NICER

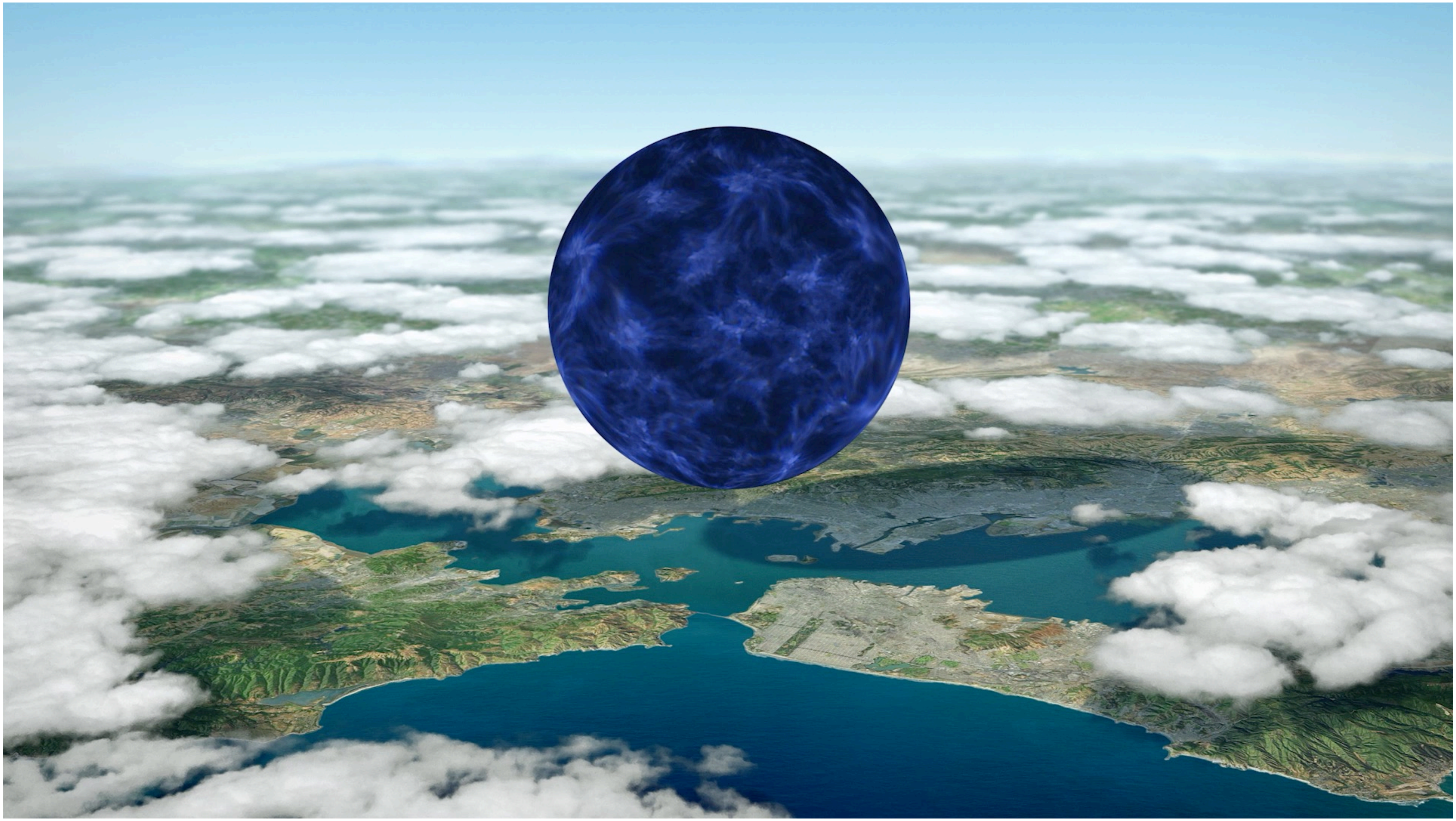
Neutron star Interior Composition ExploreR

Sizing up Neutron Stars with NICER

Z. Arzoumanian (for the NICER Lightcurve Modeling WG)

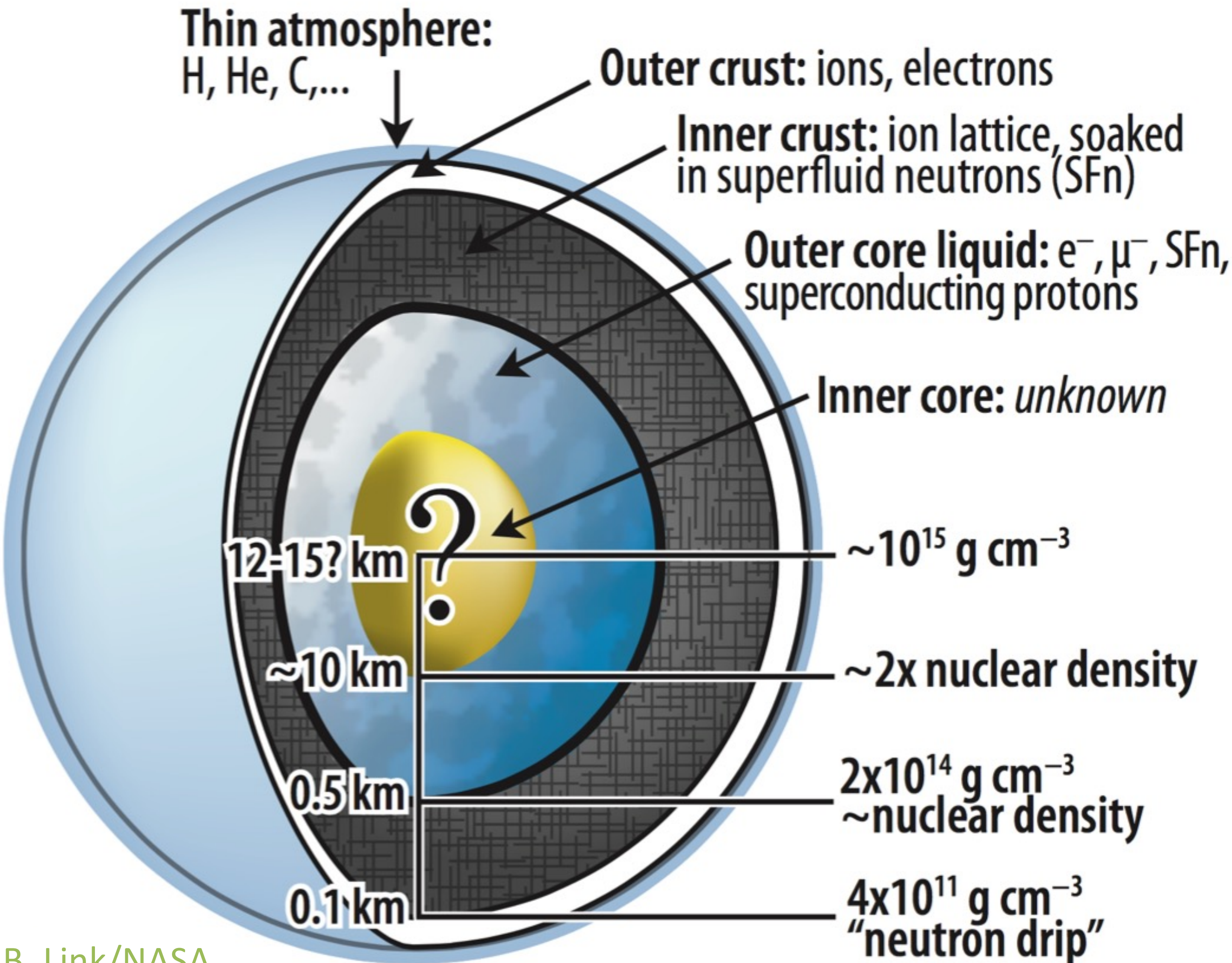
Why neutron stars?

Extreme properties and enduring mysteries…



NICER's key motivation

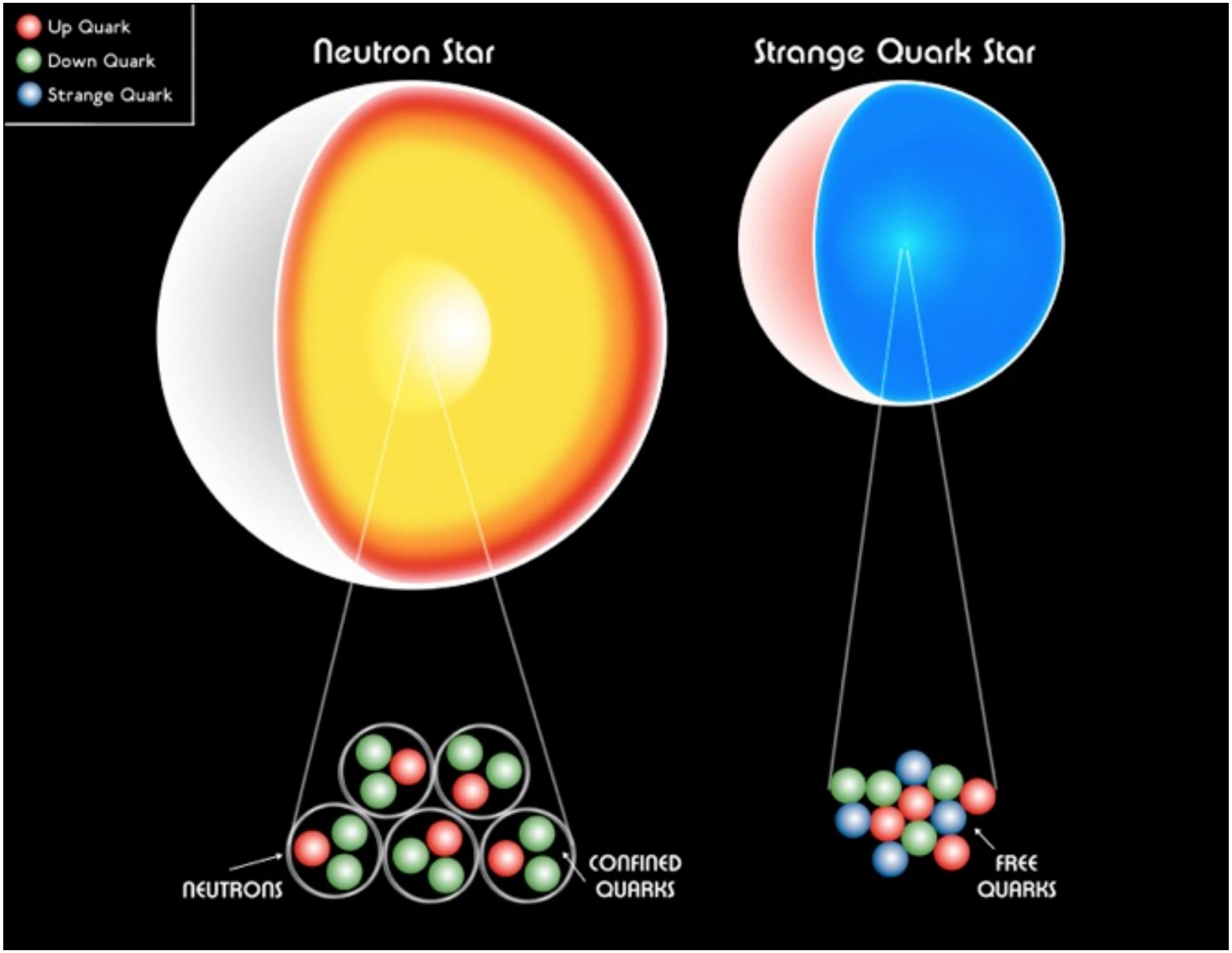
An 85-year-old question — the nature of ultra-dense matter



Credit: B. Link/NASA

NICER's key motivation — Neutron star structure (& dynamics, energetics)

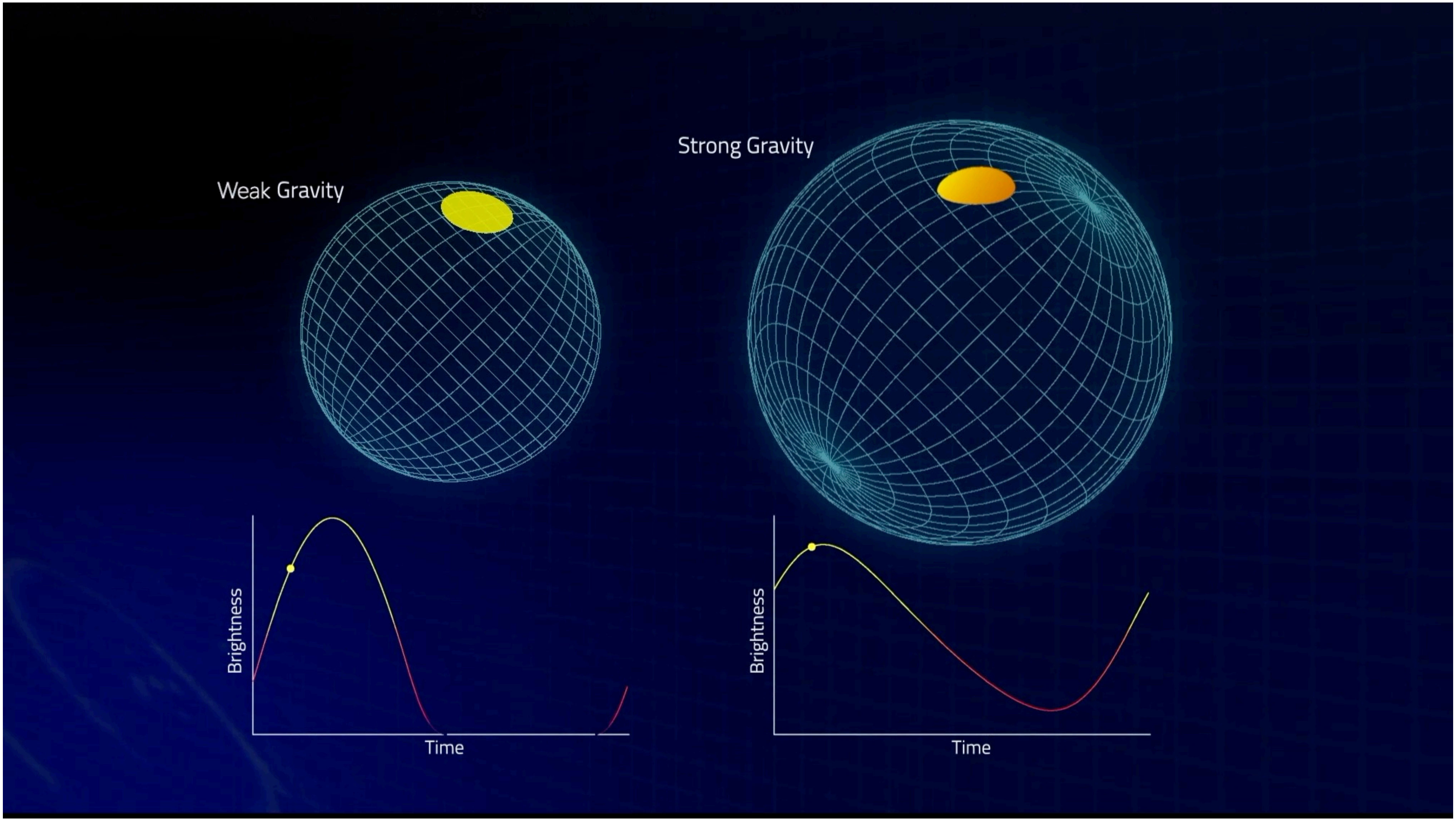
Radius and mass probe interior composition



Credit: CXC/ M. Weiss

How do you infer mass and radius?

Pulse shapes are altered by gravitational light-bending

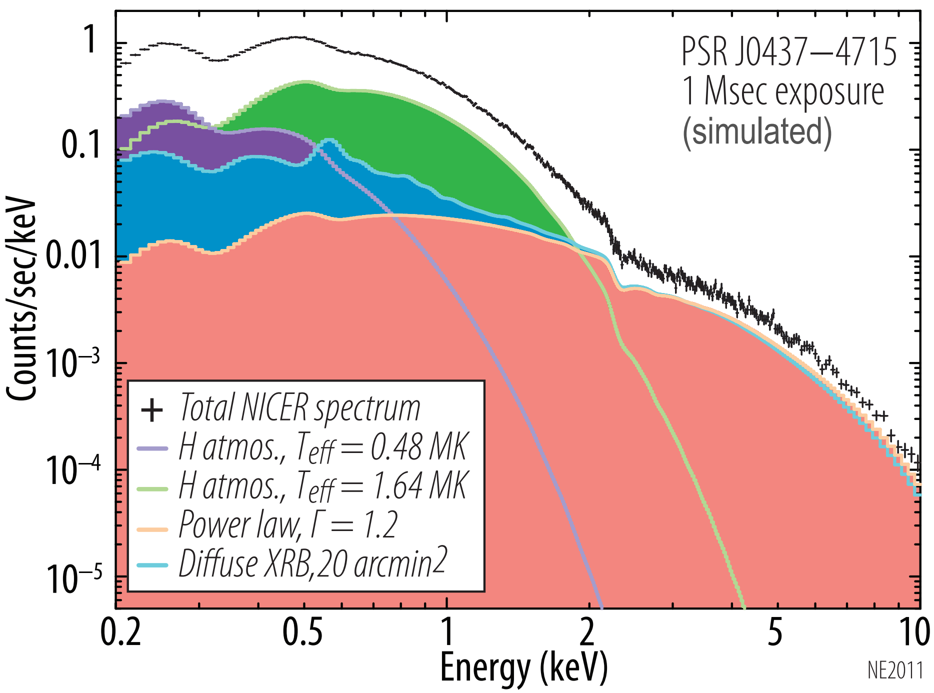


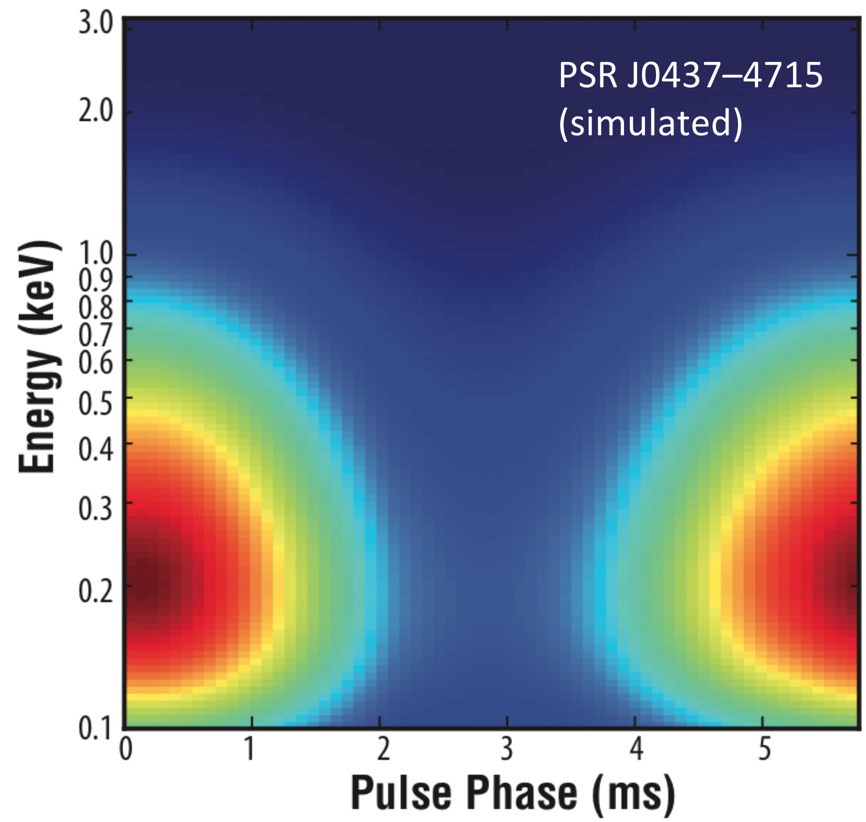
Credit: S. Morsink & NASA

Inferring M,R through lightcurve modeling in phase and energy

Targeting thermal emission from rotation-powered MSPs

- Broad pulses ⇒ surface emission, subject to GR effects
- Non-magnetic hydrogen atmosphere
  - ➢ harder than blackbody for same T_{eff}
  - ➢ anisotropic emission
  - ➢ expect fully ionized, may be partial or contain helium



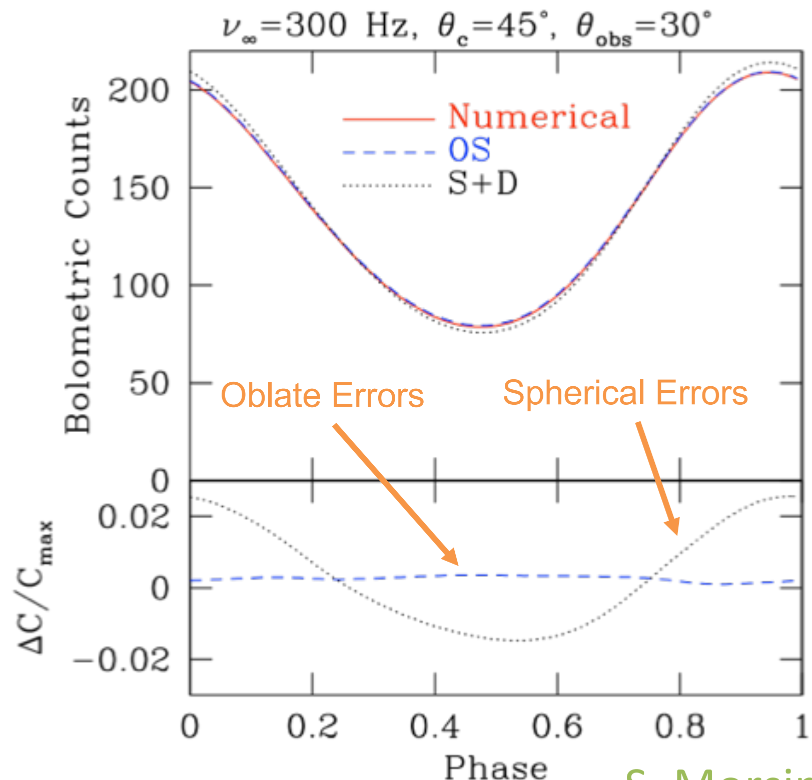


- Energy resolution enables phase-resolved spectroscopy
- Absolute time stamps enable coherent light curve integration over years

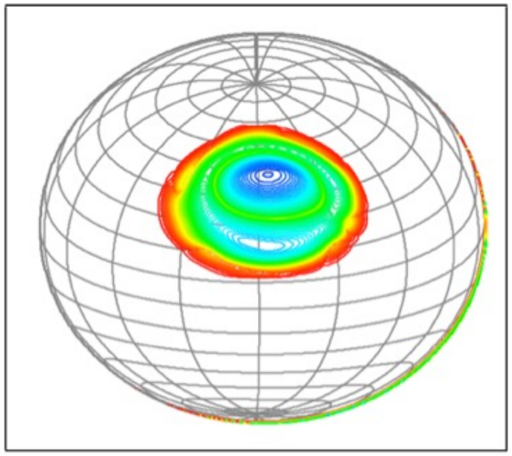
Inferring M,R through lightcurve modeling — systematics

Some known unknowns…

- Uncertainties in model
  - ✓ GR calculations (approximations & numerical accuracy)
  - ✓ Atmosphere model (depth of heating, hydrogen vs. helium, fully ionized?)
- Instrument calibration
  - o Energy-dependent effective area
- X-ray background
  - o Unpulsed hot-spot emission may be confused with instrument/sky background
- Unknown or weakly constrained properties of the neutron star
  - ✓ Non-thermal emission (pulsed or not?)
  - o Polar cap size/shape and temp. distribution
  - o Magnetic inclination and viewing angle
  - o Surface magnetic field strength (if non-dipolar)



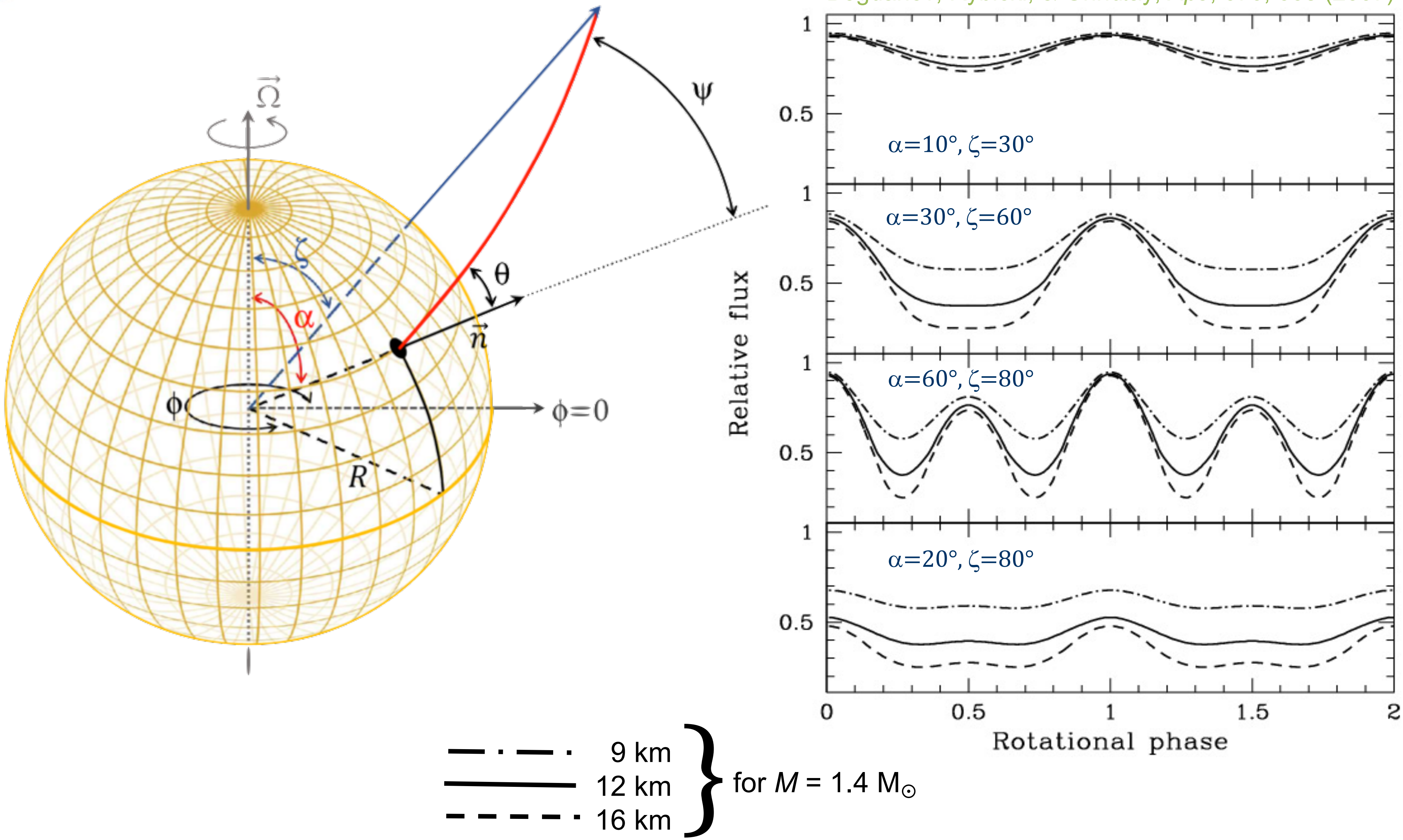
S. Morsink



D. Psaltis

Inferring M,R through lightcurve modeling — geometry

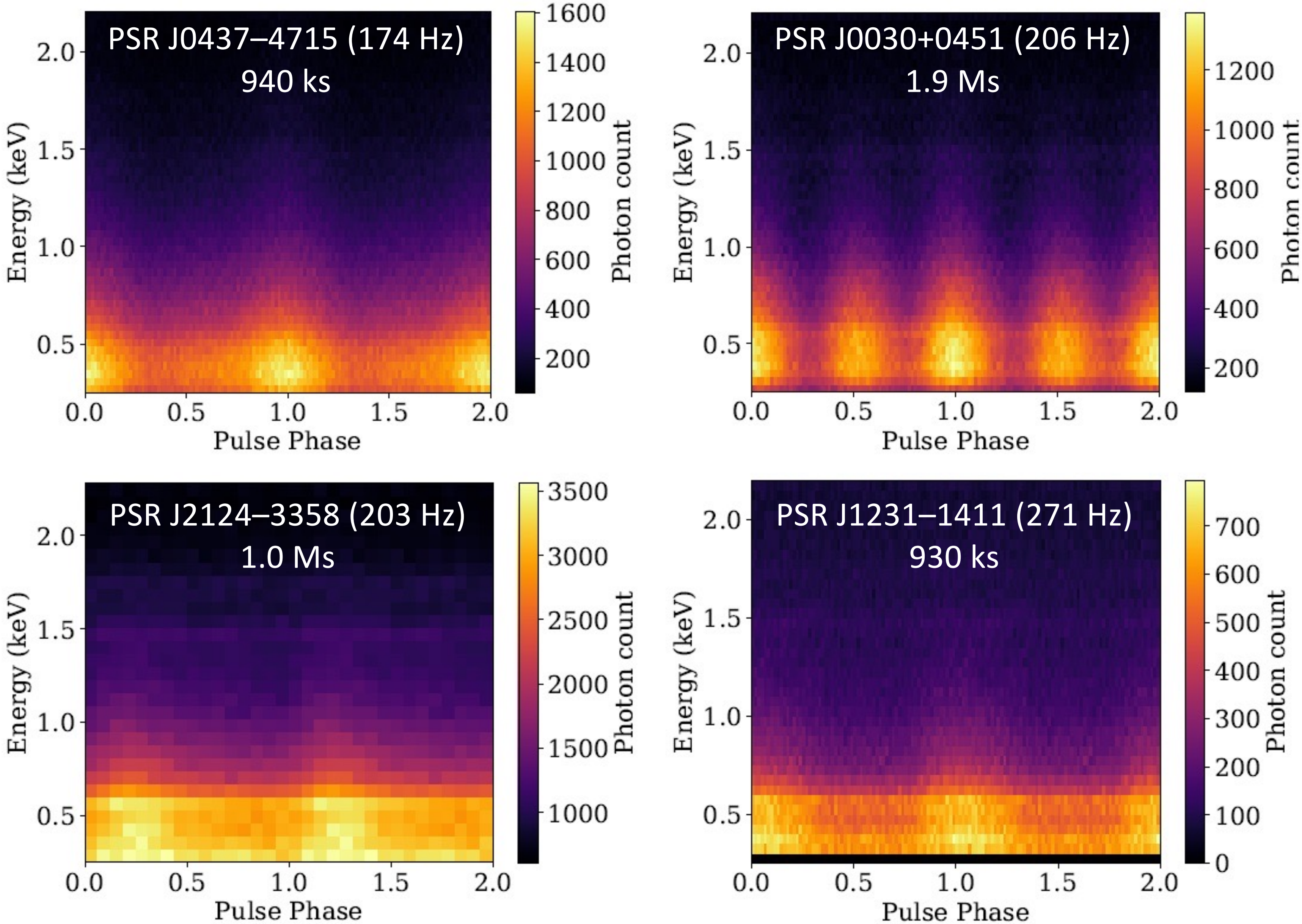
Bogdanov, Rybicki, & Grindlay, *ApJ*, 670, 668 (2007)



Deep NICER pulse profiles

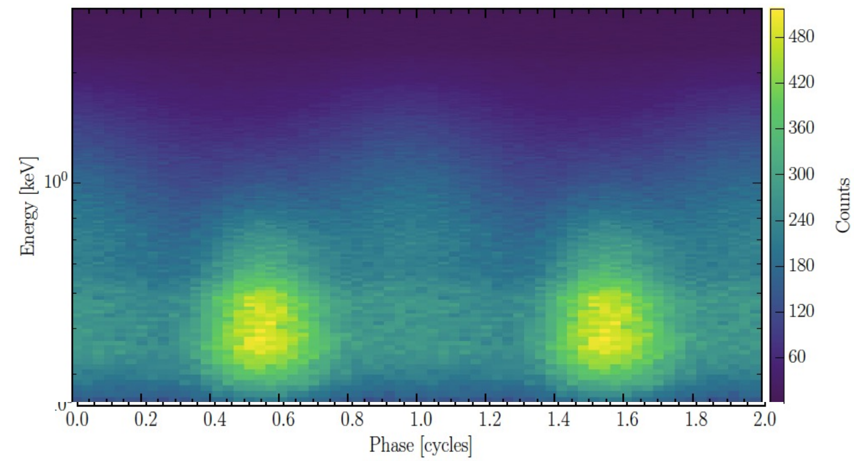
With more to come...

Bogdanov et al. 2019

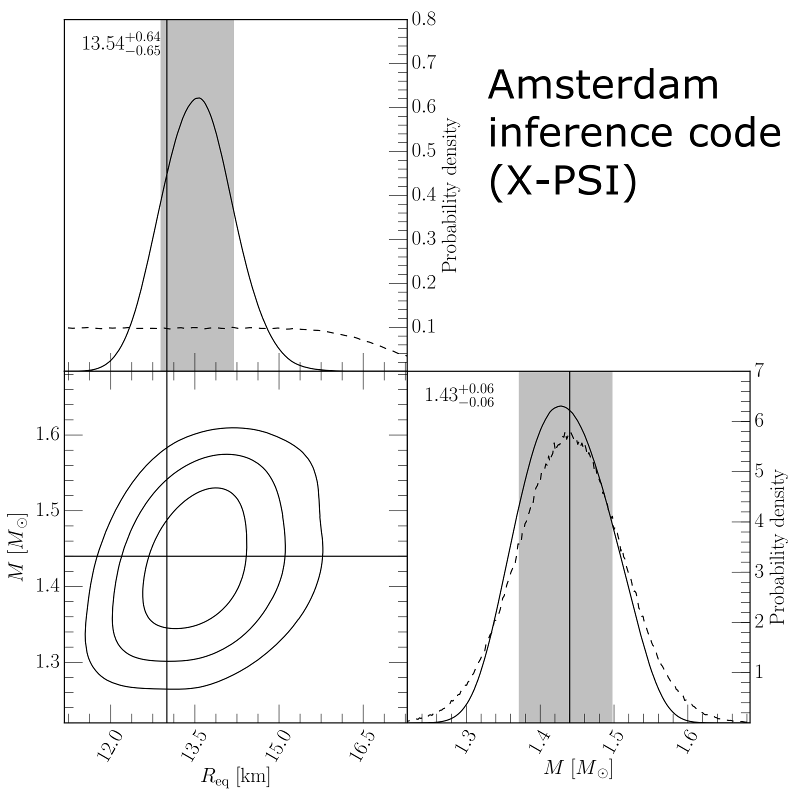


M-R inference code tests

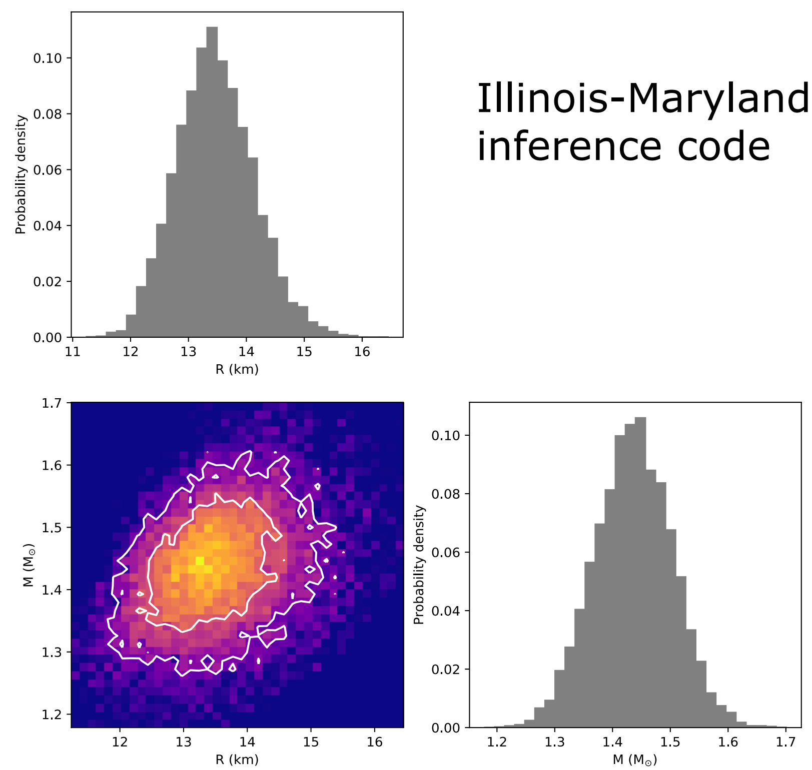
Synthetic data: 2-spot, single-temperature NSX hydrogen atmosphere (Ho & Heinke 2009)



Amsterdam inference code (X-PSI)

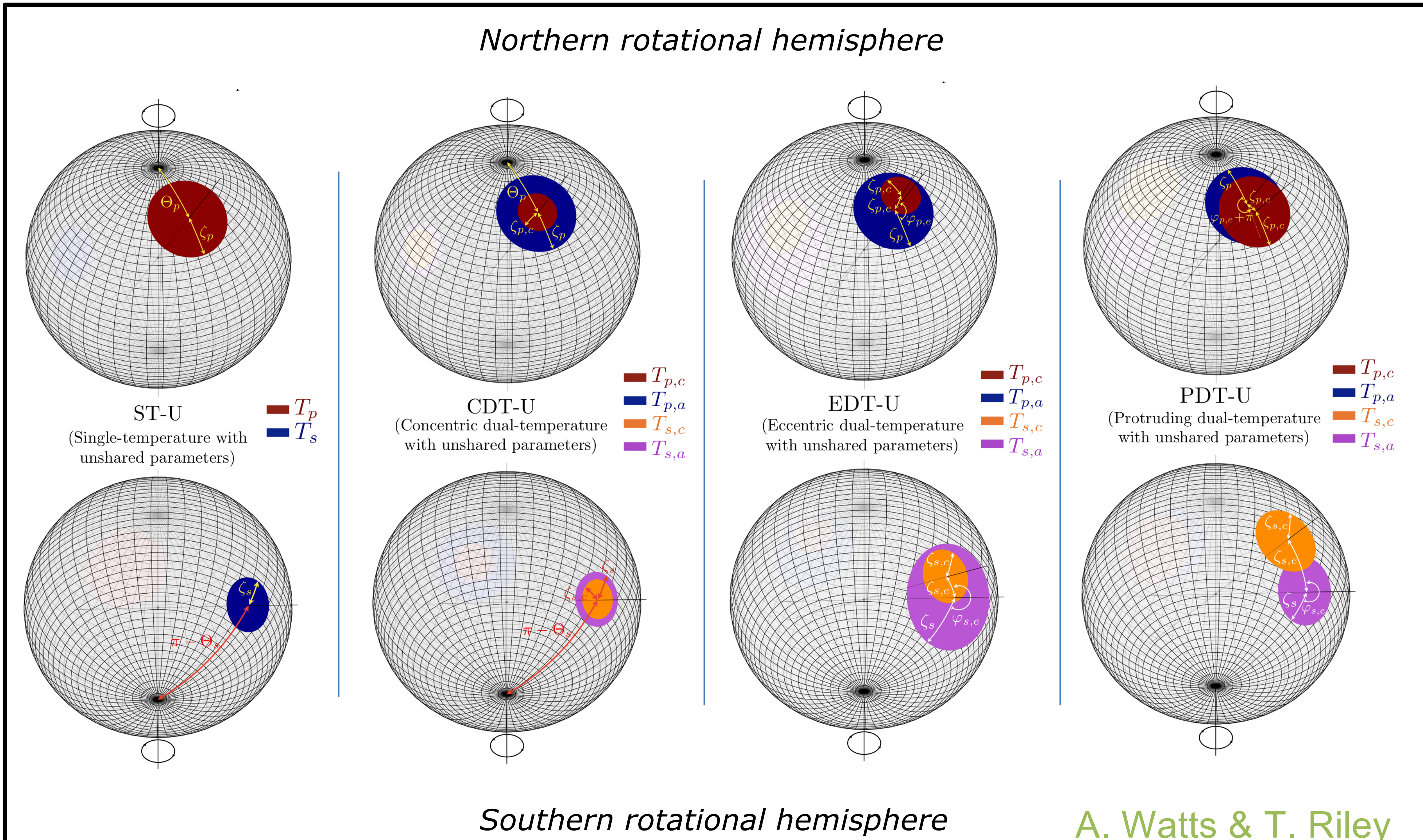


Illinois-Maryland inference code



"Spot" configurations (X-PSI)

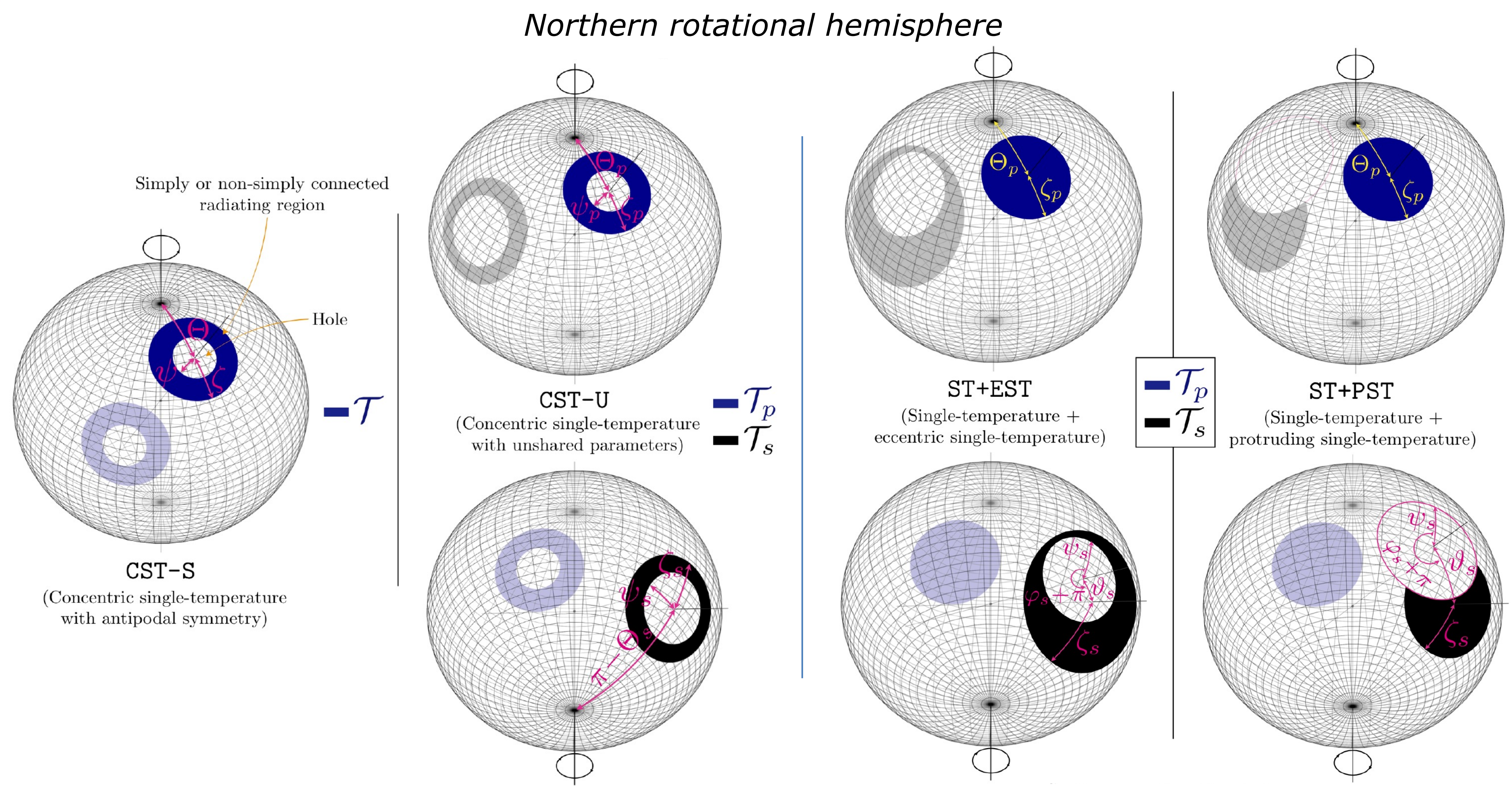
Two-cap models of increasing surface pattern complexity...



A. Watts & T. Riley

"Spot" configurations (X-PSI), cont.

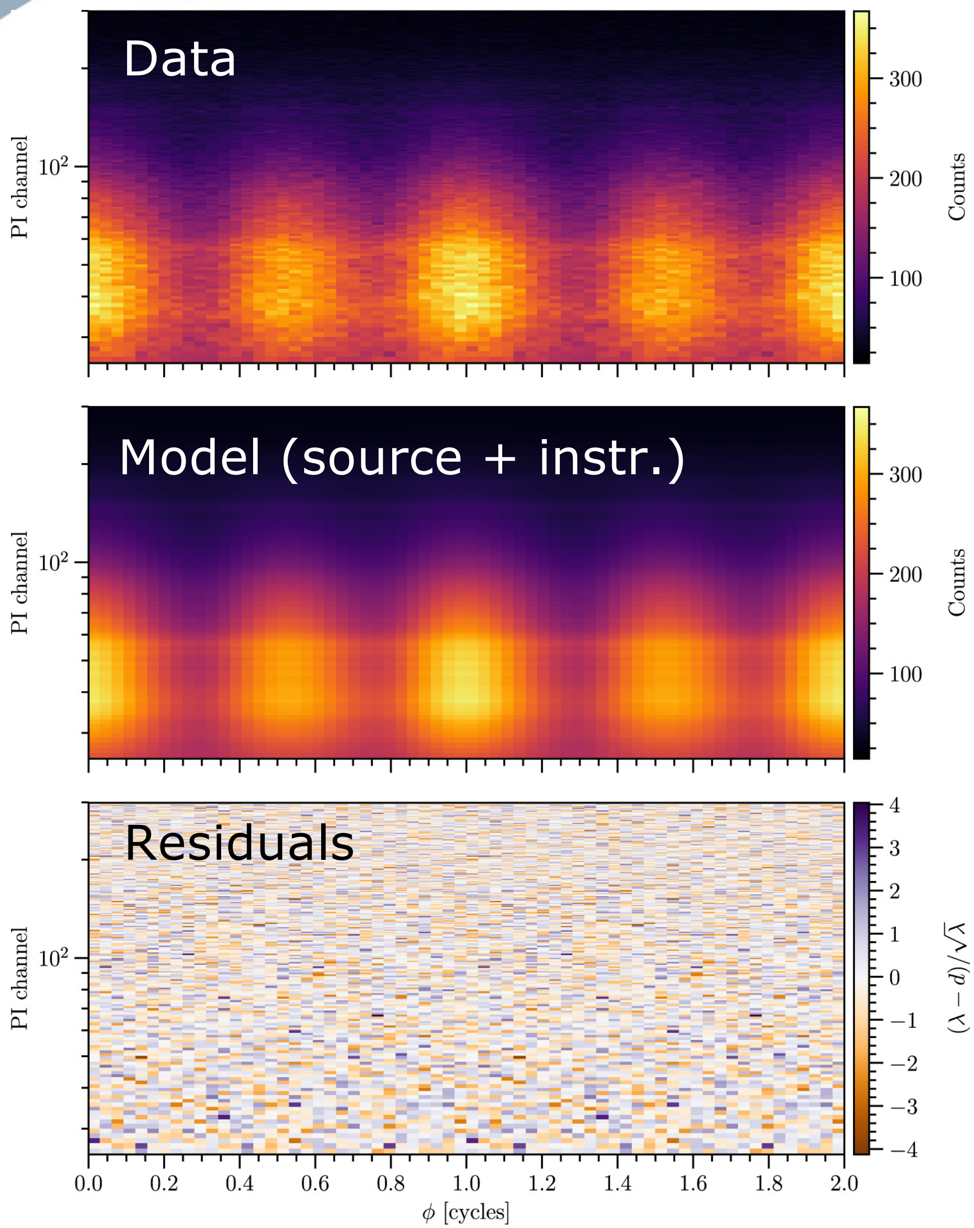
... not all are required by the data but must be tested!



A. Watts & T. Riley

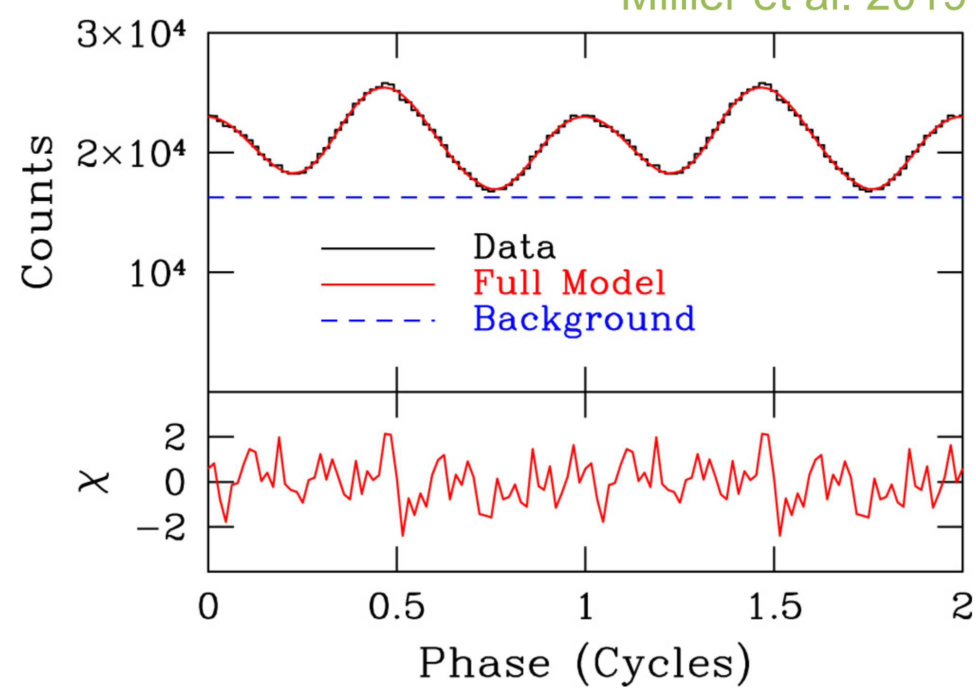
J0030+0451 profile fitting

Riley et al. 2019

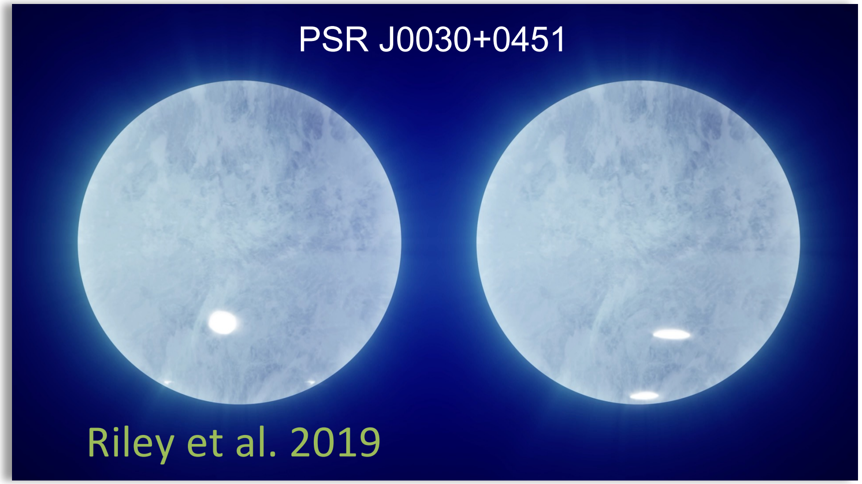


Spin frequency: 206 Hz
Distance: 325 pc
NICER Exposure: 1.94 Ms

Miiller et al. 2019



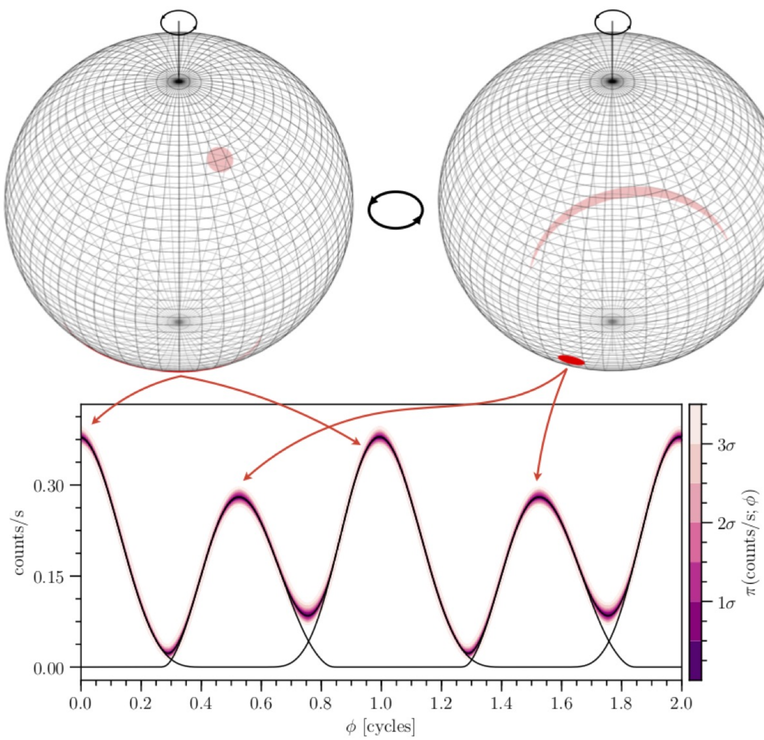
NICER Measures and Maps J0030

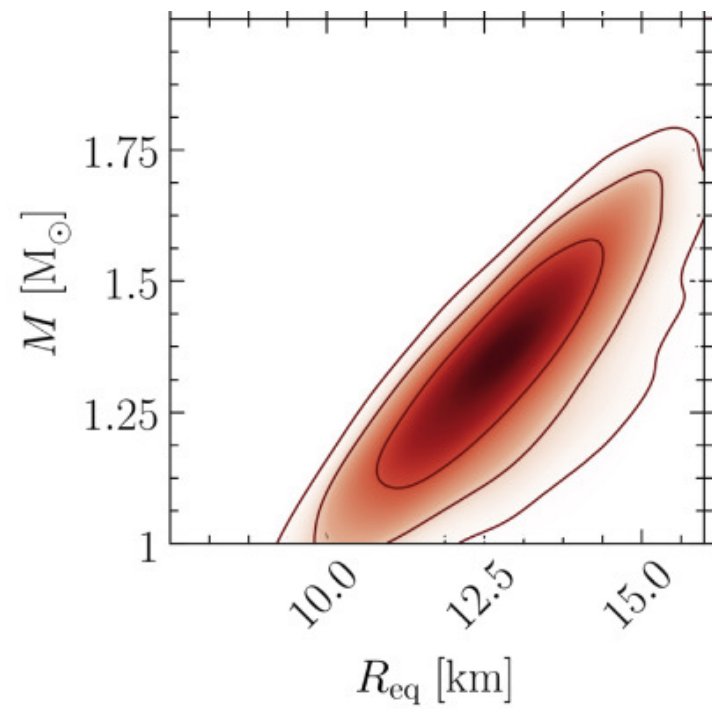


- First precise (±10%) mass *and* radius measurements for the same star
  - First mass of an isolated (i.e., non-binary) pulsar
- First map of surface “hot spot” locations, shapes, sizes, and temperatures
  - Robust demonstration of non-dipolar magnetic field
- New constraint on the equation of state of ultra-dense matter
  - Tightened uncertain pressure-density range by 30%

$M = 1.34 \pm 0.15\ M_{\odot}$

$R = 12.71 \pm 1.17$ km





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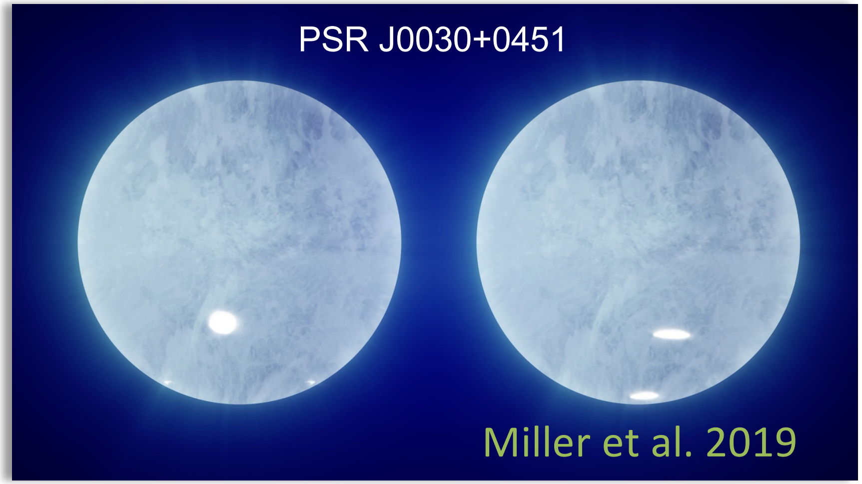

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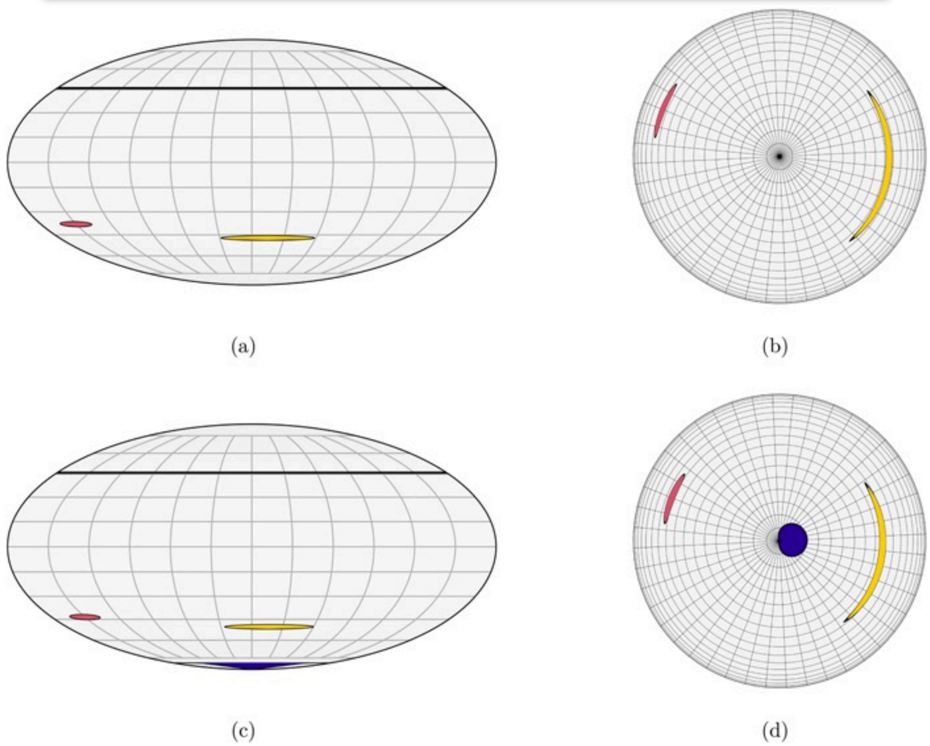
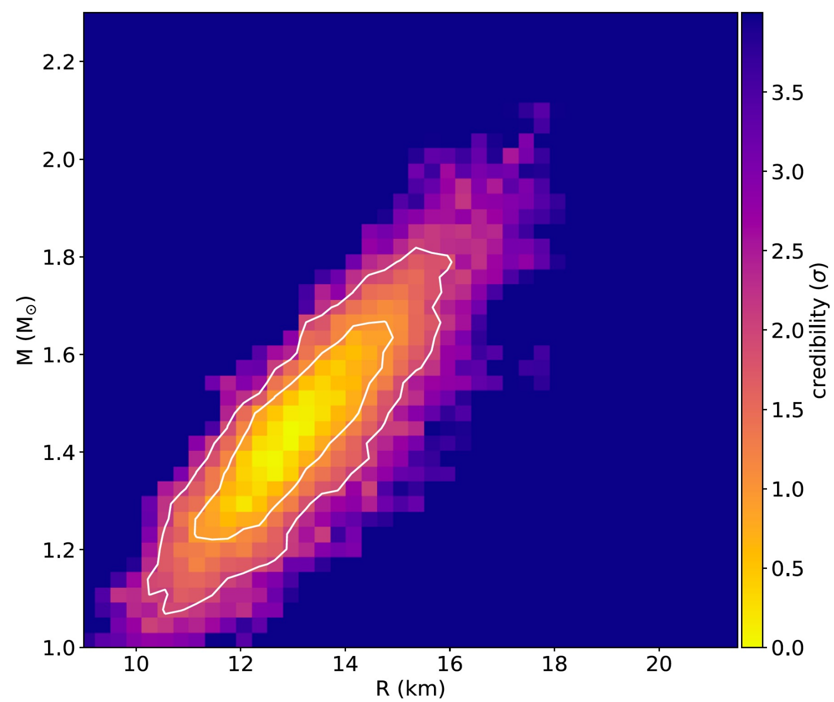
$M = 1.44 \pm 0.15\ M_\odot$

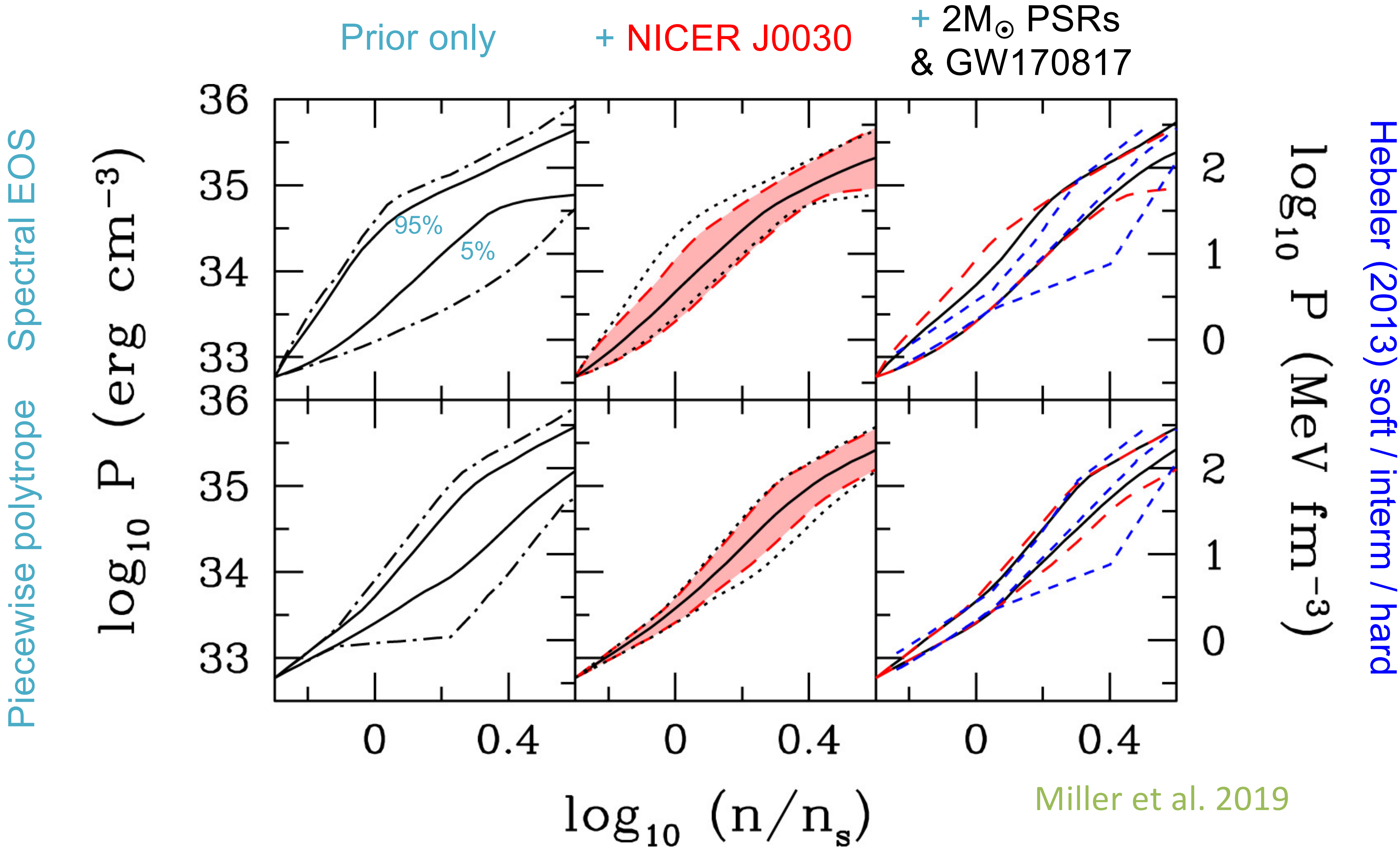
$R = 13.02 \pm 1.15$ km





EOS implications

Chipping away at pressure-density relation of ultra-dense matter



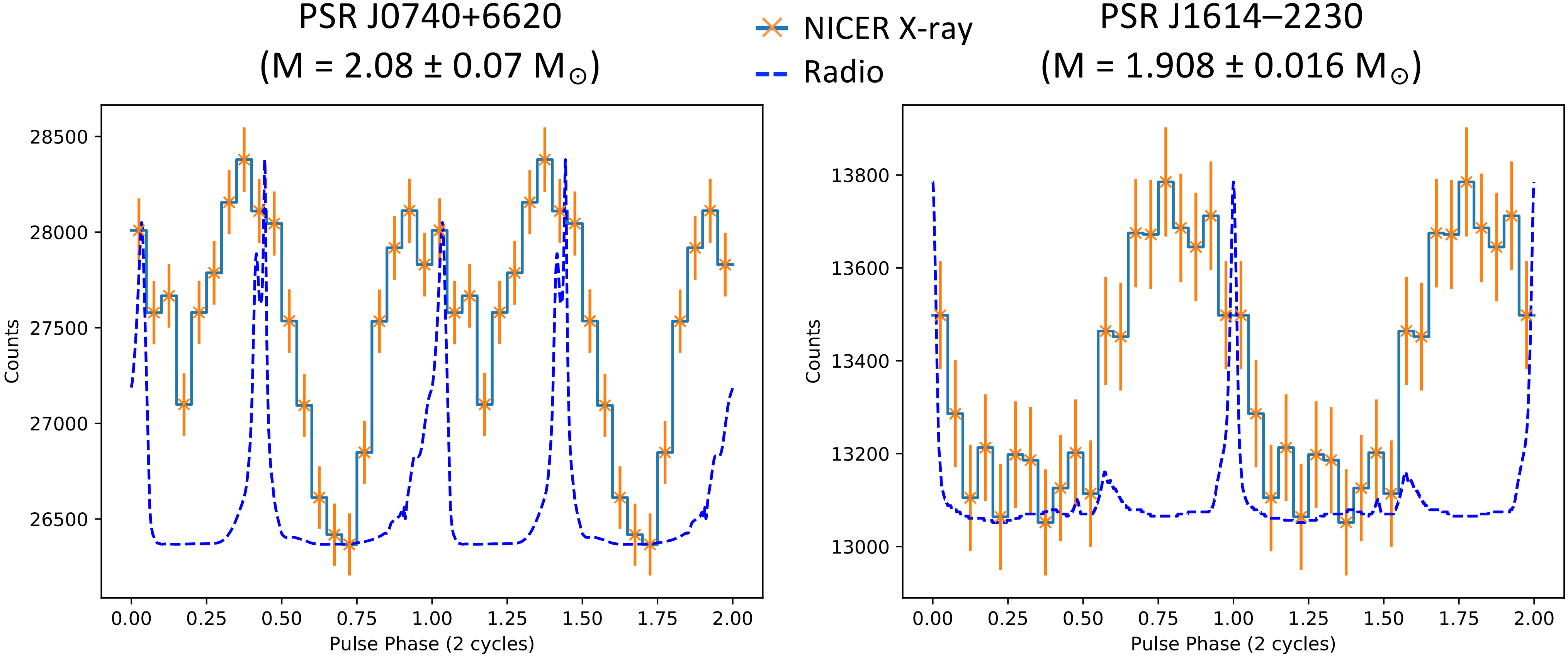
Miller et al. 2019

Two high-mass pulsars

Current and future lightcurve-modeling targets

PSR J0740+6620
(M = 2.08 ± 0.07 $M_\odot$)

PSR J1614–2230
(M = 1.908 ± 0.016 $M_\odot$)



Wolff et al., submitted

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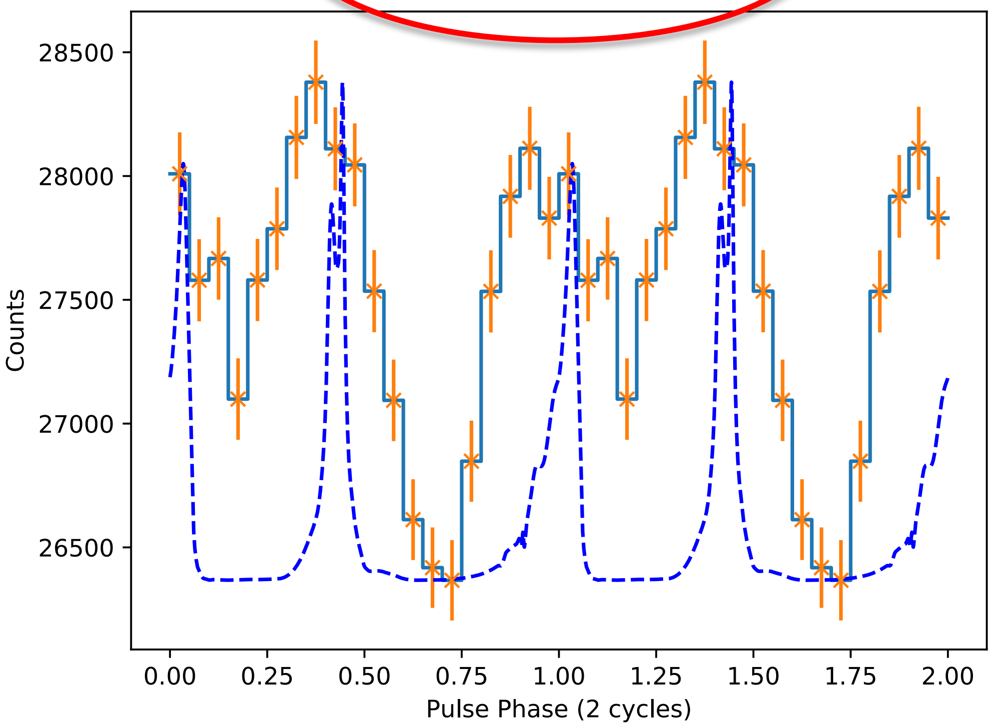

NICER X-ray
Radio

PSR J1614–2230
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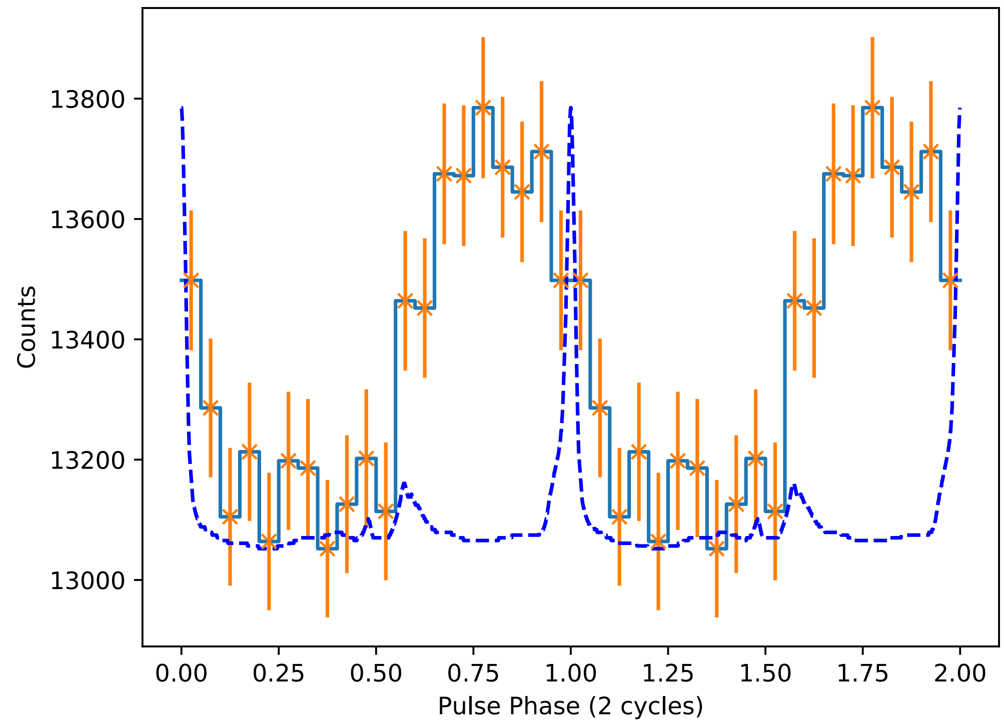


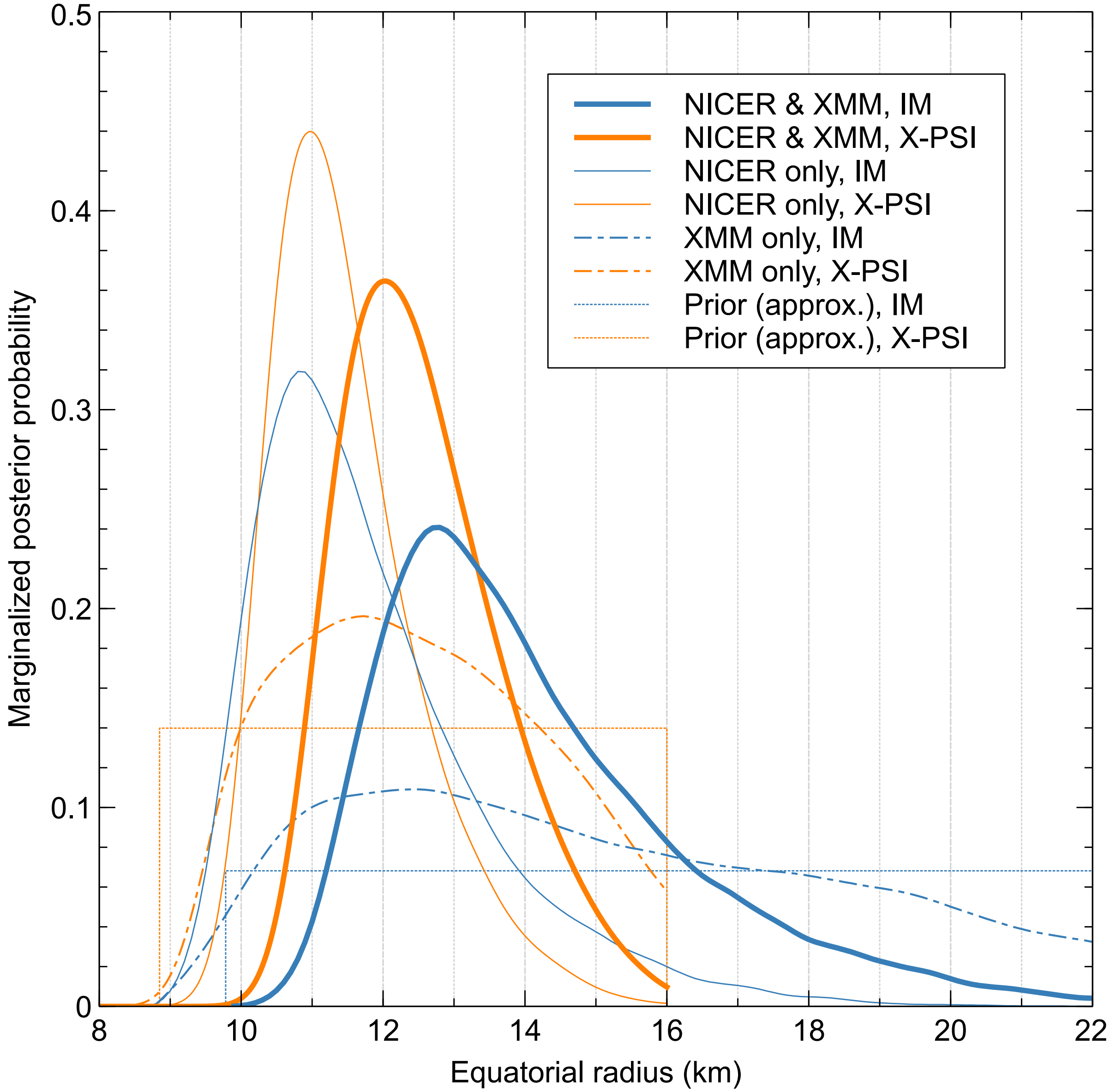
Wolff et al., submitted

Fonseca et al. (2021) radio timing:

- Shapiro delay → mass and near-equatorial viewing geometry;
- parallax → distance

PSR J0740+6620 radius inference

The most massive well-measured neutron star known



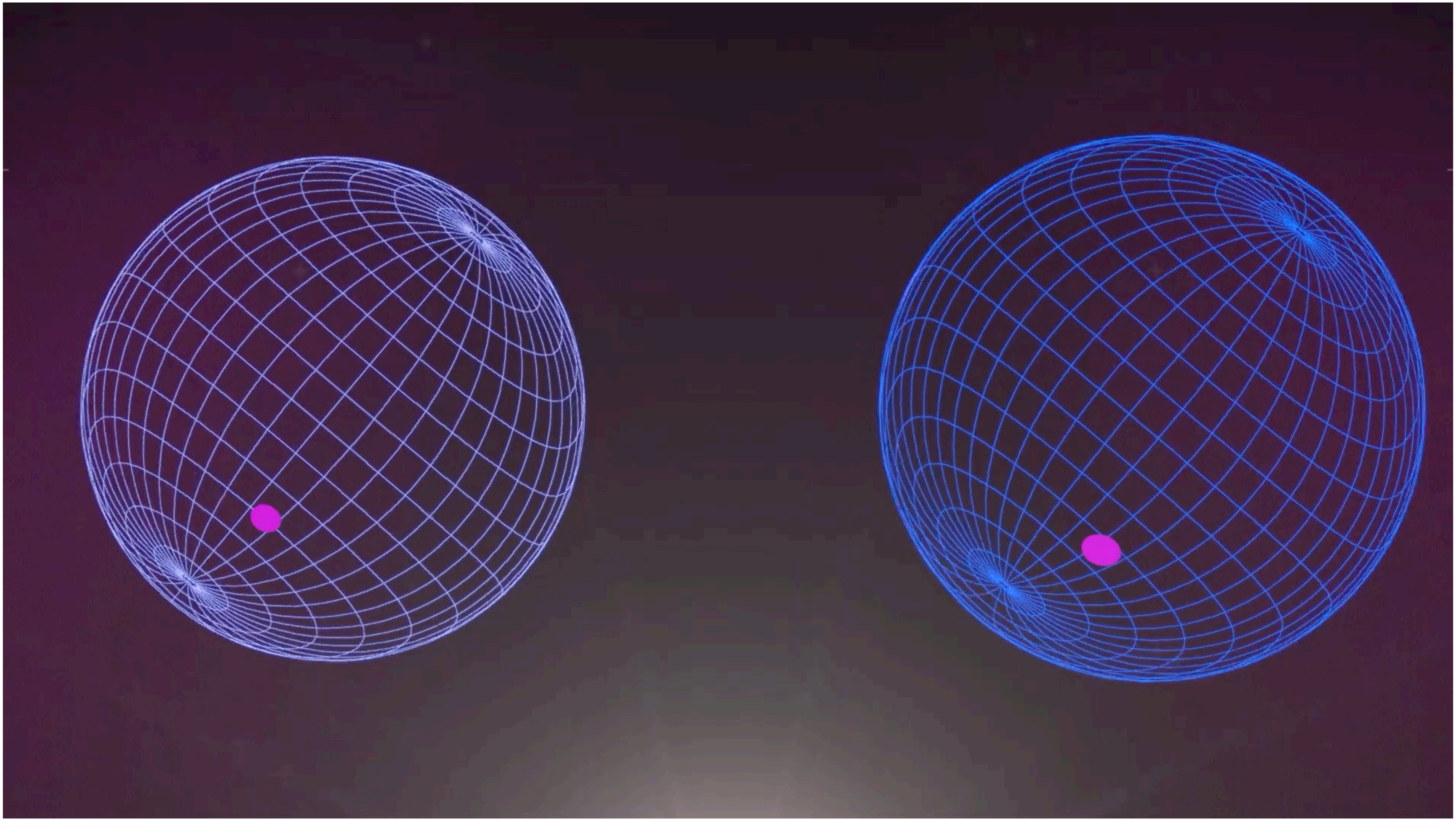
With different treatments of priors, background, and NICER/XMM cross-calibration:

$R = 12.4^{+1.3}_{-1.0}$ km (Riley et al.)

$R = 13.7^{+2.4}_{-1.5}$ km (Miller et al.)

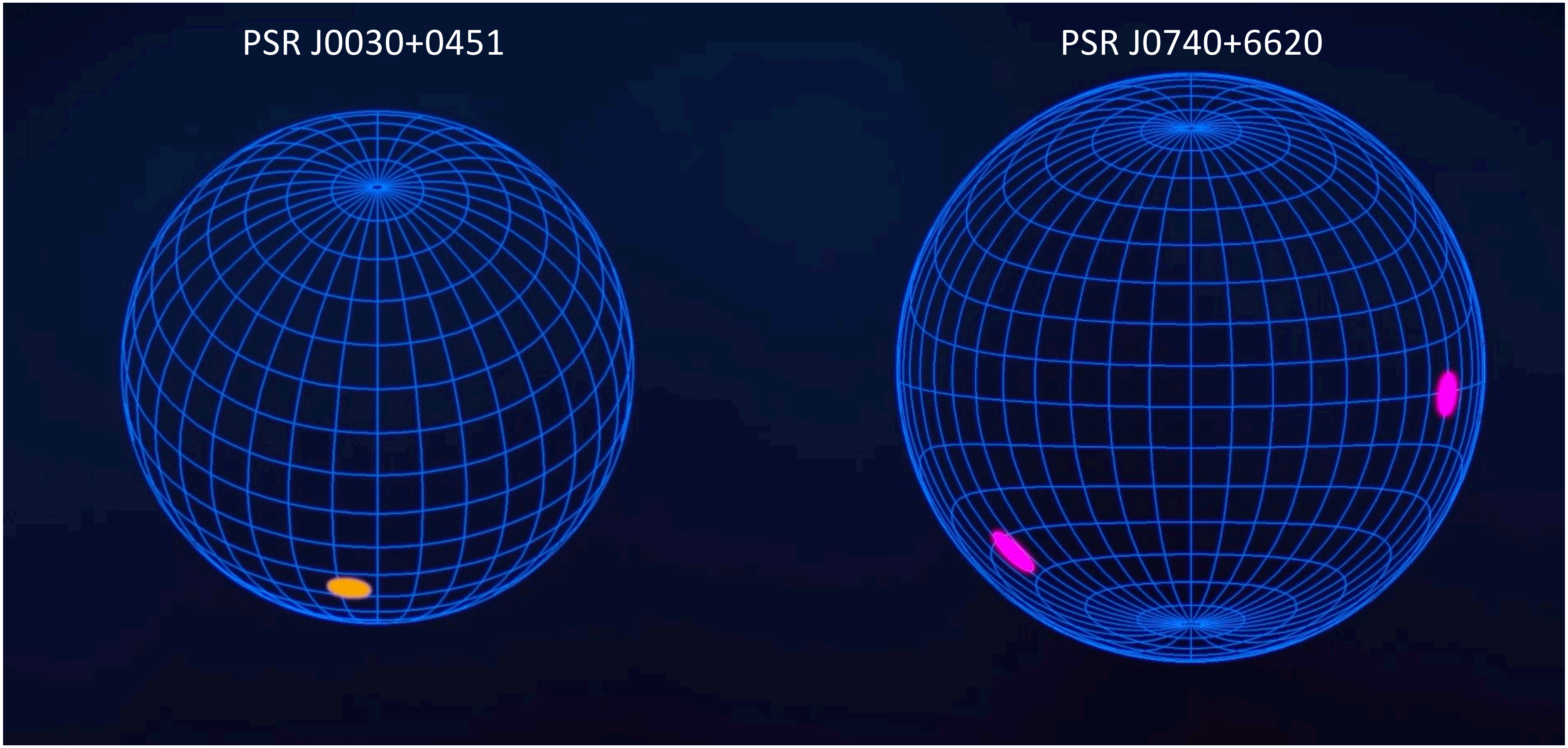
PSR J0740 spot configuration

Two small circular spots, closer to dipolar than J0030



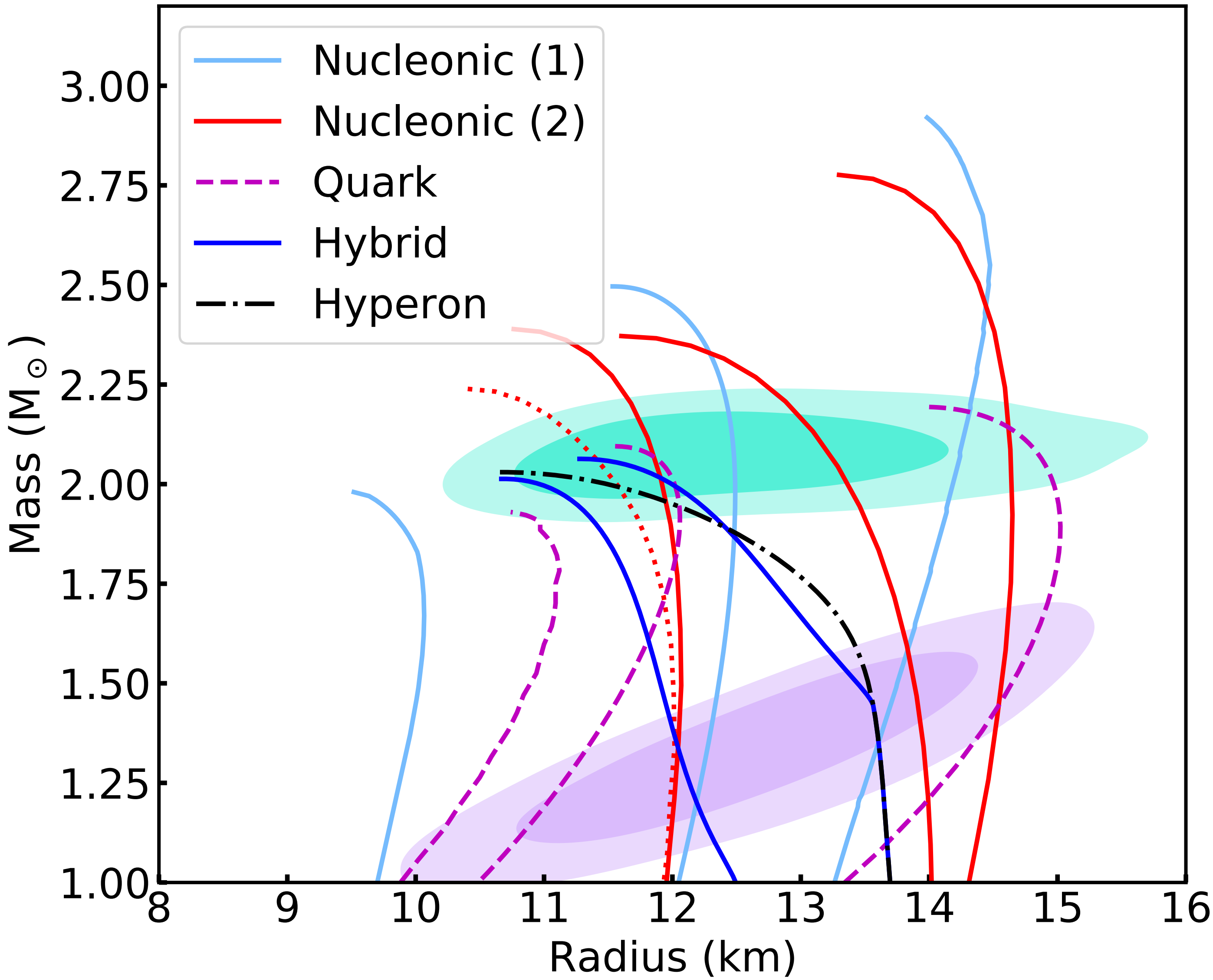
J0030 and J0740 side by side

As seen from Earth, to scale (X-PSI models)



Taken together…

Very similar radii, despite very different masses — softest EOS disfavored



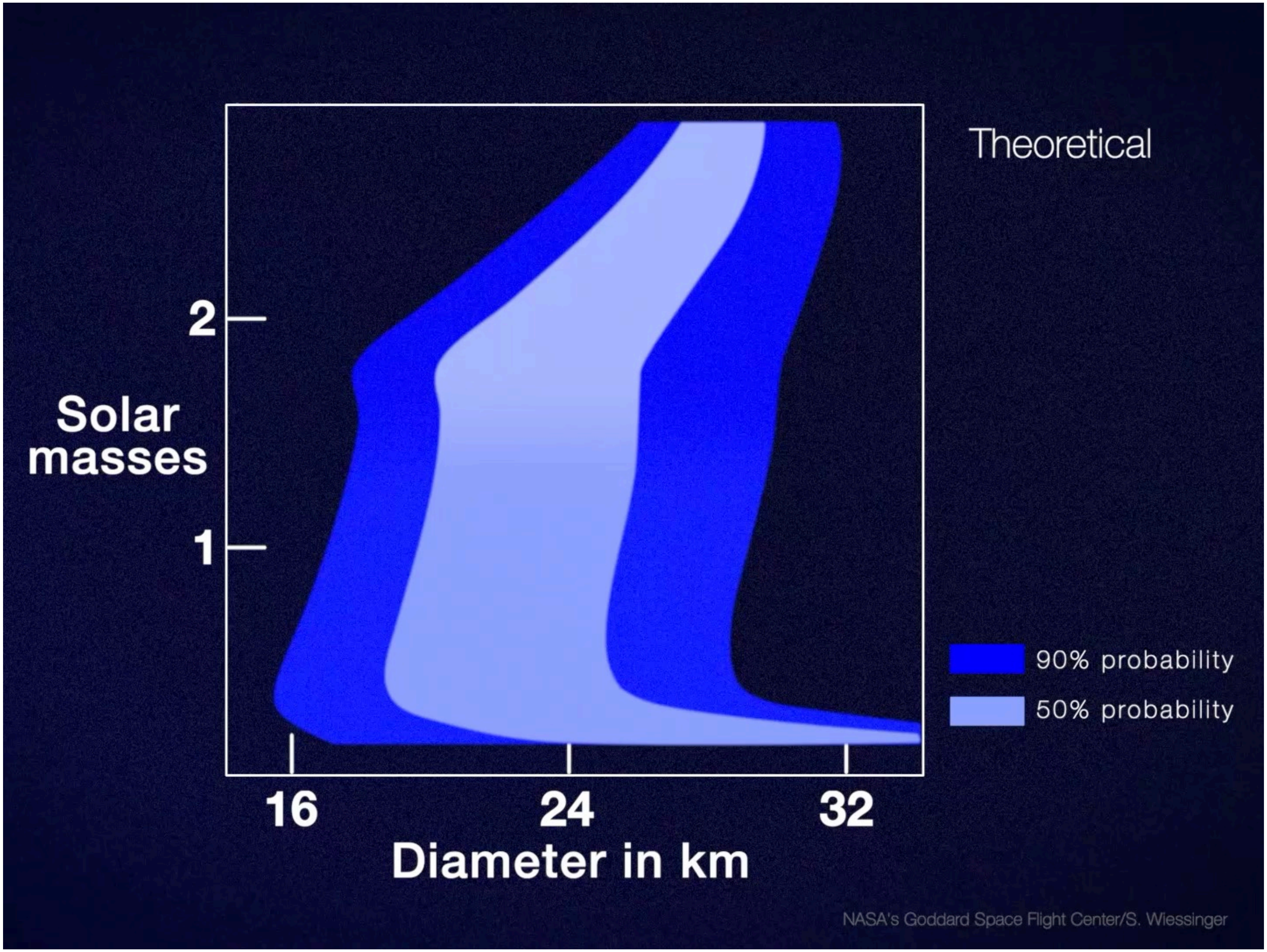
68% and 95% uncertainty contours

PSR J0740+6620

PSR J0030+0451

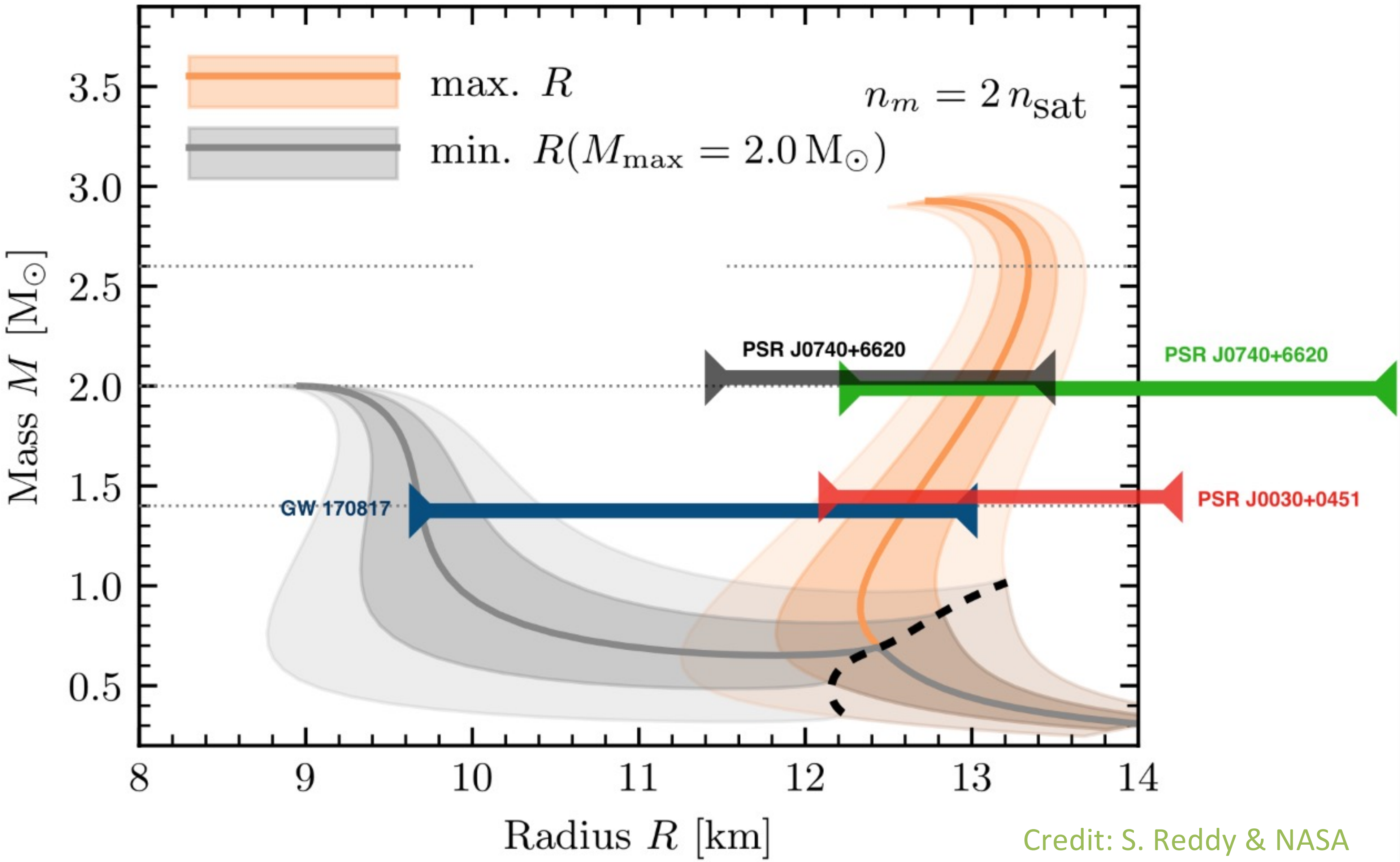
Credit: A. Watts

Inferred mass-radius relationship



Credit: C. Miller & NASA

Constraining the dense-matter EOS



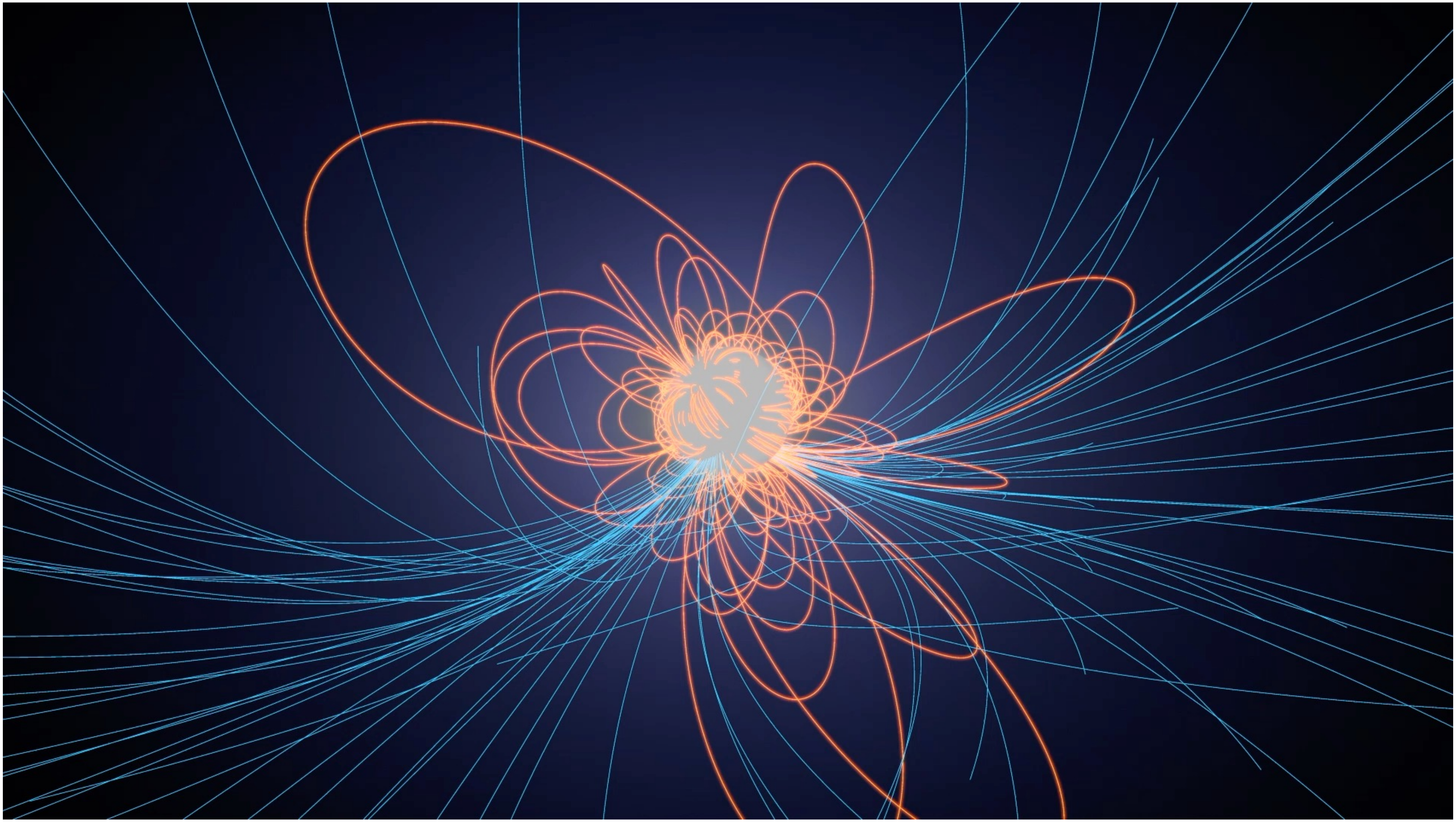
Credit: S. Reddy & NASA

Key-science summary

- NICER has accumulated > 6 Ms of data on five key-science targets
  - Achieved first mass-radius constraints at the 10% level (including first mass measurement of a non-binary pulsar), with two independent analyses producing consistent results
  - Measured radius of most massive neutron star known — favors stiff EOS and *reconsideration of quark interactions at high density*
  - Remaining calibration uncertainties are accounted for, will improve with time
  - Next round of results, on PSR J0437–4715, expected this summer.
- Previously unknown X-ray pulsations have been detected from a handful of additional rotation-powered pulsars
  - Too dim for 5–10% goal, but sample a wide range of masses.
- Data demonstrate robustly that canonical assumptions of surface “hot spots” (small & single temp., antipodal & dipole B field) are not viable
  - First surface temperature maps of a neutron star, with sizes, shapes, locations of heated regions
  - Elaborate parameterizations reduce precision of M-R inference, but Bayesian evidence isolates the needed level of model complexity.

Redrawing “textbook” pulsar magnetic fields

Much more complex than a simple dipole!



Credit: C. Kalapotharakos & NASA

NICER logo hack!

NICER logo hack!

Credit: A. Bilous & NASA

Last but not least…

Multi-messenger tests of GR enabled by NICER!

PHYSICAL REVIEW LETTERS **126,** 181101 (2021)

Editors' Suggestion Featured in Physics

Astrophysical and Theoretical Physics Implications from Multimessenger Neutron Star Observations

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(Received 24 December 2020; accepted 18 March 2021; published 3 May 2021)

The Neutron Star Interior Composition Explorer (NICER) recently measured the mass and equatorial radius of the isolated neutron star PSR J0030+0451. We use these measurements to infer the moment of inertia, the quadrupole moment, and the surface eccentricity of an isolated neutron star for the first time, using relations between these quantities that are insensitive to the unknown equation of state of supranuclear matter. We also use these results to forecast the moment of inertia of neutron star A in the double pulsar binary J0737-3039, a quantity anticipated to be directly measured in the coming decade with radio observations. Combining this information with the measurement of the tidal Love number with LIGO/Virgo observations, we propose and implement the first theory-agnostic and equation-of-state-insensitive test of general relativity. Specializing these constraints to a particular modified theory, we find that consistency with general relativity places the most stringent constraint on gravitational parity violation to date, surpassing all other previously reported bounds by 7 orders of magnitude and opens the path for a future test of general relativity with multimessenger neutron star observations.

DOI: 10.1103/PhysRevLett.126.181101

Introduction.—Neutron stars are some of the most extreme objects in nature. Their mass (typically around 1.4 $M_{\odot}$) combined with their small radius (between 10–14 km) result in interior densities that can exceed

insensitive to either (or both) the equation of state and the gravitational theory exist. Fortunately, they do. For instance, when properly nondimensionalized, the moment of inertia (I), the rotational quadrupole moment (Q), and