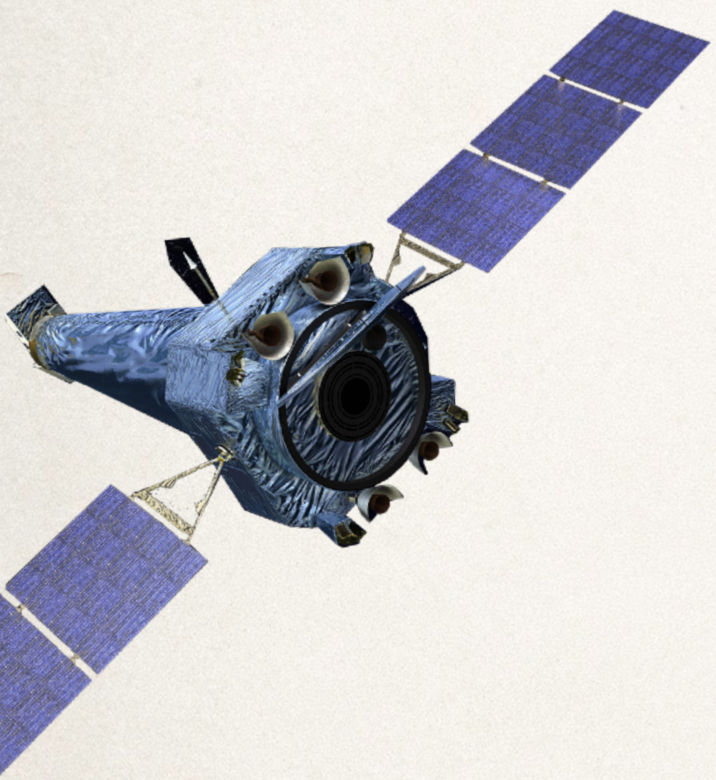
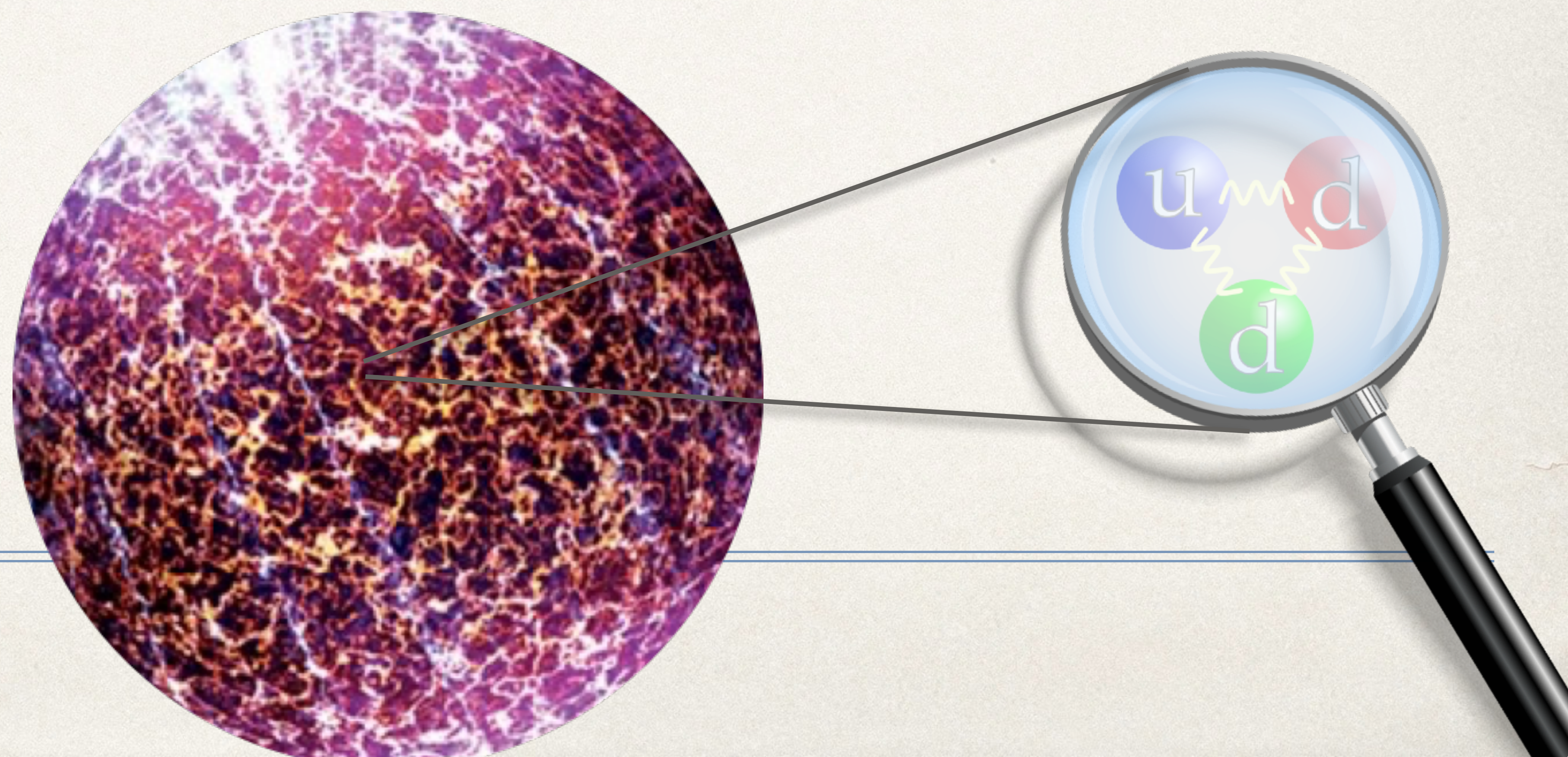
The contribution of X-ray astrophysics to the understanding of strongly interacting matter

Sebastien Guillot

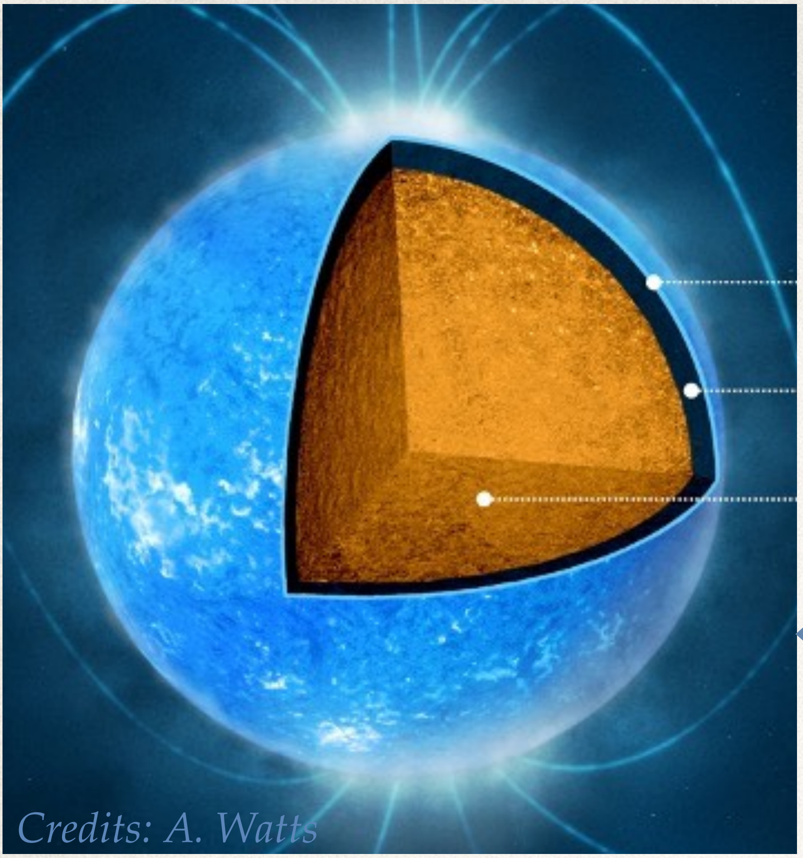
irap

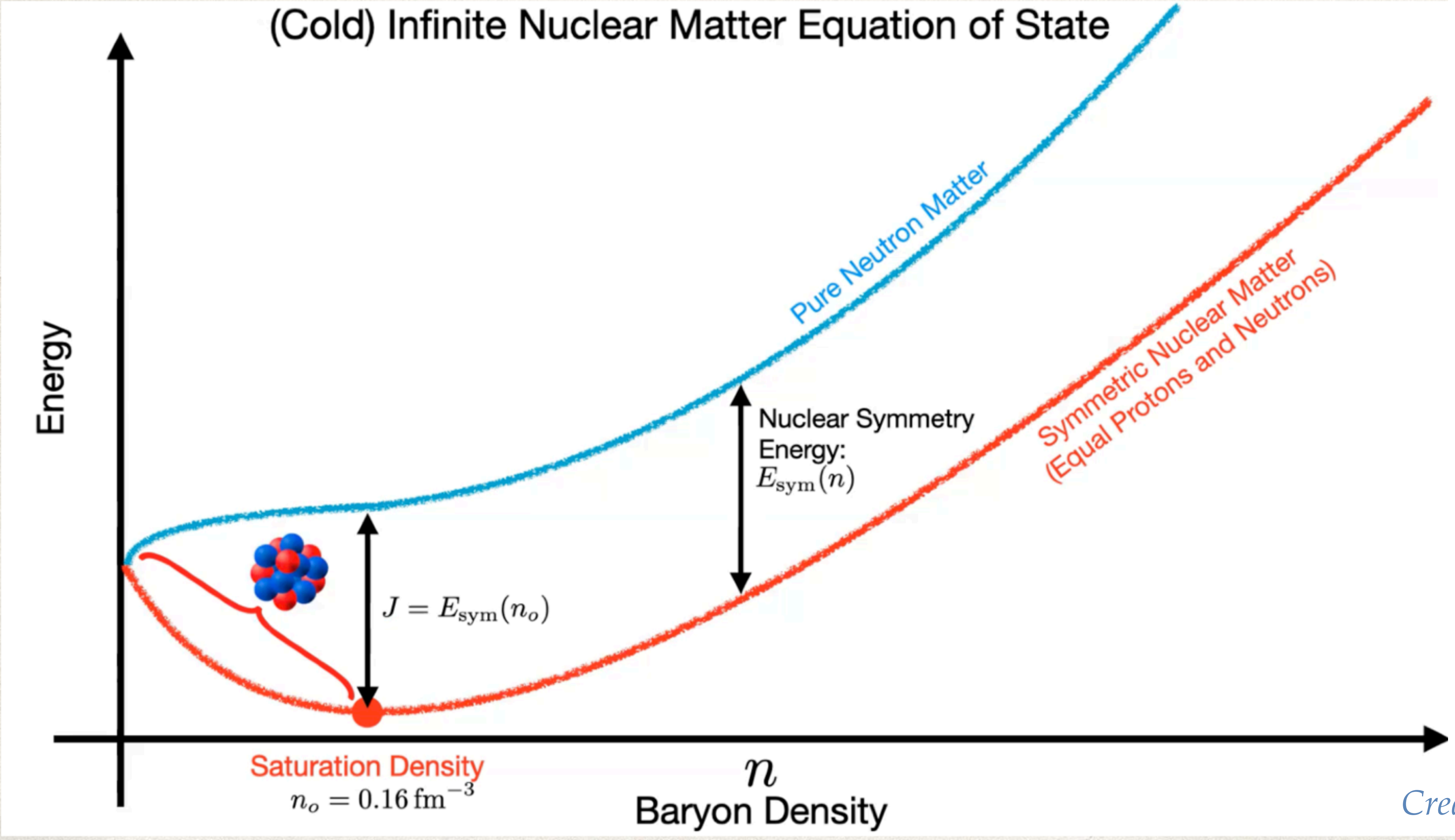
astrophysique & planétologie

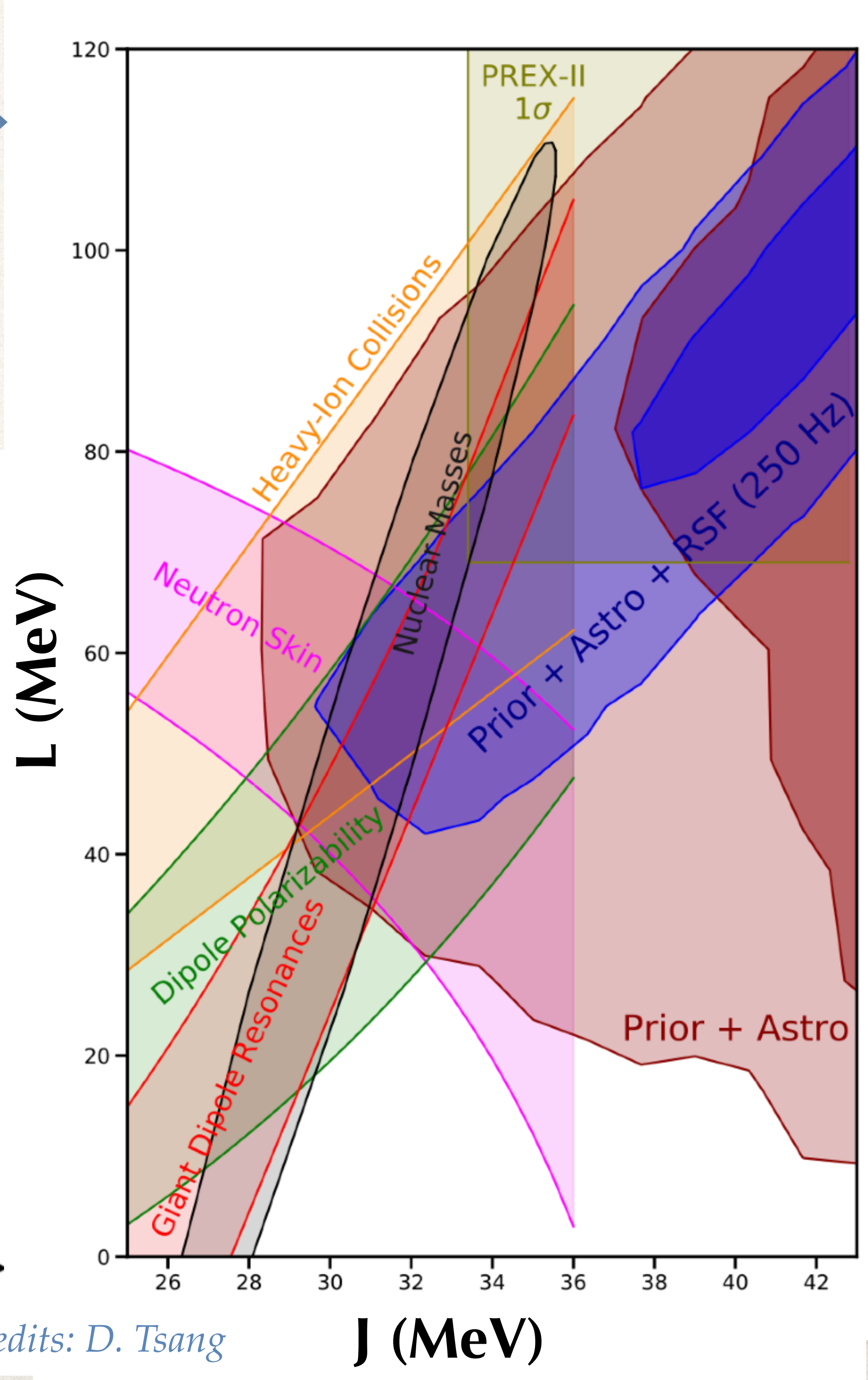




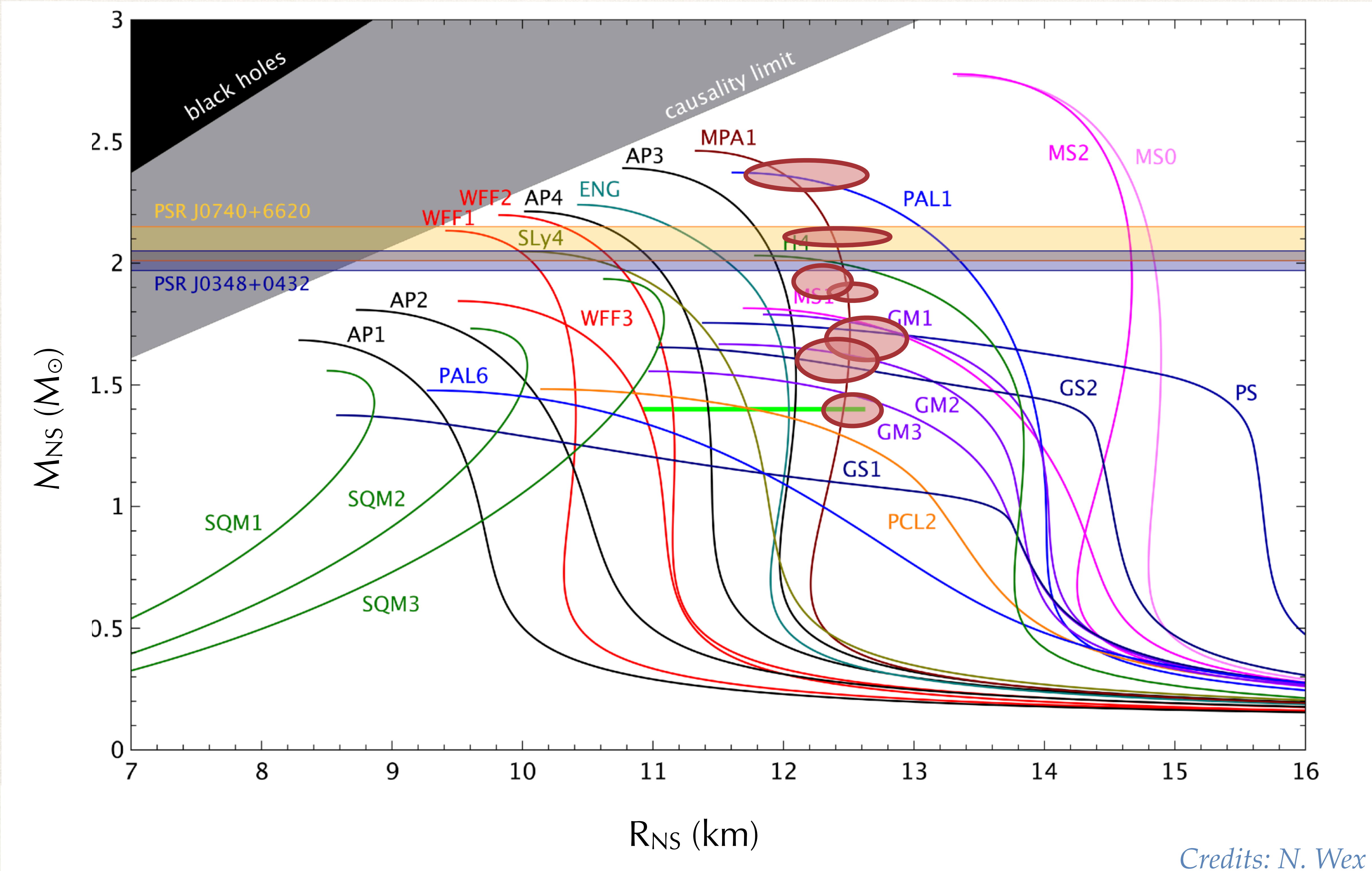
From neutron stars to nuclear physics



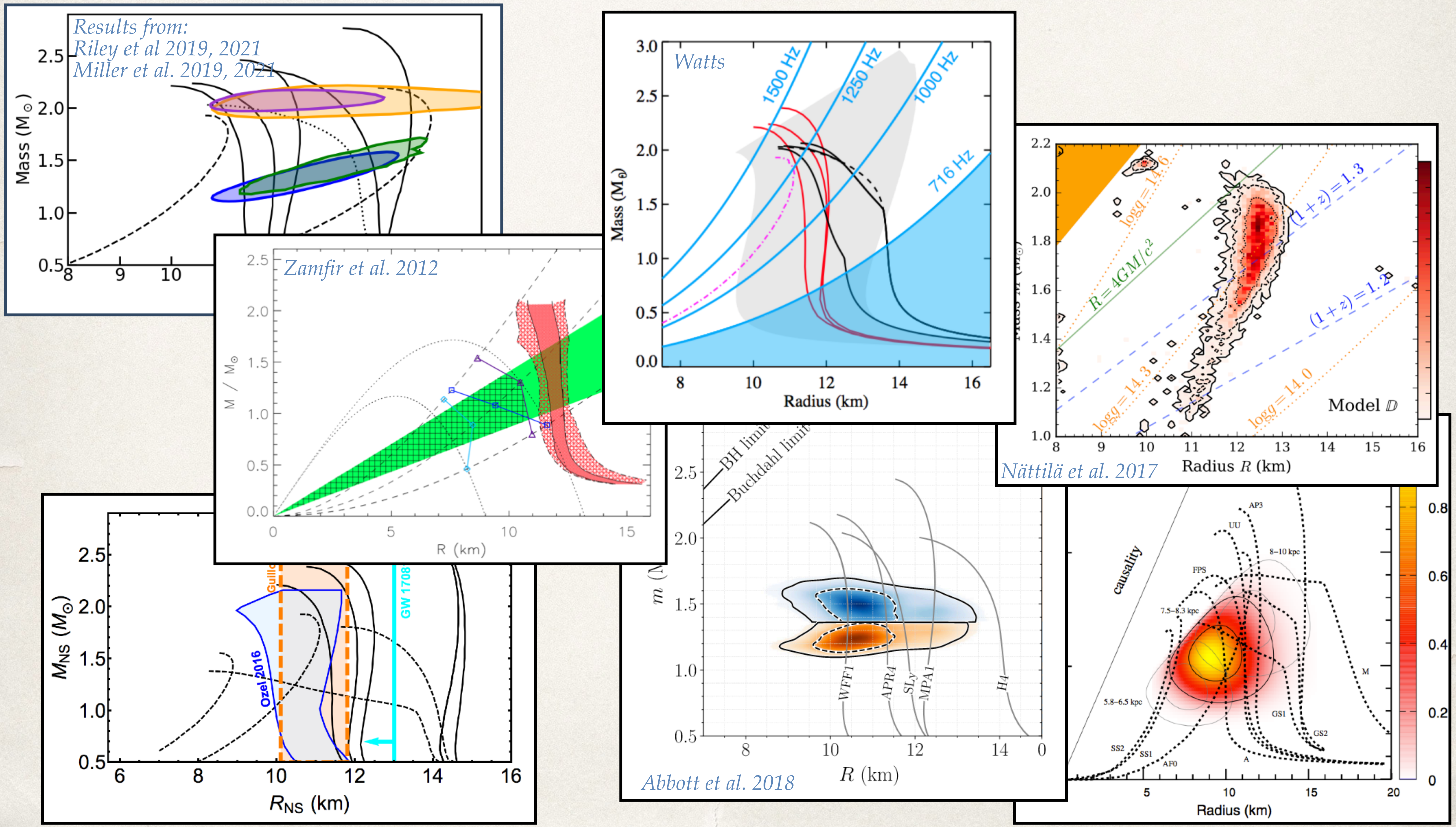




To determine the equation of state P(ρ), one needs to measure M_{NS} and/or R_{NS}.



There are many methods to measure M_{NS}, R_{NS}, or Λ_{NS}, with many different results, but there is still a long way to determine the EoS of dense matter.



How to exploit all these measurements ?

- They come in wide variety of forms, such as :
  - *median and confidence level(s)*
  - *confidence contours on a figure*
  - *MCMC samples*
  - *posterior samples*

- They have their specificities:
  - *assumptions*
  - *model dependencies*
  - *systematic uncertainties*

CompARE, a database of observational constraints on the EOS

- Facilitating the distribution of measurements to **modellers**.
- Explicit all assumptions and caveats affecting the results.
- Encourage observers to provide machine-readable outputs in a unique format.

CompARE

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Welcome to CompARE

CompARE is a repository containing published data sets of astrophysical measurements of neutron star properties made easily accessible and exploitable to equation of state practitioners. Electromagnetic observations of these compact objects yield measurements of their masses and radii thanks to various spectral or temporal analyses methods. The gravitational signal from neutron star merger events result in measurements on the masses and tidal deformabilities of these objects. Together they provide constraints on the yet-unknown dense matter equation of state.

CompARE aims at proposing a curated, organized and exhaustive repository of these constraints for equation of state modellers. Under the form of a database, users are able to browse all existing constraints by type of sources or events, explore the relevant caveats or analysis assumptions, and select the ones they want to download to compare or adjust their equation of state models.

Tuomo Salmi, Jérôme Margueron, Jocelyn Read, Bruno Giacomazzo, Ingo Tews, David Tsang, Joonas Nättilä, Serena Vinciguerra, Thankful Cromartie, Debarati Chatterjee, Anna Watts, Rahul Somasundaram, Devarshi Chouhdury, Alessio Marino, Francesco Coti Zelati, Denis Gonzalez, Constanza Echiburu, Melissa Mendes, Lami Suleiman, Mickael Fernandez, Pierre Lambin

To be deployed soon…

CompARE, a database of observational constraints on the EOS

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Database classes

- [ ] NS Spin
- [ ] Transiently Accreting NS
- [ ] NS Mass
- [ ] NS-NS Mergers
- [x] PPM
- [x] qLMXB
- [x] Cold MSP
- [ ] Thermal INSs
- [ ] Type-I X-ray bursts

More filters | Search | Download Files | Download Bibtex | Show plot

More info	Source name	Database Class	Method	Method details	Constraint Type	Constraint Version	Constraint Variable	Model dependencies	Analysis assumptions	Reference	Download	
+	PSR J0437-4715	Cold MSP	Thermal emission	Spectral fitting (FUV and Xray data)	MCMC samples	1	M-R	atmosphere: Gonzalez2019 absorption: tbabs redenning: Clayton2003 hot spots model: ignored	Atmosphere Composition: helium Magnetic field: non-magnetic Rotation: non-rotating Emitting fraction: uniform full surface Interstellar medium: solar abundances Prior: distance prior Prior: mass prior	Gonzalez-Canuilef 2019		
+	PSR J0437-4715	Cold MSP	Thermal emission	Spectral fitting (FUV and Xray data)	MCMC samples	1	M-R	atmosphere: Gonzalez2019 absorption: tbabs redenning: Clayton2003 hot spots model: 2 blackbodies	Atmosphere Composition: hydrogen Magnetic field: non-magnetic Rotation: non-rotating Emitting fraction: uniform full surface Interstellar medium: solar abundances Prior: distance prior Prior: mass prior Prior: reddening prior	Gonzalez-Canuilef 2019		
+	PSR J0030+0451	PPM	Phase-resolved thermal emission	Phase-resolved spectral timing	Posterior samples	1	M-R	atmosphere: nsx absorption: tbabs ray-tracing: oblate Schwarzschild and Doppler eos dependence: oblateness background: no assumed background sampler: hybrid PT-emcee + multinest	Gravitation theory: General relativity Atmosphere composition: hydrogen Ionization degree: fully ionized Magnetic field: non-magnetic Insterstellar medium: solar abundances Spot pattern: two oval spots Non-thermal emission: ignored Prior: distance prior Prior: absorption prior	Miller 2019		

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PSR J0030+0451

PPM_PSRJ0030+0451_2019_massradius_2spots_Miller_1_PosteriorSamples.txt

Model dependencies

atmosphere: nsx

The atmosphere model used in this analysis is the nsx model (Ho and Heinke 2009) available under the form of precalculated tables.
2009Natur.462...71H

absorption: tbabs

The absorption of X-rays was calculated using tbabs absorption model of Wilms et al. 2000 (updated in 2016) available under the form of precalculated tables.
2000ApJ...542..914W

ray-tracing: oblate Schwarzschild and Doppler

The ray-tracing model accounting for the trajectory of photons and other effects of gravity adopts the Schwarzschild metric, assumes an oblate neutron star (using the oblateness-frequency relation of AlGendy and Morsink (2014), and includes the Doppler effects. The full ray-tracing model is described in Bogdanov et al. 2019 (Paper II).
2014ApJ...791...78A
2019ApJ...887L..26B

eos dependence: oblateness

The oblateness-frequency relation of AlGendy and Morsink (2014) is EOS-independent. However, it was quantified from nucleonic EOS. Different interior compositions may affect this relation, and therefore

Assumptions

Gravitation theory: General relativity

The ray-tracing model of this analysis (described in Bogdanov et al. 2019, Paper II) assumes general relativity as the theory of gravitation.
2019ApJ...887L..26B

Atmosphere composition: hydrogen

At the surface of a neutron star, elements stratify on time scales of minutes/hours leaving the lightest on top (Romani 1987). Also, the thickness of the last scattering layer of a NS is on the order of a few cm. Therefore, it is common to assume a single composition, being that of the lightest element. Hydrogen is therefore a reasonable assumption for the composition, especially for a NS that has accreted matter from a companion star, as is the case for a millisecond pulsar. Other effects are in competition and may put some uncertainties on the surface composition, namely, accretion from the interstellar medium, diffuse nuclear burning of light of H into He (Chang & Bildsten 2003, 2004), and spallation of heavier elements into lighter ones (Bildsten et al. 1992).
1987ApJ...313..718R
1992ApJ...384..143B
2003ApJ...585..464C
2004ApJ...616L.147C

Ionization degree: fully ionized

Source info

Source name: PSR J0030+0451

Database class: PPM

Simbad name: PSR J0030+0451

Simbad class: Psr

RA: 7.6142820000

Declination: 4.8610310000

Localisation file: None

Event date: None

Method

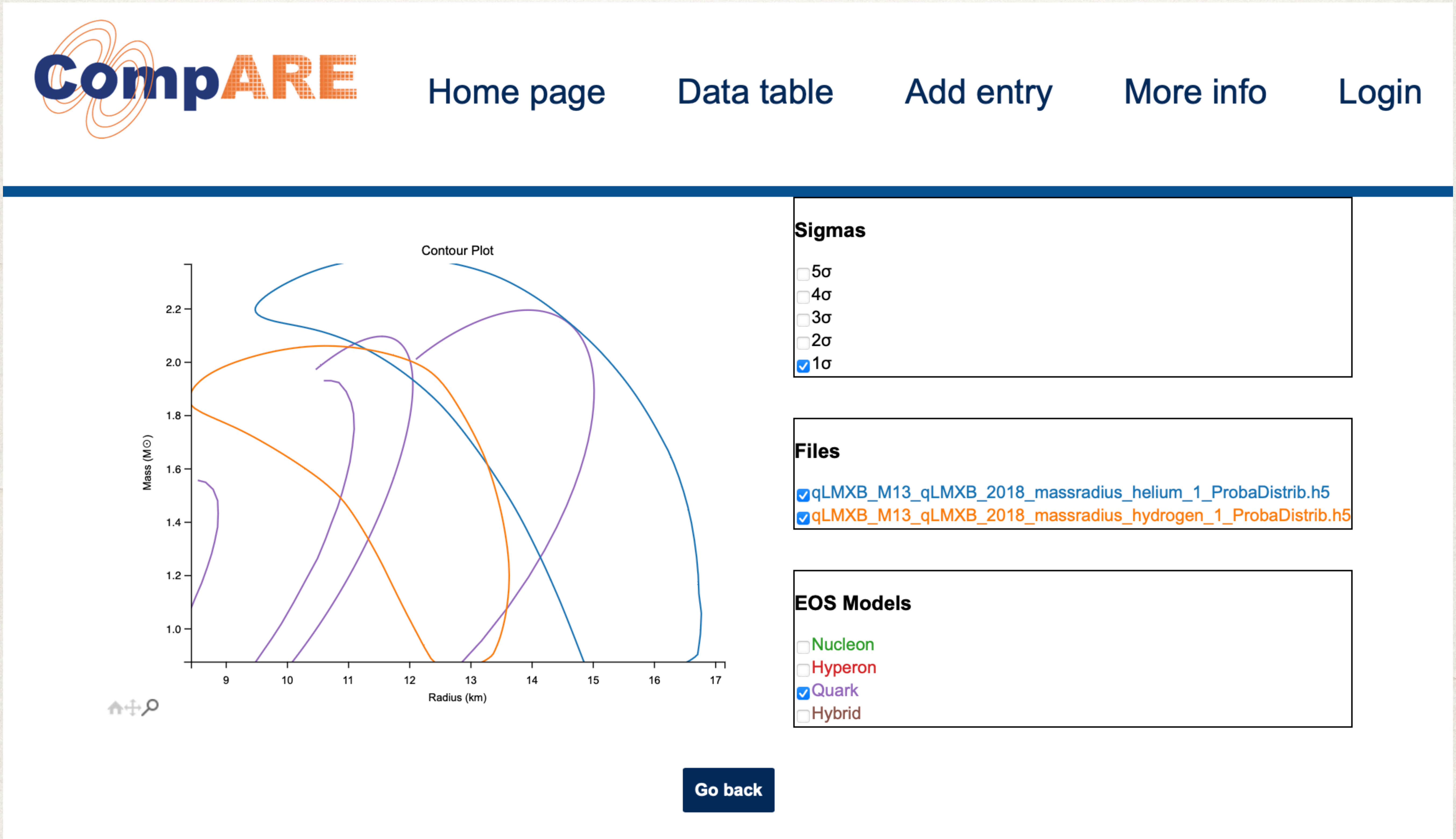
Method: Phase-resolved thermal emission

Specific method: Phase-resolved spectral timing

Data date: NICER (July 2017 to December 2018)

Processing info: NICERDAS v5, CALDB 20181105 (optmv7), see Bogdanov et al. 2019 for processing details

CompARE, a database of observational constraints on the EOS



Outline

- **Constraints from GW of NS-NS mergers** (*J. Read's talk*)
- **Constraints of NS masses and I_A** (*M. Kramer's talk*)
- **1-slide crash course on X-ray astrophysics**
- **Constraints from NS in low-mass X-ray binaries**
  - Non-accreting
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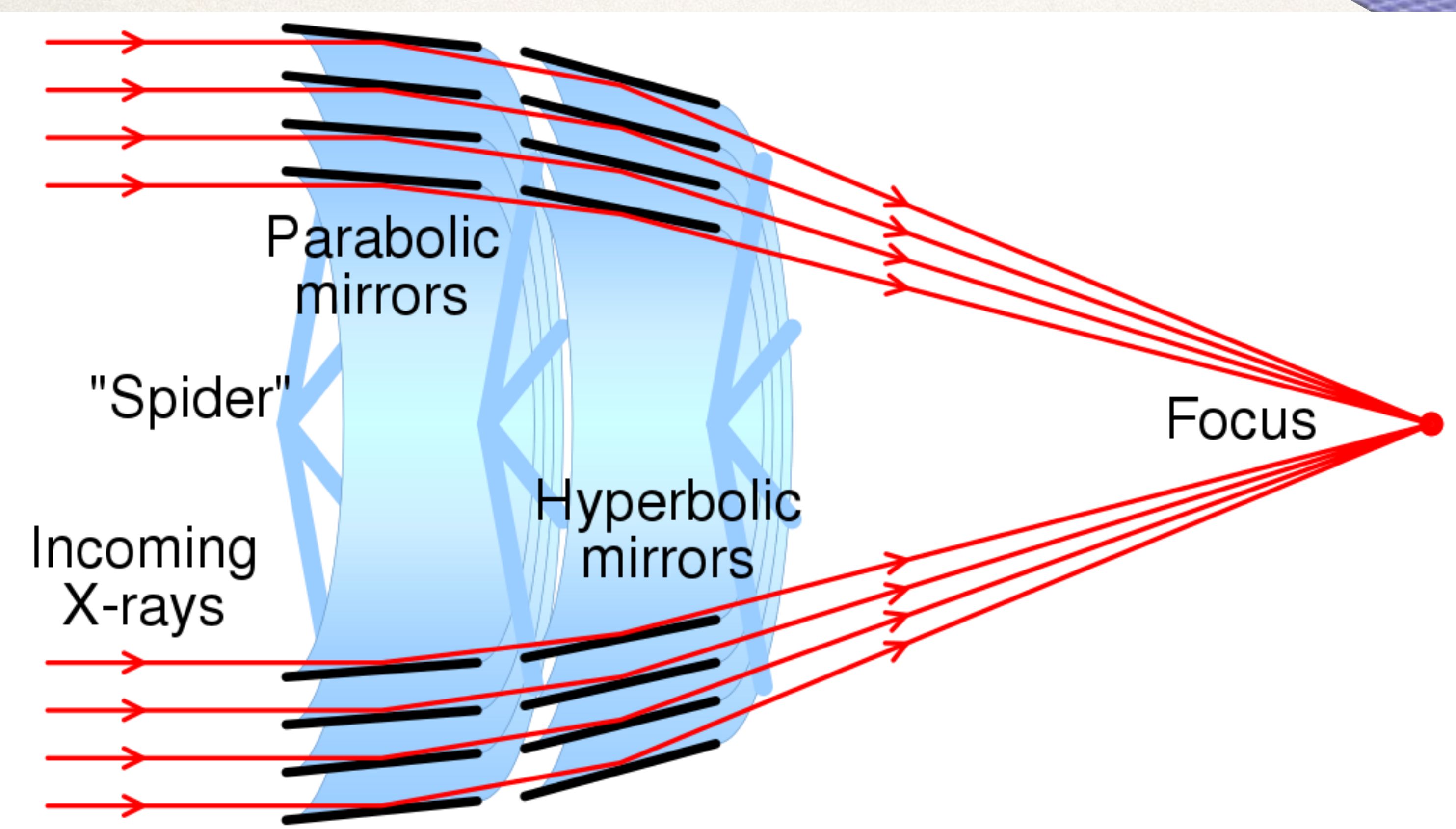
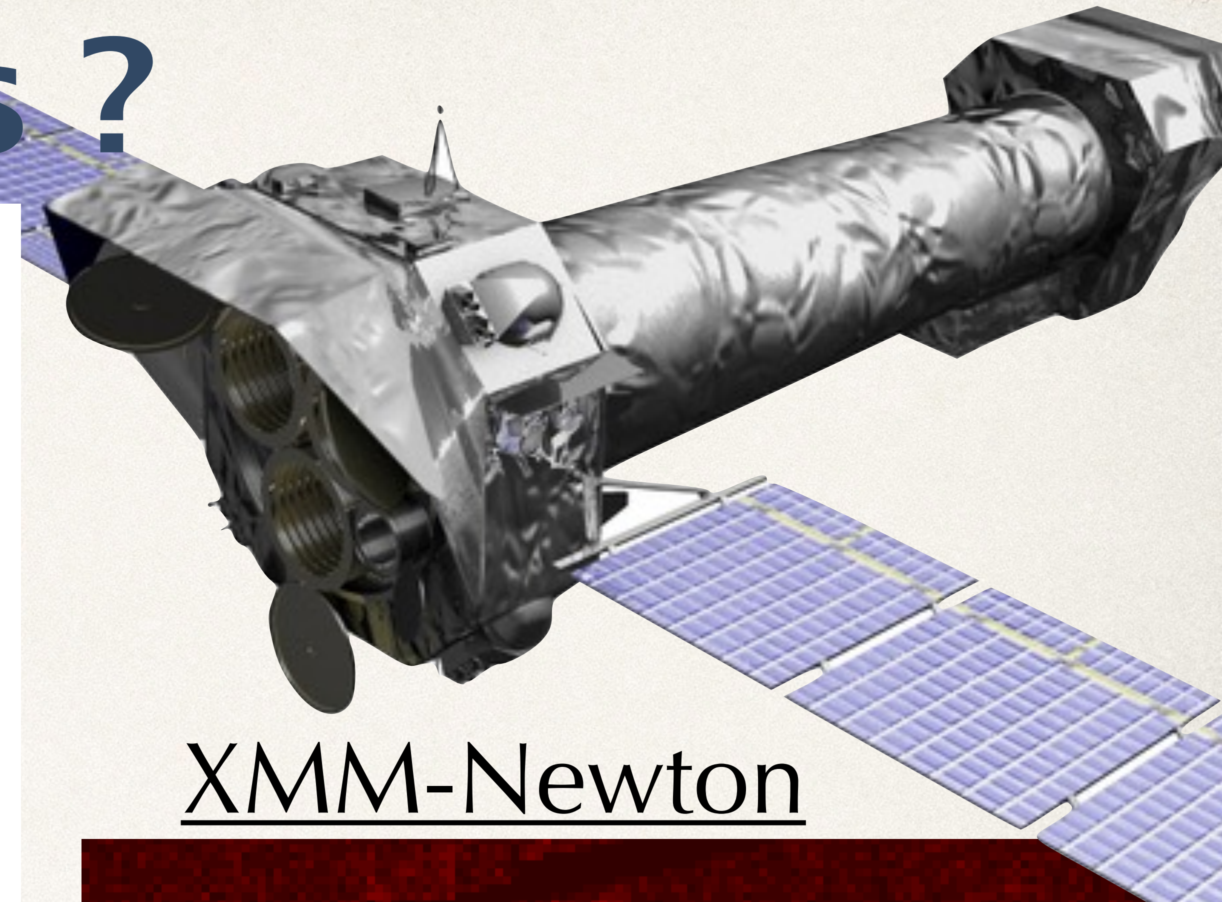
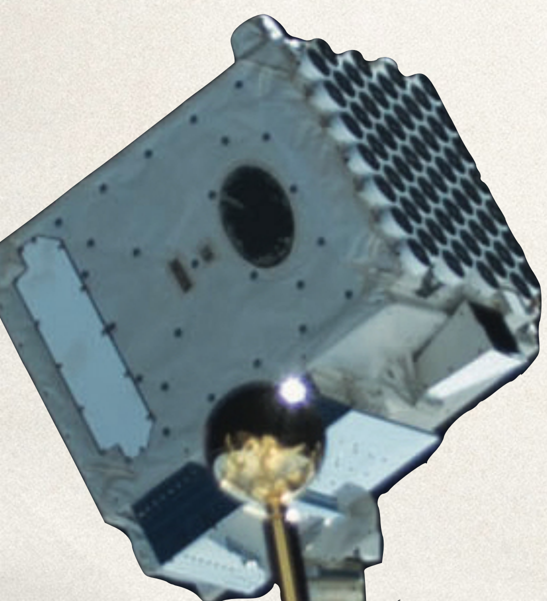
How do we collect X-ray photons from neutron stars ?



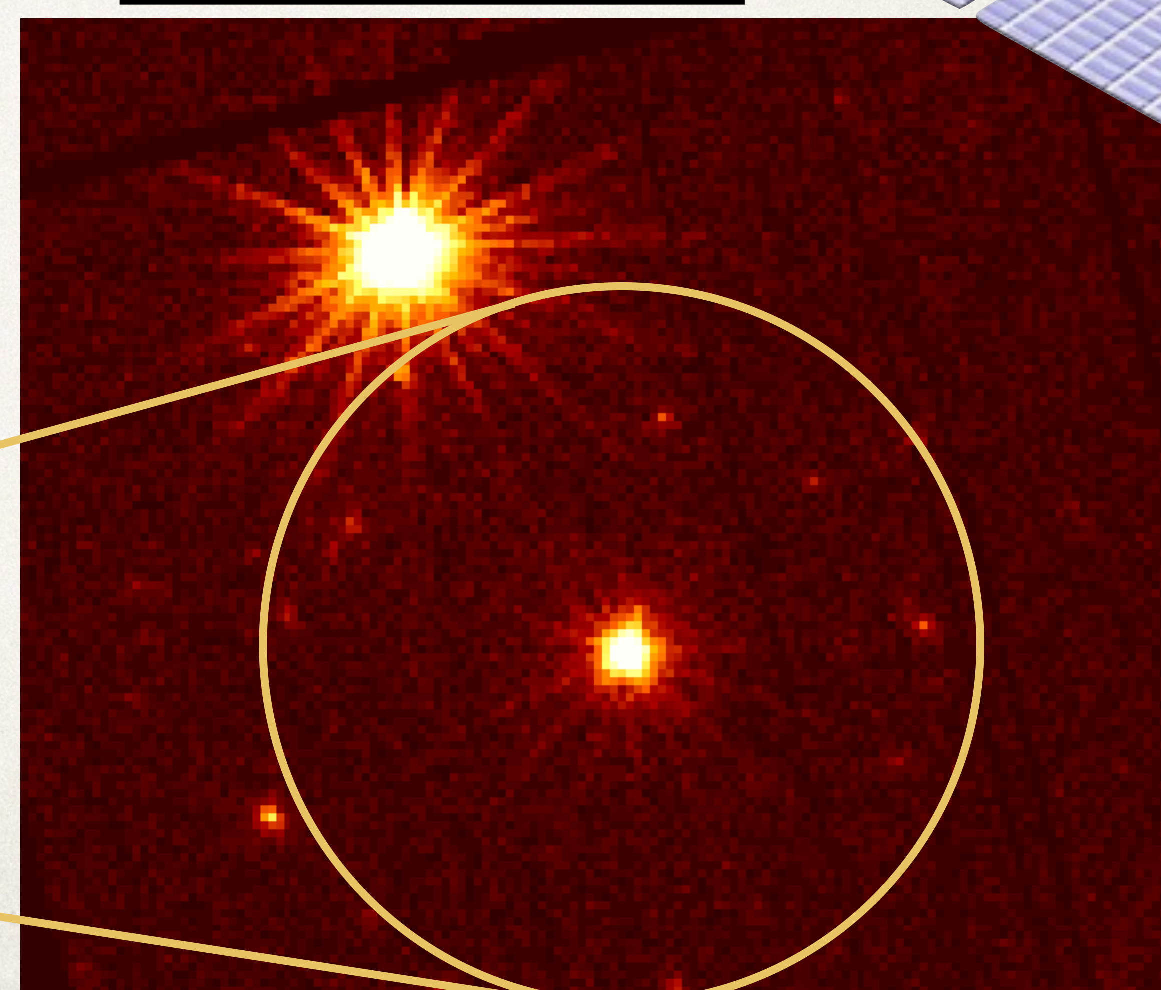


XMM-Newton



NICER

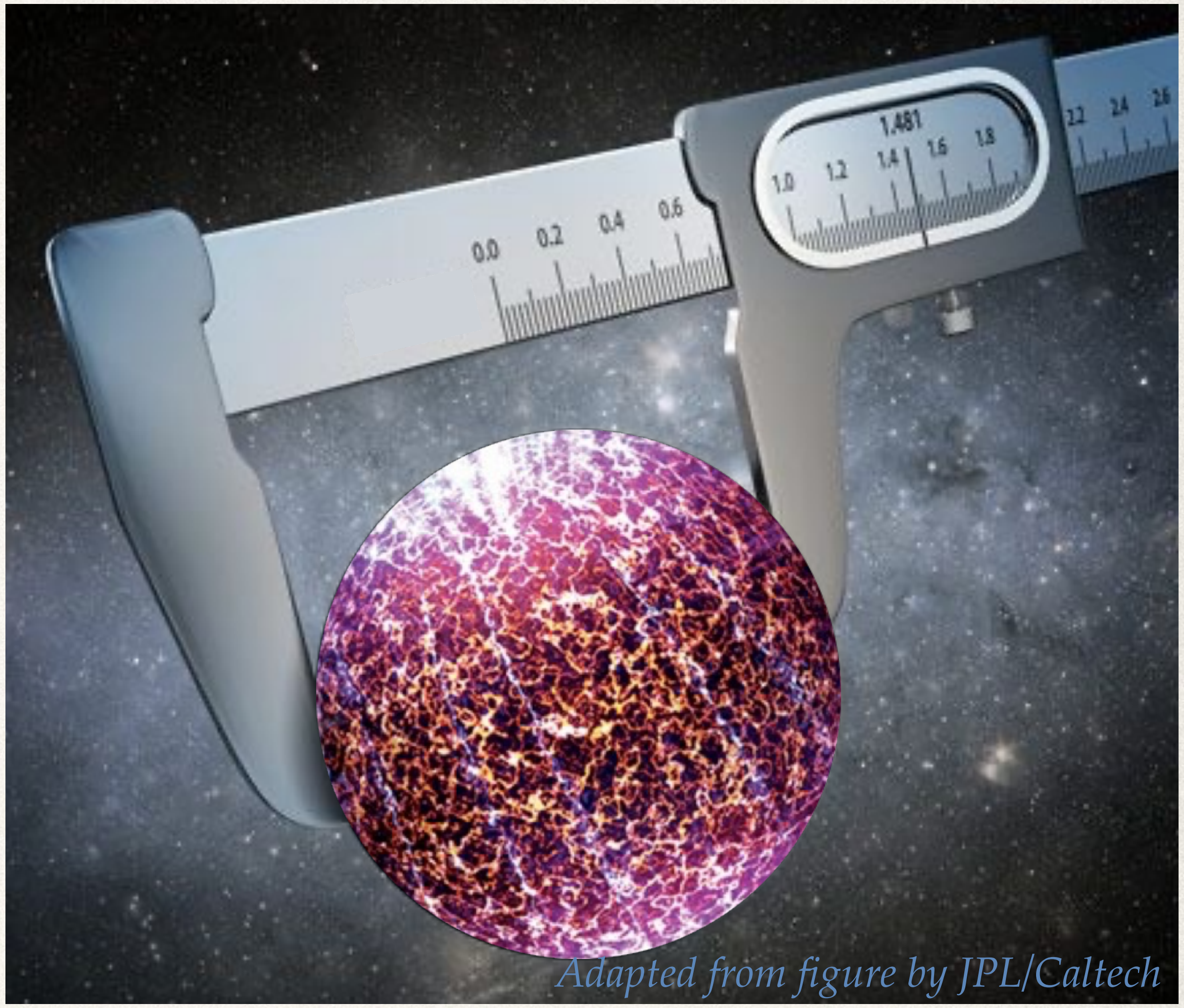
1 pixel



Measuring the radius precisely is rather difficult for neutron stars.

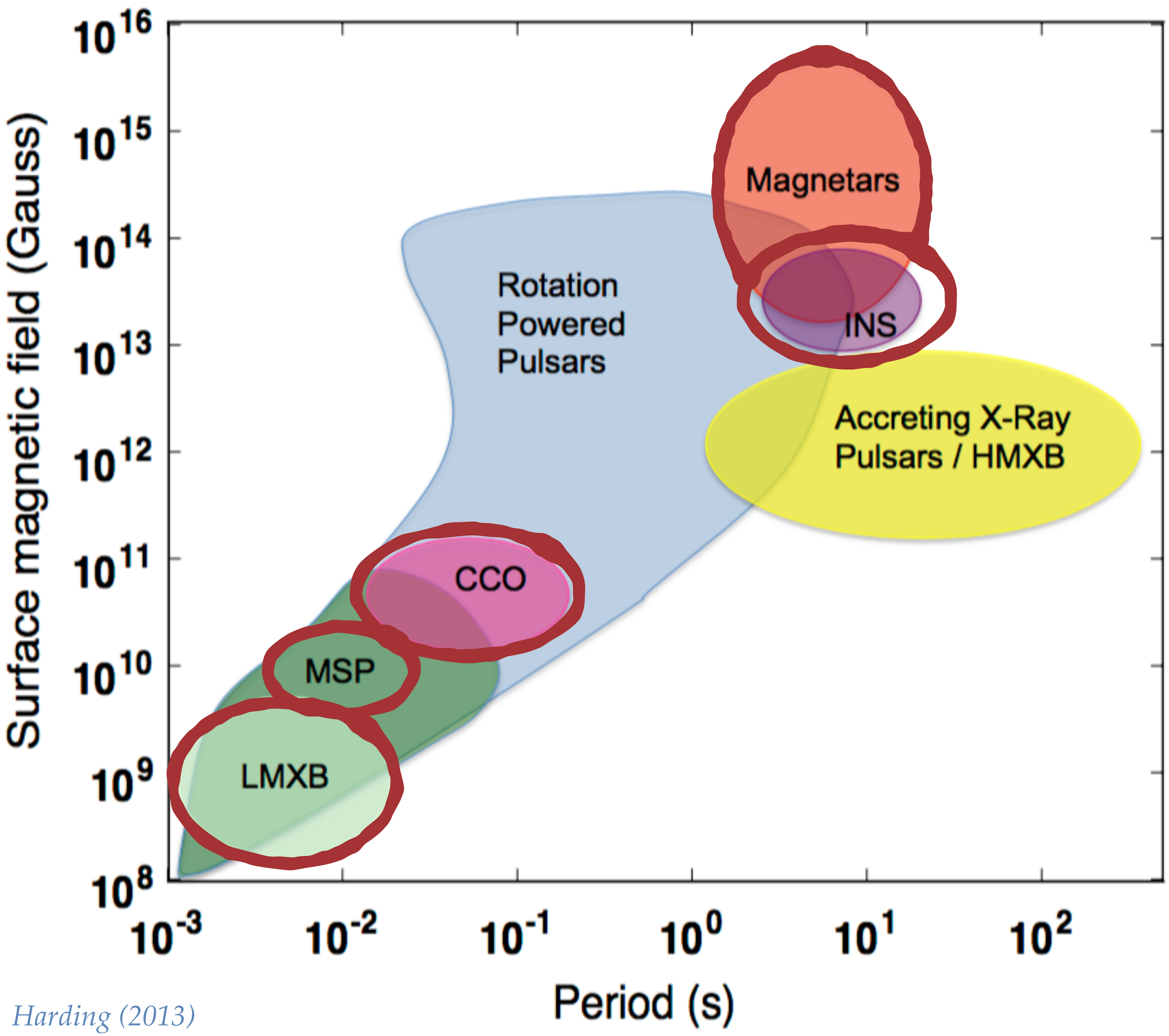
To measure the radius of a star, we need to:

1. observe the surface thermal emission
2. correctly model this emission
3. know the distance



$$L = 4\pi R^2 \sigma T_{\text{eff}}^4 \longrightarrow F = \left(\frac{R}{D}\right)^2 \sigma T_{\text{eff}}^4$$

Neutron stars come in many flavours, with different properties and observational signatures.



Harding (2013)

The surface emission needs to be visible

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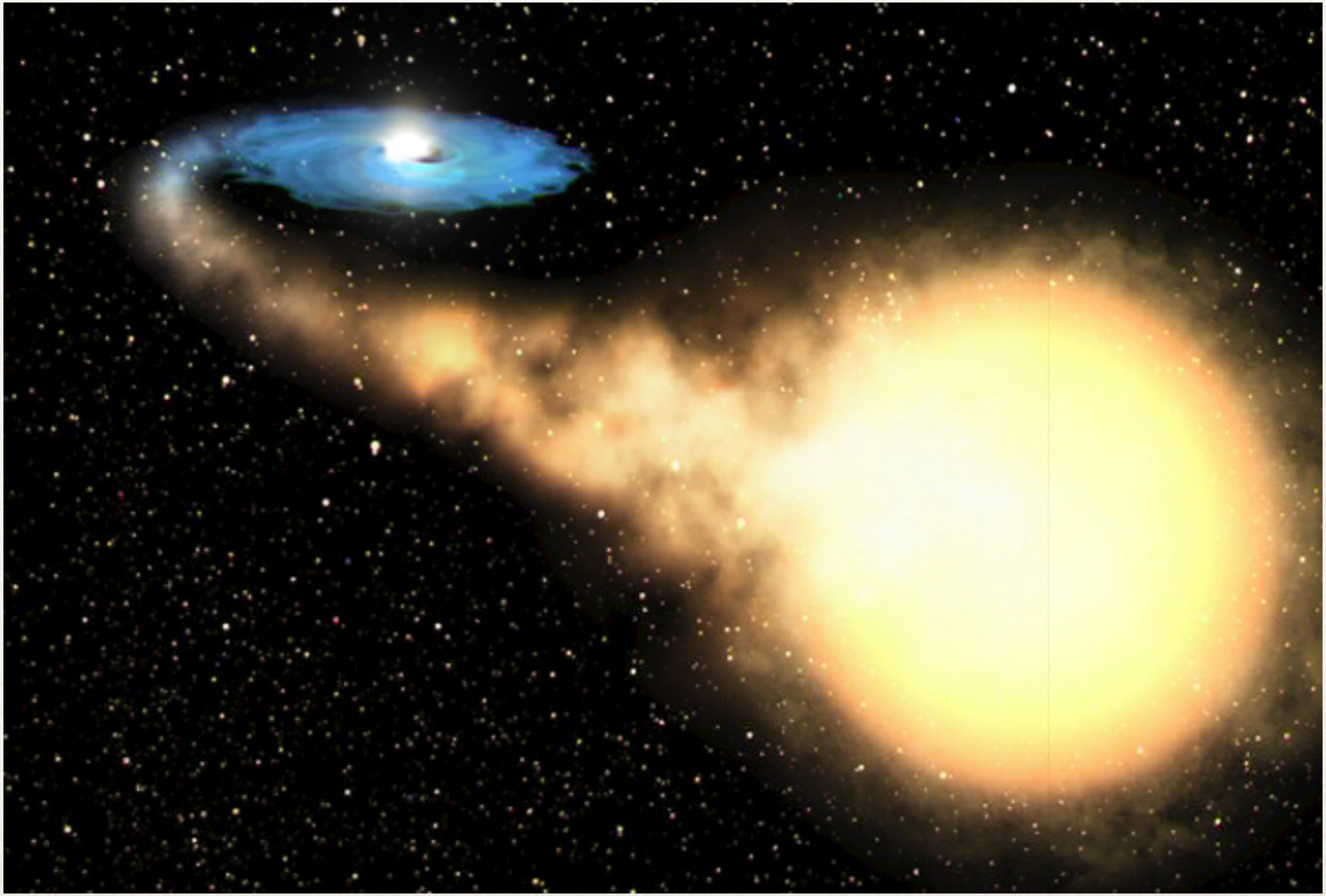
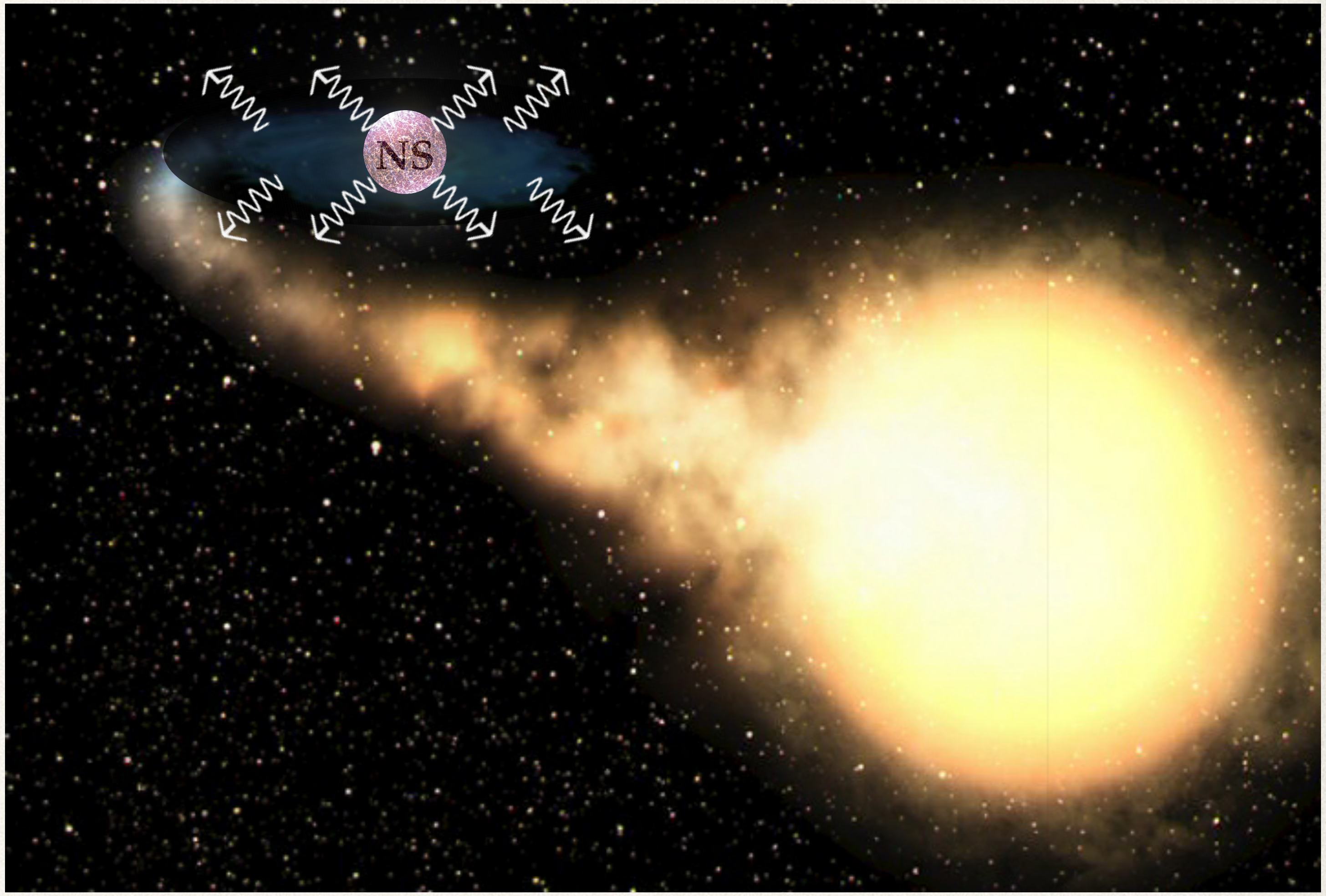
Let’s start with NS in low-mass X-ray binaries.



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

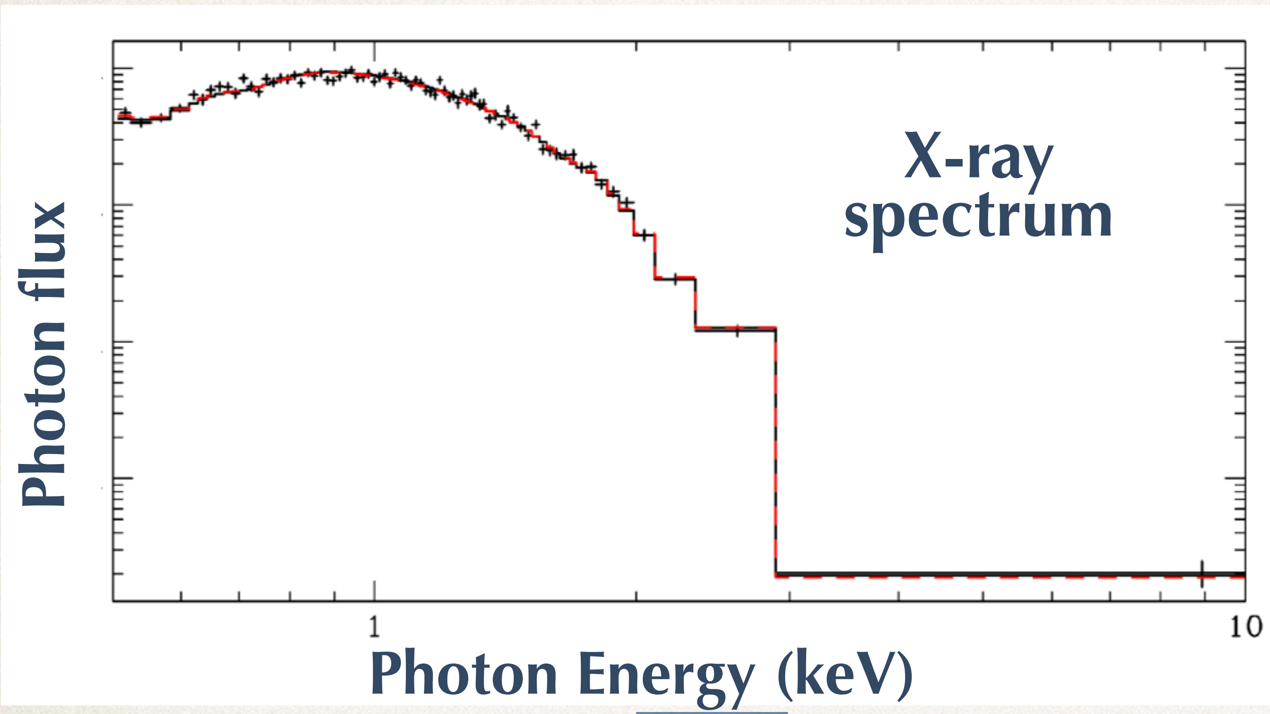
Surface thermal emission at $T_{eff} \sim 10^6$ K, powered by residual heat from the deep crust radiating outwards through the **atmosphere** with $L_X = 10^{32-33}$ erg/sec



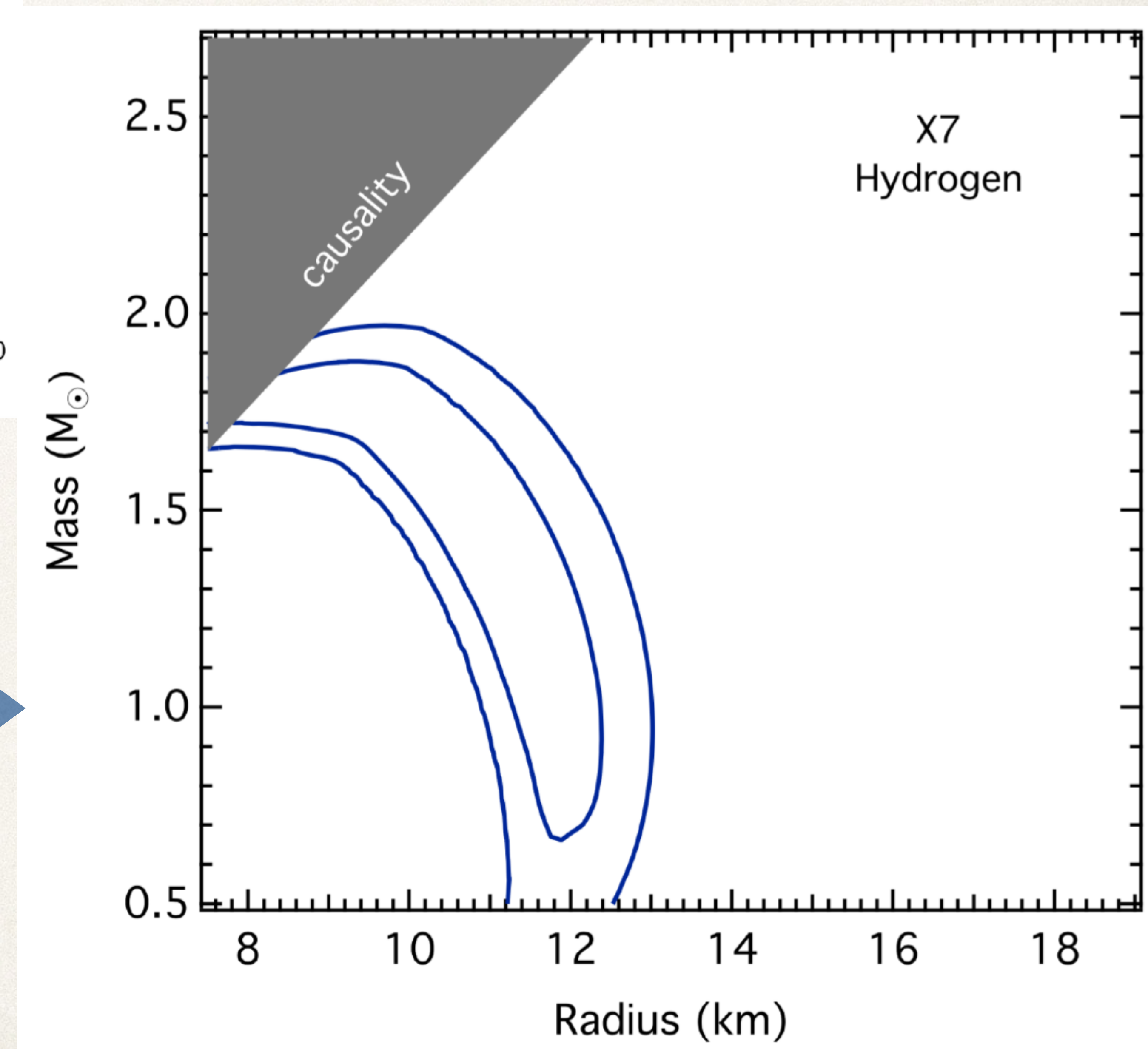
Spectral fitting of this surface emission gives us T_{eff} and $F_X \propto (R_\infty/D)^2$

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

Because of gravitational redshift, the radius is degenerate with the unknown mass.



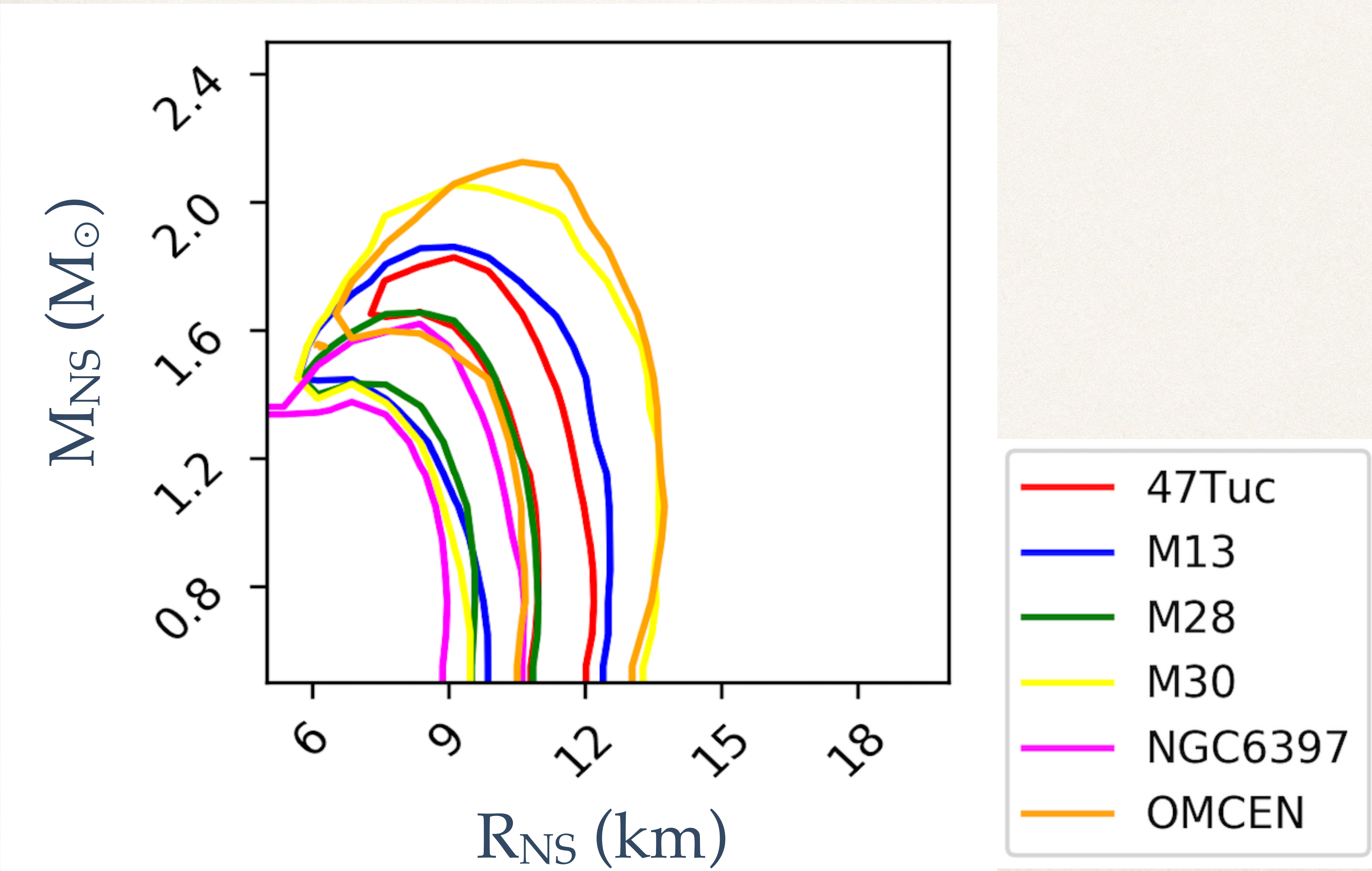
Atmosphere model



$$F \propto \left(\frac{R_\infty}{d}\right)^2 \sigma\, T_{\mathrm{eff},\infty}^4$$

Bogdanov et al. 2016

There is half a dozen qLMXBs for which one can measure R_∞ with X-ray spectroscopy.



There remains some discussion points and possible caveats!

- Why only use qLMXBs in globular clusters ? → Field LMXB may not return to full quiescence
- What is the **composition** of the neutron star atmosphere ? → Hydrogen, Helium or something else
- Is the **surface magnetic** field really negligible ? → No measurement, but expected for LXMBs
- Is the emission really from the **entire surface** ? → No constraint exists, but it is expected
- What are the effects of assuming **slowly rotating** neutron stars? → Fast rotation biases the R measurement

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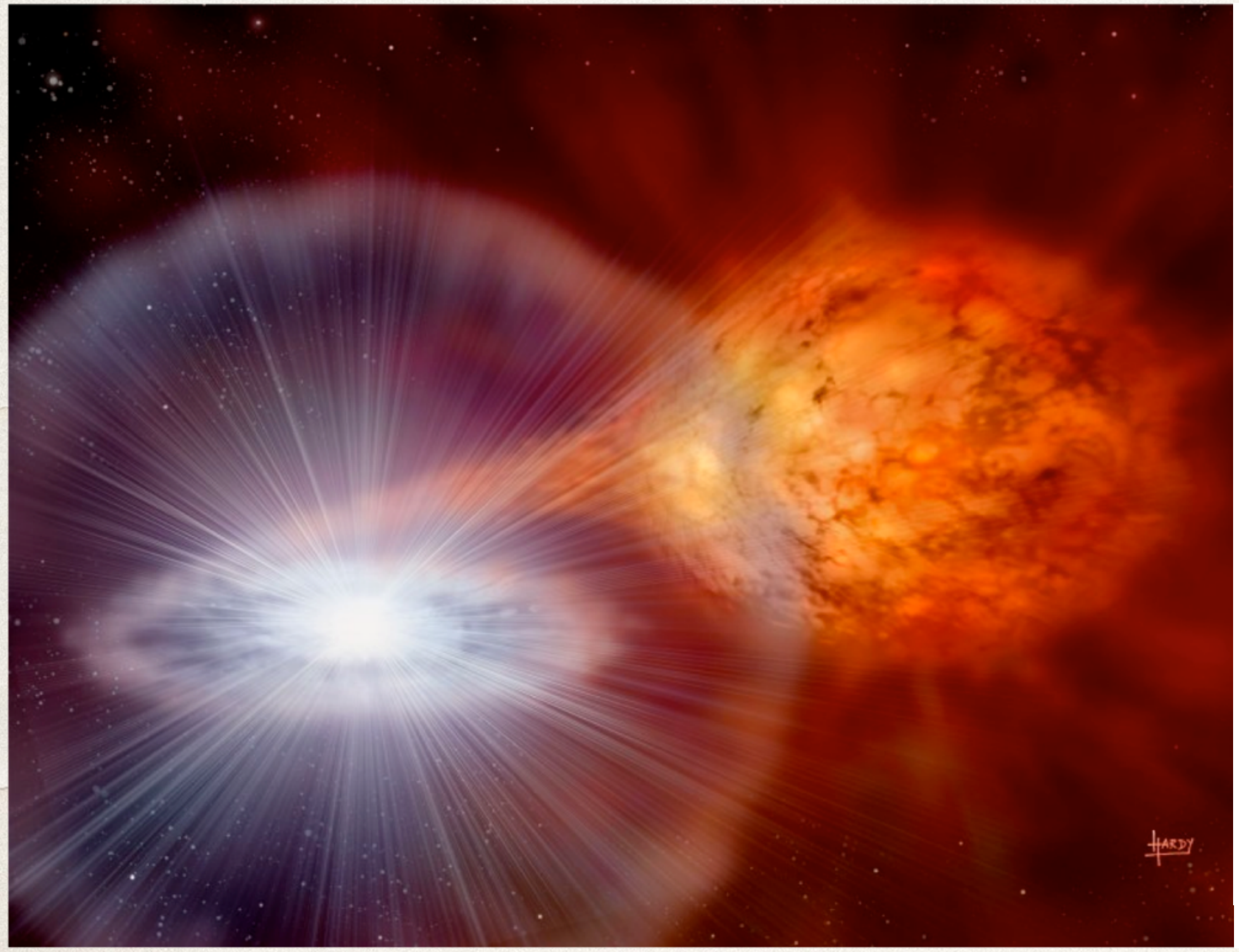
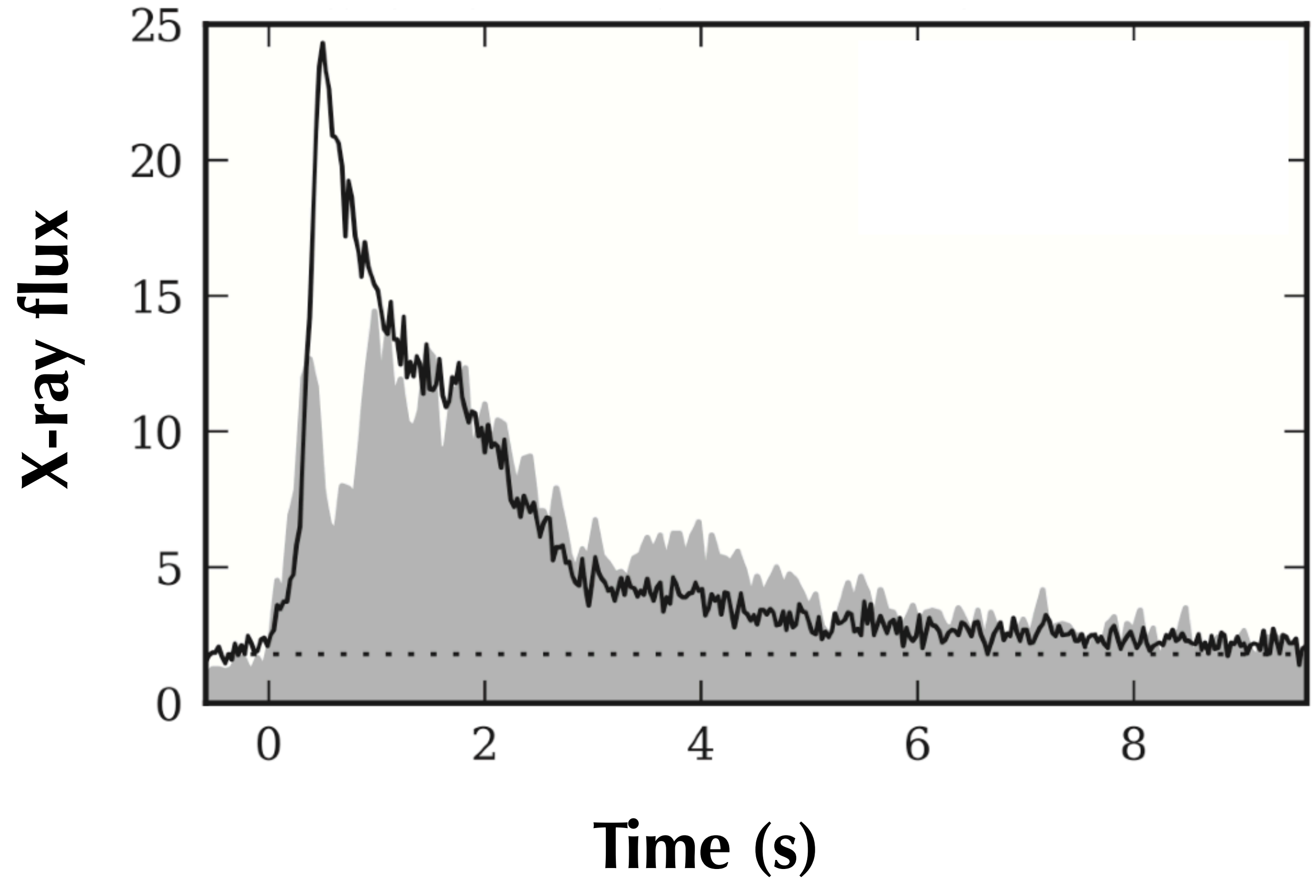
NS in low-mass X-ray binaries are generally in accretion and experience thermonuclear bursts.

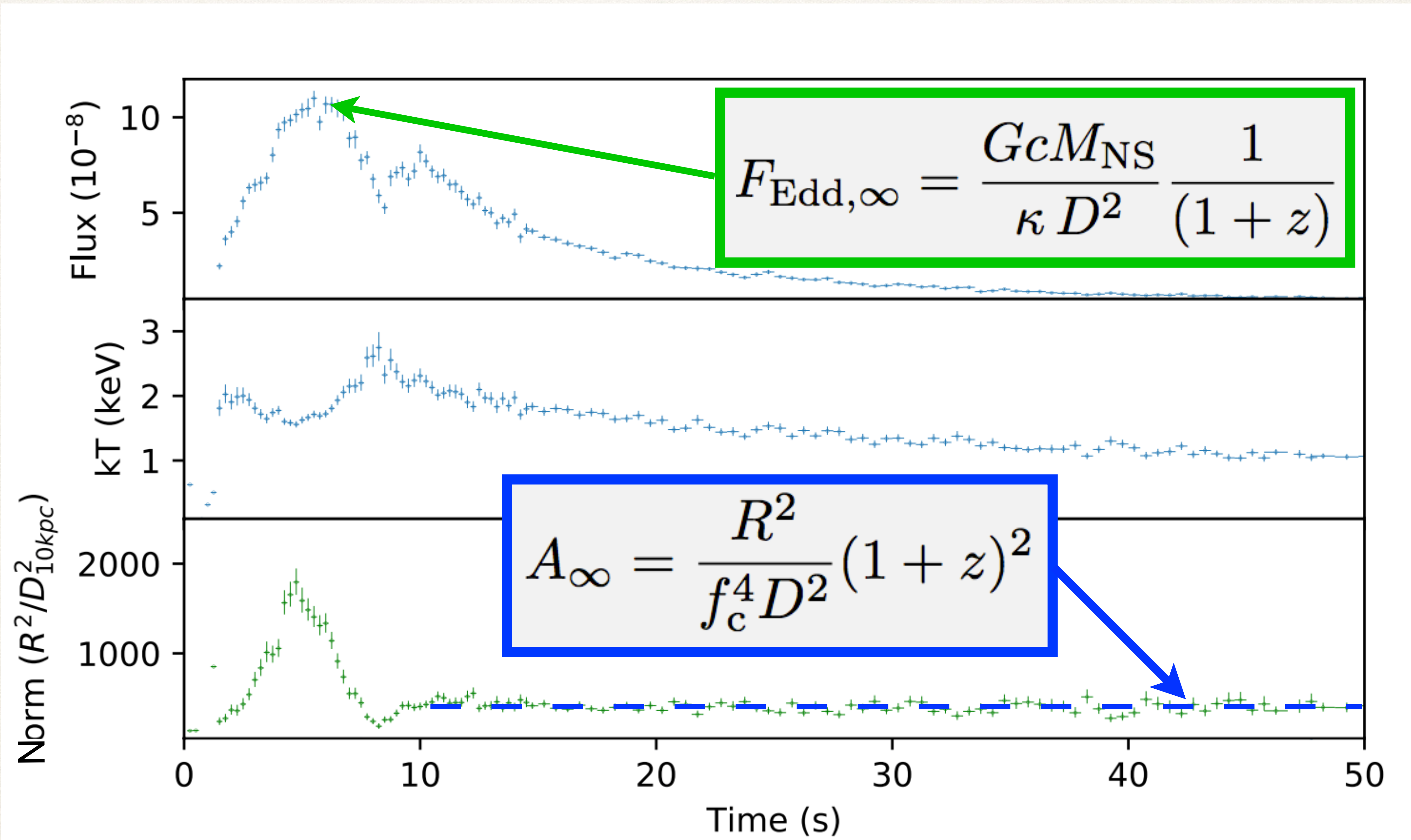




Fusion of accreted elements cause of dramatic increase of the X-ray luminosity

Some of these thermonuclear bursts reach a critical luminosity and push out the photosphere.

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

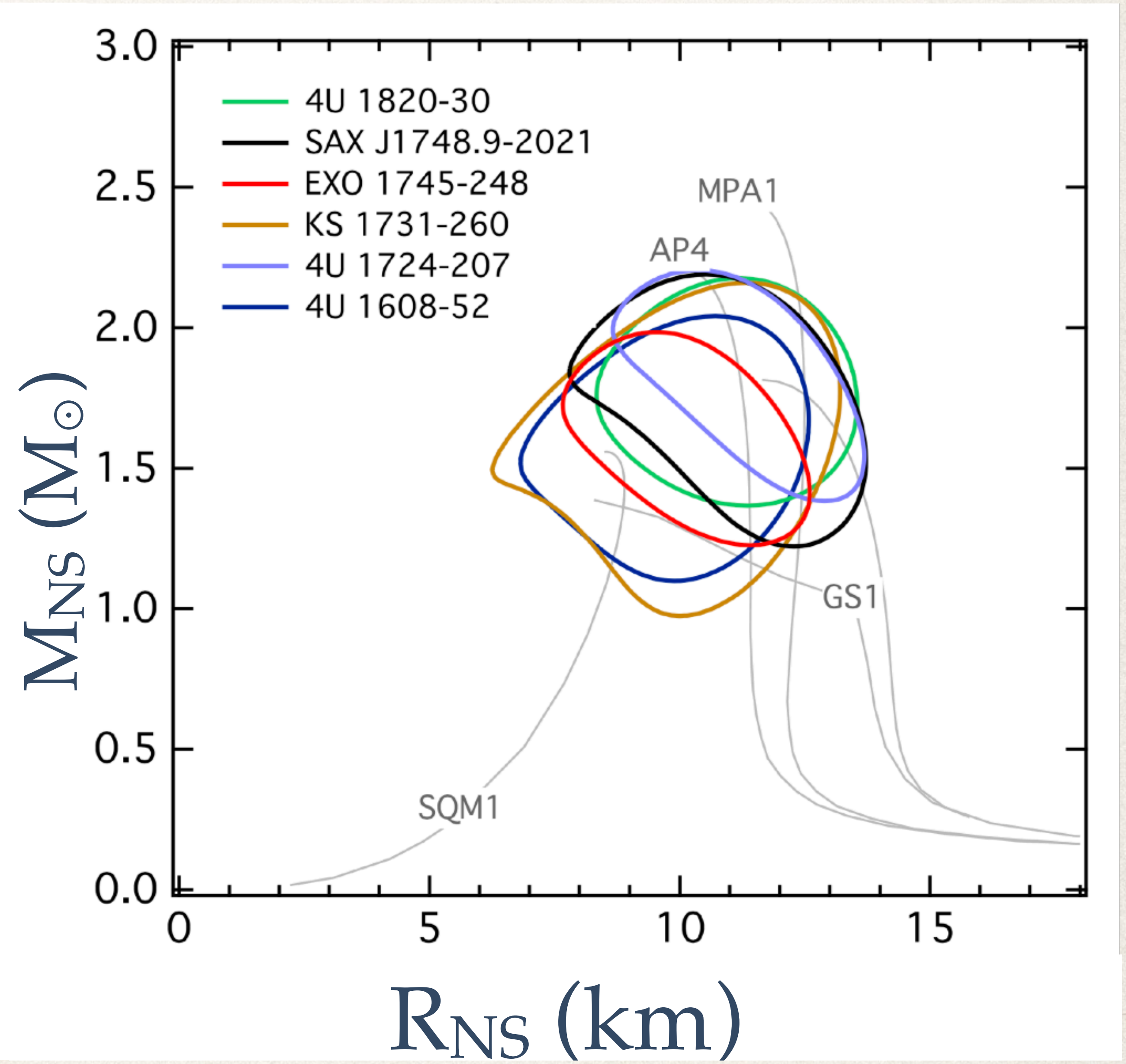


with $$(1+z) = \left(1 + \frac{2GM_{\rm NS}}{c^2 R_{\rm NS}}\right)^{-1/2}$$

A lot of uncertainties remain and make the measurements poorly constrained.

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

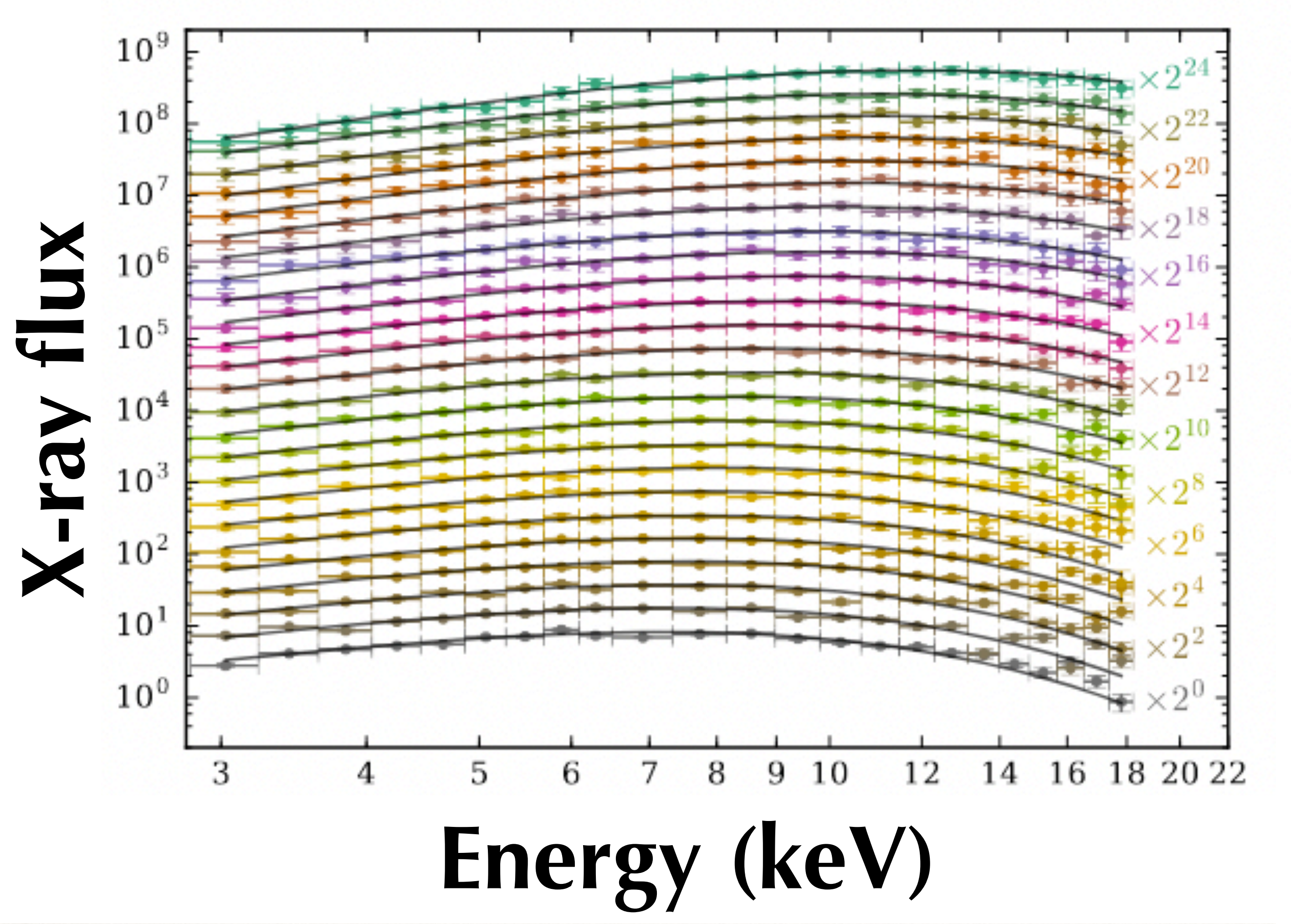
$$A_\infty = \frac{R^2}{f_c^4 D^2}(1+z)^2$$



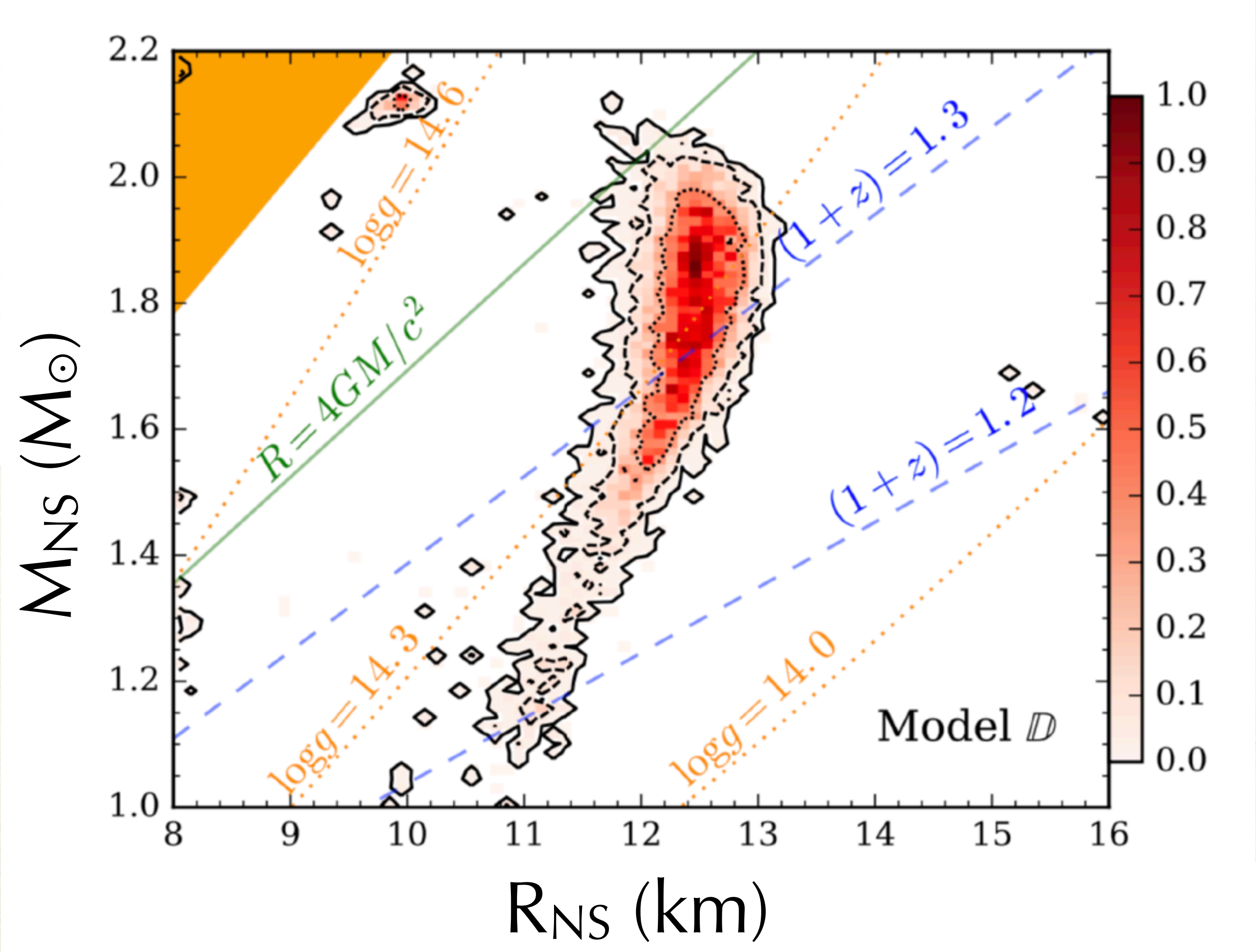
Sources of uncertainty include:

- Distance
- Atmospheric composition (via κ)
- Atmospheric modelling (via f_c)

The direct spectral fits with realistic models during the burst evolution avoids using color-correction factors.



A new method

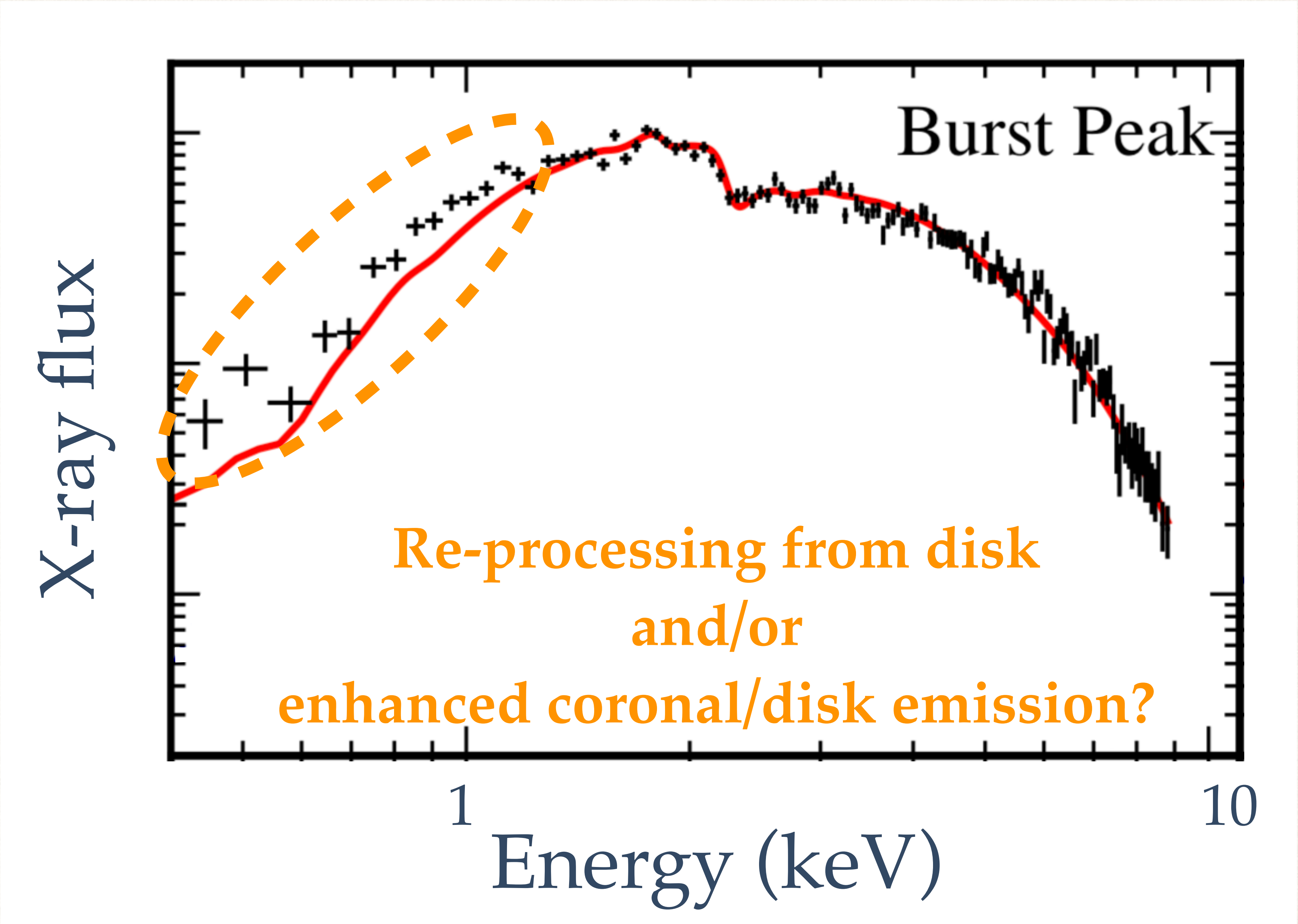


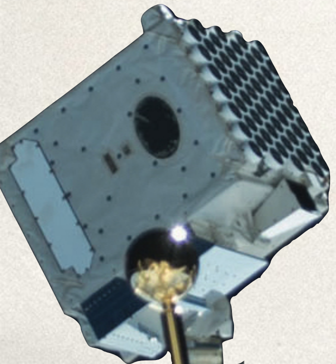
Nättilä et al. 2017

There are some caveats for these sources too!

- What is the **composition** of the atmosphere ? → Unknown. Could be inferred from donor
- The results seem to depend on the **source accretion state**. → Debate about which state to select data
- Is the model internally consistent ? → Some models produce unphysical M-R
- What is the distance to the source ? → Some have large distance uncertainties

NICER observations of type I X-ray burst also showed the presence of a un-modelled excess at low energies.

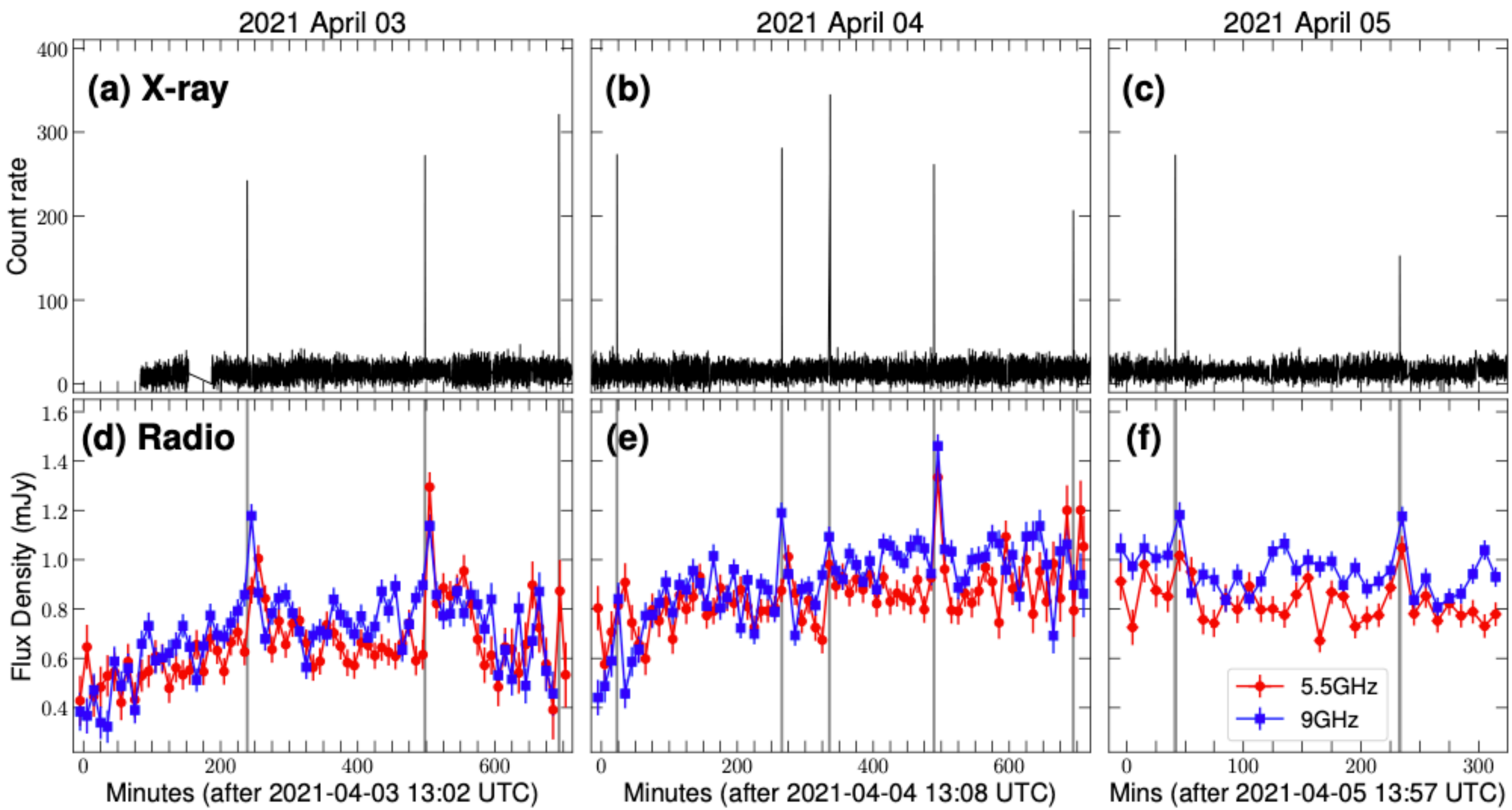




Keek et al. 2018

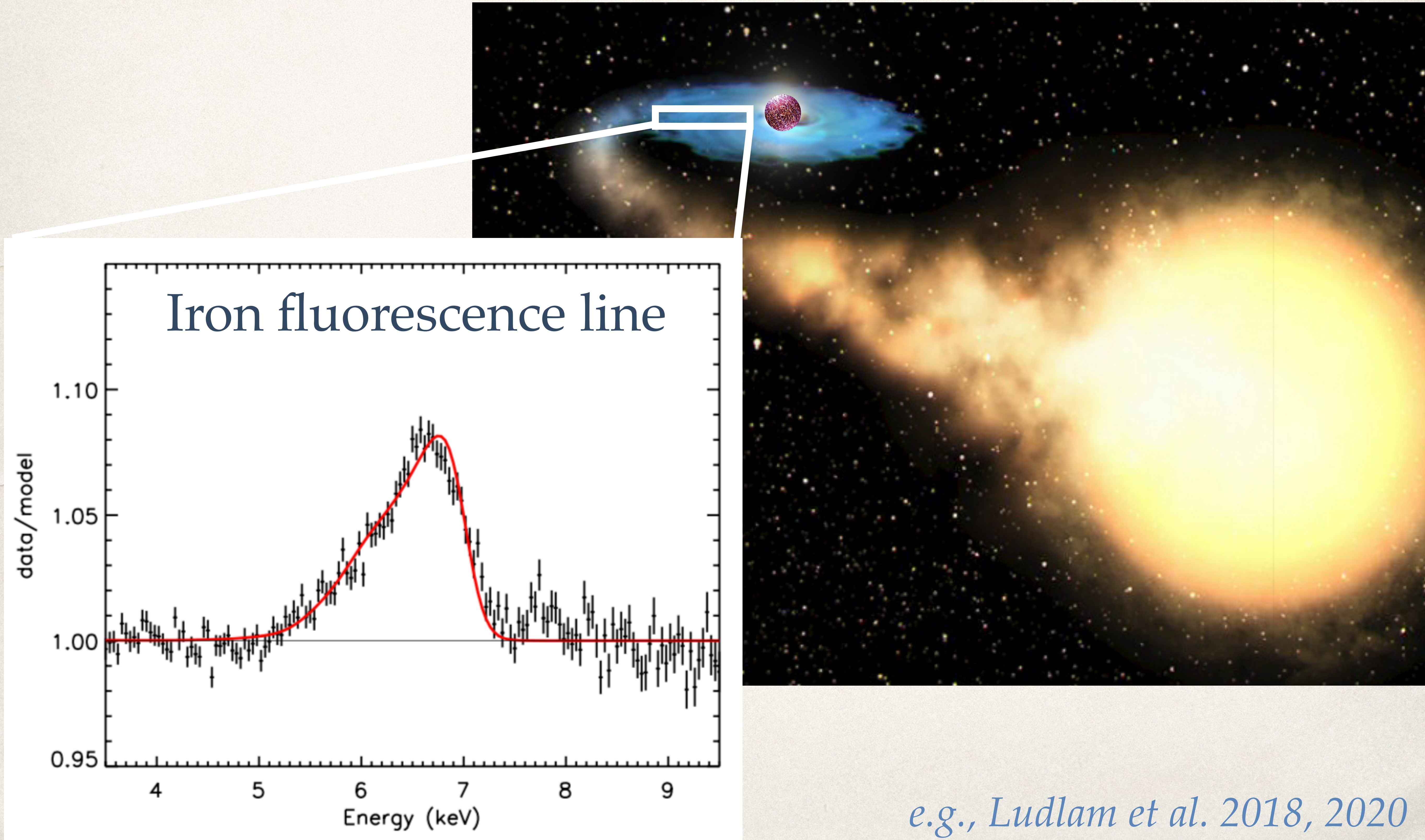
Güver et al. 2021, 2022

There is also some evidence of enhanced accretion during a Type I X-ray burst.



Russell et al. 2024

The inner extent of an accretion disk gives an upper limit on the neutron star size.



e.g., Ludlam et al. 2018, 2020

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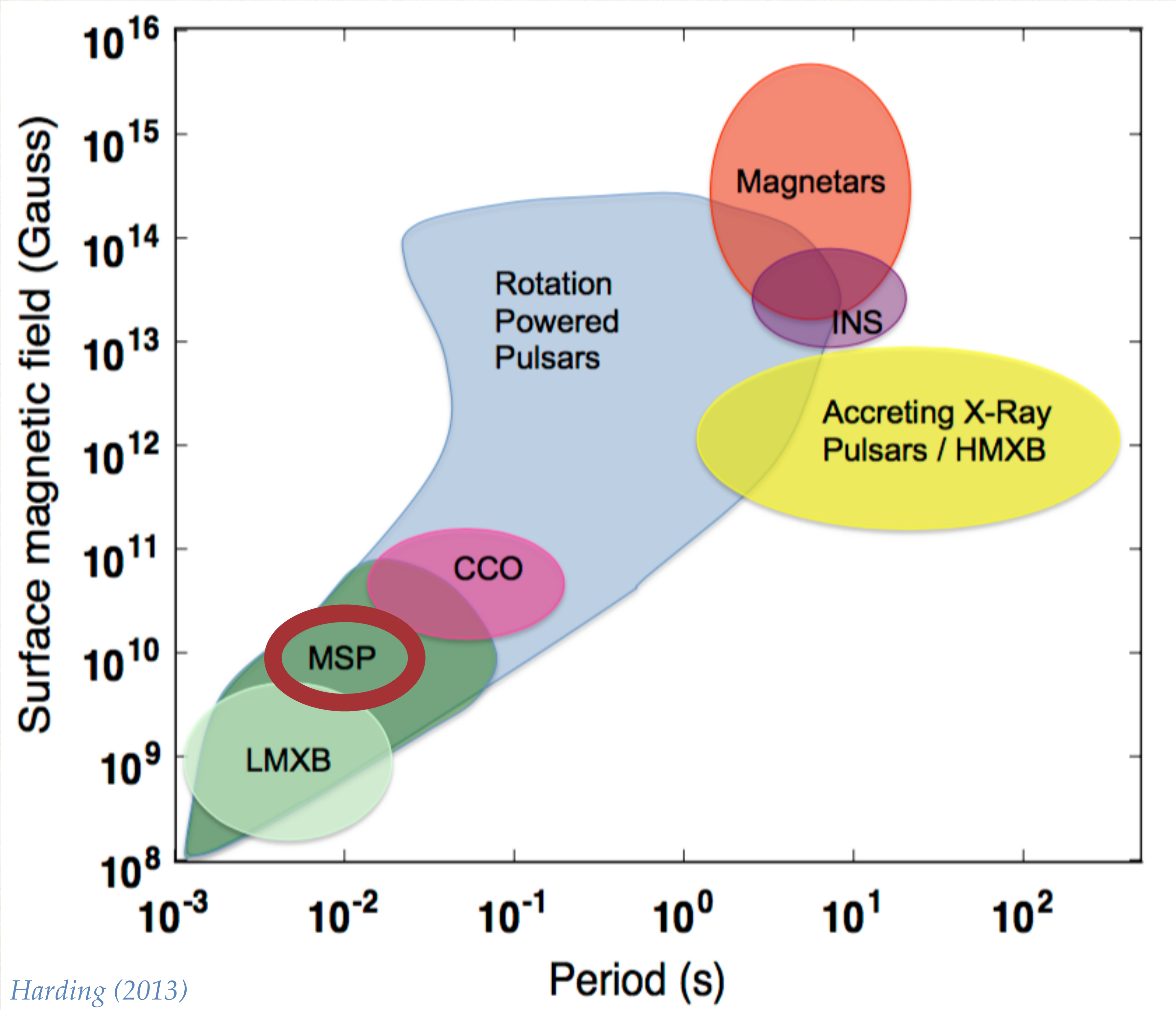
Rotation powered millisecond pulsars also have thermal surface emission.

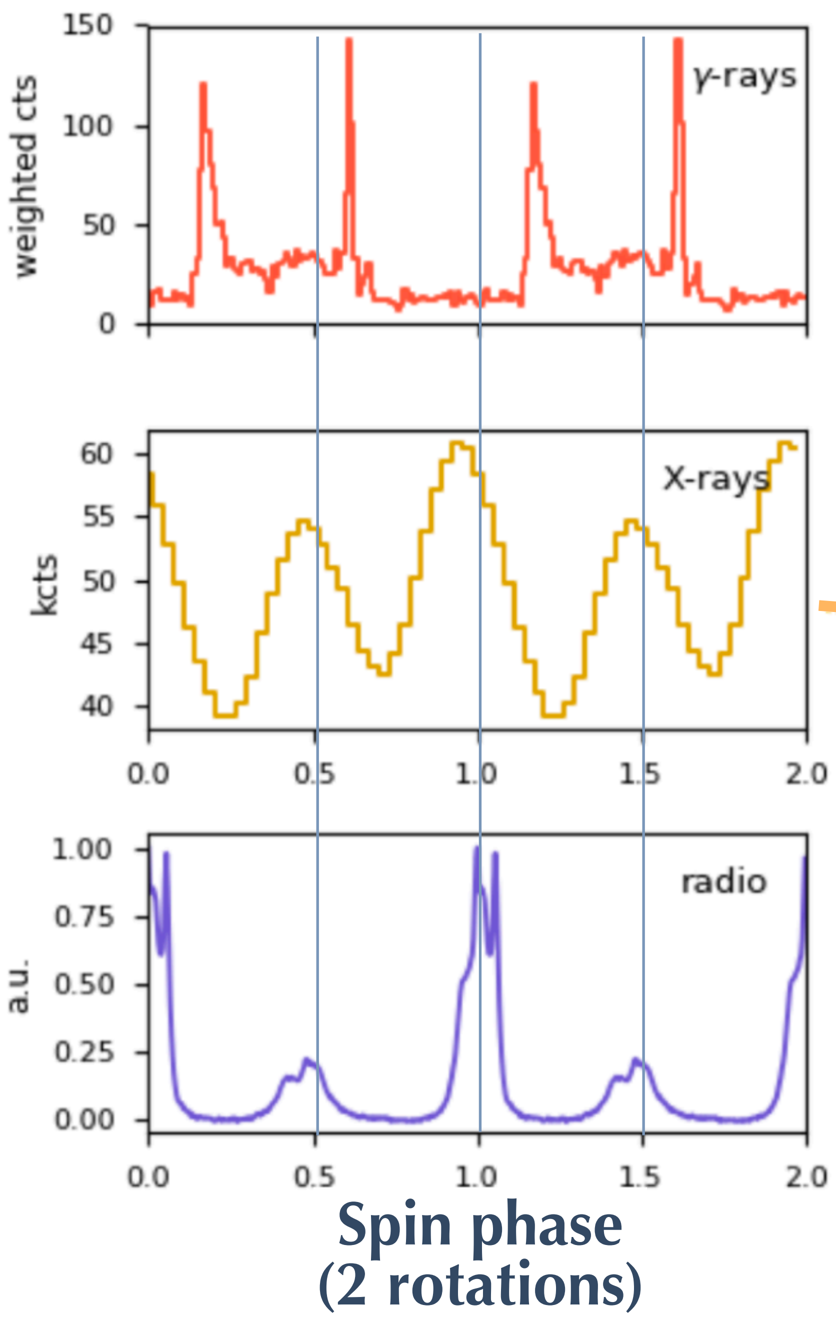


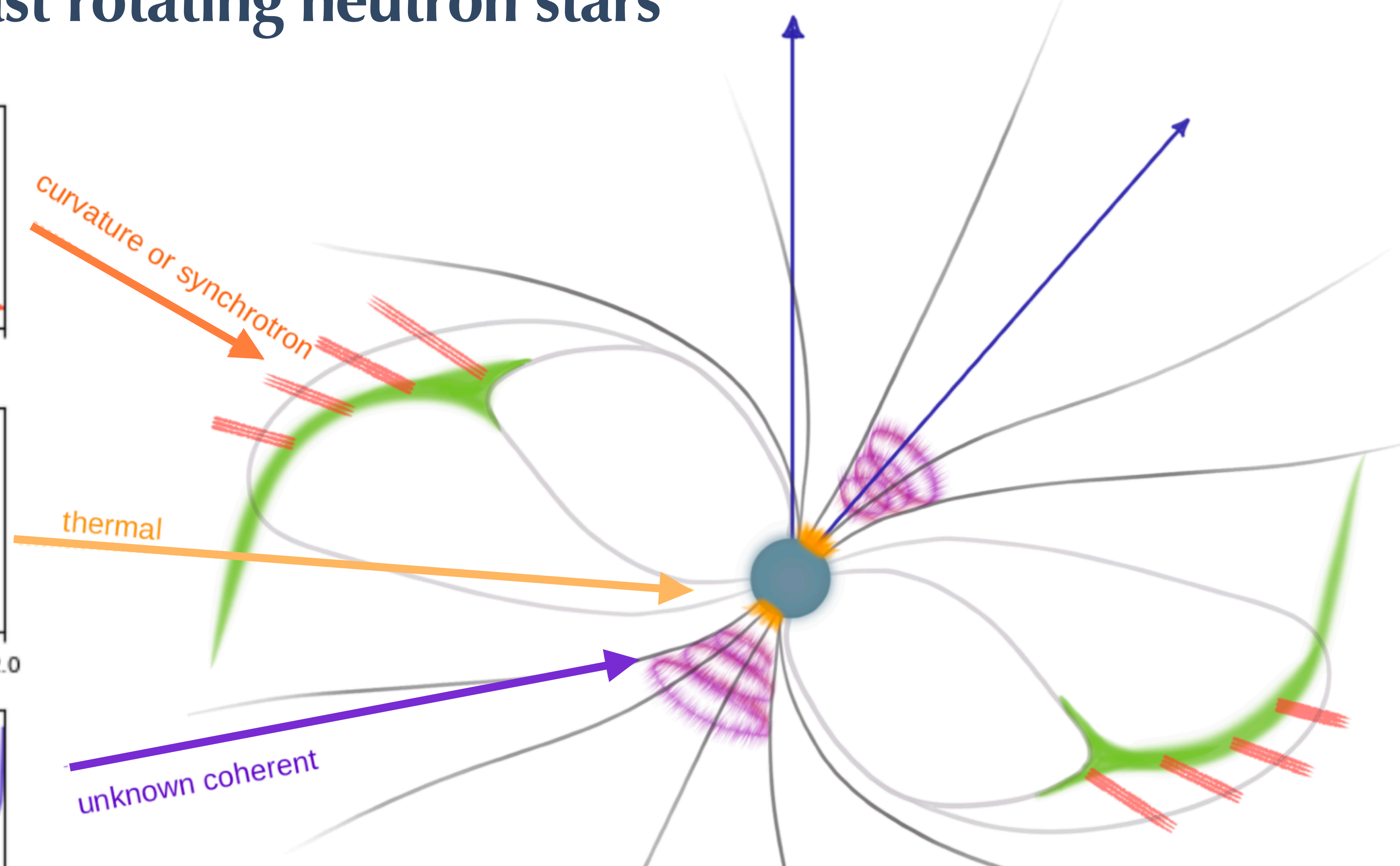
Harding (2013)

The NICER mission observes the X-ray emission from millisecond pulsars

$B \sim 10^8 - 10^9$ G
$P_{spin} \sim 2 - 5$ msec

Old fast rotating neutron stars



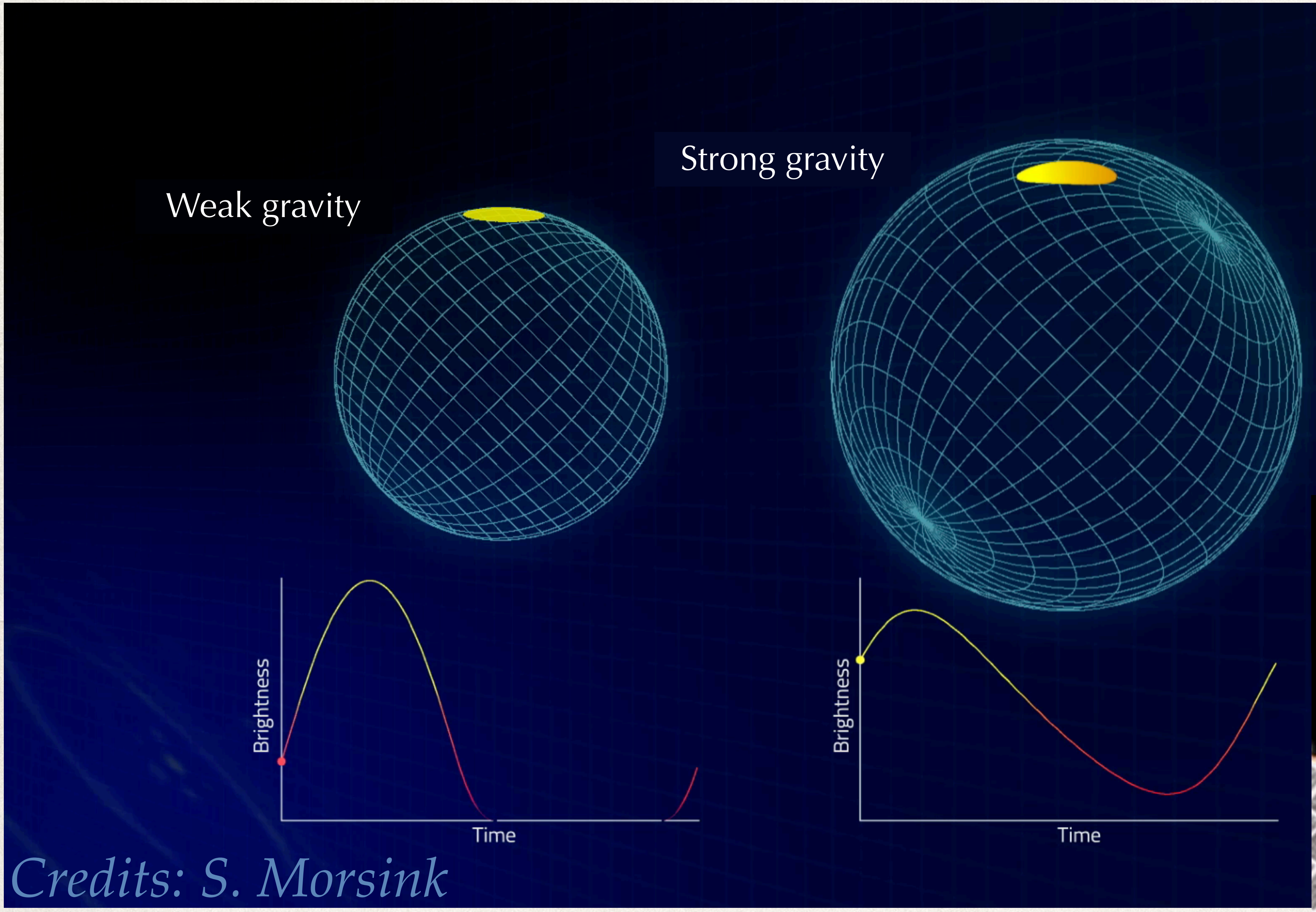


Advantages of millisecond pulsars:

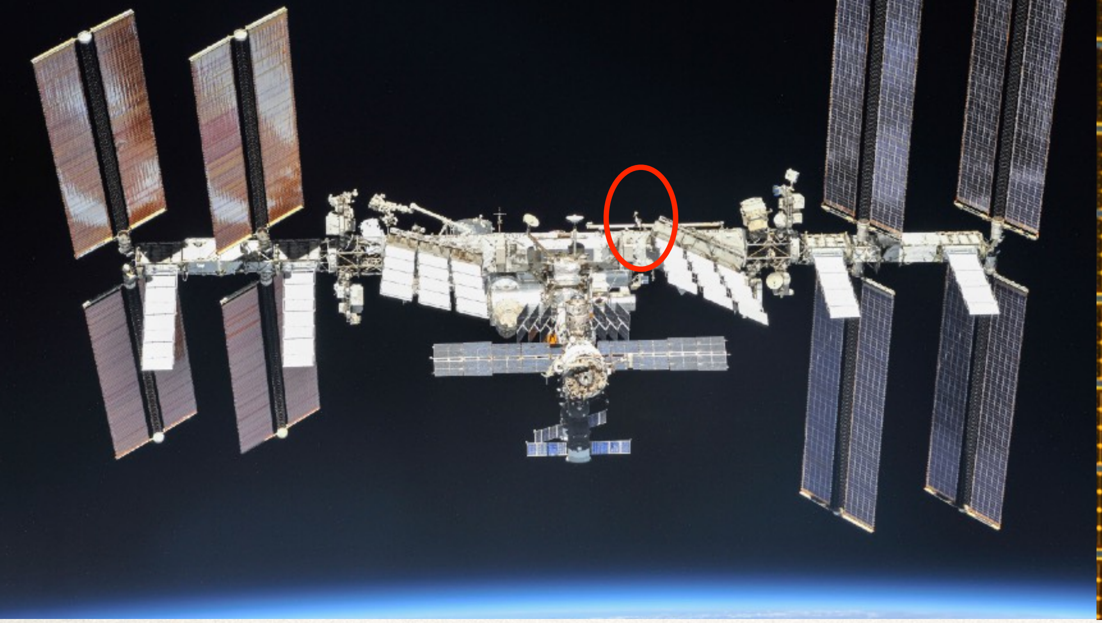
- **Very stable on long time scales**
- **Low B-fields and no accretion**
- **Purely thermal X-ray emisson**

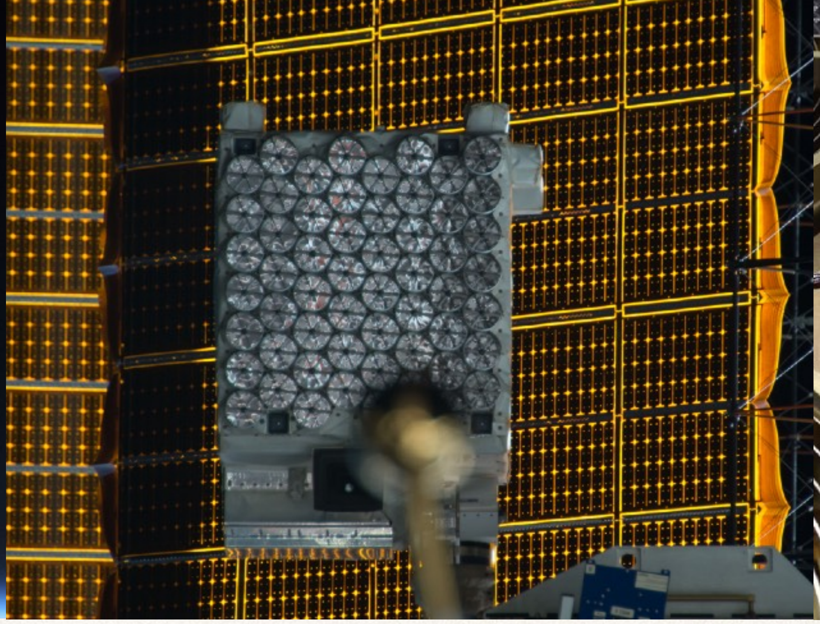
Credits: A. Bilous

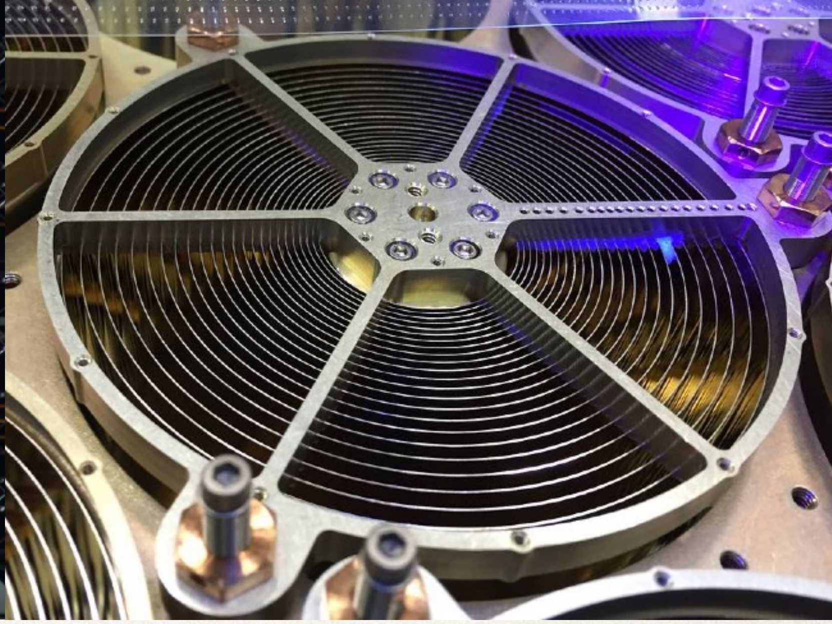
Strong gravity permits seeing beyond the hemisphere of the neutron star, leaving imprints on the lightcurves of millisecond pulsars.



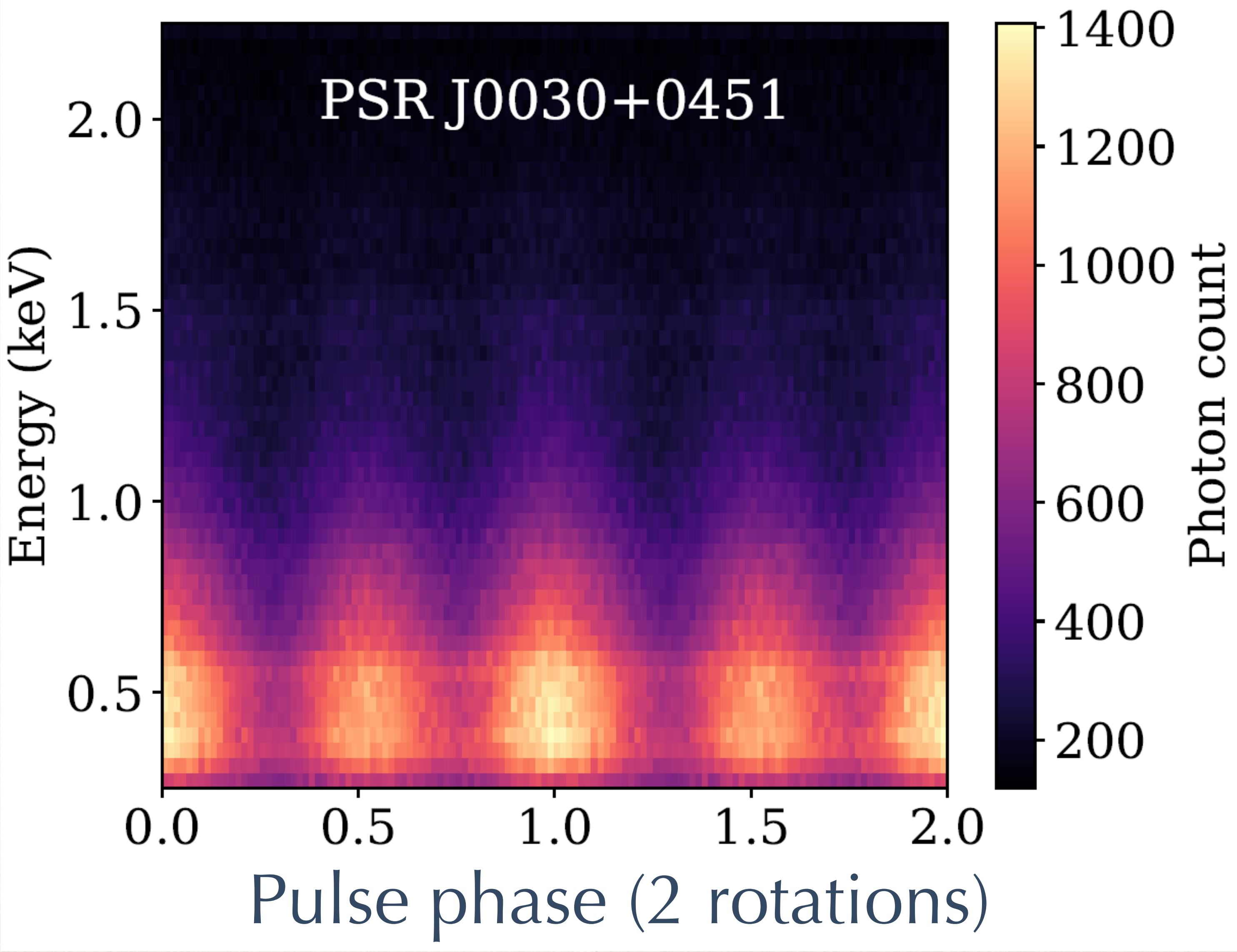
NICER was launched for this science goal.



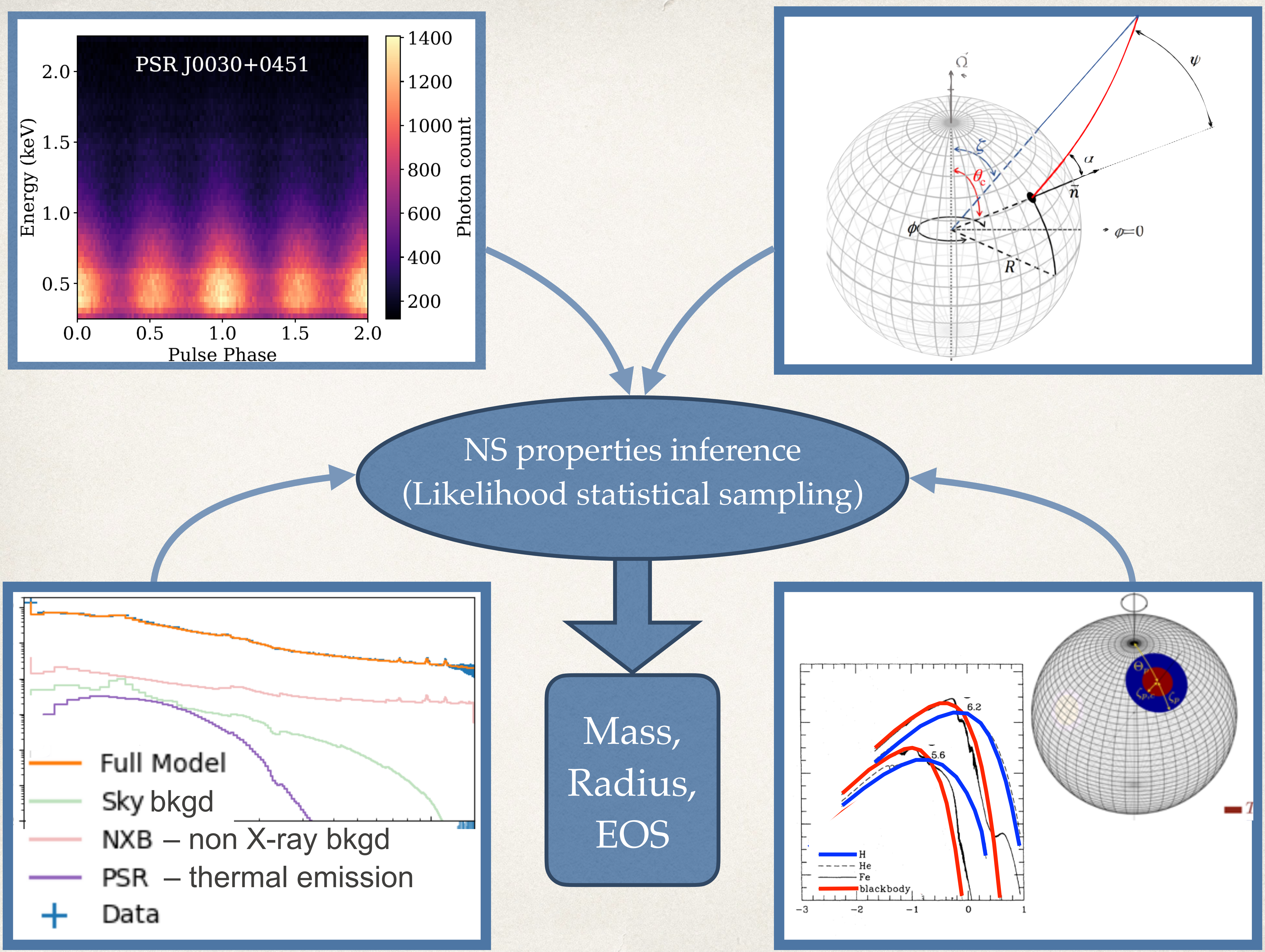




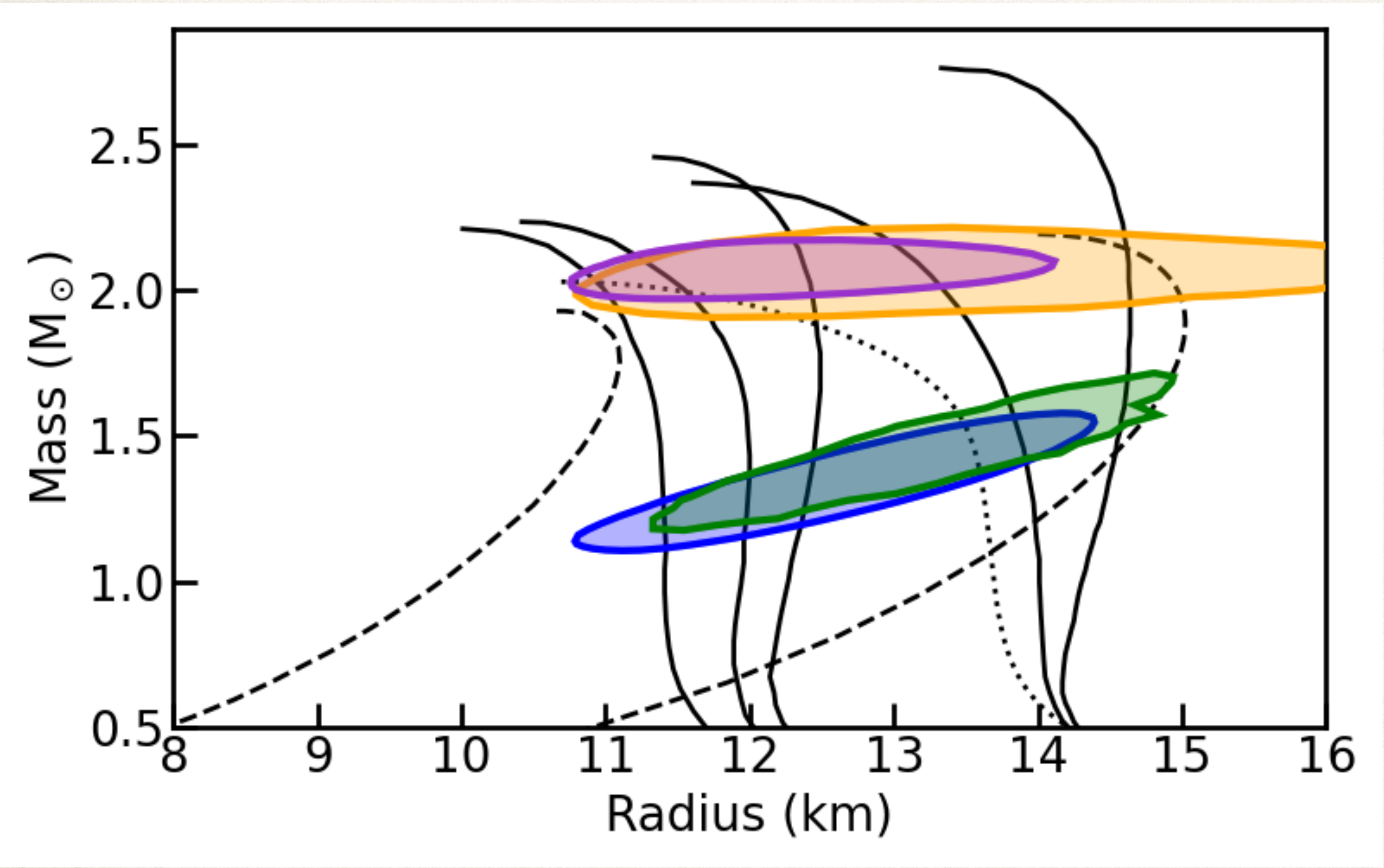
NICER has provided beautiful data sets to perform pulse profile modelling.



Bogdanov, SG et al. (2019a)


PSR J0030+0451
Energy (keV)
Pulse Phase
Photon count
ψ
α
θc
ζ
φ
φ=0
R
NS properties inference
(Likelihood statistical sampling)
Mass,
Radius,
EOS
Full Model
Sky bkgd
NXB – non X-ray bkgd
PSR – thermal emission
Data
H
He
Fe
blackbody
6.2
5.6

The NICER Science Team published the results for two pulsars.

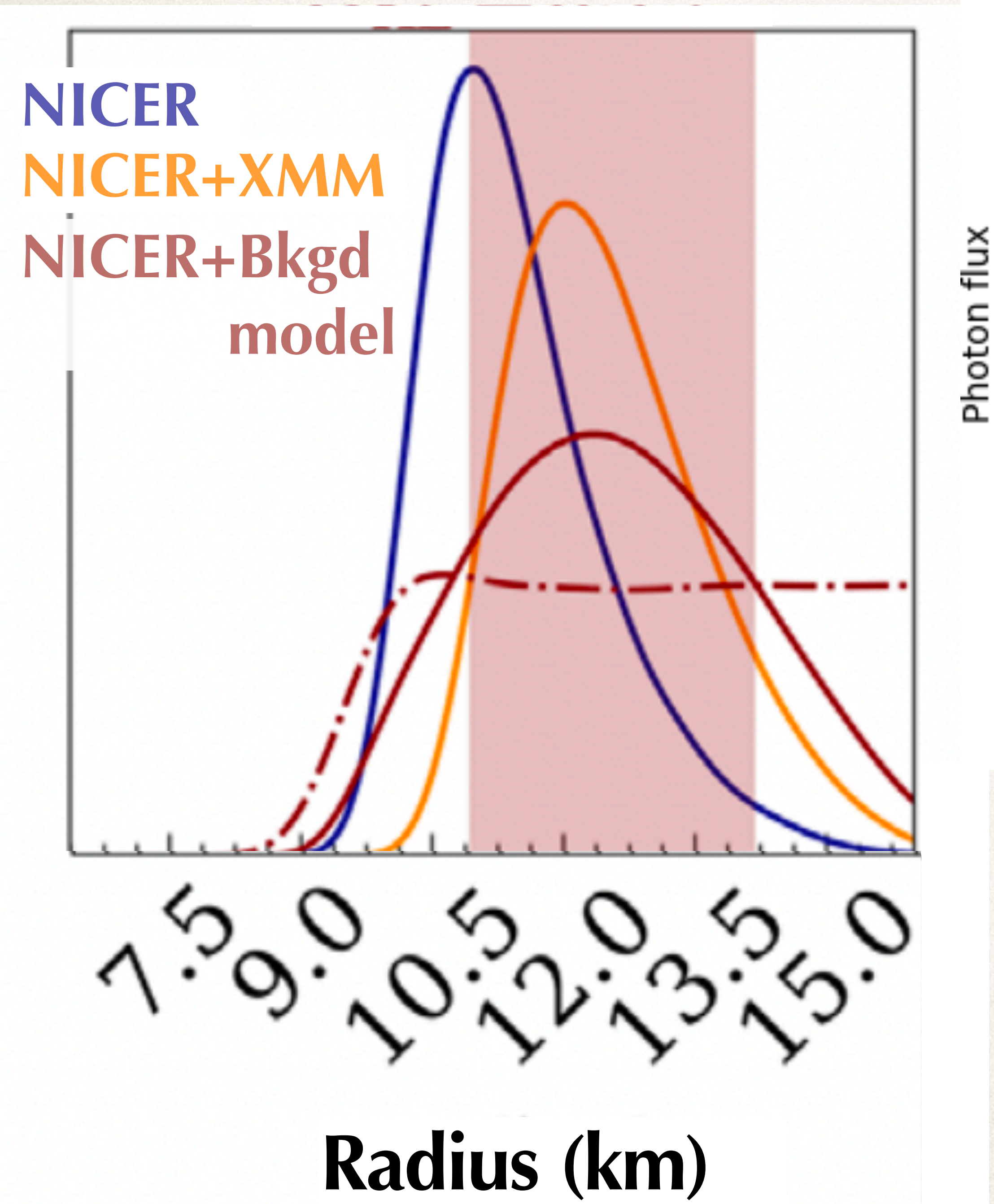


The two independent analyses for each target are consistent

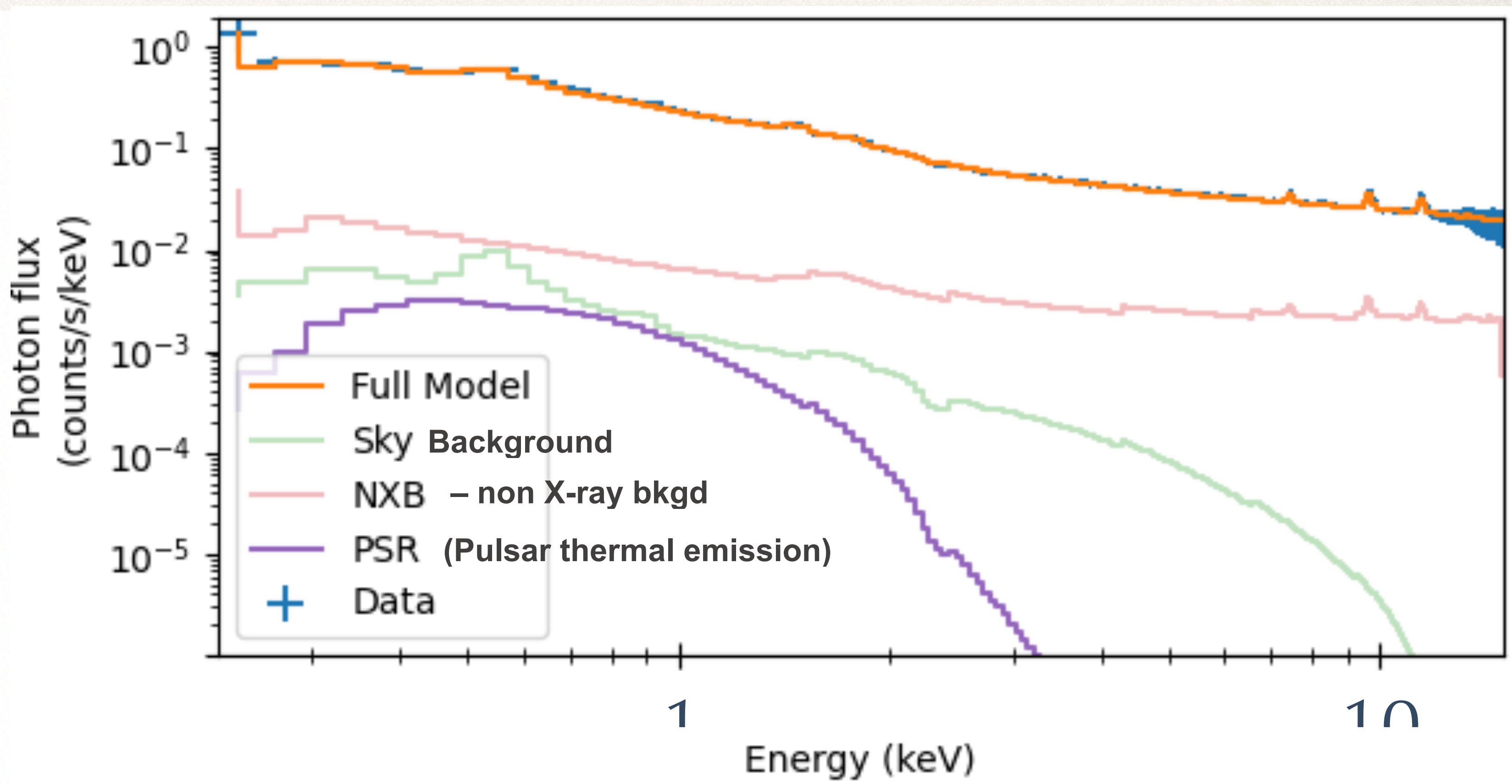
- **PSR J0030+0451**
  - Riley et al. 2019
  - Miller et al. 2019
- **PSR J0740+6620**
  - Riley et al. 2021
  - Miller et al. 2021

See also a third independent re-analysis of PSR J0030+0451 by Afle et al. 2023 finding consistent results

The modelling of the background matters for the inference of the radius.



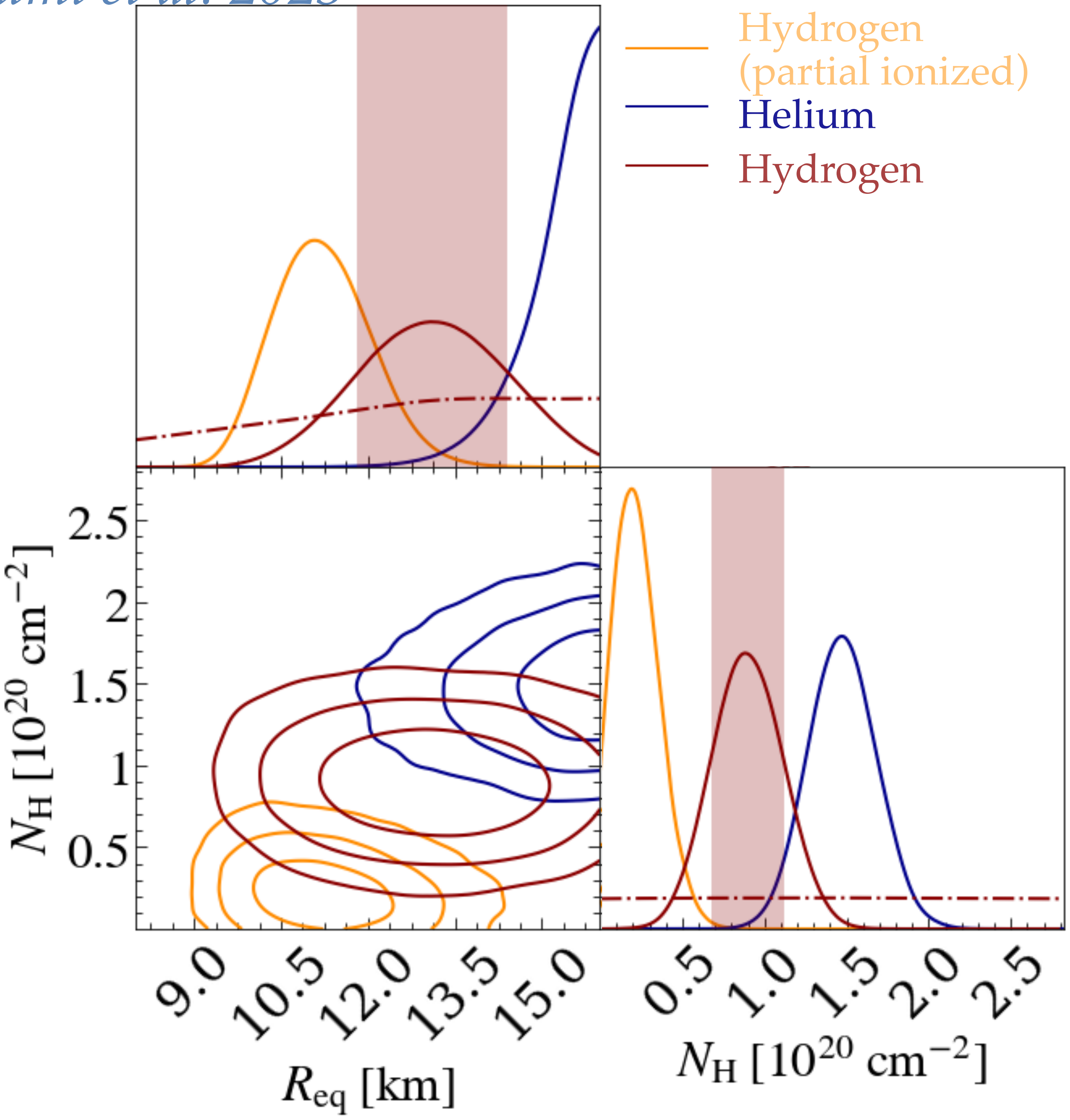
Salmi et al., 2022



NICER is a non-imaging instrument with a high background that needs to be independently modelled or constrained

The atmospheric composition also has an effect on the inferred radius.

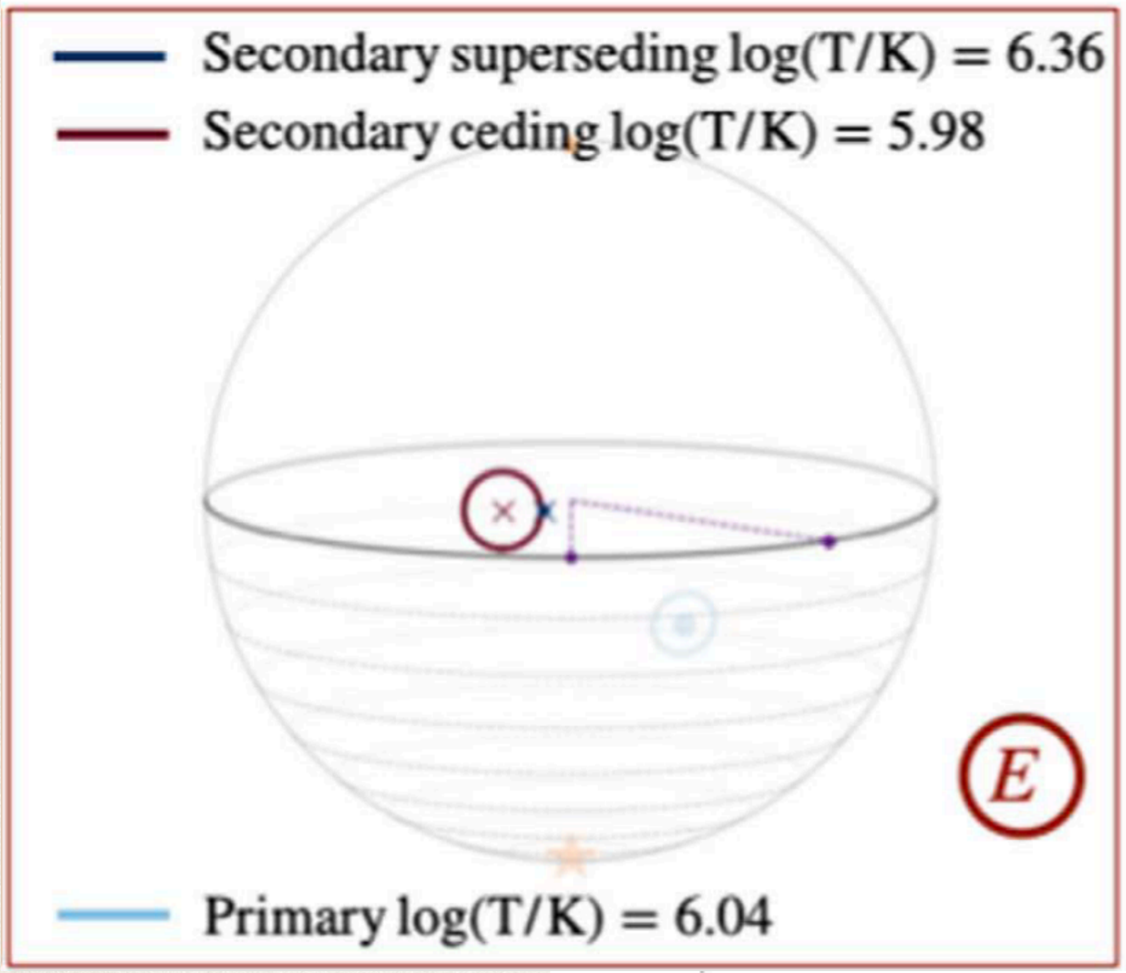
Salmi et al. 2023

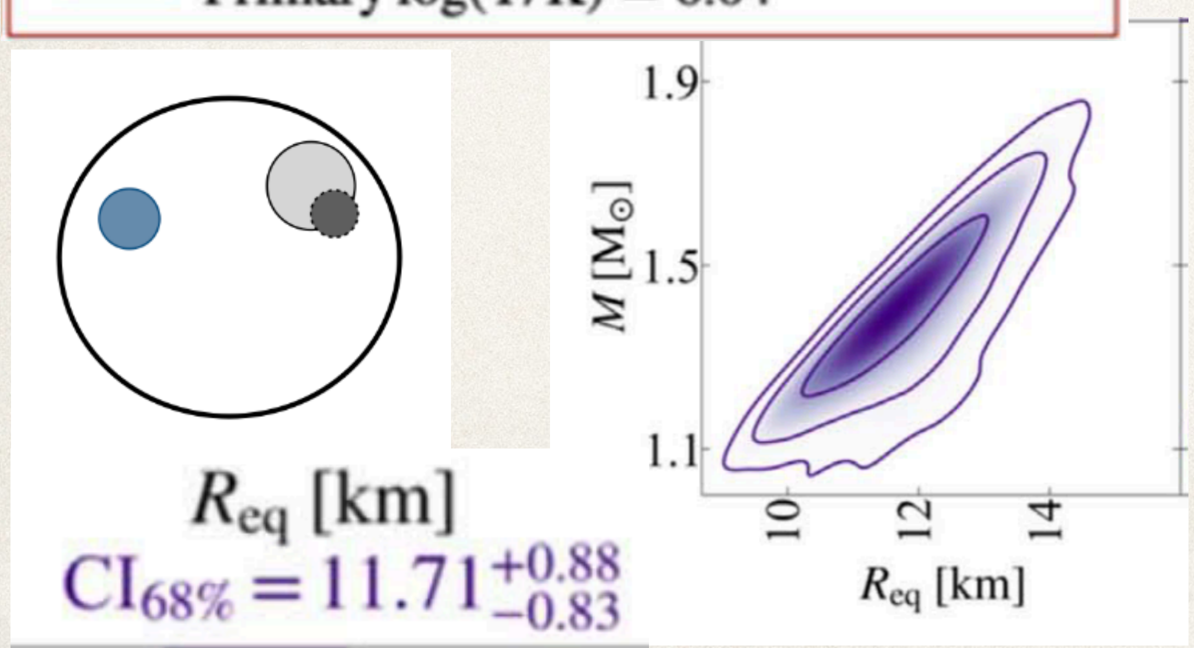


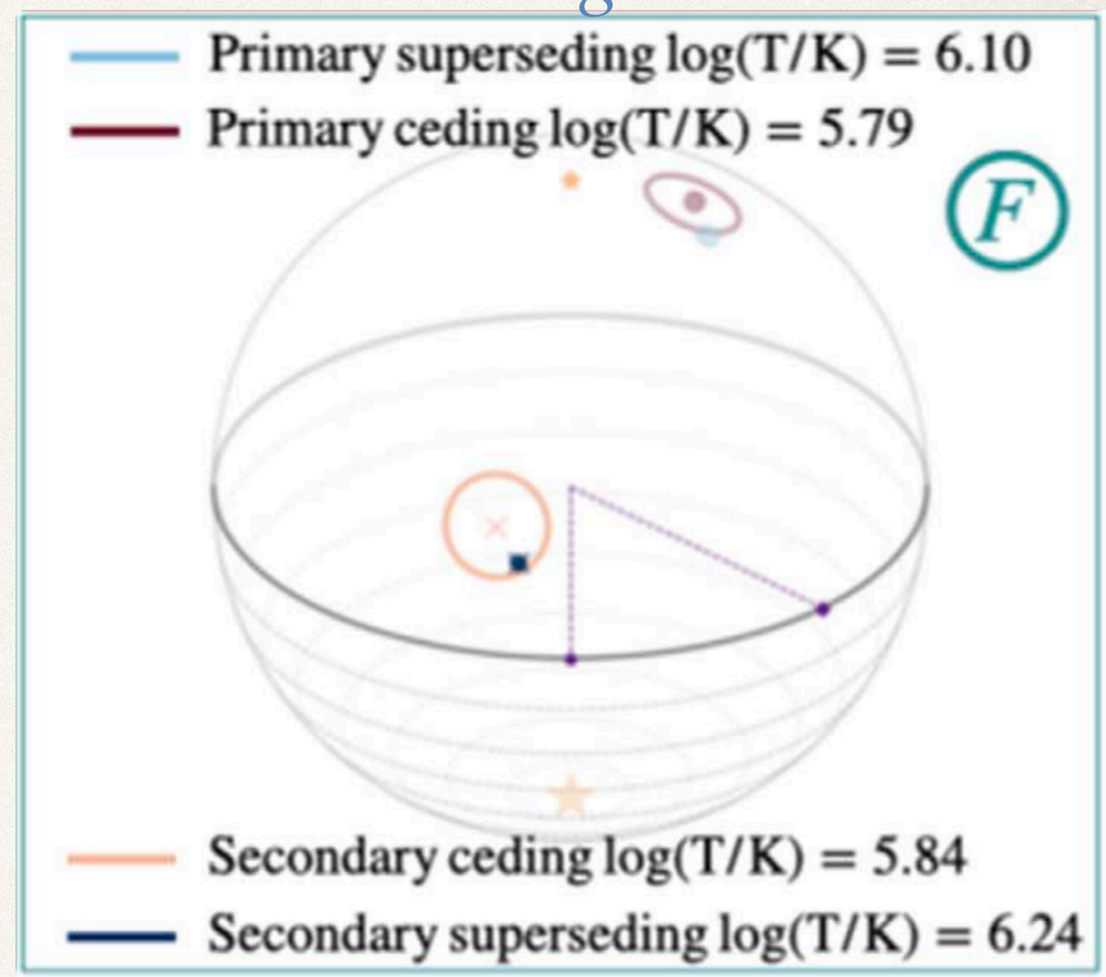
Several arguments favour a hydrogen composition of the pulsar's atmosphere

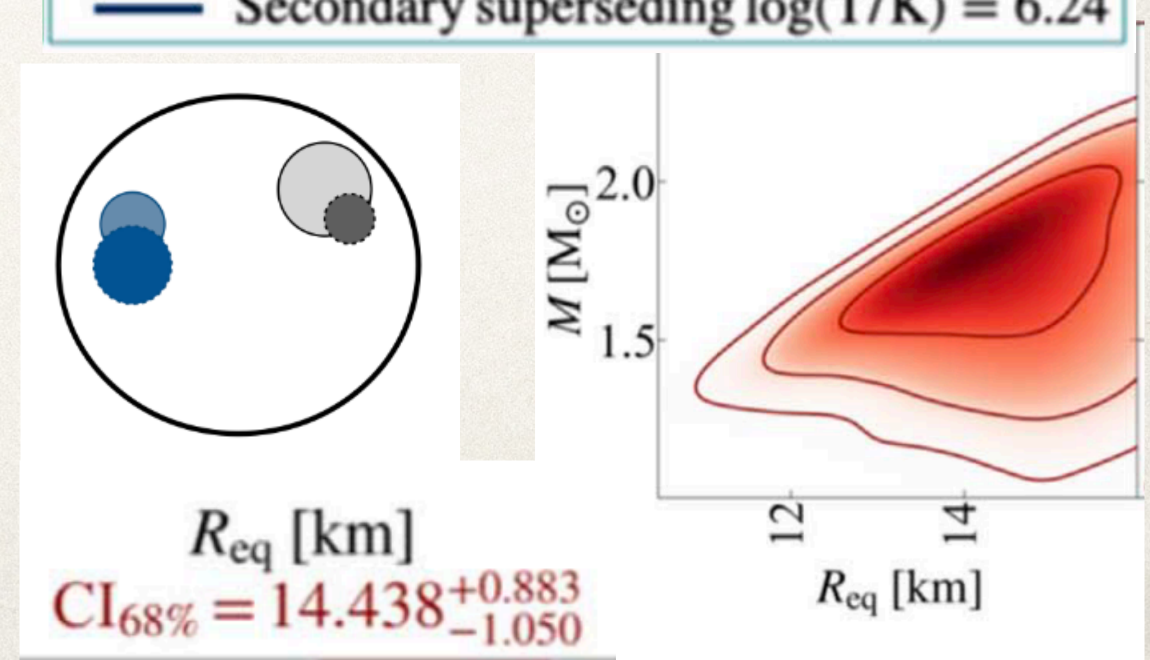
The choice of spot pattern also changes the inferred radius and mass.

Vinciguerra et al. 2024



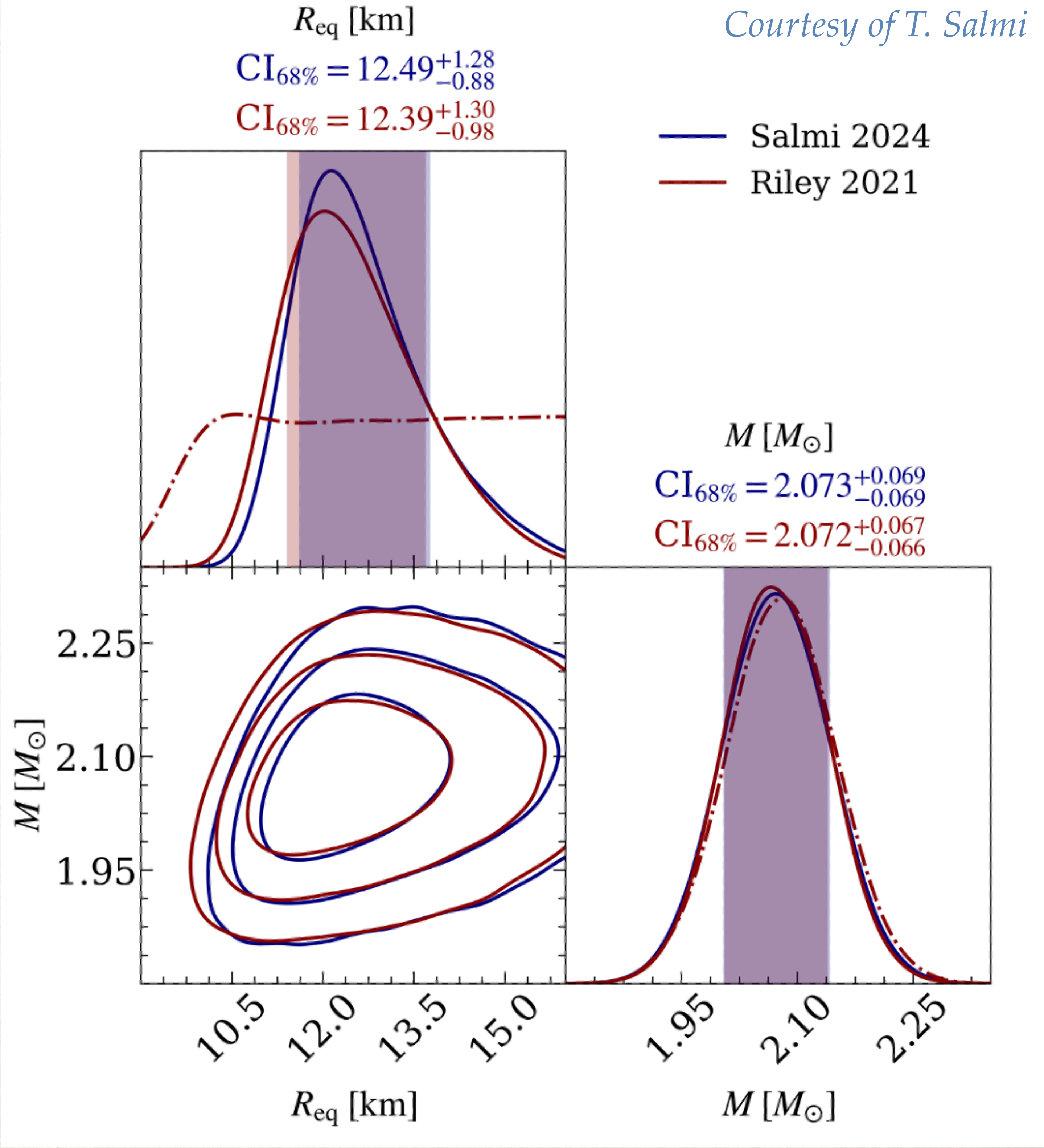






Some recently announced results:

Updated measurements for PSR J0740



<u>From 1.6 Msec to 2.7 Msec</u>

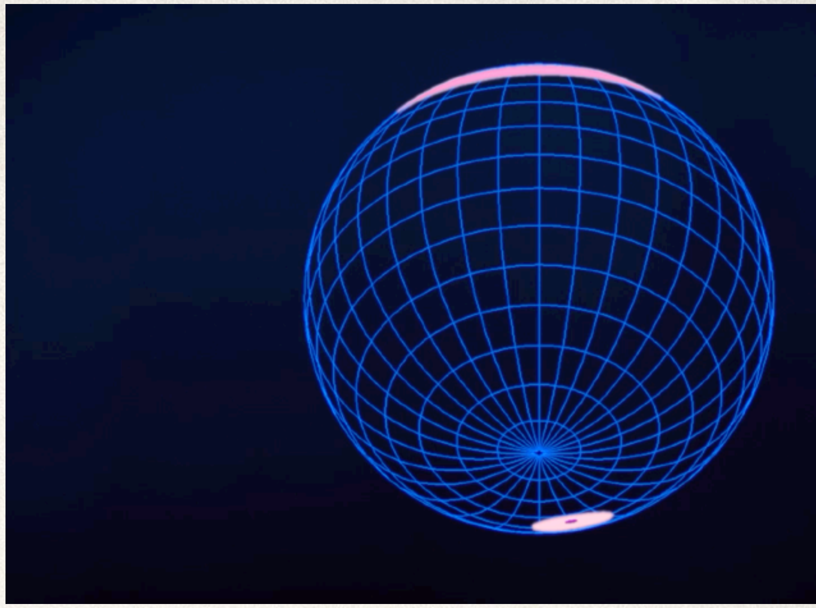
Slightly more constrained lower limit on R_{NS}:

$$R_{\rm NS} = 12.5^{+1.3}_{-0.9}\ \rm km$$

Salmi et al. 2024 (submitted)

Some recently announced results:

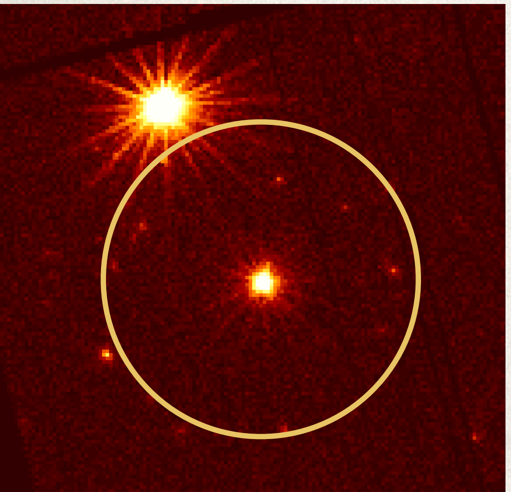
PSR J0437–4715, the nearest MSP

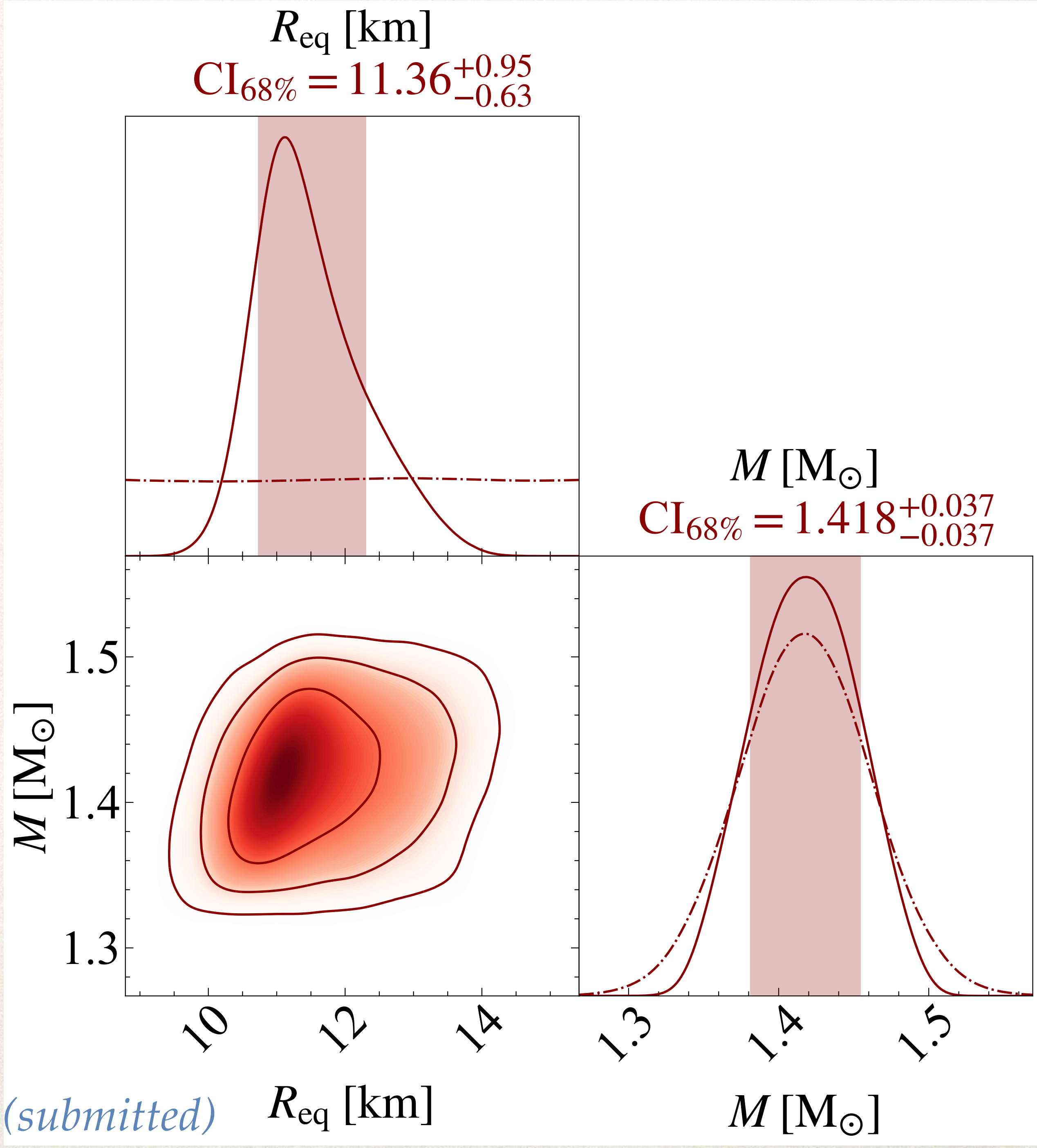


$$R_{NS} = 11.4^{+0.9}_{-0.6}\ \mathrm{km}$$

Reardon et al. 2024 (submitted)

- **Advantages**
  - Priors on mass, inclination and distance (156.98±0.16 pc)
  - Bright source!
- **Drawbacks**
  - Bright source!
  - Nearby very bright source

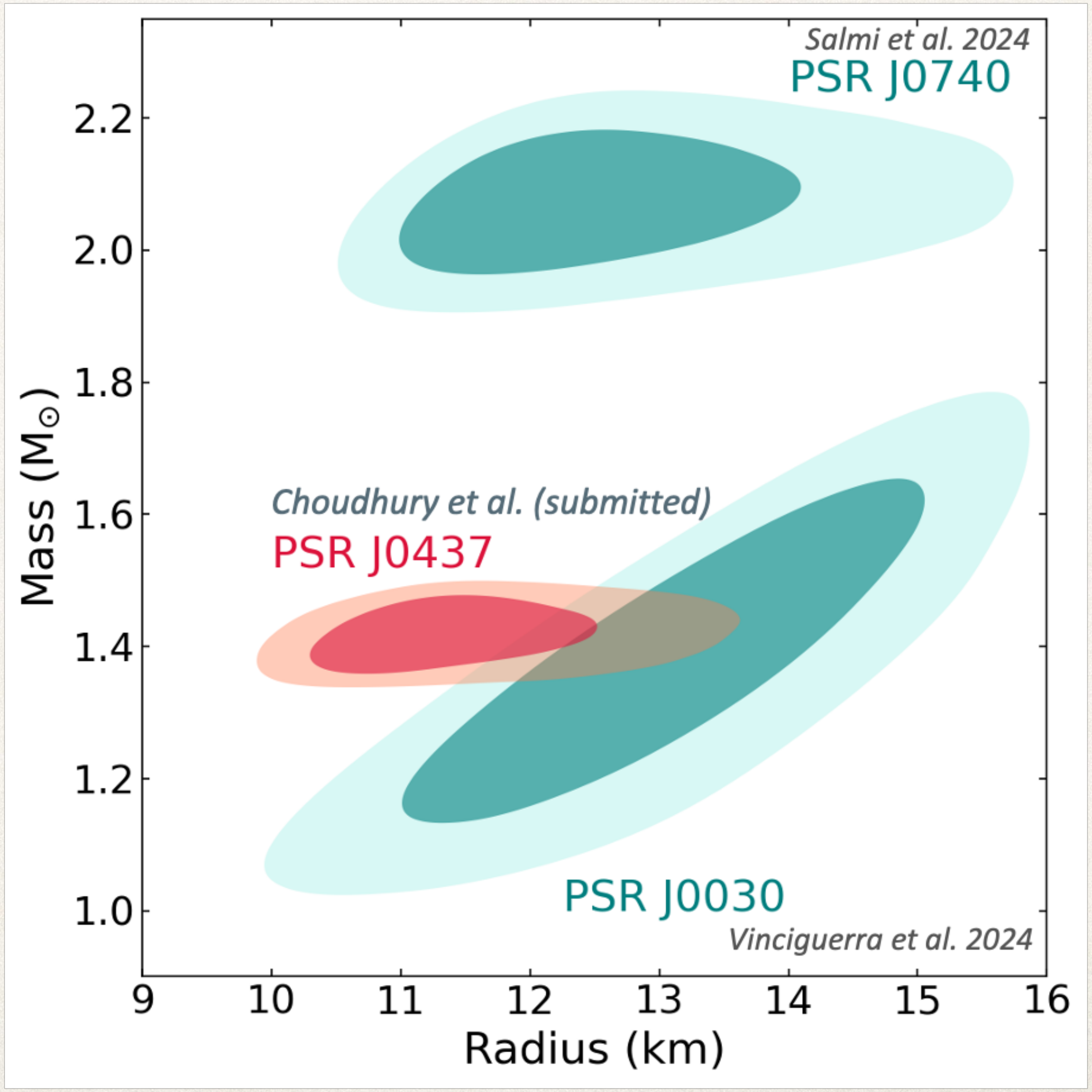




Choudhury et al. 2024 (submitted)

What does this mean for the EOS ?

See Melissa Mendes' talk



Courtesy of D. Choudhury

Outline

- **Constraints from GW of NS-NS mergers** (*J. Read's talk*)
- **Constraints of NS masses and I_A** (*M. Kramer's talk*)
- **1-slide crash course on X-ray astrophysics**
- **Constraints from NS in low-mass X-ray binaries**
  - Non-accreting
  - Accreting
- **Constraints from millisecond pulsars**
  - Results from NICER
  - Other results
- **Future prospects**

For some MSPs, the rest of the surface, although much colder than the hot spots, can be detected in the soft X-ray and the far UV.

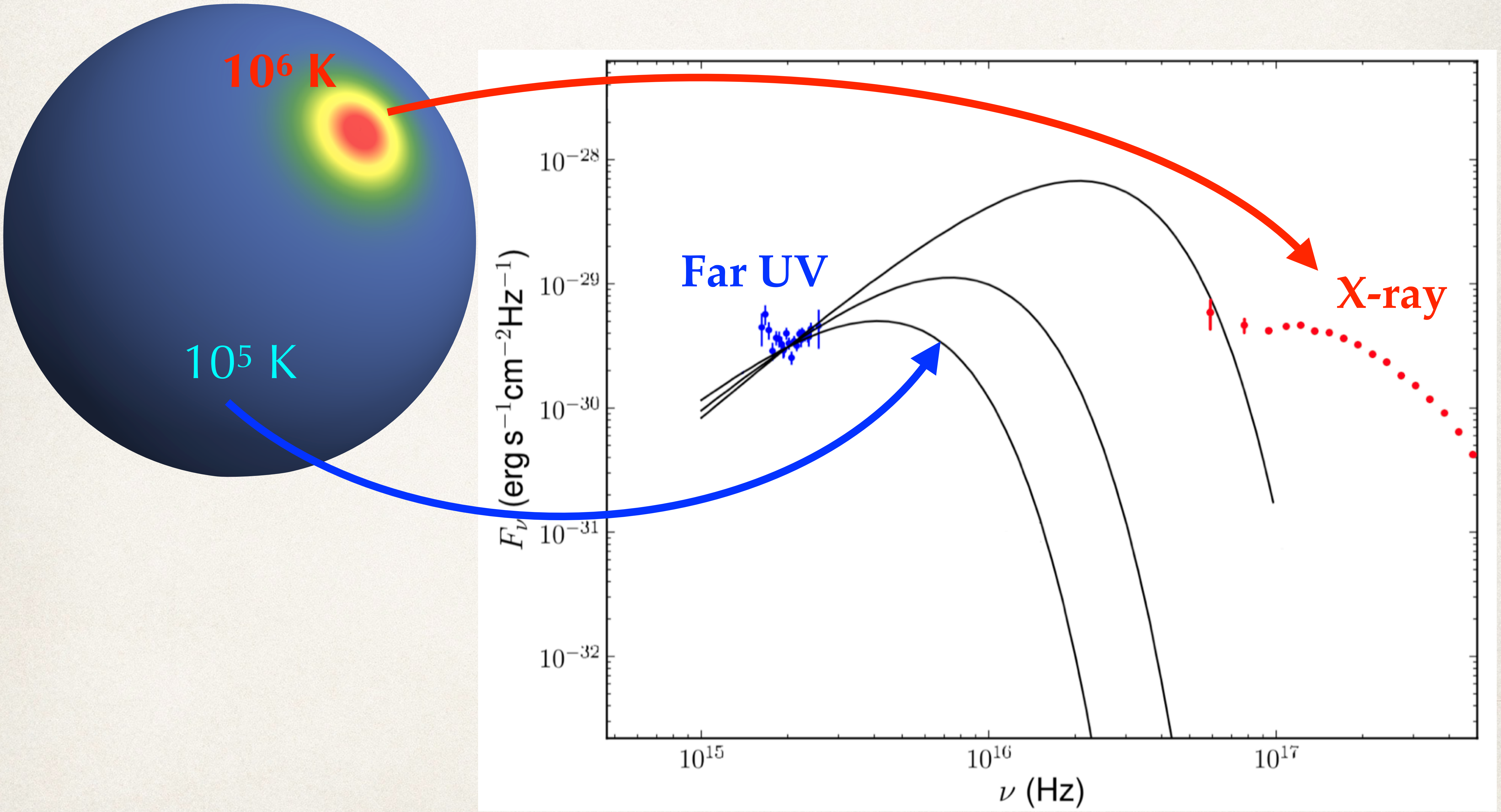
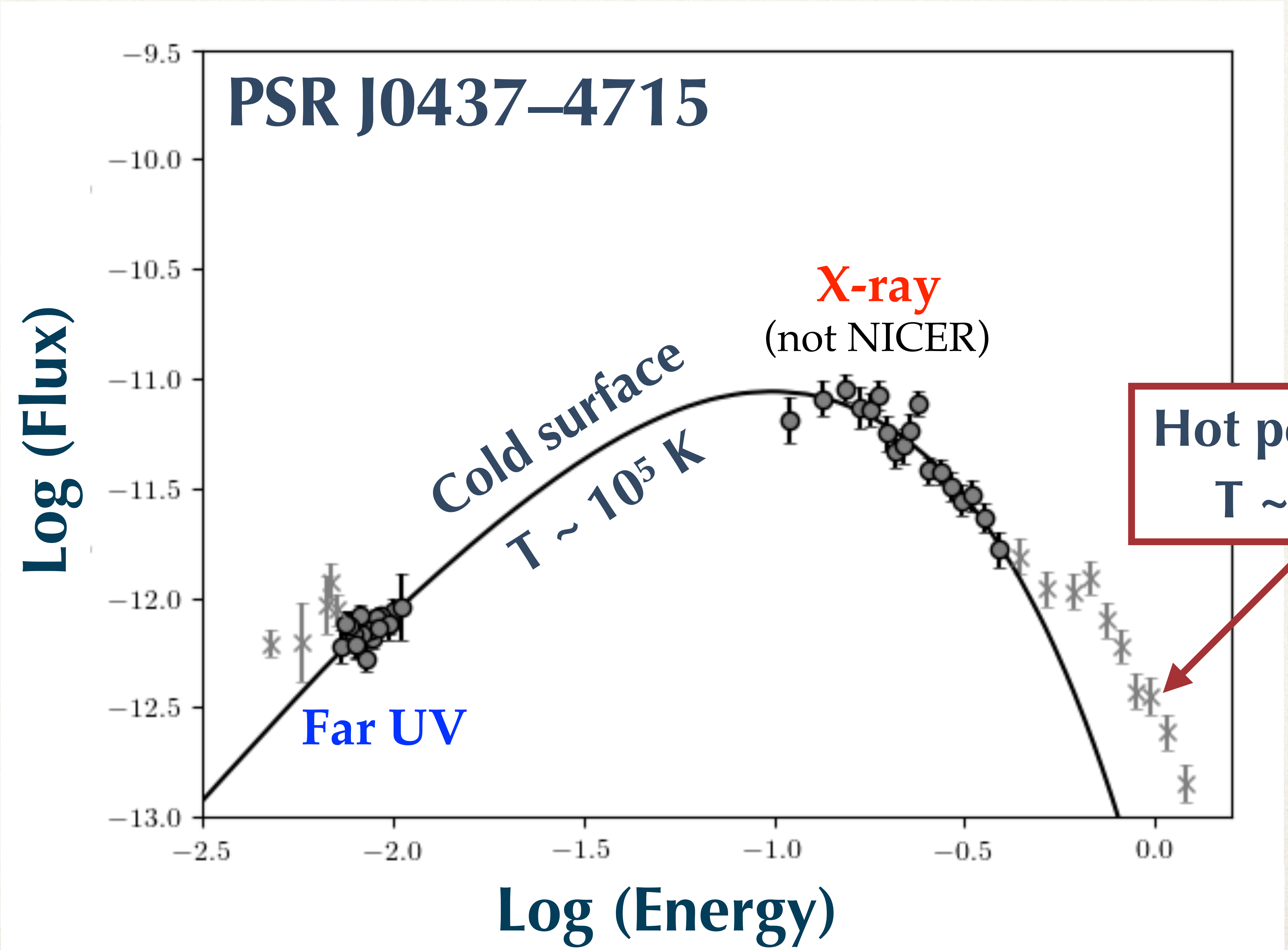


Figure adapted from Durant et al. (2012)

In the far UV, the Rayleigh-Jeans tail of the surface thermal emission gives the handle to constrain the neutron star size.

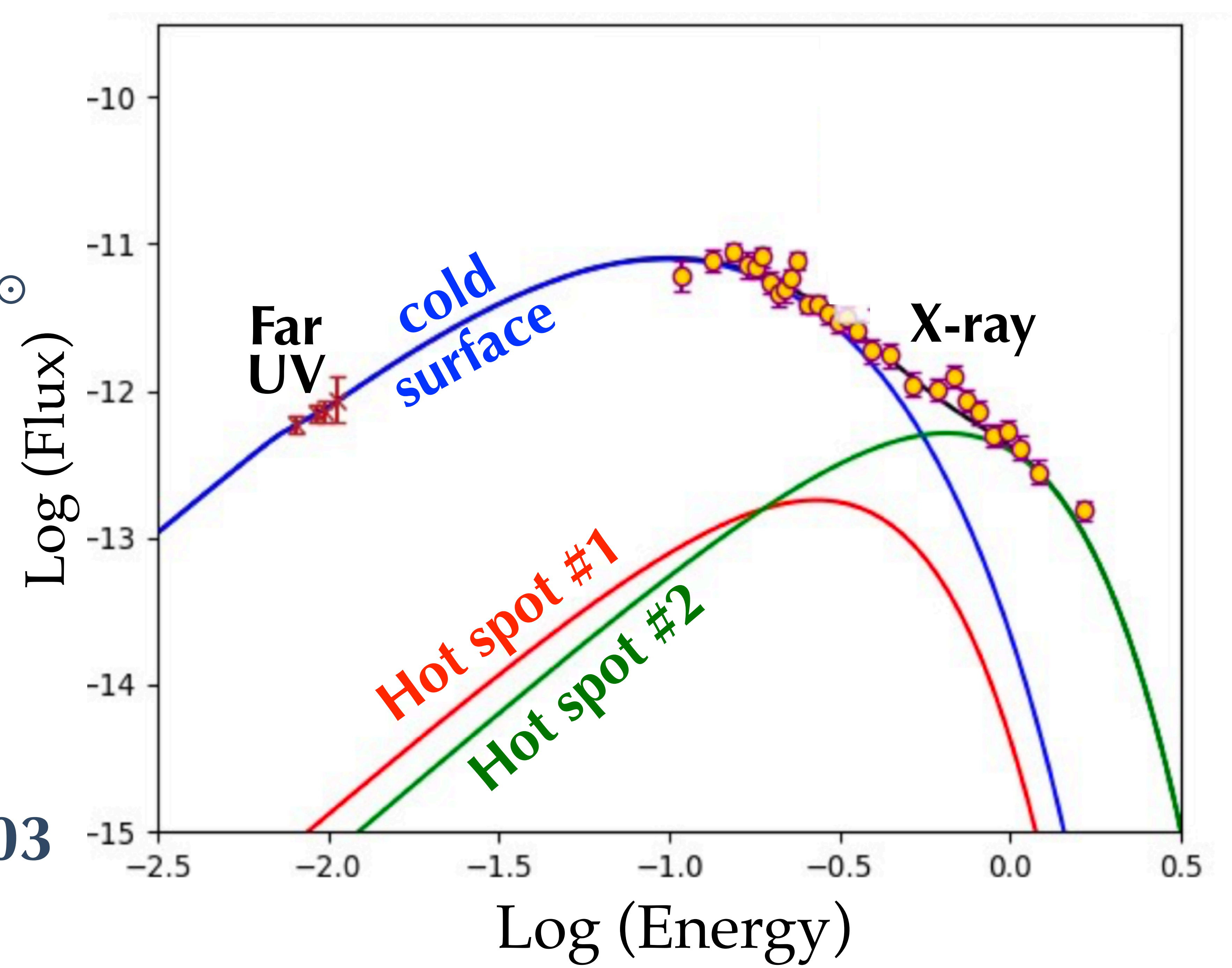


Gonzalez-Canuilef, Guillot & Reisenegger, 2019

Updated work on PSR J0437-4715

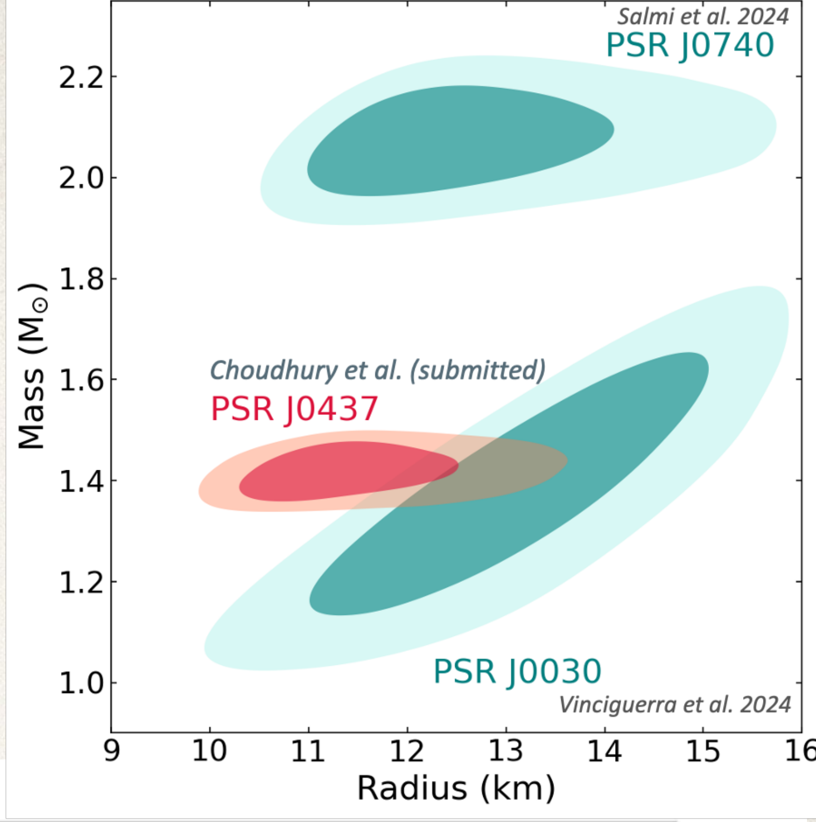
Preliminary work by
PhD student Pierre Stammler

- Excluding some UV points
- Including priors on distance and mass: $M_{\rm PSR} = 1.44 \pm 0.07\ \mathrm{M}_\odot$
- Including modelling of hot spots
- Updated priors on reddening



Updated prior:
E(B-V) = 0.005 ± 0.003
(Vergely et al. 2022)

Updated work on PSR J0437-4715



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- Including modelling of hot spots
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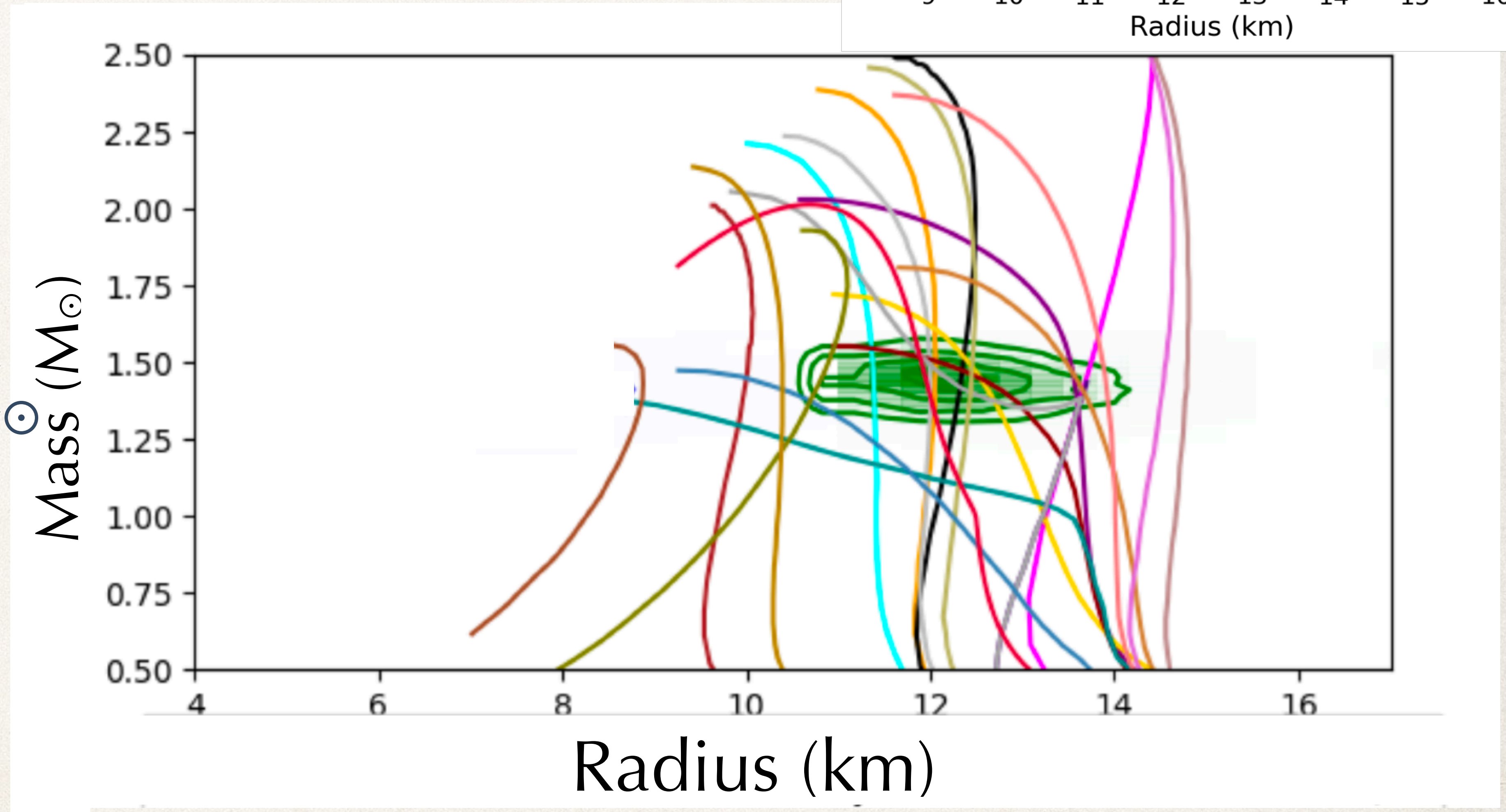

R_{NS} = 12.3 ± 0.9 km
i.e. uncertainties: ± 7.3 %

Outline

- **Constraints from GW of NS-NS mergers** (*J. Read's talk*)
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  - Accreting
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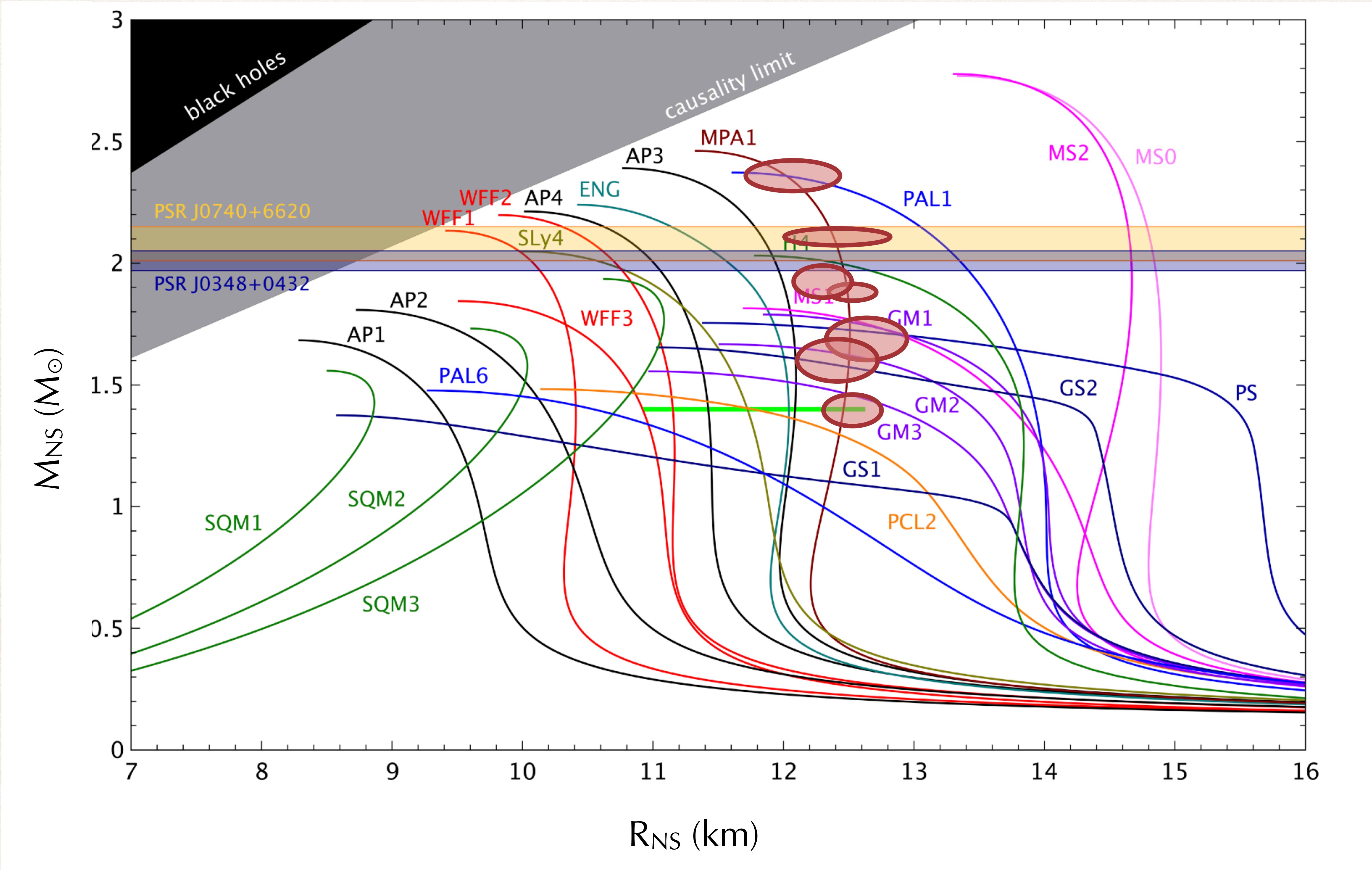
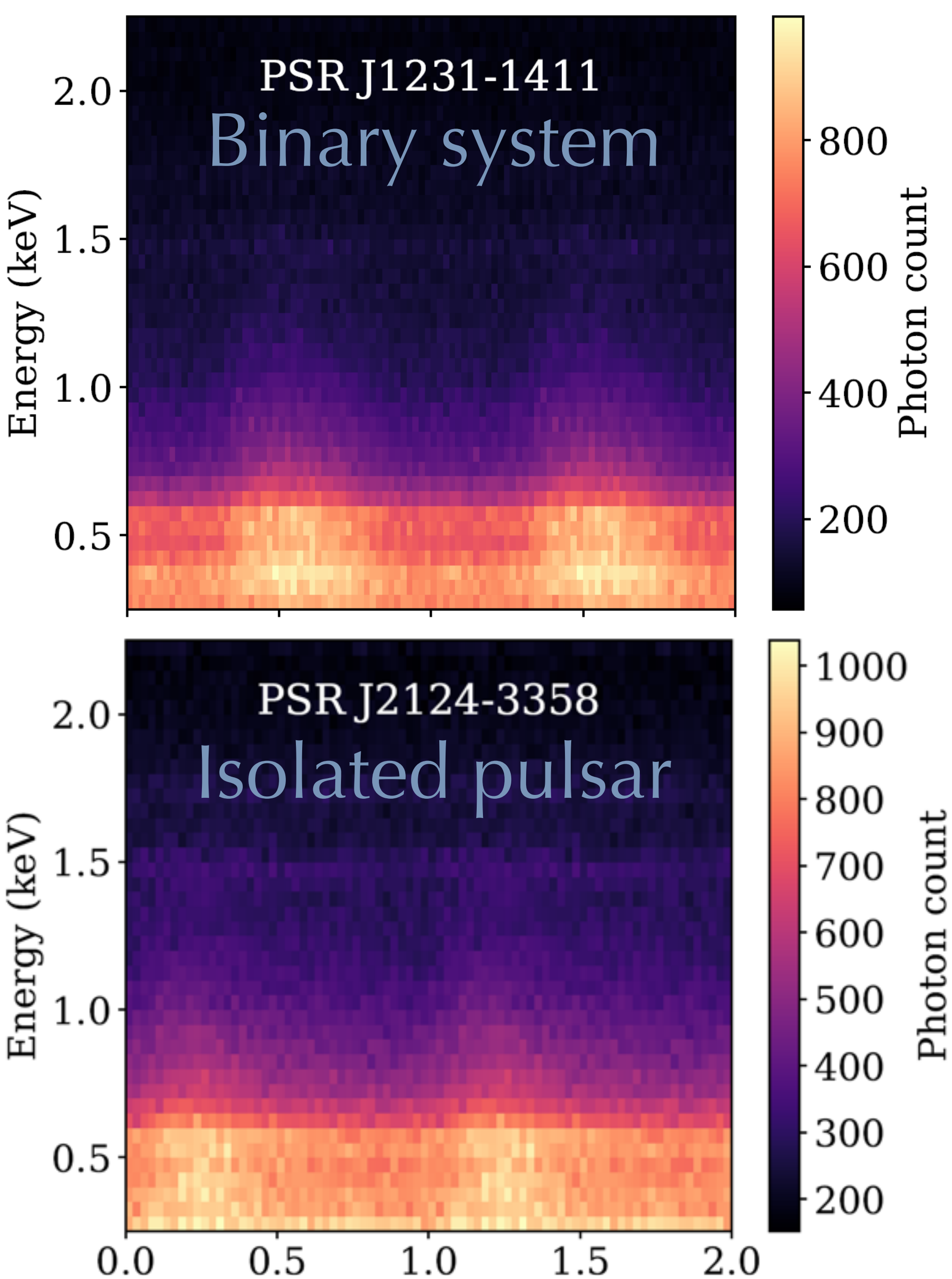
  - Results from NICER
  - Other results
- **Future prospects**

Future prospects: Will we get there ?



Let’s start with MSPs observed by NICER

There are still many data sets to analyse, including newly discovered millisecond pulsars.

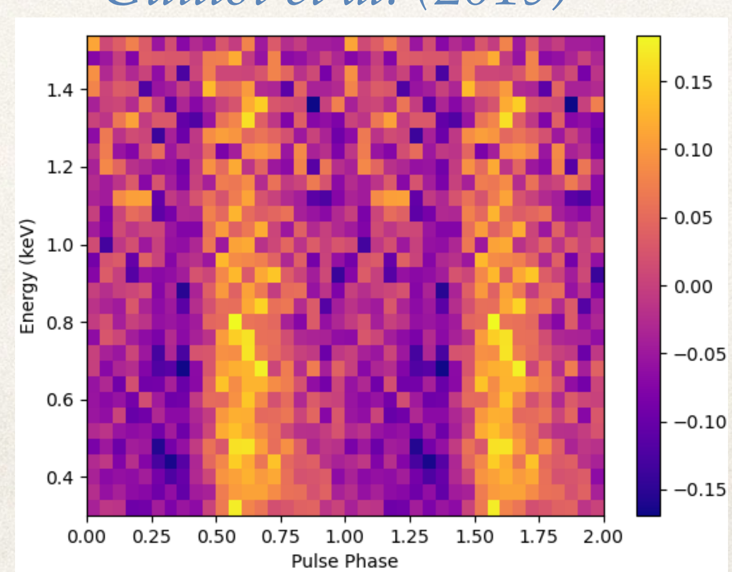


Bogdanov et al. (2019)

PhD work of Lucien Mauviard

PSR J0614–3329

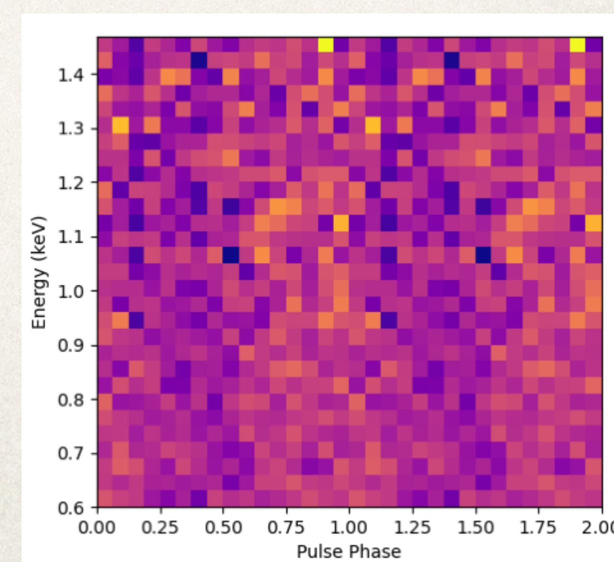
Guillot et al. (2019)



PSR J1614-2230

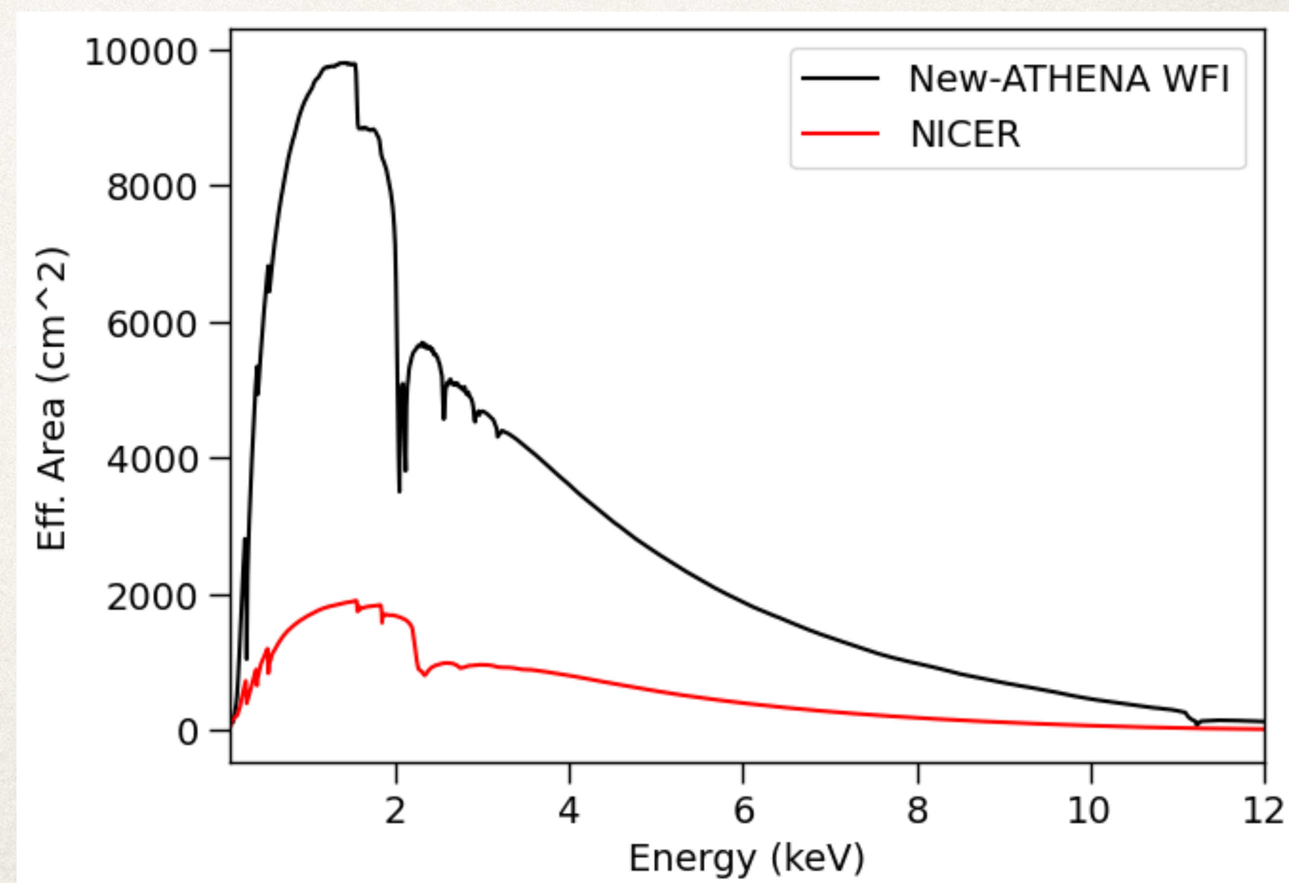
Known high mass:

$M = 1.908 \pm 0.016\ M_\odot$



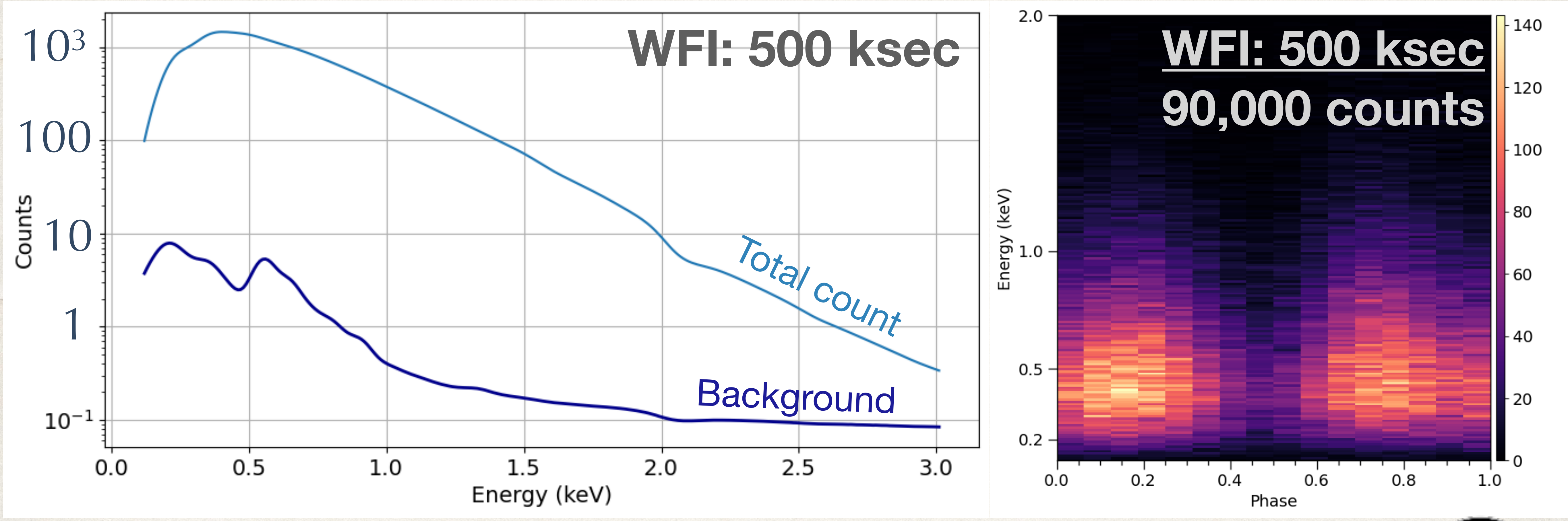
New-ATHENA

- Sensitivity: about x5 that of NICER
- Time resolution:
  - 10 µsec (X-IFU)
  - ~100 µsec (WFI)
- Low-background: ~ 0.001 c/s



Future prospects for pulse profile modelling with new-Athena are quite promising.

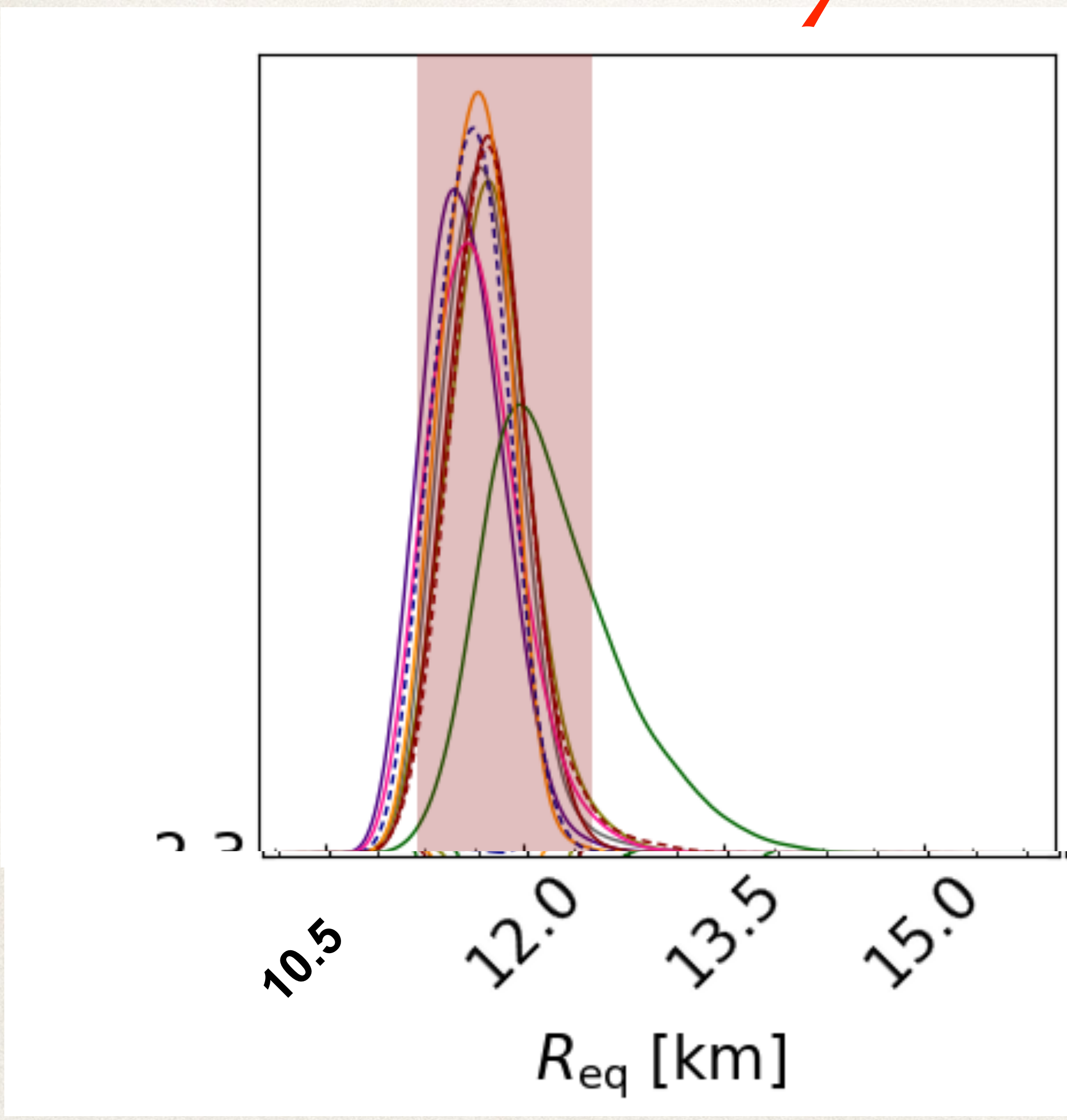
Simulations based on PSR J0740+6620



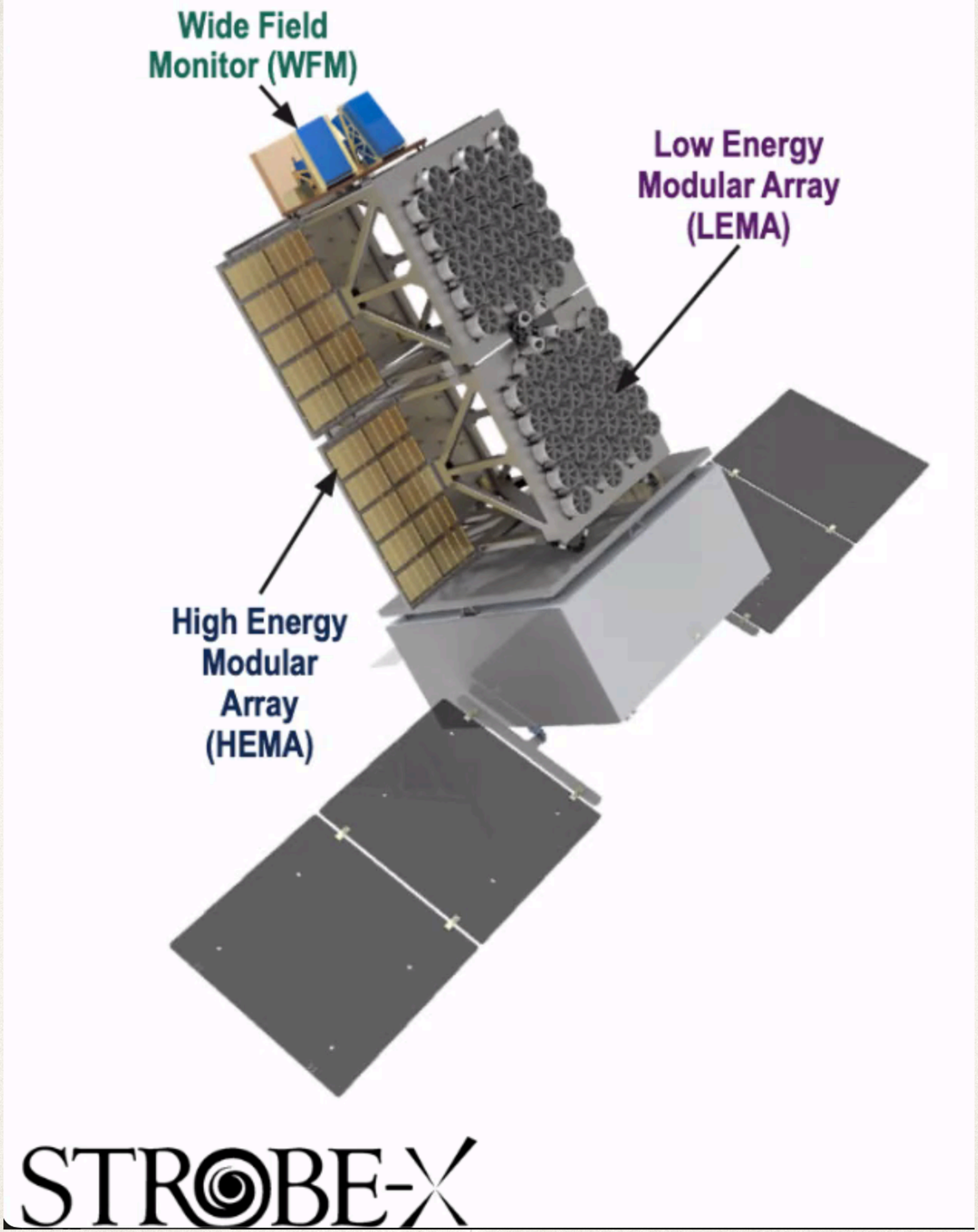
X-PSI

Inference on the radius of PSR J0740+6620 from 500 ks with New−Athena WFI

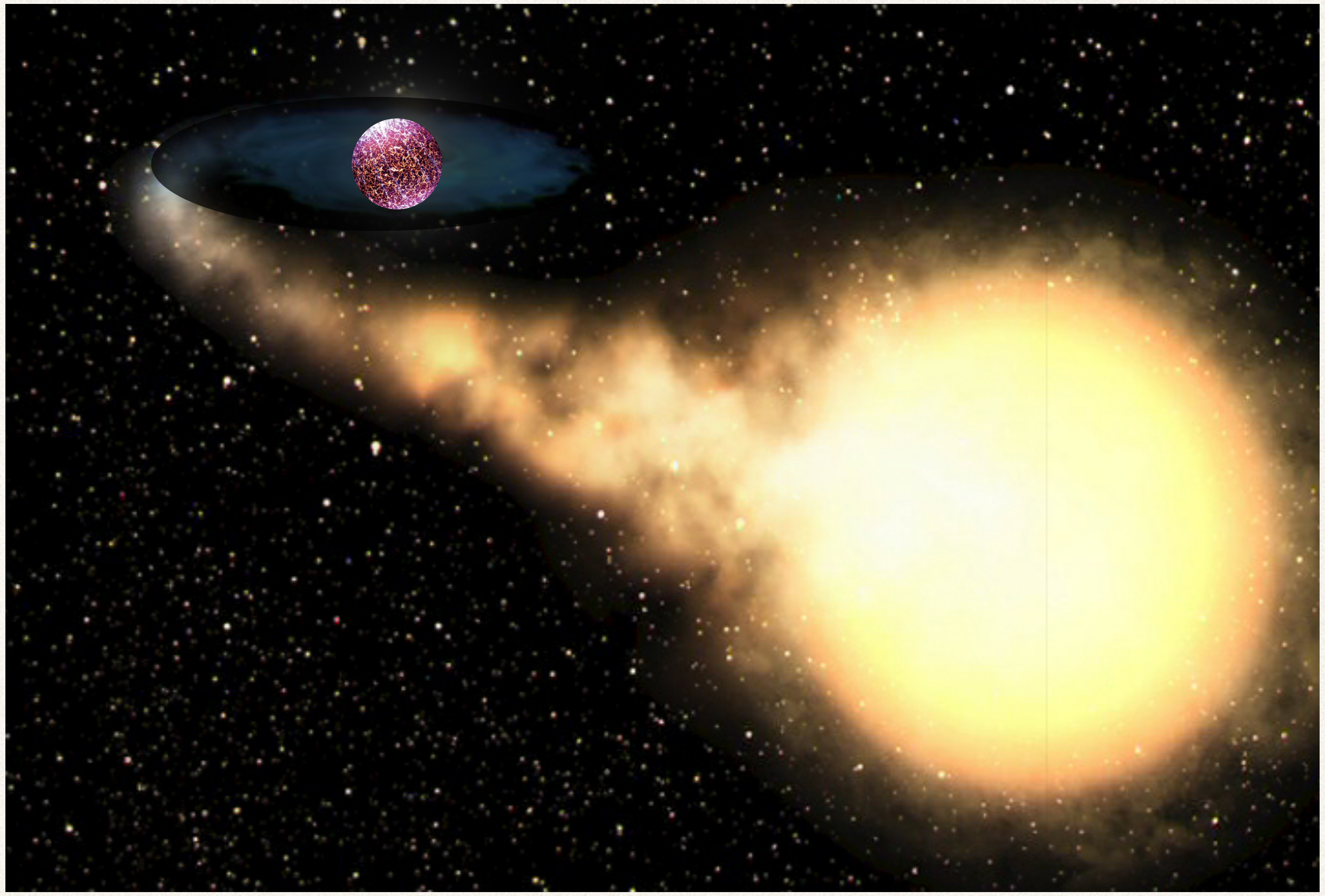
Preliminary



- **Radius 1-sigma uncertainties**
  - NICER 1600 ksec: ~10%
  - ATHENA 500 ksec: ~3% average (±0.3 km)
- **New-Athena distinguishes between H and He atmosphere composition**
- **Can Athena distinguish between spot patterns ?**


Wide Field Monitor (WFM)
Low Energy Modular Array (LEMA)
High Energy Modular Array (HEMA)
STROBE-X

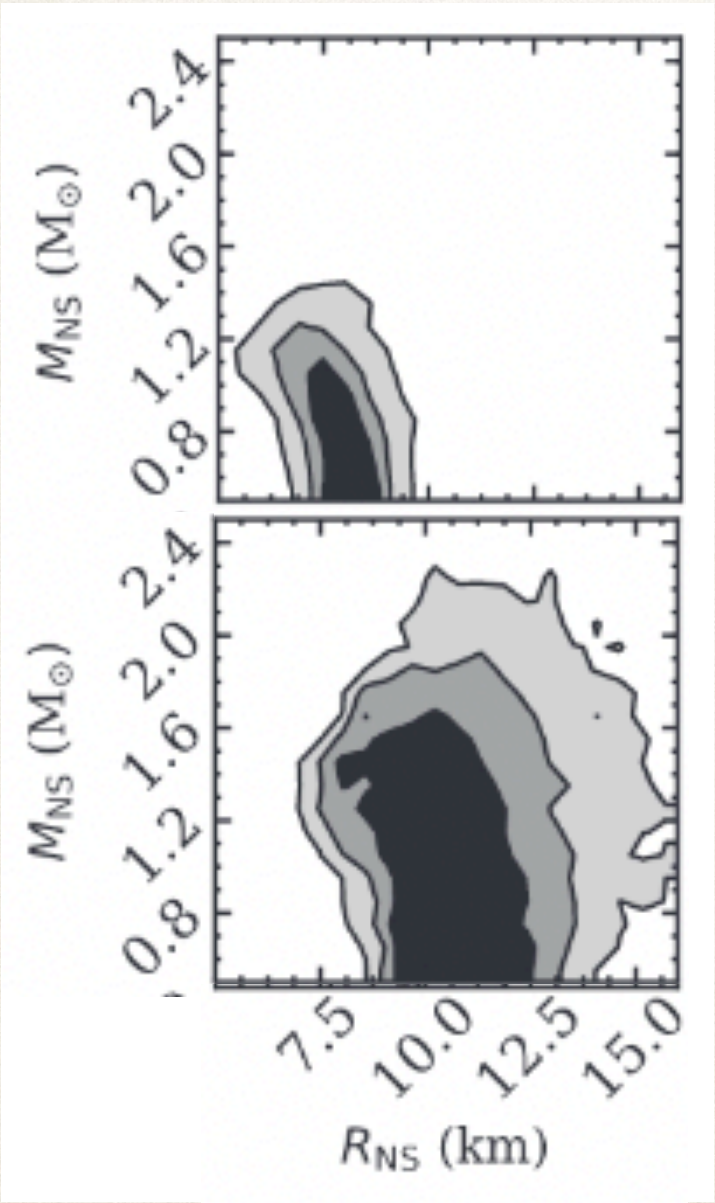
Let's continue with NS in low-mass X-ray binaries.



- What is the **composition** of the neutron star atmosphere ? → Hydrogen, Helium or something else
- Is the emission really from the **entire surface** ? → No measurement, but expected for LXMBs

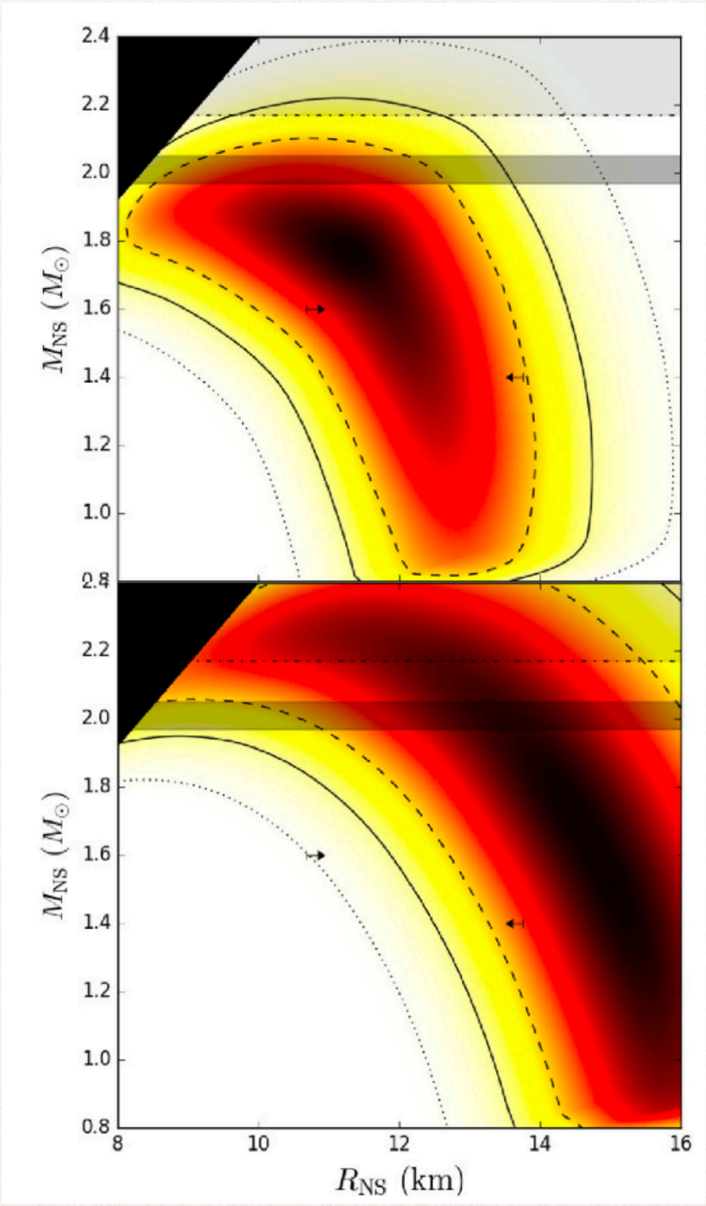
Assuming the wrong composition may severely bias the result.

qLMXB in M30



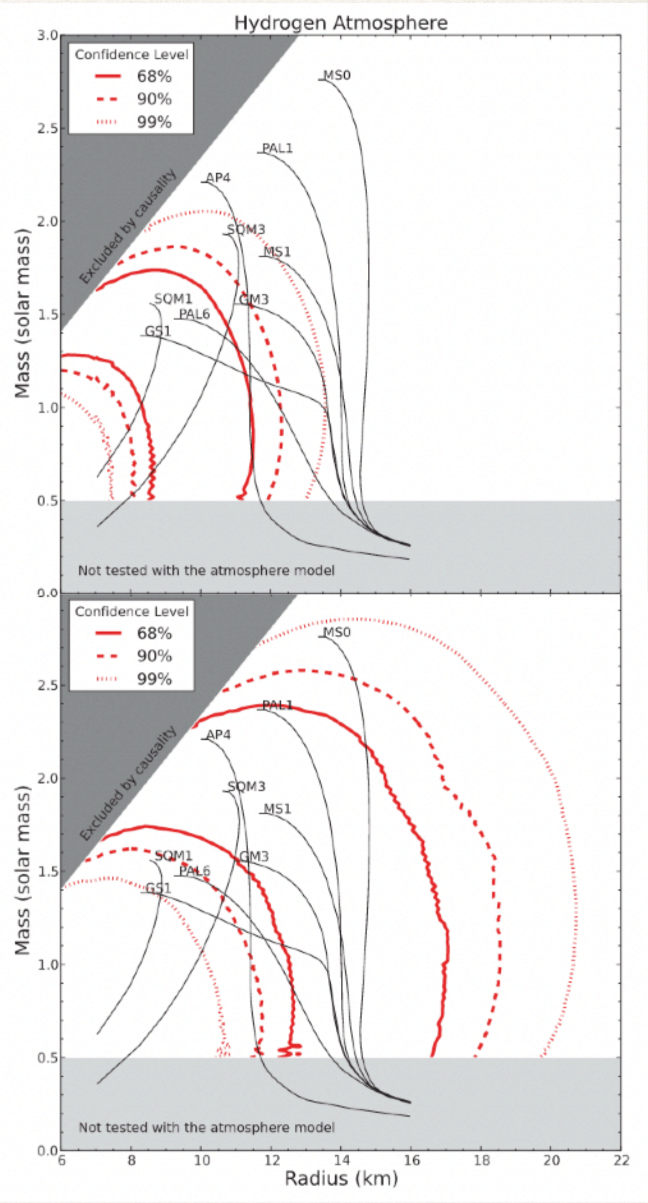
Echiburú, SG et al. 2020

qLMXB in M13



Shaw et al. 2018

qLMXB in M28



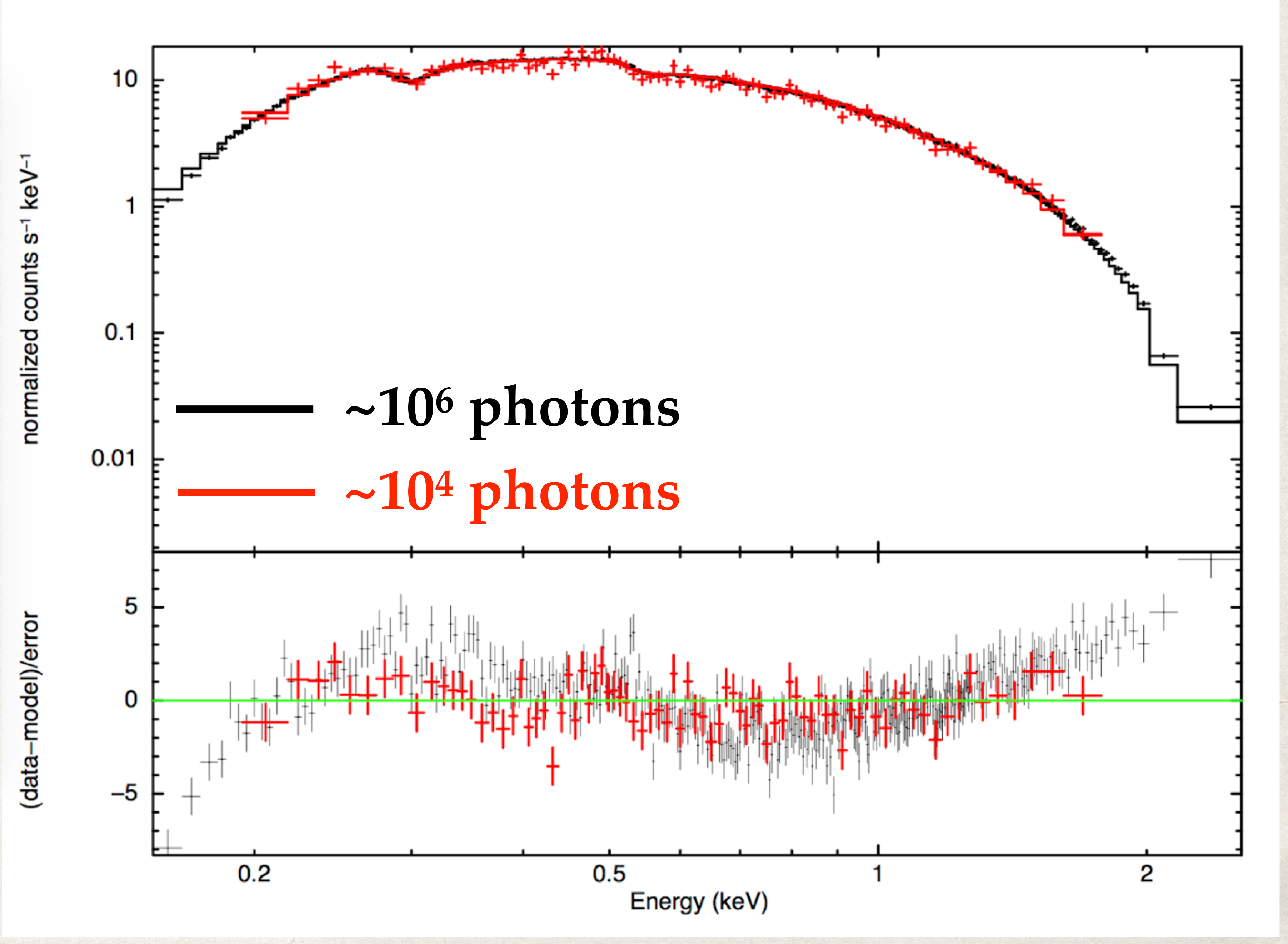
Shaw et al. 2012

Can we tell if a neutron star atmosphere is composed of H or He?

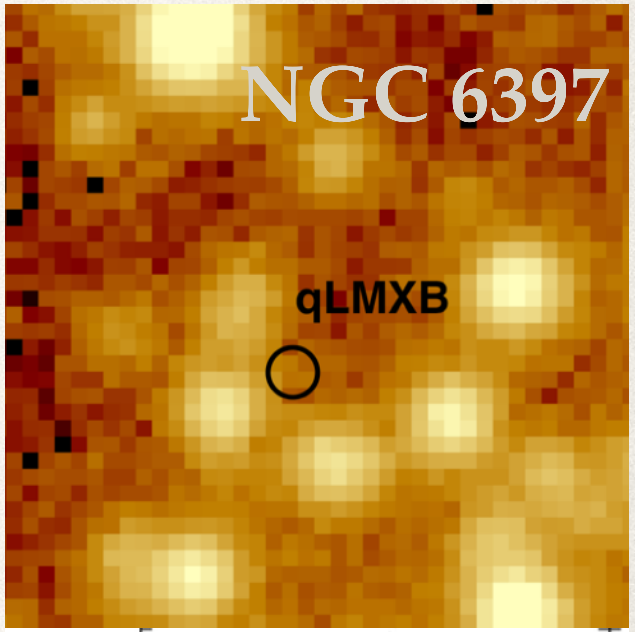
Extremely high S/N spectra permit detection of the subtle variations between H and He atmospheres

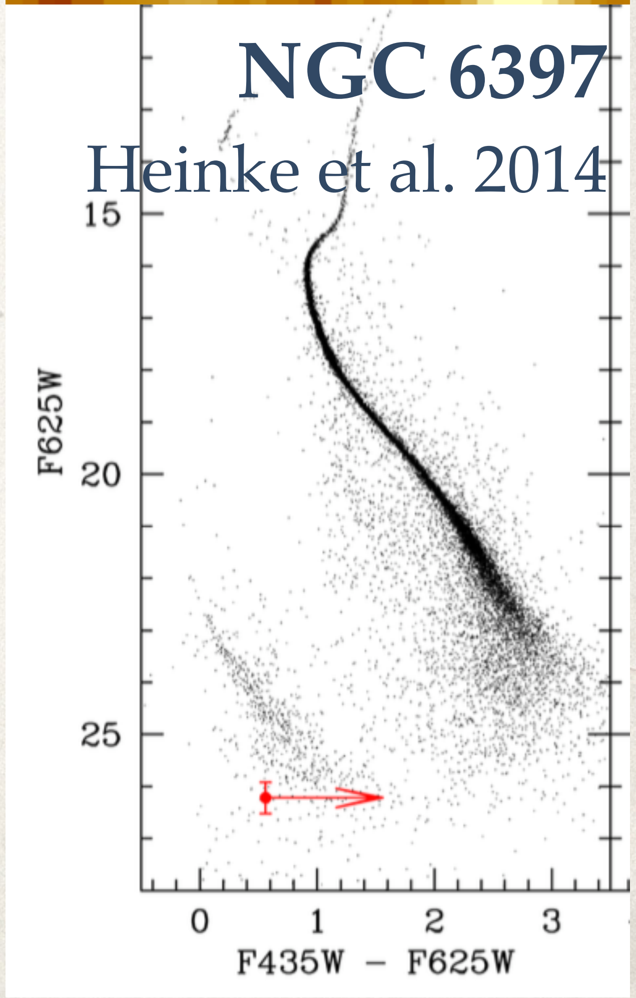
NS atmosphere simulated with helium and fitted with hydrogen

Simulations for proposed mission ***Lynx***



Can we tell if a neutron star atmosphere is composed of H or He?

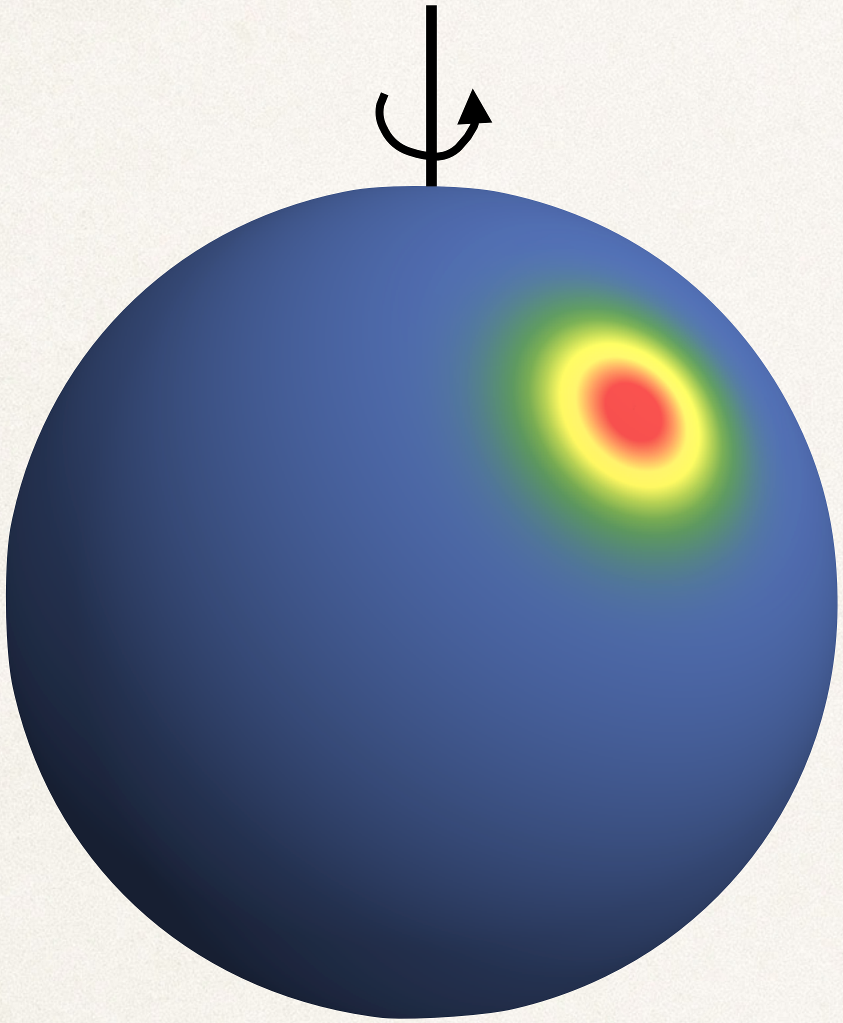




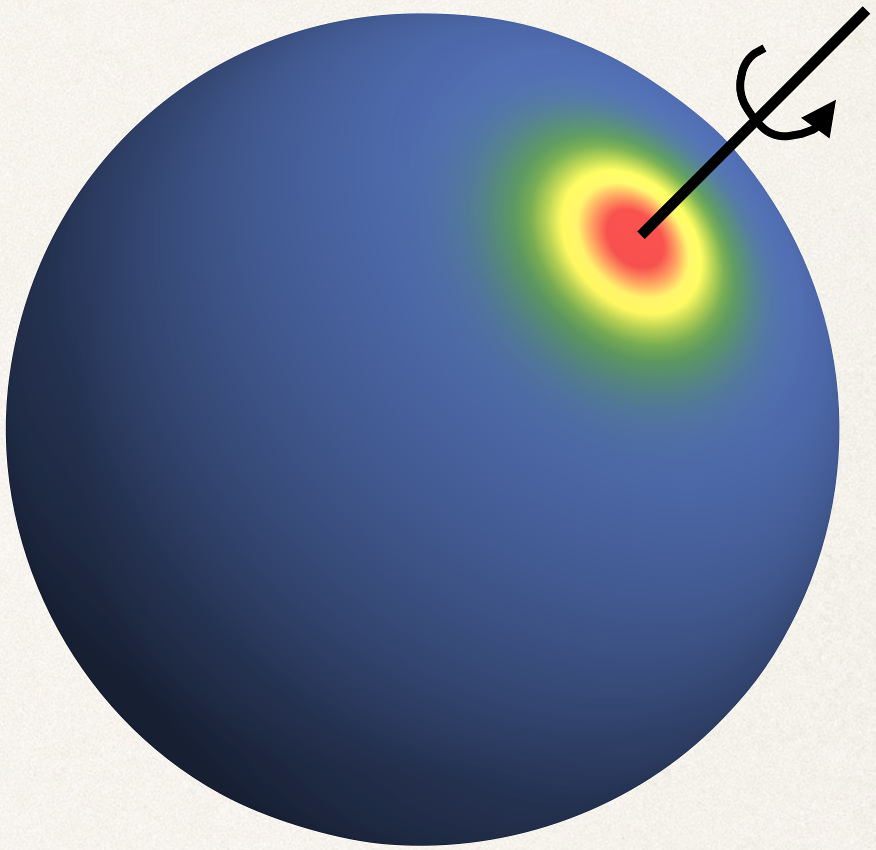
<u>Identifying the donor star in the crowded environments of globular clusters</u>

- Very difficult with ground based (e.g., VLT), even with AO
- Difficult with Hubble Space Telescope
- Easier with JWST

Can we tell whether the surface temperature is uniform or not?



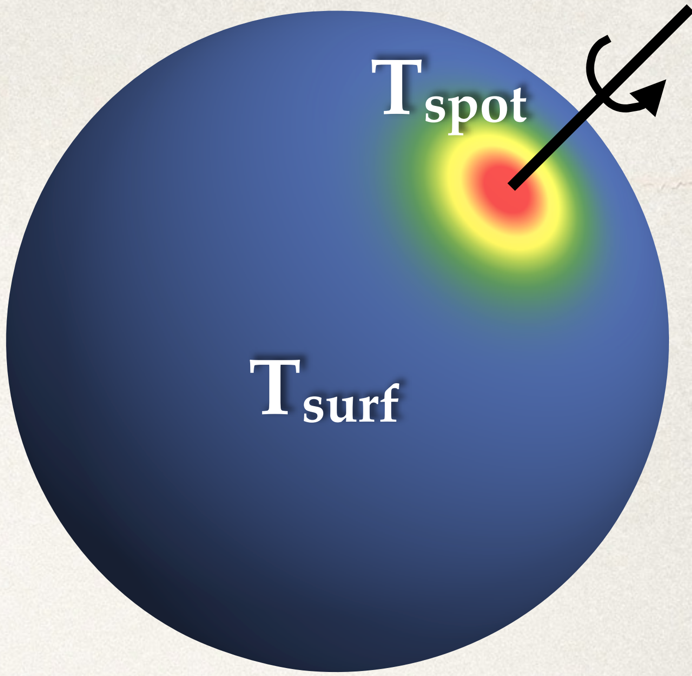
Non-uniform surface manifests as X-ray pulsations

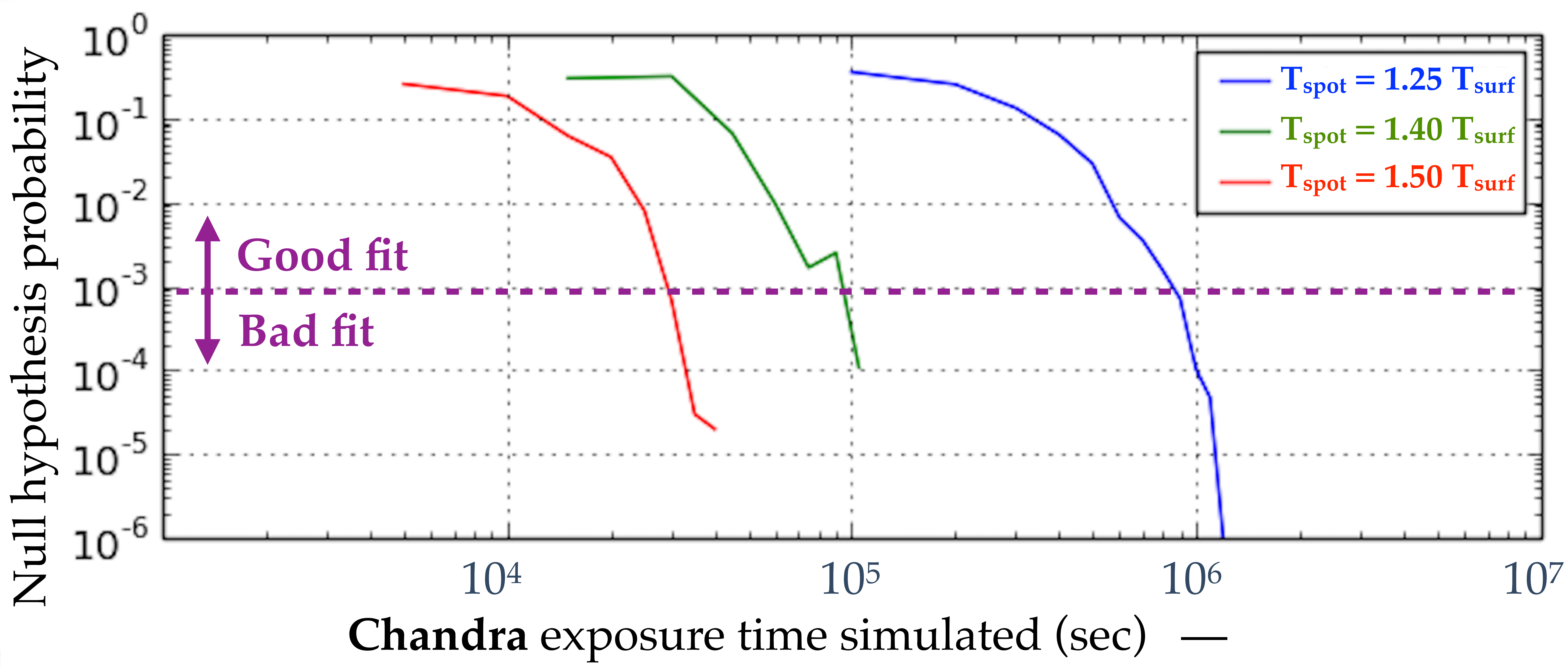


No X-ray pulsations for some specific geometries

Can we tell from the X-ray spectra?

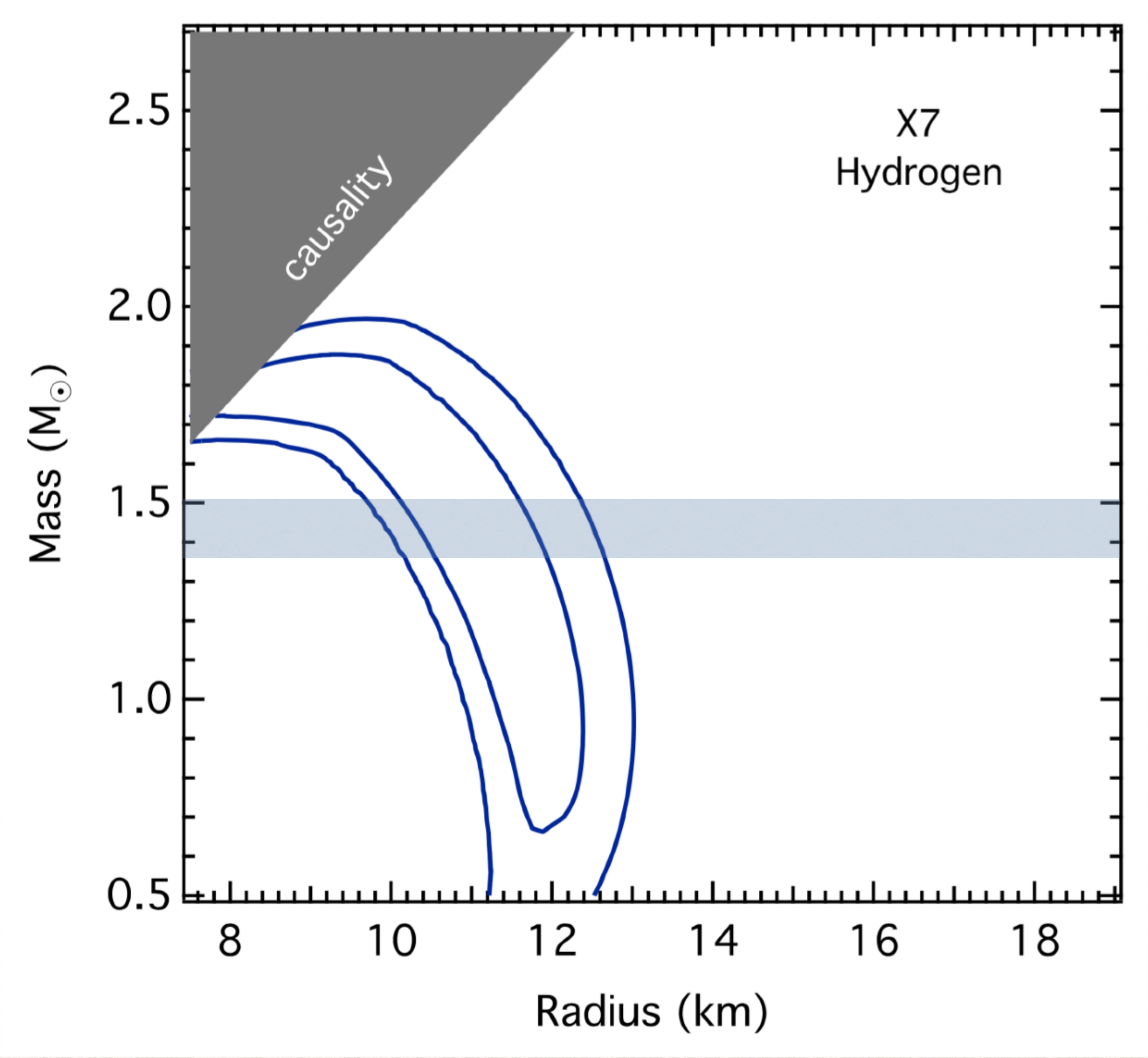
A hot spot that does not generate X-ray pulsations may be detected spectrally.





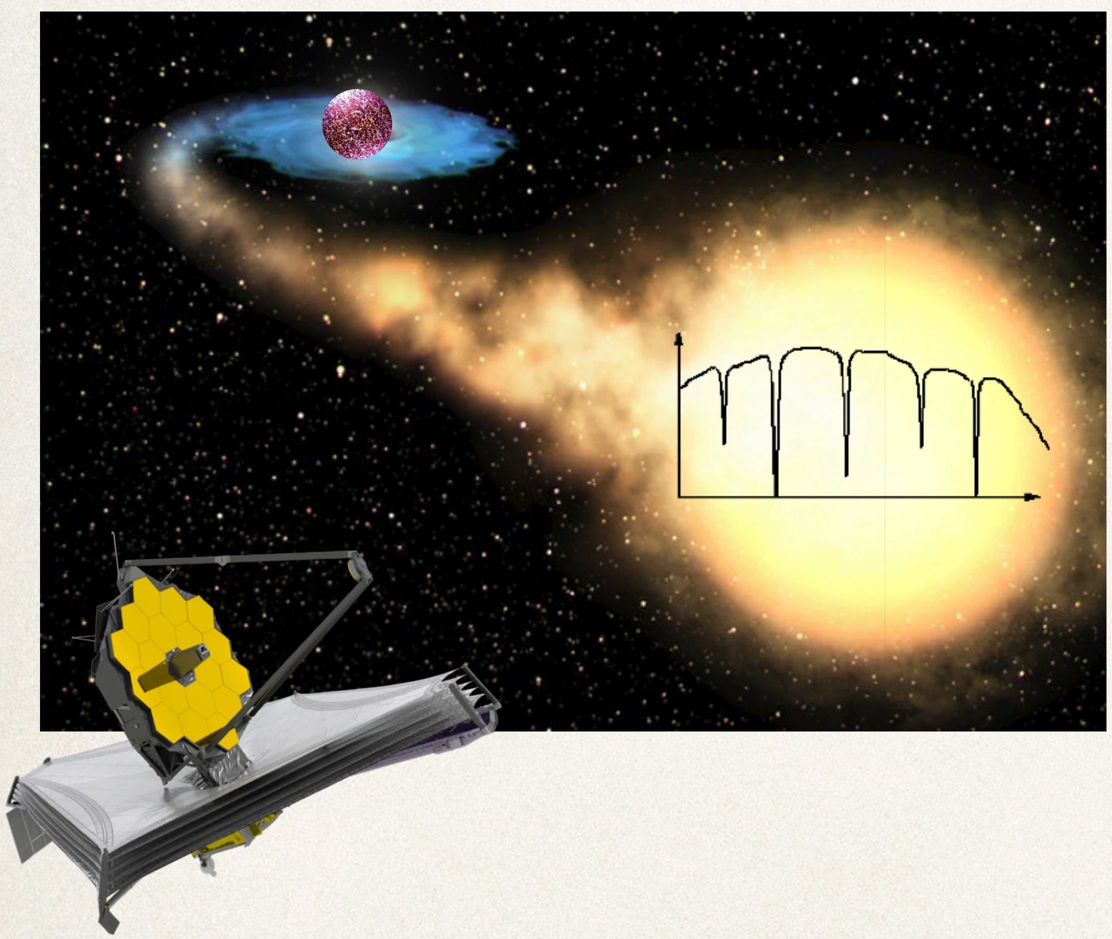
Simulations by Goran Doll Carriel

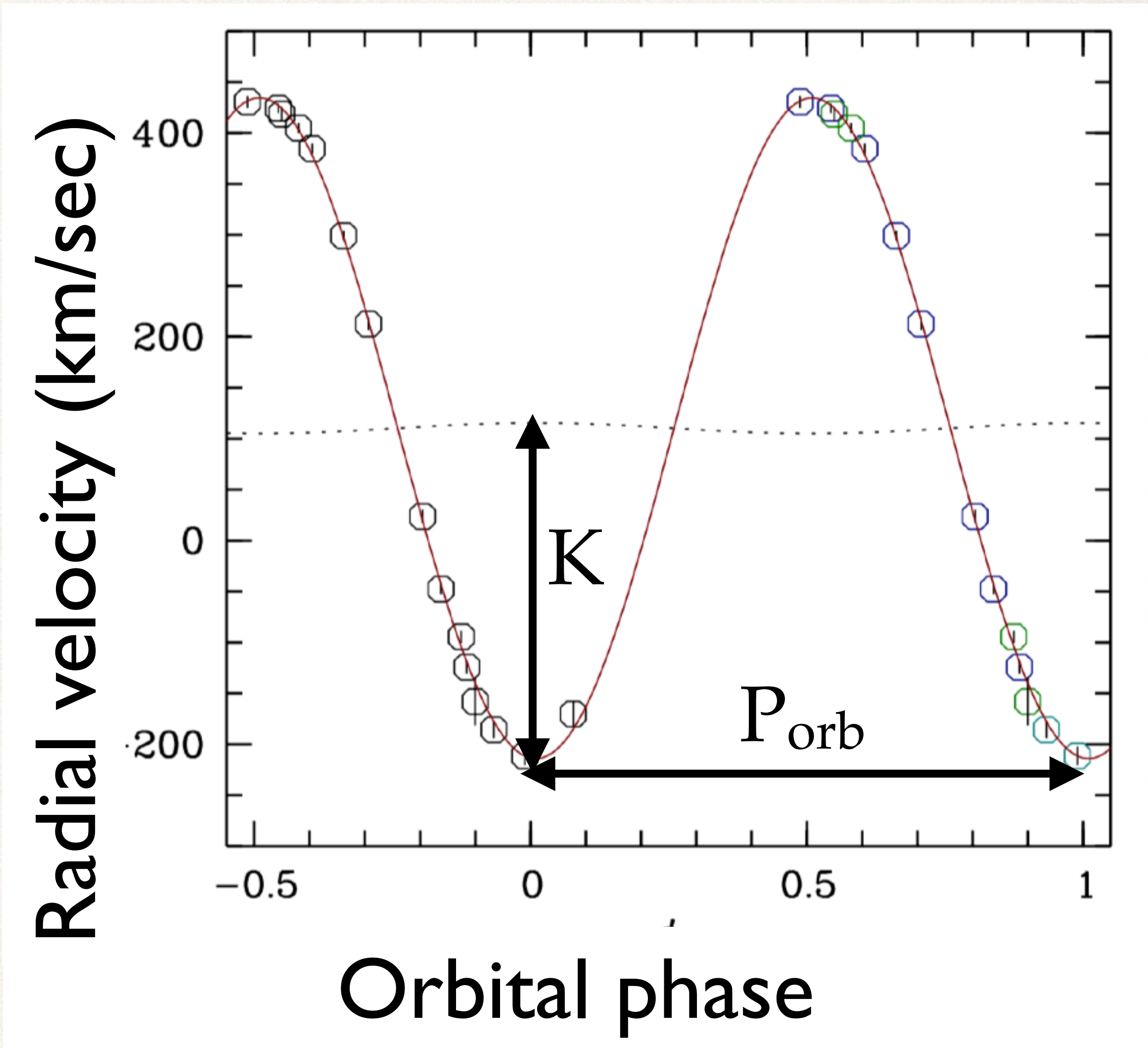
Another question: Could we measure the mass to break the M–R degeneracy?



This requires identifying the companion star and determining the orbital parameters

Observing the binary companion to the NS

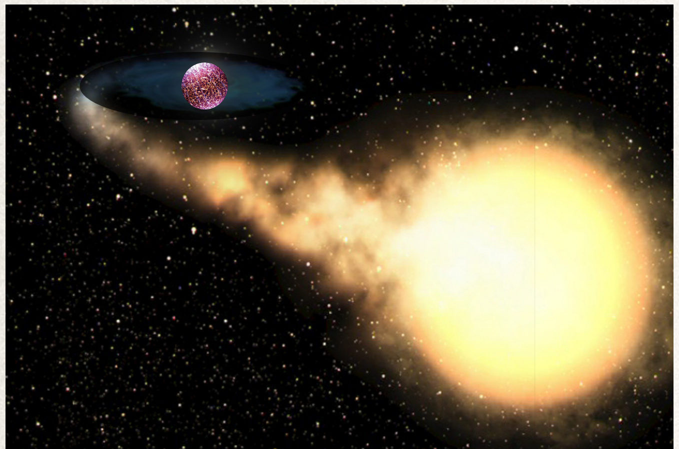


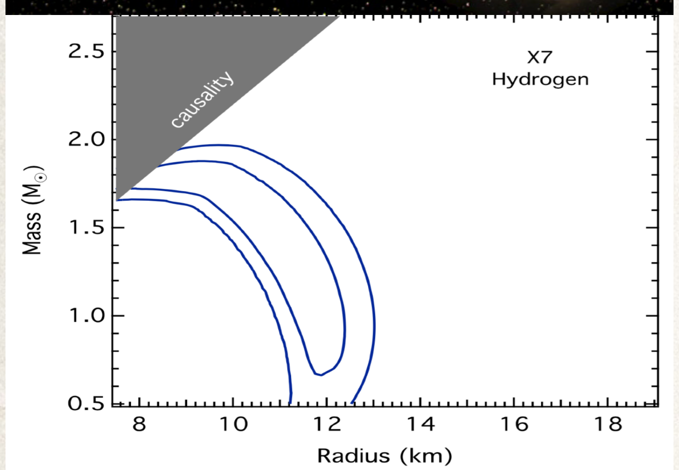


$$\frac{M_{\rm NS}^3 \sin^3 i}{(M_{\rm NS} + M_{\rm comp})^2} = \frac{P_{\rm orb} K^3}{2\pi G}$$

CONCLUSIONS

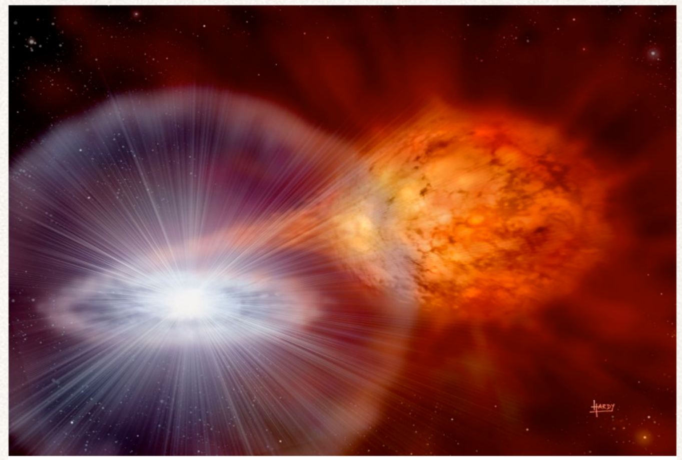
LMXB in quiescence

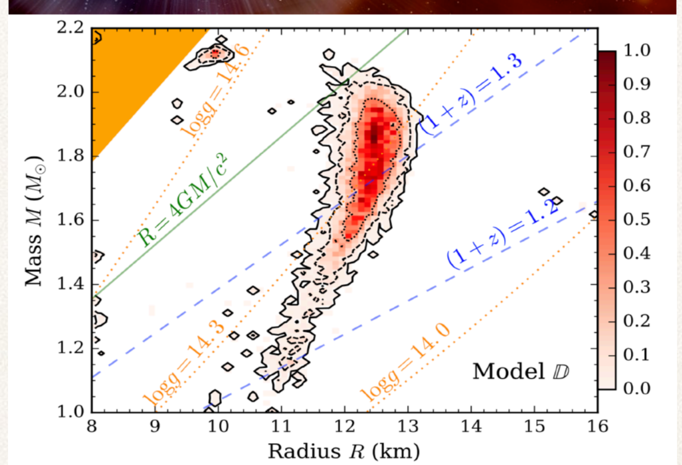




Requires many observations to limit systematics

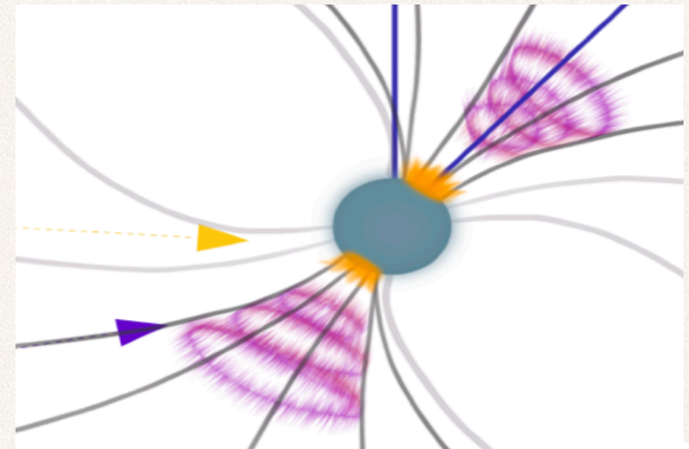
LMXB with X-ray bursts

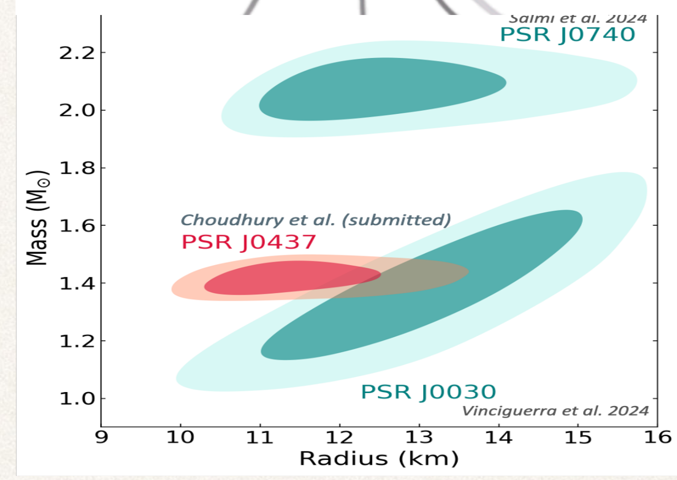




Needs understanding of interplay between burst and disk

MSP with hot spots

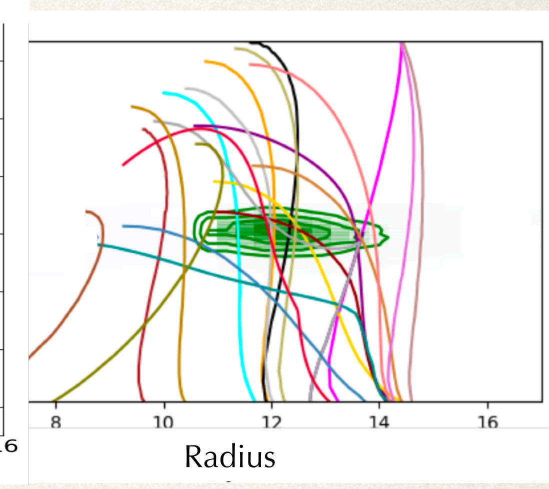




Handle the spot patterns and the background

ATHENA

STROBE-X



Add the "cold" surface in modelling

CompARE