Finding new, X-ray bright neutron stars with which to constrain the equation of state

Natalie Webb

Institut de Recherche en Astrophysique et Planétologie, Toulouse, France

S. Guillot, J. Margueron, N. Baillot d'Etivaux, B. Chalot, ….

XMM-Newton

4XMM-DR10

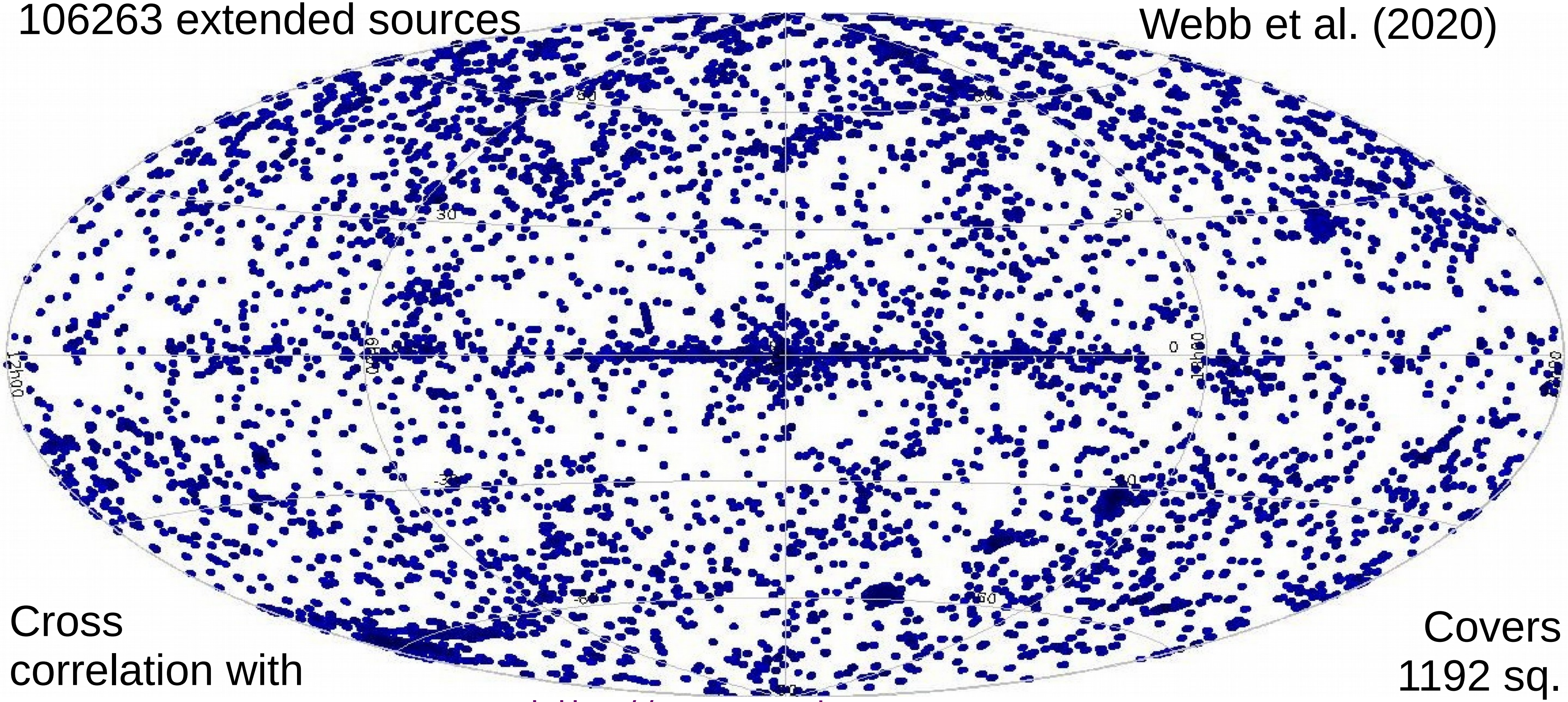
3 Feb. 2000–14 Dec. 2019 Released : 10th December 2020

849991 detections, 575158 unique sources - detected up to 74 times

303023 (36%) sources with spectra and lightcurves

106263 extended sources

Webb et al. (2020)



Cross correlation with 222 catalogues

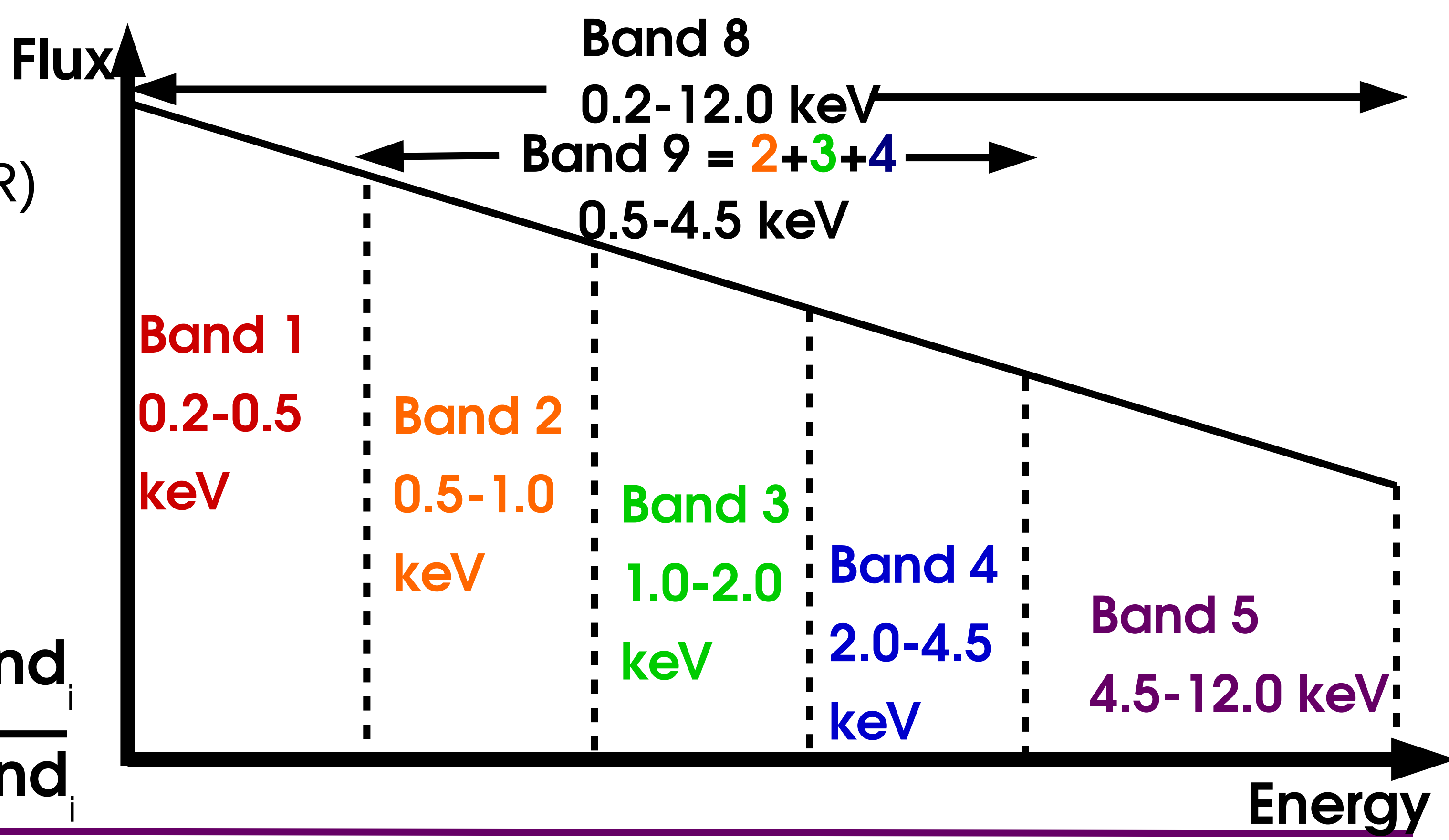
http://xmmssc.irap.omp.eu

Covers 1192 sq. deg of sky

4XMM-DR10 – data proposed

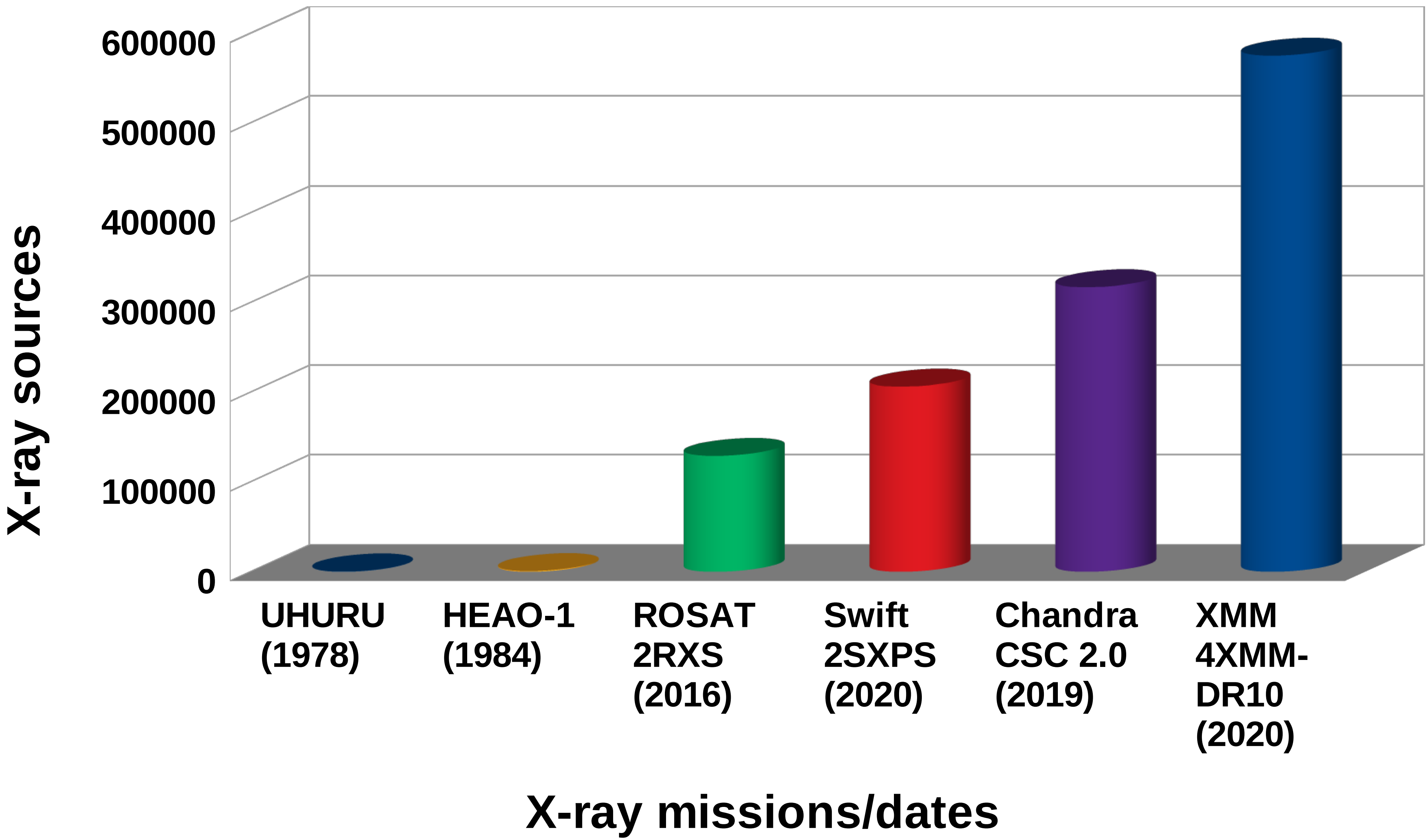
336 columns of information including :

- Identifiers/coordinates
- Observation date/time and observing mode
- Exposure /background info
- Extent
- Counts/fluxes/rates
- Hardness ratios (HR)
- Maximum likelihood
- Quality flags
- Variability



$$HR_i = \frac{Band_{i+1} - Band_i}{Band_{i+1} + Band_i}$$

4XMM-DR10 – relative size



4XMM-DR10 – MSPs

Modelling X-ray light curves from thermally emitting MSPs can constrain mass & radius

Only a dozen so far observable with NICER

47 ATNF MSPs observed with XMM-Newton (25 more than Lee et al. 2018)

Reanalysis of all 47 MSPs (P < 30 ms)

32 considered thermal emitters, 4 have NICER mass-radius constraints

6 others with NICER observations of thermal pulsations

7 further with XMM/pn timing mode observations (pulsation search)

No significant pulsations found

A couple of fairly bright MSPs could become good NICER targets

Others will be good for Athena

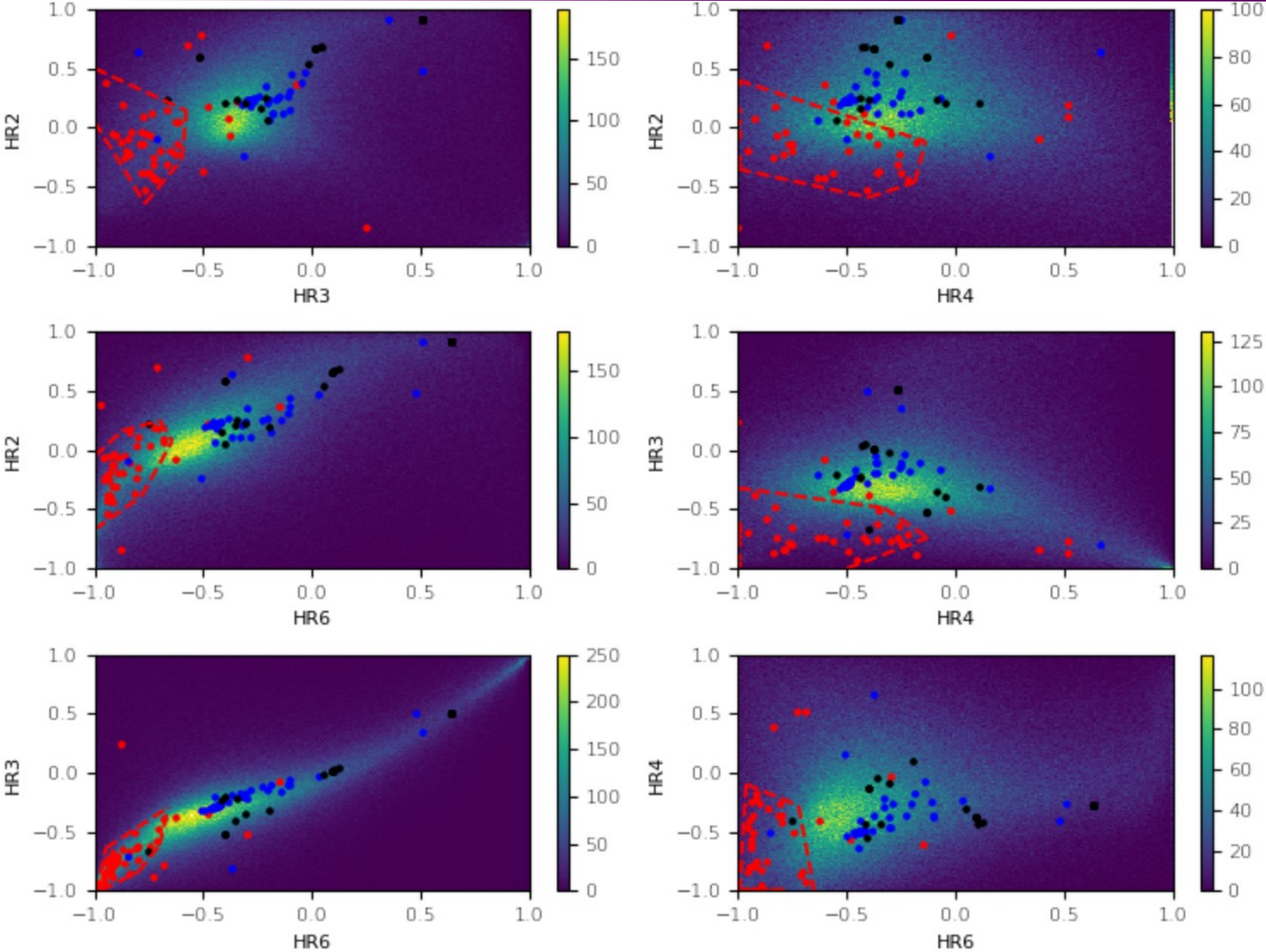
4XMM-DR10 – MSPs

From space density of neutron stars around Sun $n_0 = 1{-}5\times10^{-4}$ pc^{-3} (Sartore et al. 2010) and 13.8 % of ATNF pulsars are MSPs, could expect ~10^5 MSPs observed by XMM-Newton (~5 % sky observed)

New MSPs potentially detected by XMM-Newton

Search for these in 4XMM-DR10 using characteristics from sample of 47

Pulsar sample and characteristics



Thermal

Non thermal

Globular cluster

6 of 10 plots studied

Thermally emitting MSP candidates

7340 thermally emitting neutron star candidates identified

Sample contains 17 of the thermal MSPs from our sample (1 non-thermal)

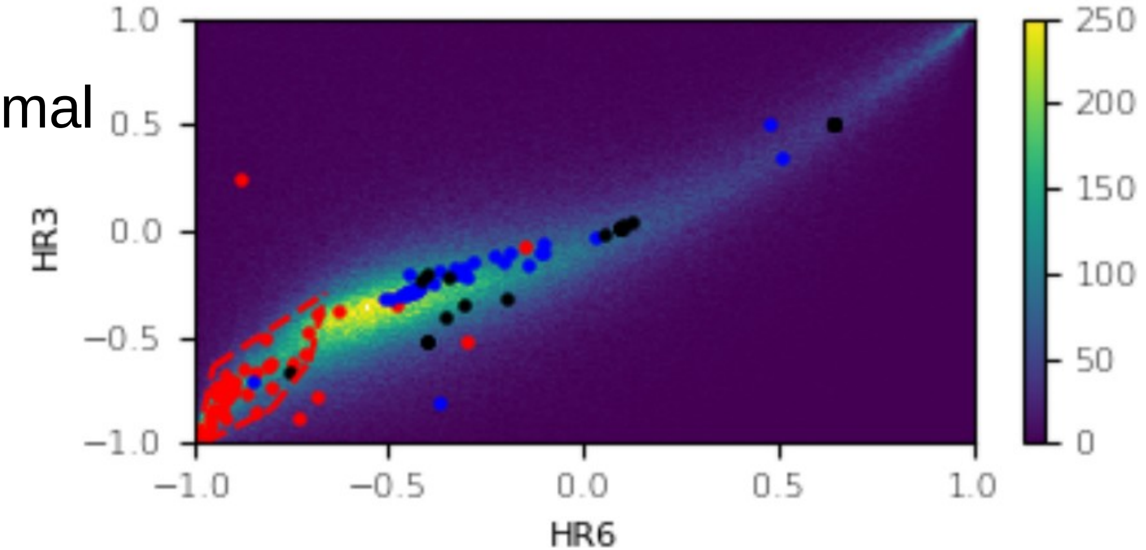
2587 with no Gaia counterpart

Many are bright enough to be easily detected with NICER

Further work required to definitively identify the neutron stars

Observations indicate smooth transition from thermal to non-thermal

Thermal nature may simply be linked to viewing angle



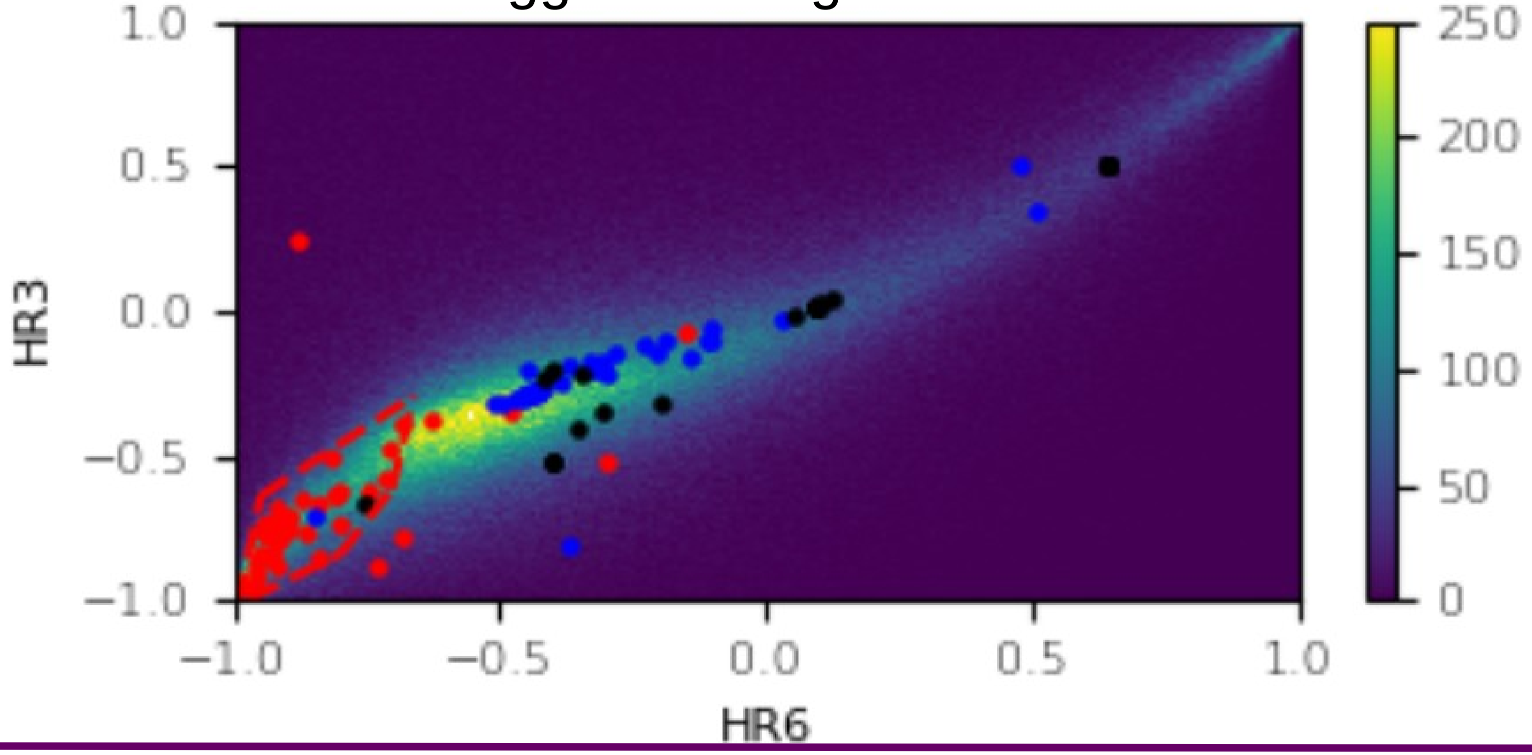
Other MSPs in XMM-Newton data

Globular clusters contain many MSPs

Many thought to be thermal emitters (e.g. Grindlay et al. 2002)

Long observations of nearby globular clusters could provide many lightcurves to model, providing the ephemerides are known

But, these observations suggest most globular cluster MSPs non-thermal



Constraining the neutron star equation of state with X-ray data

Type I X-ray bursts (e.g. Dohi et al. 2021)

Magnetar photospheric radius expansion bursts (e.g. Watts et al. 2010)

Cooling curves (e.g. Cheng et al. 2017)

Spectral fitting of populations of thermal neutron stars (e.g. Guillot et al. 2014, Özel et al. 2016, etc)

Combining thermal neutron star X-ray data + nuclear physics

7 globular cluster neutron star low mass X-ray binaries

Modelling of thermal XMM-Newton & Chandra spectra (nsatmos)

Empirical parameterization of the eq. of state (Margueron et al. 2018a, b) with MCMC to fit spectra

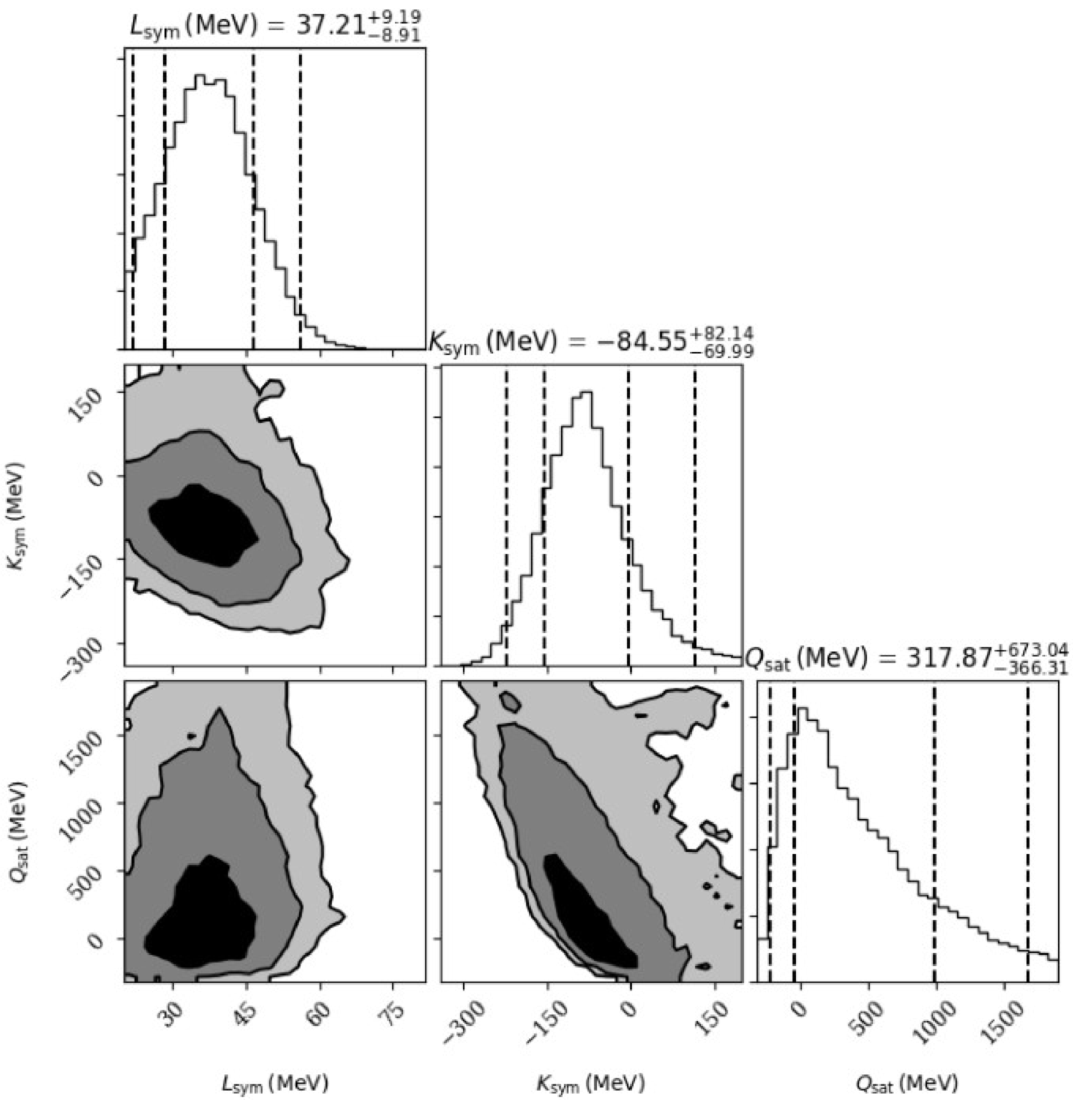
Based on Taylor expansion in baryon density at ~nuclear saturation density $n_{sat} \approx 0.16 \text{ fm}^{-3}$

$$e_{\rm sat} = E_{\rm sat} + \frac{1}{2}K_{\rm sat}x^2 + \frac{1}{3!}Q_{\rm sat}x^3 + \frac{1}{4!}Z_{\rm sat}x^4 + \ldots \qquad e_{\rm sym} = E_{\rm sym} + L_{\rm sym}x + \frac{1}{2}K_{\rm sym}x^2 + \frac{1}{3!}Q_{\rm sym}x^3 + \frac{1}{4!}Z_{\rm sym}x^4 + \ldots$$

$E_{\rm sat} = -15.8$ MeV, $E_{\rm sym} = 32$ MeV, $n_{\rm sat} = 0.155 \text{ fm}^{-3}$ and $K_{\rm sat} = 230$ MeV

(Baillot d'Etivaux et al., 2019)

Combining thermal neutron star X-ray data + nuclear physics

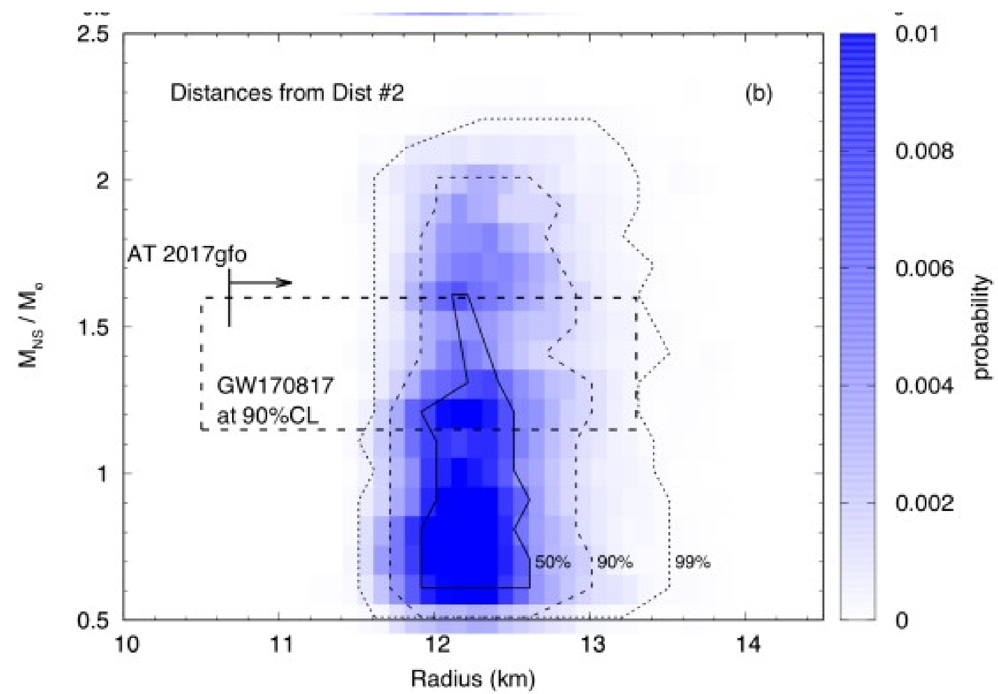


~ 12.4 km radius for M=1.45 $M_{\odot}$

~3 % error on radius

(Baillot d'Etivaux et al., 2019)

Improvements to be made to the eq. of state



Conclusions

32/47 MSPs observed with XMM-Newton are thermal emitters

2 of these may be good candidates for NICER

Smooth transition of thermal to non-thermal spectra could be due to viewing angle

1000s potential new NS candidates in catalogue – need follow-up work

New candidates for NICER

Others may be observed with Athena

XMM-Newton observations globular cluster MSPs may provide constraints

Constraints can also be made from other types of X-ray observations

Combining spectral fitting and realistic equations of state constrains nuclear parameters as well as the equation of state