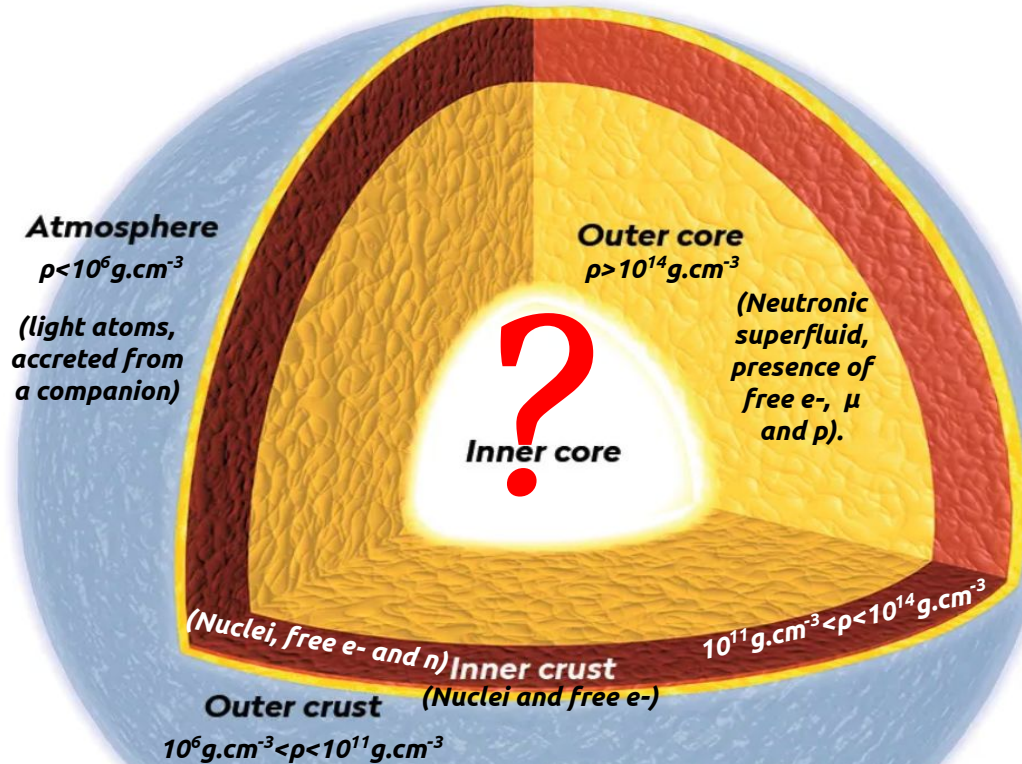


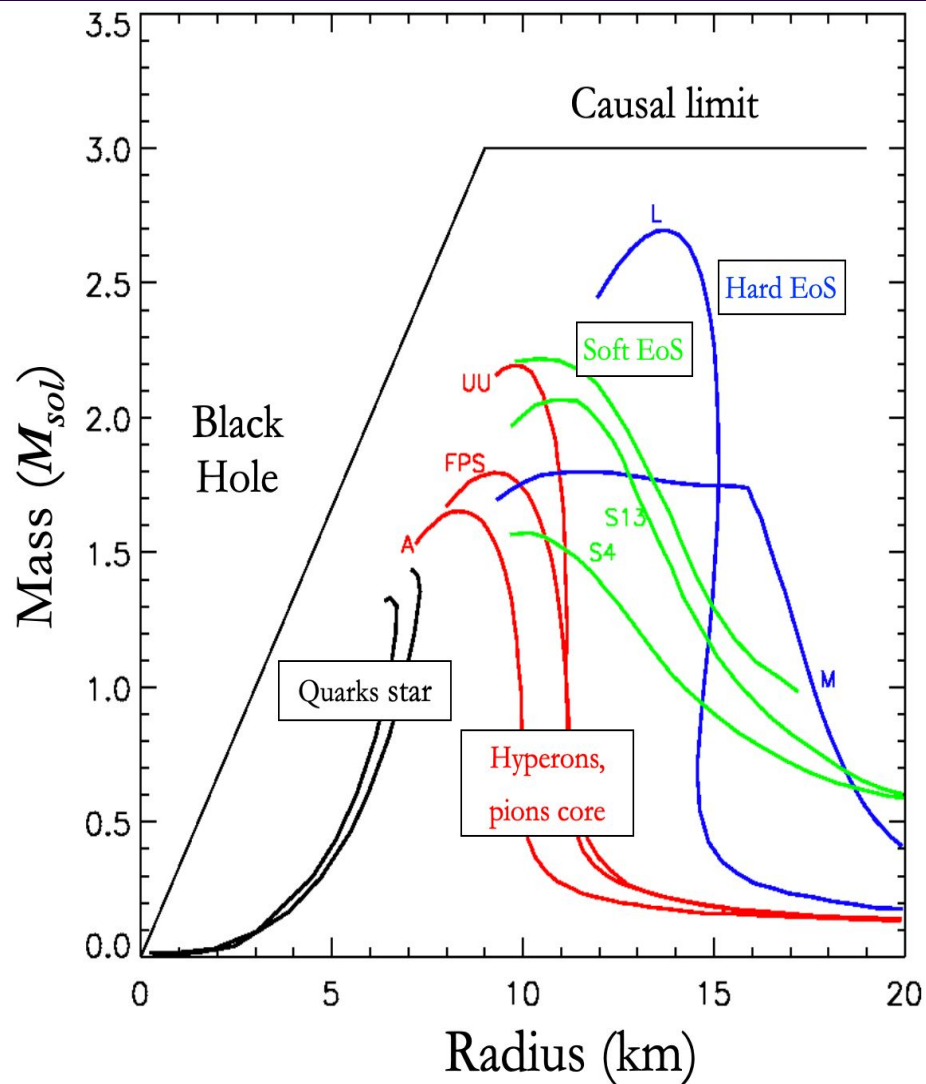
***Multi-wavelengths analyses of
the millisecond pulsar
PSR J0437-4715 to constrain
dense matter physics***

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The mystery of the ultra-dense matter :



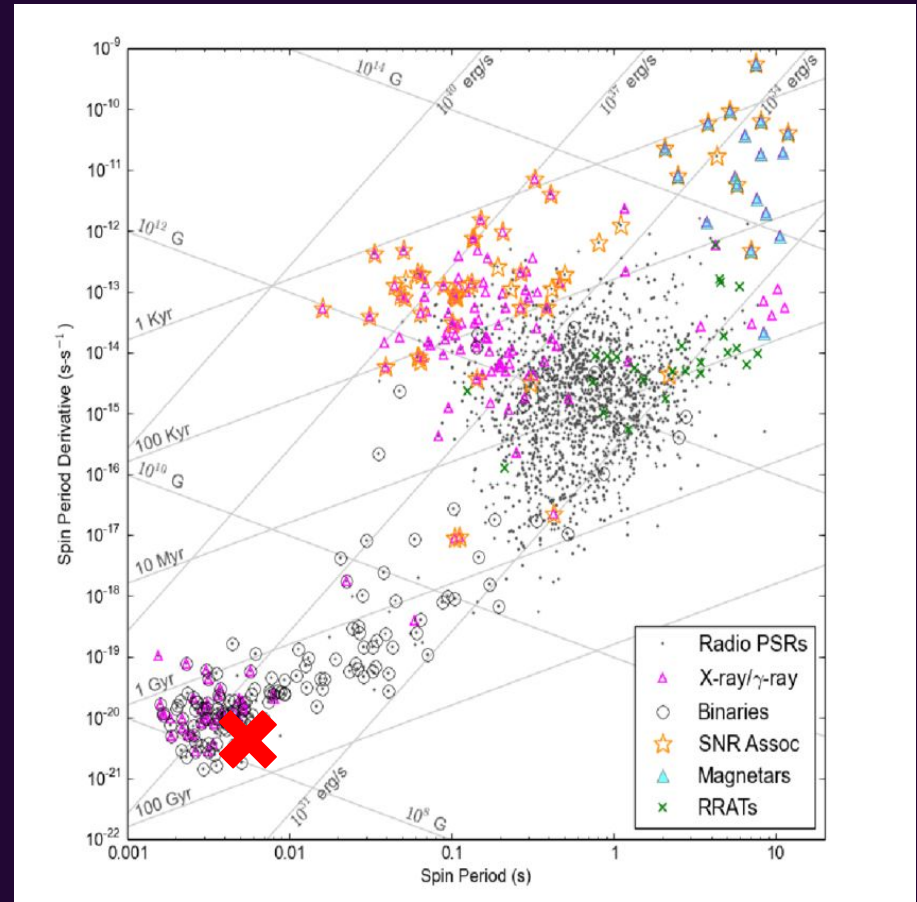
- What are neutron stars (NSs) made up ?
- The composition and the behaviour of their ultra-dense cores remain a challenge to find out!



- There are different ultra-dense matter models for NS cores.
- In nuclear physics, they are associated with Equations of State (EoS), which link pressure and density.
- The aim is to find new constraints on the EoSs.
- How? With NS masses and radii measurements obtained from multi-wavelength analyses.

Our target : PSR J0437-4715

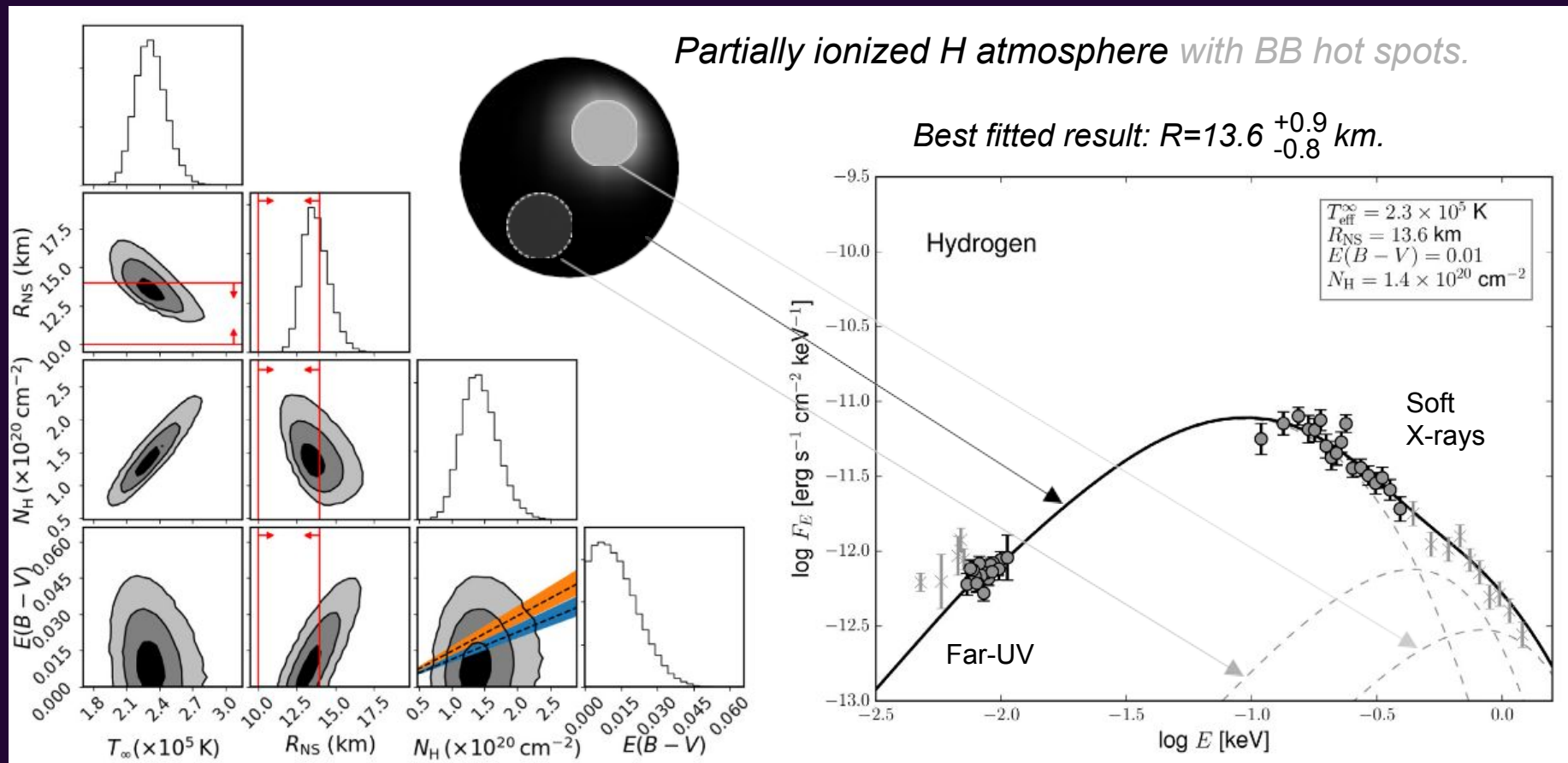
- The nearest ($d=156.98\pm 0.15$ pc) and the brightest millisecond pulsar (MSP) in X-rays.
- Spin period of $P=5.7575$ ms.
- In a binary system with a white dwarf.
- Last radio timing analysis (PPTA3, Reardon et al. 2024) gave $M=1.418\pm 0.044 M_{\odot}$.



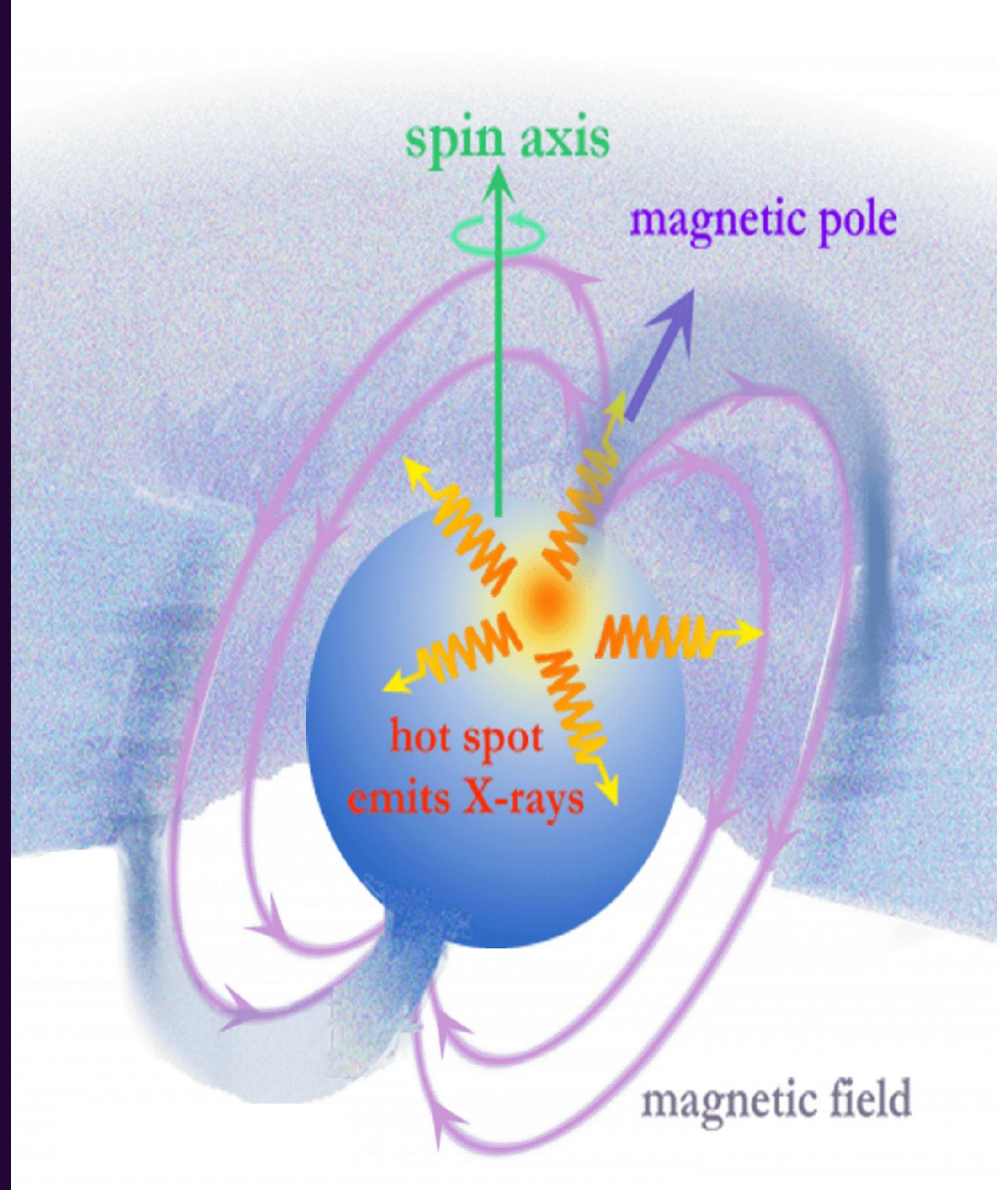
P-Ḑ diagram of all NSs.

Act I : A spectroscopic analysis of J0437

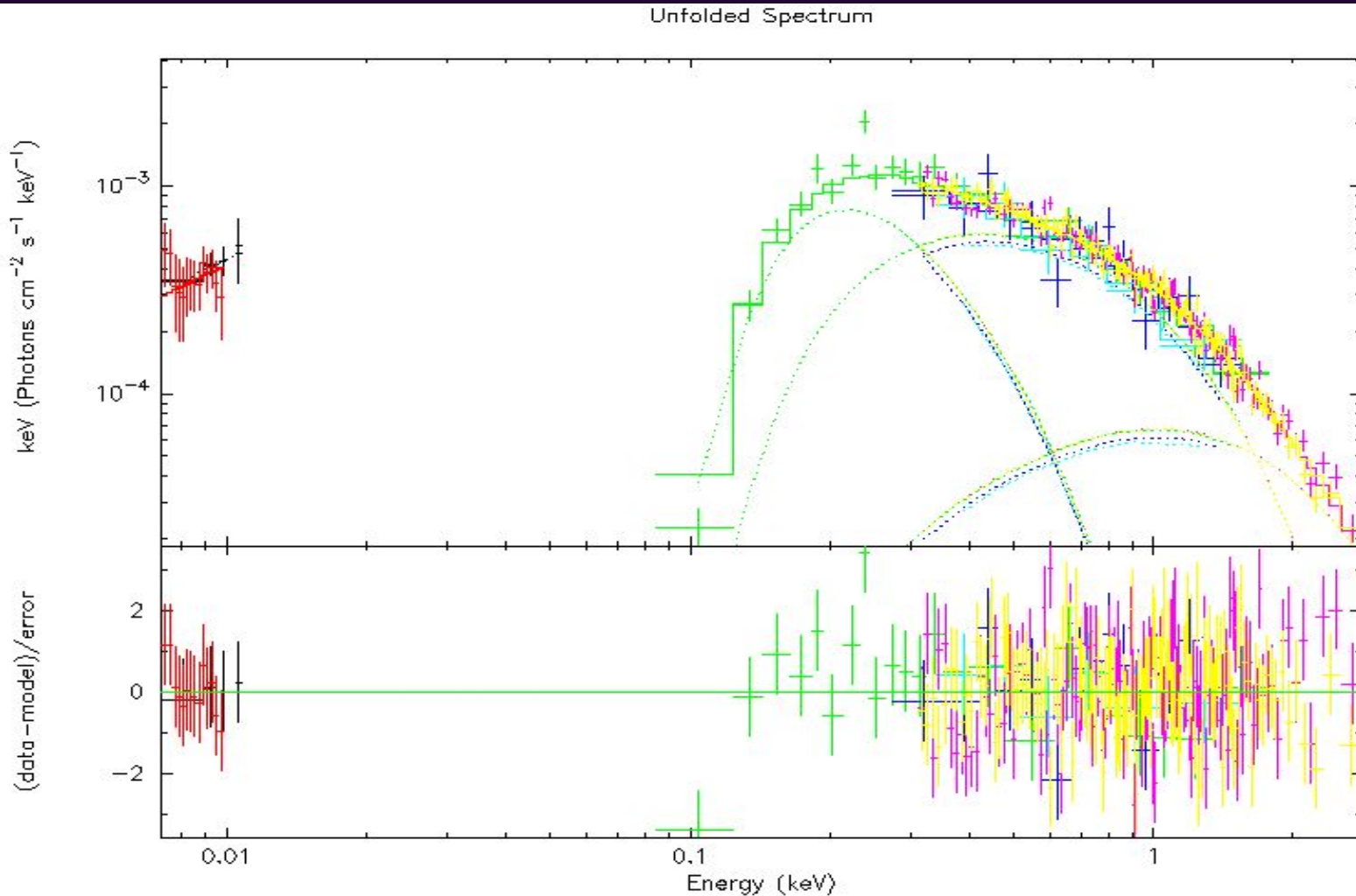
- First steps in González-Caniulef et al. (2019):



- Why hot spots? What are the heating mechanisms?
 - **Hot spots** ($T \sim 10^6 \text{K}$) formed from magnetospheric currents causing charged particles to heat up the atmosphere.
 - The rest of the NS surface ($T \sim 10^5 \text{K}$) cooled after accretion stopped.



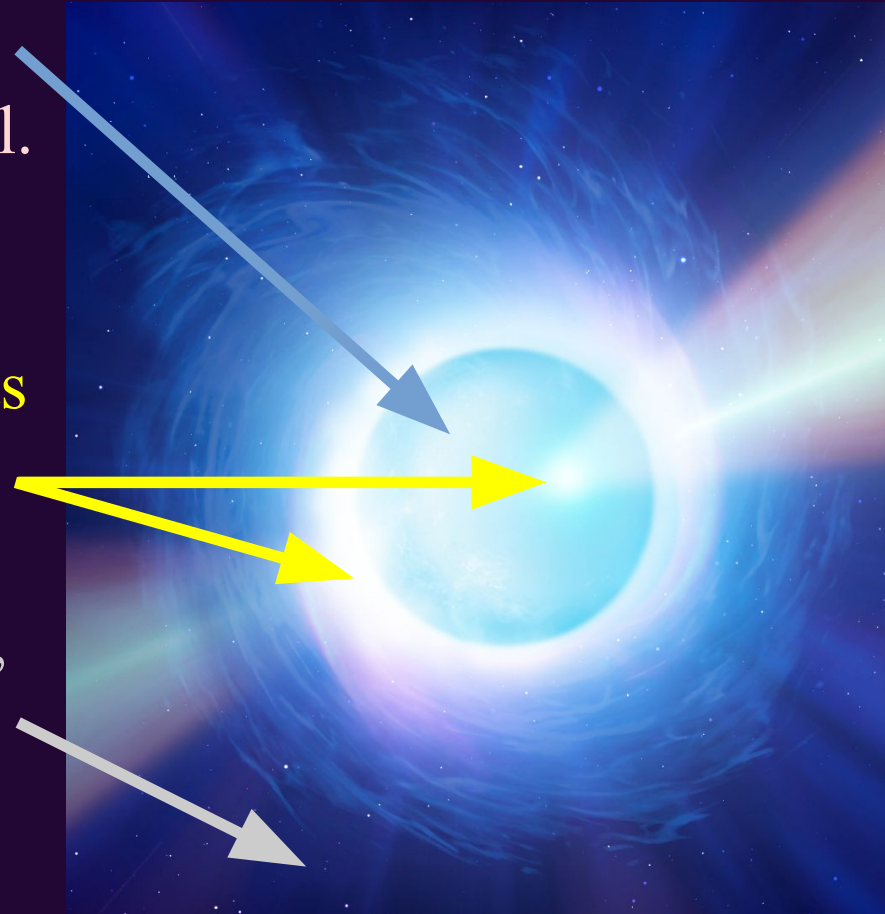
- Observational dataset for the analyses:

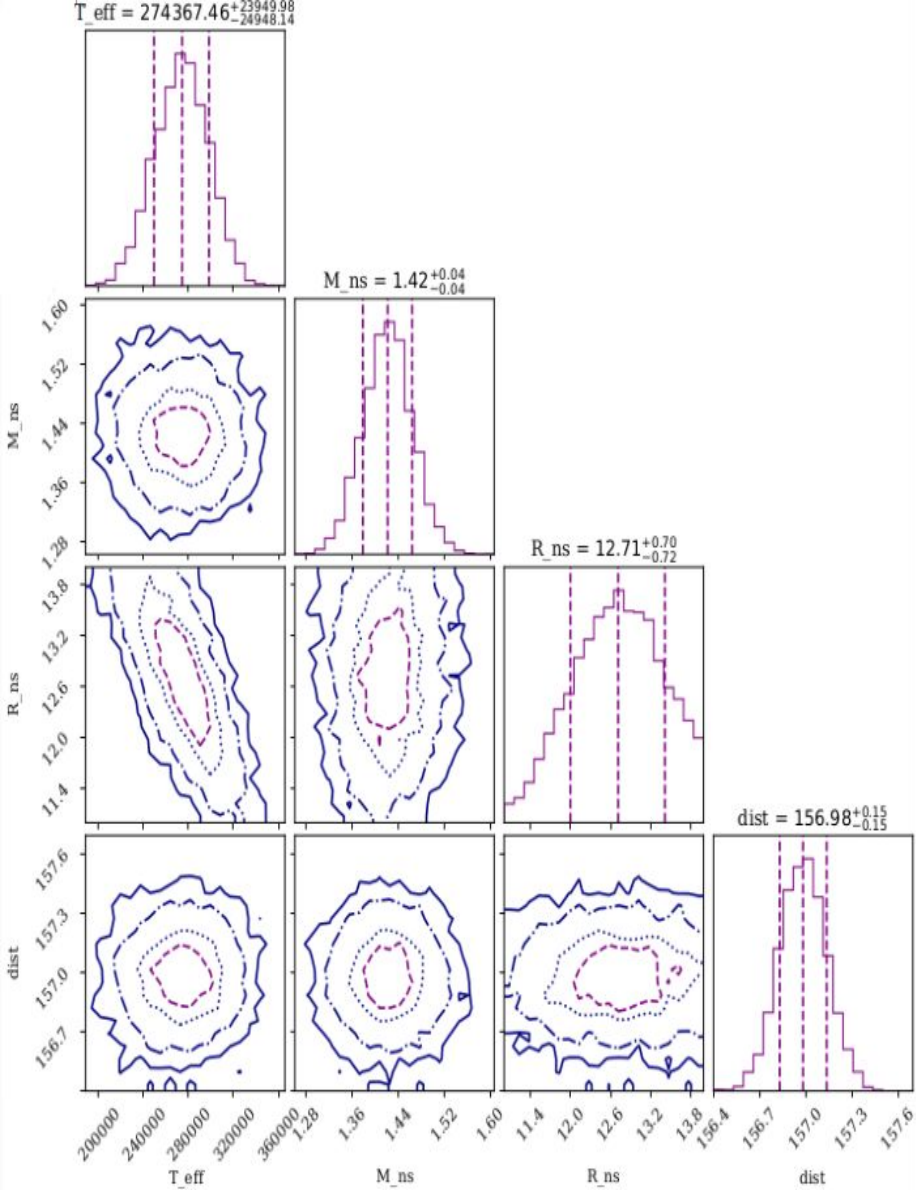


We model J0437 surface emission using records from far-UV (HST) to soft X-rays (ROSAT, eROSITA, XMM-Newton and CHANDRA) energy domains.

Model building by XSPEC :

- A partially ionized H atmosphere component for the cold surface ($T \sim 10^5 \text{K}$), from González-Caniulef et al. (2019), compiled and loaded into XSPEC.
- **Fully ionized H atmosphere components for the magnetic hot spots ($T \sim 10^6 \text{K}$)** (NSatmos, Ho & Heinke, 2006).
- Interstellar medium attenuation models, both in UV (Clayton et al. 2003, compiled and loaded for XSPEC) and X-rays (Tbabs, Wilms et al. 2000) energies.





- Model parameters fitted into BXA (Bayesian X-ray Analysis), a nested sampling package derived from UltraNest.

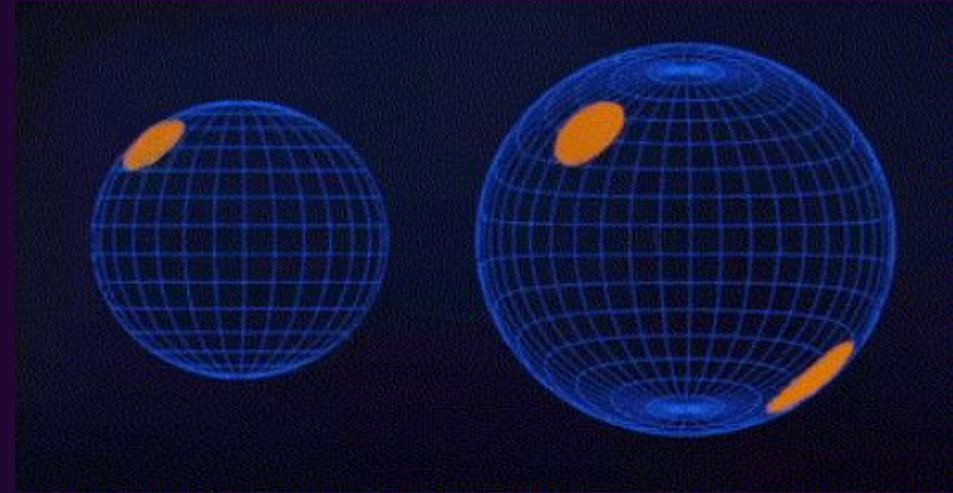
- Fits include priors from independent measurements of M , d and $E(B-V)$.
- Current best result:

$$R = 12.71^{+0.70}_{-0.72} \text{ km.}$$

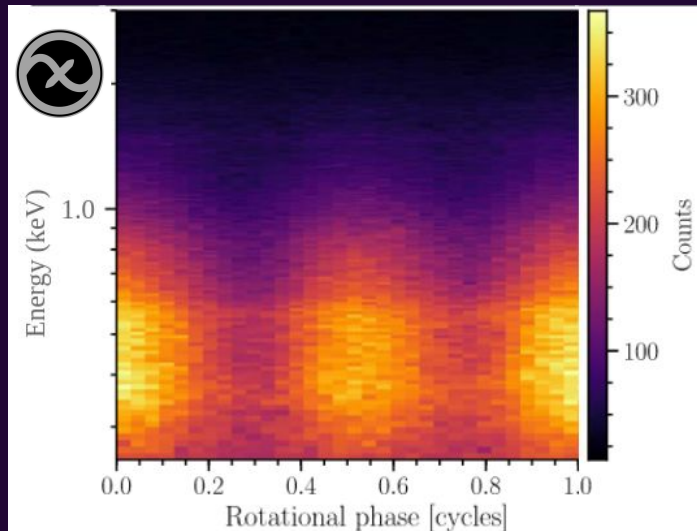
Preliminary posterior results for the cold surface temperature, the mass, the radius and the distance, respectively in units of K, M_{\odot} , km and pc, using HST and ROSAT observations.

Act II: Pulse profile modeling of J0437:

- PPM: A spectro-timing technique for compactness measurements accounting for general and special relativistic effects induced by the MSP gravitational field and spin.

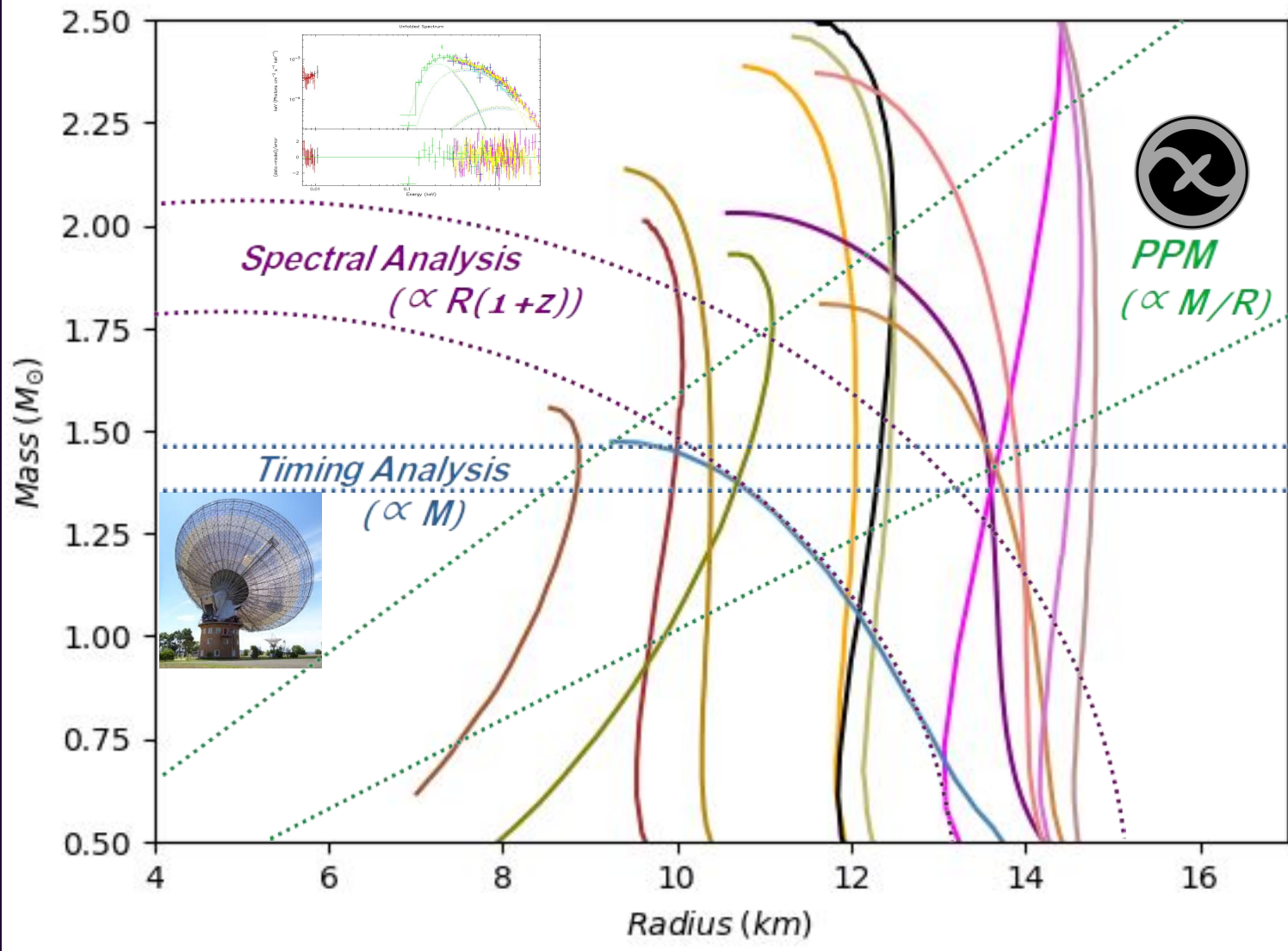


- Use of the X-PSI (X-ray Pulse Simulation and Inference) ray-tracing package.
- Implementation of customized modules to extend the PPM to far-UV energies.

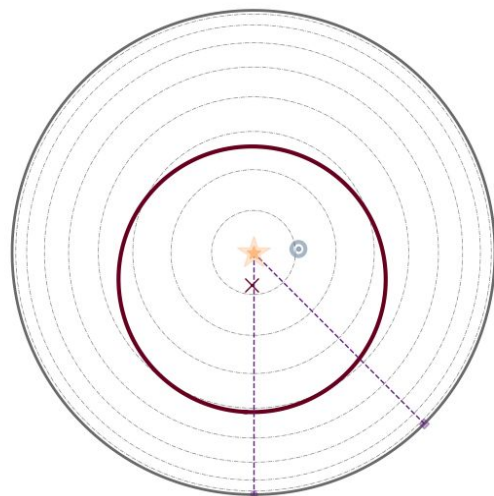
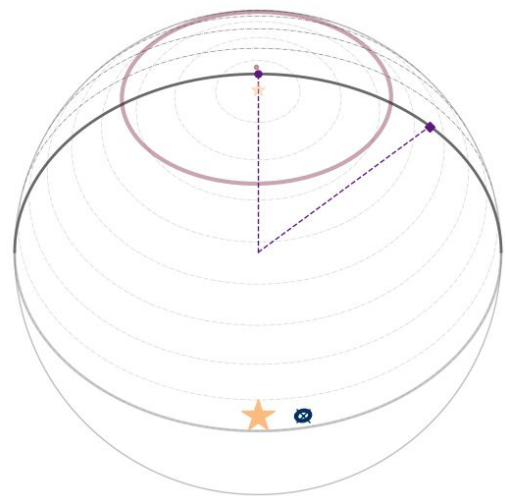


- Ultimately, combined analyses of all datasets of J0437 shall return new constraints for the models of MSPs cores.

Schematic representation of the complementarity of the mass-radius constraints from different methods.



- First PPM tests using the **Single-Temperature Unshared (ST-U) hot spots + Elsewhere** geometric configuration, with each NS surface regions described with a fully-ionized H atmosphere model.



- Equator
- Primary $\log(T/K) = 6.07$
- × Hot Region centers
- Secondary $\log(T/K) = 6.12$
- Hot Region centers -Opposite Hemisphere
- $\phi = 0$ [cycle], $\theta = \pi/2$ [rad]
- $\phi = 0.125$ [cycle], $\theta = \pi/2$ [rad]
- ★ Projected North Pole
- ★ Projected South Pole -Opposite Hemisphere

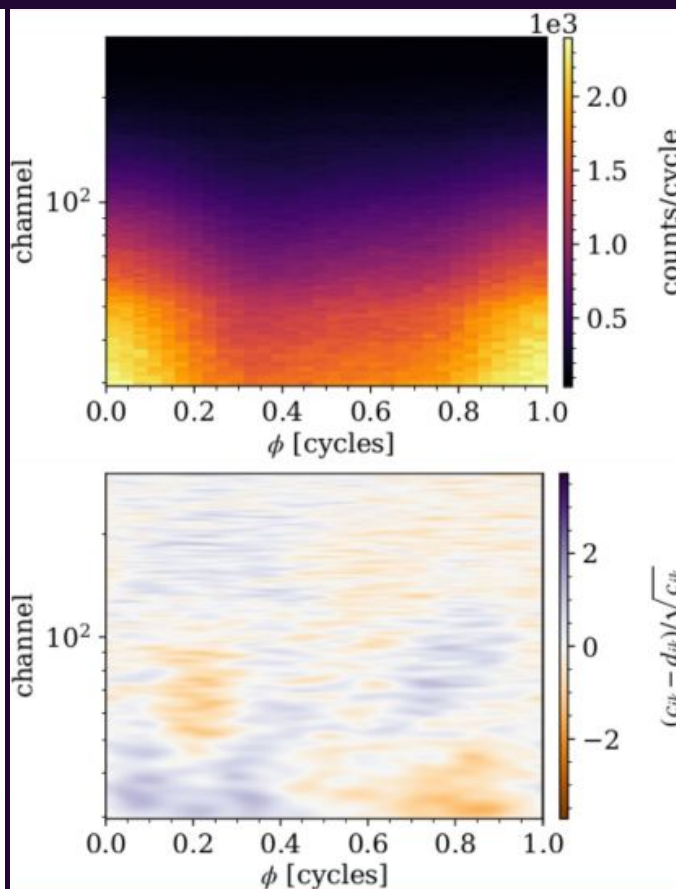
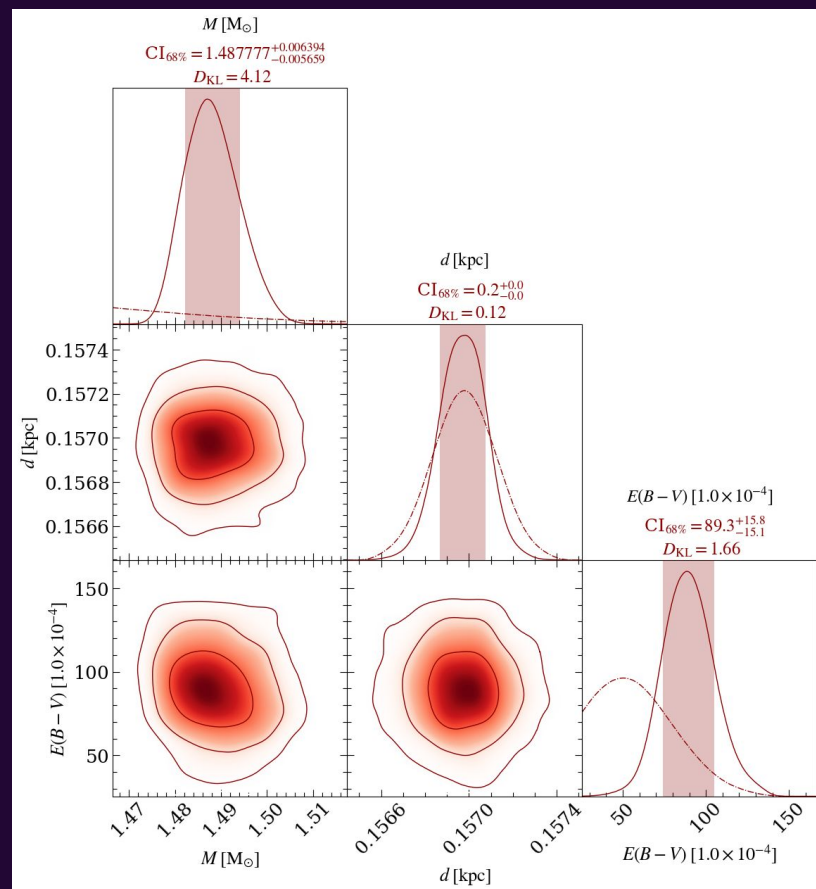
Maximum likelihood geometry for J0437, with NICER, CHANDRA and HST data.

- However, once converged, we have:

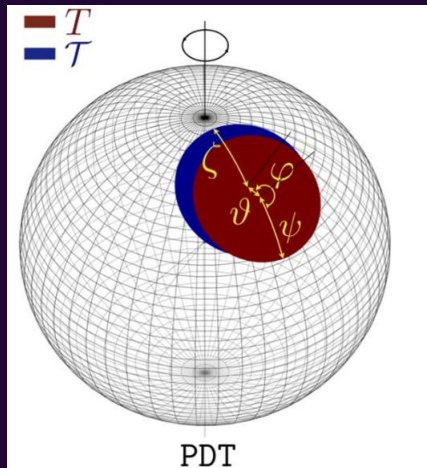
- Strong shifts between prior and posterior distributions.

- Presence of non-negligible residuals structures

- We obtained similar results with a partially ionized (Miller et al. 2021) elsewhere.
- So ST-U+ elsewhere cannot fully fit J0437 emission.



Perspectives :



PDT spot geometry (Riley et al. 2019).

- For the spectral analysis:
 - A computationally expensive BXA test with all datasets is still converging.
 - Cross-checks with other sampling tools (JAXSPEC, Dupourqué et al. 2024) will be required.
- For the PPM:
 - Extension to more complex hot spot geometries.

Conclusion :

- NSs ultra-dense matter properties can be constrained thanks to masses and radii measurements.
- For PSR J0437-4715:
 - The spectral analysis of its far-UV and soft-X rays thermal emission gave a preliminary radius of $R=12.71^{+0.70}_{-0.72}$ km.
 - For our first multi-wavelength PPM tests, the **ST-U+elsewhere** configuration is less likely to fit J0437 surface emission.
- The final results from both analyses shall ultimately help us to select the best EoS to describe NSs cores.