Spectral analysis of the quiescent low-mass X-ray binary in the globular cluster M30

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Outline

- General description of neutron stars (NSs)
- Quiescent low-mass X-ray binaries (qLMXBs)
- Spectral analysis of the qLMXB in M30
- Discussion of the results
- Conclusion

INTRODUCTION

General properties of neutron stars

- Remnants of massive stars $9 - 25\,\mathrm{M}_\odot$
- Typical masses $M_{\mathrm{NS}} \sim 1.4\,\mathrm{M}_\odot$

  and radii $R_{\mathrm{NS}} \sim 10\,\mathrm{km}$

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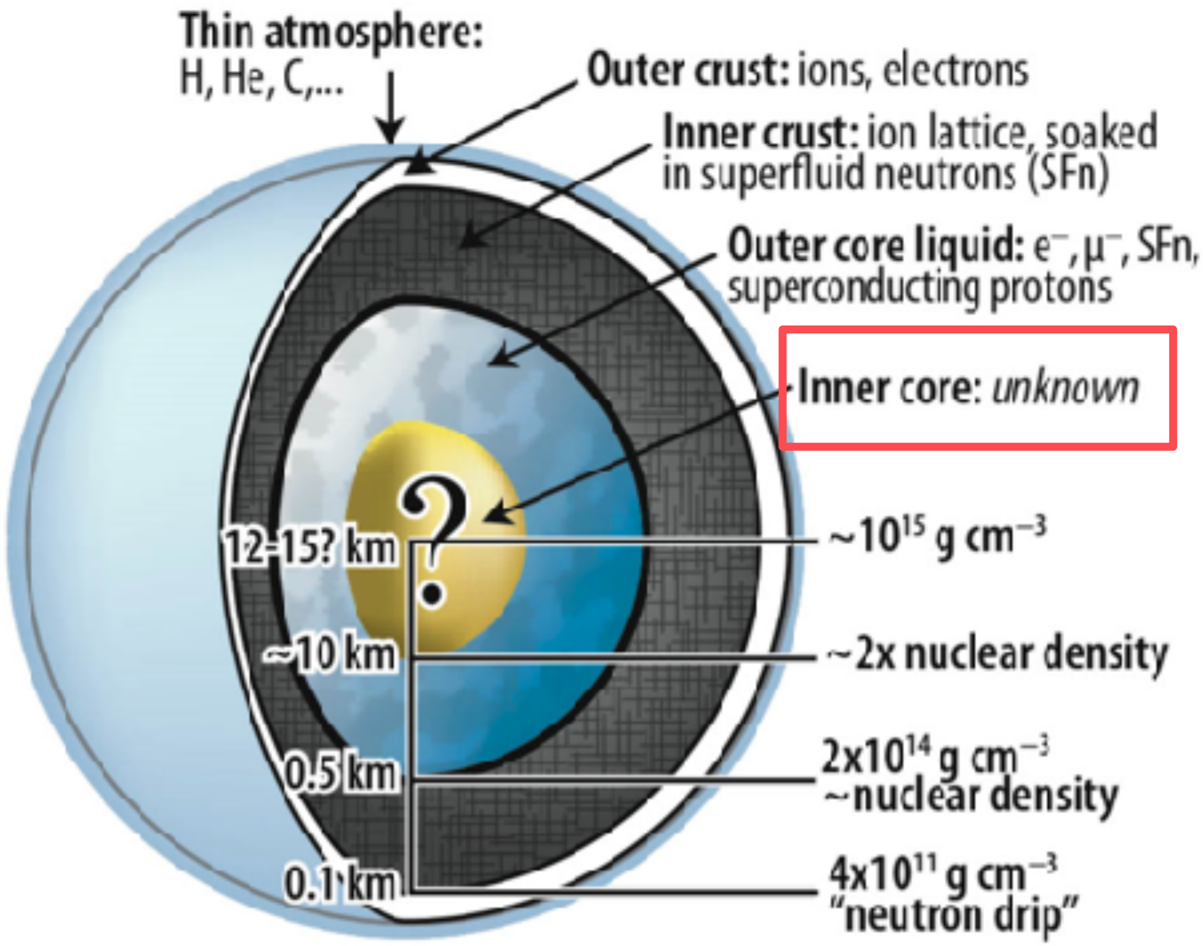
MATTER IN EXTREME CONDITIONS

General properties of neutron stars

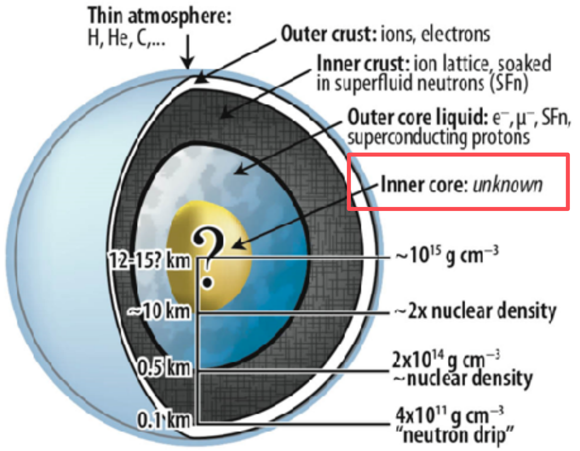
State of matter changes with increasing density



Credit: www.eurekalert.org/

General properties of neutron stars

Matter in the core above nuclear density



www.eurekalert.org/

Cannot reproduce these conditions on Earth

Neutron stars are unique laboratories

Dense matter equation of state

General properties of neutron stars

Dense matter equation of state

- Describes behaviour of matter and its composition at any point in the stellar interior
- Relate pressure with energy density $P = P(\varepsilon)$
- When combined with the equations of stellar structure, one can obtain

$$P,\ \varepsilon \longrightarrow \boxed{M_{\mathrm{NS}},\ R_{\mathrm{NS}}}$$

General properties of neutron stars

Dense matter equation of state

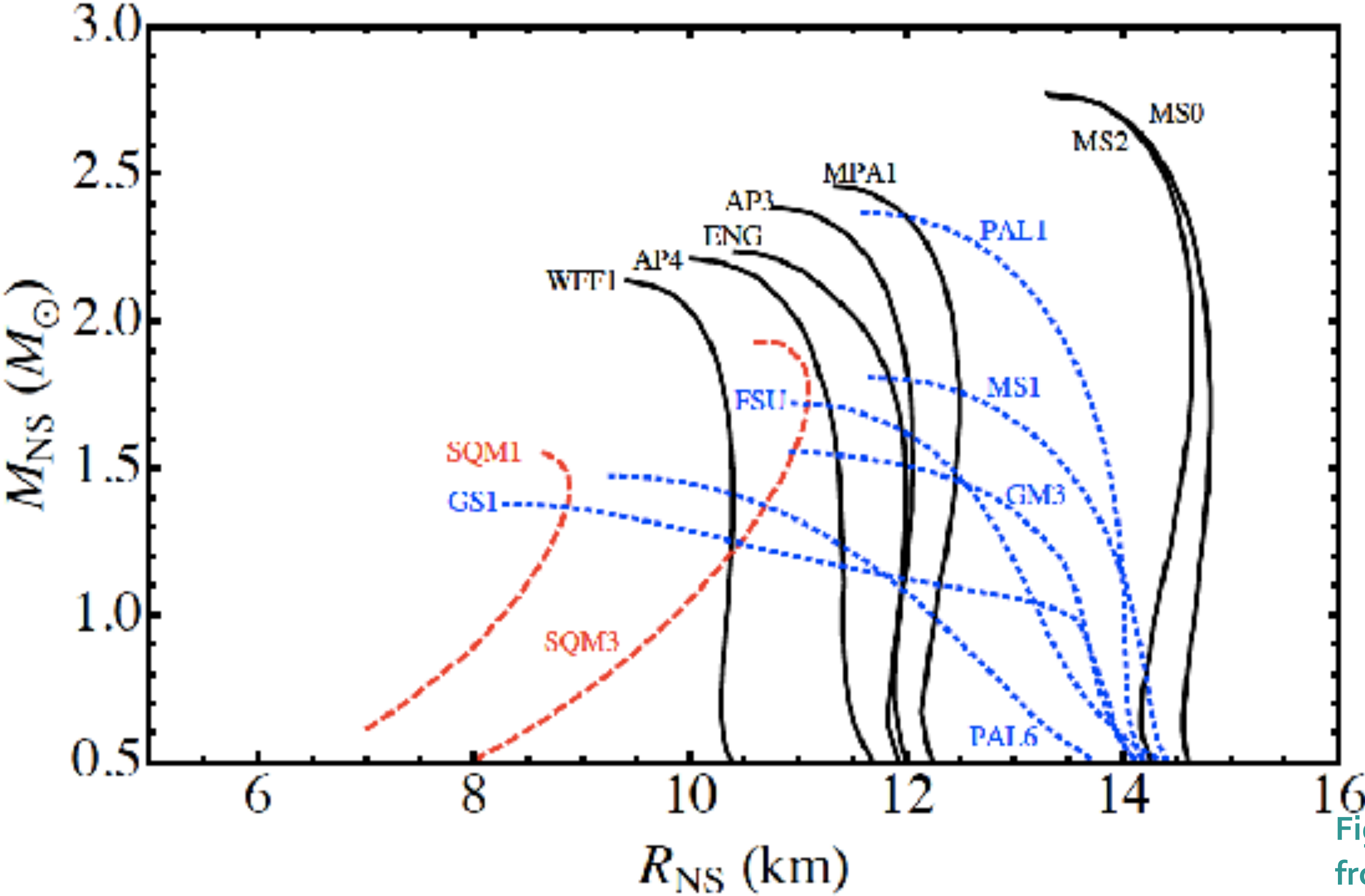


Figure adopted from Guillot (2014)

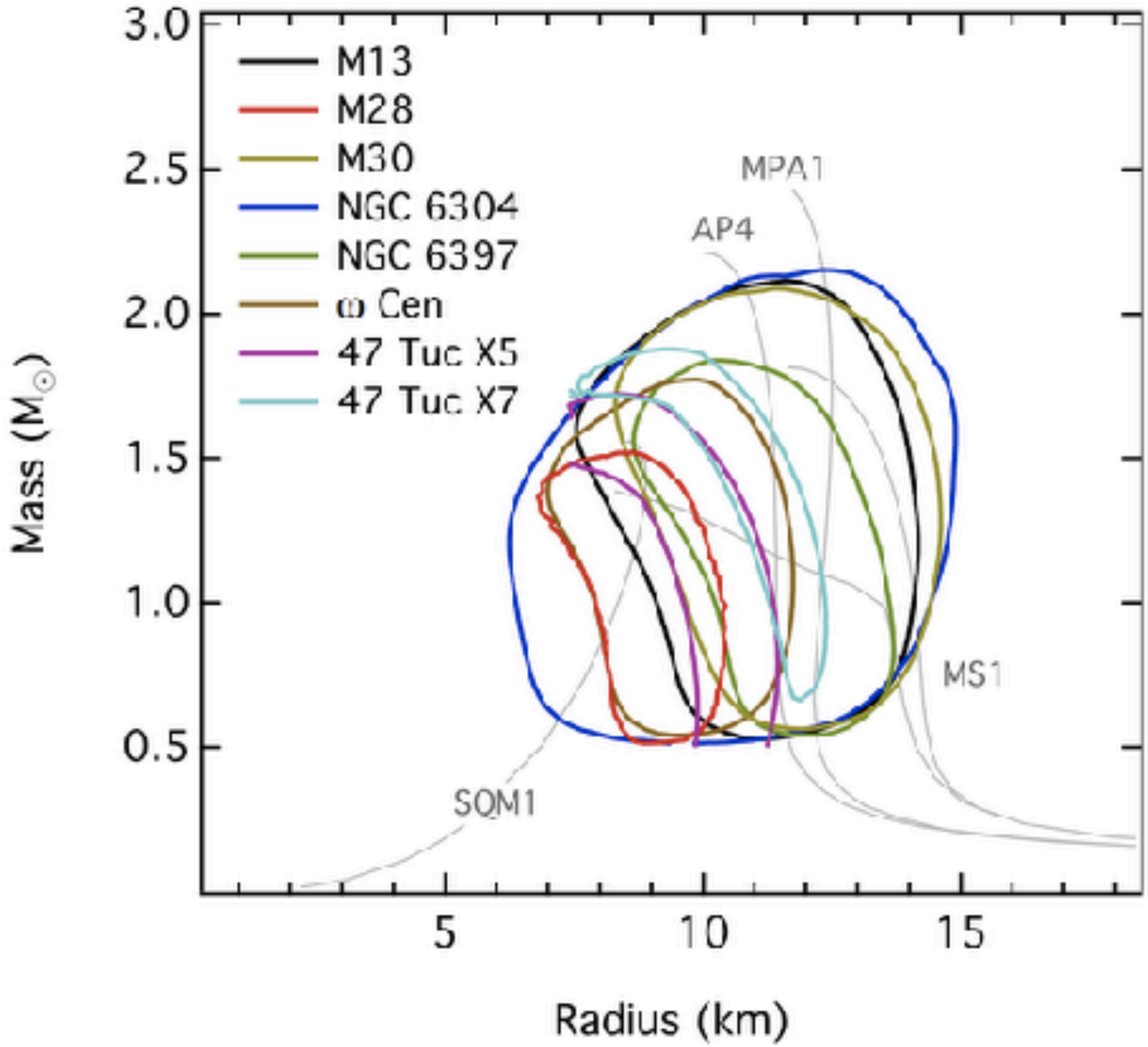
How can we measure R_{NS} ?

Radius measurements

See Özel & Freire 2016, Annual Reviews of Astronomy and Astrophysics!

- Spectroscopic measurements
  - **Low-mass X-ray binaries in quiescence**
  - Thermonuclear bursts
- Pulse Profile Modeling
  - Rotation powered pulsars
  - Accretion powered pulsars
  - Thermonuclear burst oscillations

General properties of neutron stars



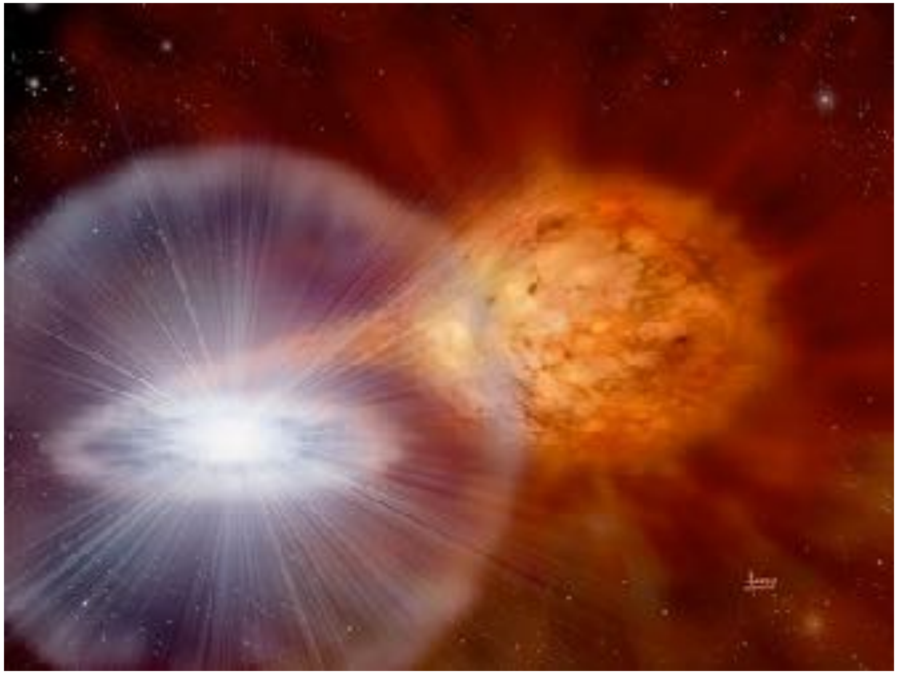
68% confidence contours obtained from all NSs in LMXBs during quiescence

Figure adopted from Özel & Freire (2016)

Radius measurements - systematics

- Atmosphere chemical composition
- Distance
- Non-thermal component (Power-law)
- Interstellar Extinction
- Surface temperature inhomogeneities (Hot spots)
- Rotation effects
- Magnetic fields
- Instrumental calibration
- Pile-up
- Extraction region size (?)

Low-mass X-ray binaries



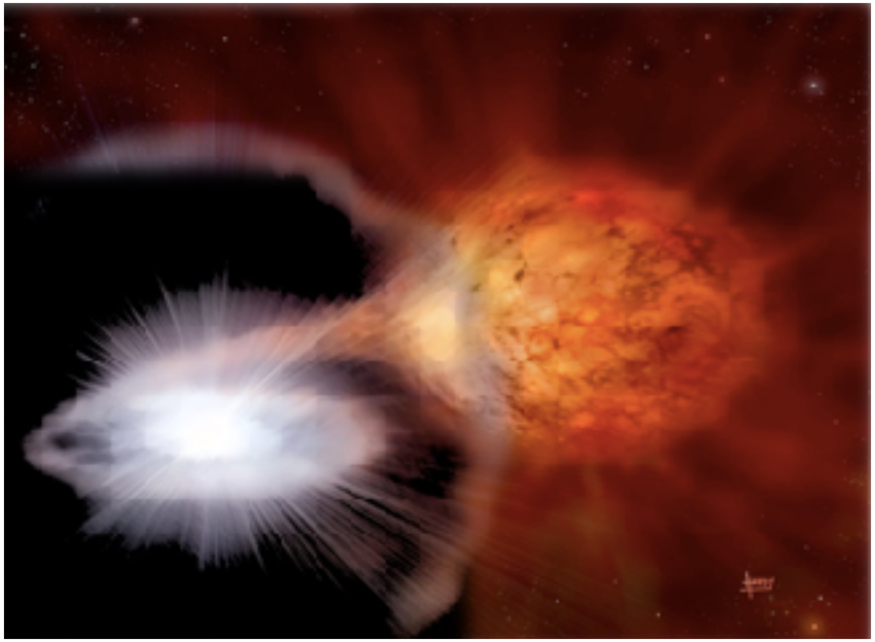
Neutron star accretes material from a low-mass companion

$$L_X \sim 10^{36} - 10^{38}\,\mathrm{erg\,s^{-1}}$$

Infalling material releases energy

Light-element surface

Quiescent low-mass X-ray binaries



- Accretion at low level

$$\sim 10^{-10}\,\mathrm{M_\odot\,yr^{-1}}$$

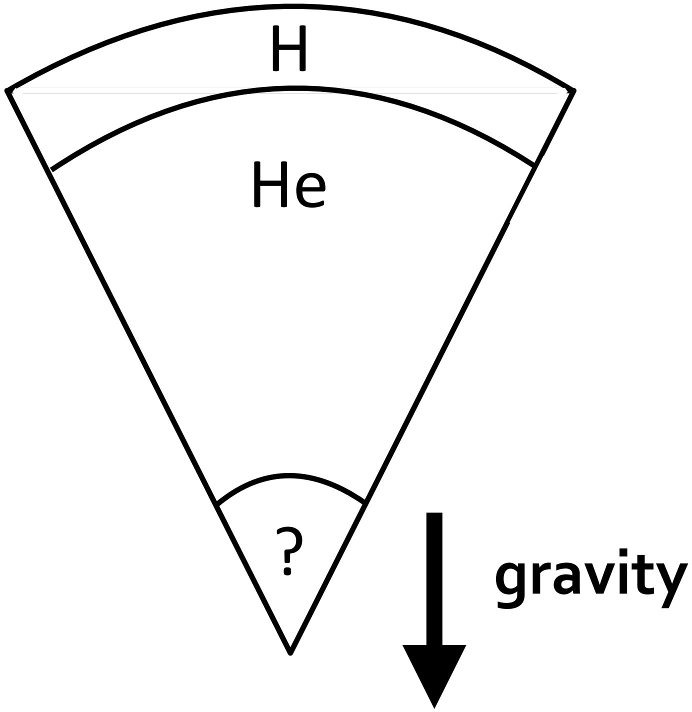
- Luminosity comes from the heated core, after repeated accretion events

$$L_X \sim 10^{32} - 10^{33}\,\mathrm{erg\,s^{-1}}$$

Deep crustal heating

(Brown et al. 1998)

Quiescent low-mass X-ray binaries



Sedimentation occurs
on short timescales
~ minutes

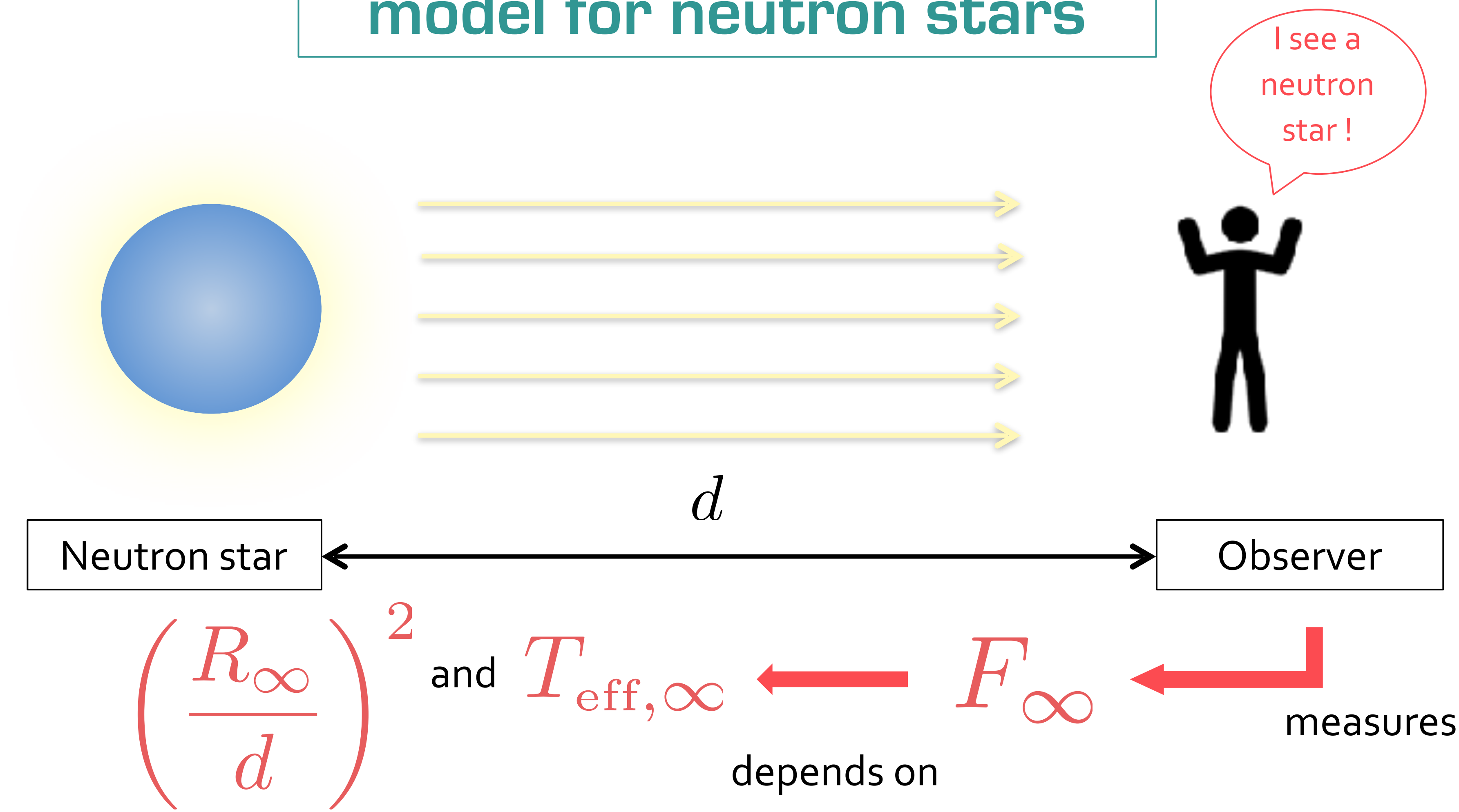
Alcock & Illarionov 1980, Bildsten et al. 1992

H atmosphere is
expected

**but it depends on
the nature of the
companion star!**

Emission from qLMXBs

Hydrogen atmosphere model for neutron stars



Emission from qLMXBs

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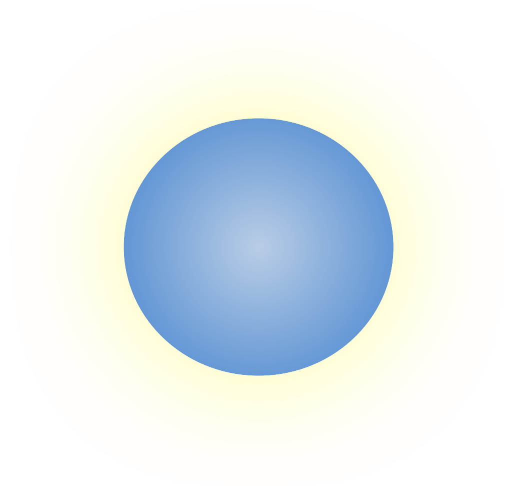


$$R_\infty = R_{\rm NS}(1+z) = R_{\rm NS}\left(1 - \frac{2GM_{\rm NS}}{R_{\rm NS}c^2}\right)^{-1/2}$$

This is what we measure

This is what we want

Emission from qLMXBs

- Hydrogen fully ionized due to high surface temperatures:

$$T_{\mathrm{eff}} \sim 10^6\,\mathrm{K}$$

- Free-free absorption processes: $\kappa \sim E^{-3}$ (Romani, 1987)

↓

We observe the **X-ray spectrum** emerging from the hydrogen atmosphere

Emission from qLMXBs

X-ray spectrum → We need an X-ray observatory

CHANDRA

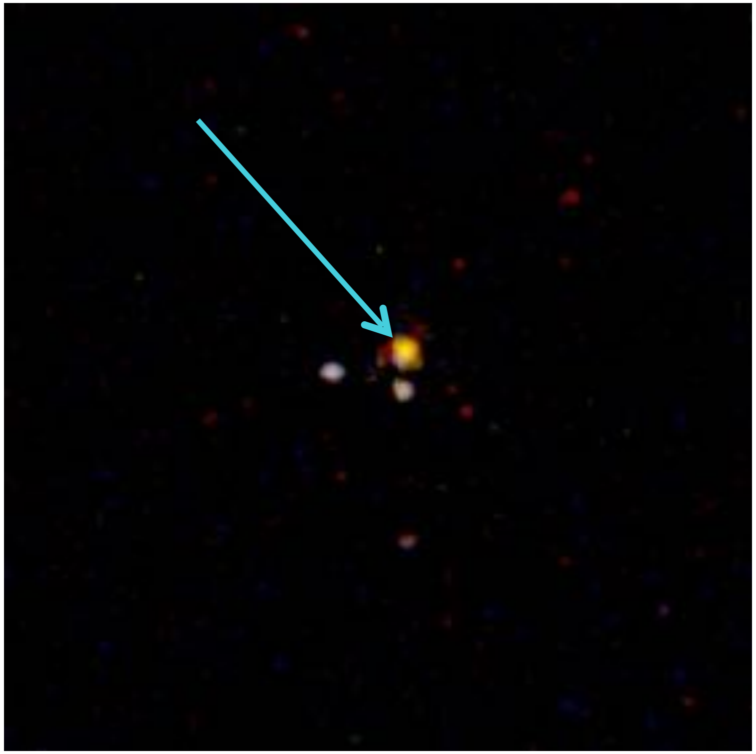
Why are qLMXBs promising for measuring NS radii?

- In quiescence, we observe the NS surface
- They have low magnetic fields: $B \ll 10^{10}\, G$
- We can model their thermal emission: Hydrogen atmospheres
- If they are in globular clusters: We know the distance

MY WORK

My work

- Consists in analyzing data from the globular cluster M30



Source: http://chandra.harvard.edu

Distance to M30 is 8.2 kpc

(O'Malley et al. 2017)

Chandra X-ray image of M30

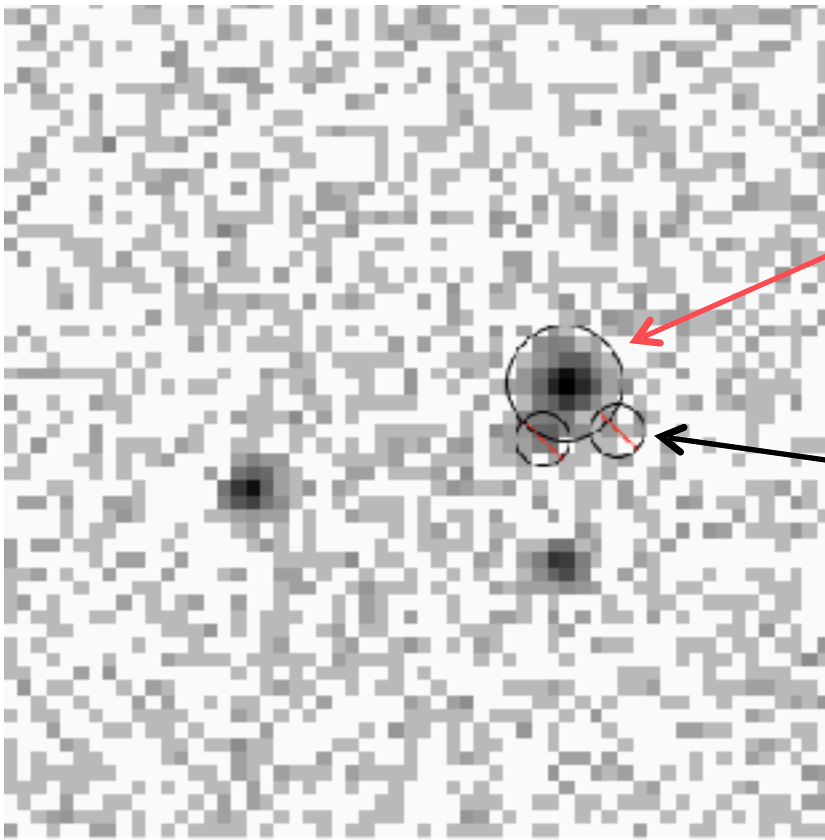
My work

- Chandra observed the globular cluster M30 in two ocassions

2001	→	Data analyzed by **Lugger et al. 2007**
2017	→	Data analyzed by **me** (including the previous one)

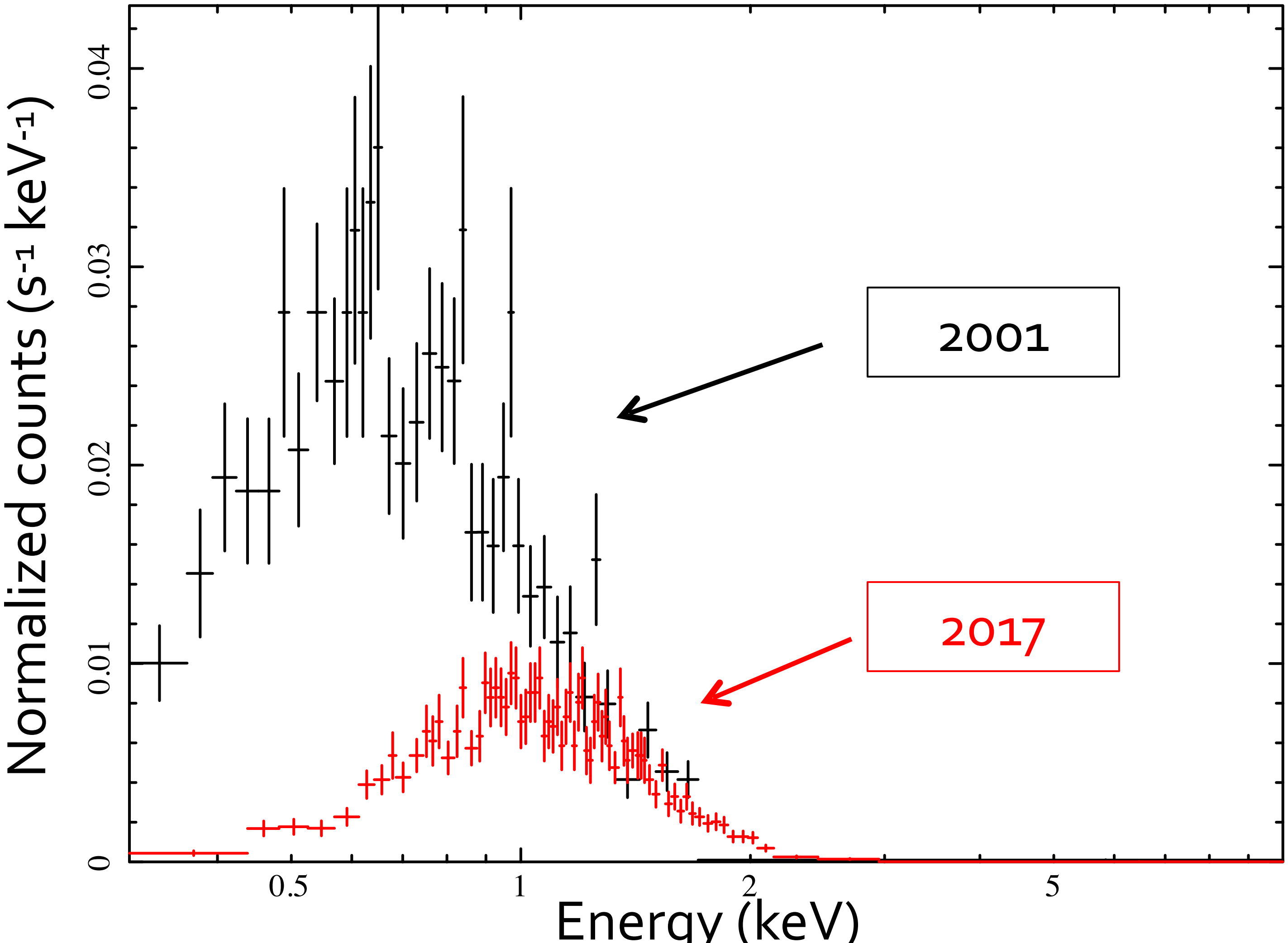
My work

- Extraction of the spectra

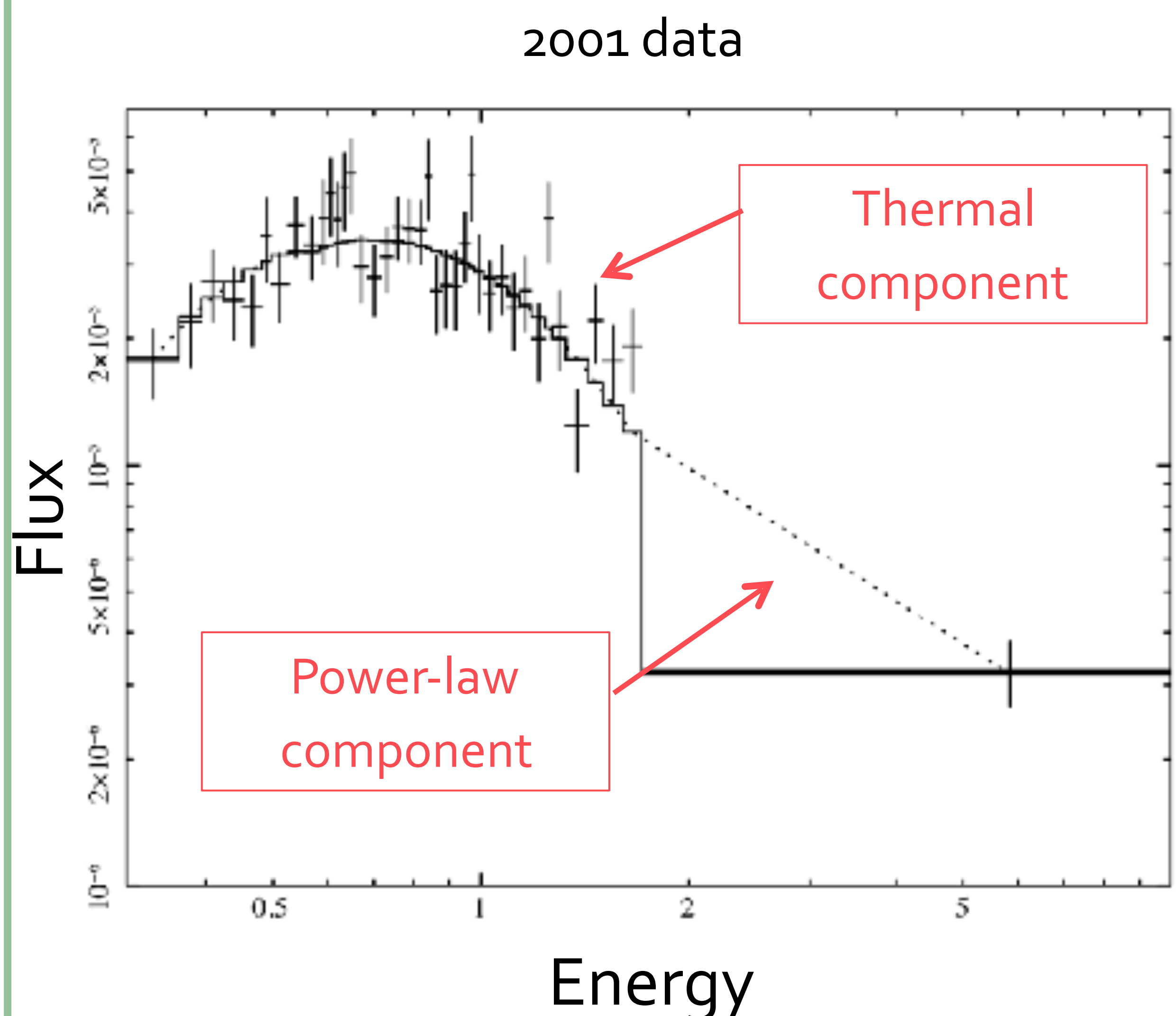


My work

- Extraction of the spectra



My work - Modelling emission



High-energy excess has been observed in the tail of LMXBs during quiescence

(e.g., Campana et al. 1998, Rutledge et al. 2002, Campana et al. 2004, Denegaar et al. 2011, Bahramian et al. 2014)

My work - Modelling emission

Our model accounts for:

Thermal emission →	Hydrogen atmosphere (Heinke et al. 2006a)
Power-law tail →	Typical photon index **1-2** (Guillot et a. 2013, Bahramian et al. 2014)
Galactic absorption →	Verner et al. 1996, Wilms et al. 2000
pile-up →	Davis 2001

My work - Modelling emission

- The atmosphere model depends on the parameters we are looking for

Hydrogen atmosphere → T_{eff}, M_{NS}, R_{NS}, distance, fraction of emitting area

My work - spectral analysis

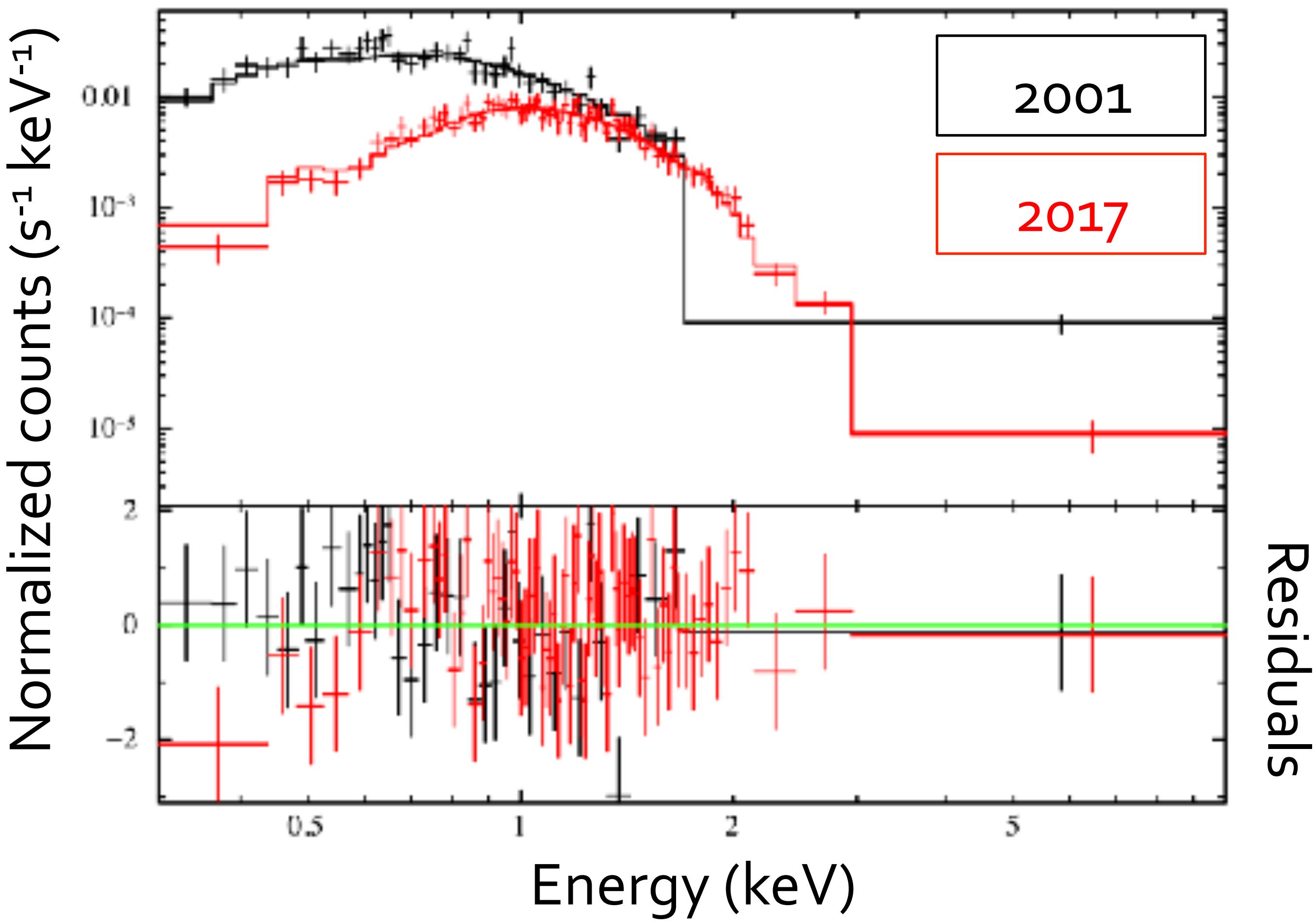
- **First** we search for signs of flux variations over the 16 years between observations
- Lack of variability allow us to **fit the spectra simultaneously**, and with tied NS parameters
- We confirm the equilibrium state of the NS by comparing fluxes:

$$\log_{10}(F_{2001}/\mathrm{erg\,cm^{-2}\,s^{-1}}) = -13.12^{+0.03}_{-0.03}$$

$$\log_{10}(F_{2017}/\mathrm{erg\,cm^{-2}\,s^{-1}}) = -13.11^{+0.03}_{-0.03}$$

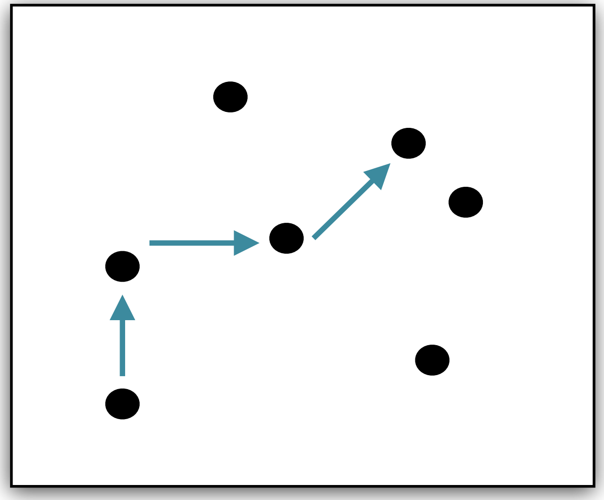
My work - spectral analysis

- **Second:** spectral fitting using the X-ray Spectral Fitting Package (XSPEC)



Markov Chain Monte Carlo Simulations (MCMC)

MCMC is a sampler, that explores the parameter space and tells us how well our model describes the data, given a set of parameters.



parameter space

- At each step, compares the new model to the old model (previous step) by computing its probability
- Keeps a record of every set of parameters tried
- Climbs to regions of higher probability —> **convergence**

Markov Chain Monte Carlo Simulations (MCMC)

MCMC is useful because:

- Allows to include known information in the model
- Exploration of parameter space results in posterior probability density functions of each parameter
- Shows how the parameters are correlated with each other
- It's easy to quantify the uncertainties of each parameter

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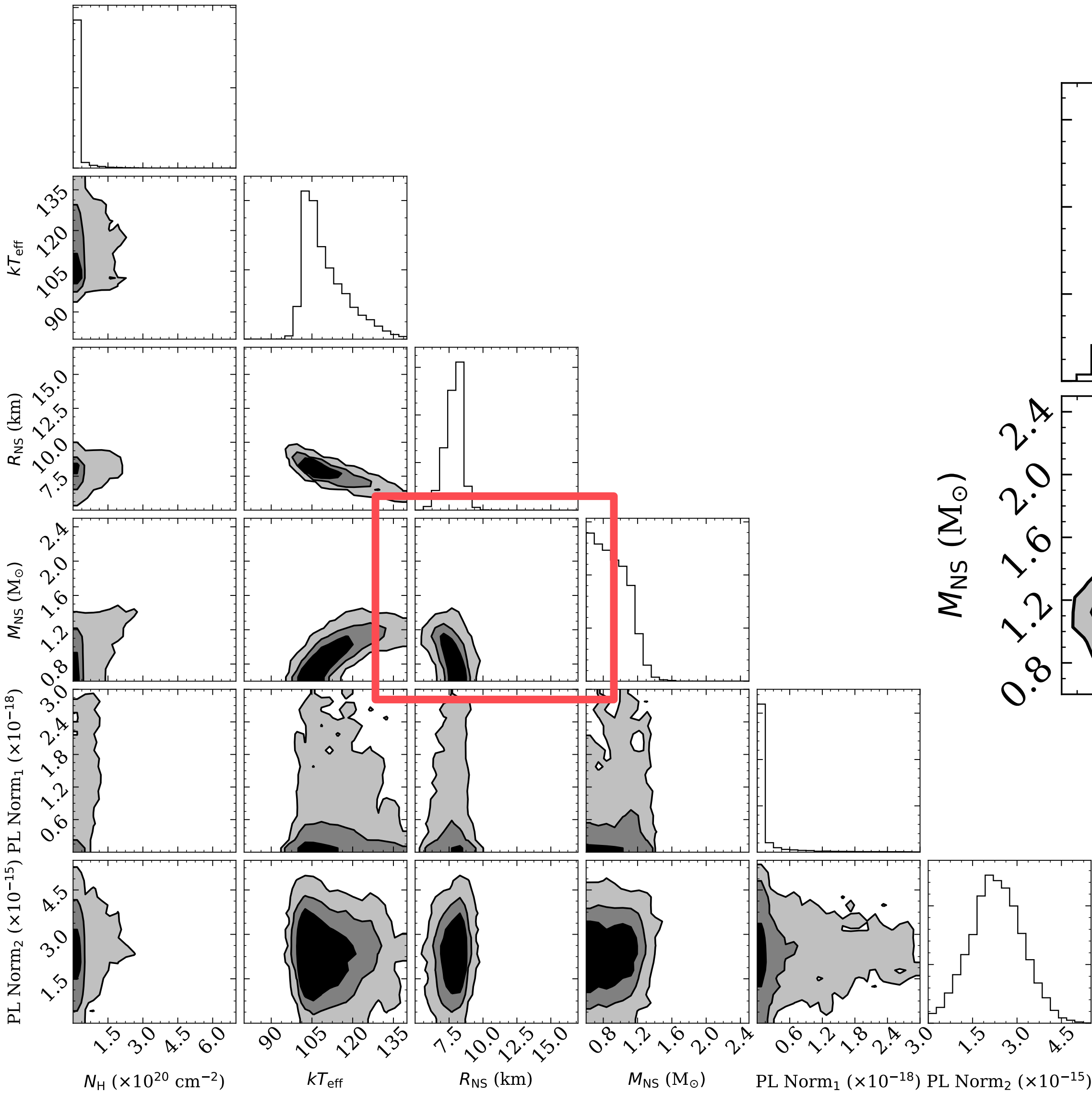
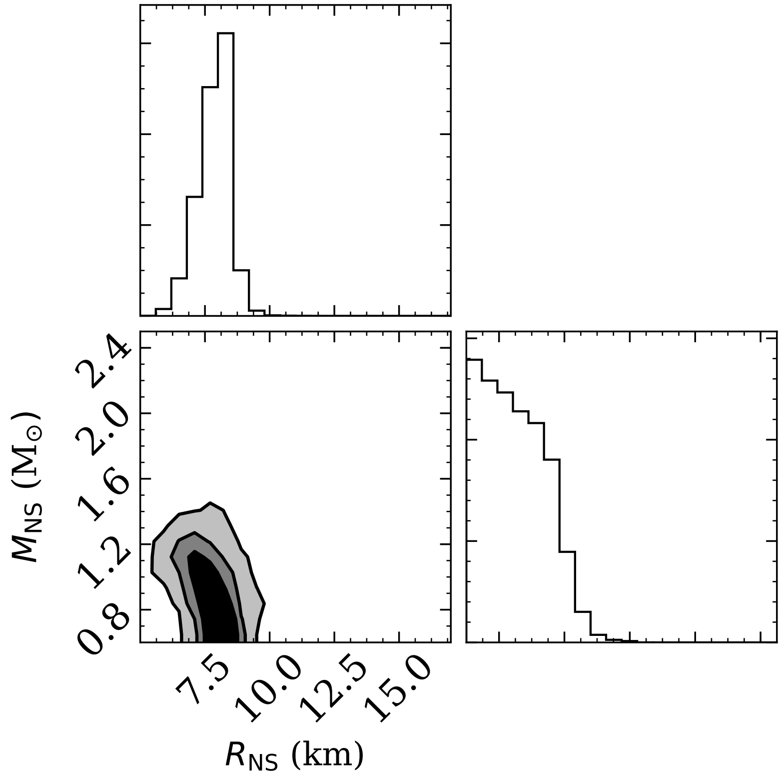
Mass-Radius contours!

Markov Chain Monte Carlo Simulations (MCMC)

- **Third:** extract the mass and radius contour





My work - spectral analysis

MY RESULTS
(90% confidence)

$$6.7 \leq R_{\mathrm{NS}} \leq 8.7\,\mathrm{km}$$

$$M_{\mathrm{NS}} \leq 1.2\,\mathrm{M}_{\odot}$$

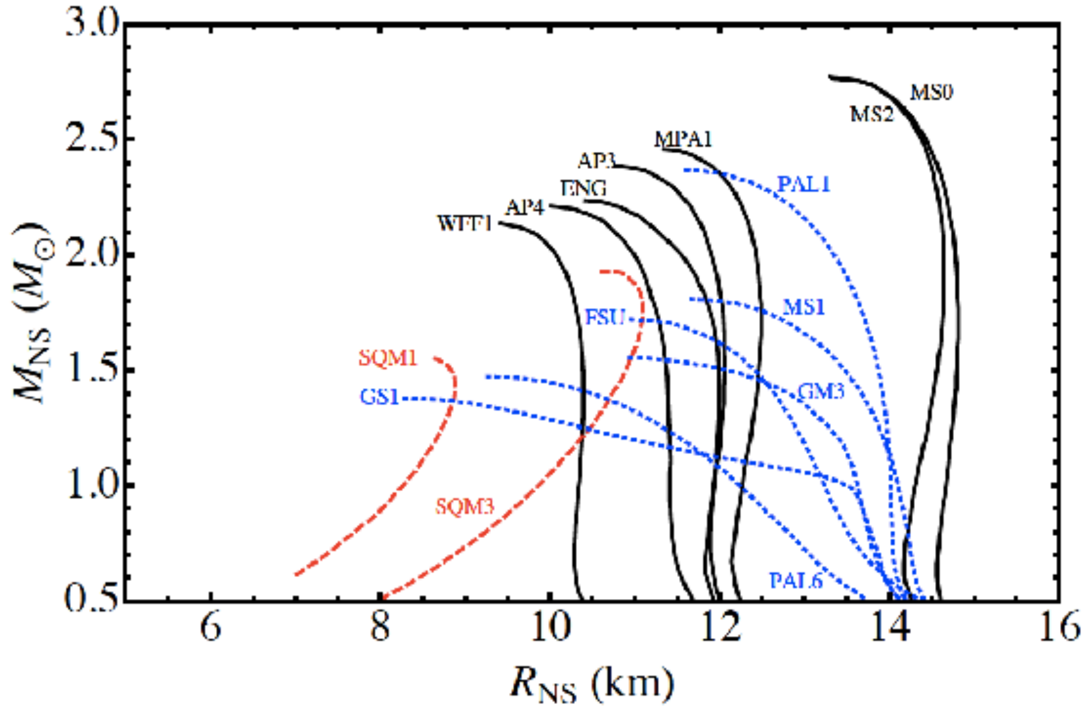
Lugger et al. 2007
RESULTS
(90% confidence)

$$7.0 \leq R_{\mathrm{NS}} \leq 19.2\,\mathrm{km}$$

$$M_{\mathrm{NS}} \leq 1.2\,\mathrm{M}_{\odot}$$

My work - spectral analysis

Figure adopted from Guillot (2014)



Only quark matter EoS reproduce these radii

no NSs with measured radii < 8 km

MY RESULTS
(90% confidence)

$$6.7 \leq R_{\rm NS} \leq 8.7\,{\rm km}$$

$$M_{\rm NS} \leq 1.2\,{\rm M}_\odot$$

Why such a small radius?

Why such a small radius?

- **He atmosphere models:** underestimated radii by 20- 50%

  Servillat et al. (2012), Catuneanu et al. (2013), Heinke et al. (2014), Bogdanov et al. (2016), Steiner et a. (2018)

- **Un-modelled hot spots:** bias up to 28% smaller radii

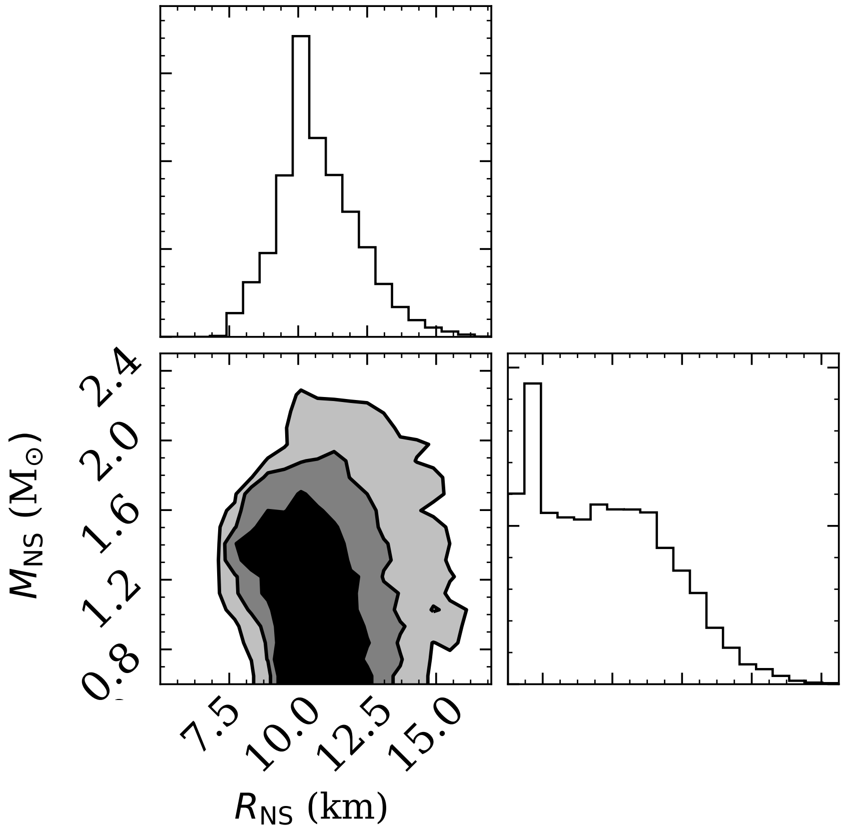
  Elshamouty et al. (2016)

- **Rotational corrections:** 3.5% underestimation compared to true radii

  Bauböck et al. (2015)

Testing He atmosphere

Testing He atmosphere

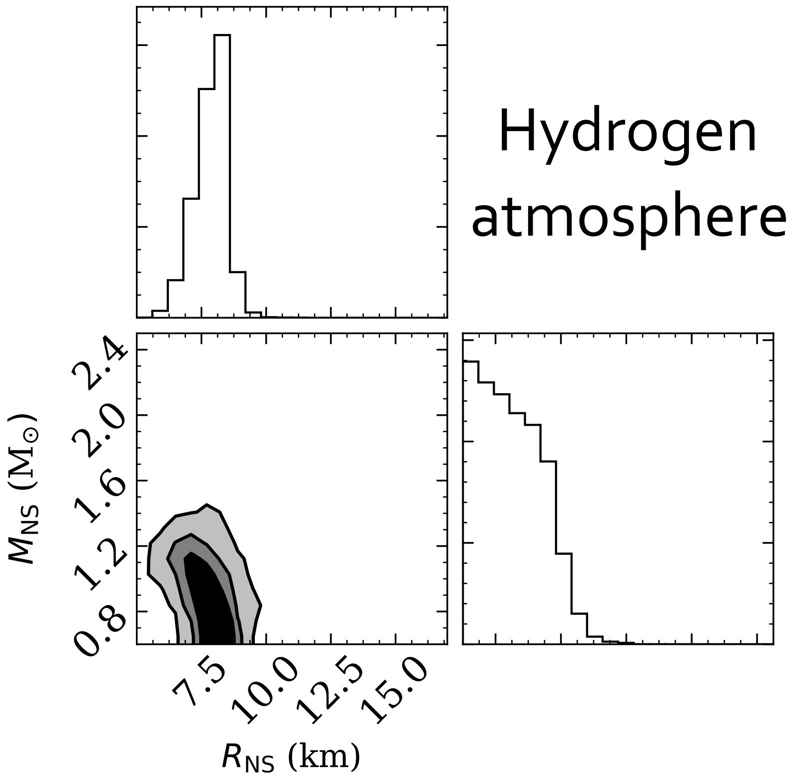


$$8.5 \leq R_{\rm NS} \leq 13.4\,{\rm km}$$

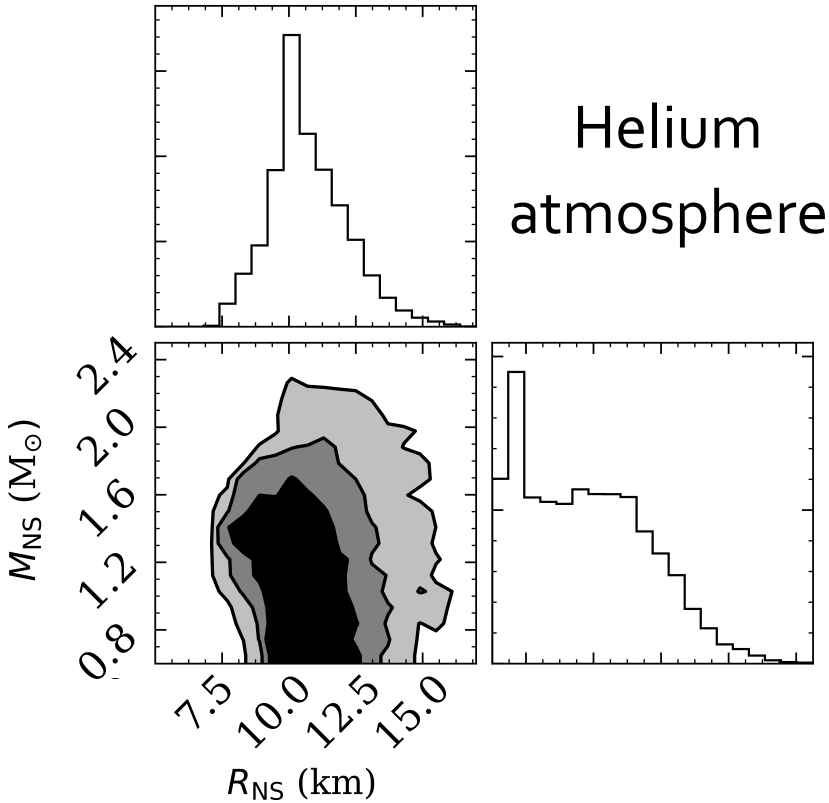
$$M_{\rm NS} \leq 1.8\,{\rm M}_\odot$$

Consistent with typical NS radii in the 11-14 km range

Testing He atmosphere



Hydrogen atmosphere



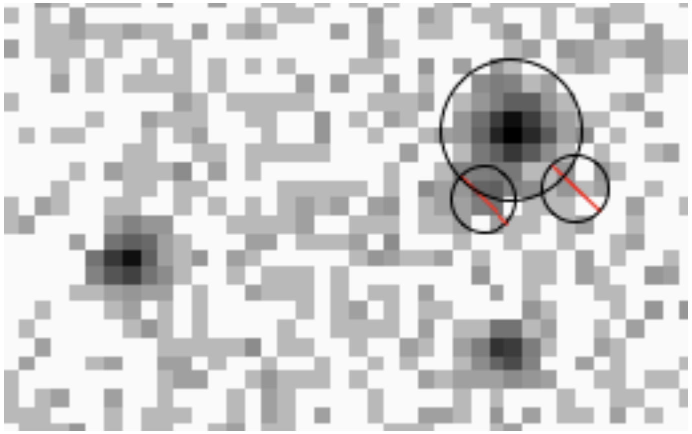
Helium atmosphere

Our best chance to distinguish between them is to search for X-ray pulsations → NICER

WORK IN PROGRESS

Work in progress

- The source region size matters!



- It introduces an additional systematic error that has not been incorporated in spectral fitting so far
- Our results may be slightly different —> **still debating!**

Summary and conclusions

Conclusion

- H atmosphere results in a relatively small radius, but consistent with previous reported results
- He atmosphere results in a radius that is consistent with qLMXB radii measurements and other NSs
- The spectral model to be used will be determined by additional tests: identifying companion star (e.g. Haggard et al. 2004) or presence of surface Hot spots

THANKS