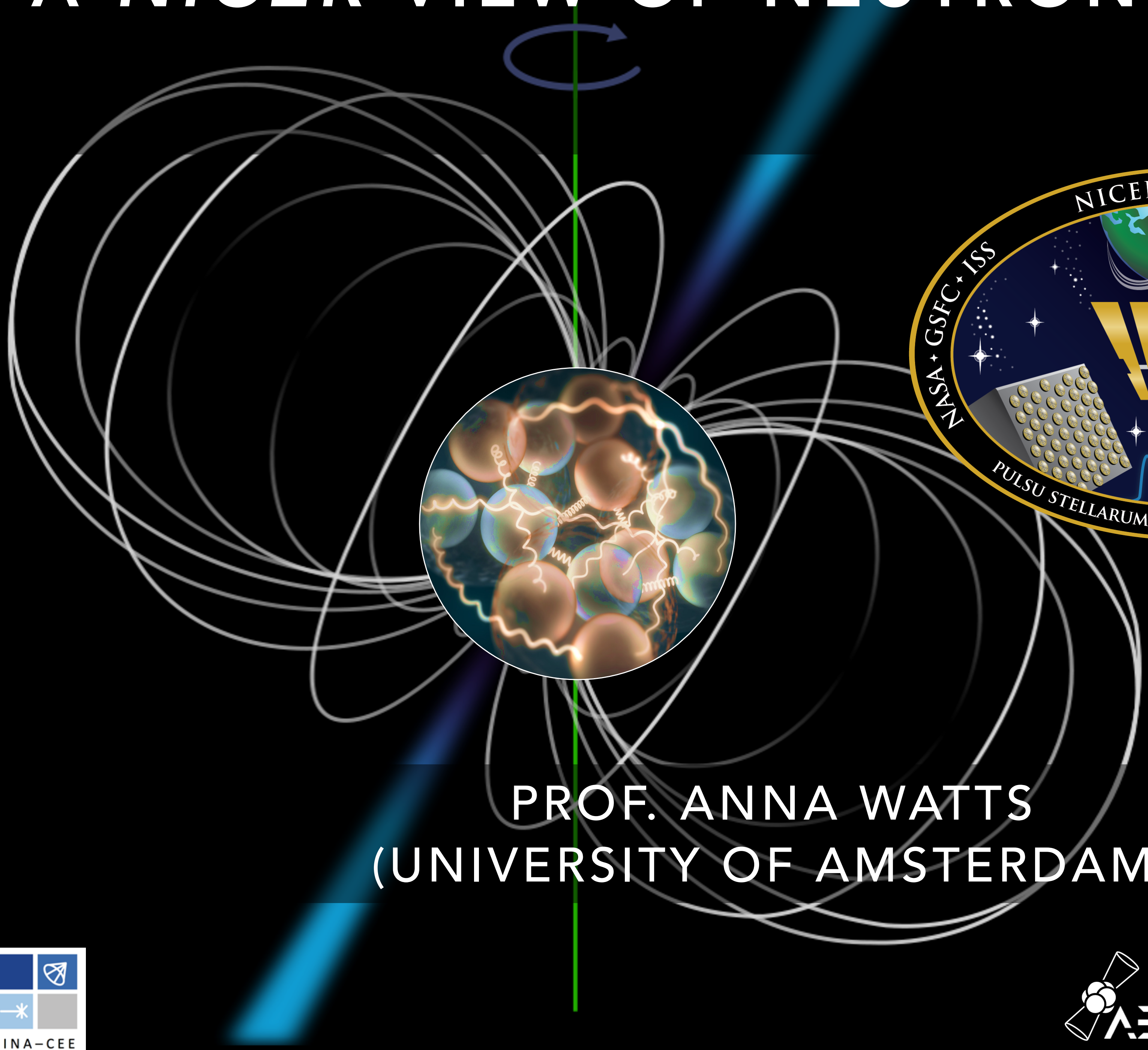
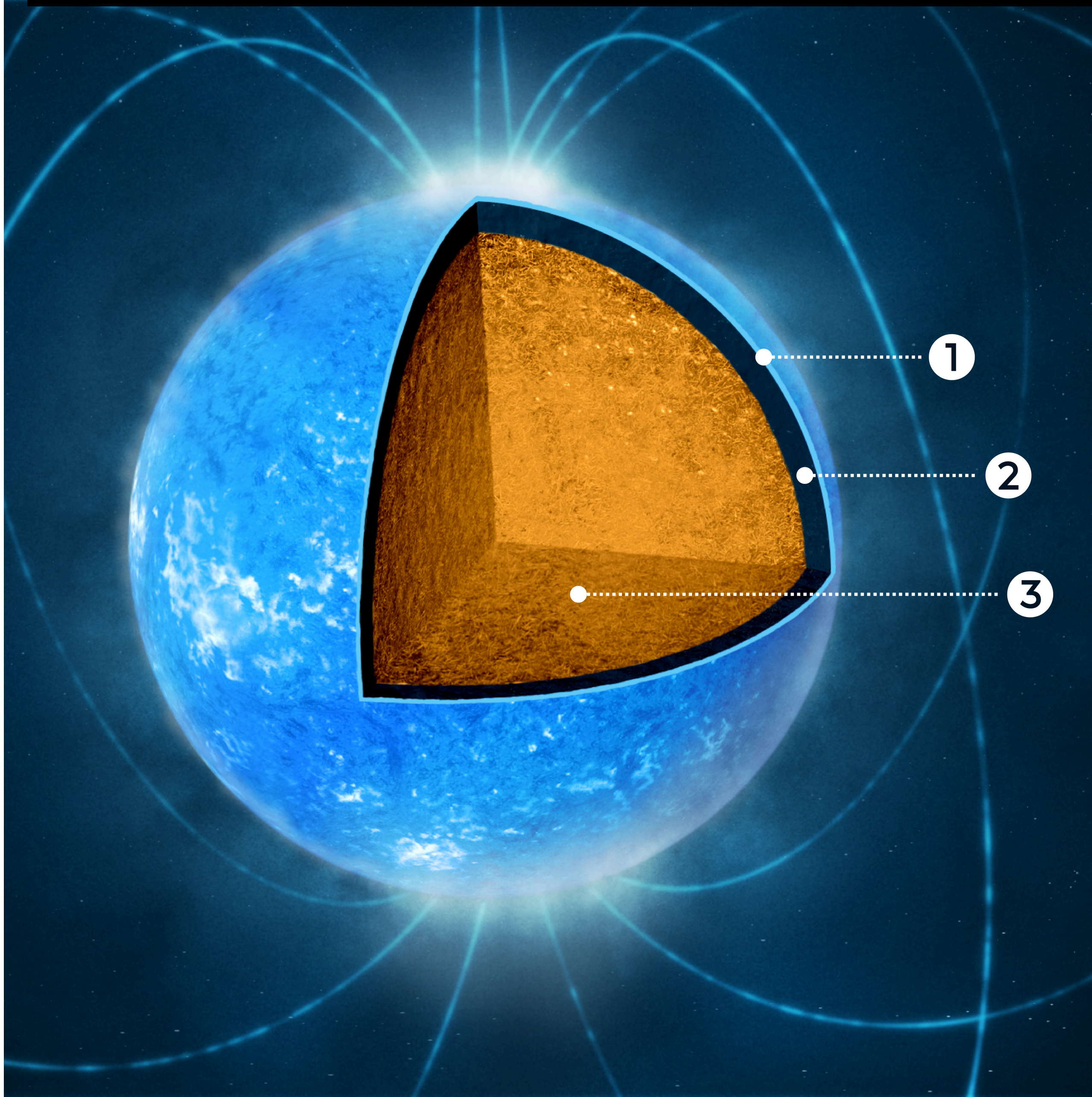
A *NICER* VIEW OF NEUTRON STARS



PROF. ANNA WATTS
(UNIVERSITY OF AMSTERDAM)

THE NEUTRON STAR INTERIOR



1 | OUTER CRUST

NUCLEI
ELECTRONS

2 | INNER CRUST

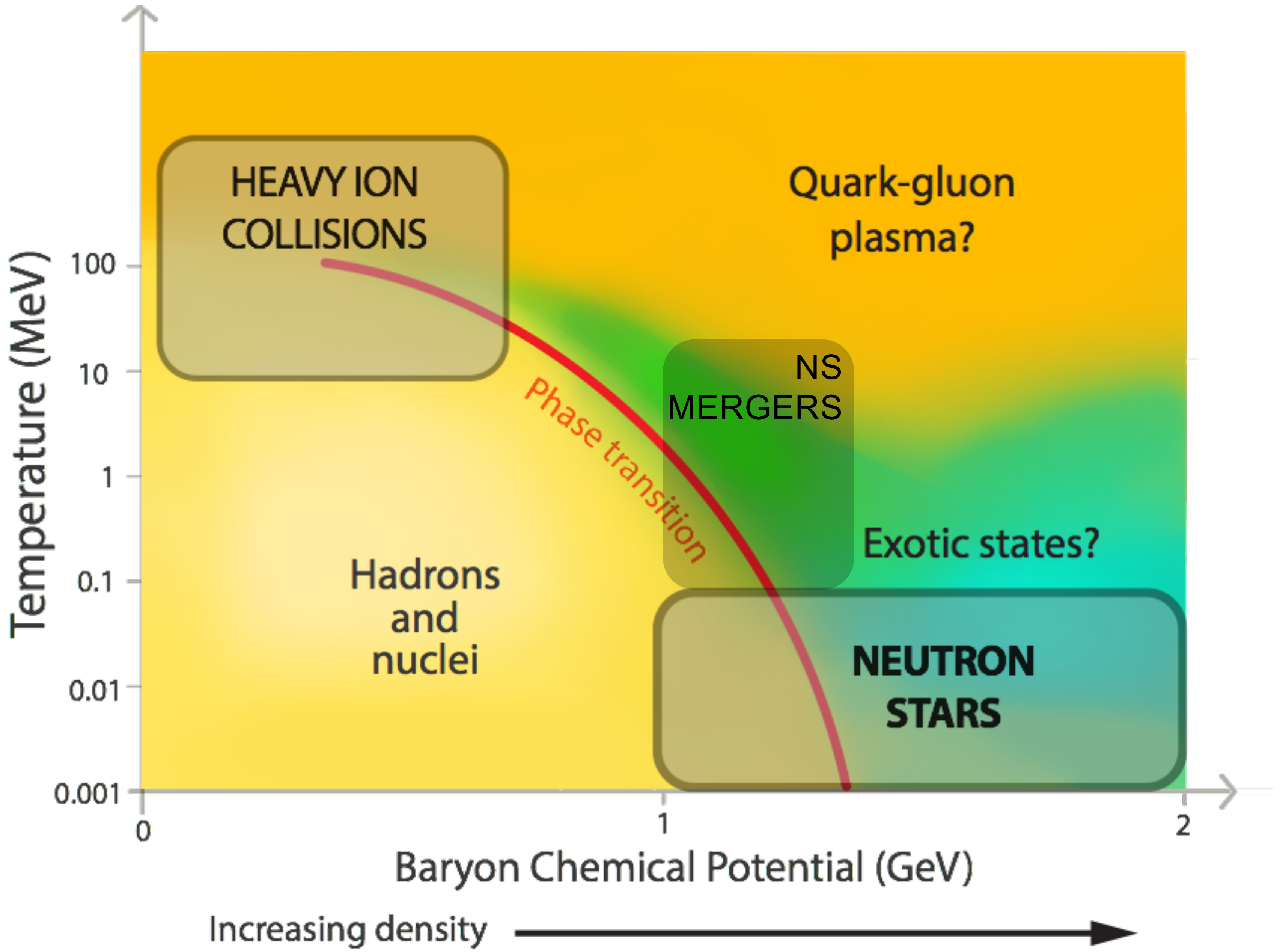
NUCLEI
ELECTRONS
SUPERFLUID NEUTRONS

3 | CORE

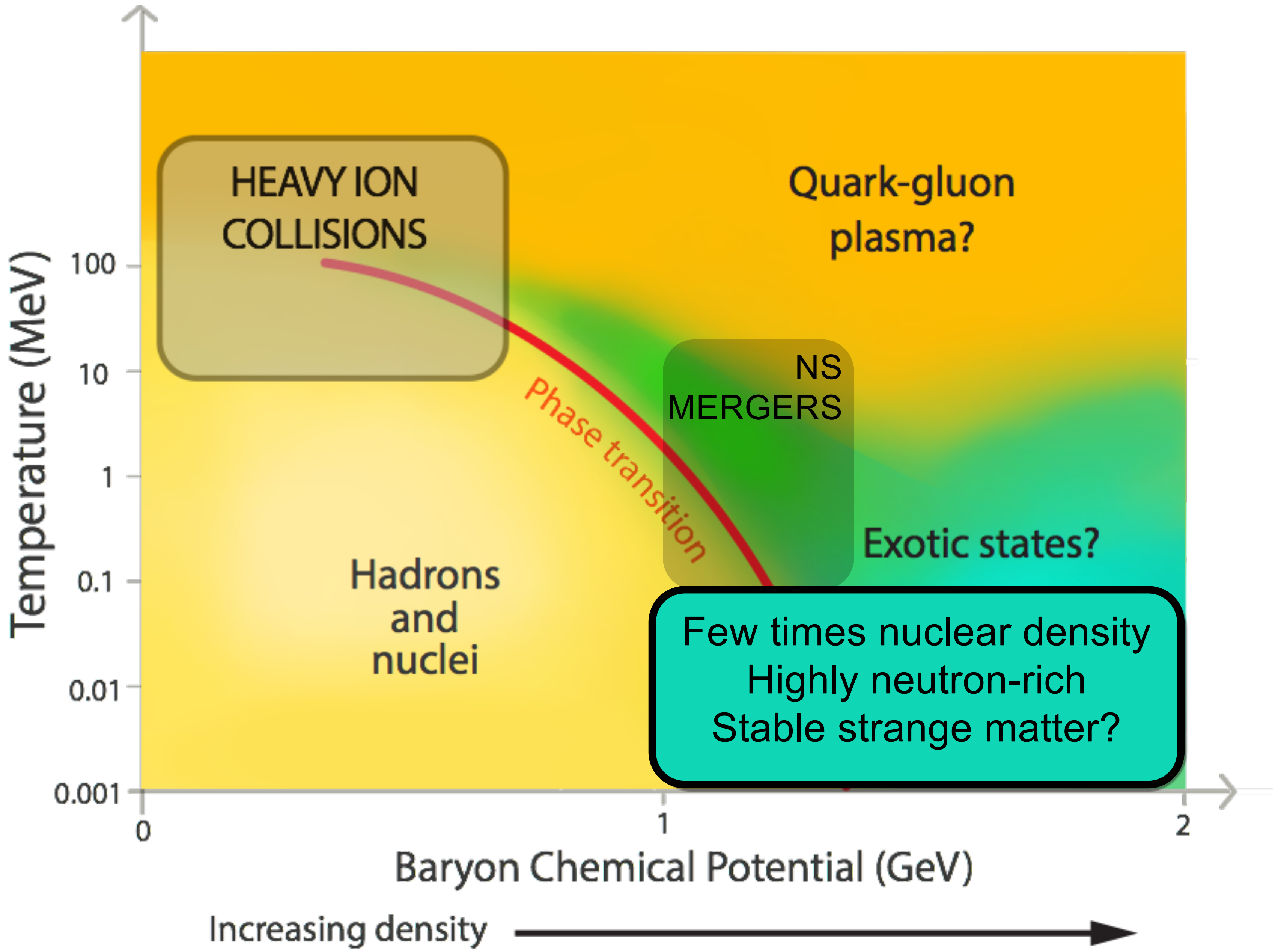
SUPERFLUID NEUTRONS
SUPERCONDUCTING PROTONS
HYPERONS?
DECONFINED QUARKS?
COLOR SUPERCONDUCTOR?

Figure: Watts et al. 2016

UNKNOWNS IN STRONG FORCE PHYSICS



UNKNOWNS IN STRONG FORCE PHYSICS



FROM NUCLEAR PHYSICS TO TELESCOPE

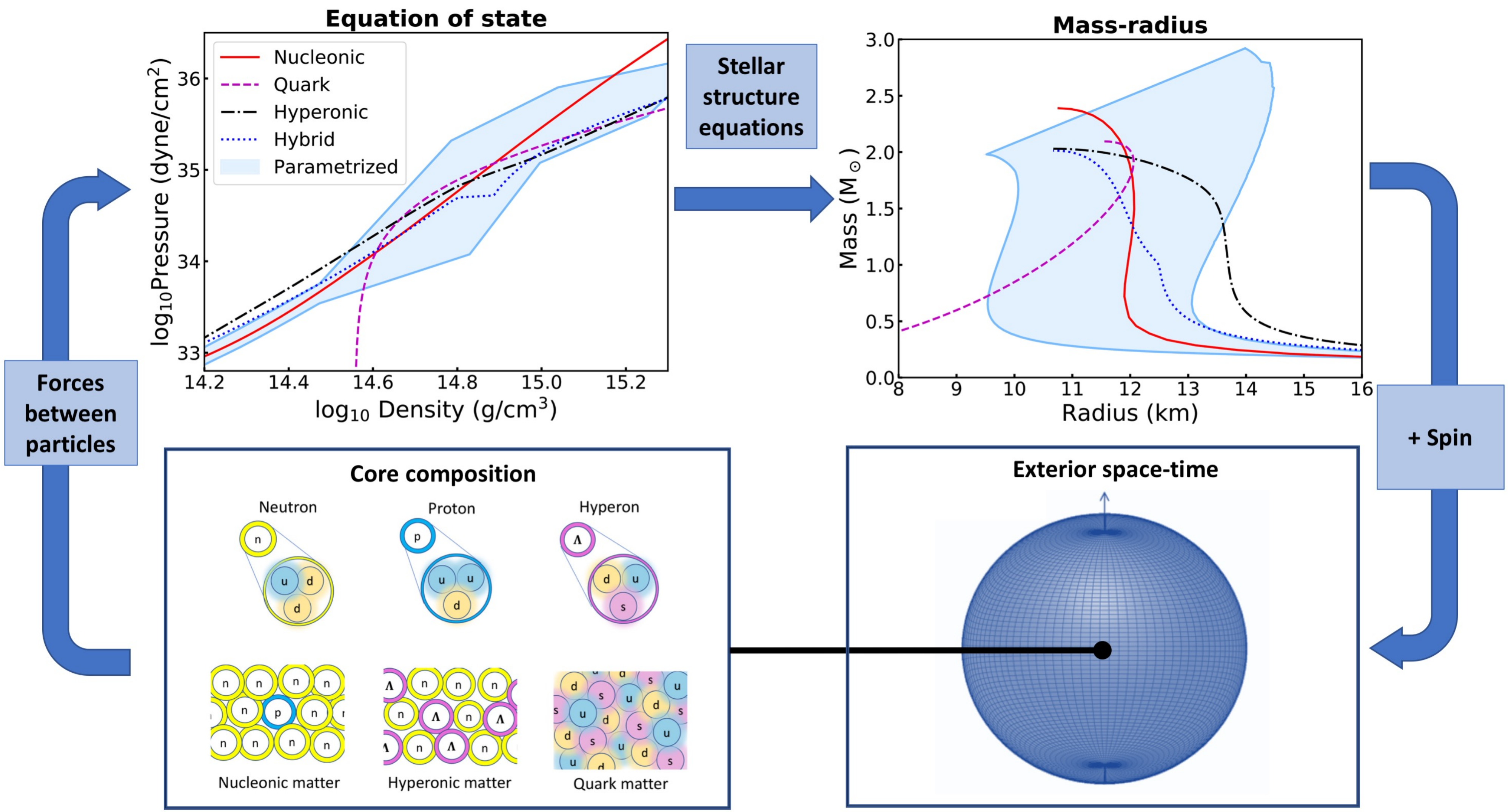


Figure: Adapted from Ray et al. 2019

NICER PRE-LAUNCH

Photo: Keith Gendreau (NASA)

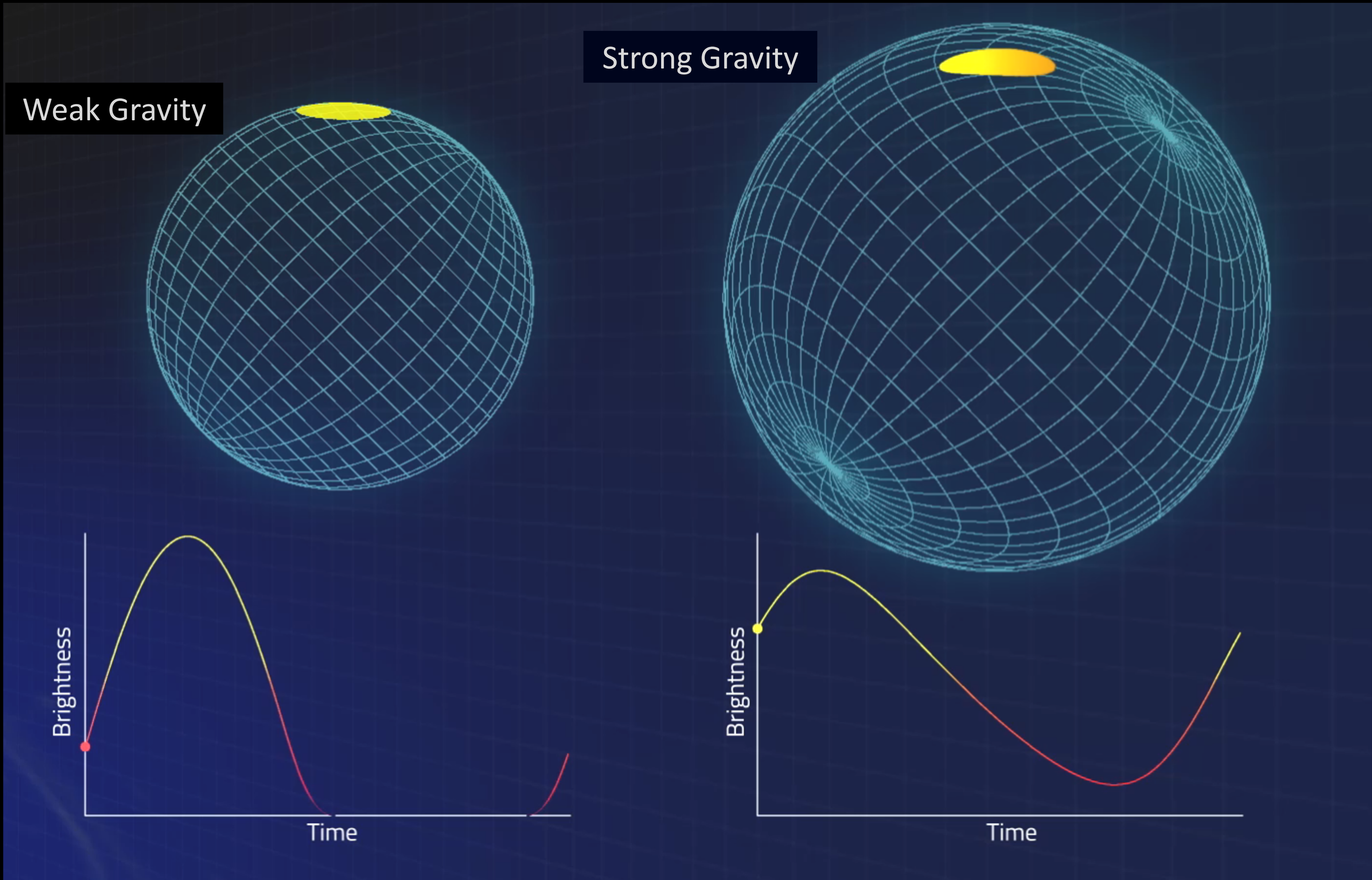
NICER LAUNCH

NICER ON THE ISS

Movie of NICER on the International Space Station

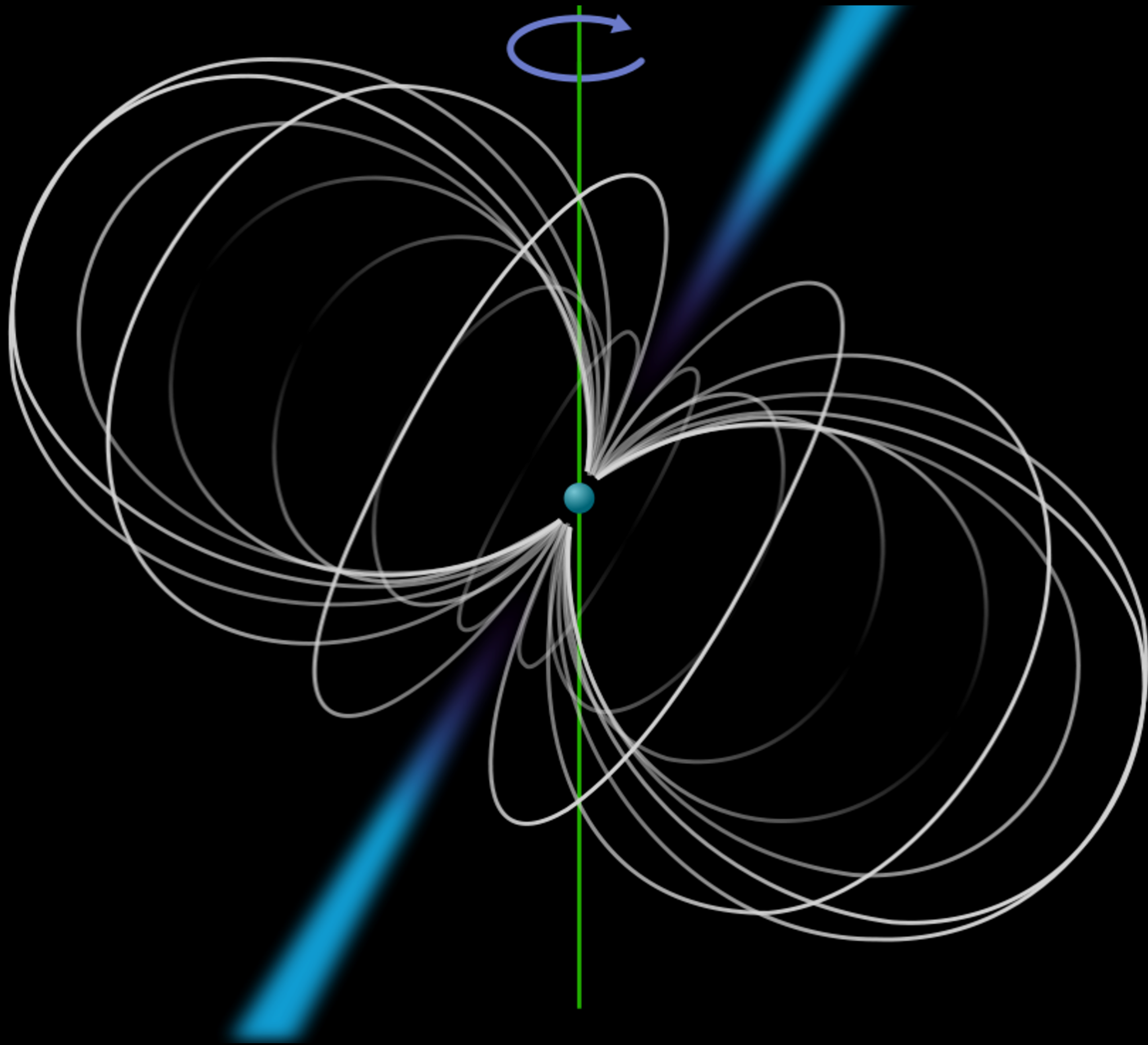
https://www.youtube.com/watch?v=kk0ry3_R2pE

PULSE PROFILE MODELING

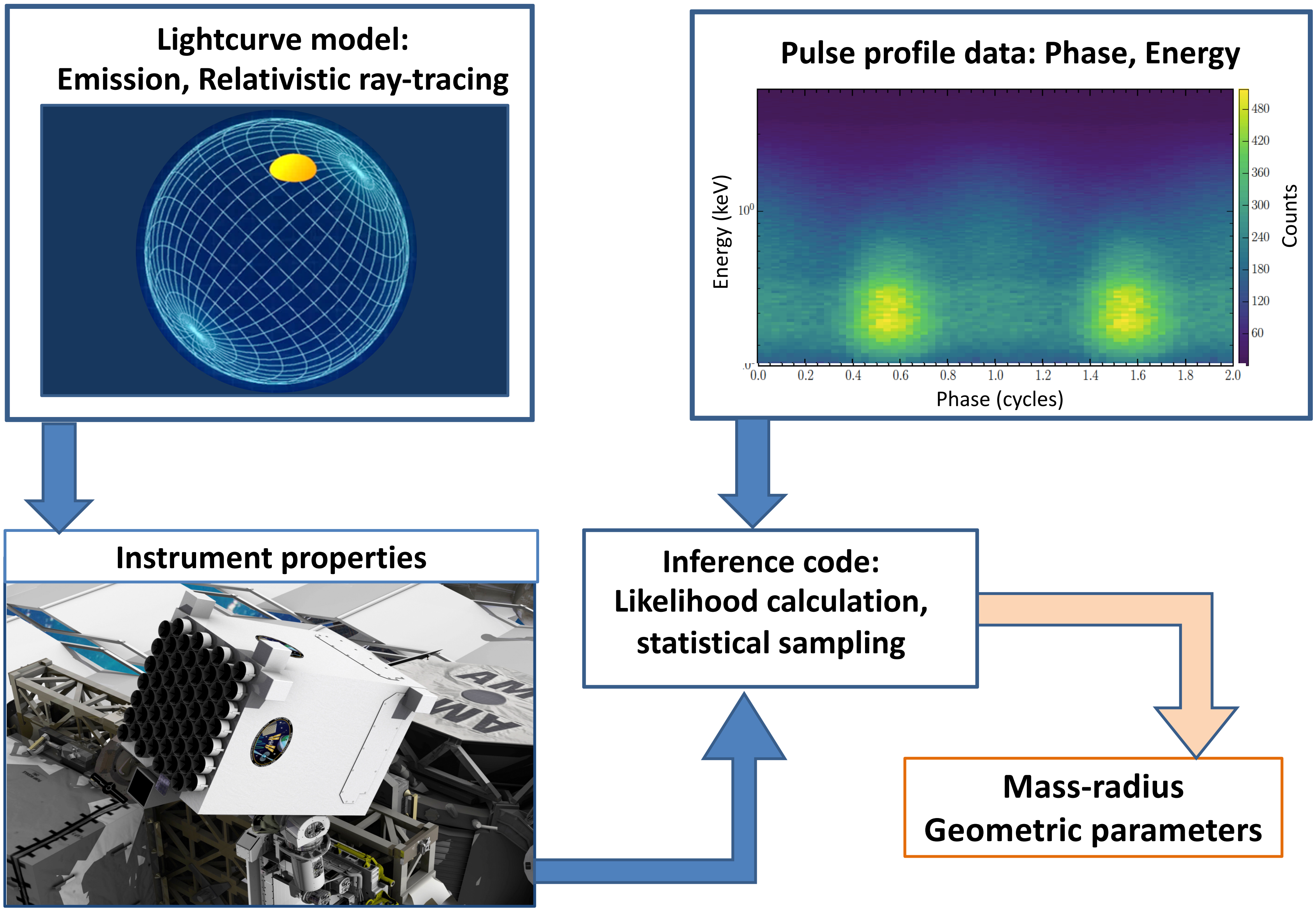


Credit: Morsink/Moir/Arzoumanian/NASA-GSFC

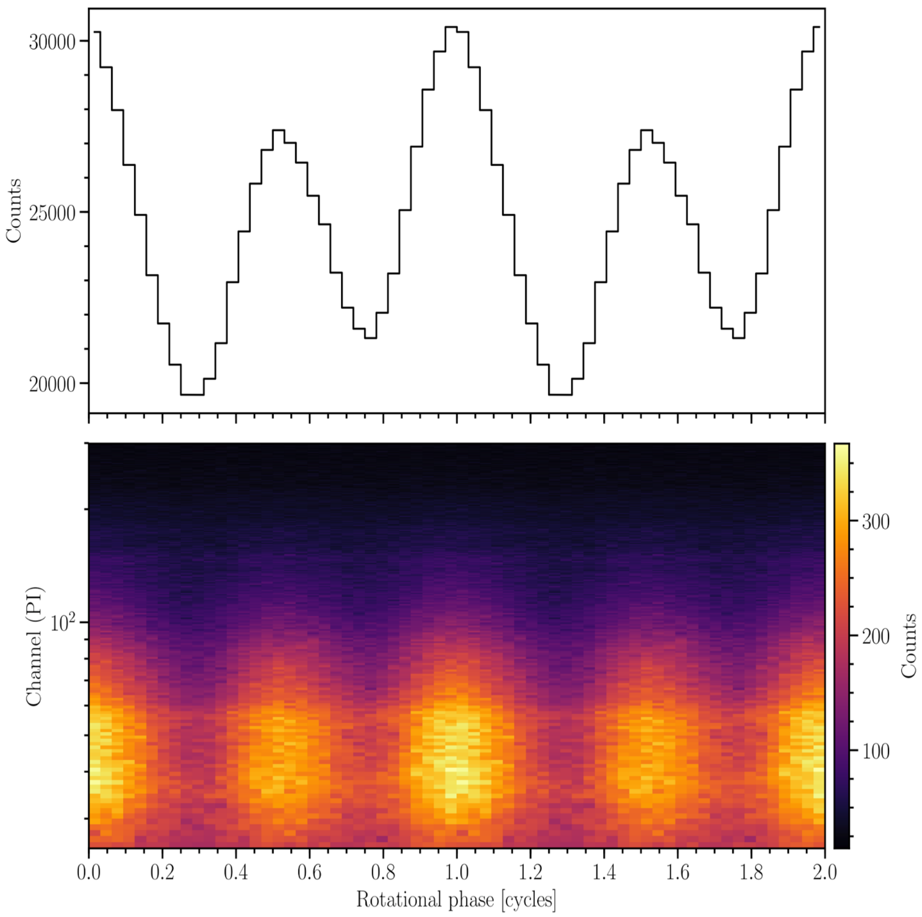
ROTATION-POWERED MILLISECOND X-RAY PULSARS



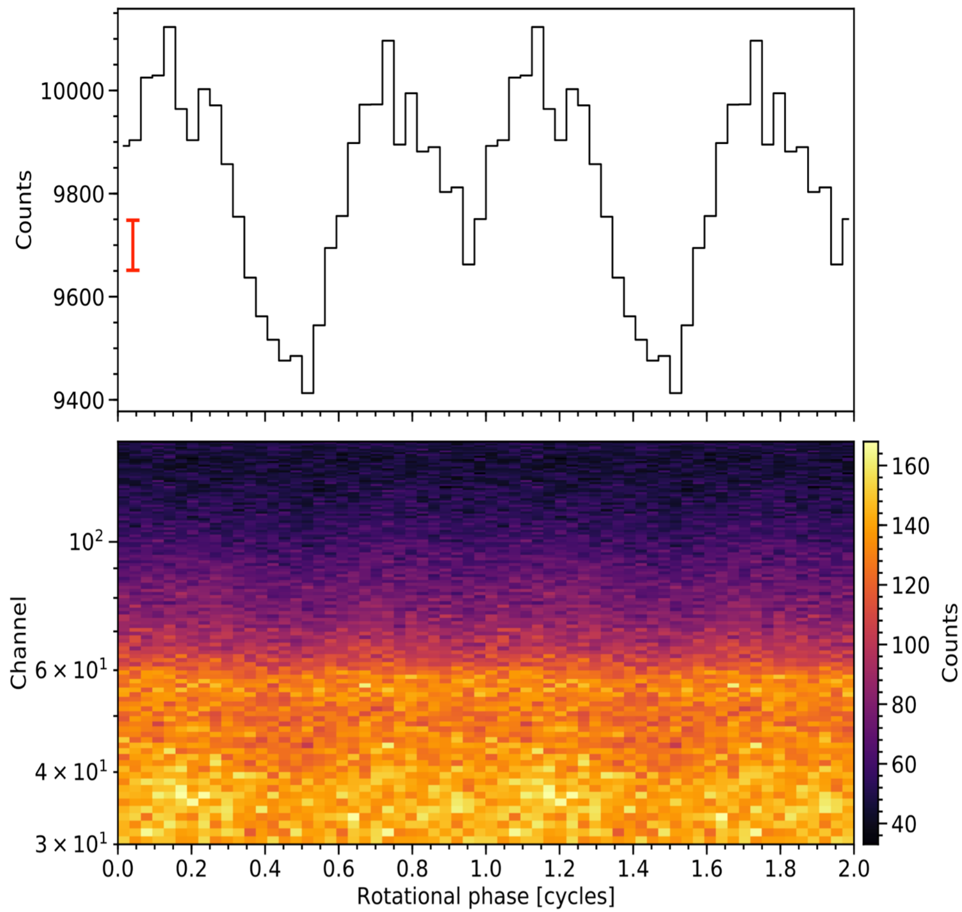
THE PULSE PROFILE MODELING PROCESS



PULSE PROFILE DATA



PSR J0030+0451
(Bogdanov et al. 2019)



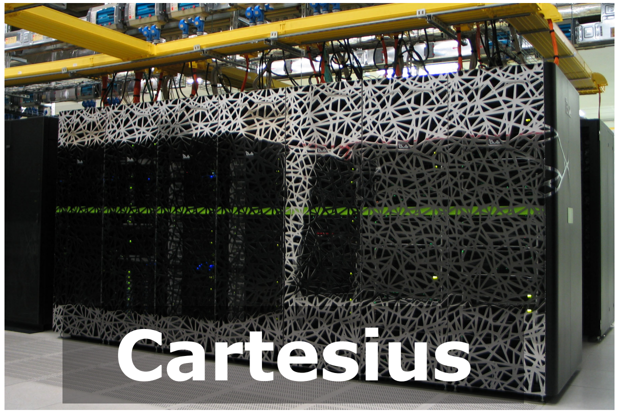
PSR J0740+6620
(Wolff et al. 2021)

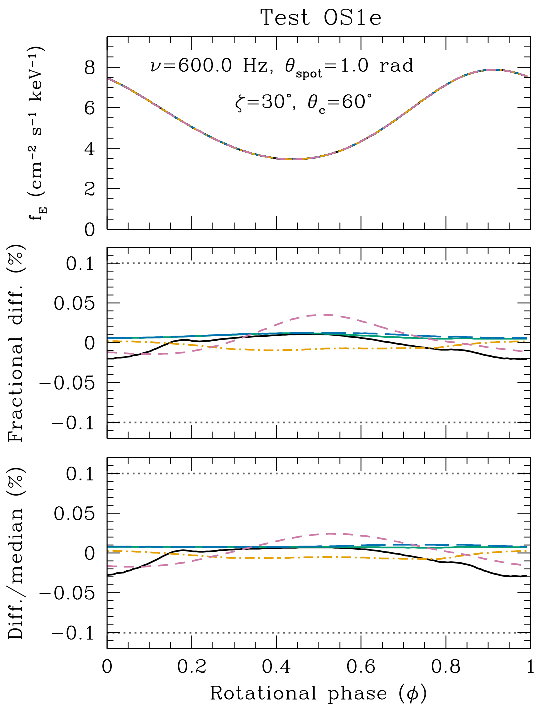
SIMULATION AND INFERENCE CODES

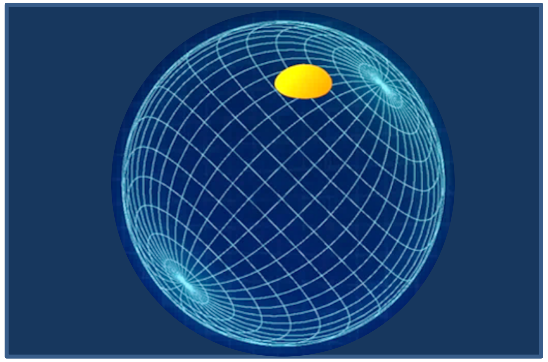
X-PSI

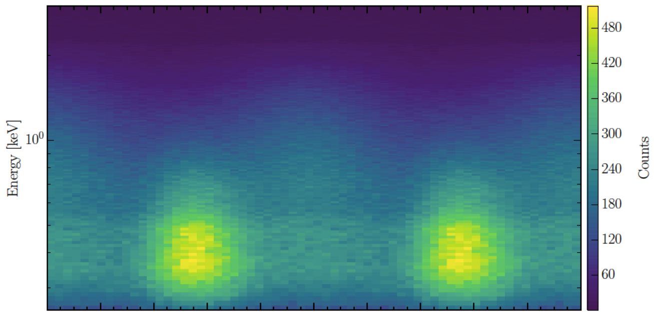
X-ray Pulse Simulation
and Inference package
https://xpsi-group.github.io/xpsi/

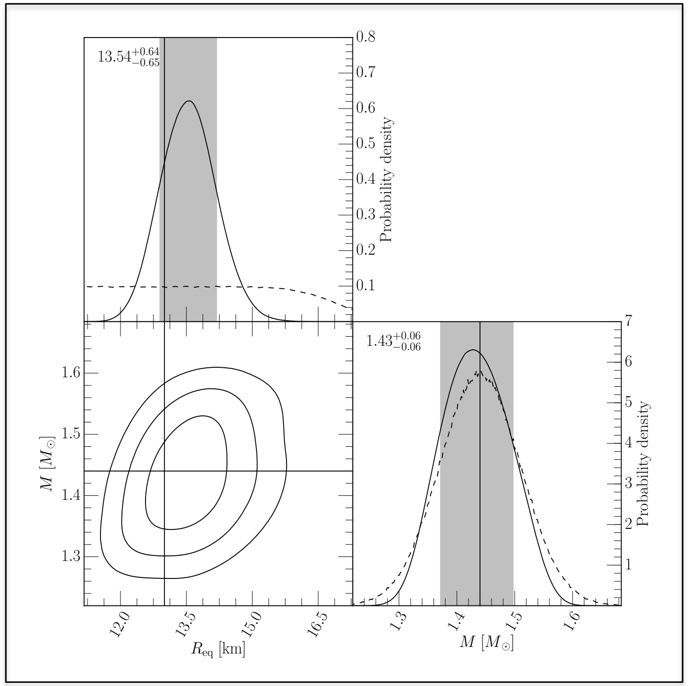
Uses open source samplers
(primarily MultiNest).







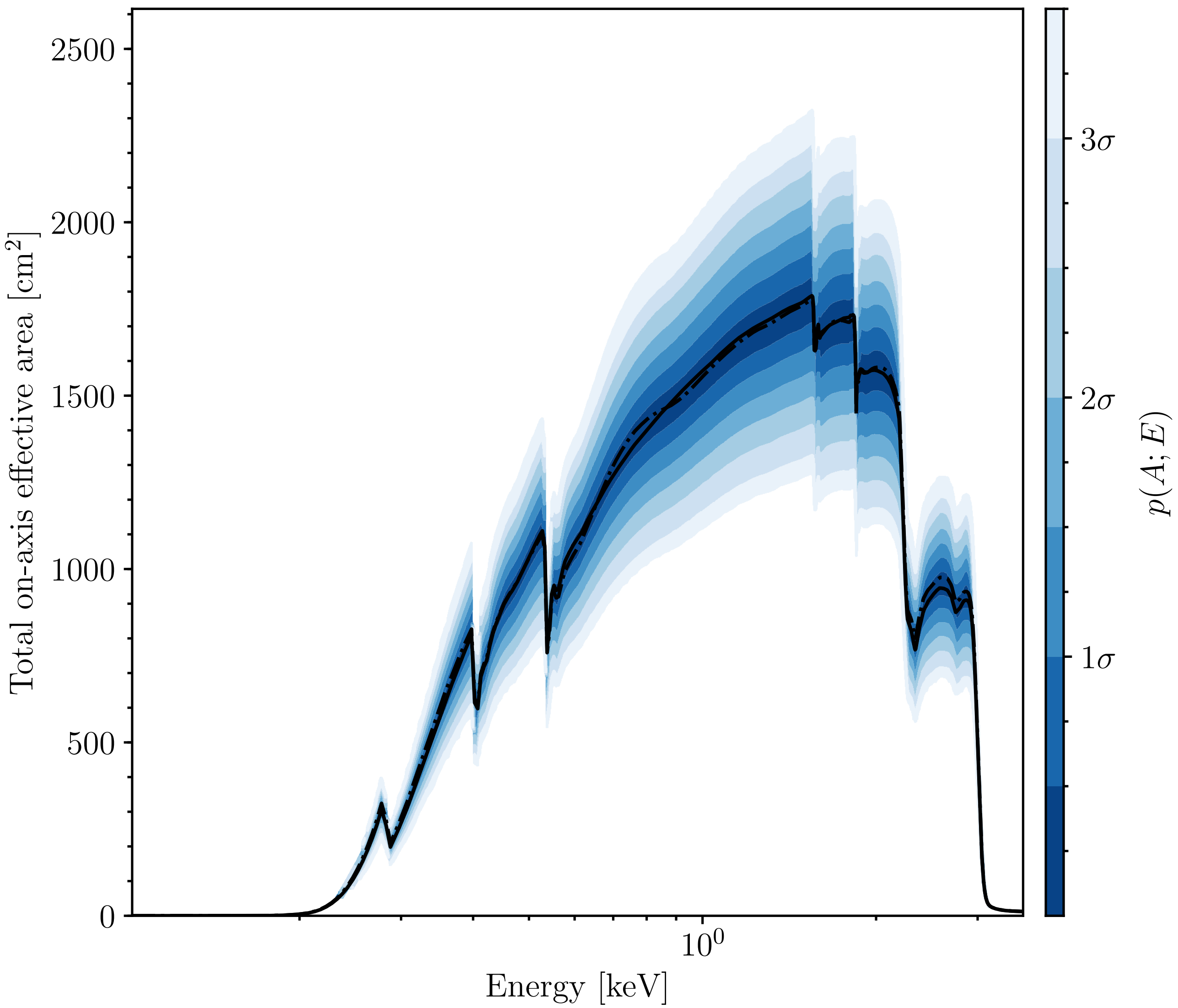




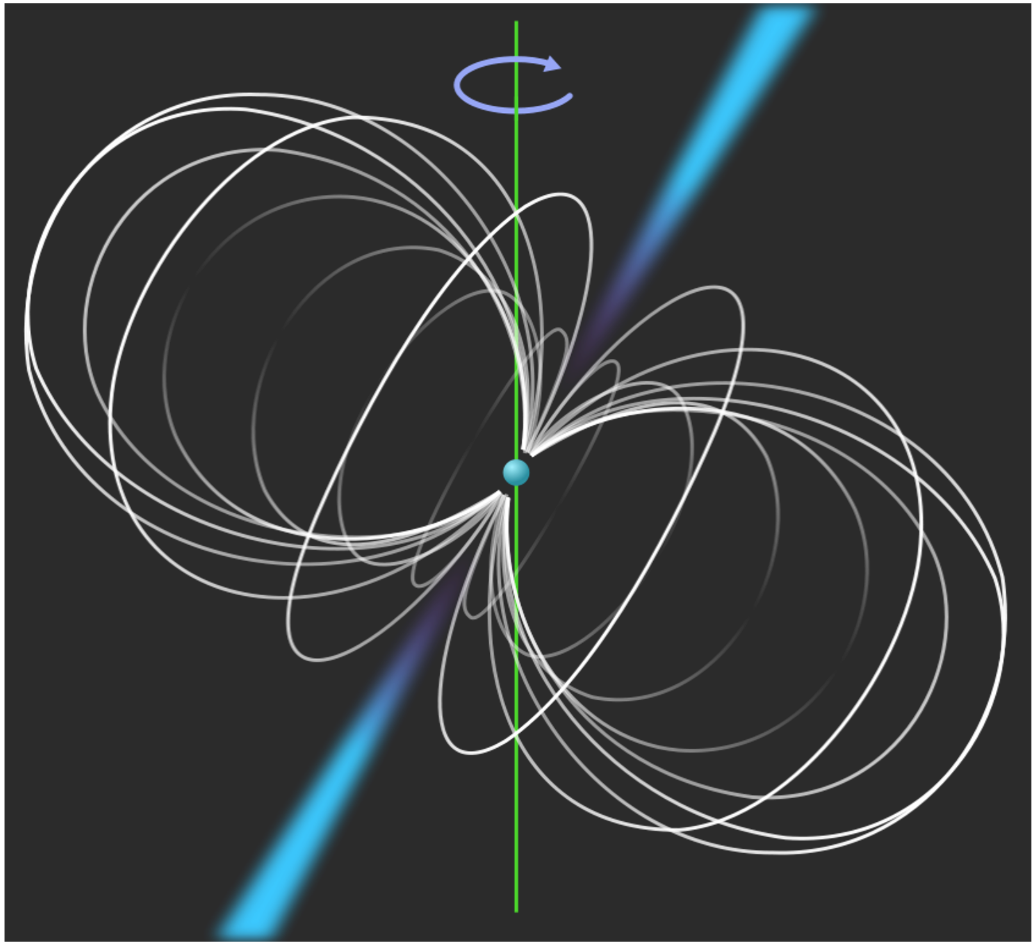
Ray-tracing and inference routines tested by multiple groups using synthetic data (Bogdanov et al. 2019b, 20, 21, Riley PhD thesis 2019)

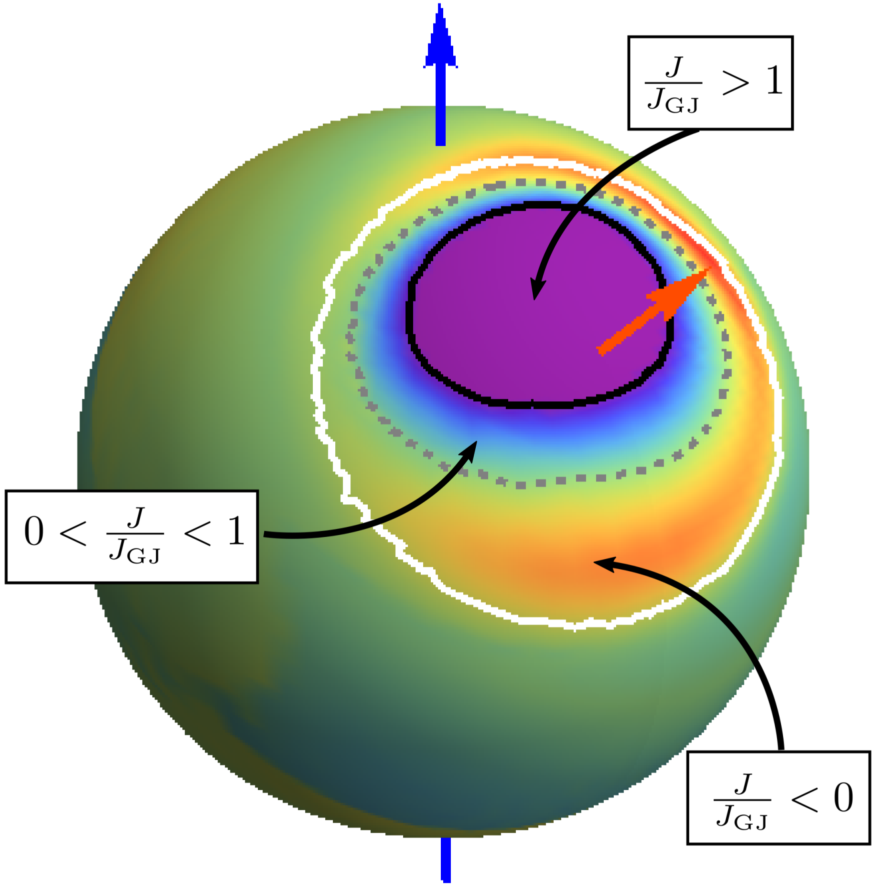
THE NICER INSTRUMENT RESPONSE

- We include parametrized models of instrument response to reflect calibration uncertainty.



PULSAR SURFACE EMISSION PATTERNS



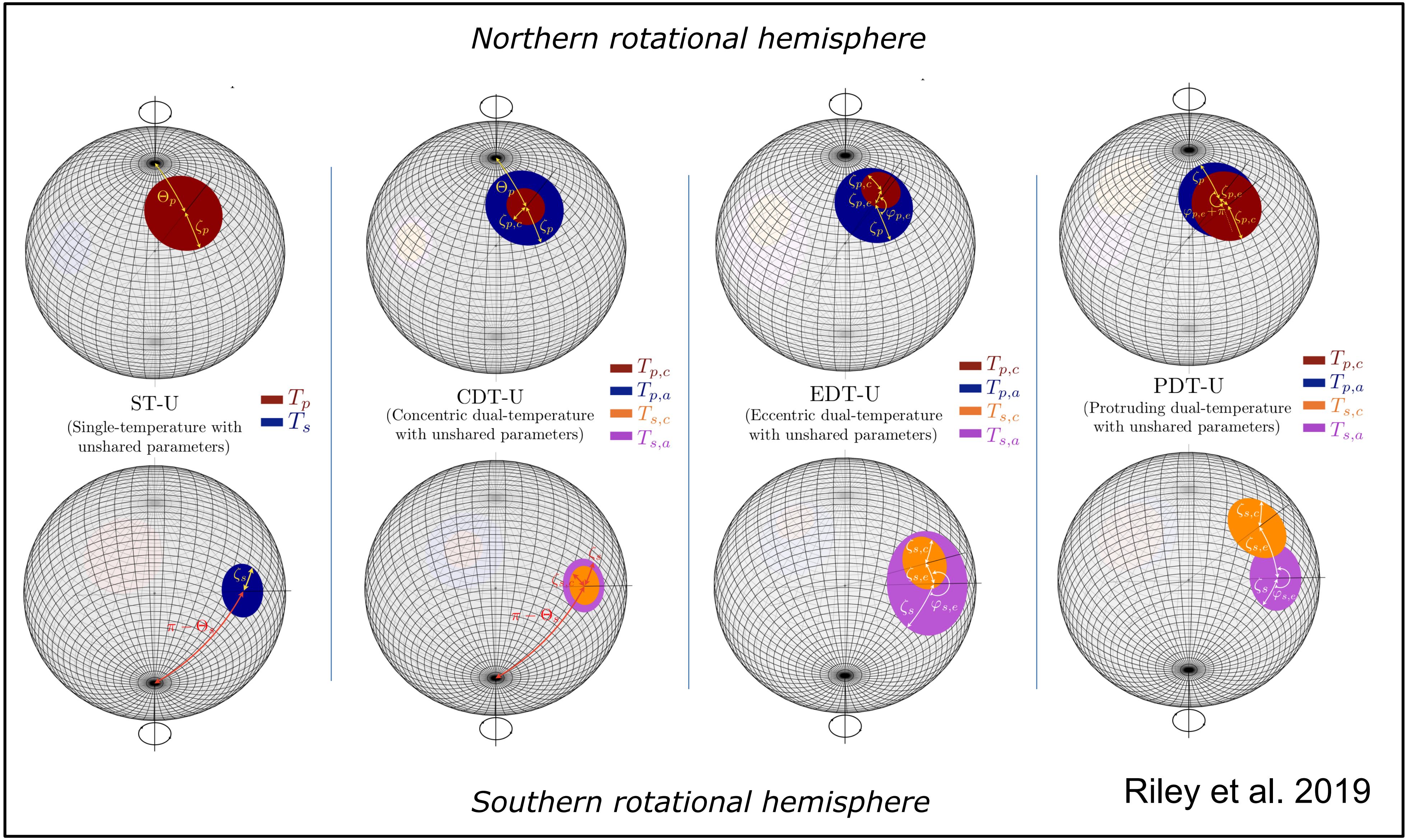


Surface heating pattern due to return currents a priori poorly constrained.

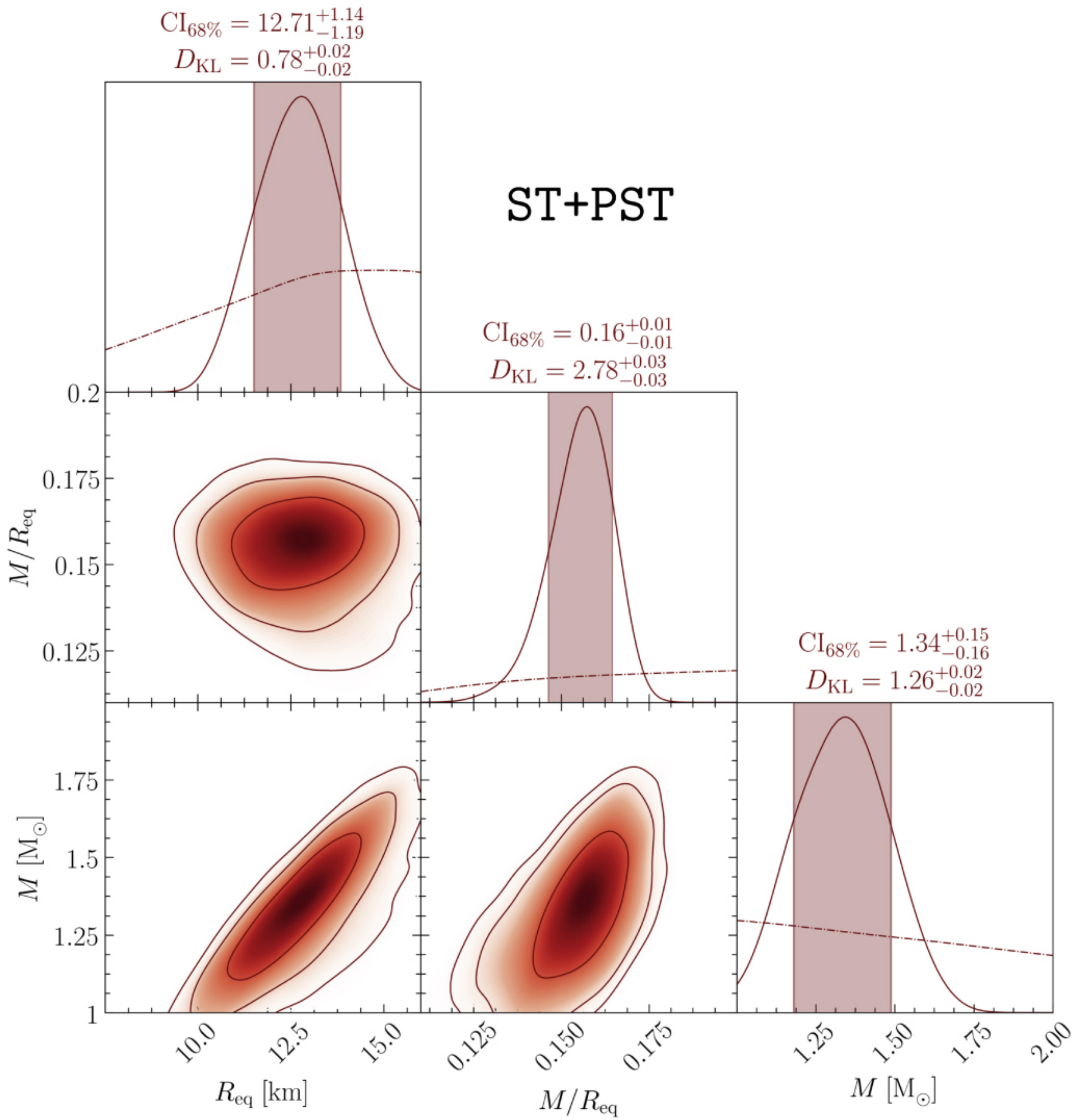
(Figure courtesy of Kostas Kalapotharakos, see also Harding & Muslimov 2011)

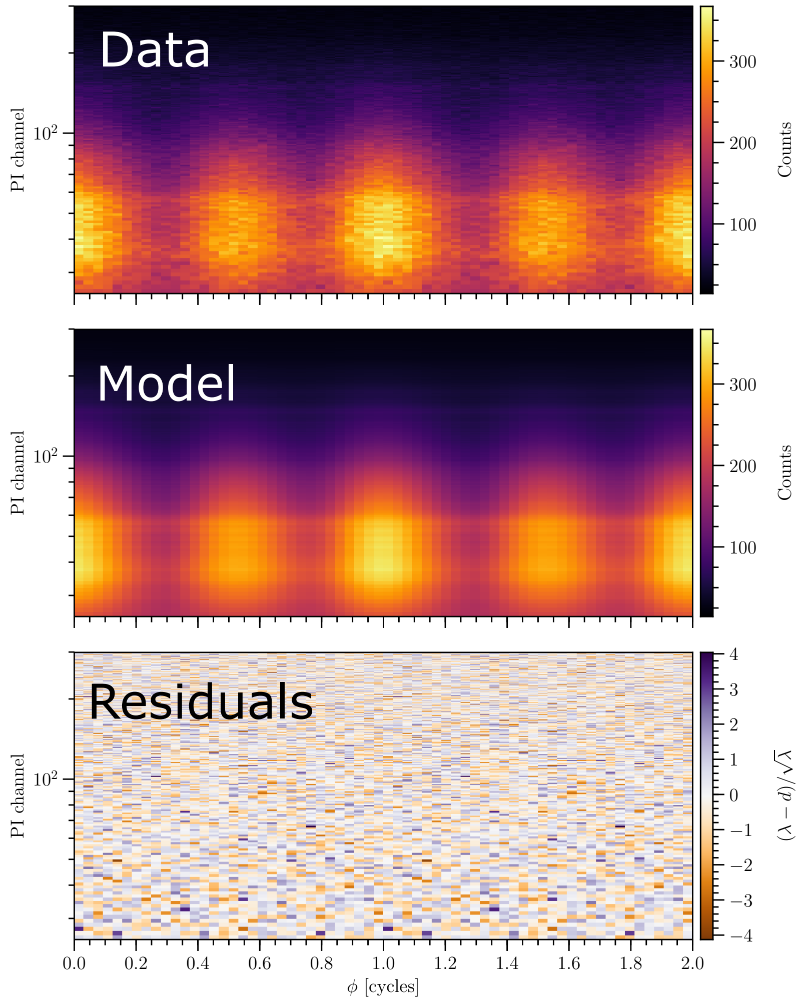
POLAR CAP MODELS

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



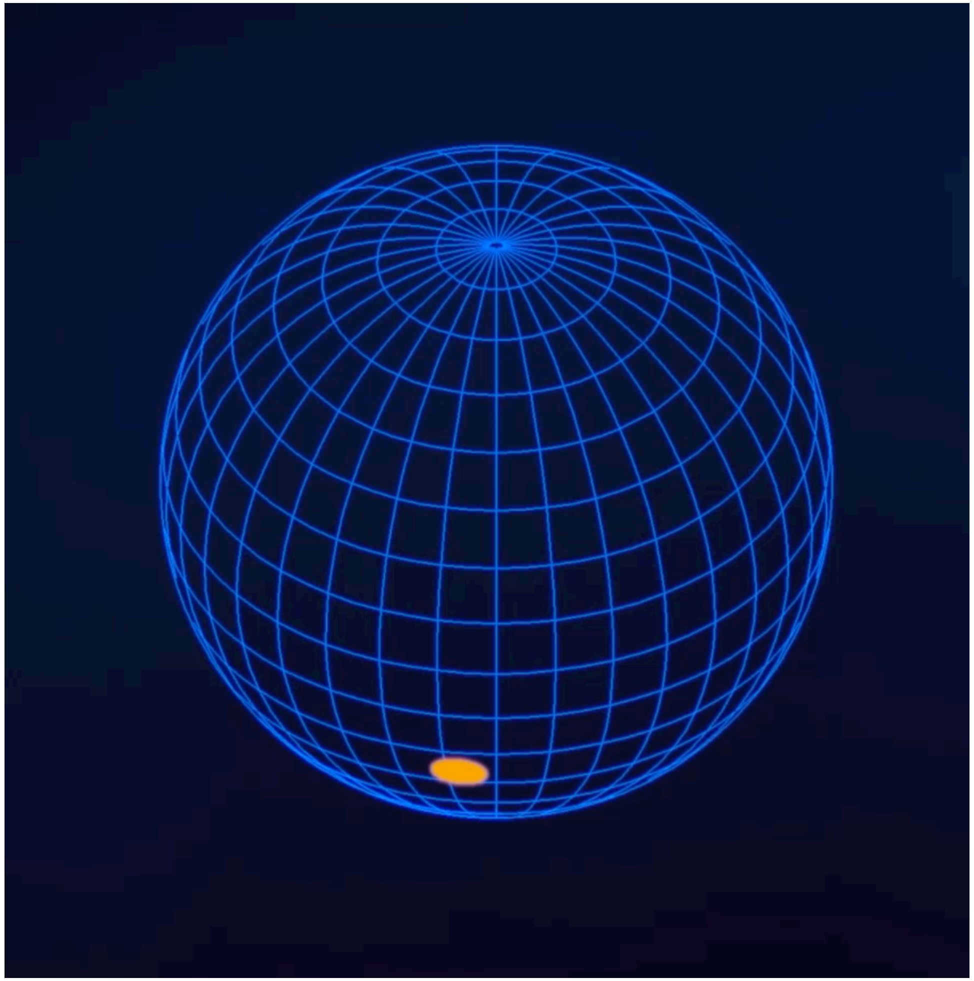
PSR J0030+0451 - PREFERRED CONFIGURATION

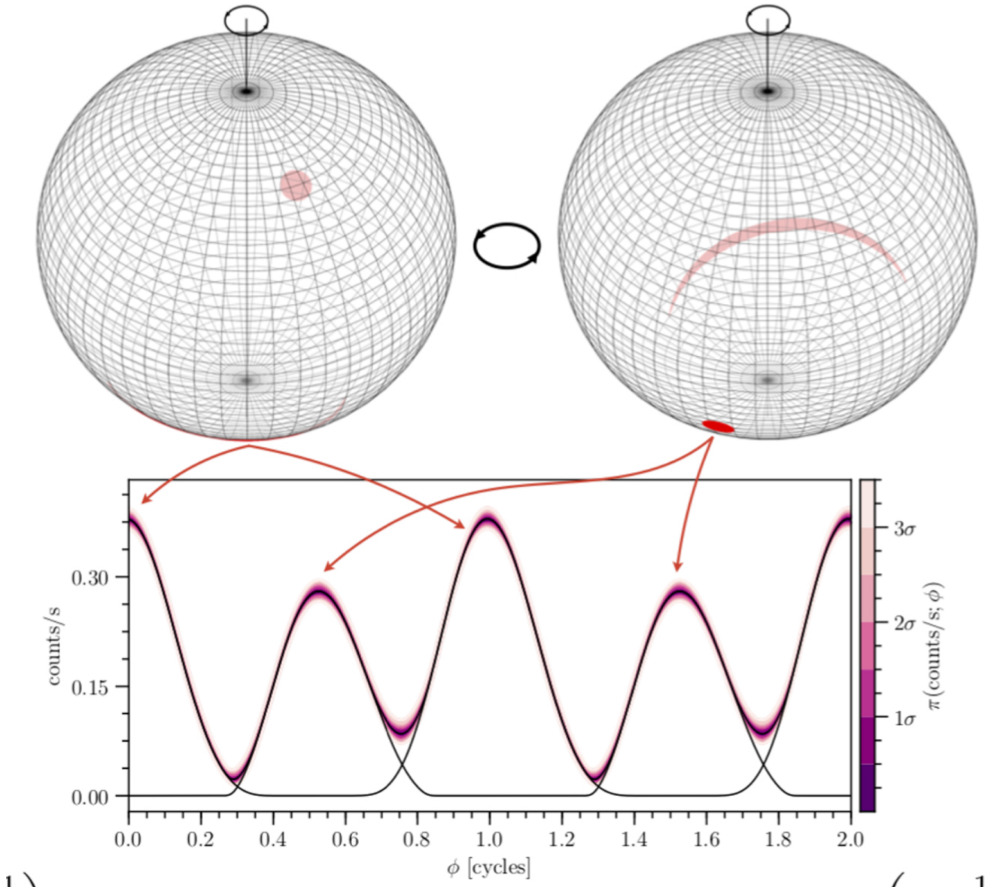




Riley et al. 2019

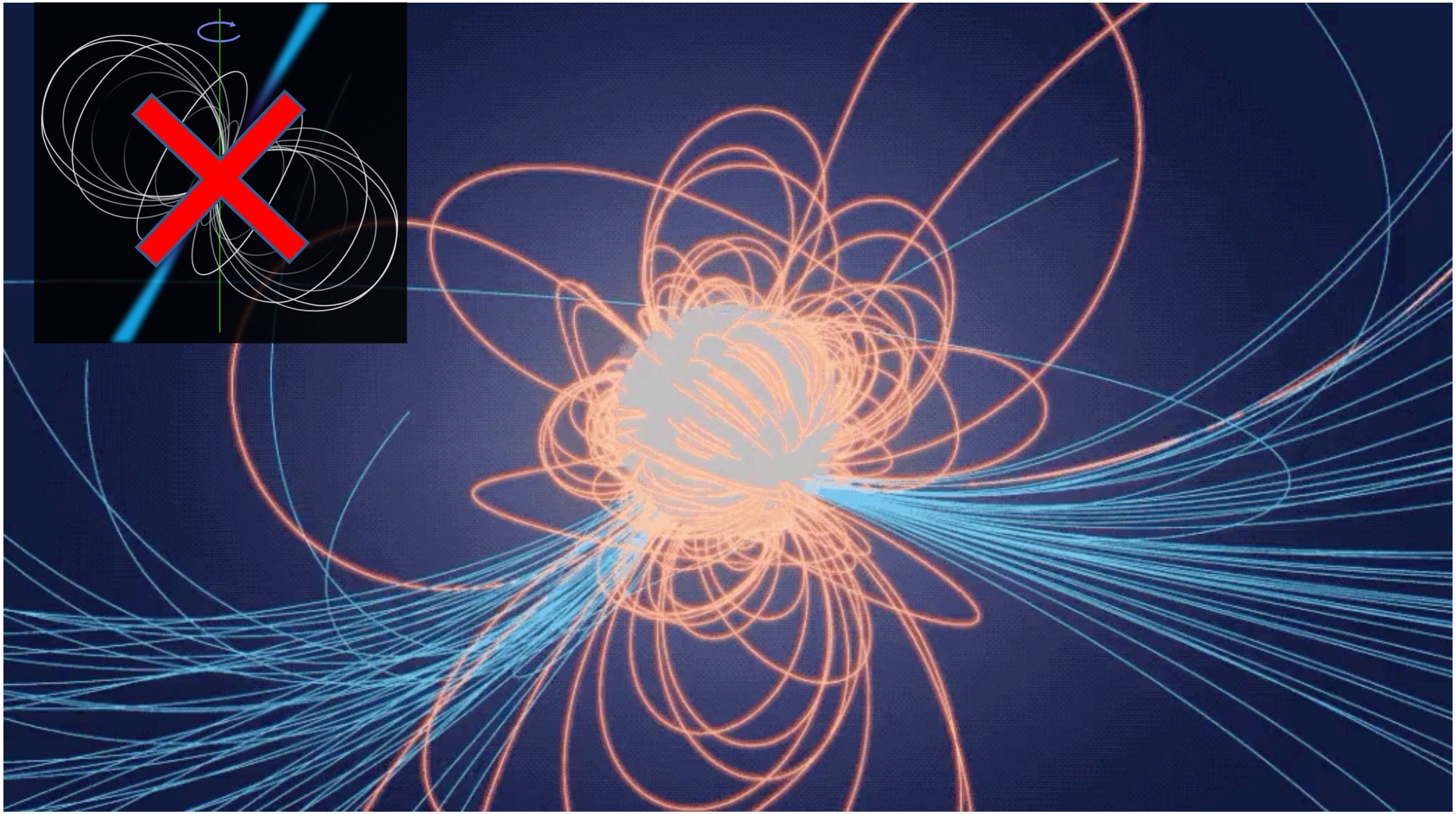
PSR J0030+0451 - PREFERRED CONFIGURATION





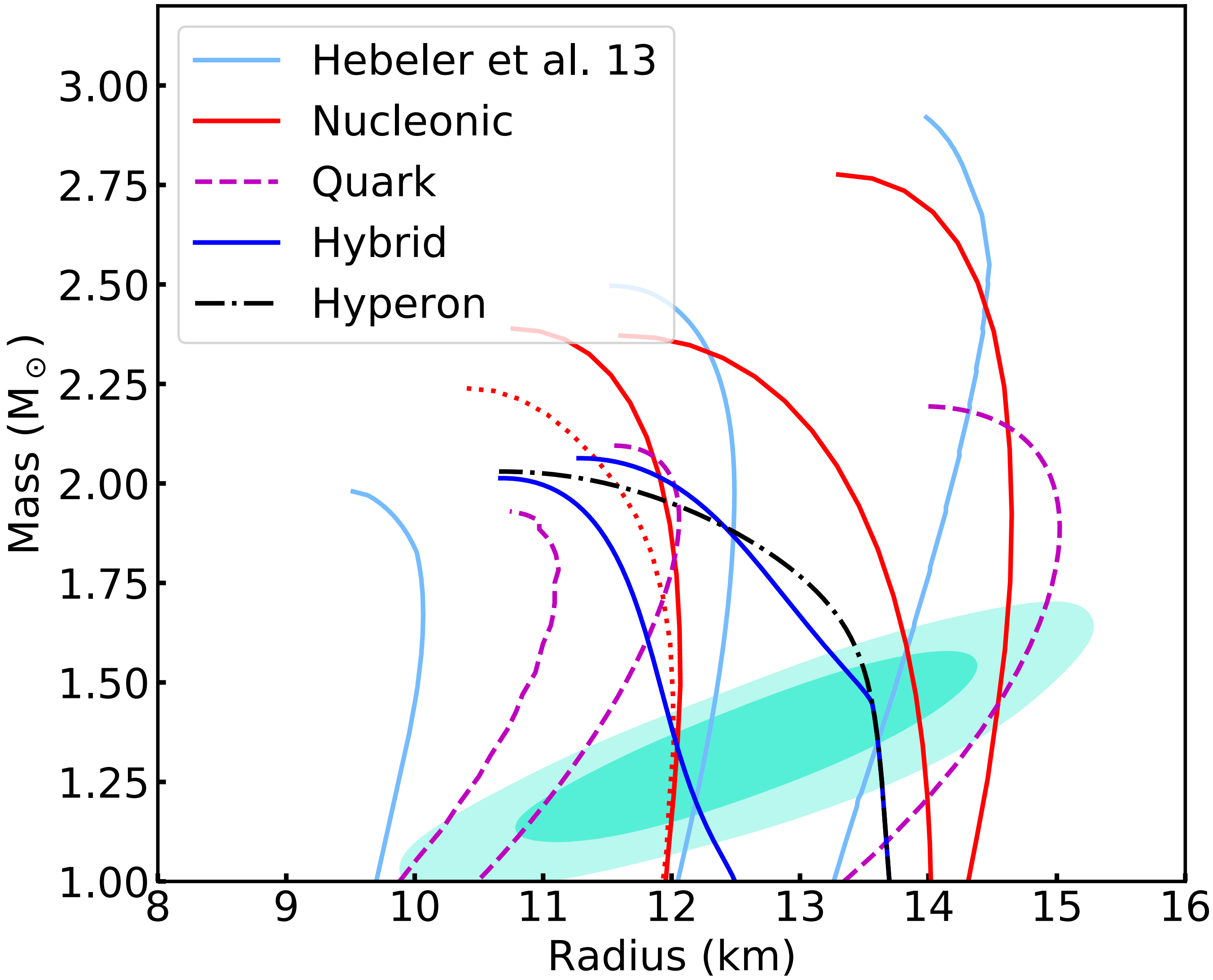
Riley et al. 2019

NON-DIPOLAR MAGNETIC FIELD



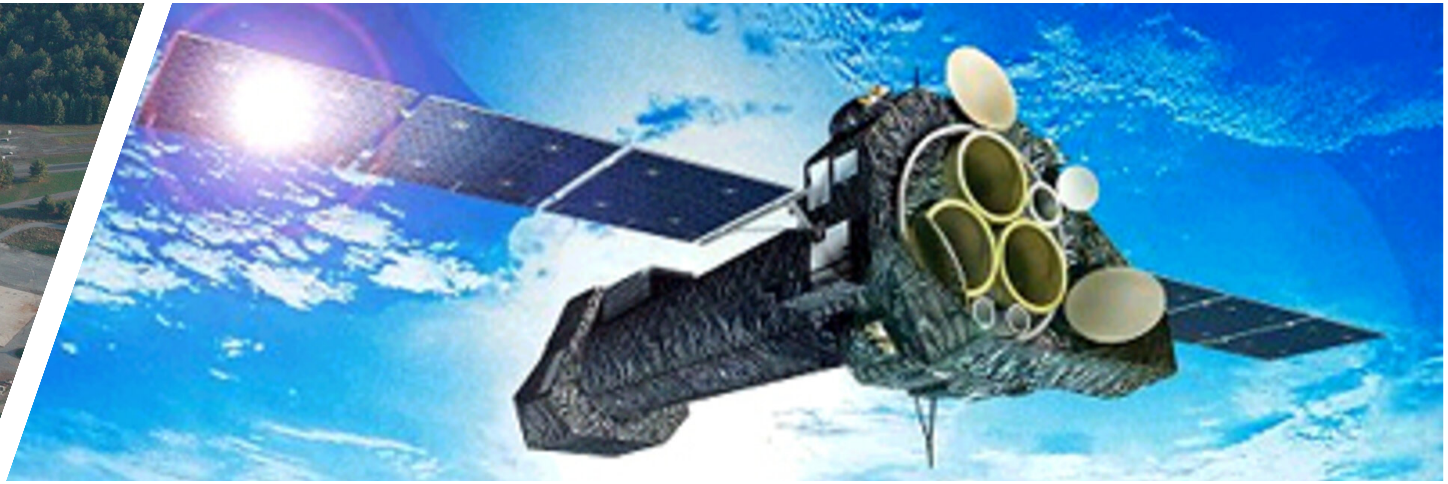
Credit: NASA's Goddard Space Flight Center/Harding, Kalapotharakos, Wadiasingh.

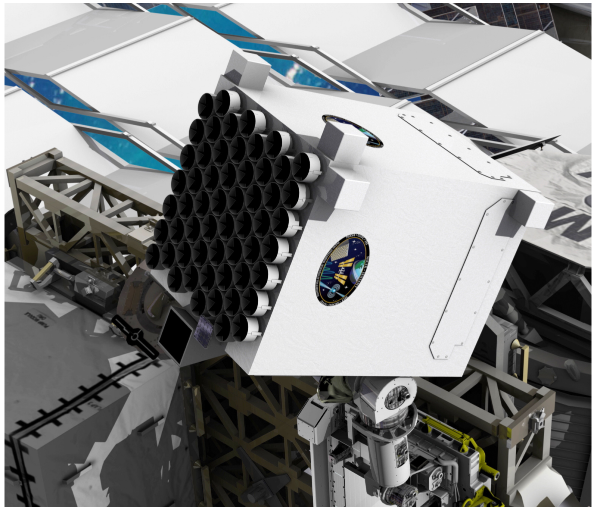
PSR J0030+0451 – MASS AND RADIUS



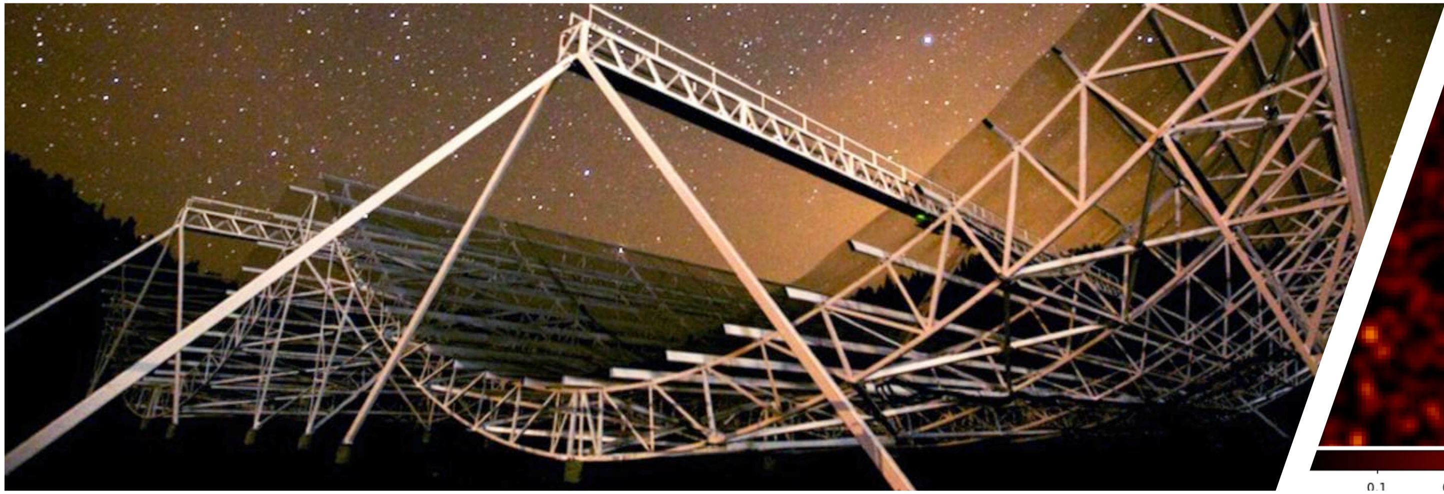
68%, 95% uncertainty

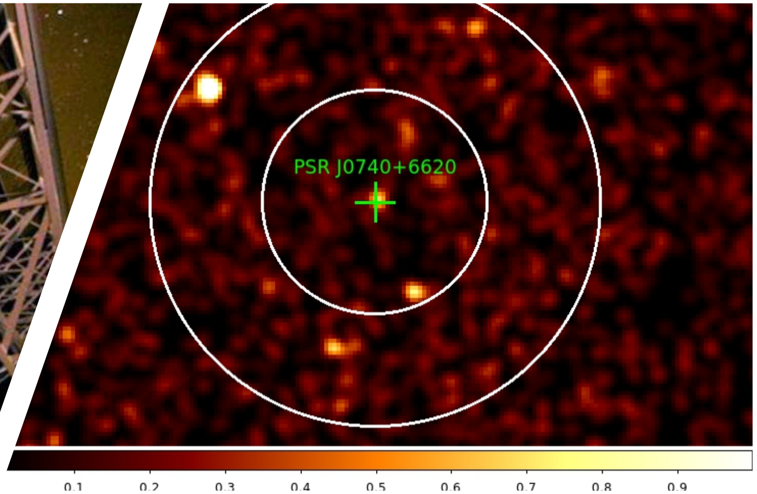
NICER team J0030 papers: Bogdanov et al. 2019a,b, 2021 (data and supporting analysis);
X-PSI (Riley et al. 2019, Raaijmakers et al. 2019, Bilous et al. 2019);
Maryland-Illinois (Miller et al. 2019).



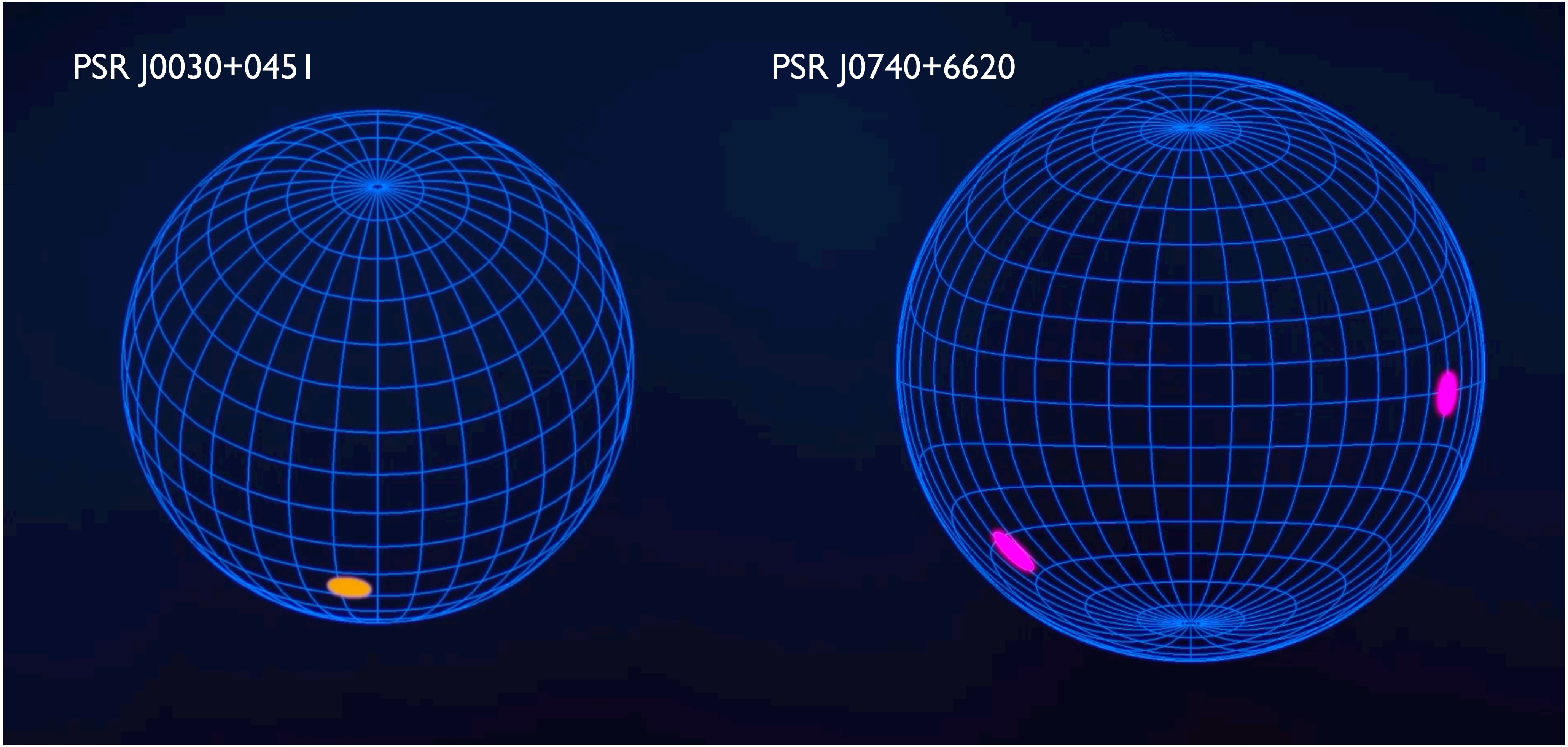


THE HIGH MASS PULSAR PSR J0740+6620



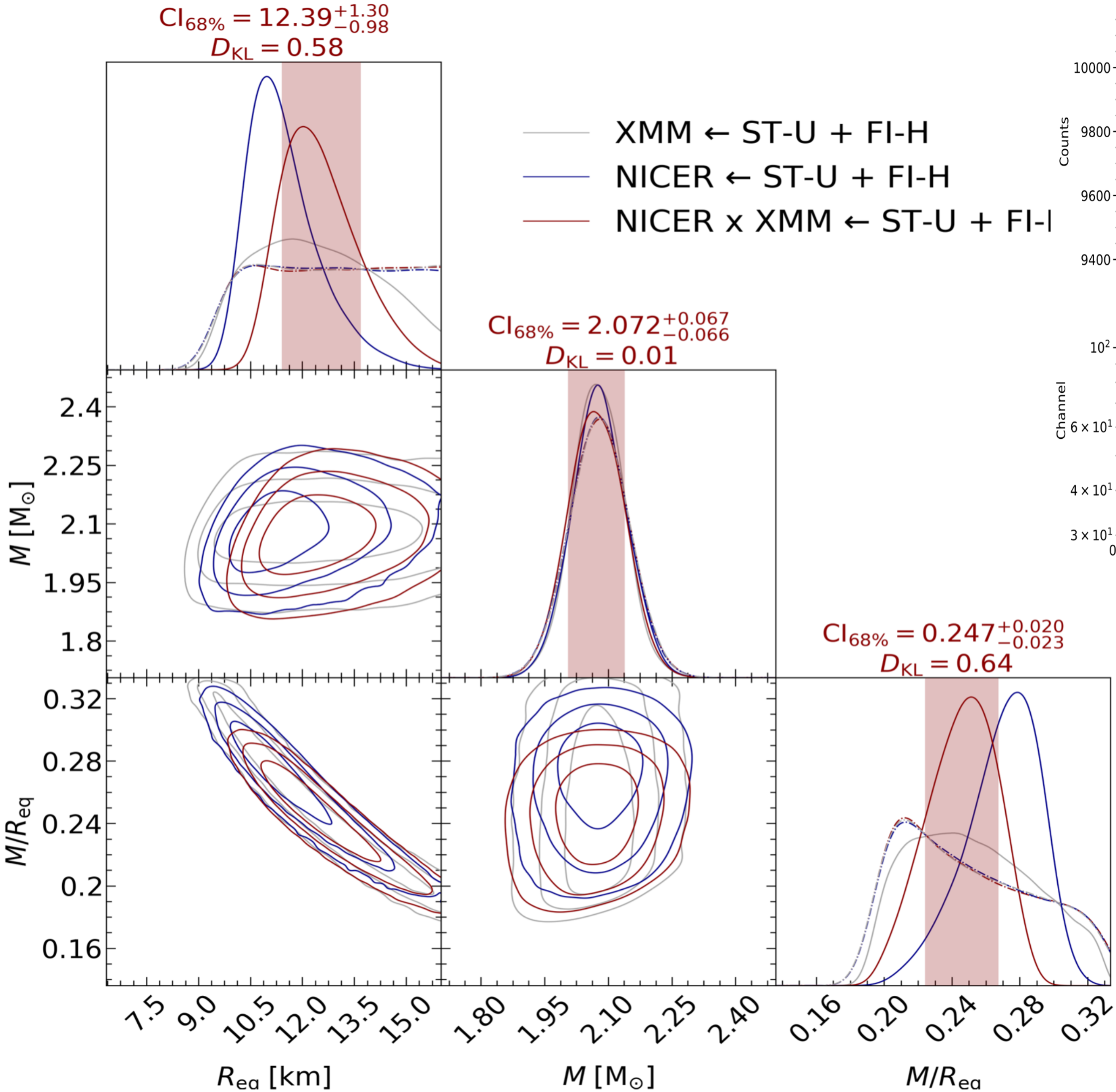


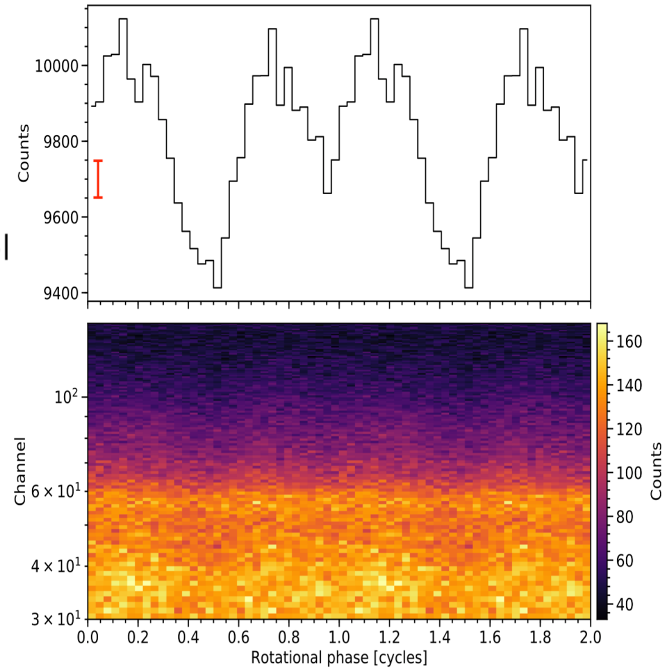
PSR J0740+6620: SURFACE MAP



Movie: Sharon Morsink, NASA

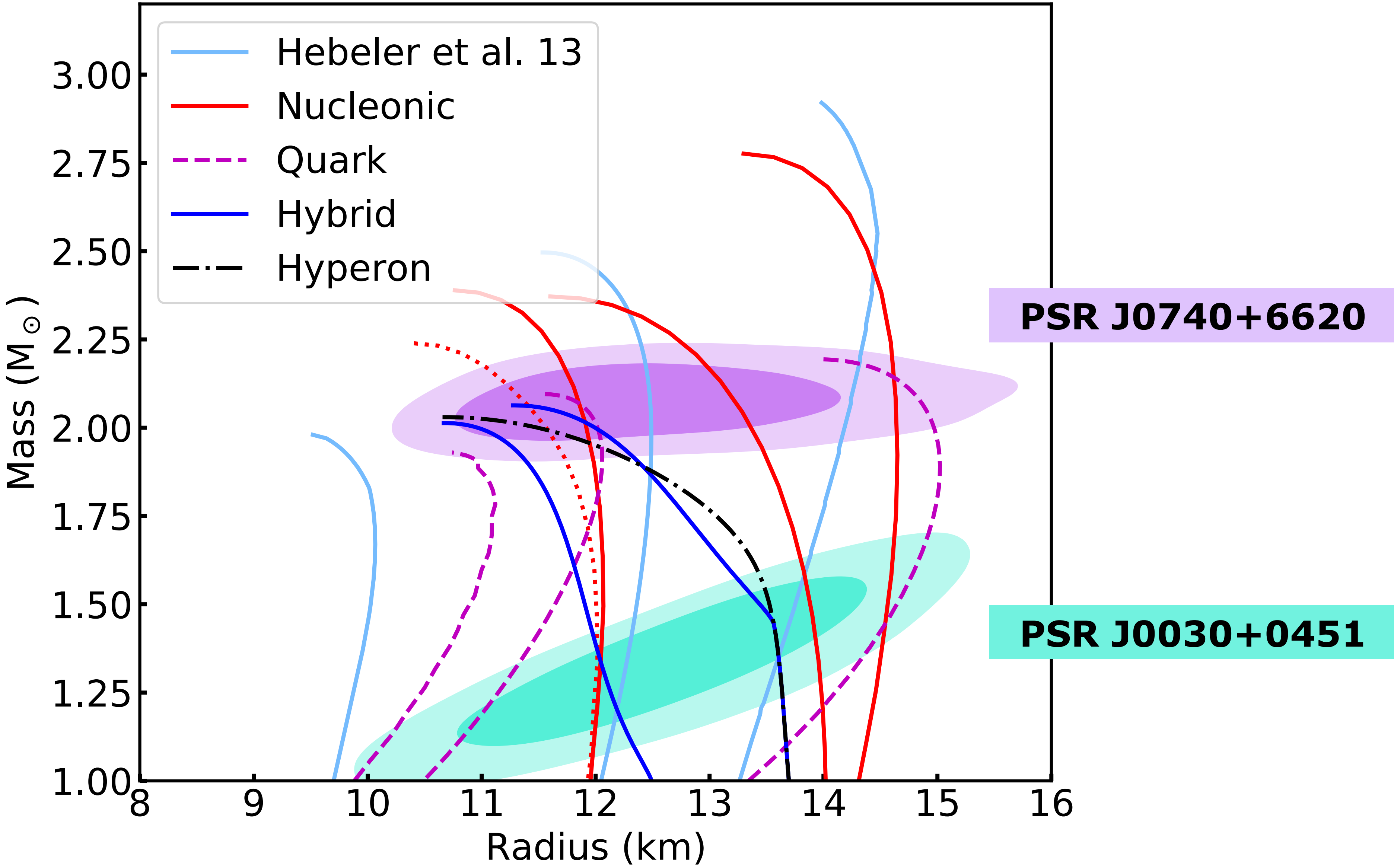
PSR J0740+6620 – MASS AND RADIUS





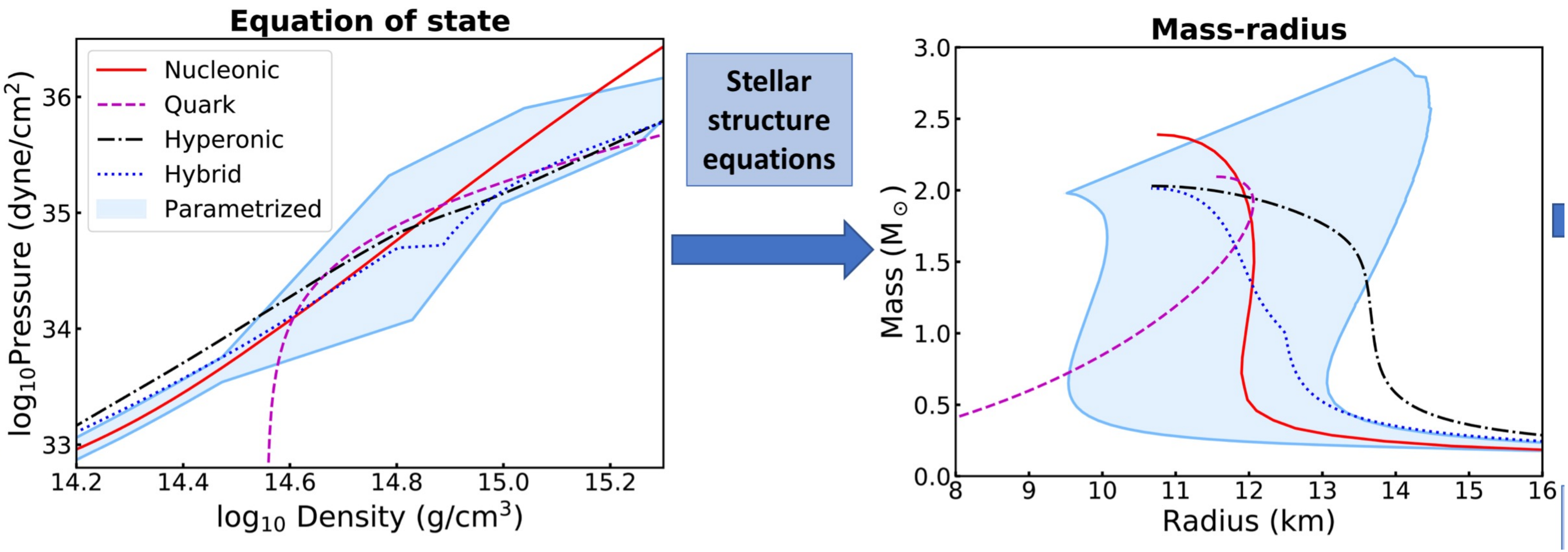
Riley et al. 2021

PSR J0740+6620 – MASS AND RADIUS



NICER team J0740 papers: Wolff et al. 2021, Riley et al. 2021, Raaijmakers et al. 2021, Miller et al. 2021.

EQUATION OF STATE INFERENCE

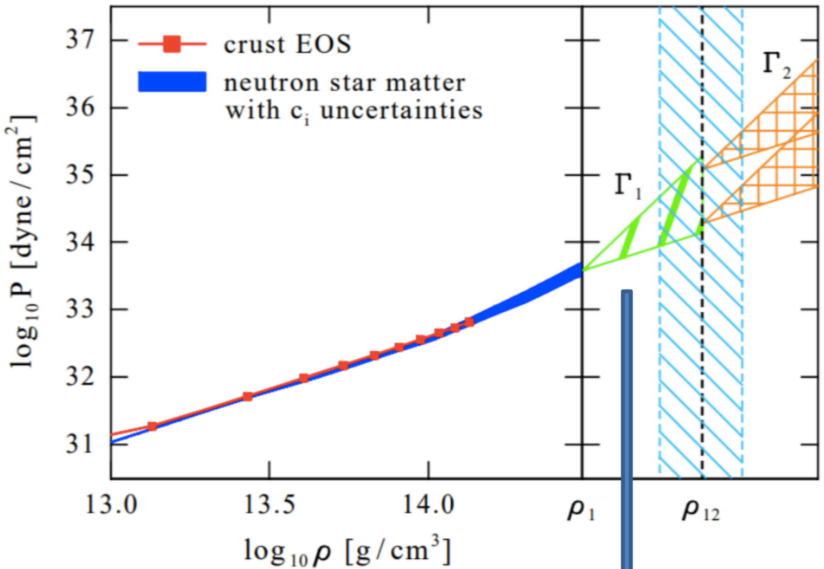


- Start with our inferred mass-radius posteriors
- Select an EOS model (with parameters and priors on those parameters)
- Infer EOS model parameters and central densities -> Inferred EOS
- This then translates into an inferred mass-radius **relation**

EQUATION OF STATE INFERENCE

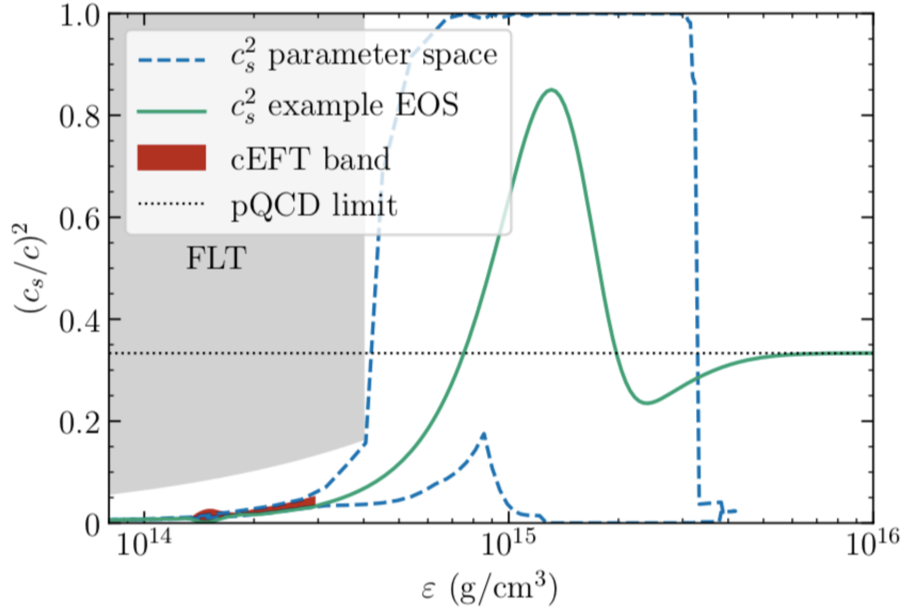
- EOS model: Pressure expressed as function of density.

Piecewise polytropes



$$P = P_1 \left(\frac{\rho}{\rho_1}\right)^{\Gamma_1}$$

Speed of sound



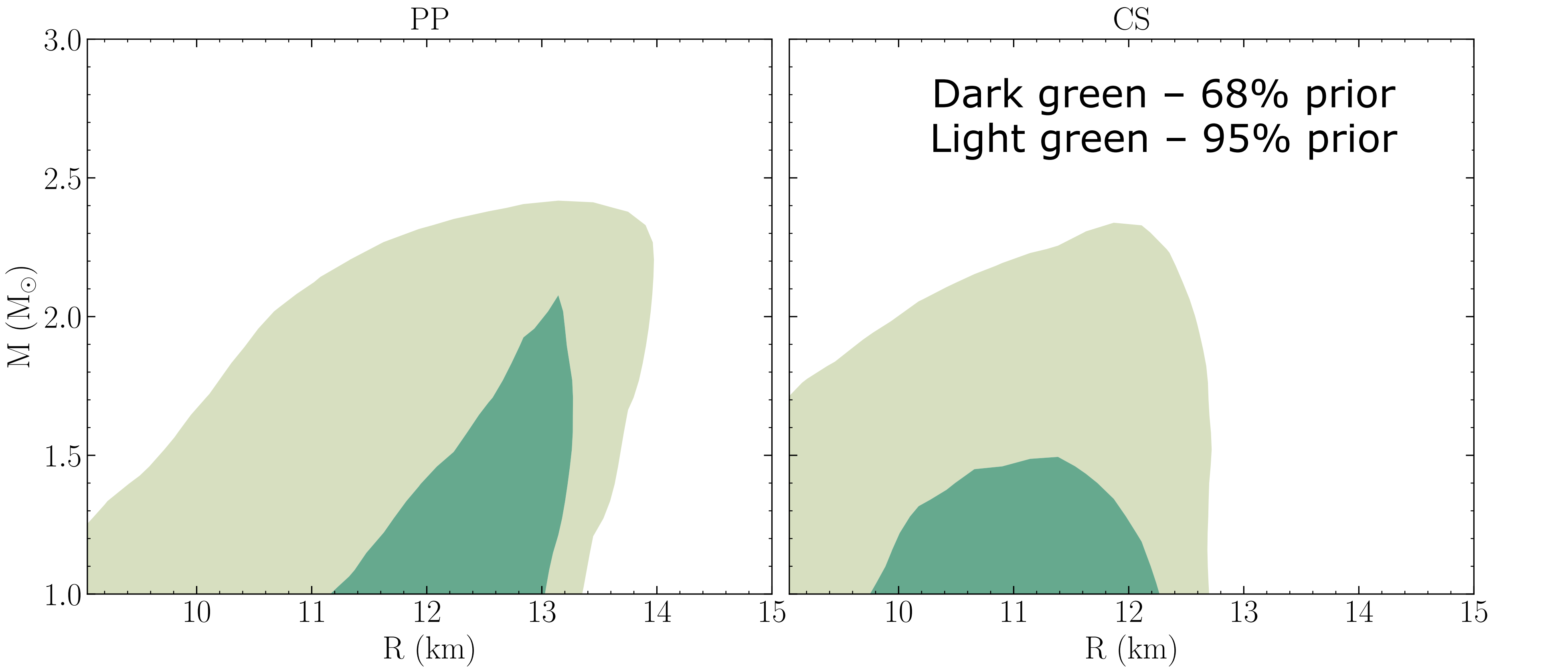
$$c_s^2(x)/c^2 = a_1\, e^{-\frac{1}{2}(x-a_2)^2/a_3^2} + a_6 + \frac{\frac{1}{3} - a_6}{1 + e^{-a_5(x-a_4)}}$$

$$P(\varepsilon) = \int_0^{\varepsilon} d\varepsilon'\, c_s^2(\varepsilon')/c^2$$

Hebeler et al. 2010, 13

Greif, Raaijmakers et al. 2019

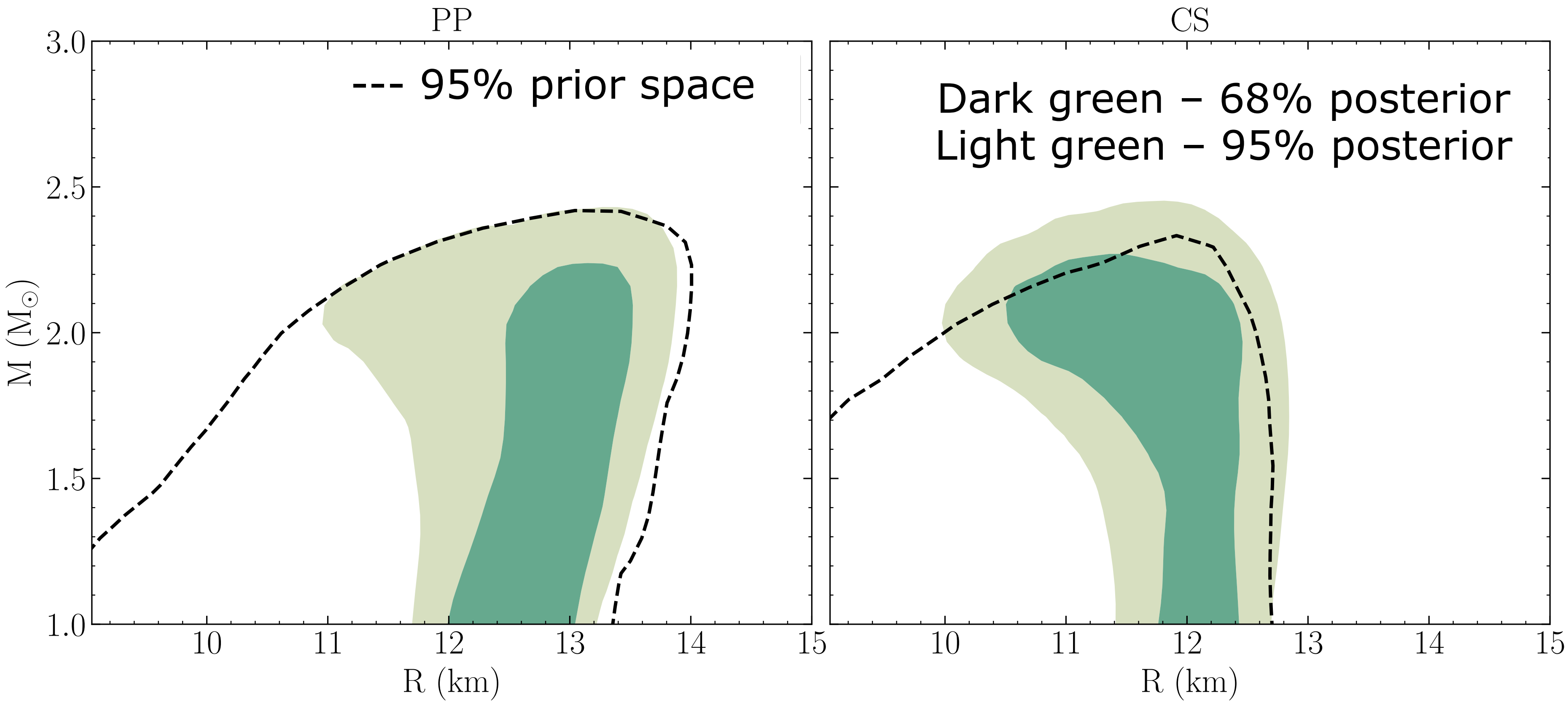
MULTI-MESSENGER CONSTRAINTS



- Prior is not uniform in M-R space even before constraints applied.
- This is mathematical not physical!

Raaijmakers et al. 2021 (building on Greif, Raaijmakers et al 19, Raaijmakers et al. 19, 20)

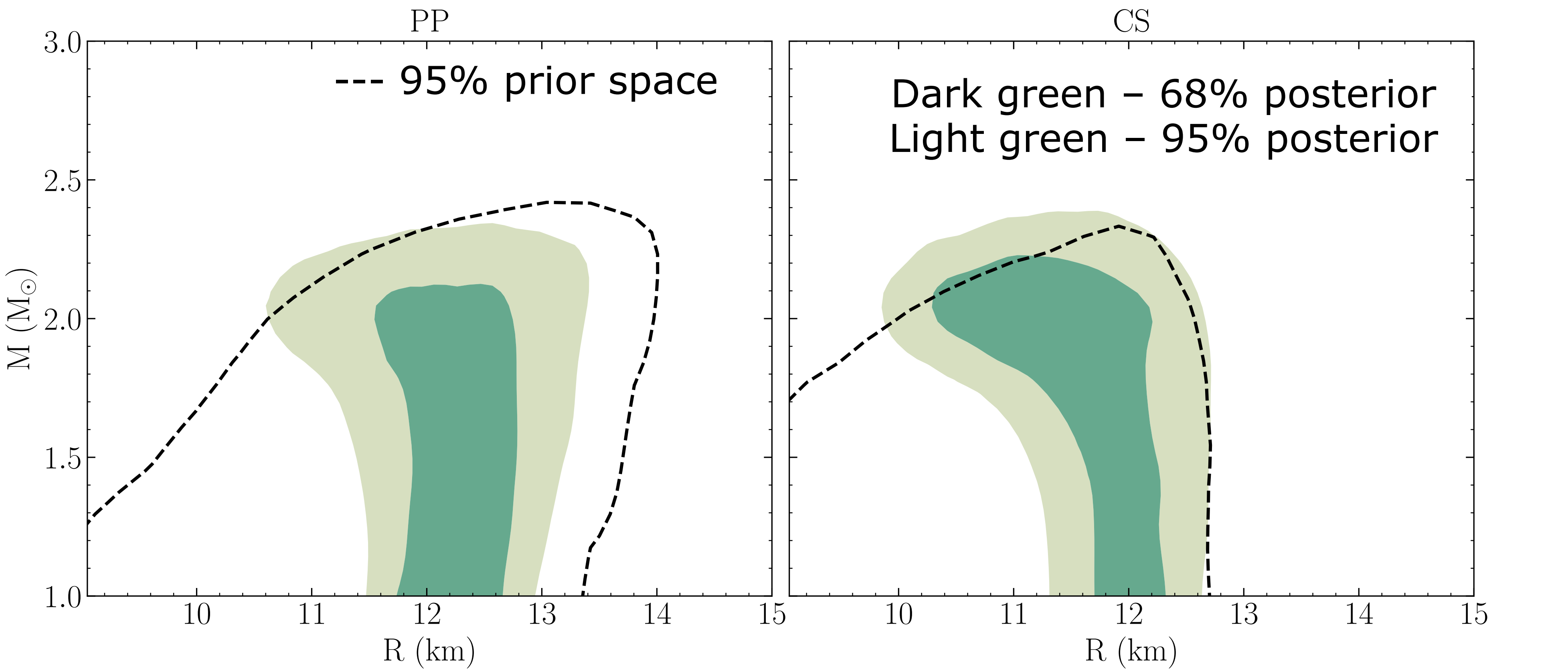
MULTI-MESSENGER CONSTRAINTS



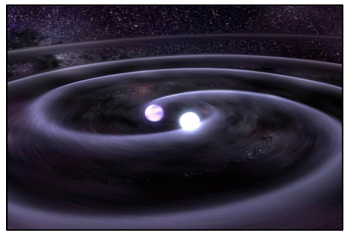
- Radio-derived mass - existence of a 2.1 solar mass neutron star already reduces space a lot (Cromartie et al. 2020, Fonseca et al. 2021).

Raaijmakers et al. 2021 (building on Greif, Raaijmakers et al 19, Raaijmakers et al. 19, 20)

MULTI-MESSENGER CONSTRAINTS

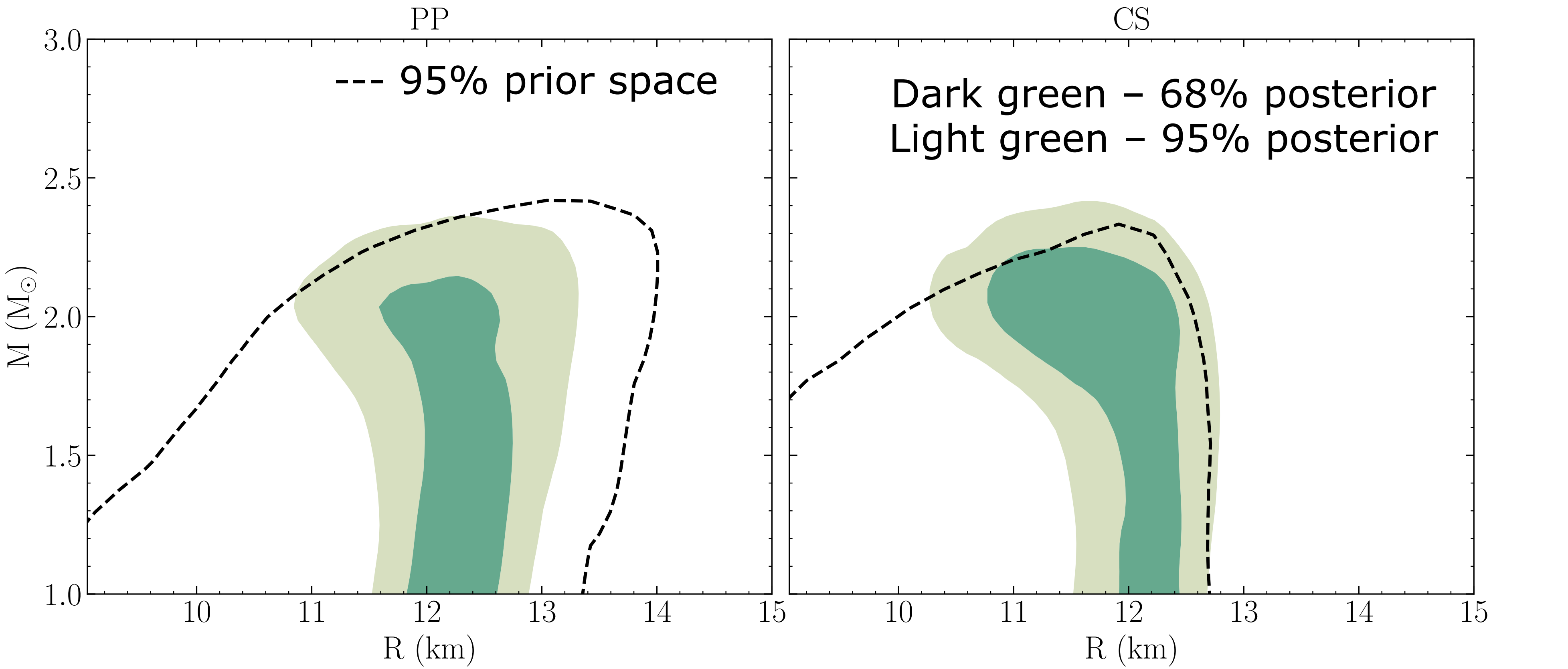


- NICER J0030 mass-radius measurement
- Tidal deformabilities from two binary neutron star mergers, GW170817, GW190425 + kilonova from the former



Raaijmakers et al. 2021

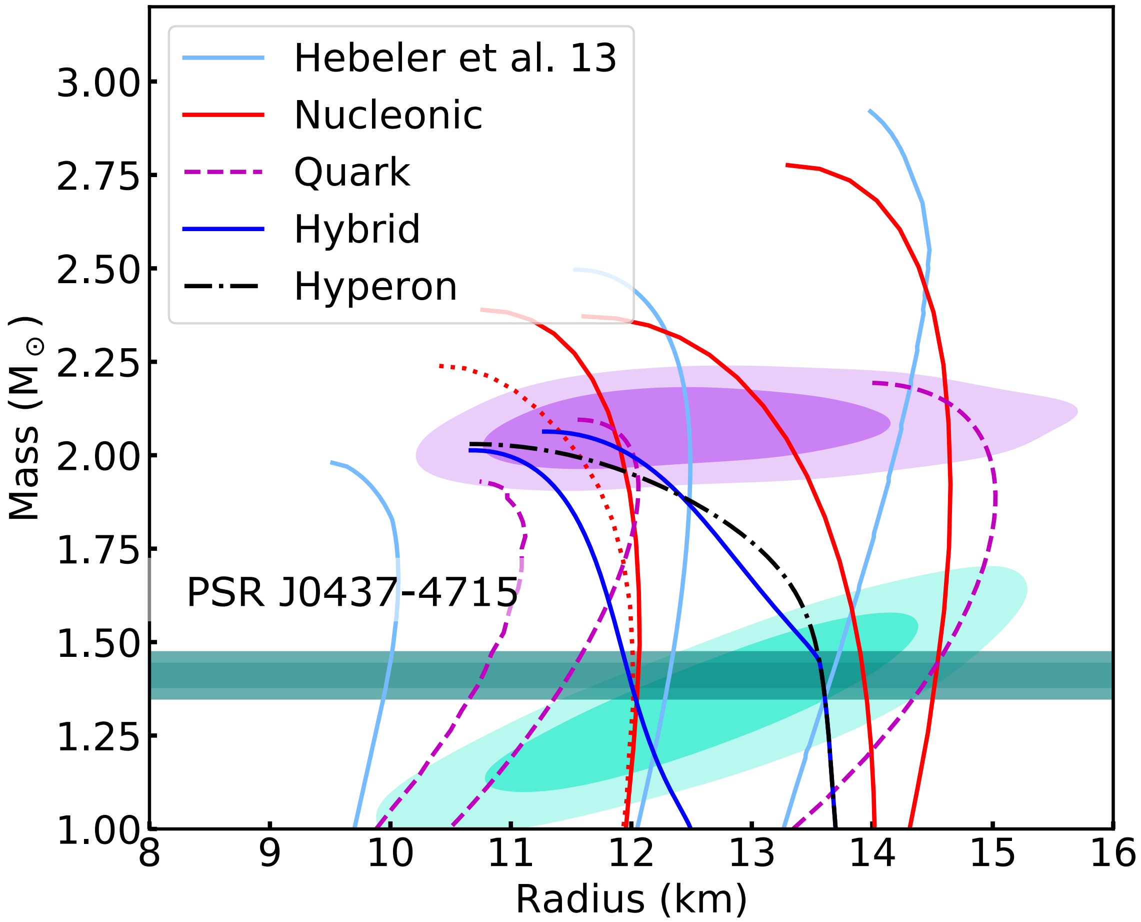
MULTI-MESSENGER CONSTRAINTS



- Add NICER x XMM PSR J0740+6620 mass-radius measurement
- Mass-radius band narrowing, although priors/model still important!

Raaijmakers et al. 2021

NEXT STEPS FOR NICER

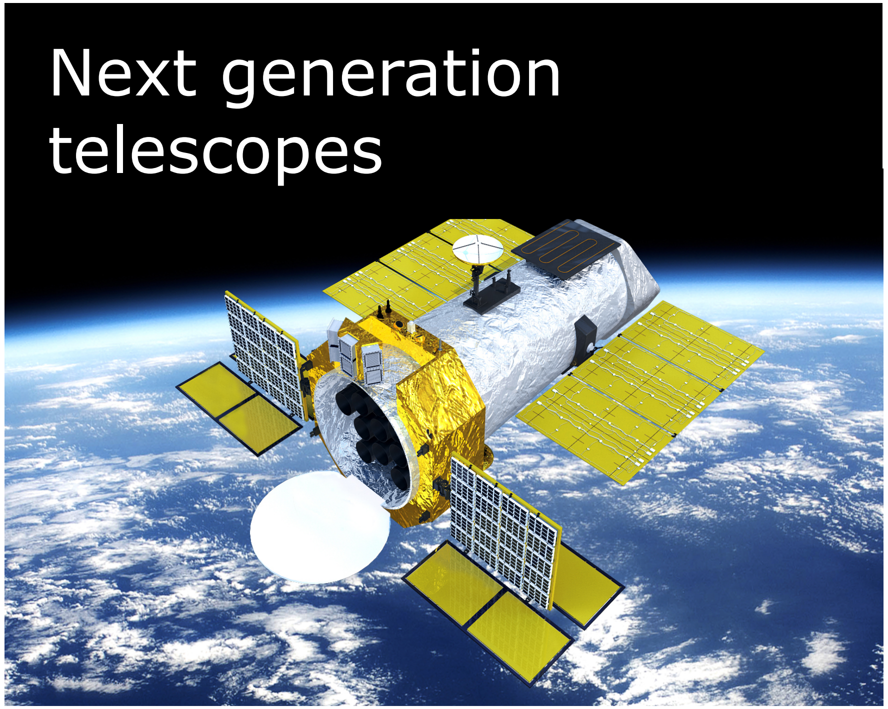


- 4 new sources coming!
- Updates to already-published results.
- Improved instrument response.
- Better NICER background models.
- Interaction with pulsar astrophysics.

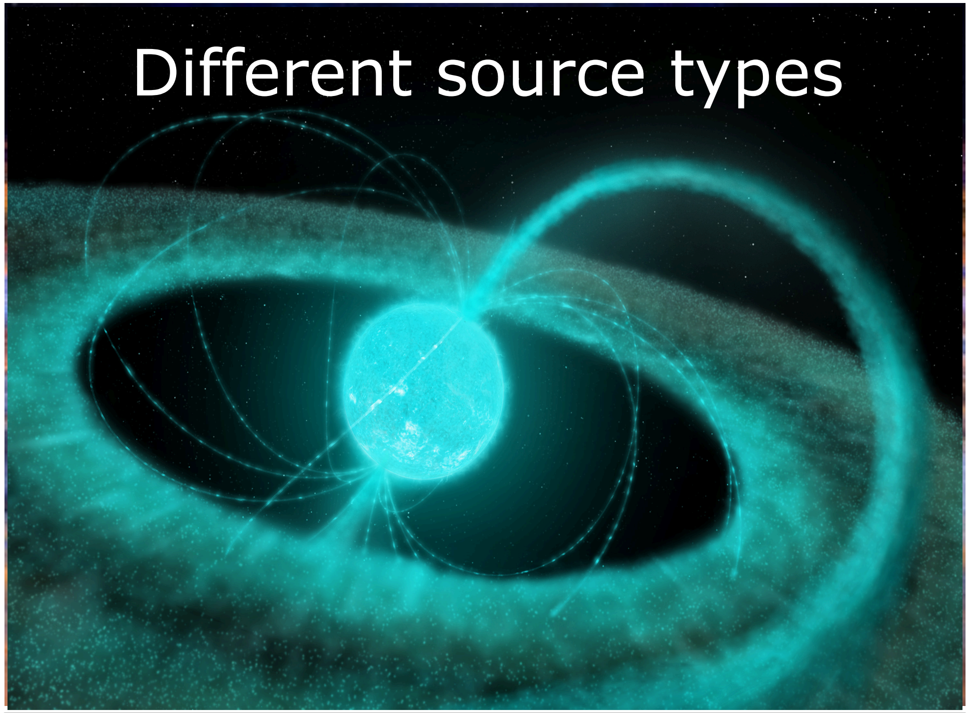
And we are getting ready for the next generation of Pulse Profile Modelling missions!!

UNLOCKING RAPID ROTATORS

The relativistic effects pulse profile modeling exploits are larger for the more rapidly-rotating **accreting** neutron stars.



eXTP (Zhang et al. 2019)
STROBE-X (Ray et al. 2019)



New astrophysical modeling and analysis challenges!

SUMMARY

- NICER continues to push the envelope on a completely new technique.
- We have measured the size of two neutron stars, including the highest mass neutron star known.
- We are making maps of tiny stars thousands of light years from Earth.