ANTON PANNEKOEK INSTITUUT

UNIVERSITY OF HELSINKI

X-ray pulse profile modeling - Recent results

NWO

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In collaboration with: Anna Watts, Devarshi Choudhury, Bas Dorsman, Yves Kini, Serena Vinciguerra, NICER team, Joonas Nättilä, Juri Poutanen, Valery Suleimanov, Alessandro Di Marco, John Rankin, and Alessandro Papitto

erc

European Research Council

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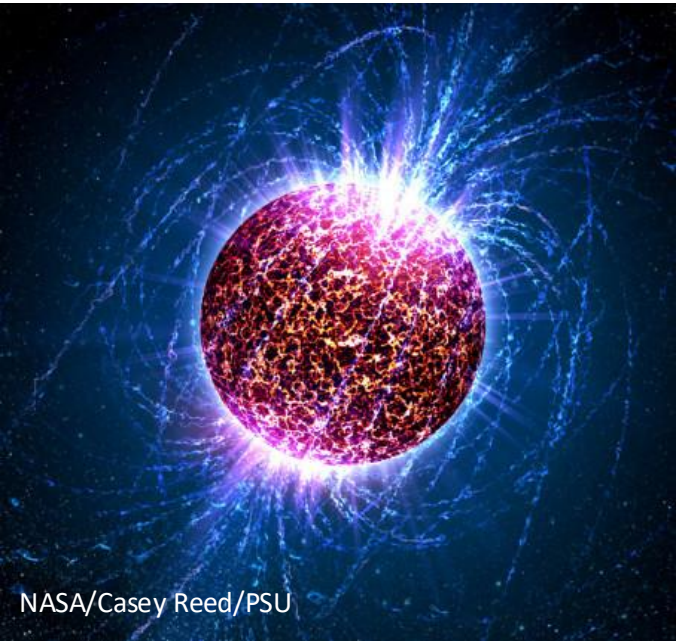
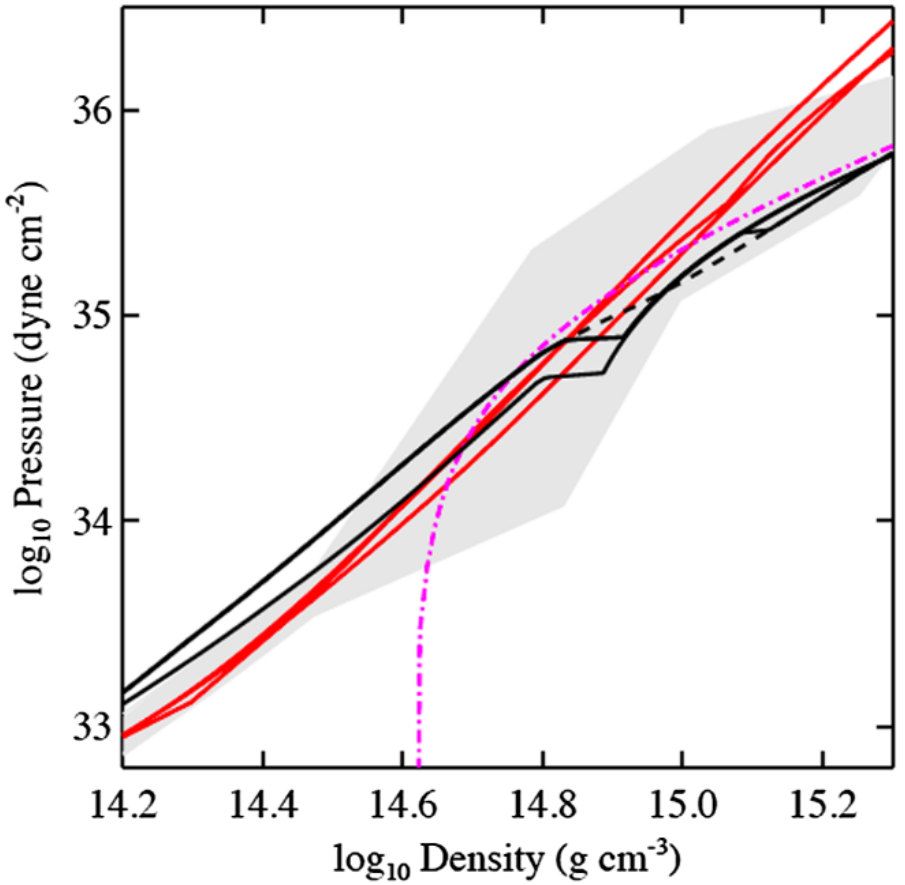
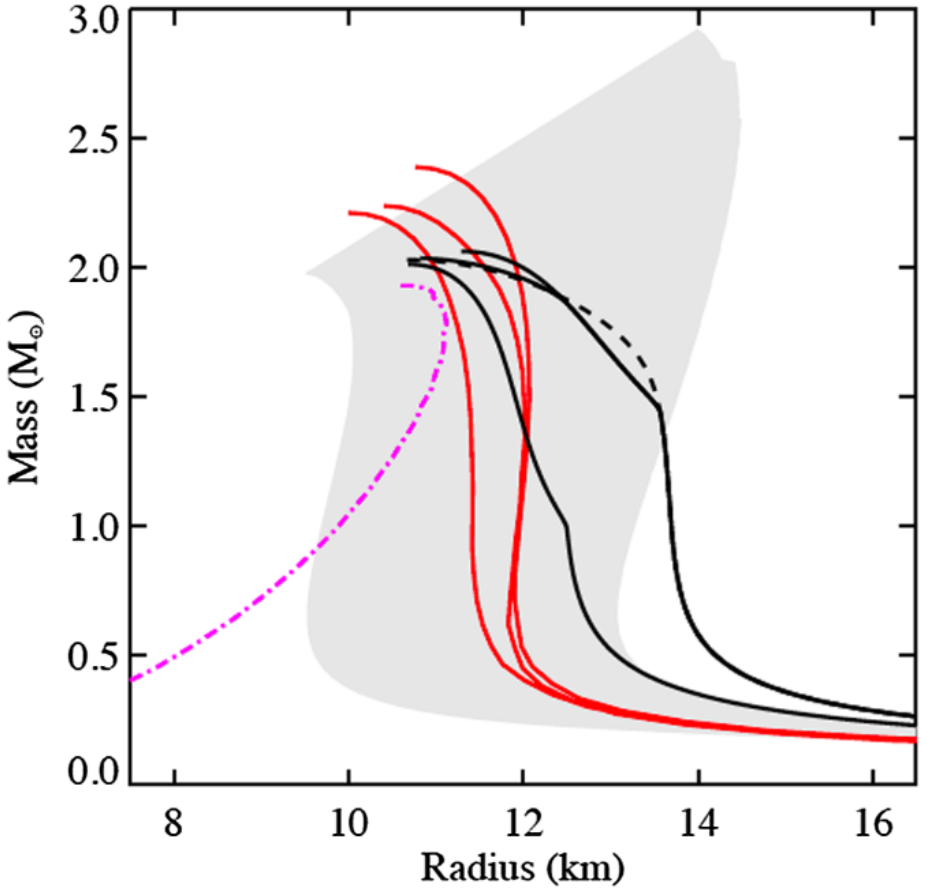
Neutron Stars: Mass-Radius vs Equation of State (EOS)



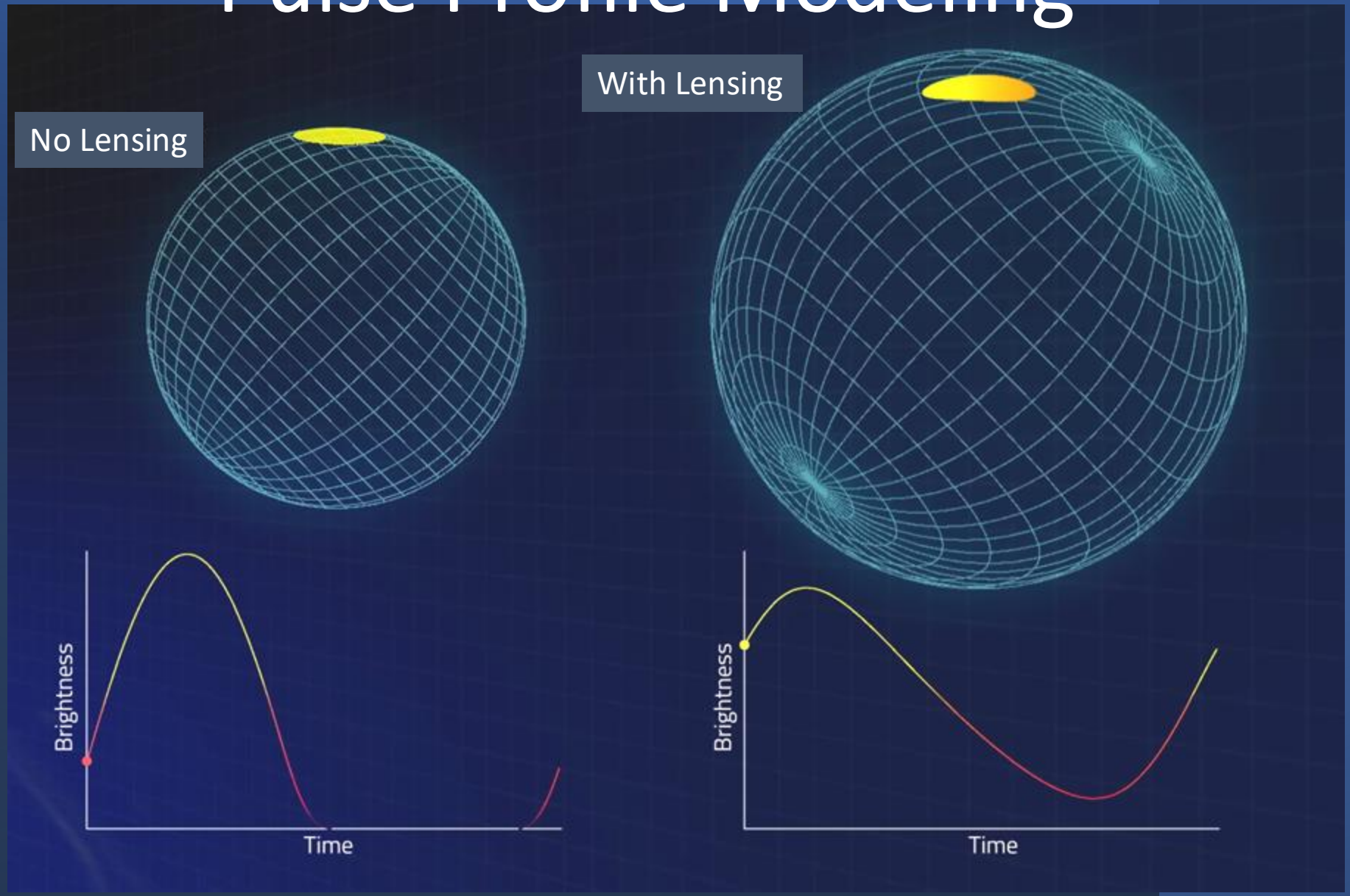
Core:
Nucleonic, quark, hyperonic, hybrid?



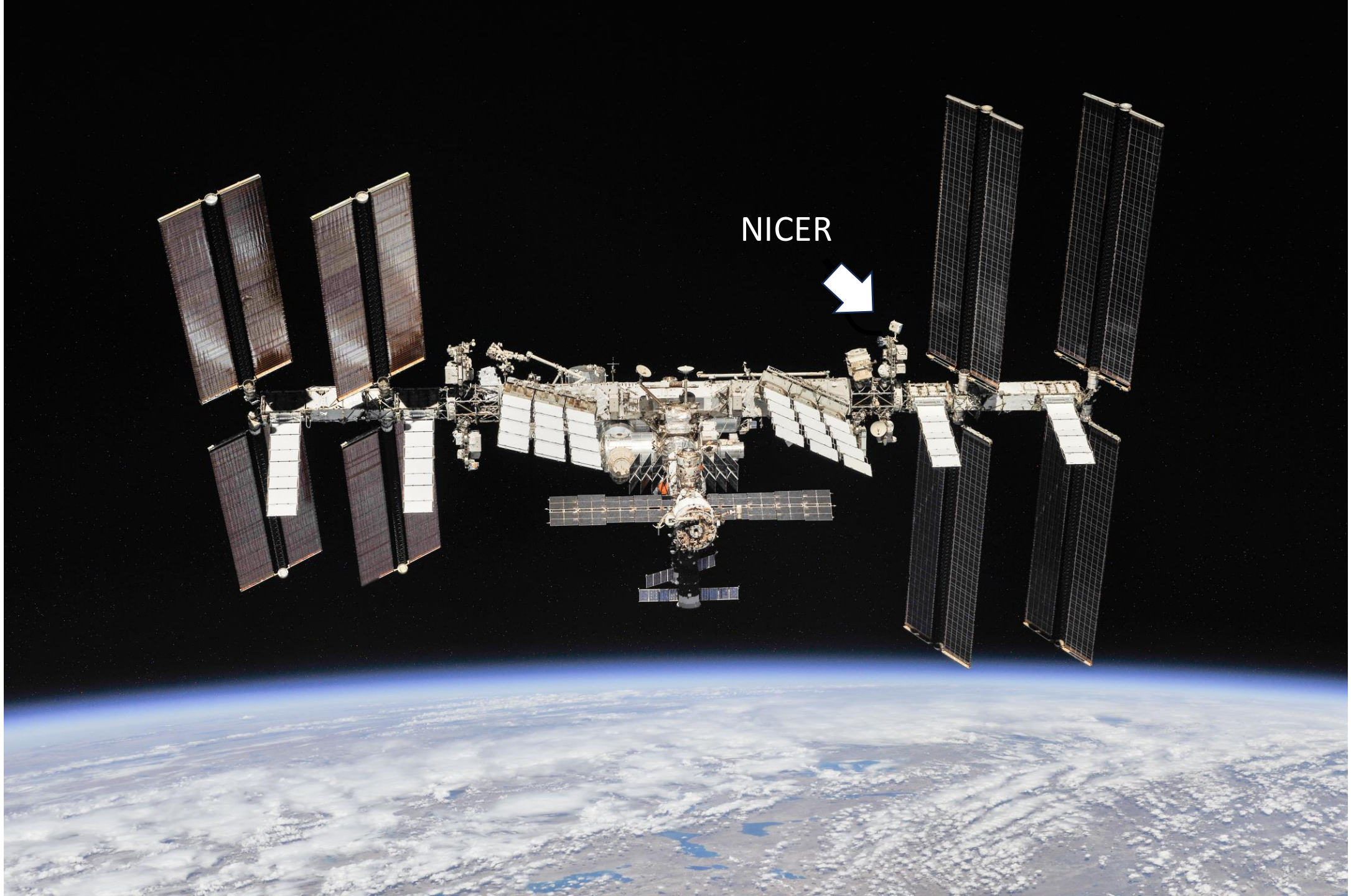


Watts et al. 2016, Rev. Mod. Phys.

Pulse Profile Modeling

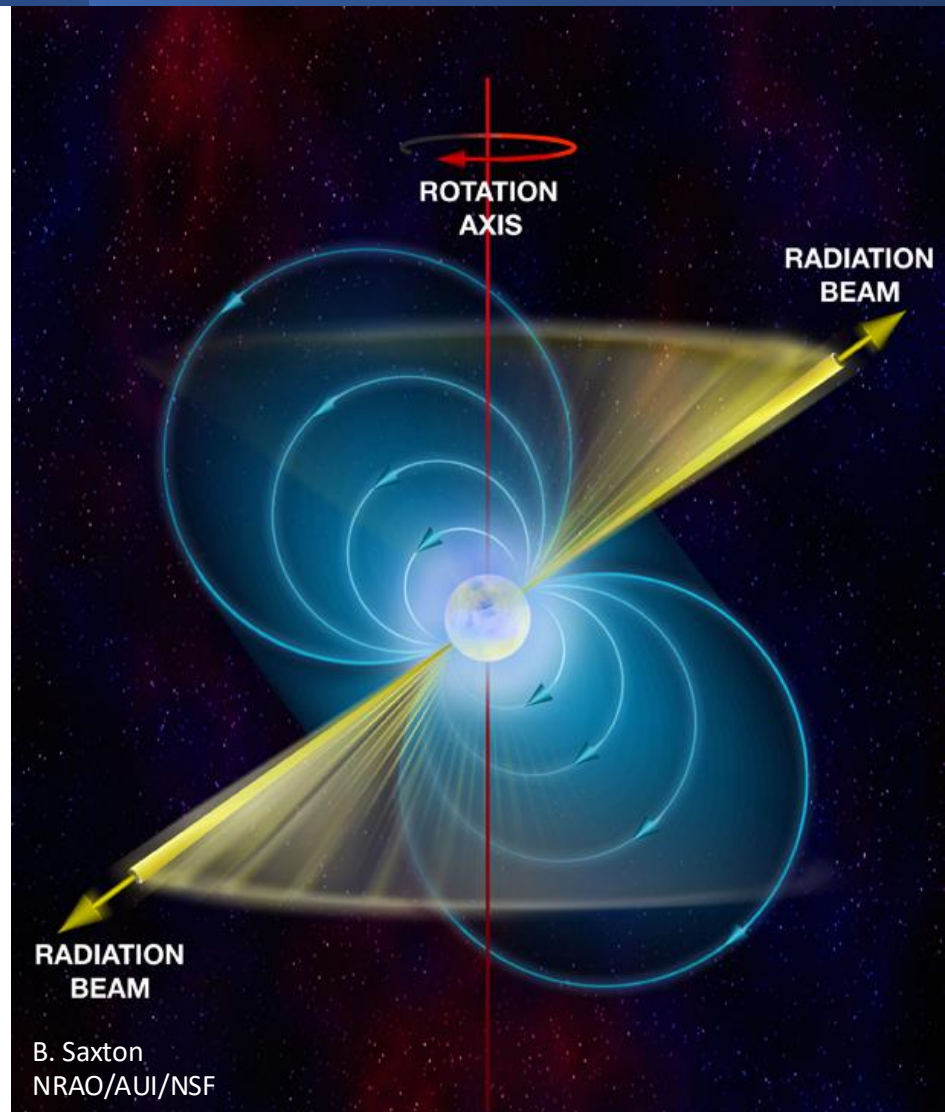


Credit: Morsink/Moir/Arzoumanian/NASA-GSFC


NICER

Rotation-powered millisecond pulsars (RMPs)

- Primary NICER targets
- Persistent pulsations
- Return-current heated polar caps
- Recycled pulsar with no accretion



X-ray Pulse Simulation and Inference (X-PSI)

https://github.com/xpsi-group/xpsi
(Riley et al. 2023)

Oblate+Schwarzshild space-time
(Poutanen & Gierlinski 2003, Morsink et al. 2007)

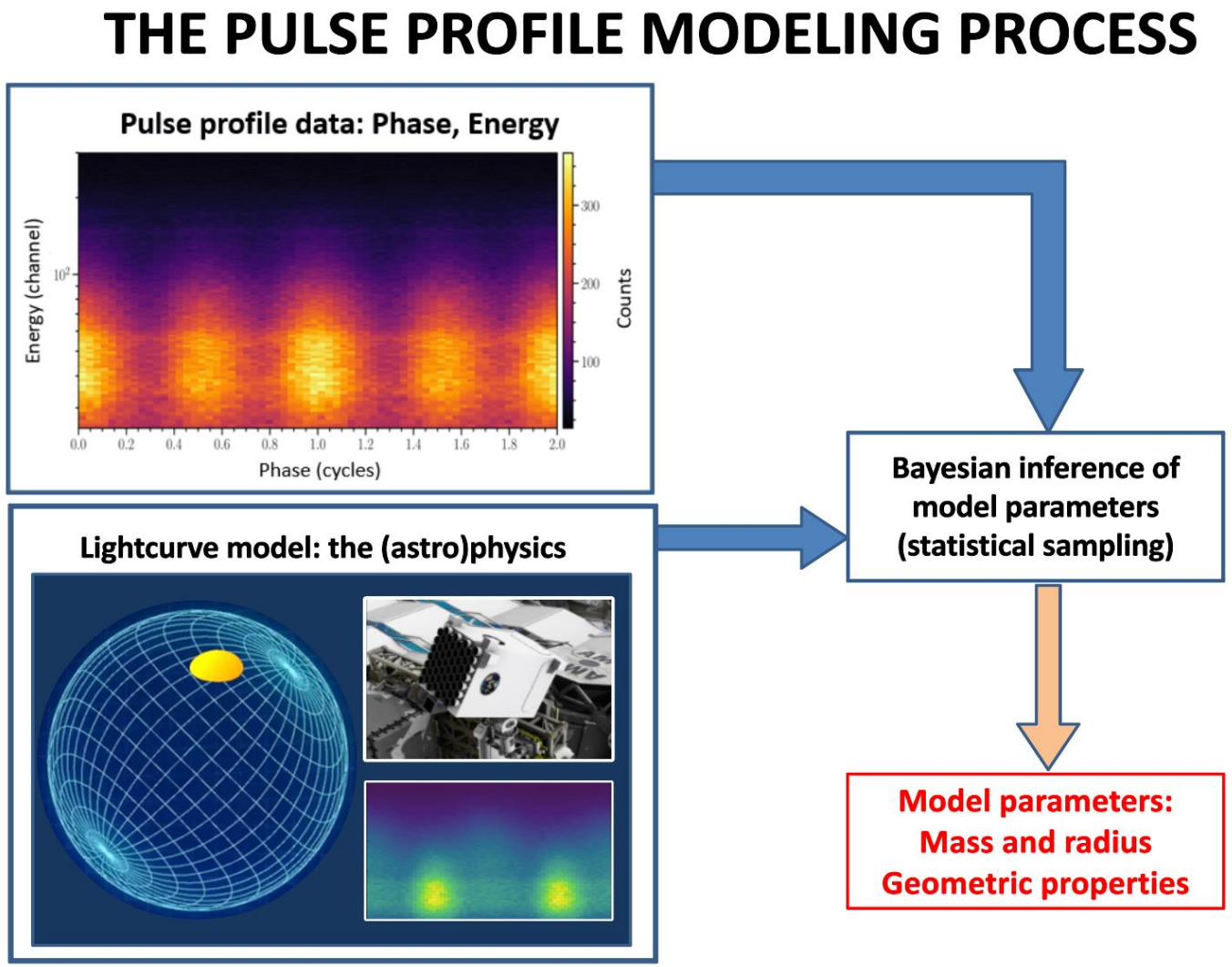


Image credit: Bogdanov/Morsink/NASA/Riley/Watts

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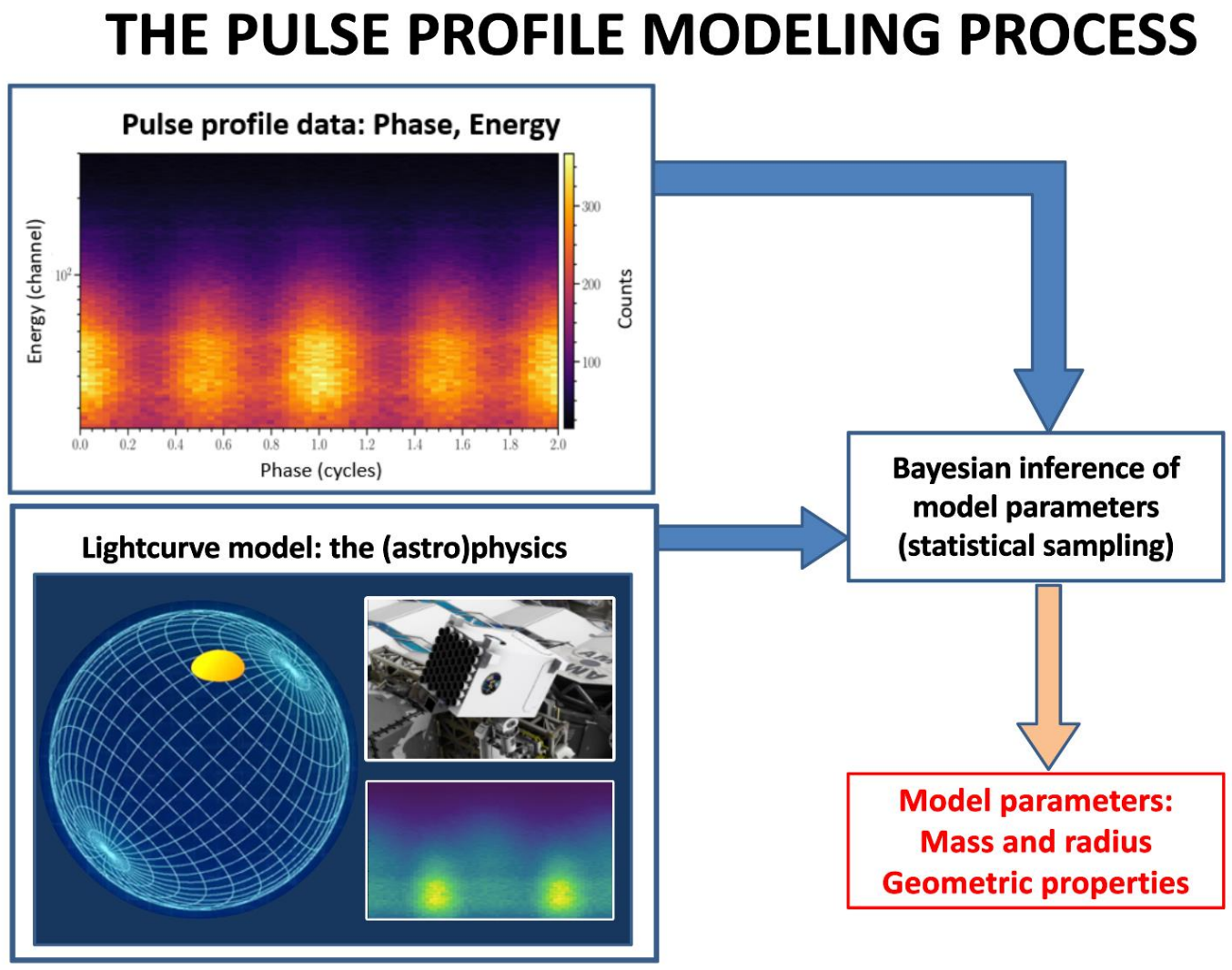
Neutron star atmosphere models
(Ho & Lai 2001, Salmi et al. 2020)

$$\mathrm{d}F_E = I_E \mathrm{d}\Omega = (1-u)^{1/2}\delta^4 I'(\sigma', E')\cos\sigma \frac{\mathrm{d}\cos\alpha}{\mathrm{d}\cos\psi}\frac{\mathrm{d}S'}{D^2}$$



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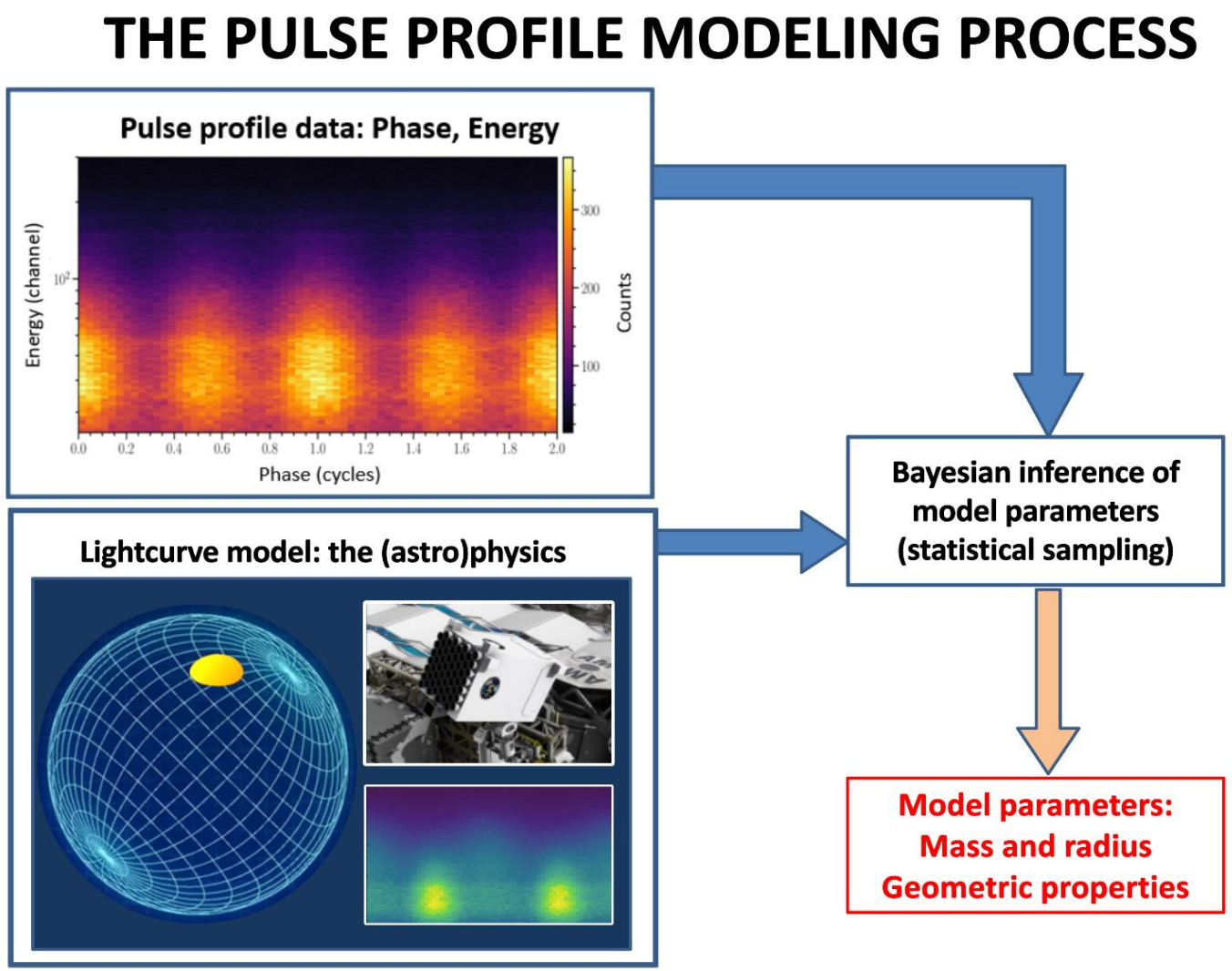
Hot region surface models (circles)



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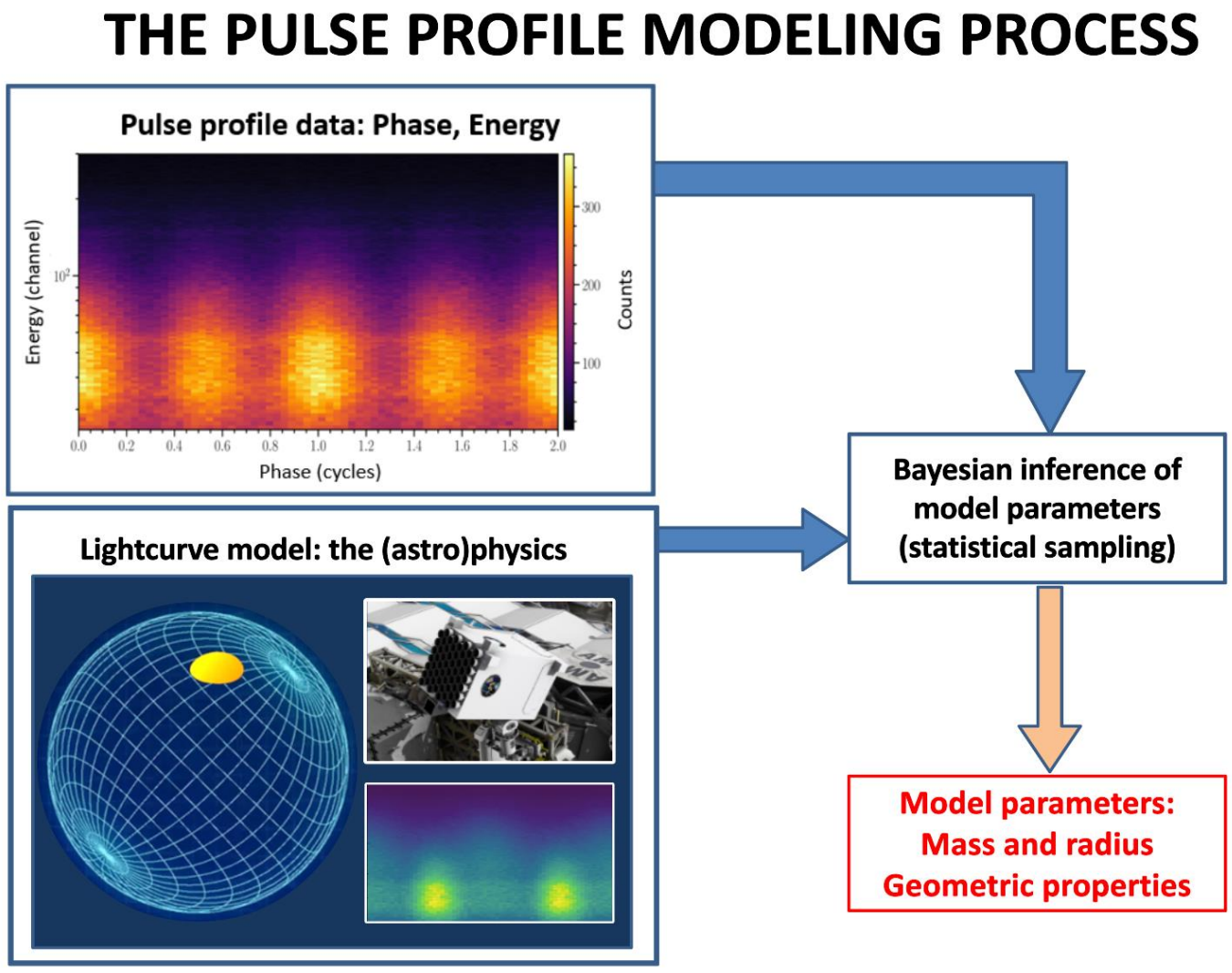
Hot region surface models (circles)

Sampling with MultiNest
(Feroz et al. 2009)

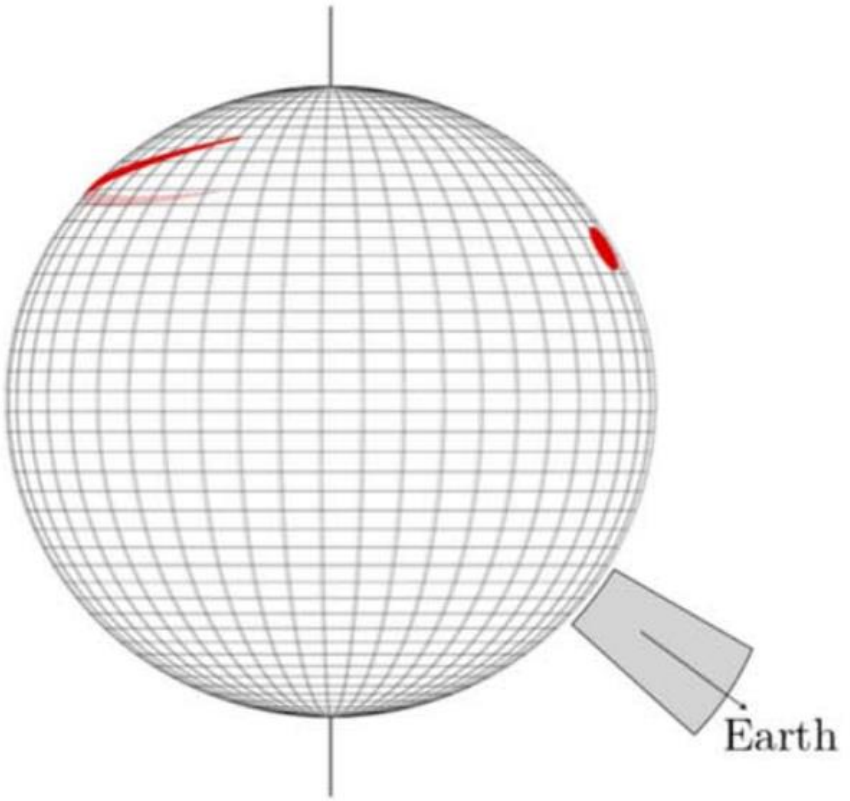
Image credit: Bogdanov/Morsink/NASA/Riley/Watts



NICER results: J0030

PSR J0030+0451: Isolated pulsar spinning at 205 Hz.

First analysis by
Miller et al. 2019 (IM); Riley et al. 2019 (X-PSI):
Highly non-antipodal hot region geometry.



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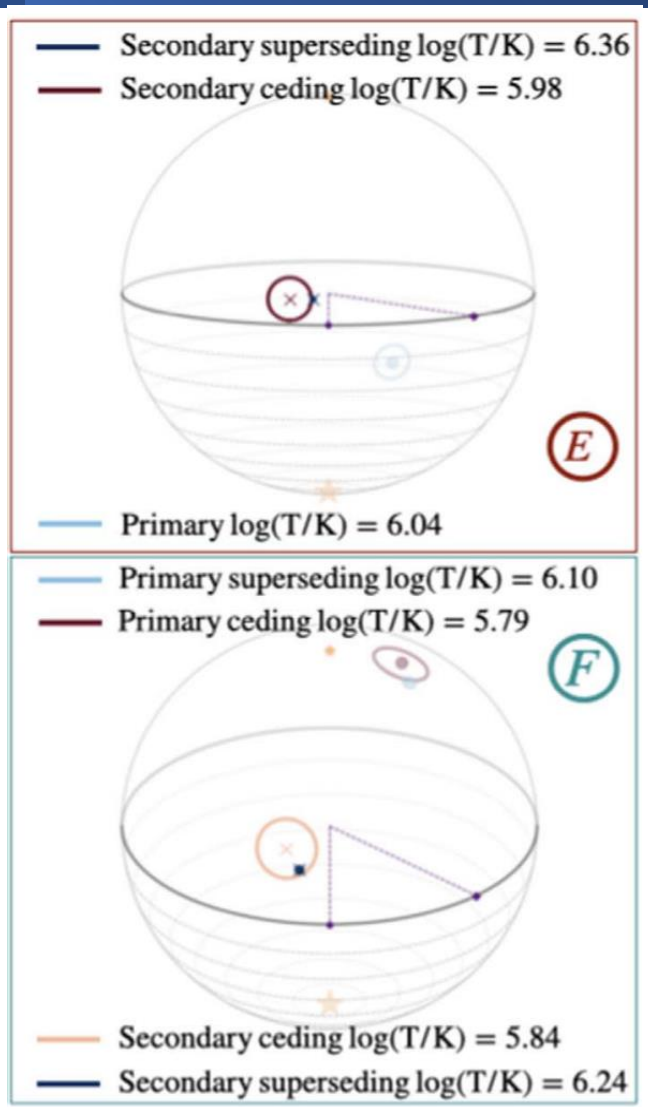
Other modes also possible and agree better with XMM-Newton data.



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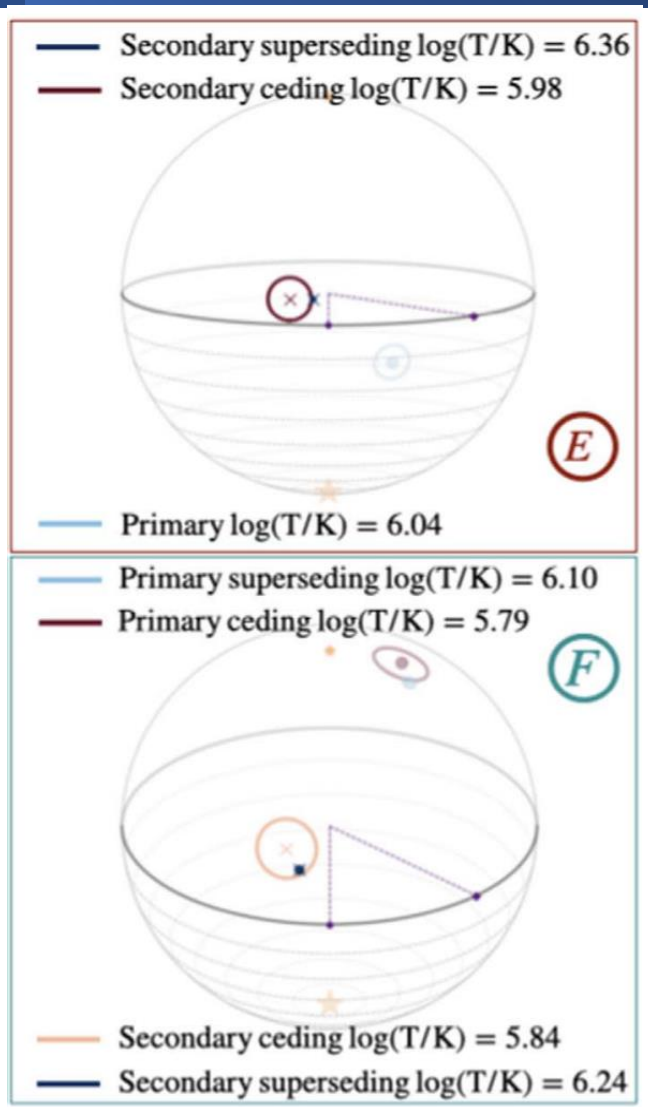
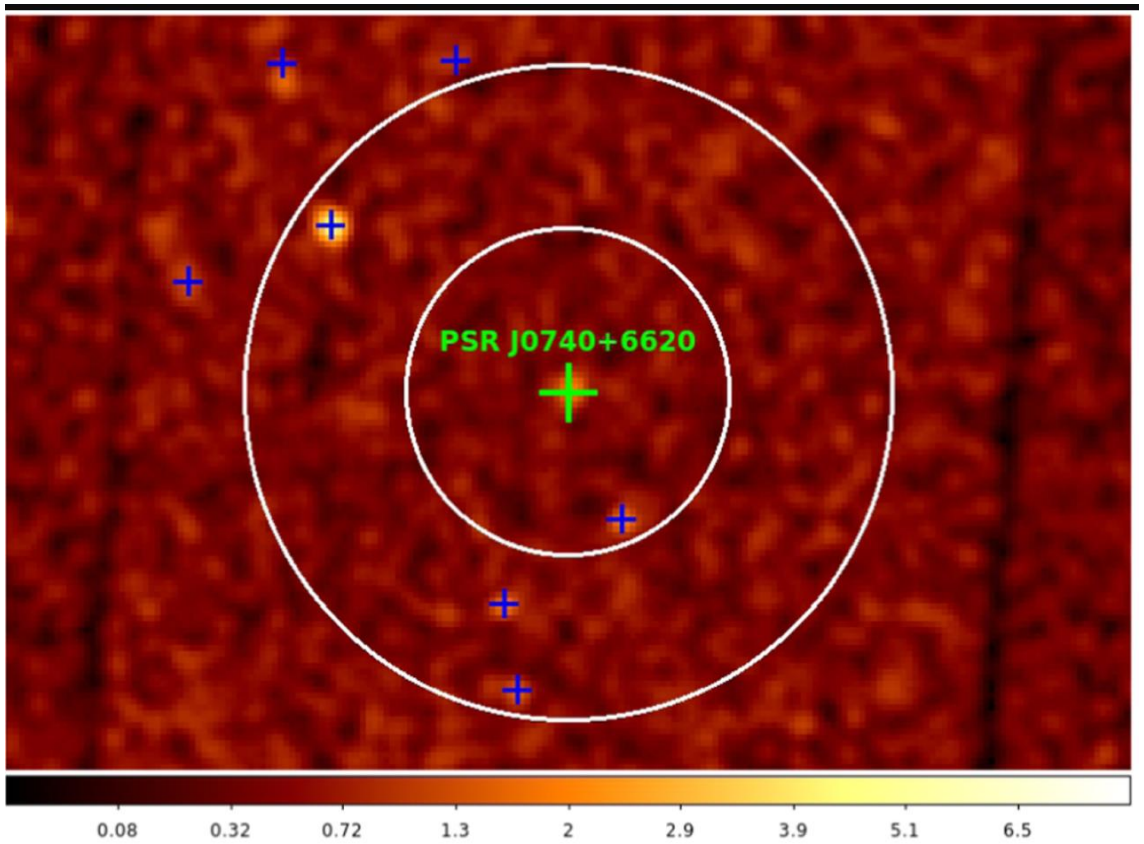
Different modes correspond to different masses and radii (see later!)

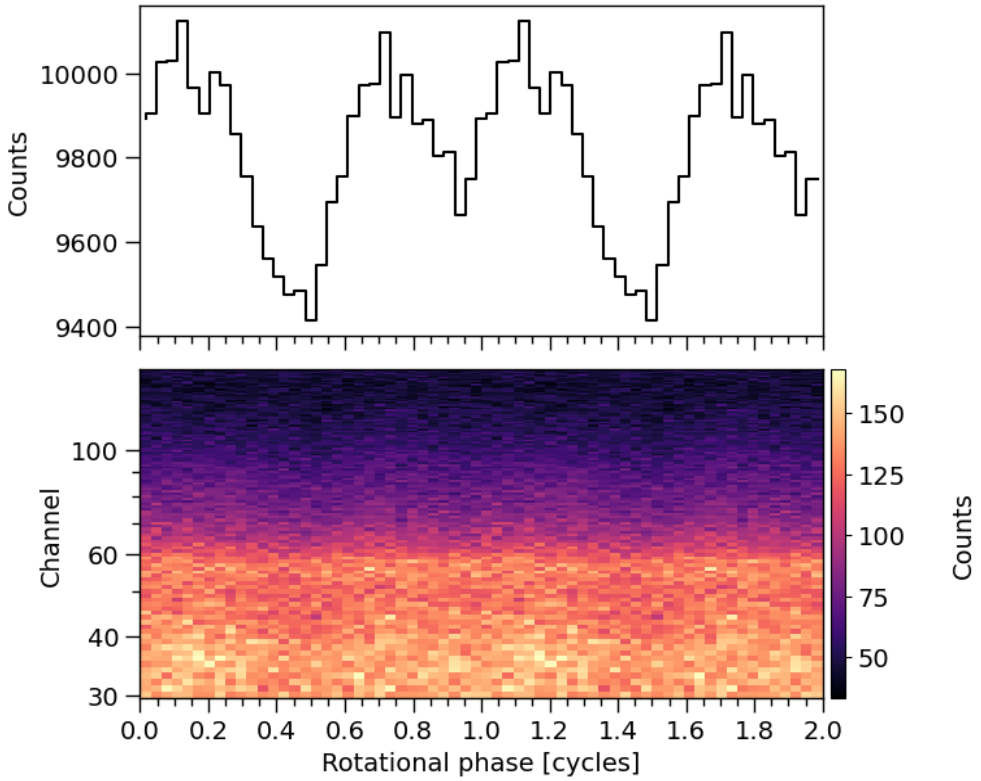


NICER results: J0740

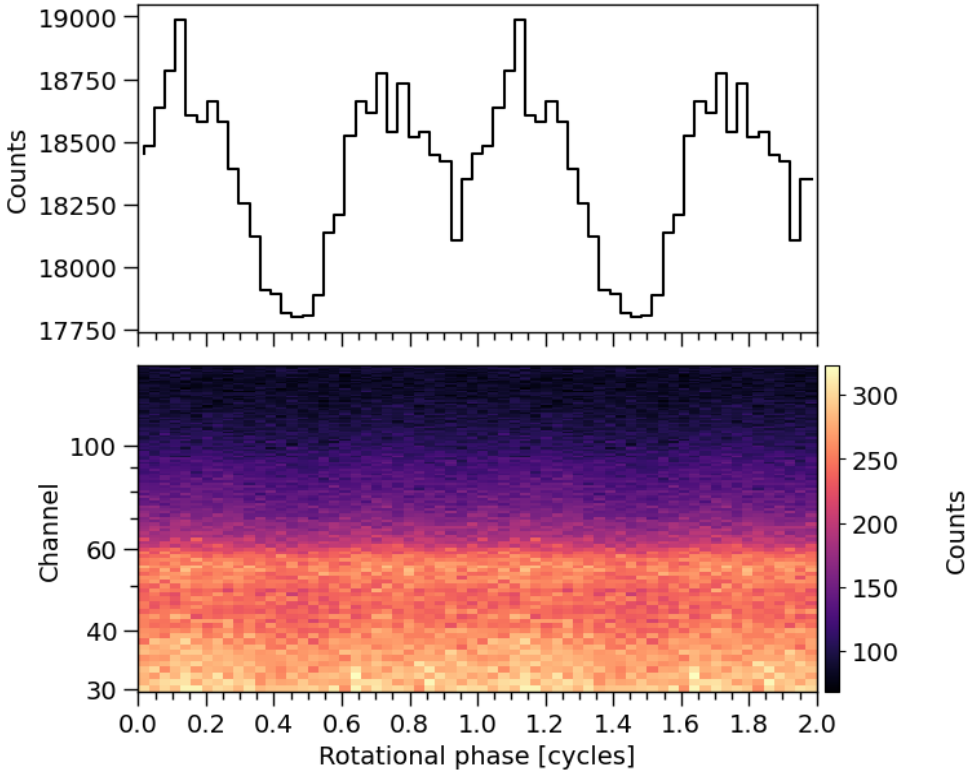
PSR J0740+6620: Faint but spinning at 346 Hz in a binary system with a known mass:
$M = 2.1\ M_{\odot}$ (Cromartie et al. 2020, Fonseca et al. 2021, Wolff et al. 2021)



New J0740 NICER data with 90% more counts



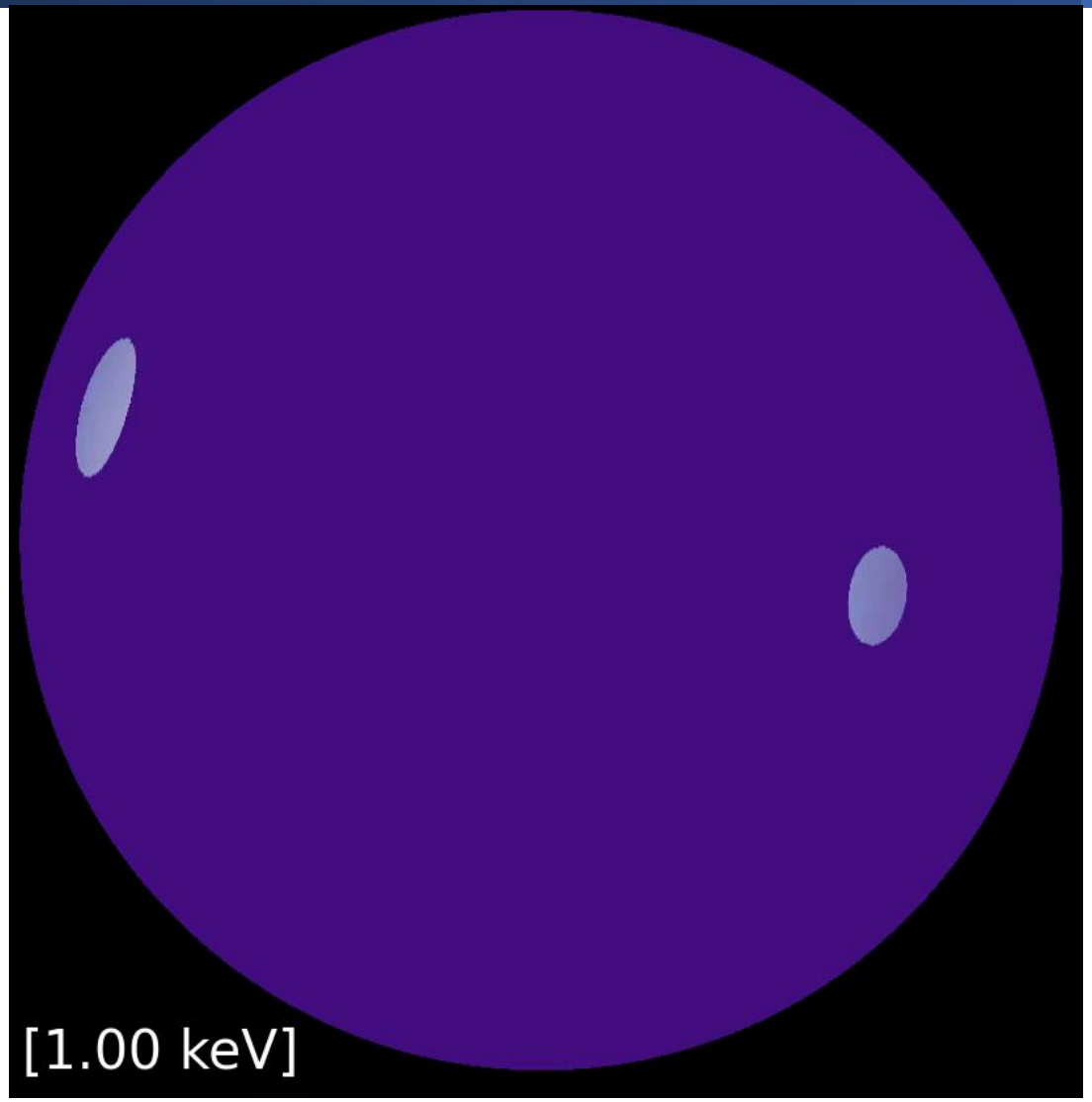
Miller et al. 2021, **Riley et al. 2021**,
Wolff et al. 2021, Salmi et al. 2022



Dittmann et al. 2024 (in press),
Salmi et al. 2024 (in press)

+ XMM Newton data

J0740 results: Hot Spot Properties



J0740 results: Radius

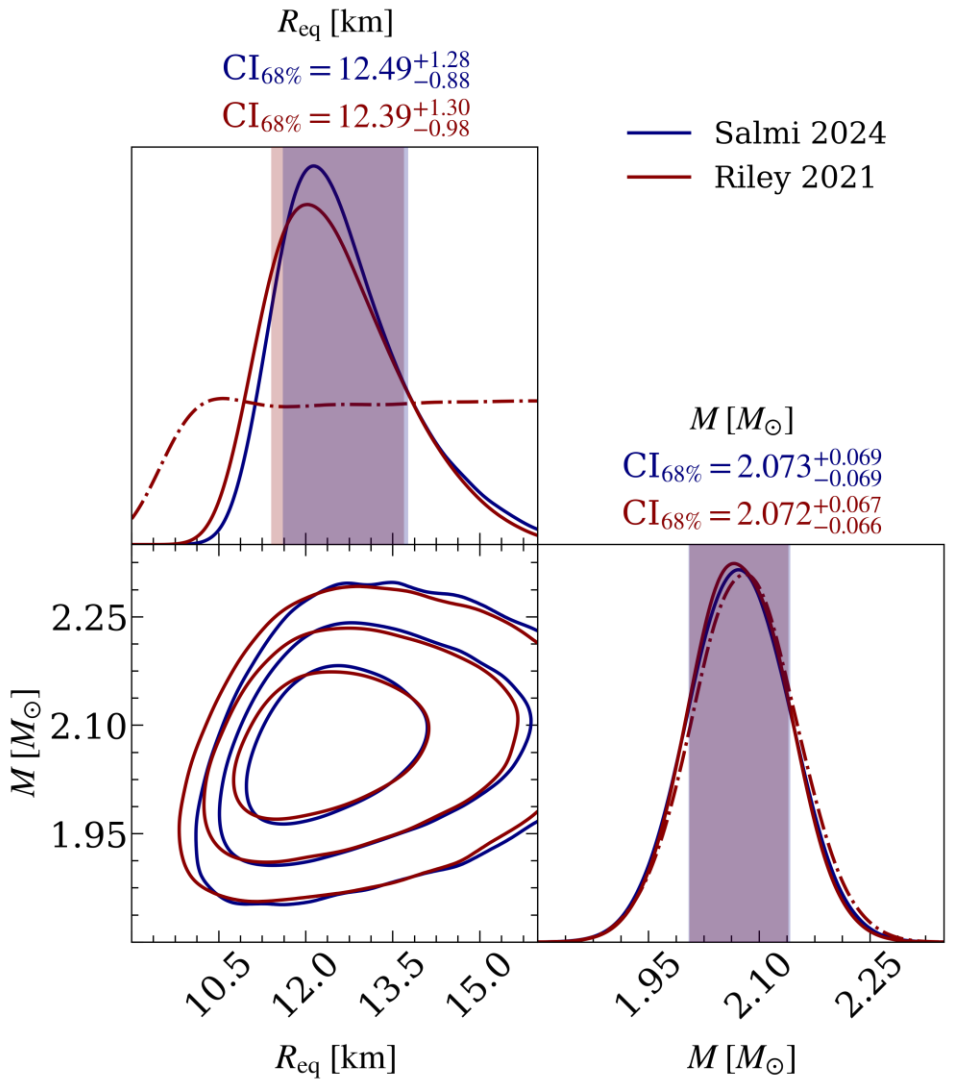
Riley et al. 2021 (1.6 yr data):

R = 12.4 + 1.3 - 1.0 km (CI 68%)

Salmi et al. 2024 (3.6 yr data, better sampling):

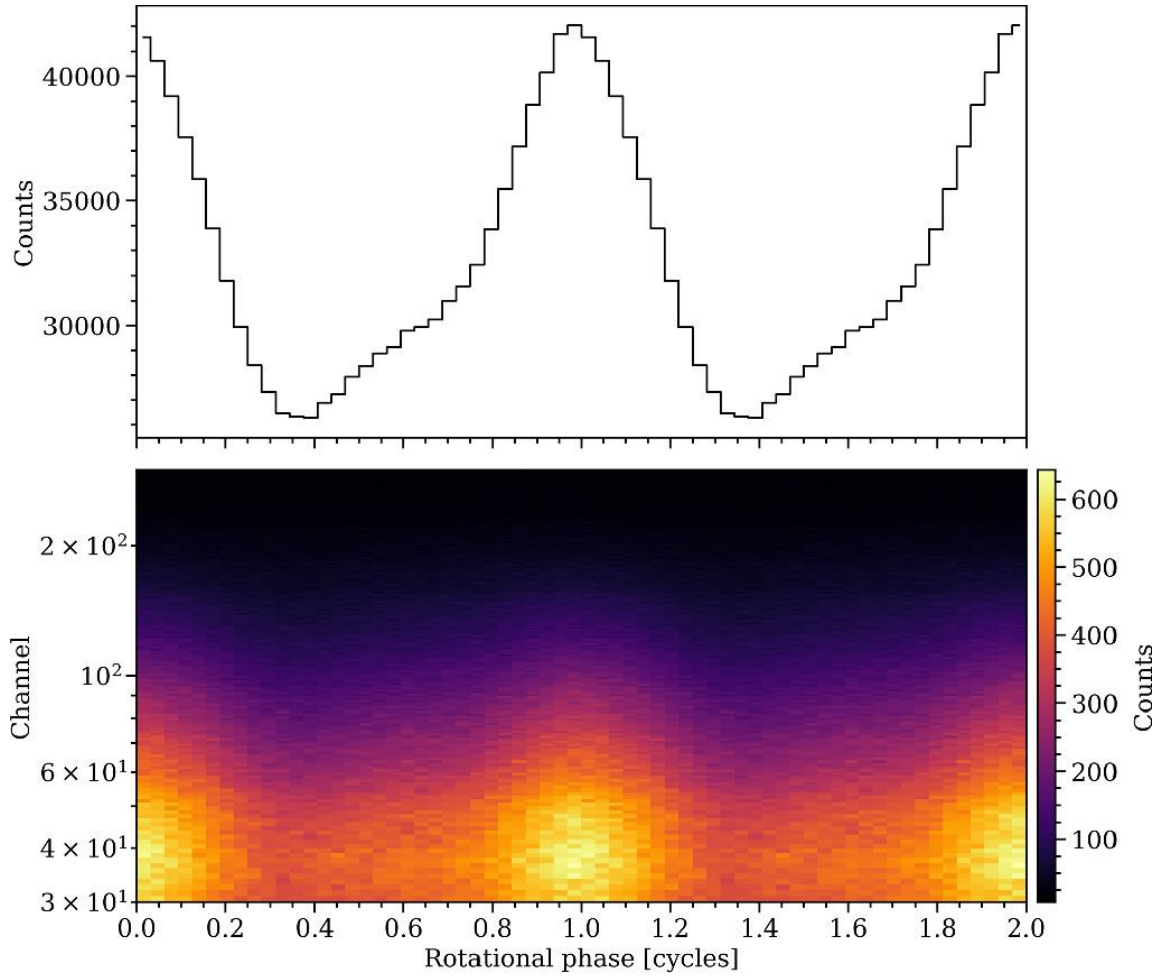
R = 12.5 + 1.3 - 0.9 km

- E.g. 95% lower limit: 10.7 km -> 11.0 km
- Rules out softest EOS
- Consequences for e.g quark matter, color-superconducting gap (Annala et al. 2023, Kurkela et al. 2024)



NICER results: J0437

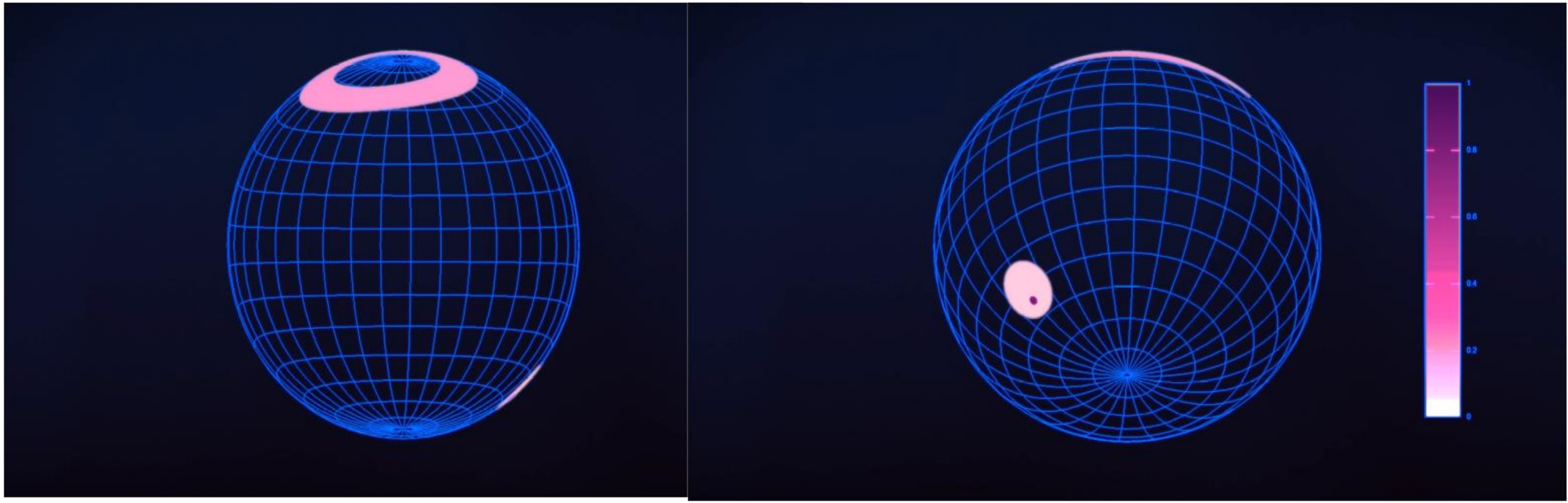
PSR J0437-4715: The nearest and brightest pulsar spinning at 174 Hz. In a binary system with a known M: 1.4 $M_\odot$ (Reardon et al. 2024)



Choudhury et al. 2024

NICER results: J0437

Choudhury et al. 2024: Likely an offset dipolar or quadrudipolar magnetic field.



NICER results: J0437

Choudhury et al. 2024:

Radius: $11.36^{+0.95}_{-0.63}$ km (68% CI)

Mass: $1.418 \pm 0.037\ M_\odot$ (68% CI)

Consistent with GW obs:

- $M = 1.36 - 1.62\ M_\odot$, $R = 10.7^{+2.1}_{-1.5}$ km
  (Abbott et al. 2018, 90% CI)

Less consistent with PREX:

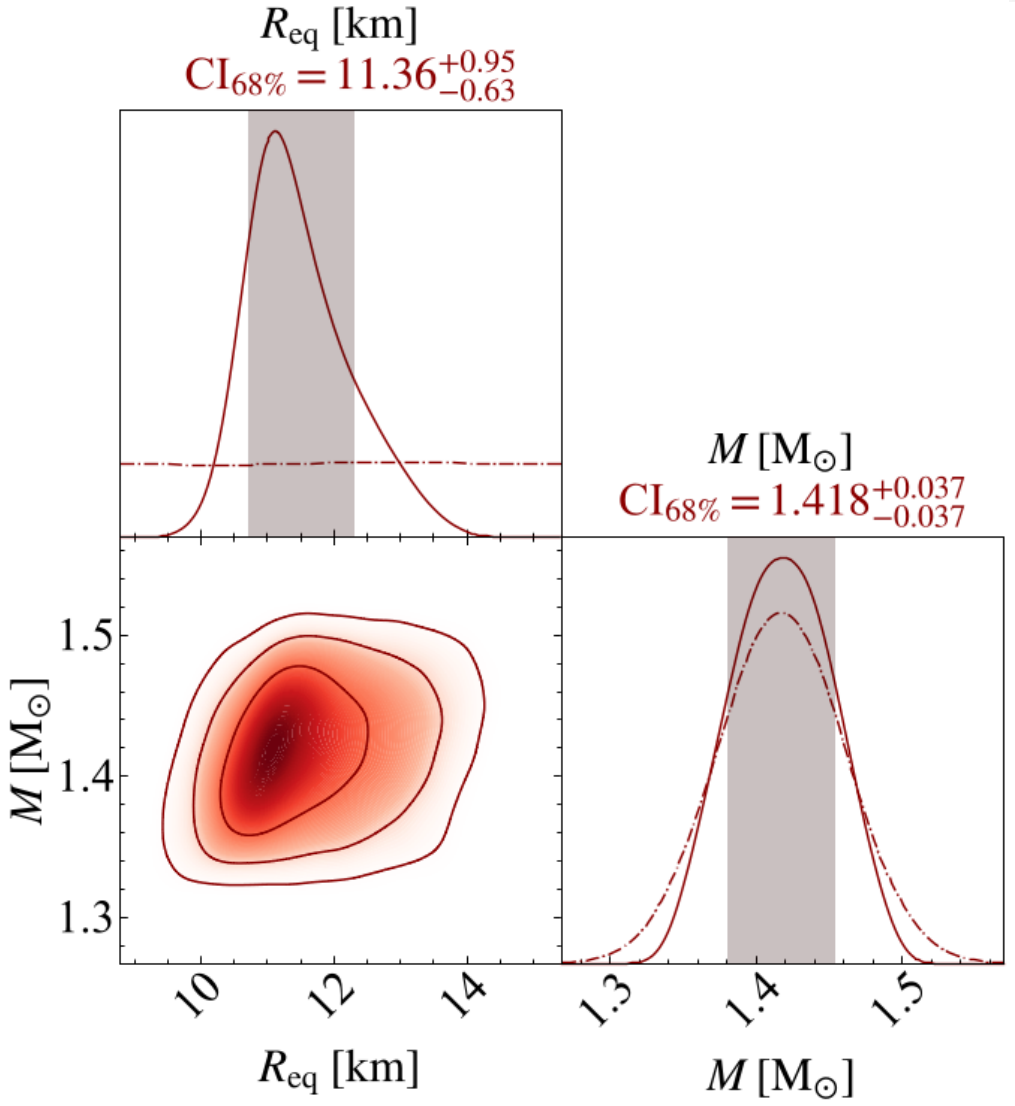
- $R_{1.4M_\odot} \geq 13.25$ km *(Reed et al. 2021, 1σ)*

Consistent with models satisfying PREX and CREX:

- $R_{1.4M_\odot} = 11.6 \pm 1.0$ km *(Lattimer 2023, 68% CI)*

EOS inference using NICER + GW + new-χEFT:

- $R_{1.4M_\odot} = 12.01^{+0.56}_{-0.75}$ km (CS); $12.28^{+0.50}_{-0.76}$ km (PP)
  (95% CI constraint of $\sim \pm 5.4\%$)
  (Rutherford et al. 2024)



NICER results: Summary

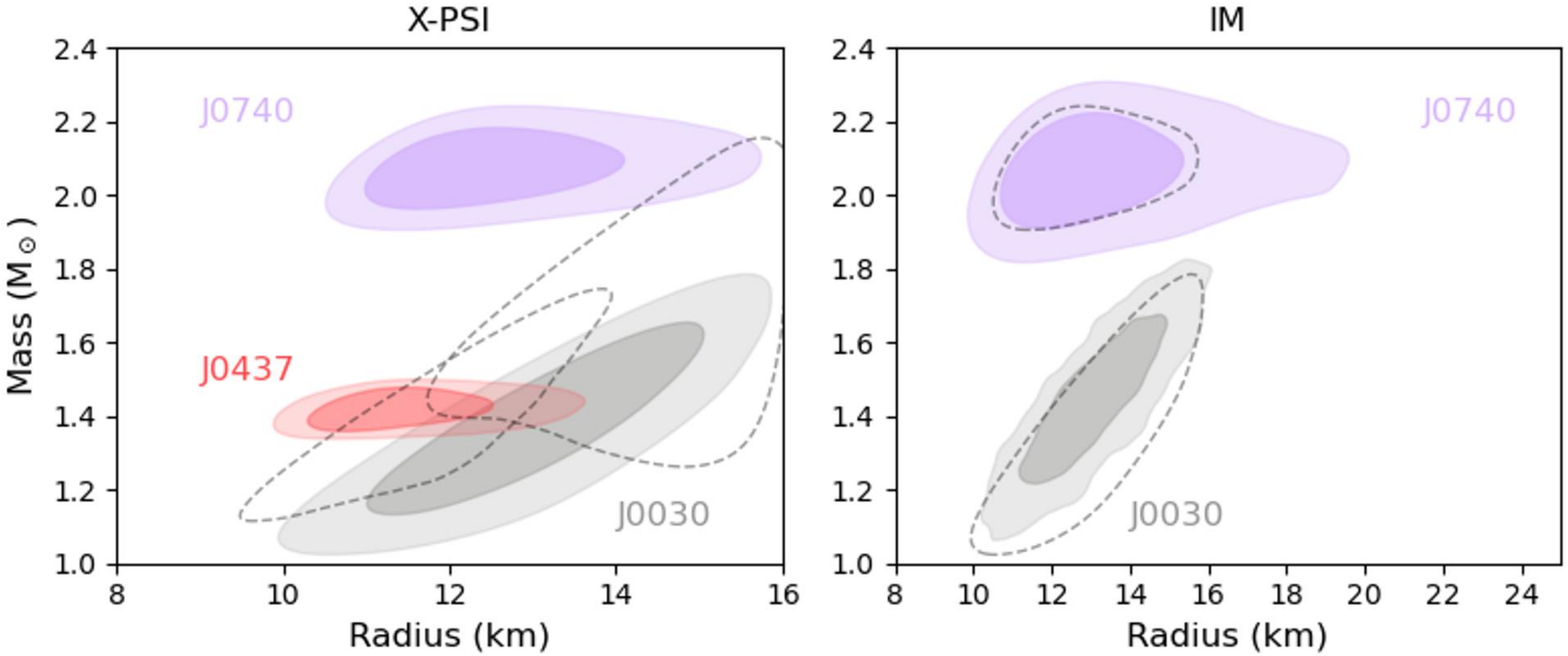


Image credit: A. Watts

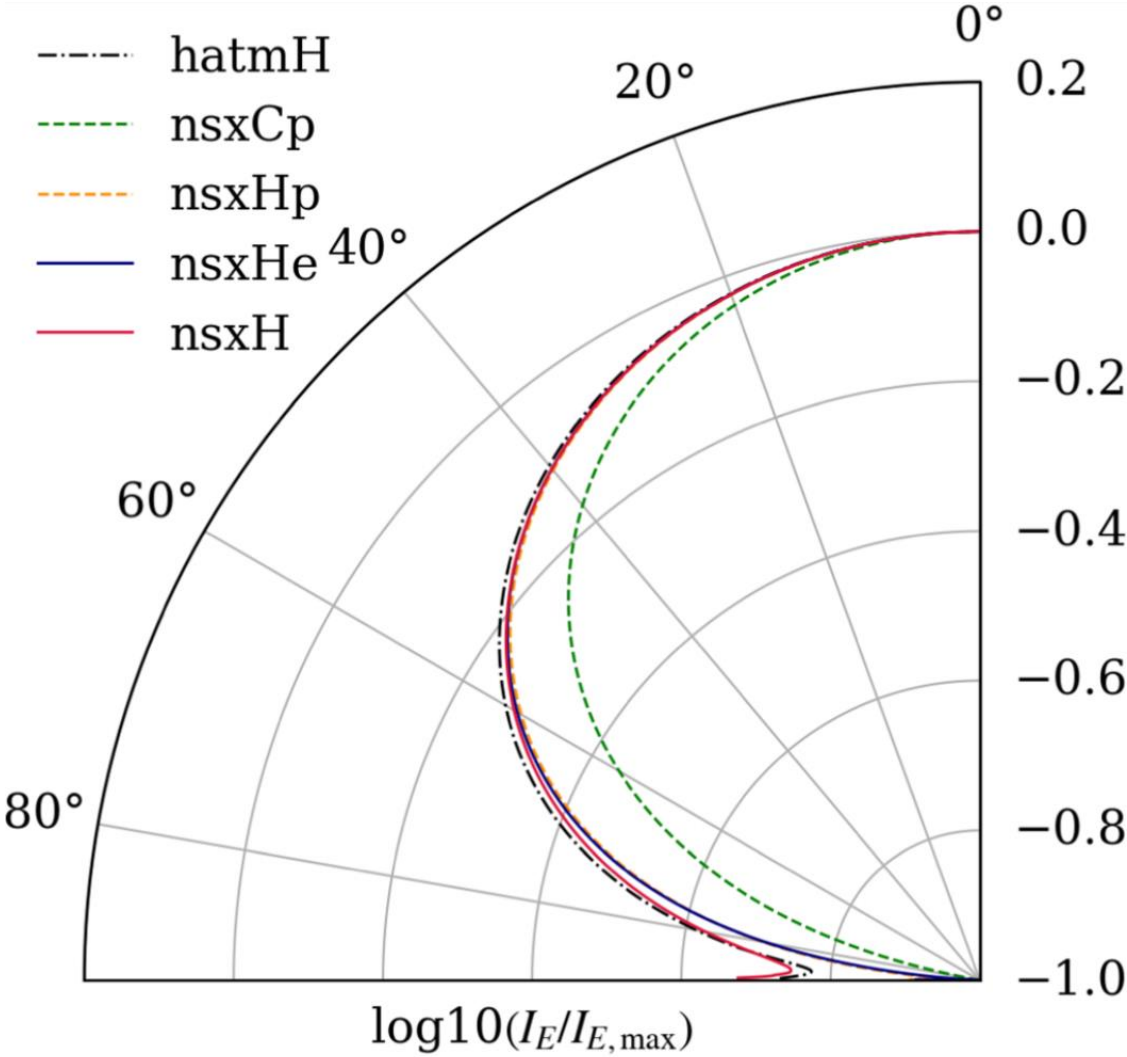
NICER: Other updates

Influence of atmospheric assumptions
(see beaming patterns right, [Salmi et al. 2023]): M&R of J0030 affected, M&R of J0740 not.

Comparison of waveforms between codes
([Choudhury et al. 2024, in press])

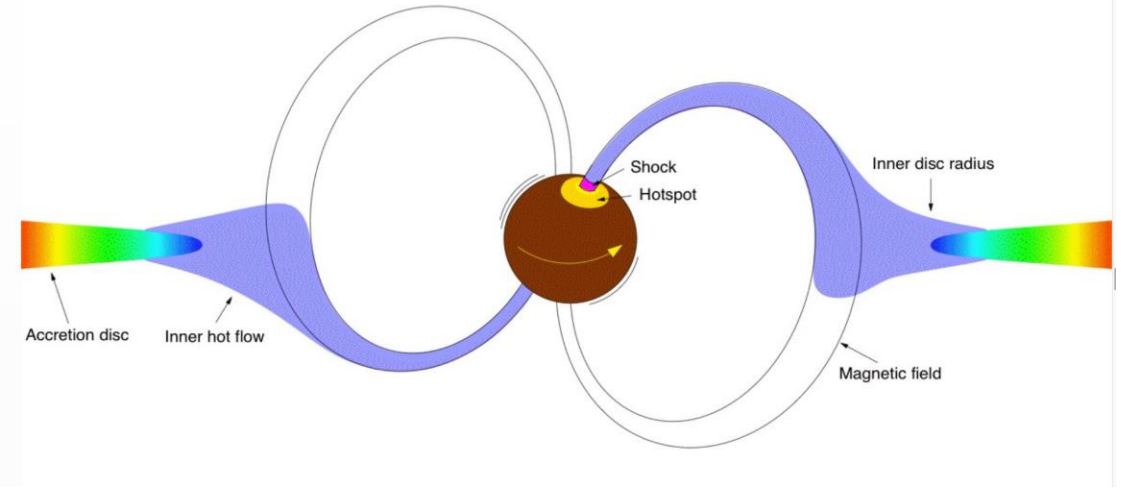
Parameter inferences with synthetic data
([Bogdanov et al. 2021], [Vinciguerra et al. 2023])

Other stars being analyzed/submitted:
PSR J1231-1411, PSR J0614-3329, ...

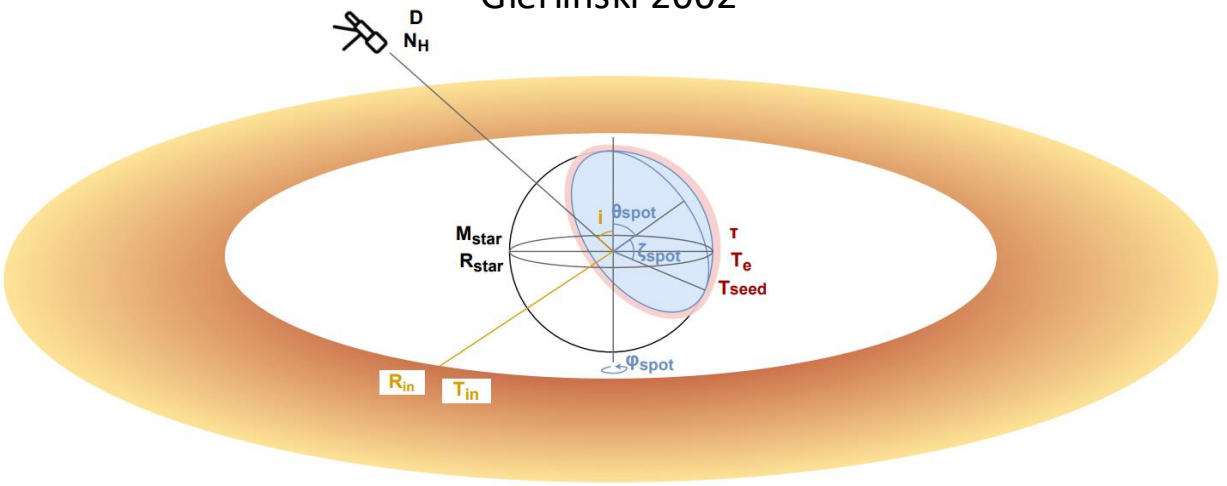


Accretion-powered millisecond pulsars (AMPs)

- Spots heated by accreted gas
- Pulsations during outbursts
- Bright and rapid rotators
- Accretion disk and column
- Compton scattering:
  X-rays polarized and higher energy
  (Salmi et al. 2018, Bobrikova et al. 2023)
- NICER may still infer M&R from AMPs with
  ± 5-10% accuracy (**Dorsman et al. 2024, submitted**)



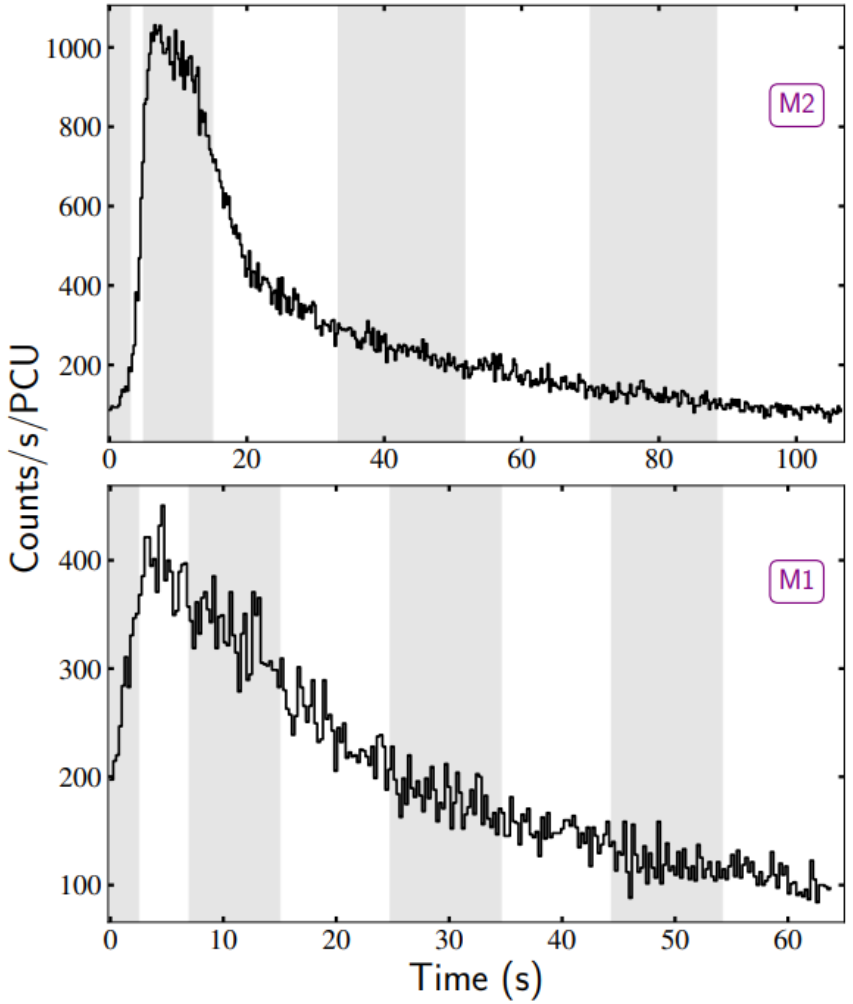
Gierlinski 2002



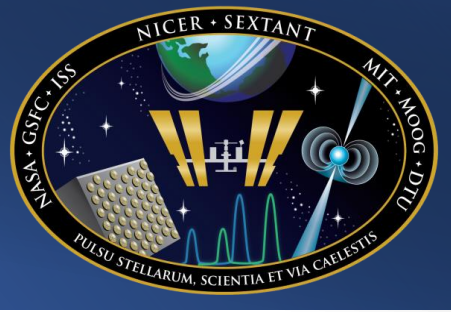
Credit: B. Dorsman

Thermonuclear-powered millisecond pulsars (TMPs)

- Spots heated by thermonuclear burning of accreted matter
- Burst oscillations (pulsations) for some bursts, but not always
- Bright and rapid rotators
- Origin of the surface anisotropy still debated
- Spot properties variable during the burst:
  More expensive modeling **(Kini et al. 2022, 2023, 2024)**
- Modeling J1814−338 RXTE data with a single spot model gave R ~7 km, M ~ 1.2 $M_{\odot}$, but bad fit to the first harmonic. **(Kini et al. 2024)**



Conclusions



- X-ray pulse profile modeling has been applied to infer neutron star M, R and other parameters.

- RMPs (re-)analyzed with NICER:
  - J0030: Multiple solutions with different geometries and M&R
  - J0740: Excluding the softest EOS, tighter constraints with new data
  - J0437: Tightest constraints so far: Softer EOS.

- AMPs: Promising targets for new analyses, including polarimetry to constrain the geometry (recent IXPE discovery of a polarized AMP J1444 by **Papitto et al. 2024**)

- TMPs: Challenge with variable spot properties, but analyses can inform about burst physics

Extra comparisons