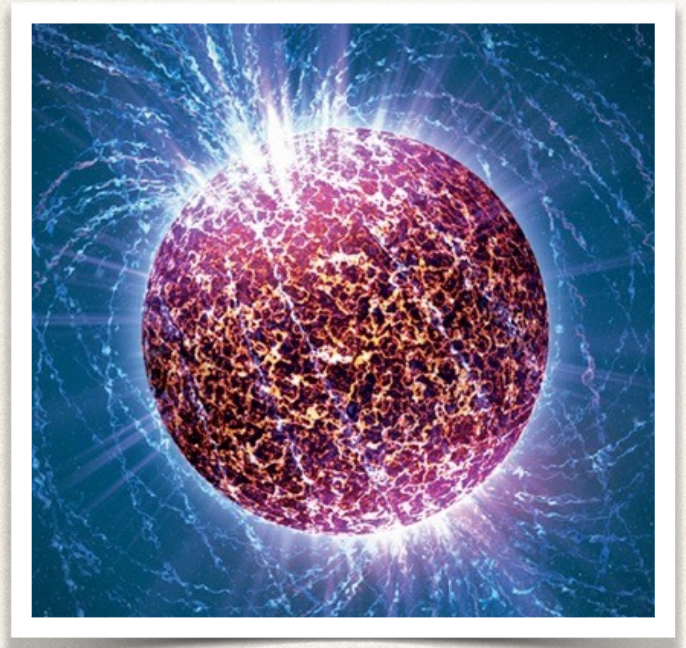
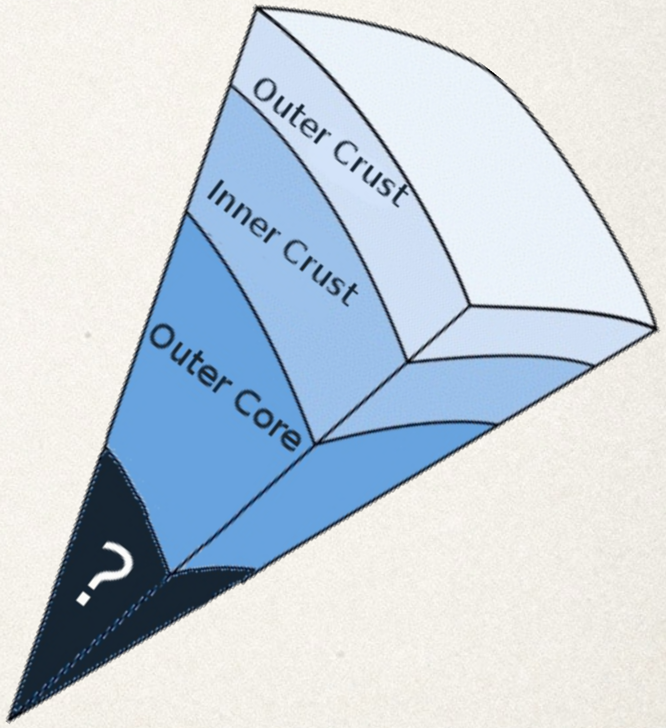
Updates and prospects on measurements of neutron stars masses and radii

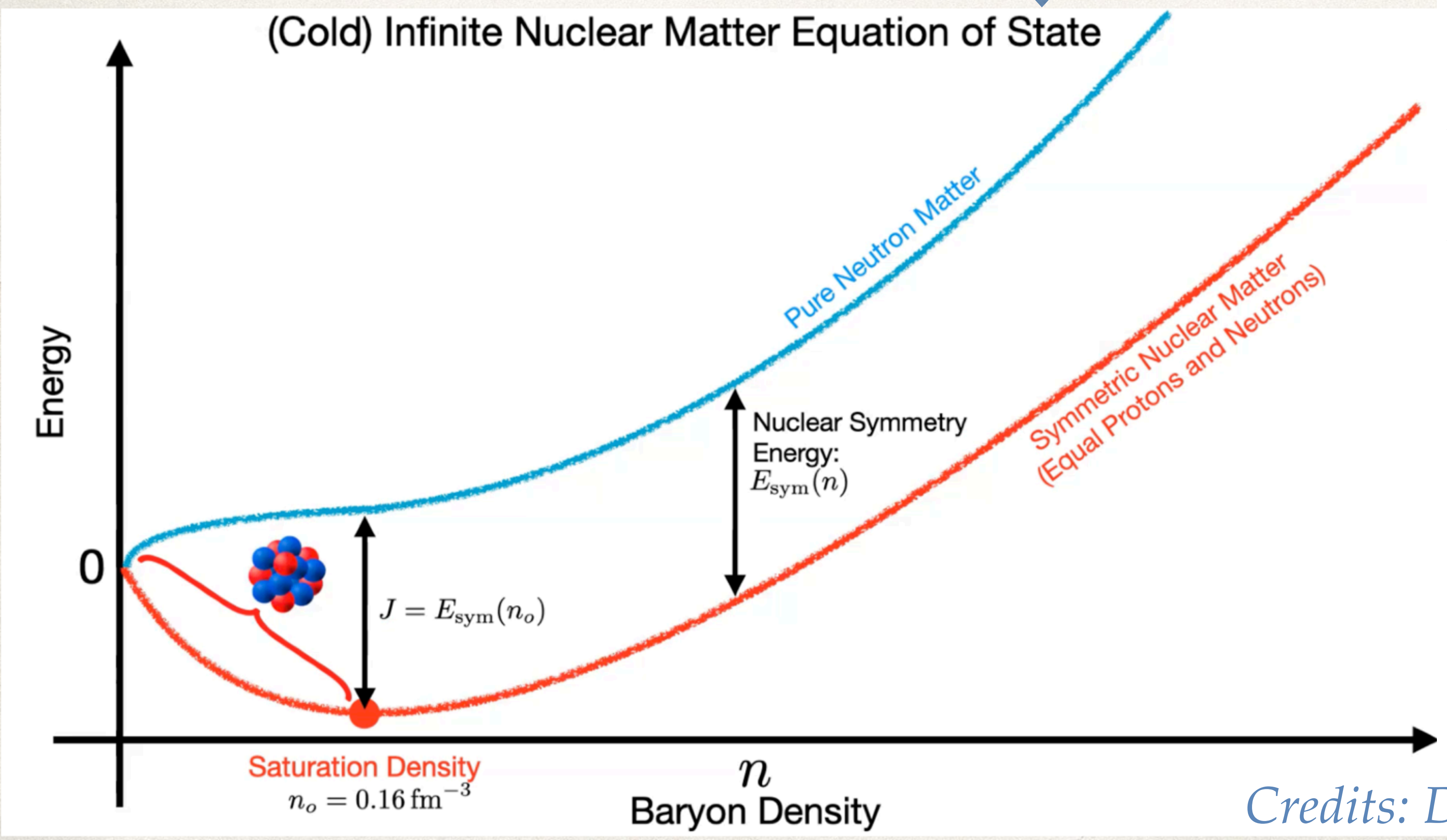
Sebastien Guillot

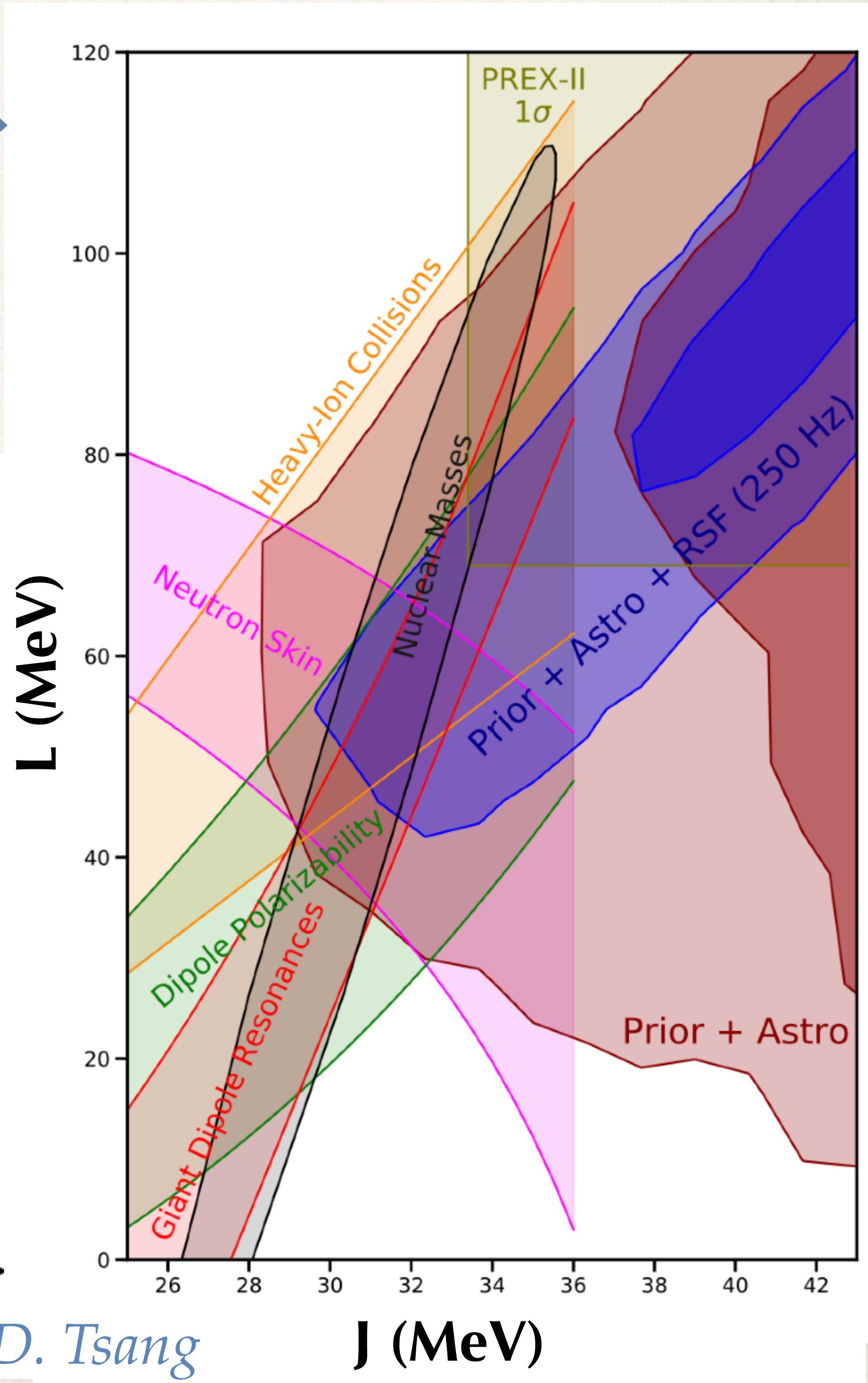
irap
astrophysique & planétologie





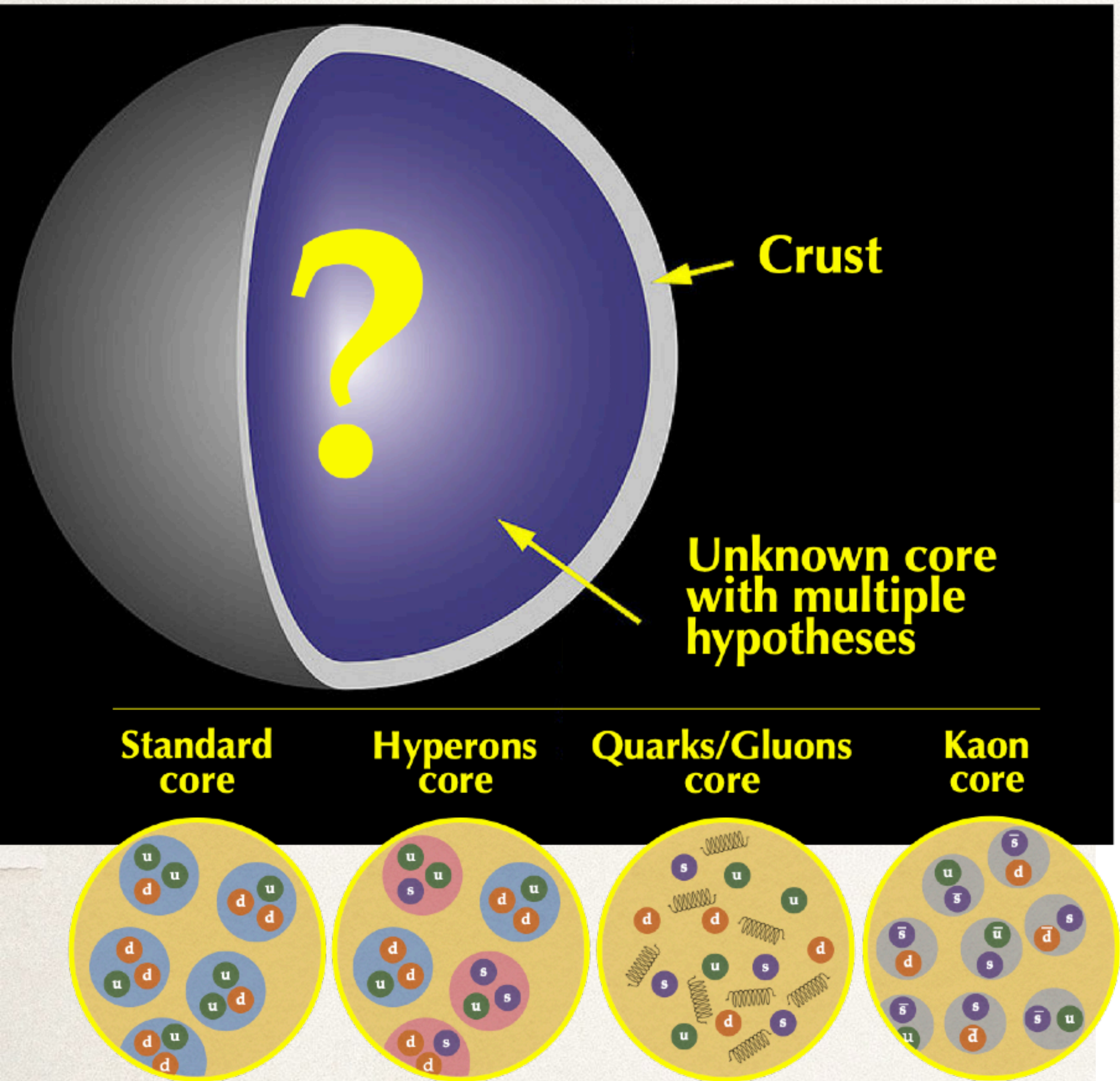
From neutron stars to nuclear physics





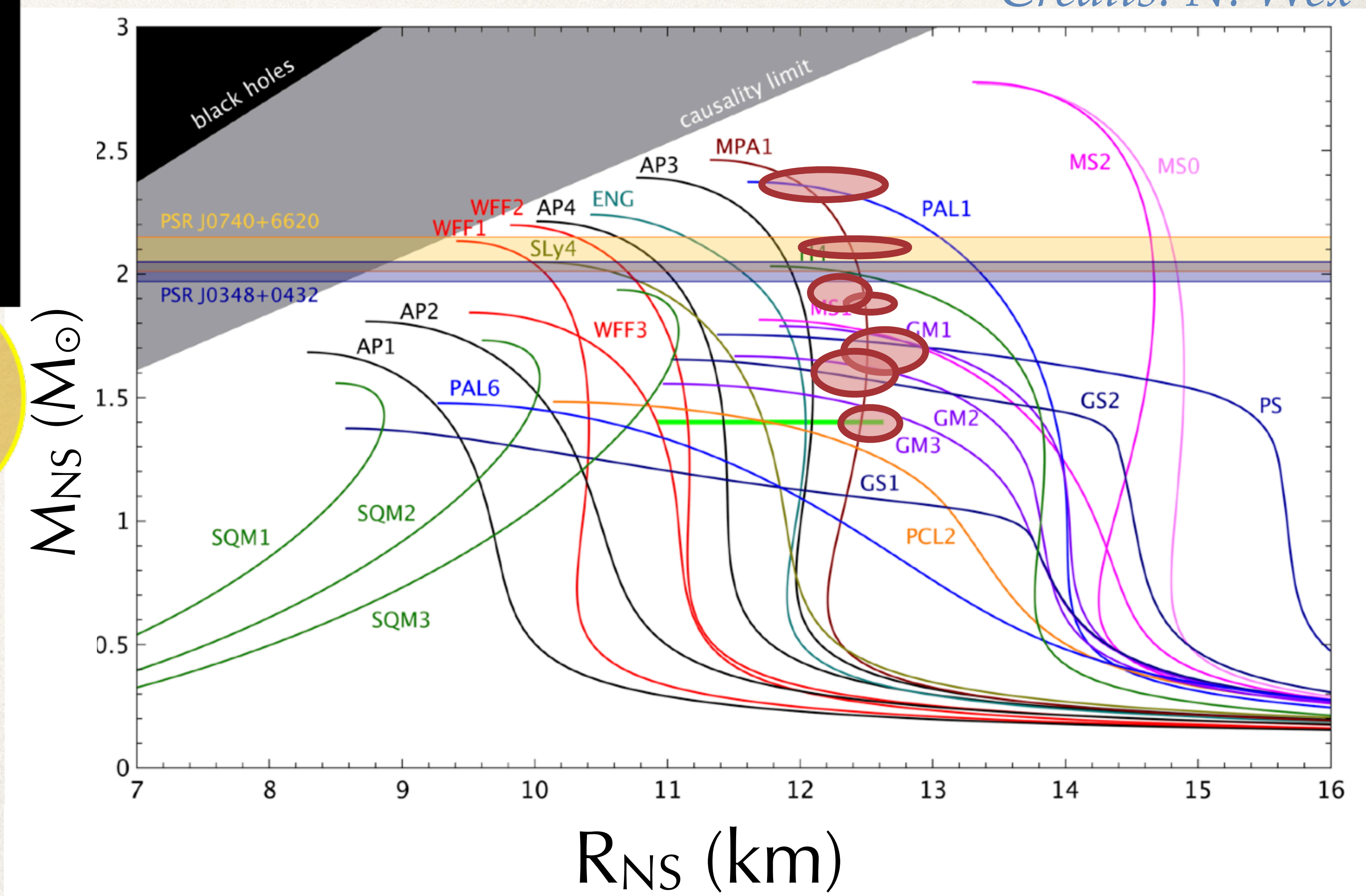
Credits: D. Tsang

The equation of state P(ρ) of the unknown interior of neutron stars can be determined with measurements of M_{NS} – R_{NS} with a few % precision.



$$P\left(\rho\right) \rightleftarrows M\left(R\right)$$

Credits: N. Wex



Outline

This icon
More details
available
if questions

- Measurements of masses and radii
- Results from the NICER mission
  - Method, results, lessons…
- A new tool for future measurements
- Future prospects

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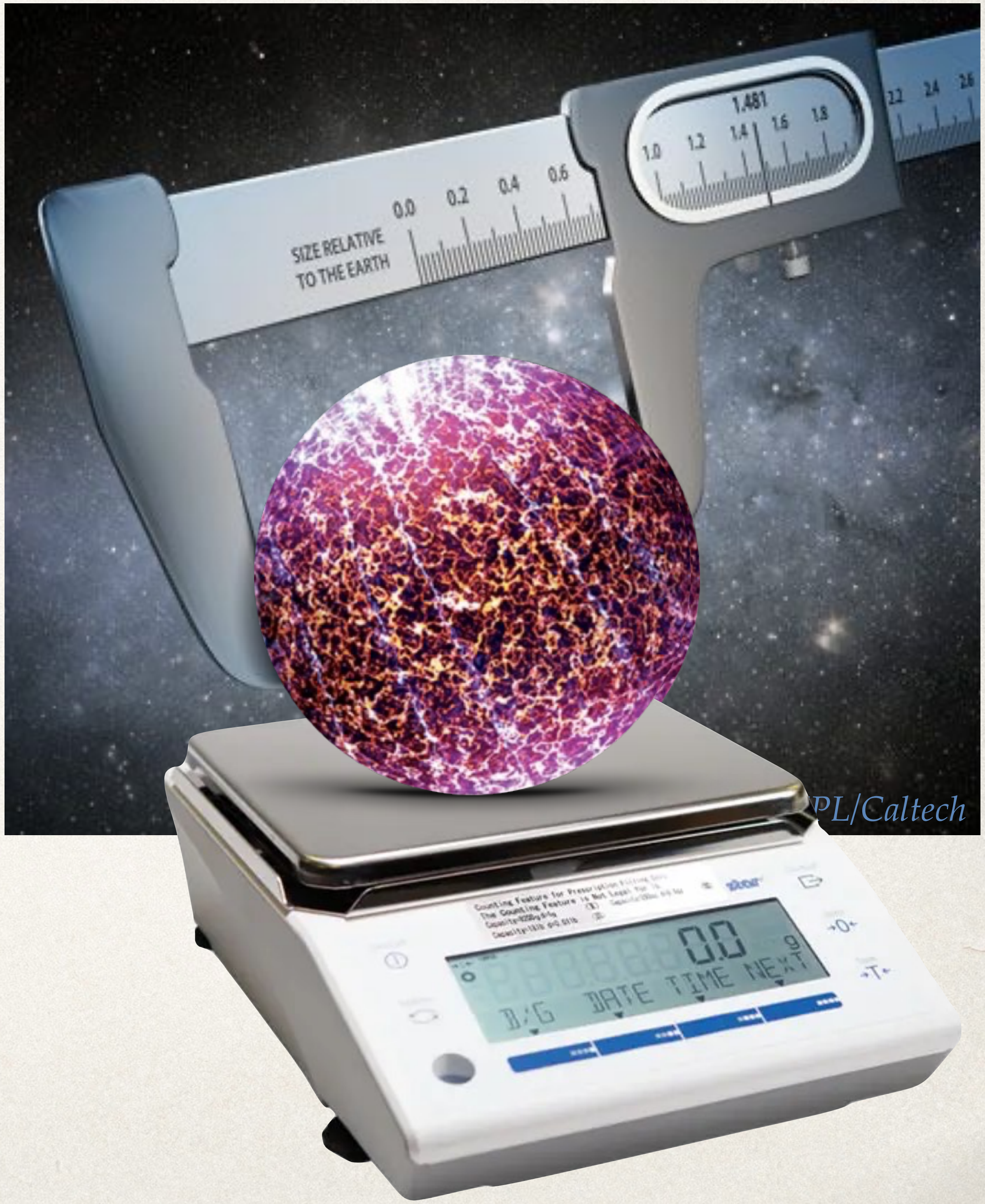
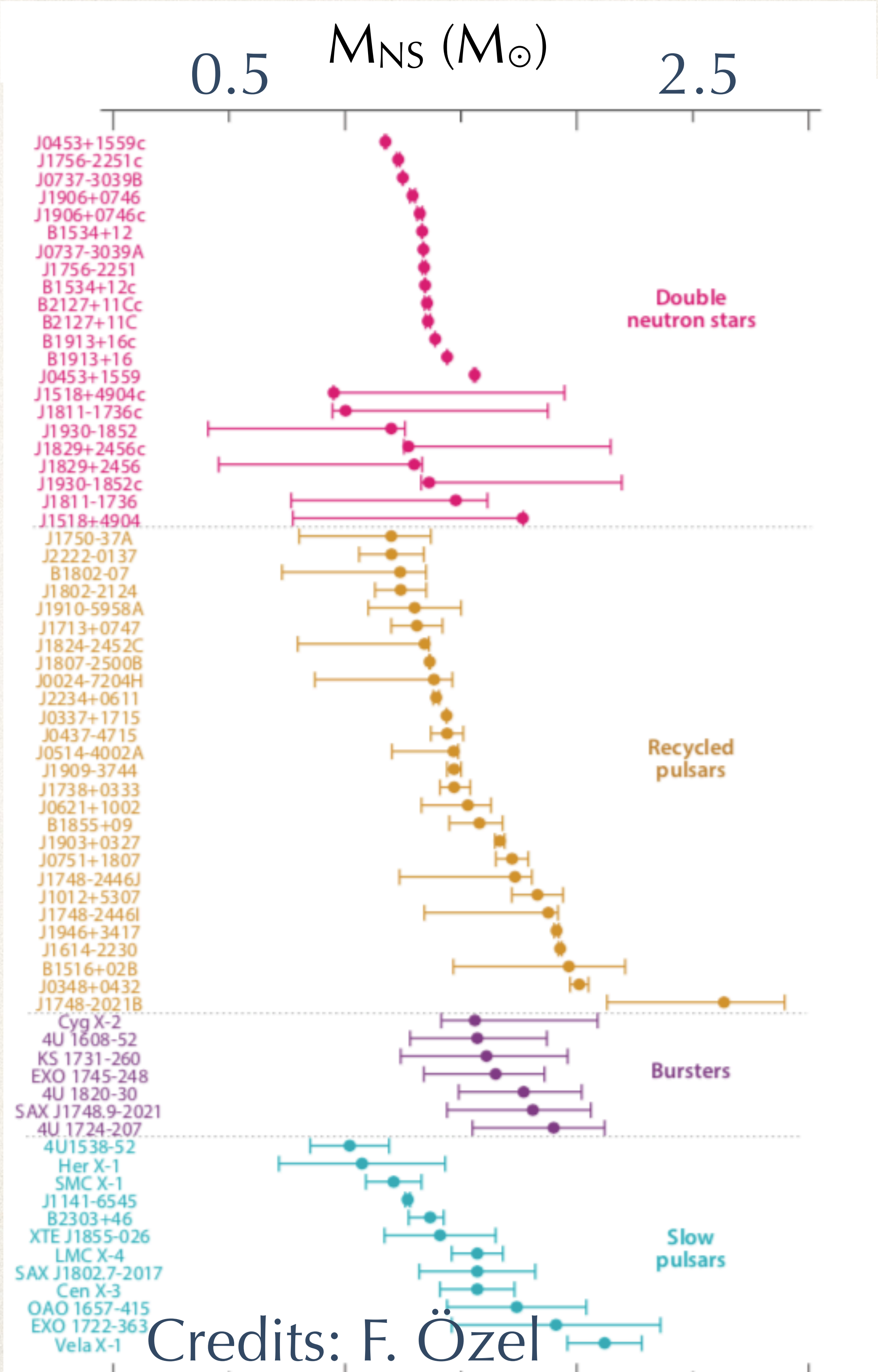
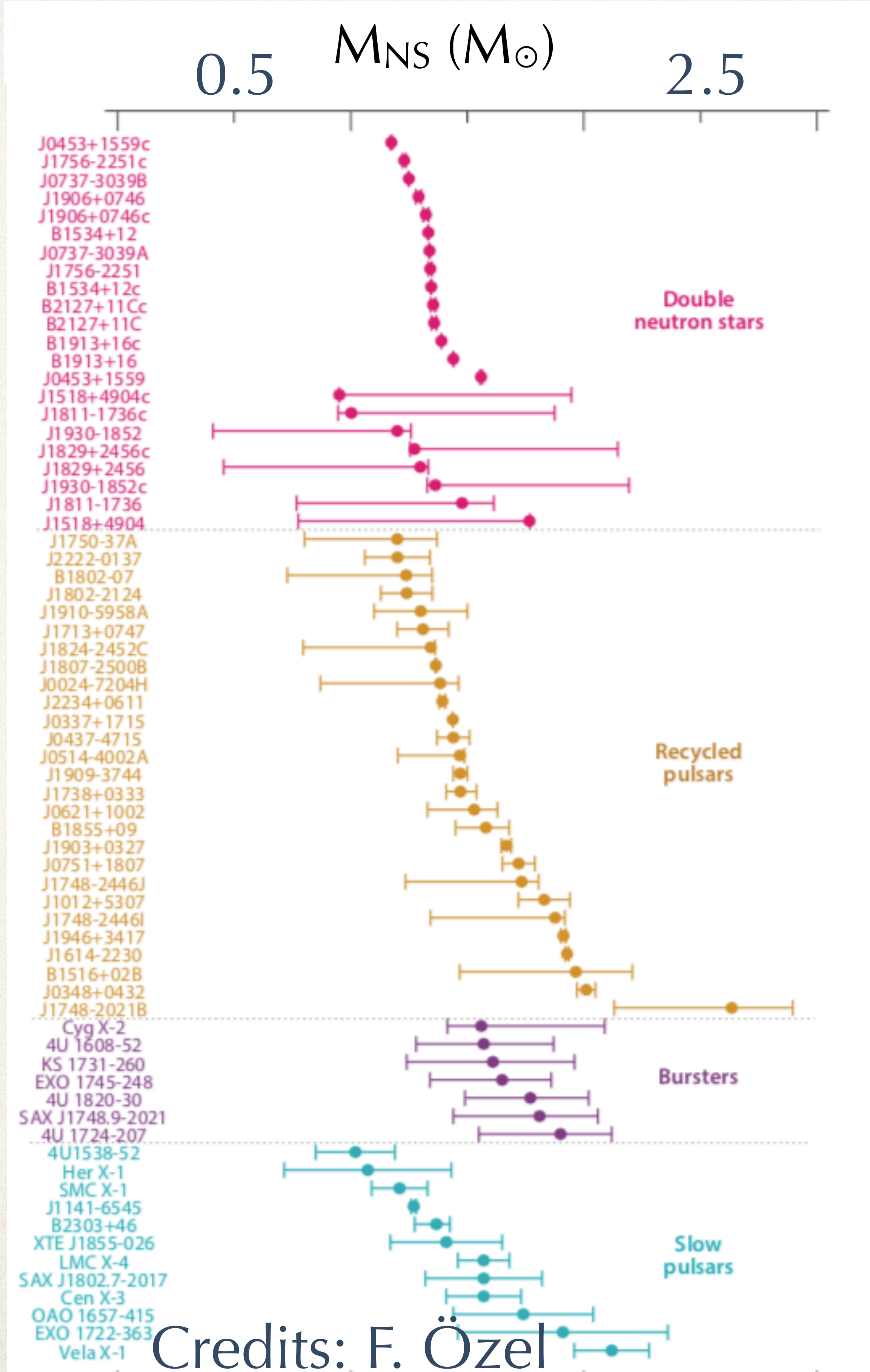


Masses of neutron stars

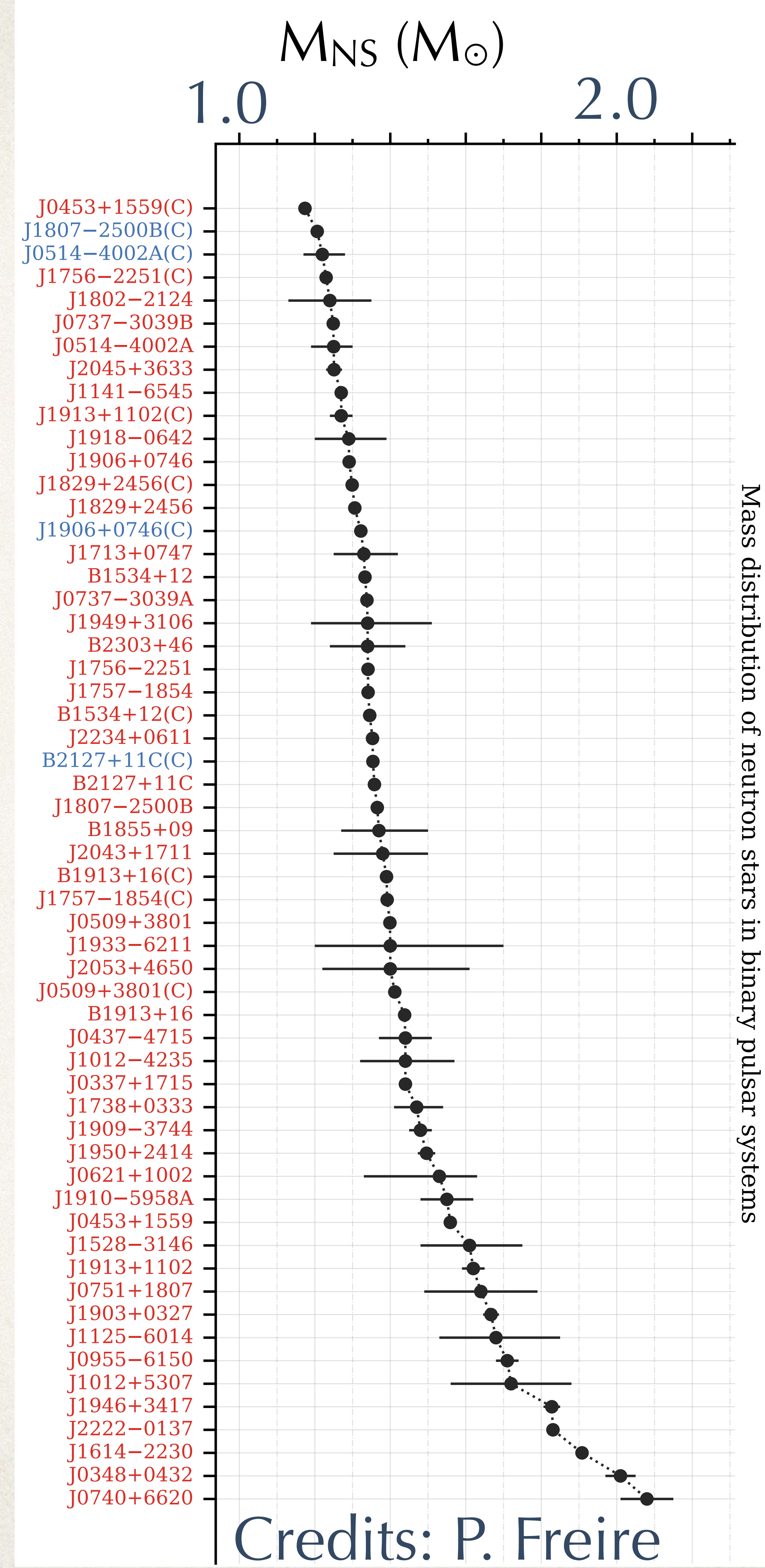


Credits: F. Özel

Masses of neutron stars

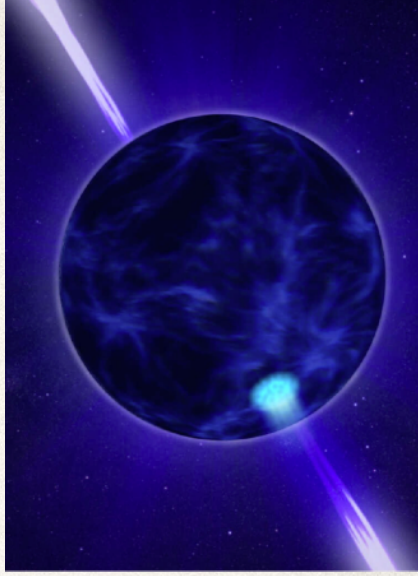


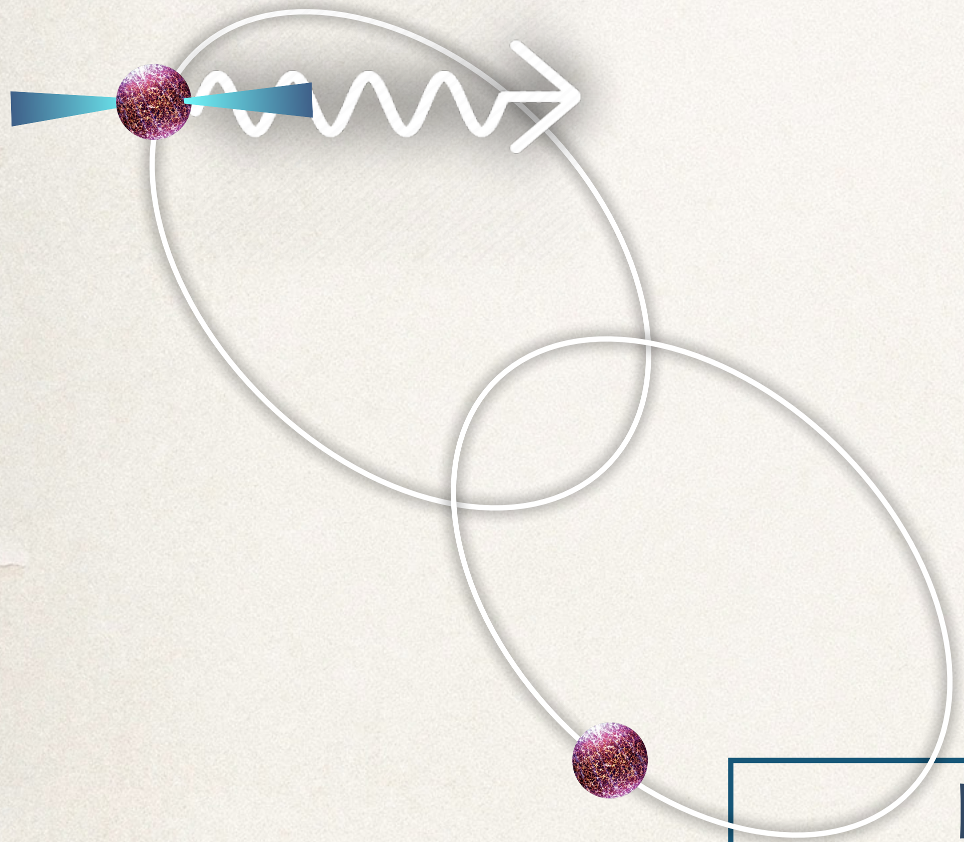
Credits: F. Özel

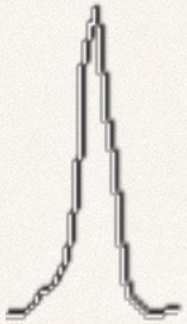


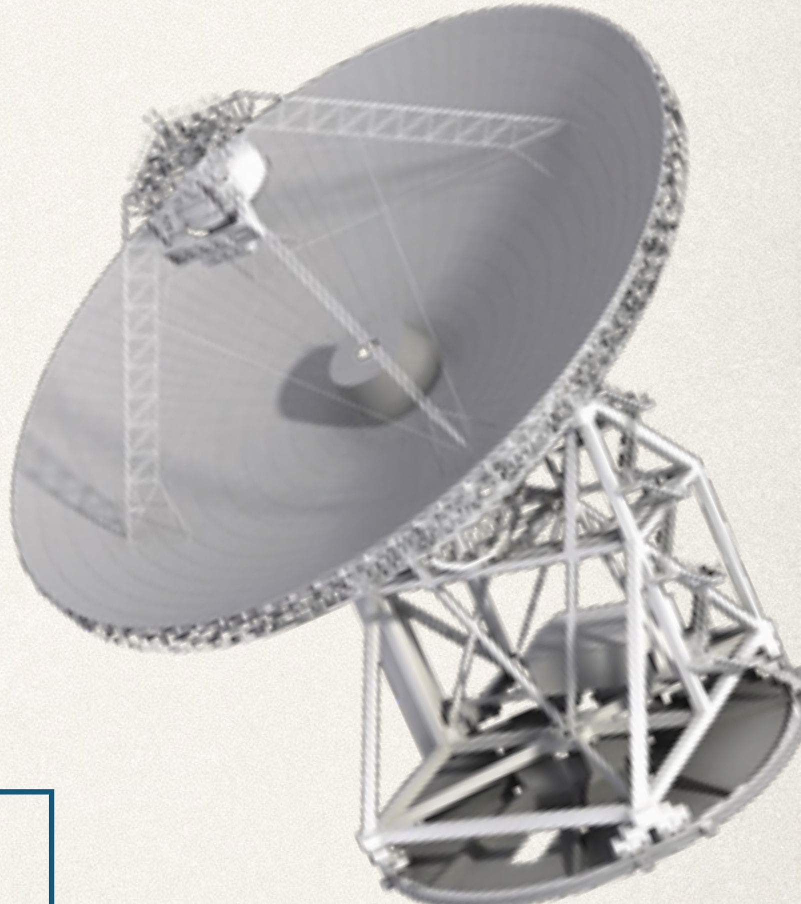
Credits: P. Freire

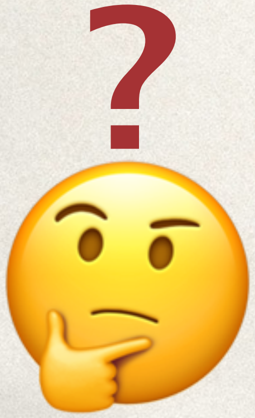
Radio timing of pulsars in binary systems permits measurements of orbital parameters.







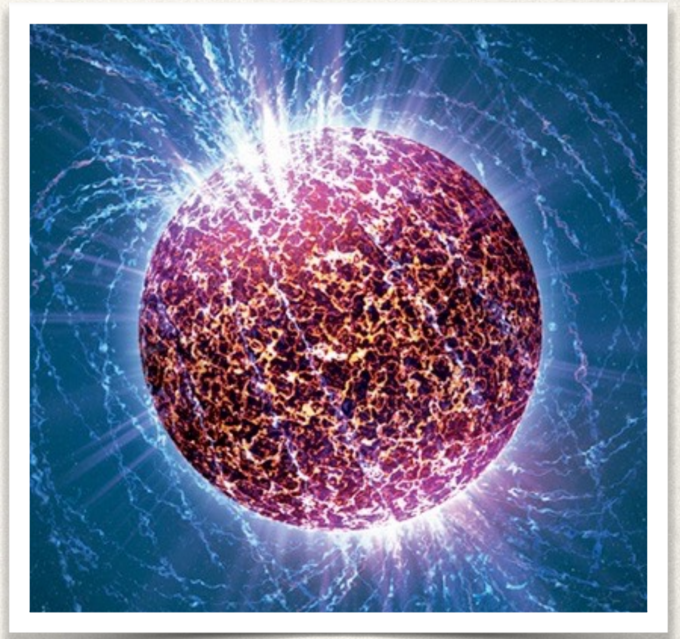




Best M_{NS} measurement
Double-NS system PSR B1913+16
$M_{PSR} = 1.4414 \pm 0.0002\ M_{\odot}$

Weisberg et al. 2005

Measuring the radius with precision is much more difficult.



To measure the radius, we need to:

- observe the surface thermal emission,
- correctly model this emission,
- know the distance independently.

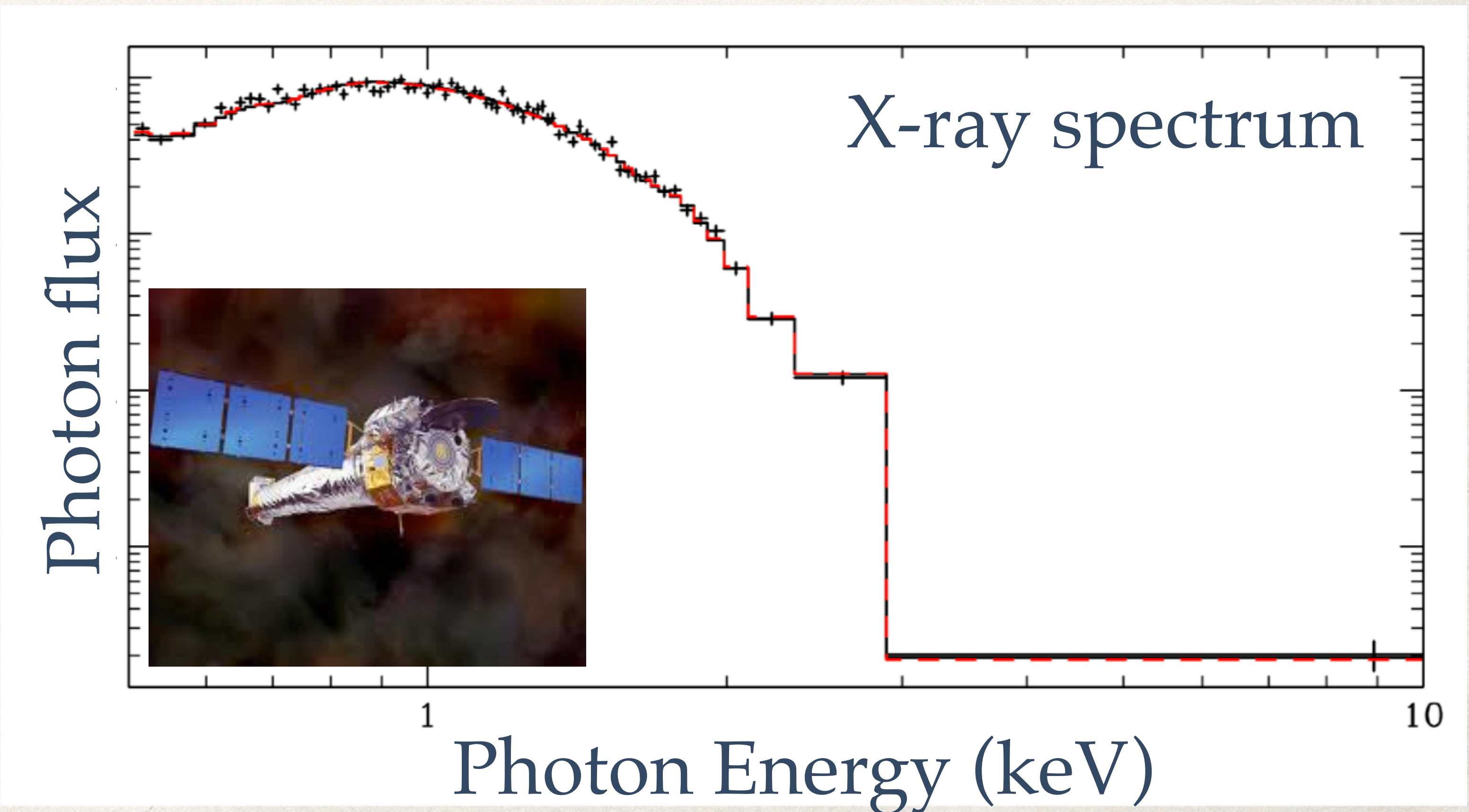
Luminosity

$$L = 4\pi R^2 \sigma T_{\rm eff}^4$$

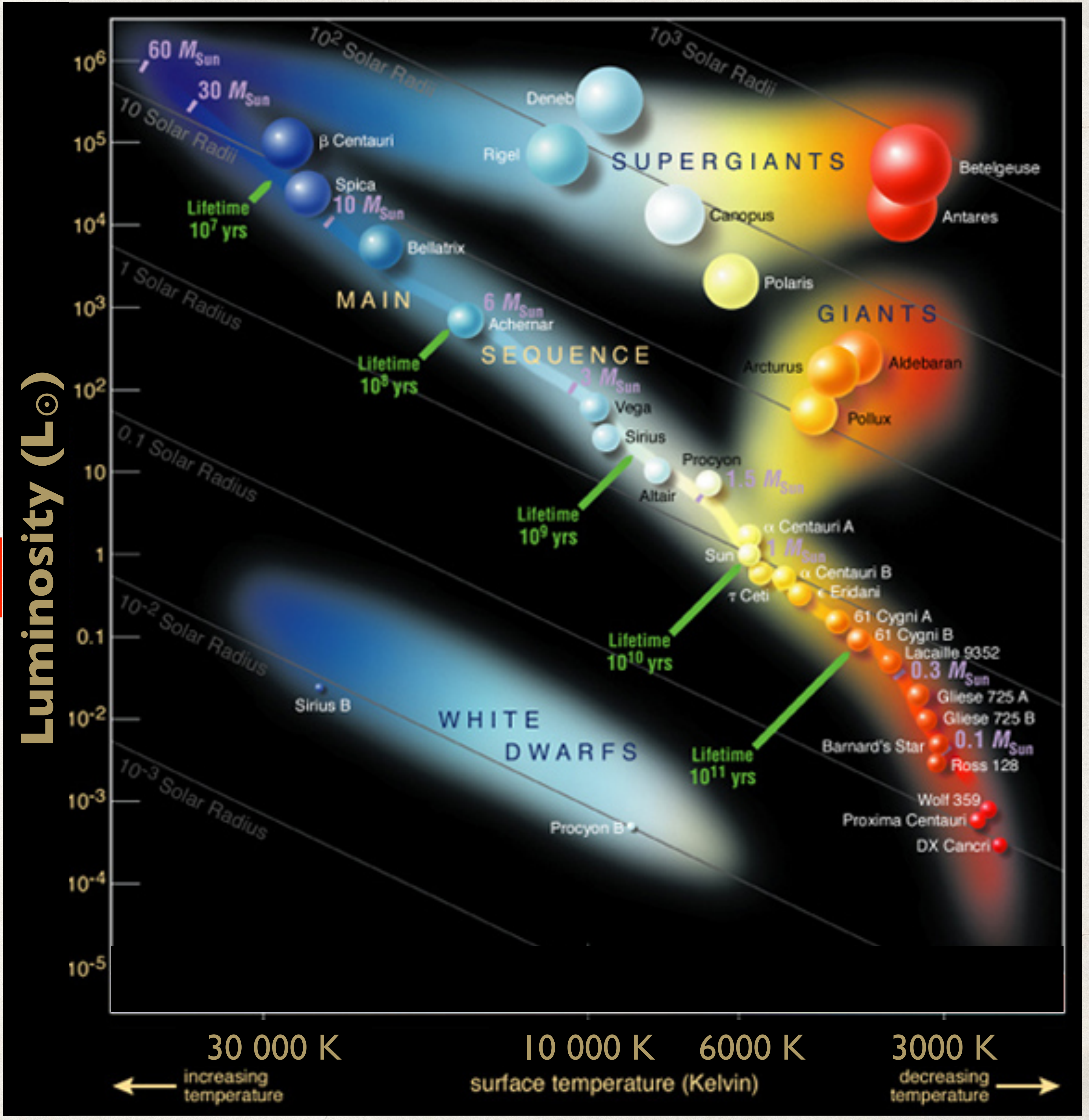
↓

Flux

$$F = \left(\frac{R}{D}\right)^2 \sigma T_{\rm eff}^4$$

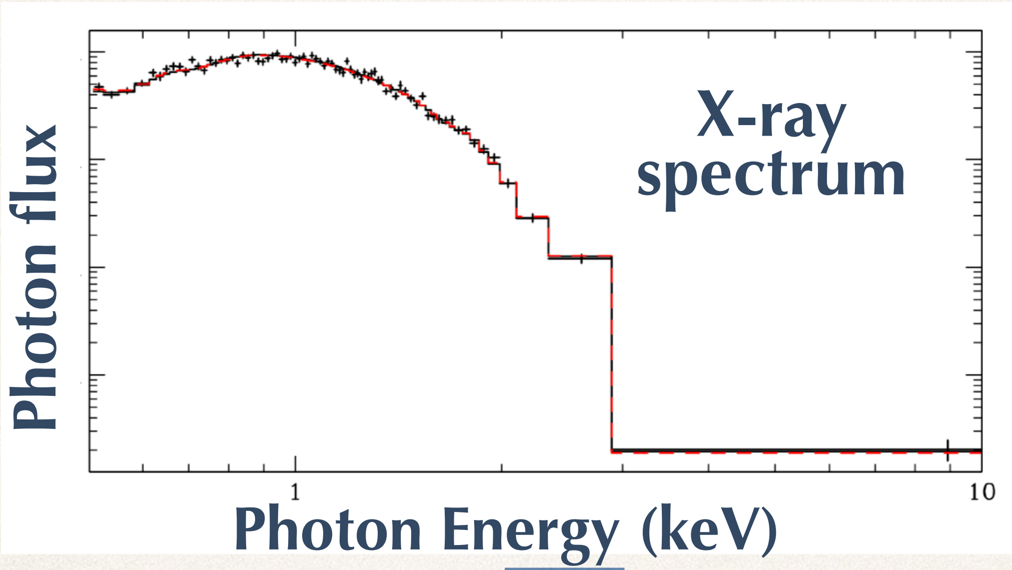


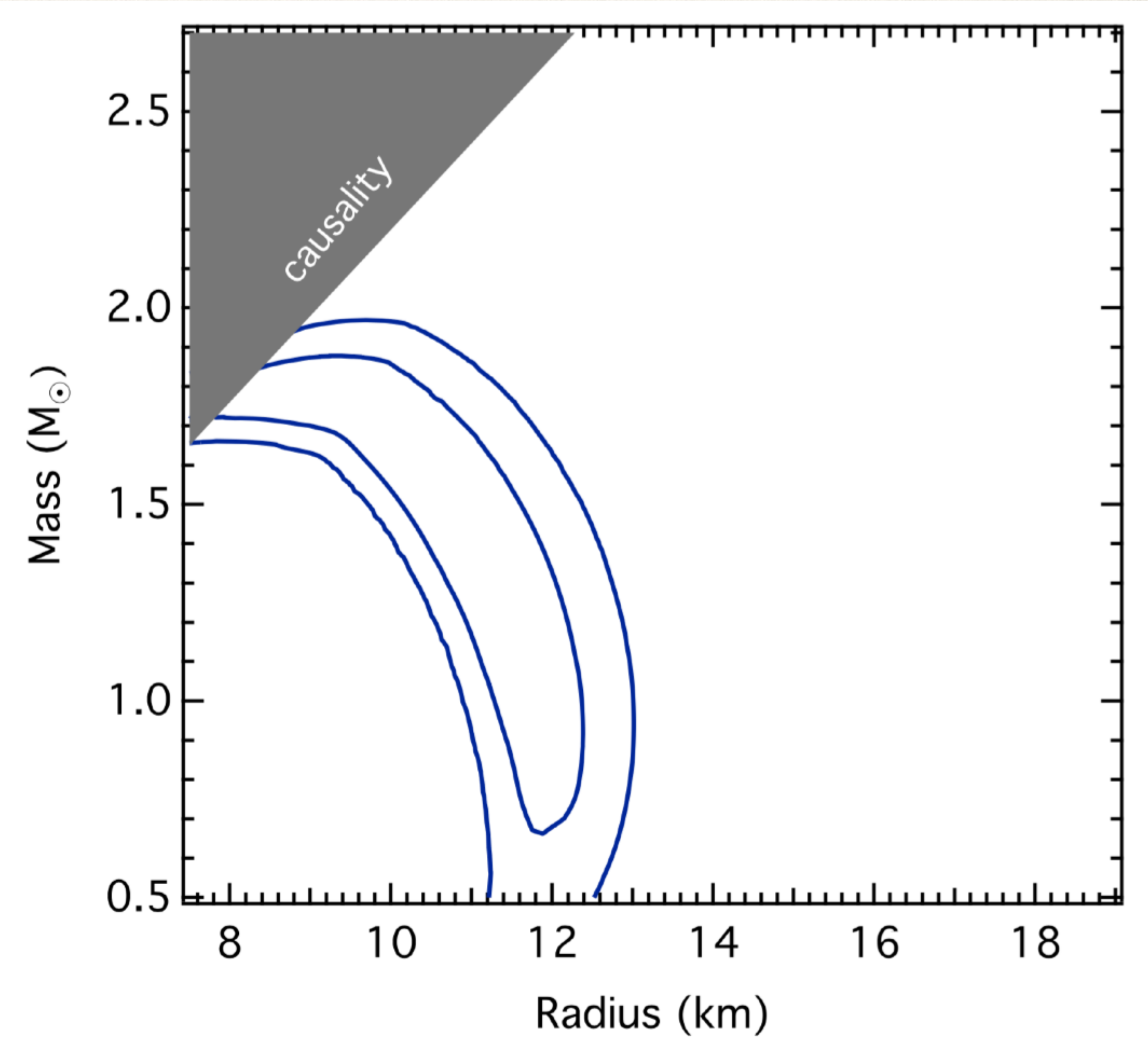
Question: Where would neutron stars be on the color-mag. diagram?



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

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





$$F_{\rm X} \propto \left(\frac{R_\infty}{D}\right)^2 \sigma T^4_{\rm eff,\infty}$$

Bogdanov et al. 2016

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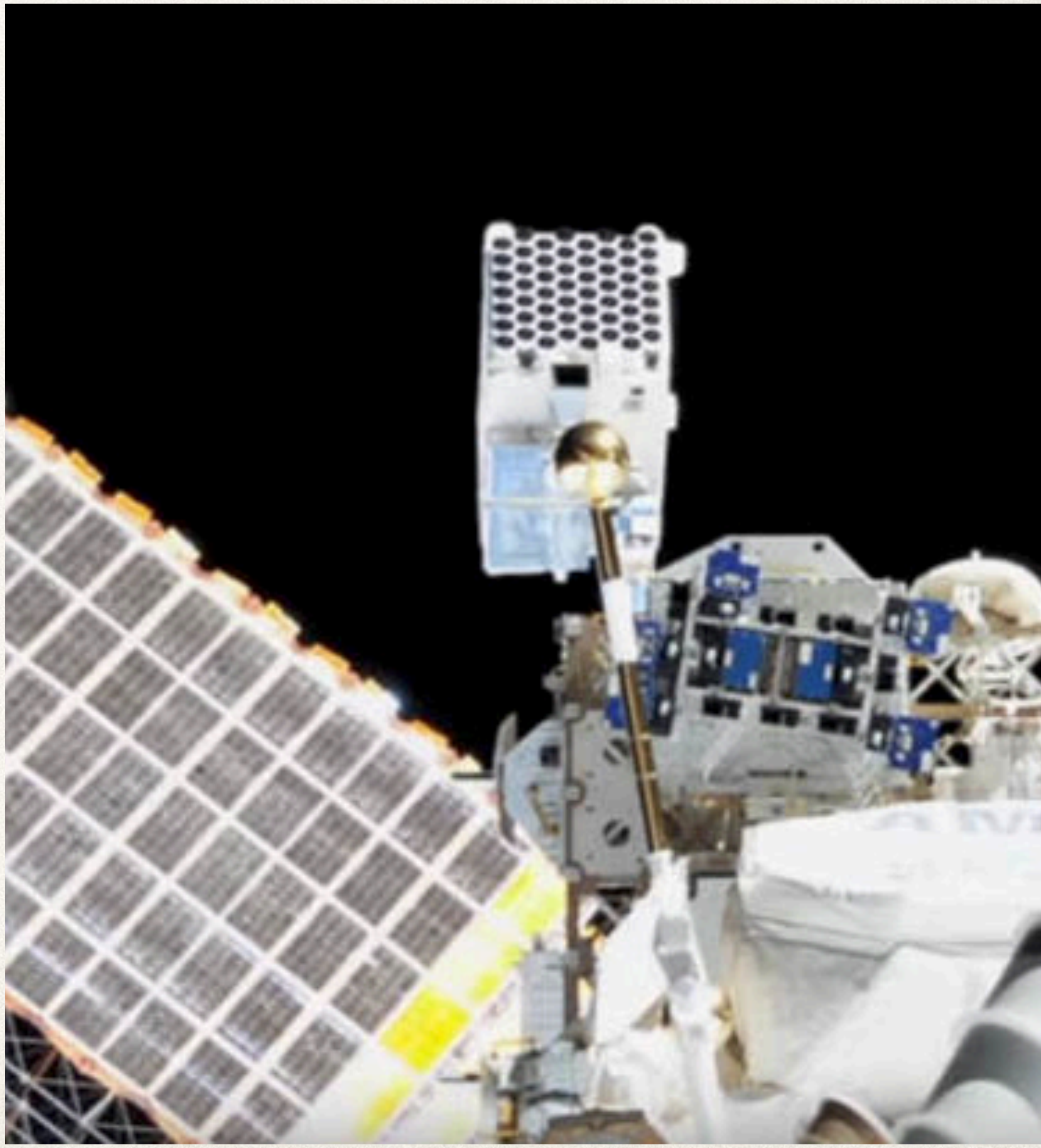
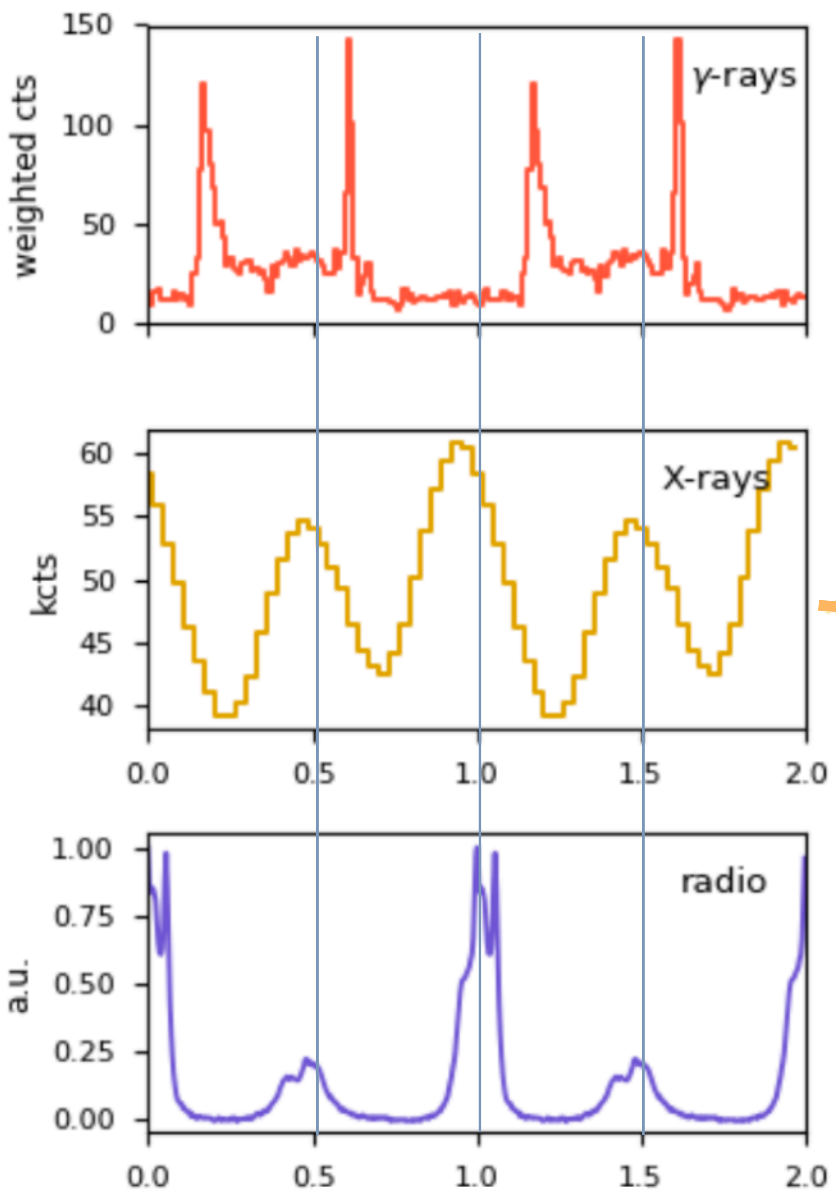


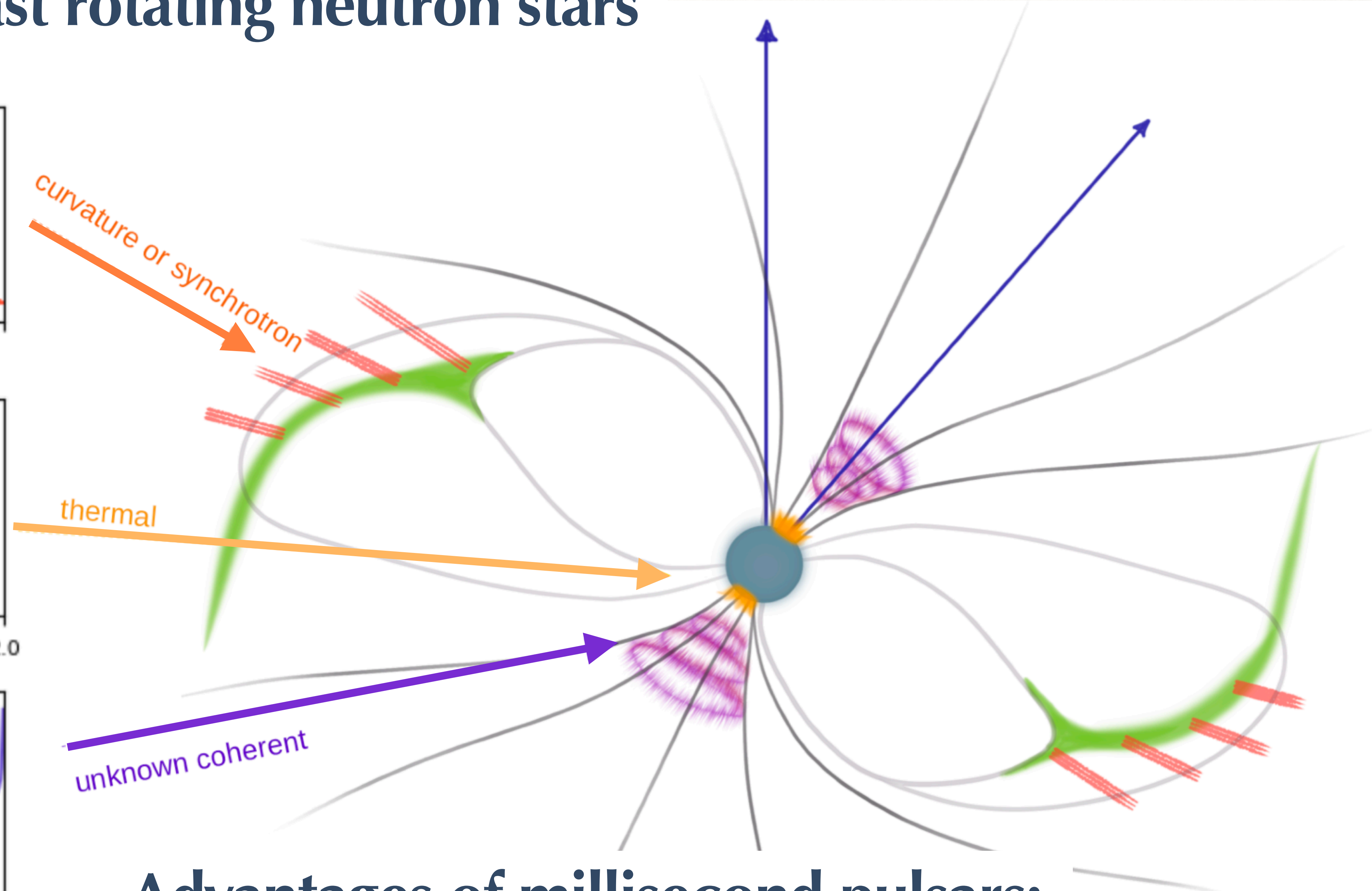
The NICER mission observes the X-ray emission from millisecond pulsars

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

Old fast rotating neutron stars



Spin phase
(2 rotations)

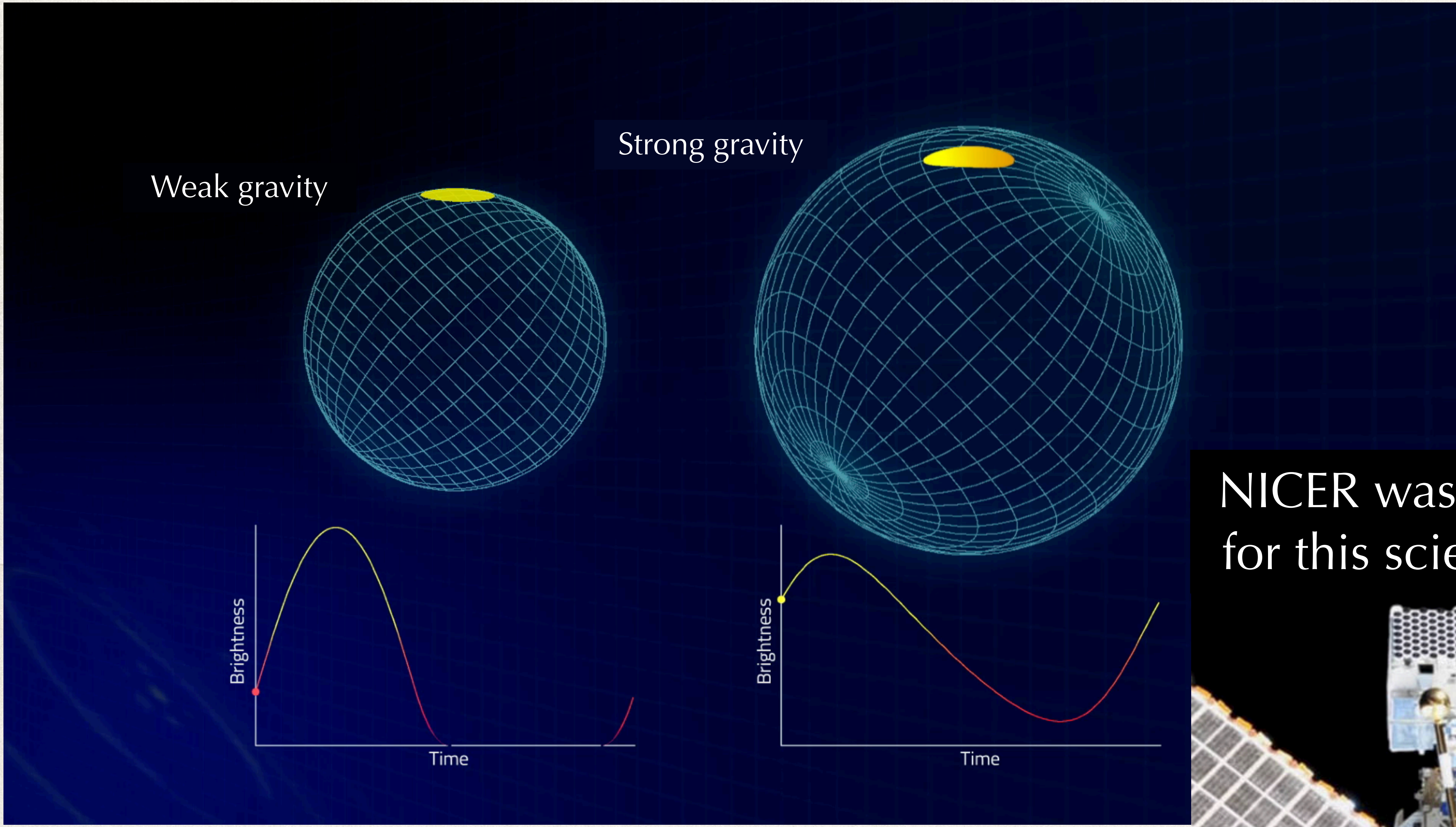


Advantages of millisecond pulsars:

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

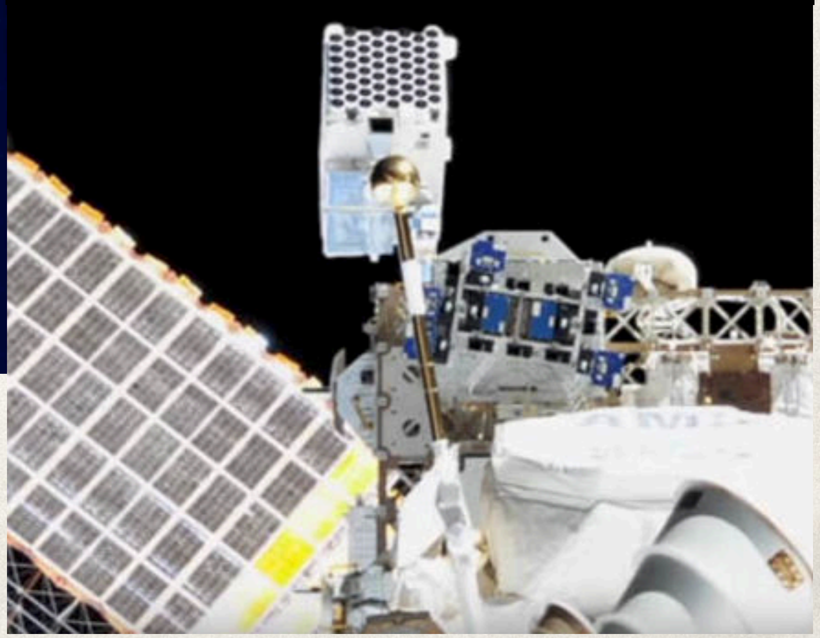
Credits: A. Bilous

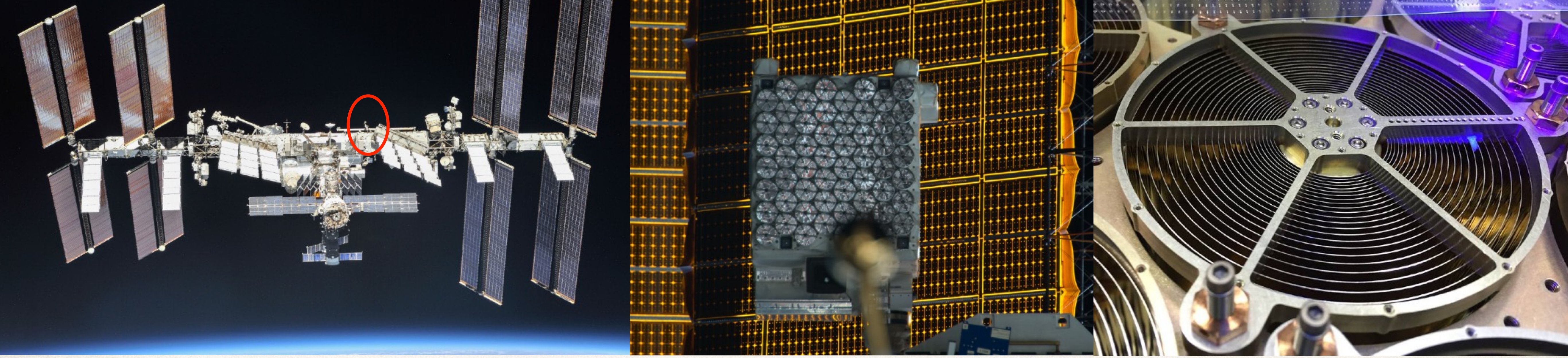
Strong gravity permits seeing beyond the hemisphere of the neutron star, leaving imprints on the lightcurves of millisecond pulsars.



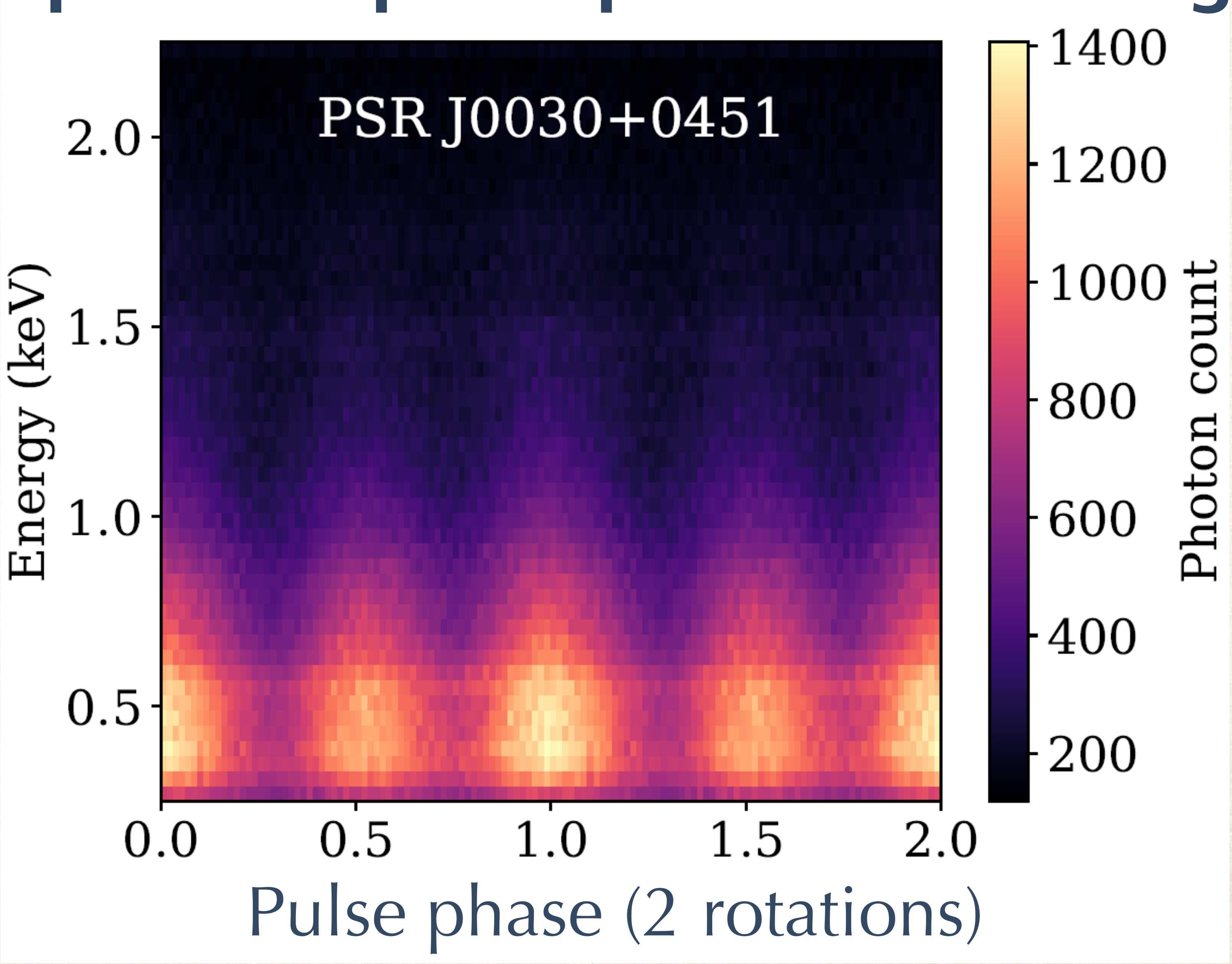
Credits: S. Morsink

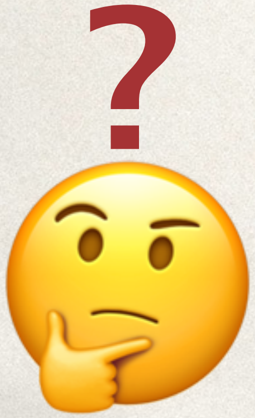
NICER was launched for this science goal.



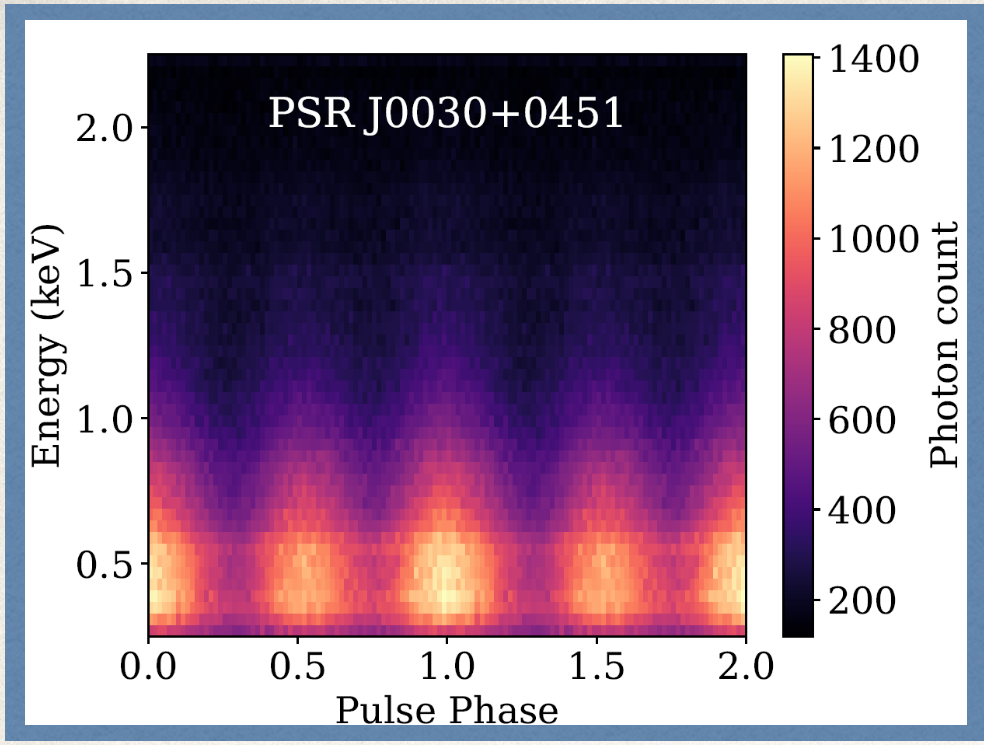


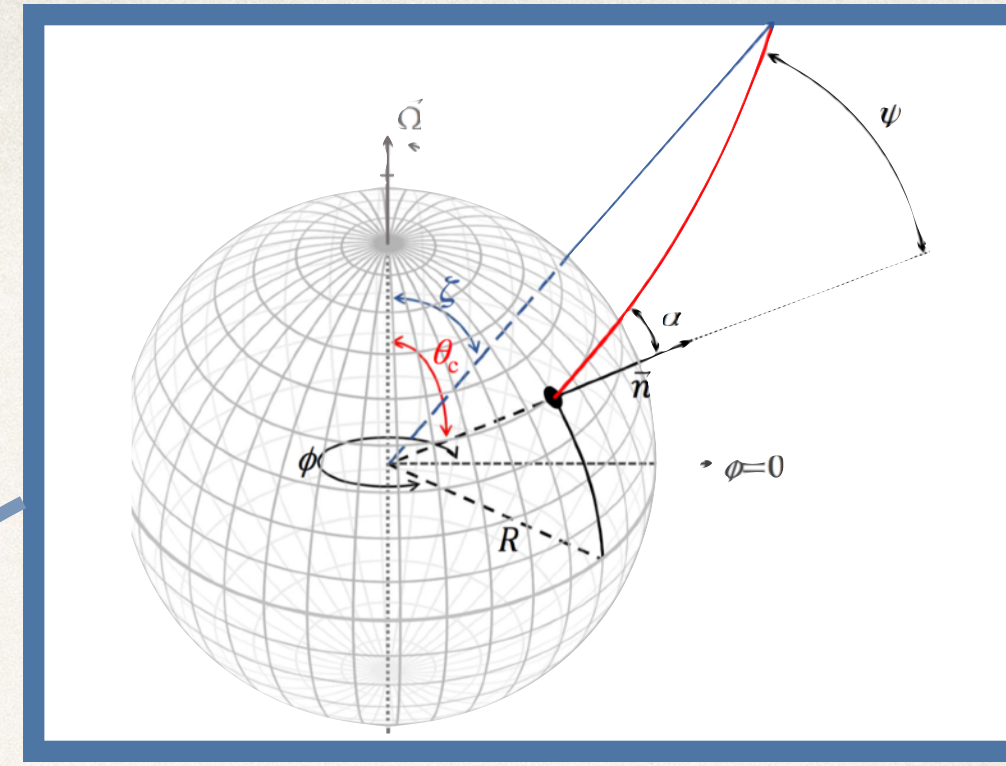
NICER has provided beautiful data sets to perform pulse profile modelling.





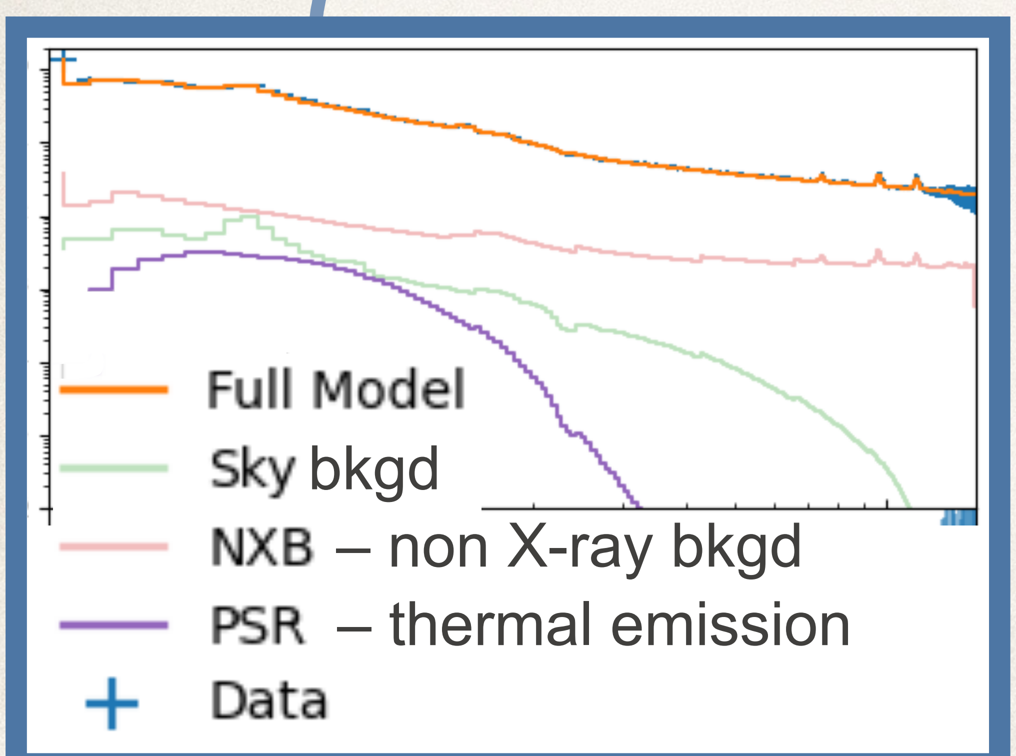
Bogdanov, SG et al. (2019a)

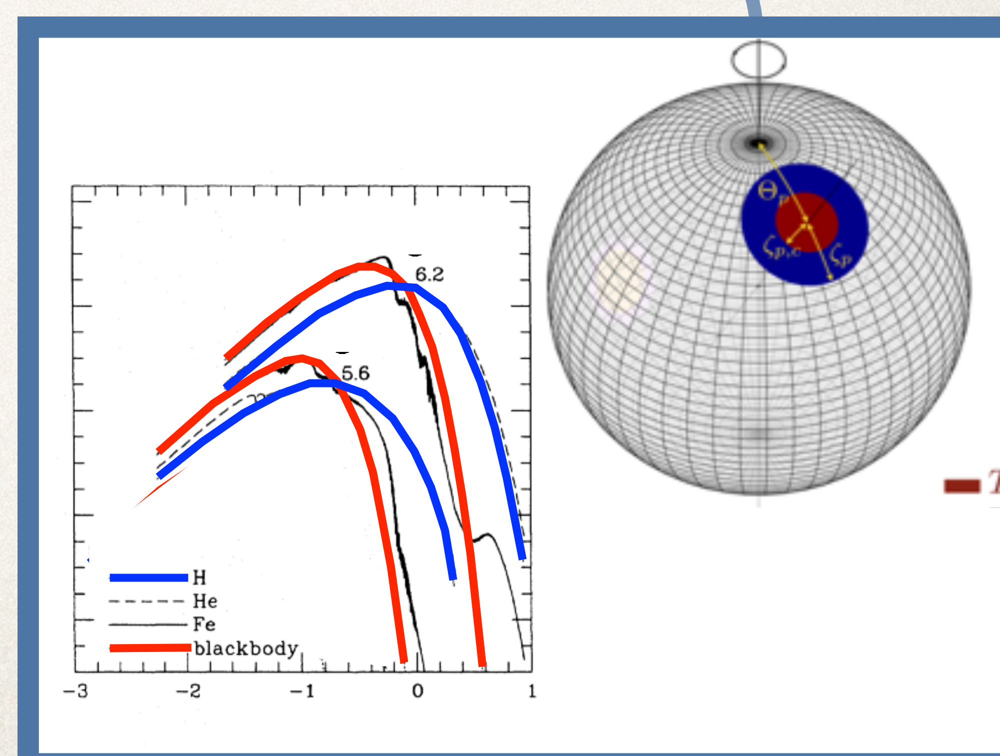




NS properties inference
(Likelihood statistical sampling)

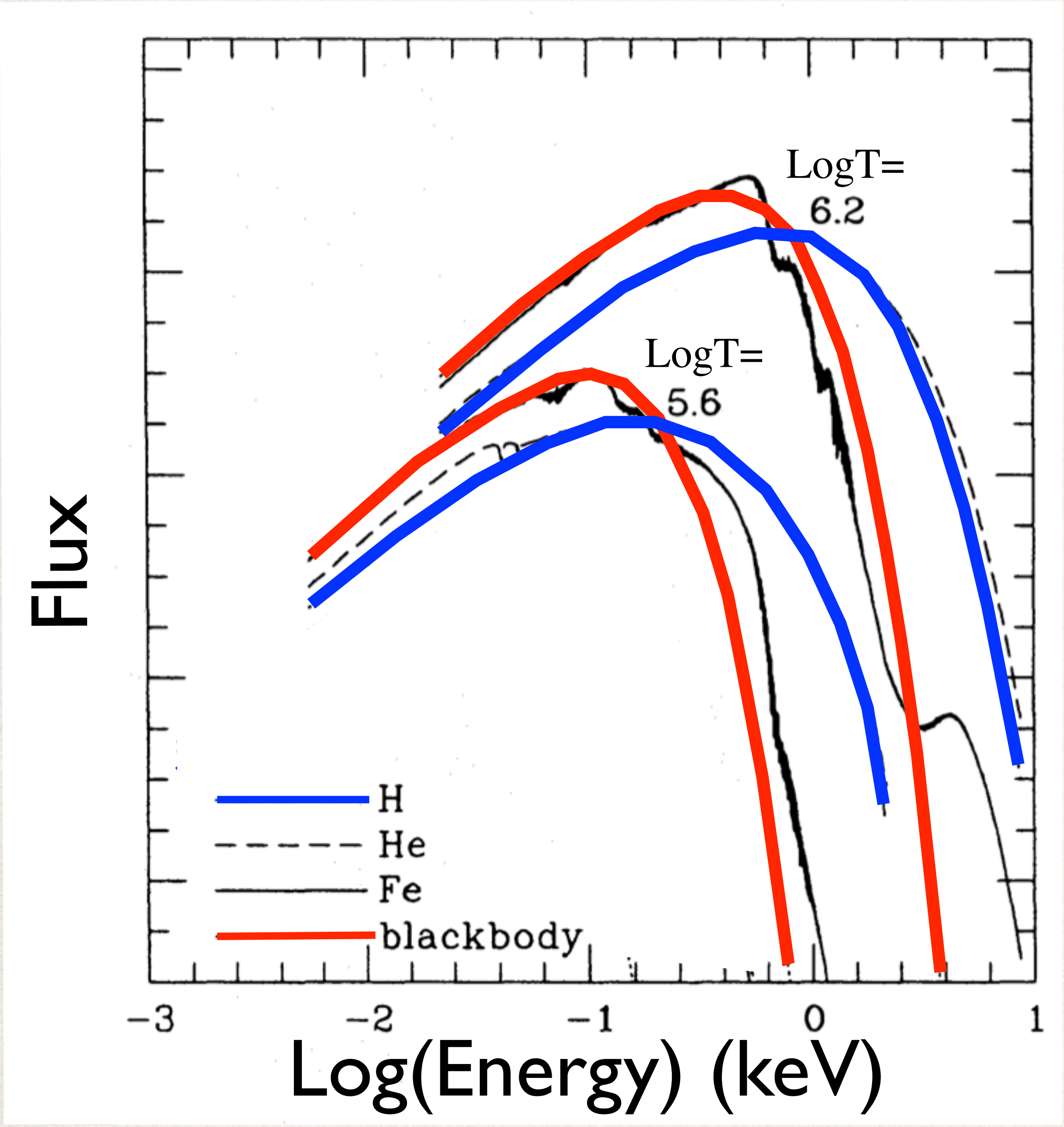
Mass,
Radius,
EOS

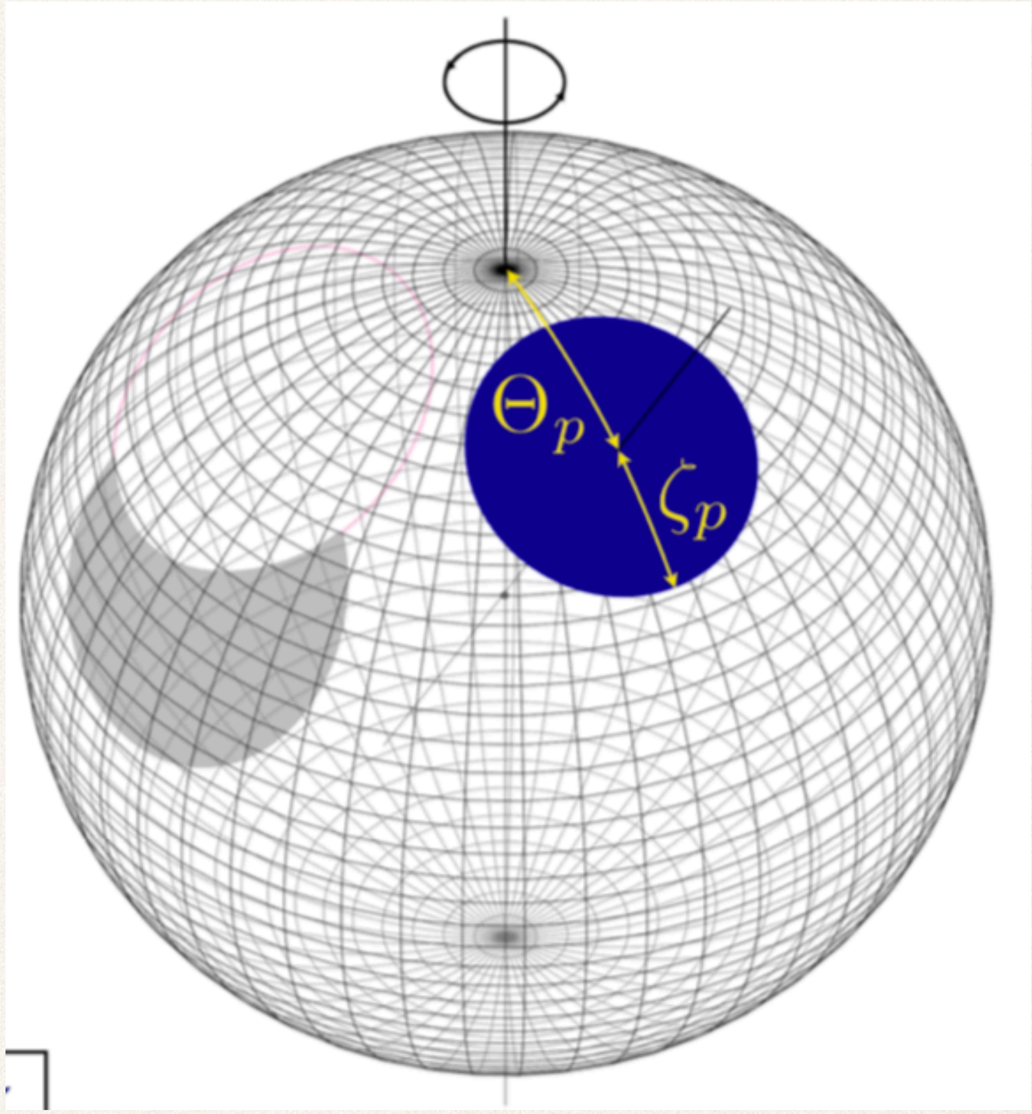




Analysing the pulse profile of millisecond pulsars requires modelling the emerging emission and the corresponding emission regions (hot spots).

Zavlin et al. (1996)

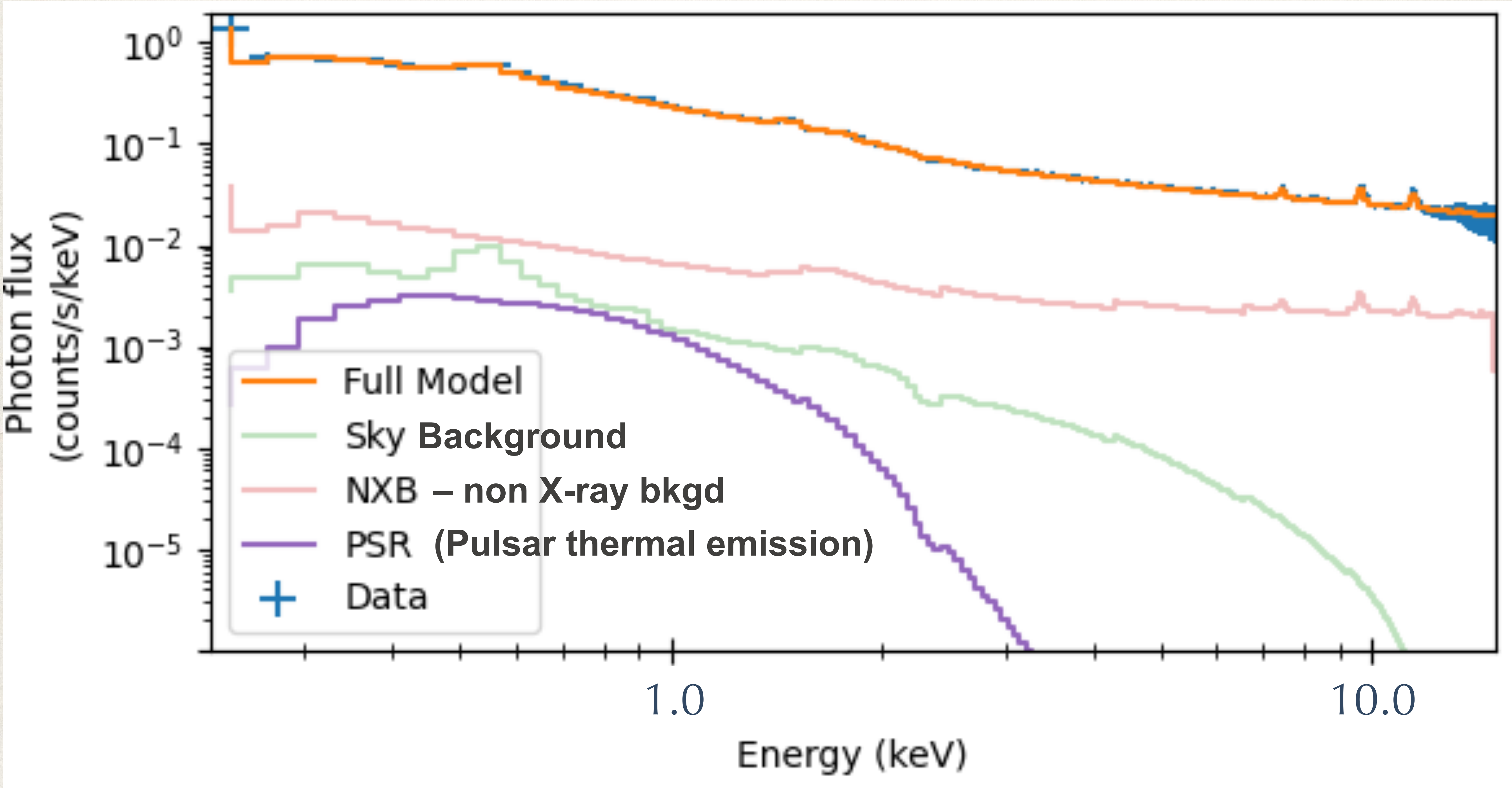


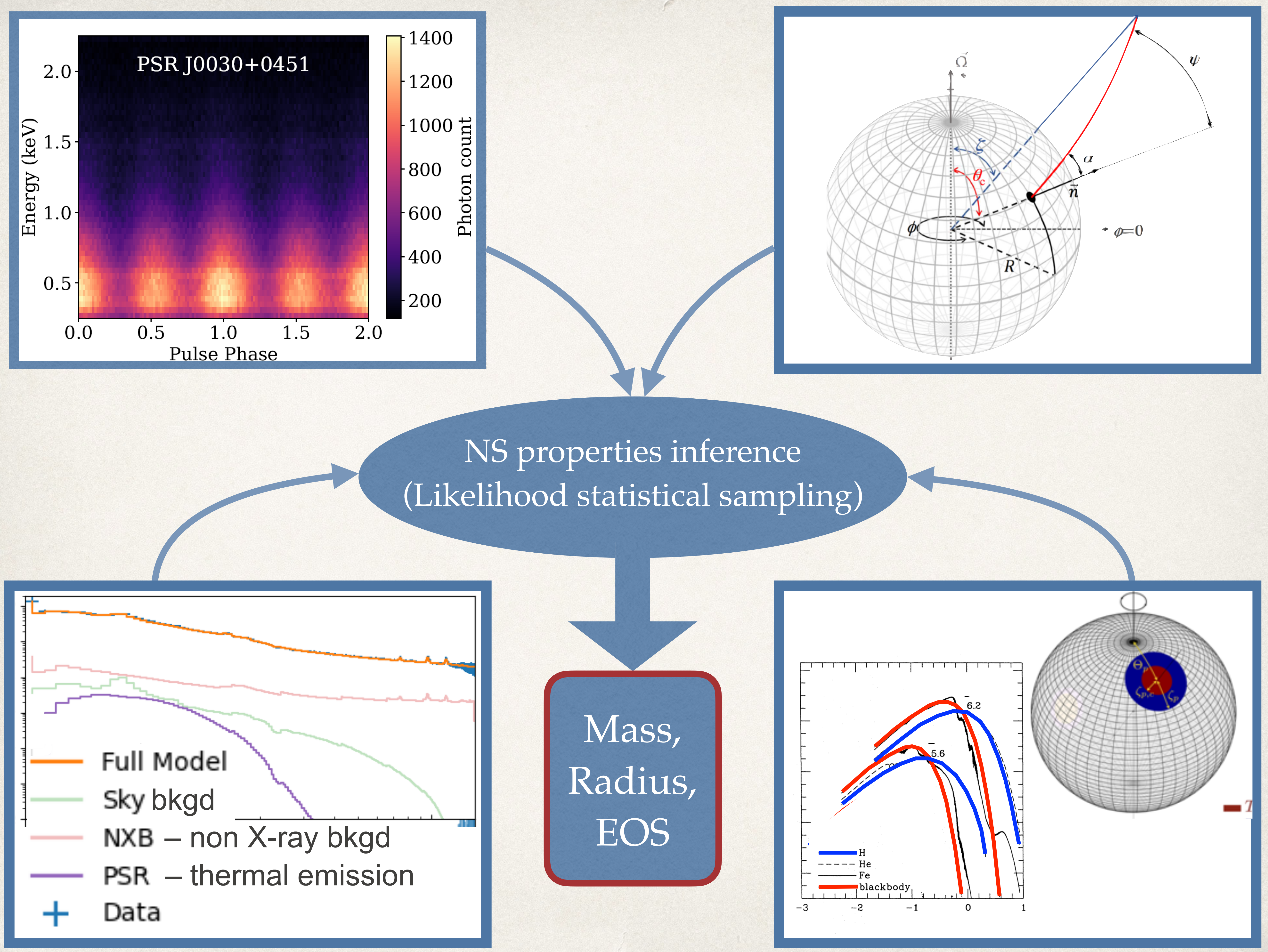


In the following, we used Hydrogen atmosphere models

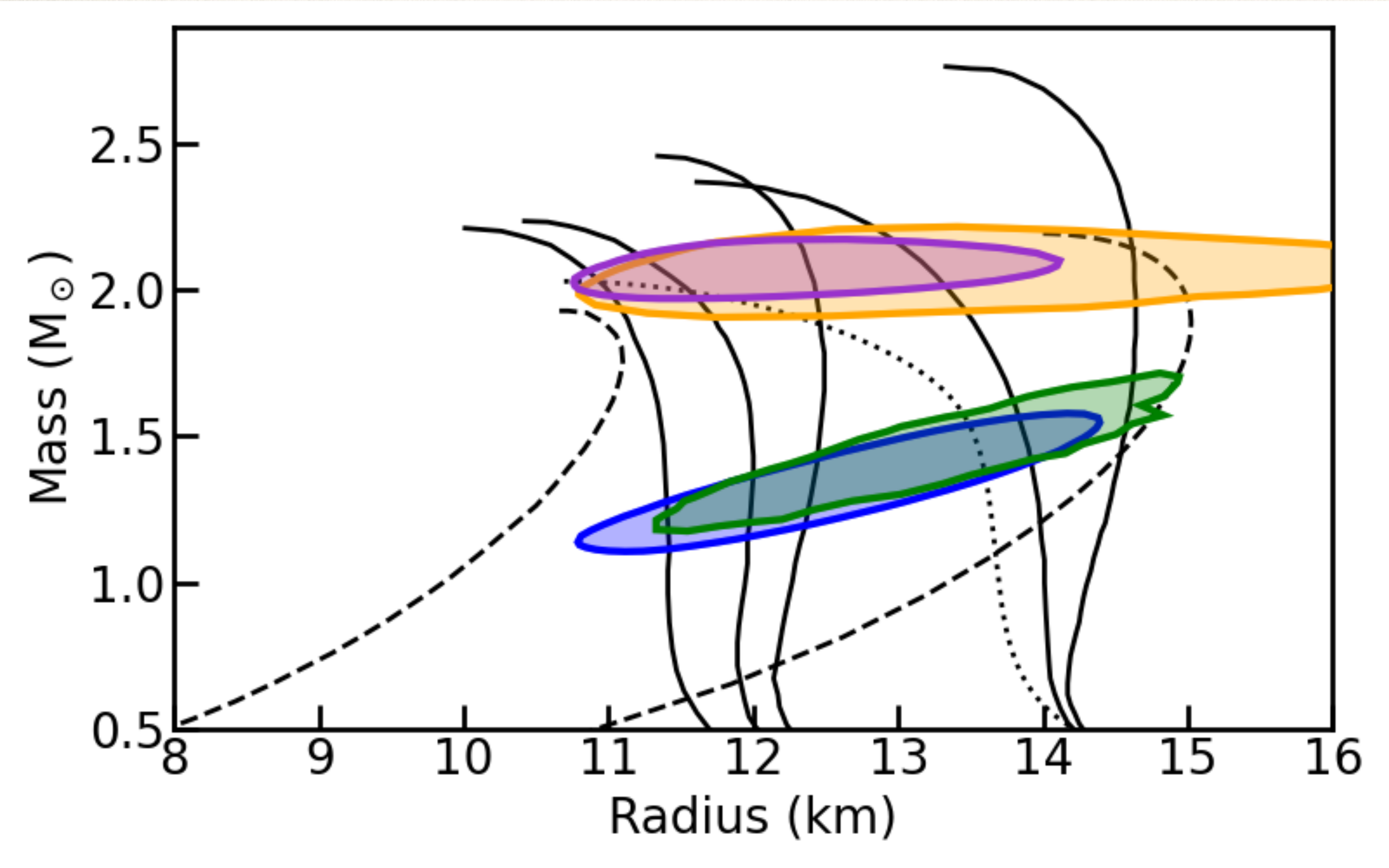
The hot spots are geometrically described as a combination of circles

The high background in the NICER data also needs to be modelled (or estimated).




PSR J0030+0451
Energy (keV)
Pulse Phase
Photon count
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

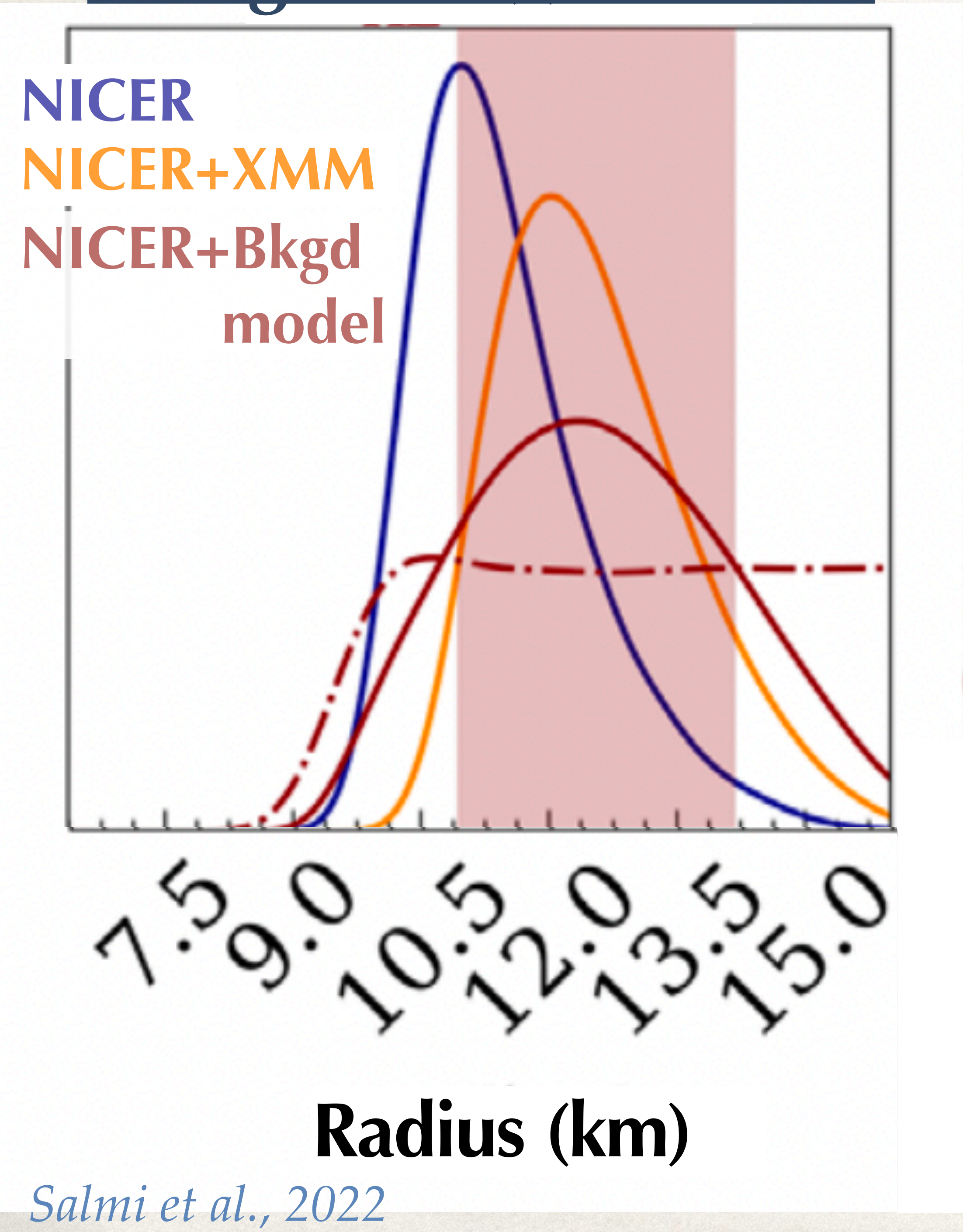
- **PSR J0030+0451**
  - Riley et al. 2019
  - Miller et al. 2019
- **PSR J0740+6620**
  - Riley et al. 2021
  - Miller et al. 2021

See also additional analyses in
Salmi et al. 2022, 2023
Vinciguerra et al. 2023, 2024

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

What else did we learn from the analysis of NICER observations of millisecond pulsars?

Modelling of the background(s) matters!



Salmi et al., 2022

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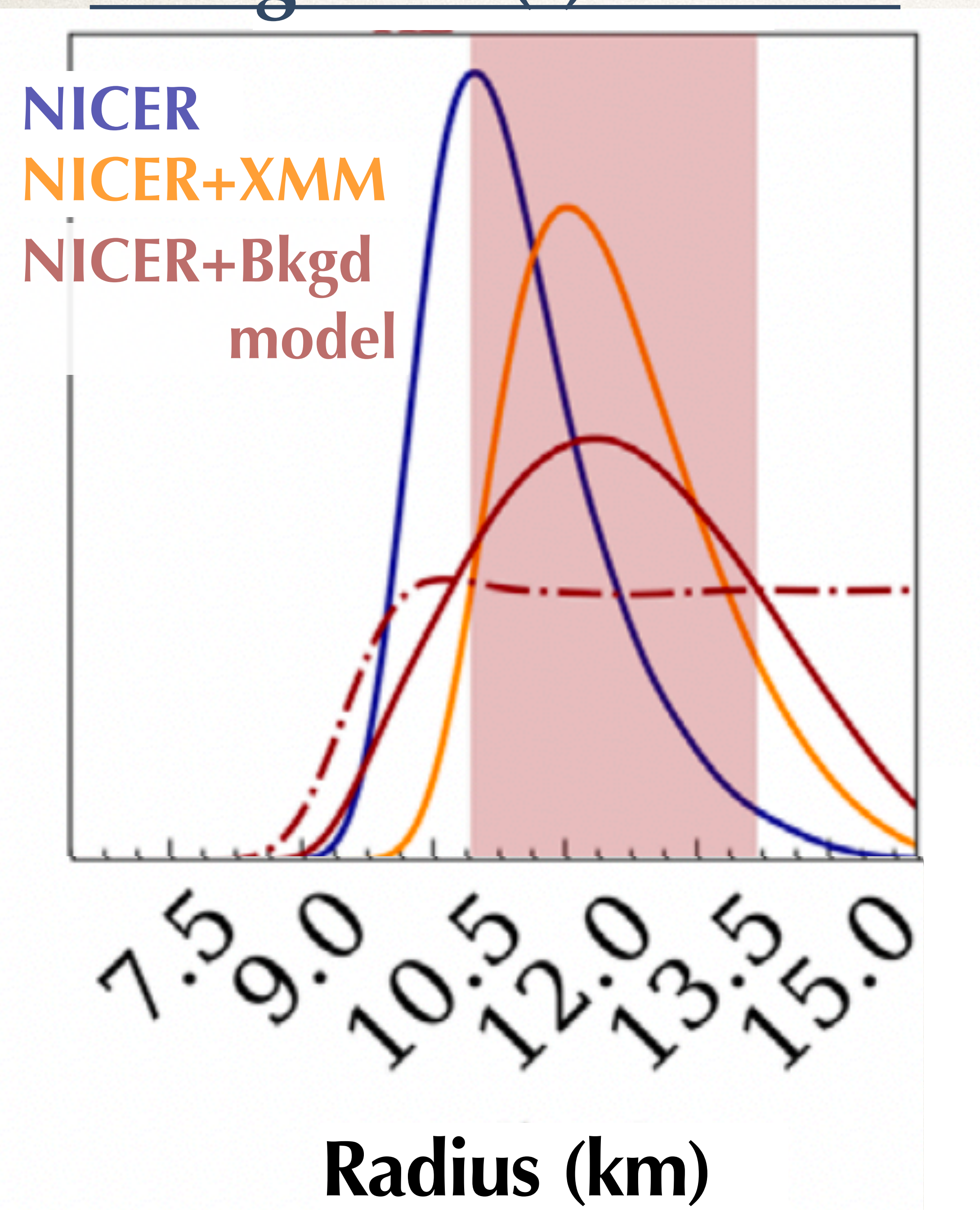
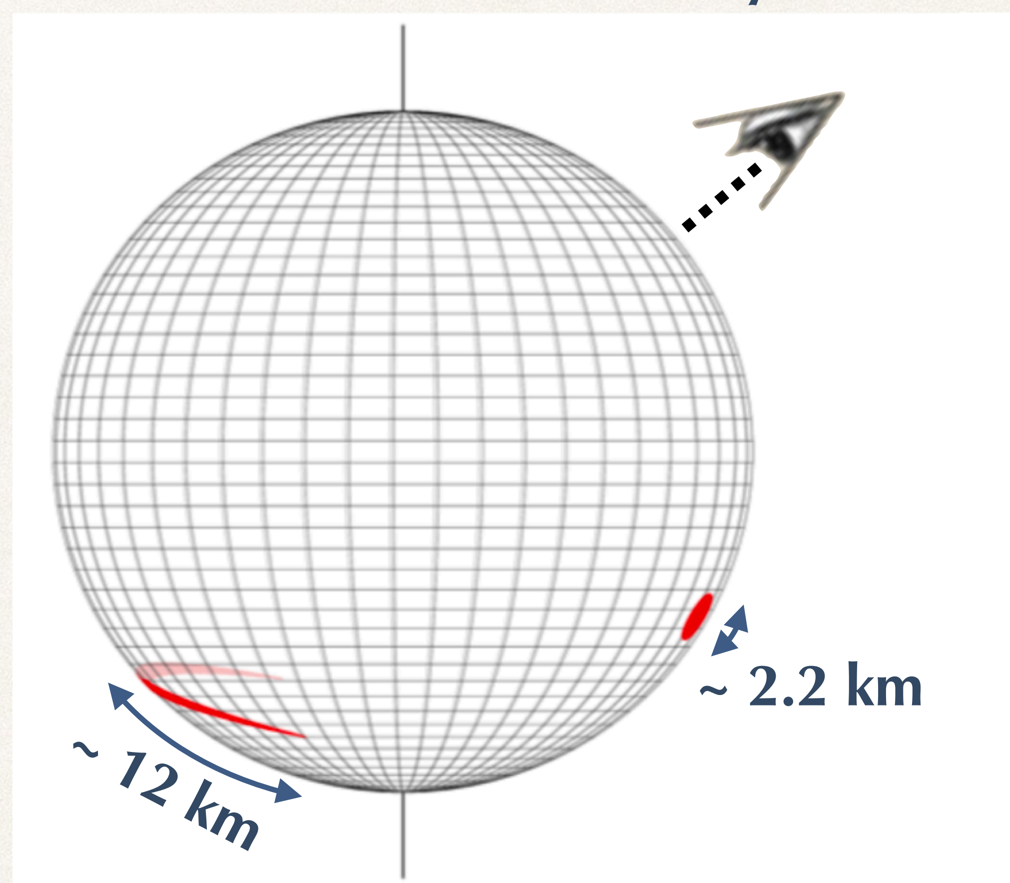
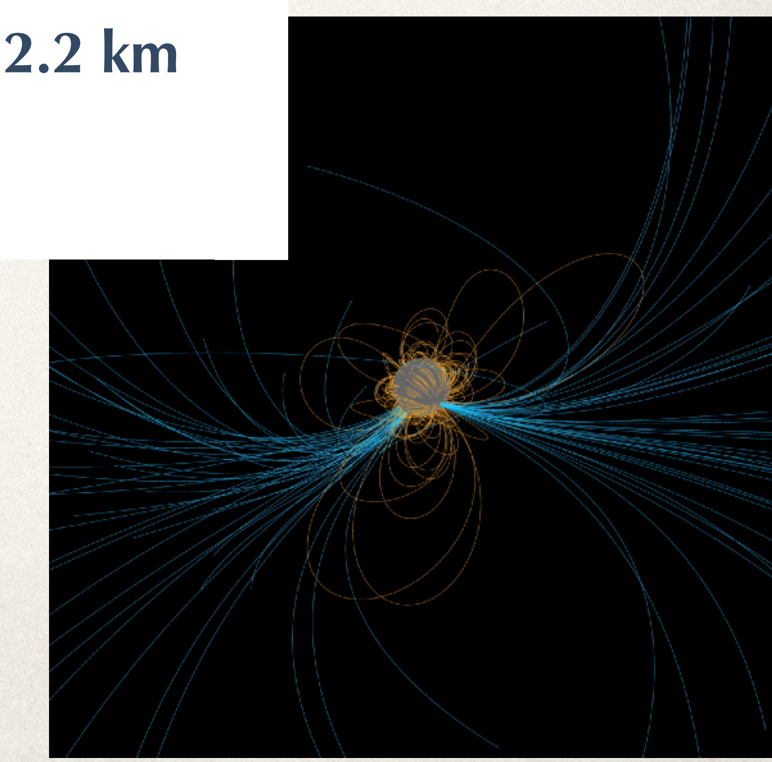


Salmi et al., 2022

The geometry was not as simple as initially anticipated!

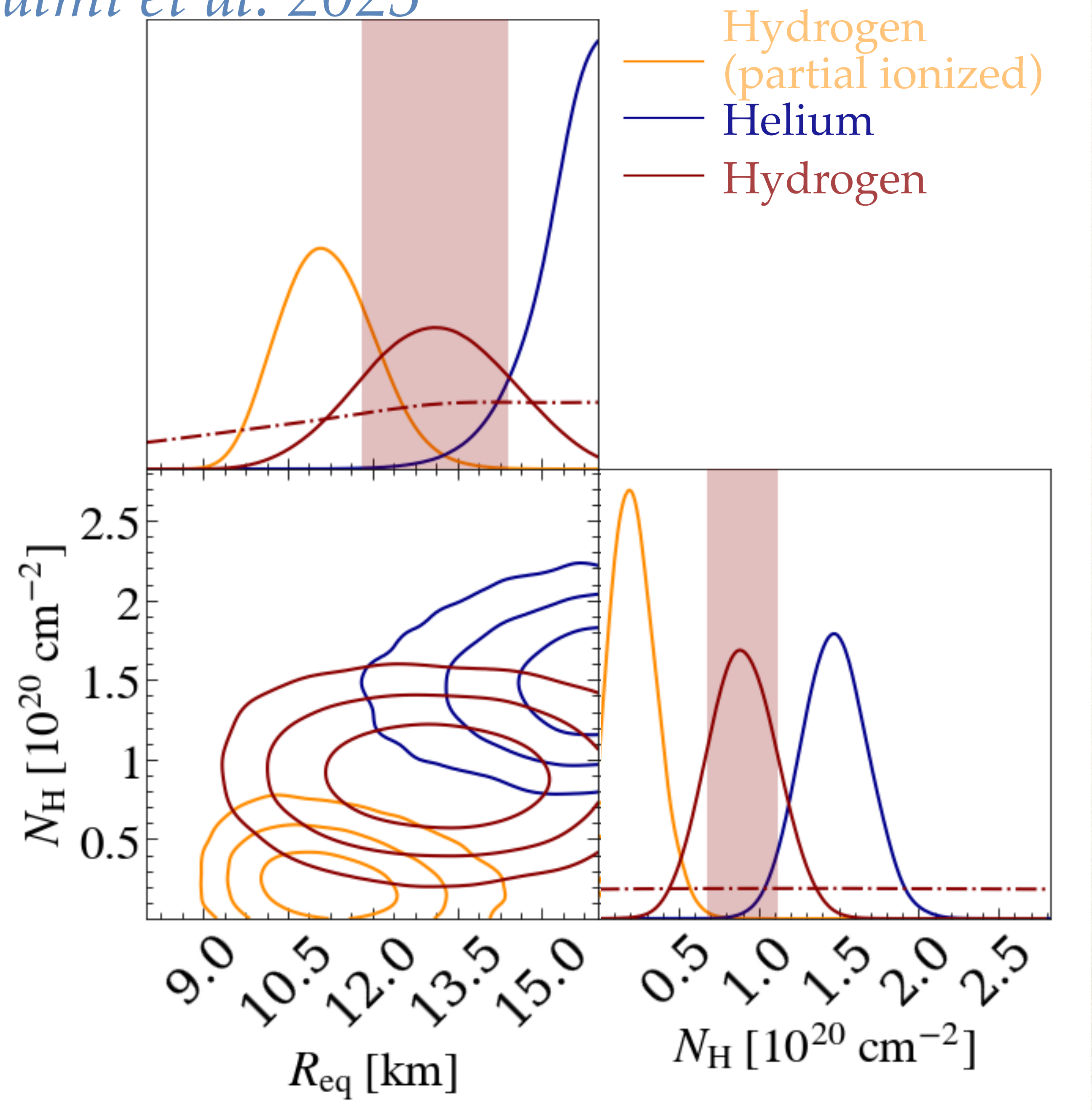




What else did we learn from the analysis of NICER observations of millisecond pulsars?

The choice of the emergent emission model matters too!

Salmi et al. 2023

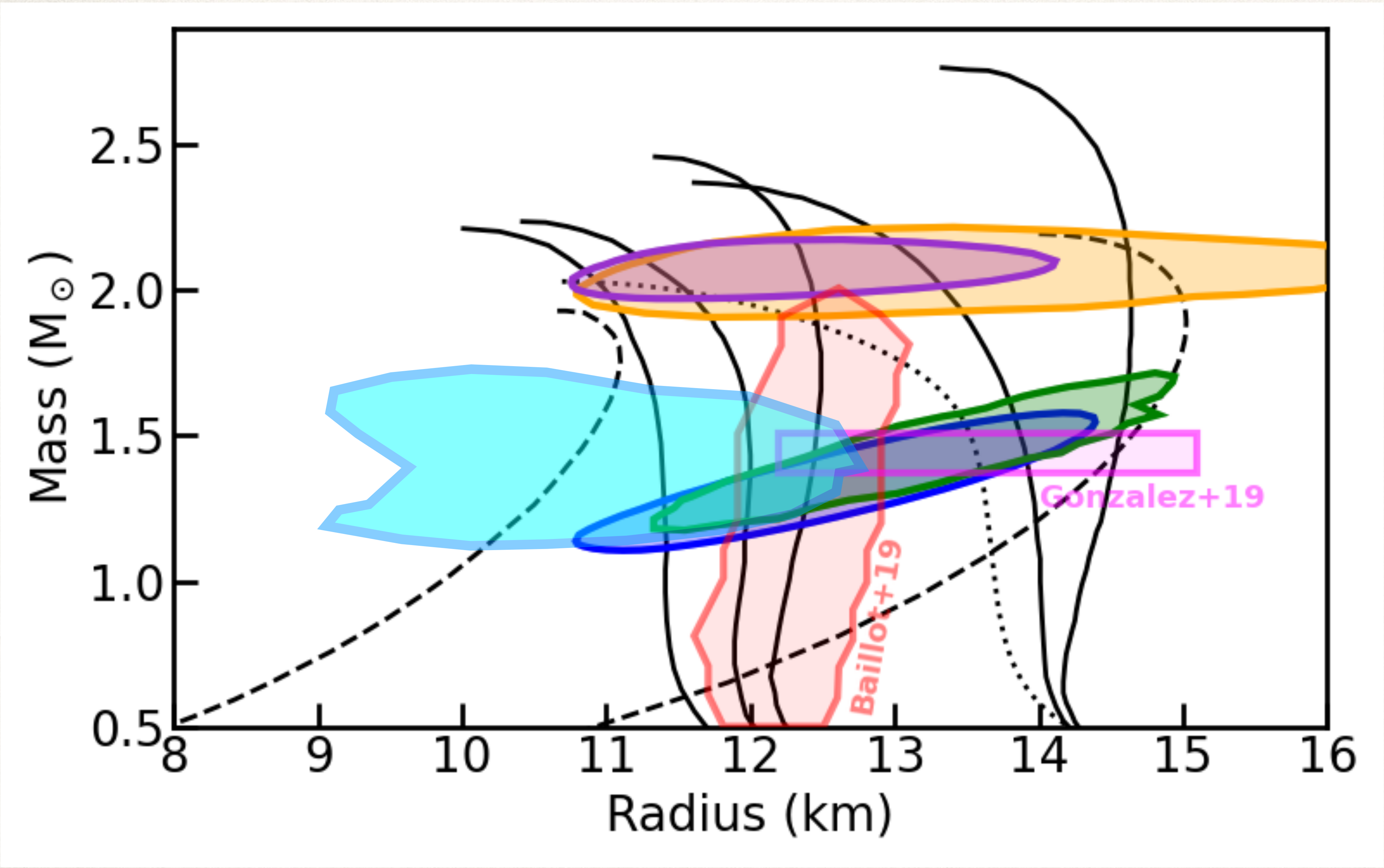


Several arguments favour a hydrogen composition of the pulsar's atmosphere

What else did we learn from the analysis of NICER observations of millisecond pulsars?

- **Vinciguerra et al. 2023A, 2024 studied PSR J0030+0451 and the effects of:**
  - Adding data from other instruments (XMM-Newton)
  - Different geometries (more detailed than in Riley et al. 2019)
  - Different options of the sampler (resolution, convergence, etc…)
  - Multimodes of the parameter space
- **Salmi et al. 2024 & Dittmann et al. 2024 (both to be submitted) looked at PSR J0740+6620 with a lot more NICER data**

These results are also consistent with previous measurements.



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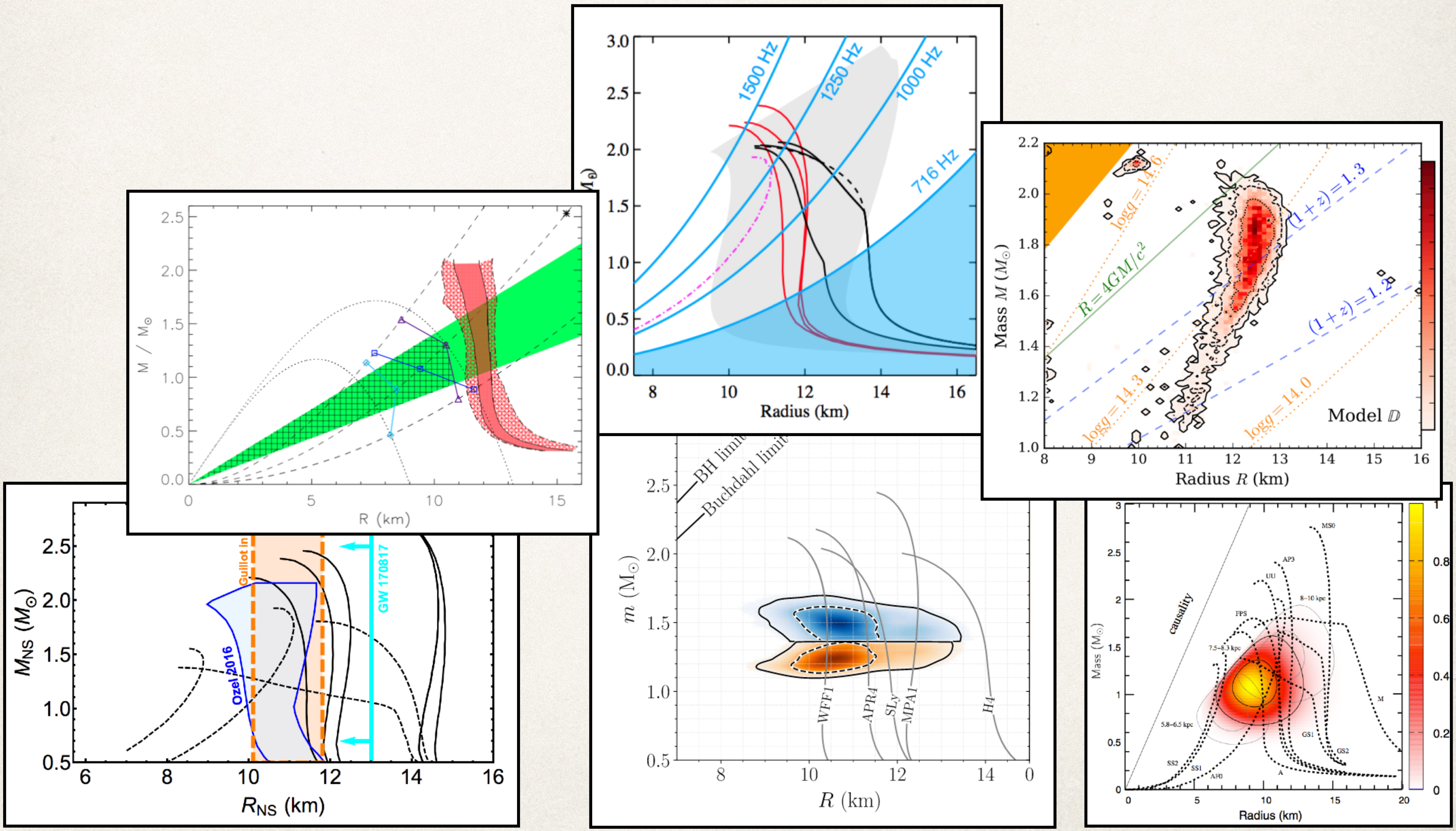
- **PSR J0740+6620**
  - Riley et al. 2021
  - Miller et al. 2021

Cold Surface of MSP: Gonzalez-Caniulef et al. 2019

Multiple thermally-emitting NS: Baillot-d'Etivaux et al. 2019

GW170817: Abbott et al. 2018

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



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CompARE

CompARE

- A **<u>repository of observational constraints on the EOS</u>**
  - Mass, radius, tidal deformability, etc.
- Facilitating the distribution of these constraints by **<u>observers</u>** to **<u>nuclear physics modellers</u>**.
- Explicit all model dependencies and assumptions possibly affecting results.
- Encourage observers to provide machine-readable outputs (with a uniform format).
- Encourage modellers to use the machine-readable outputs of the observers, and not just a values in the abstracts :-)

CompARE – List of constraints

CompARE

Home page | Data table | Add entry | More info | Login

- NS Spin
- Transiently Accreting NS
- NS Mass
- NS-NS_mergers
- PPM
- qLMXB
- Cold MSP
- Thermal INSs
- Type-I X-ray bursts

More filters | Search | Download Files | Download Bibtex

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 J0740+6620	NS mass	Pulsar timing	PK Parameters (Shapiro)	mean +/- 1 sigma	1	M	Dispersion measure: DMX	Gravitation theory: General relativity	Fonseca 2021		
+	PSR J1614-2230	NS mass	Pulsar timing	PK Parameters (Shapiro)	mean +/- 1 sigma	2	M	Shapiro delay: m_c sini parametrization	Gravitation theory: General relativity	Arzoumanian 2018		
+	PSR J1614-2230	NS mass	Pulsar timing	PK Parameters (Shapiro)	mean +/- 1 sigma	1	M	Shapiro delay: m_c sini parametrization	Gravitation theory: General relativity	Agazie 2023		
+	PSR J1748-2446ad	NS spin	Pulsar timing	Frequency measurement	mean +/- 1 sigma	1	F	None: None	None: None	Hessels 2006		
									Gravitation theory:			

CompARE – Details of an entry

CompARE | Home page | Data table | Add entry | More info | Login

PSR J0437-4715

Cold_MSP-PSRJ0437-4715-2019-massradius-helium-1.npy

Down

Model dependencies

atmosphere: Gonzalez2019
The atmosphere model used in this analysis was calculated for low-temperature atmosphere (<10^5.5 K) and includes the effect of plasma.
2019MNRAS.490.5848G

absorption: tbabs
The absorption of X-rays was calculated using absorption tables based on the tbabs model of Wilms et al. 2000 (updated in 2016).
2000ApJ...542..914W

redenning: Clayton2003
The frequency-dependent reddening has been implemented based on results of Clayton et al. 2003 (Fig.1).
2003ApJ...585..464C

hot spots model: ignored
The contribution of the hot spots to the X-ray spectrum analysed (<0.3 keV) was ignored.
2019MNRAS.490.5848G

Assumptions

Atmosphere Composition: helium
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. If no Hydrogen is present in the system, the next expected element is Helium, which is a possibility if the NS has accreted only Helium from a companion star. 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

Magnetic field: non-magnetic
This analyses also assume emission from a low-magnetic field neutron stars (as typically measured for MSPs, specifically B_dip ~ 2.8e8 G for PSR J0437-4715). The atmosphere model is that of a non-magnetised atmosphere, which is a good approximation as B-field effect (modified opacities) become important above 1e10 G (Kaminker et al., 1983; Zavlin et al., 1996). However, this neglects potential high-magnetic loop near the NS surface.
1983Ap&SS..91..167K
1996A&A...315..141Z
2019MNRAS.490.5848G

Rotation: non-rotating
The relativistic effects of rotation on the emergent spectrum are neglected in this analysis. However, the effects on the radius are < 1 % at the rotational frequency of PSR J0437-4715 (173.6 Hz), see Baubock et al. 2015.
2015ApJ...799...22B

Emitting fraction: uniform full surface
The analysis assumes that the full surface is emitting uniformly at the same temperature (modulo the contribution of the hot spots).
2019MNRAS.490.5848G

Interstellar medium: solar abundances
The modelling of the x-ray absorption (with the tbabs model) assumes solar abundances for the interstellar medium, a reasonable assumption for a pulsar located at 156 pc.
2000ApJ...542..914W

Prior: distance prior

Source info

PSR J0437-4715

Cold MSP

PSR J0437-47

Psr

69.3158310000

-47.2523730000

None

None

Method

Thermal emission

Spectral fitting (FUV and Xray data)

FUV (Kargalstev2004 + Durant2012), X-ray (Guillot2016, Rosat, up to 0.3 keV)

See Kargalstev2004, Durant2012, Guillot2016

References

DOI: Gonzalez-Canuilef 2019

ADS: 2019MNRAS.490.5848G

▸ Bibtex

Data Repository DOI: None

Data link: None

Constraints

Type: MCMC samples

Variable: M-R

Version: 1

CompARE – Details of an entry

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absorption: tbabs

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

redenning: Clayton2003

The frequency-dependent reddening has been implemented based on results of Clayton et al. 2003 (Fig.1).
2003ApJ...585..464C

hot spots model: ignored

The contribution of the hot spots to the X-ray spectrum analysed (<0.3 keV) was ignored.
2019MNRAS.490.5848G

Assumptions

Atmosphere Composition: helium

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. If no Hydrogen is present in the system, the next expected element is Helium, which is a possibility if the NS has accreted only Helium from a companion star. 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

Magnetic field: non-magnetic

This analyses also assume emission from a low-magnetic field neutron stars (as typically measured for MSPs, specifically B_dip ~ 2.8e8 G for PSR J0437-4715). The atmosphere model is that of a non-magnetised atmosphere, which is a good approximation as B-field effect (modified opacities) become important above 1e10 G (Kaminker et al., 1983; Zavlin et al., 1996). However, this neglects potential high-magnetic loop near the NS surface.
1983Ap&SS..91..167K
1996A&A...315..141Z
2019MNRAS.490.5848G

Rotation: non-rotating

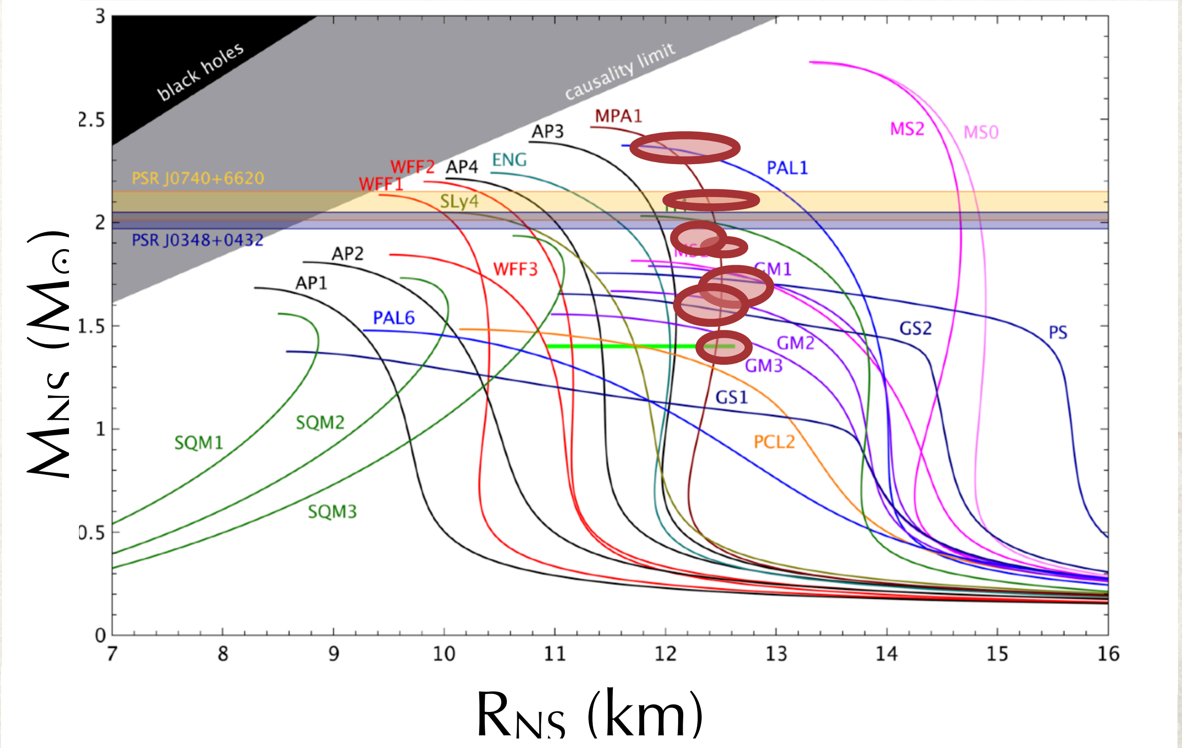
The relativistic effects of rotation on the emergent spectrum are neglected in this analysis. However, the effects on the radius are < 1 % at the rotational frequency of PSR J0437-4715 (173.6 Hz), see Baubock et al. 2015.
2015ApJ...799...22B

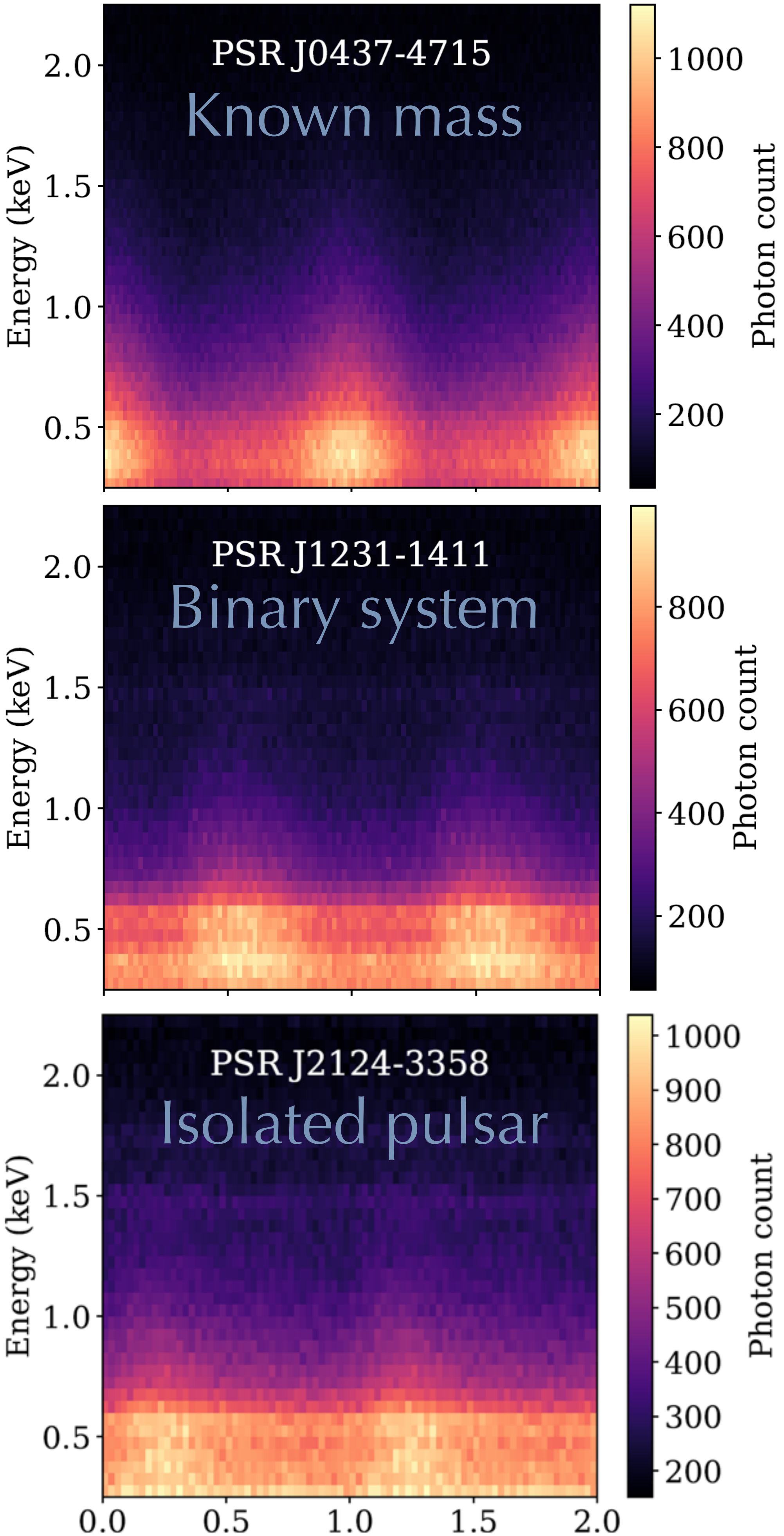
Emitting fraction: uniform full surface

The analysis assumes that the full surface is emitting uniformly at the same temperature (modulo the contribution of the hot spots).
2019MNRAS.490.5848G

Outline

- Measurements of masses and radii
- Results from the NICER mission
  - Method, results, lessons…
- A new tool for future measurements
- **<u>Future prospects</u>**



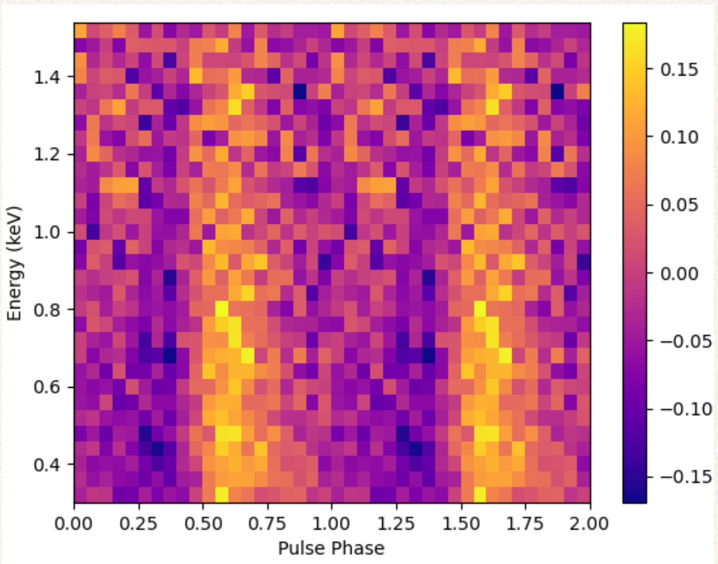


Bogdanov et al. (2019)

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

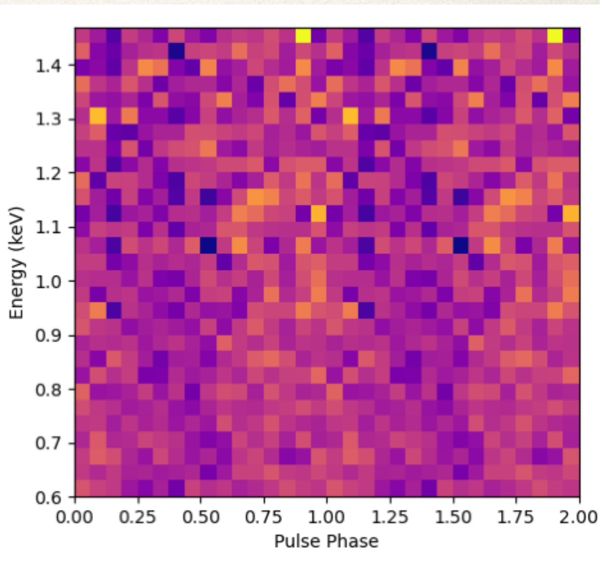
PSR J0614–3329

Guillot et al. (2019)

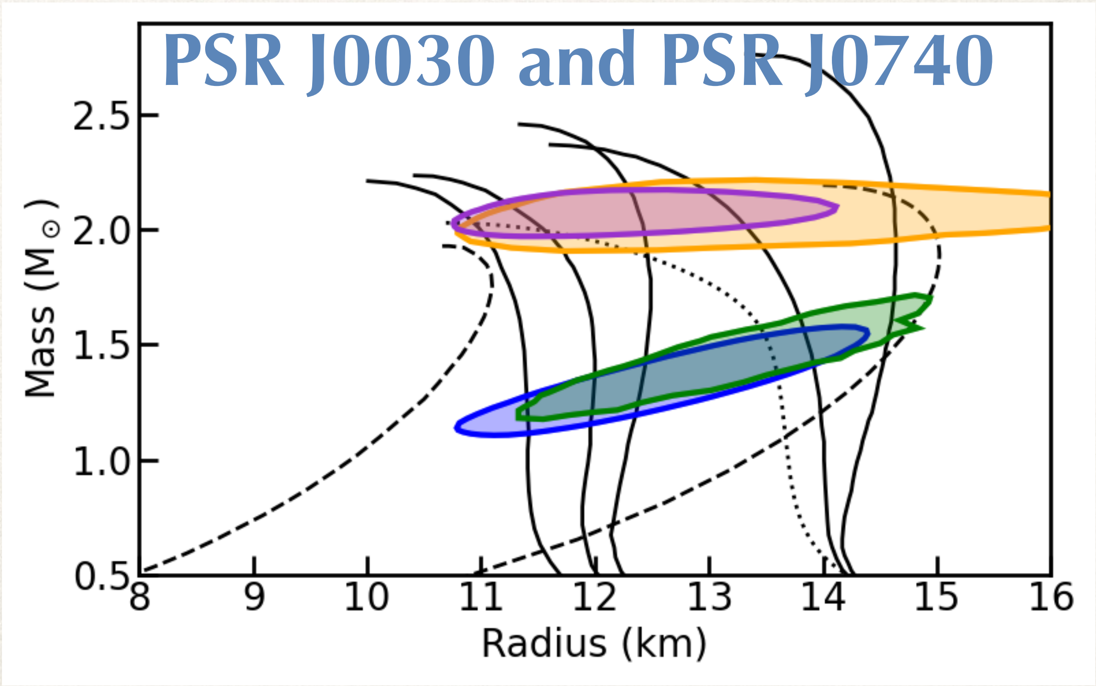


PSR J1614-2230

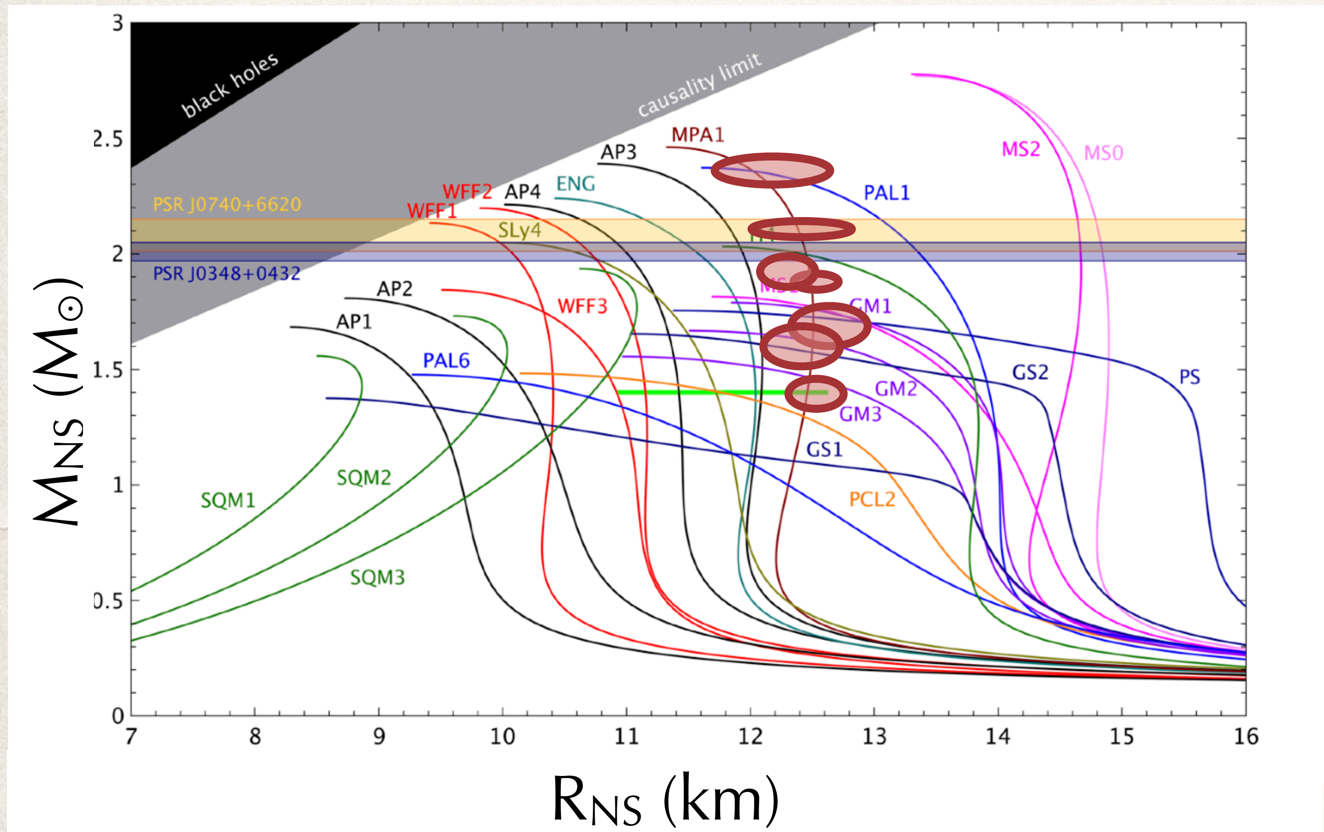
Known high mass:
M = 1.908±0.016 $M_\odot$

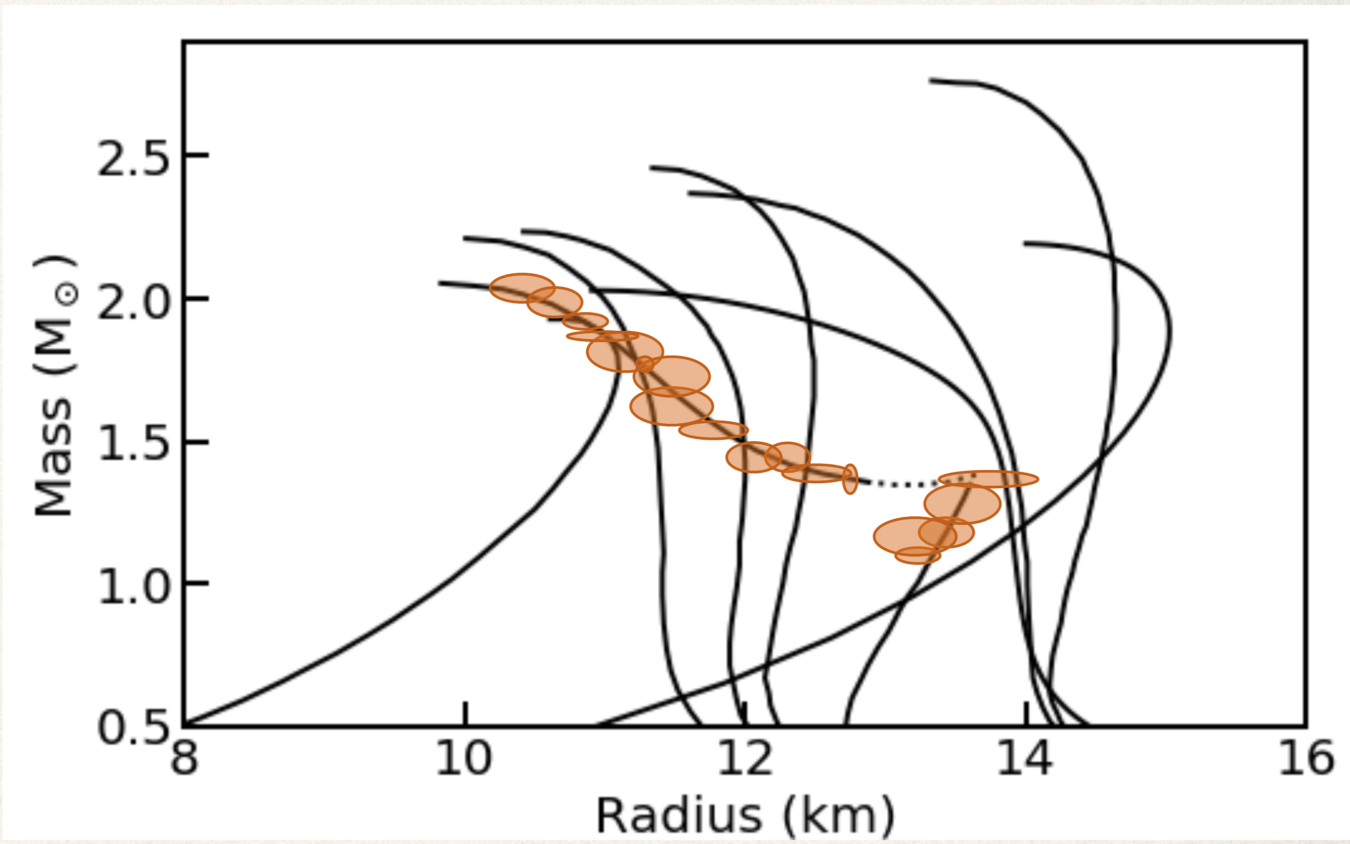


And more data for PSR J0030 and PSR J0740



Measurements of a dozen of NS radii with precisions of few % will require the next generation of observatories!



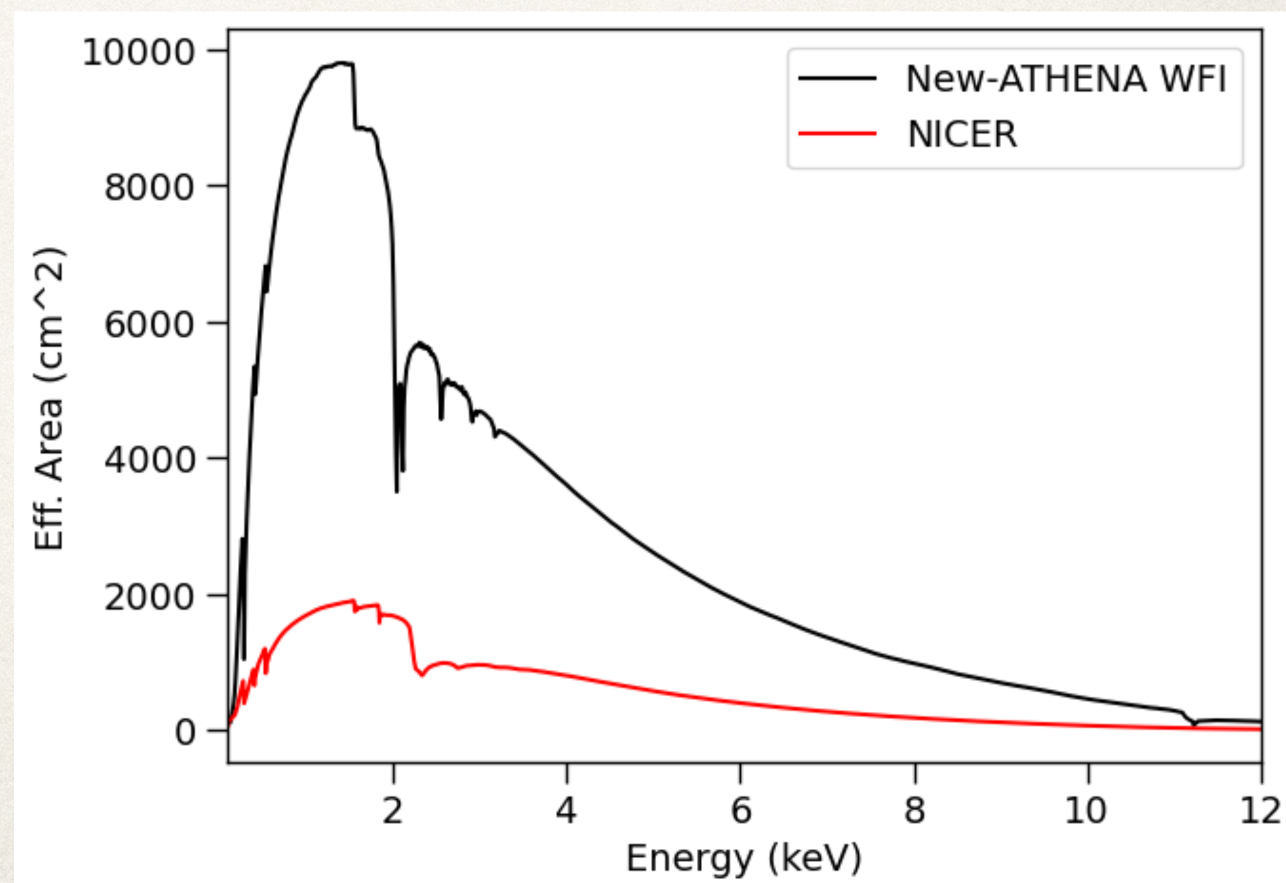


New-ATHENA

WFI ATHENA

IFU

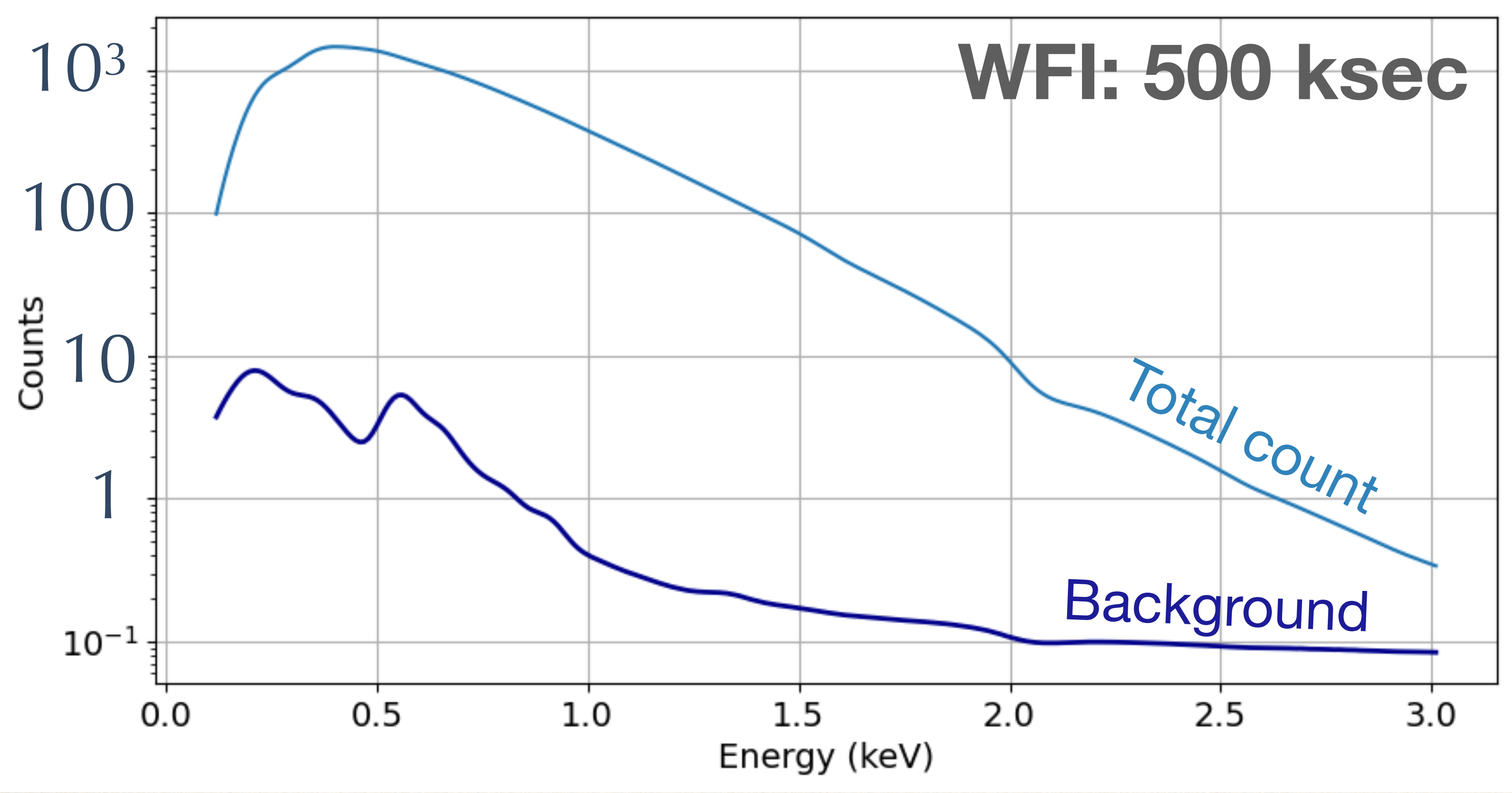
- Sensitivity: about x5 that of NICER
- Time resolution:
  - 10 µsec (X-IFU)
  - ~100 µsec (WFI)
- Low-background: ~ 0.001 c/s

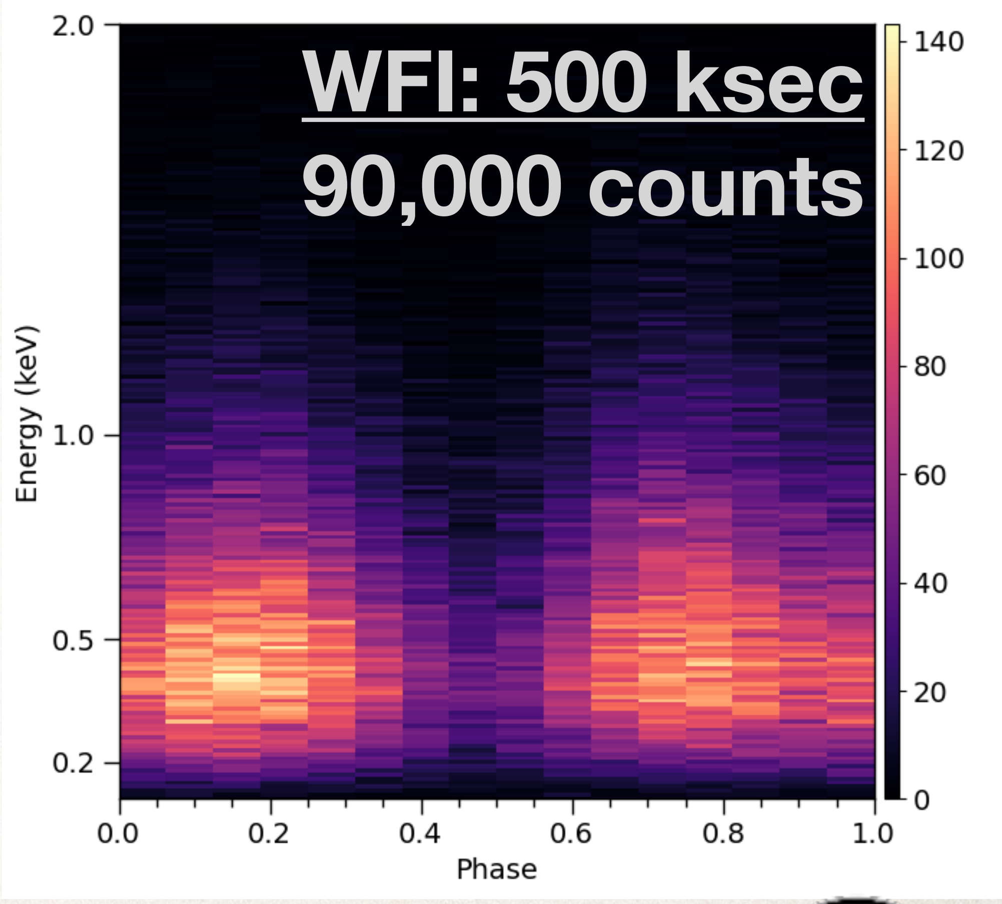


Future prospects for pulse profile modelling with new-Athena are quite promising.

Simulations of PSR J0740+6620 with P_{spin} = 2.88 msec and d=1.2 kpc

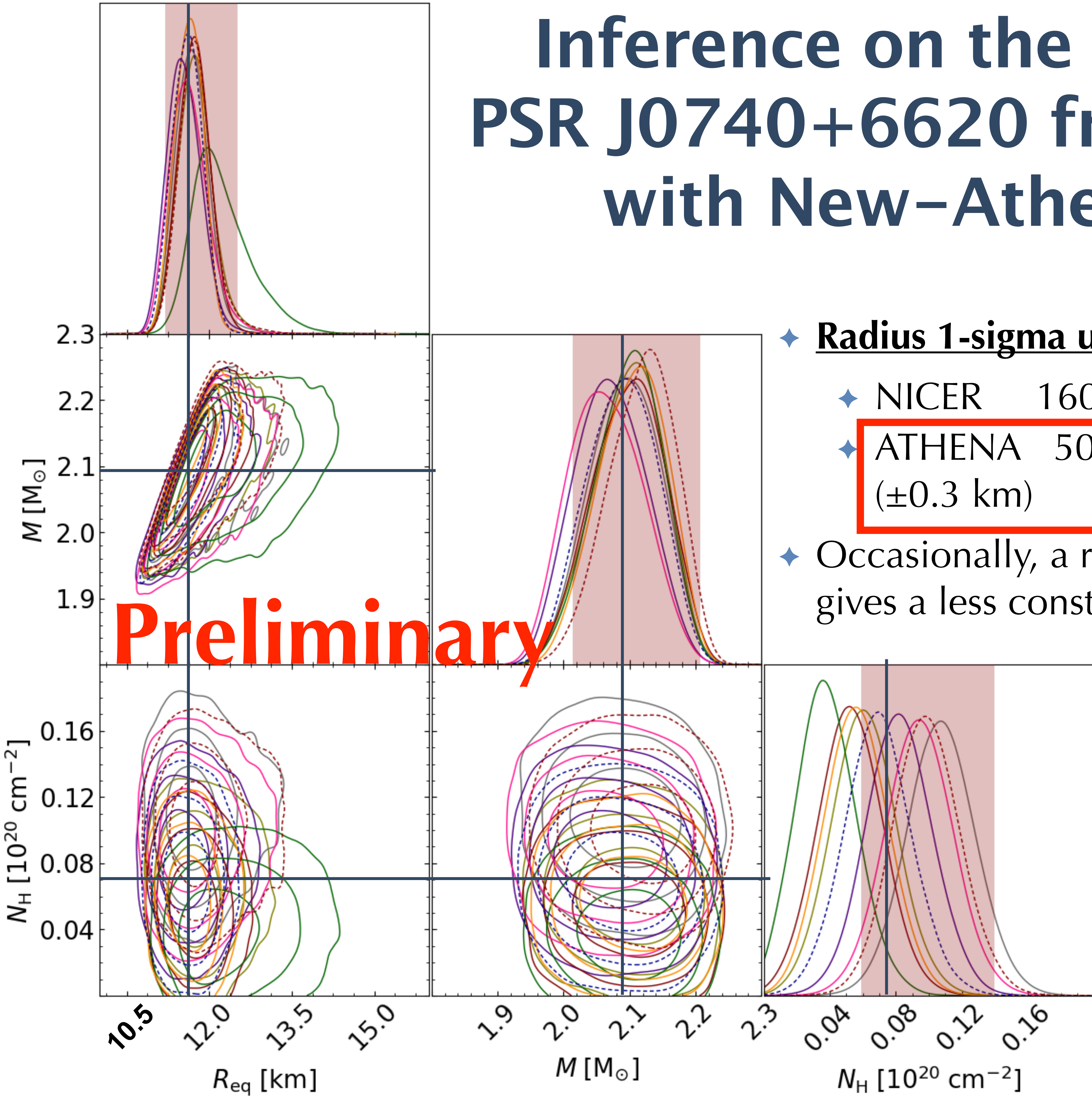
R~11.5 km, M=2.08 $M_{\odot}$ with 2 circular hot spots
Simulation of 500 ksec observations





X-PSI

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



- **<u>Radius 1-sigma uncertainties</u>**
  - NICER 1600 ksec: ~10%
  - ATHENA 500 ksec: ~3% average (±0.3 km)
- Occasionally, a random noise realisation gives a less constrained radius

Conclusions

- Multiple methods exist to measure the radii and masses of neutron stars, and most have room for improved measurements.
- NICER has **demonstrated of the feasibility** of the pulse profile modelling
  - Measurement of the radii of two millisecond pulsars
  - A few more measurements are expected soon.
  - NICER also revealed new observational and modelling challenges.
- In the X-ray band, New-Athena has the potential of bringing us much closer to **understanding the interior of neutron stars**, with its numerous advantages:
  - High sensitivity
  - Very low (and known!) background
  - **Unmatched capabilities** compared to current/planned observatories
  - Can New-Athena distinguish between different surface spot patterns ?
- **CompARE**: Beta-version release this summer hopefully.

Lorentz Center Workshop (proposed)

XMXS 2024

eXtreme Matter in eXtreme Stars

Tentatively in Septembre 2024