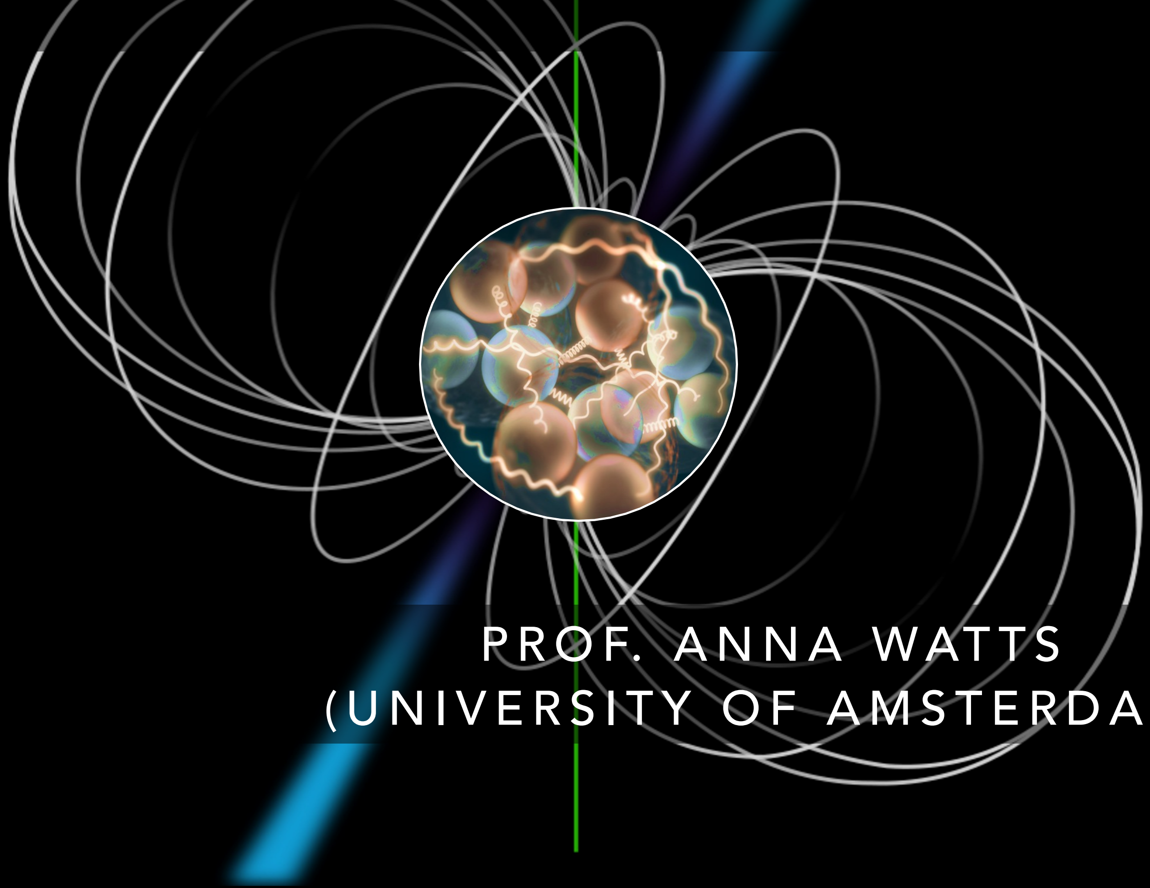
ULTRADENSE MATTER IN NEUTRON STARS: FROM NICER TO NEWATHENA



PROF. ANNA WATTS
(UNIVERSITY OF AMSTERDAM)

THE NEUTRON STAR INTERIOR

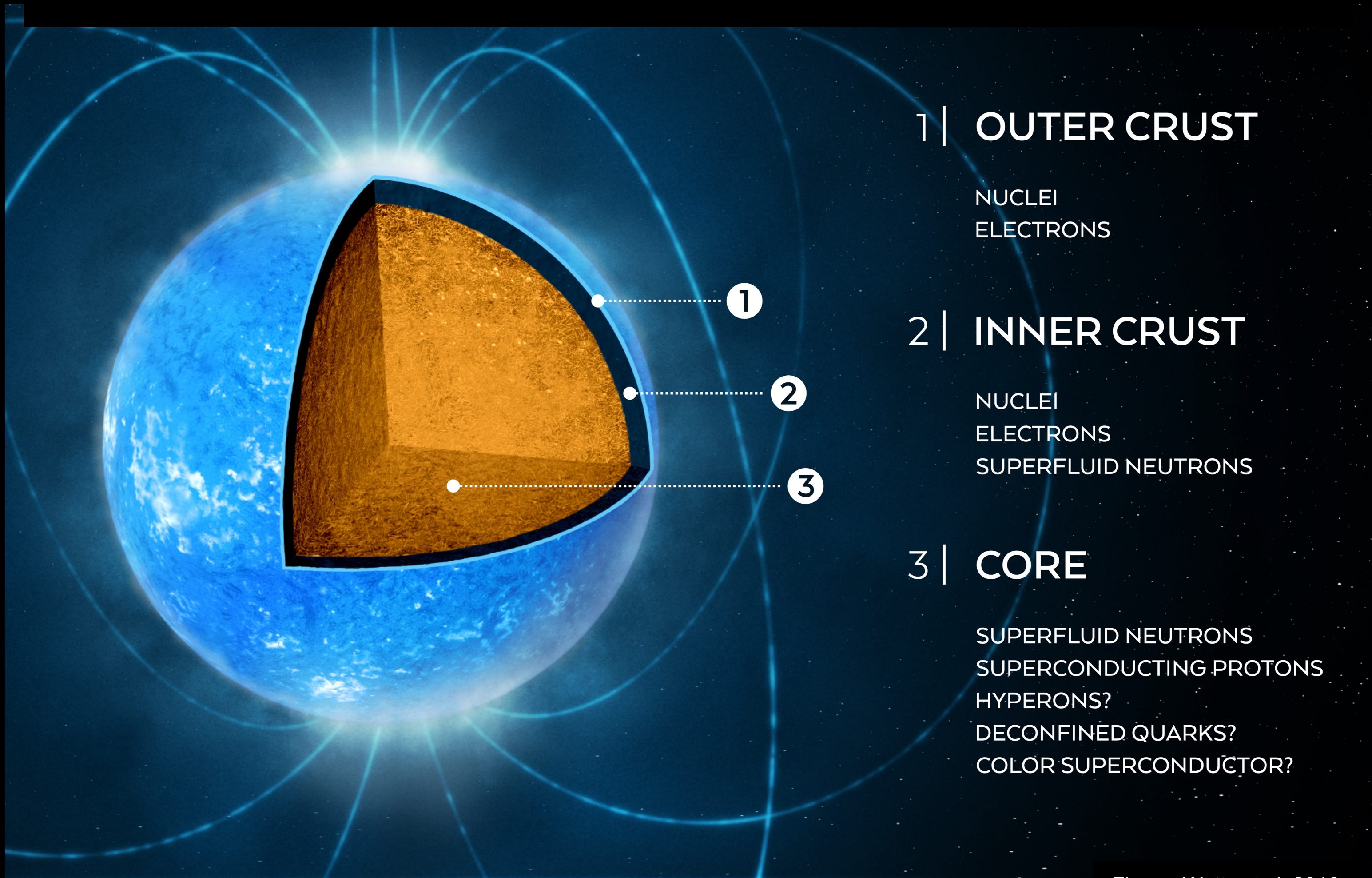


Figure: Watts et al. 2016

UNKNOWNS IN STRONG FORCE PHYSICS

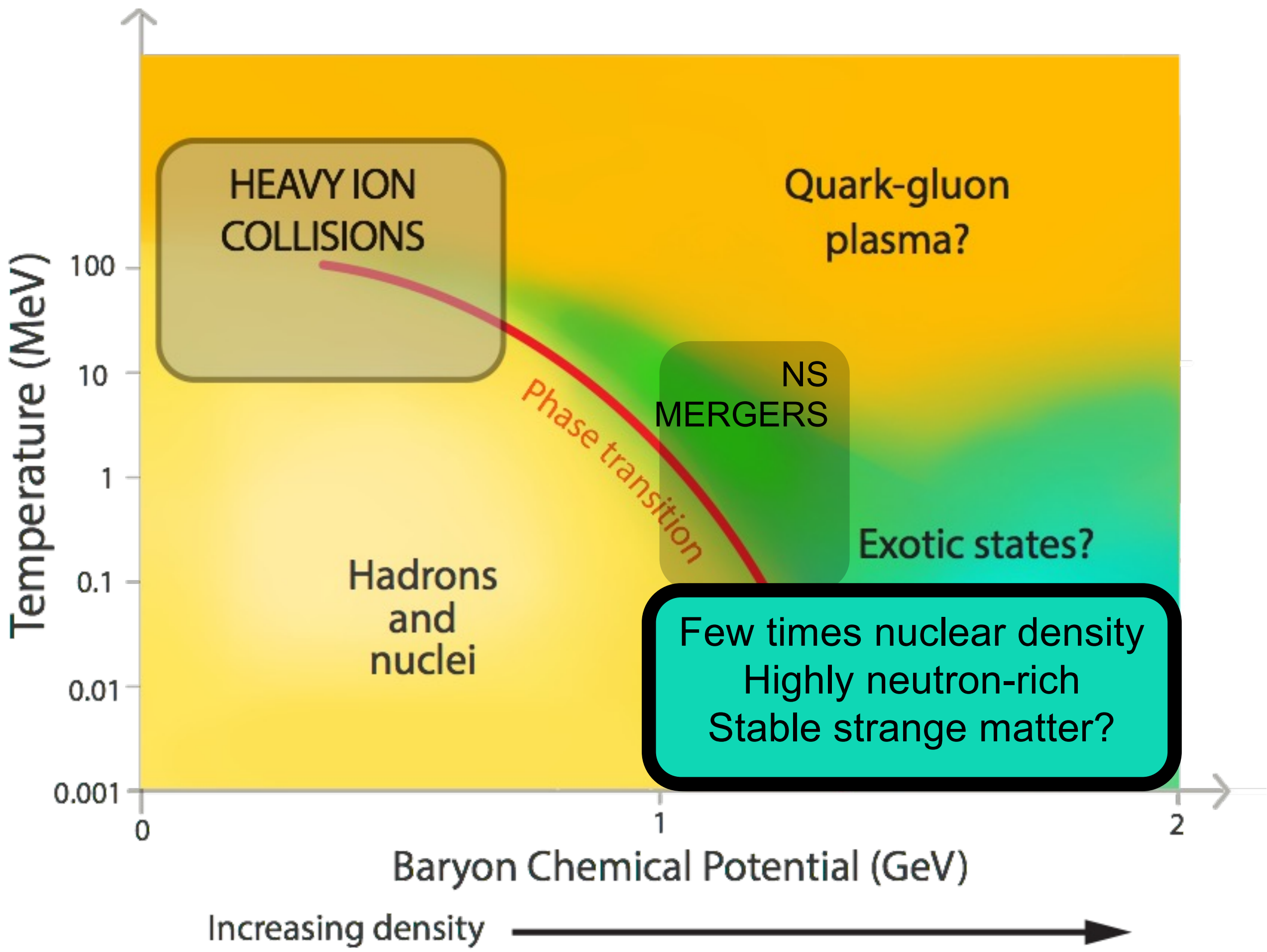


Figure: Adapted from Watts et al. 2016

FROM NUCLEAR PHYSICS TO TELESCOPE (AND BACK)

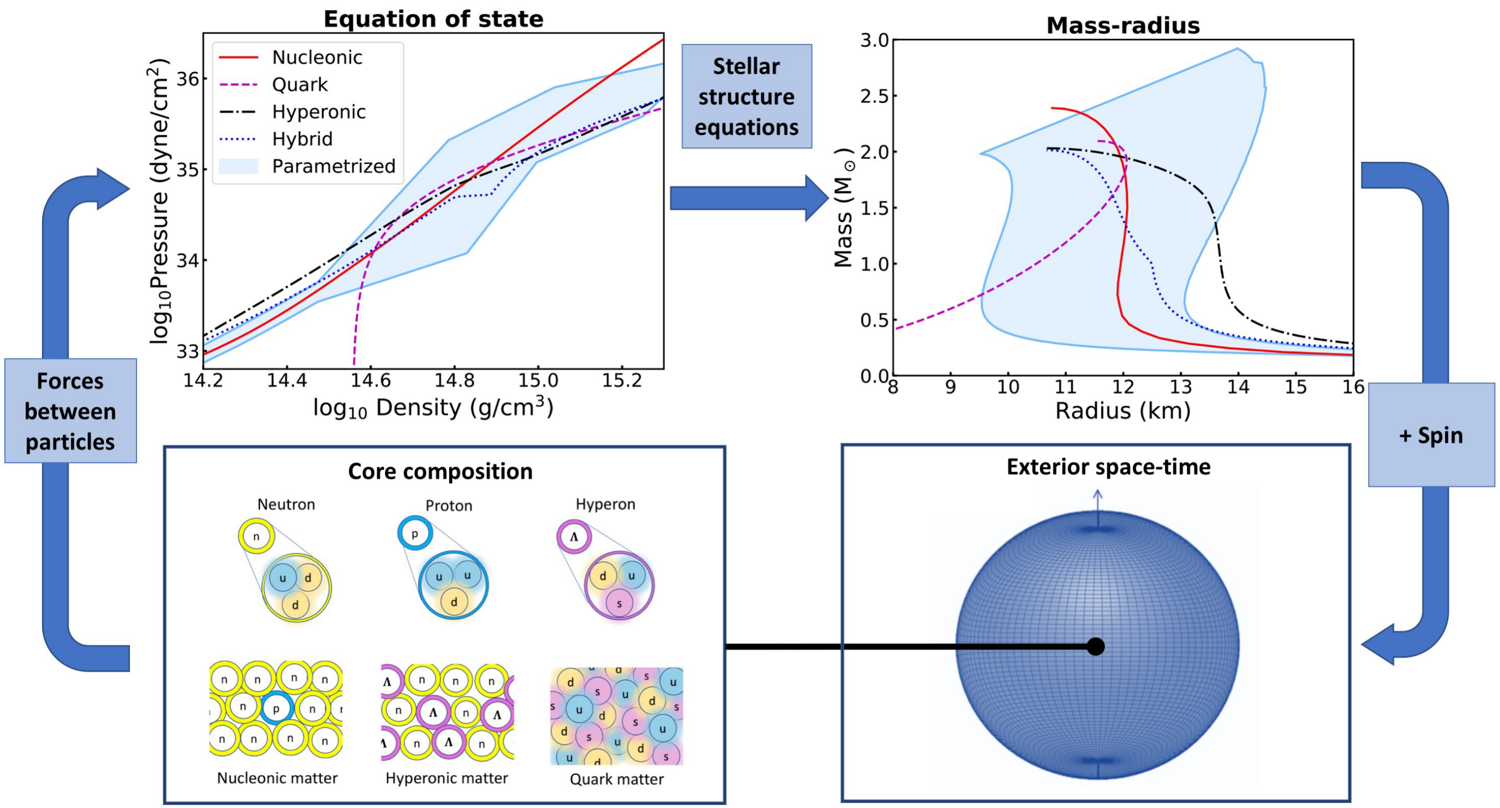
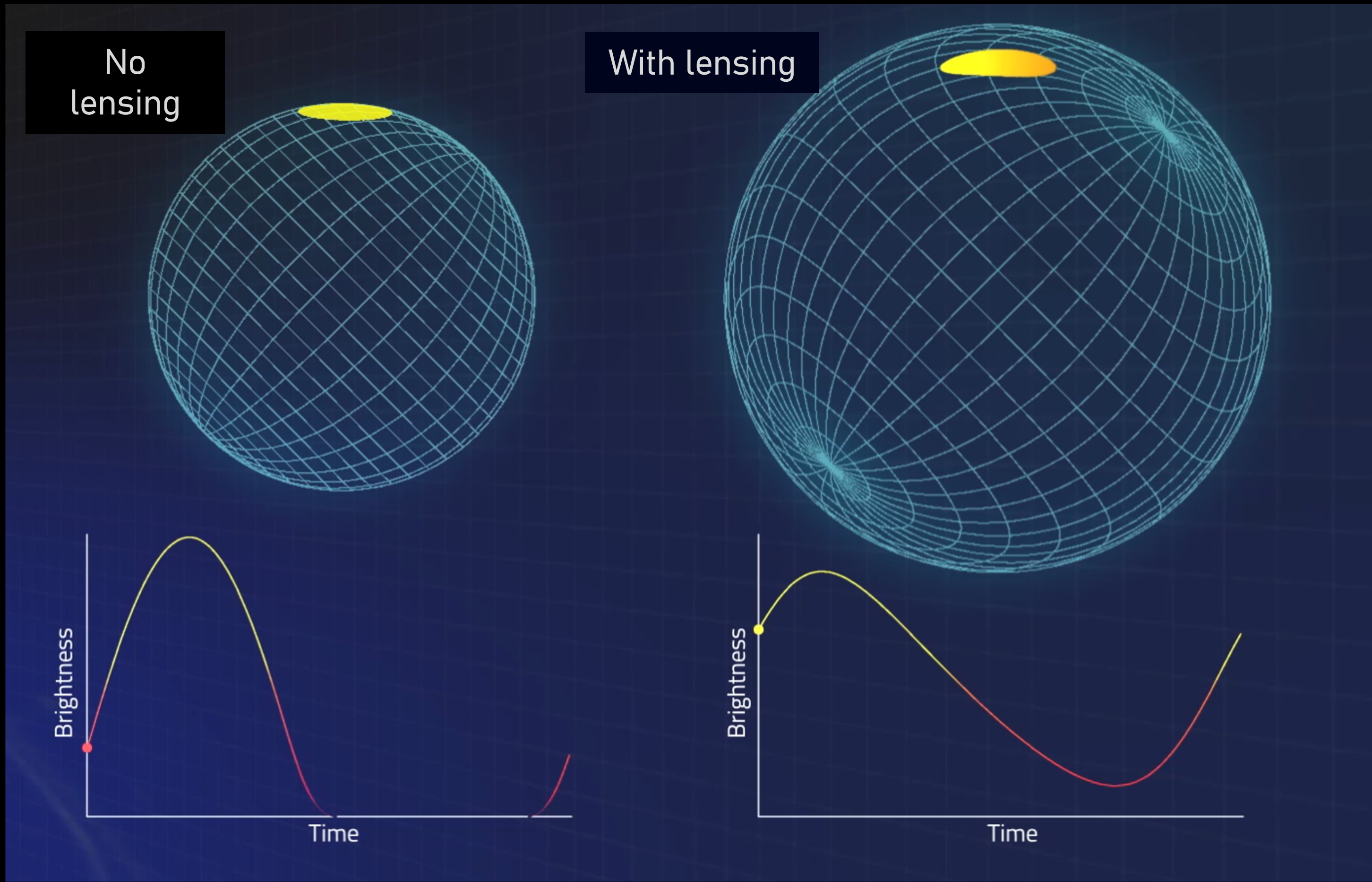


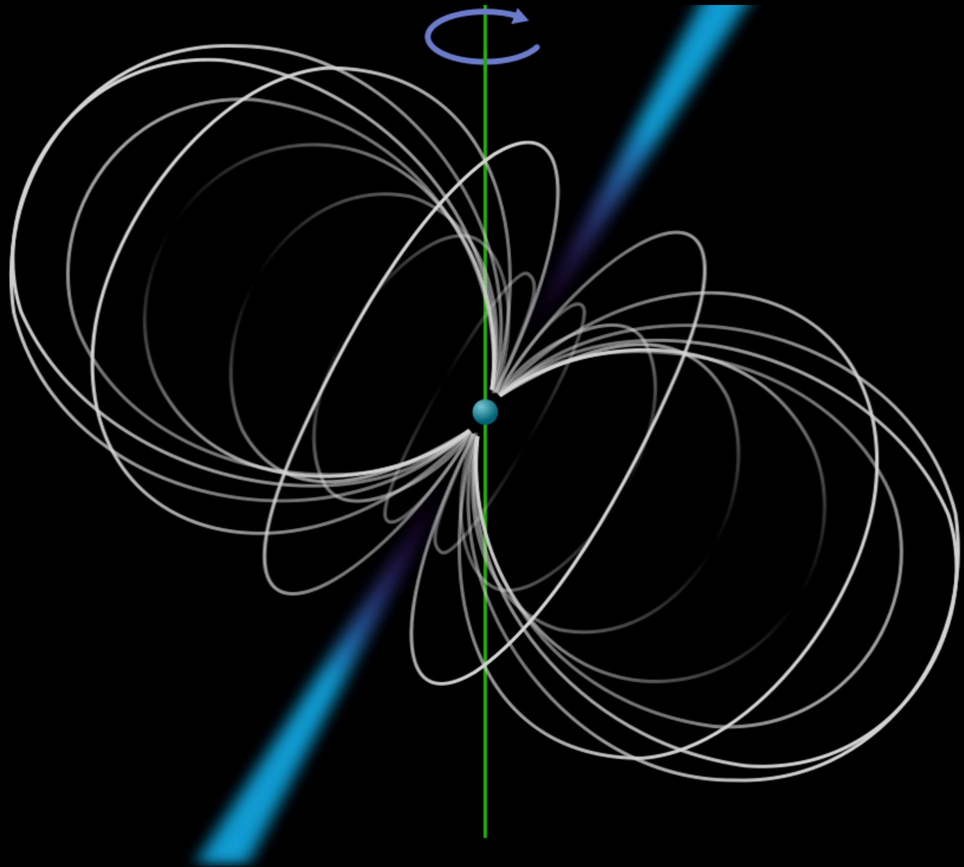
Figure: Adapted from Ray et al. 2019

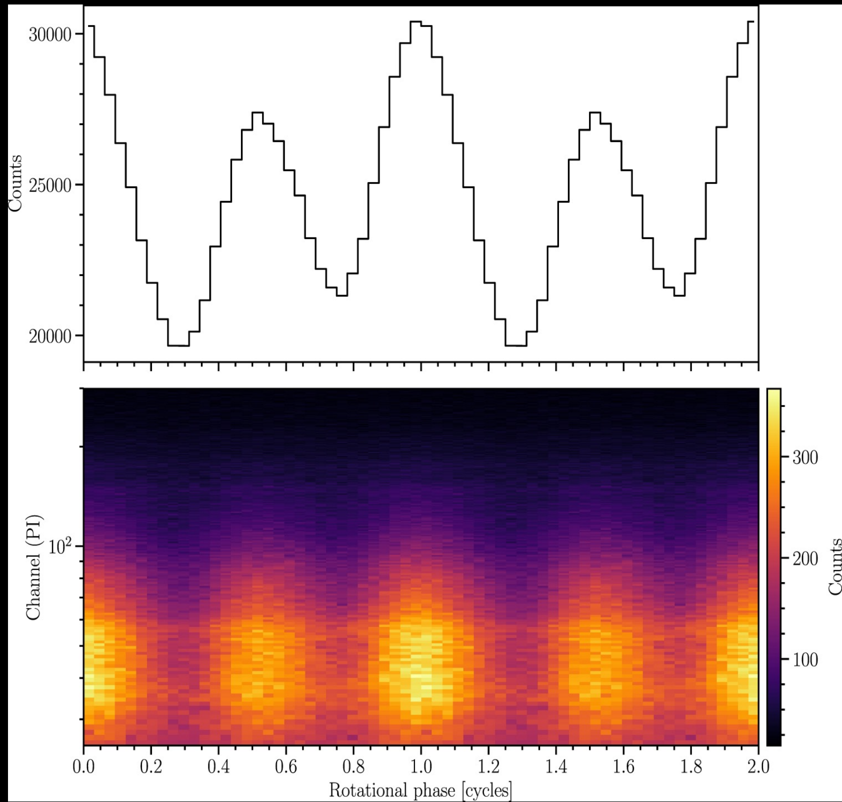
PULSE PROFILE MODELING (PPM)



Credit: Morsink/Moir/Arzoumanian/NASA-GSFC

ROTATION-POWERED MILLISECOND X-RAY PULSARS

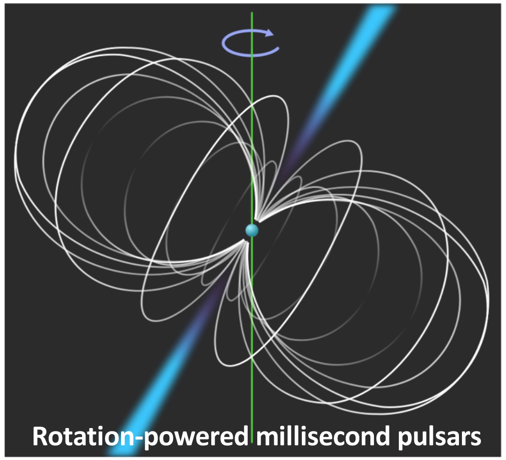




NICER – A PPM MISSION

Photo: Keith Gendreau (NASA)

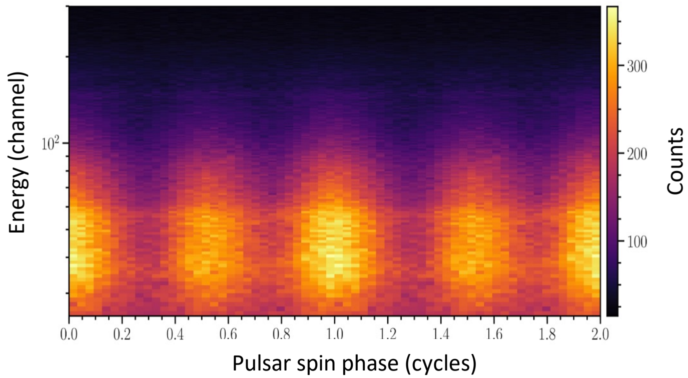
THE PULSE PROFILE MODELING TECHNIQUE



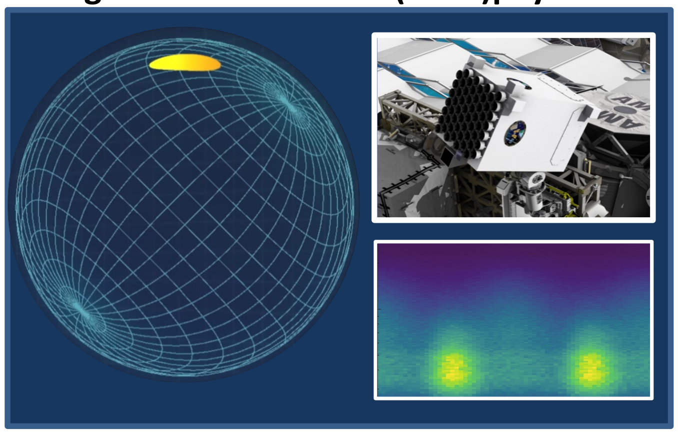
Physics and priors

- Hotspot properties (magnetic poles)
- Atmospheric beaming
- Relativistic ray-tracing in rotating NS space-time (mass, radius, spin)
- Distance and observer inclination
- Interstellar absorption
- Instrument response including calibration uncertainty
- Background
- May have priors on mass, distance, inclination from radio timing
- ‘EOS-agnostic’ priors on radius

Pulse profile data: Phase, Energy



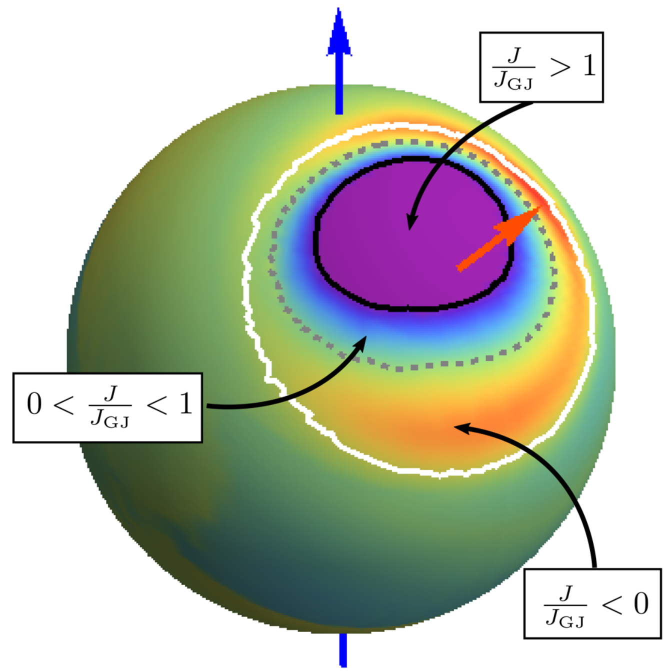
Lightcurve model: the (astro)physics



Bayesian inference of model parameters (statistical sampling)

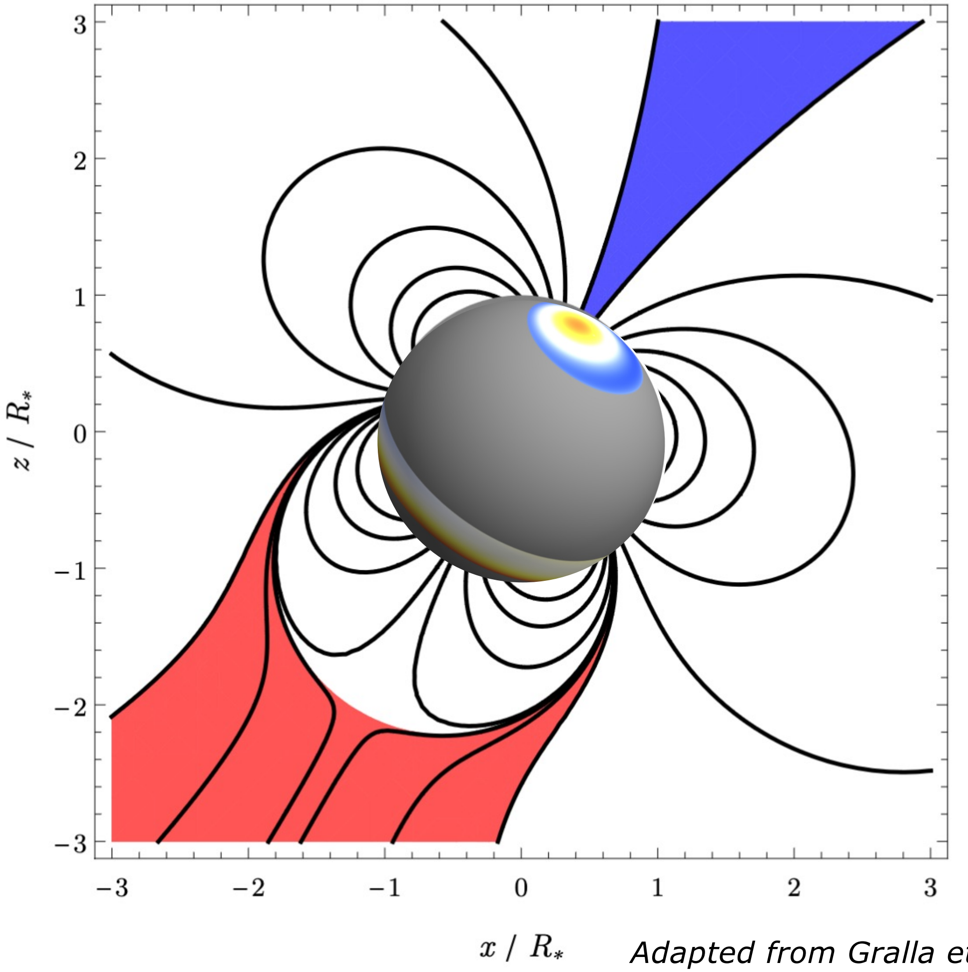
Mass and radius ⇒ dense matter
Hotspot properties ⇒ magnetic pole/field geometry

PULSAR SURFACE EMISSION PATTERNS



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

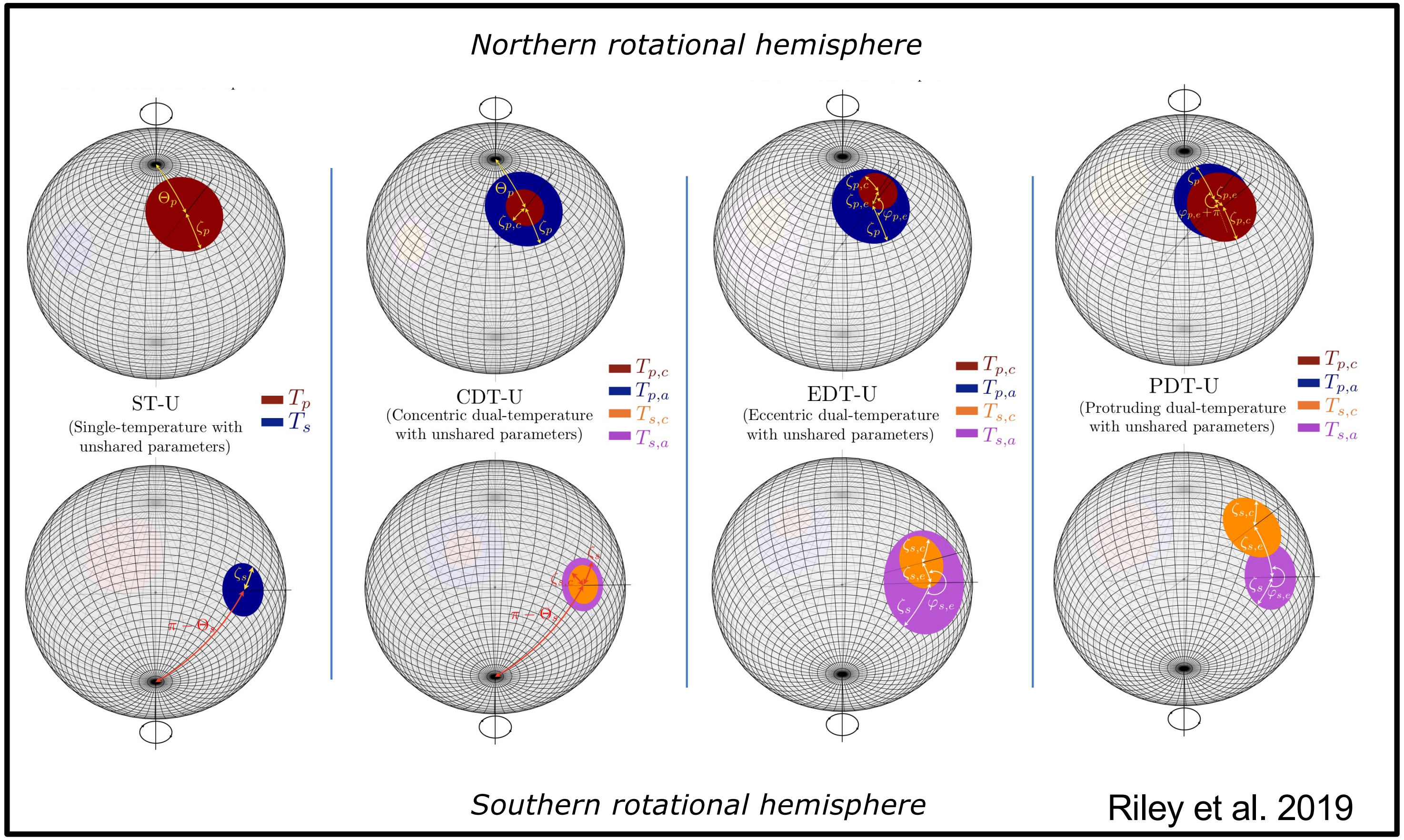
(Figure courtesy of Kostas Kalapotharakos, see also Harding & Muslimov 2011)



Adapted from Gralla et al. 2017

POLAR CAP MODELS

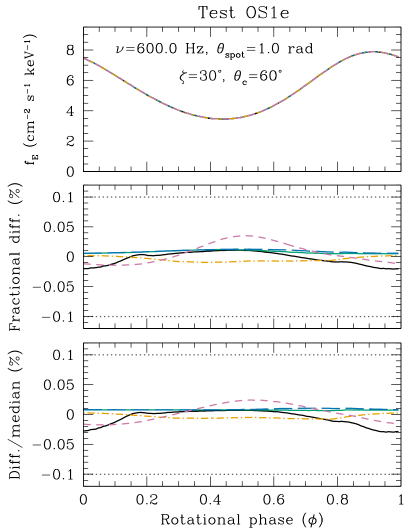
- We use 2-cap models of increasing surface pattern complexity.

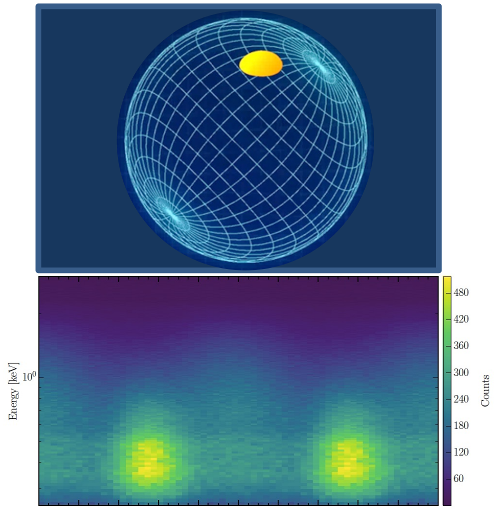


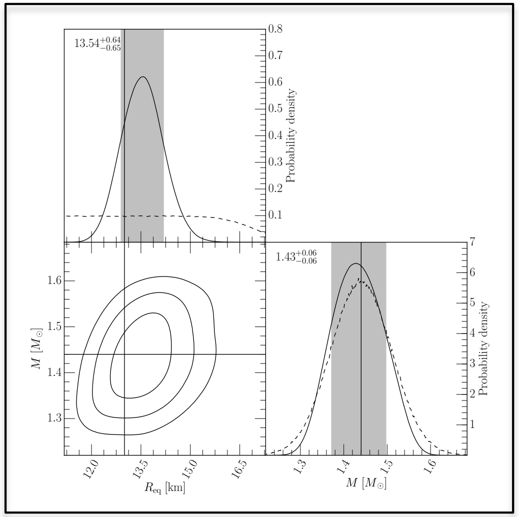
TESTING OUR PIPELINES

X-PSI

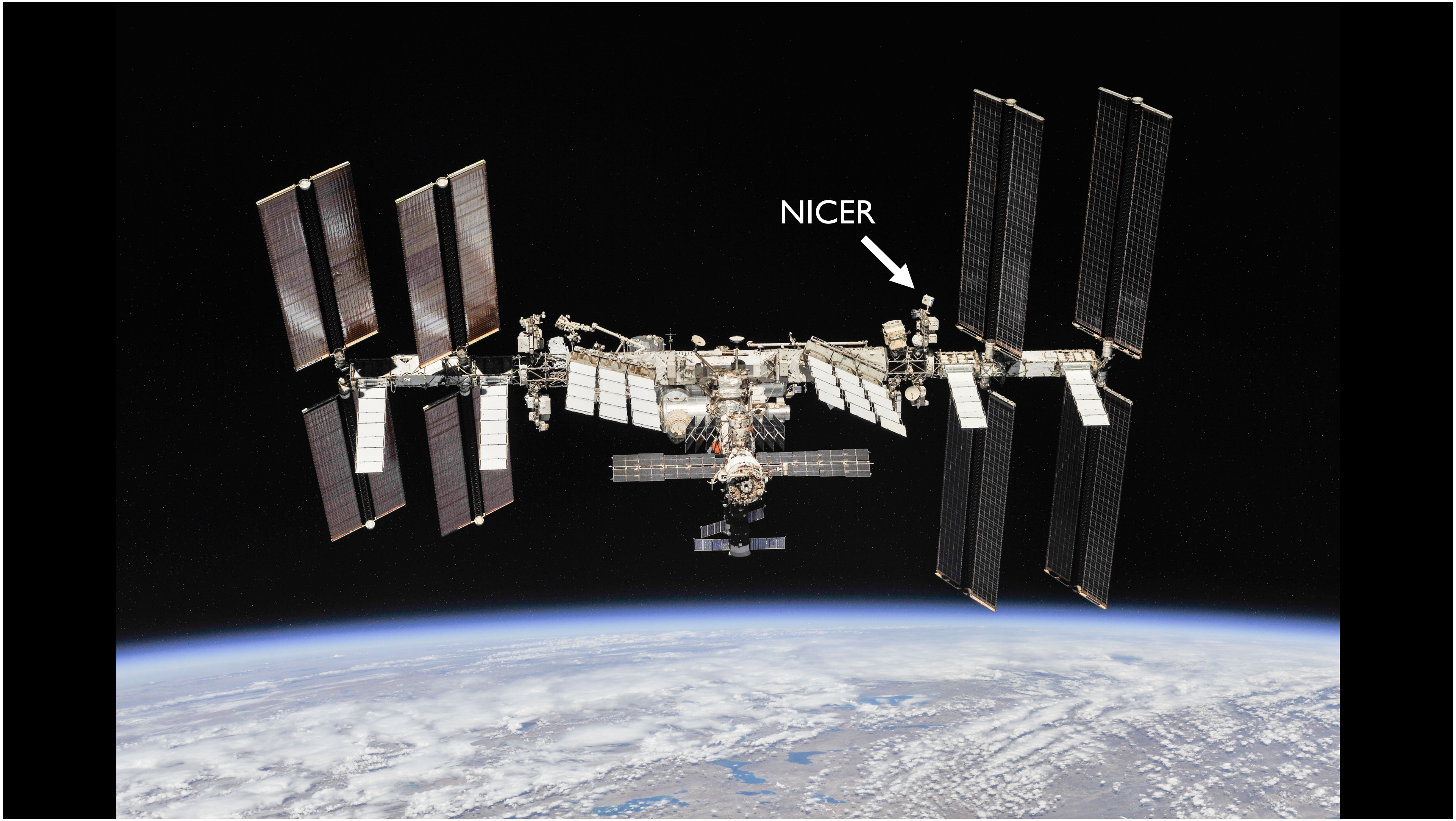
X-ray Pulse Simulation
and Inference package
https://xpsi-group.github.io/xpsi/
Riley et al. 2023 (JOSS paper)
Uses open source samplers
(MultiNest, now also Ultranest).







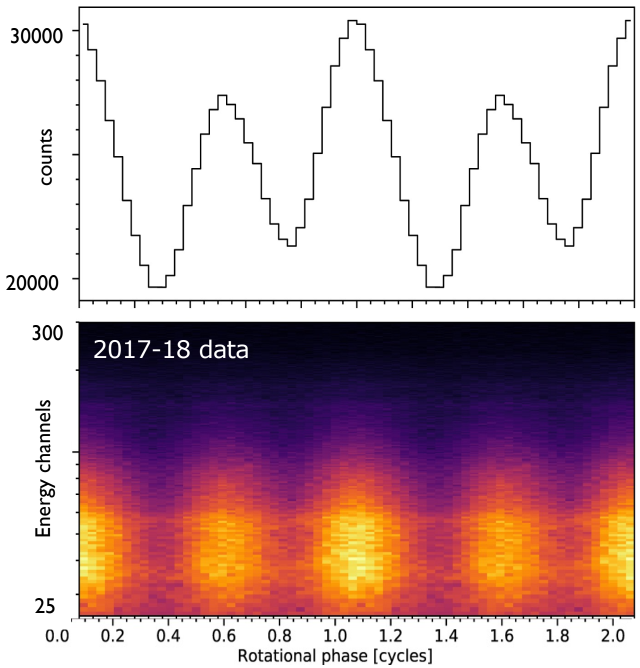
Ray-tracing and inference routines using synthetic data
(Bogdanov et al. 2019b, 2021, Choudhury et al. 2024b)


NICER

PULSE PROFILE DATA SETS

PSR J0030+0451

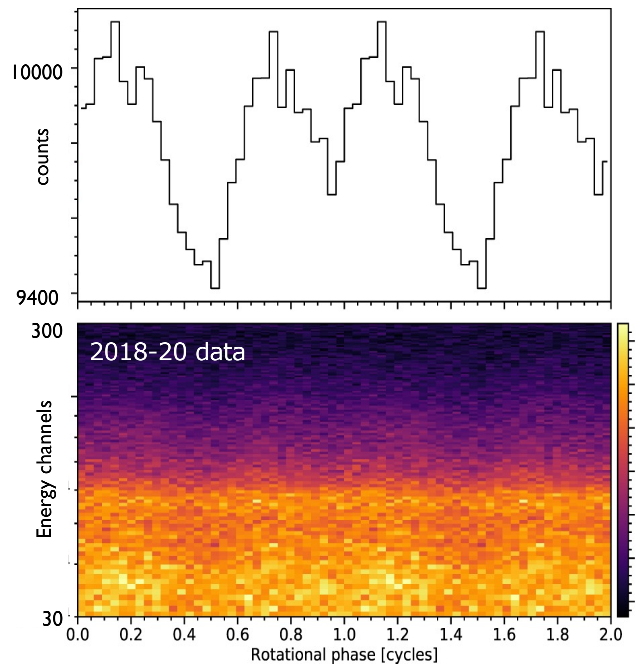
- Bright source
- Isolated system



Riley et al. 2019, *Miller et al. 2019*
Salmi et al. 2023, Vinciguerra et al. 2023, 2024,
Kini et al. 2026

PSR J0740+6620

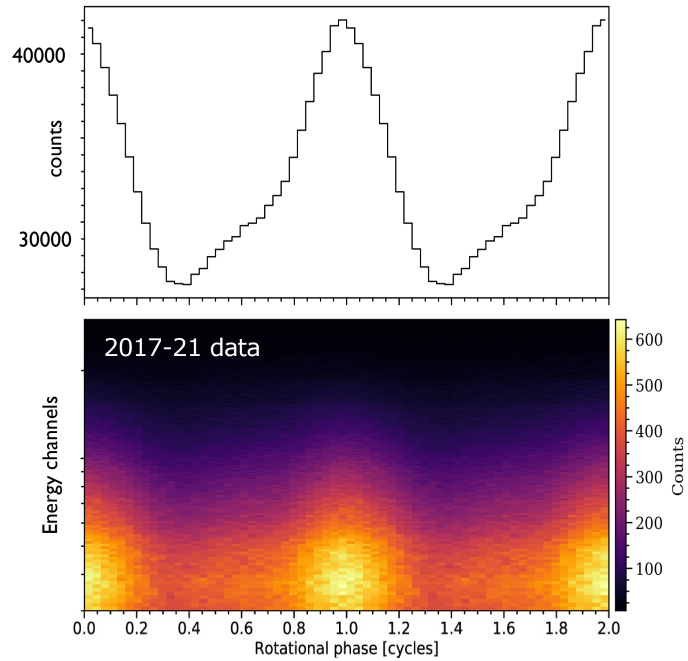
- Faint source
- Binary - mass $2.1 M_{\odot}$



Riley et al. 2021, *Miller et al. 2021*
Salmi et al. 2022, 2023, 2024a,
Dittmann et al. 2024, Hoogkamer et al. 2025

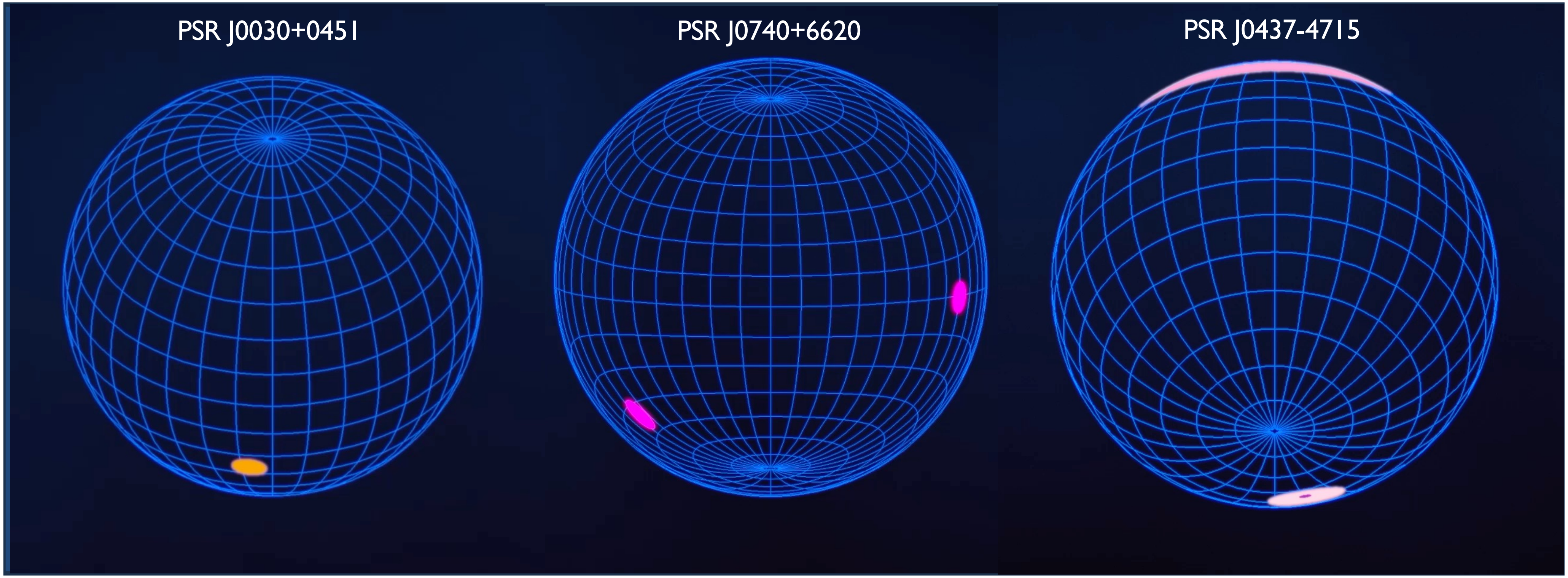
PSR J0437–4715

- Closest and brightest source
- Binary: mass $1.4 M_{\odot}$



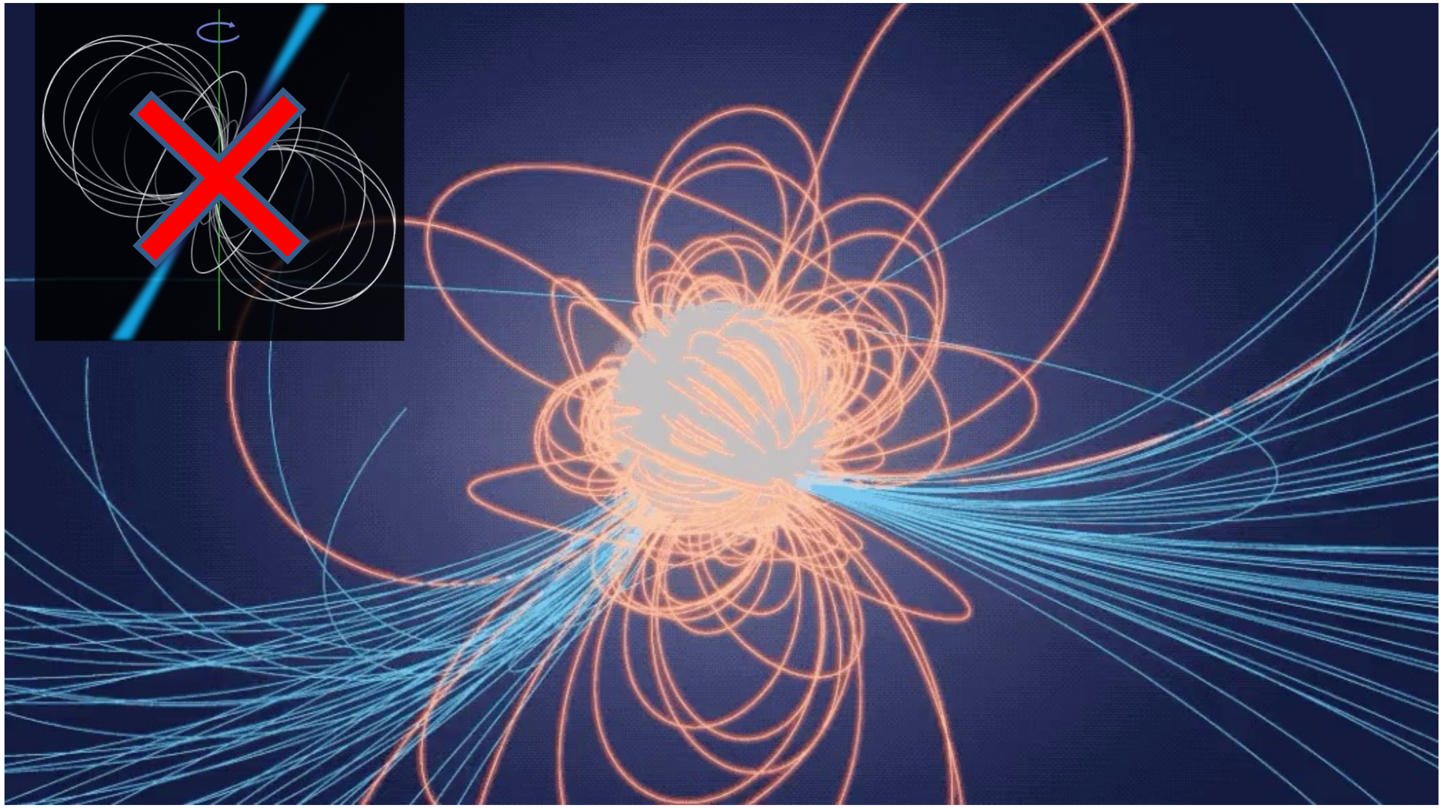
Choudhury et al. 2024, *Miller et al. 2026*

MAPPING THE HOT MAGNETIC POLES



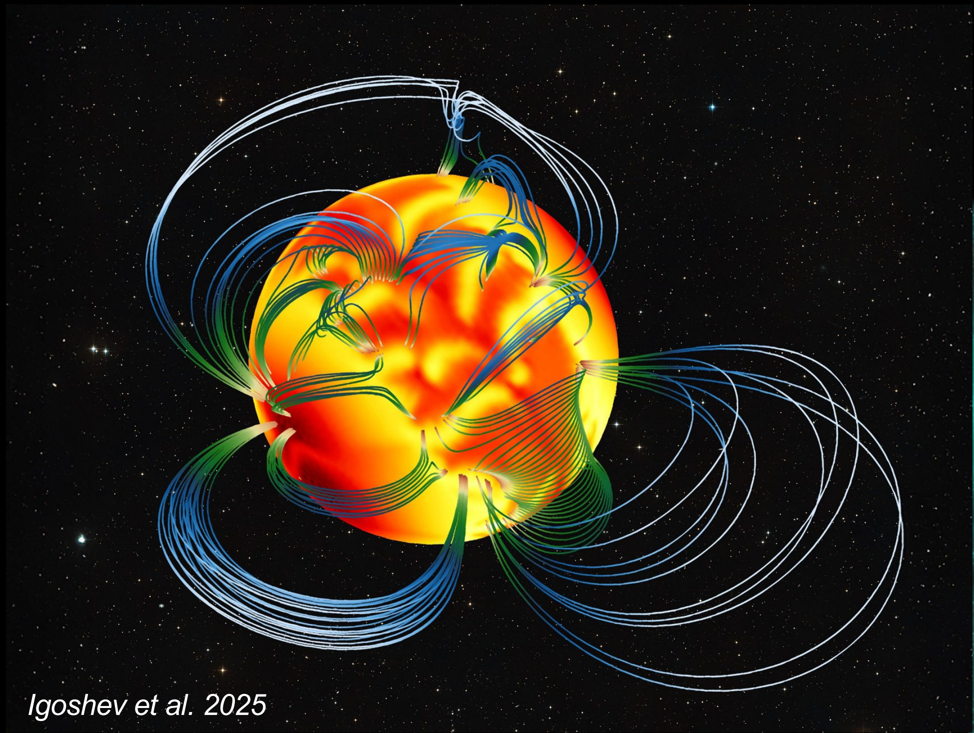
As seen from Earth
Results from the X-PSI pipeline (https://github.com/xpsi-group/xpsi, also Riley et al. 2023 JOSS)
Maps from Riley et al. 2019, Riley et al. 2021, Choudhury et al. 2024 + Morsink/NASA

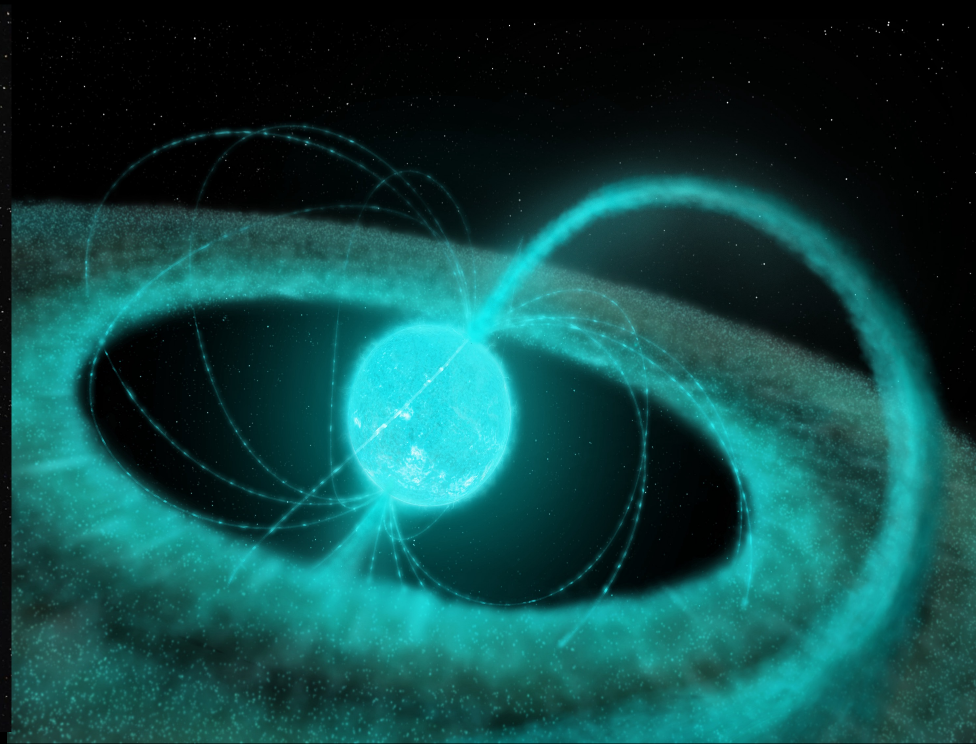
NON-DIPOLAR MAGNETIC FIELD?



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

HOW DID SUCH FIELDS FORM?

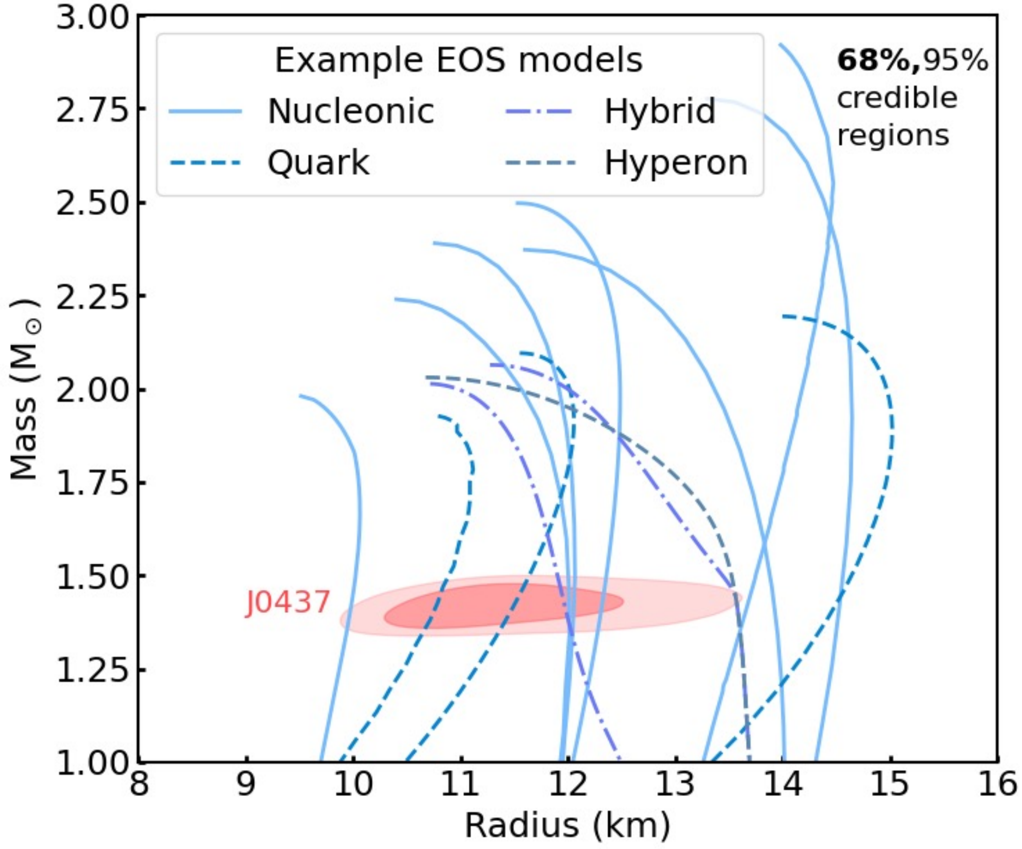




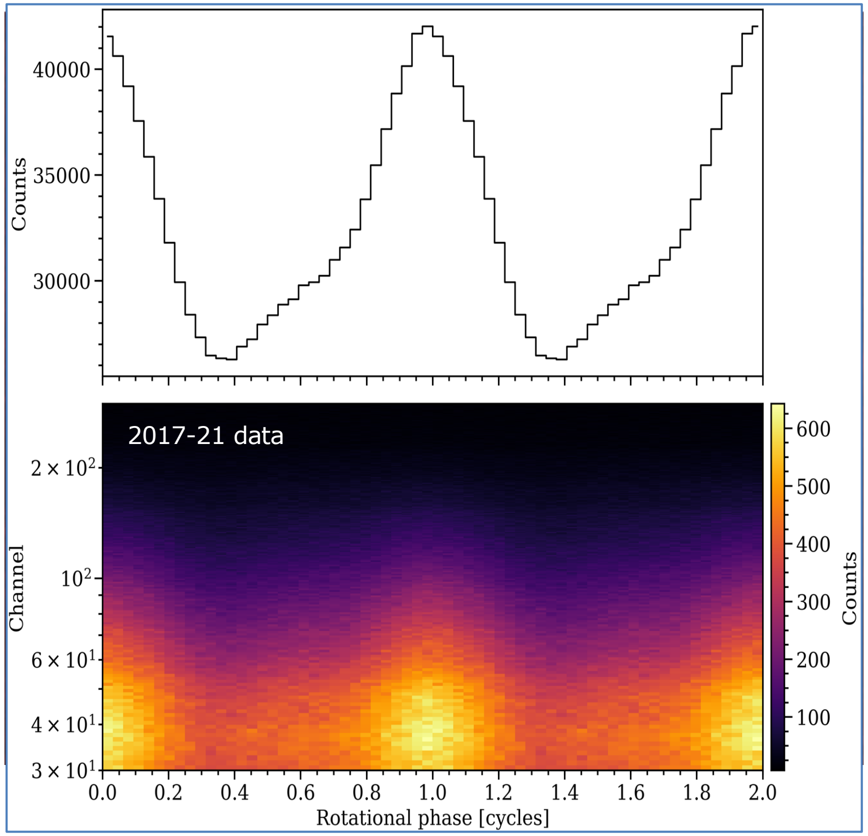
Early in life, perhaps during supernova?

During accretion phase that recycled these pulsars to millisecond periods?

PSR J0437-4715: A BRIGHT 1.4 $M_\odot$ PULSAR

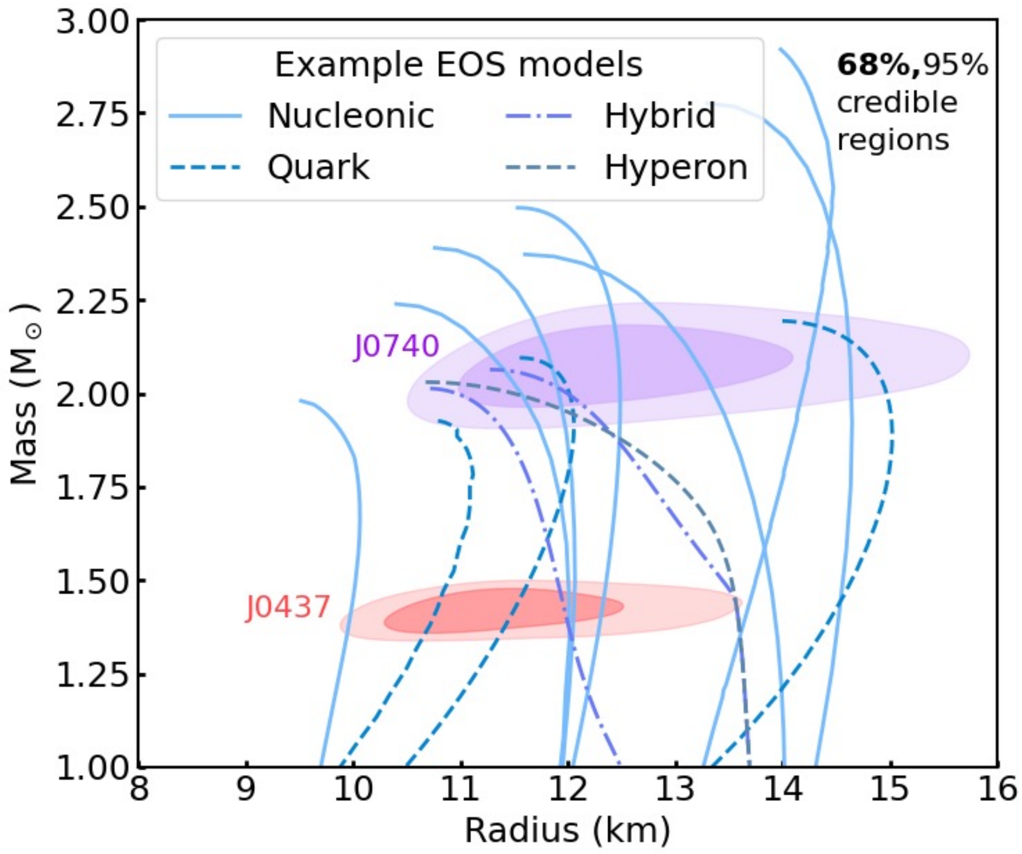


Choudhury et al. 2024, Mass prior from Reardon et al. 2024



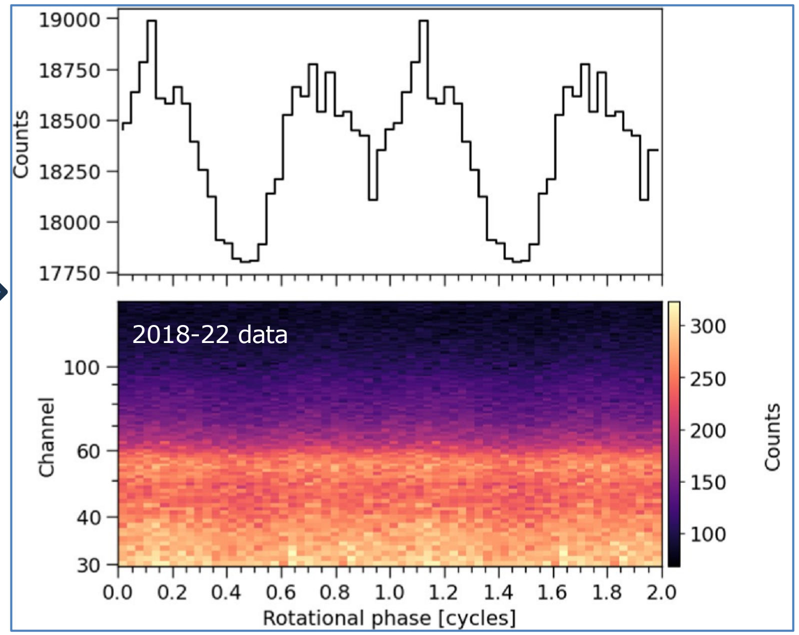
Bogdanov et al. 2019

PSR J0740+6620: A FAINT 2.1 $M_\odot$ PULSAR

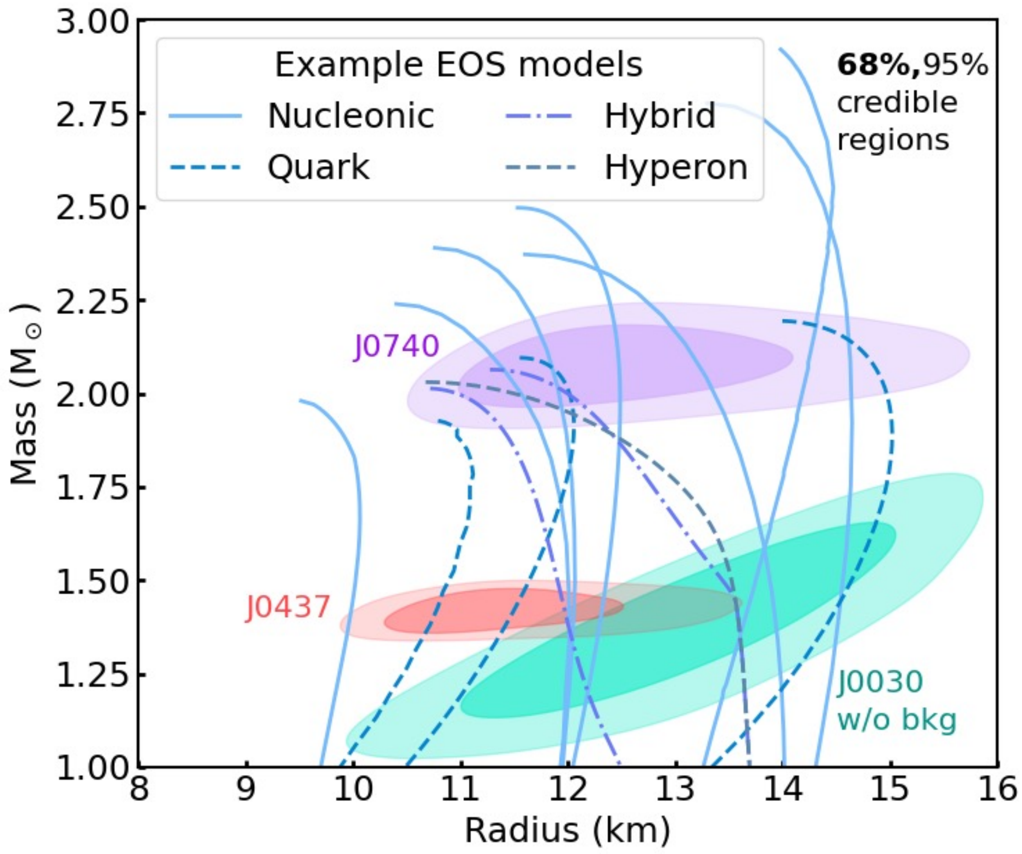


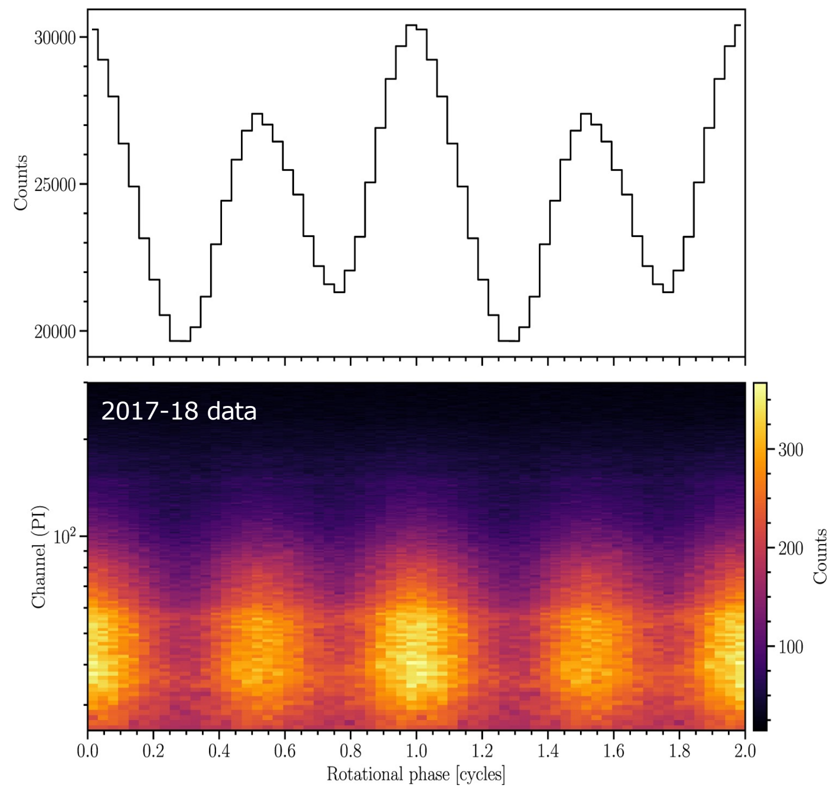
Salmi et al. 2024a, Mass prior from Fonseca et al. 2021

"Unpulsed" component:
- Astrophysical background
- Particle background (high for NICER)
- Spots not vanishing from view - geometry or strong lightbending



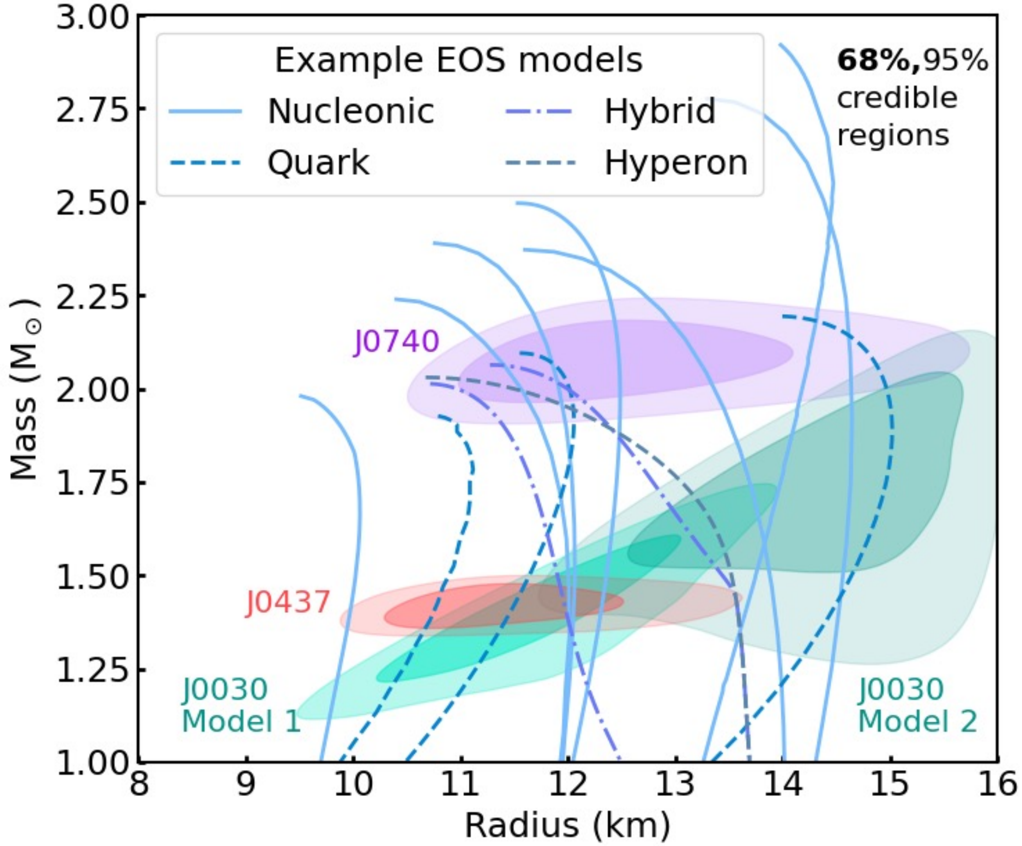
PSR J0030+0451: AN ISOLATED PULSAR

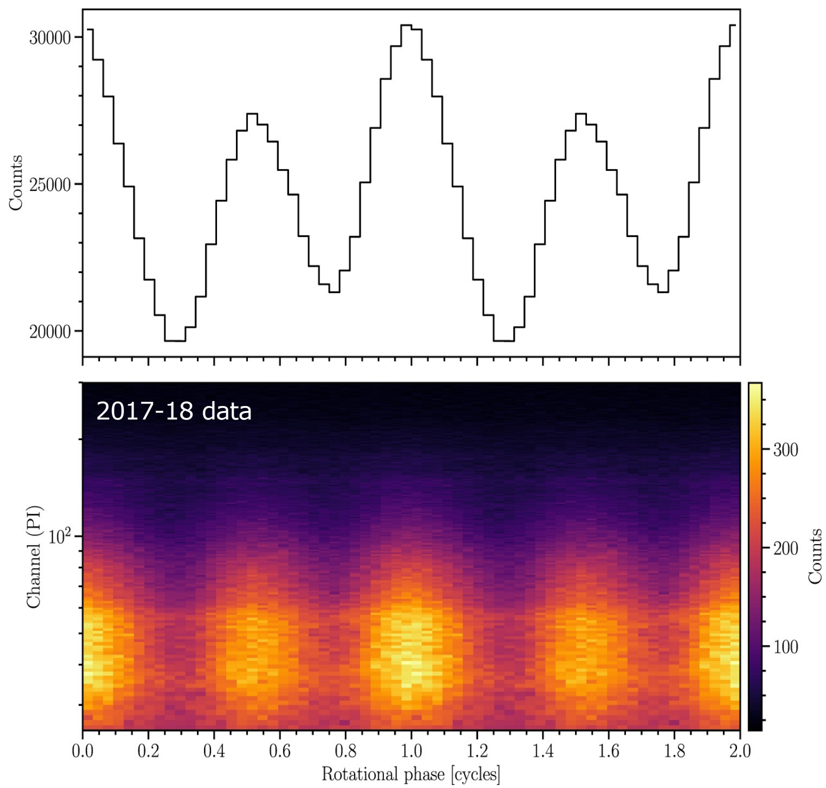




Riley et al. 2019

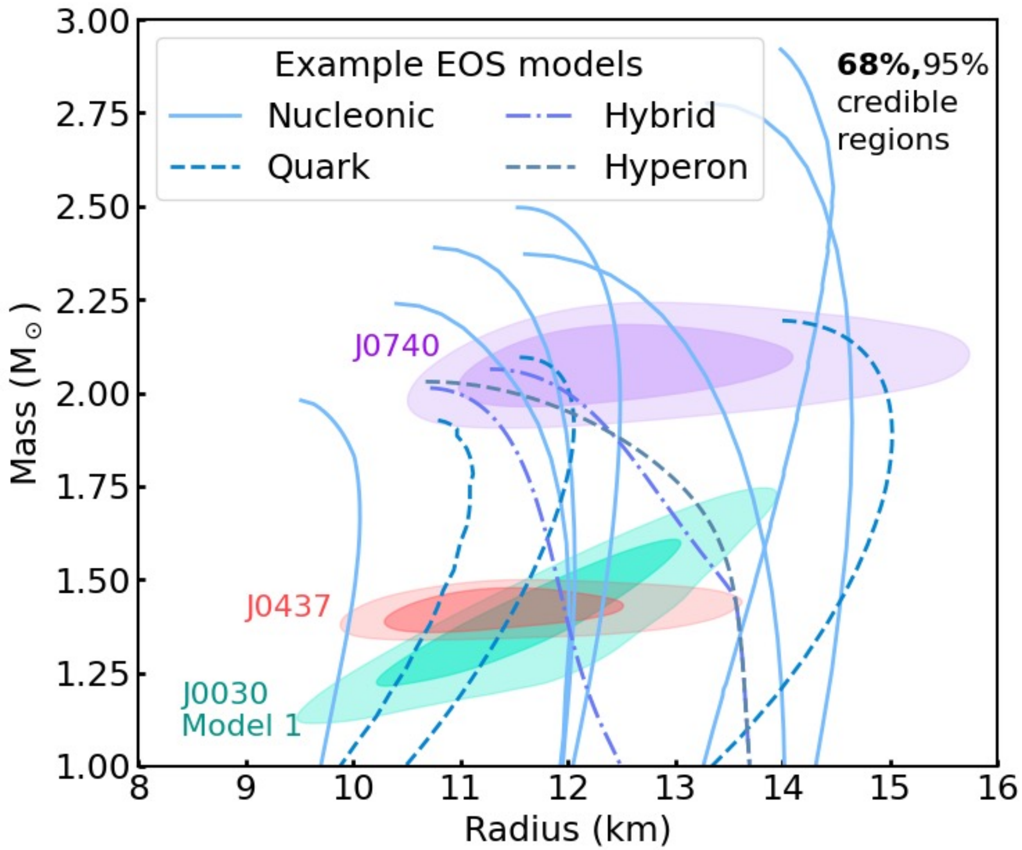
PSR J0030+0451: AN ISOLATED PULSAR

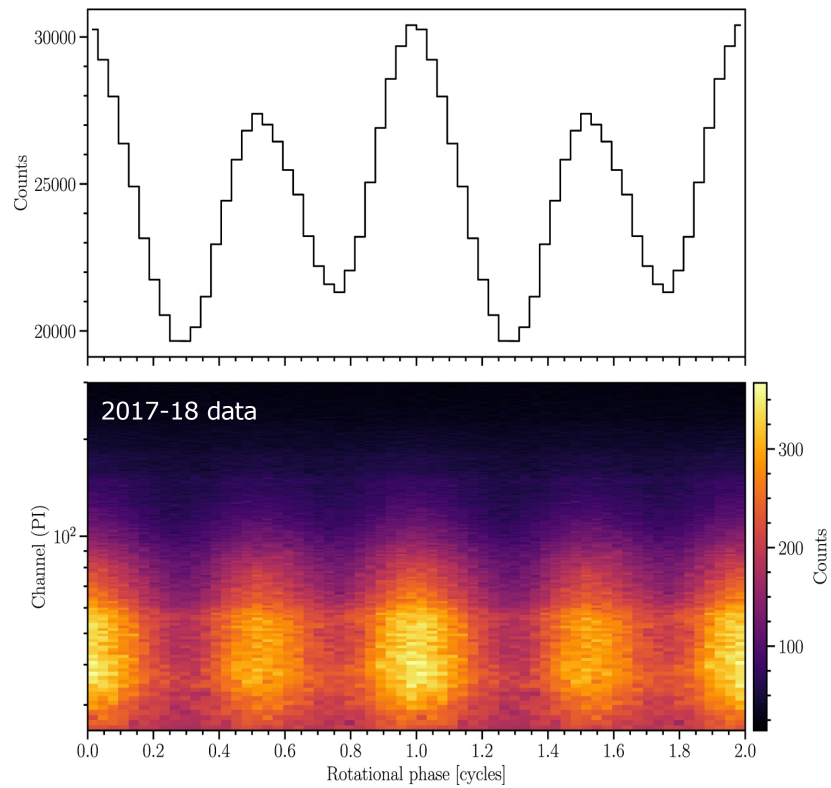




Vinciguerra et al. 2024: Include background constraints - different hotspot geometries possible.

PSR J0030+0451: AN ISOLATED PULSAR





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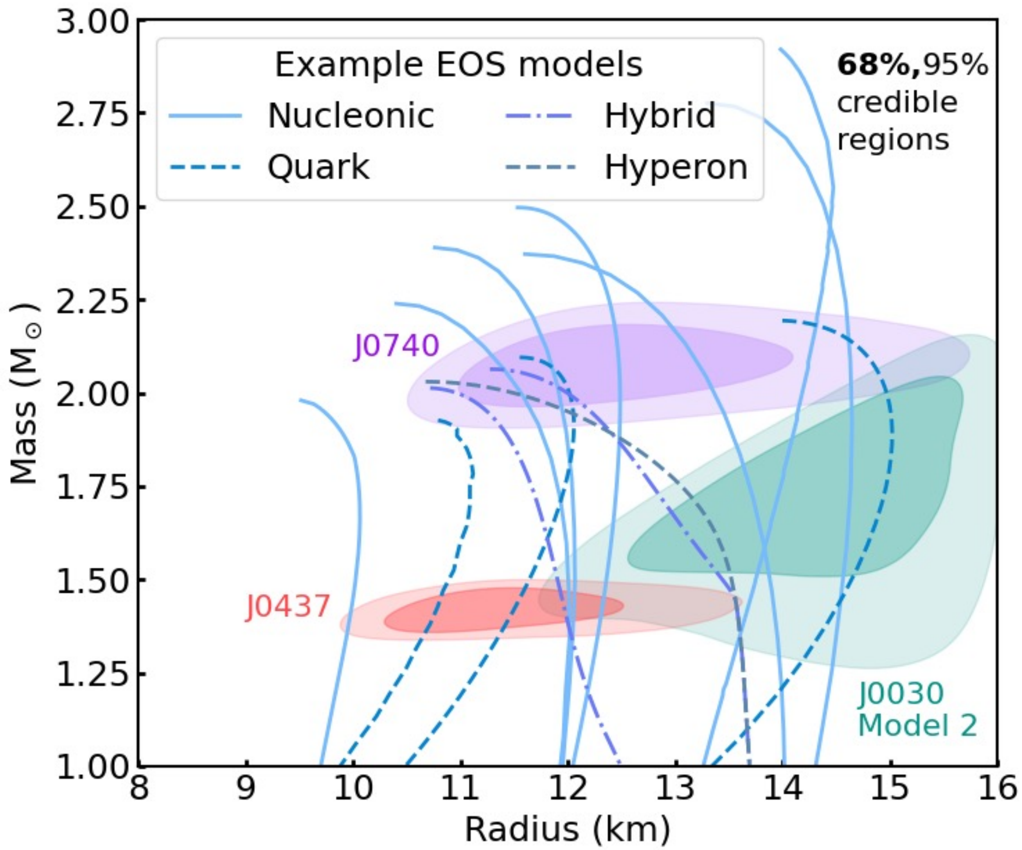
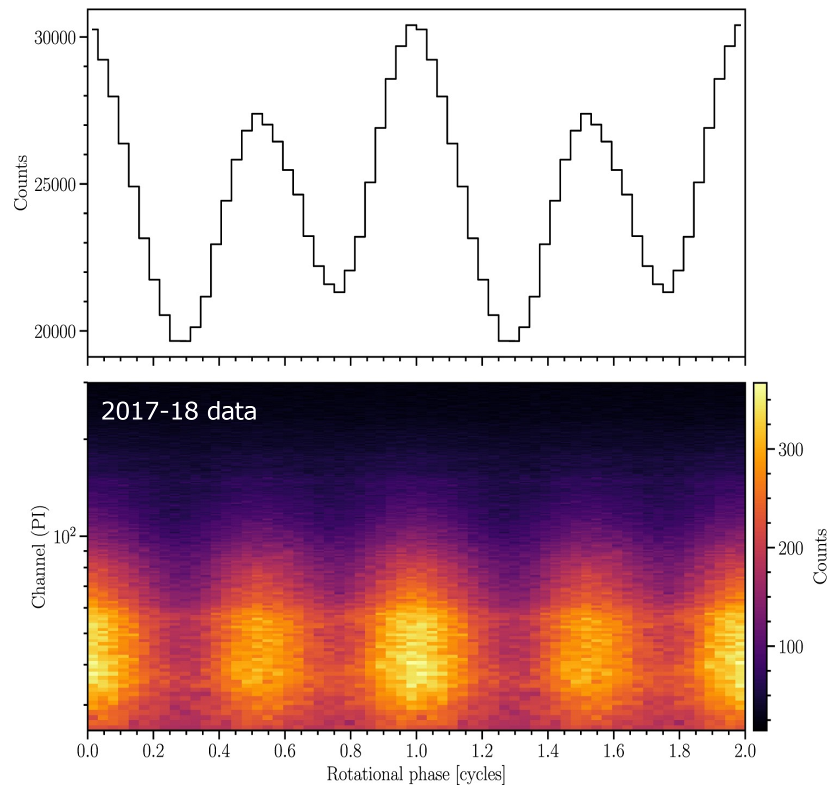
PSR J0030+0451: AN ISOLATED PULSAR





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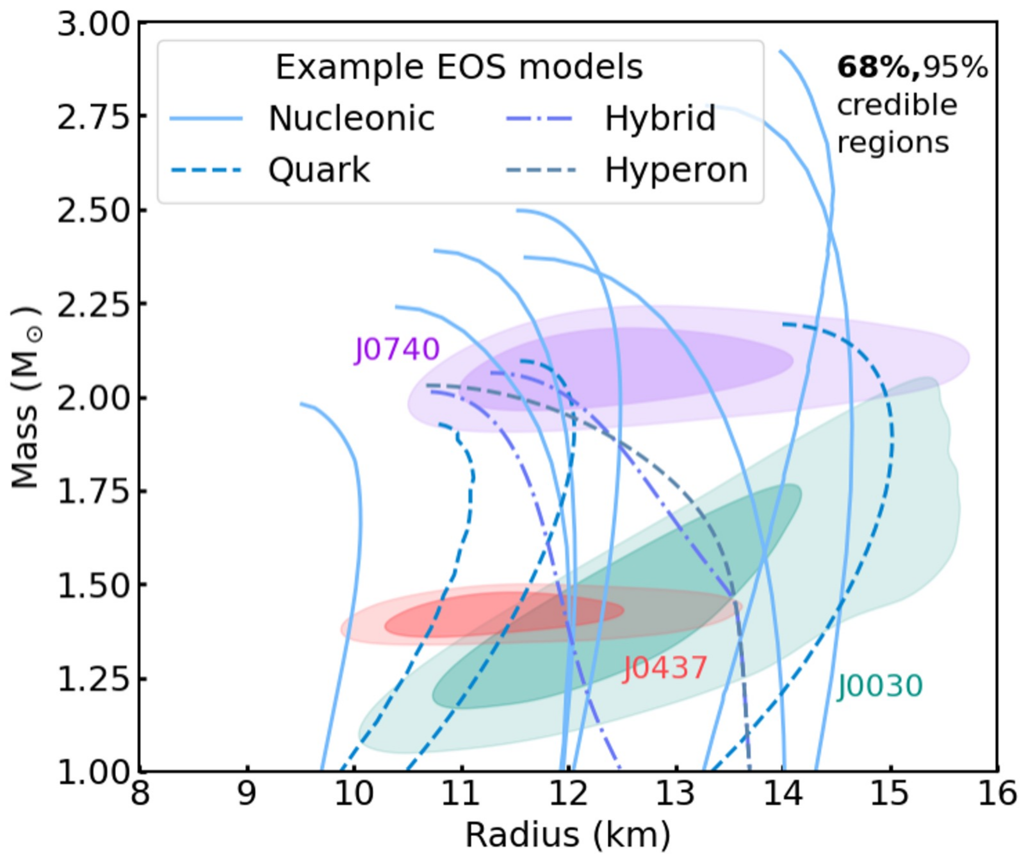
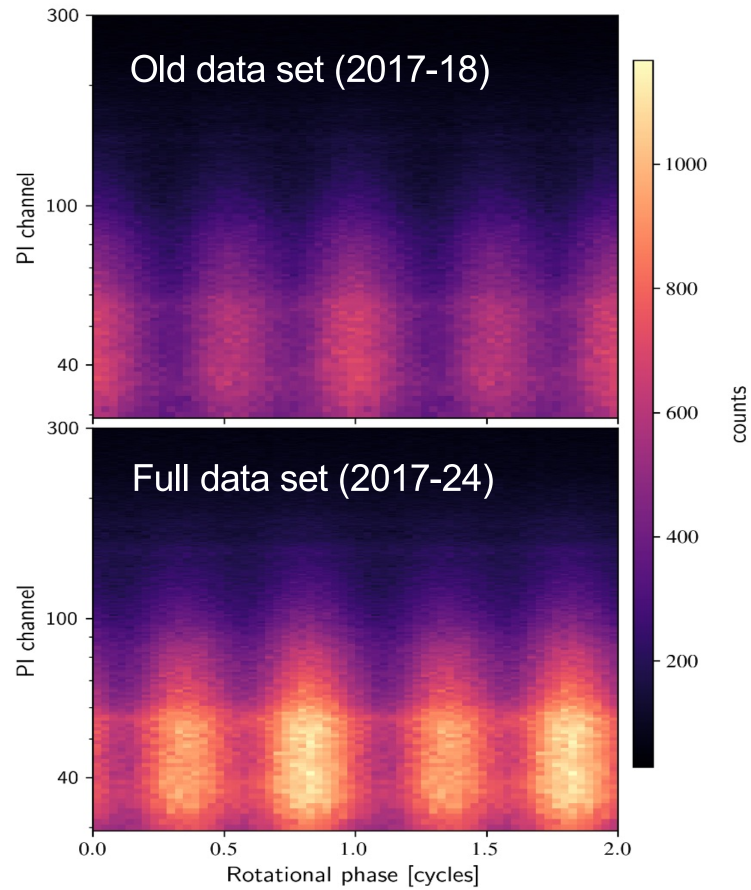
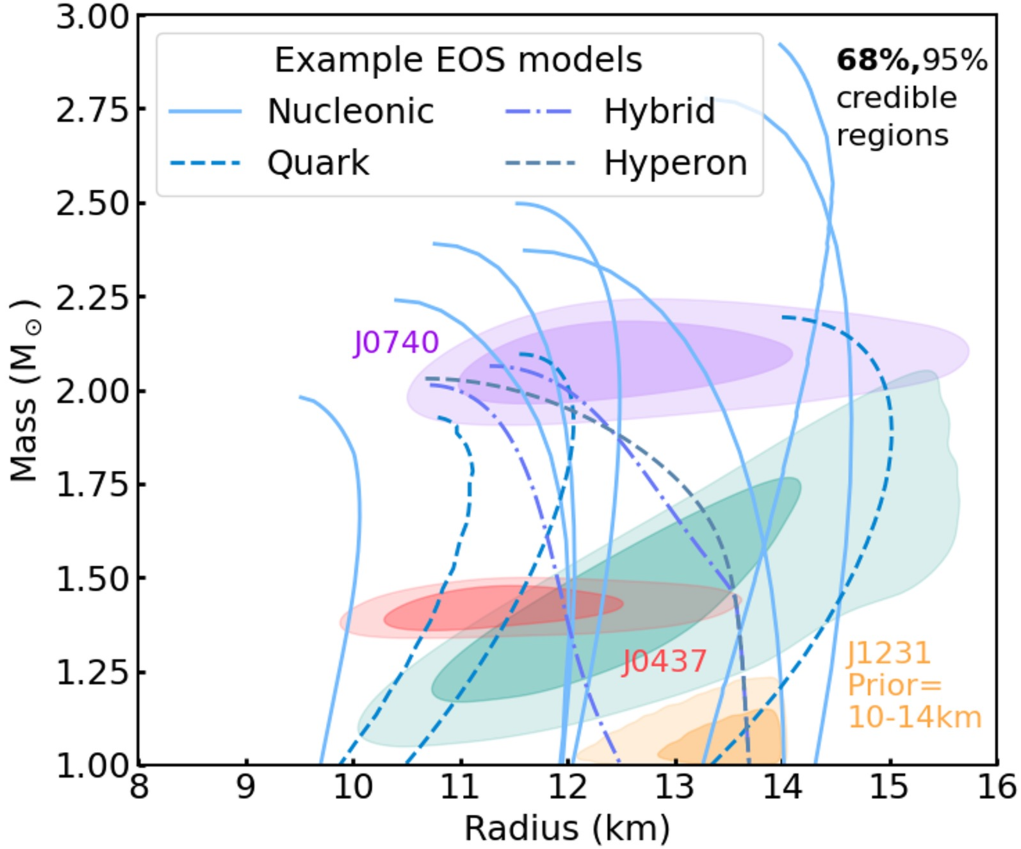


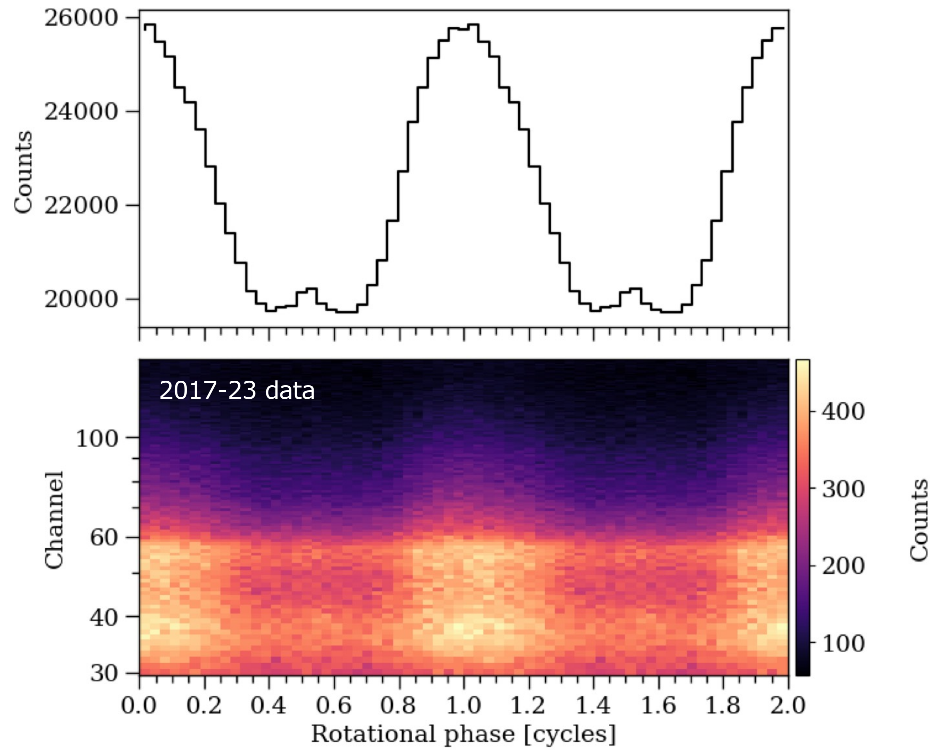
Kini et al. 2026



PSR J1231-1411: AN UNCOOPERATIVE PULSAR

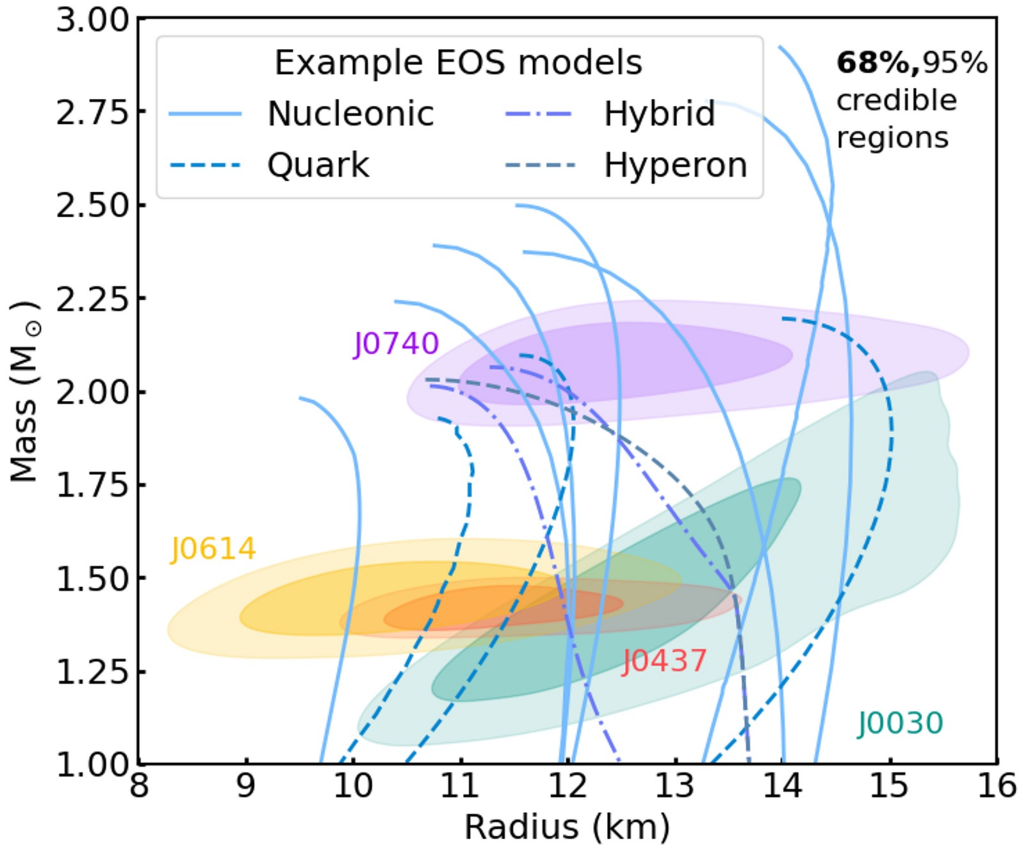


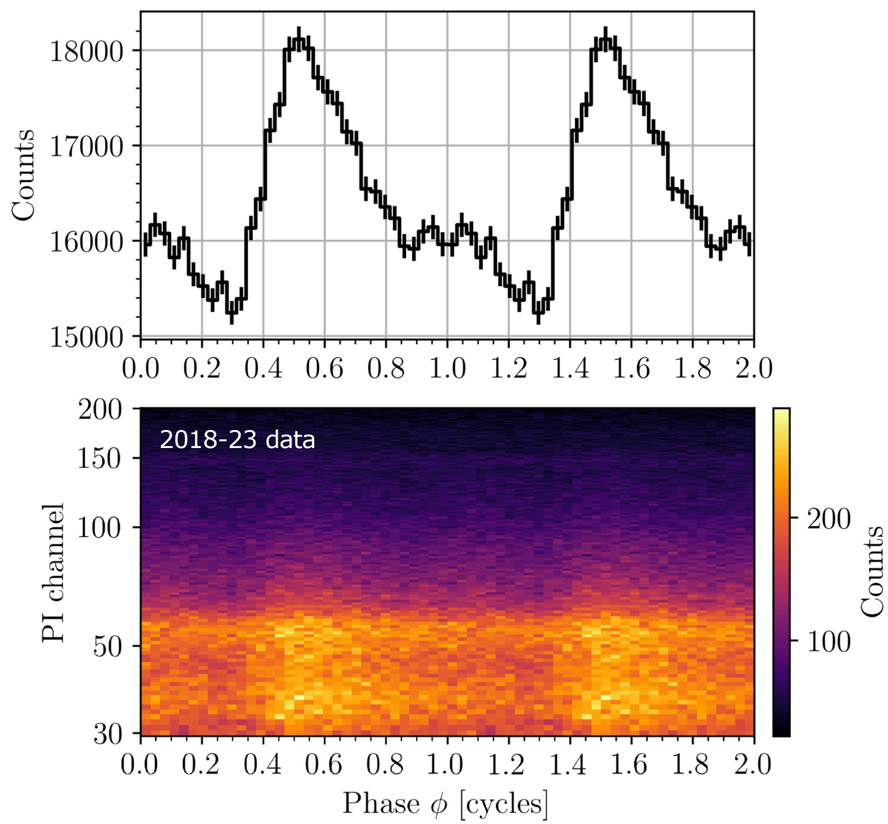
Salmi et al. 2024b, Mass prior from Cromartie et al. 2026



Why so weird? Unusual geometric modes (Rowan van den Brink student project).

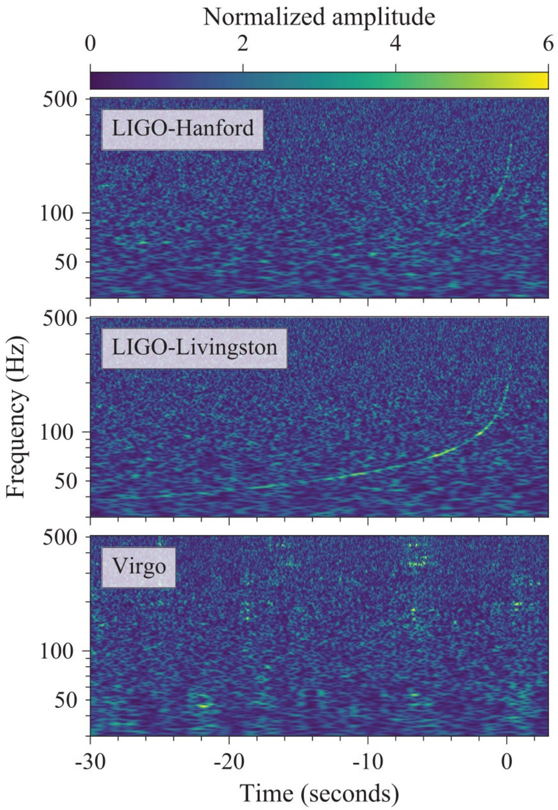
PSR J0614-3329: ANOTHER 1.4 $M_\odot$ PULSAR



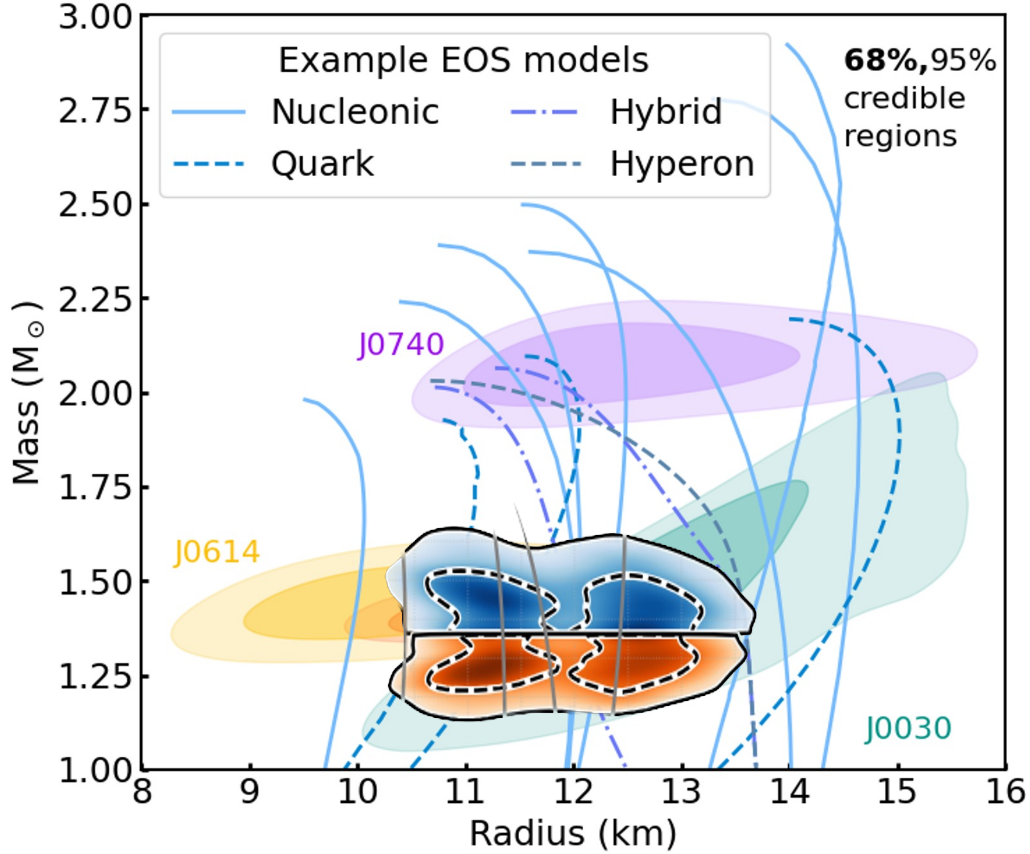


Mauviard et al. 2025

CONSISTENCY WITH GW RESULTS? YES!

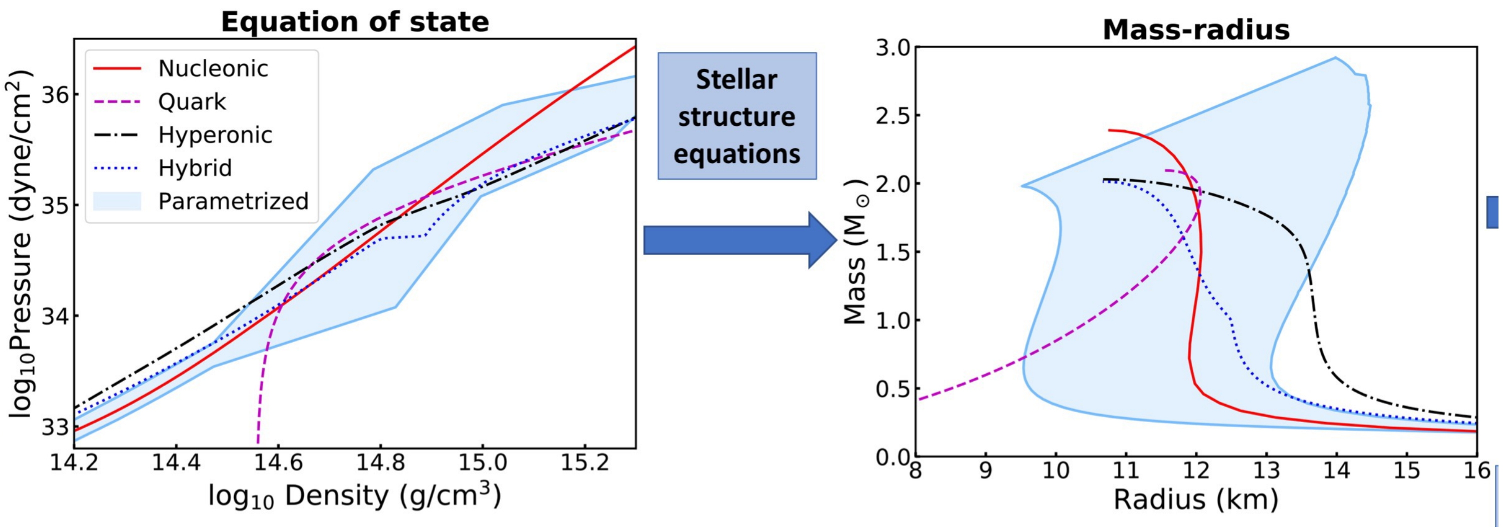


GW170817: LIGO Scientific Collaboration and Virgo Collaboration (2017, 2018)



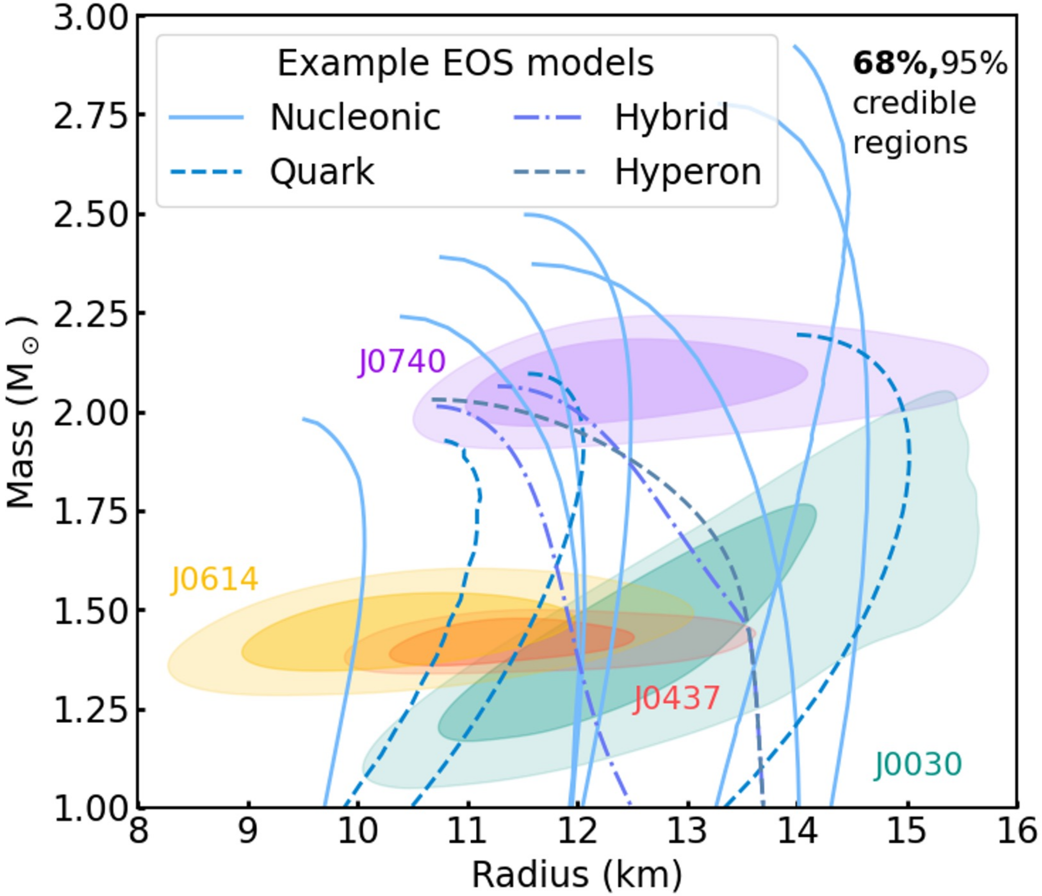
Note: GW probes mass/tidal deformability – converted to radius assuming a specific (quite generic) EOS model family

EQUATION OF STATE INFERENCE



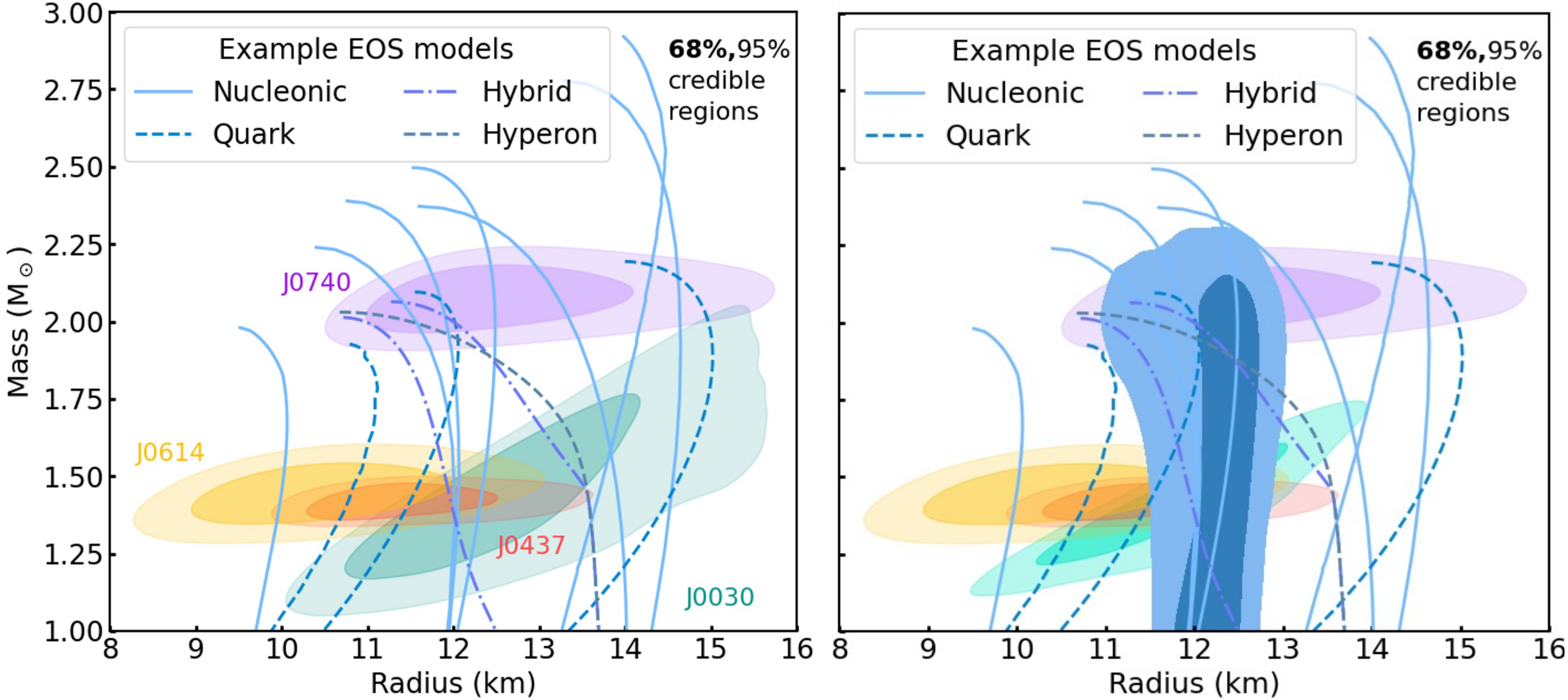
- Start with our inferred mass-radius posteriors
- Select an EOS model (with parameters and priors on those parameters)
- Infer EOS model parameters and central densities -> Inferred EOS
- This then translates into an inferred mass-radius **relation**

WHAT HAVE WE LEARNED ABOUT DENSE MATTER?



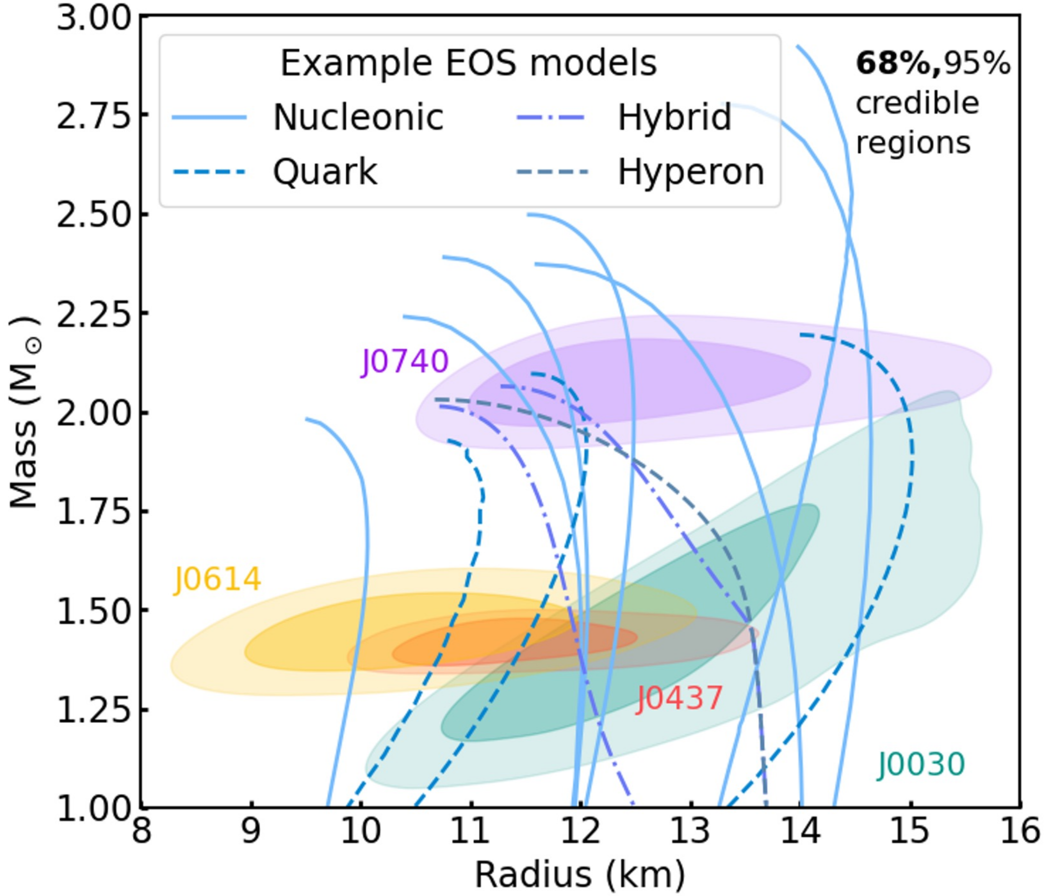
NICER results currently favour soft to medium stiffness Equations of State – extremes seem ruled out.

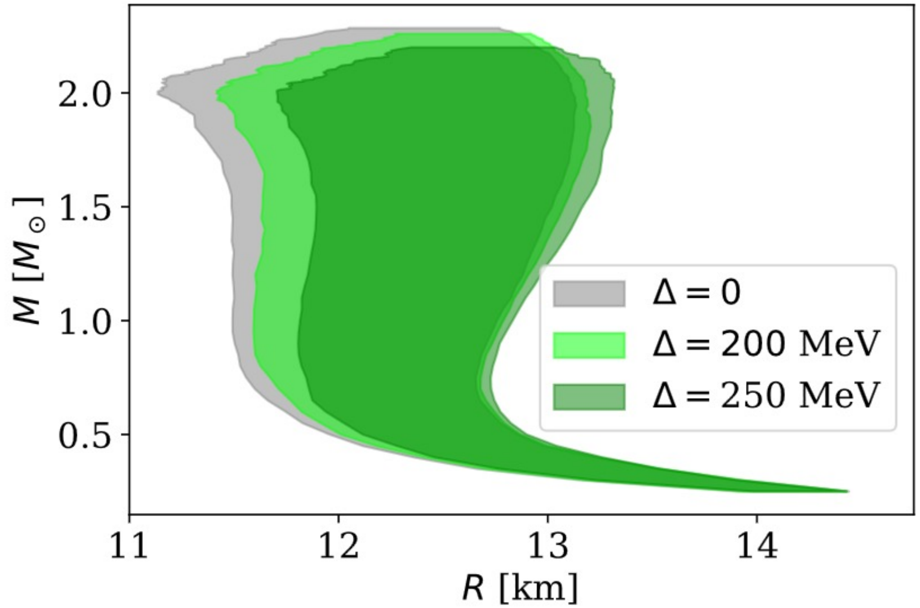
WHAT HAVE WE LEARNED ABOUT DENSE MATTER?



Nucleonic models perform well (e.g. Rutherford et al. 2024, Mauviard et al. 2025)

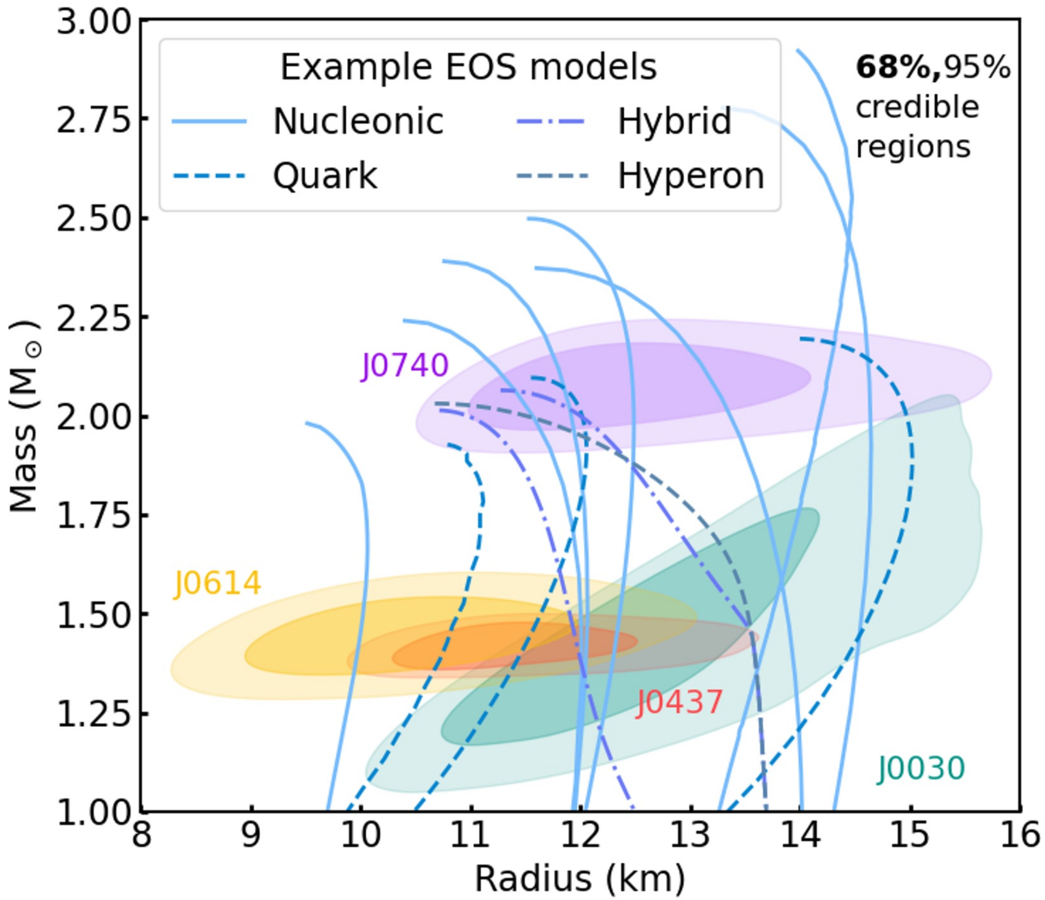
WHAT HAVE WE LEARNED ABOUT DENSE MATTER?

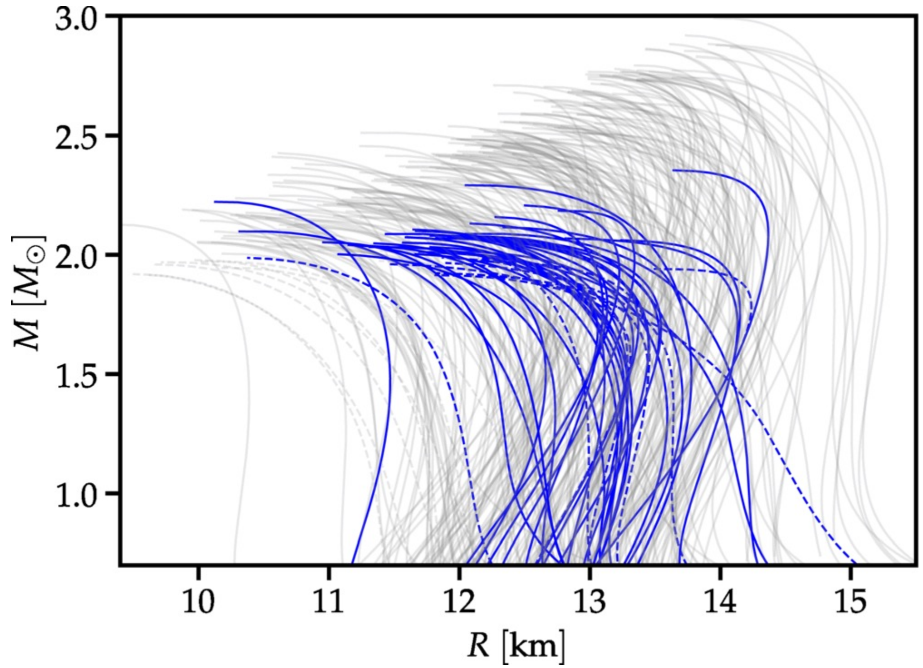




Limits on how quark matter can behave (color superconductivity) (Kurkela et al. 2024, 25)

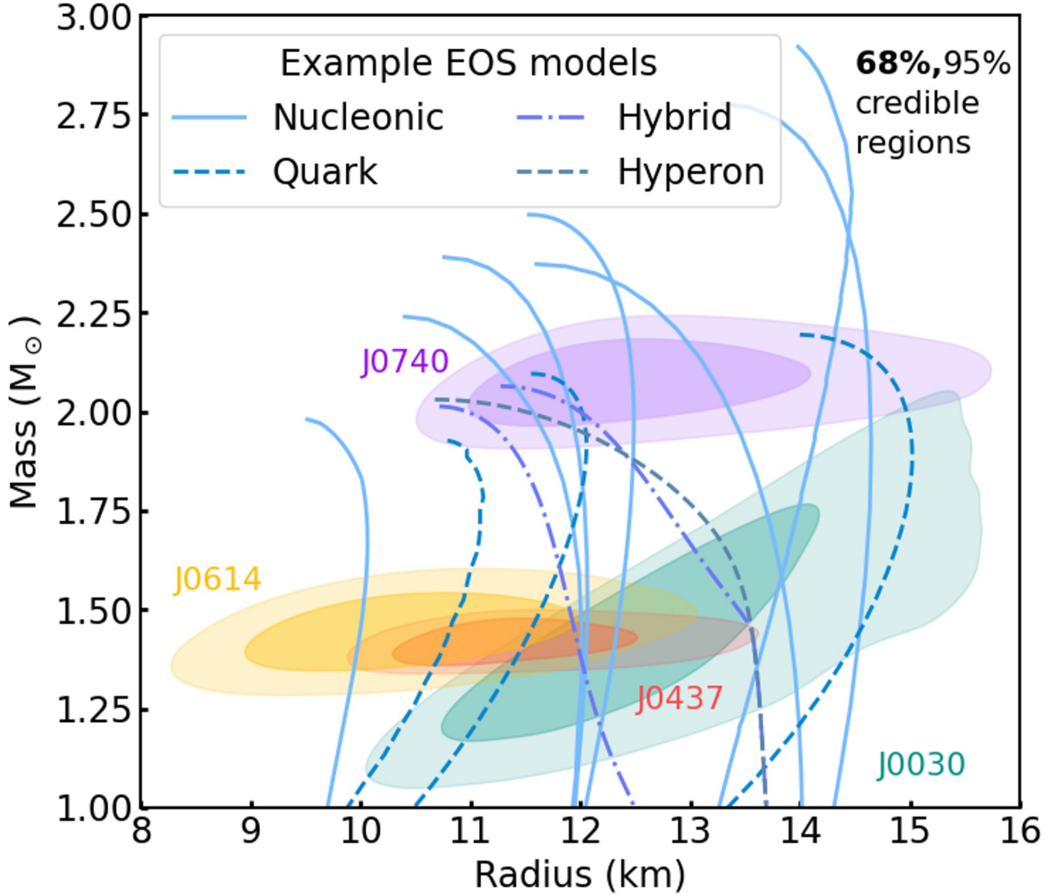
WHAT HAVE WE LEARNED ABOUT DENSE MATTER?





Hyperon models struggle
(Bauswein et al. 2026

WHAT HAVE WE LEARNED ABOUT DENSE MATTER?



The existence of 2 solar mass neutron stars **rules out pion/kaon condensates**

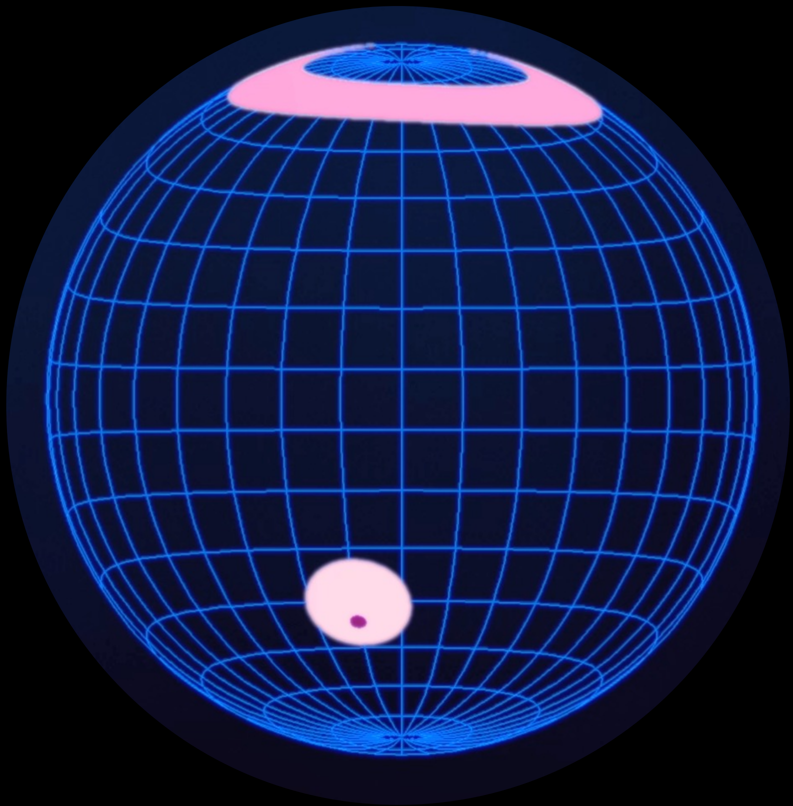
Gradient of the mass radius curve: high radius at low mass, and low radius at high mass, are disfavored by data.

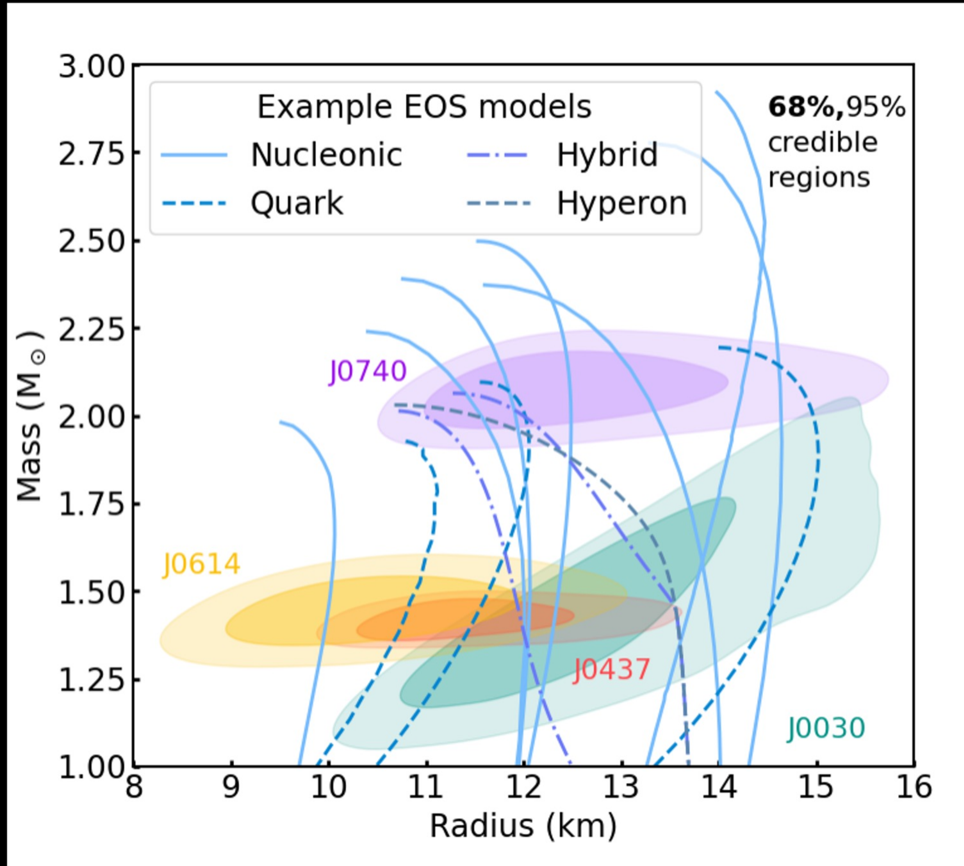
Are there **deconfined quarks**? Maybe!

Hyperons survived high masses, but will are struggling with radius measurements

What is the **mass boundary between neutron stars and black holes**?

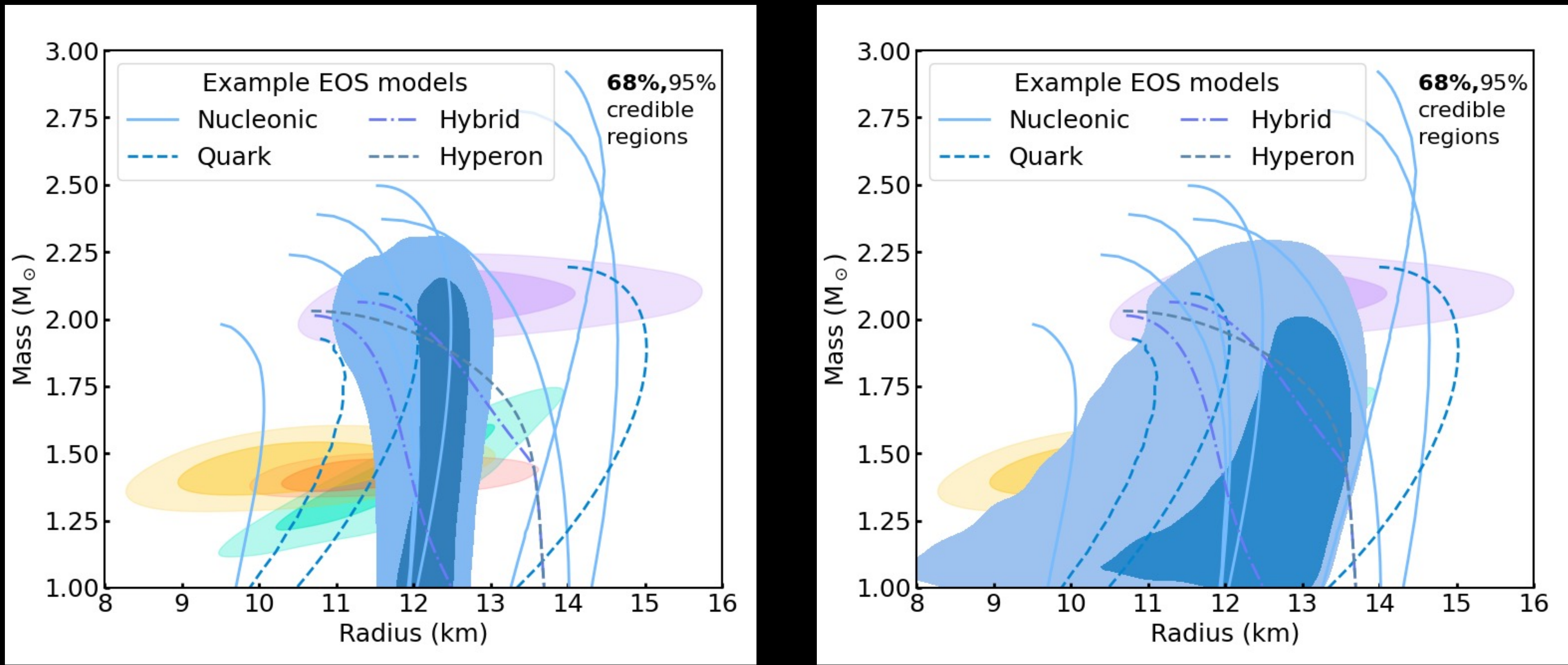
SO WHAT NEXT?





Better magnetosphere/multiwavelength emission modeling

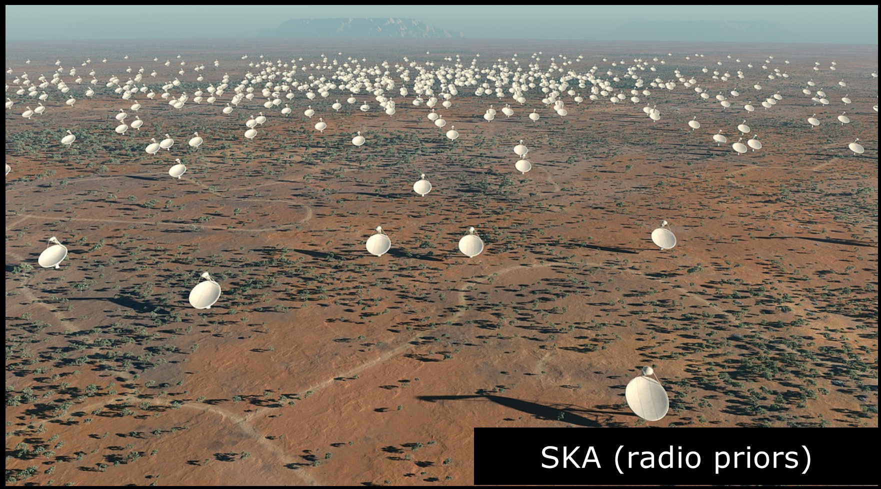
SO WHAT NEXT?



Use dense matter information earlier? (Hoogkamer et al. 2026)

SO WHAT NEXT?

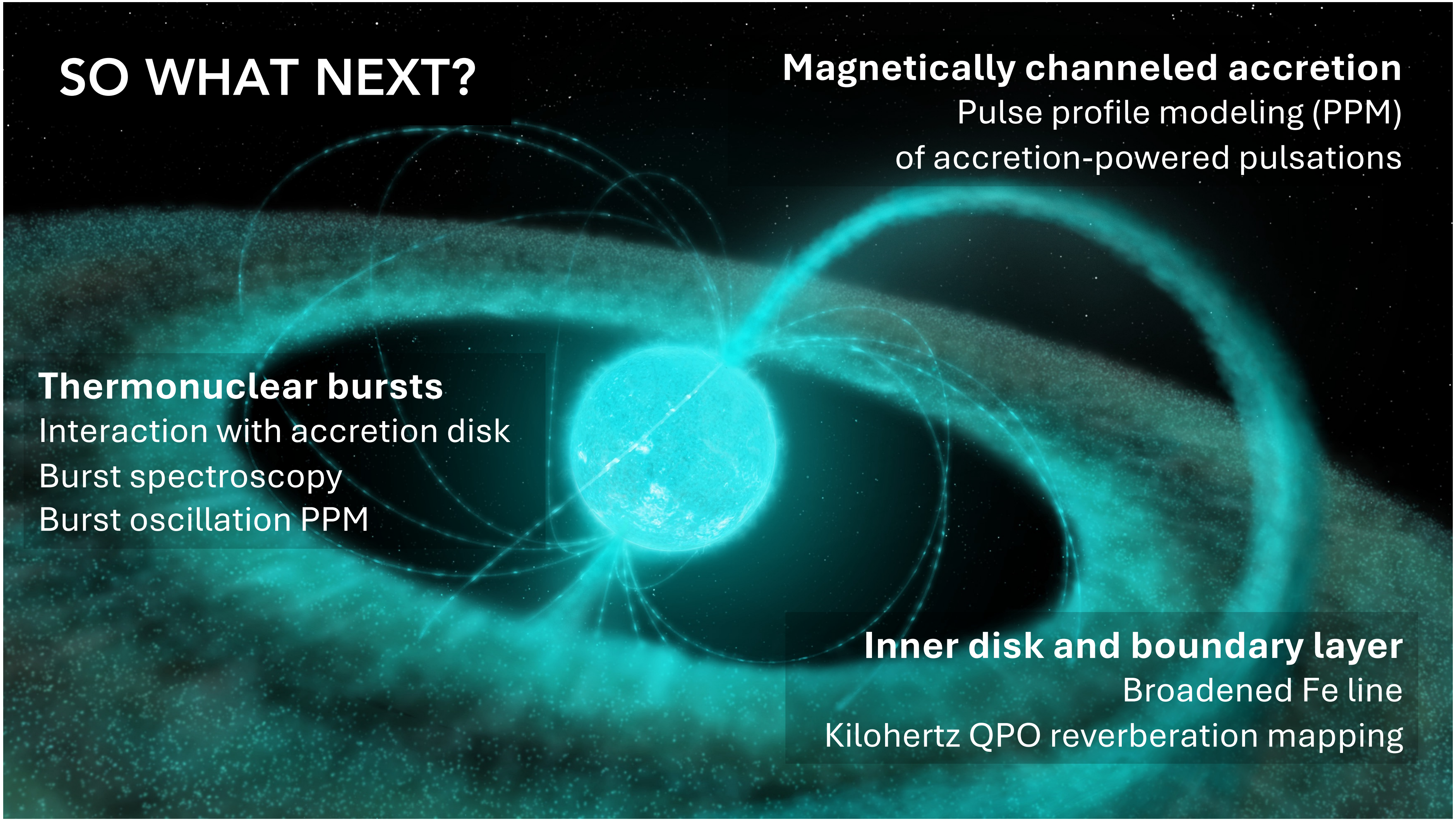
NewAthena (late 2030s)



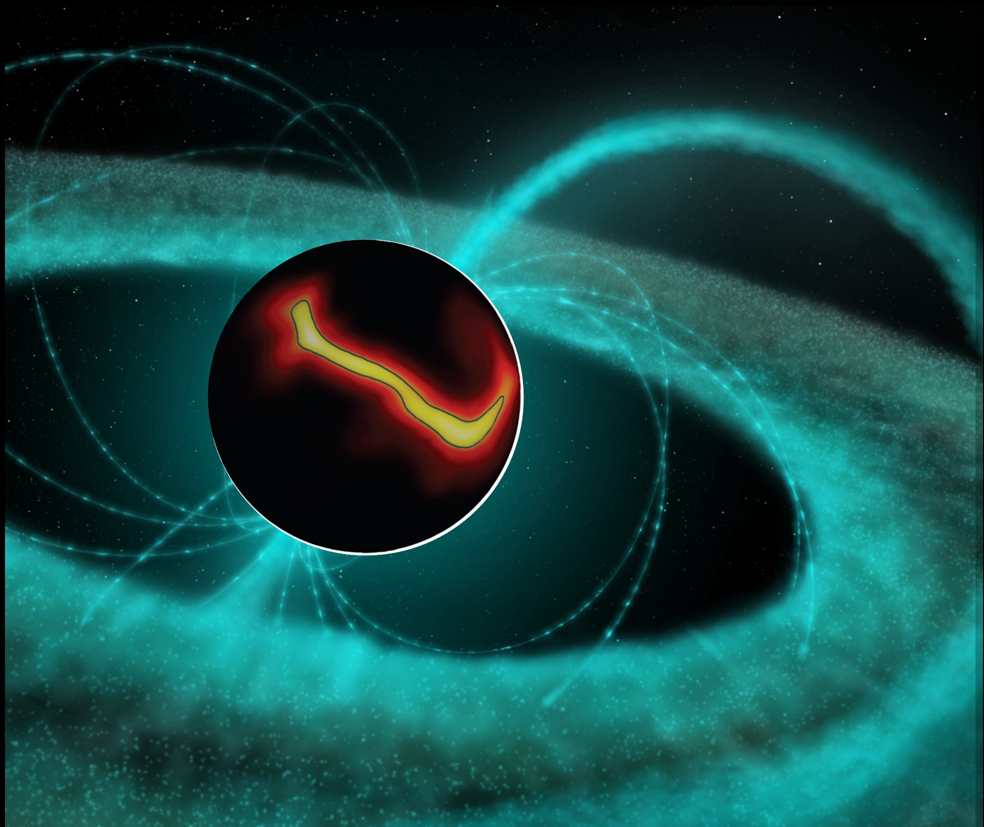
SKA (radio priors)

eXTP (2030)

New telescopes - wider band, low/~no background, larger area


SO WHAT NEXT?
Magnetically channeled accretion
Pulse profile modeling (PPM)
of accretion-powered pulsations
Thermonuclear bursts
Interaction with accretion disk
Burst spectroscopy
Burst oscillation PPM
Inner disk and boundary layer
Broadened Fe line
Kilohertz QPO reverberation mapping

PPM FOR ACCRETING MILLISECOND PULSARS



Spot shapes are complex
(Das et al. 2025)

- New physics and information: atmosphere, disk, polarimetry (Dorsman et al. 25, Salmi et al. 25)
- AMP PPM analyses: SAX J1808.4-3658 (Salmi et al.18, Dorsman et al. 26a), SGRA 144459.2-604207 (Dorsman, Salmi et al. 26b). Results are complicated! Models and pipeline need work.
- NewAthena's wide band, spectral resolution, larger effective area should help!

SUMMARY

- NICER has unlocked a completely new technique for determining neutron star properties.
- We have measured the size of four (technically five) neutron stars! And are using this to understand matter at supranuclear densities.
- We are making maps of tiny stars thousands of light years from Earth.
- NewAthena offers outstanding prospects for PPM!