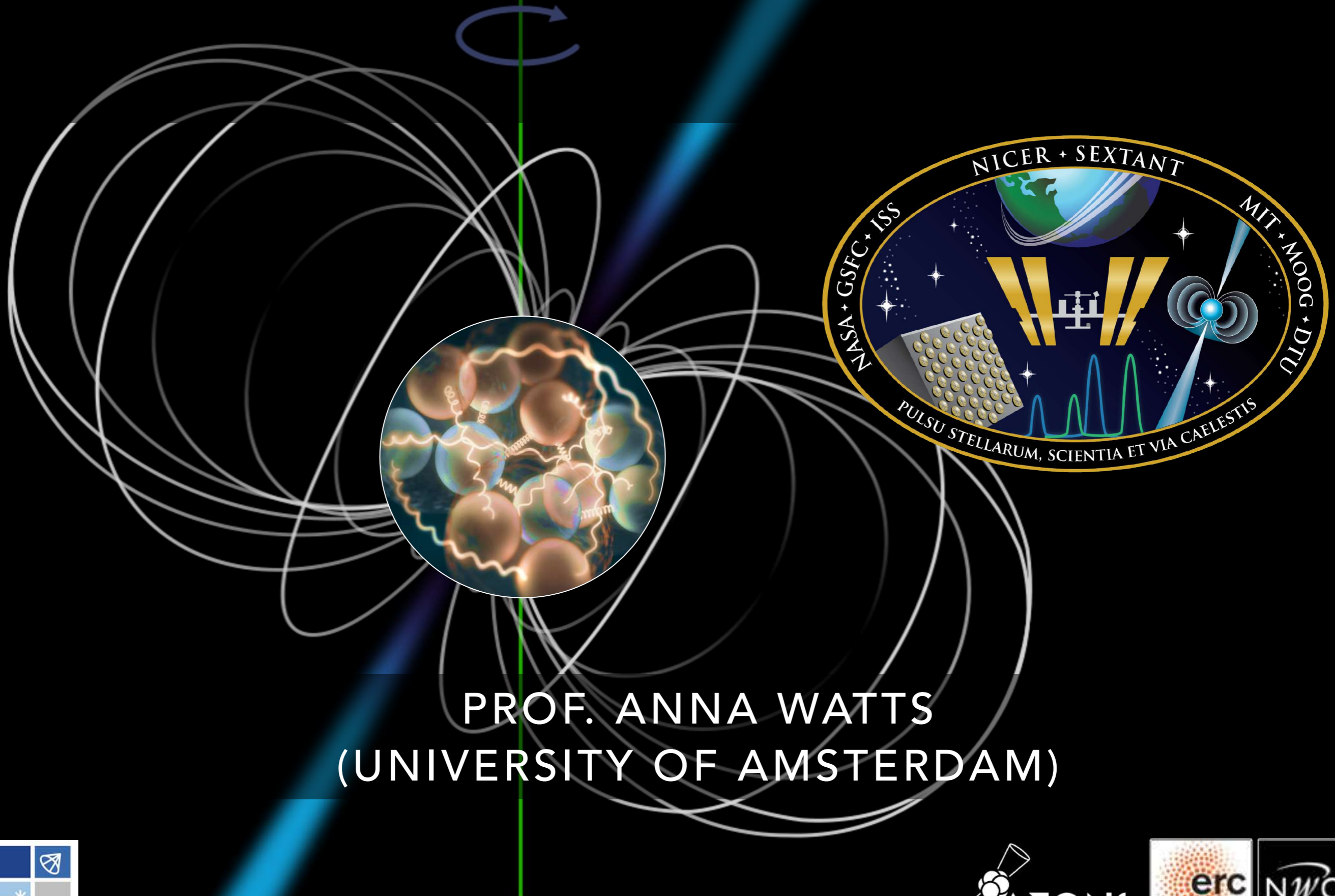
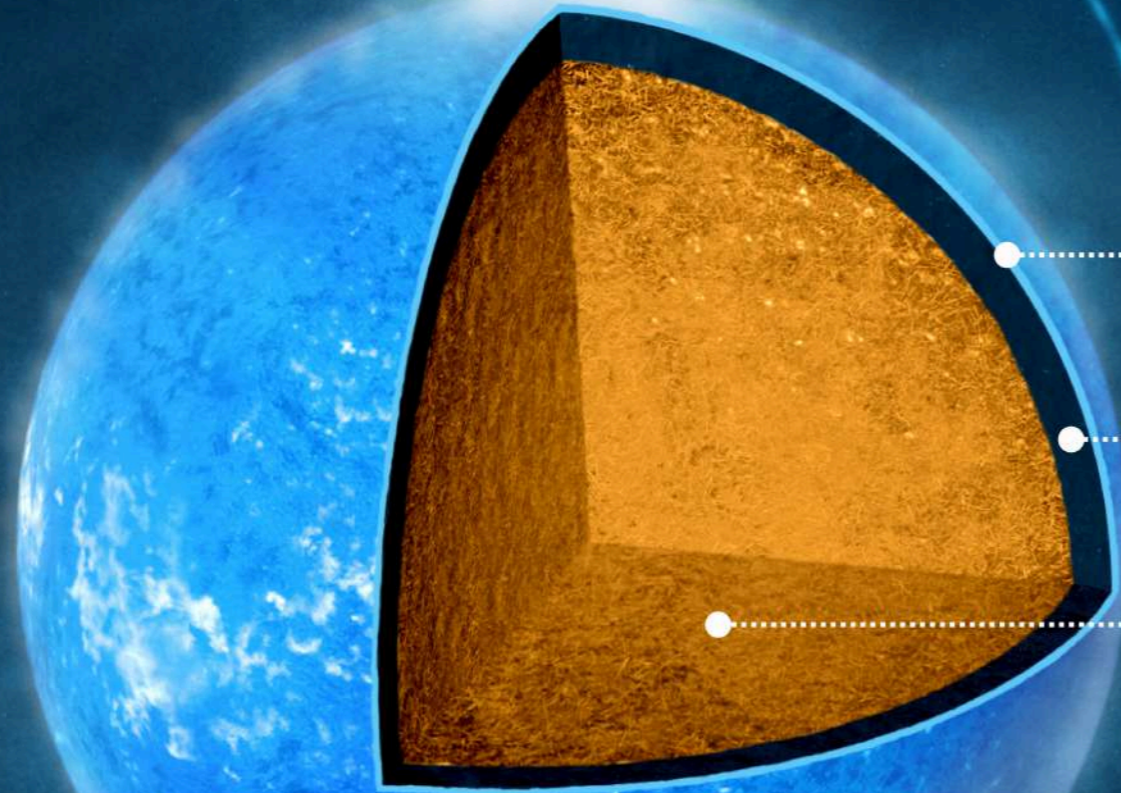


A NICER VIEW OF NEUTRON STARS



PROF. ANNA WATTS
(UNIVERSITY OF AMSTERDAM)

THE NEUTRON STAR INTERIOR



1 | OUTER CRUST

NUCLEI
ELECTRONS

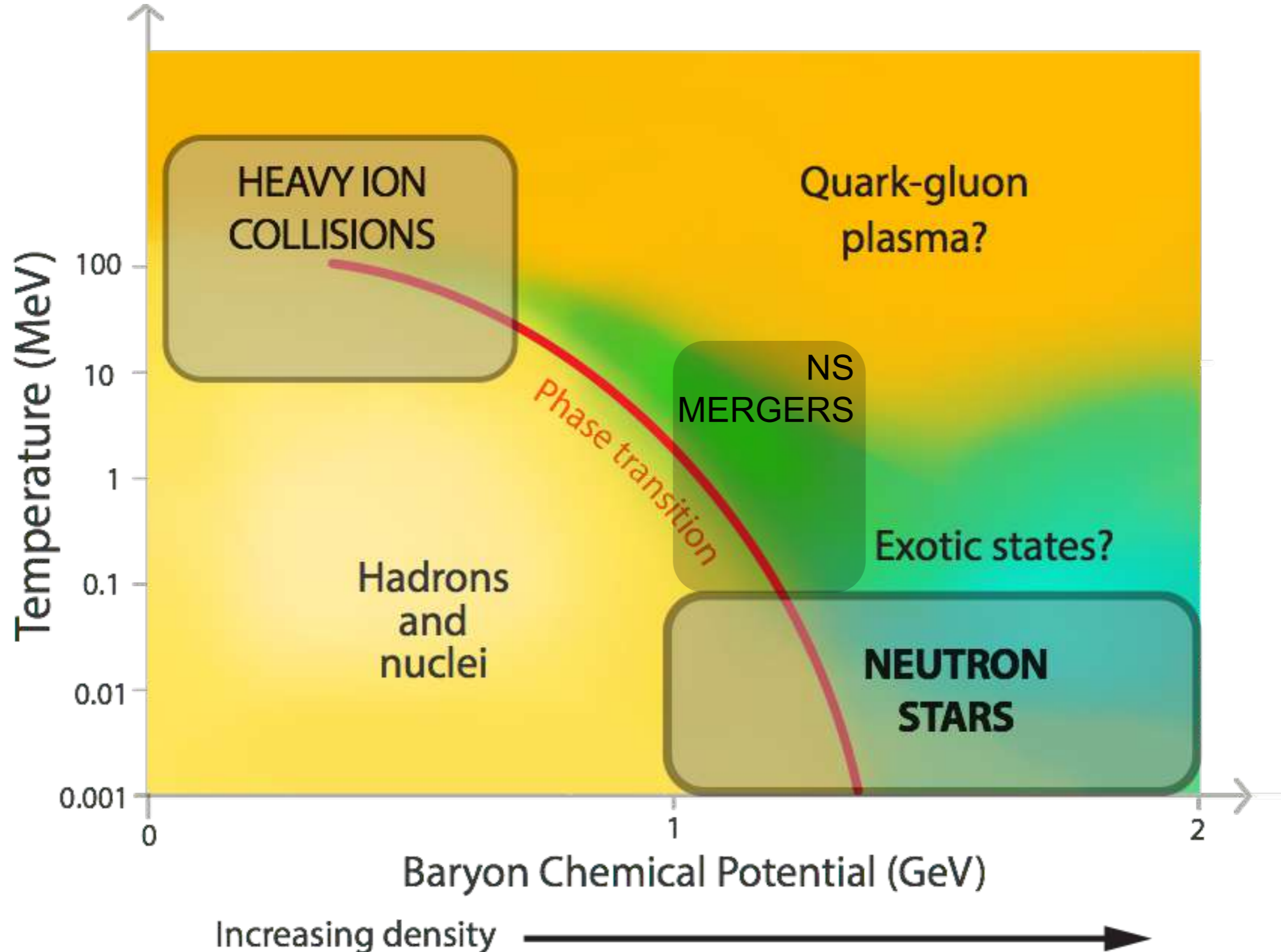
2 | INNER CRUST

NUCLEI
ELECTRONS
SUPERFLUID NEUTRONS

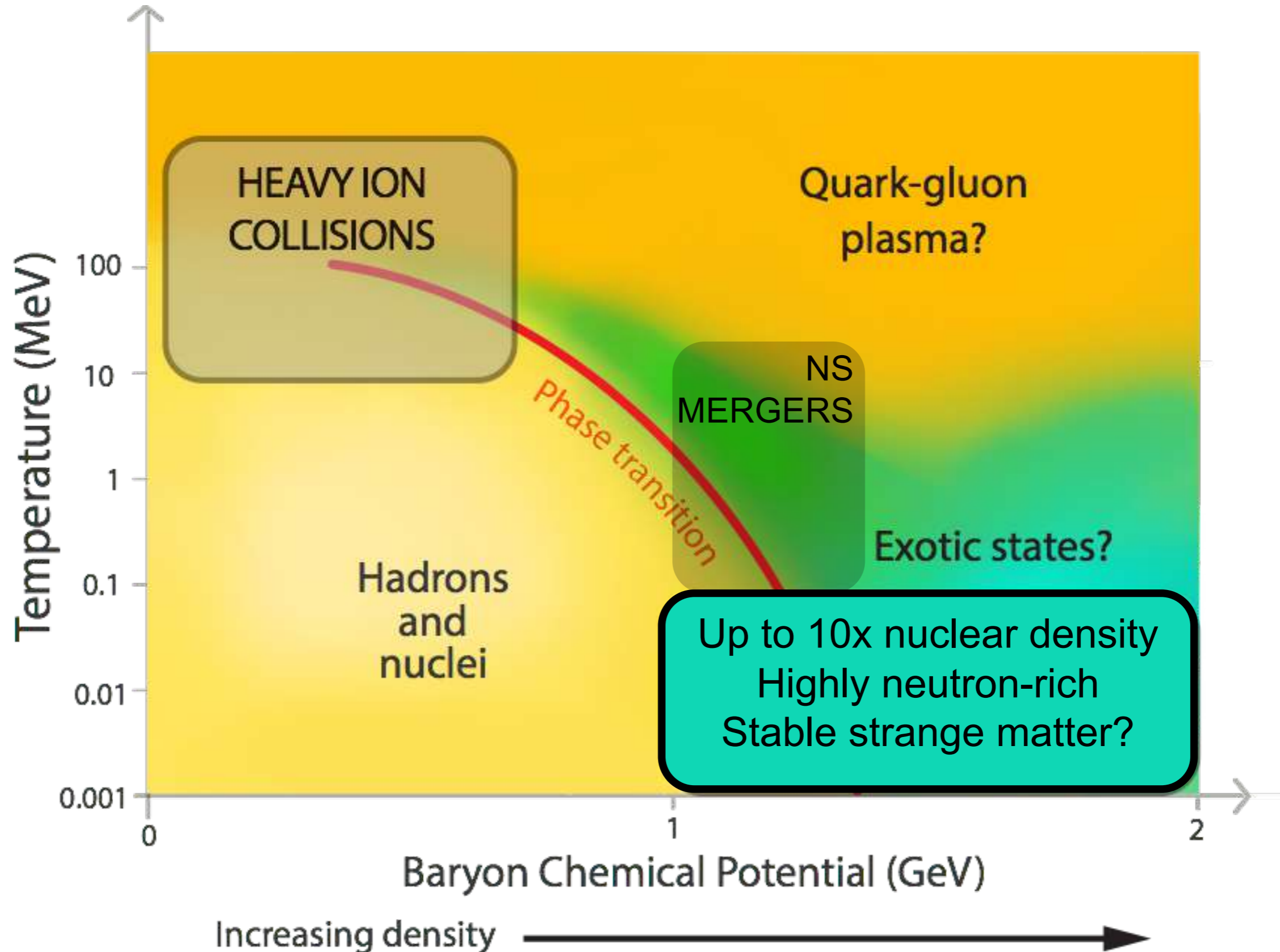
3 | CORE

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

UNKNOWNNS IN STRONG FORCE PHYSICS



UNKNOWNNS IN STRONG FORCE PHYSICS



FROM NUCLEAR PHYSICS TO TELESCOPE

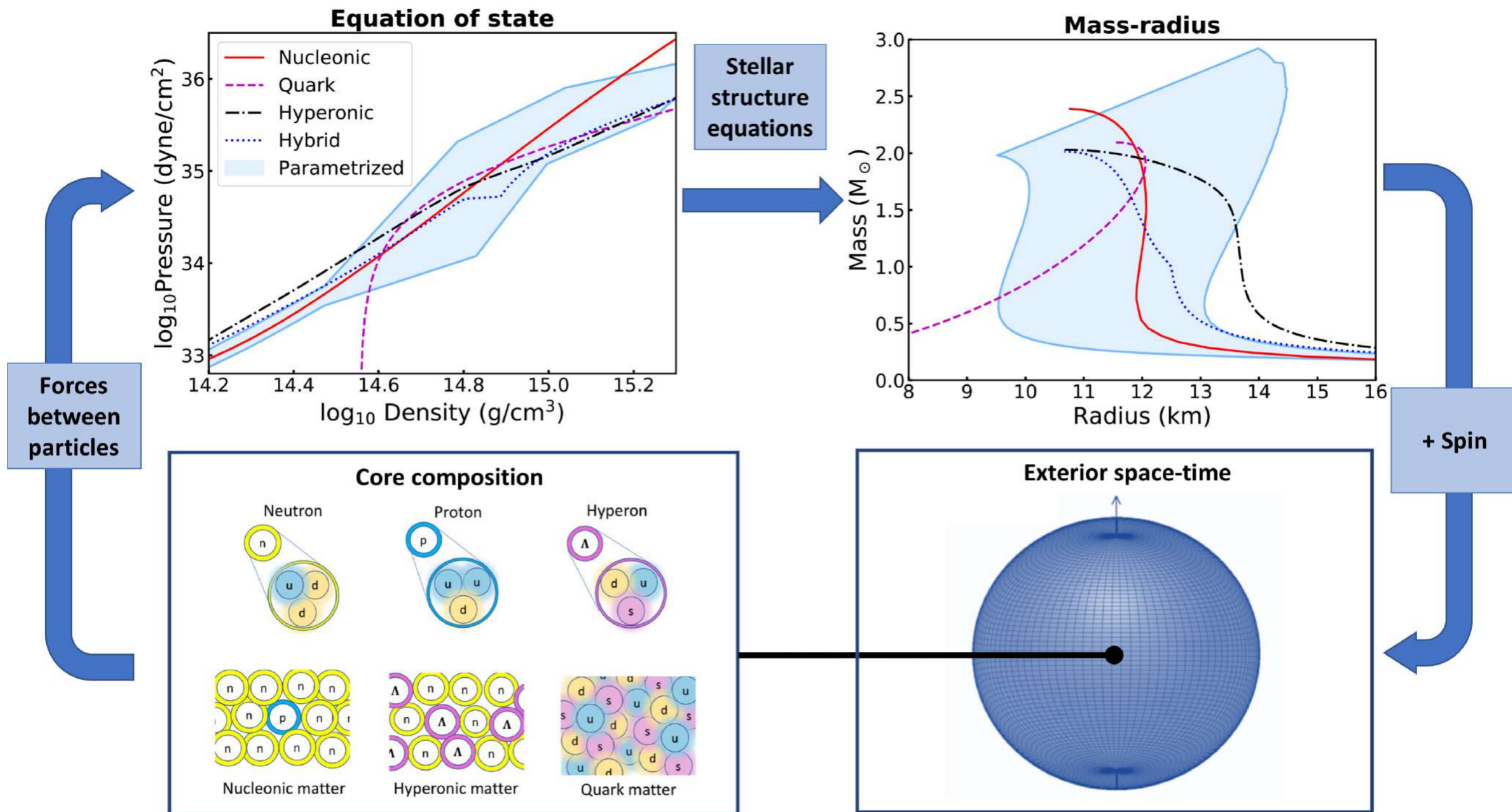


Figure: Adapted from Ray et al. 2019

NICER PRE-LAUNCH



Photo: Keith Gendreau (NASA)

NICER LAUNCH

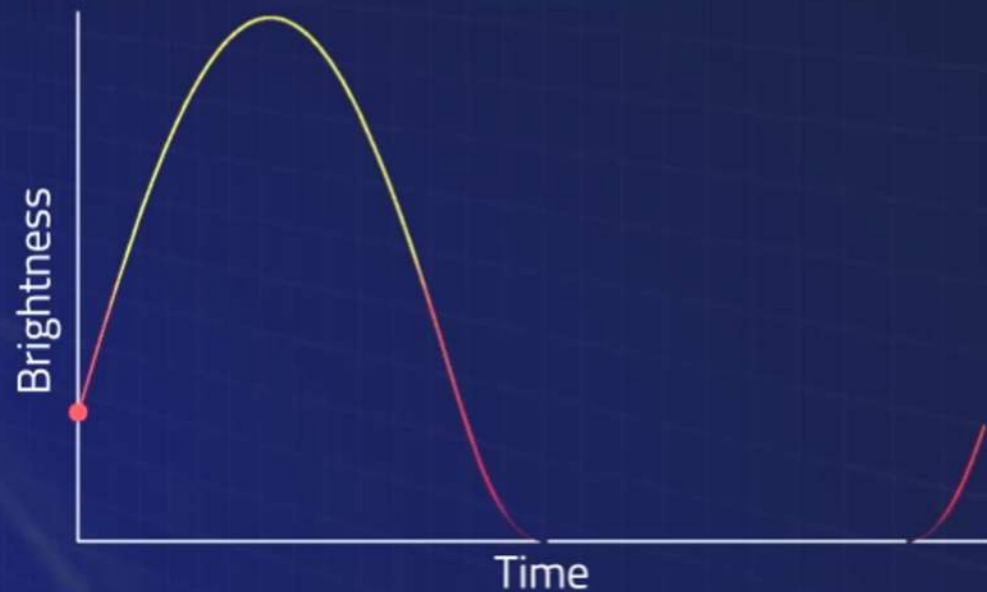
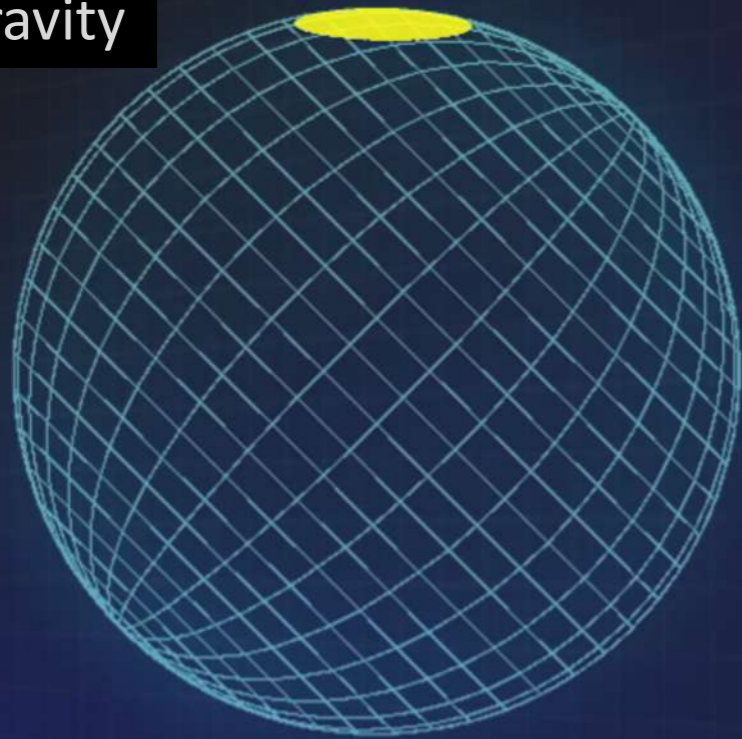


NICER ON THE ISS

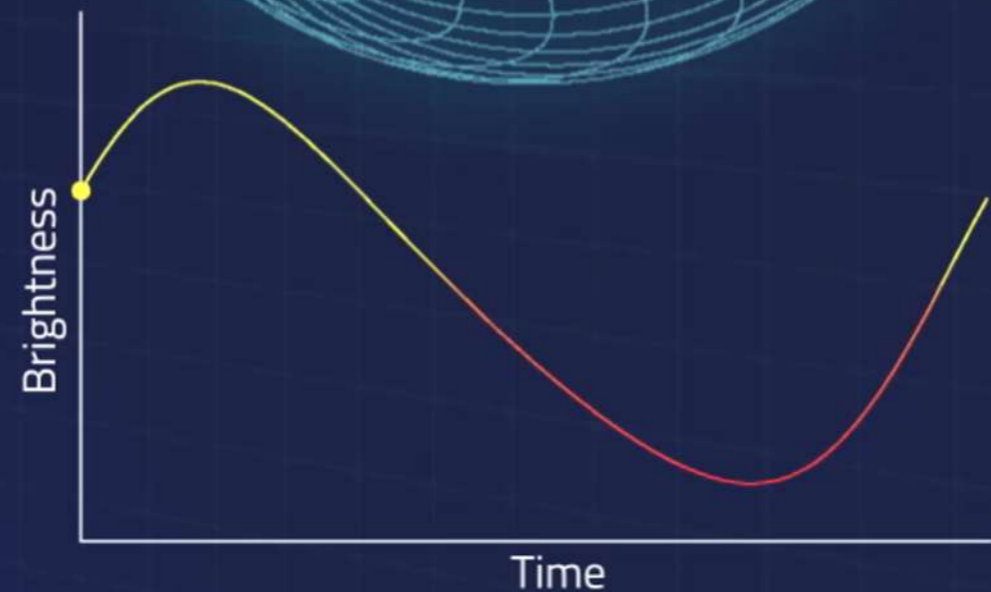
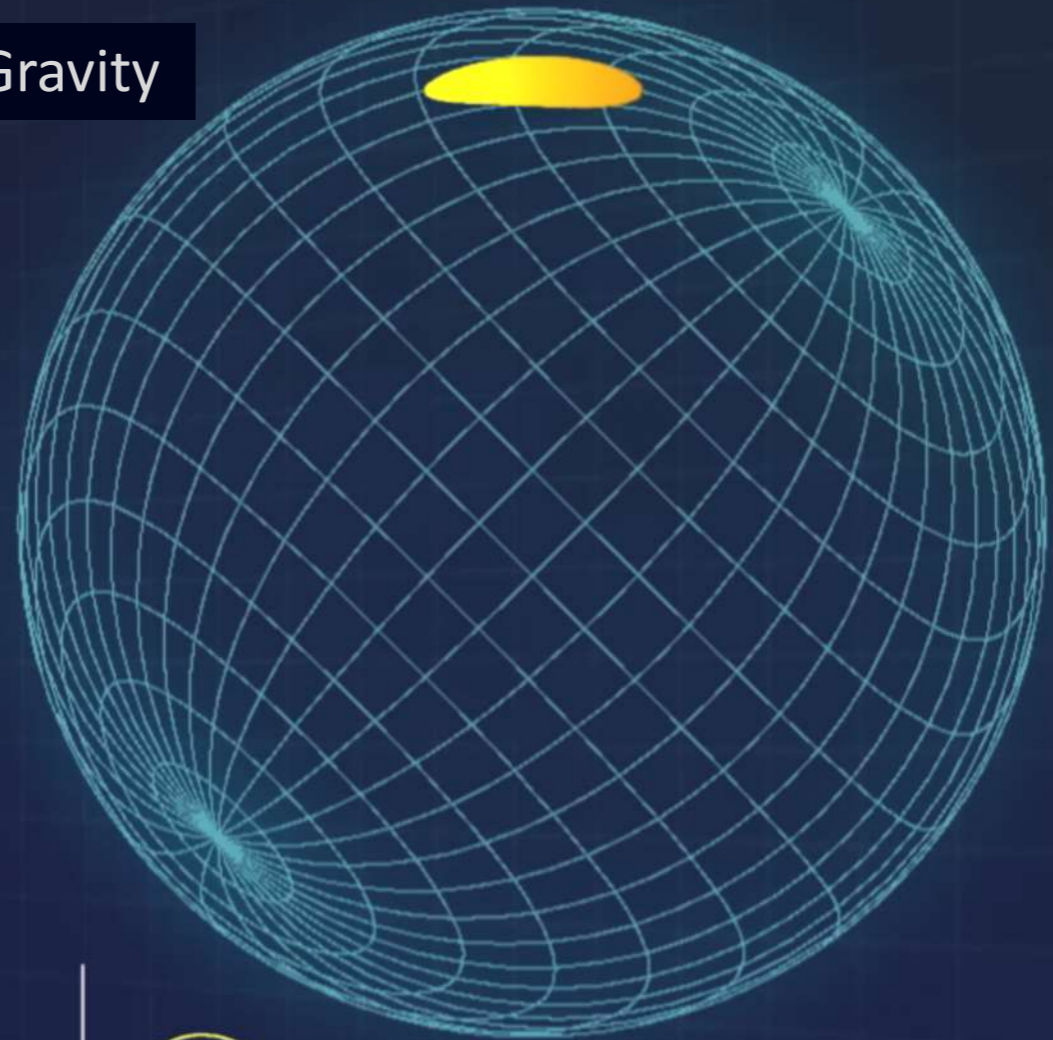
Movie of NICER on the ISS – see
https://www.youtube.com/watch?v=kk0ry3_R2pE

PULSE PROFILE MODELING

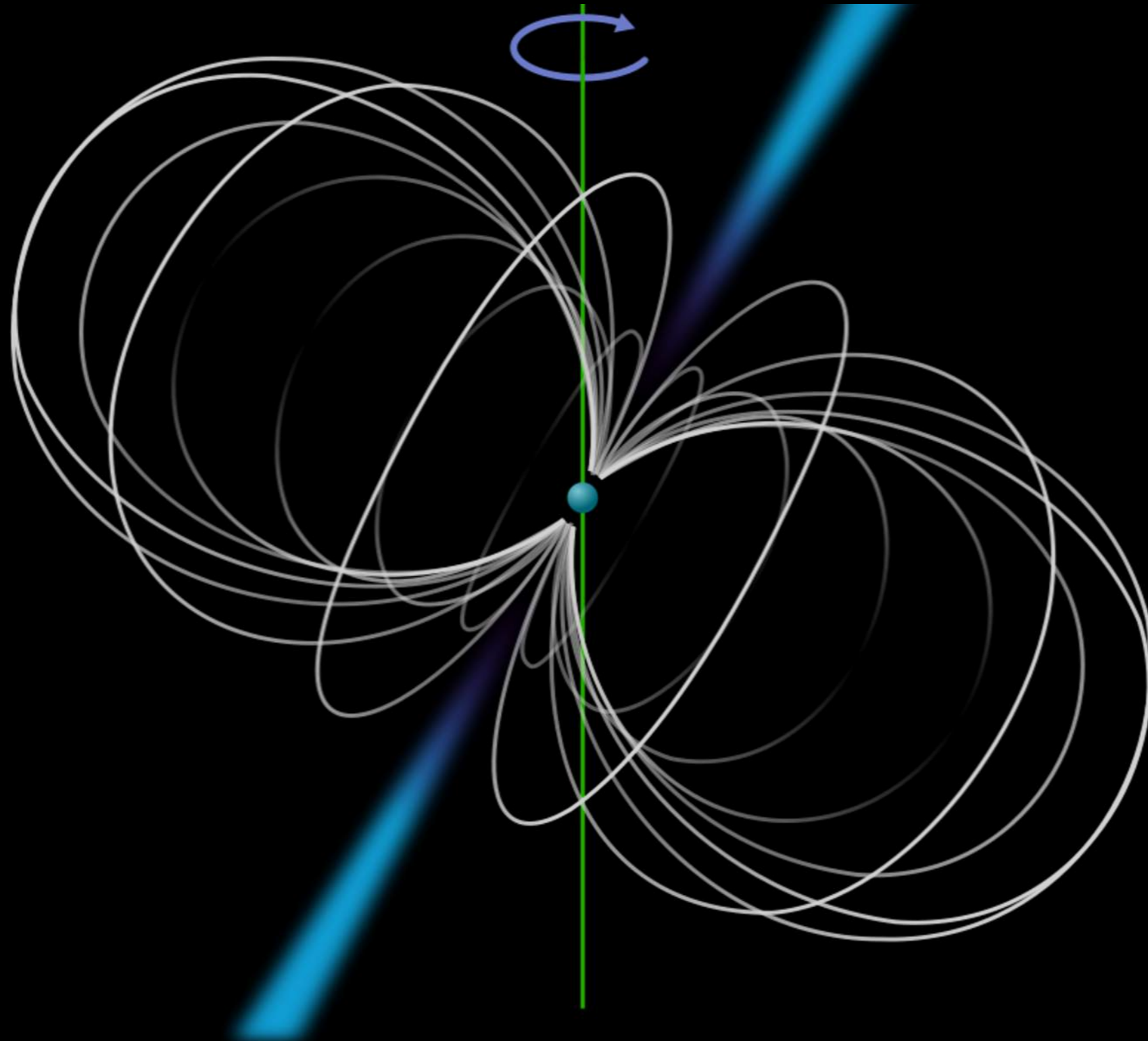
Weak Gravity



Strong Gravity

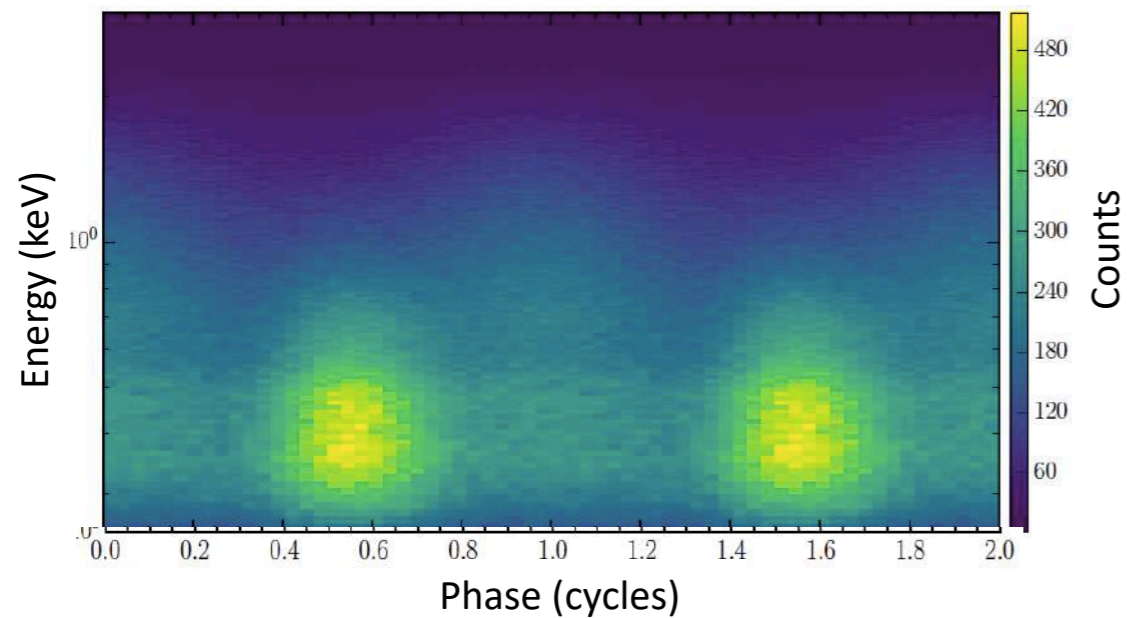


ROTATION-POWERED MILLISECOND X-RAY PULSARS

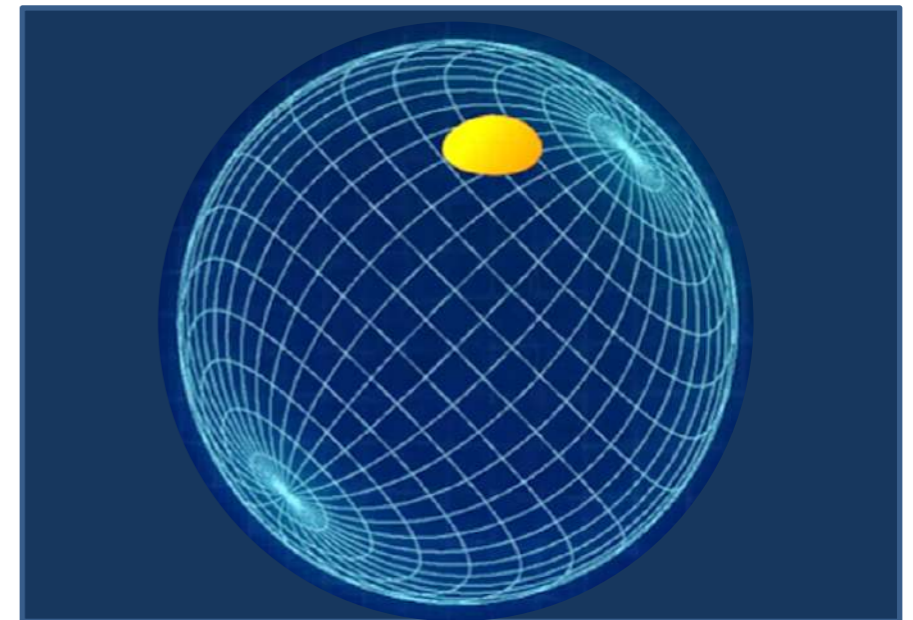


THE PULSE PROFILE MODELING PROCESS

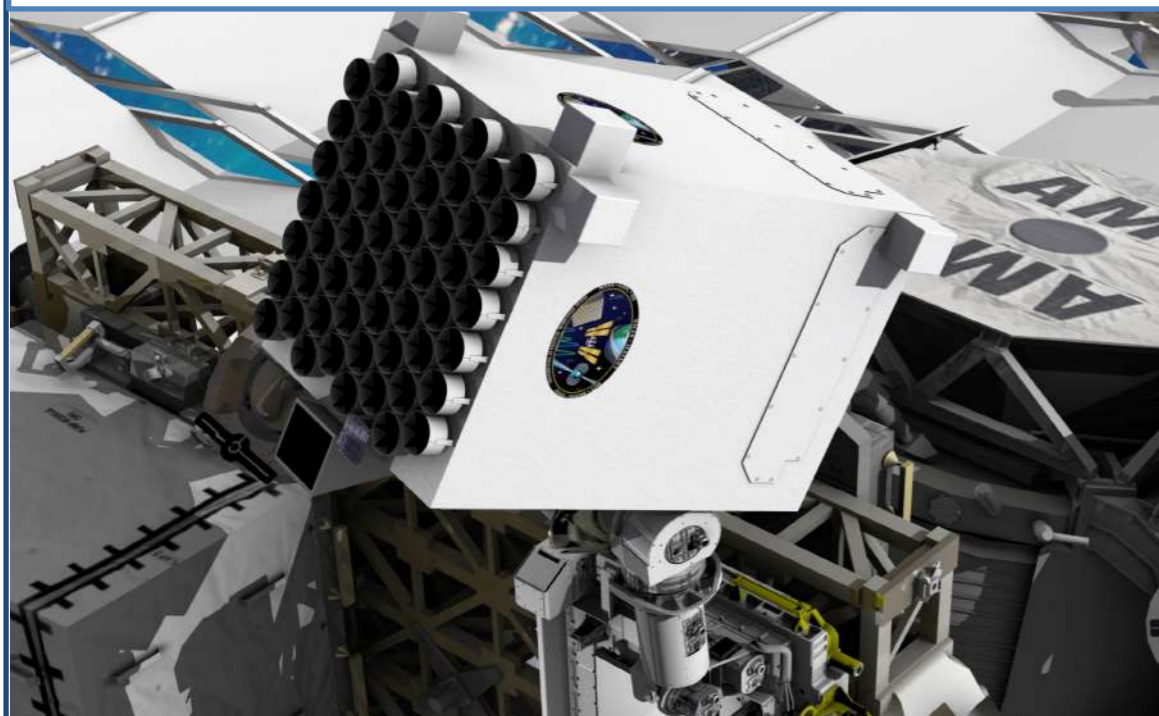
Pulse profile data: Phase, Energy



Lightcurve model:
Emission, Relativistic ray-tracing



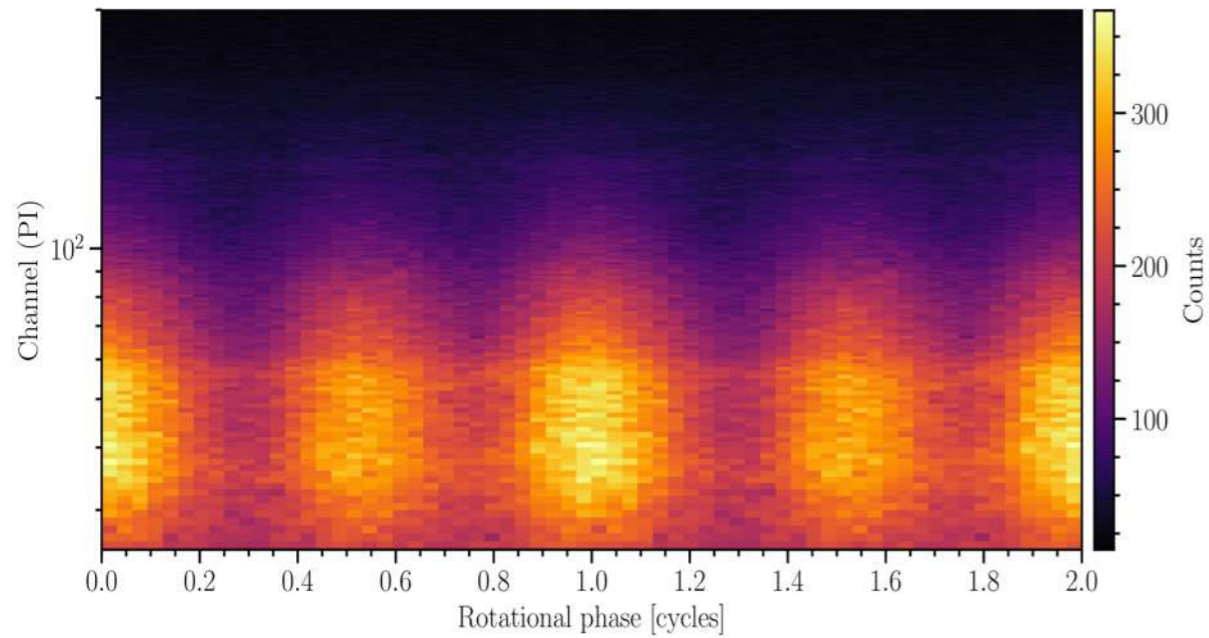
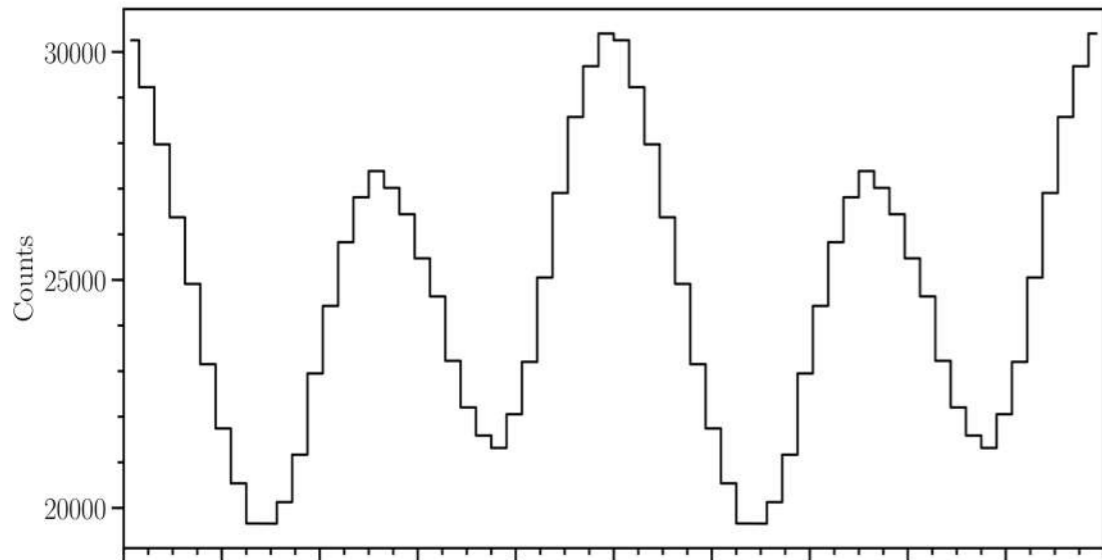
Instrument properties



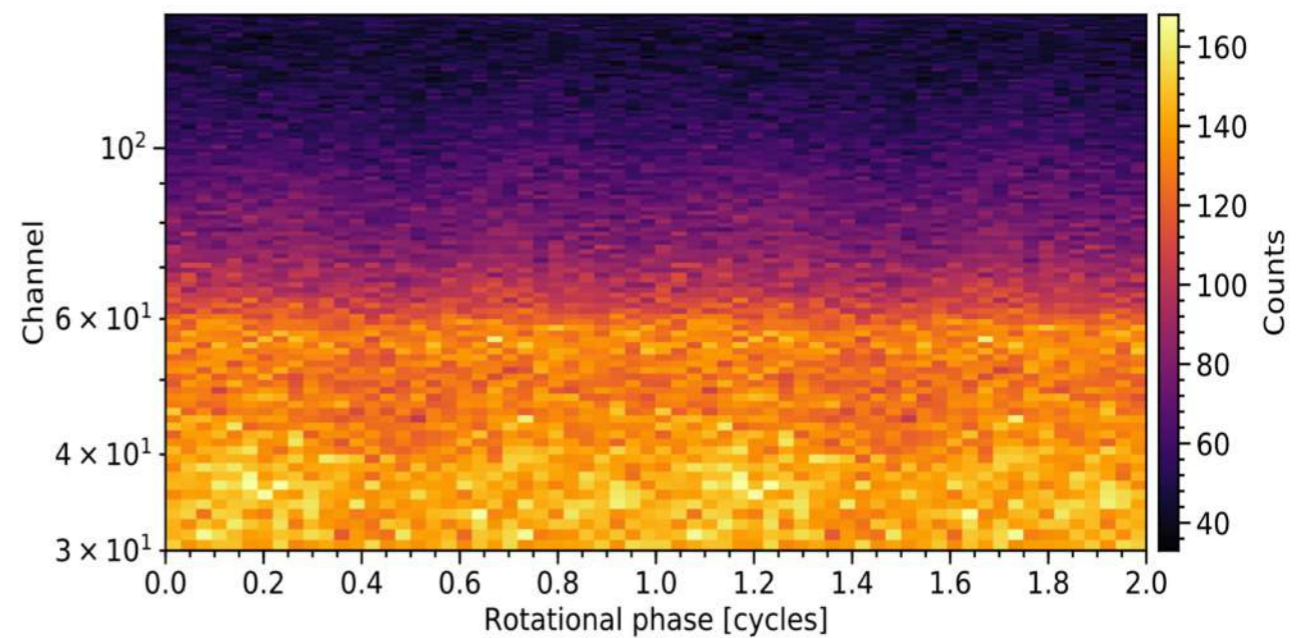
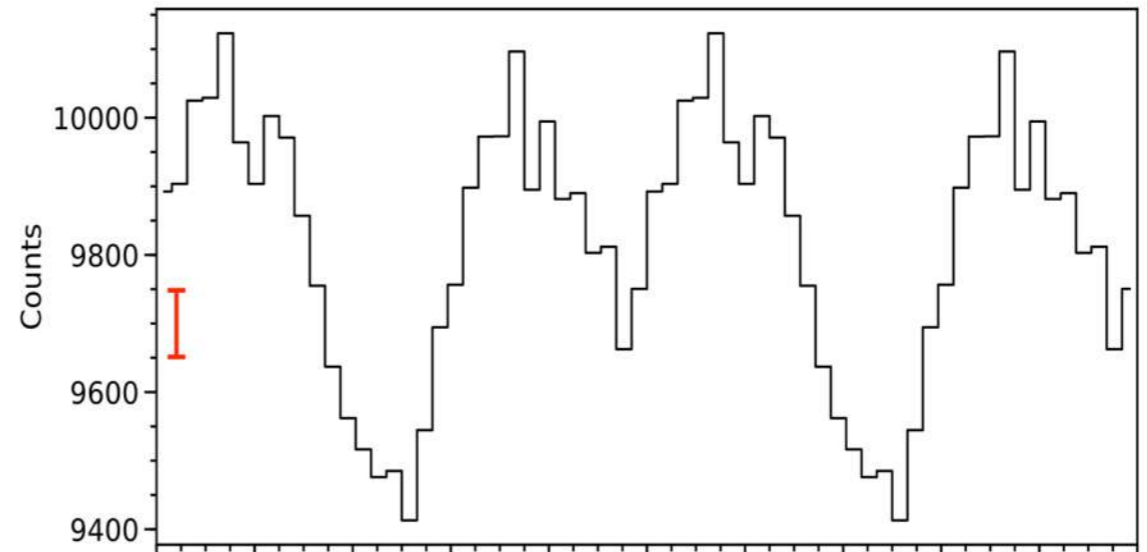
Inference code:
Likelihood calculation,
statistical sampling

Mass-radius
Geometric parameters

PULSE PROFILE DATA



PSR J0030+0451
(Bogdanov et al. 2019)



PSR J0740+6620
(Wolff et al. 2021)

SIMULATION AND INFERENCE CODES



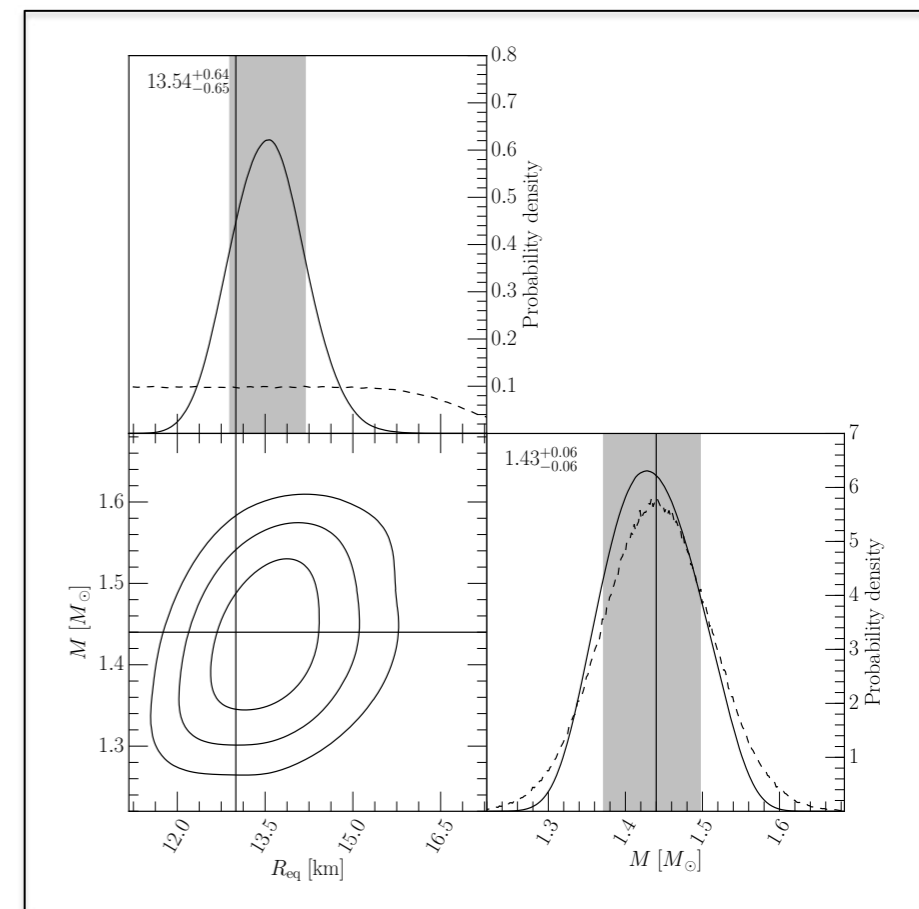
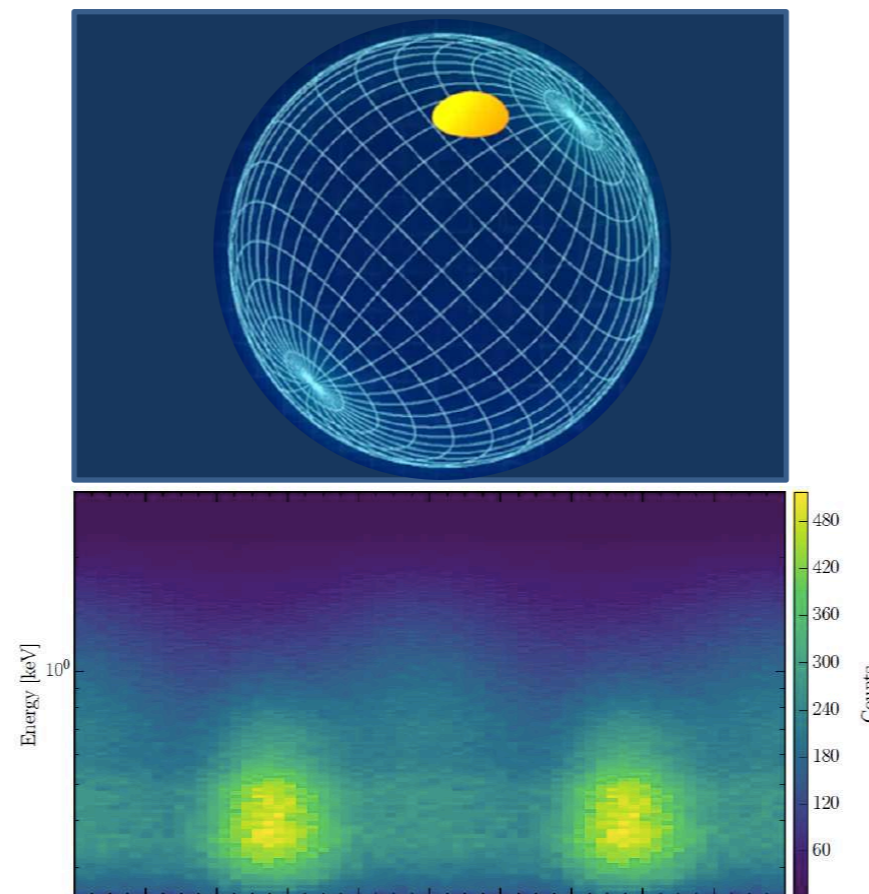
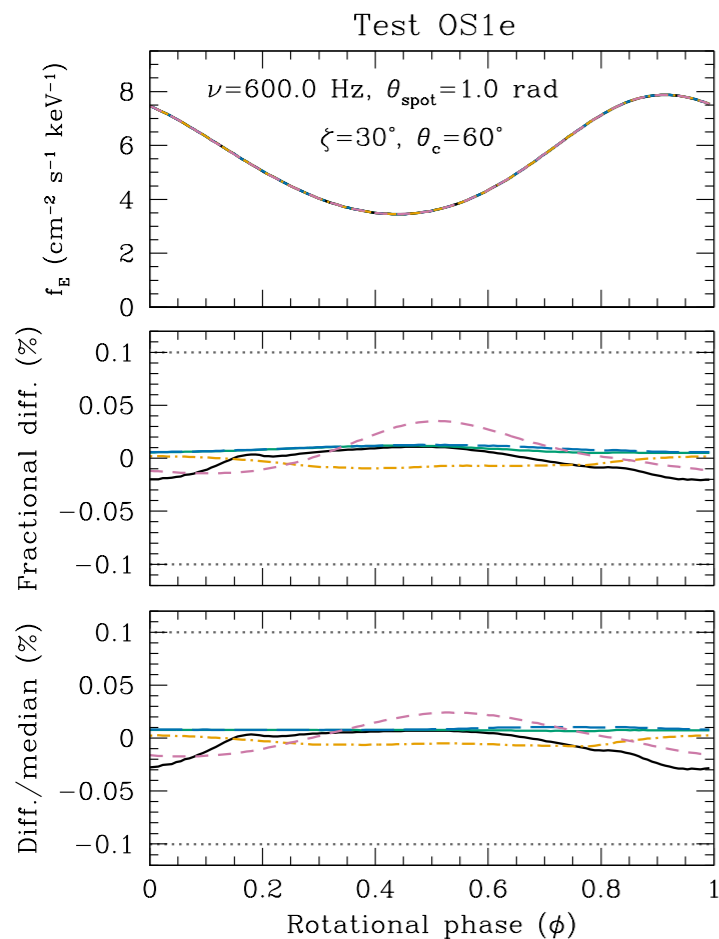
X-PSI

X-ray Pulsation, Simulation
and Inference code
(Riley & Watts 2021).
github.com/ThomasEdwardRiley/xpsi

Uses open source samplers
(primarily MultiNest).



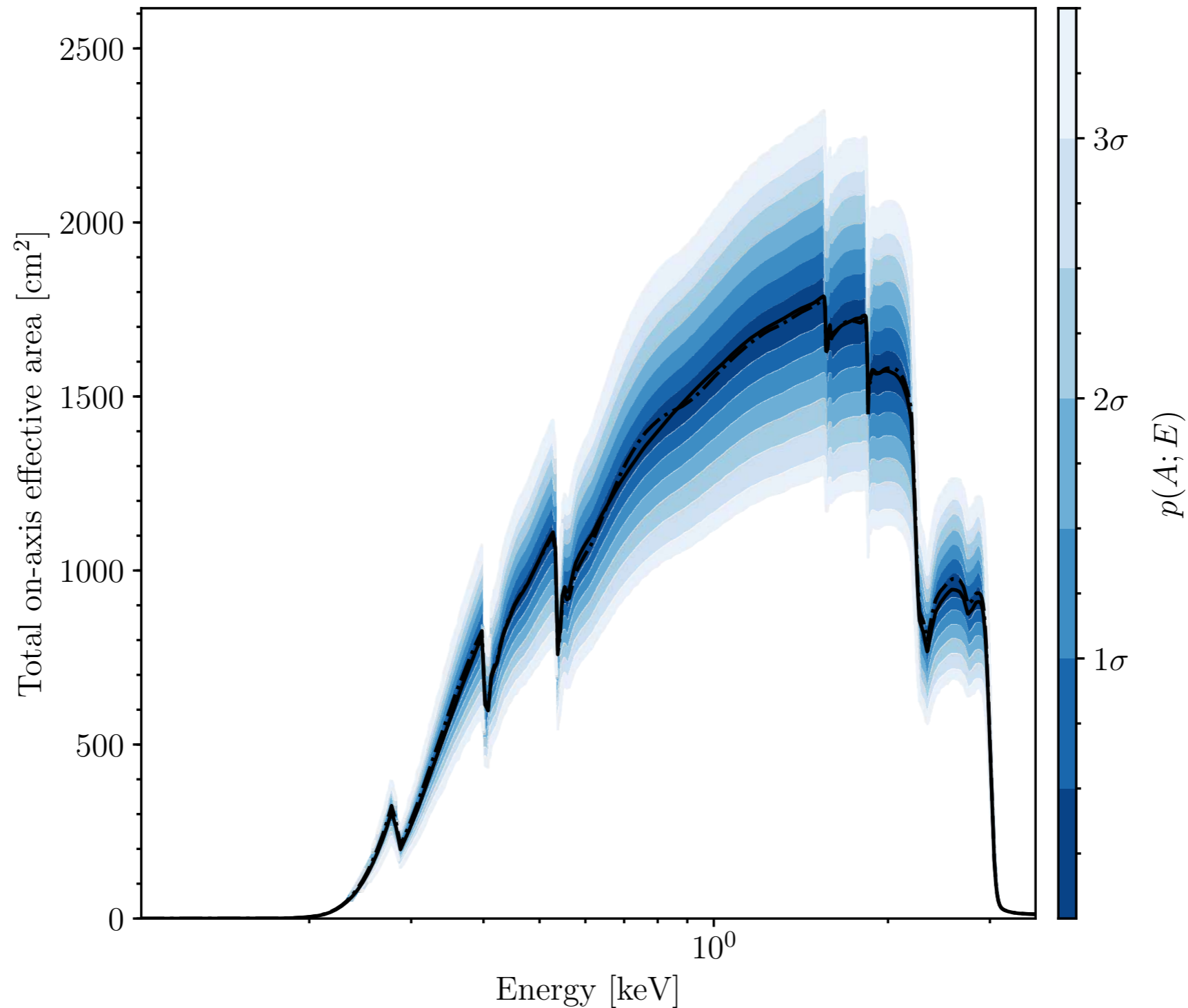
Cartesius



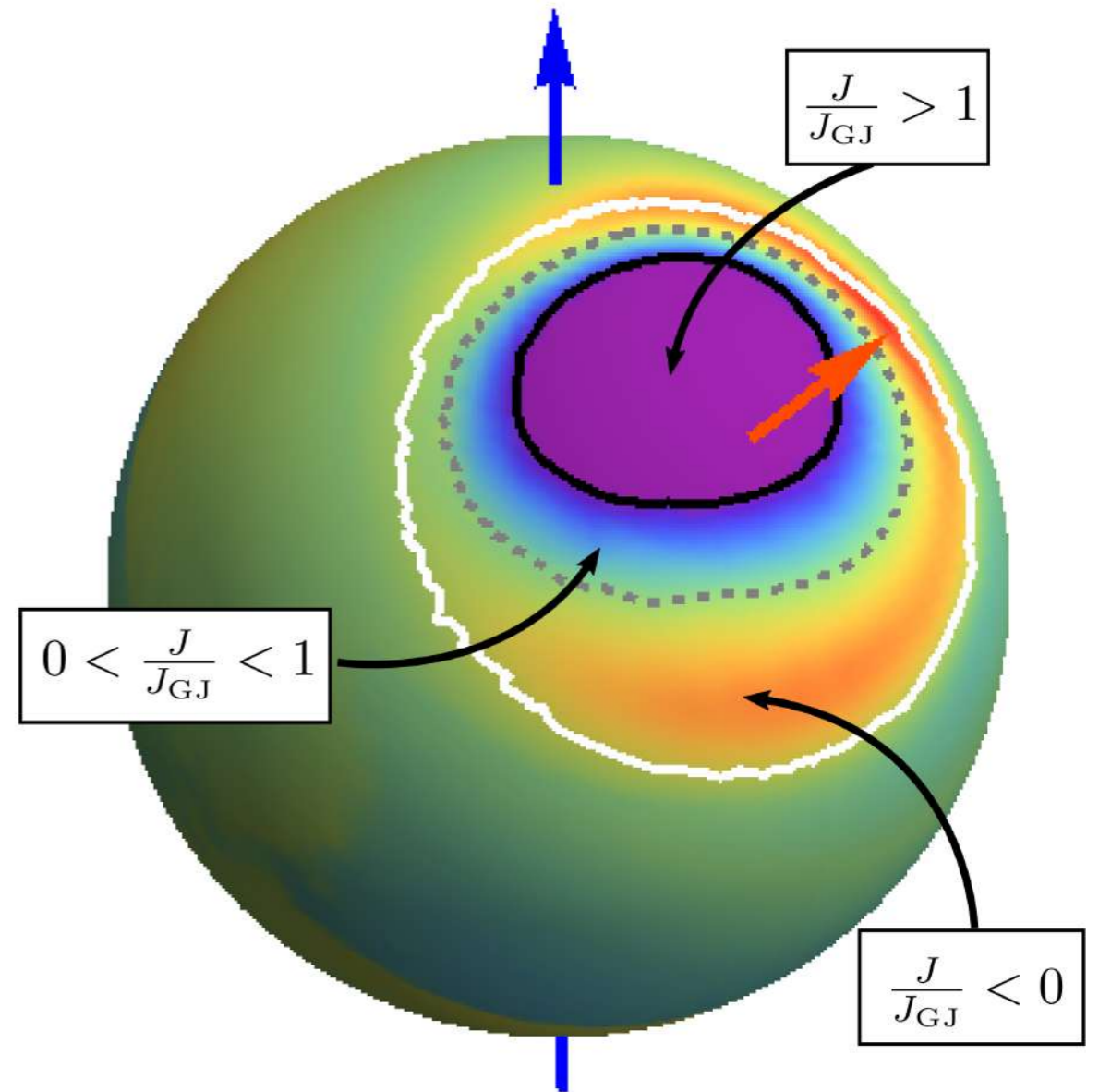
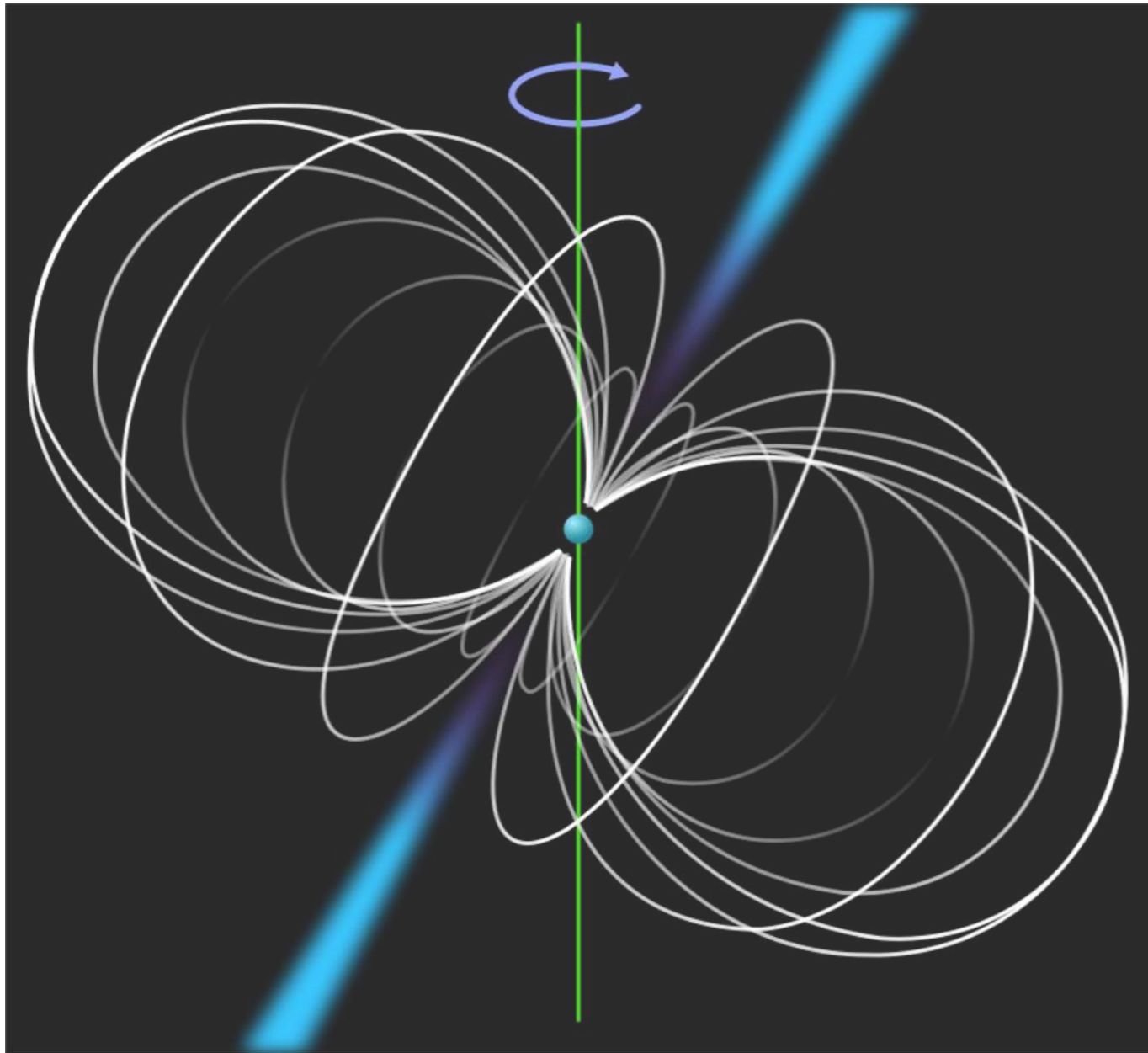
Ray-tracing and inference routines tested by multiple groups using synthetic data (Bogdanov et al. 2019b, 2020, Riley PhD thesis 2019)

THE NICER INSTRUMENT RESPONSE

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



PULSAR SURFACE EMISSION PATTERNS



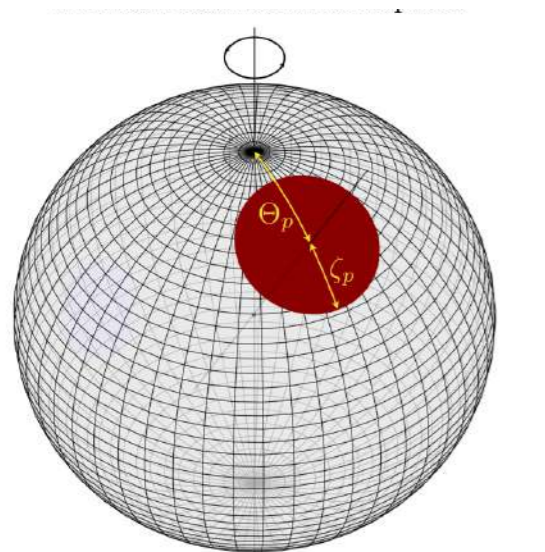
Surface heating pattern due to return currents a priori poorly constrained.

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

POLAR CAP MODELS

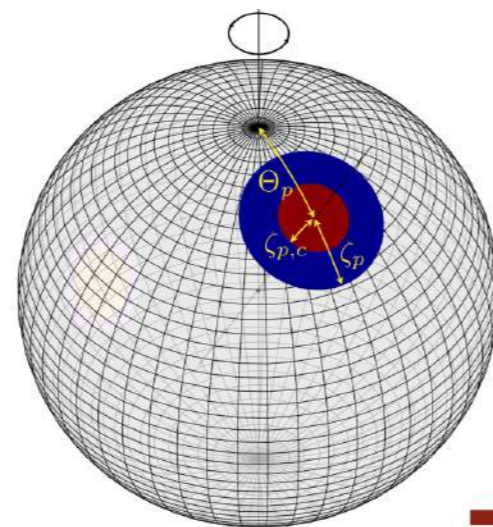
- We use 2-cap models of increasing surface pattern complexity.

Northern rotational hemisphere



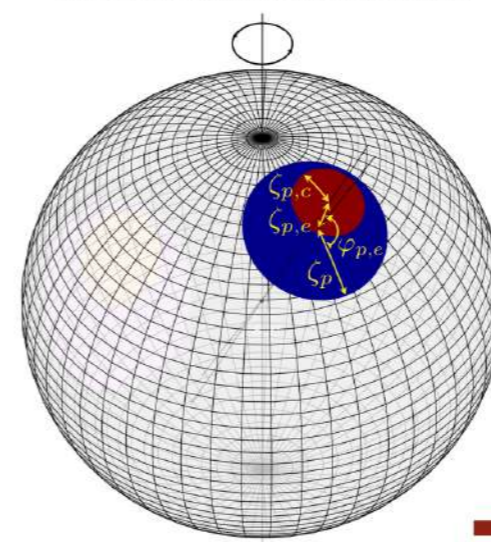
ST-U
(Single-temperature with unshared parameters)

T_p
 T_s



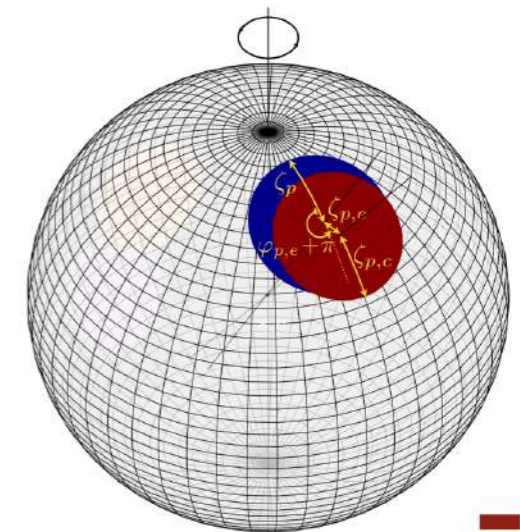
CDT-U
(Concentric dual-temperature with unshared parameters)

$T_{p,c}$
 $T_{p,a}$
 $T_{s,c}$
 $T_{s,a}$



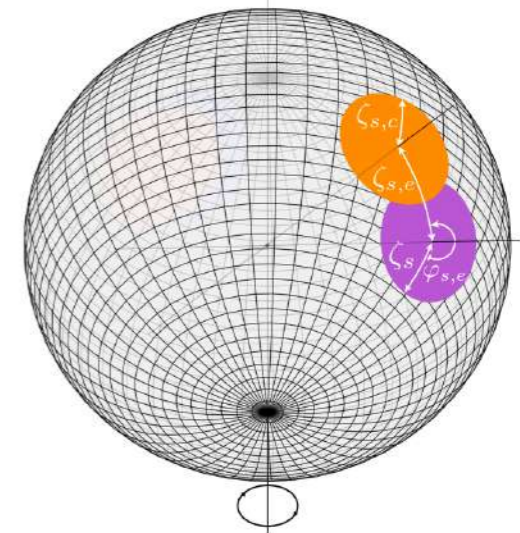
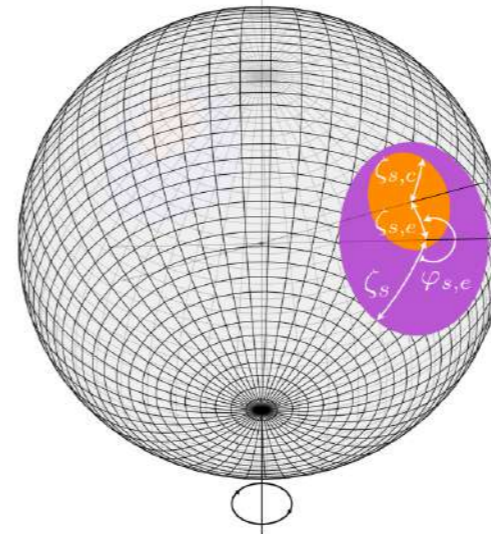
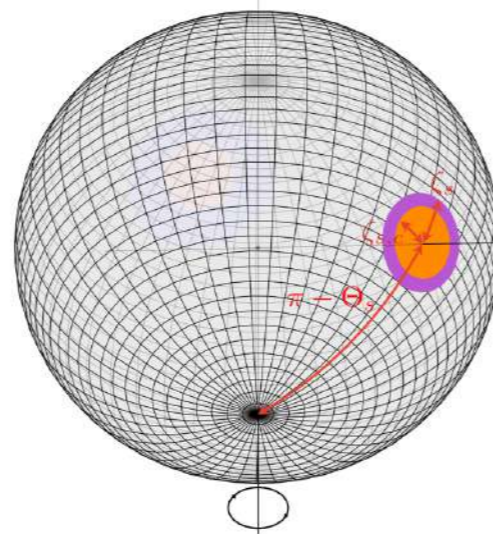
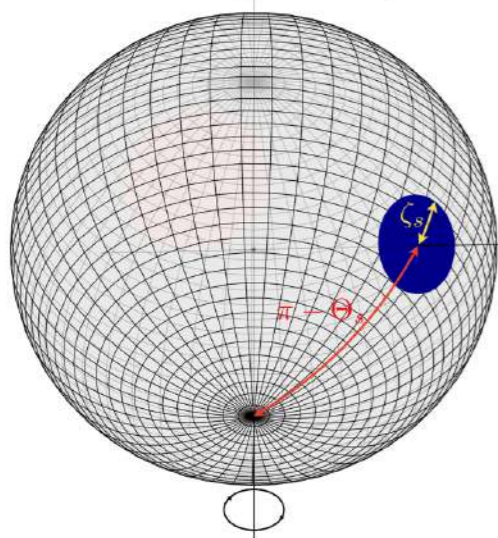
EDT-U
(Eccentric dual-temperature with unshared parameters)

$T_{p,c}$
 $T_{p,a}$
 $T_{s,c}$
 $T_{s,a}$



PDT-U
(Protruding dual-temperature with unshared parameters)

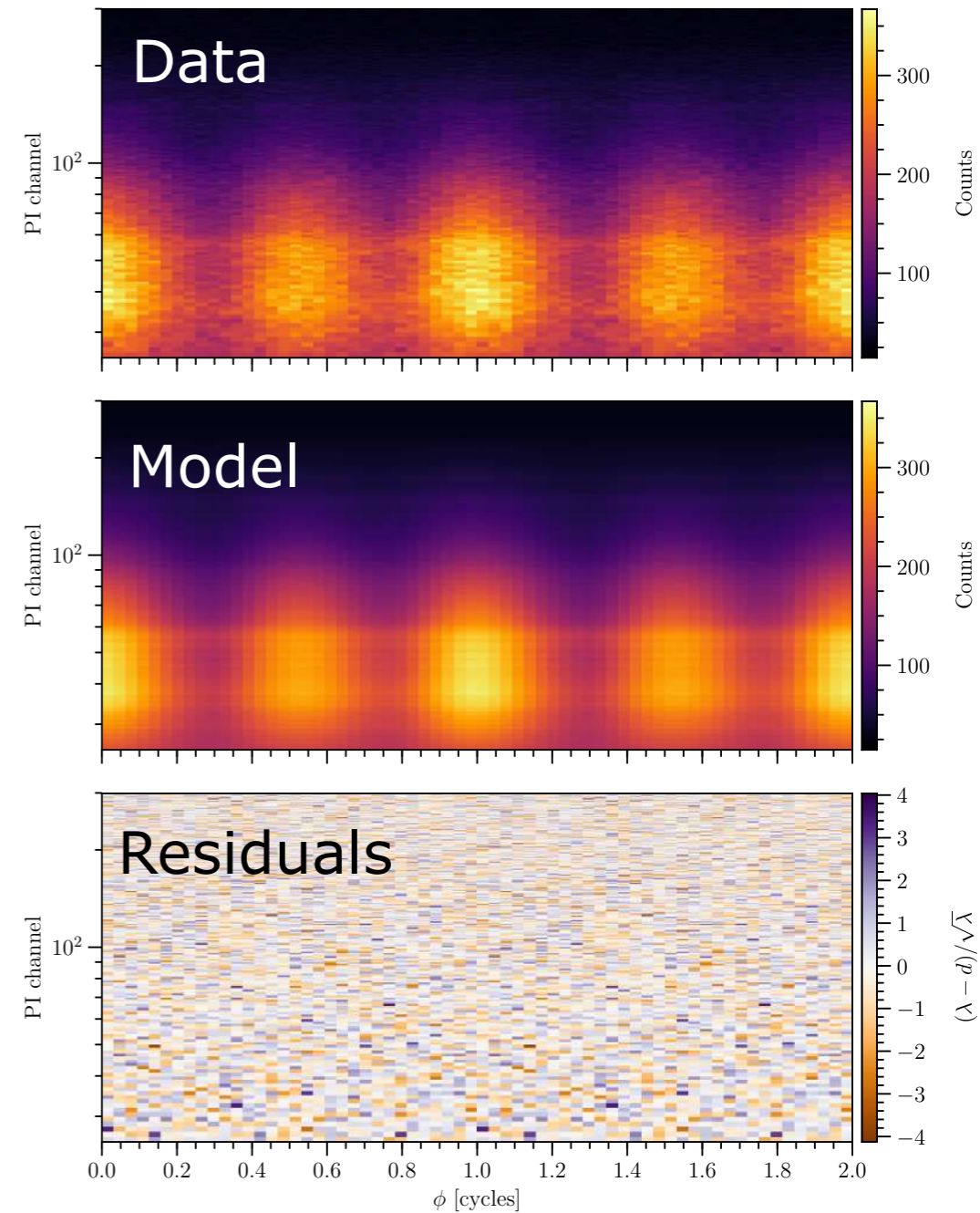
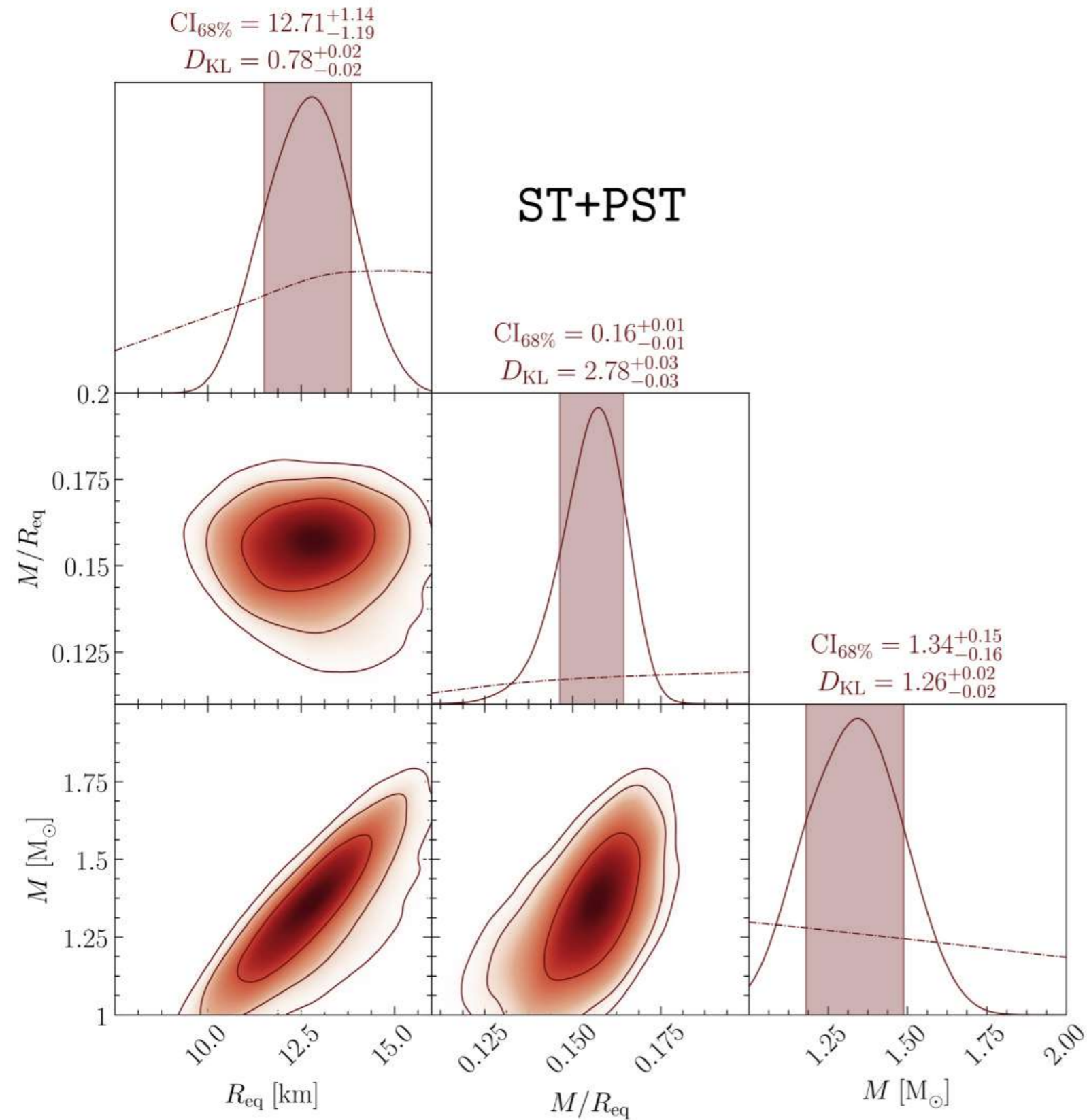
$T_{p,c}$
 $T_{p,a}$
 $T_{s,c}$
 $T_{s,a}$



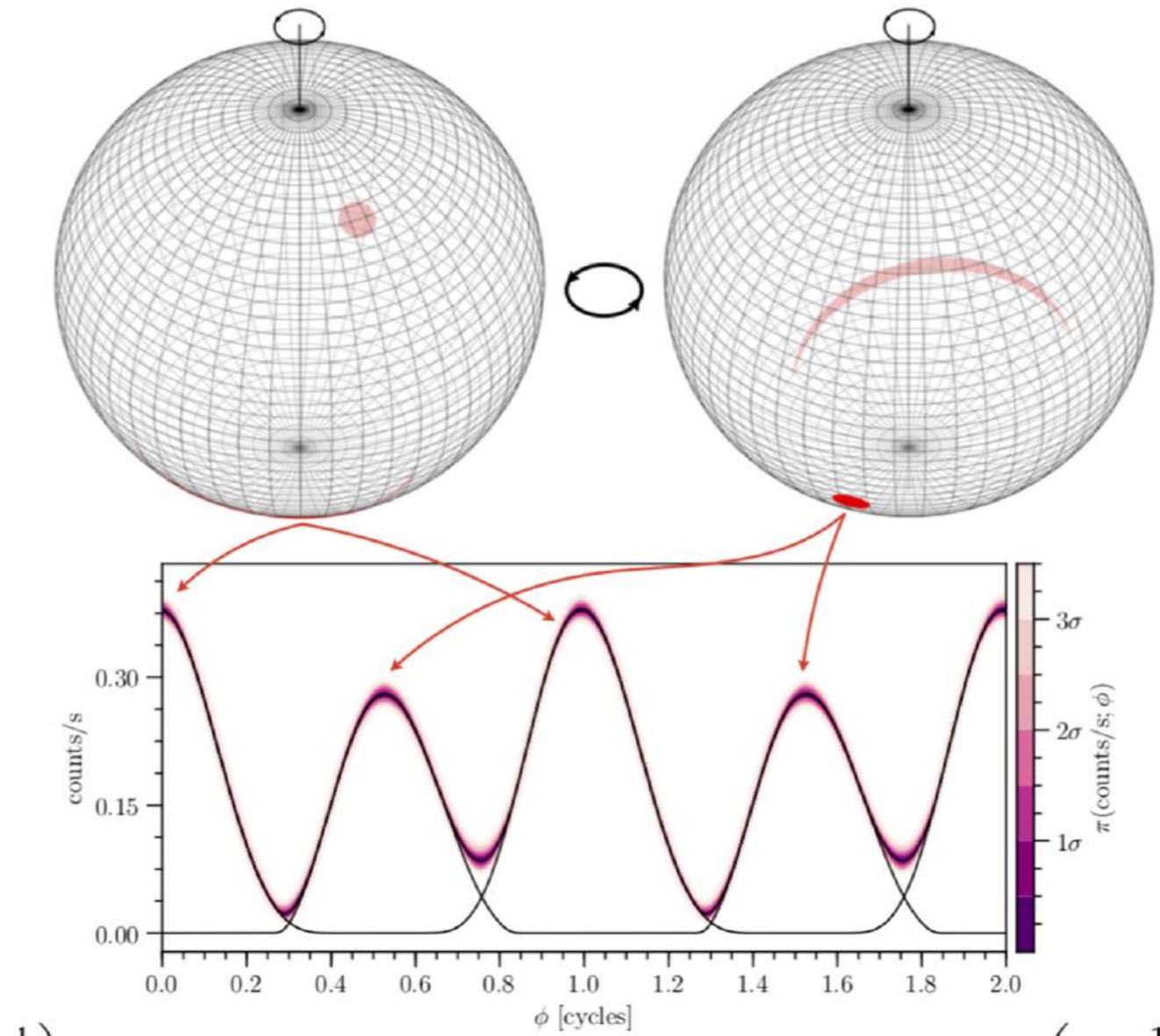
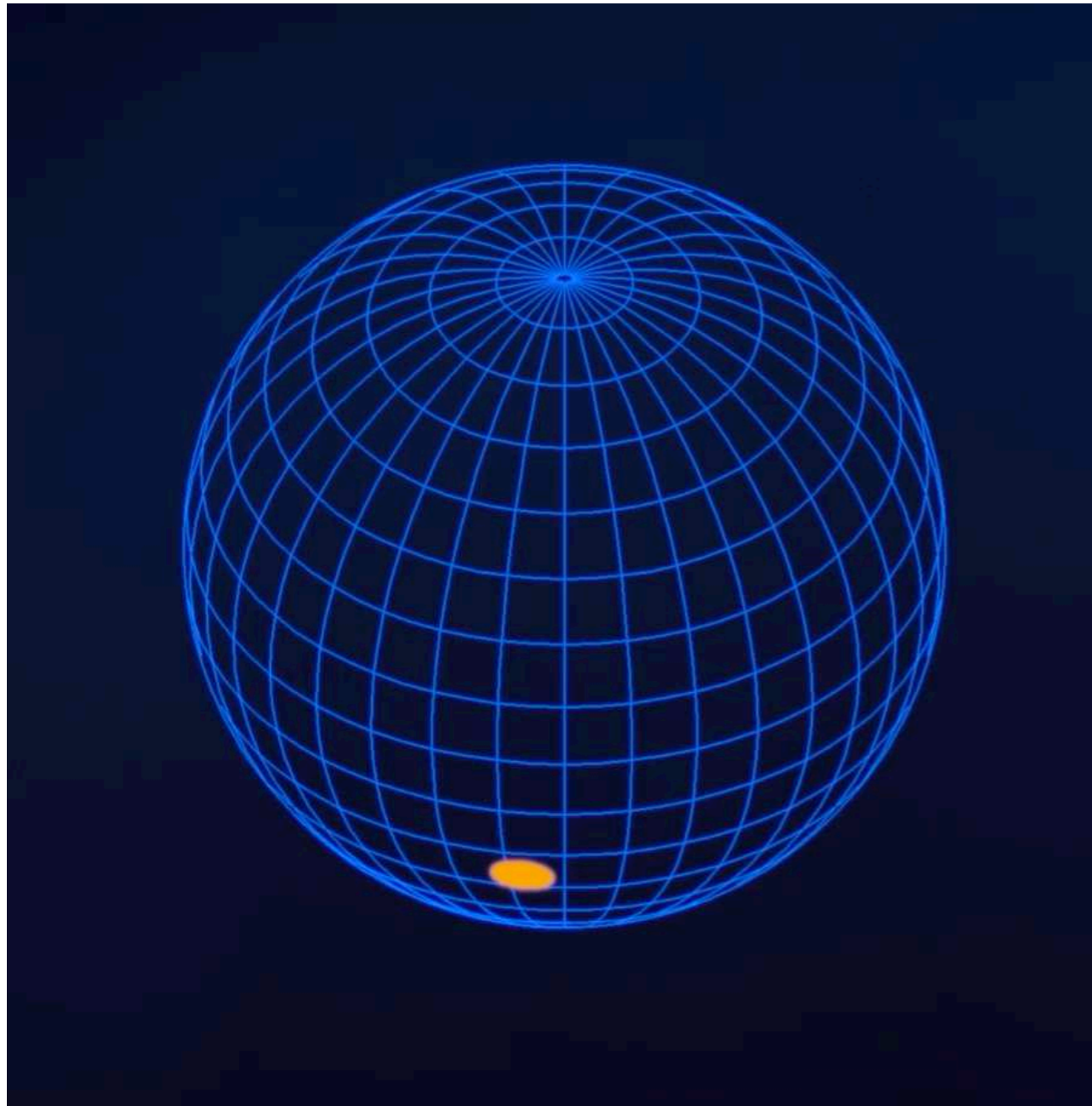
Southern rotational hemisphere

Riley et al. 2019

PSR J0030+0451 - PREFERRED CONFIGURATION

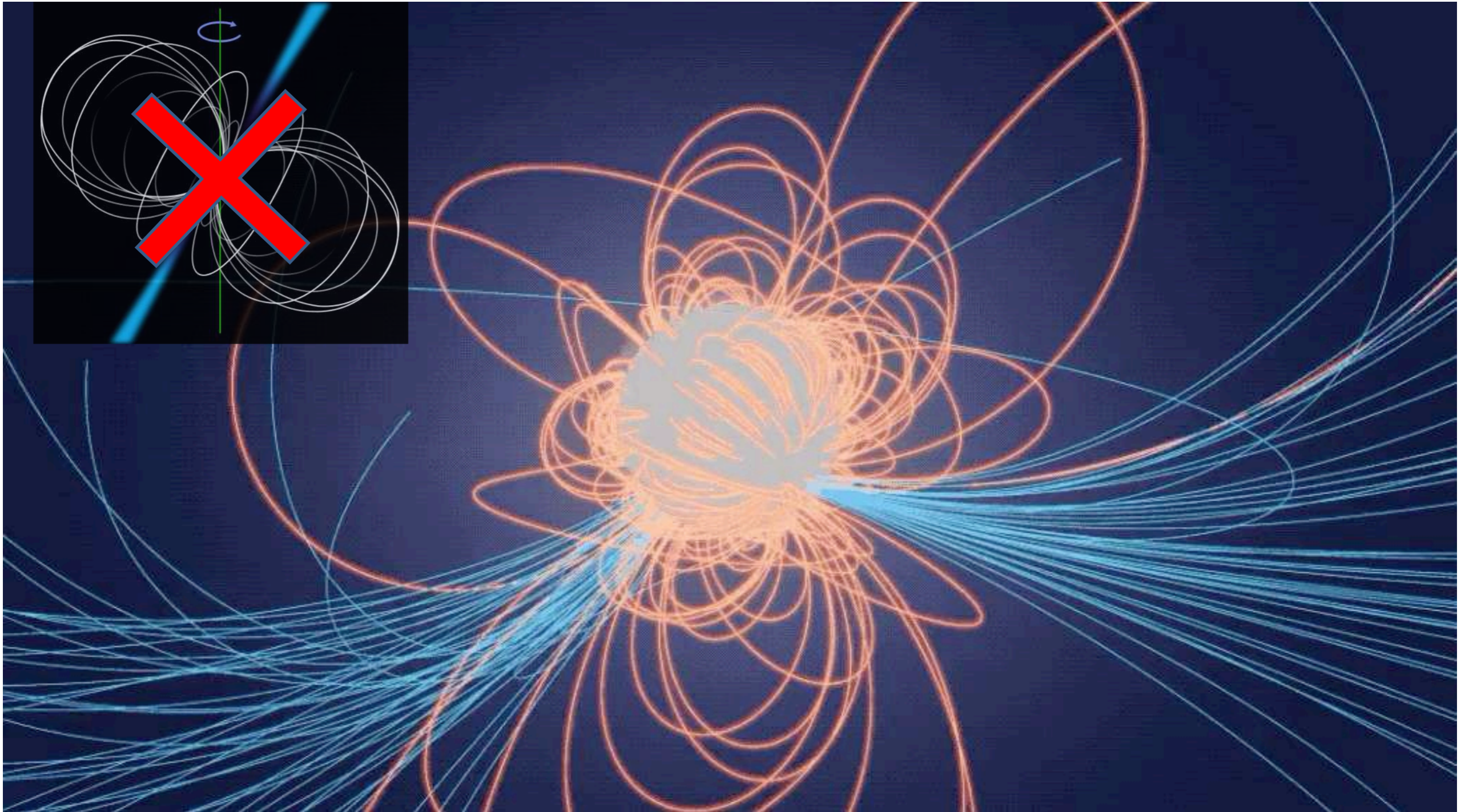


PSR J0030+0451 - PREFERRED CONFIGURATION



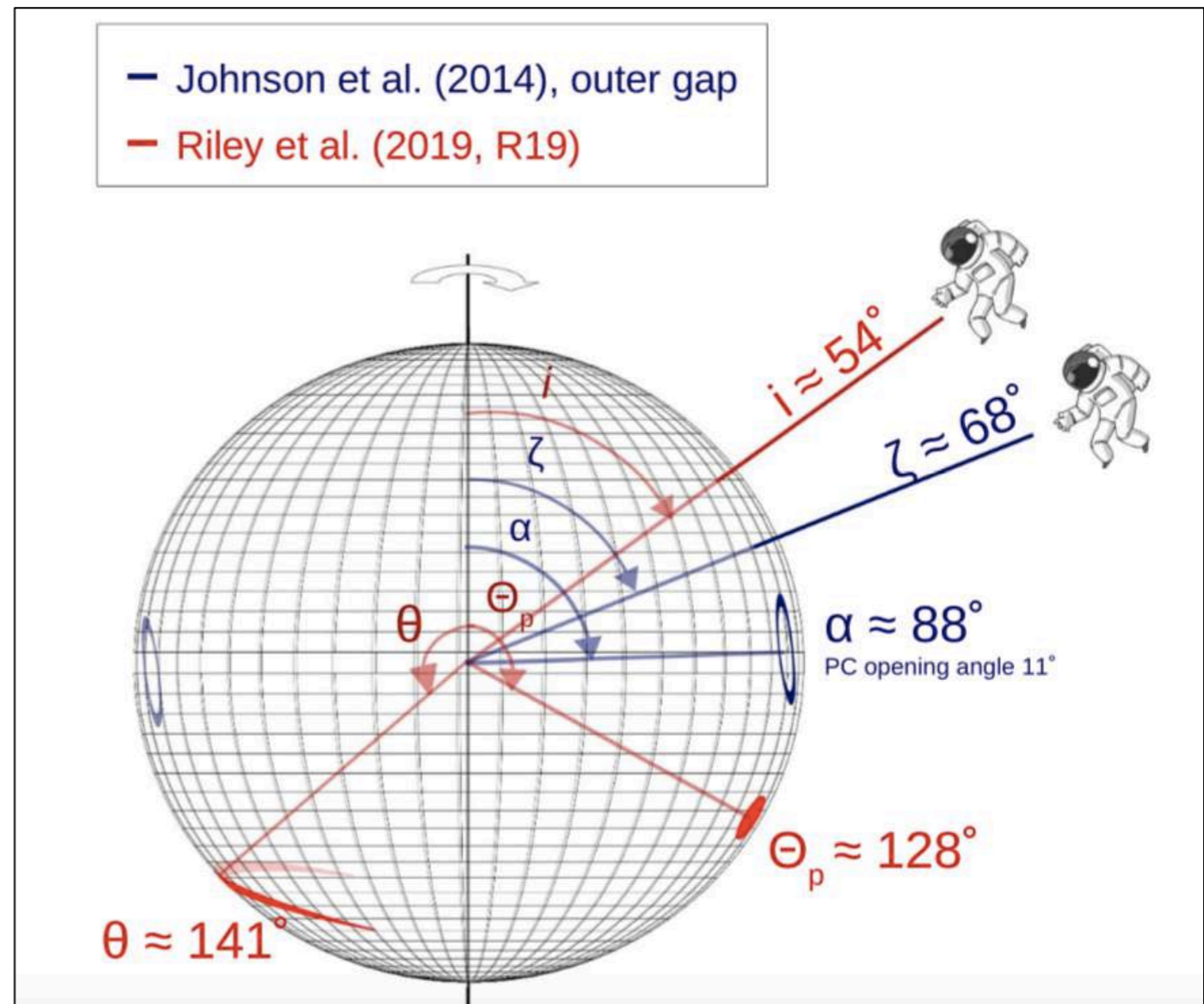
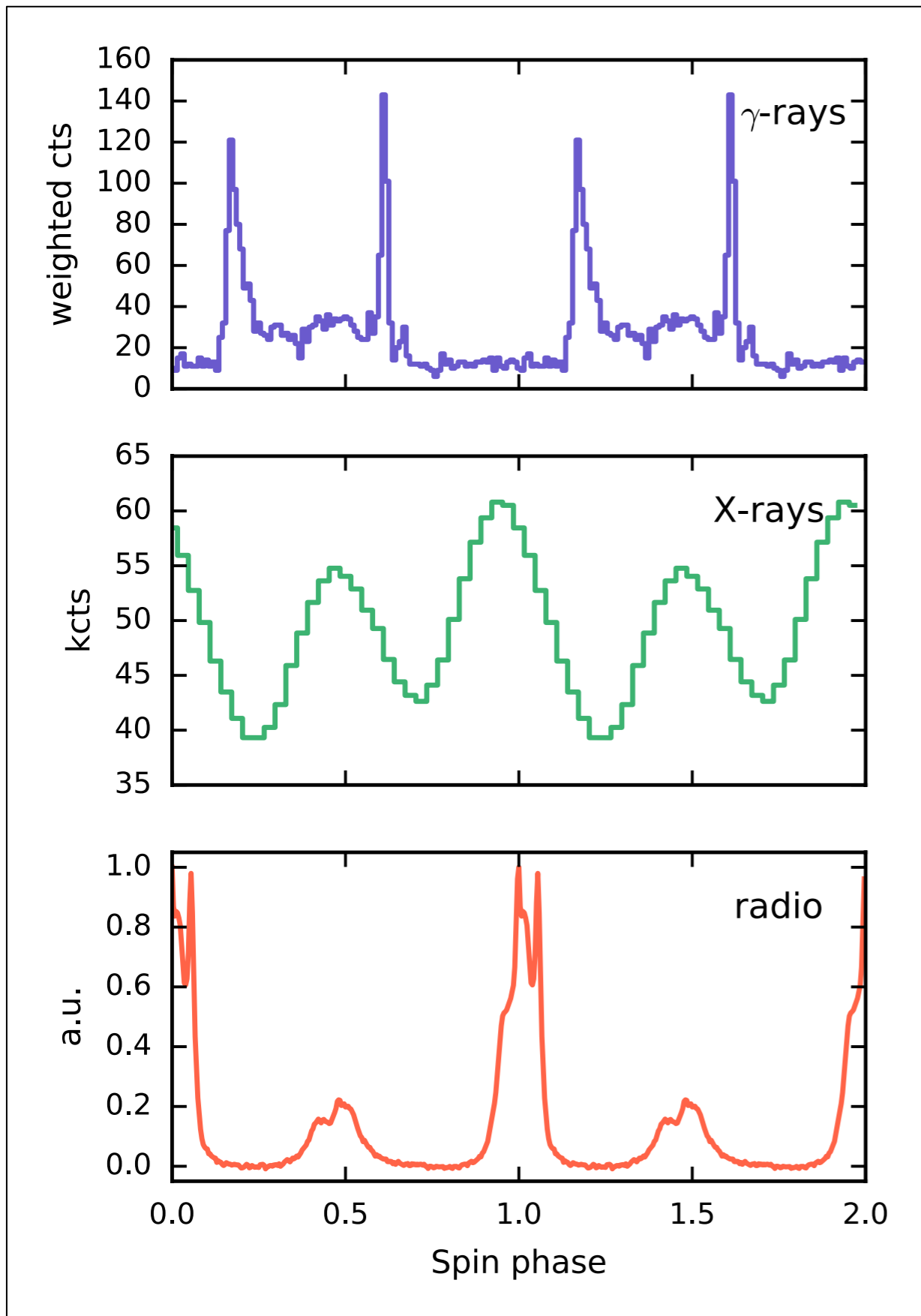
Riley et al. 2019 - link for movie given in later slides

NON-DIPOLAR MAGNETIC FIELD



Credit: NASA's Goddard Space Flight Center/Harding, Kalapotharakos, Wadiasingh. Movie here: <https://www.nasa.gov/feature/goddard/2019/nasa-s-nicer-delivers-best-ever-pulsar-measurements-1st-surface-map>.

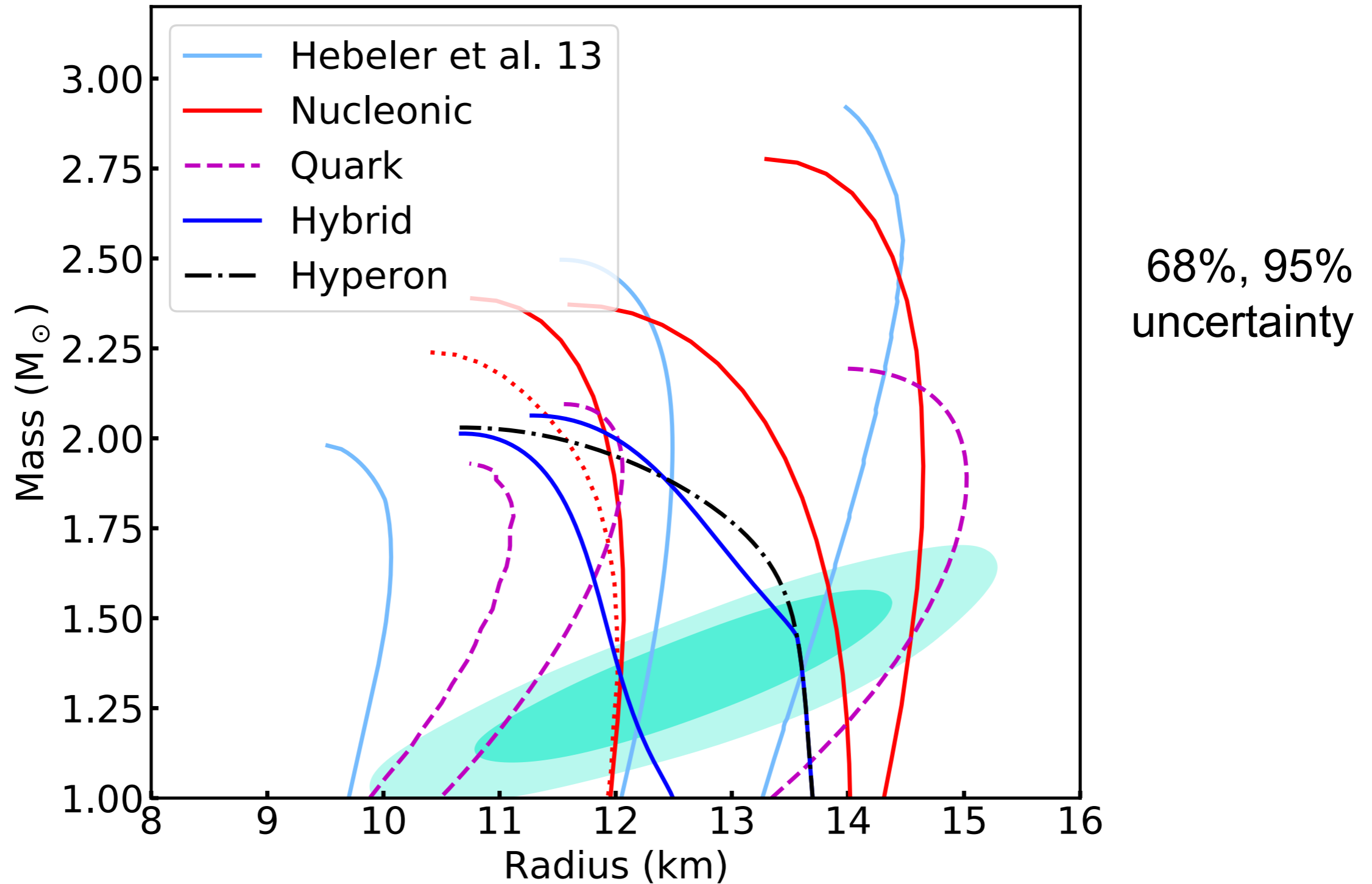
PULSAR EMISSION



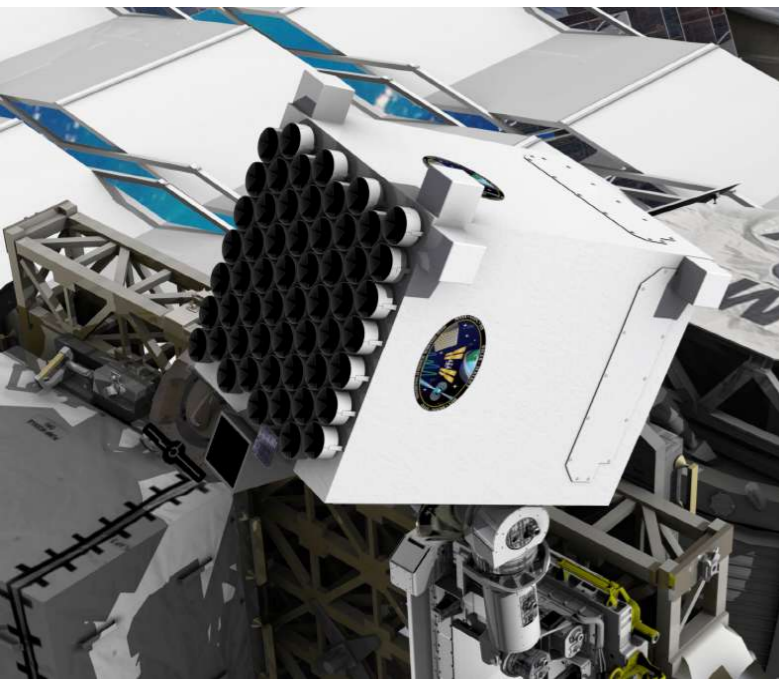
Bilous et al. 2019

May be possible to explain this
(see Chen et al. 2020).

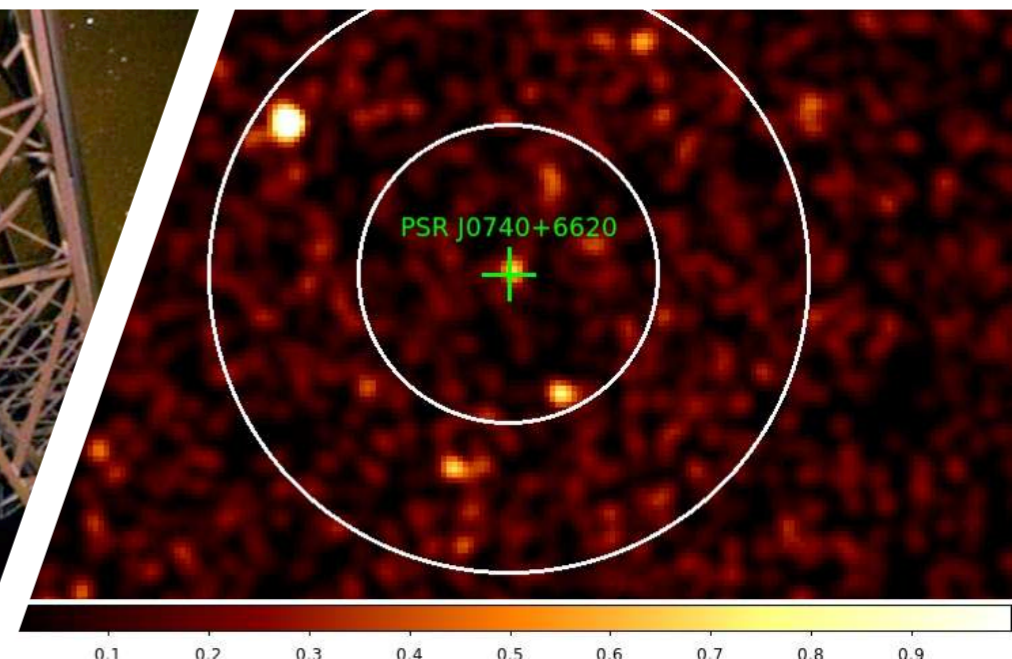
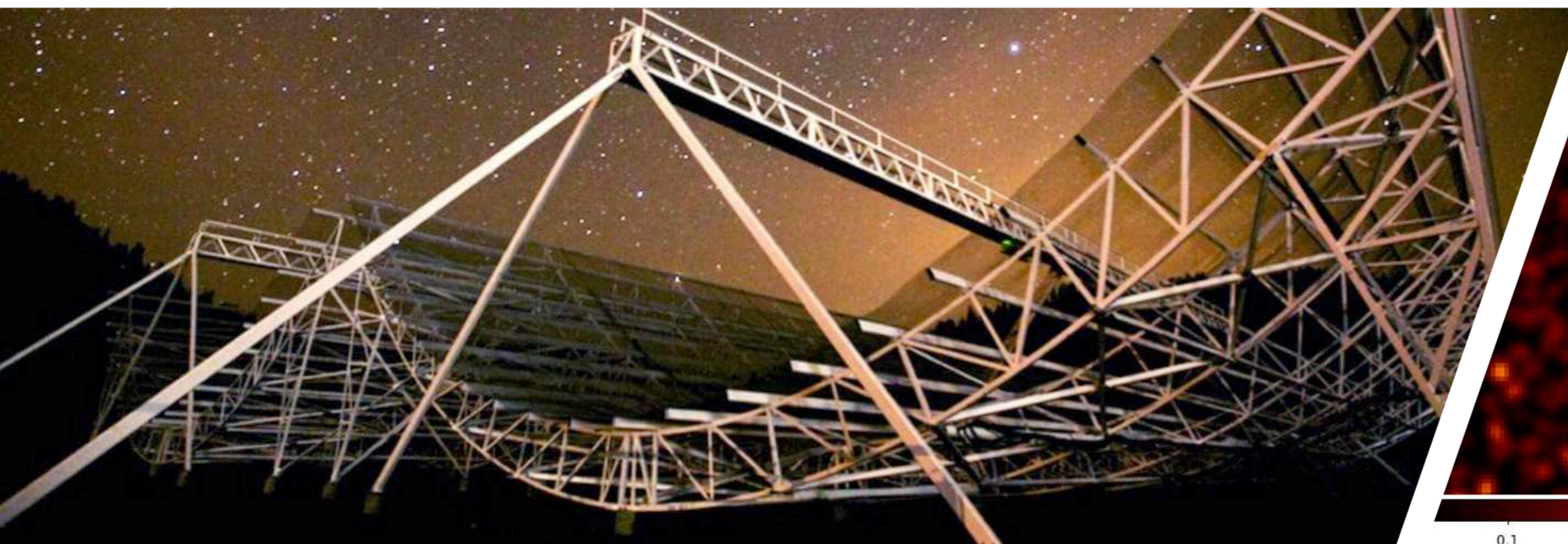
PSR J0030+0451 – MASS AND RADIUS



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

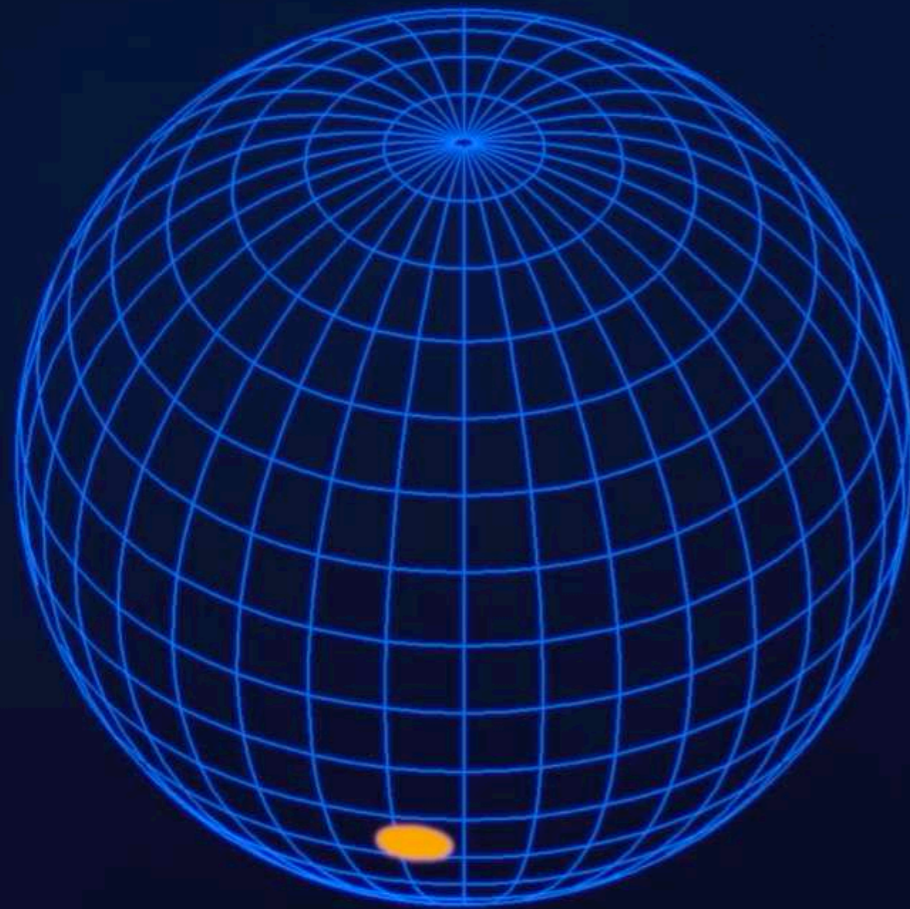


THE HIGH MASS PULSAR PSR J0740+6620

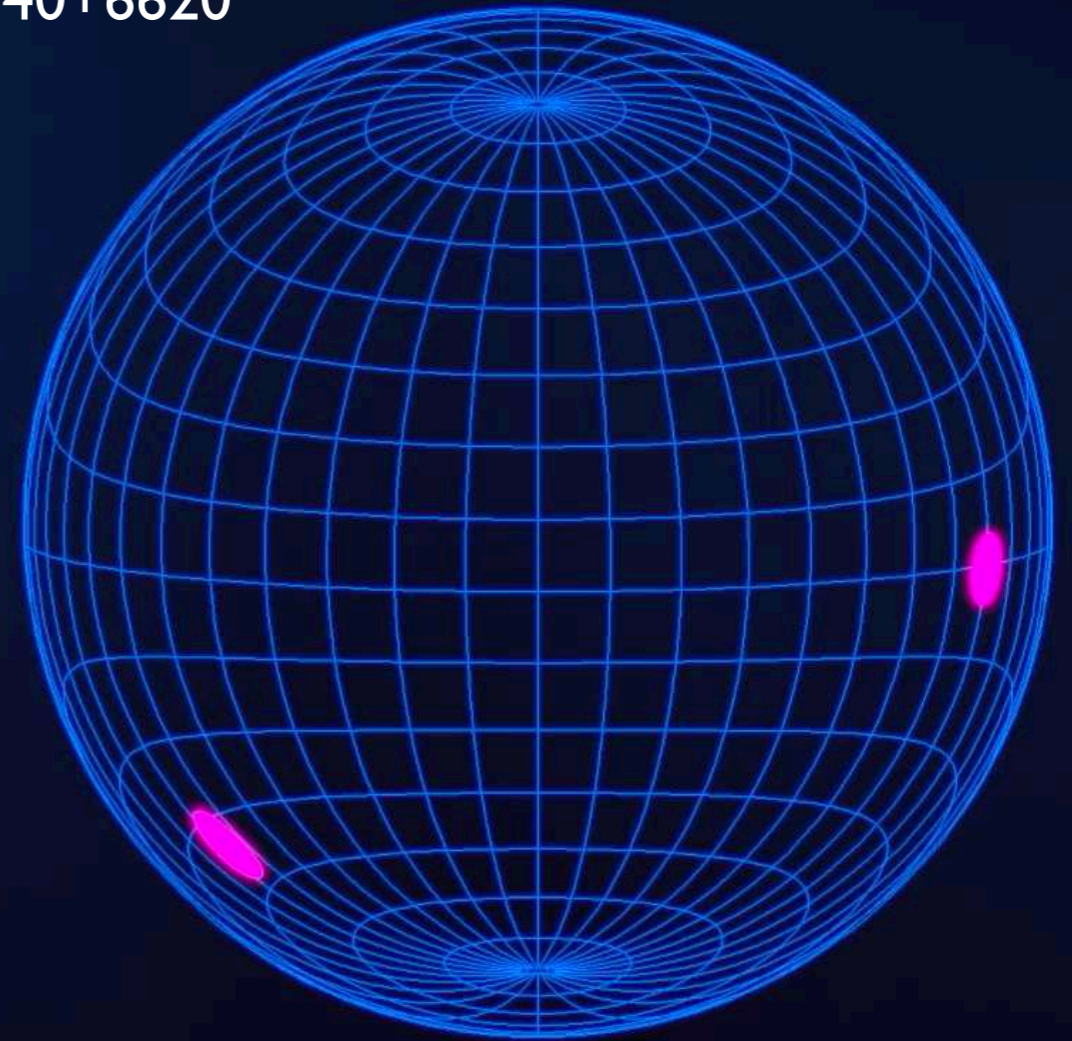


PSR J0740+6620: SURFACE MAP

PSR J0030+0451

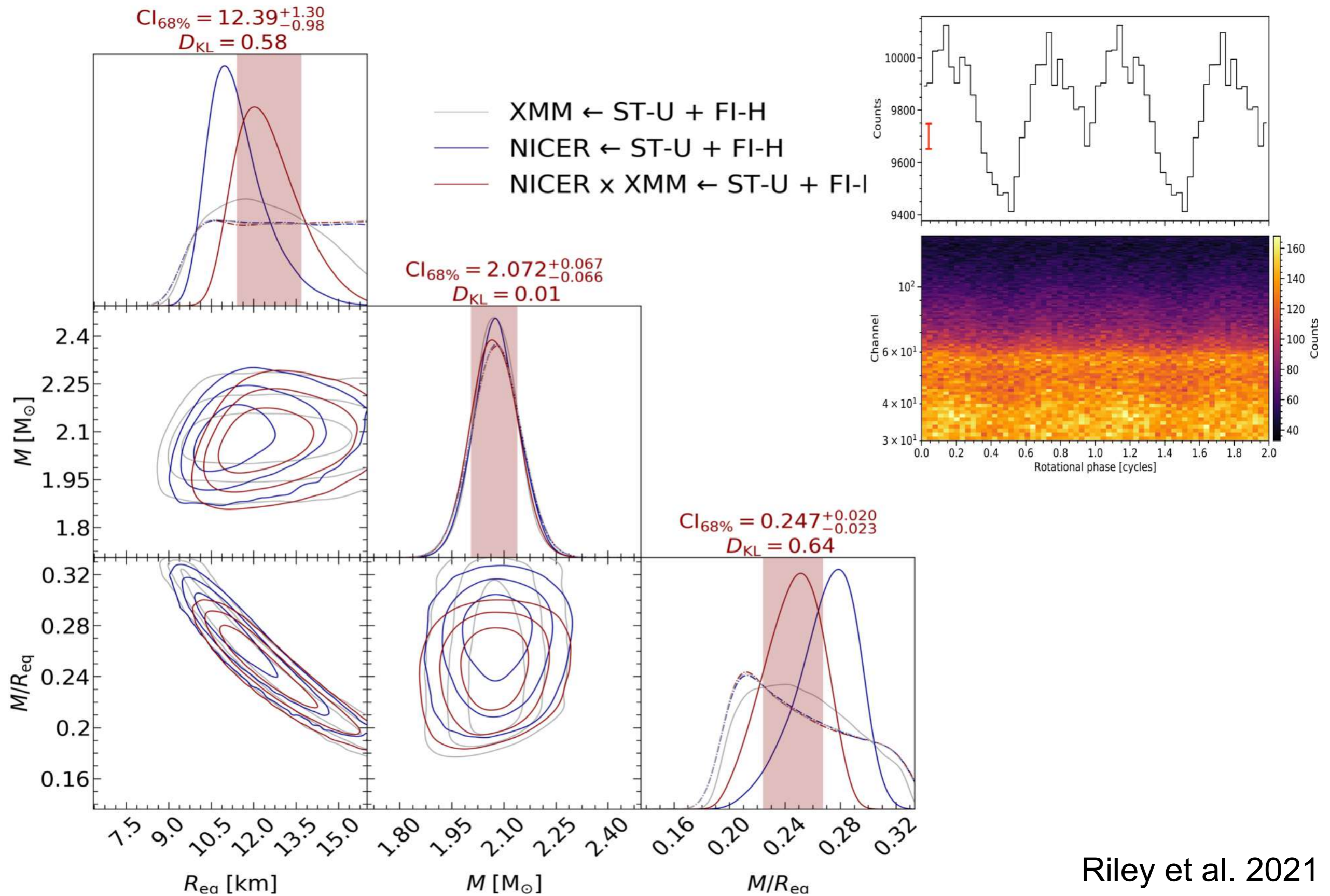


PSR J0740+6620

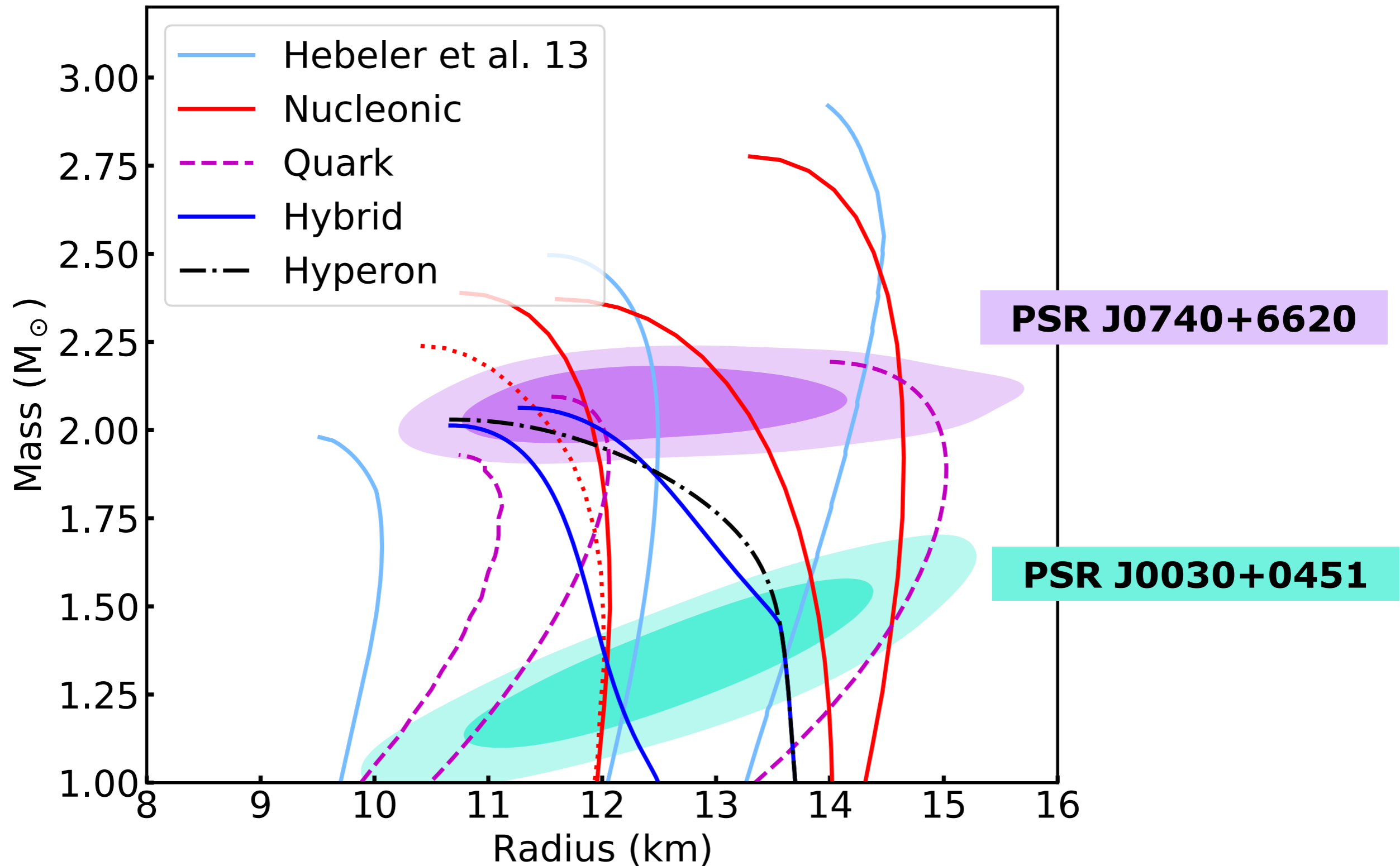


Movie: Sharon Morsink, NASA
See: <https://www.nasa.gov/feature/goddard/2021/nasa-s-nicer-probes-the-squeezability-of-neutron-stars/>

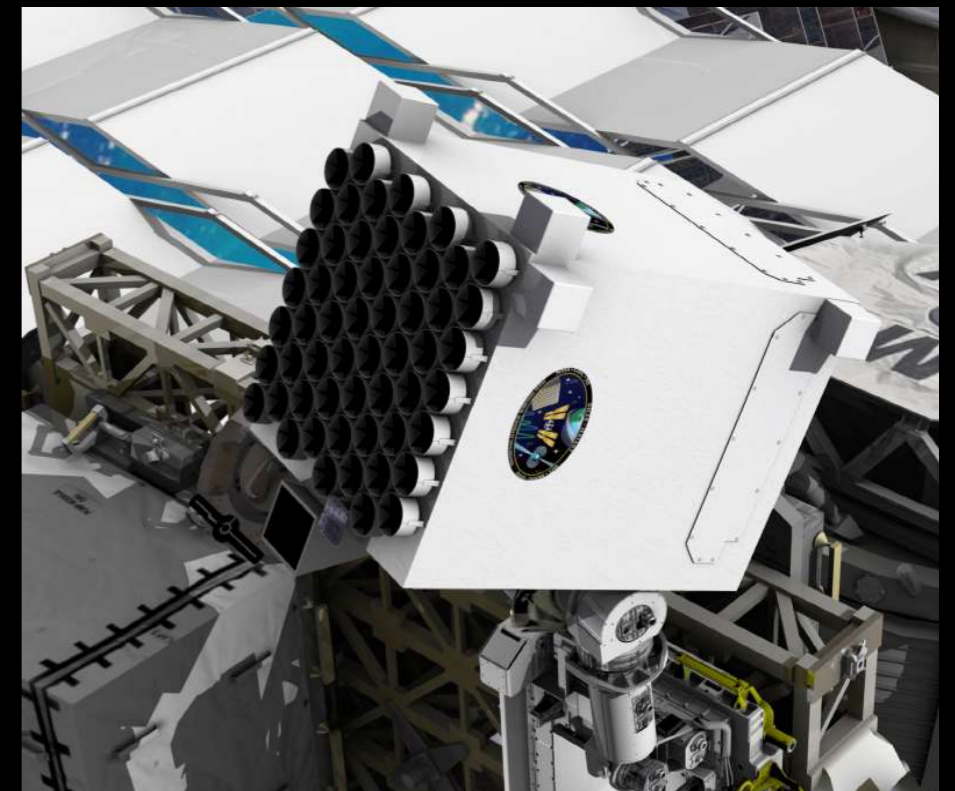
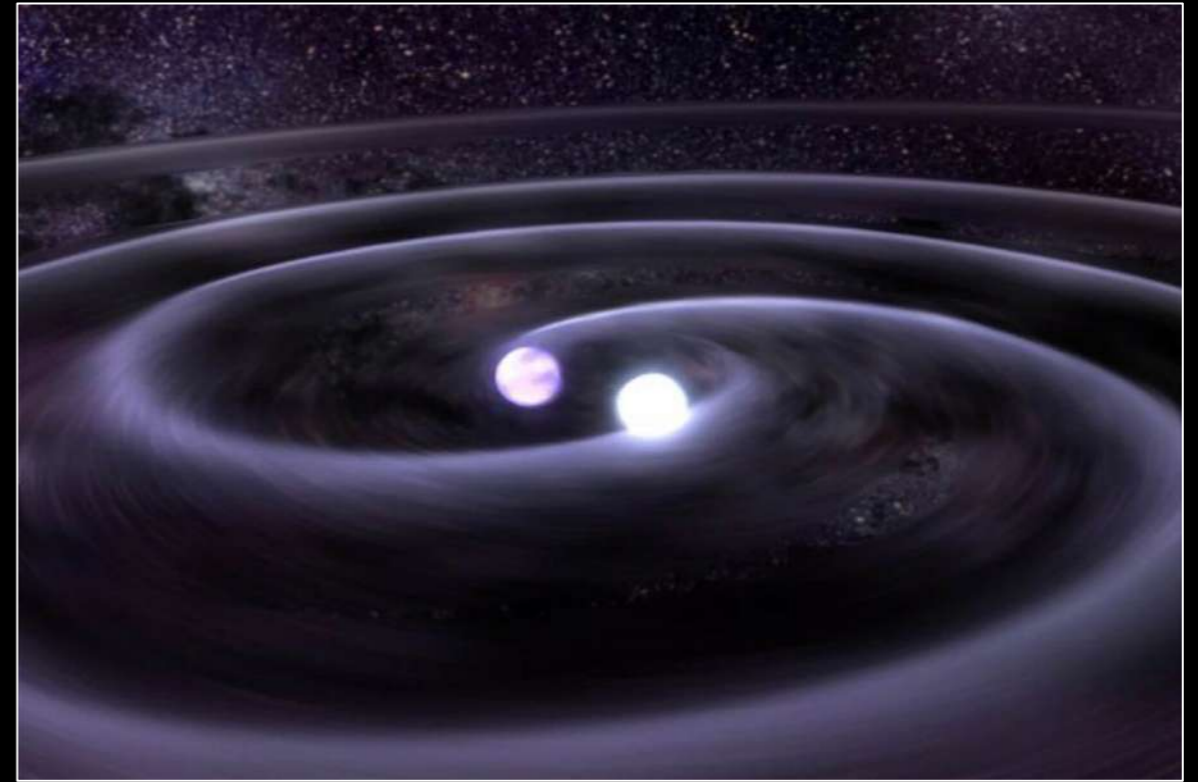
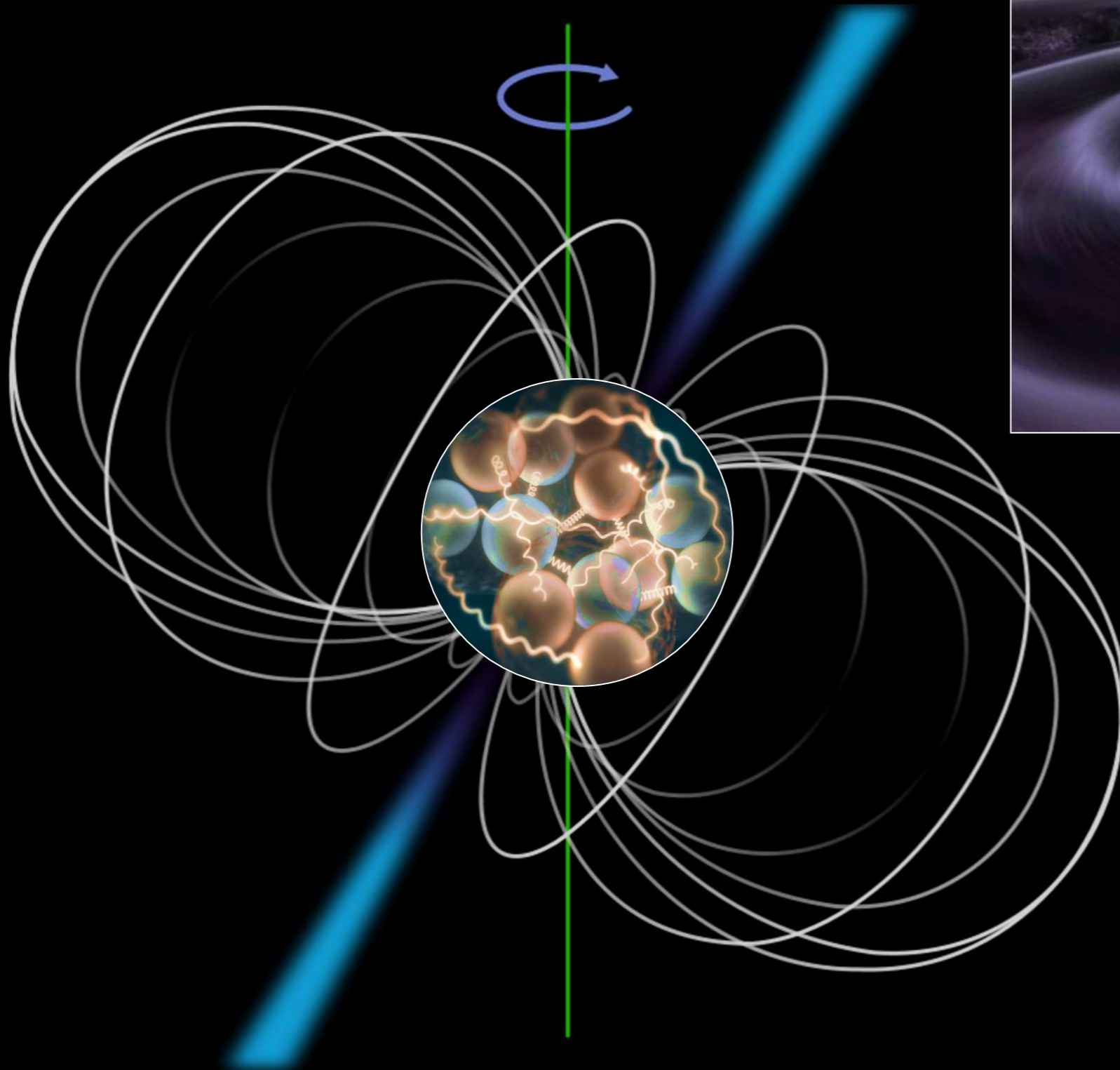
PSR J0740+6620 – MASS AND RADIUS



PSR J0740+6620 – MASS AND RADIUS



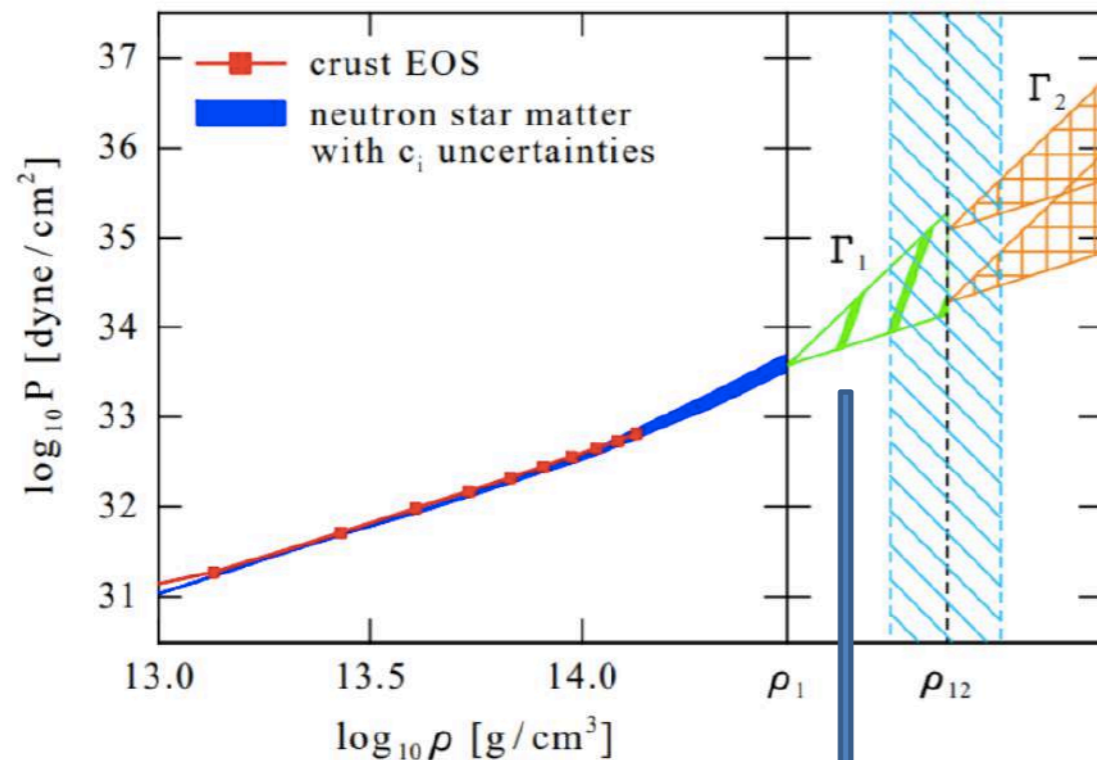
DENSE MATTER IMPLICATIONS



EQUATION OF STATE INFERENCE

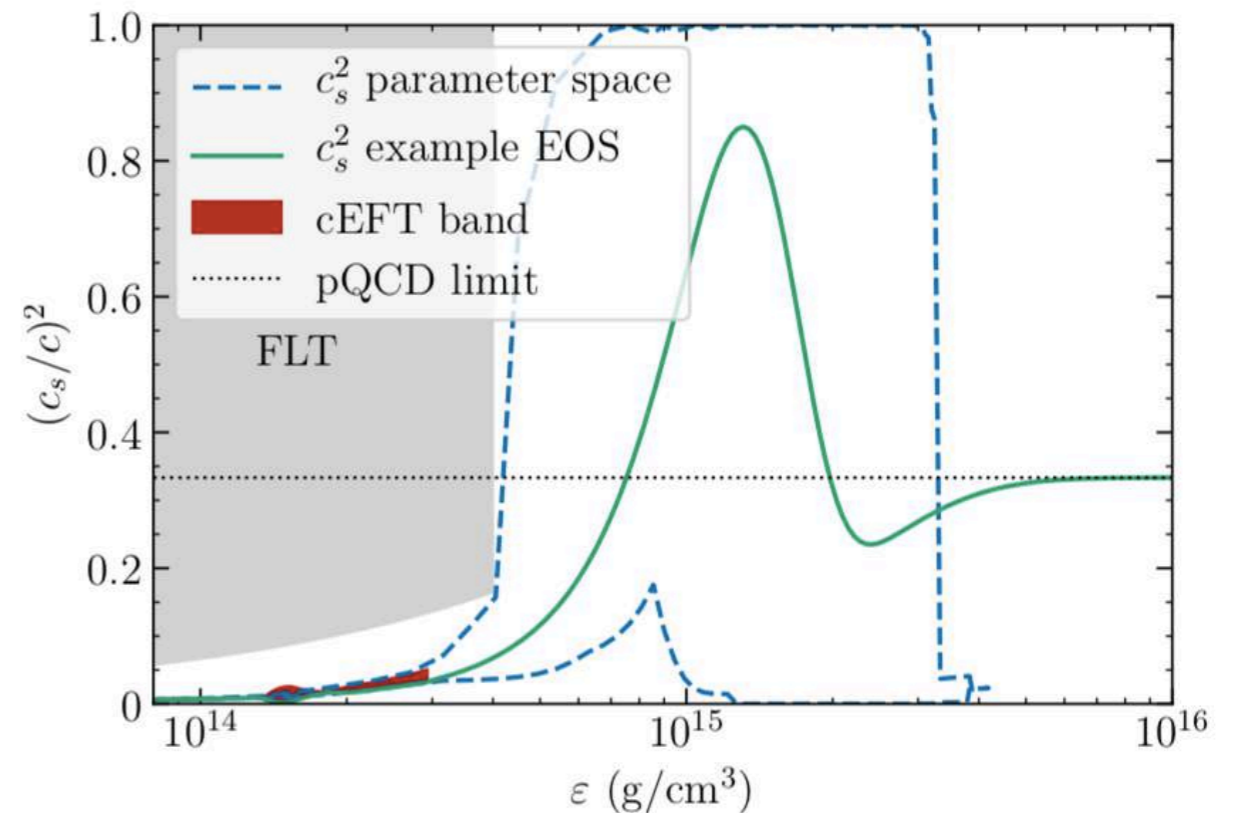
- EOS model: Pressure expressed as function of density.

Piecewise polytropes



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

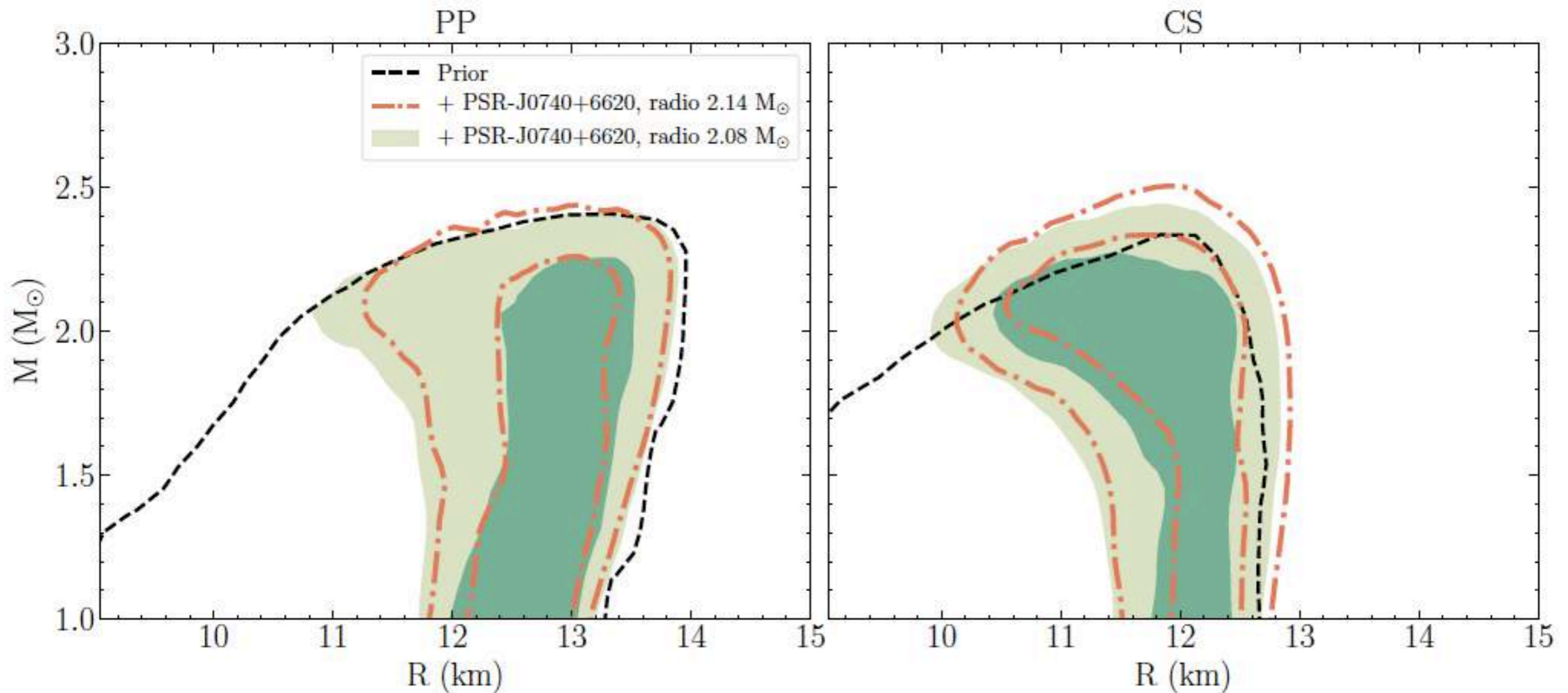
Speed of sound



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

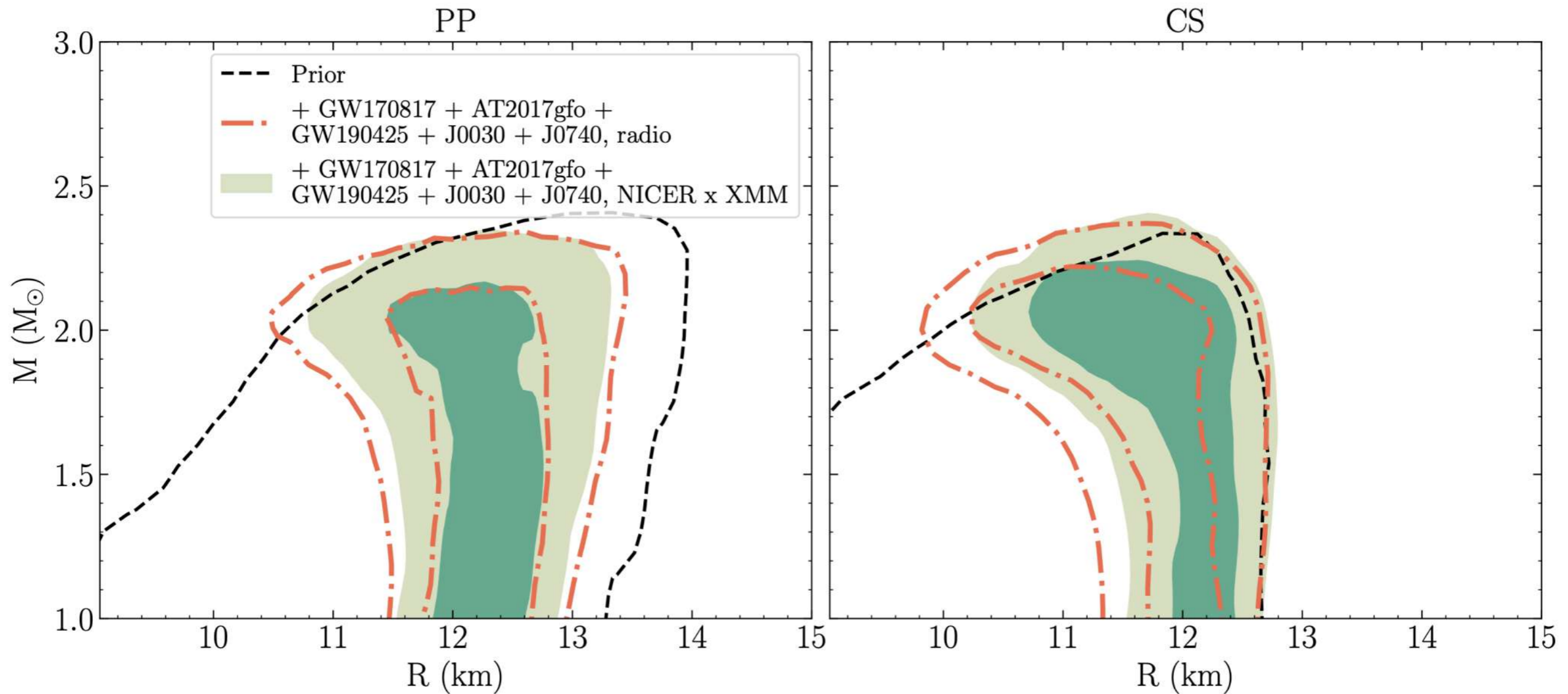
$$P(\epsilon) = \int_0^\epsilon d\epsilon' c_s^2(\epsilon')/c^2$$

MULTI-MESSENGER CONSTRAINTS



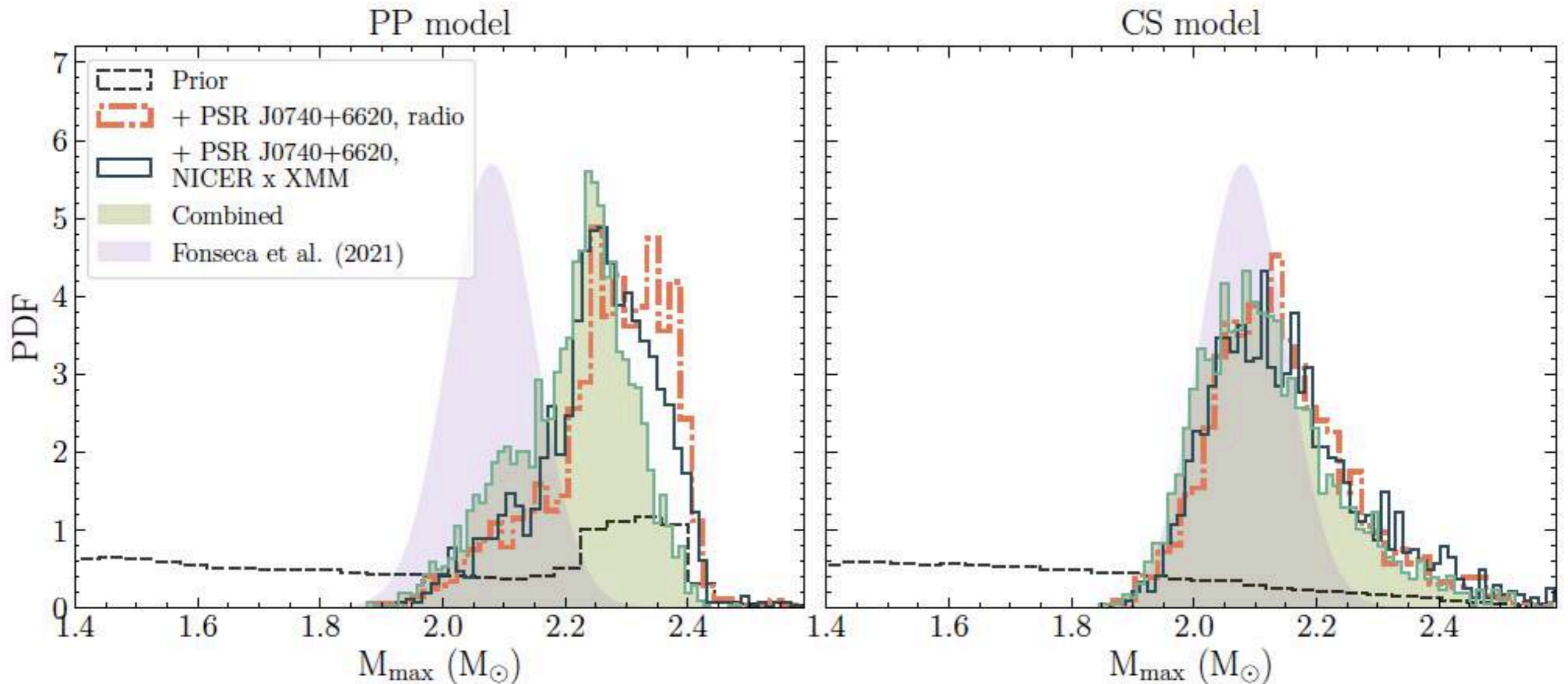
- Note: Prior is not uniform even before astrophysical constraints applied.
- First consider just the mass measurement for PSR J0740+6620.

MULTI-MESSENGER CONSTRAINTS



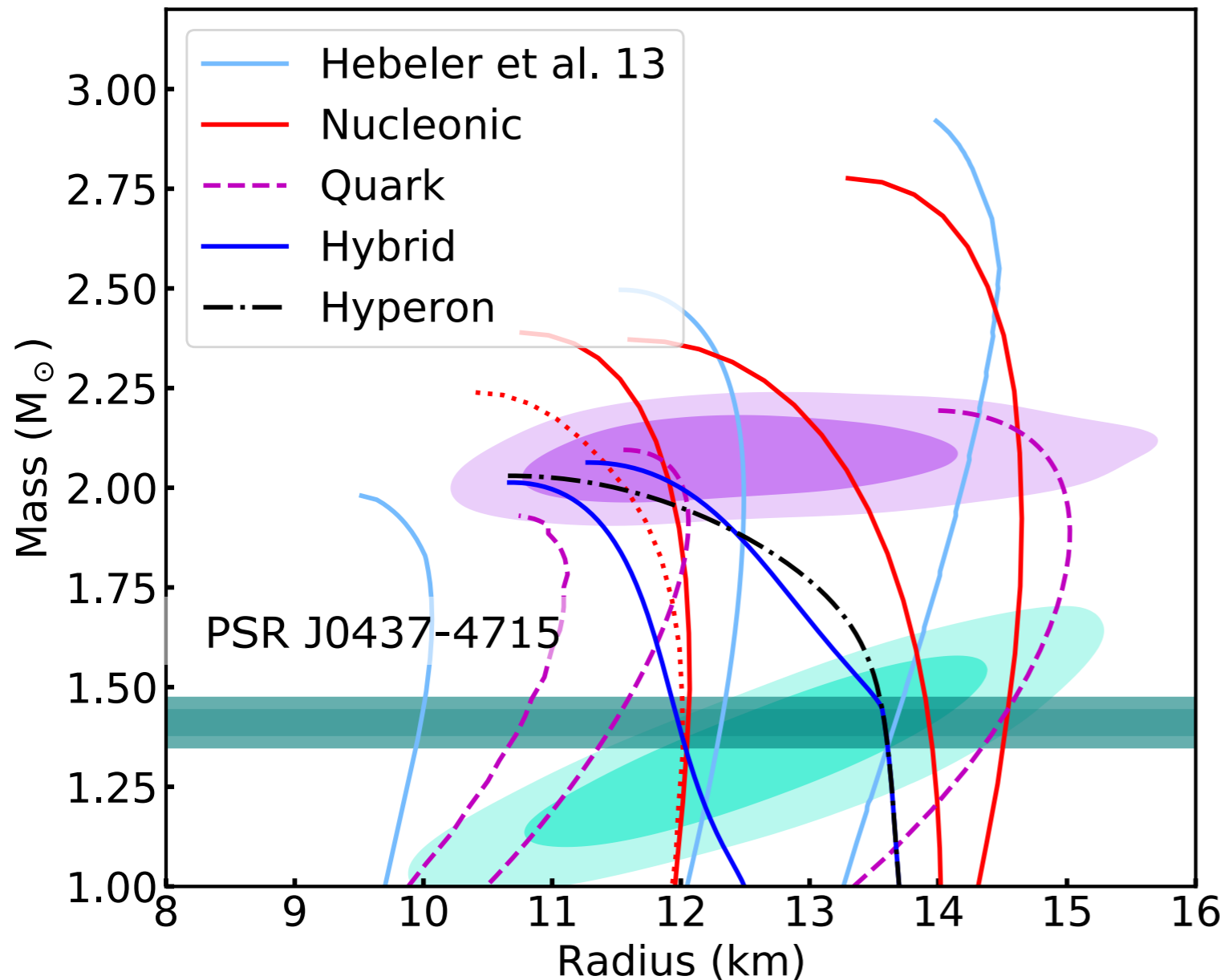
- Red: Add NICER's result for PSR J0030+0451, tidal deformabilities from two neutron star mergers, and the kilonova from one of these.
- Green: include our NICER x XMM radius measurement.

NEUTRON STAR MAXIMUM MASS



- We can use this to infer other parameters, like the neutron star maximum mass.

NEXT STEPS FOR NICER



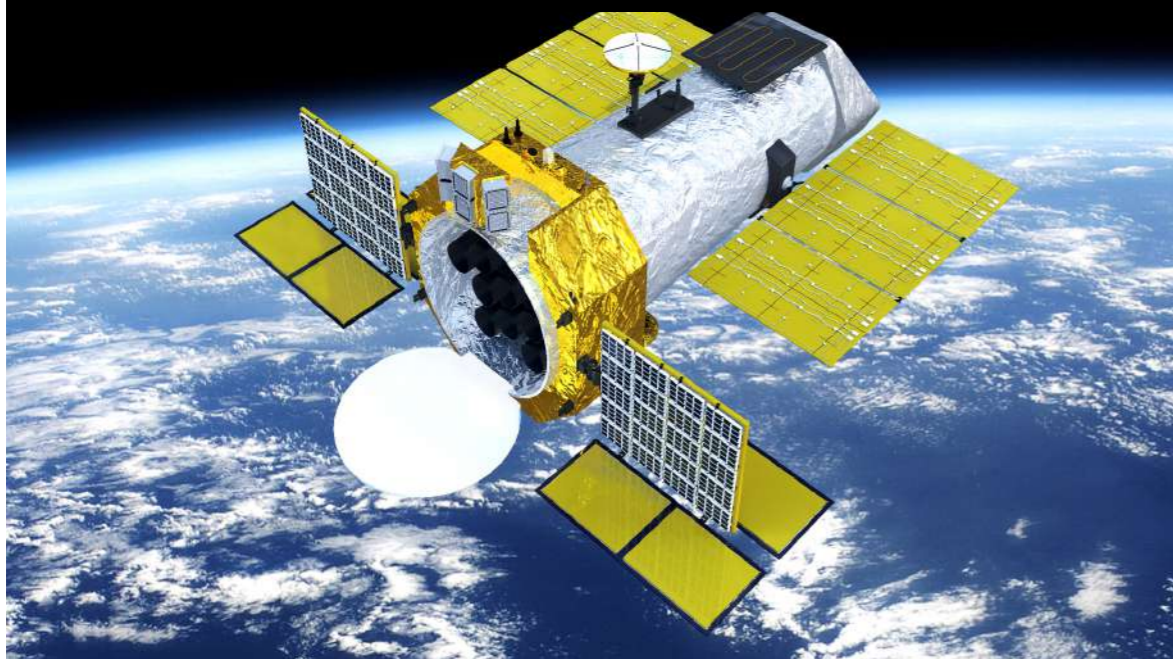
- 4 new sources coming!
- Updates to existing sources.
- NICER background modelling.
- Joint analysis with telescopes like XMM, cross-calibration.
- Interaction with pulsar astrophysics.

PSR J0740+6620 papers, ApJ Letters in press: Wolff et al. 2021 (data);
X-PSI papers (Riley et al. 2021, Raaijmakers et al. 2021);
Illinois-Maryland (independent team) analysis by Miller et al. 2021.

UNLOCKING RAPID ROTATORS

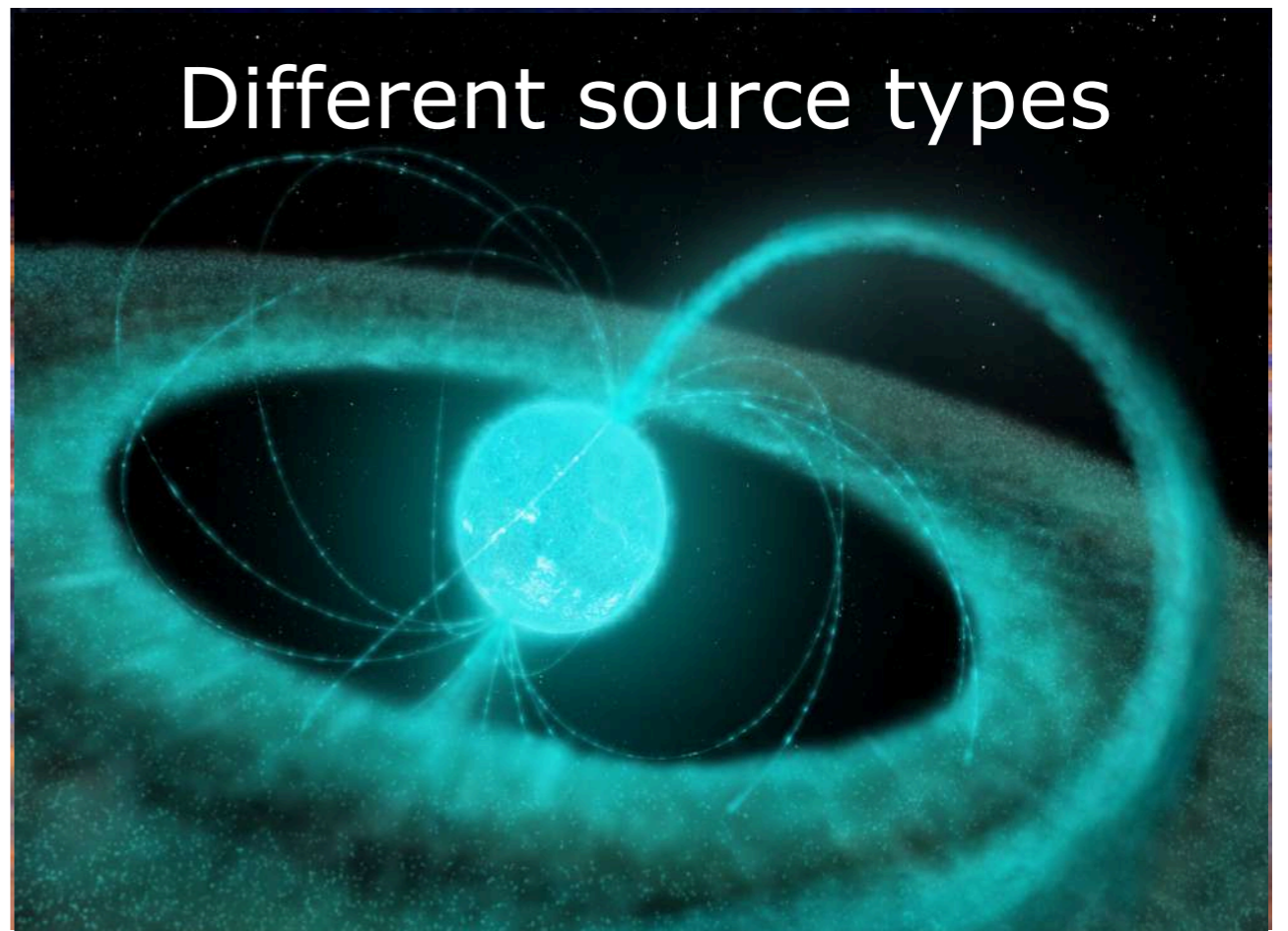
The relativistic effects pulse profile modeling exploits are larger for the more rapidly-rotating **accreting** neutron stars.

Next generation
telescopes



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

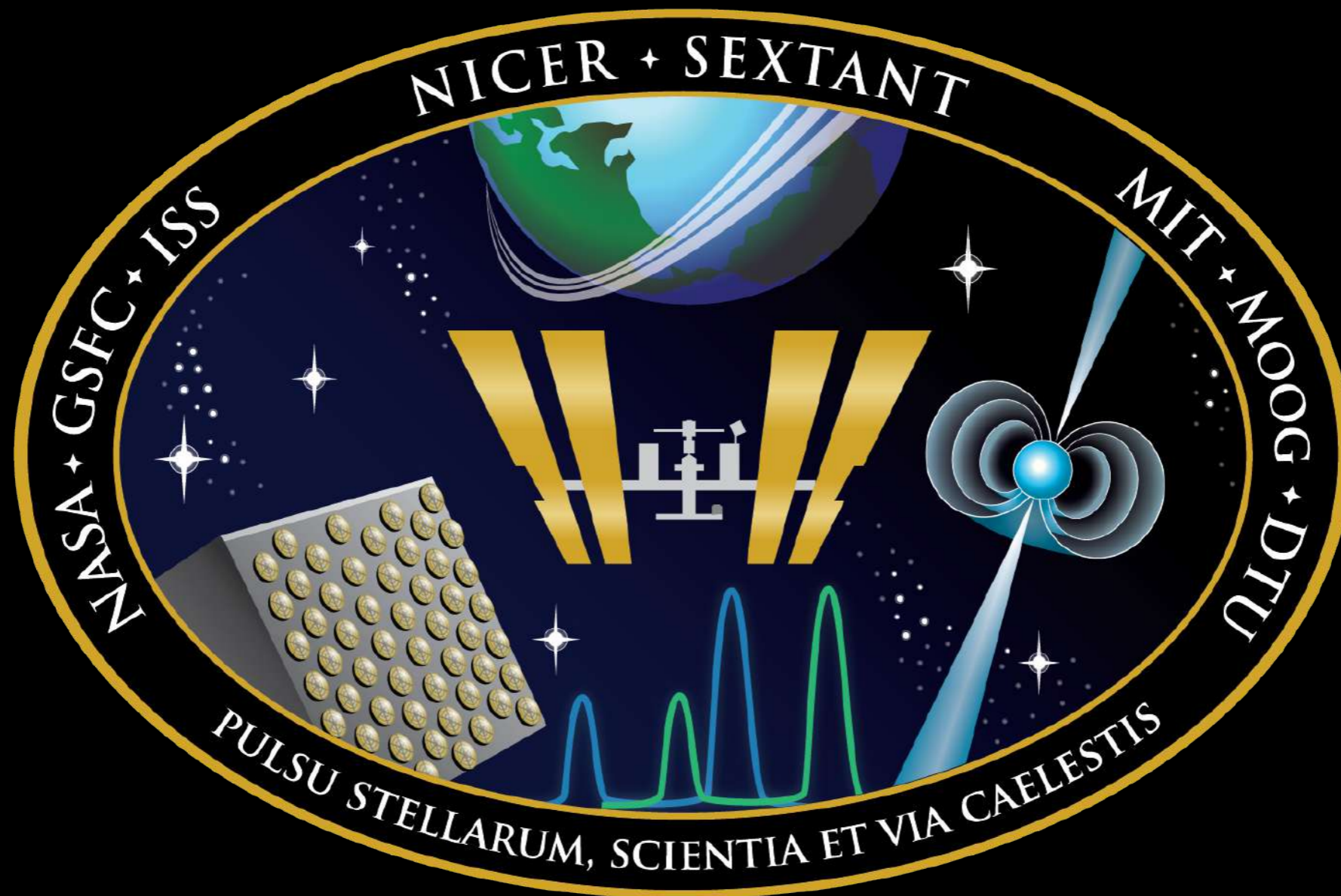
Different source types



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.



SUMMARY

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