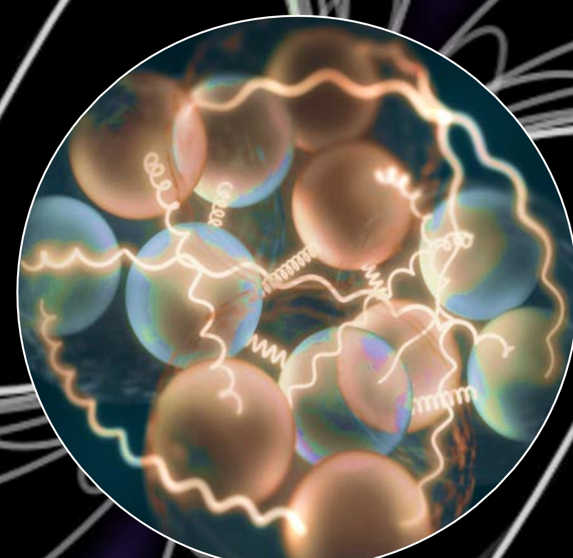
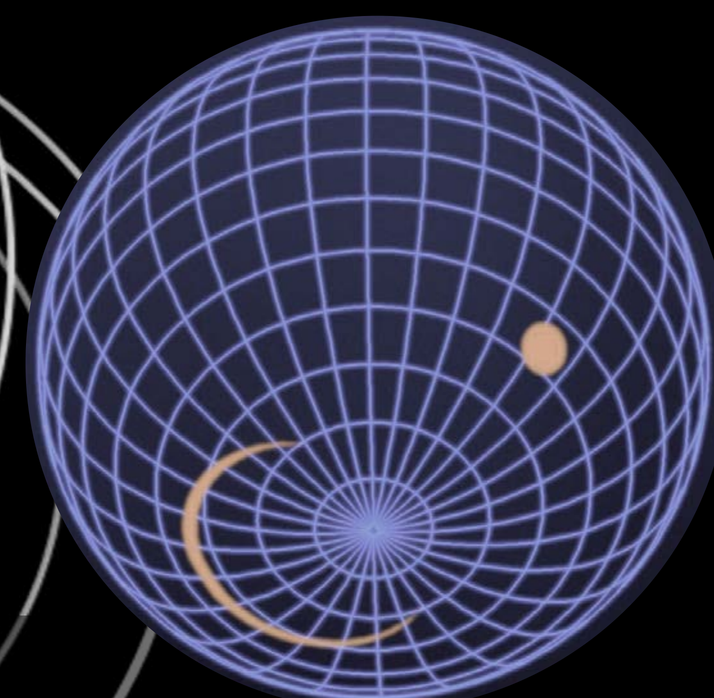
NICER AND ITS VIEW OF NEUTRON STARS





PROF. ANNA WATTS
UNIVERSITY OF AMSTERDAM

FROM NUCLEAR PHYSICS TO TELESCOPE

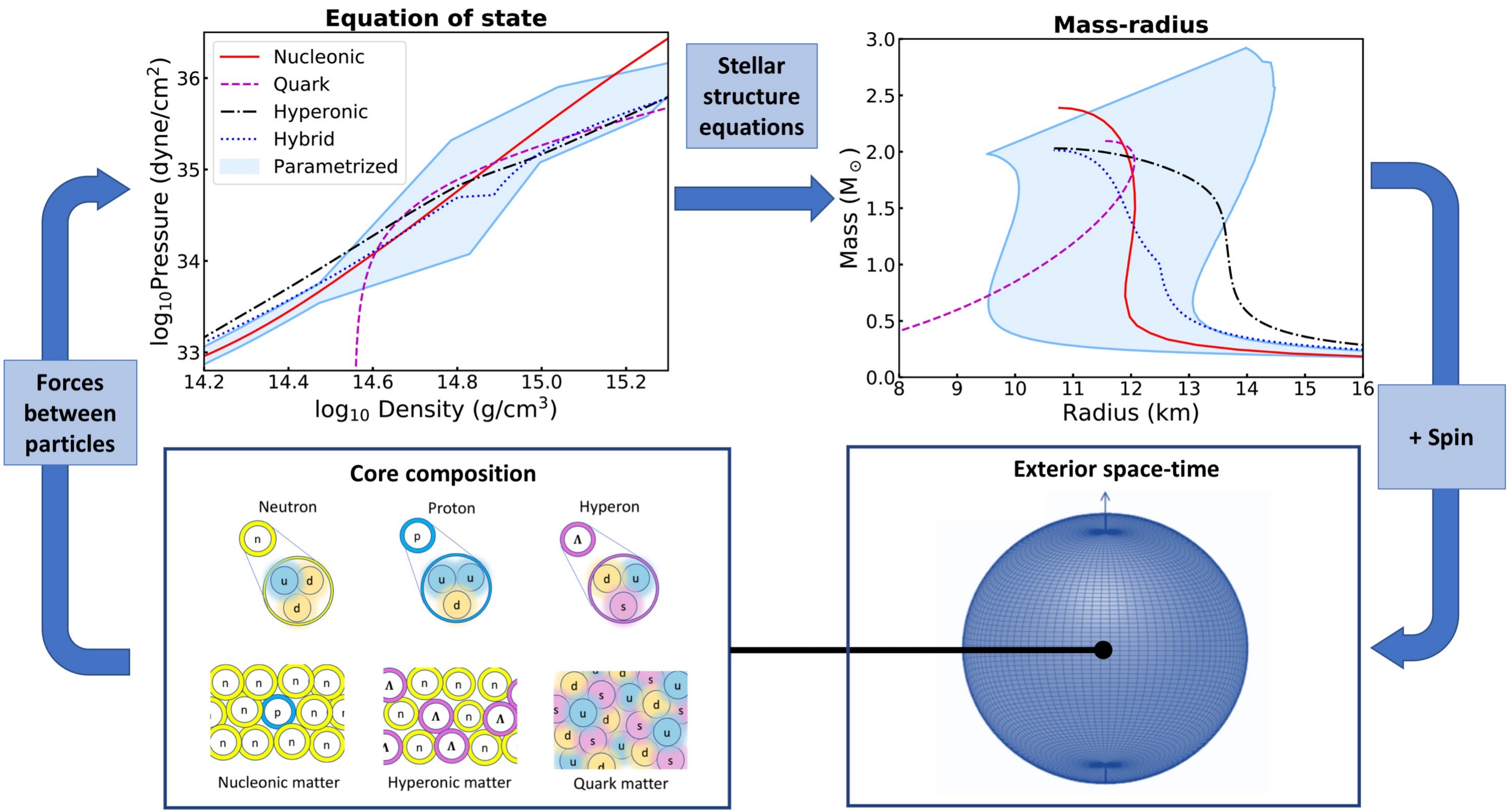
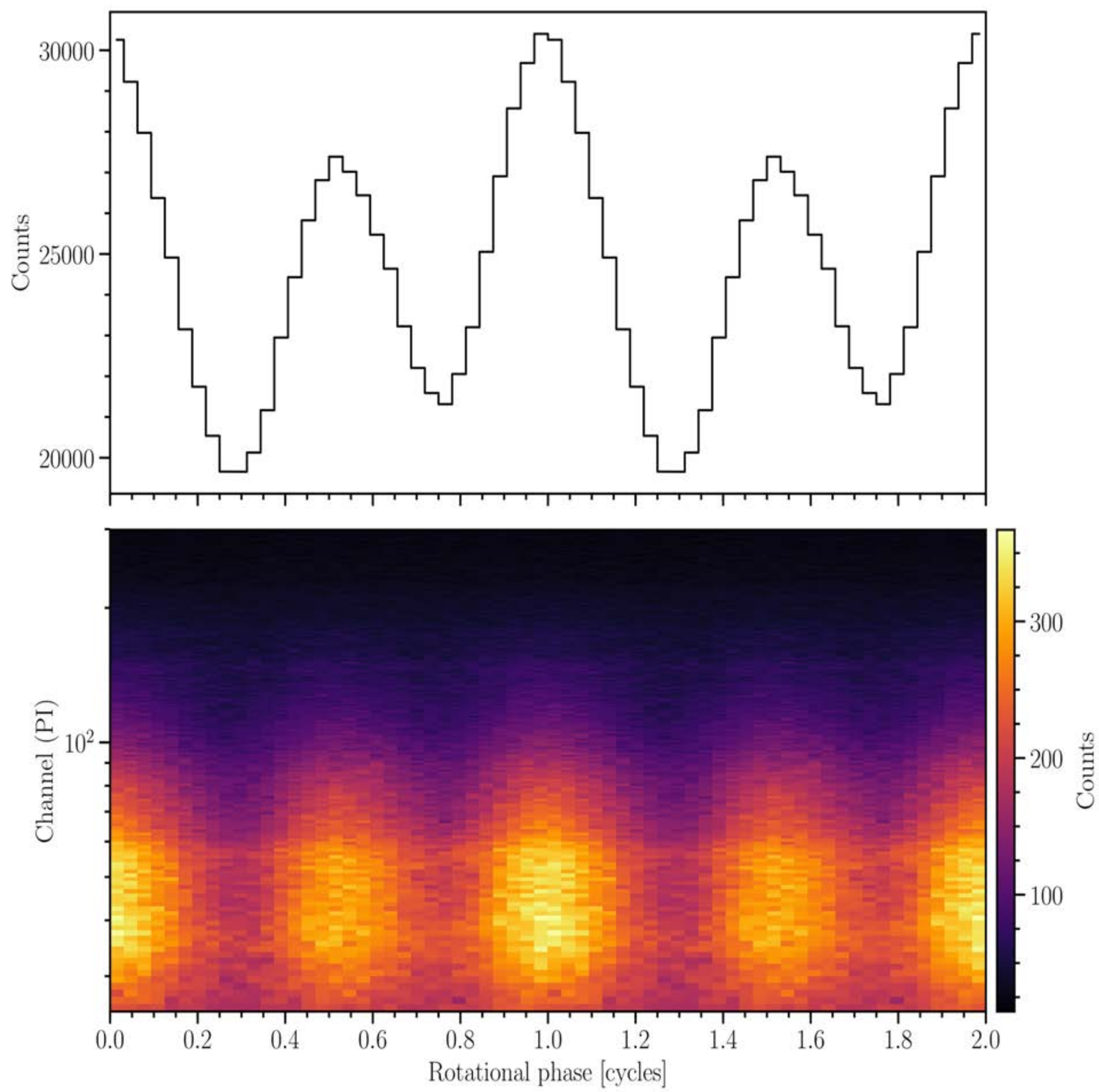
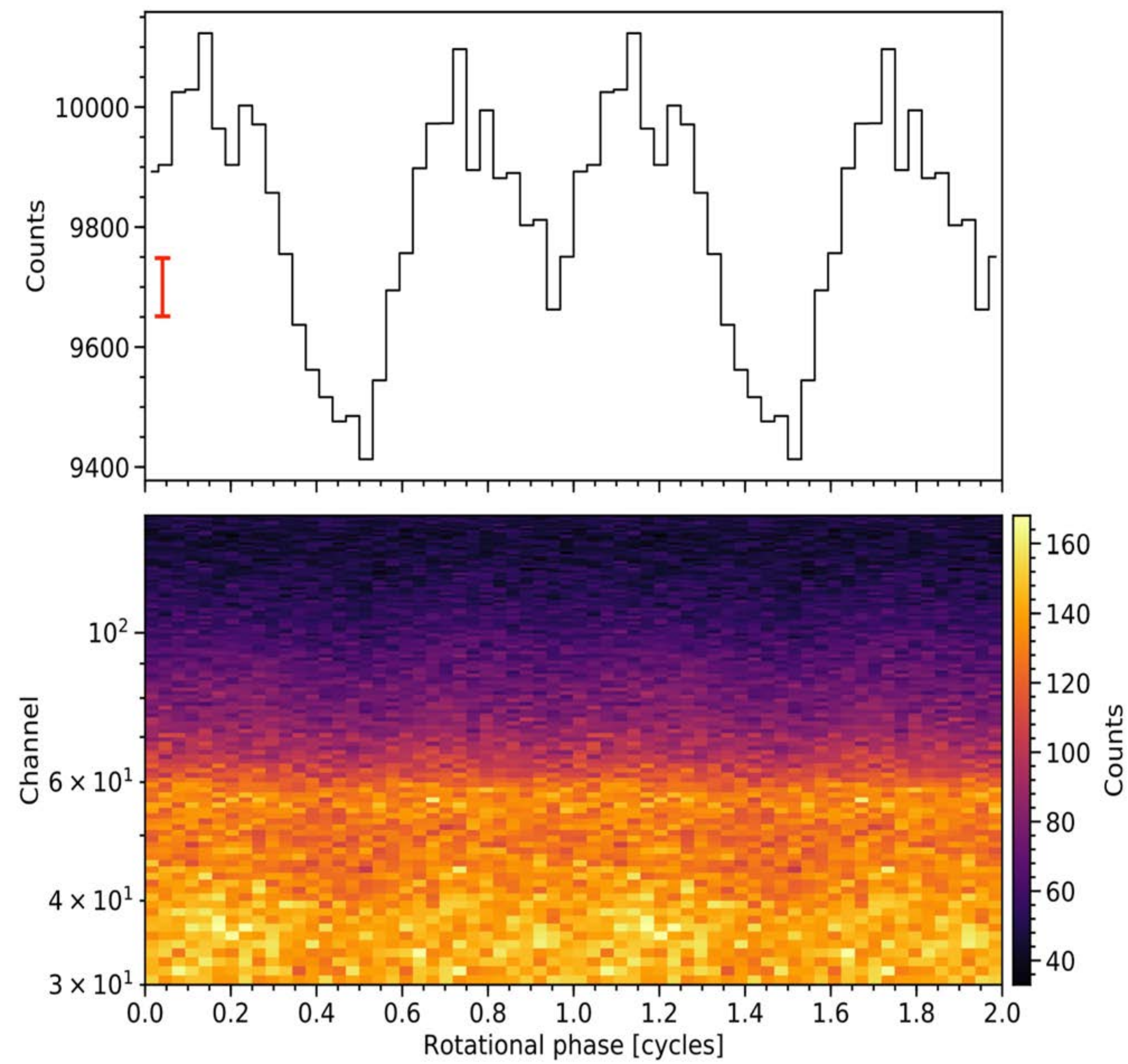


Figure: Adapted from Ray et al. 2019

NICER PULSE PROFILE DATA
ROTATION-POWERED MILLISECOND PULSARS



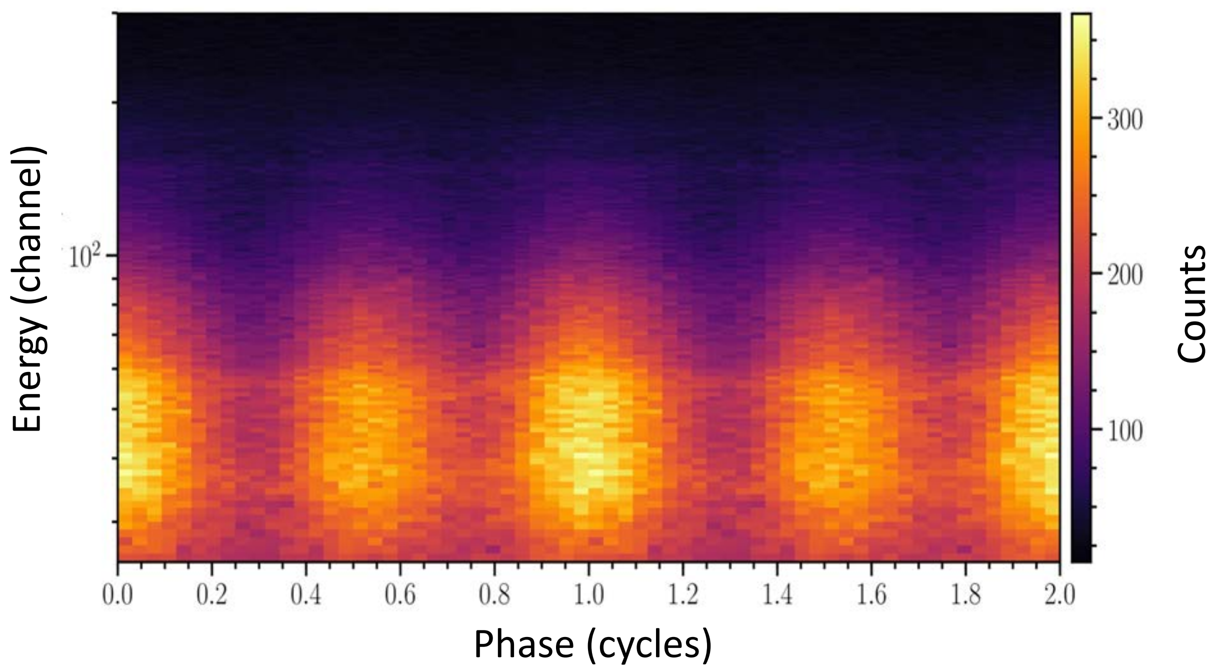
PSR J0030+0451
(Bogdanov et al. 2019)



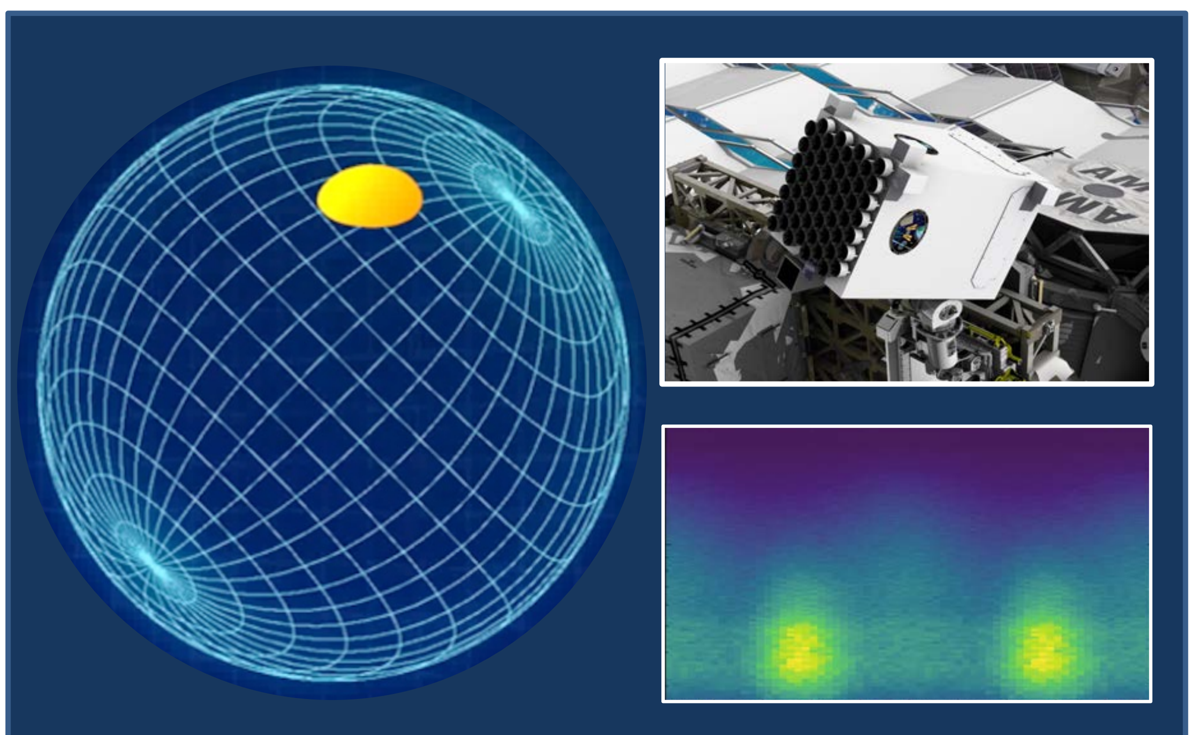
PSR J0740+6620
(Wolff et al. 2021)

OUR PULSE PROFILE MODELING PROCESS

Pulse profile data: Phase, Energy



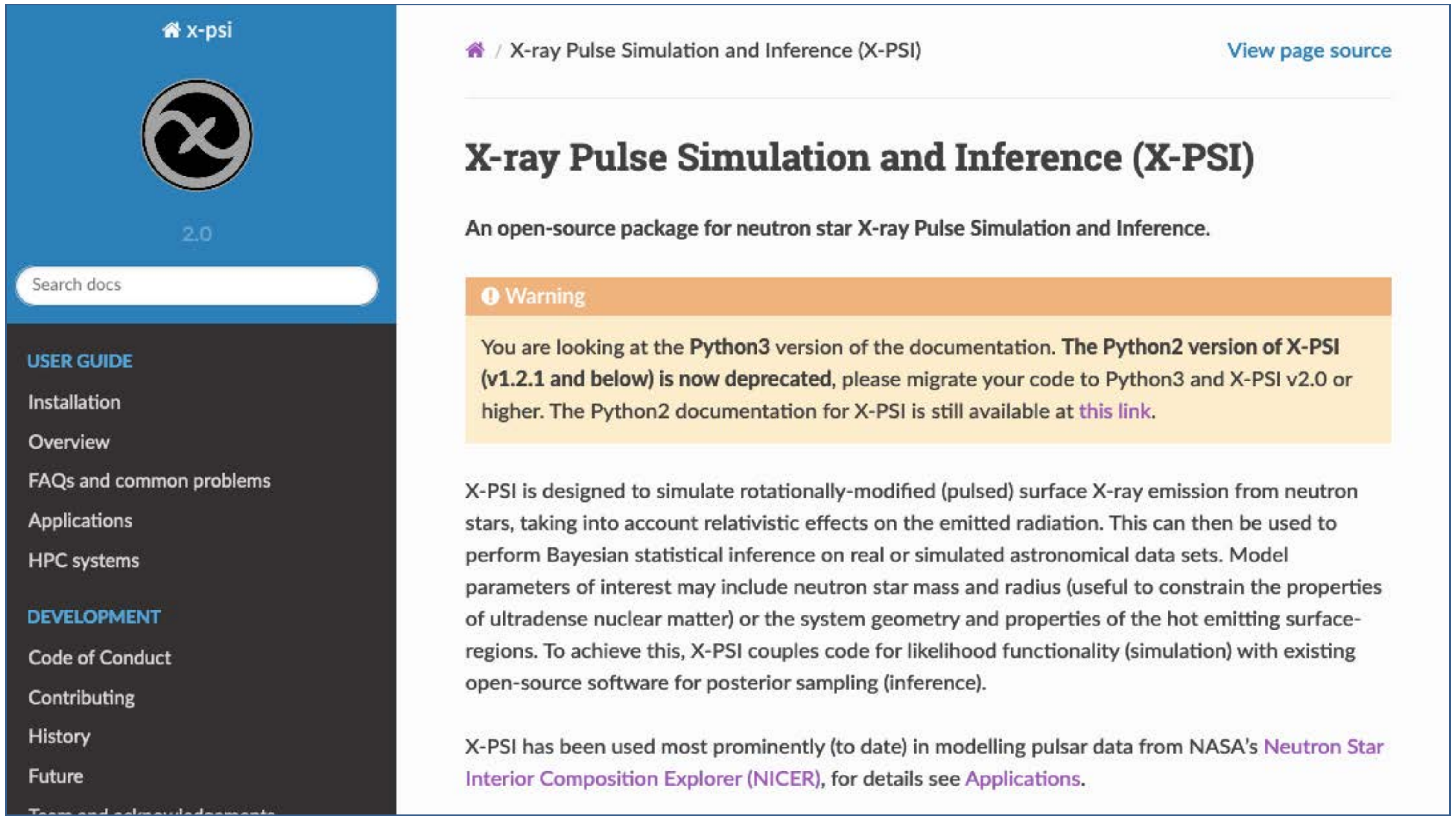
Lightcurve model: the (astro)physics



Bayesian inference of model parameters (statistical sampling)

Model parameters:
Mass and radius
Geometric properties

X-RAY PULSE SIMULATION AND INFERENCE (X-PSI) PACKAGE



x-psi

2.0

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- Future

/ X-ray Pulse Simulation and Inference (X-PSI) — View page source

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

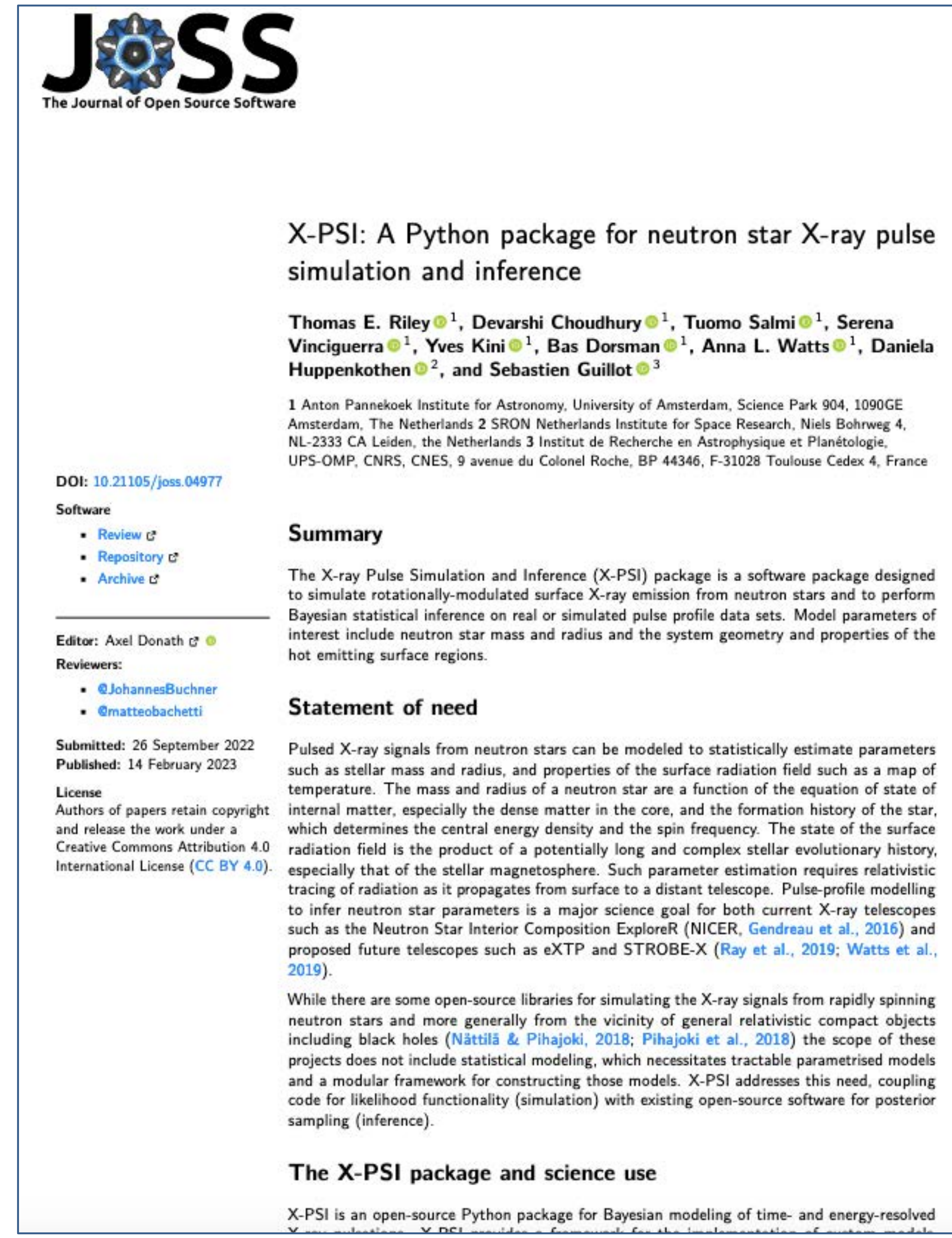
An open-source package for neutron star X-ray Pulse Simulation and Inference.

Warning

You are looking at the **Python3** version of the documentation. **The Python2 version of X-PSI (v1.2.1 and below) is now deprecated**, please migrate your code to Python3 and X-PSI v2.0 or higher. The Python2 documentation for X-PSI is still available at this link.

X-PSI is designed to simulate rotationally-modified (pulsed) surface X-ray emission from neutron stars, taking into account relativistic effects on the emitted radiation. This can then be used to perform Bayesian statistical inference on real or simulated astronomical data sets. Model parameters of interest may include neutron star mass and radius (useful to constrain the properties of ultradense nuclear matter) or the system geometry and properties of the hot emitting surface-regions. To achieve this, X-PSI couples code for likelihood functionality (simulation) with existing open-source software for posterior sampling (inference).

X-PSI has been used most prominently (to date) in modelling pulsar data from NASA's Neutron Star Interior Composition Explorer (NICER), for details see Applications.



JOSS
The Journal of Open Source Software

X-PSI: A Python package for neutron star X-ray pulse simulation and inference

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Software
- Review
- Repository
- Archive

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Summary

The X-ray Pulse Simulation and Inference (X-PSI) package is a software package designed to simulate rotationally-modulated surface X-ray emission from neutron stars and to perform Bayesian statistical inference on real or simulated pulse profile data sets. Model parameters of interest include neutron star mass and radius and the system geometry and properties of the hot emitting surface regions.

Statement of need

Pulsed X-ray signals from neutron stars can be modeled to statistically estimate parameters such as stellar mass and radius, and properties of the surface radiation field such as a map of temperature. The mass and radius of a neutron star are a function of the equation of state of internal matter, especially the dense matter in the core, and the formation history of the star, which determines the central energy density and the spin frequency. The state of the surface radiation field is the product of a potentially long and complex stellar evolutionary history, especially that of the stellar magnetosphere. Such parameter estimation requires relativistic tracing of radiation as it propagates from surface to a distant telescope. Pulse-profile modelling to infer neutron star parameters is a major science goal for both current X-ray telescopes such as the Neutron Star Interior Composition ExploreR (NICER, Gendreau et al., 2016) and proposed future telescopes such as eXTP and STROBE-X (Ray et al., 2019; Watts et al., 2019).

While there are some open-source libraries for simulating the X-ray signals from rapidly spinning neutron stars and more generally from the vicinity of general relativistic compact objects including black holes (Nättilä & Pihajoki, 2018; Pihajoki et al., 2018) the scope of these projects does not include statistical modeling, which necessitates tractable parametrised models and a modular framework for constructing those models. X-PSI addresses this need, coupling code for likelihood functionality (simulation) with existing open-source software for posterior sampling (inference).

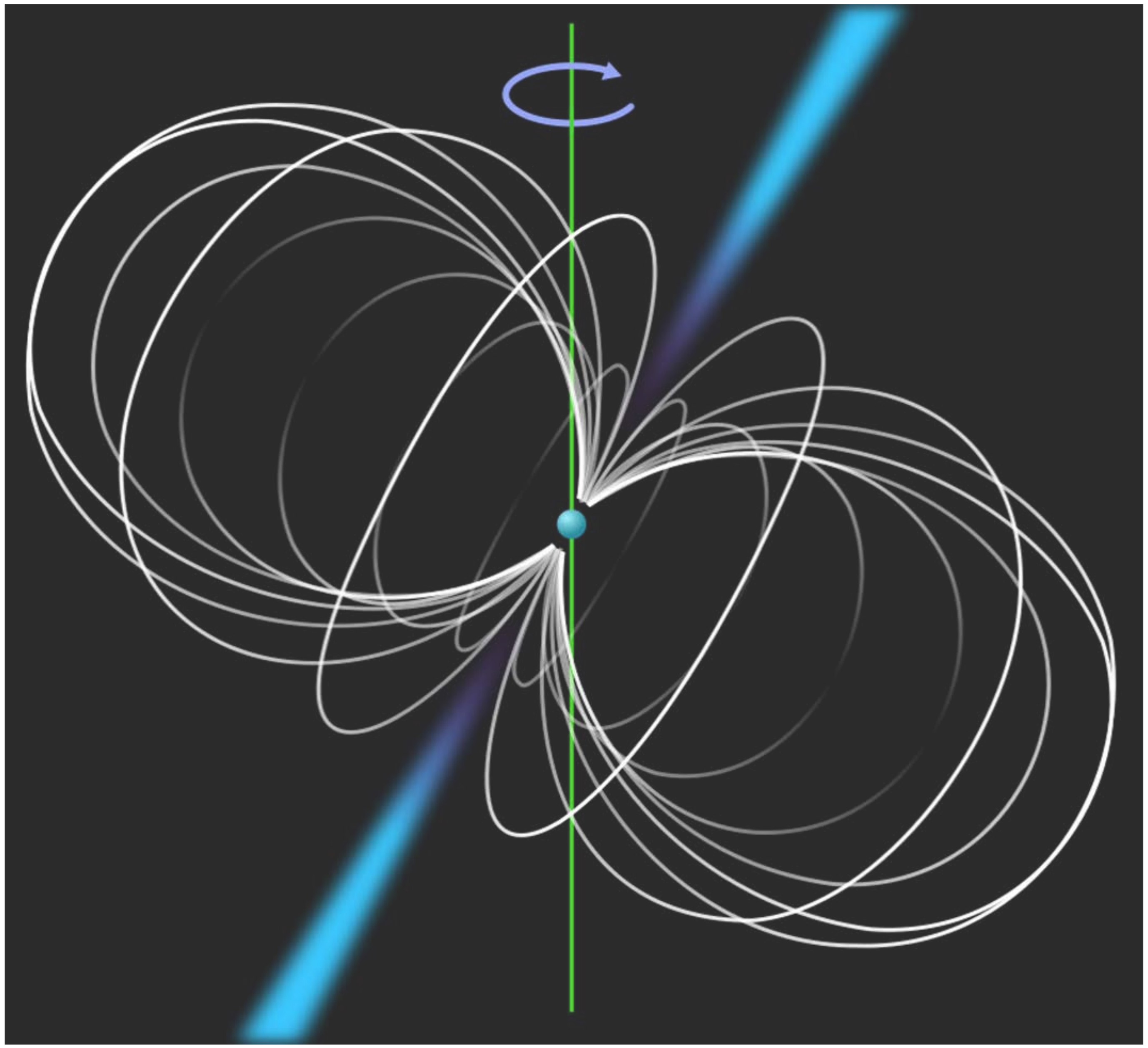
The X-PSI package and science use

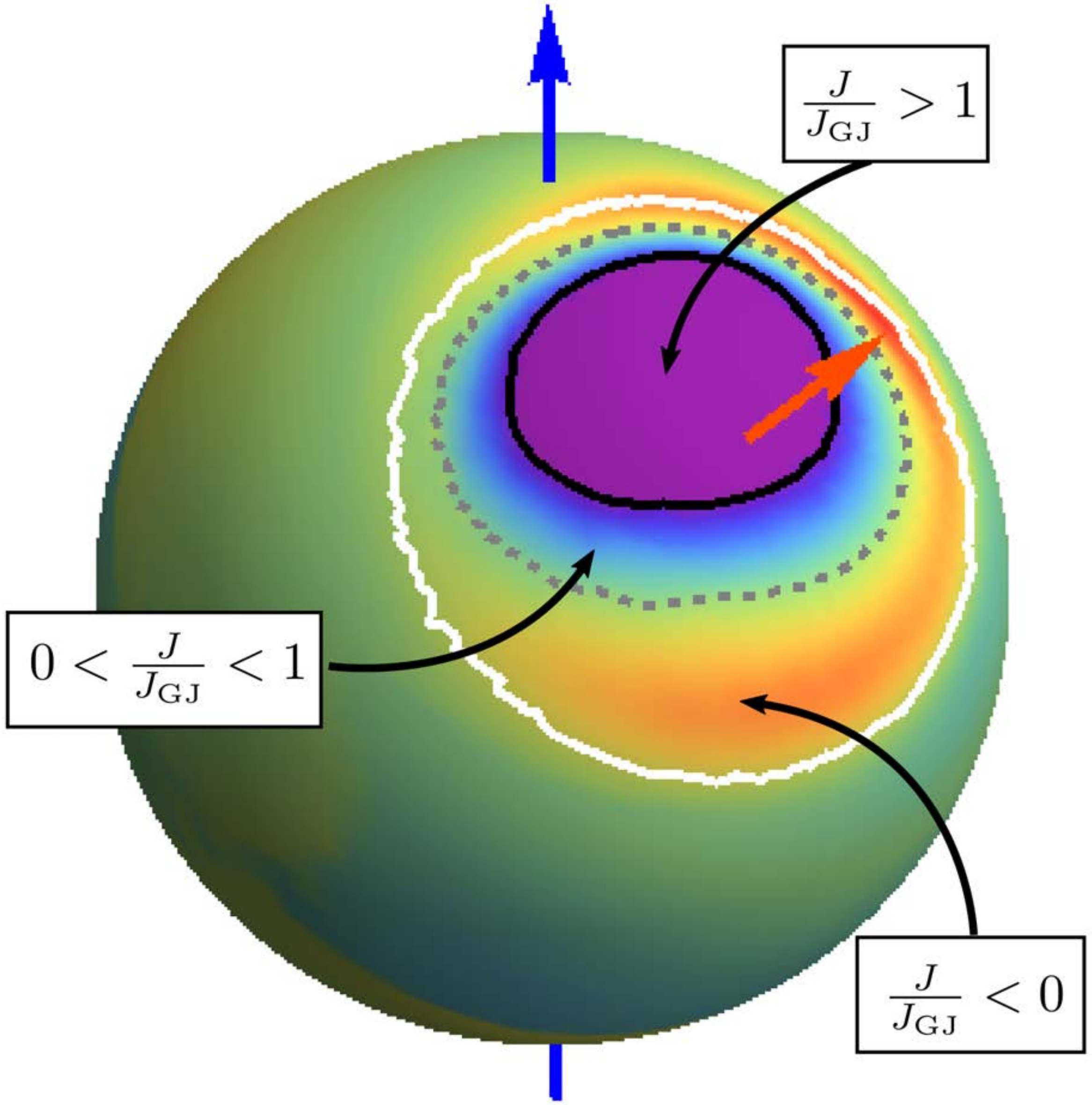
X-PSI is an open-source Python package for Bayesian modeling of time- and energy-resolved

X-PSI software (used for our NICER analysis) available via Github – finally available for Python 3 as well.
https://github.com/xpsi-group/xpsi

Full reproduction packages for all NICER analyses available via Zenodo (scripts to run X-PSI, data and model files, post-processing notebooks, full samples). Links to papers and Zenodos via 'Applications' tab on X-PSI pages.

PULSAR SURFACE EMISSION PATTERNS



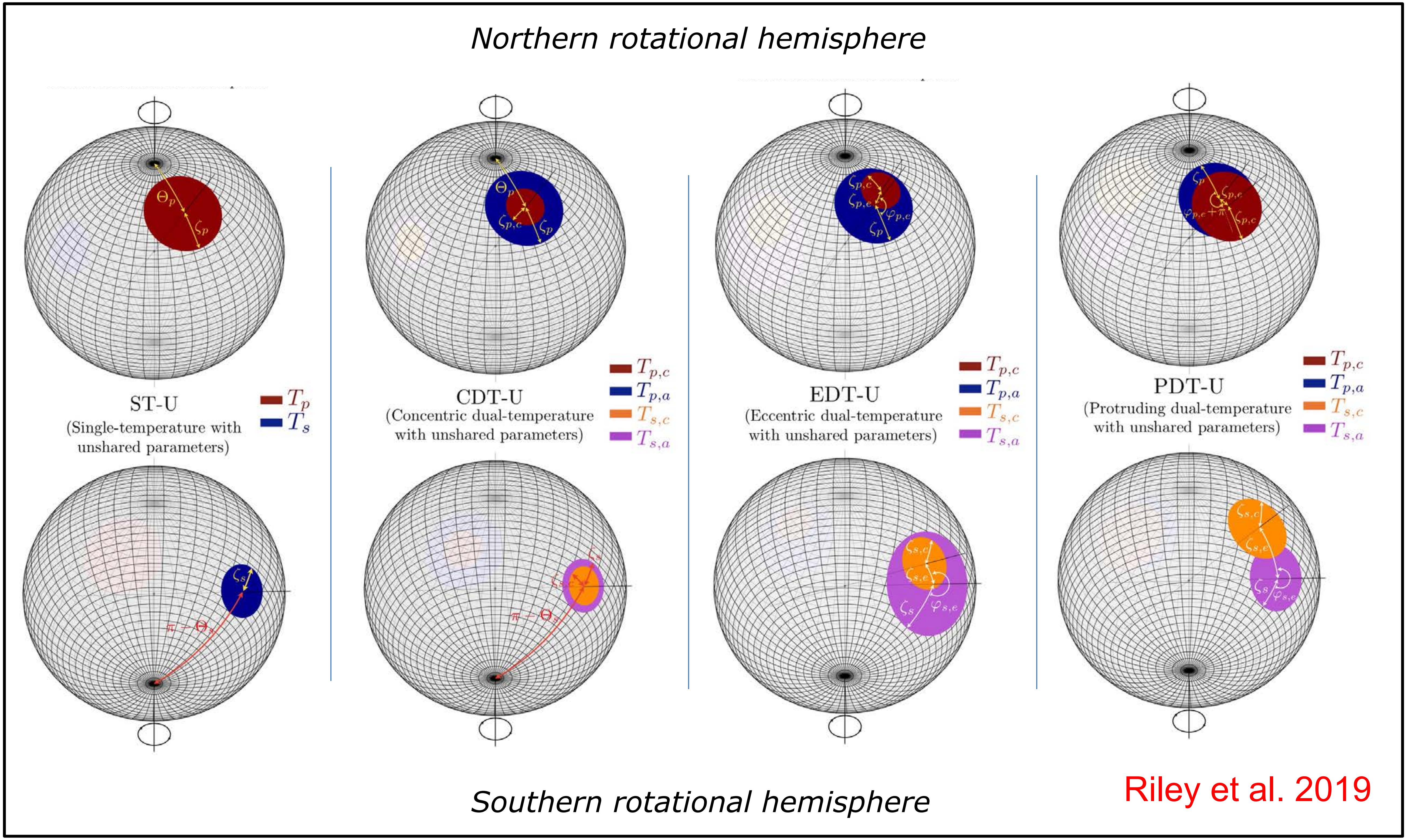


Surface heating pattern due to return currents a priori poorly constrained.

(Figure courtesy of Kostas Kalapotharakos, see also Harding & Muslimov 2011)

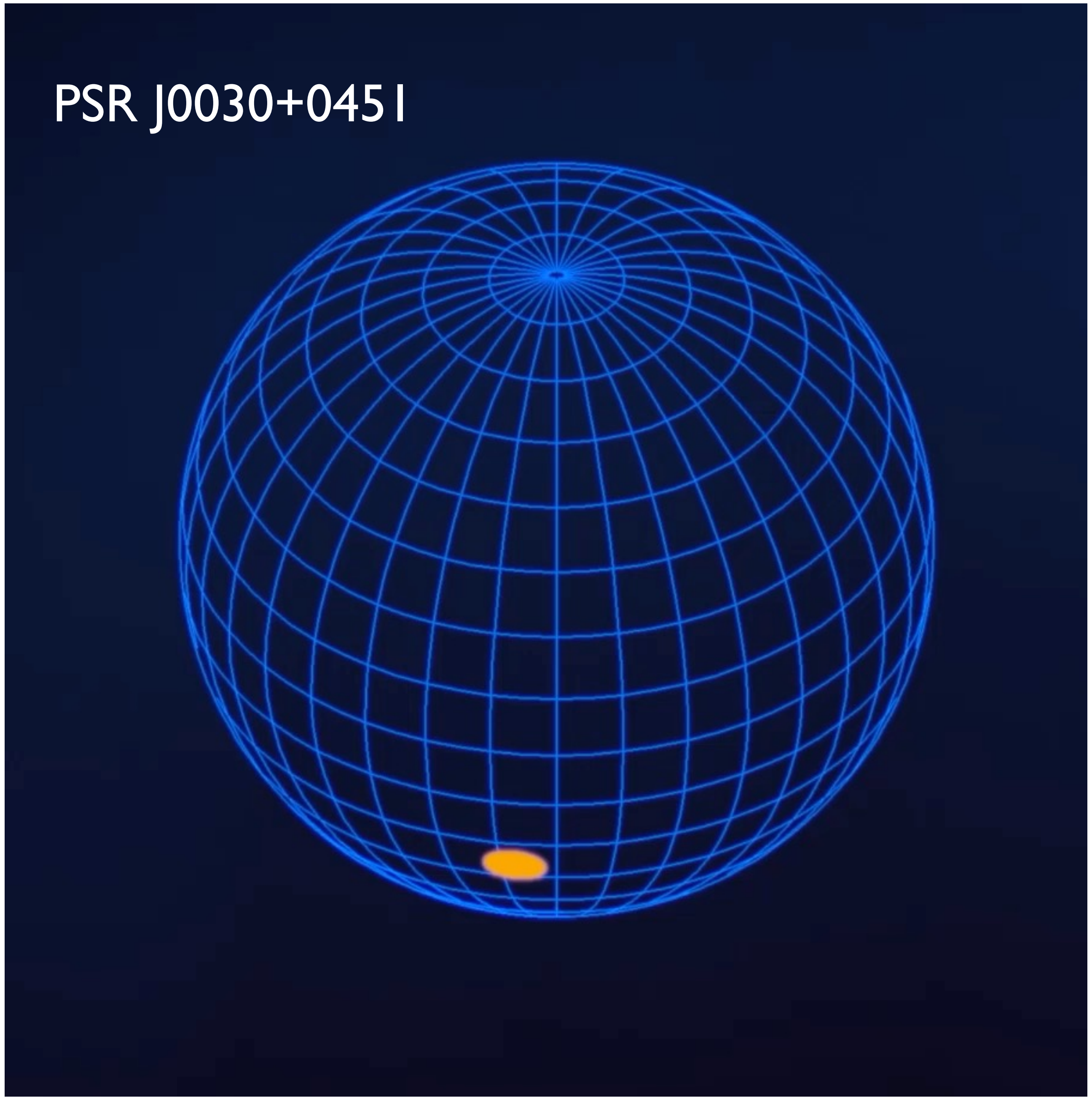
POLAR CAP MODELS

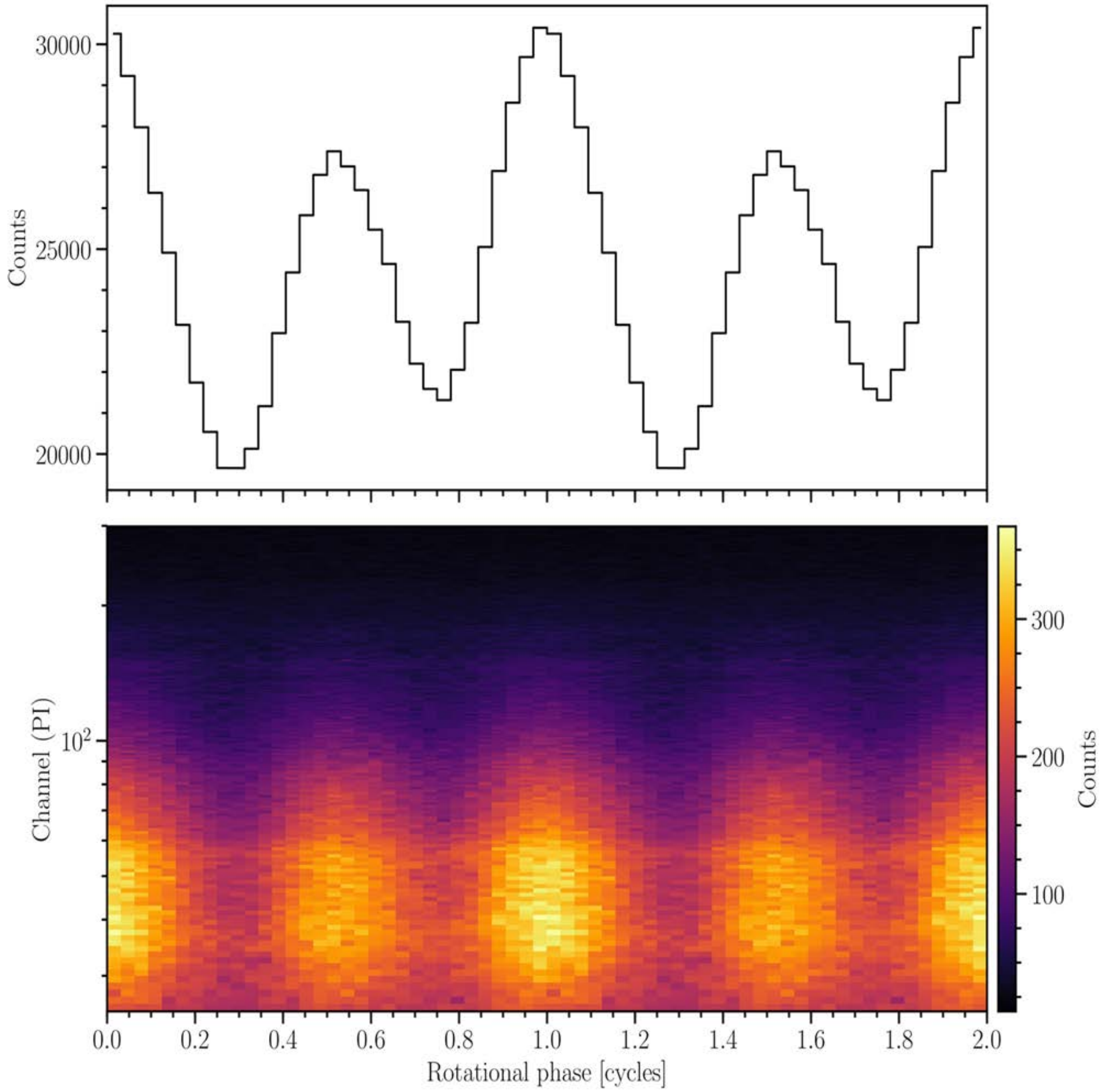
- We use 2-cap models of increasing surface pattern complexity.



Riley et al. 2019

NICER'S FIRST SURFACE MAP





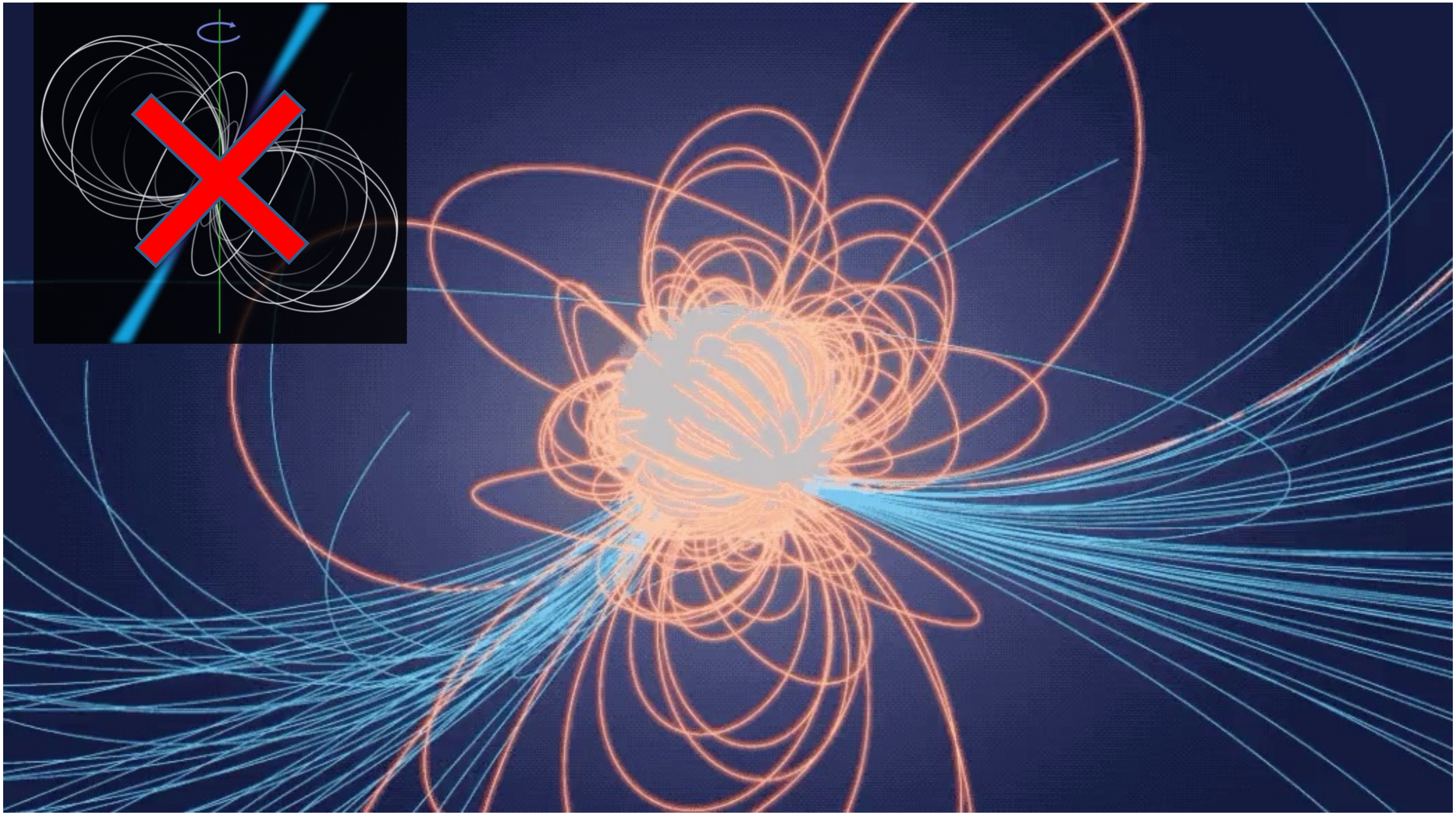
NICER team J0030 papers

Data and supporting analysis (Bogdanov et al. 2019a,b, 2021);

X-PSI analysis group (Riley et al. 2019, Raaijmakers et al.19, Bilous et al. 2019);

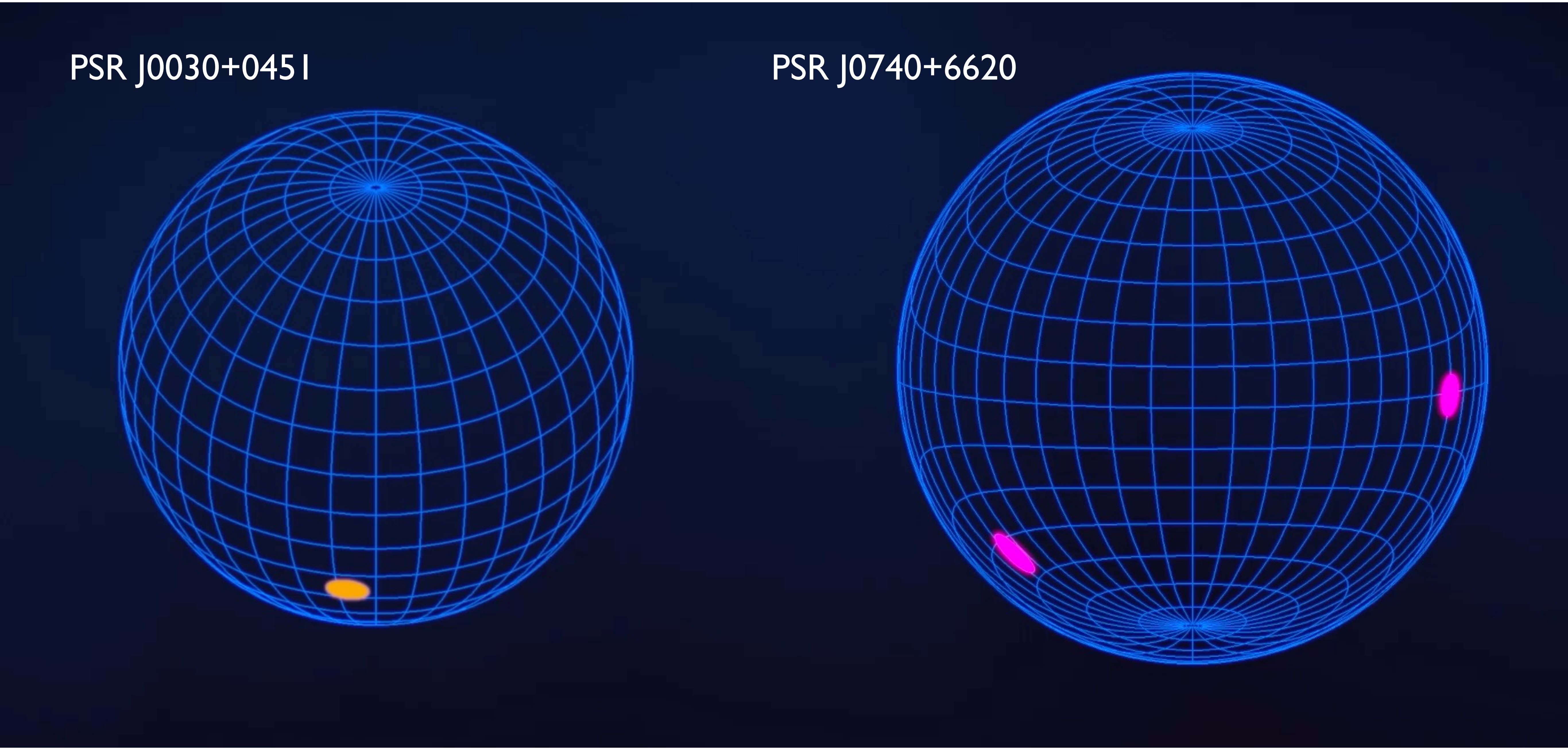
Maryland-Illinois analysis group (Miller et al. 2019).

COMPLEX MAGNETIC FIELD



Credit: NASA's Goddard Space Flight Center/Harding, Kalapotharakos, Wadiasingh.

MAPPING THE MOST MASSIVE PULSAR

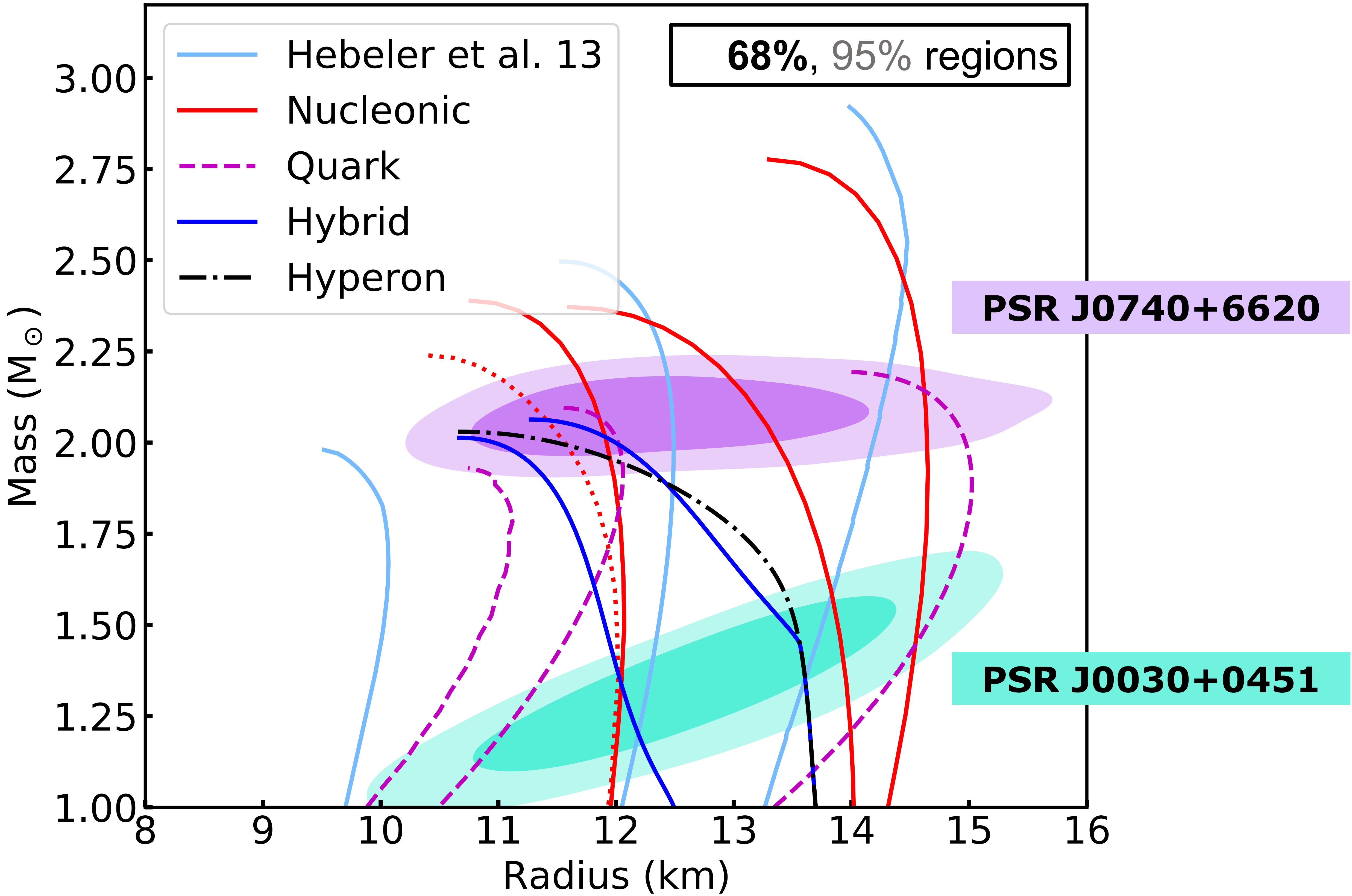


Movie: Sharon Morsink, NASA

NICER team J0740 papers

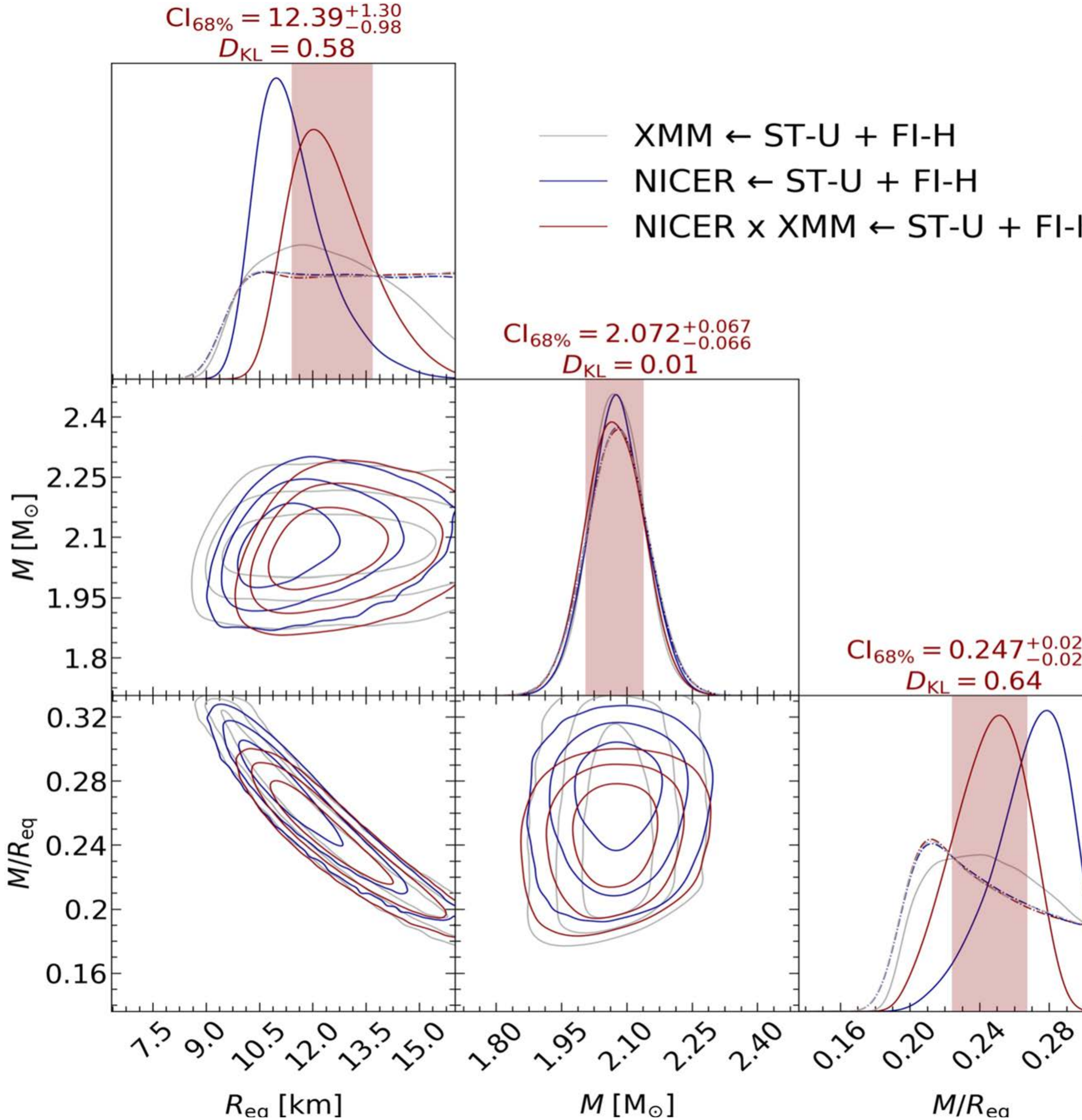
Wolff et al. 2021, Riley et al. 2021, Raaijmakers et al. 2021,
Miller et al. 2021, Salmi et al. 2022

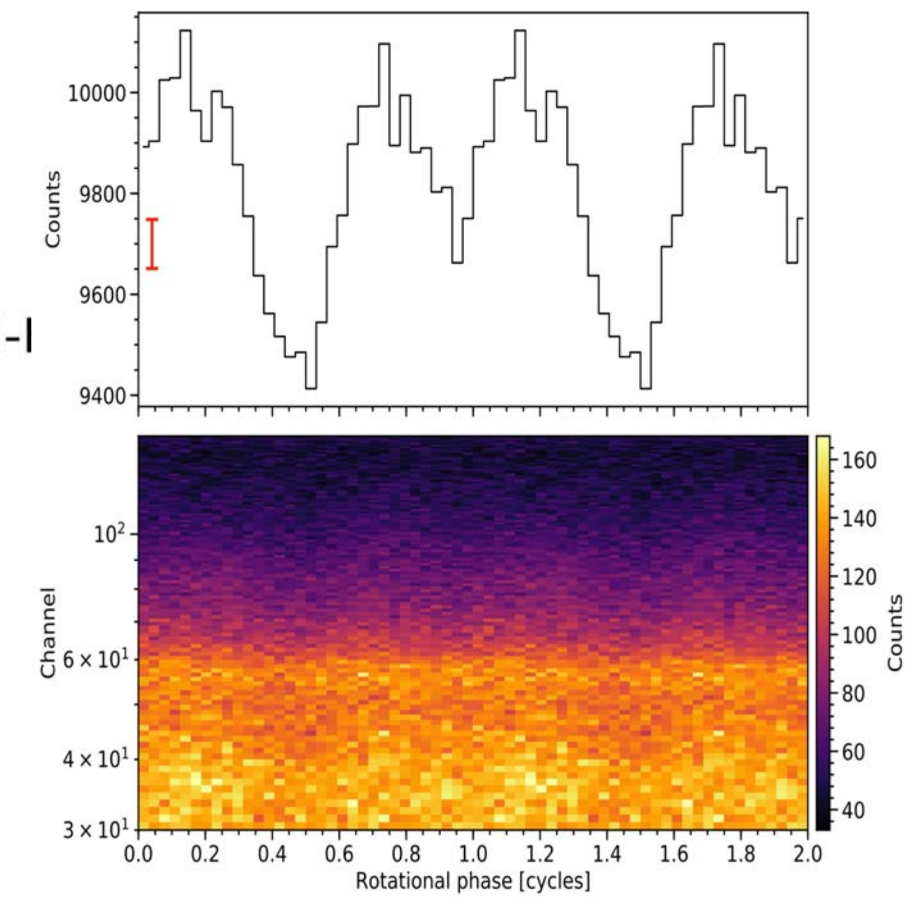
FROM SURFACE TO SUBSURFACE



NICER M-R Credible regions from Riley et al. 2019, 2021

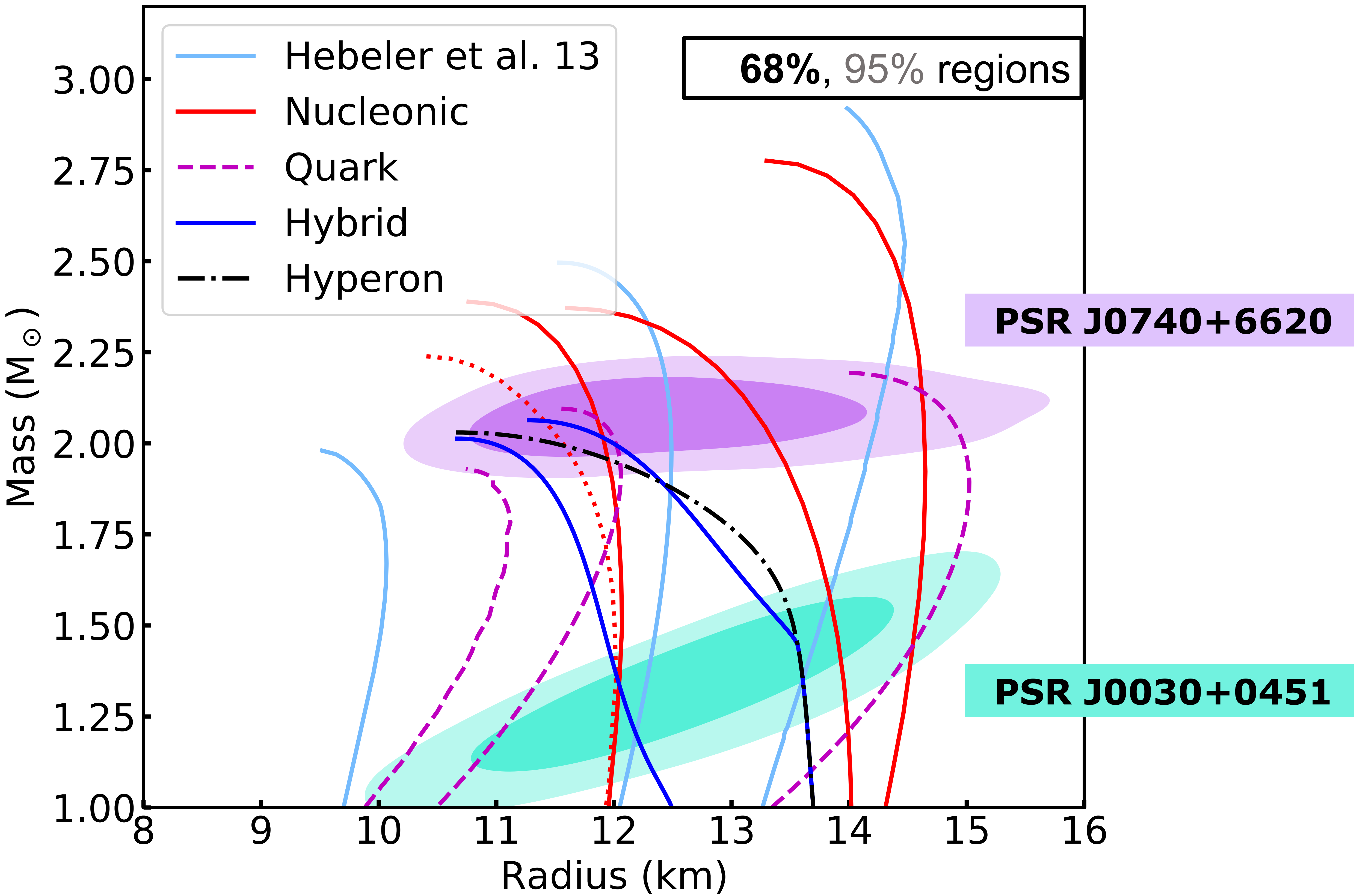
THE IMPORTANCE OF BACKGROUND





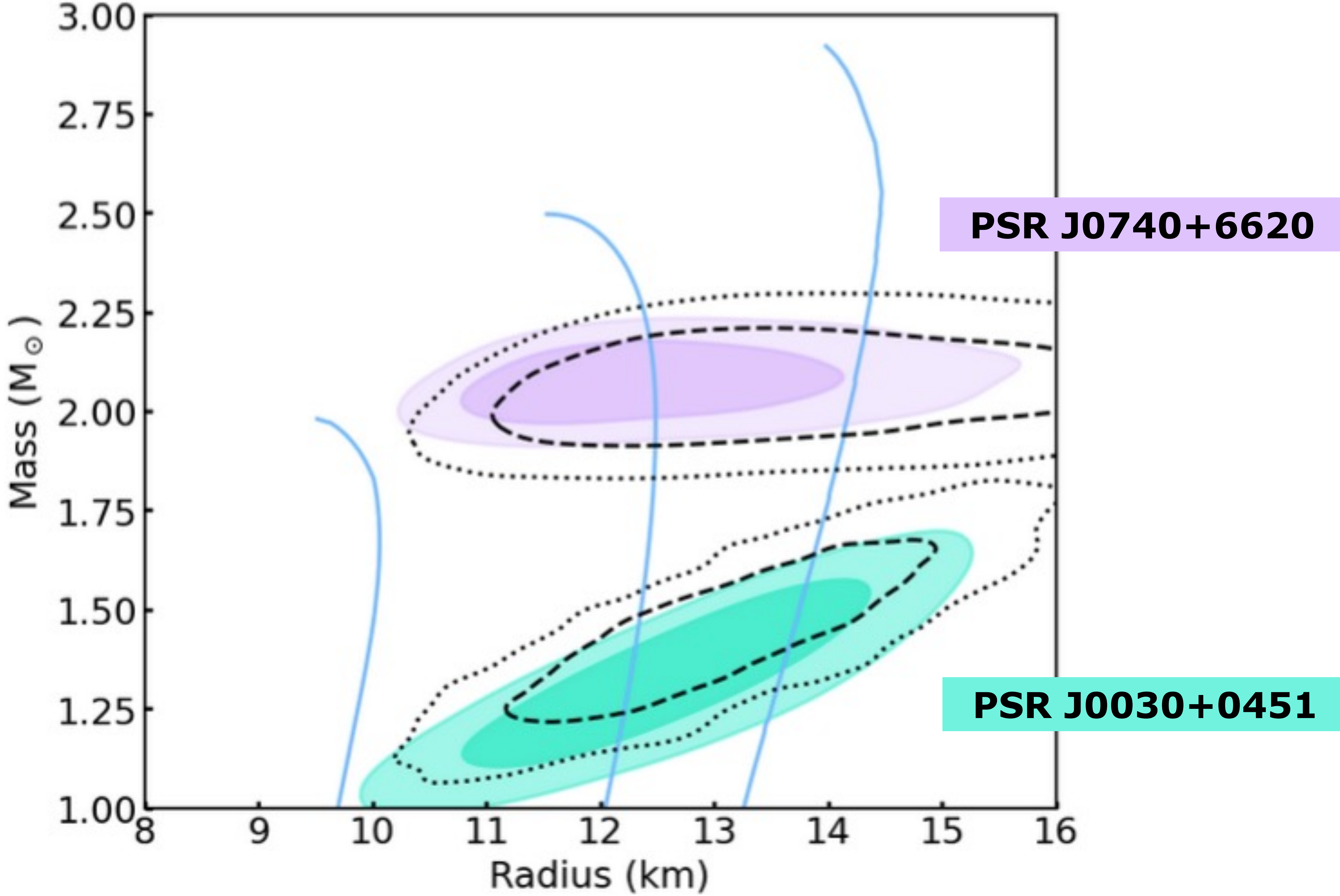
Riley et al. 2021,
Salmi et al. 2022

INFERRED MASS AND RADIUS



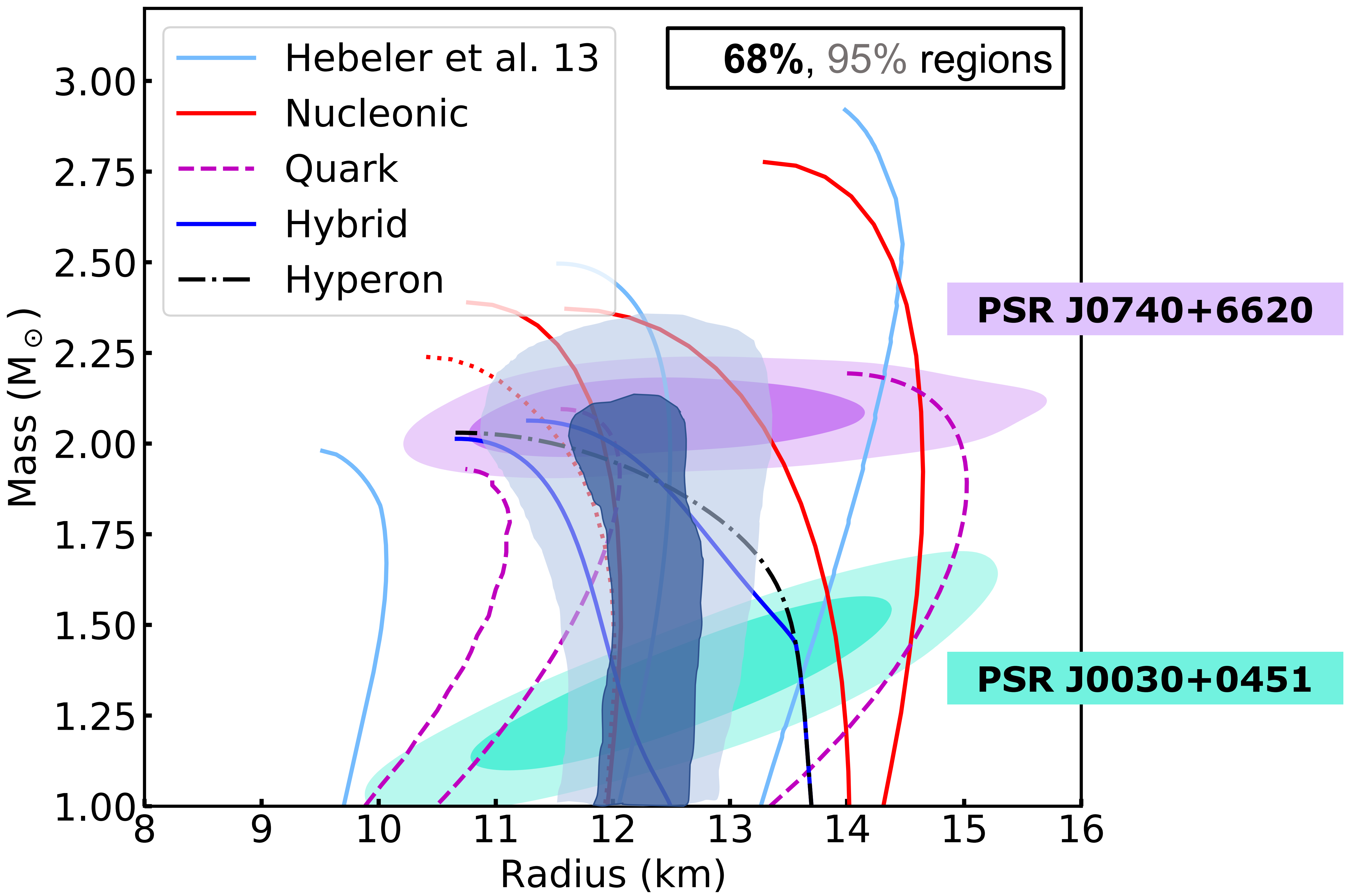
X-PSI Credible regions from Riley et al. 2019, 2021

INFERRED MASS AND RADIUS



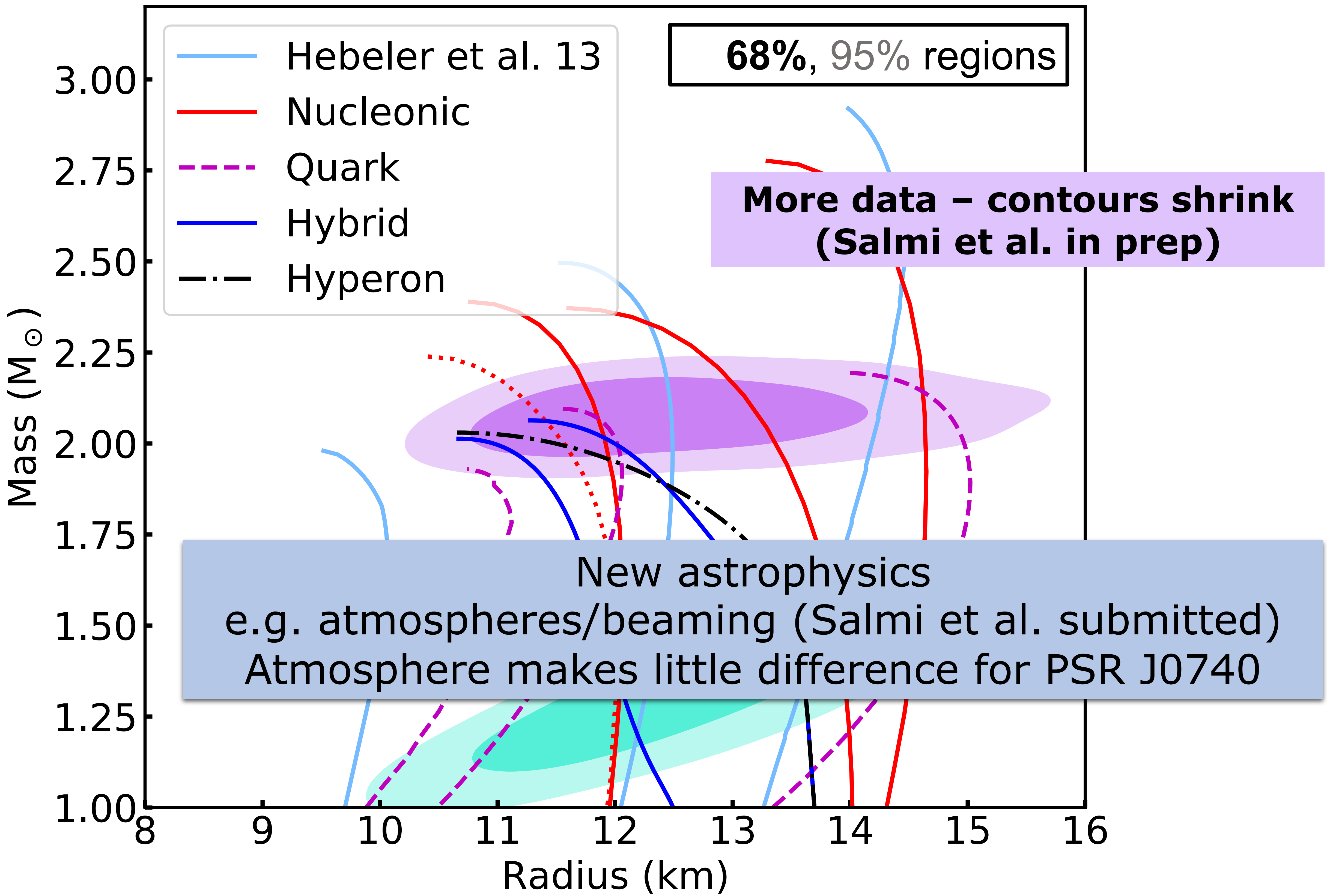
Now comparing Riley et al. 2019, 2021 to Miller et al. 2019, 2021

INFERRED EQUATION OF STATE



M-R relation (for a specific EOS parameterization) from Raaijmakers et al. 2021

WHAT'S NEXT FOR PSR J0740+6620?



X-PSI Credible regions from Riley et al. 2021, Salmi et al. 2022

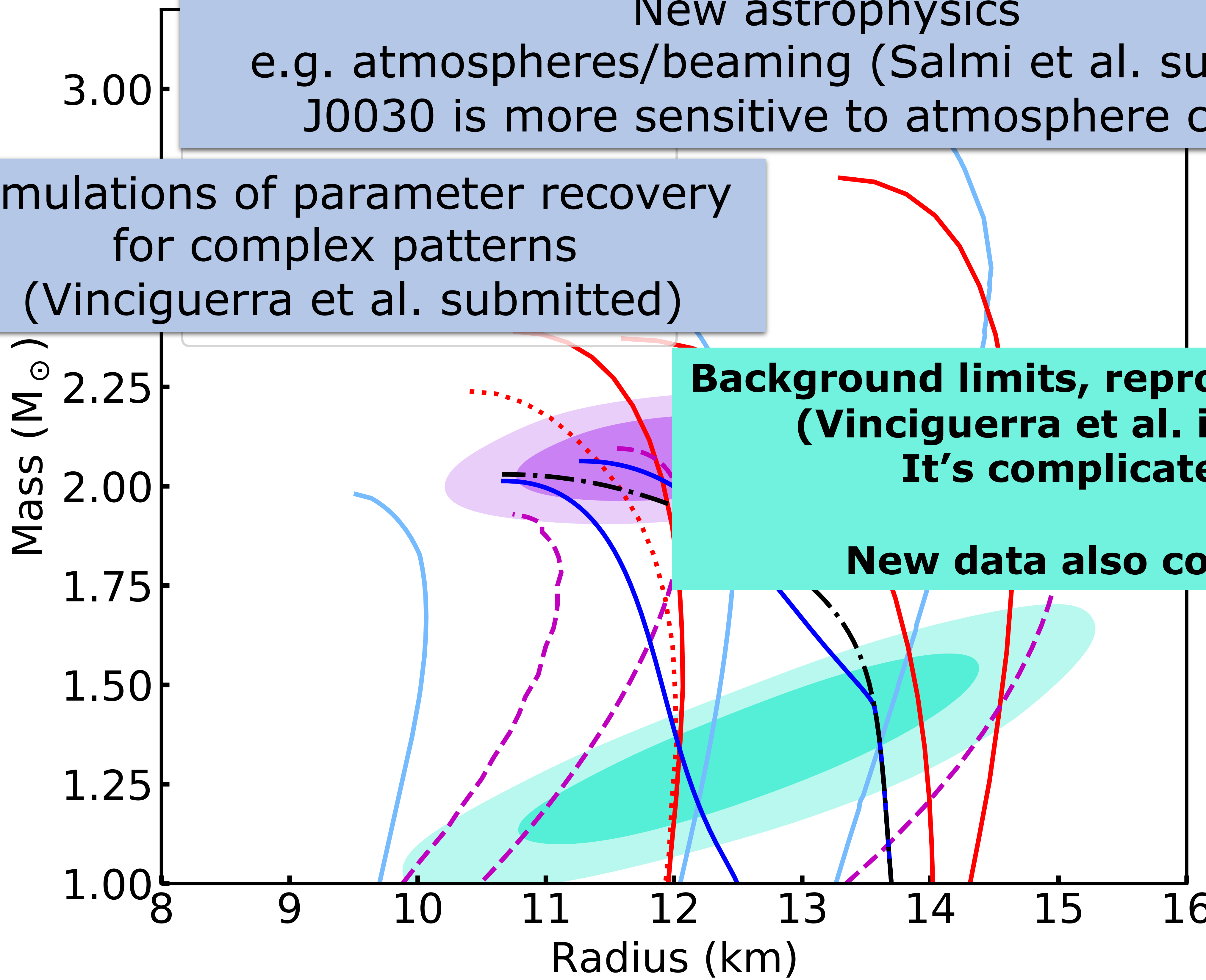
WHAT'S NEXT FOR PSR J0030+0451?

New astrophysics
e.g. atmospheres/beaming (Salmi et al. submitted)
J0030 is more sensitive to atmosphere choices

Simulations of parameter recovery
for complex patterns
(Vinciguerra et al. submitted)

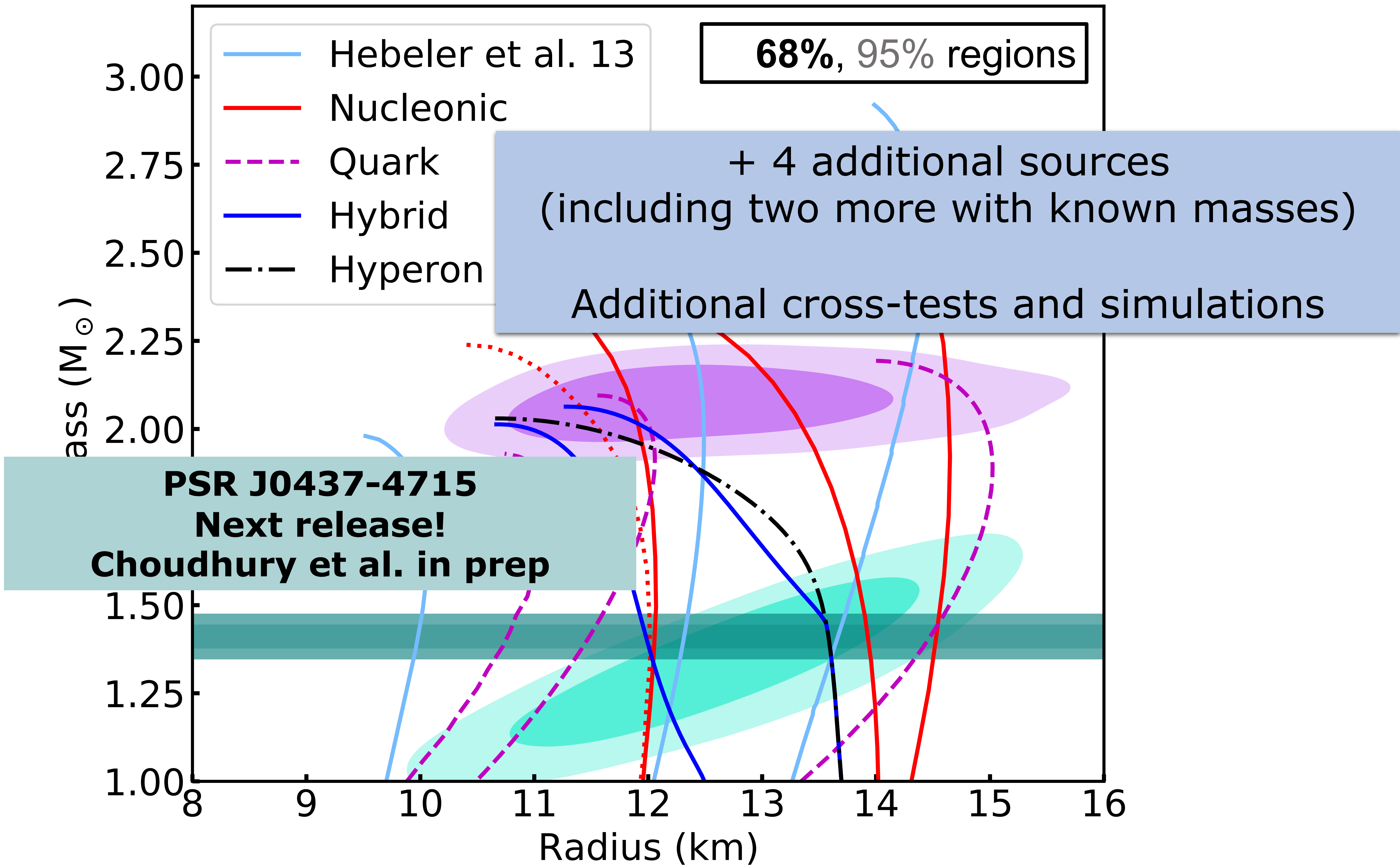
Background limits, reprocessed data
(Vinciguerra et al. in prep)
It's complicated!

New data also coming



X-PSI Credible regions from Riley et al. 2019

WHAT'S NEXT FOR NICER?



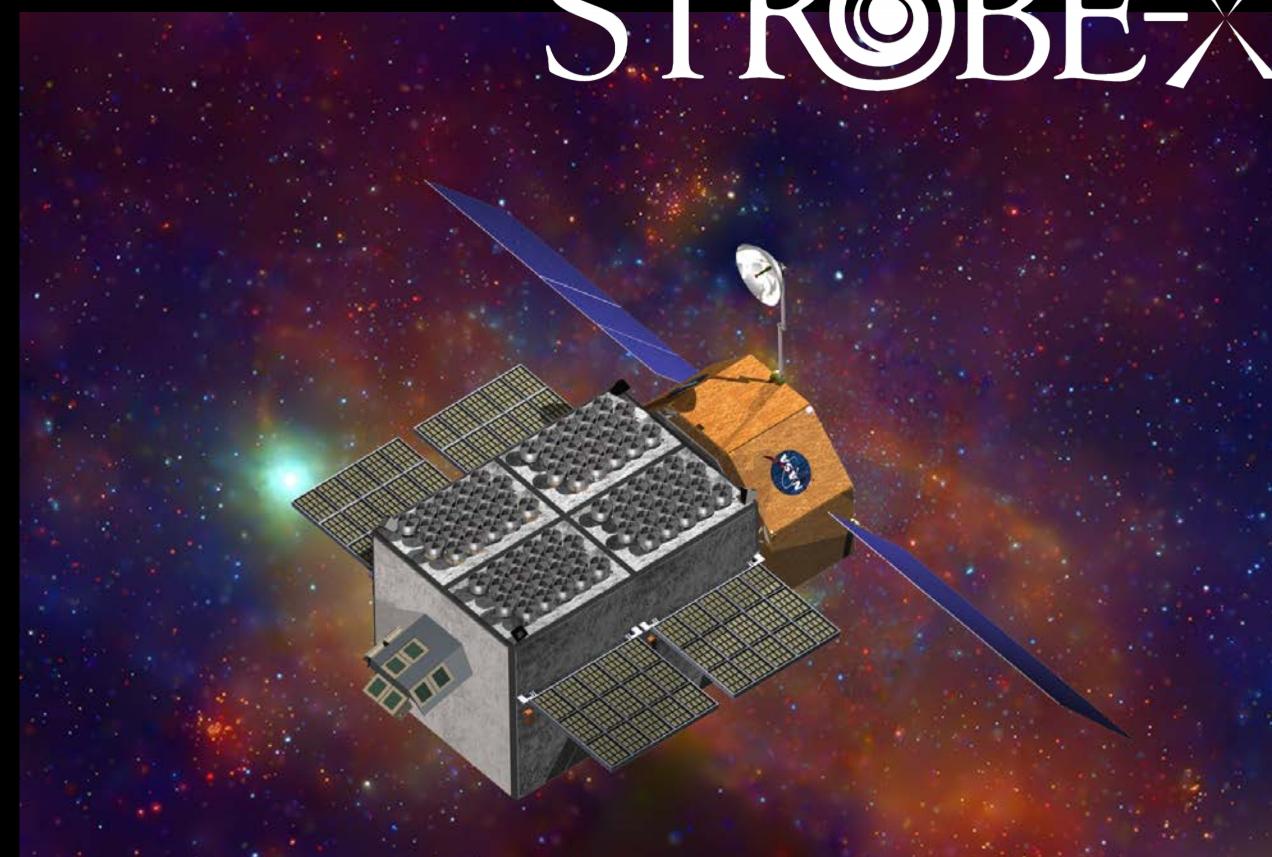
LARGE AREA X-RAY SPECTRAL-TIMING

New telescopes are being proposed –
larger area, wider X–ray band than NICER

eXTP

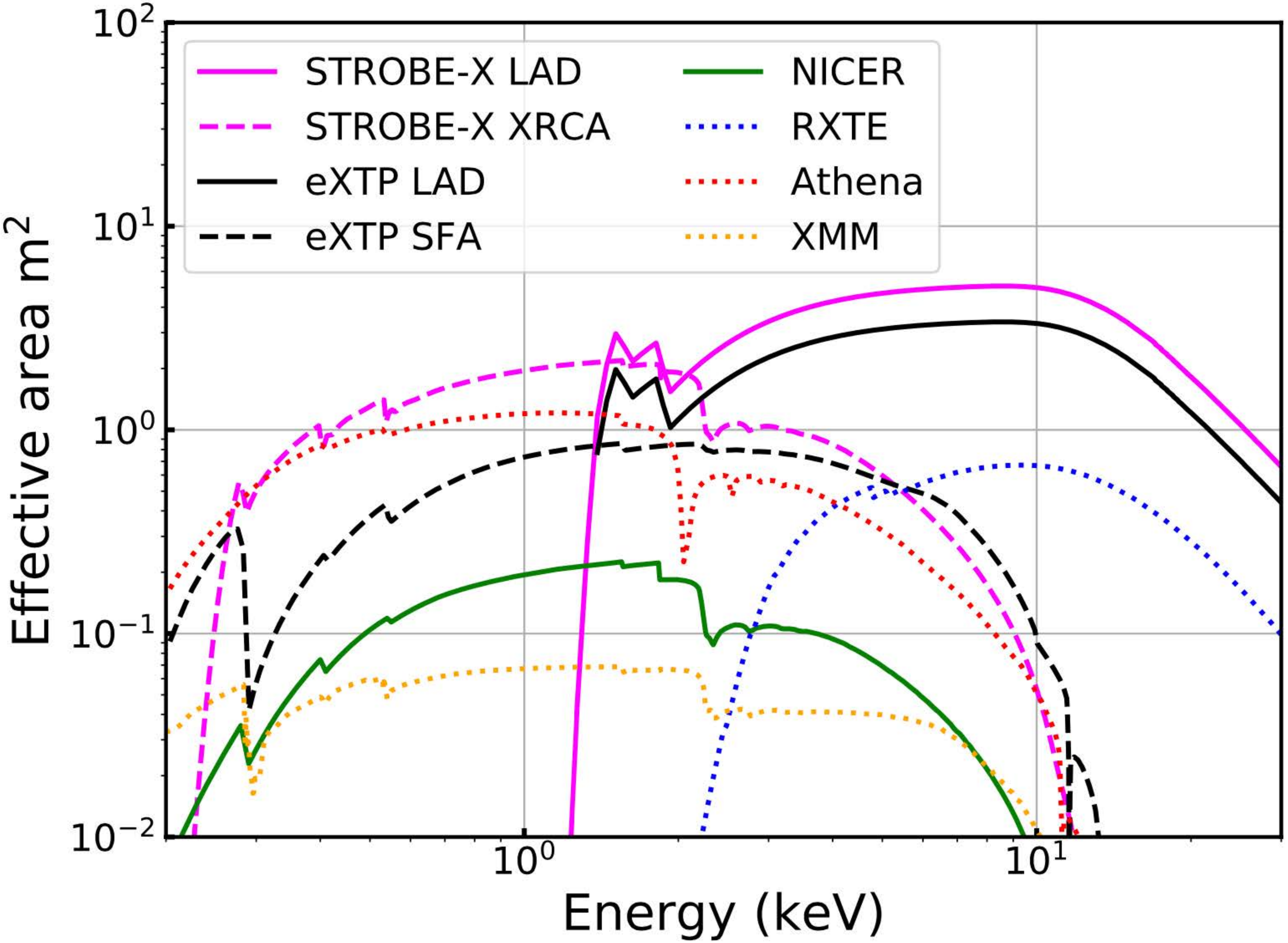
Chinese-European project
Zhang et al. 2019

STROBE-X



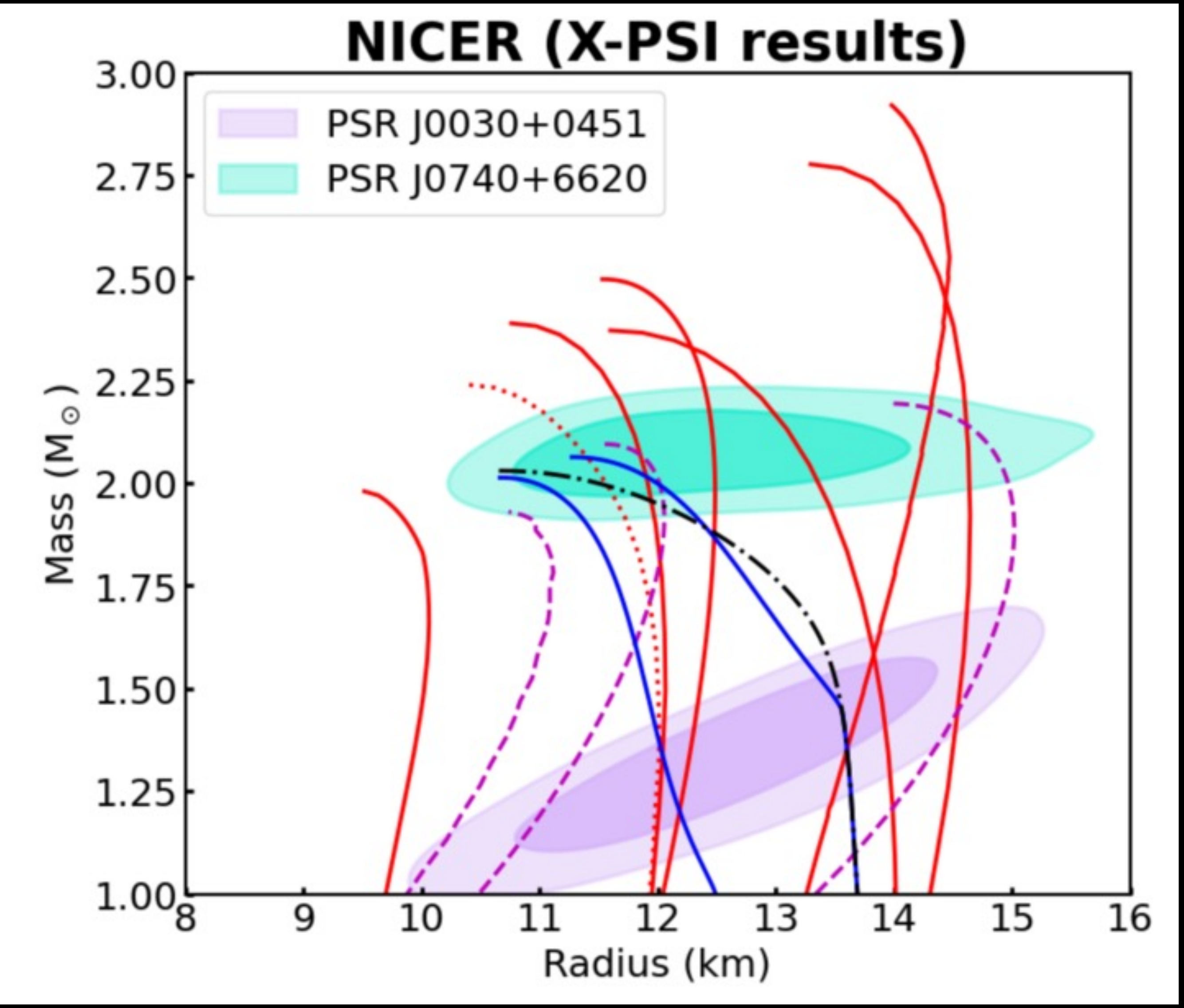
NASA probe-class proposal
Ray et al. 2019, @strobexastro

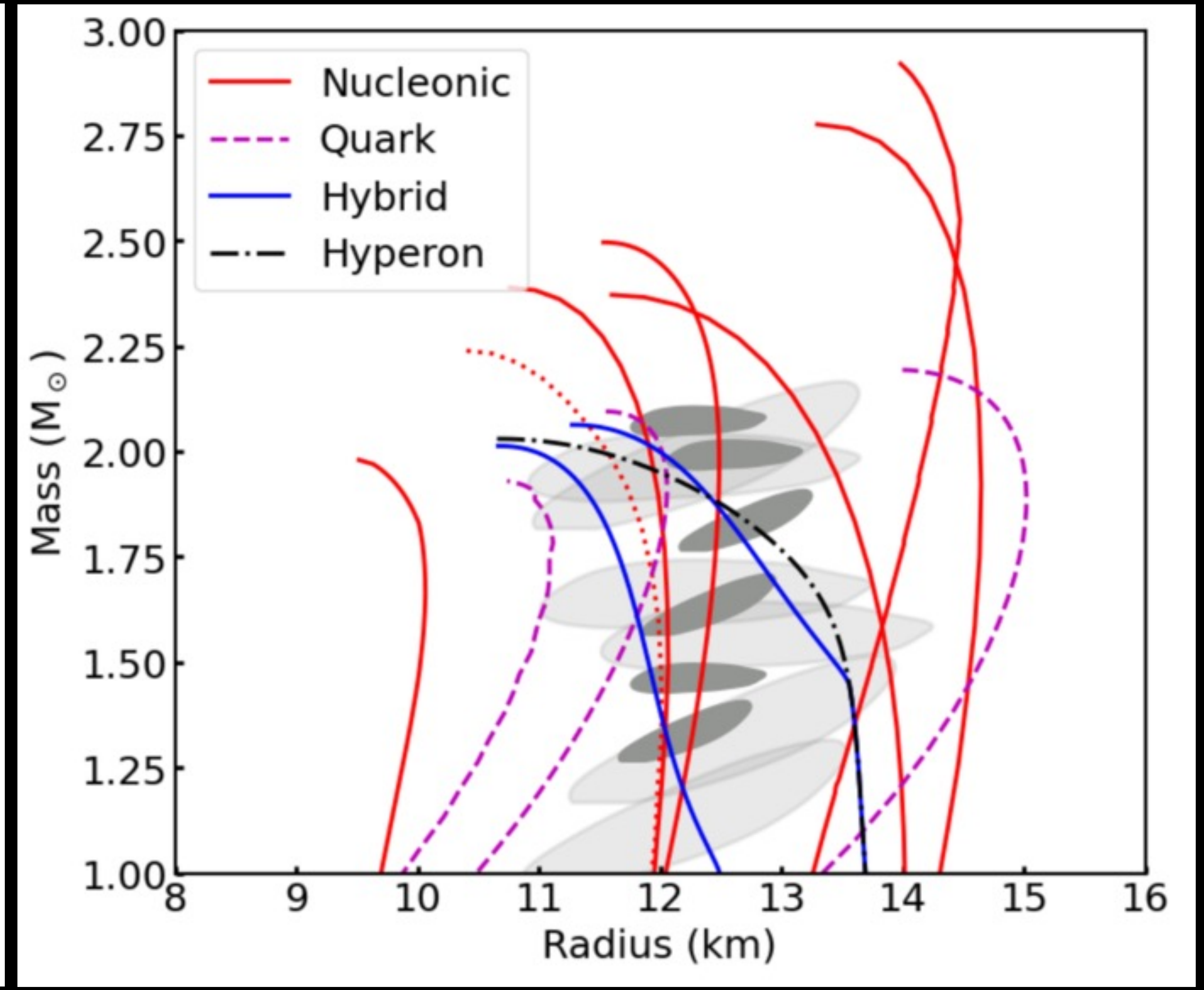
Analysis pipelines being developed and tested using
simulated and real (NICER/RXTE) data



STROBE-X LAD
STROBE-X XRCA
eXTP LAD
eXTP SFA
NICER
RXTE
Athena
XMM
Effective area m^2
Energy (keV)
10^2
10^1
10^0
10^{-1}
10^{-2}
10^0
10^1

STROBE-X/EXTP PROSPECTS





95% credible regions shown

Three different classes of neutron star: rotation-powered millisecond pulsars (more with mass priors), accretion-powered pulsars, thermonuclear burst oscillation sources.

Initial survey at +/-5%, run cross-checks to address any systematics. Deep observations to hit +/-2% for most promising sources.