Atmospheric effects with NICER

How do the assumptions on the neutron star atmosphere affect the neutron star parameter constraints with NICER?

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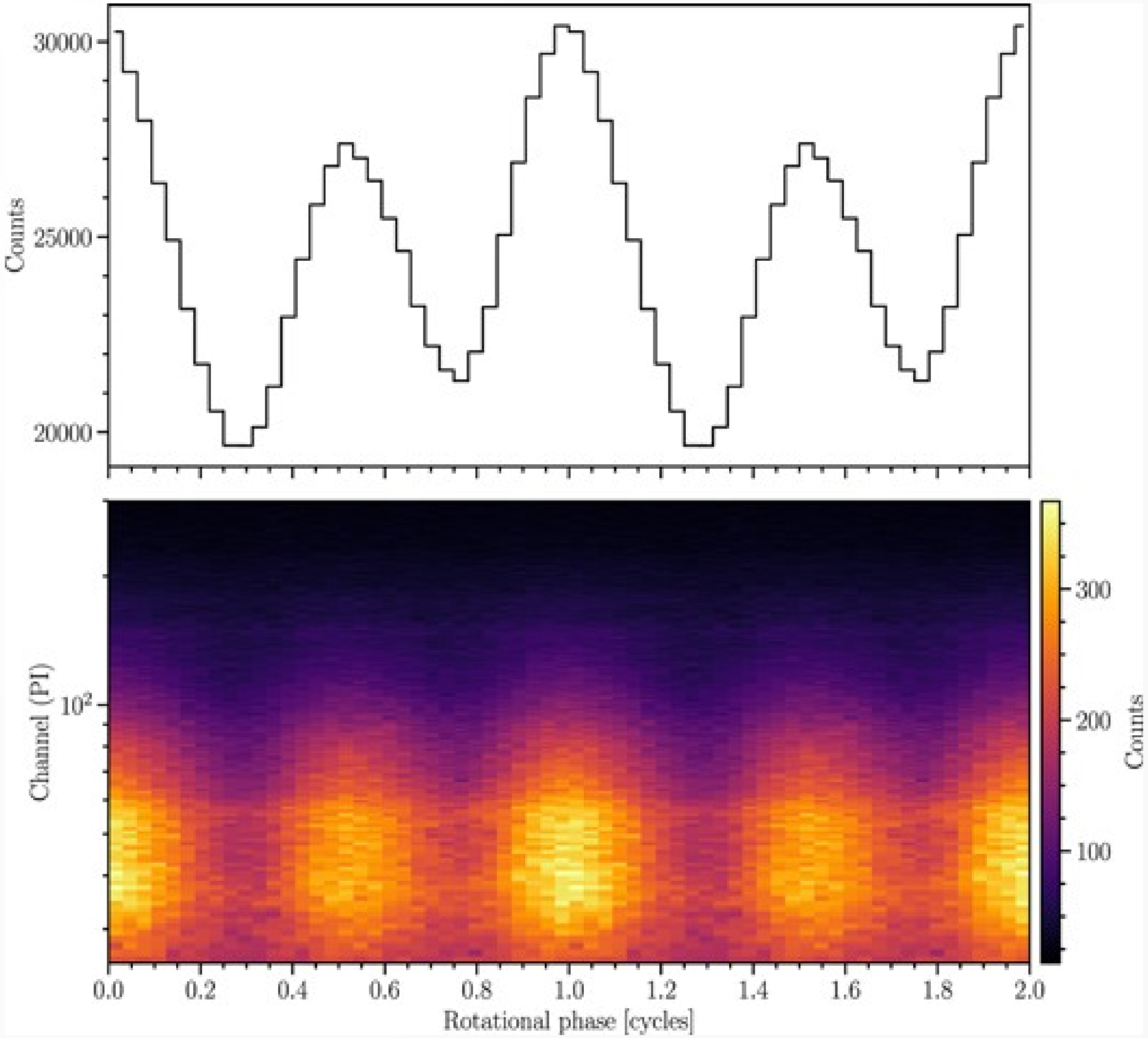
Introduction: Pulse profiles

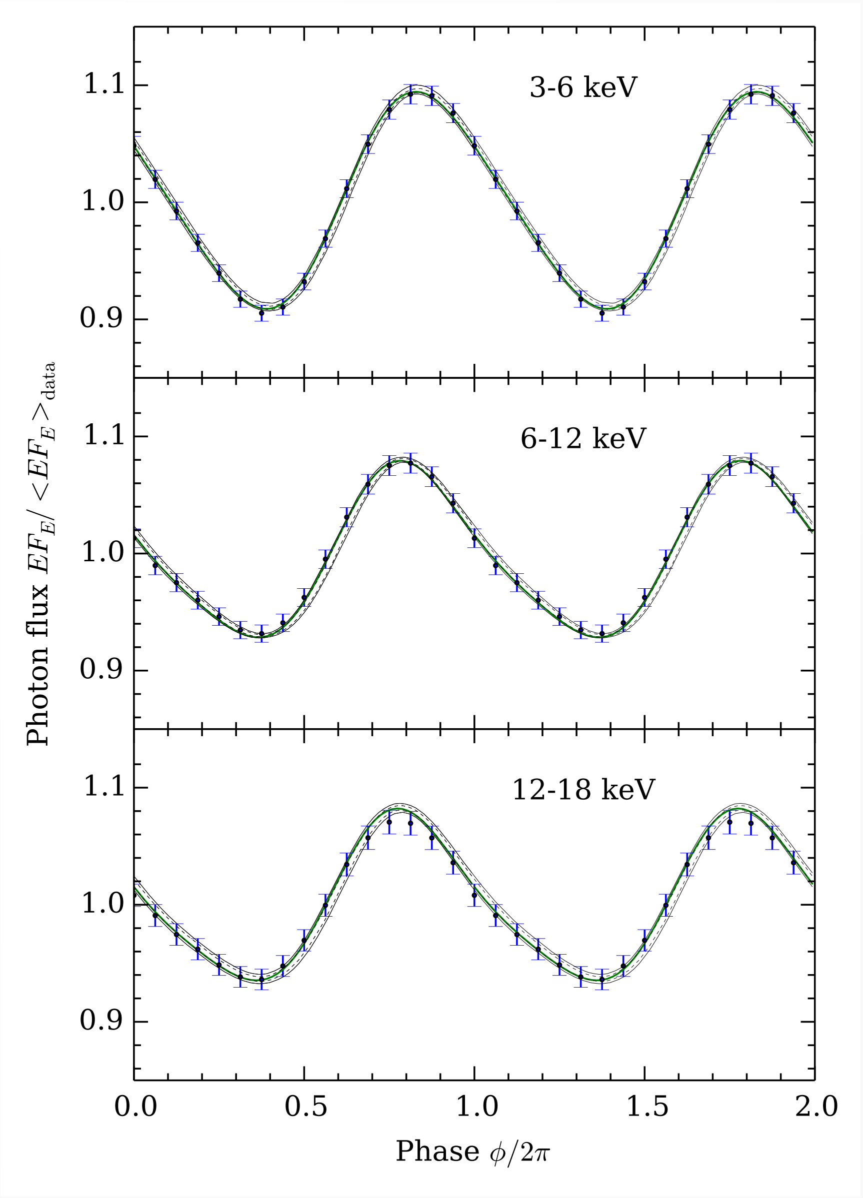
- X-ray pulses and spectra can be modeled to infer neutron star (NS) mass (M) and radius (R)
- M&R → Equation of state of high-dense matter in NS core



Riley+2019, Miller+2019

Introduction: Pulse profiles

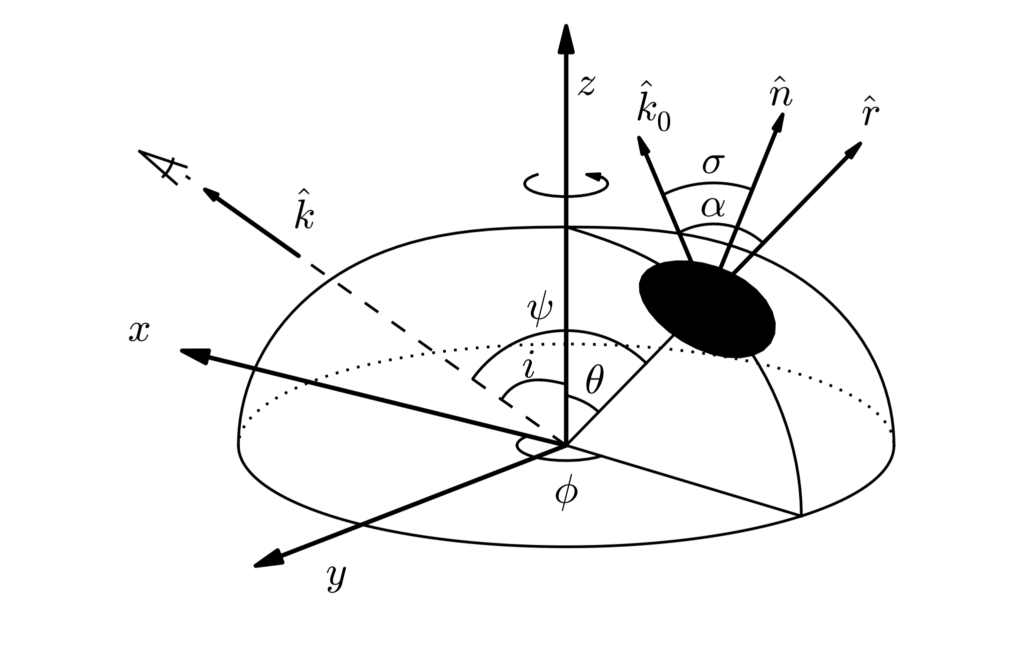
- Pulse shapes depend on relativity (light bending, Doppler boosting, etc.) and thus on M&R.
- Pulses can differ between energies.



Salmi+2018

Introduction: Pulse profiles

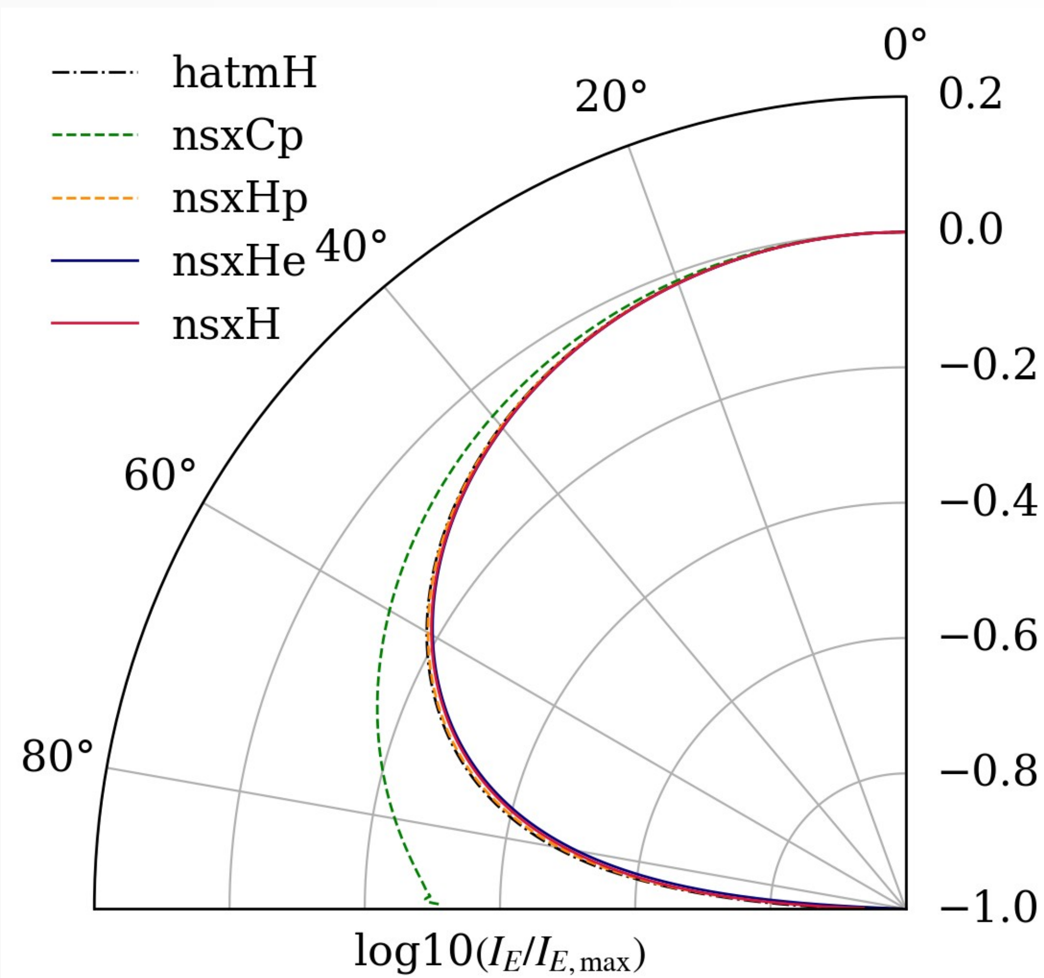
- Flux: $$\mathrm{d}F_E = I_E \mathrm{d}\Omega = (1-u)^{1/2}\delta^4 I'(\sigma', E')\cos\sigma \frac{\mathrm{d}\cos\alpha}{\mathrm{d}\cos\psi}\frac{\mathrm{d}S'}{D^2}$$
- Intensity of photons in the spot frame depends on both energy E' and emission angle σ' (and thus phase).
- Dependence on σ' called atmospheric beaming pattern.

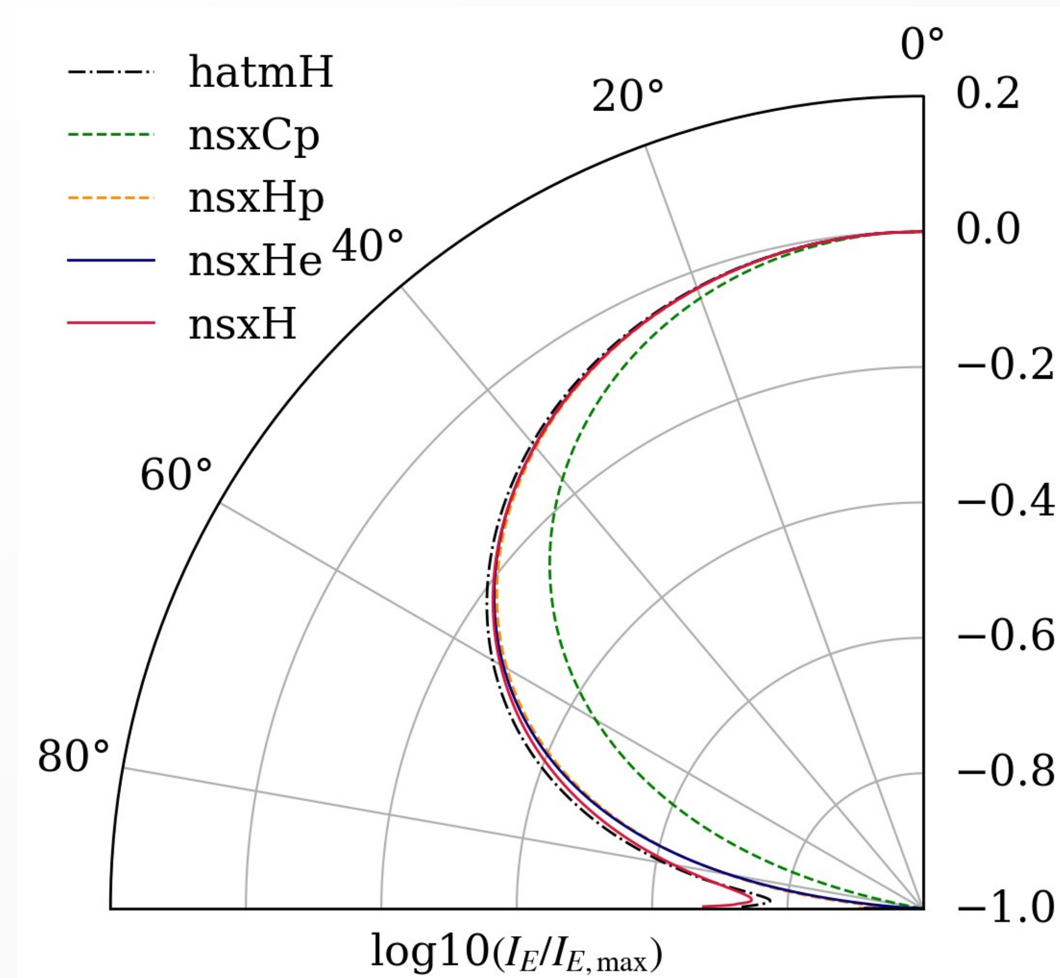


Salmi+2018

Introduction: Pulse profiles

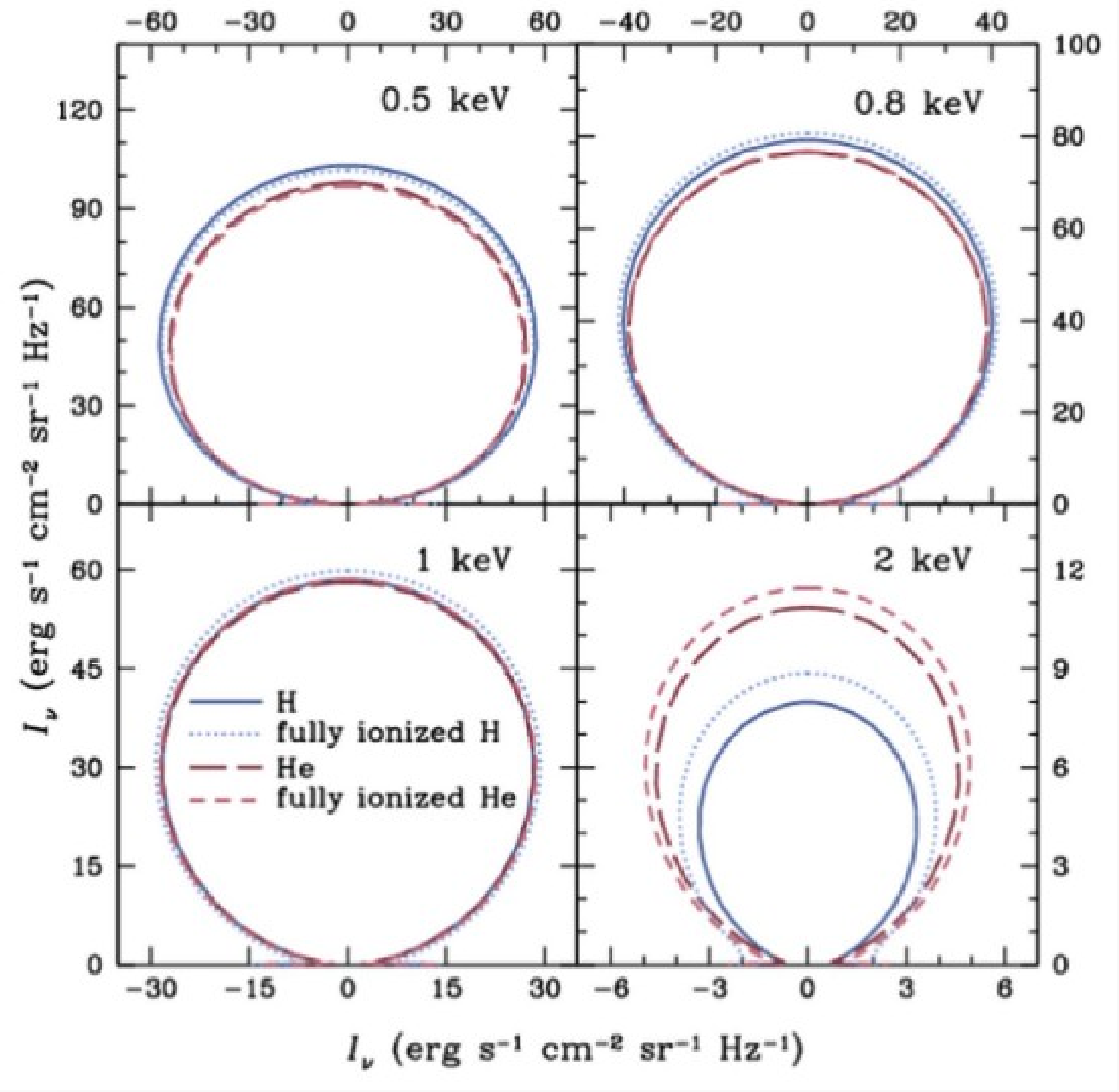
- Beaming patterns at 0.5 keV (left) and 1.0 keV (right):





Atmosphere models

- The model for I'(E',σ').
- Iterative models solving simultaneously NS **atmosphere structure** and **radiative transfer**.
- Assumptions:
  - Composition
  - Ionization state
  - Thomson vs Compton scattering
  - Depth of heat release
  - Magnetic field strength

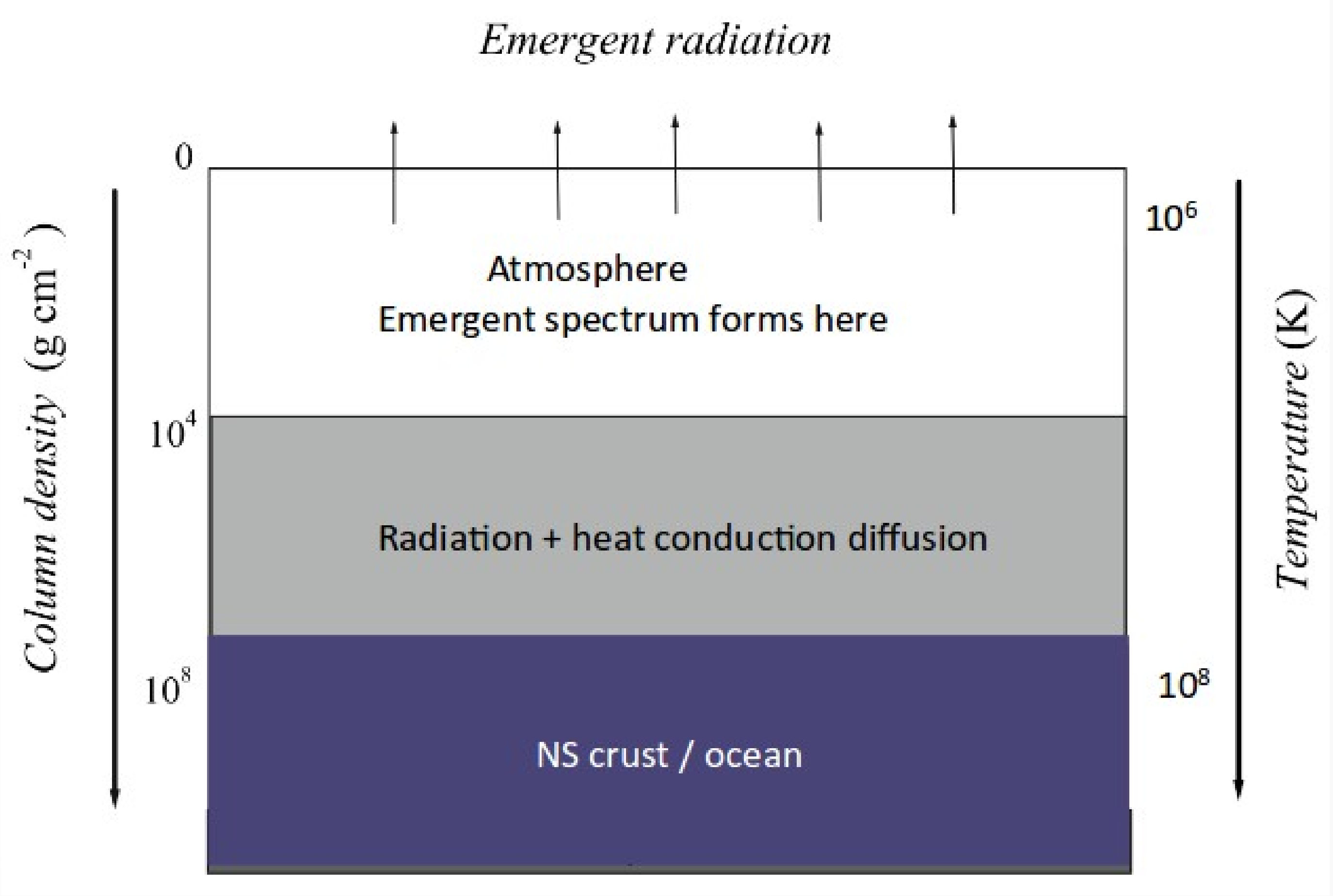


Bogdanov+2021

Atmosphere models

- Models typically too slow for direct inference:
  - Using pre-computed intensity tables for a variety of parameters (non-accreting):

$E, \sigma, T_{\rm eff}, \log(g)$ ...



Credit: V. Suleimanov

Radiative transfer equation

$$S(E,\mu)$$

$$\mu \frac{\mathrm{d}I(E,\mu)}{\mathrm{d}\tau(E,\mu)} = I(E,\mu) - S(E,\mu)$$

$$I(E,\mu)$$

$$S(x,\mu) = \frac{k(x)}{\sigma(x,\mu)+k(x)} B_x + \frac{\kappa_e}{\sigma(x,\mu)+k(x)} \times \left(1+\frac{C\,I(x,\mu)}{x^3}\right) x^2 \int_0^\infty \frac{\mathrm{d}x_1}{x_1^2} \int_{-1}^{1} \mathrm{d}\mu_1 R(x,\mu;x_1,\mu_1) I(x_1,\mu_1)$$

$$x = E$$

$$\mu = \cos\sigma'$$

Atmosphere structure

Temperature as function of depth

Radiative transfer equation

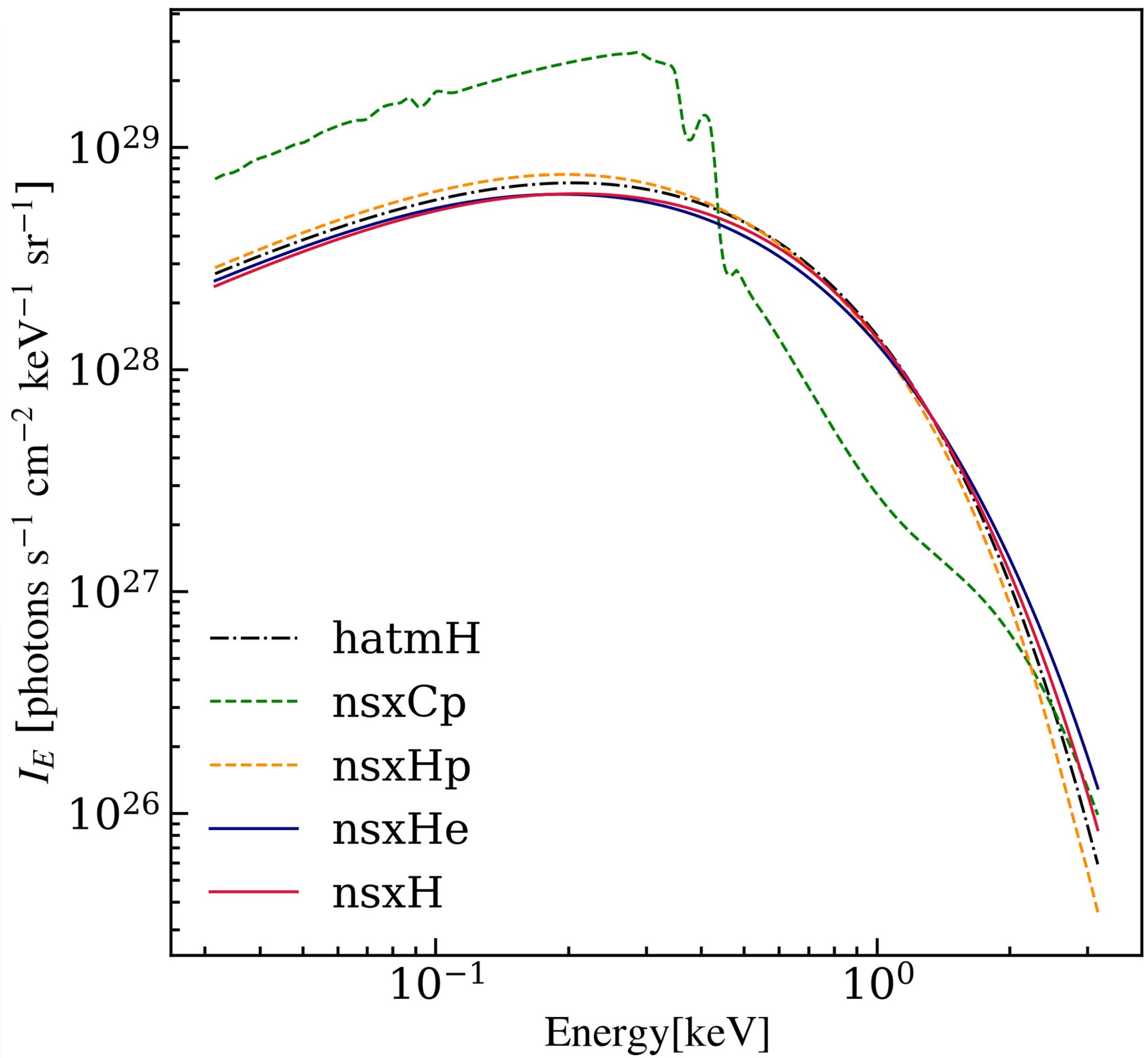
$$I(E,\mu) \quad S(E,\mu)$$

$$2\pi \int_0^\infty \mathrm{d}E \int_{-1}^{+1} [\sigma(E,\mu) + k(E)][I(E,\mu) - S(E,\mu)]\mathrm{d}\mu = -Q^+$$

Energy balance+
Surface flux corrections

Effects on M&R constraints for NICER

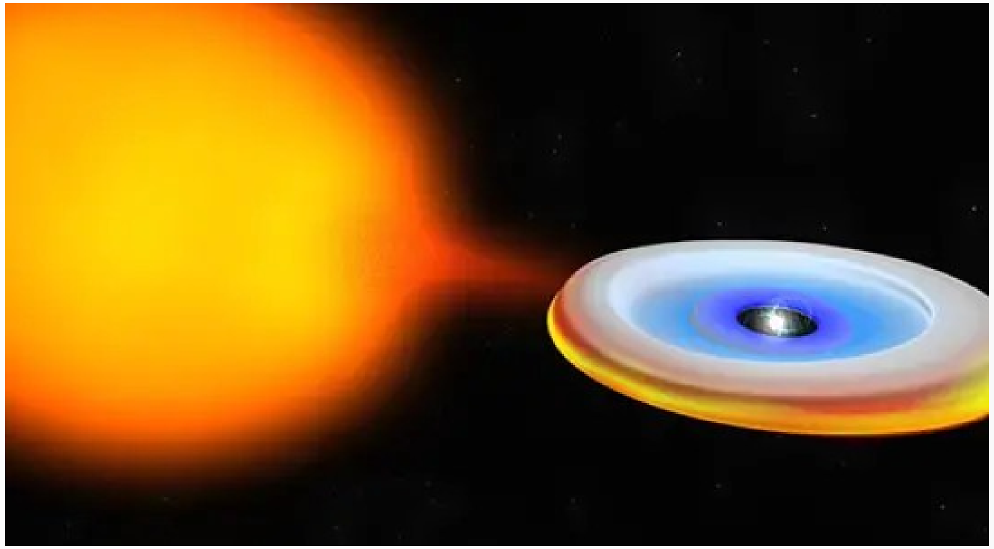
- Different models tested (Ho&Lai 2001, Ho&Heinke 2009, Salmi+2020):
  - Fully-ionized hydrogen (**nsxH**), used usually in NICER.
  - Fully-ionized helium (**nsxHe**)
  - Partially-ionized hydrogen (**nsxHp**)
  - Partially-ionized carbon (**nsxCp**)
  - Fully-ionized hydrogen but externally heated and from an independent algorithm (**hatmH**)



Salmi+2023 submitted

Effects on M&R constraints for NICER

- **Composition**: Hydrogen expected due to rapid sinking of heavier elements…. But helium (or heavier) possible if hydrogen was never accreted or there was nuclear burning.

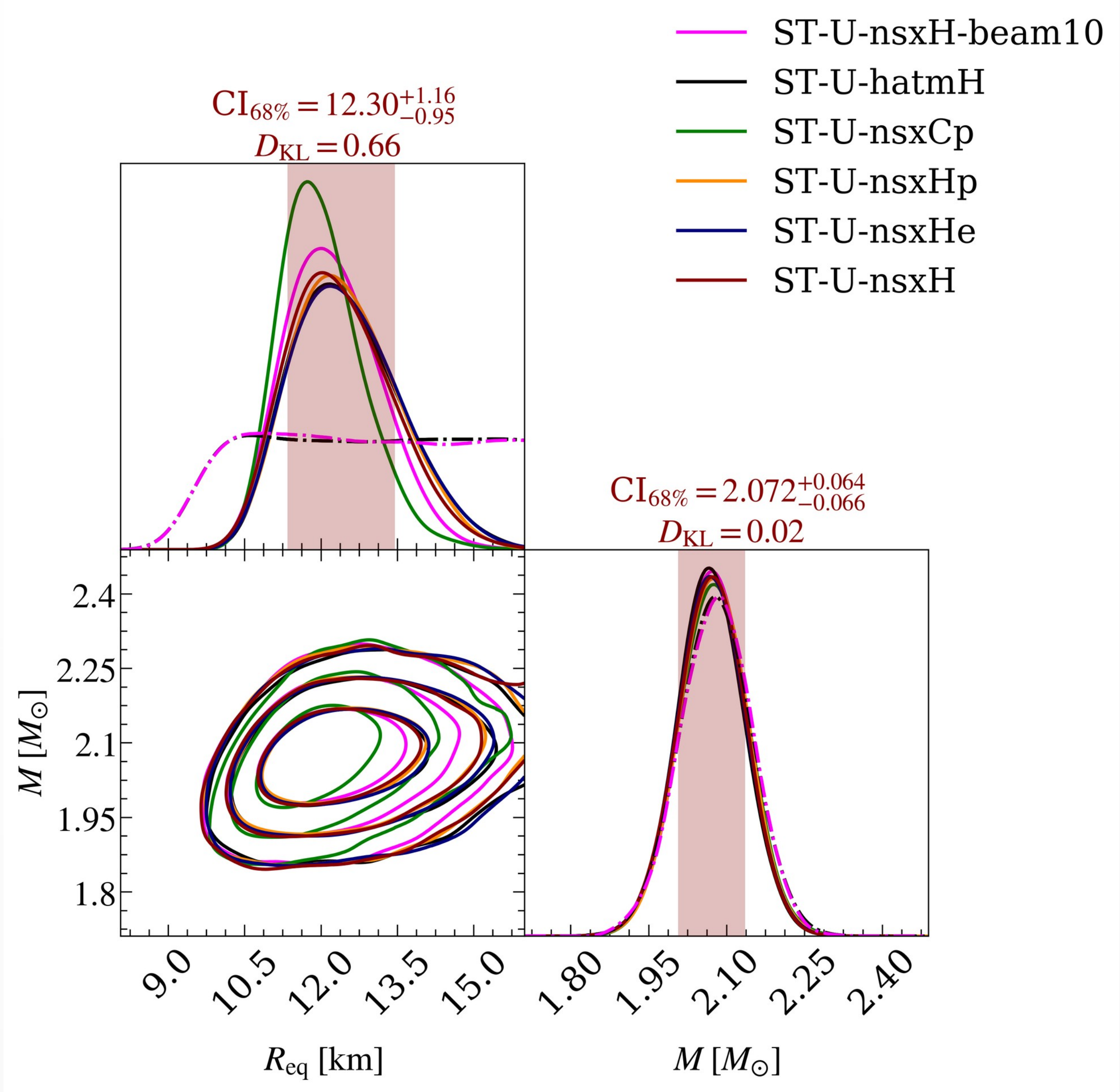


Credit: Bill Saxton; NRAO/AUI/NSF

- **Ionization state**: Accounting for it could affect but can be inaccurate for hotter neutron stars (due to limitations in opacity tables).
- **Deep-heating**: Accounting for non-deep-heating could affect if the bombarding particles are slow enough ($\gamma \sim< 100$, Salmi+2020), but typically they are expected to be much faster (Harding&Muslimov 2011).

J0740: 2 circular hot spots (ST-U)

- High-mass pulsar J0740 (studied in Miller+2021; Riley+2021; Salmi+2022).
- All choices produce consistent M&R constraints.
- Only carbon atmosphere disfavored based on Bayesian evidence.



Salmi+2023 submitted

J0030: 2 circular hot spots (ST-U)

- J0030 (studied in Miller+2019; Riley+2019).
- **Different M&R constraints, but not equally likely**.
- Deep-heating:
  No effect.
- Partial-ionization:
  Shift, but disfavored.
- C vs H:
  Shift, but disfavored.
- He vs H:
  Shift, evidence cannot distinguish.
  - 13-16 km vs 10-11 km.

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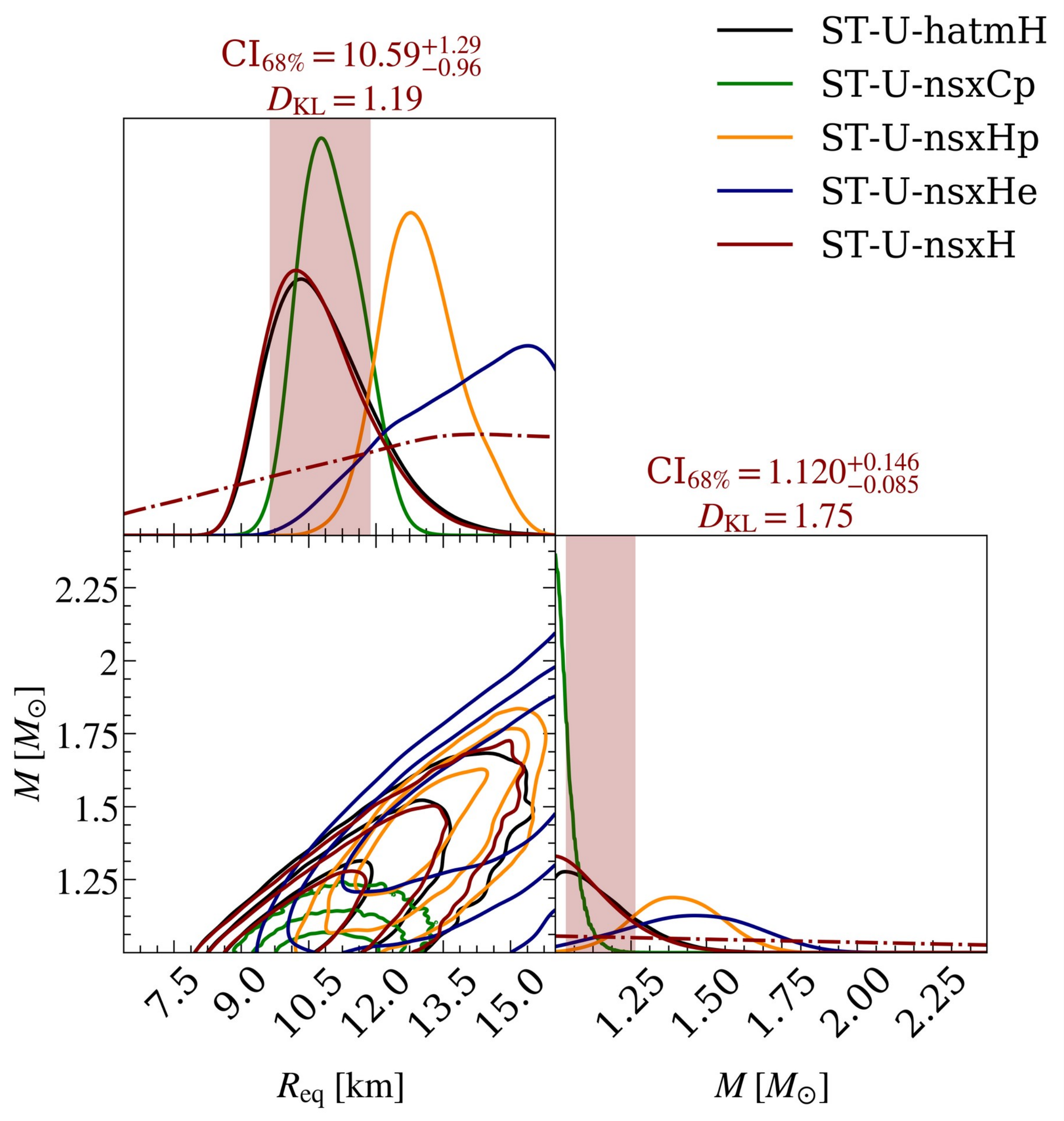

J0030: 1 circle and 1 crescent (ST+PST)

- Preferred model from Riley+2019.
- More computationally expensive, thus only 3 cases tested.
- Again, **similar evidence for fully-ionized hydrogen and helium, but different radii** (12-14 km vs 15-16 km).
- Partially-ionized hydrogen disfavored but better fitting ST-U solutions were not even found: Sampling with 10k MultiNest livepoints not enough?

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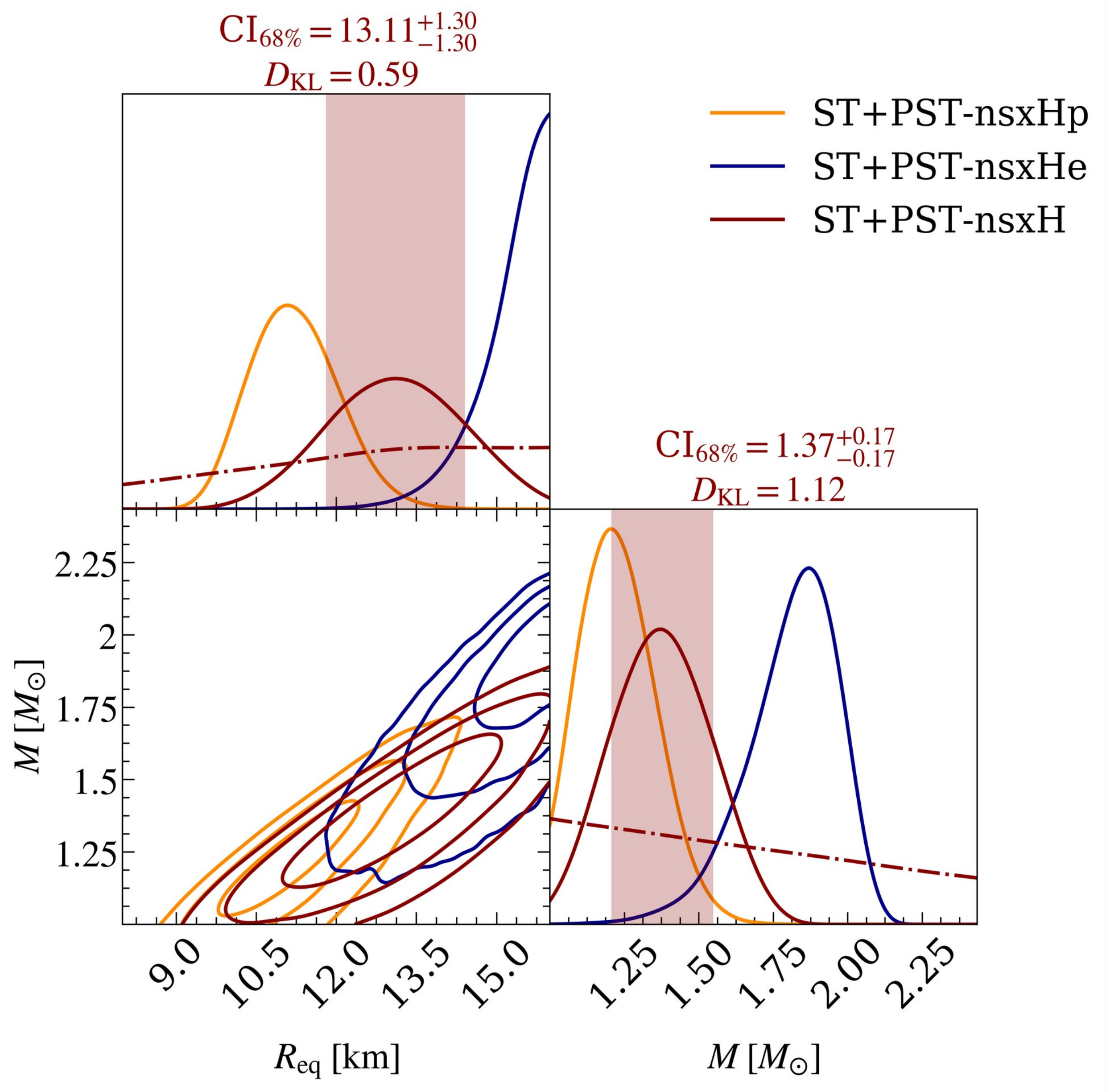

J0030: 2 circular hot spots and XMM

- Constraining NICER background by fitting simultaneously NICER and XMM data.
- Evidence favors He against H. But both hit 16 km upper limit when fully ionized.
- Partially-ionized hydrogen infers smaller R but evidence disfavored.
- Need studies with more complex spot shapes and independent background estimates.

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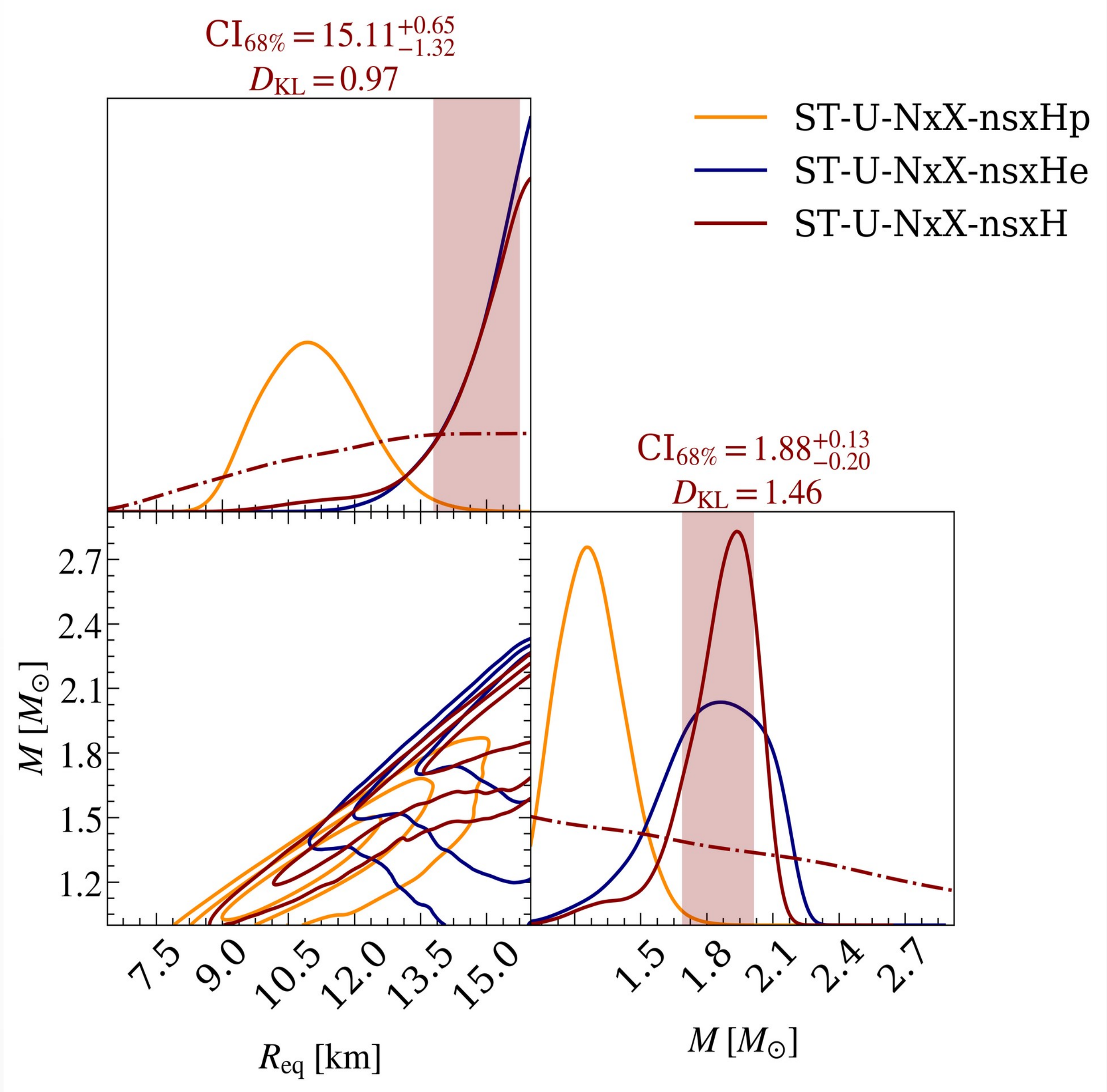
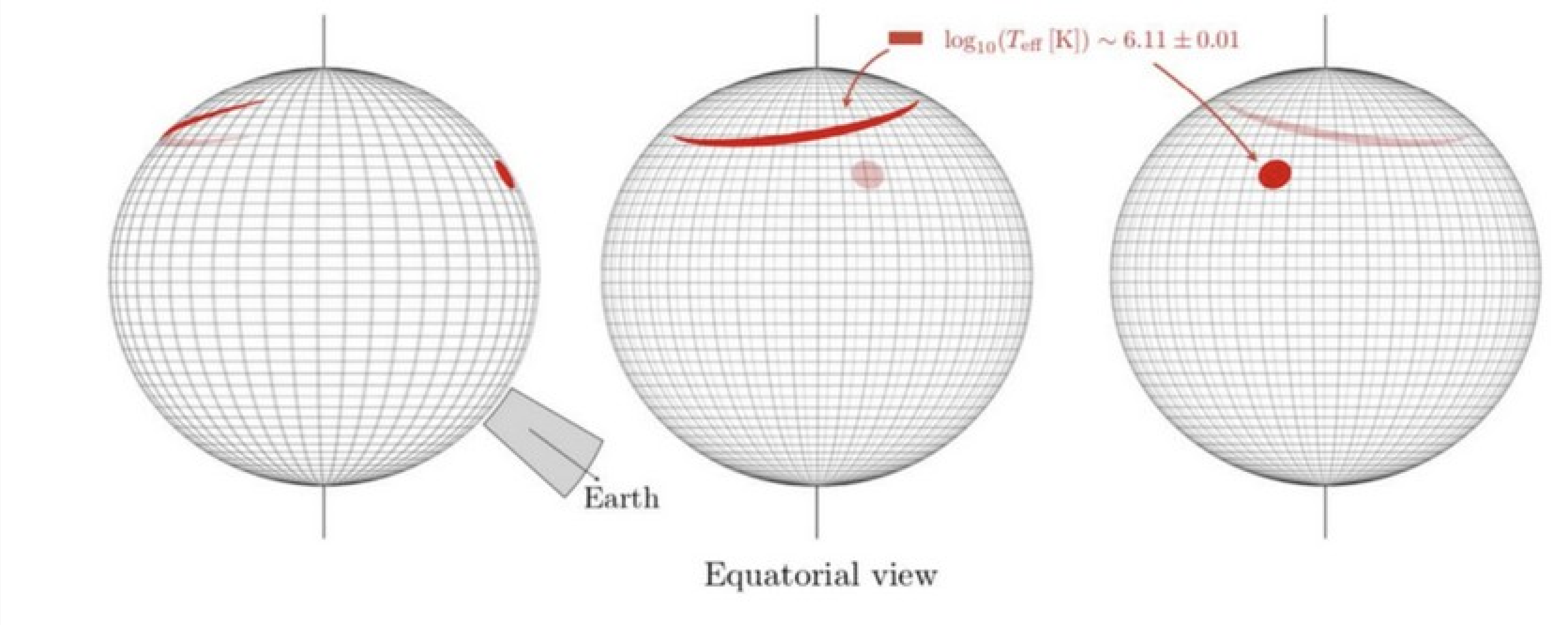


Discussion

Possible reasons why J0030 different compared to J0740:

- No external prior constraints for NS mass or geometry for J0030.
- Higher number of observed counts for J0030.
- Favoring/allowing hot spots that are only seen if photons emitted always at high angles (having largest difference in beaming).



Riley+2019

Conclusions and Future

- None of tested atmosphere assumptions affects M&R **J0740** constraints.
- H vs He assumption affects M&R **J0030** constraints, but He is considered less likely (although with higher evidence) and leads typically to unexpectedly high R for J0030.
- Other tested atmosphere assumptions either do not affect J0030 or they affect but have a much lower evidence.
- In future atmosphere models can be further explored and best ones inferred, especially with any new high-energy-resolution X-ray instruments.

Extra: Beaming parameterization

- Uncertainty in the predicted beaming pattern can also be parameterized:
- 4 new empirical beaming parameters, modifying the input from an atmosphere table.

$$I(E, \mu, a, b, c, d) = I(E, \mu)_{\mathrm{NUM}} f(E, \mu, a, b, c, d), \quad (1)$$

where

$$f(E, \mu, a, b, c, d) = C \left(1 + a \left(\frac{E}{\mathrm{keV}} \right)^{c} \mu + b \left(\frac{E}{\mathrm{keV}} \right)^{d} \mu^2 \right)$$

Extra: J0030 with beaming

- Allowing max 5% correction to intensities below 60 deg emission angles (as typically between the atmosphere models):
  - Hydrogen solution same, helium a bit shifted.

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