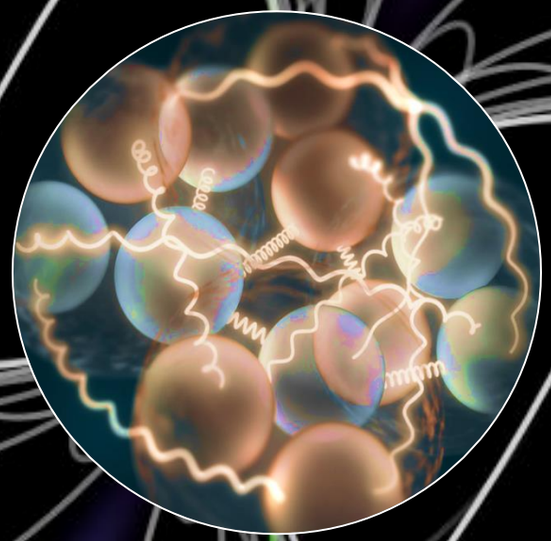
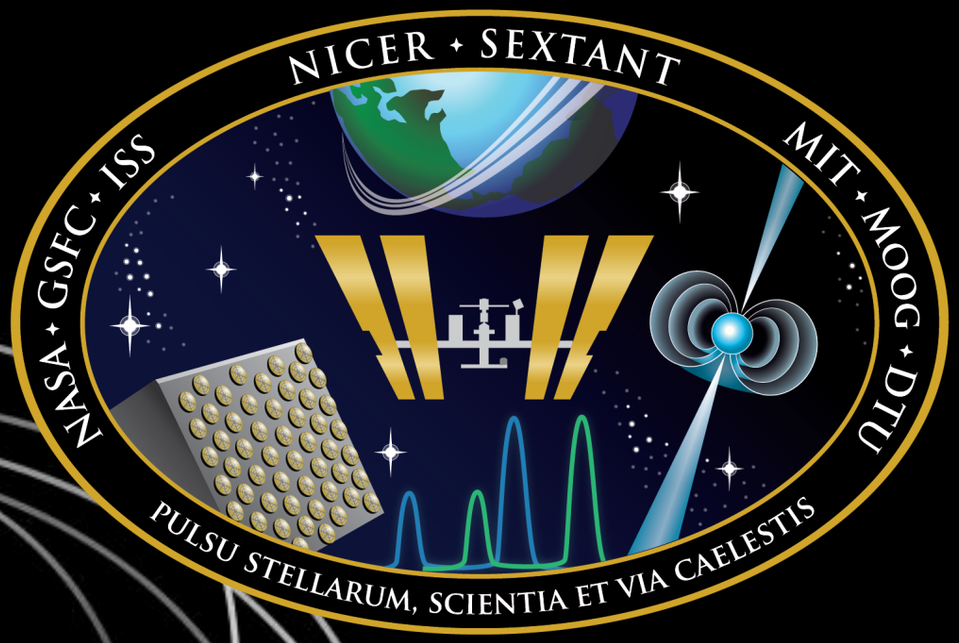
A NICER VIEW OF NEUTRON STARS





PROF. ANNA WATTS
(UNIVERSITY OF AMSTERDAM)

FROM NUCLEAR PHYSICS TO TELESCOPE

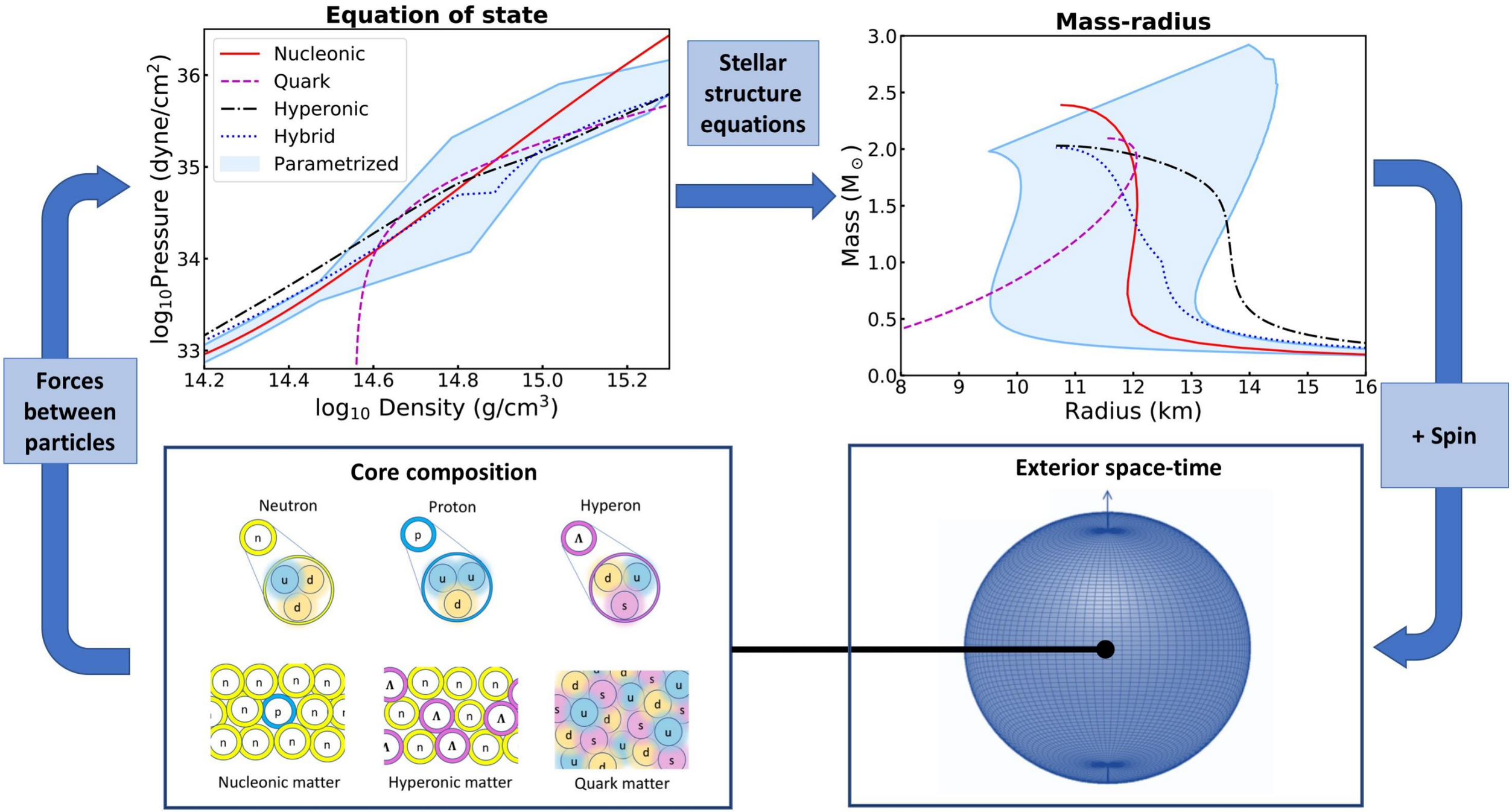
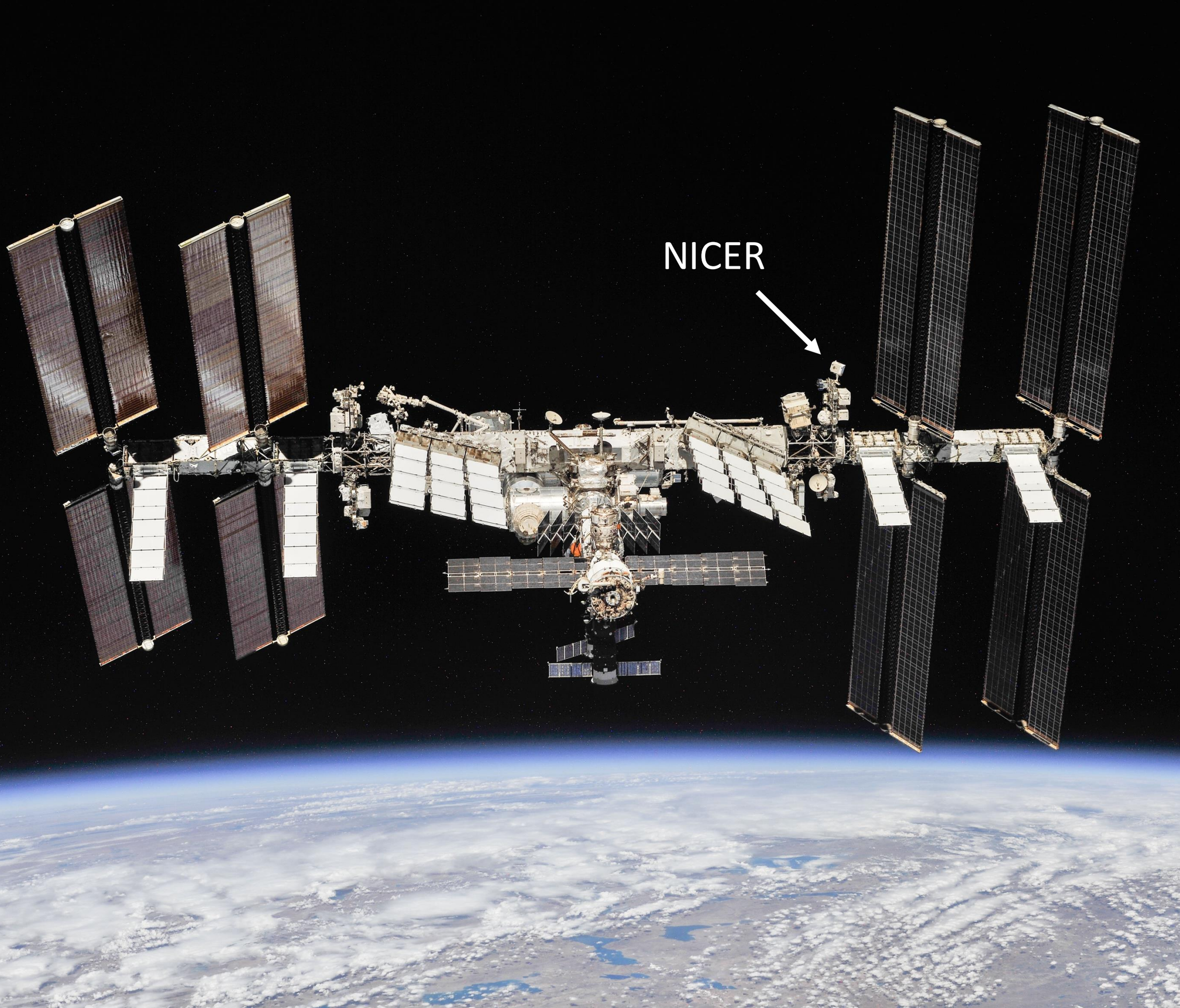
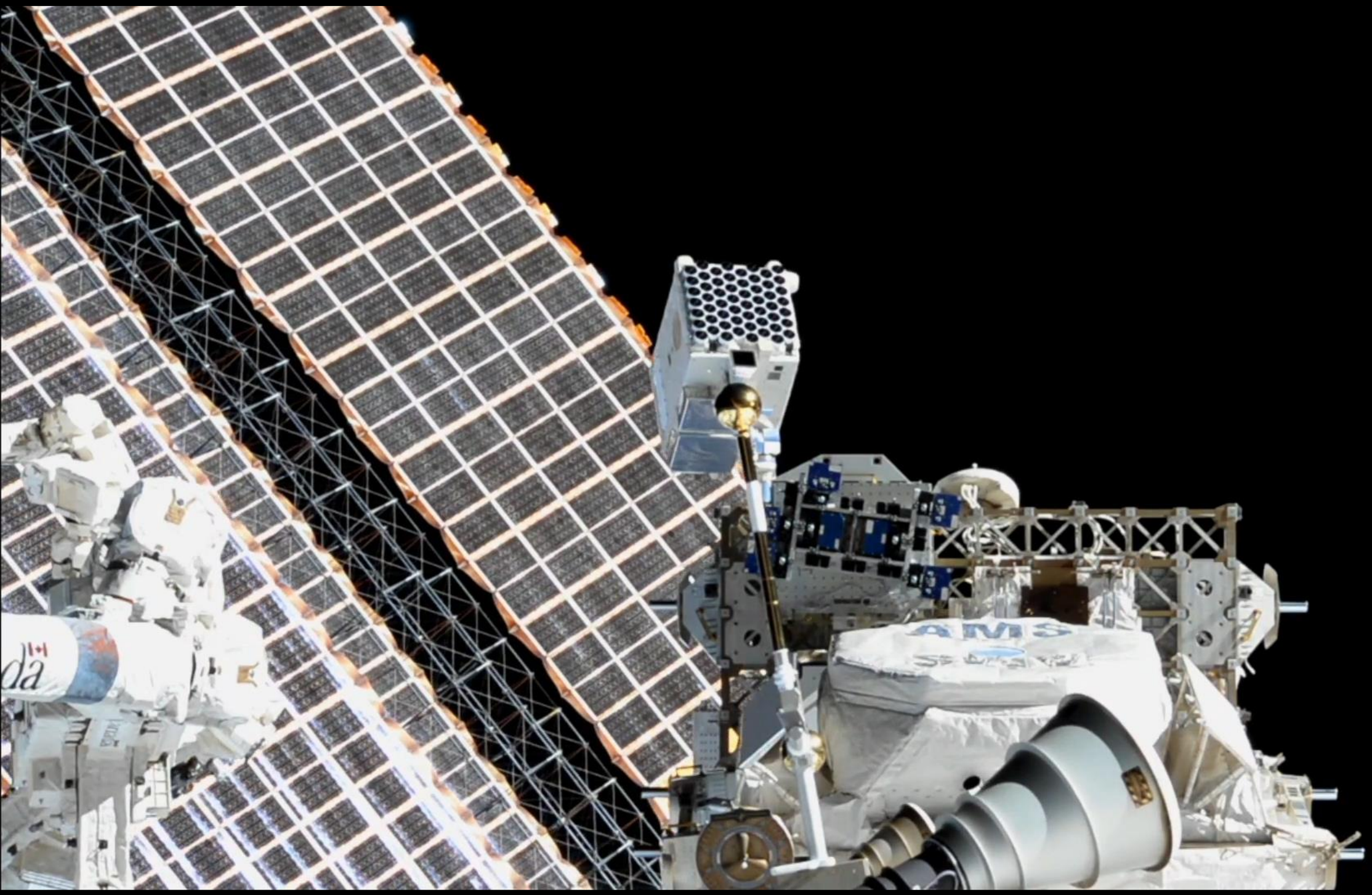


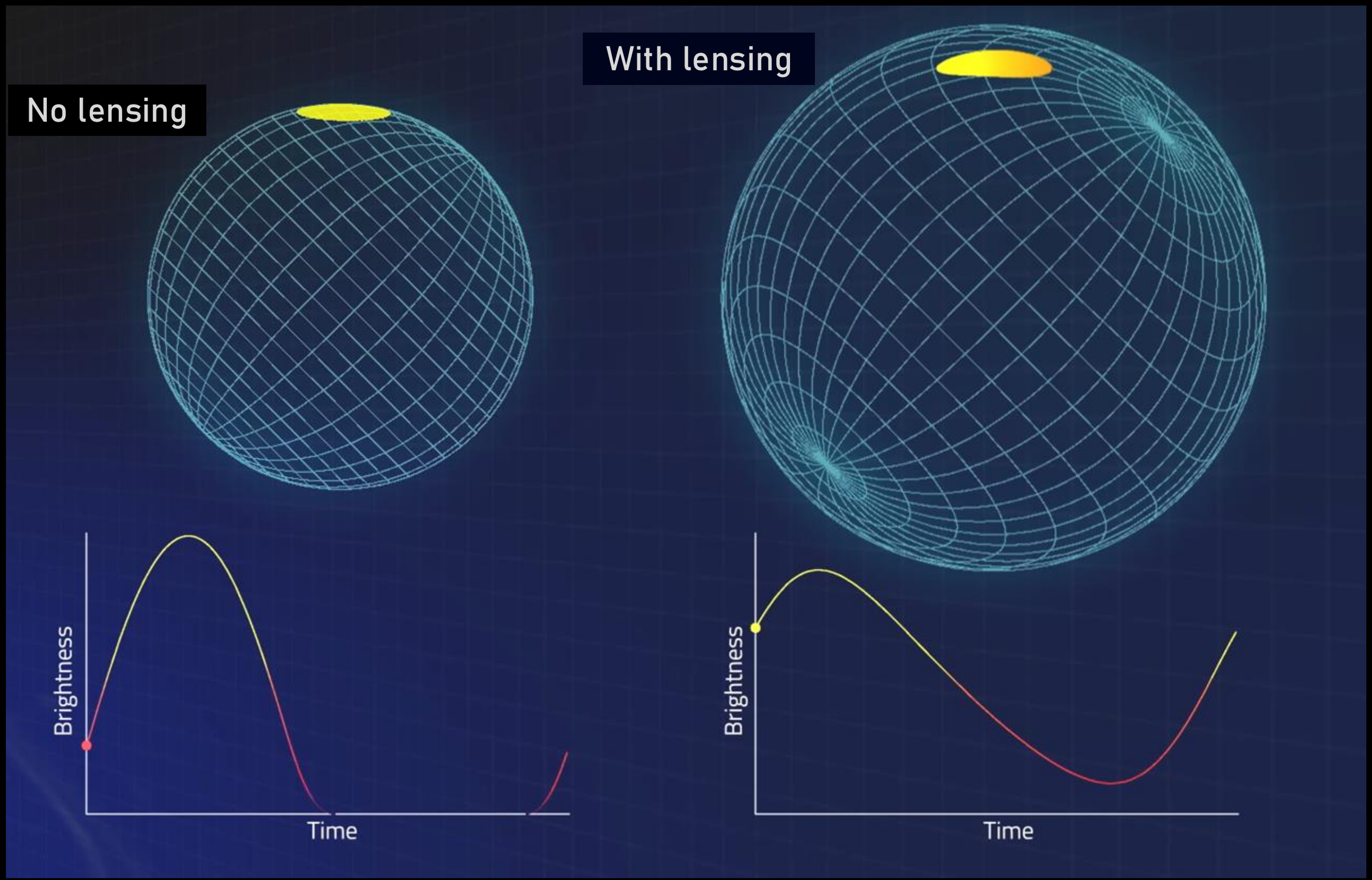
Figure: Adapted from Ray et al. 2019


NICER

NICER ON THE ISS

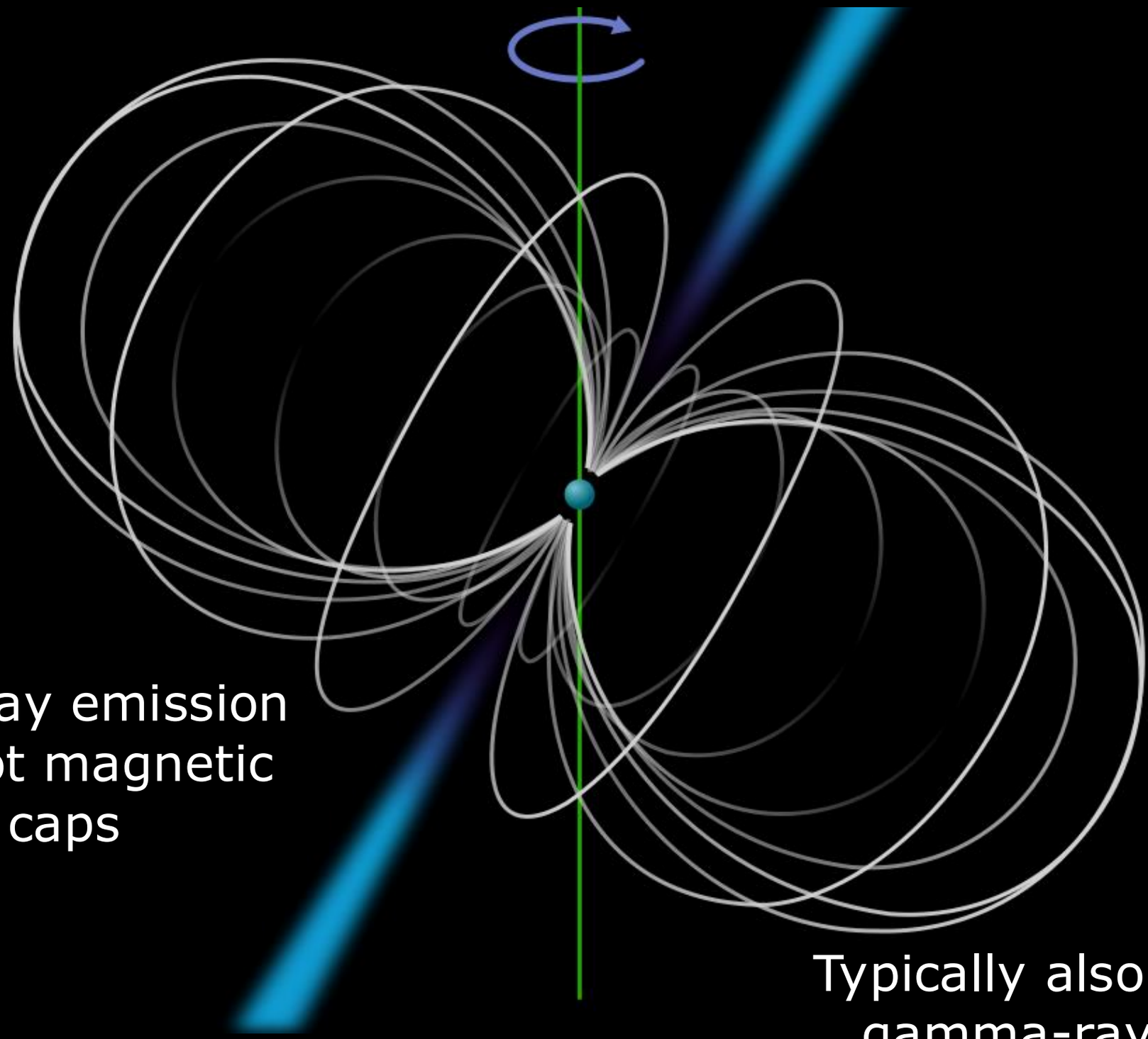


PULSE PROFILE MODELING



Credit: Morsink/Moir/Arzoumanian/NASA-GSFC

ROTATION-POWERED MILLISECOND X-RAY PULSARS

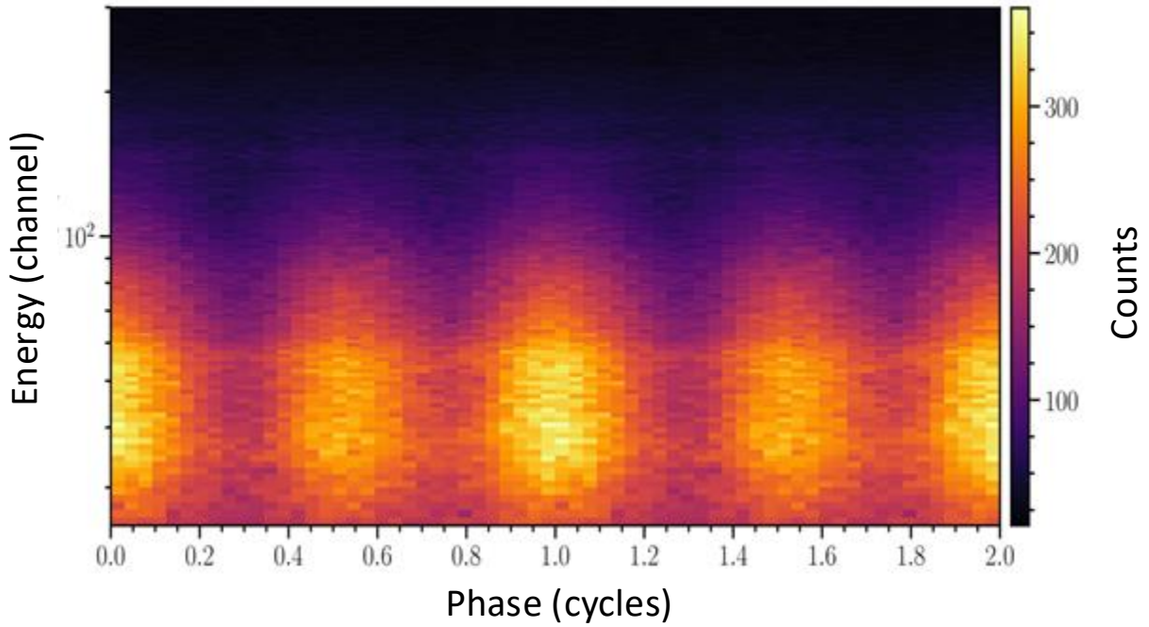


Thermal X-ray emission from the hot magnetic polar caps

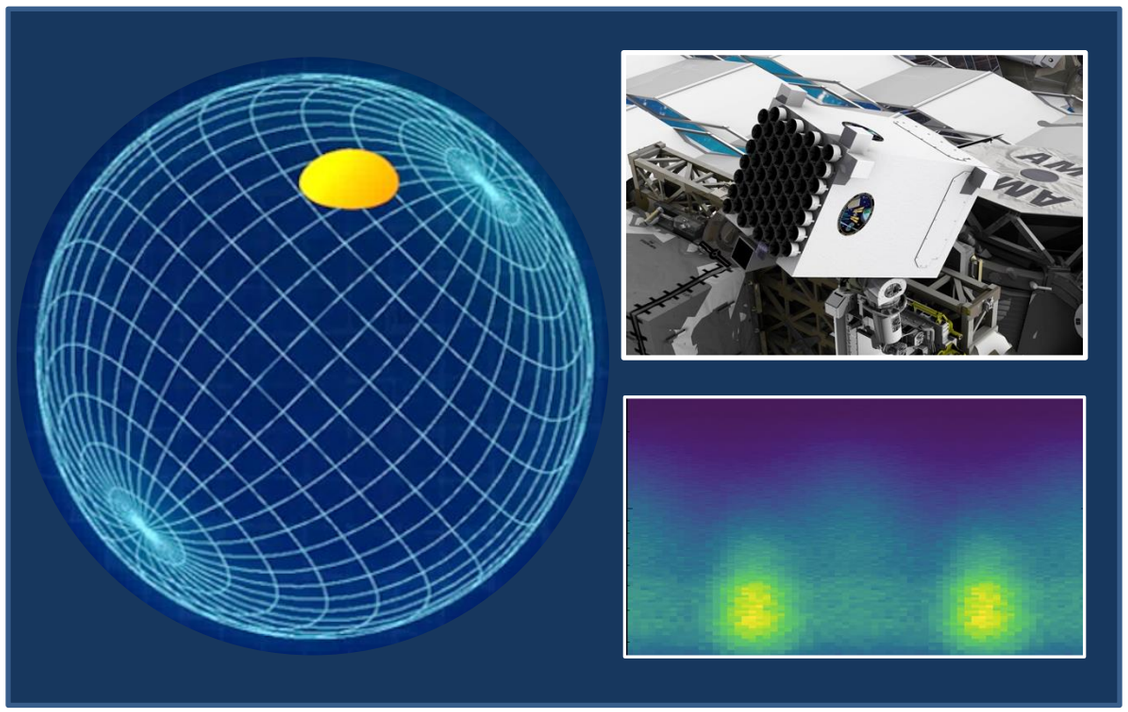
Typically also radio and gamma-ray pulsars

THE PULSE PROFILE MODELING PROCESS

Pulse profile data: Phase, Energy



Lightcurve model: the (astro)physics

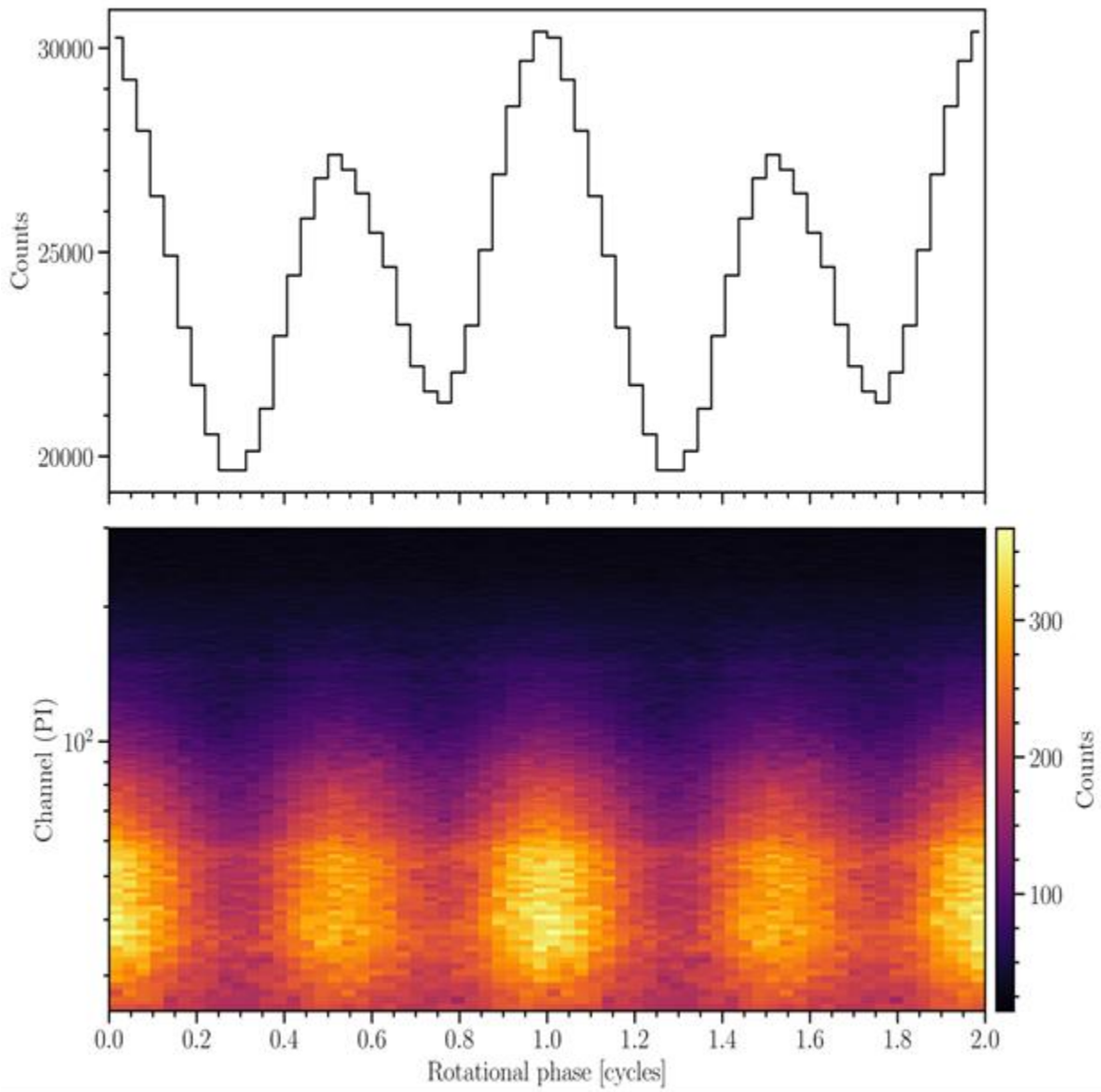


Bayesian inference of model parameters (statistical sampling)

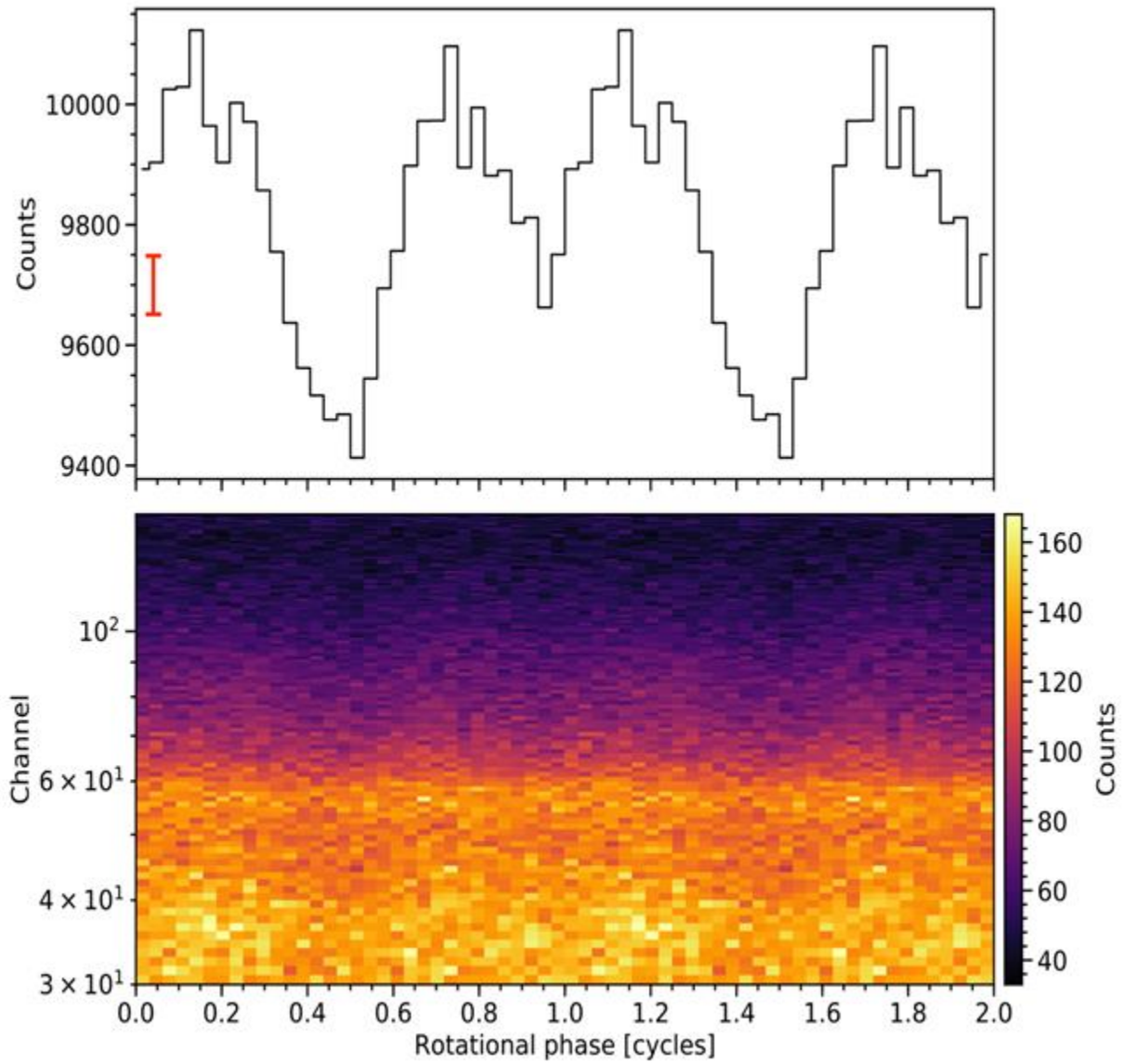
Model parameters:
Mass and radius
Geometric properties

PULSE PROFILE DATA

Bright isolated pulsar
PSR J0030+0451
(Bogdanov et al. 2019)



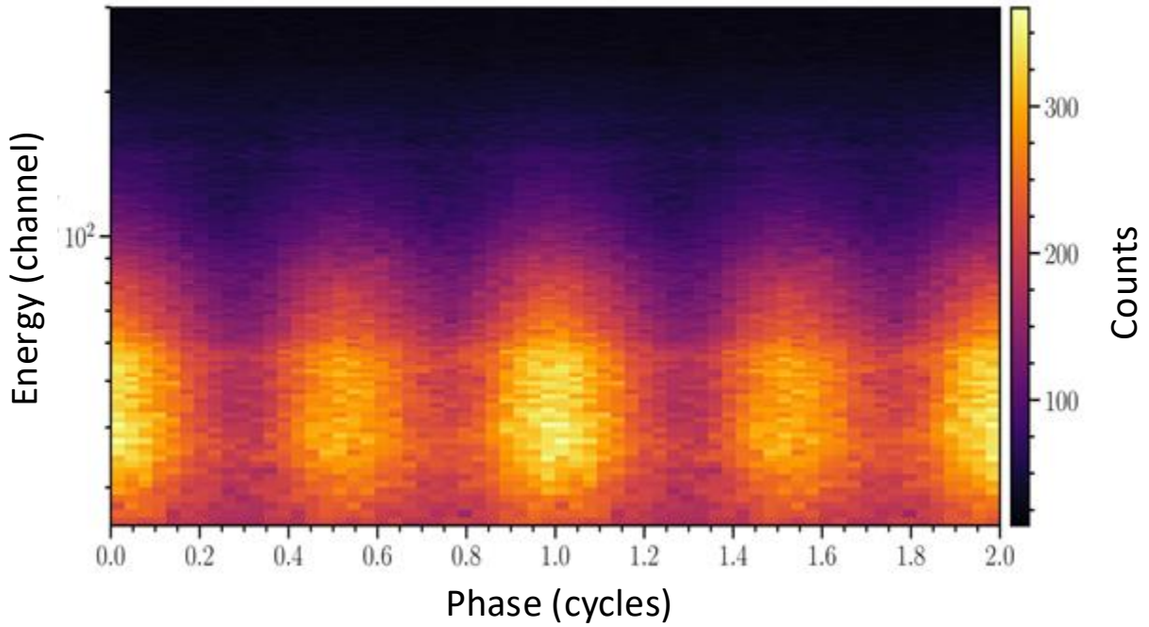
Binary system, 2.1 solar mass pulsar
PSR J0740+6620
(Wolff et al. 2021)



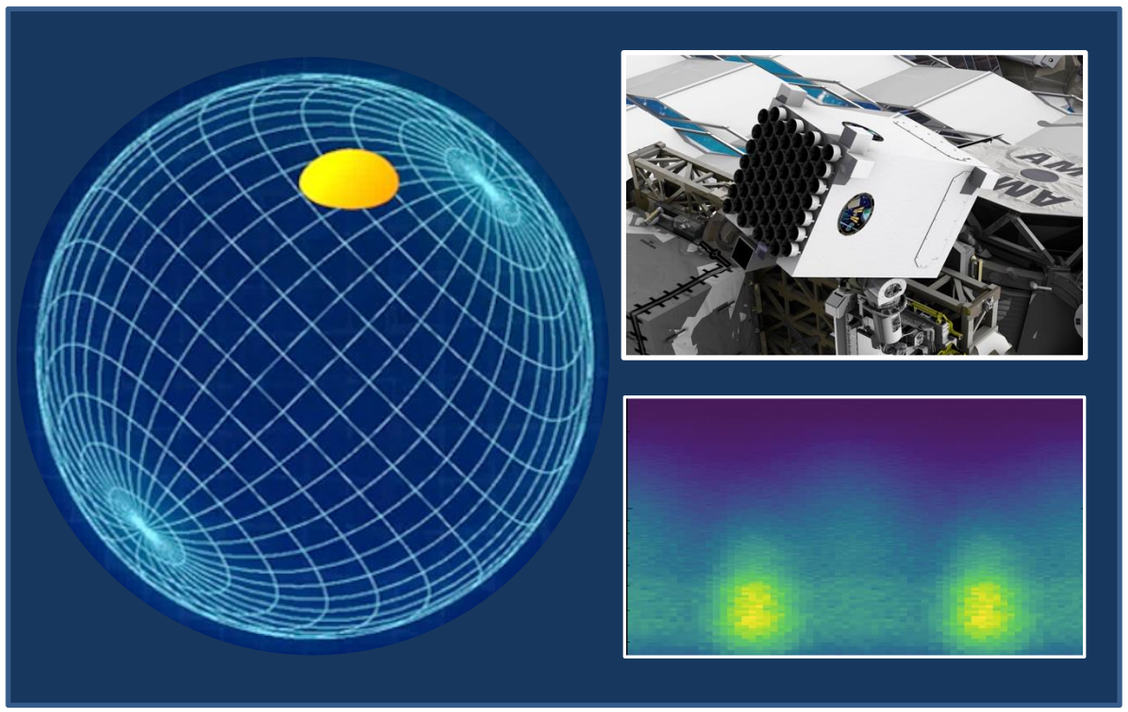
Several Ms of data required for analysis.
Background levels are high in ISS orbit.

THE PULSE PROFILE MODELING PROCESS

Pulse profile data: Phase, Energy



Lightcurve model: the (astro)physics



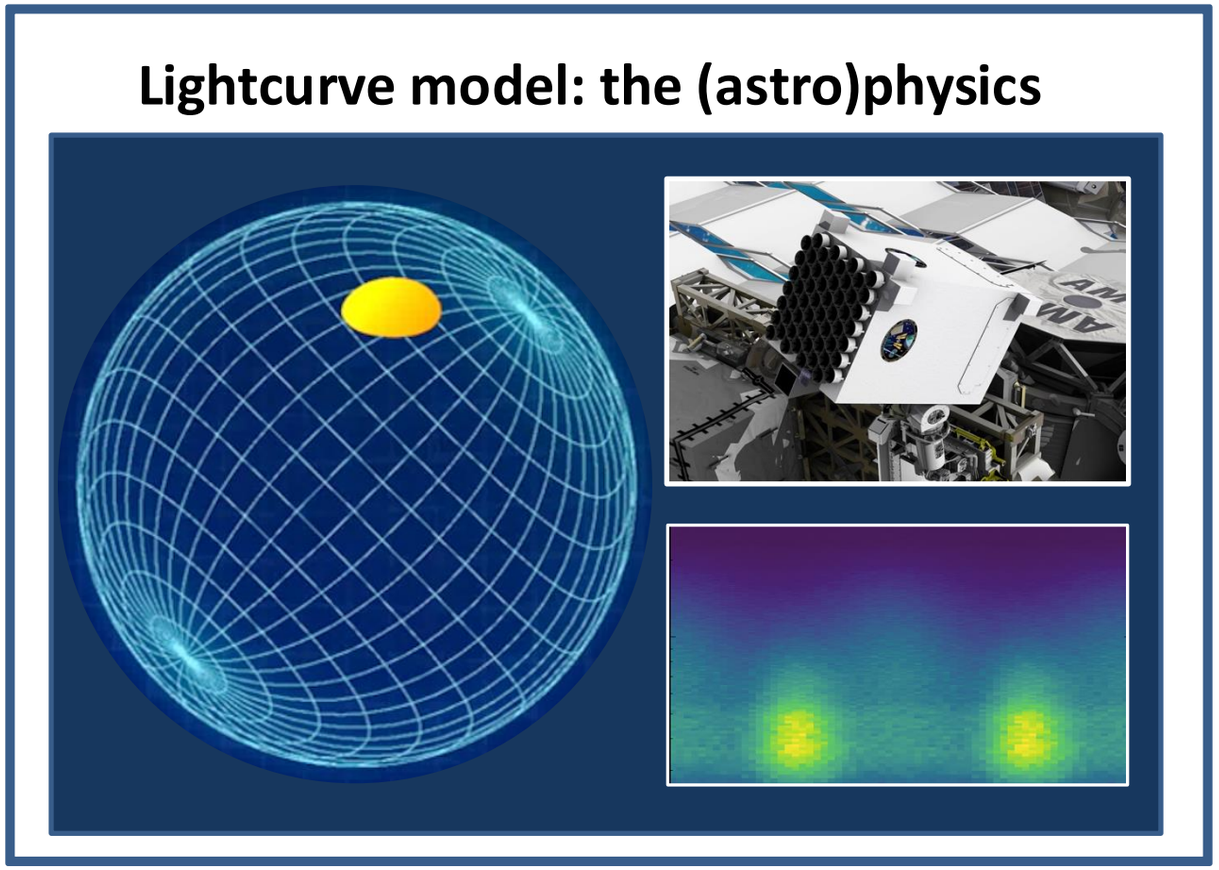
Bayesian inference of model parameters (statistical sampling)

Model parameters:
Mass and radius
Geometric properties

THE (ASTRO)PHYSICAL MODEL

Physics

- Relativistic ray-tracing (Oblate Schwarzschild + Doppler approximation for NS spacetime).
- Atmospheric beaming and interstellar absorption
- Instrument response (includes calibration uncertainty)
- Distance and observer inclination
- Hotspot properties



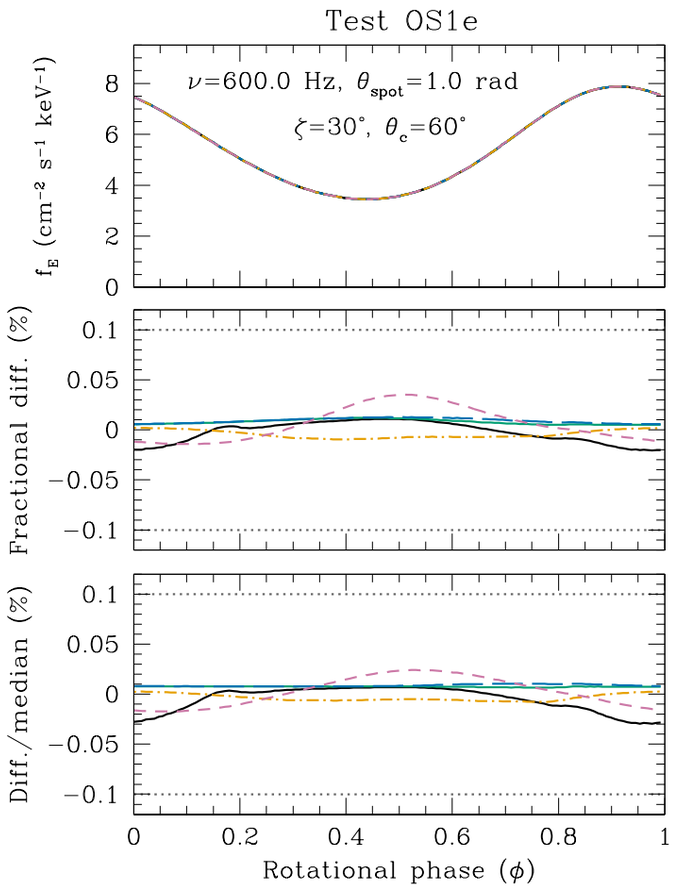
Priors

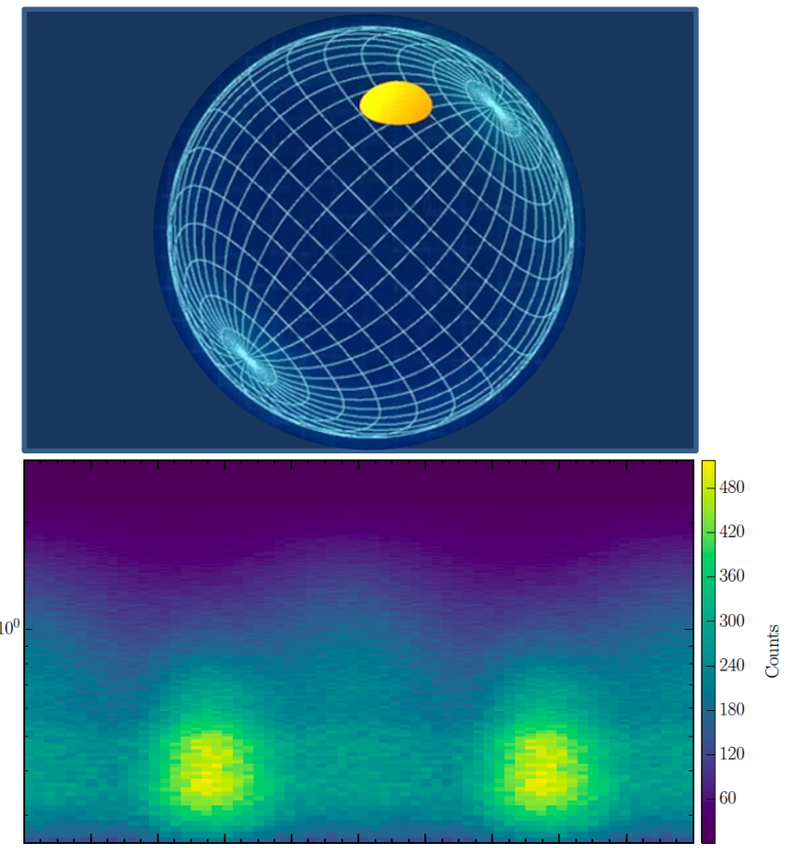
- We may have mass, distance, inclination from radio timing.
- Radius (and mass if not known): at present we choose a broad uninformative prior.

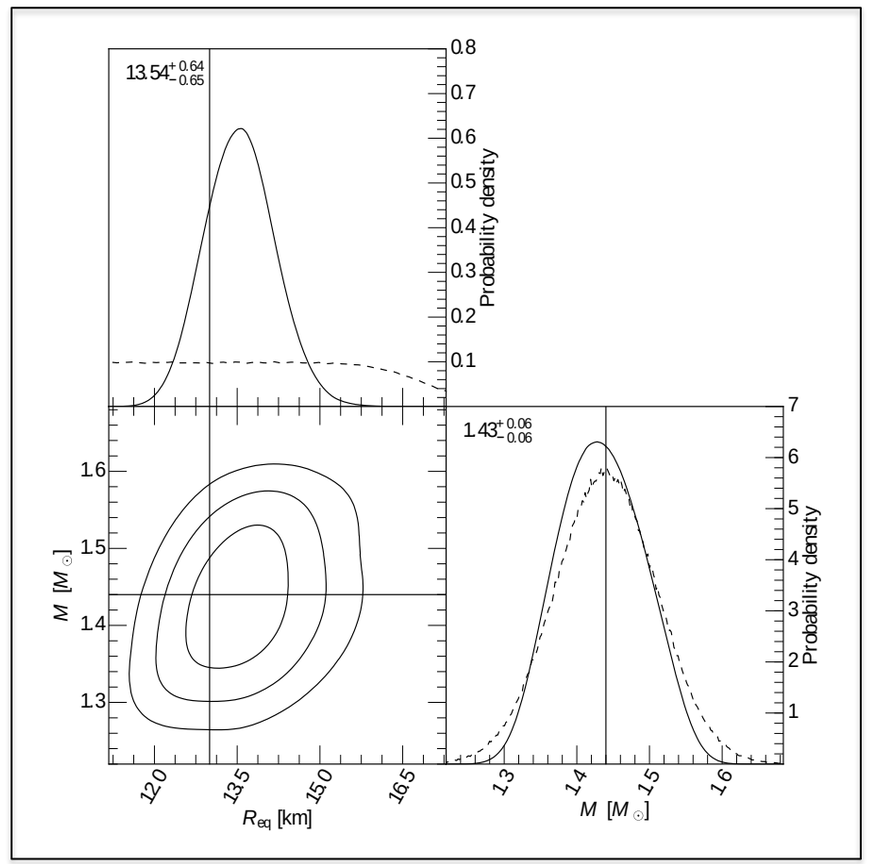
SIMULATION AND INFERENCE CODES

X-PSI

X-ray Pulse Simulation
and Inference package
https://xpsi-group.github.io/xpsi/
Riley et al. 2023 (JOSS)
Uses open source samplers
(e.g. MultiNest, Ultranest).

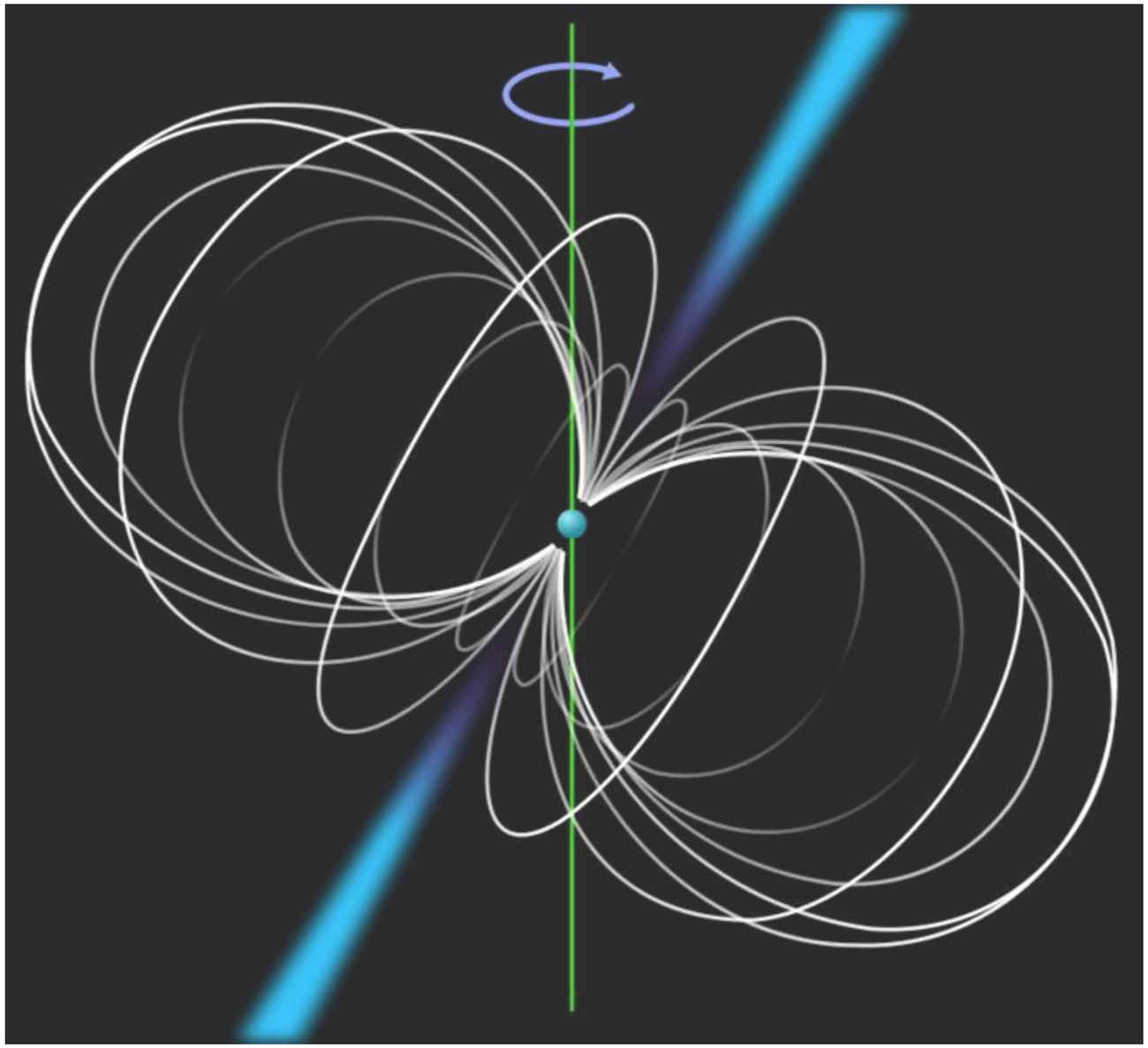


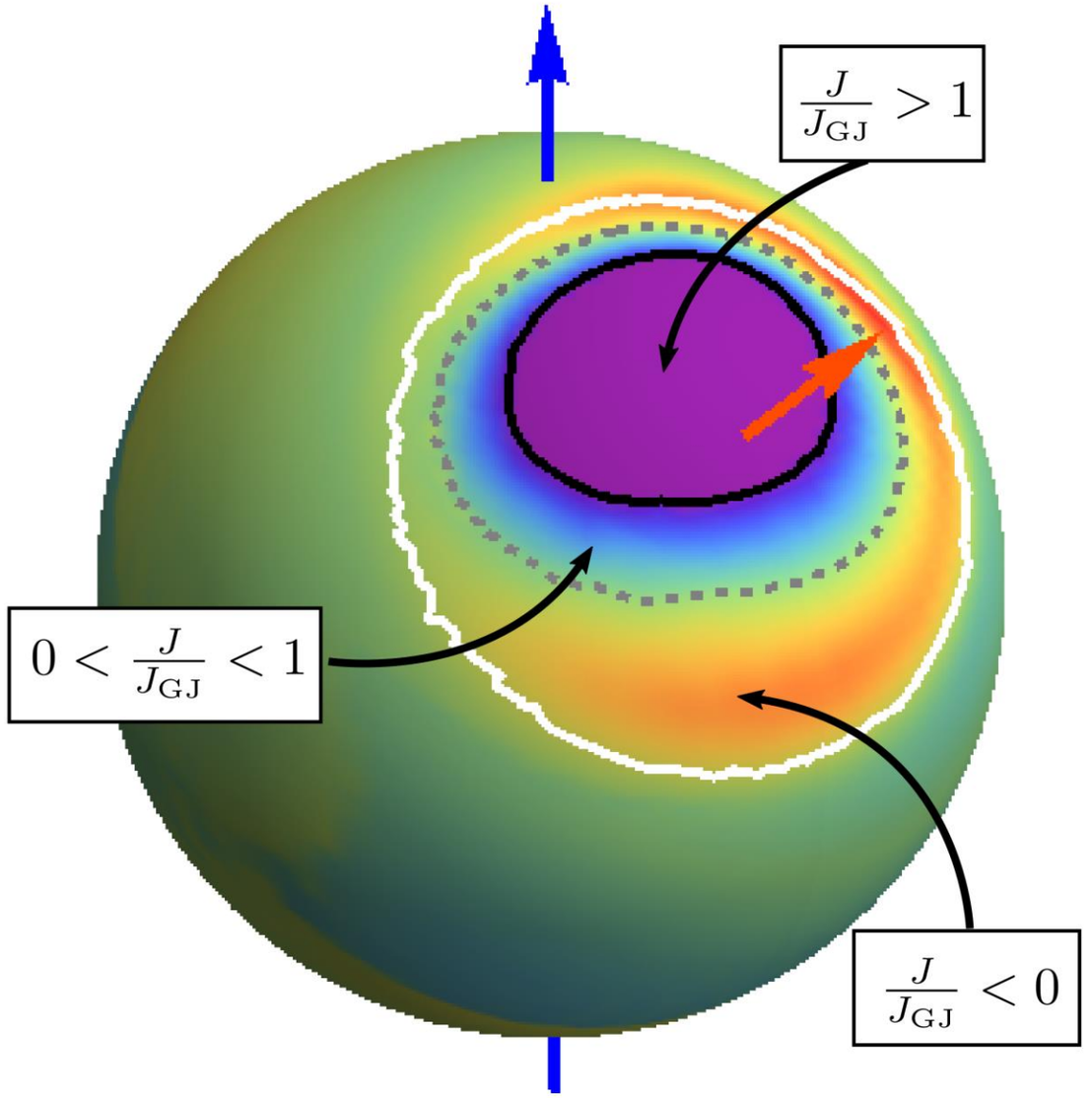




Ray-tracing and inference routines using synthetic data
(Bogdanov et al. 2019b, 2021, Choudhury et al. 2024b)

HOT SPOT PROPERTIES





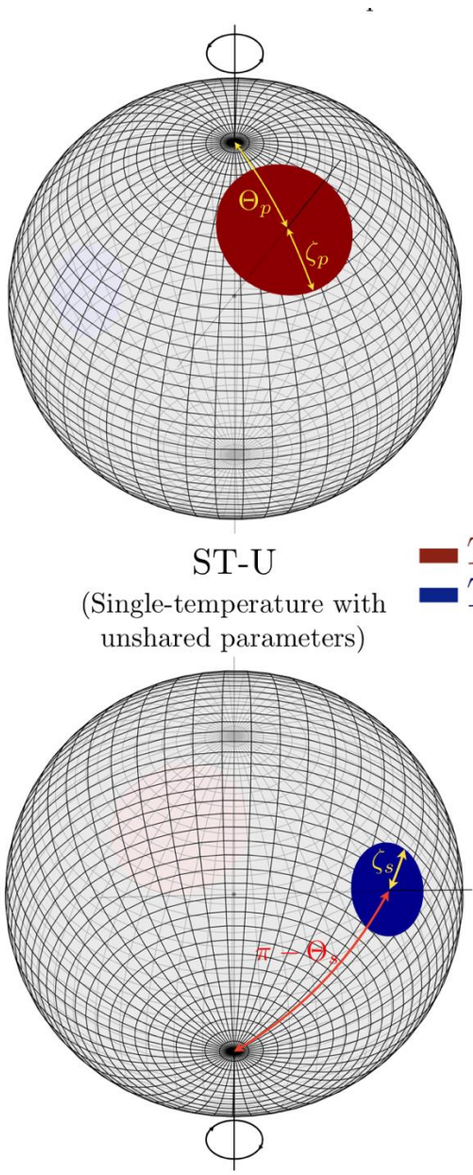
Surface heating pattern due to return currents a priori poorly constrained.

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

HOT SPOT MODELS

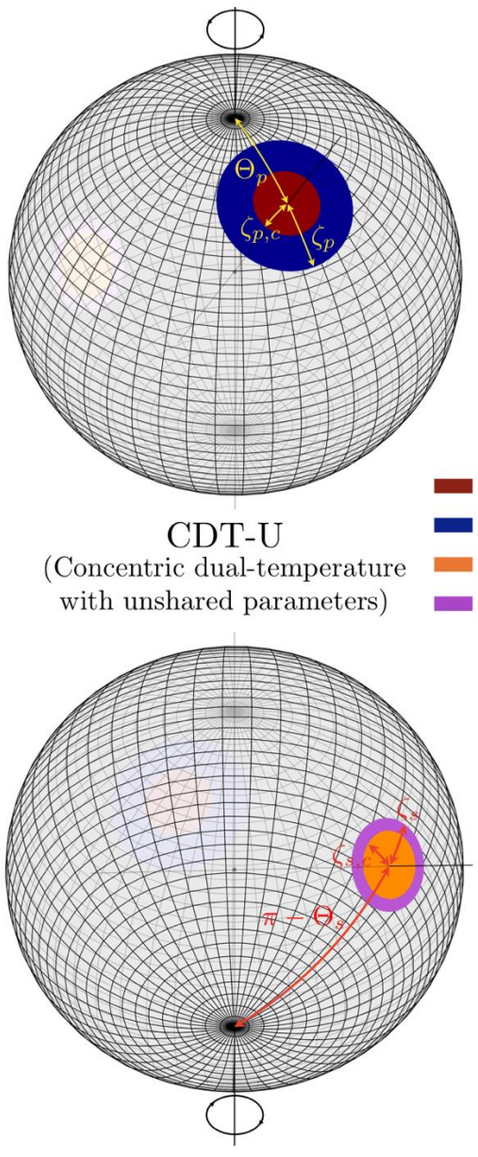
- We use 2-cap models of increasing surface pattern complexity.

Northern rotational hemisphere



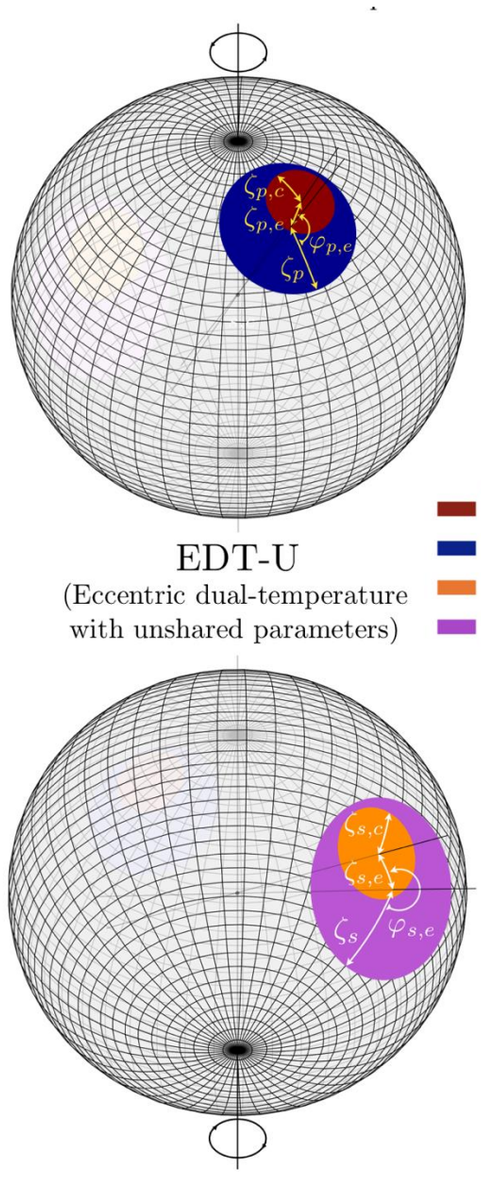
ST-U
(Single-temperature with unshared parameters)

T_p
T_s



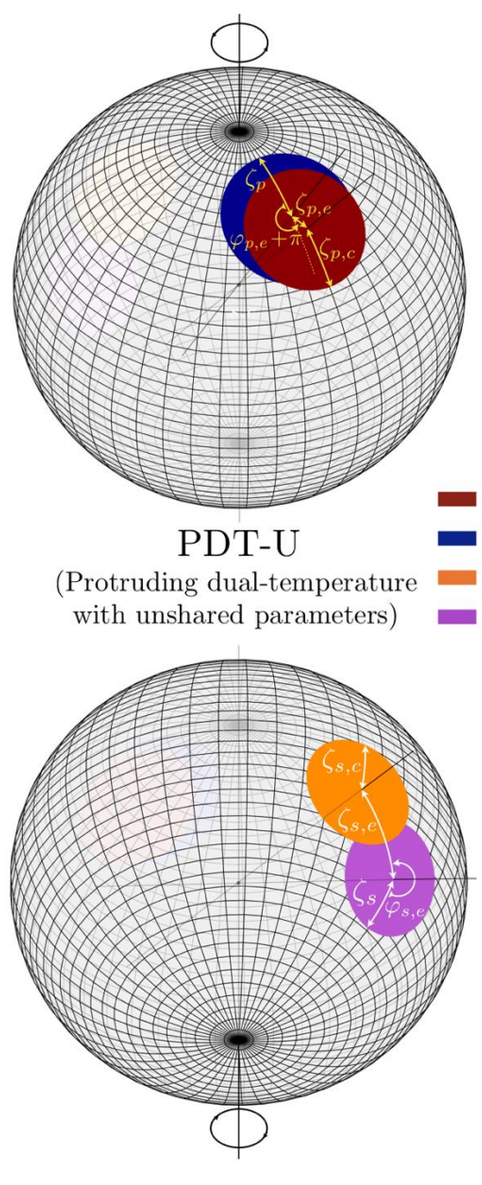
CDT-U
(Concentric dual-temperature with unshared parameters)

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



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)

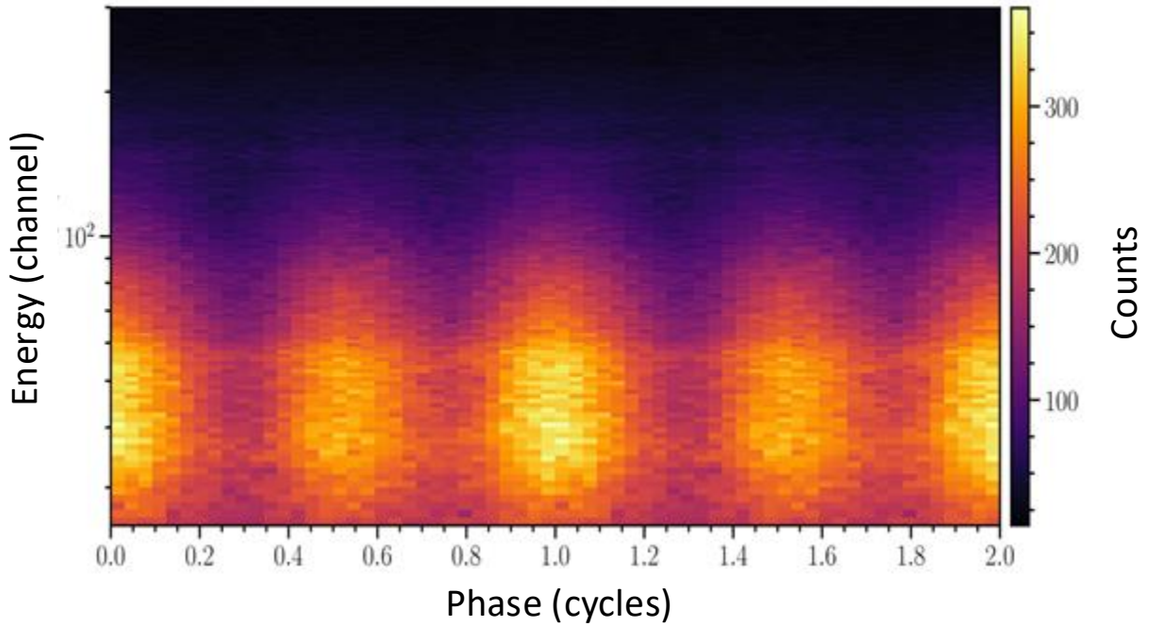
$T_{p,c}$
$T_{p,a}$
$T_{s,c}$
$T_{s,a}$

Southern rotational hemisphere

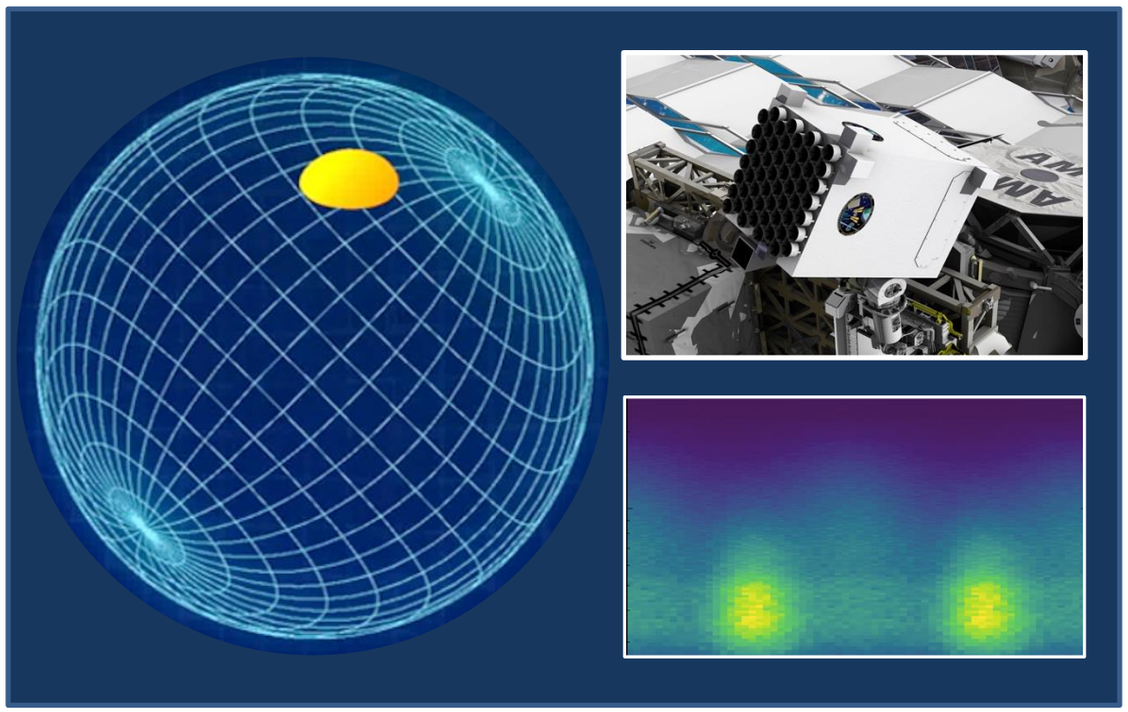
Riley et al. 2019

THE PULSE PROFILE MODELING PROCESS

Pulse profile data: Phase, Energy



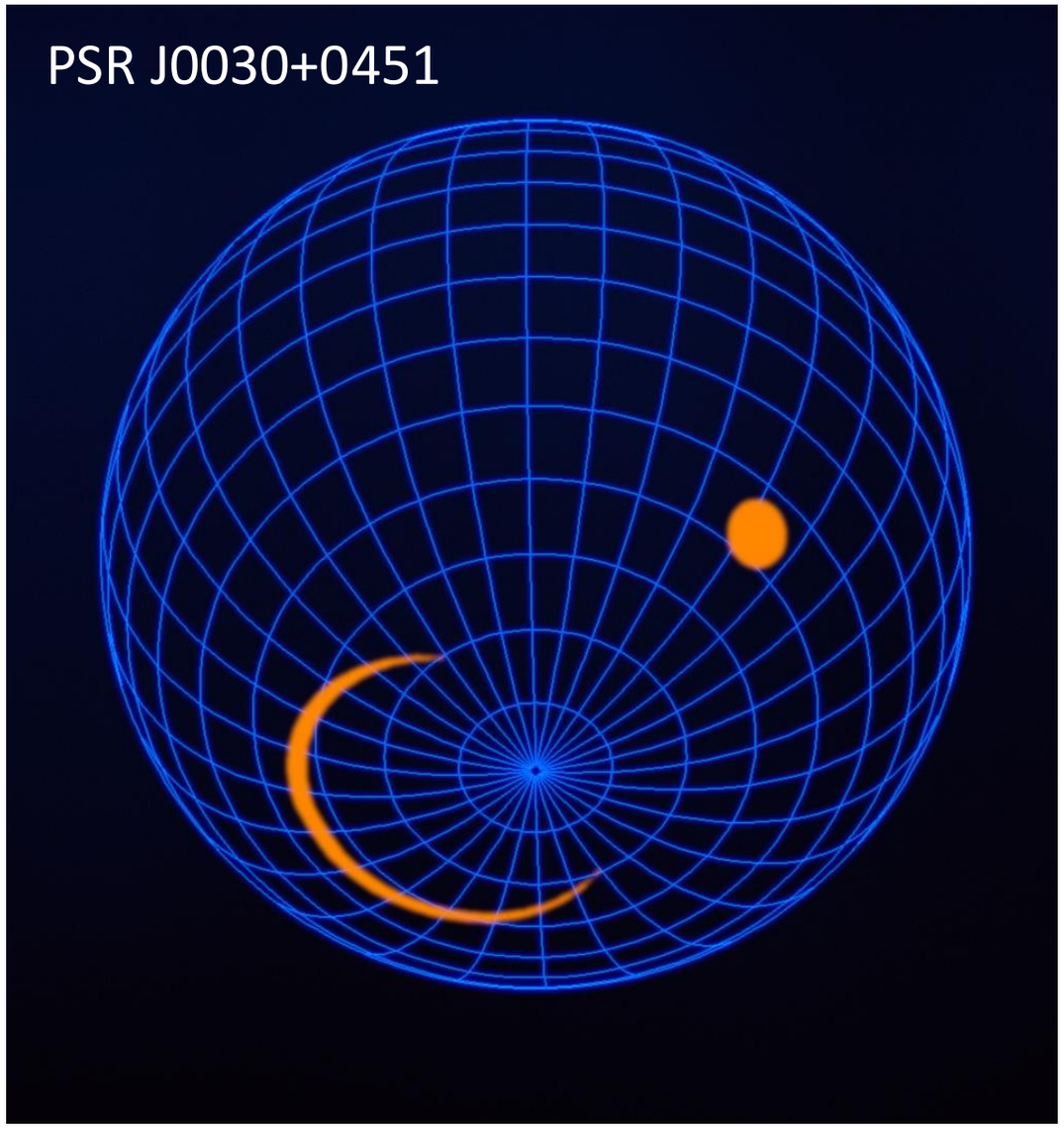
Lightcurve model: the (astro)physics

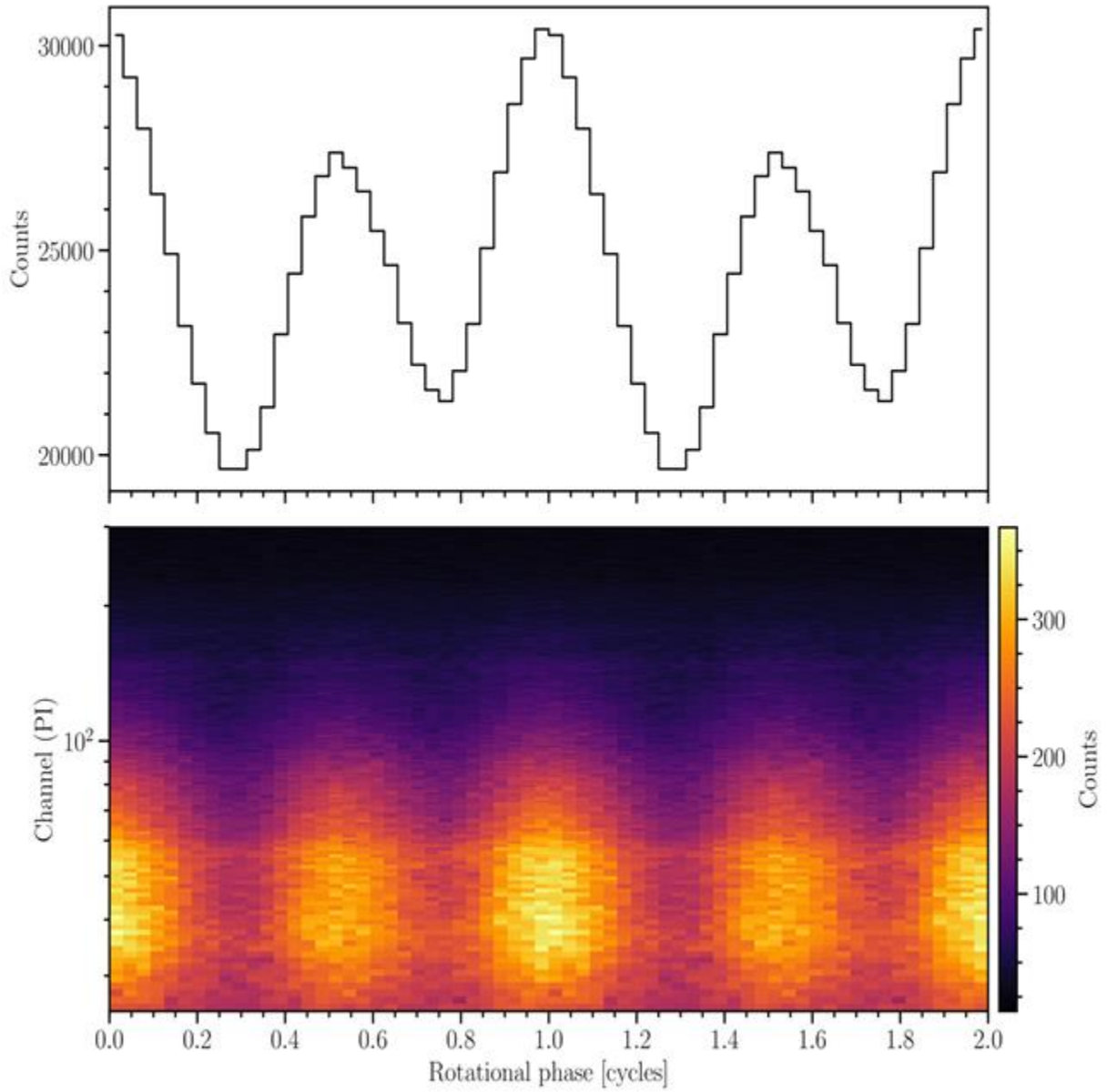


Bayesian inference of model parameters (statistical sampling)

Model parameters:
Mass and radius
Geometric properties

NICER'S FIRST SURFACE MAP





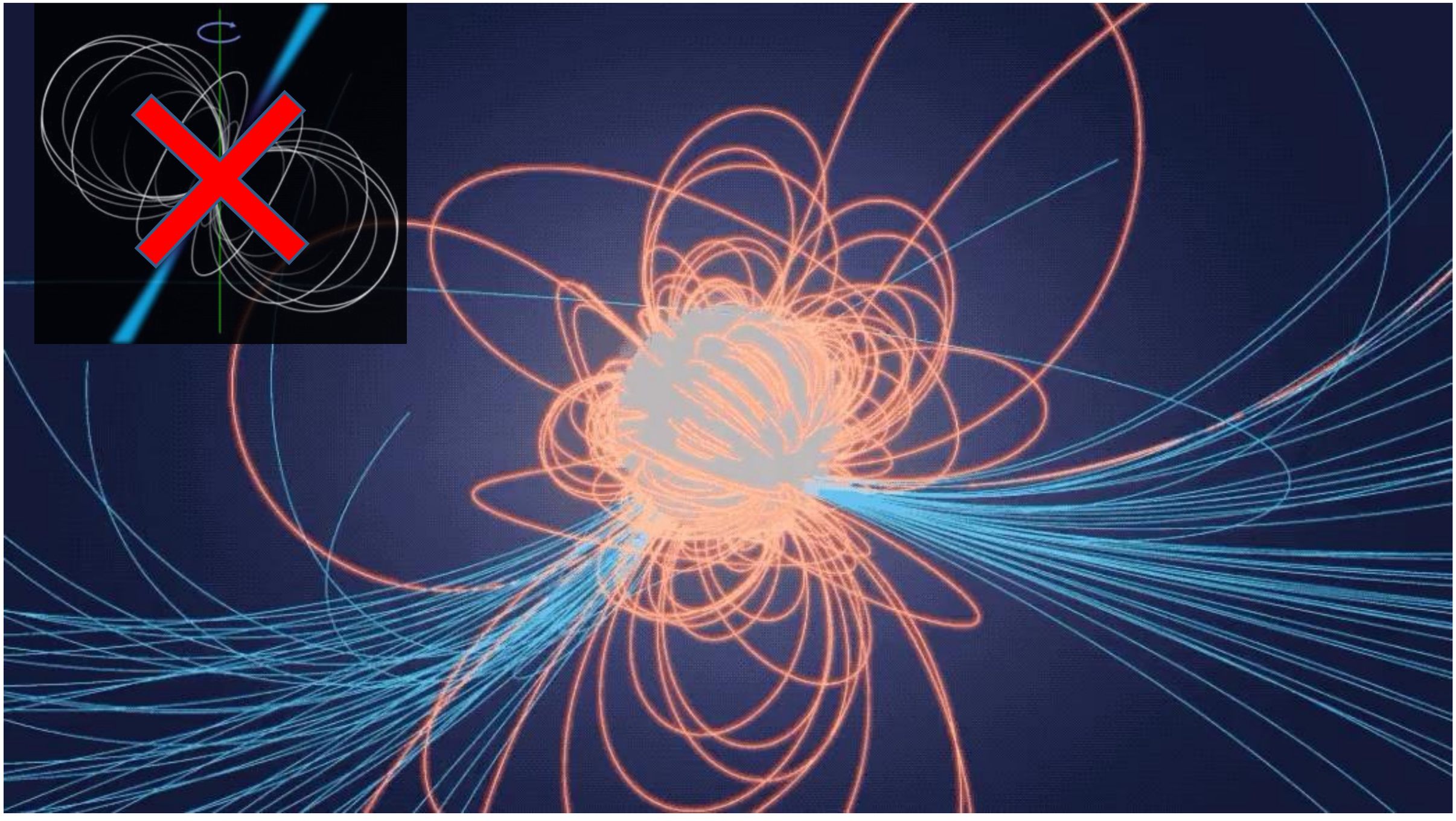
Data (Bogdanov et al. 2019a)

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

Maryland-Illinois analysis (Miller et al. 2019)

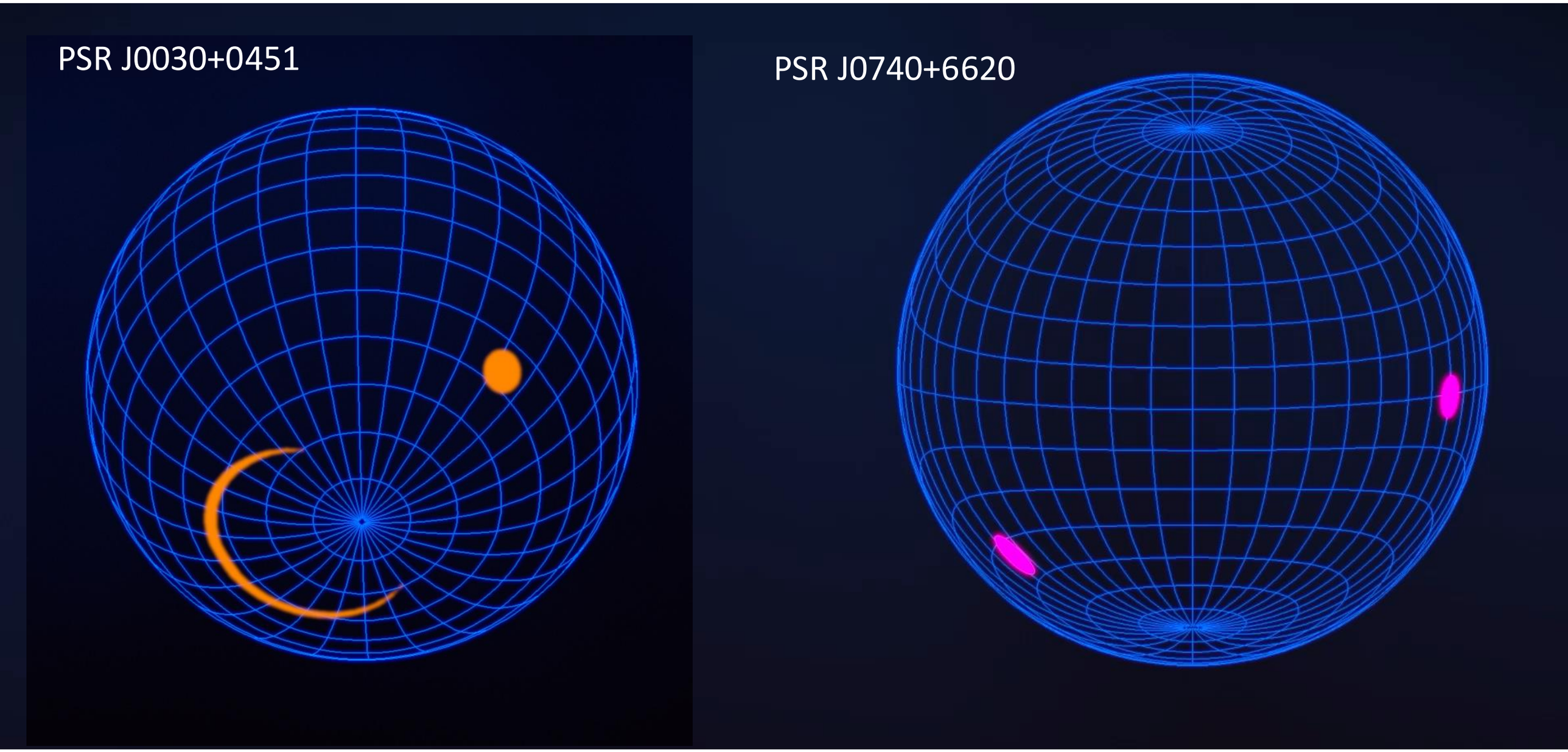
Independent replication for this data set with X-PSI by Afle et al. 2023

NON-DIPOLAR MAGNETIC FIELD



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

MAPPING THE MOST MASSIVE PULSAR



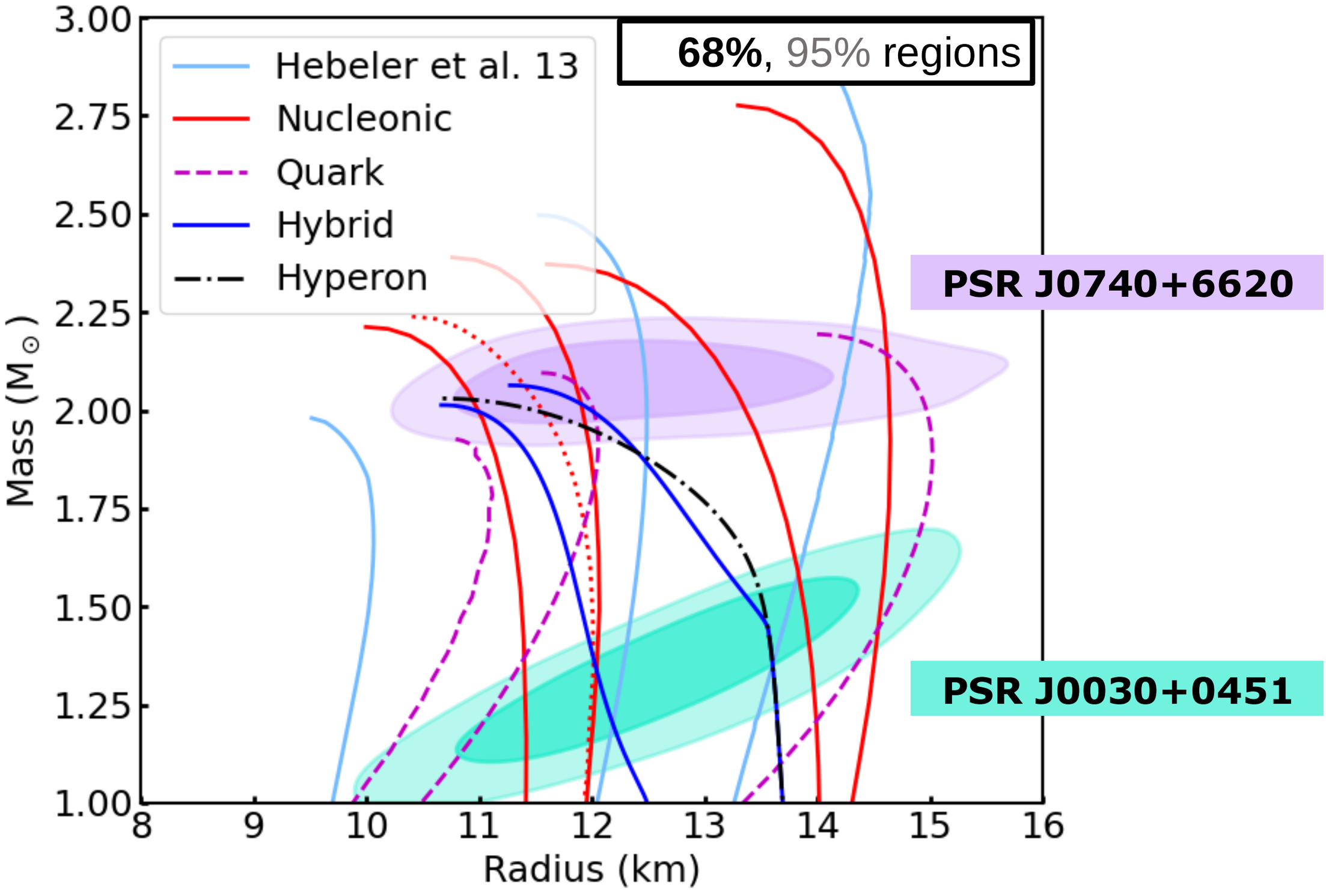
Movie: Sharon Morsink, NASA

Data: Wolff et al. 2021

X-PSI analysis: Riley et al. 2021, Raaijmakers et al. 2021,

Maryland-Illinois analysis: Miller et al. 2021

INFERRED MASS AND RADIUS

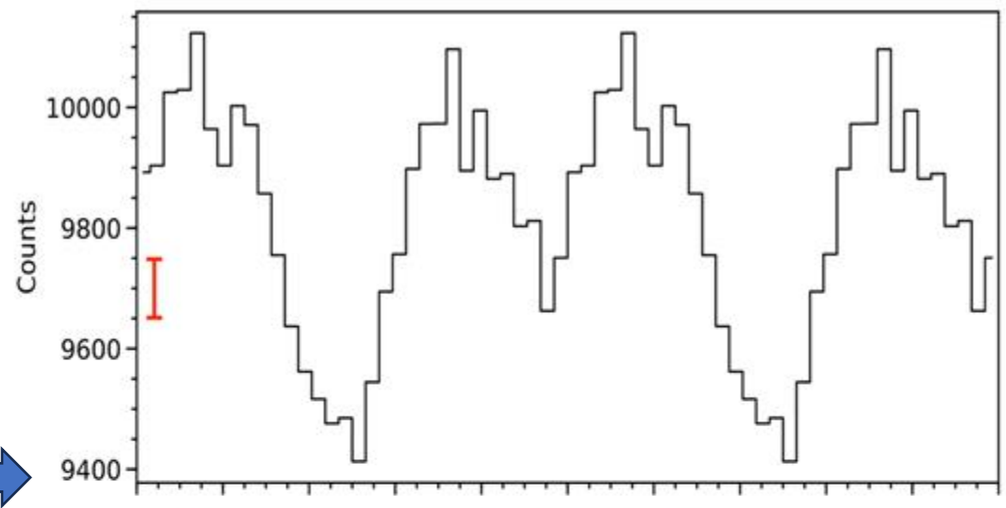


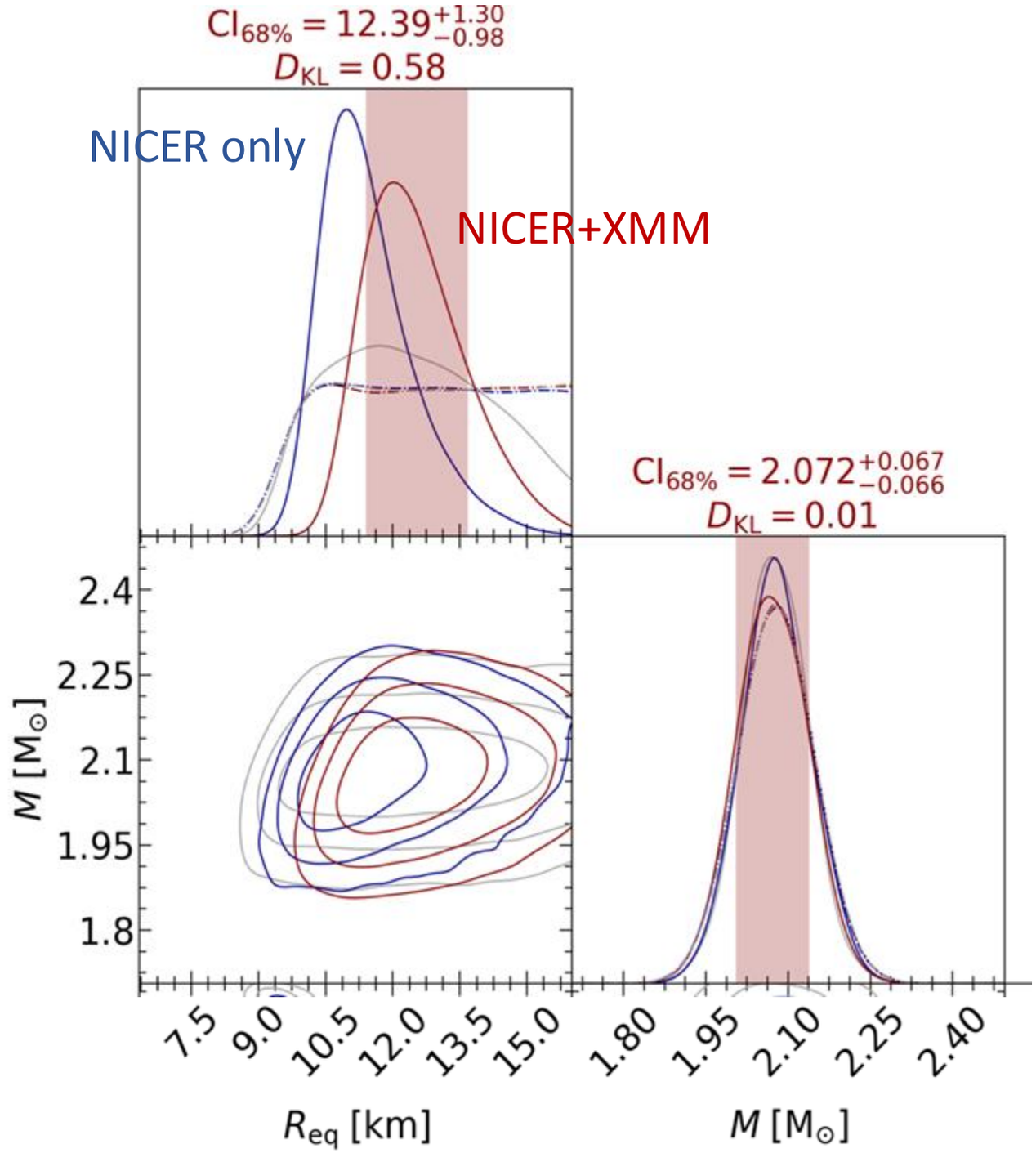
X-PSI Credible regions from Riley et al. 2019, 2021

THE IMPORTANCE OF BACKGROUND

"Unpulsed" component:

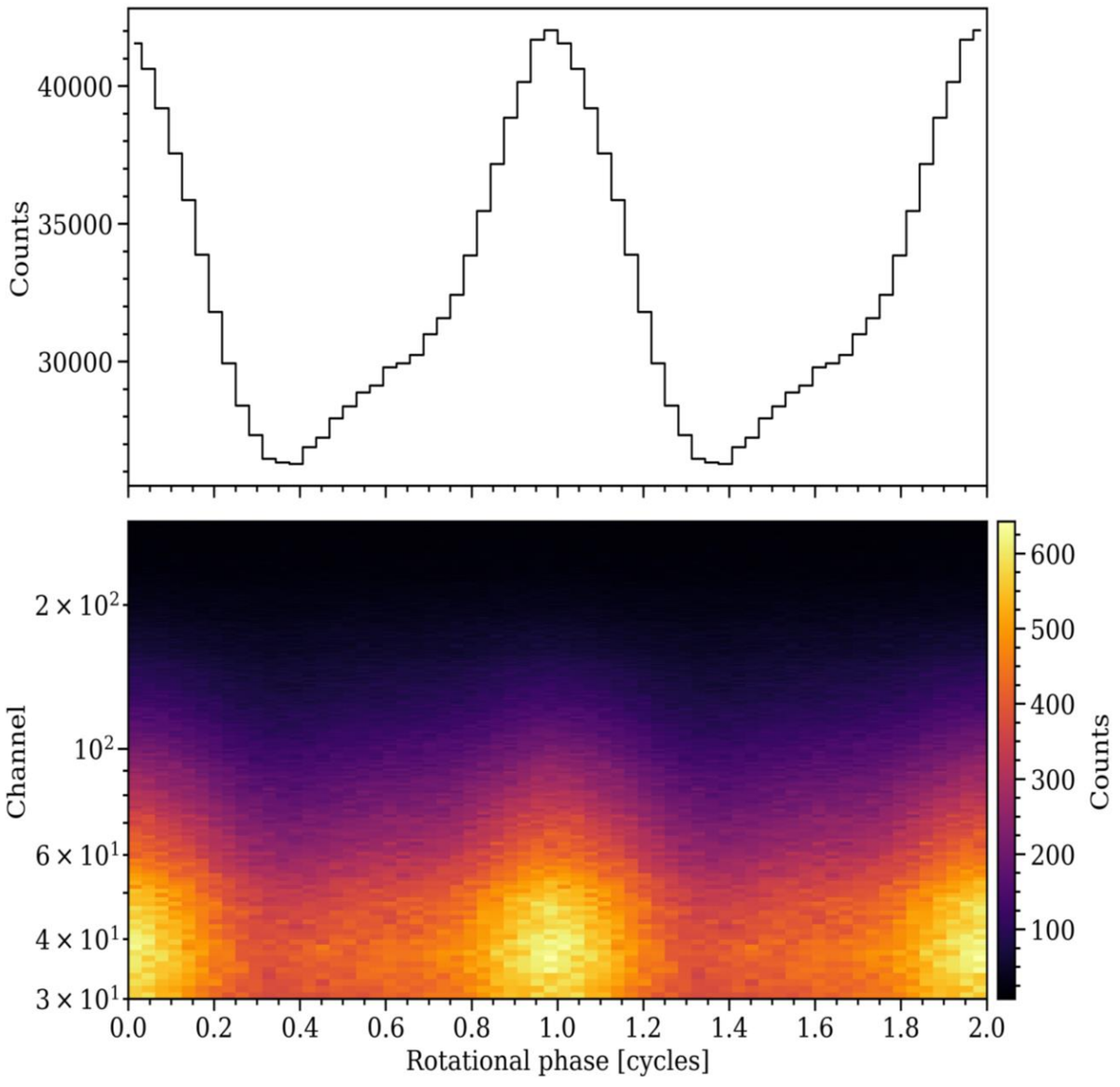
- Astrophysical background
- Particle background
- Spots not vanishing from view - geometry or strong lightbending



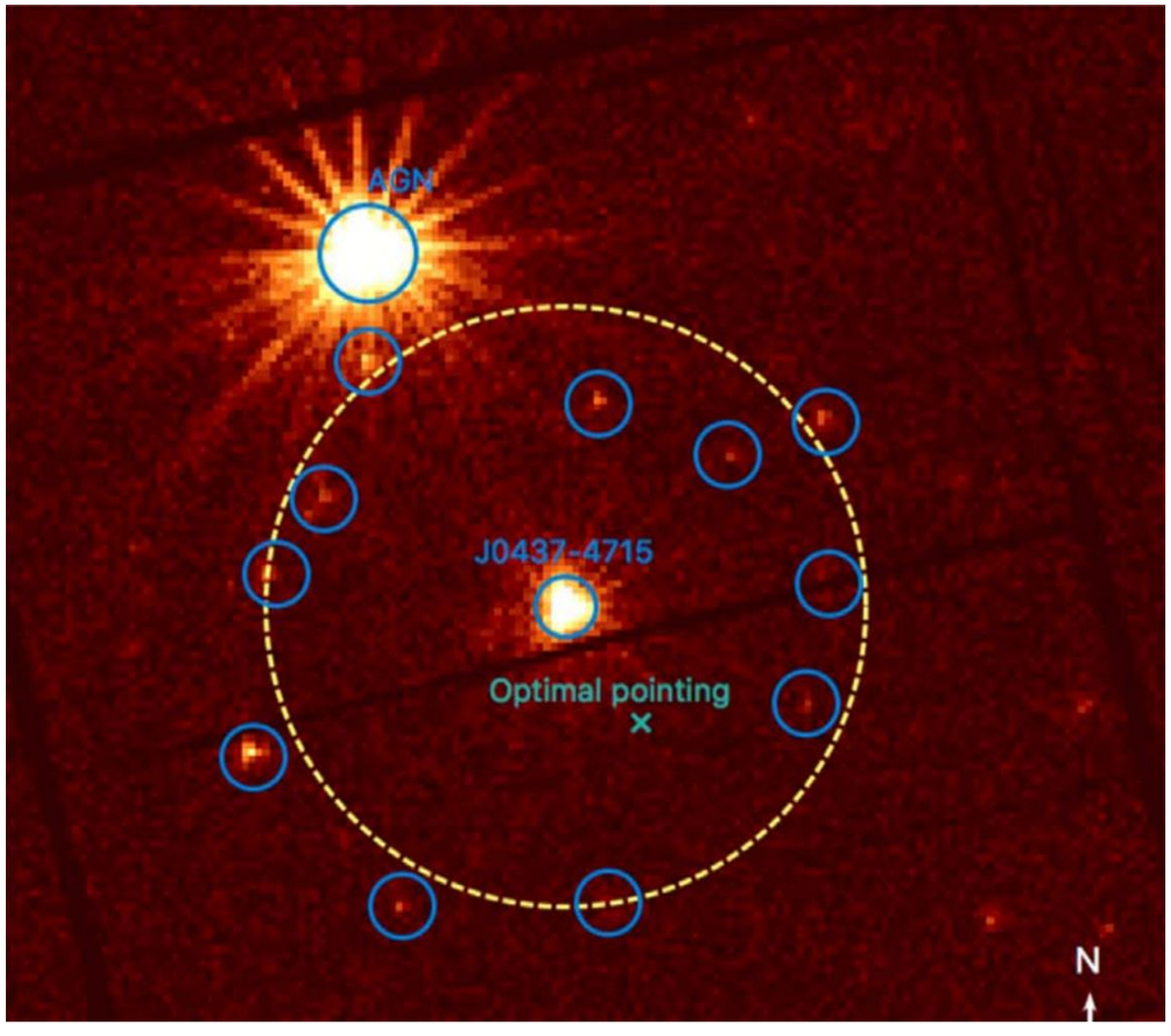


Background constraints rule out high compactness M/R, so increase radius (see also Salmi et al. 2022)

NEW - NICER'S BRIGHTEST TARGET



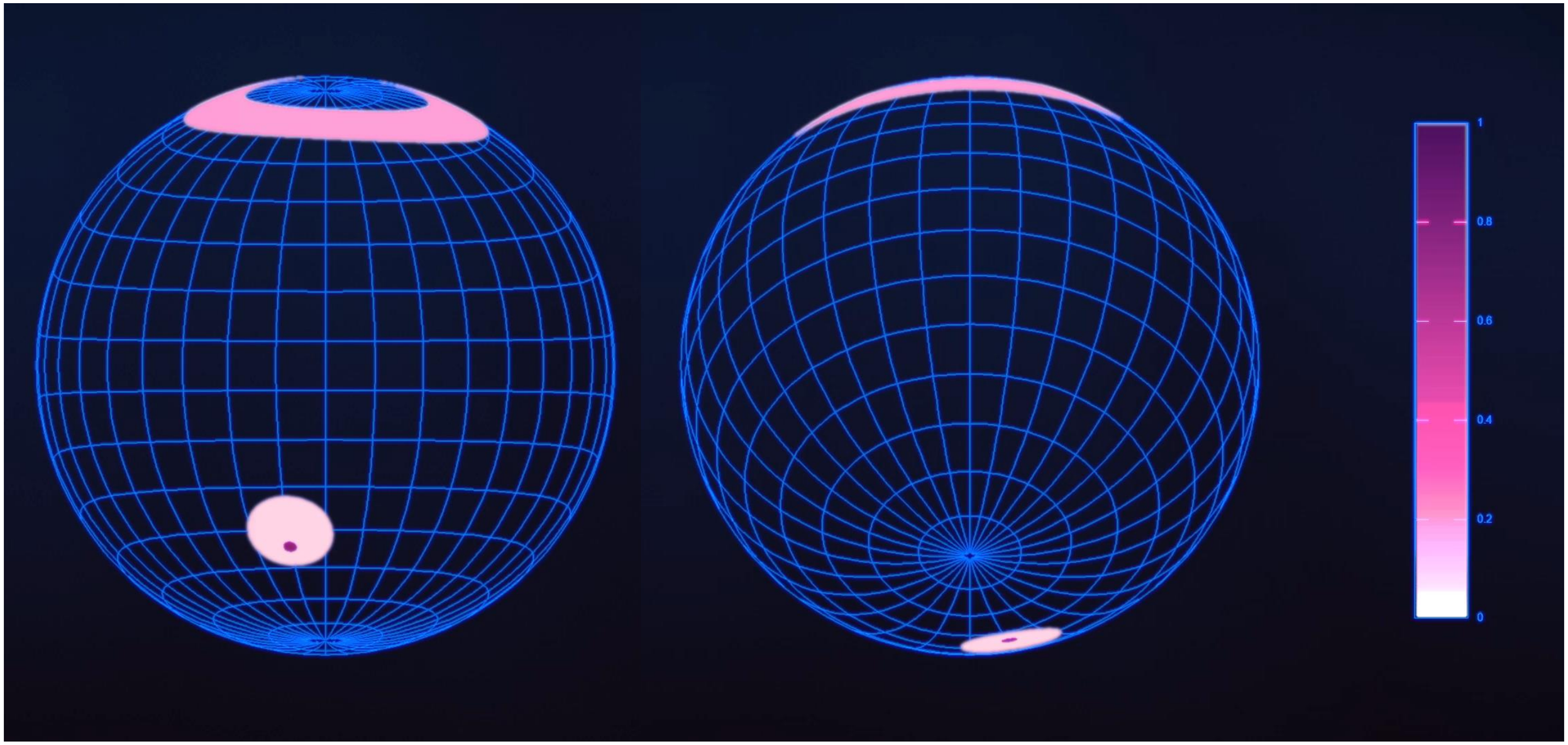
PSR J0437-4715
(Choudhury et al. 2024)



XMM-Newton image
Bogdanov et al. 2019

Mass, distance, inclination all well known from pulsar timing
(Reardon et al. 2024)

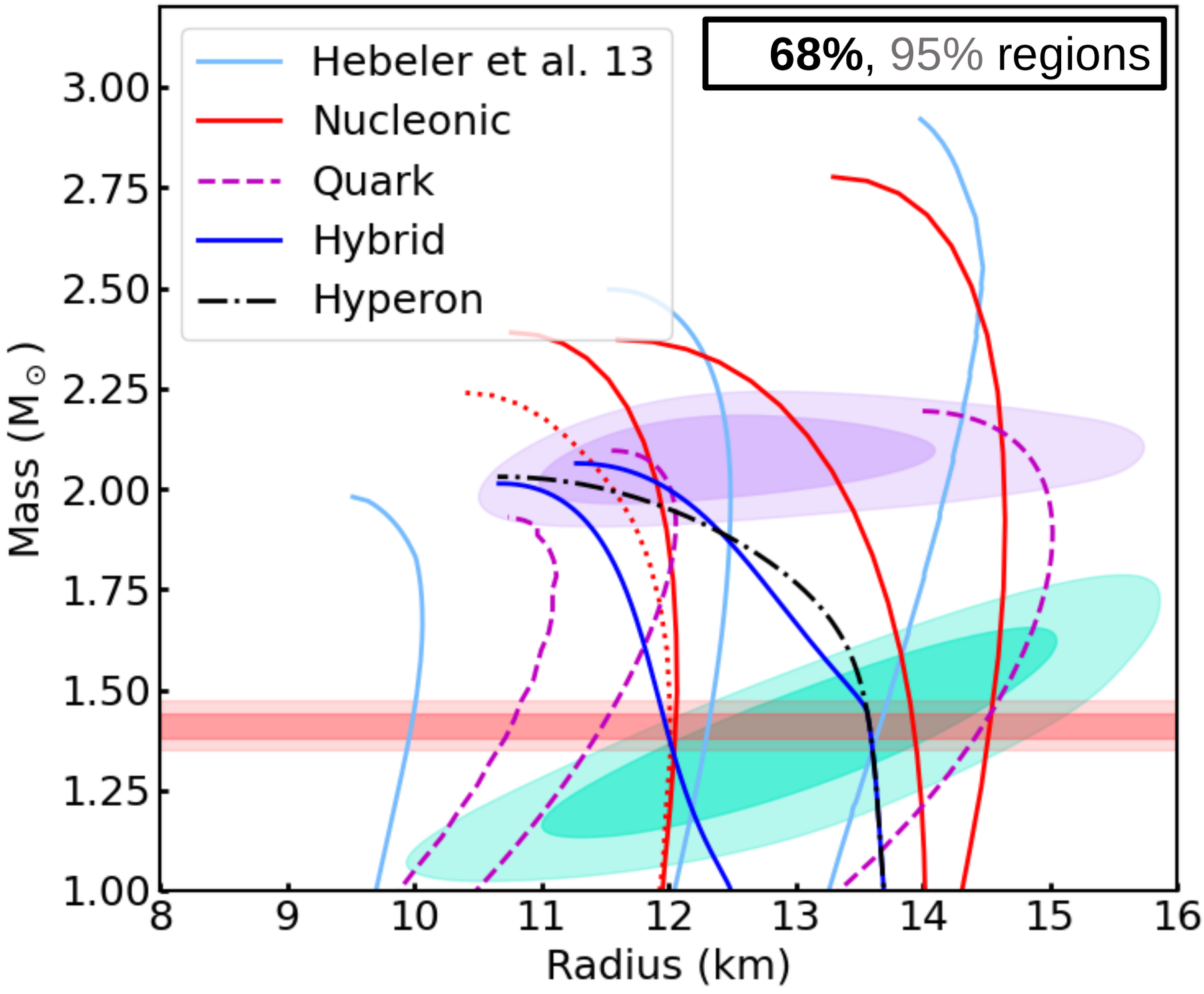
PSR J0437-4715 SURFACE MAP



Movies: NASA GSFC Conceptual Image Lab, Sharon Morsink

Choudhury et al. 2024

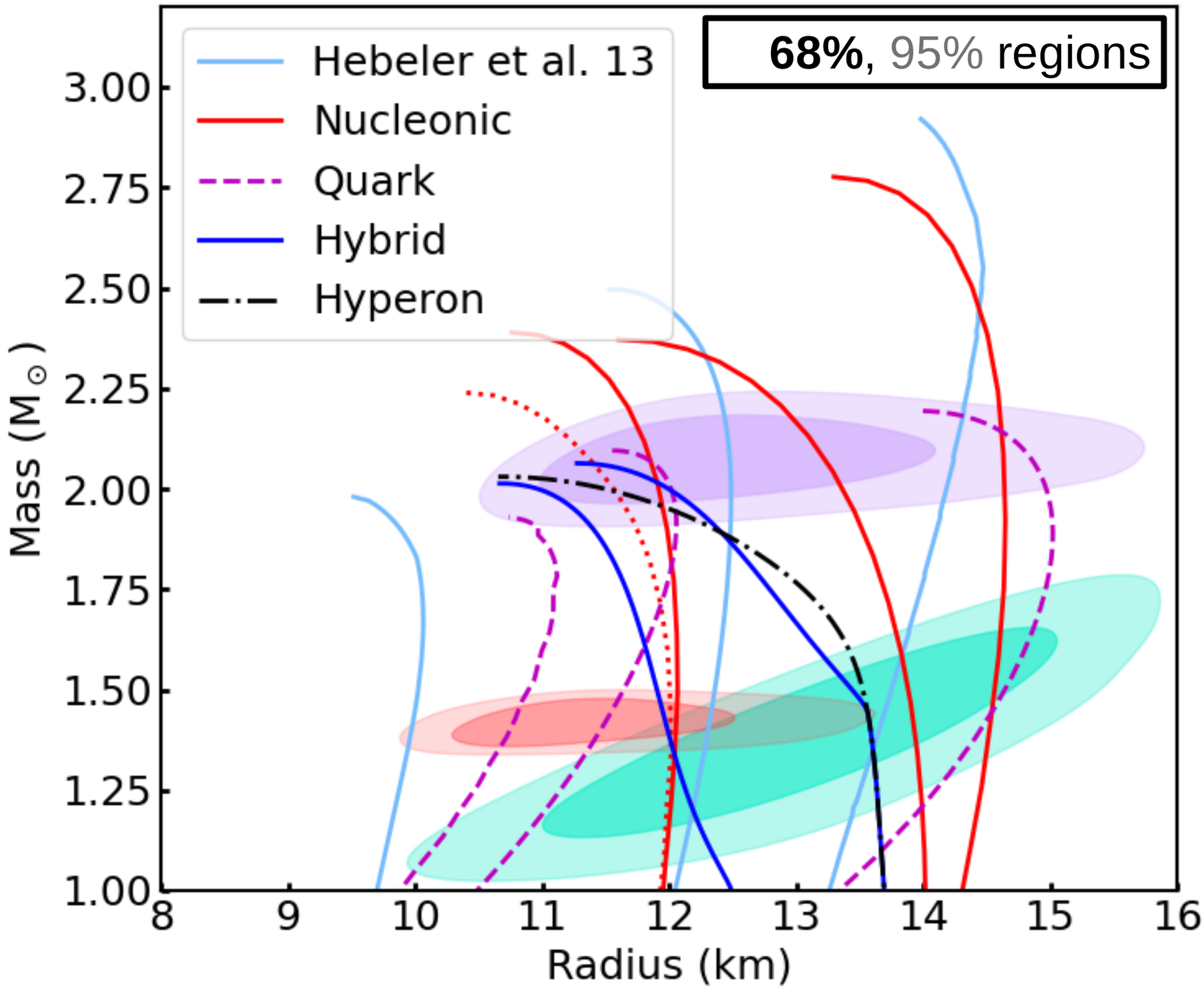
PSR J0437-4715 MASS PRIOR



Reardon et al. 2024

Note: Now showing updated X-PSI results for PSR J0030+0451 (Vinciguerra et al. 2024) and PSR J0740+6620 (Salmi et al. 2024)

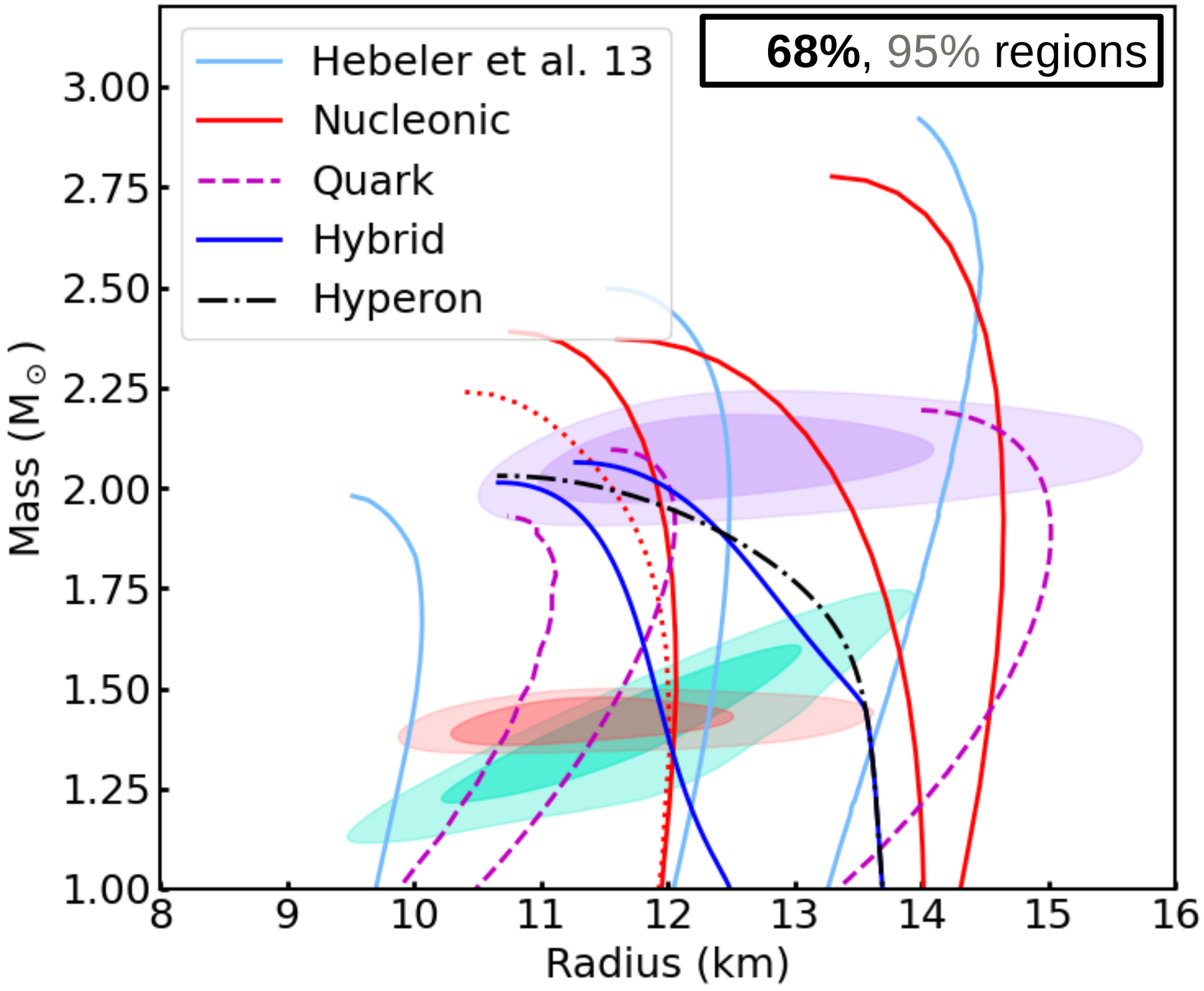
PSR J0437-4715 RADIUS



Mass, radius for PSR J0437-4715 from Choudhury et al. (2024)

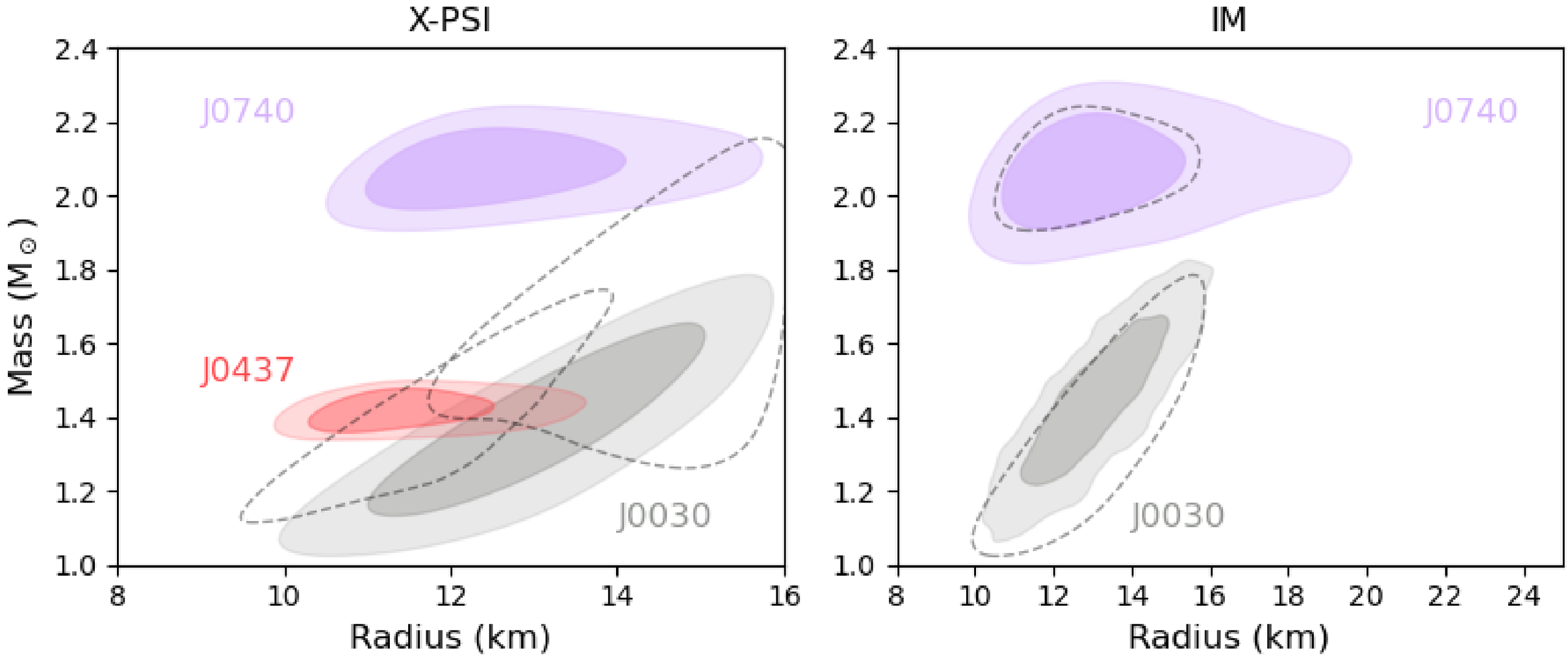
Supports somewhat softer EOS, more consistent with results from GW170817

CONSISTENCY WITH PSR J0030+0451?



PSR J0030+0451 alternative modes when background included, Vinciguerra et al. 2024

OVERALL STATUS OF NICER RESULTS



PSR J0740+6620: Salmi et al. 2024 (updates Riley et al. 2021, Salmi et al. 2022).
PSR J0030+0451: Vinciguerra et al. 2024, dashed lines are 95% regions for modes once background is included (updates Riley et al. 2019).
PSR J0437-4715: Choudhury et al. 2024

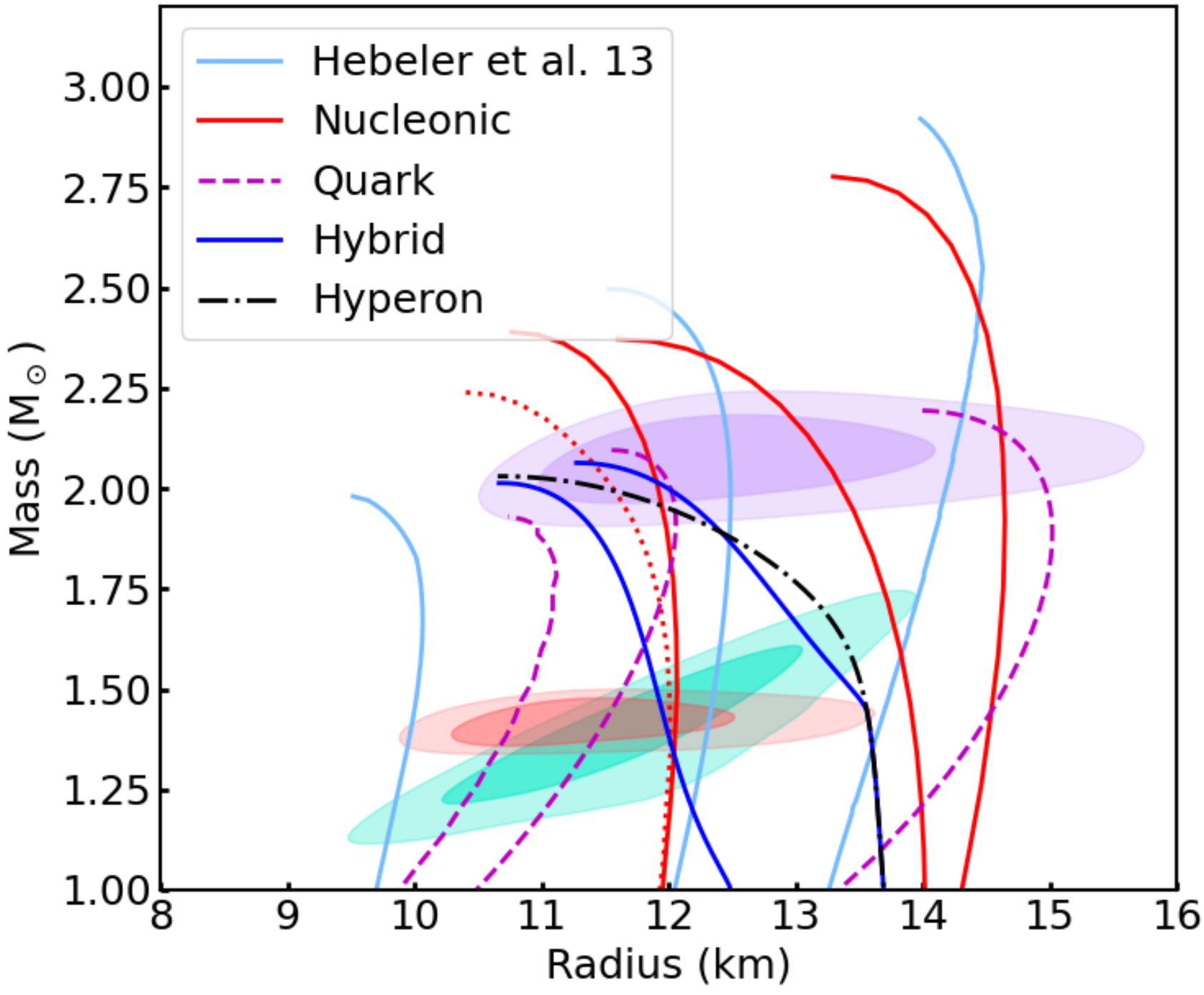
See also Salmi et al. 2023 on atmosphere sensitivity

PSR J0740+6620: Dittmann et al. 2024 (updates Miller et al. 2021)
PSR J0030+0451: Miller et al. 2019

Dashed lines are 95% regions for comparable X-PSI analyses.
Note: Several differences in analysis, including different prior range on radius.

Figure from Chatziioannou (+AW) et al. 2024, arXiv:2407.11153

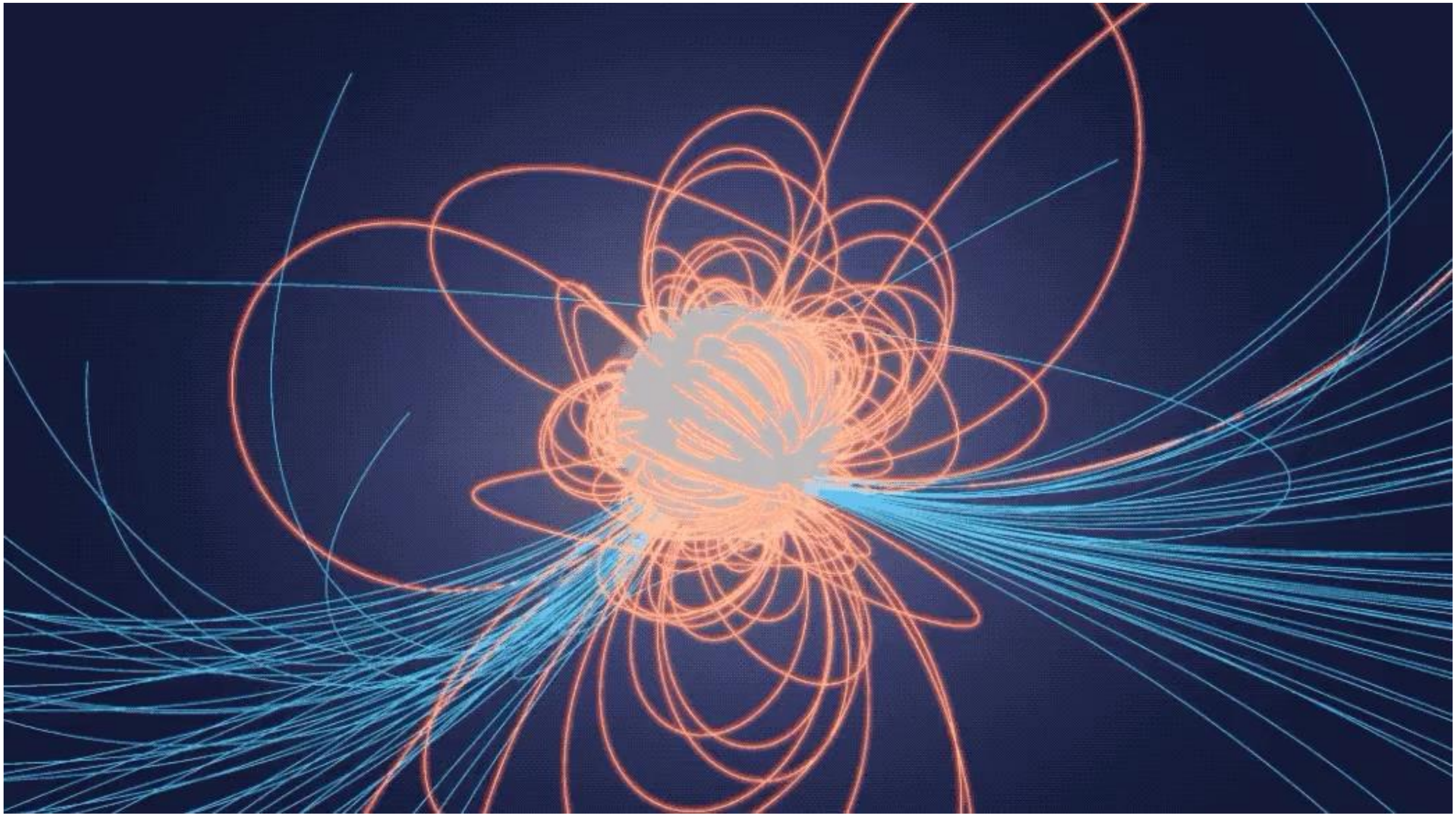
WHAT'S NEXT? MORE STARS, MORE DATA!



4 additional NS (3 with known masses) + more data on existing sources.

Question – should we be using more restrictive radius priors?

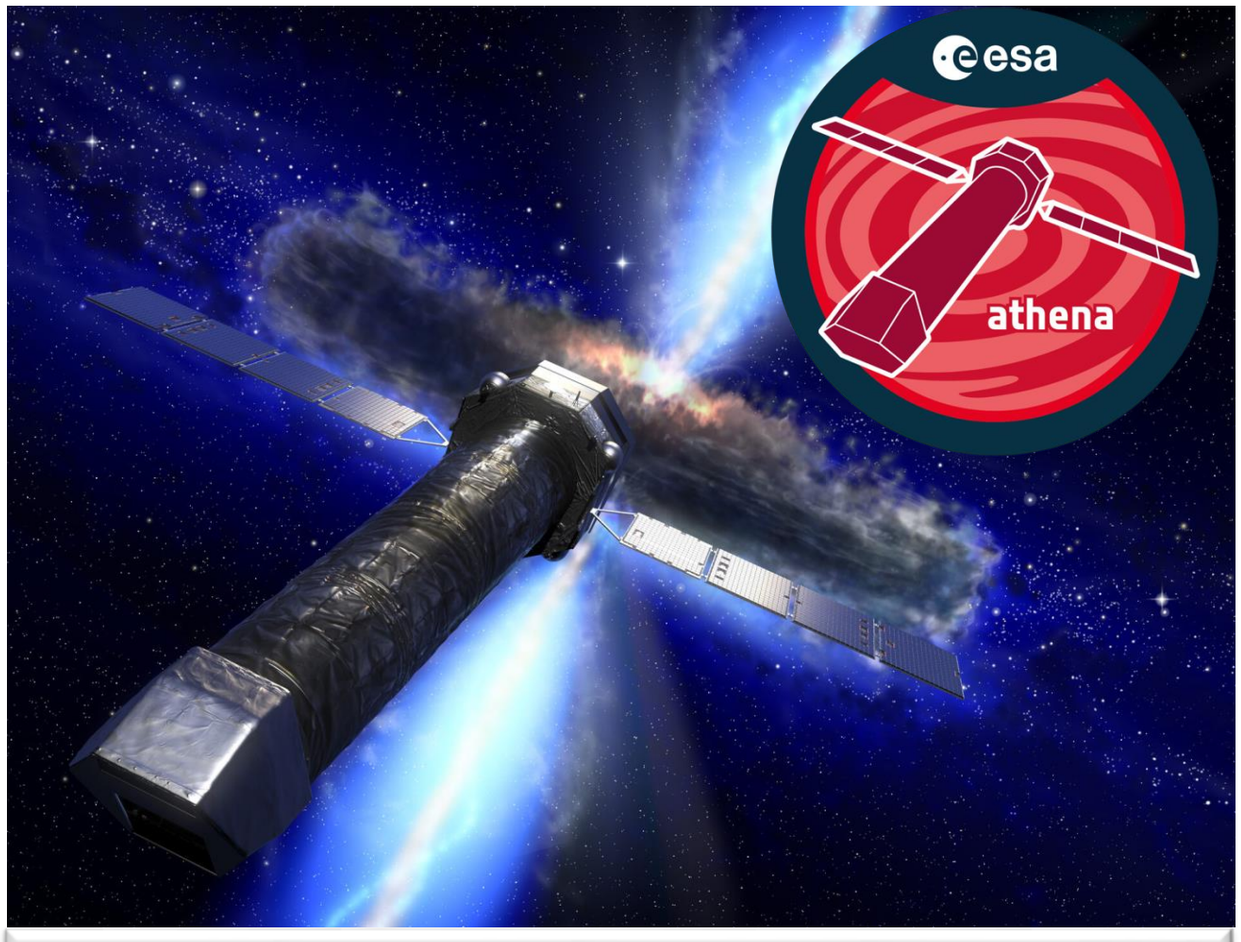
WHAT'S NEXT? BETTER PULSAR MODELS



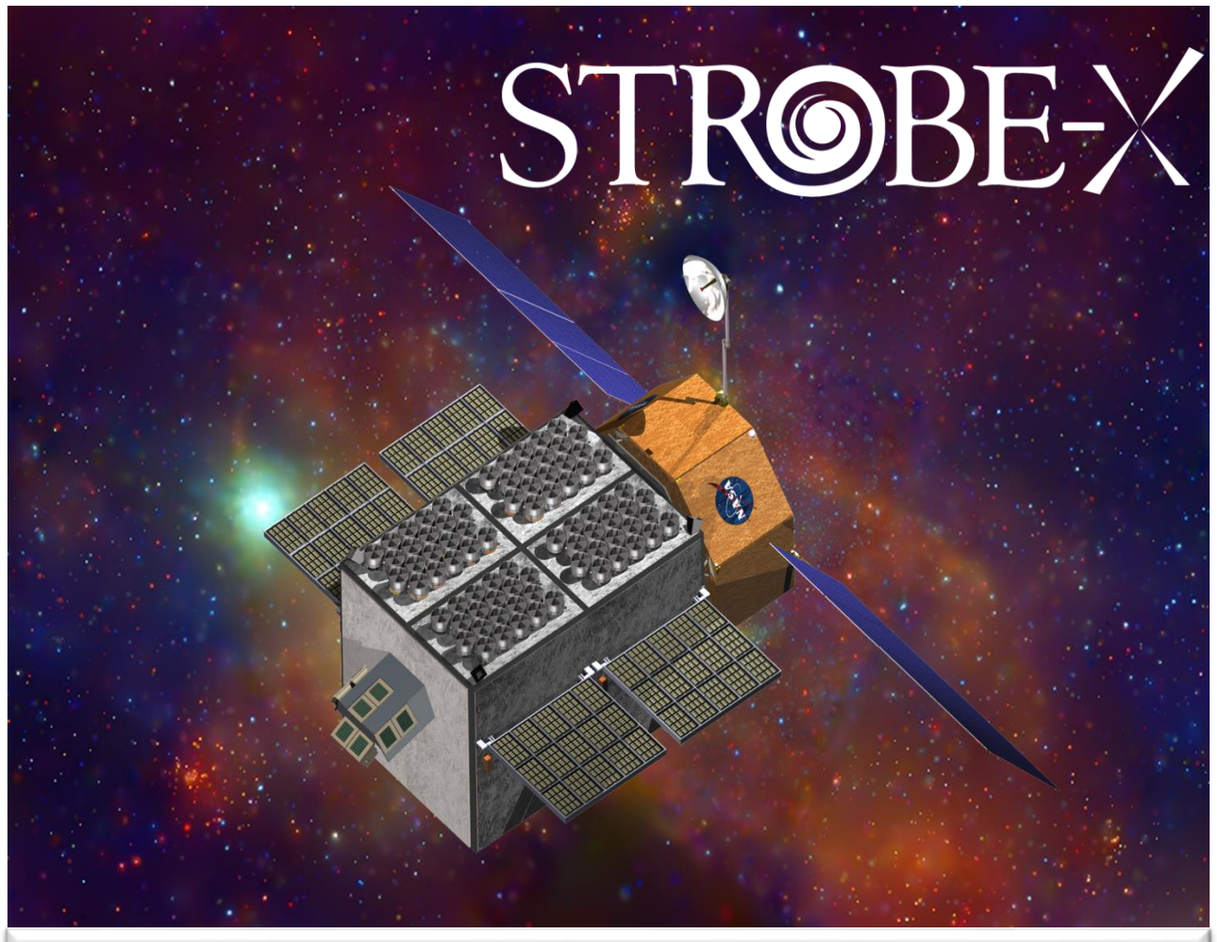
Credit: NASA's Goddard Space Flight Center/Harding, Kalapotharakos, Wadiasingh.

WHAT'S NEXT? NEW TELESCOPES

Athena – similar energy band to NICER
STROBE-X (NASA Probe candidate) - wider X–ray band



Athena (launch 2030s)

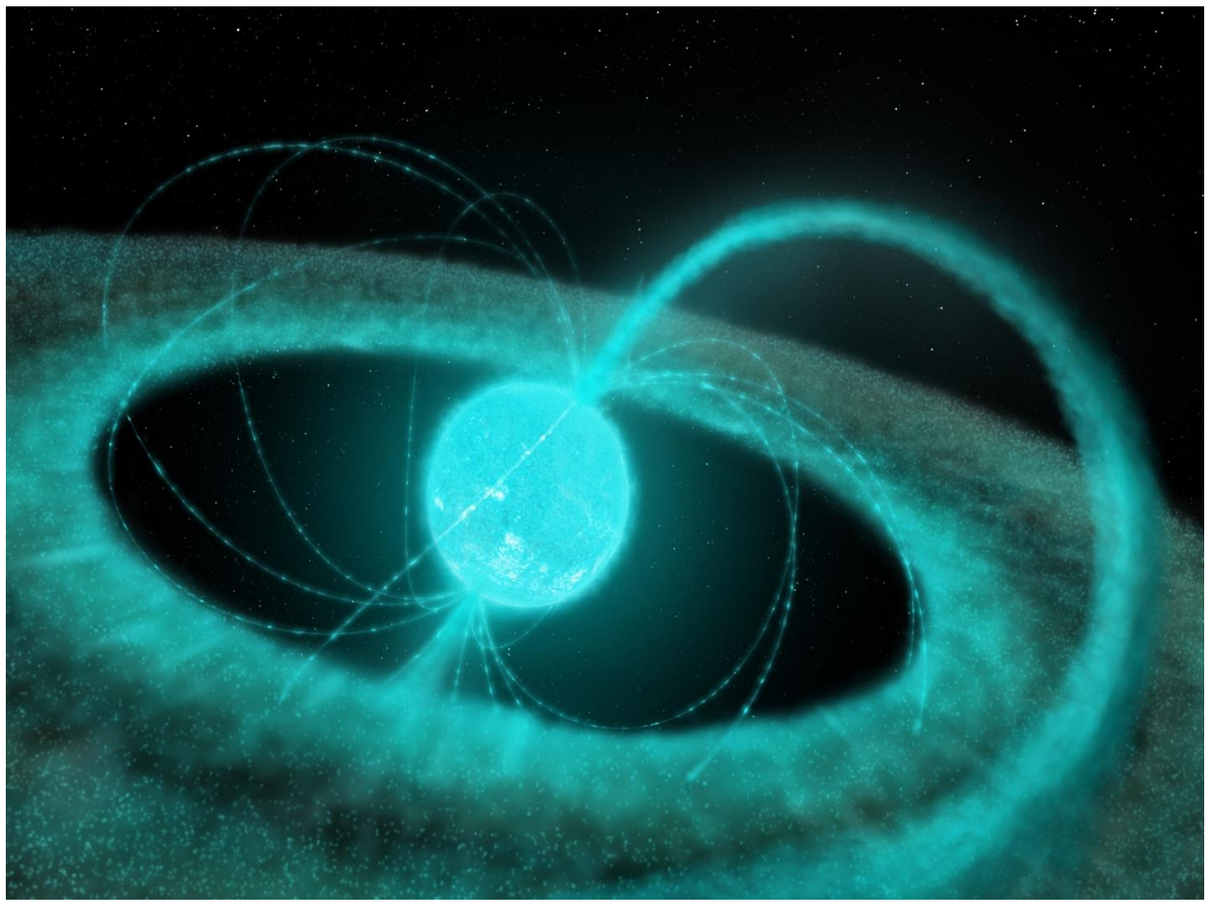


Ray et al. 2019

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

WHAT'S NEXT? NEW TYPES OF STAR

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



Accretion-powered millisecond X-ray pulsars

Thermonuclear burst oscillation sources

New challenges e.g. different atmosphere models, unknown surface pattern, variability (Kini et al. 23,24a,b; Dorsman+, Salmi+ in prep)

SUMMARY

- NICER is pioneering a completely new technique for determining neutron star properties.
- We have measured the size of three neutron stars!
- We are making maps of tiny stars thousands of light years from Earth.