Measuring a neutron star radius from ultraviolet and X-ray observations

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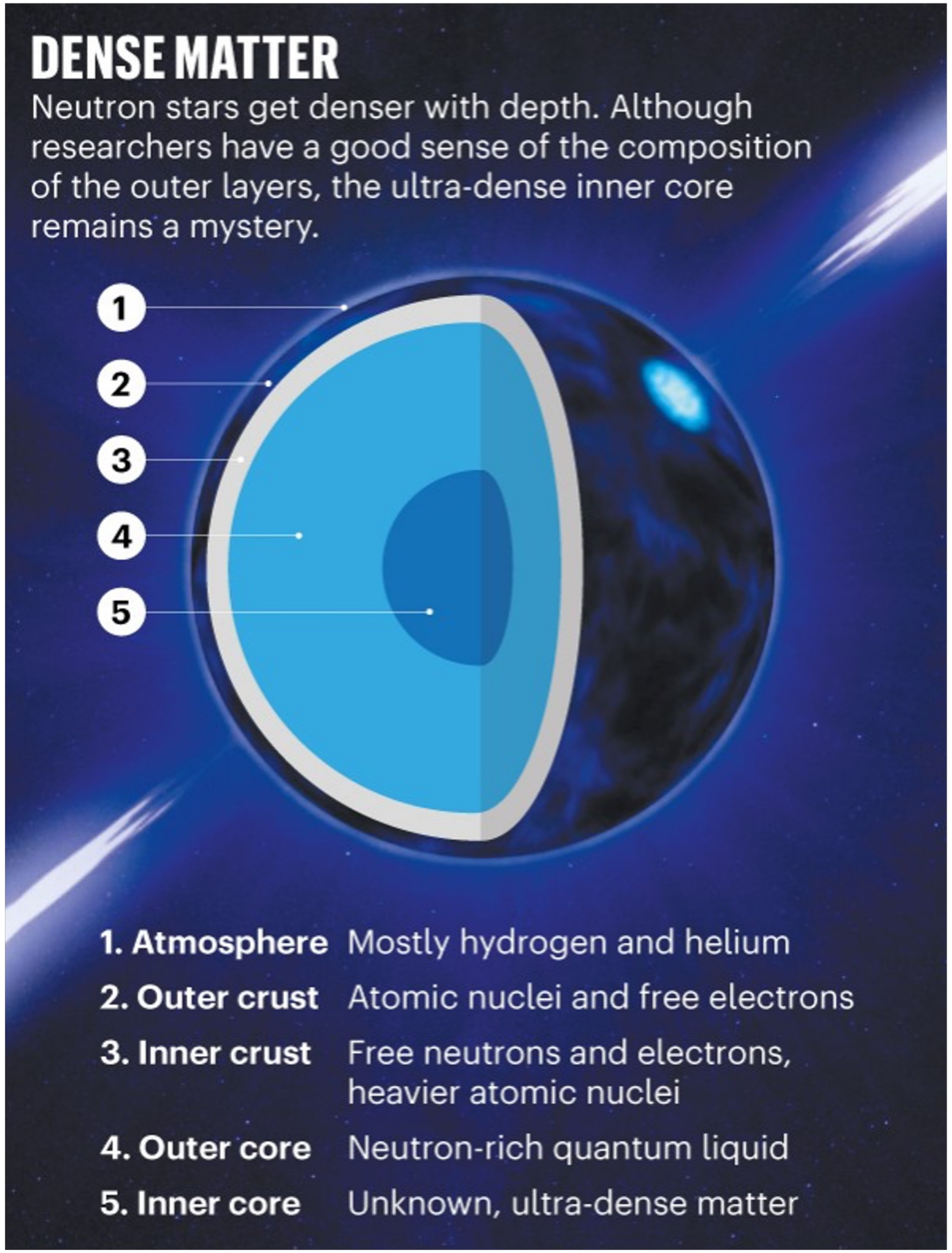
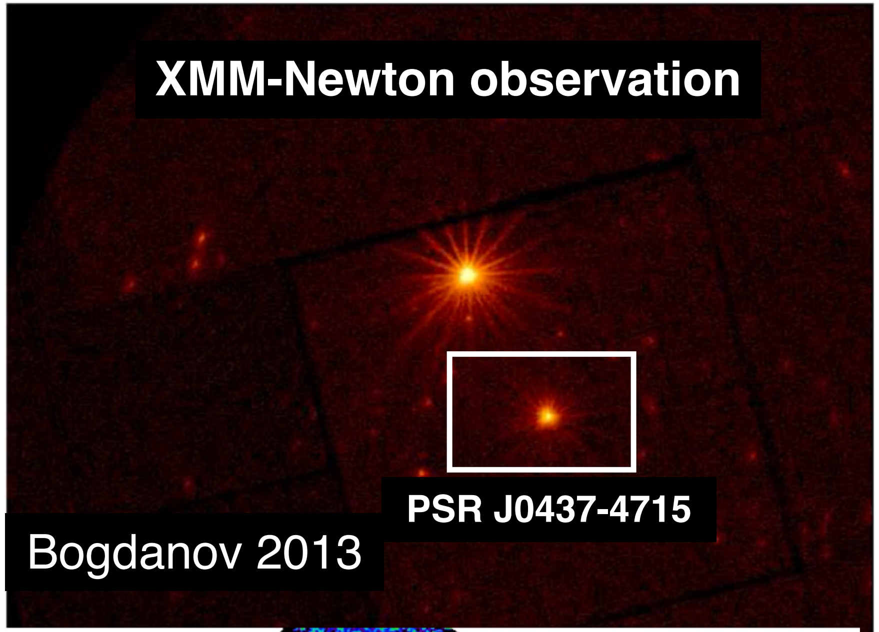
Introduction

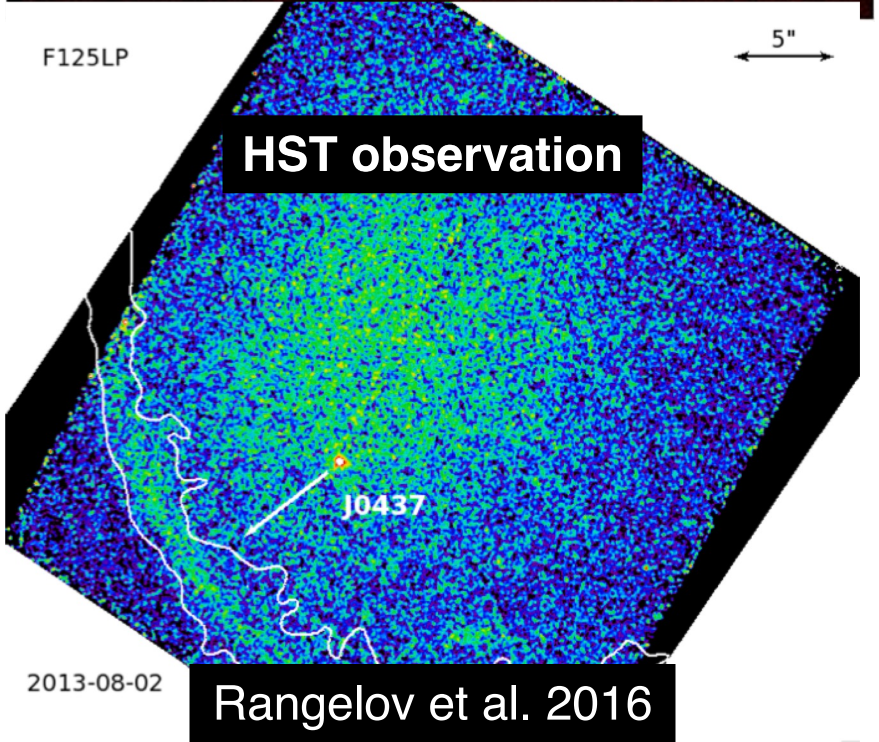
- Neutron stars (NSs) are compact objects with a rich phenomenology: isolated sources, binary systems, fast radio bursts, gamma ray bursts, gravitational wave emission, etc.
- The density in the interior of NSs can exceed several times the nuclear saturation density $\rho_0 = 3{\times}10^{14}\ g\ cm^{-3}$.
- Radius and mass measurements of neutron stars can allow us both to infer the equation of state (EOS) of super-dense matter and to establish constraints on fundamental physics.



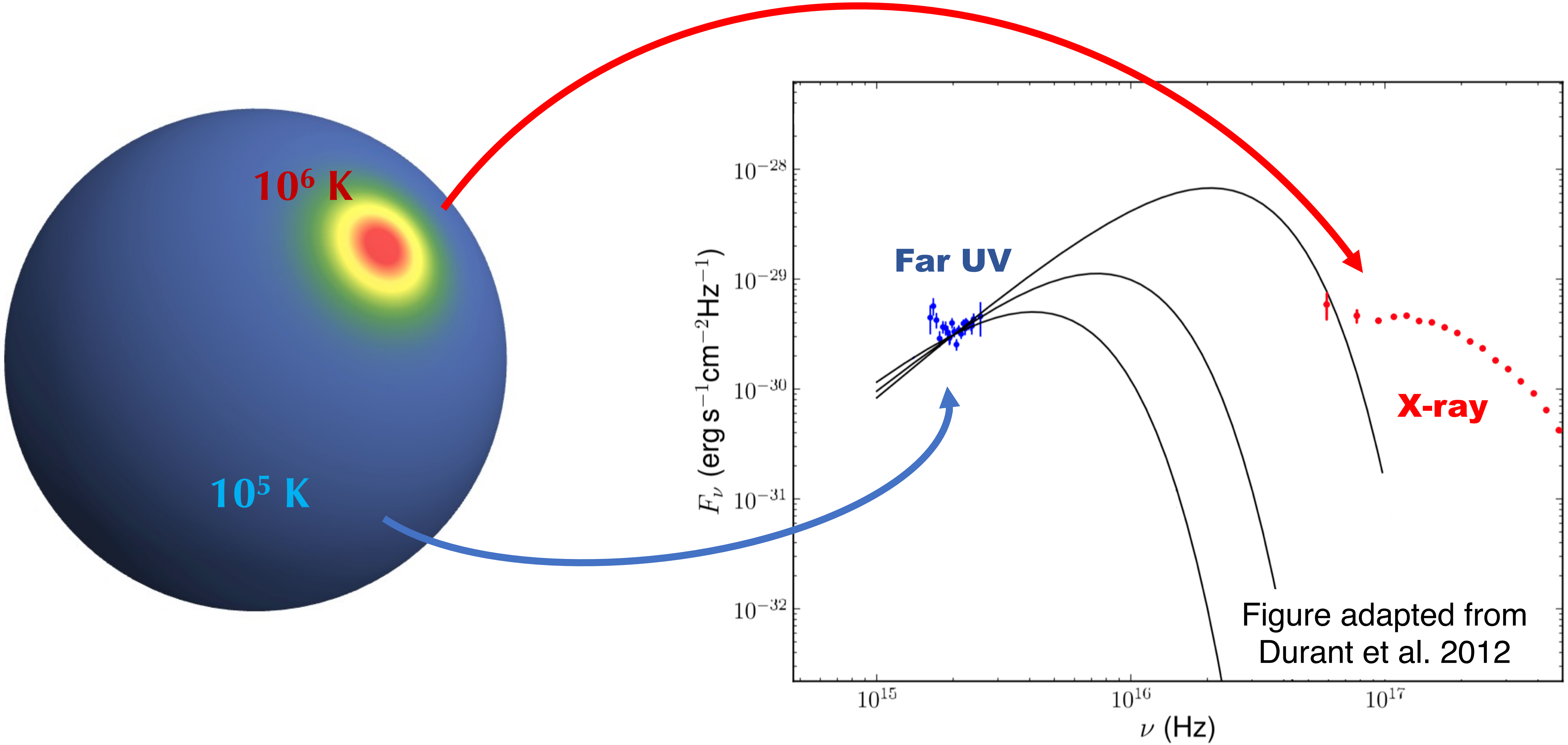
Millisecond Pulsars

- Millisecond pulsars (MSPs) are fast spinning neutron stars, with typical periods of few millisecond.
- They are thought to have been spun up by accretion of matter from a binary companion.
- PSR J0437-4715 is the brightest and nearest millisecond pulsar, at a well-measured distance $d = 156.79 \pm 0.25$ pc. In addition, this MSP is in a binary system (with a white dwarf companion), which has allowed to measure its mass with high precision: $M = 1.44 \pm 0.07\, M_{\odot}$
- Ultraviolet and X-ray observations have revealed thermal emission from the entire surface of PSR J0437-4715.



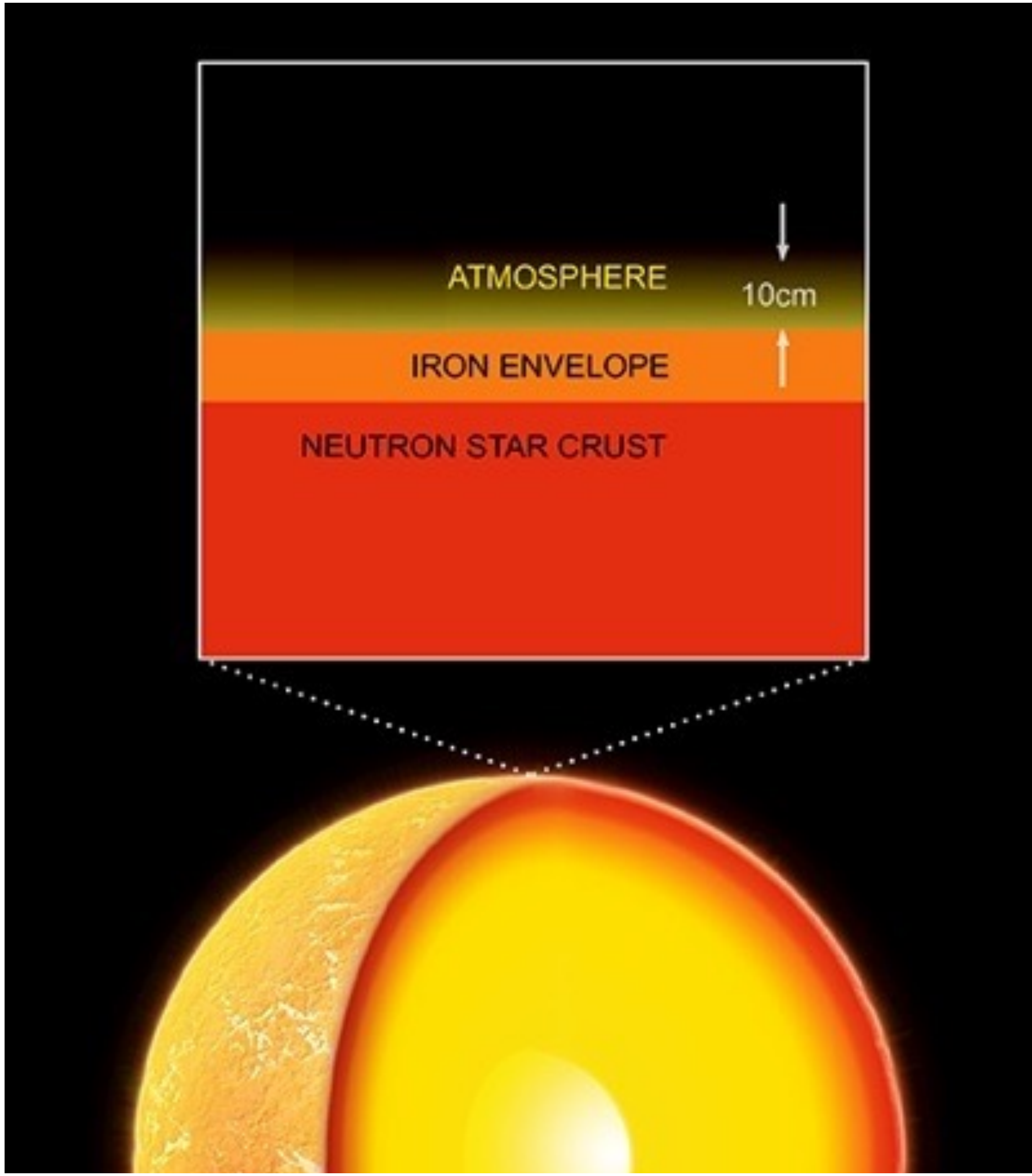


Spectrum of PSR J0437-4715



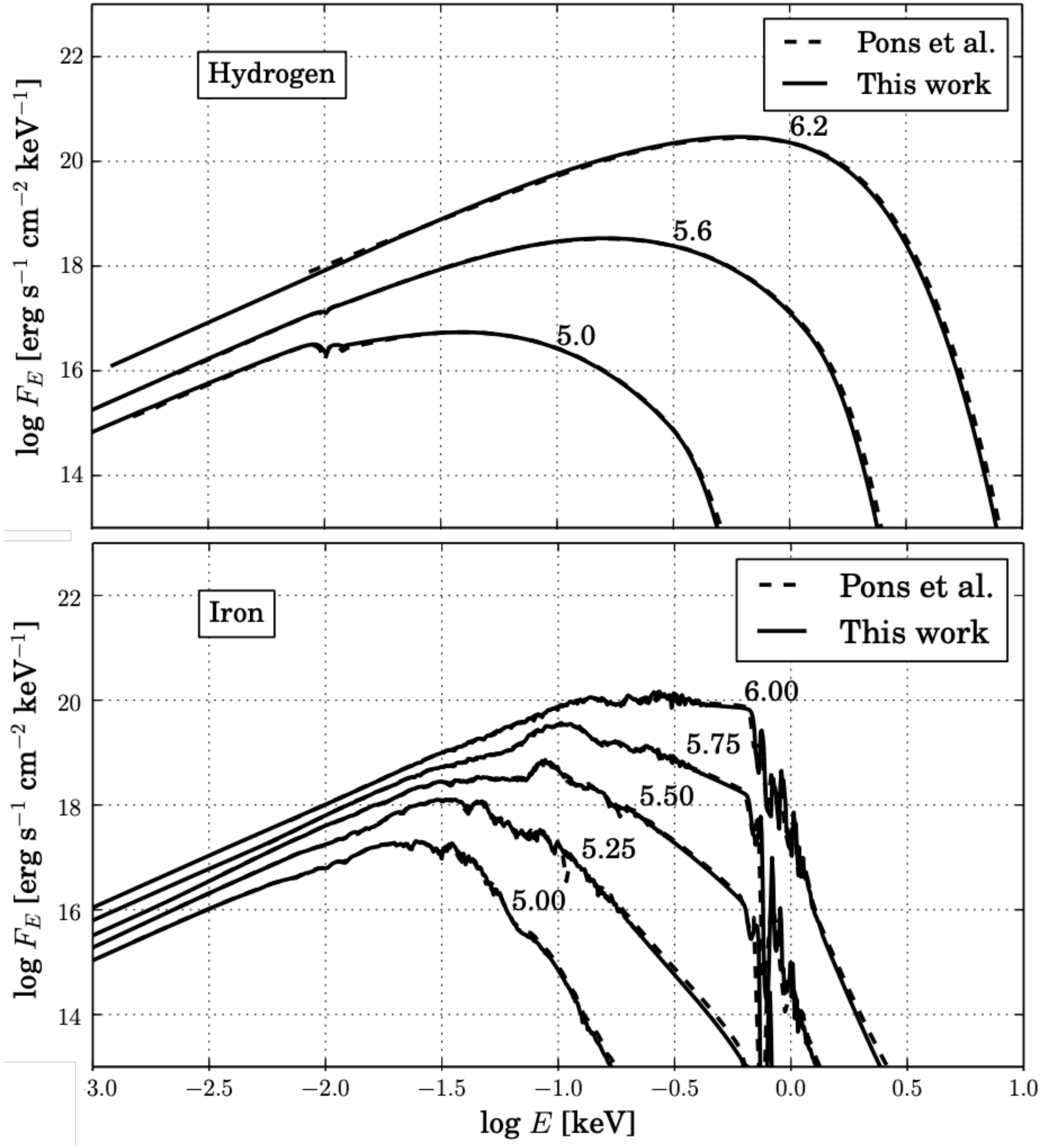
Atmospheric emission

- Thermal radiation reprocessed by an atmosphere.
- Stratified atmosphere composition.
  - Light elements on top.
  - Heavy elements sink to deep layers.
- Key simplification: magnetic field does not affect radiative transfer.
  - Magnetic field $B \sim 10^8\ G$
  - Cyclotron energy $E_c \sim 1\ eV$
  - Temperature $kT \sim 20\ eV \gg E_c$



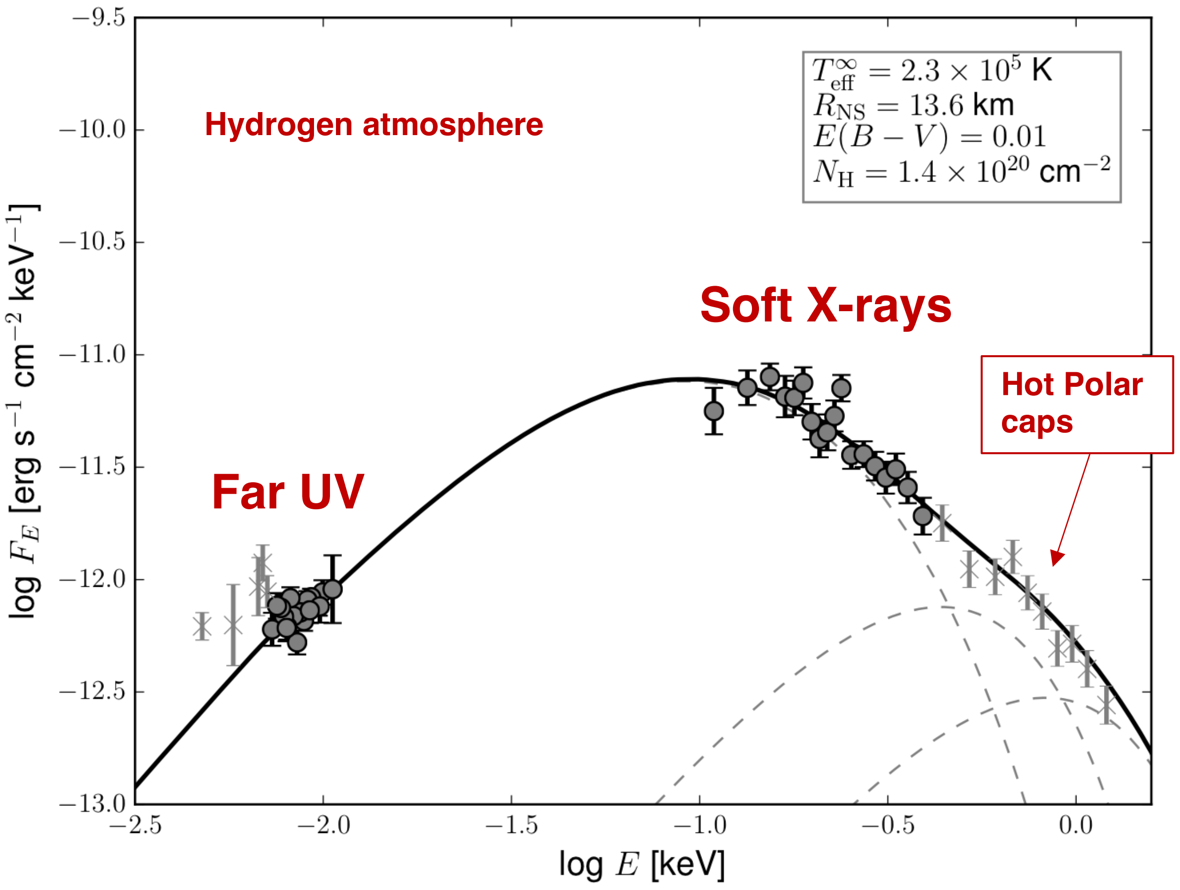
Atmospheric emission

- Plane parallel atmosphere, partially ionized gas, in hydrostatic equilibrium
- Opacity tabled and ionization state from Los Alamos National Laboratory.
- Iterative scheme (Romani 1987, Rajagopal & Romani 1996, Pons et al. 2002):
    1. Initial temperature: grey atmosphere.
    2. Structure of the atmosphere
    3. Radiative flux at different optical depths
    4. Heat source below the atmosphere.
    5. Temperature correction that satisfy constant flux in all layers.



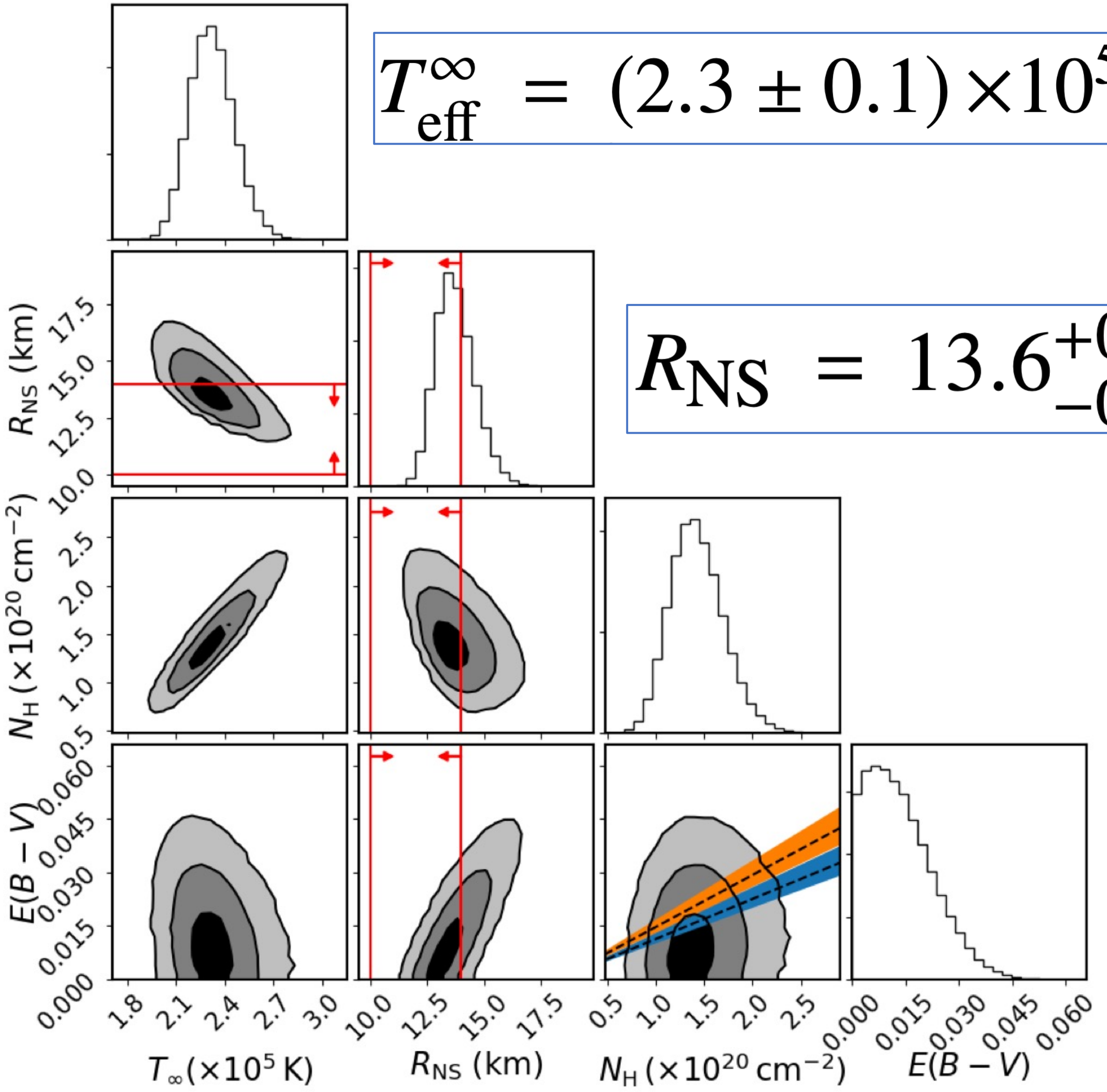
Spectral Fit PSR J0437-4715

- We modelled the cool thermal component observed in the UV (HST) and soft X-rays (ROSAT), considering realistic atmosphere models of neutron stars for H, He, Fe composition, as well as blackbody emission
- We perform a MCMC analysis considering four parameters: radius, temperature, dust extinction, and neutral hydrogen column density.
- We found that a **hydrogen atmosphere** yields the best spectral fits.



González-Caniulef, Guillot, and Reisenegger (2019)

Spectral Fit PSR J0437-4715



$$T_{\rm eff}^{\infty} = (2.3 \pm 0.1) \times 10^5 \text{ K}$$

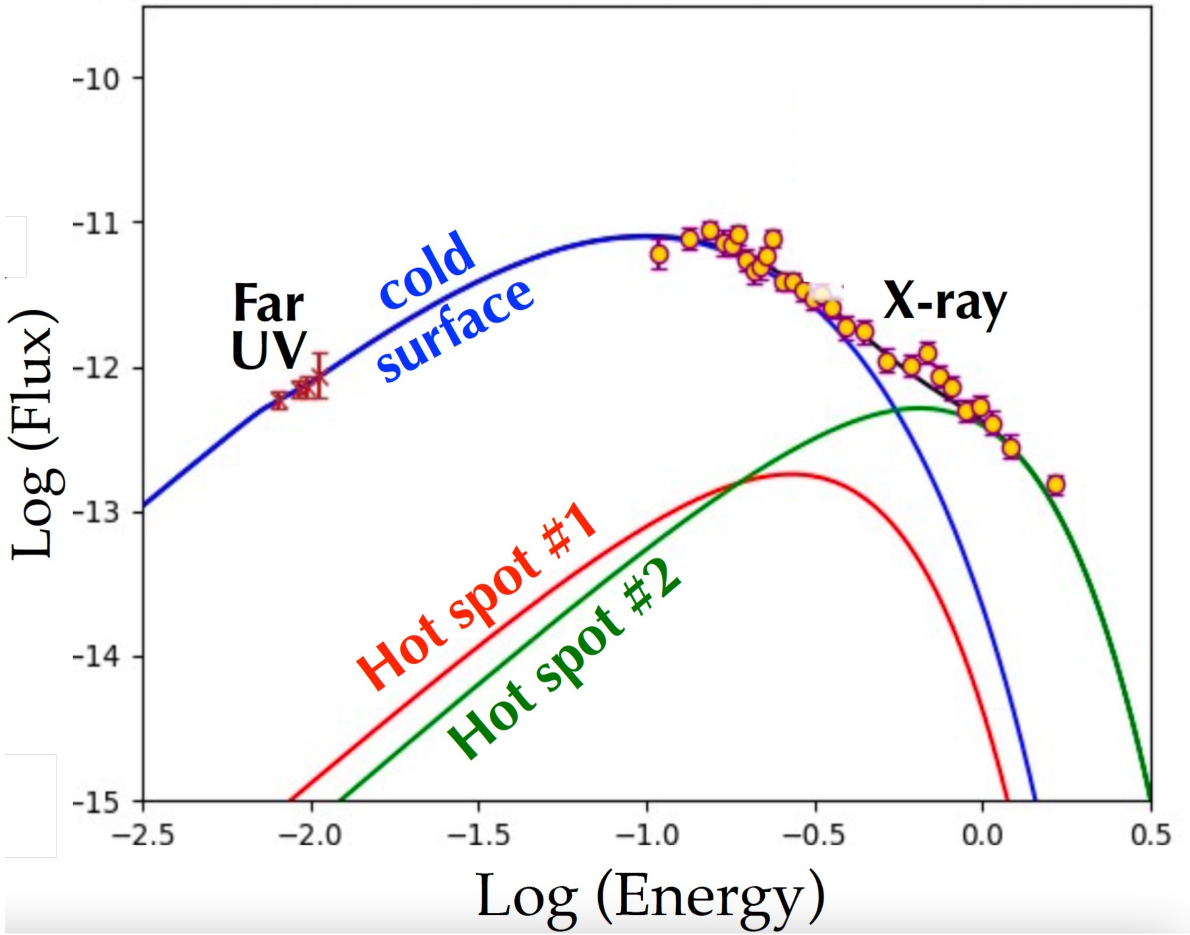
$$R_{\rm NS} = 13.6^{+0.9}_{-0.8} \text{ km}$$

Using a prior:
E(B-V) = 0.002 ± 0.014
(Lallement et al. 2018)

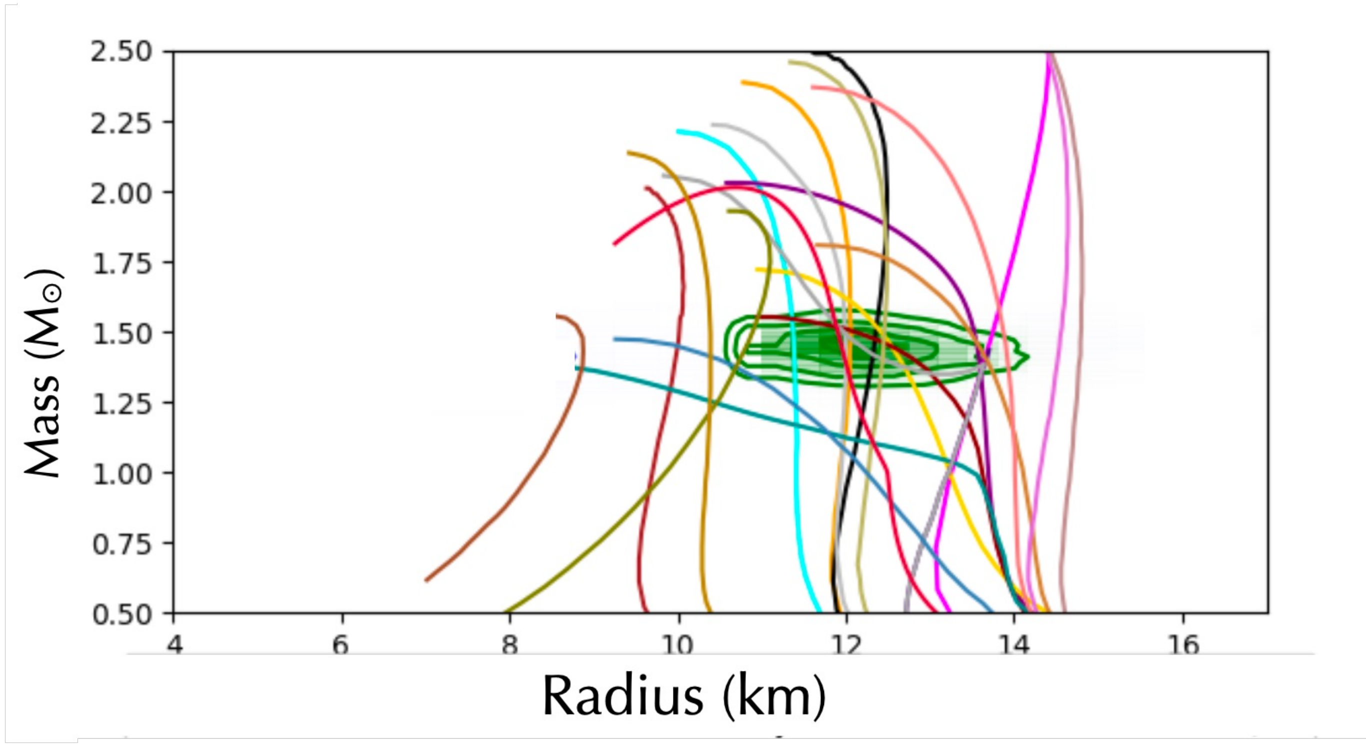
González-Caniulef, Guillot, and Reisenegger (2019)

Updated work on PSR J0437-4715

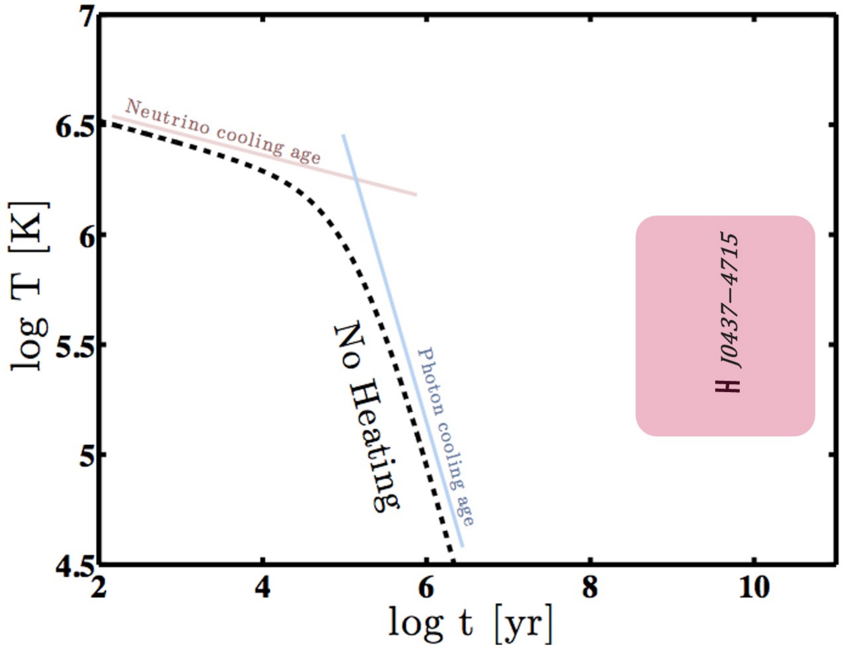
- Preliminary work by PhD student **Pierre Stammler**
- Excluding some UV points
- Including prior on distance: $\boldsymbol{d = 156.79 \pm 0.25}$ **pc**
- Including prior on mass: $\boldsymbol{M = 1.44 \pm 0.07\ M_\odot}$
- Improving the modelling of hot spots.
- Updated prior on redenning.



Updated work on PSR J0437-4715



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



Talk by Luis Rodríguez

Conclusions

- Combined **ultraviolet and X-ray** observations of MSPs are promising to constrain the radius and determine the equation of state of dense matter.
- Besides PSR J0437-4715, few pulsar have a detected $\boldsymbol{T \sim 10^5\ K}$ surface emission (Talk by Luis Rodríguez).
- Currently, only HST has the required capabilities to observe this kind of sources in the far ultraviolet.

Thanks!