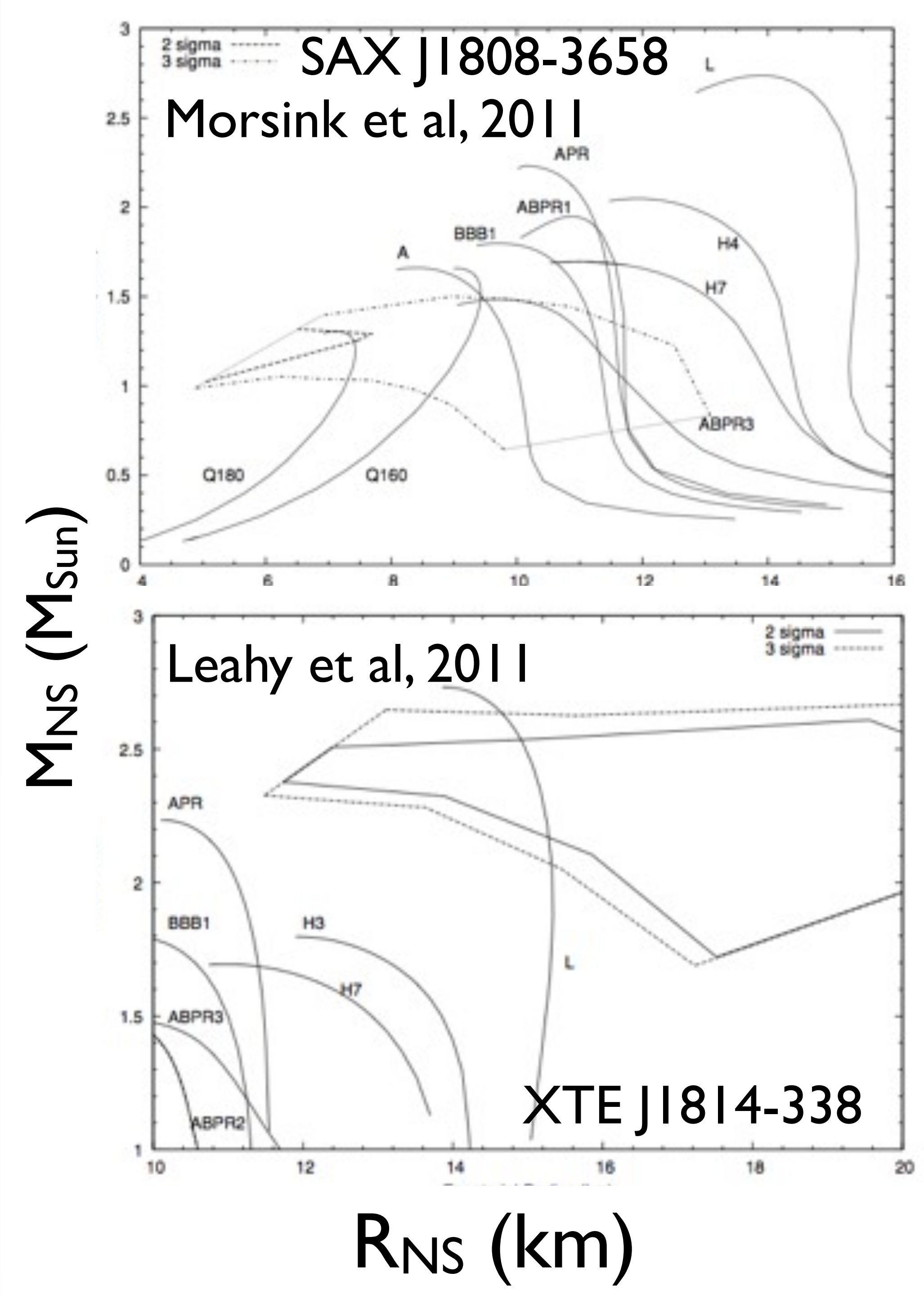
Now, measuring M_{NS}/R_{NS}

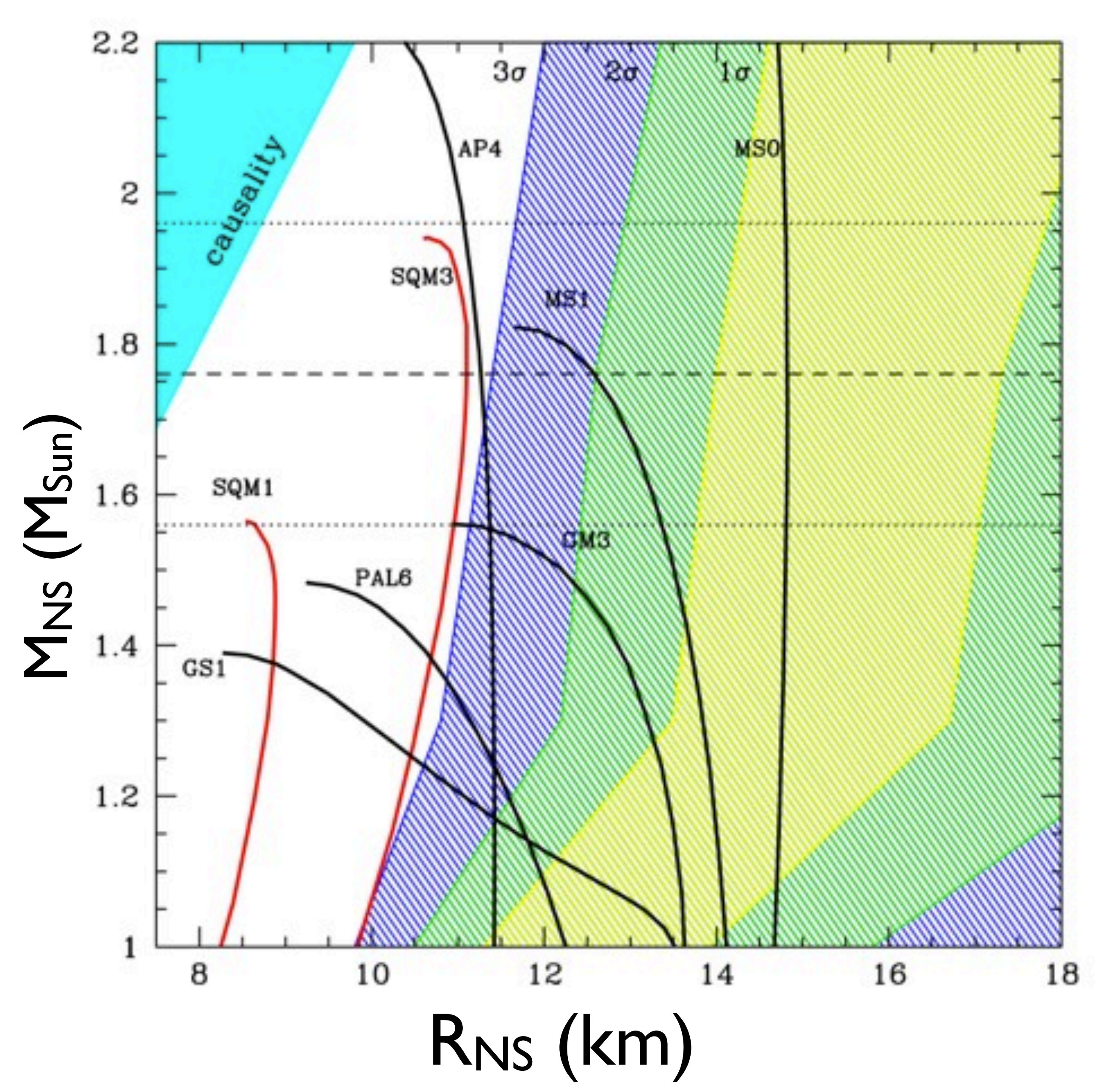
Analyzing the pulse profiles caused by hot spots on a rotating a neutron star can be used to measure the compactness.



$M_{NS}=1.4M_{\odot}$, $R_{NS}=10$km
(Bodganov et al. 2008)

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





Bogdanov (2013)
Method described in Bogdanov et al. (2009)

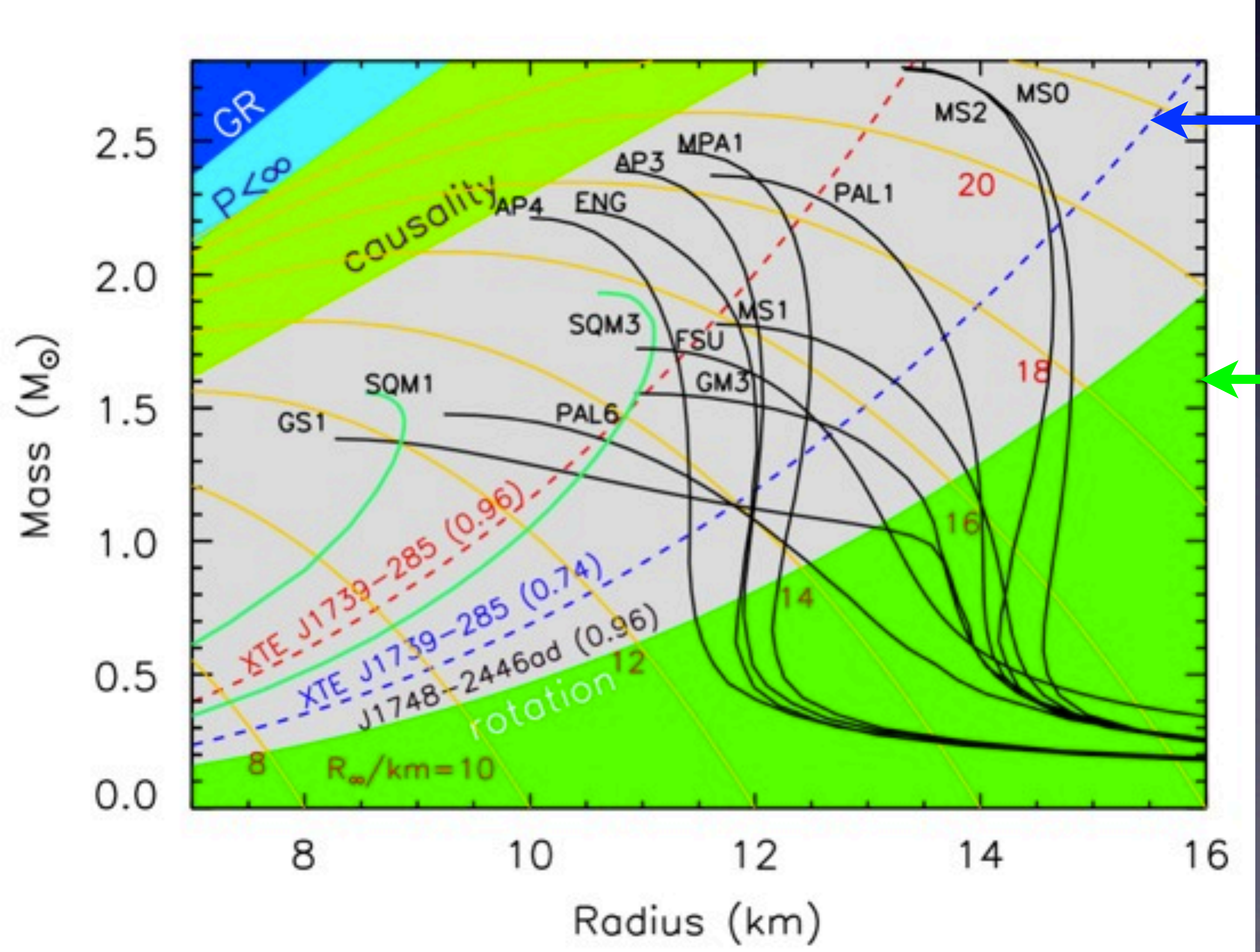
Or placing limits on M_{NS} and R_{NS}

Extremely fast rotating neutron star can place limits on M_{NS} and R_{NS}

$$R_{\rm sph} < 10.4 \left(\frac{1000\,{\rm Hz}}{\nu} \right)^{2/3} \left(\frac{M_{\rm sph}}{{\rm M}_\odot} \right)^{1/3} {\rm km},$$

Because

$$v_{\rm K} = (2\pi)^{-1} \sqrt{GM/R^3}$$



1122 Hz
not confirmed!

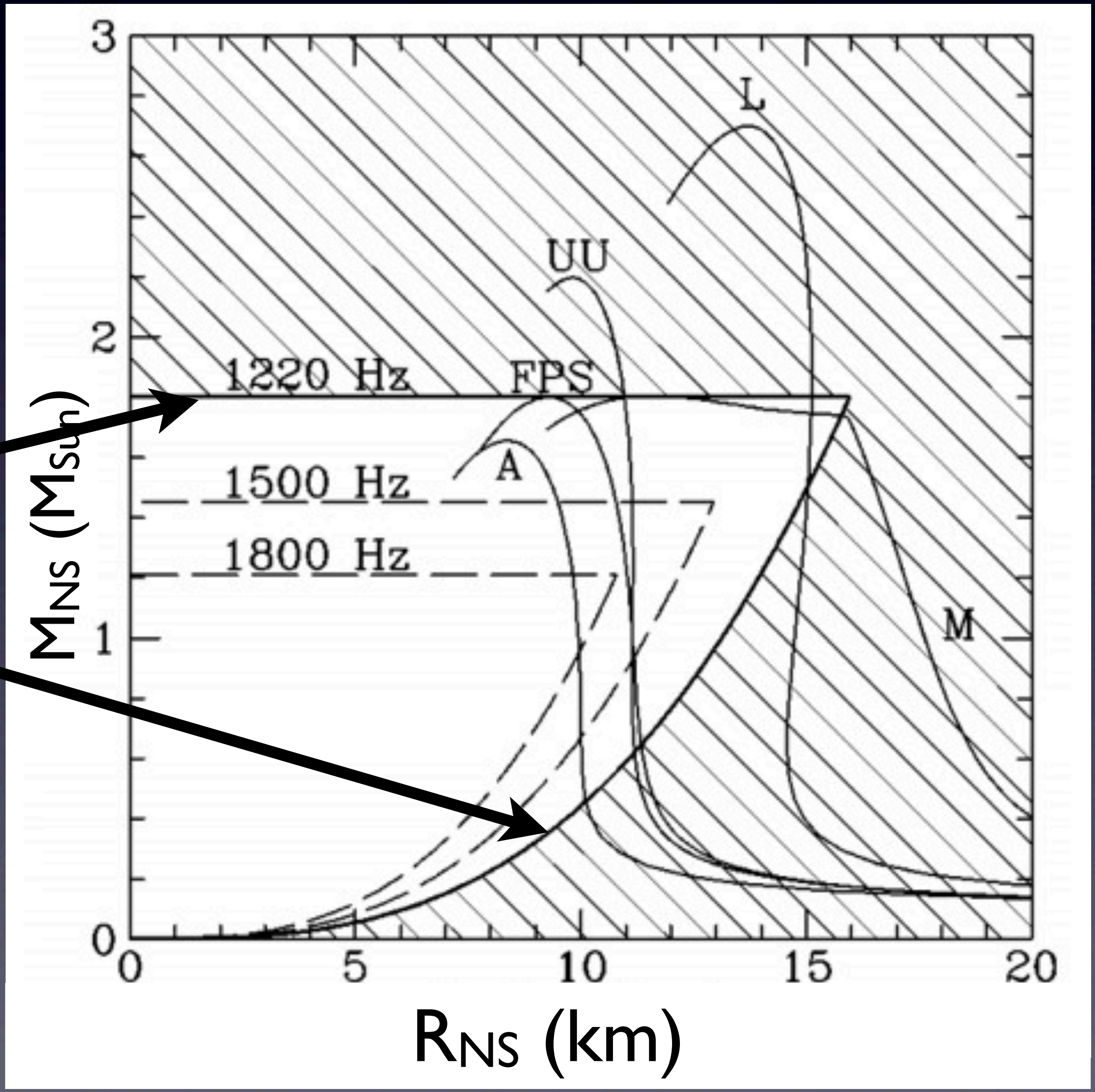
716 Hz

Lattimer et Prakash, 2007

kHz quasi periodic oscillations could also constrain M_{NS} and R_{NS}

$$M \leq \left(\frac{2200\,\mathrm{Hz}}{\nu_{\mathrm{ISCO}}}\right)\left(1+0.75\frac{2\pi c f_{\mathrm{spin}} I}{GM^2}\right) M_\odot$$

$$R \leq \left(\frac{1950\,\mathrm{Hz}}{\nu_{\mathrm{ISCO}}}\right)\left(1+0.20\frac{2\pi c f_{\mathrm{spin}} I}{GM^2}\right) \mathrm{km}$$



van der Klis 2000

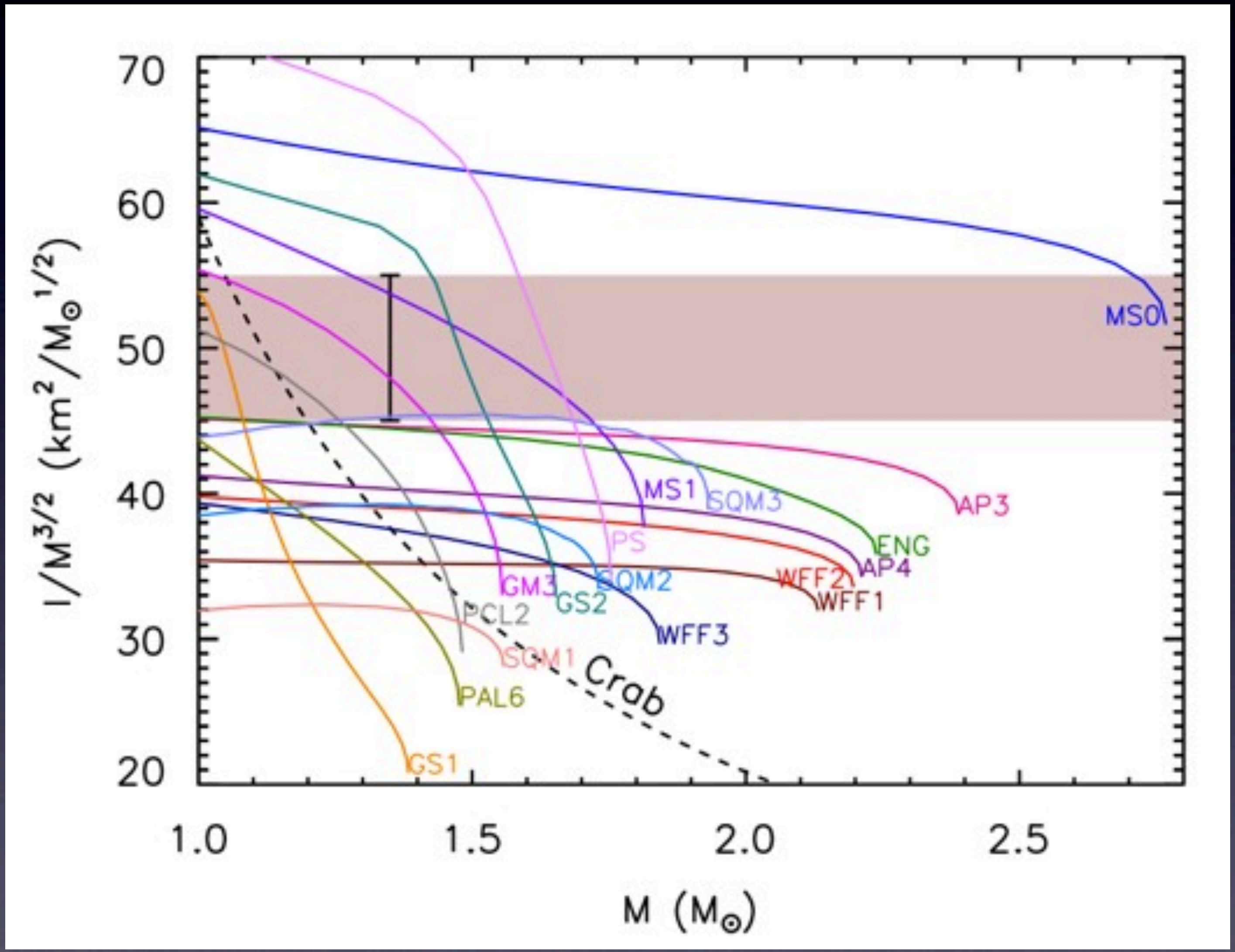
Highest frequency QPO is 1310 Hz, 4U 1728-34 (Barret et al. 2006)

Measuring I_{NS} directly

Spin-orbit coupling measurements can be used to determine the moment of inertia

Combining I_{NS} to known M_{NS} can be very constraining!

But, the acceleration of the centre of mass of the binary system in the gravitational potential of the Galaxy is unknown!

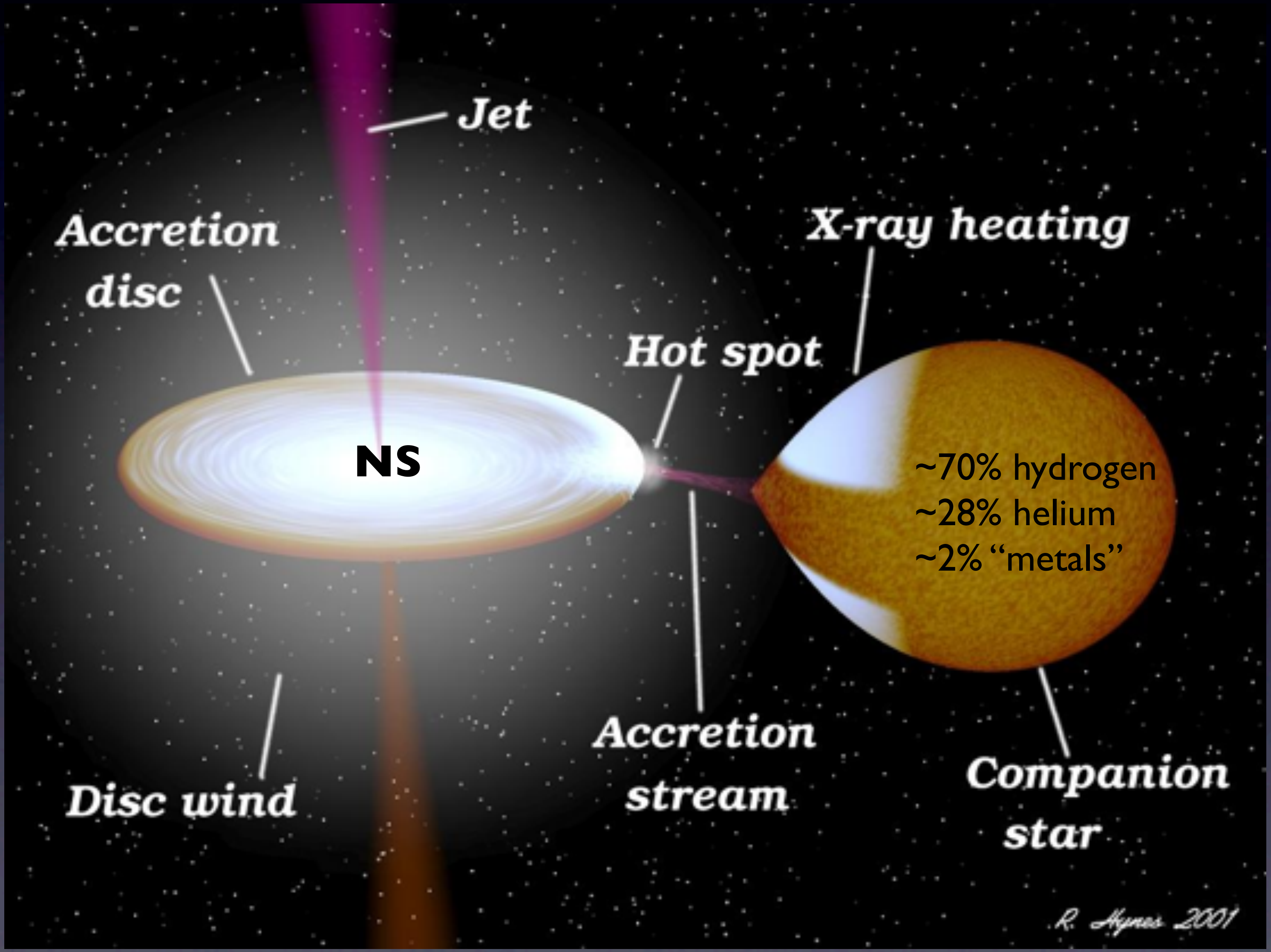


Hypothetical I_{NS} measurement with 10% precision for double pulsar system (Lattimer & Schutz, 2005)

Measuring R_∞

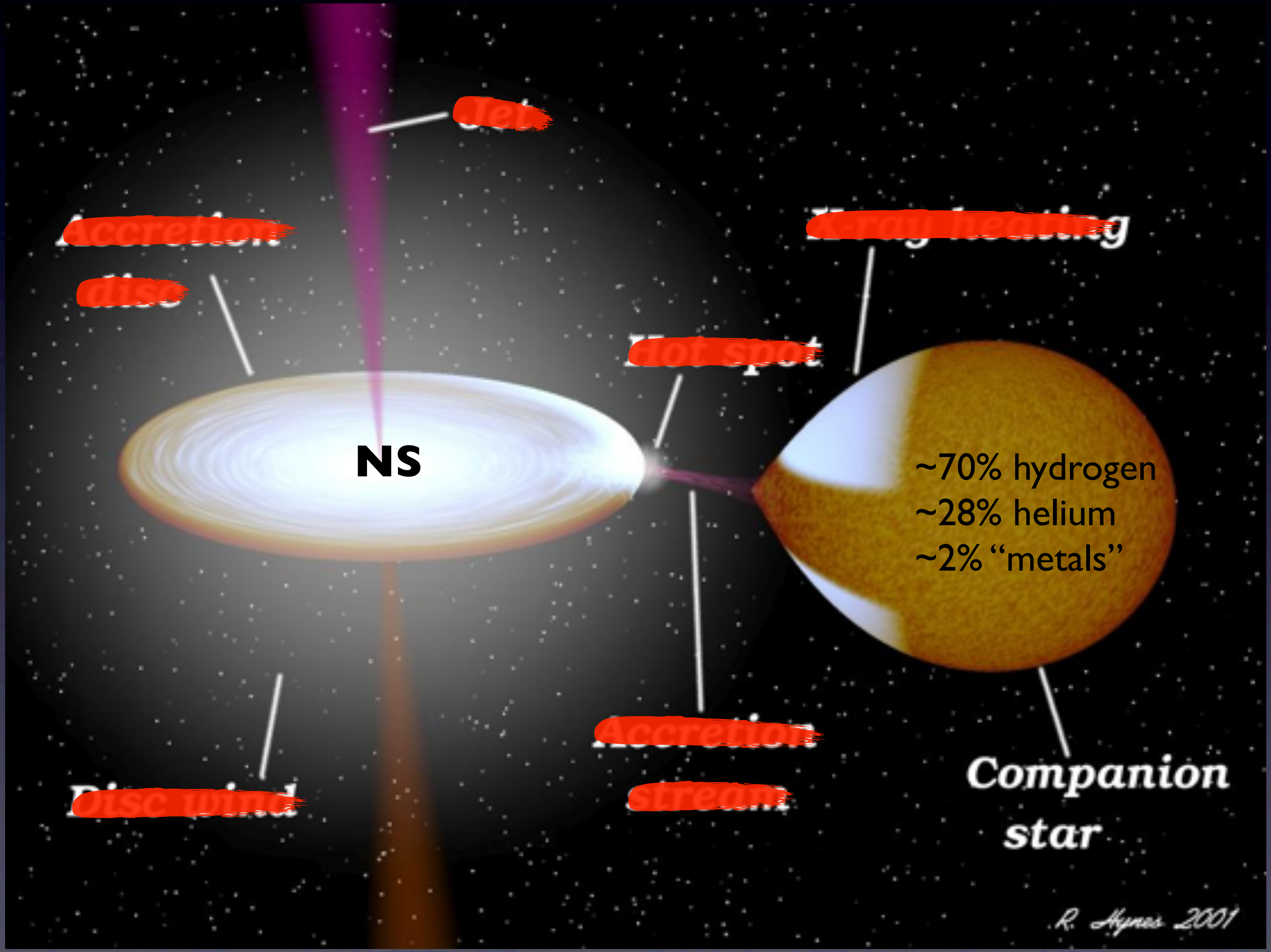
$$R_\infty = R_{\mathrm{NS}}\,(1+z) = R_{\mathrm{NS}}\left(1-\frac{2GM_{\mathrm{NS}}}{R_{\mathrm{NS}}\;c^2}\right)^{-1/2}$$

Quiescent low-mass X-ray binaries are ideal systems for R_∞ measurements.



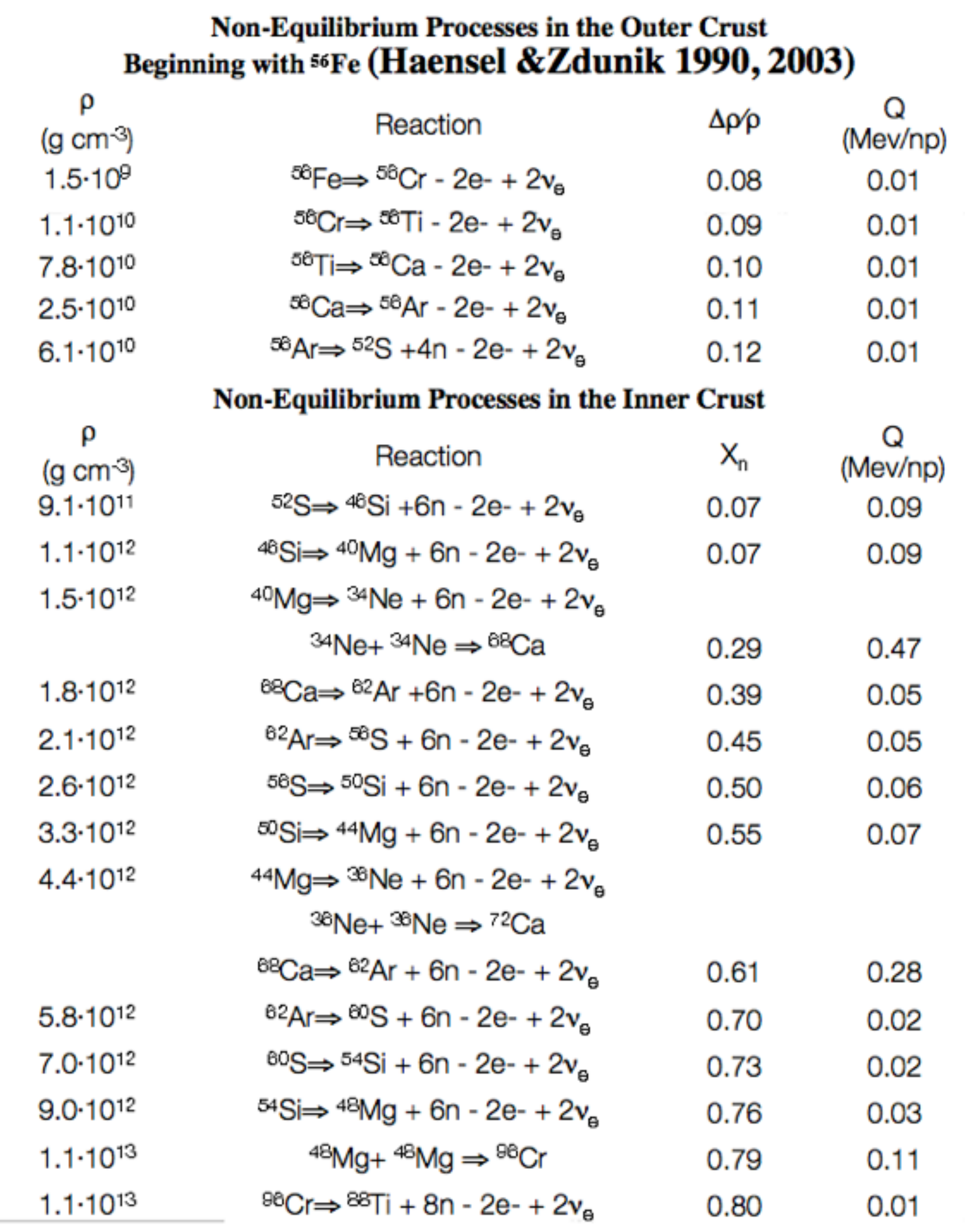
Quiescent low-mass X-ray binaries are ideal systems for R∞ measurements.

- 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 $L_X=10^{32\text{-}33}$ erg/sec
- Neutron star has a weak magnetic field



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

Brown et al. 1998

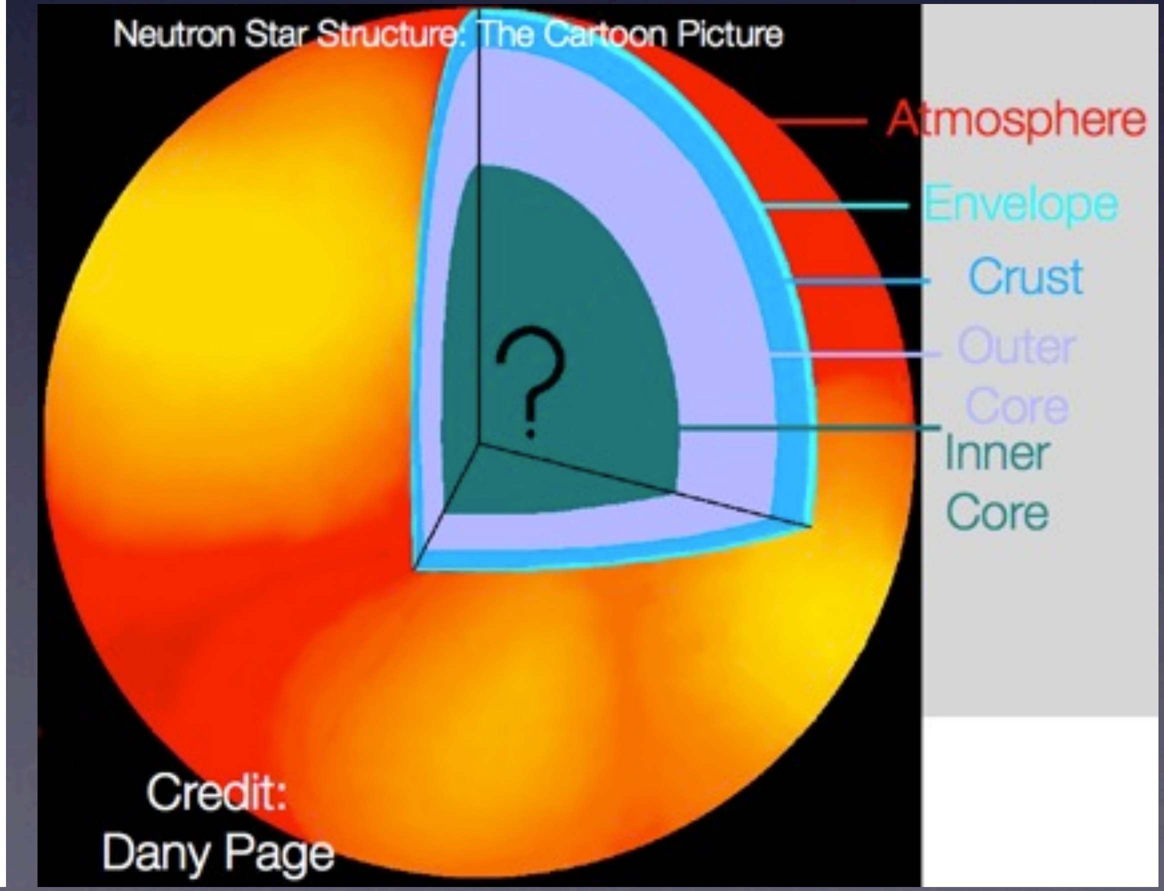


Non-Equilibrium Processes in the Outer Crust
Beginning with ^{56}Fe (Haensel &Zdunik 1990, 2003)

ρ (g cm^{-3})	Reaction	Δρ/ρ	Q (Mev/np)
$1.5\cdot10^{9}$	$^{56}\mathrm{Fe}\Rightarrow {}^{56}\mathrm{Cr} - 2e^- + 2\nu_e$	0.08	0.01
$1.1\cdot10^{10}$	$^{56}\mathrm{Cr}\Rightarrow {}^{56}\mathrm{Ti} - 2e^- + 2\nu_e$	0.09	0.01
$7.8\cdot10^{10}$	$^{56}\mathrm{Ti}\Rightarrow {}^{56}\mathrm{Ca} - 2e^- + 2\nu_e$	0.10	0.01
$2.5\cdot10^{10}$	$^{56}\mathrm{Ca}\Rightarrow {}^{56}\mathrm{Ar} - 2e^- + 2\nu_e$	0.11	0.01
$6.1\cdot10^{10}$	$^{56}\mathrm{Ar}\Rightarrow {}^{52}\mathrm{S} + 4n - 2e^- + 2\nu_e$	0.12	0.01

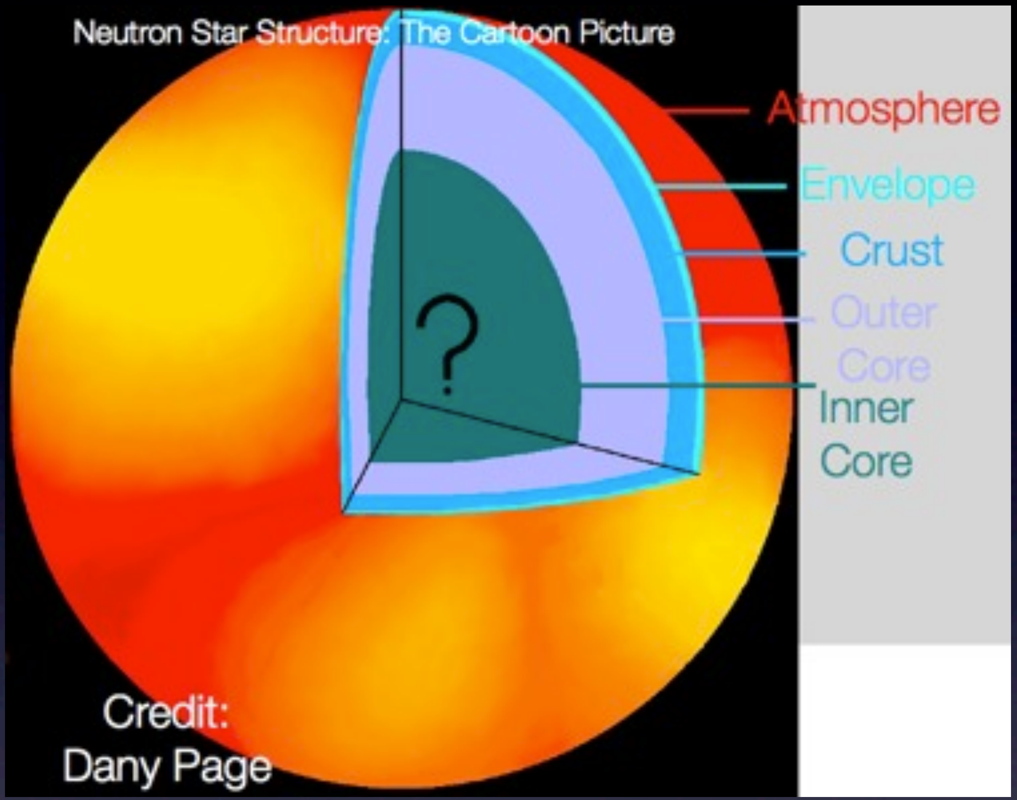
Non-Equilibrium Processes in the Inner Crust

ρ (g cm^{-3})	Reaction	X_n	Q (Mev/np)
$9.1\cdot10^{11}$	$^{52}\mathrm{S}\Rightarrow {}^{46}\mathrm{Si} + 6n - 2e^- + 2\nu_e$	0.07	0.09
$1.1\cdot10^{12}$	$^{46}\mathrm{Si}\Rightarrow {}^{40}\mathrm{Mg} + 6n - 2e^- + 2\nu_e$	0.07	0.09
$1.5\cdot10^{12}$	$^{40}\mathrm{Mg}\Rightarrow {}^{34}\mathrm{Ne} + 6n - 2e^- + 2\nu_e$		
	$^{34}\mathrm{Ne} + {}^{34}\mathrm{Ne} \Rightarrow {}^{68}\mathrm{Ca}$	0.29	0.47
$1.8\cdot10^{12}$	$^{68}\mathrm{Ca}\Rightarrow {}^{62}\mathrm{Ar} + 6n - 2e^- + 2\nu_e$	0.39	0.05
$2.1\cdot10^{12}$	$^{62}\mathrm{Ar}\Rightarrow {}^{56}\mathrm{S} + 6n - 2e^- + 2\nu_e$	0.45	0.05
$2.6\cdot10^{12}$	$^{56}\mathrm{S}\Rightarrow {}^{50}\mathrm{Si} + 6n - 2e^- + 2\nu_e$	0.50	0.06
$3.3\cdot10^{12}$	$^{50}\mathrm{Si}\Rightarrow {}^{44}\mathrm{Mg} + 6n - 2e^- + 2\nu_e$	0.55	0.07
$4.4\cdot10^{12}$	$^{44}\mathrm{Mg}\Rightarrow {}^{36}\mathrm{Ne} + 6n - 2e^- + 2\nu_e$		
	$^{36}\mathrm{Ne} + {}^{36}\mathrm{Ne} \Rightarrow {}^{72}\mathrm{Ca}$		
	$^{68}\mathrm{Ca}\Rightarrow {}^{62}\mathrm{Ar} + 6n - 2e^- + 2\nu_e$	0.61	0.28
$5.8\cdot10^{12}$	$^{62}\mathrm{Ar}\Rightarrow {}^{60}\mathrm{S} + 6n - 2e^- + 2\nu_e$	0.70	0.02
$7.0\cdot10^{12}$	$^{60}\mathrm{S}\Rightarrow {}^{54}\mathrm{Si} + 6n - 2e^- + 2\nu_e$	0.73	0.02
$9.0\cdot10^{12}$	$^{54}\mathrm{Si}\Rightarrow {}^{48}\mathrm{Mg} + 6n - 2e^- + 2\nu_e$	0.76	0.03
$1.1\cdot10^{13}$	$^{48}\mathrm{Mg} + {}^{48}\mathrm{Mg} \Rightarrow {}^{96}\mathrm{Cr}$	0.79	0.11
$1.1\cdot10^{13}$	$^{96}\mathrm{Cr}\Rightarrow {}^{88}\mathrm{Ti} + 8n - 2e^- + 2\nu_e$	0.80	0.01

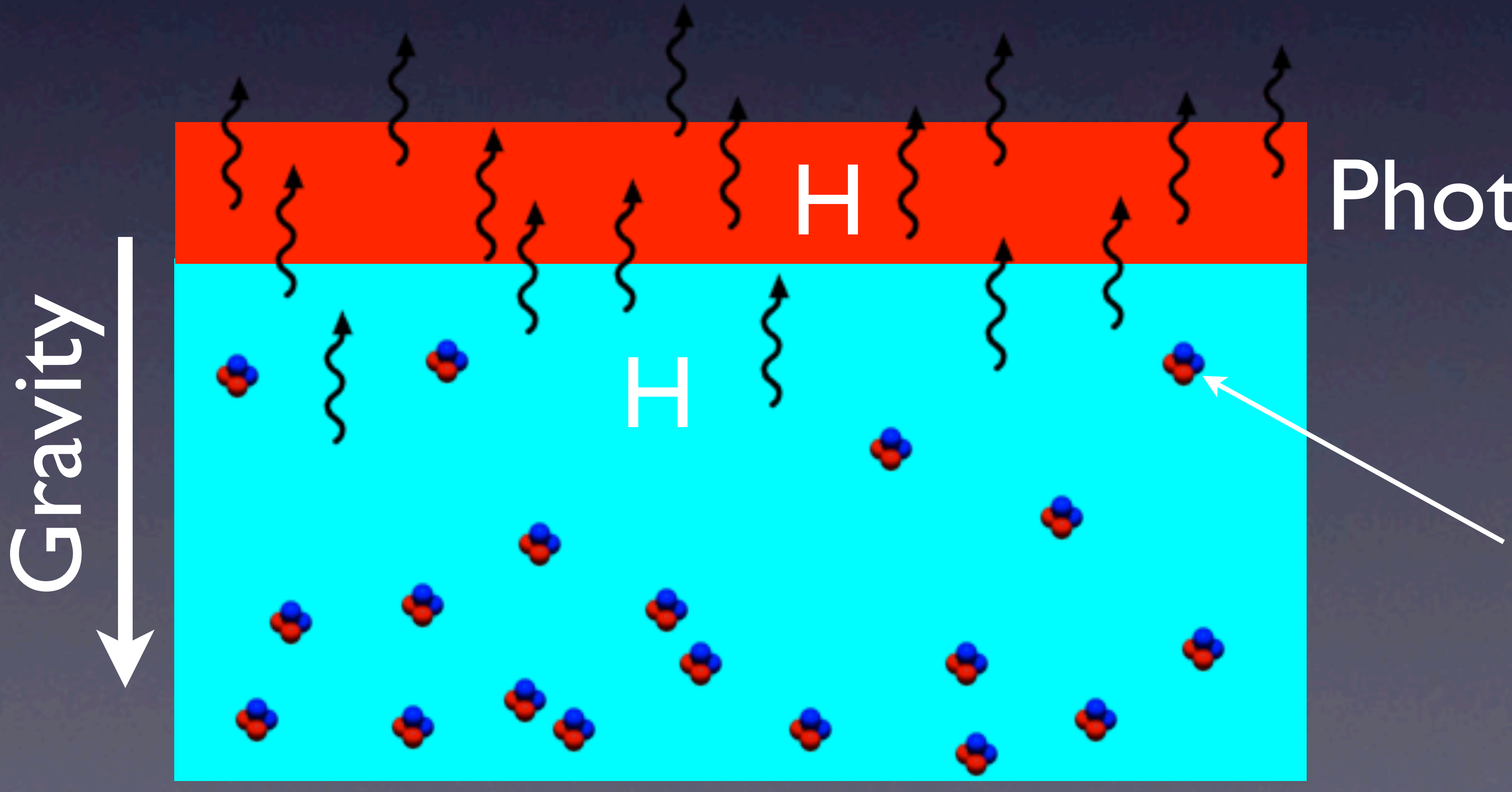


Credit:
Dany Page

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



H-atmosphere
thermal spectrum
seen by observer

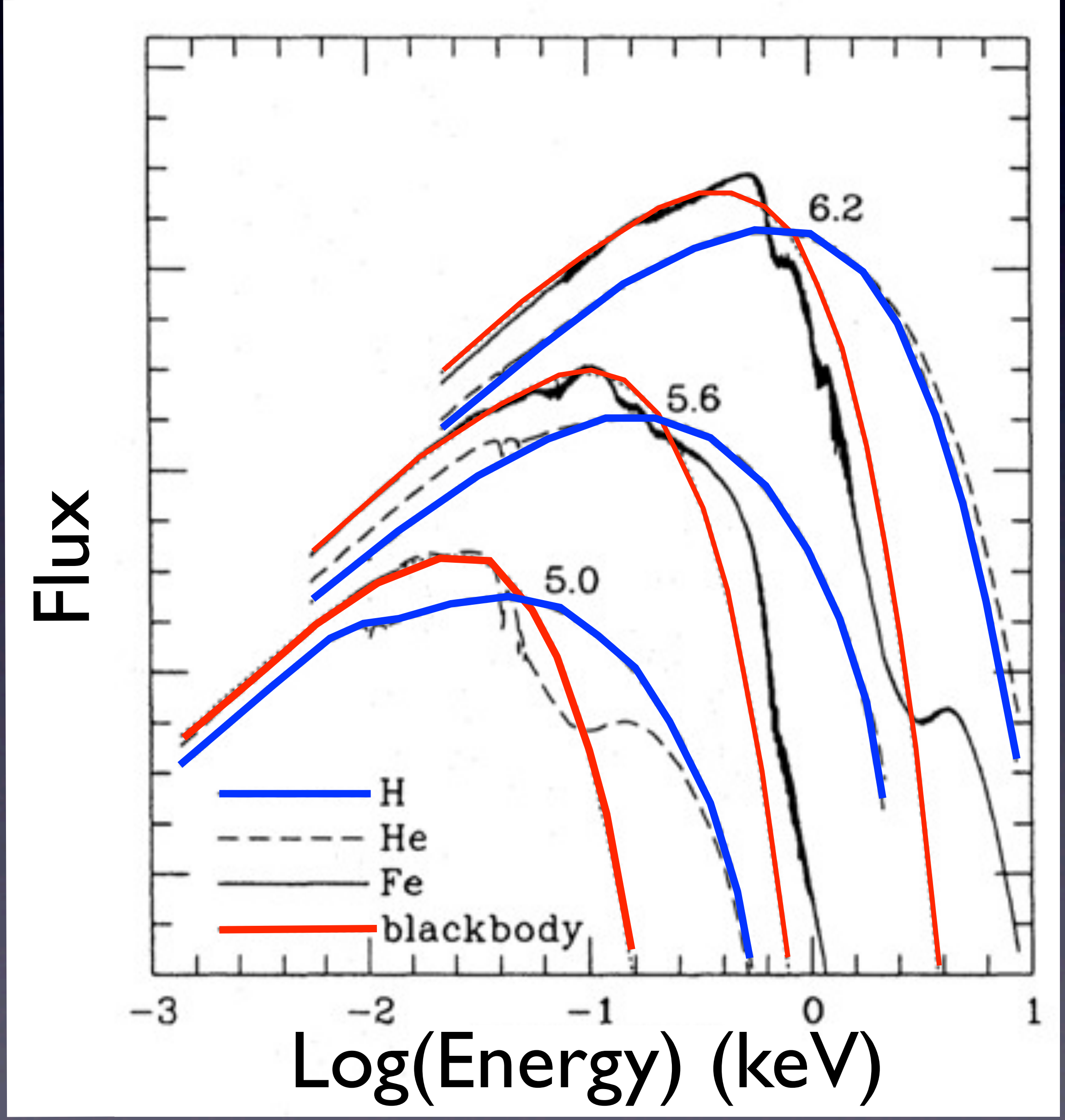


Photosphere ~ 10 cm

Helium

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

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



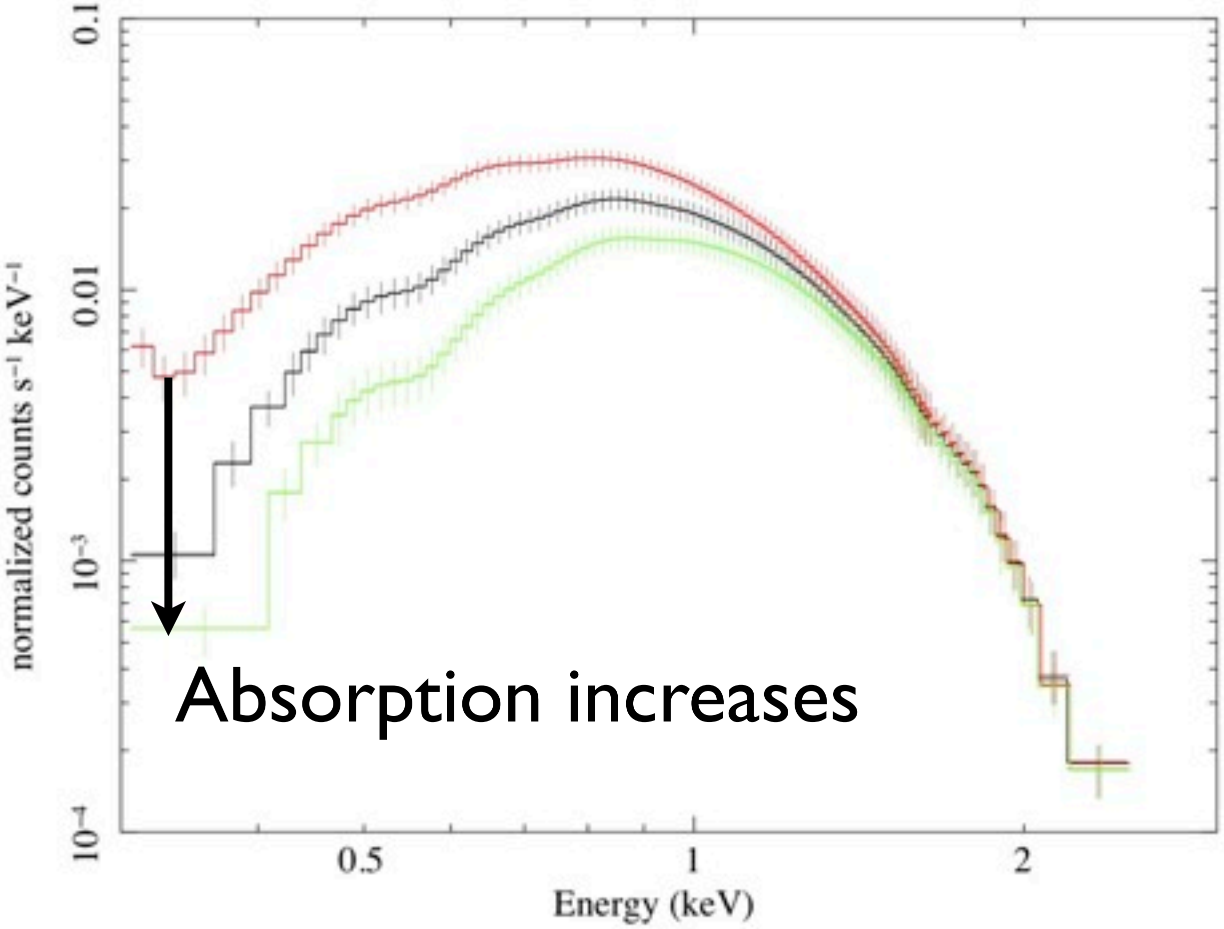
NSA, NSAGRAV models
Zavlin et al 1996, A&A 315

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

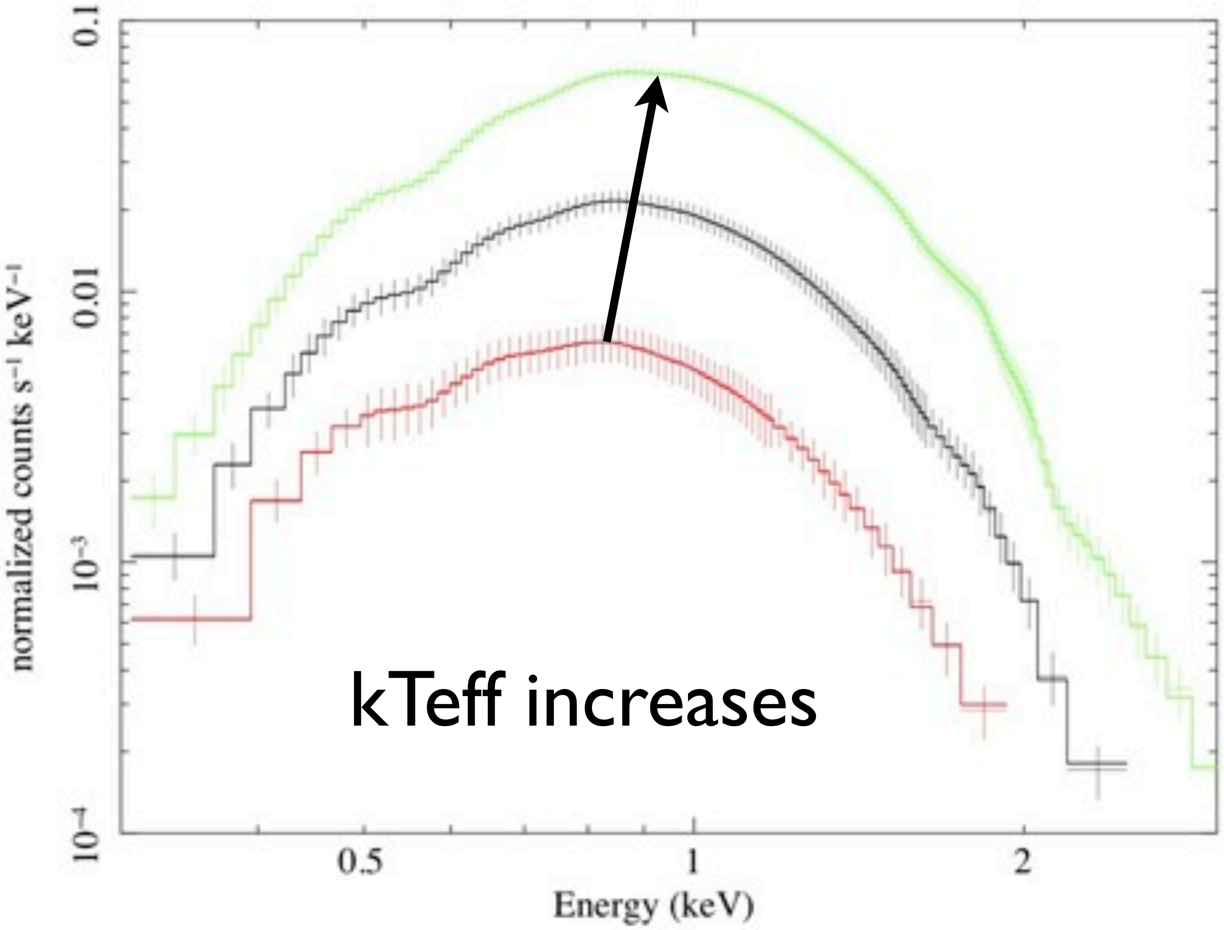
$$R_\infty = R_{\rm NS}\left(1 - \frac{2GM_{\rm NS}}{R_{\rm NS}\ c^2},\right)^{-1/2}$$

NS H-atmosphere model parameters are:

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

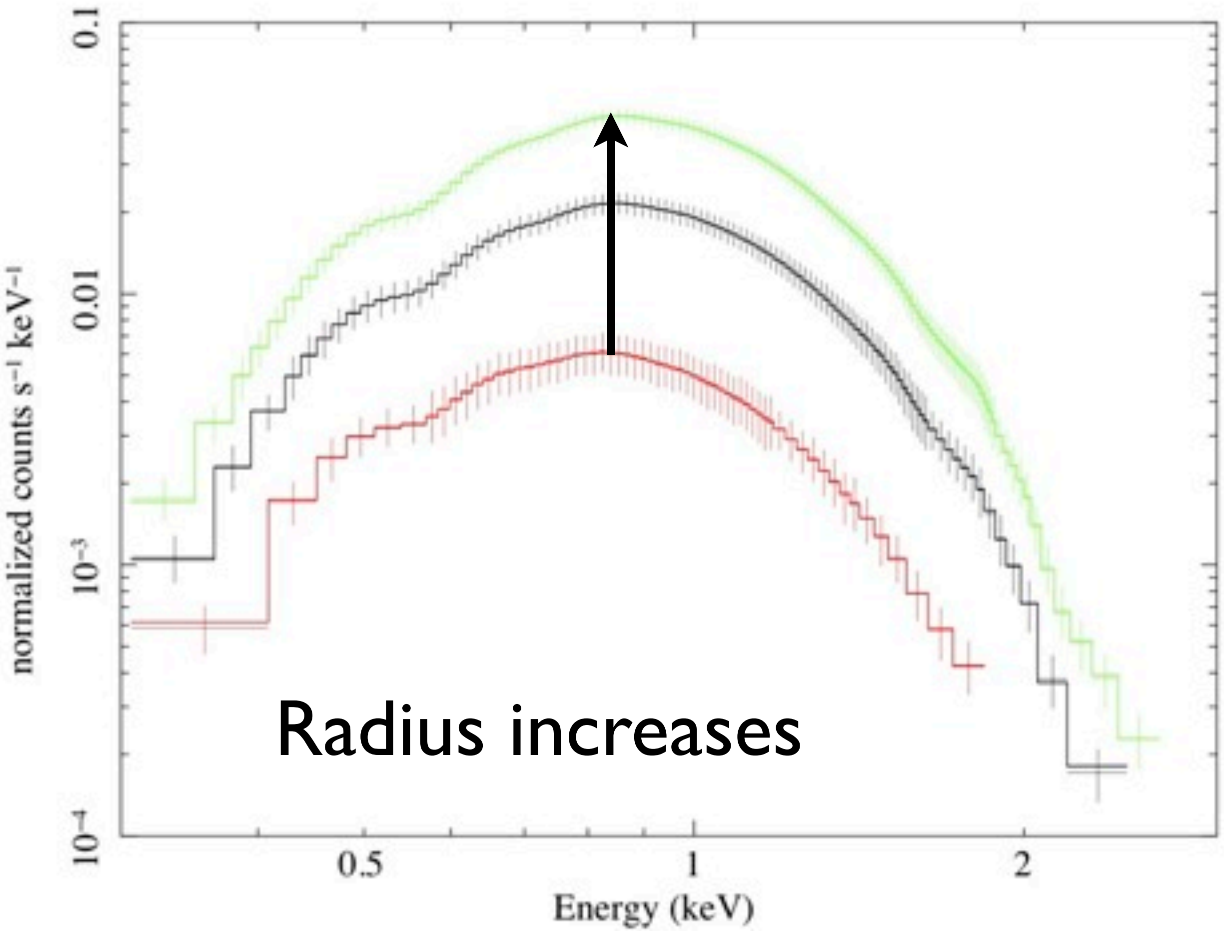


Absorption increases

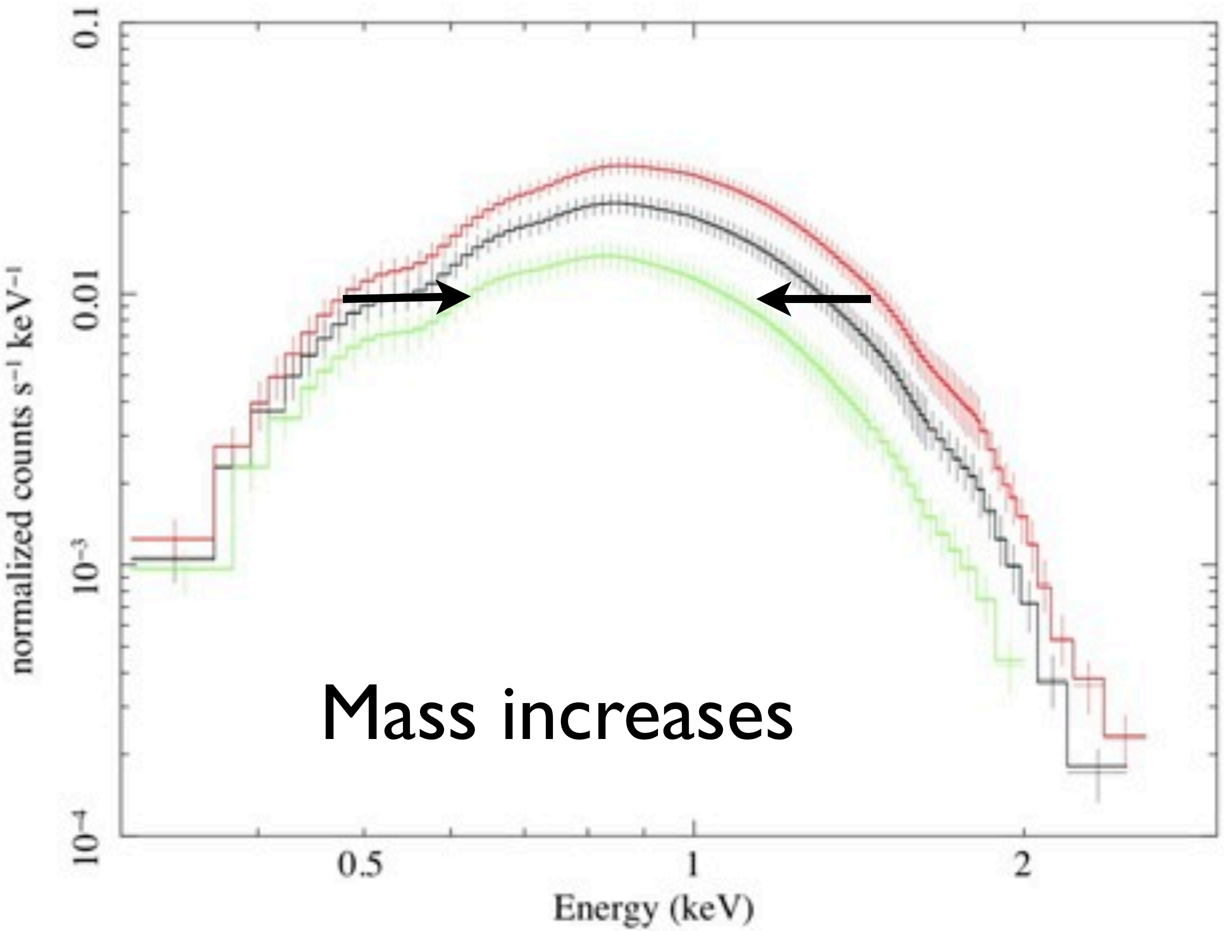


kTeff increases

Neutron stars properties are extracted from the spectra.

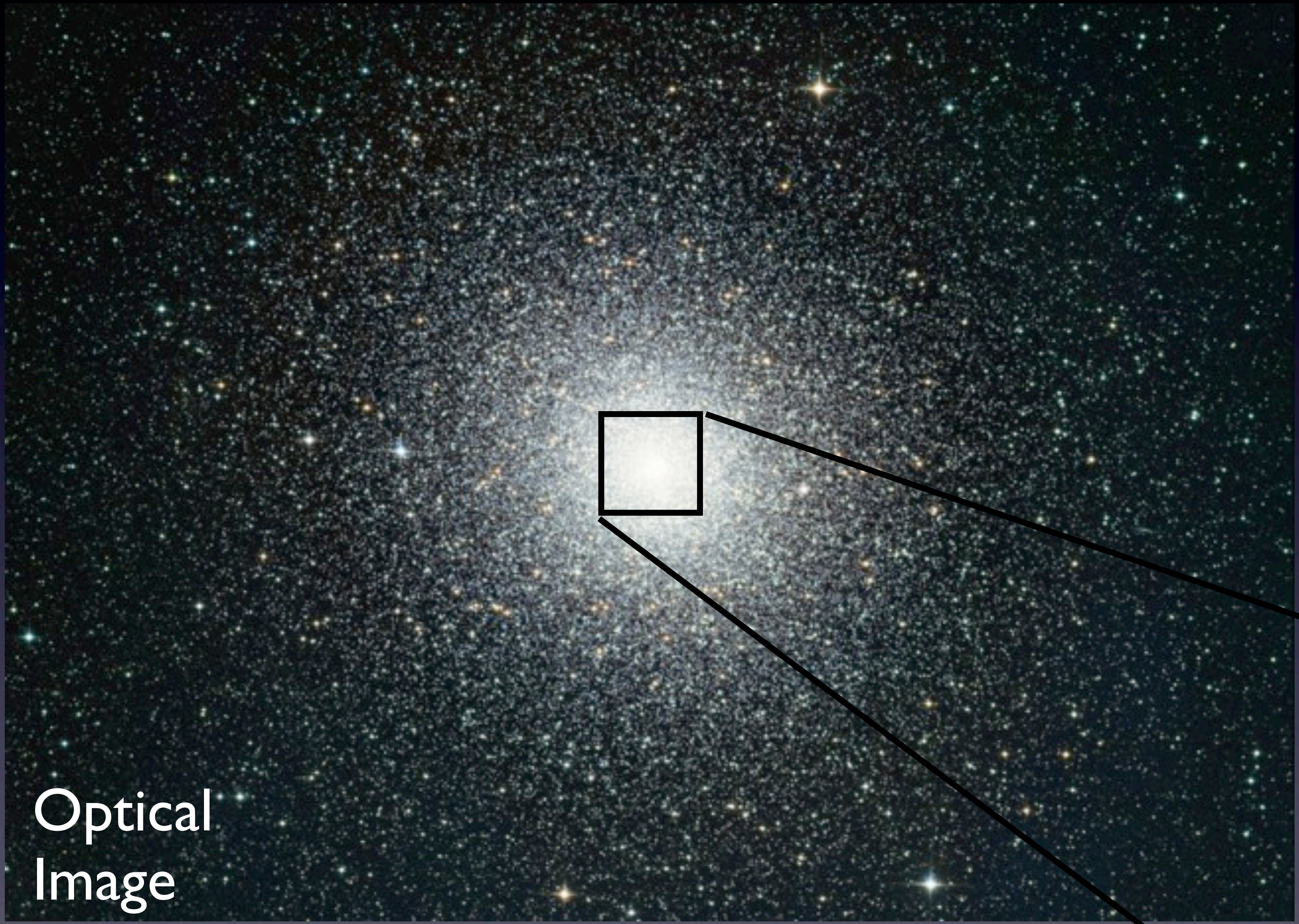


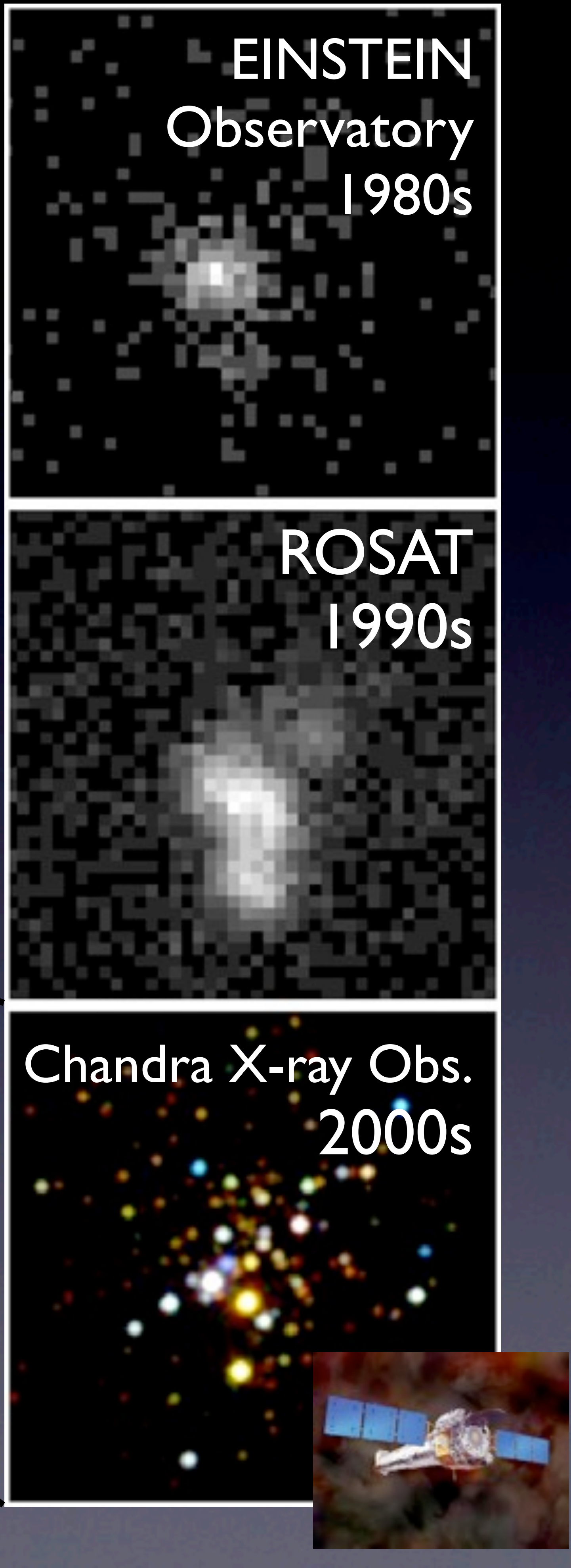
Radius increases



Mass increases

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

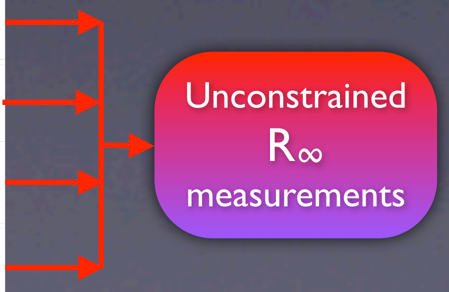




...and they have well-measured distances.

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

Host Globular Cluster	Distance (kpc)	Proxy for Absorption N_H (10^{22} cm^{-2})	Number of qLMXBs	"Useful"	Observational 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 R_∞ measurements

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

Chandra X-Ray Observatory

1” angular resolution

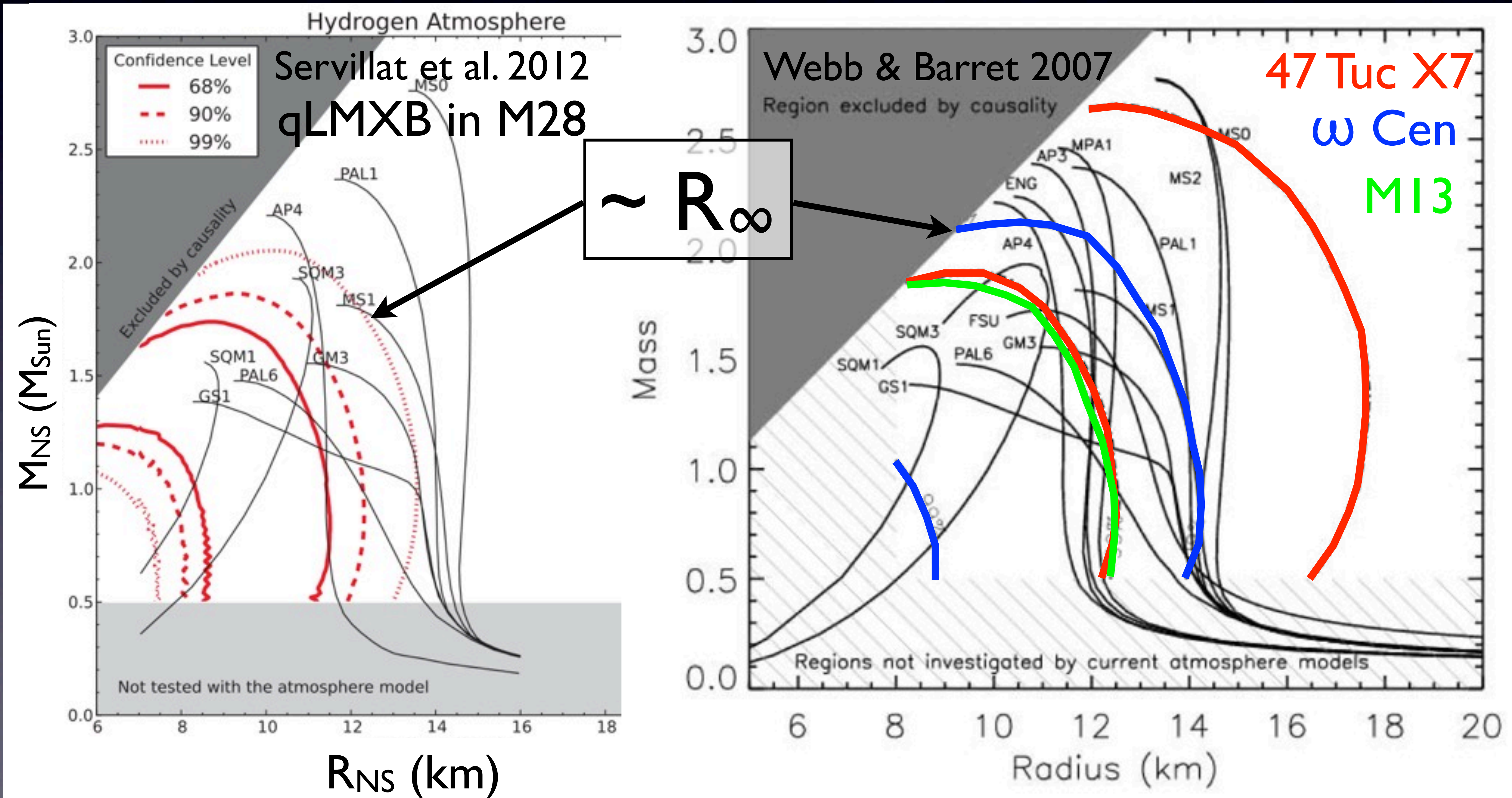
XMM-Newton

6” angular resolution
4x effective area of Chandra

In spectral imaging mode, photons are time-tagged with ~0.1–3sec resolution, and energy resolution of about 150eV at 1keV

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

X-ray



Servillat et al. 2012
qLMXB in M28

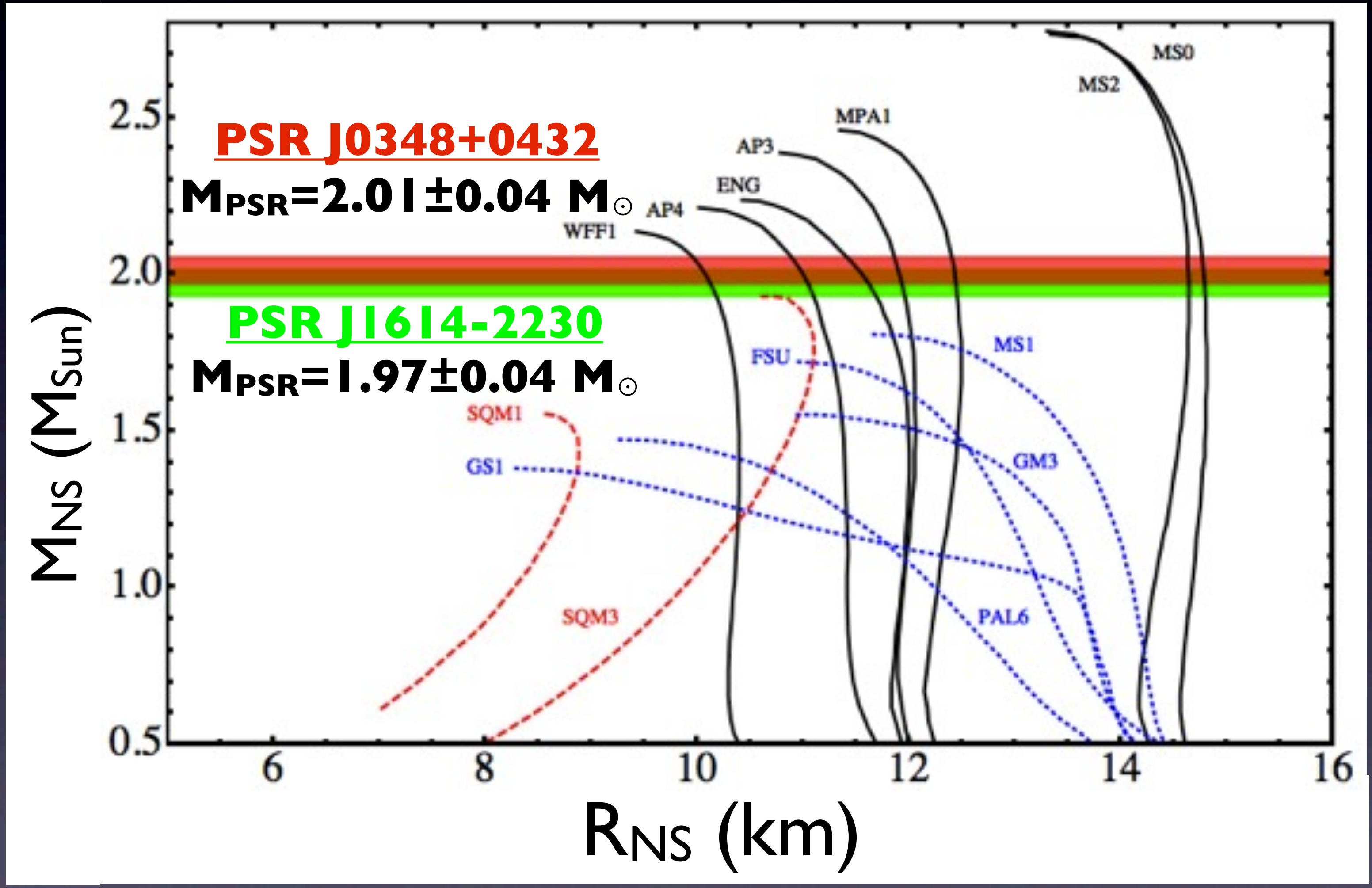
~ R_∞

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.



PSR J0348+0432

M_{PSR}=2.01±0.04 $M_\odot$

PSR J1614-2230

M_{PSR}=1.97±0.04 $M_\odot$

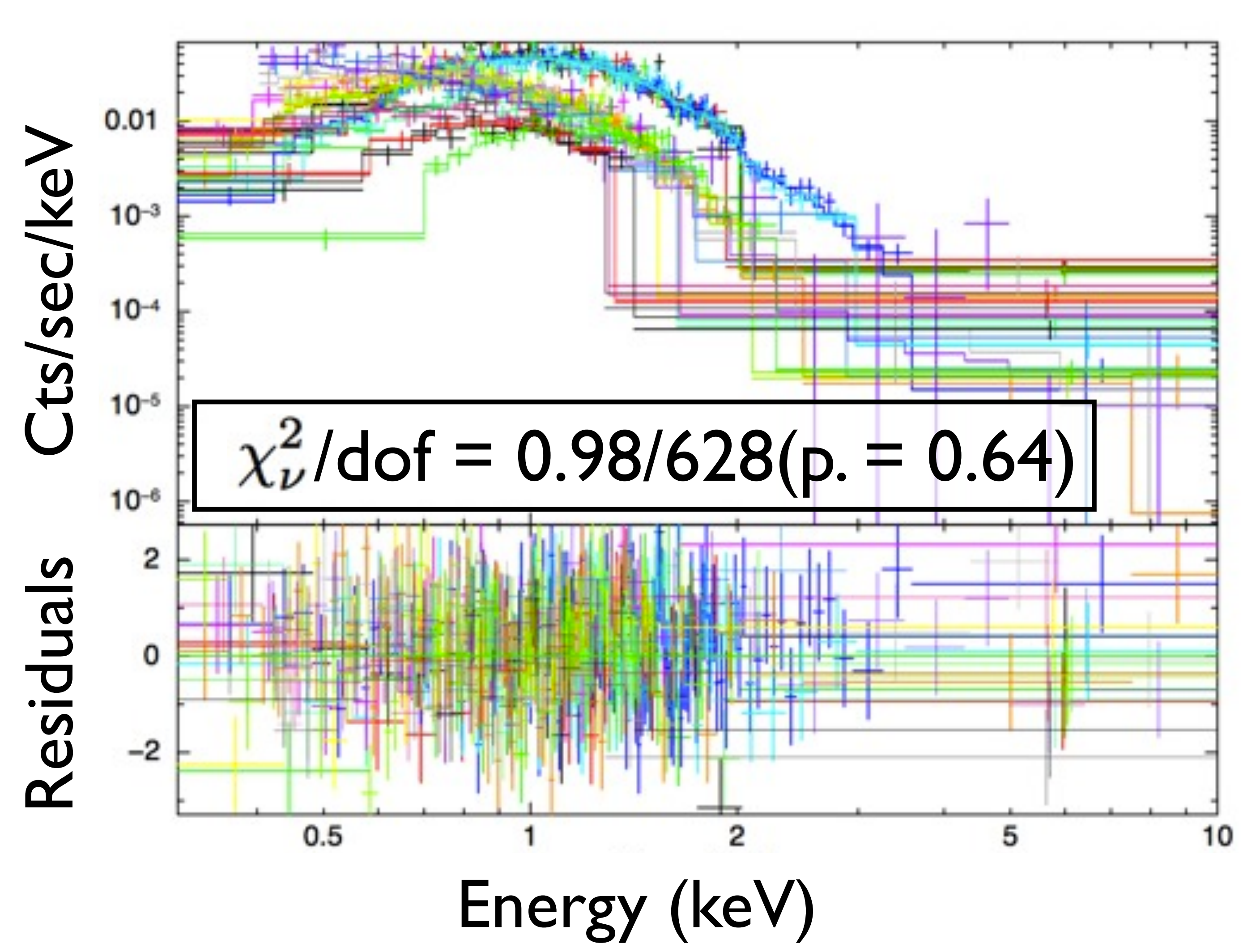
We assume that all neutron stars have the same radius

We simultaneously fit the spectra of 5 qLMXBs with H-atmosphere model

One radius to fit them all!

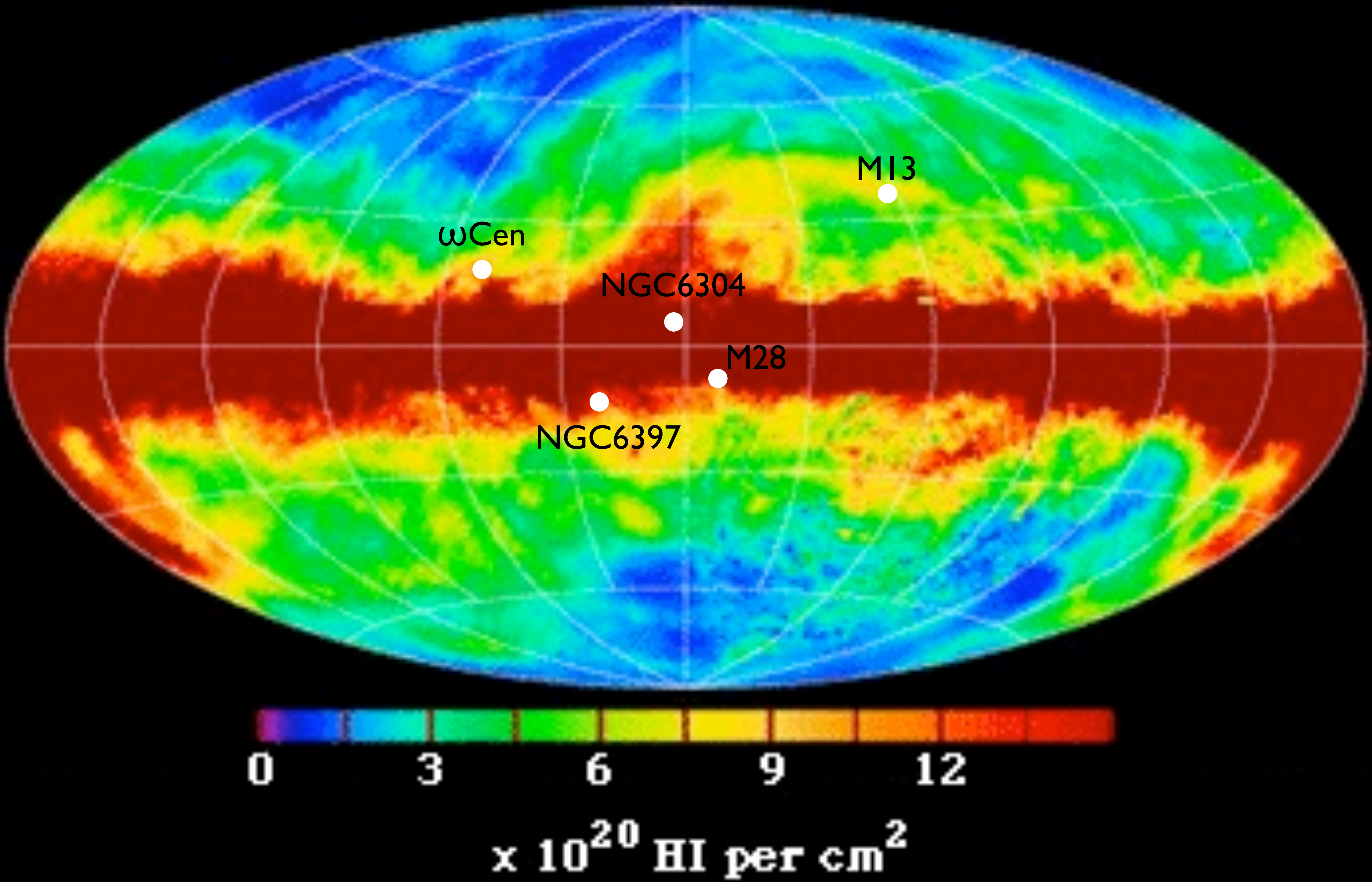
Five parameters per target:

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



Guillot et al. 2013

Targeted Globular Clusters

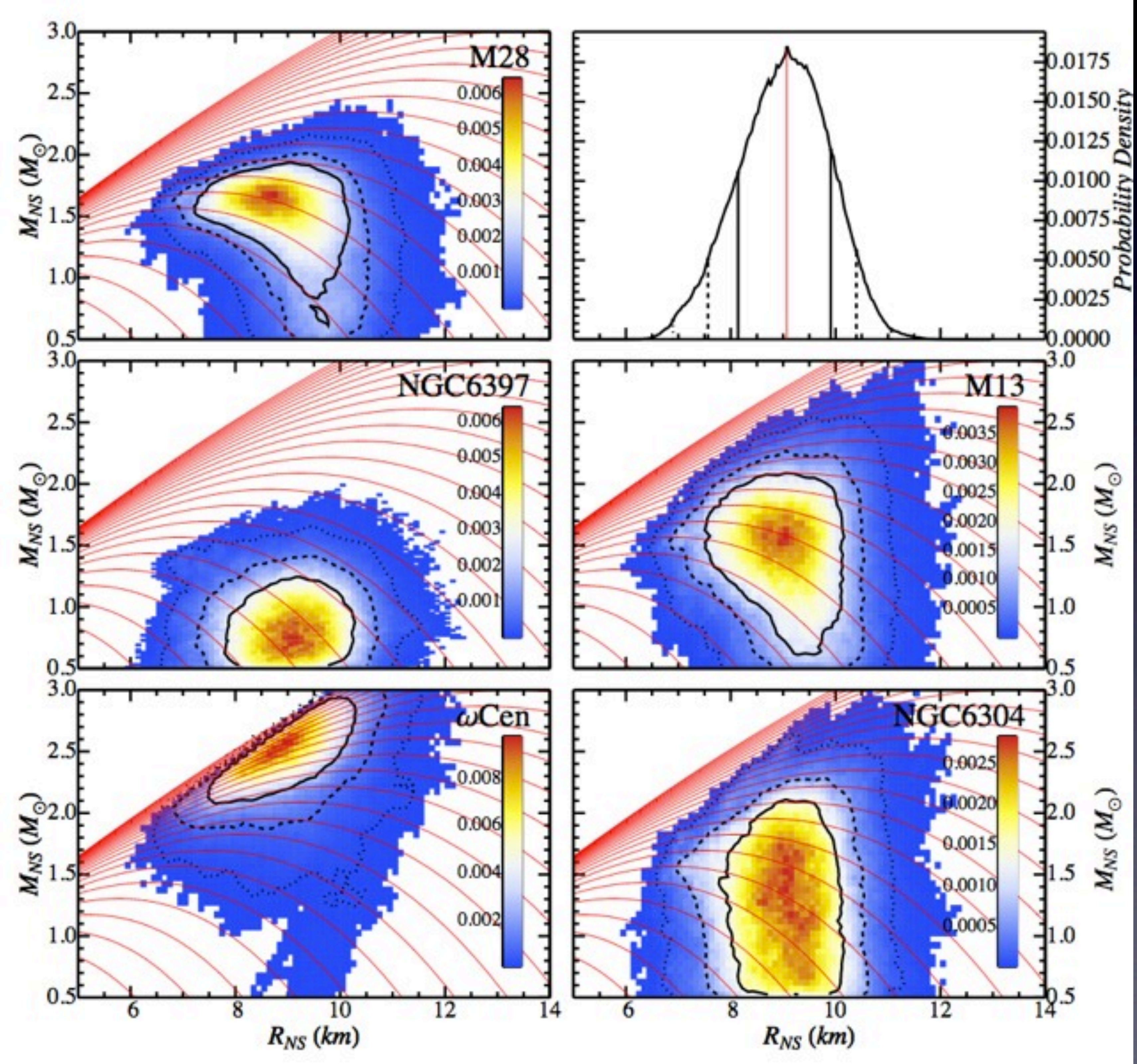


Our most conservative radius measurement relies on the least number of assumptions.

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

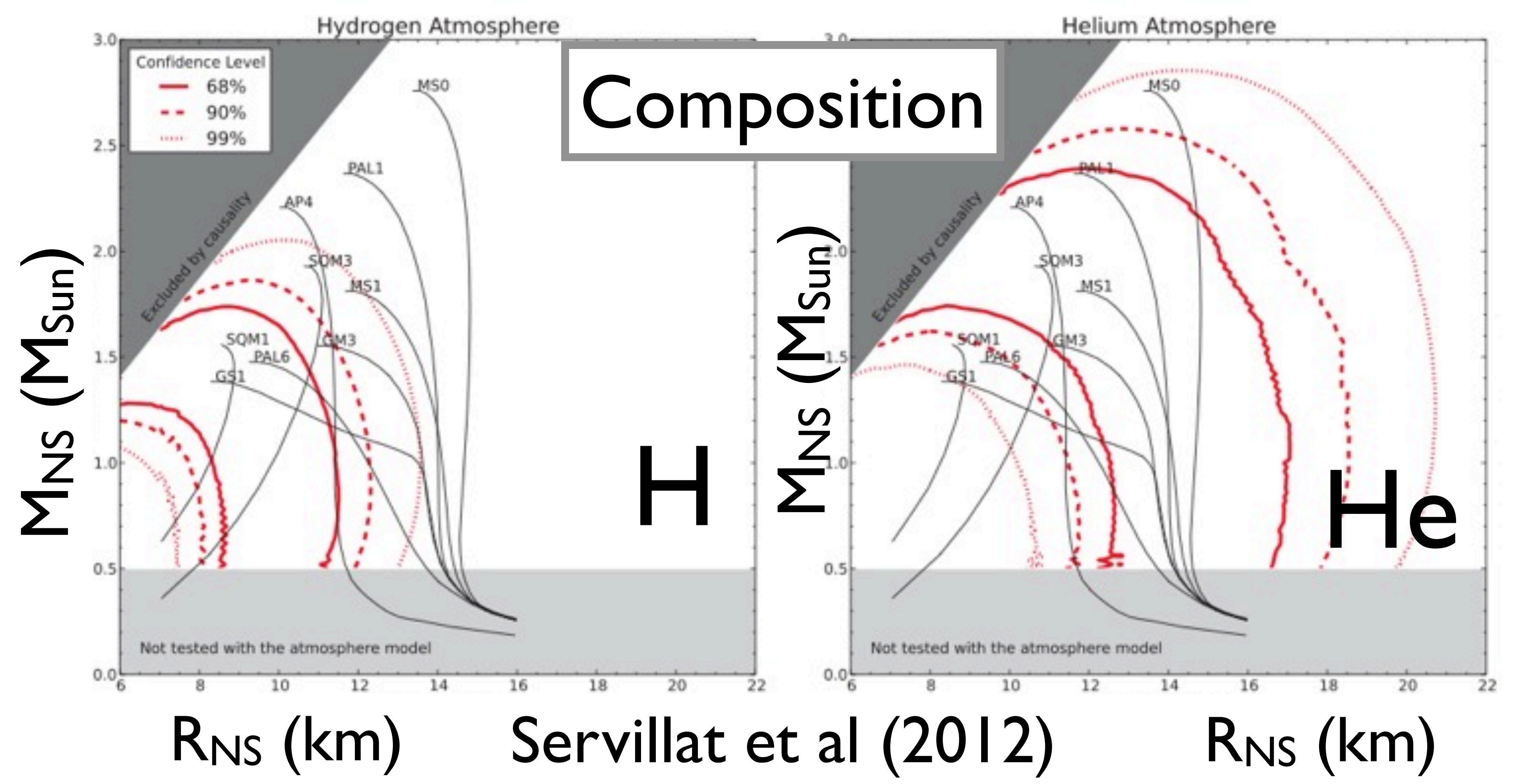
We included the uncertainties linked to:

- 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

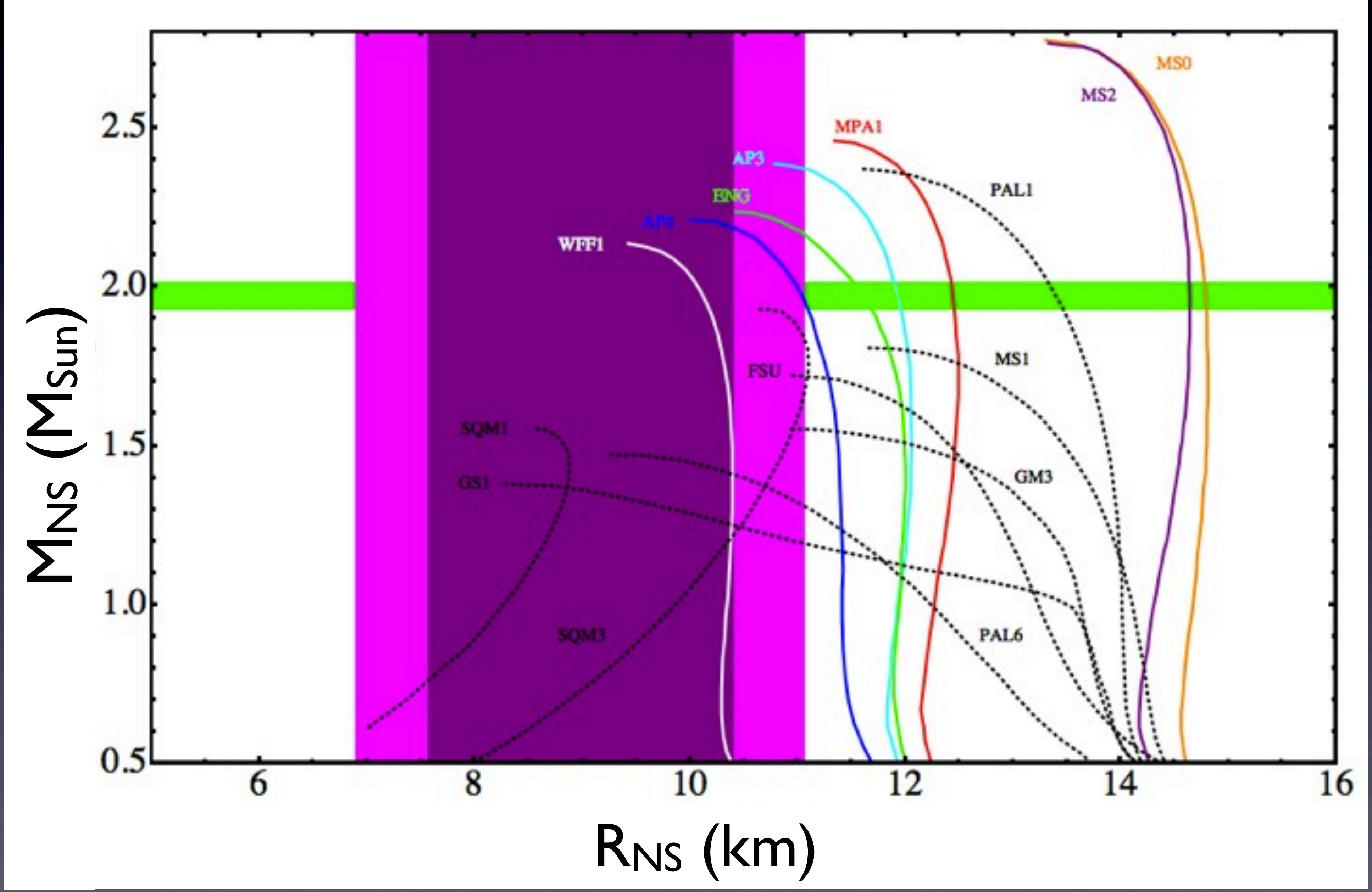


Composition

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

What about thermally-cooling isolated neutron stars?

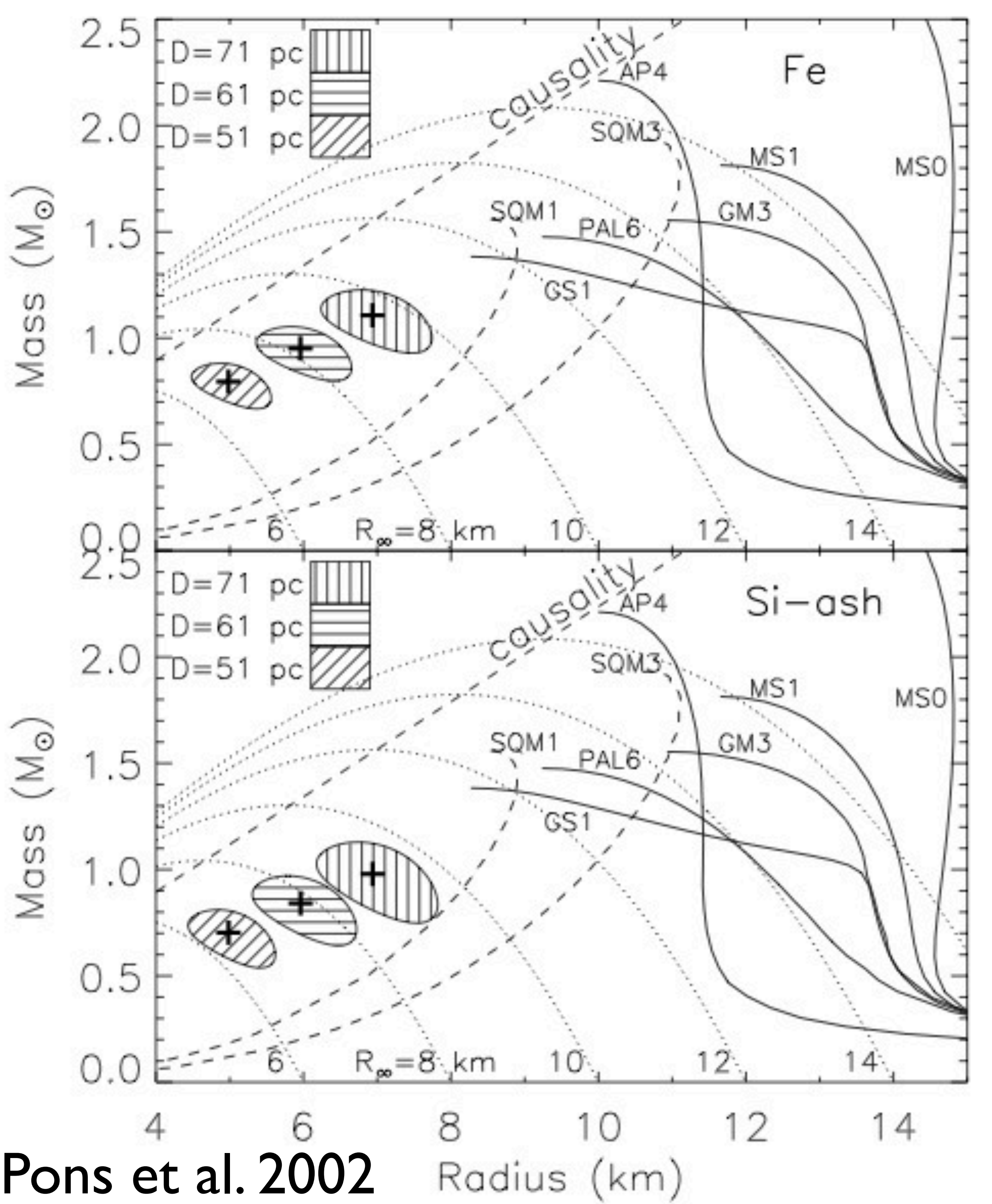
Only RX J 185635-3754 is remotely useful for this

Problems:

- What is the distance?

d = 51-177 pc

- What is the composition?
- What are the effects of the magnetic field?



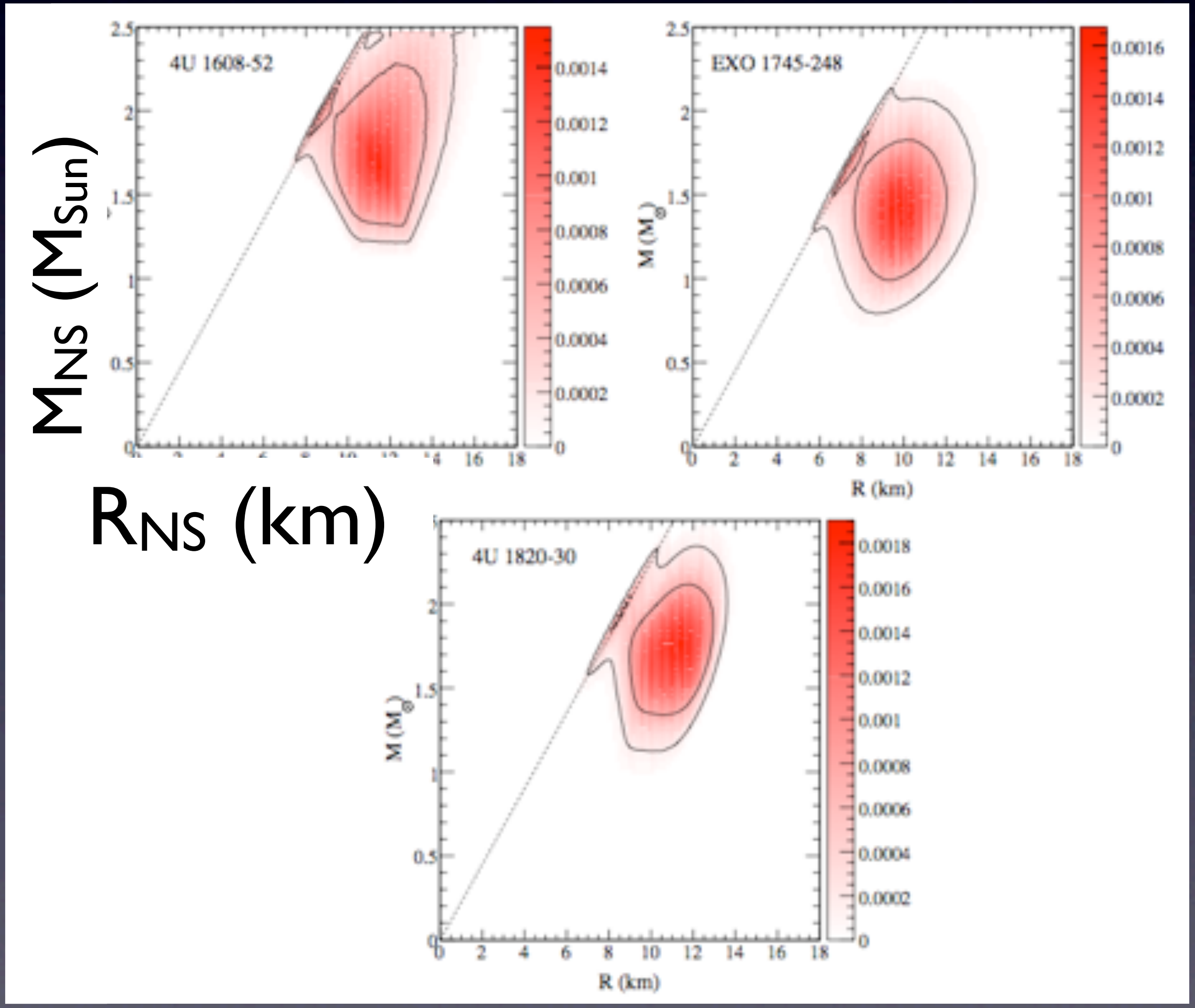
Pons et al. 2002

Combining previous results...

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

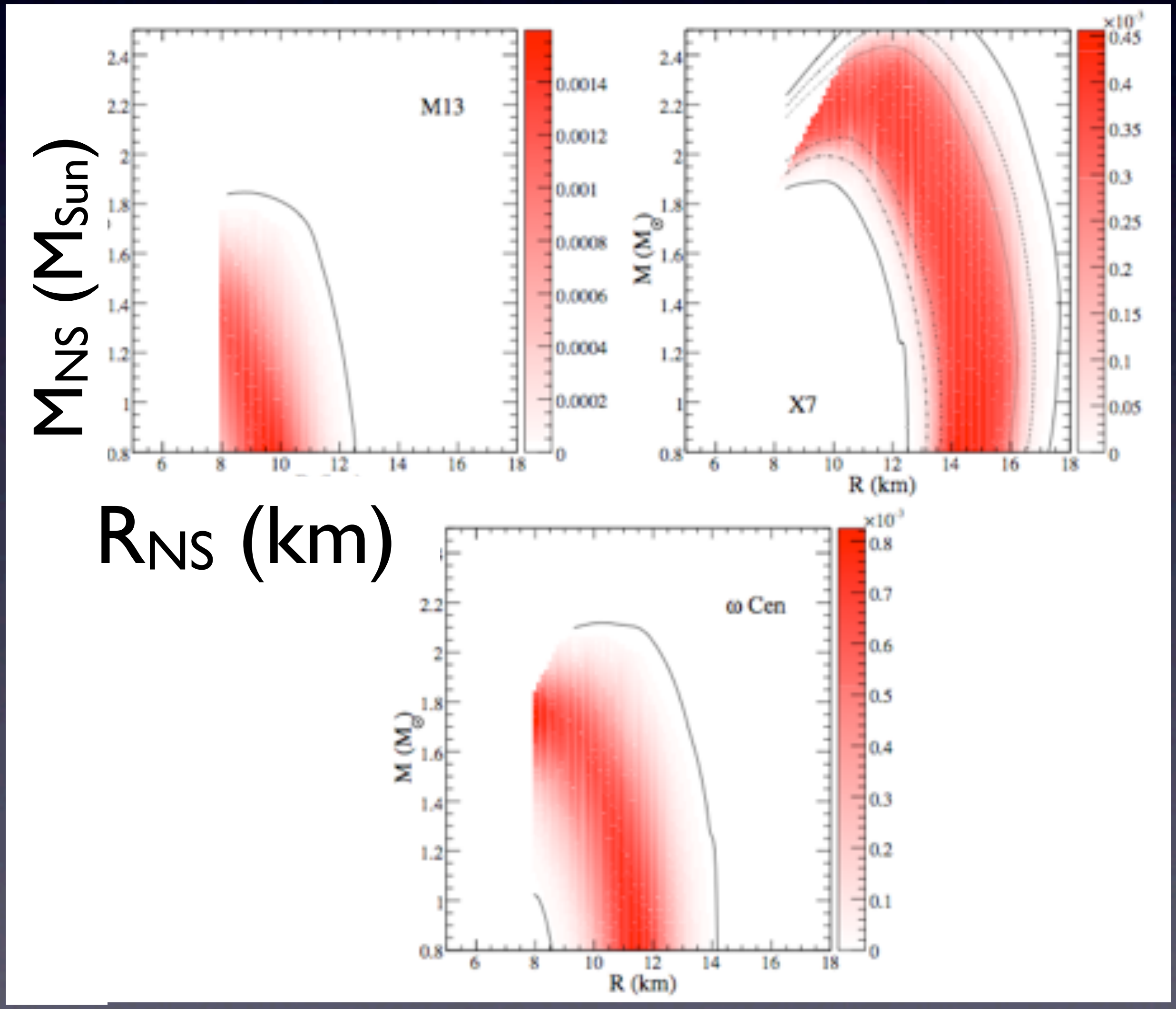
Steiner et al 2010, 2012

Type I X-ray bursts



+

Quiescent LMXBs



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

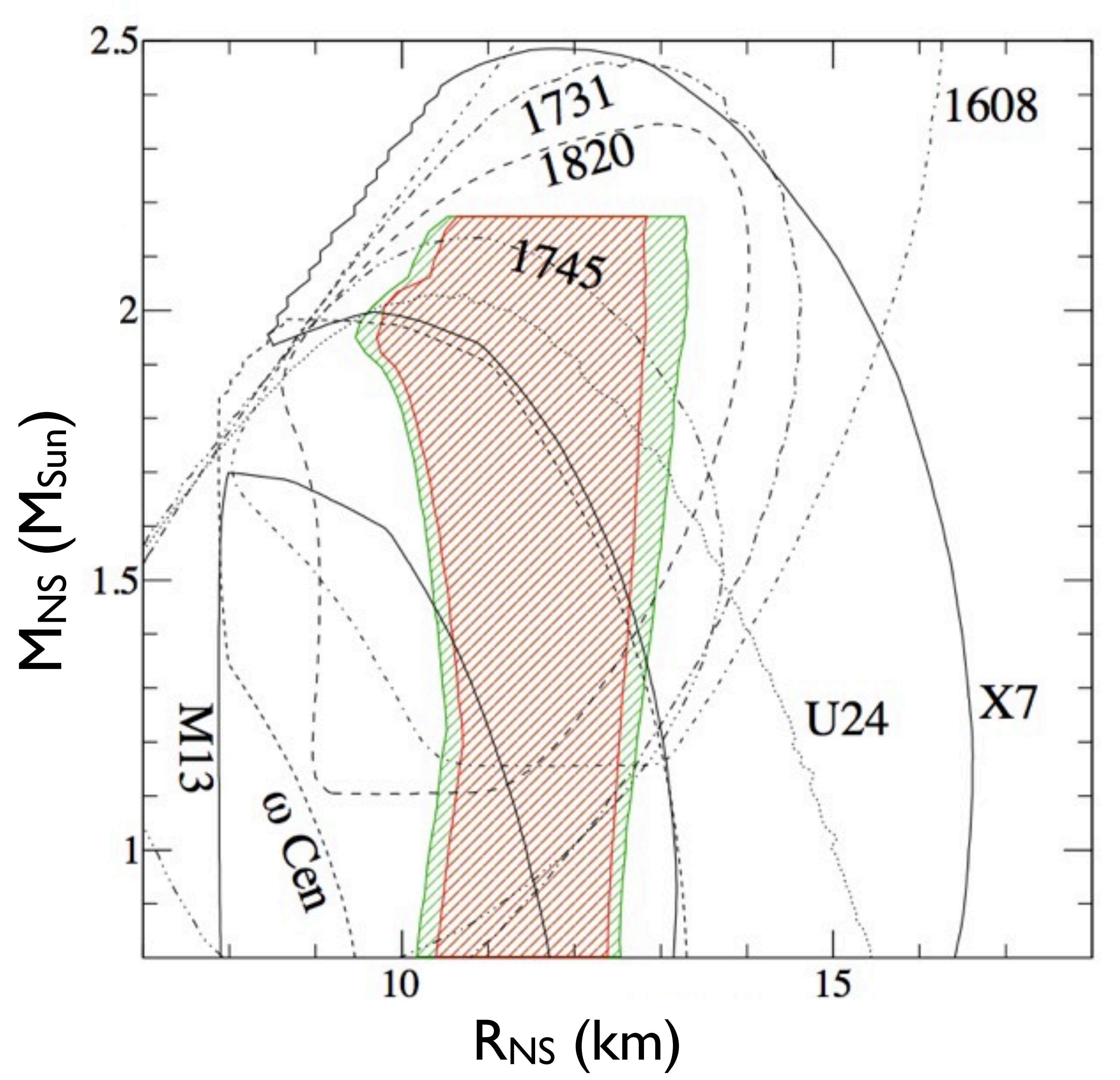
+ M-R contour of qLMXB in NGC6397
from Guillot et al. 2011

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

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

R_{NS} mostly 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 2012



Summary of methods

Measurement	Type of neutron star	Limitations
M_{NS}	Radio timing of pulsars	Only “higher than before” M_{NS} are useful
M_{NS} and R_{NS}	Type-I X-ray bursts	Modelling issues
Limits on M_{NS} and R_{NS}	Millisecond radio pulsars	Only “higher than before” f_{spin} are useful
	kHz QPOs (X-ray)	Model assumptions
I_{NS}	Radio timing of double NS systems	Difficult measurement
R_{NS} and M_{NS}/R_{NS}	Pulse-profile analysis (X-ray)	Need high S/N pulse profiles and several assumptions
R_{∞}	Quiescent low-mass X-ray binaries	Need high S/N spectra Not useful individually
	Isolated neutron stars (X-ray)	Distance? Magnetic fields?

See talks during conference March 24-28, by:

C. Heinke: "Probing the neutron star equation of state through X-ray spectroscopy"
D. Chakrabarty: "Probing the neutron star equation of state through X-ray timing"
Z. Arzoumanian: "The Neutron Star Interior Composition Explorer: An X-ray Astrophysics Facility Dedicated to Neutron Star Science"
M. Chakraborty: "X-ray Bursts from Accreting Neutron star LMXBs"
H. Stiele: "Millihertz Quasi-periodic Oscillations in 4U 1636-536: Pulse Profile and Energy Spectrum"