X-ray pulse profile modeling - Recent NICER analyses

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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, Anna Bobrikova, Vladislav Loktev, Alessandro Di Marco, John Rankin, Alessandro Papitto, ...

NICER • SEXTANT
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NWO
European Research Council
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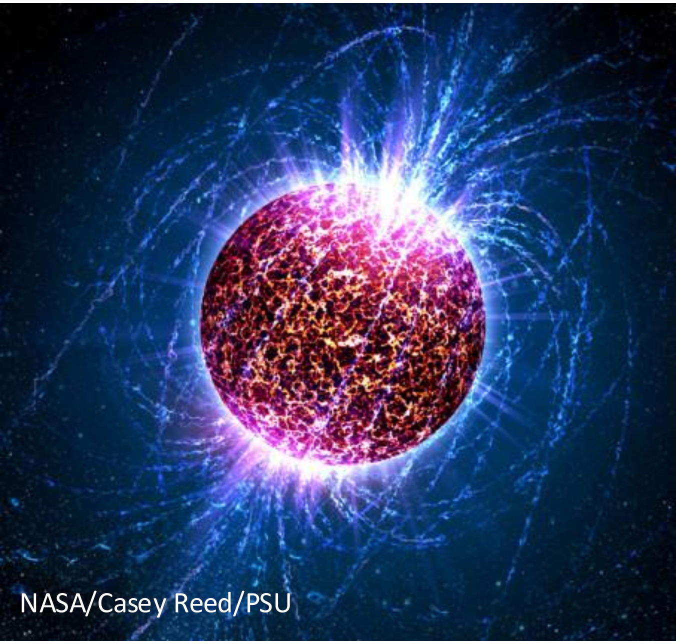
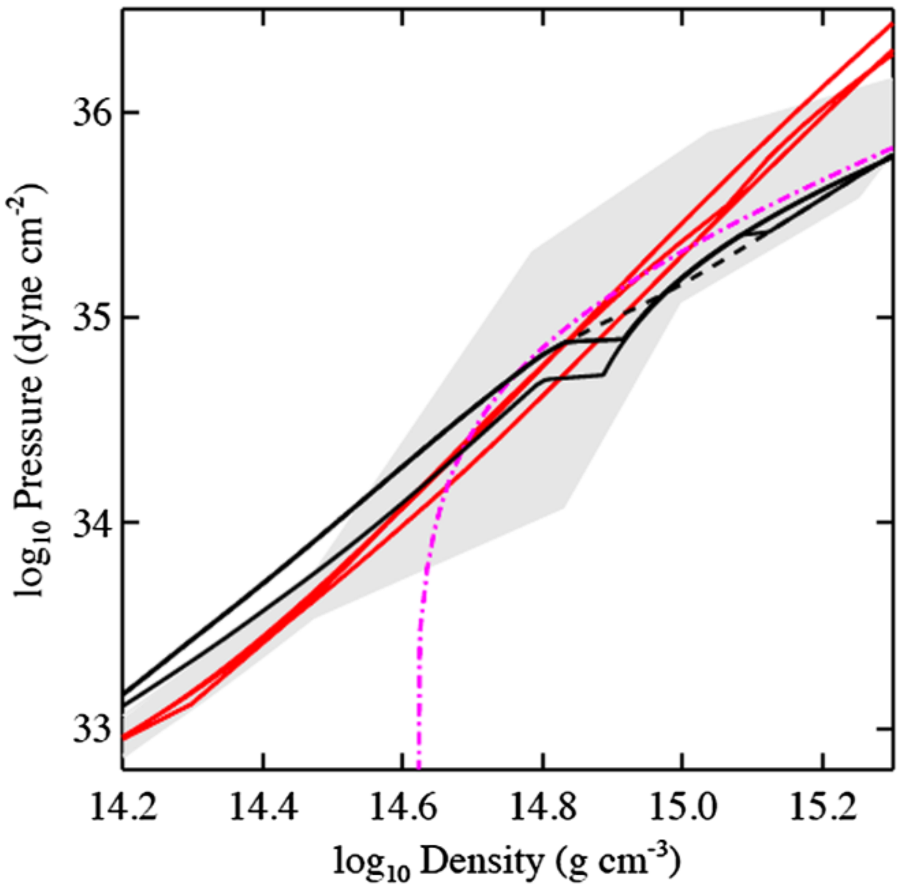
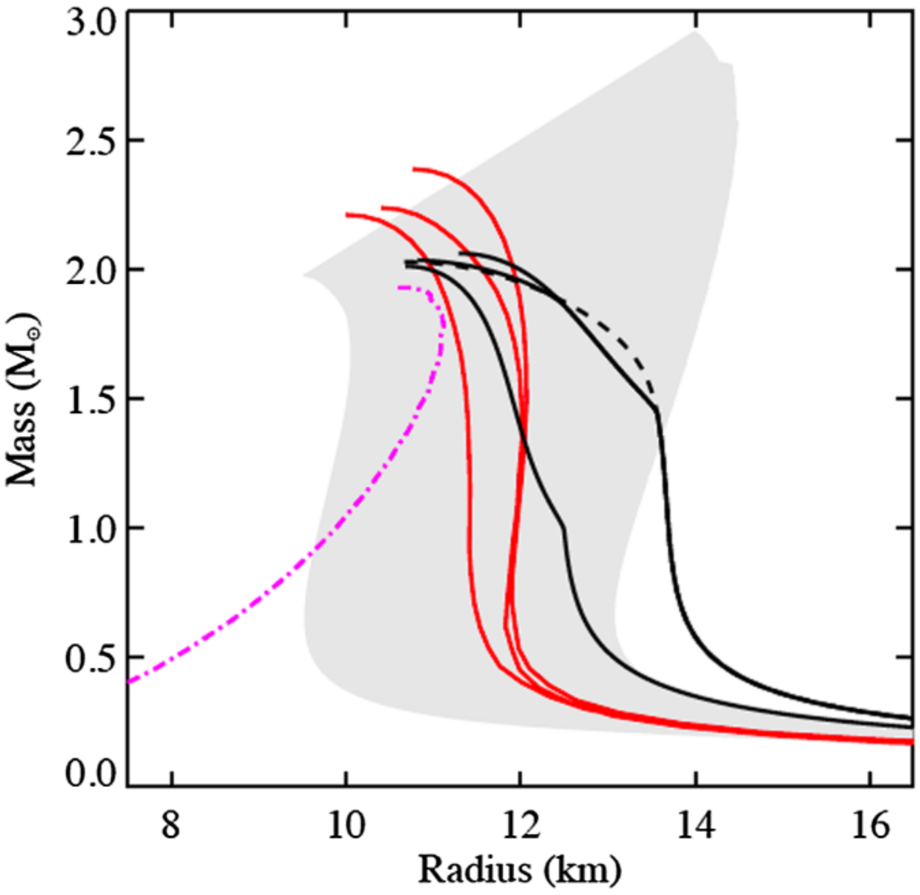
Neutron Stars: Mass-Radius vs Equation of State (EOS)



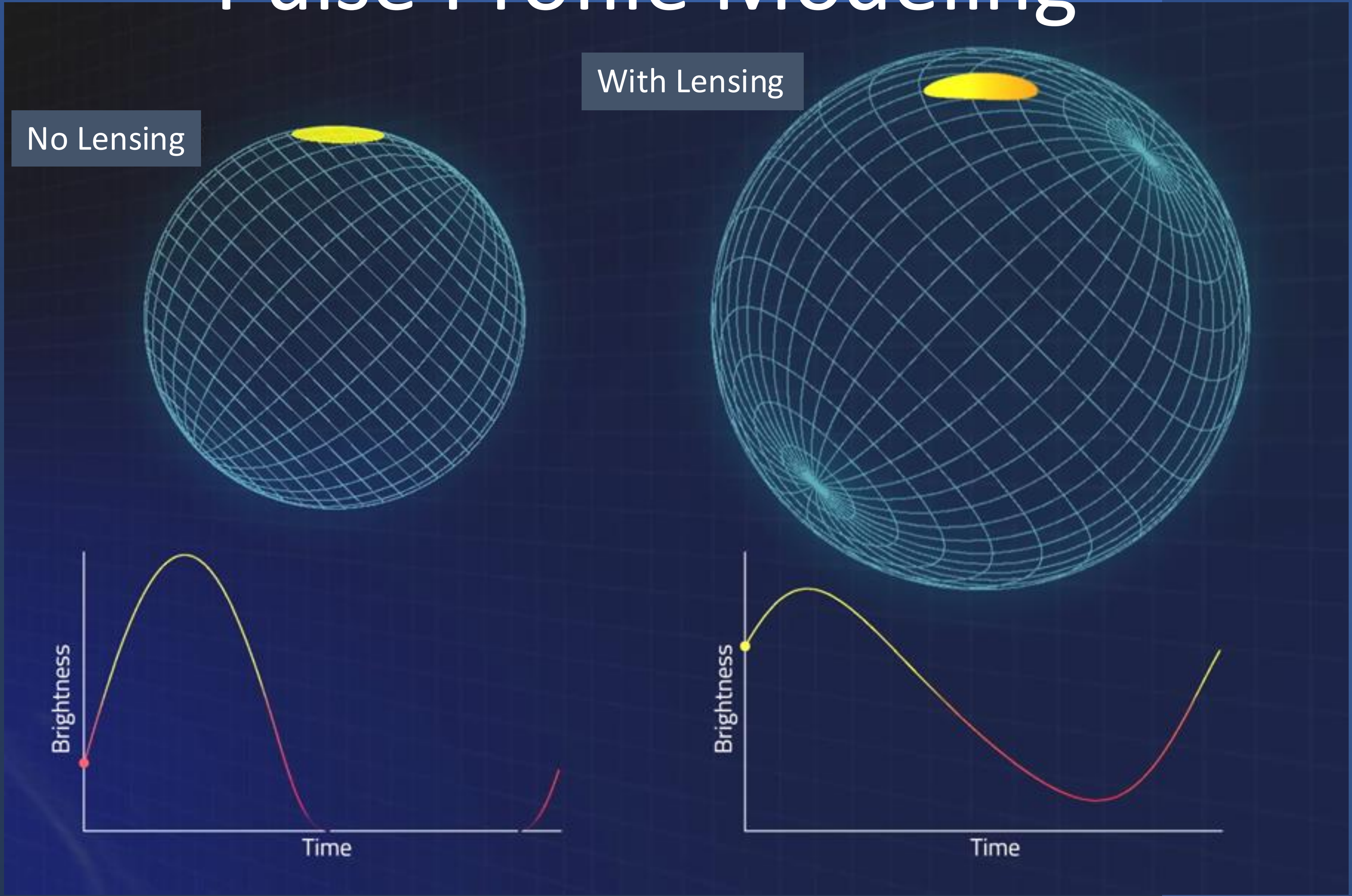
Core:
Nucleonic, quark, hyperonic, hybrid?



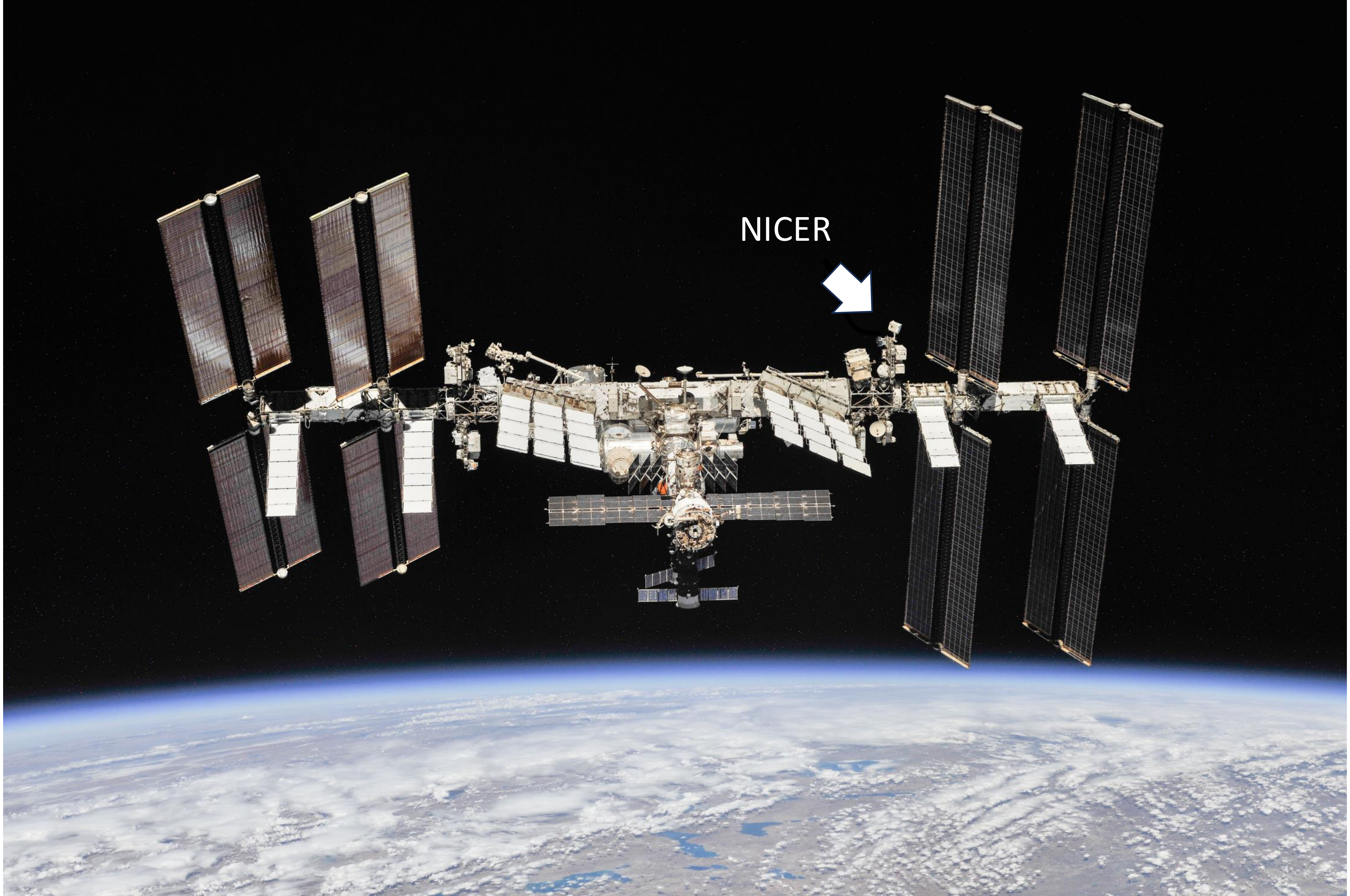


[Watts et al. 2016, Rev. Mod. Phys.]

Pulse Profile Modeling

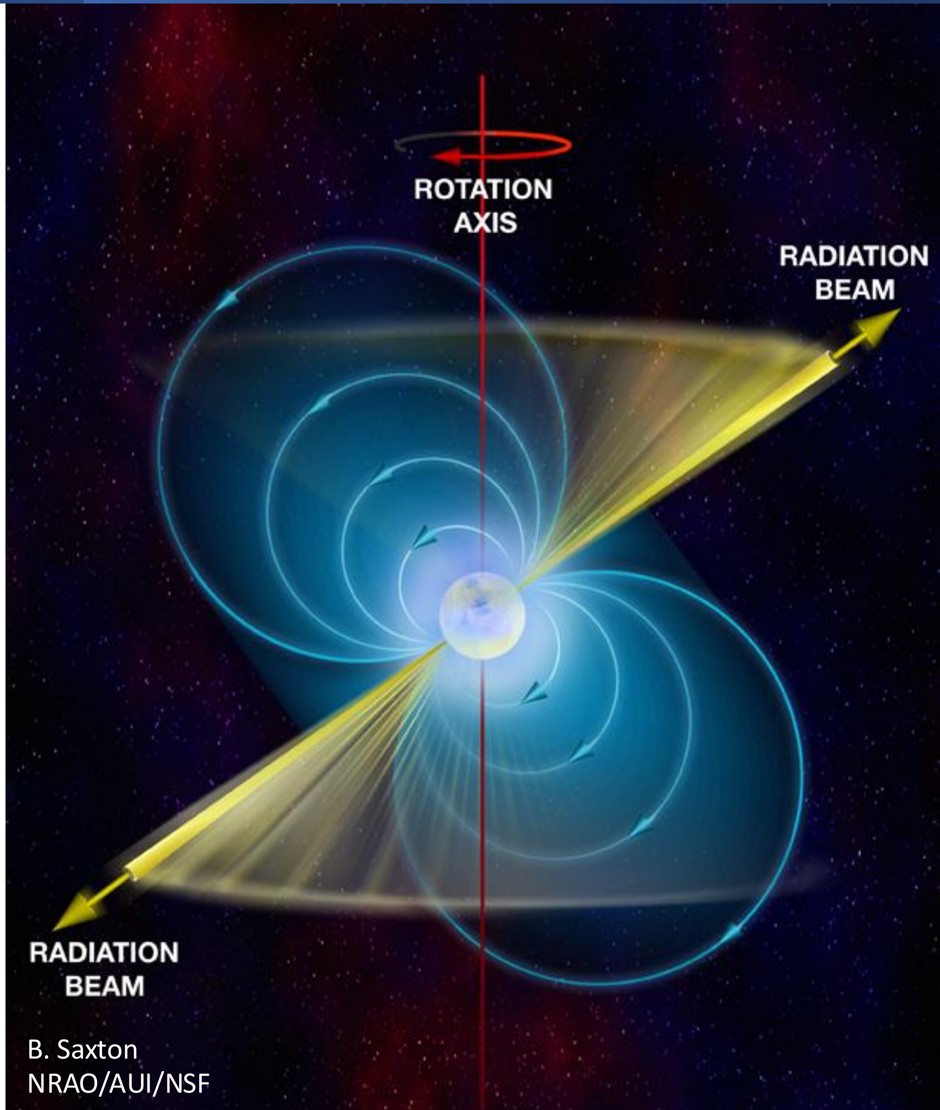


Credit: Morsink/Moir/Arzoumanian/NASA-GSFC


NICER

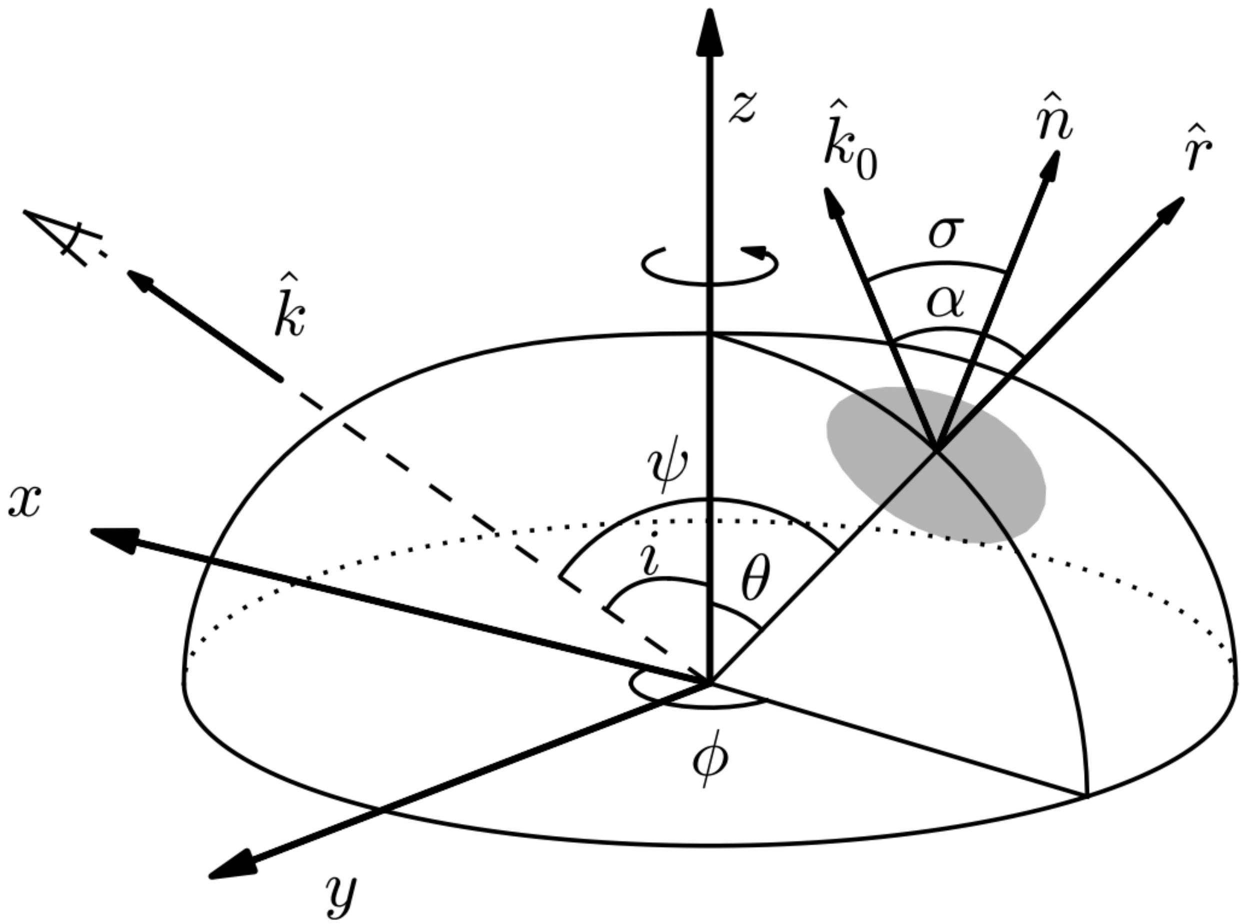
Rotation-powered millisecond pulsars (RMPs)

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



Pulse profile model

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



Salmi et al. 2018

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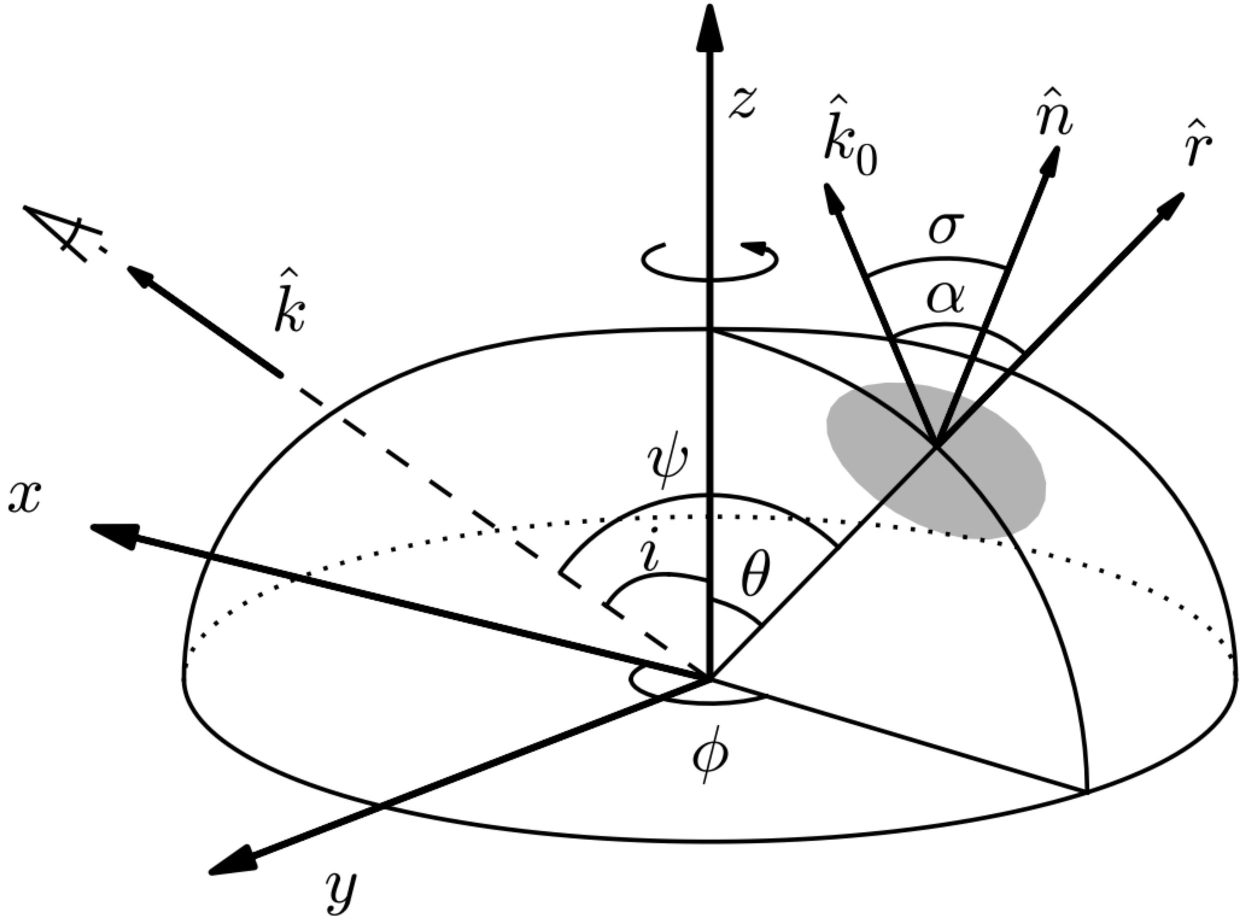

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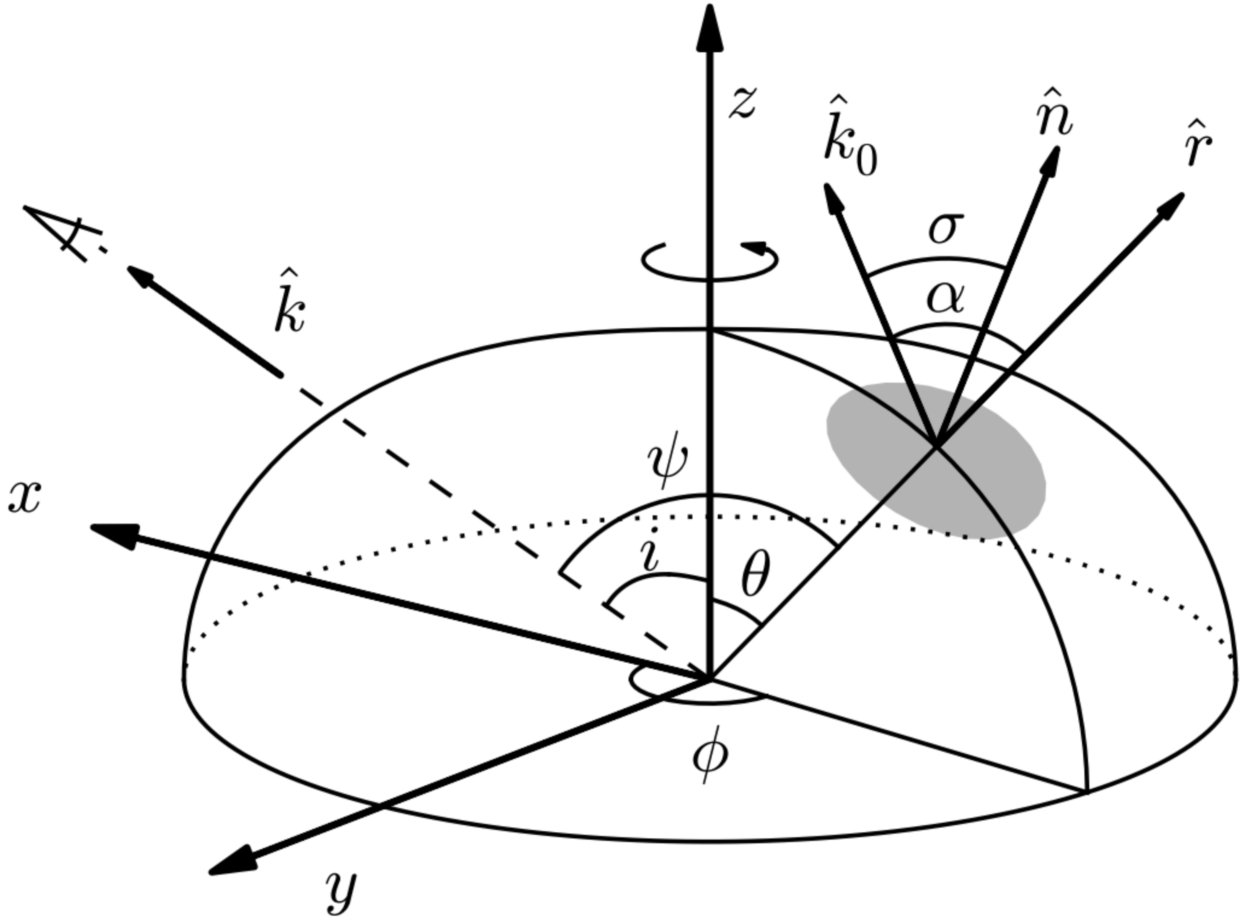
Observed flux (Bogdanov et al. 2019):

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



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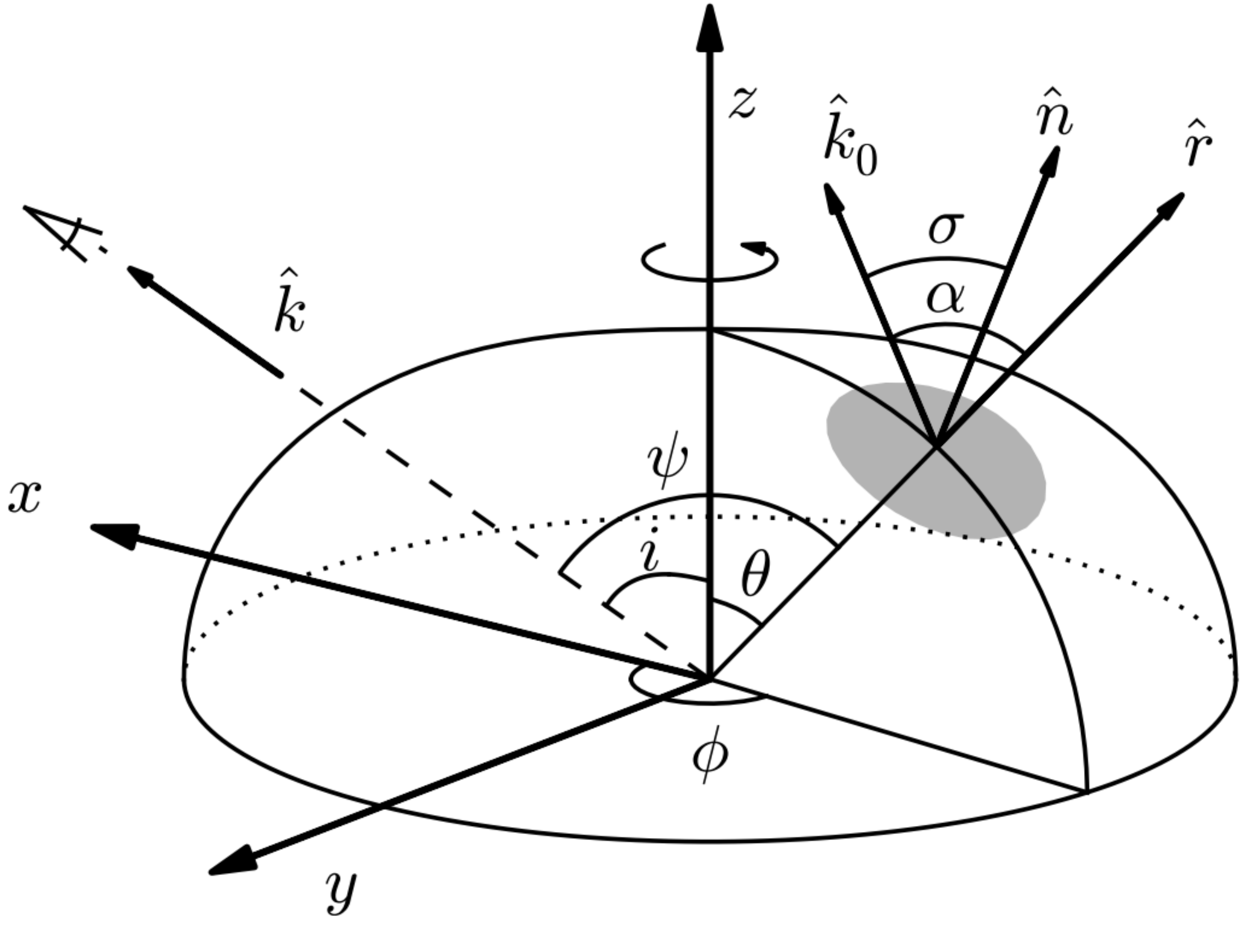
Hot region surface models (circles)



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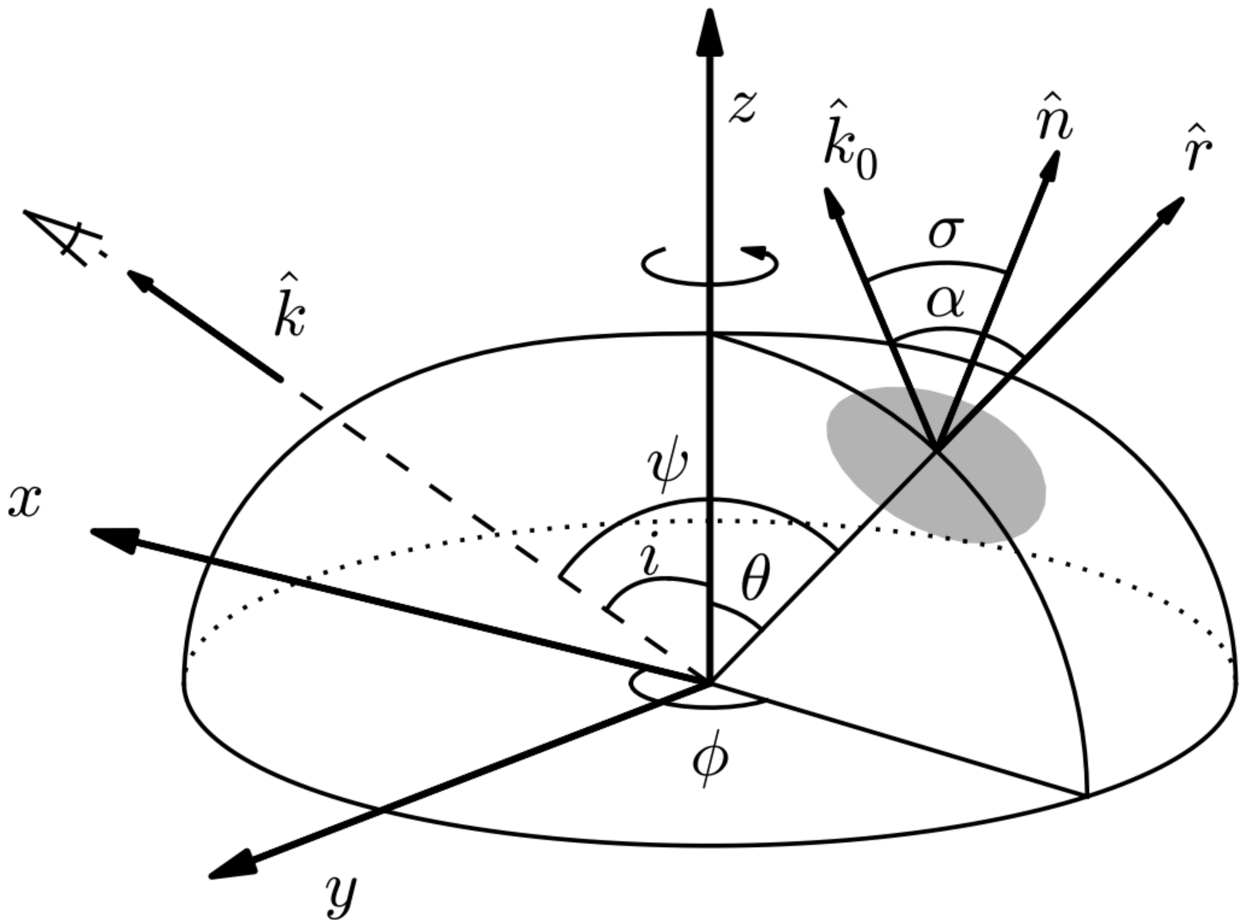
Hot region surface models (circles)

Interstellar medium



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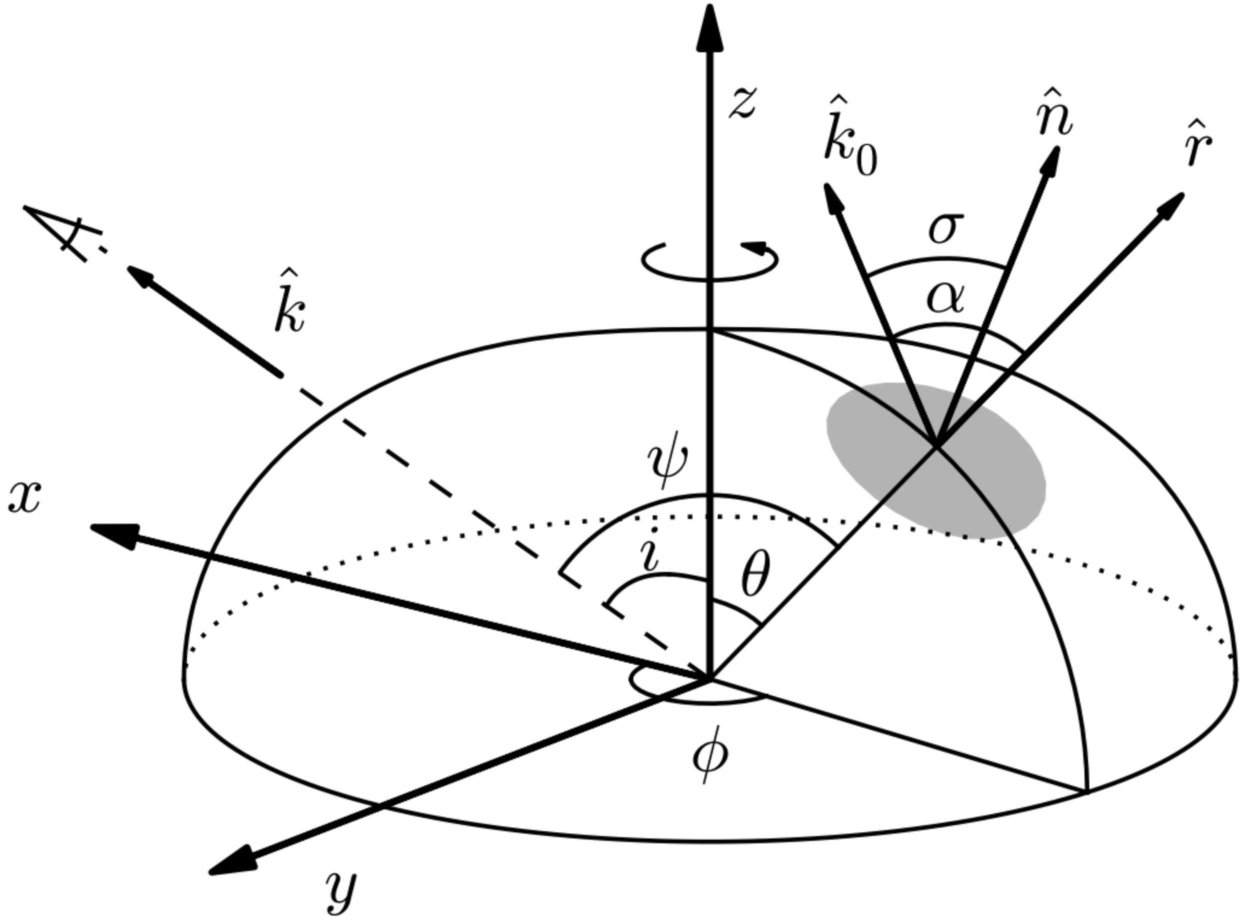
Hot region surface models (circles)

Interstellar medium

Instrumental properties



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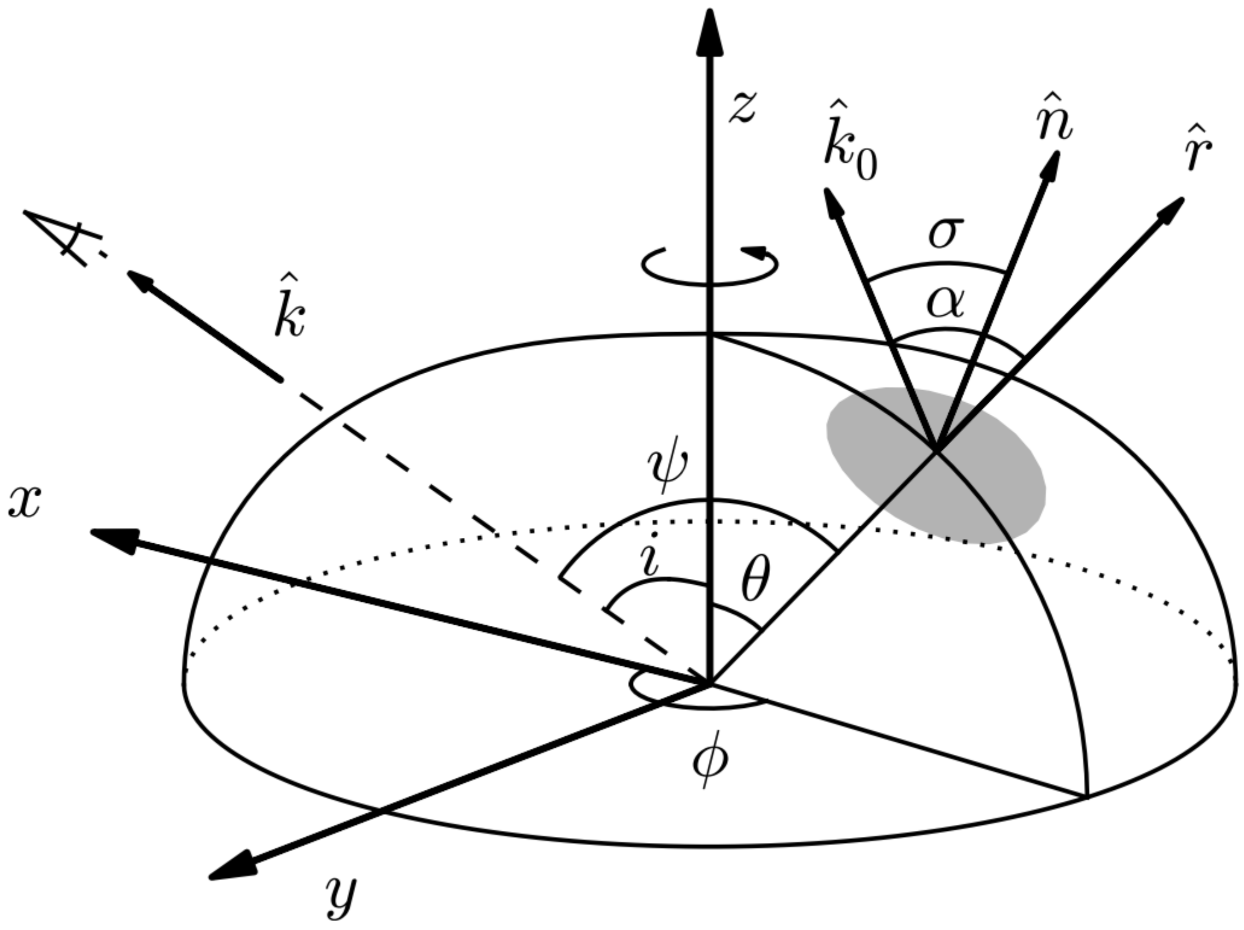
Instrumental properties

Background model



Salmi et al. 2018

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

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

Light curve model vs data

Sampling with MultiNest
([Feroz et al. 2009](#))

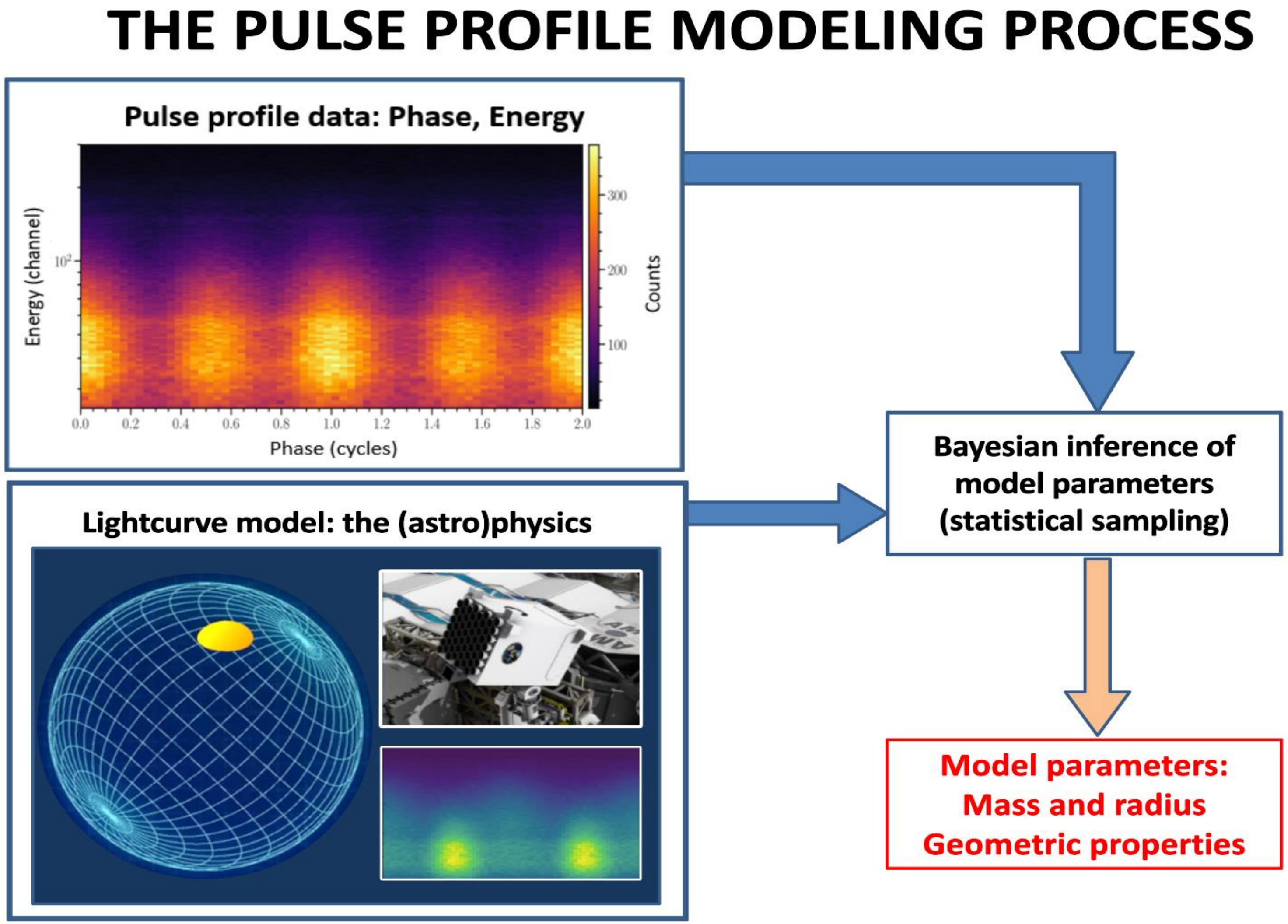


Image credit:
Bogdanov/Morsink/NASA/Riley/Watts

NICER results: Analyses so far

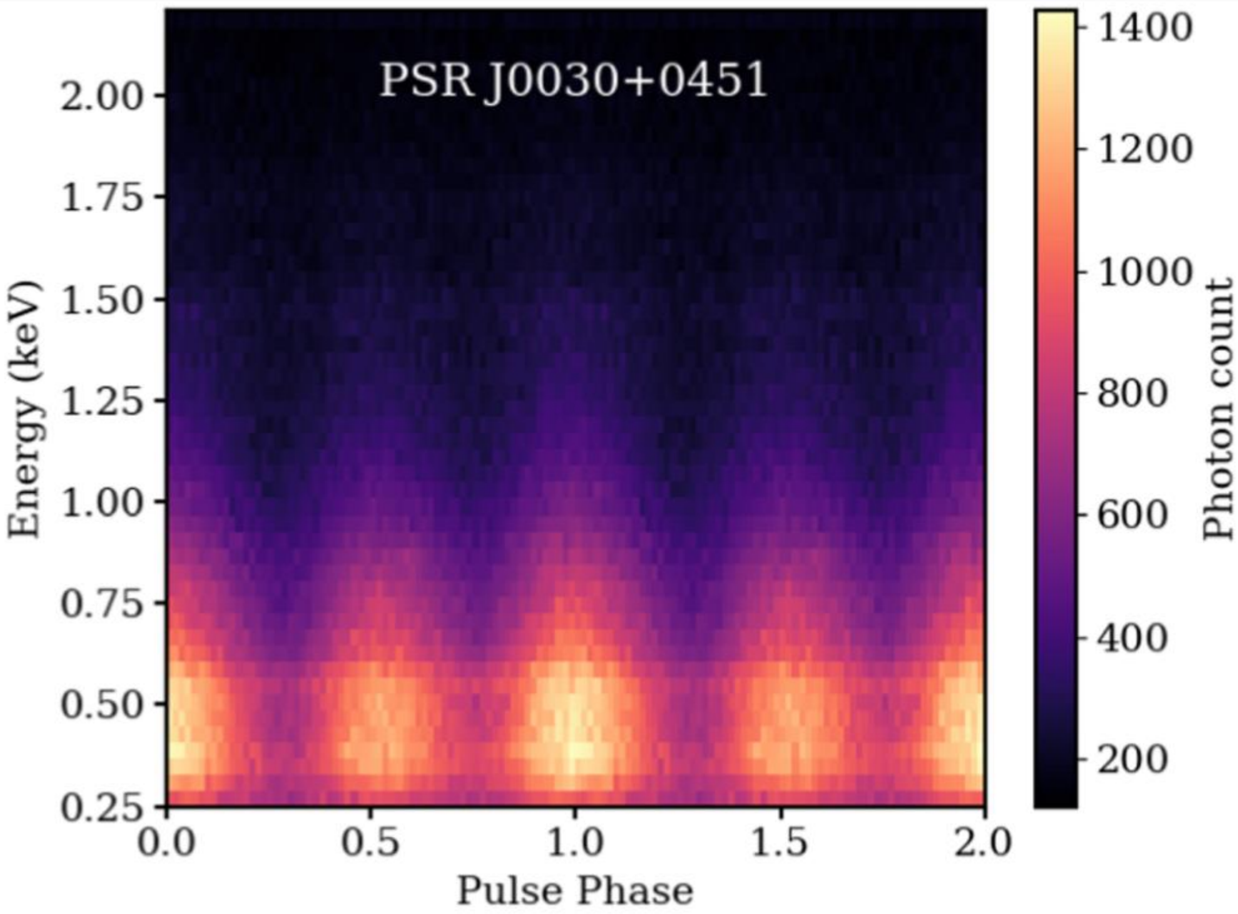
PSR J0030+0451: 2019, 2024

PSR J0740+6620: 2021, 2022, 2024

PSR J0437-4715: 2024

PSR J1231-1411: 2024

Other stars to come:
PSR J0614-3329, PSR J1614-2230,
PSR J2124-3358

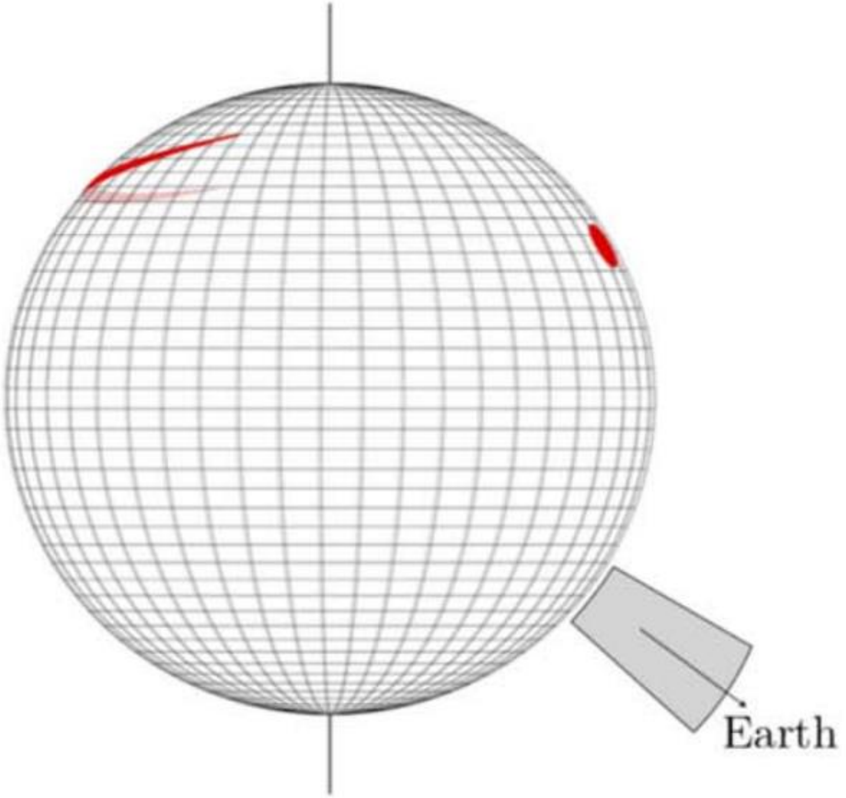


Bogdanov et al. 2019

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
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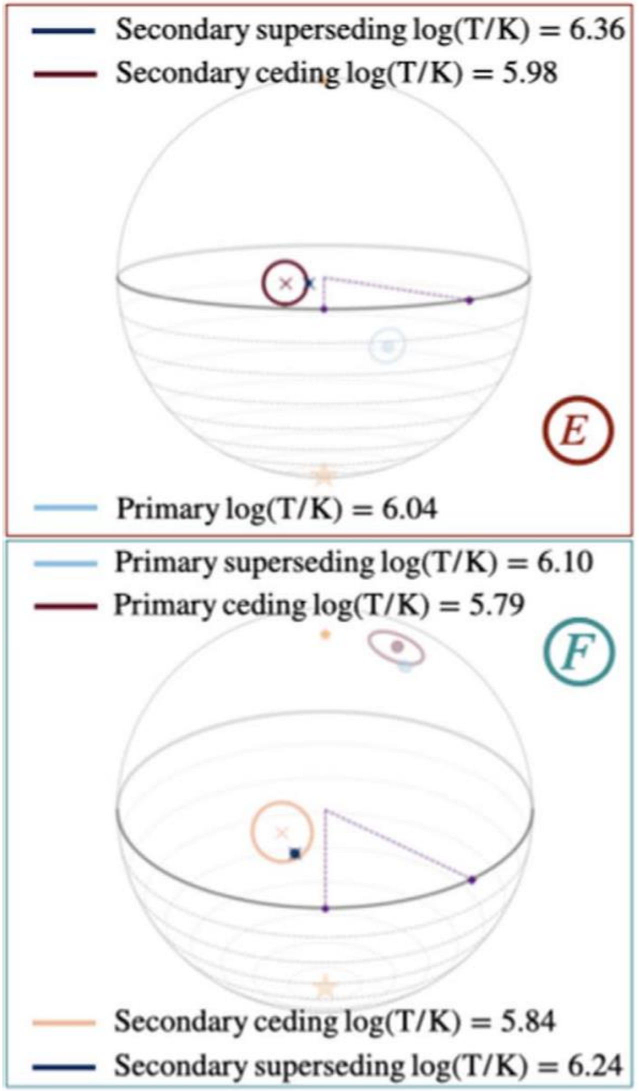

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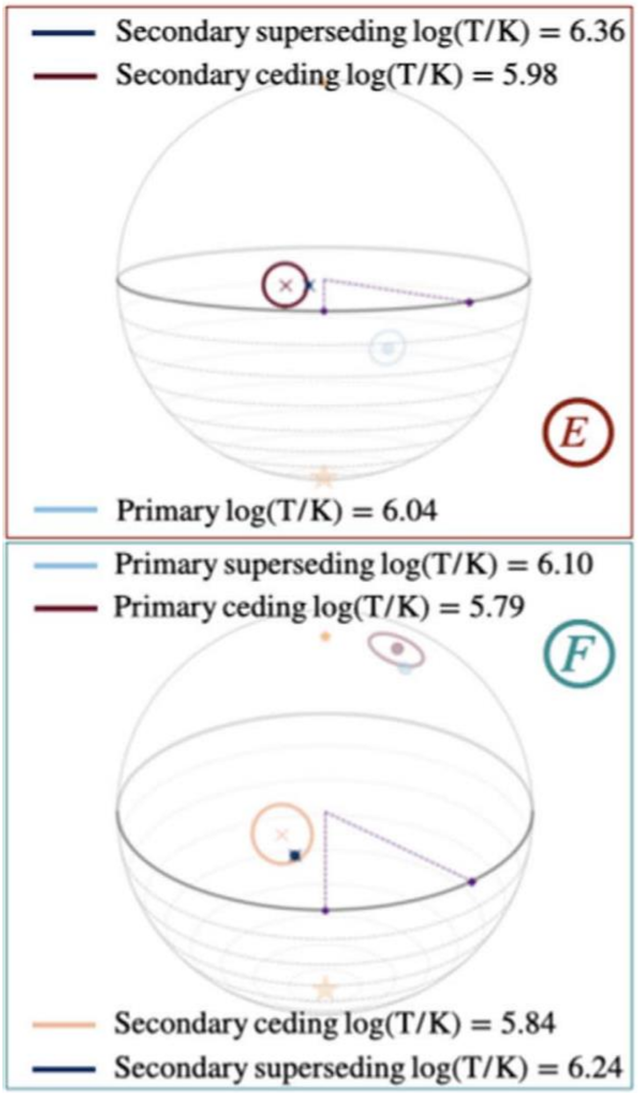
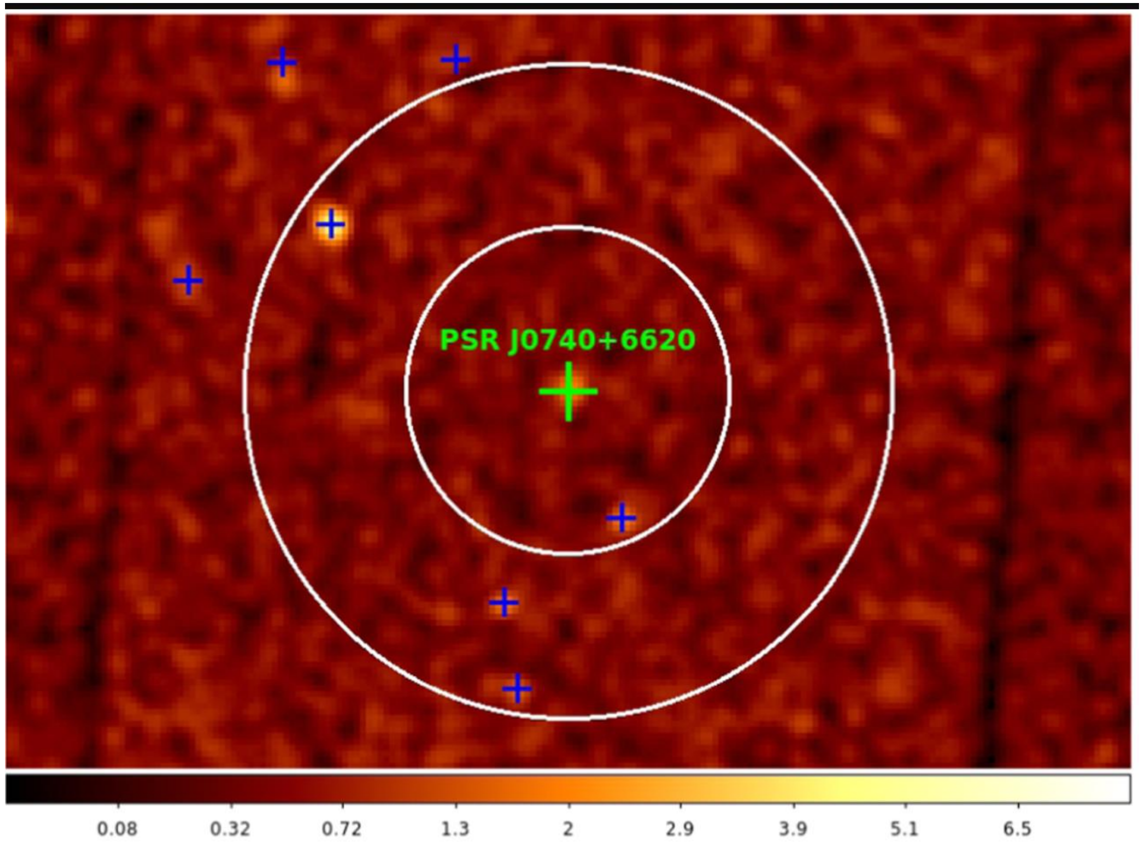
Different modes correspond to different masses
and radii (see later!)

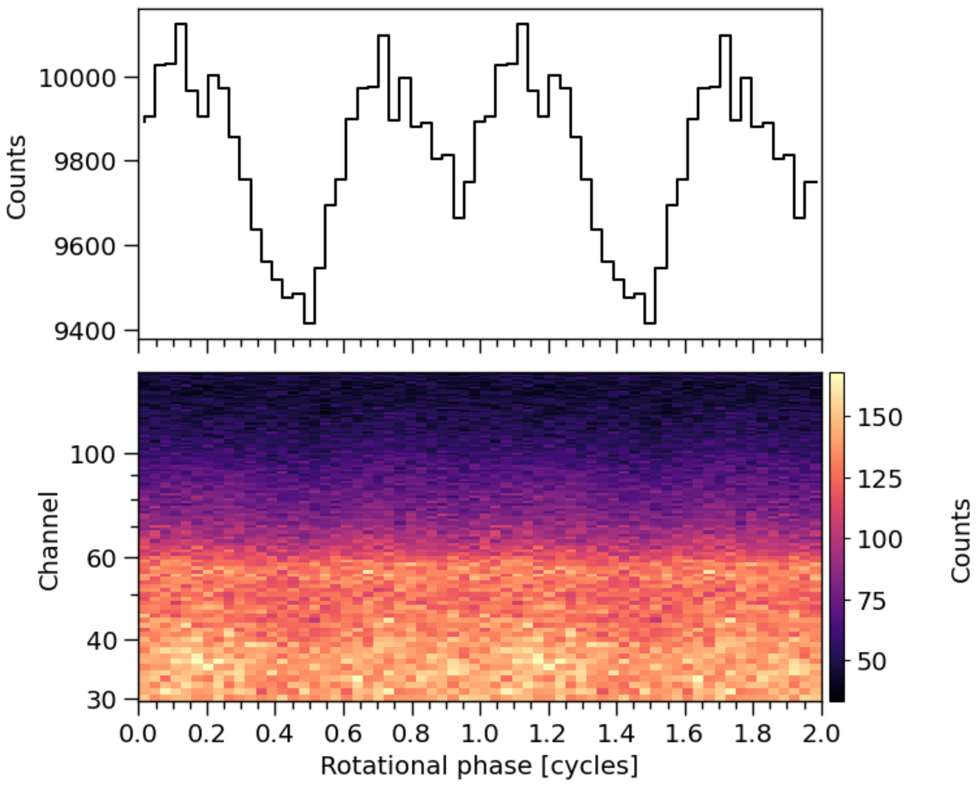


NICER results: J0740

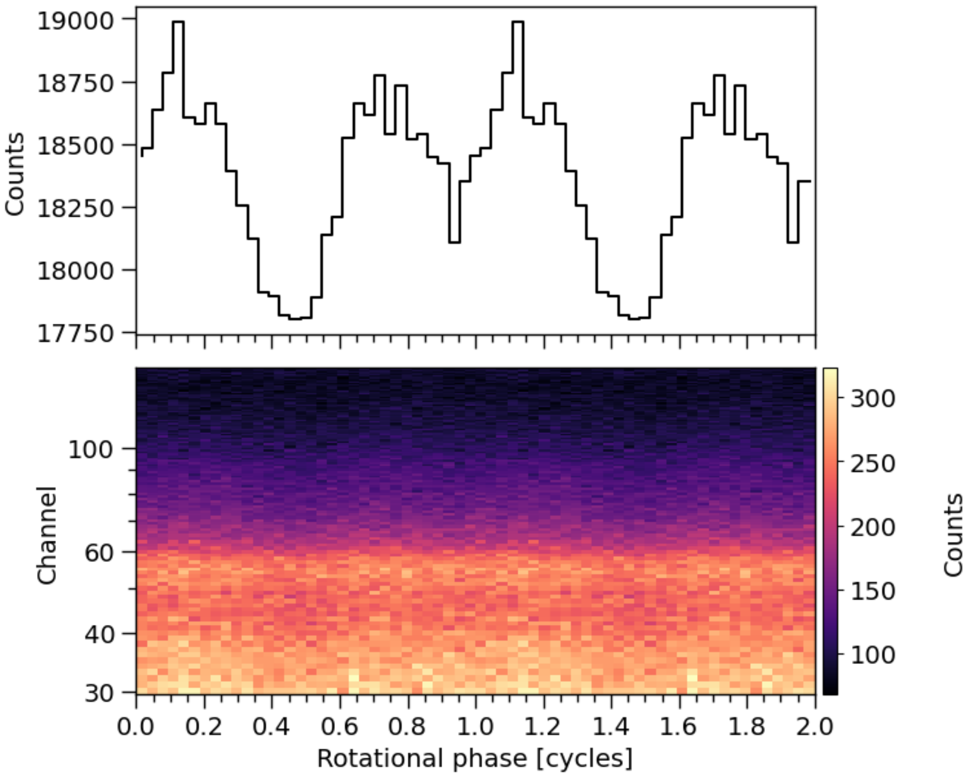
PSR J0740+6620: Faint but spinning at 346 Hz in a binary system with a known mass: $M = 2.1\ M_{\odot}$ (Cromartie et al. 2020, Fonseca et al. 2021, Wolff et al. 2021)



New J0740 NICER data with 90% more counts



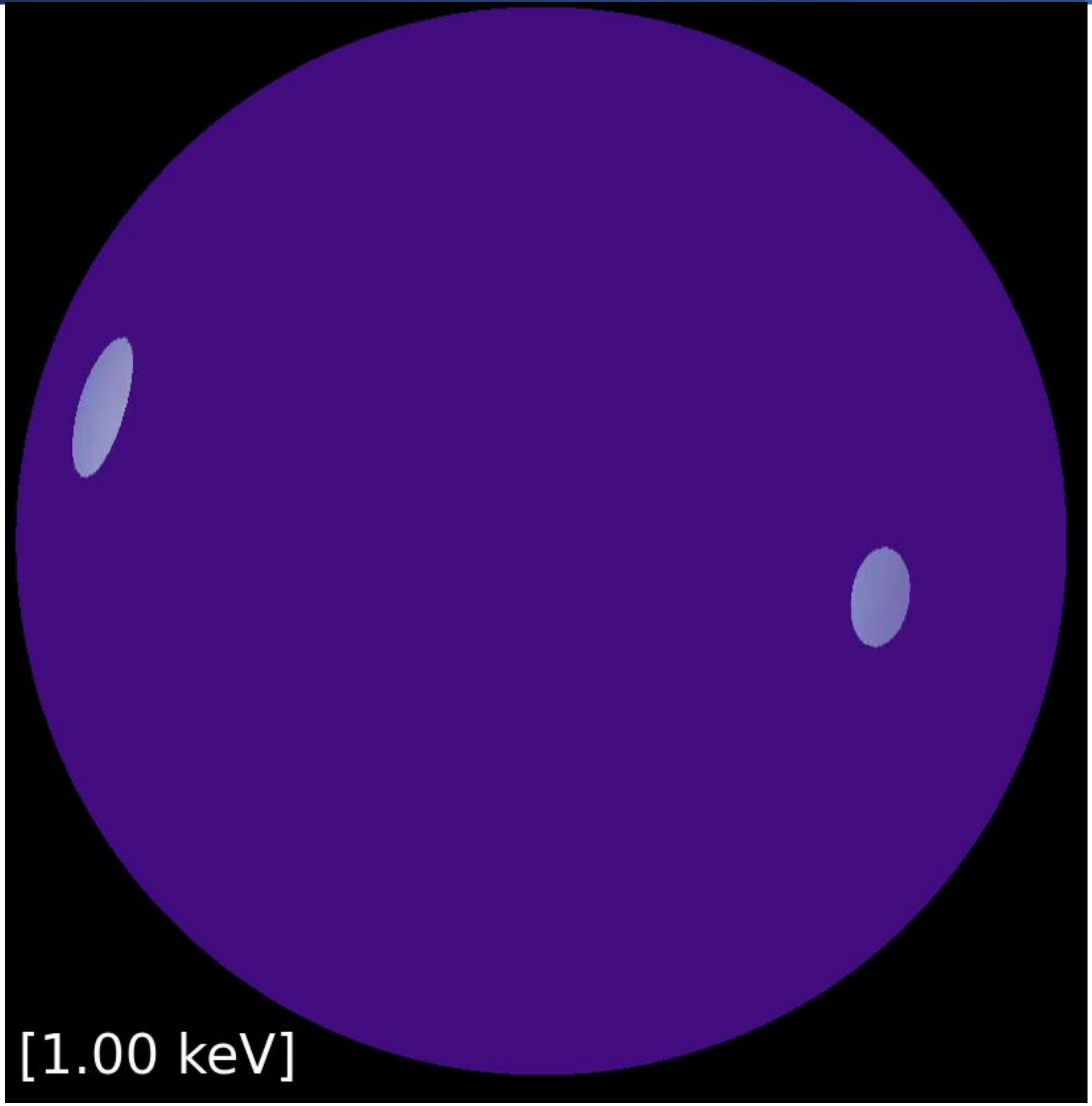
Miller et al. 2021, **Riley et al. 2021**, Wolff et al. 2021, Salmi et al. 2022



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

+ XMM Newton data

J0740 results: Hot Spot Properties



J0740 results: Radius

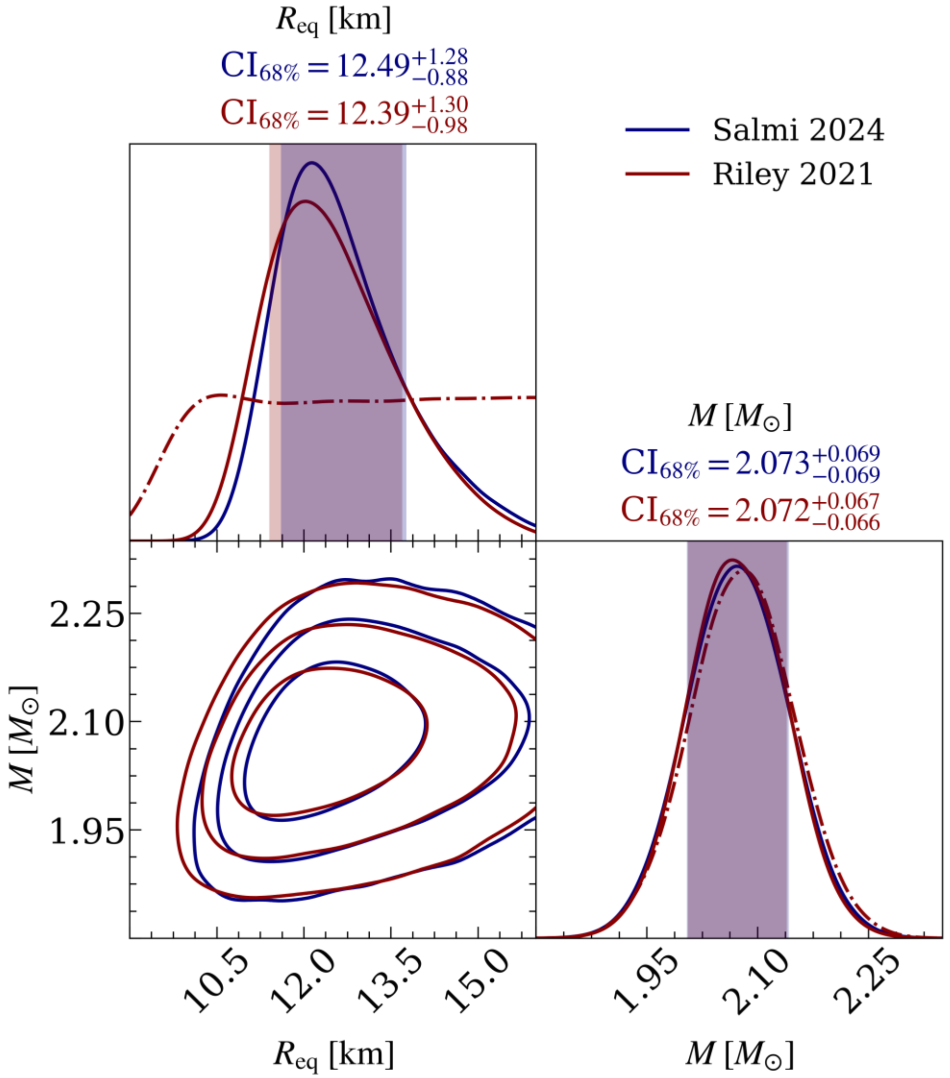
Riley et al. 2021 (1.6 yr data):

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

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

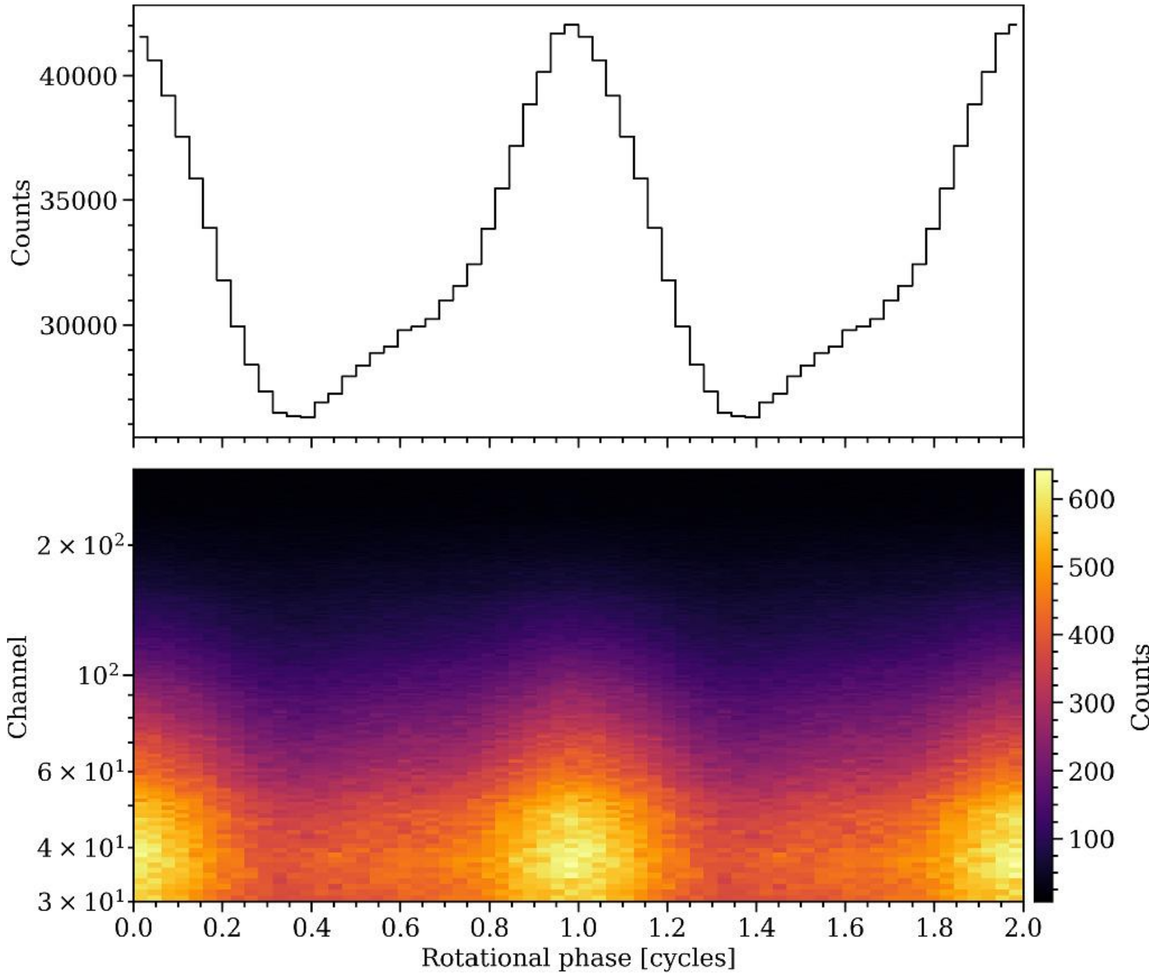
R = 12.5 + 1.3 - 0.9 km

- 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

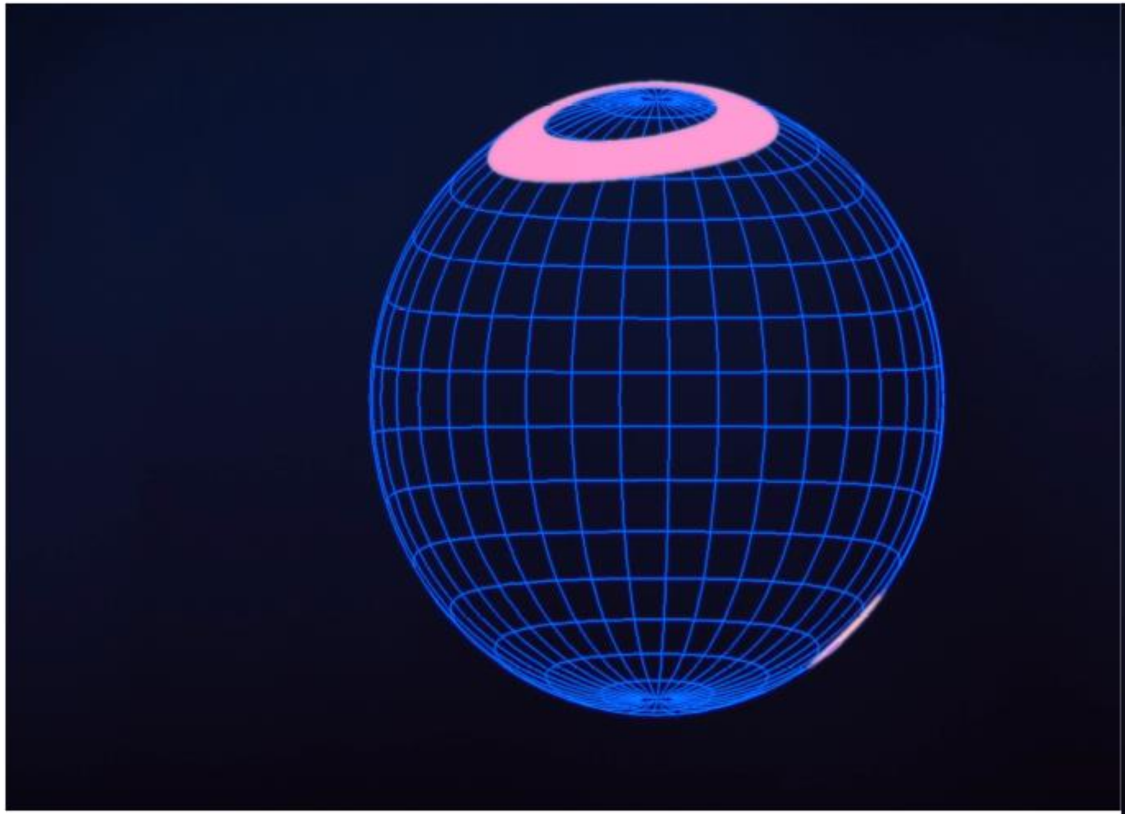
PSR J0437-4715: The nearest and brightest pulsar spinning at 174 Hz.
In a binary system with a known mass:
M = 1.4 $M_\odot$ (Reardon et al. 2024)

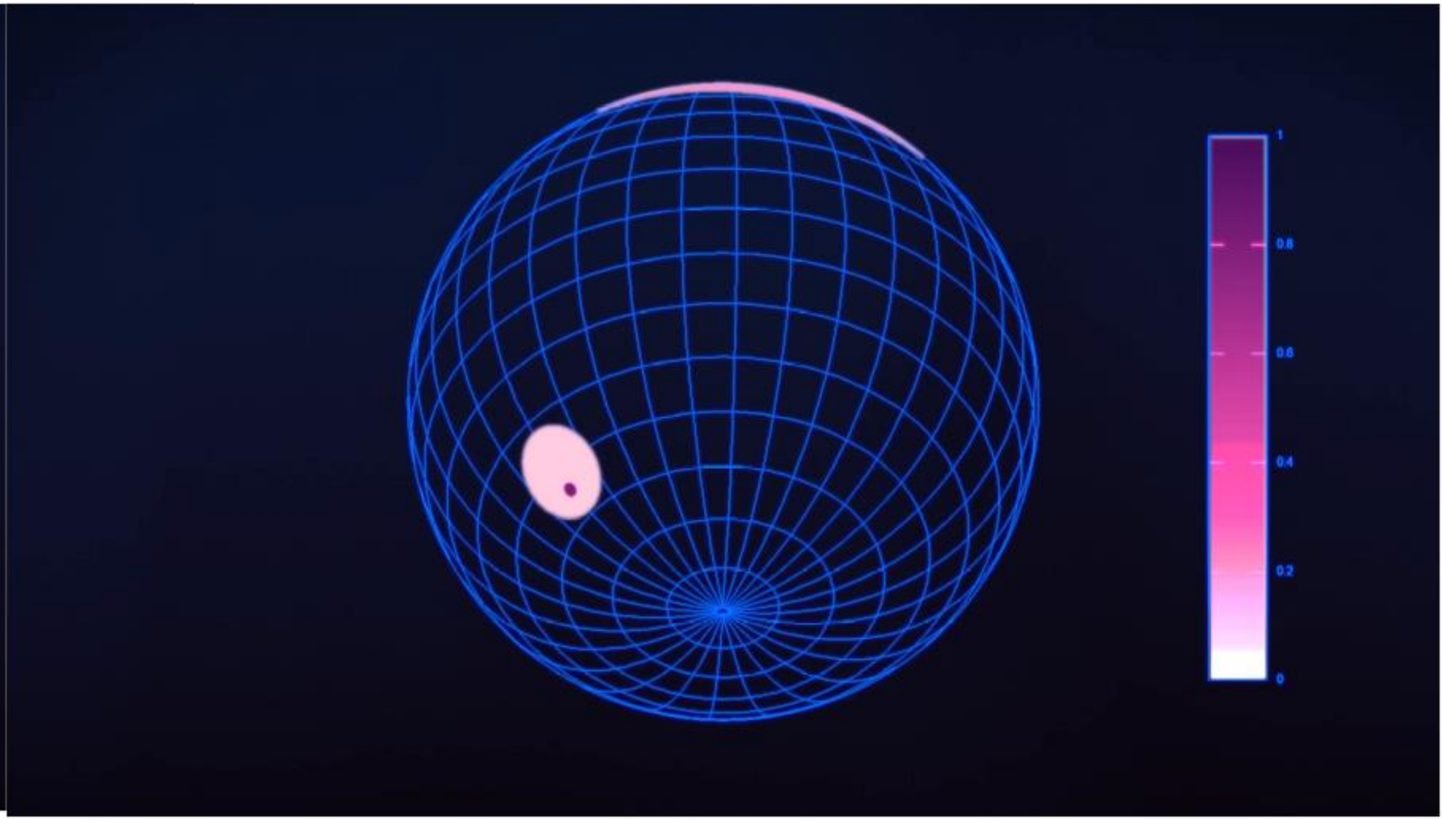


Choudhury et al. 2024

NICER results: J0437

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





NICER results: J0437

Choudhury et al. 2024a:

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:

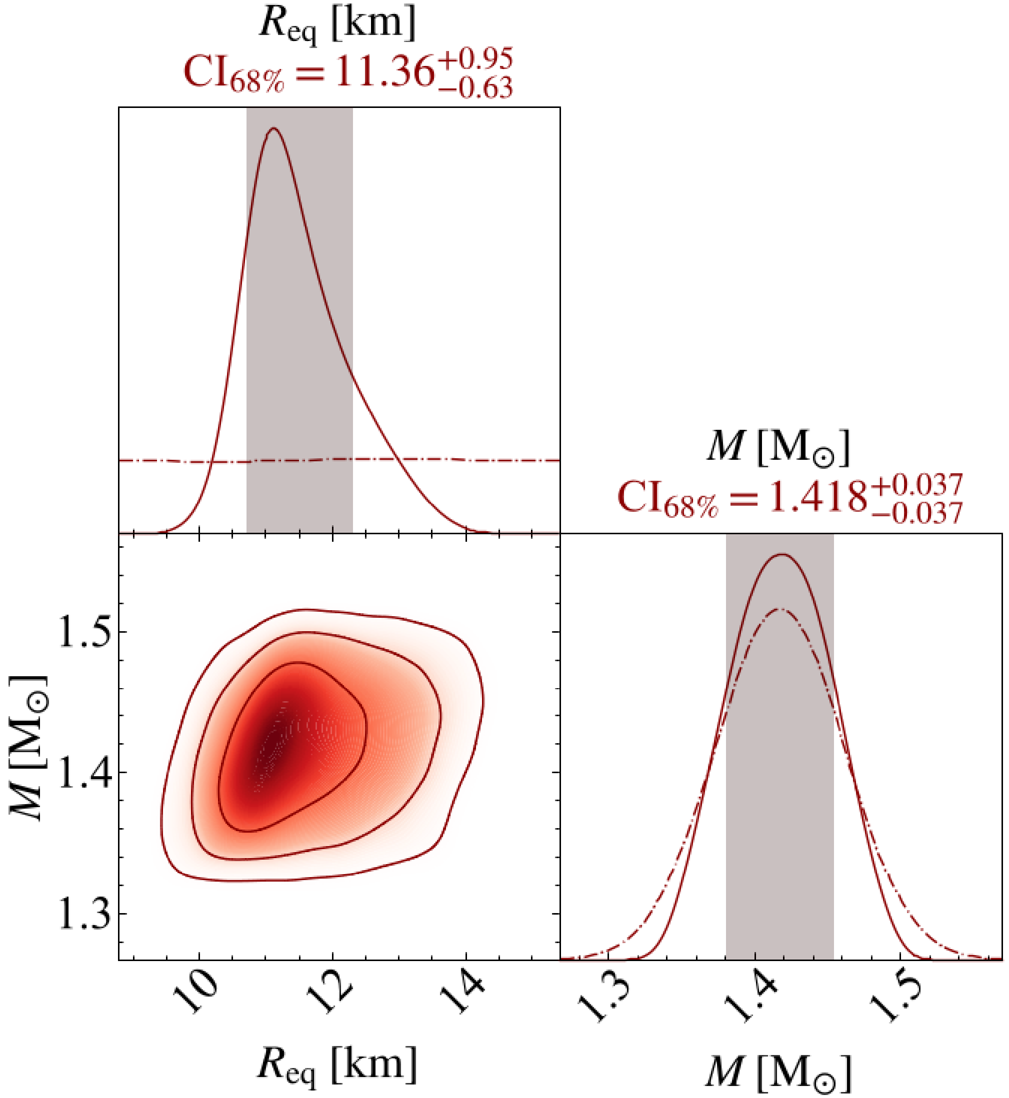
- $R_{1.4M_{\odot}} \geq 13.25$ km *(Reed et al. 2021, 1σ)*

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

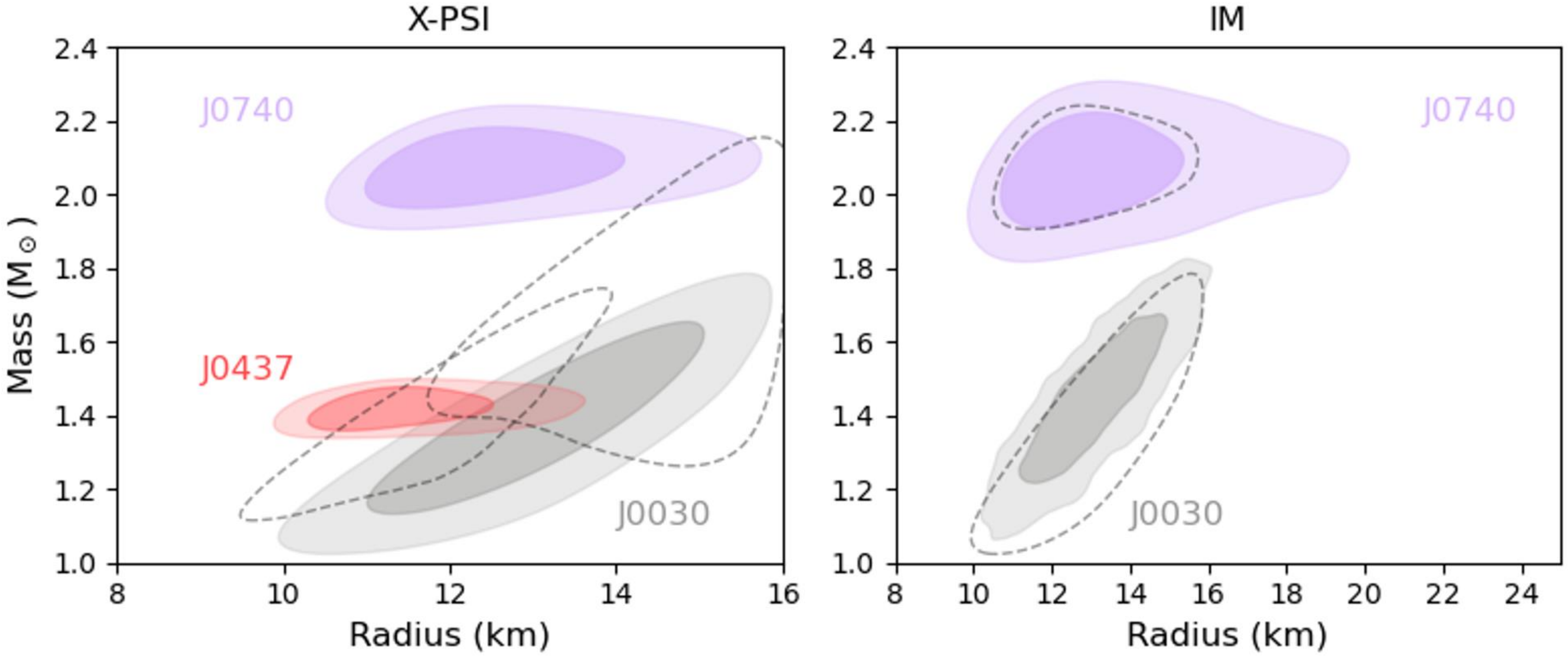
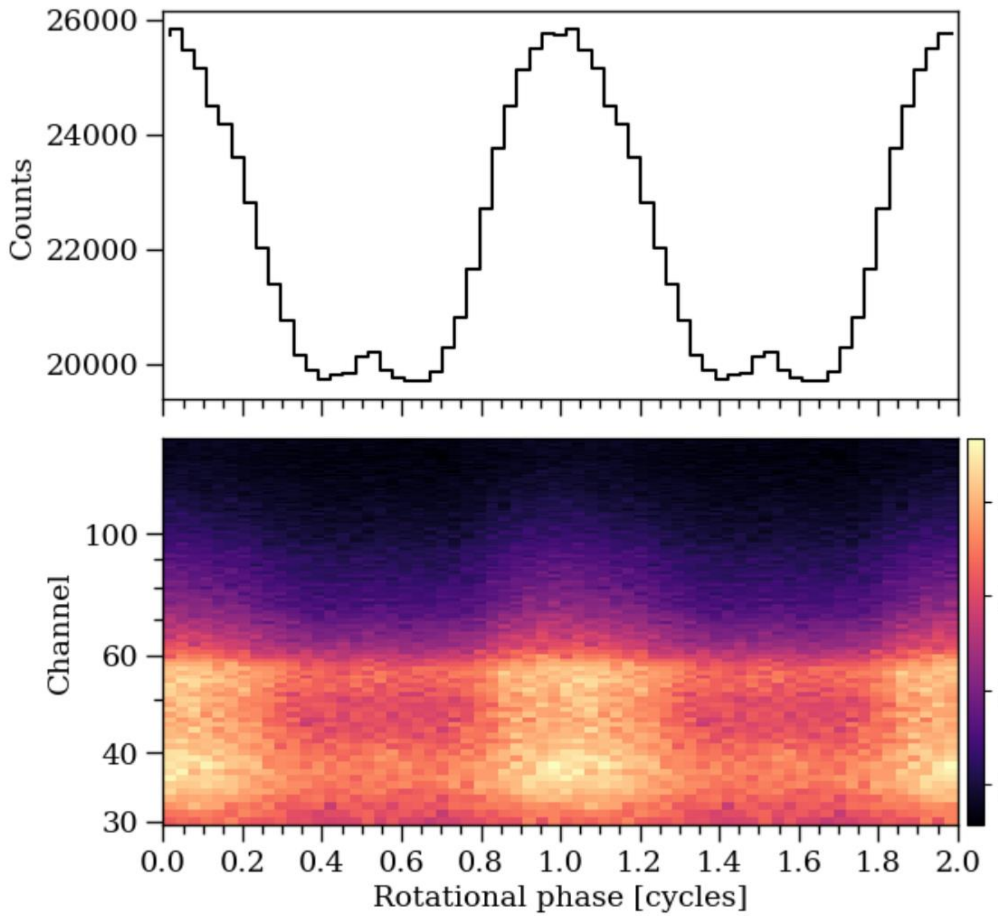


Image credit: A. Watts

NICER results: J1231

PSR J1231-1411:
A complex case with a weak interpulse
(Salmi et al. 2024b, in press)

In a binary, but only broad mass constraints from radio
(Cromartie et al. in prep.)



Salmi et al. 2024b (in press)

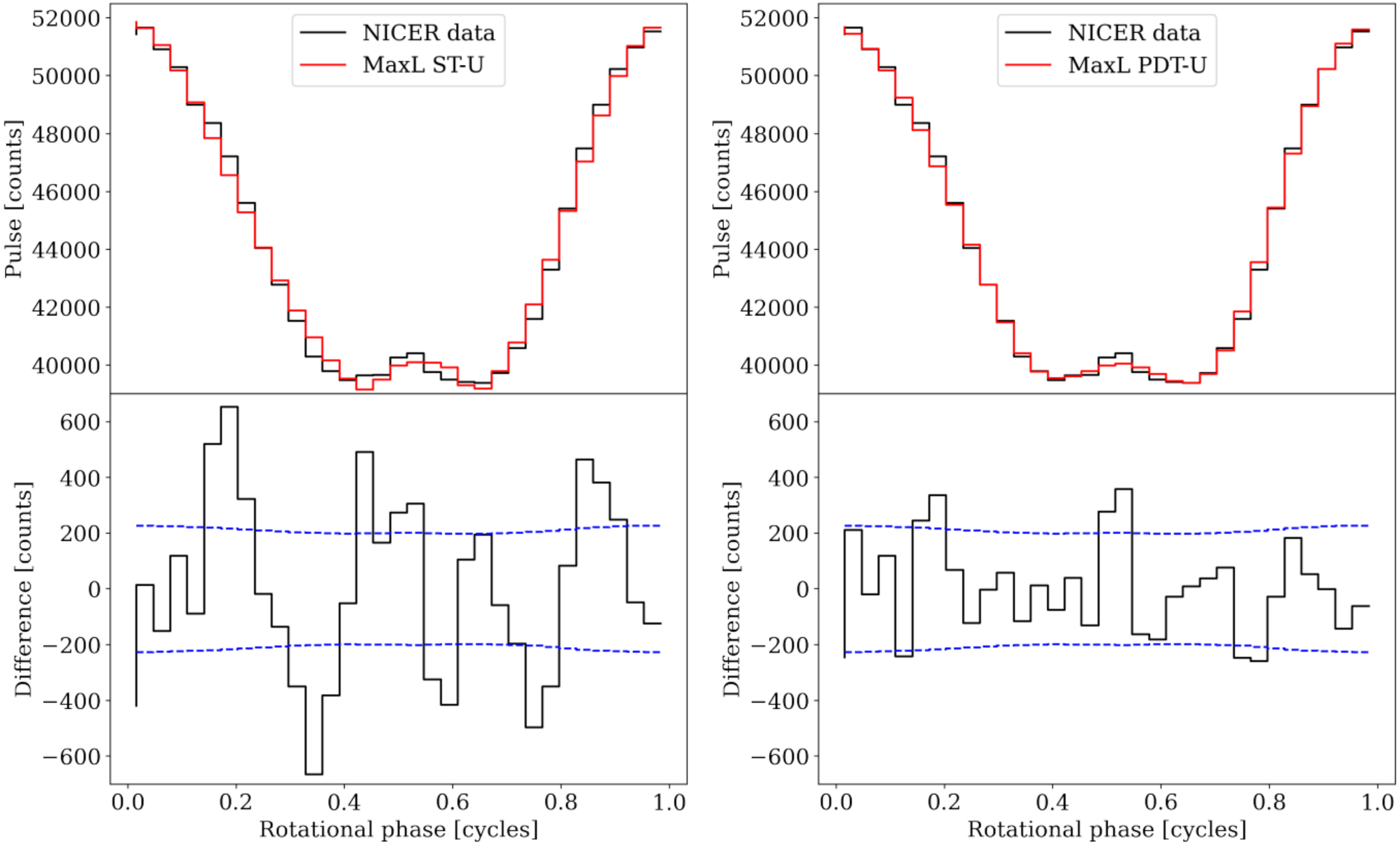
NICER results: J1231

Salmi et al. 2024b:

Simple 2-circle (ST-U) model not enough

2+2 circles (PDT-U) can explain the data, but very expensive:

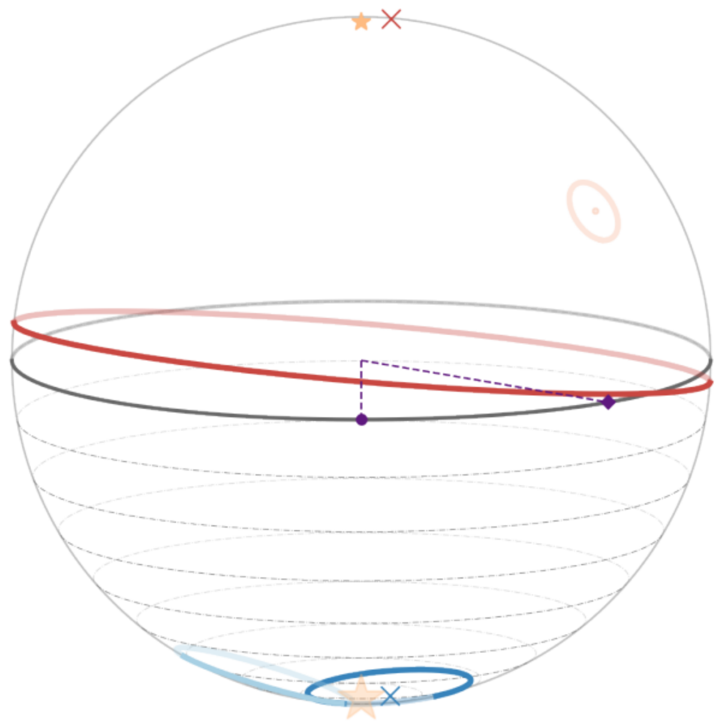
Results likely converged only if limiting the radius prior.

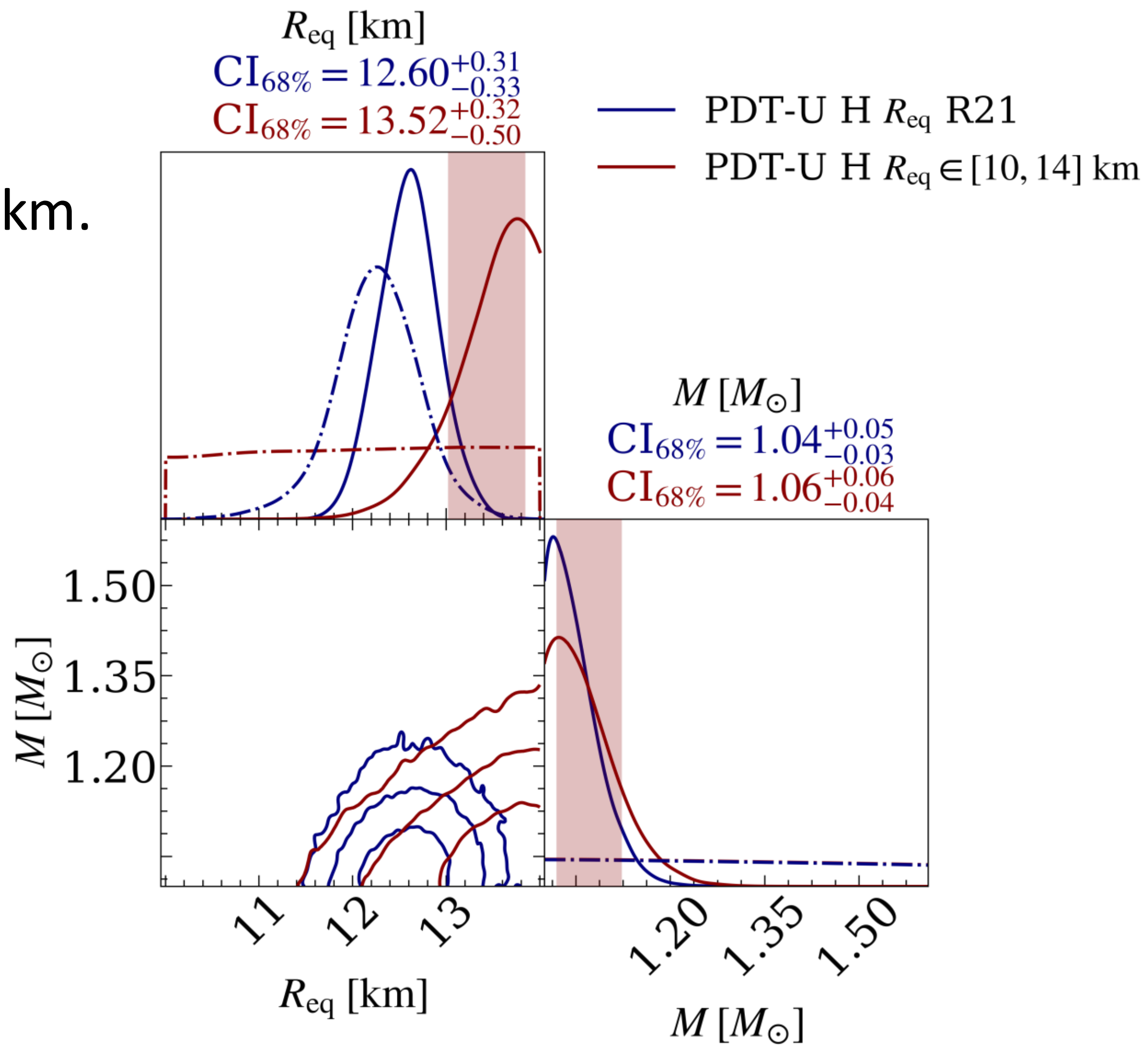


NICER results: J1231

Salmi et al. 2024b:

Best-fit obtained only if limiting radius to 10 – 14 km.
Small mass and non-antipodal geometry.



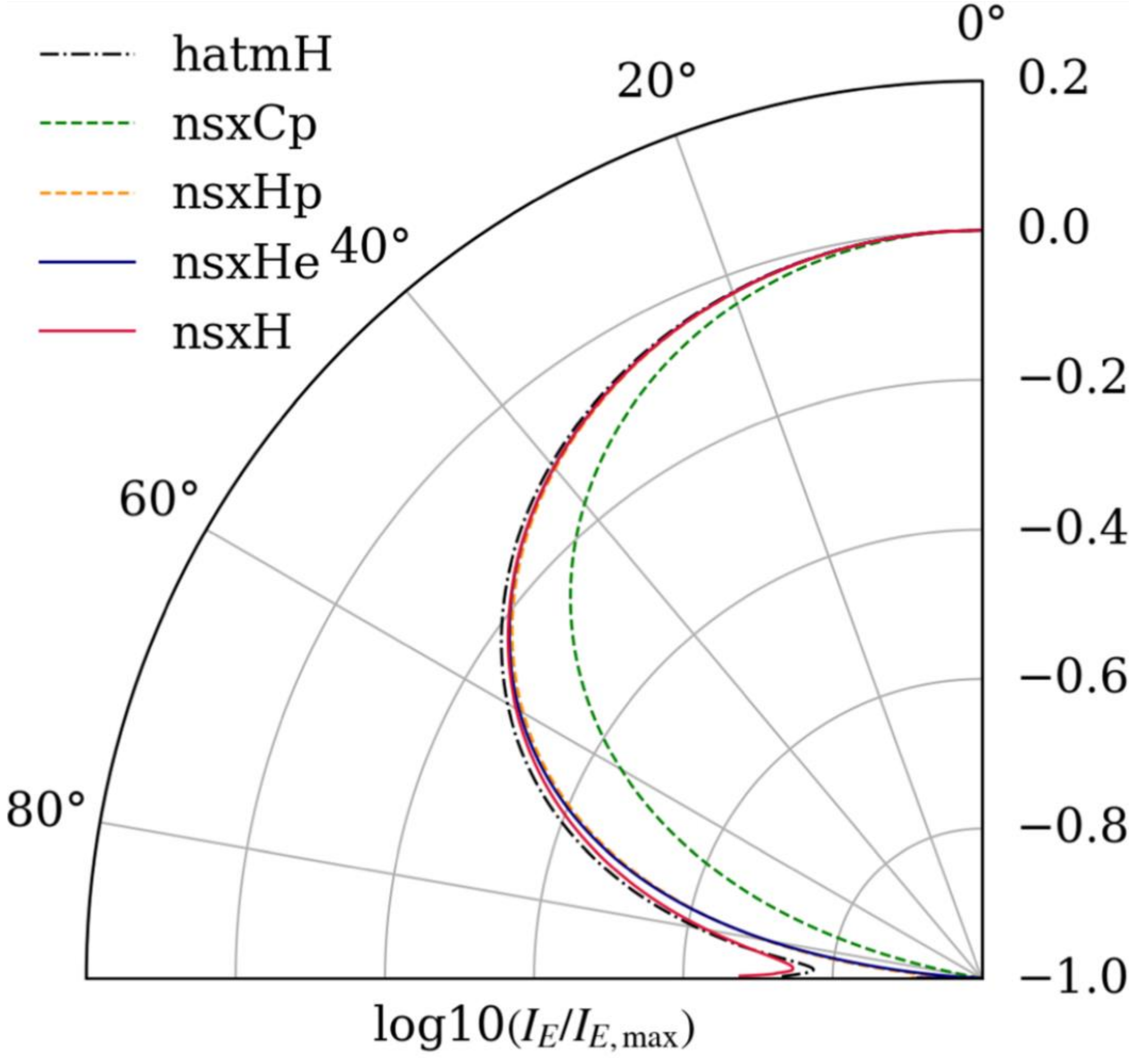


NICER: Studies of systematics

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

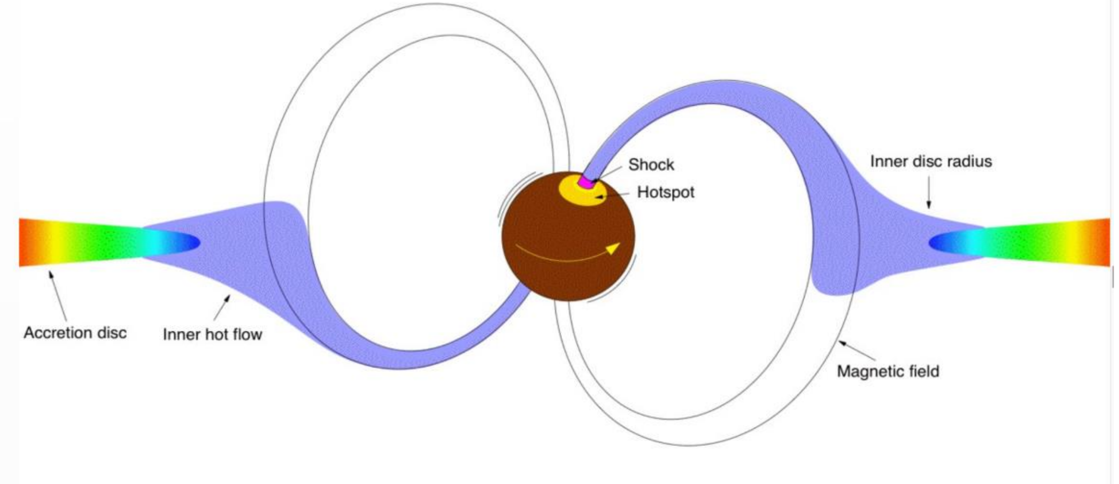
Comparison of waveforms between codes
(**Choudhury et al. 2024b, in press**)

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

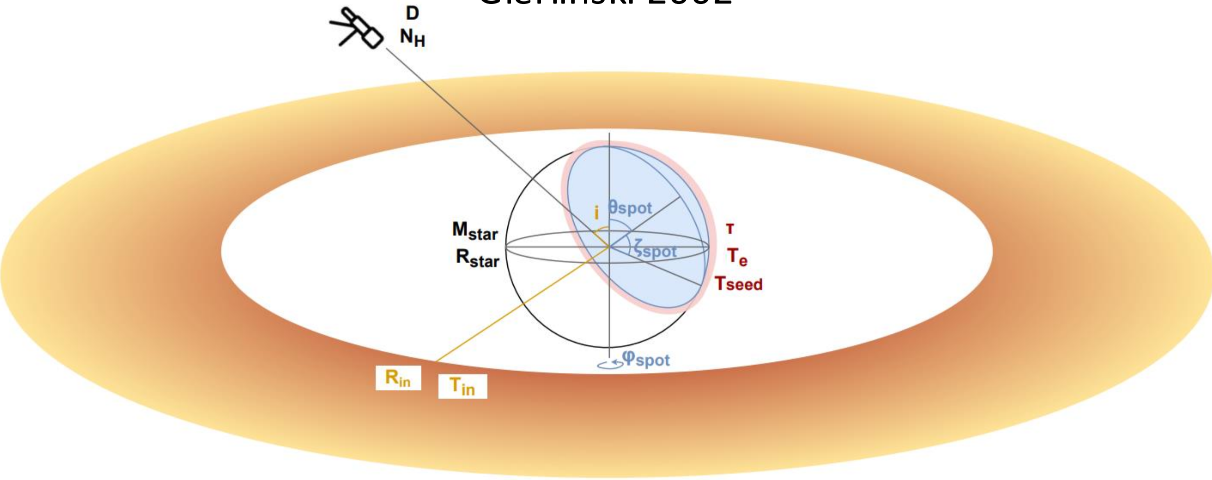


Accretion-powered millisecond pulsars (AMPs)

- 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**)



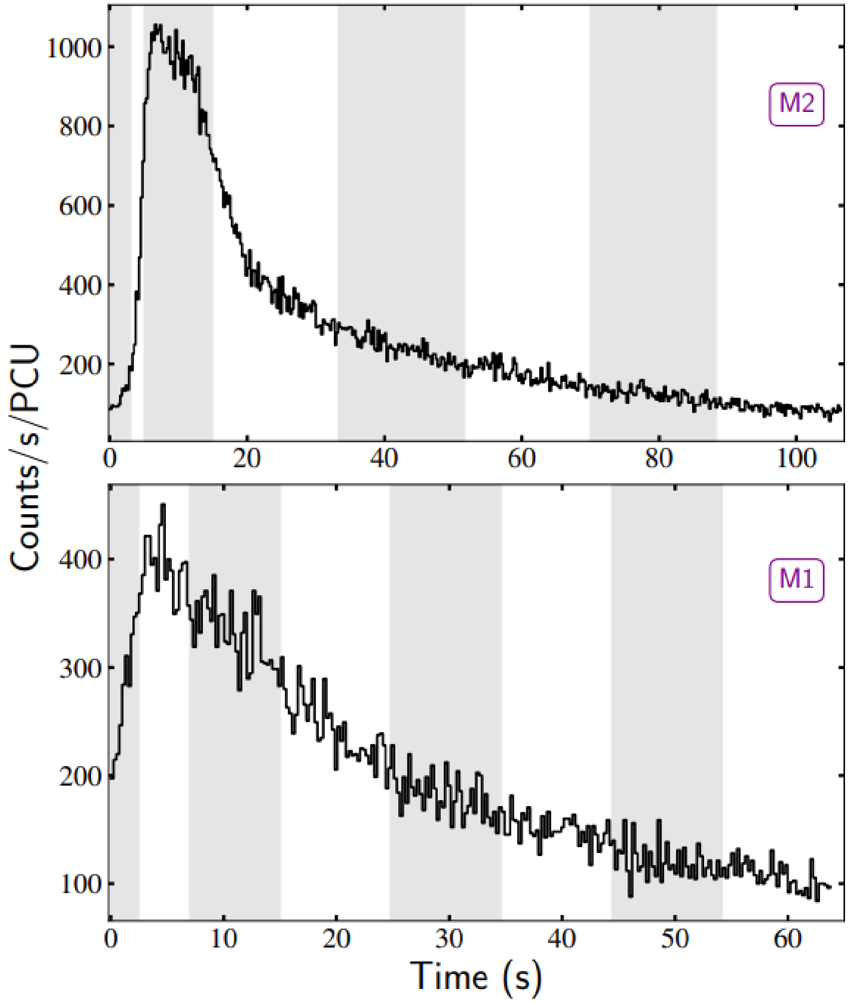
Gierlinski 2002



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. 2023a, 2023b, 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.
  - J1231: A complex case, but likely a small mass

- 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