MAPPING NEUTRON STARS INSIDE AND OUT
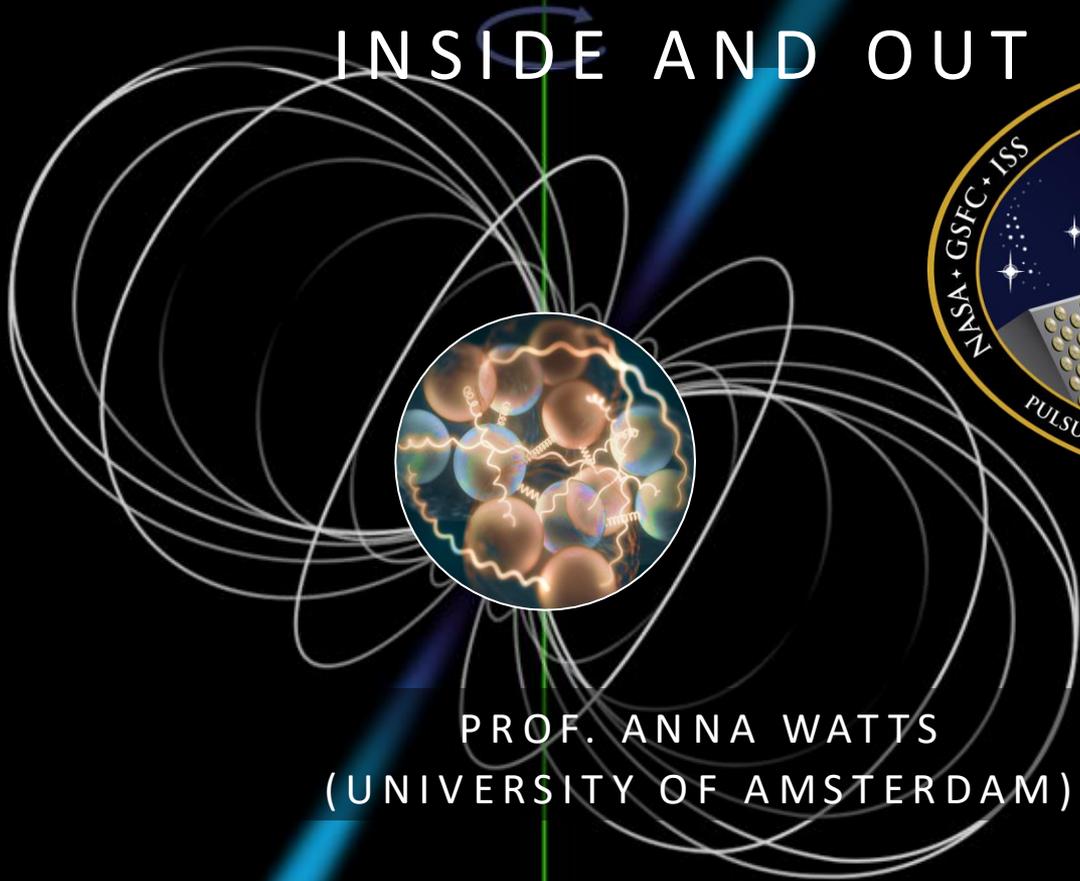
PROF. ANNA WATTS
(UNIVERSITY OF AMSTERDAM)

THE NEUTRON STAR INTERIOR

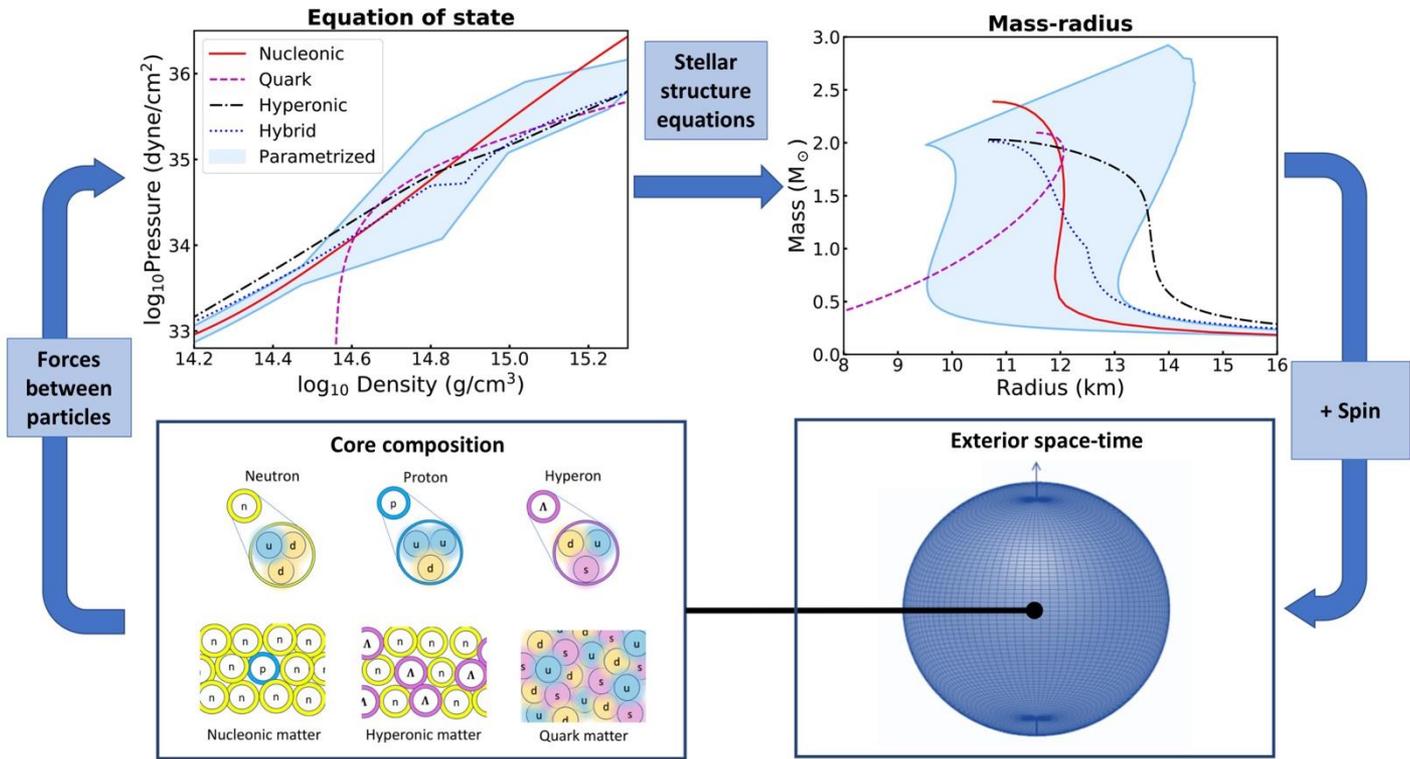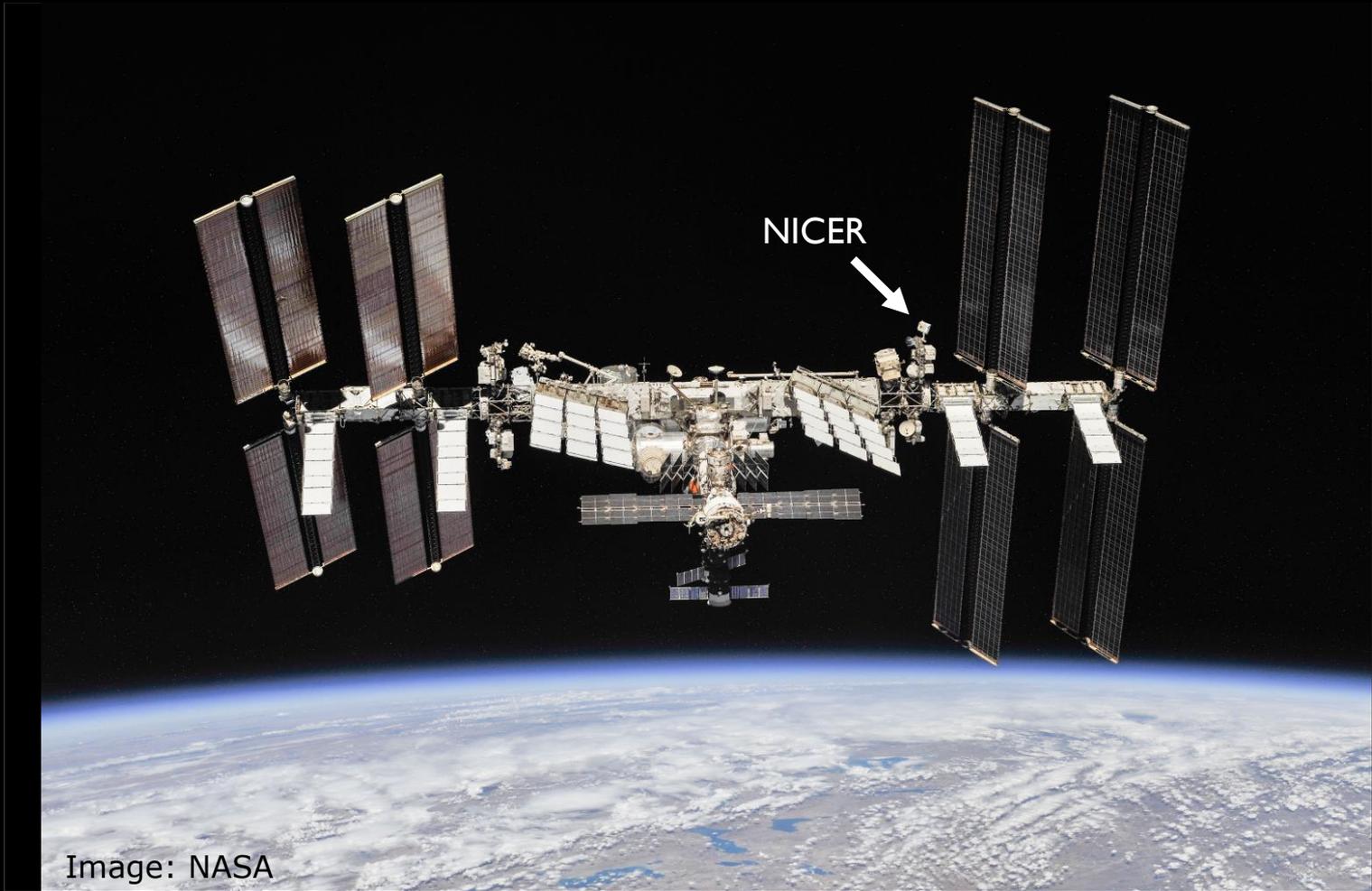Figure: Watts et al. 2016
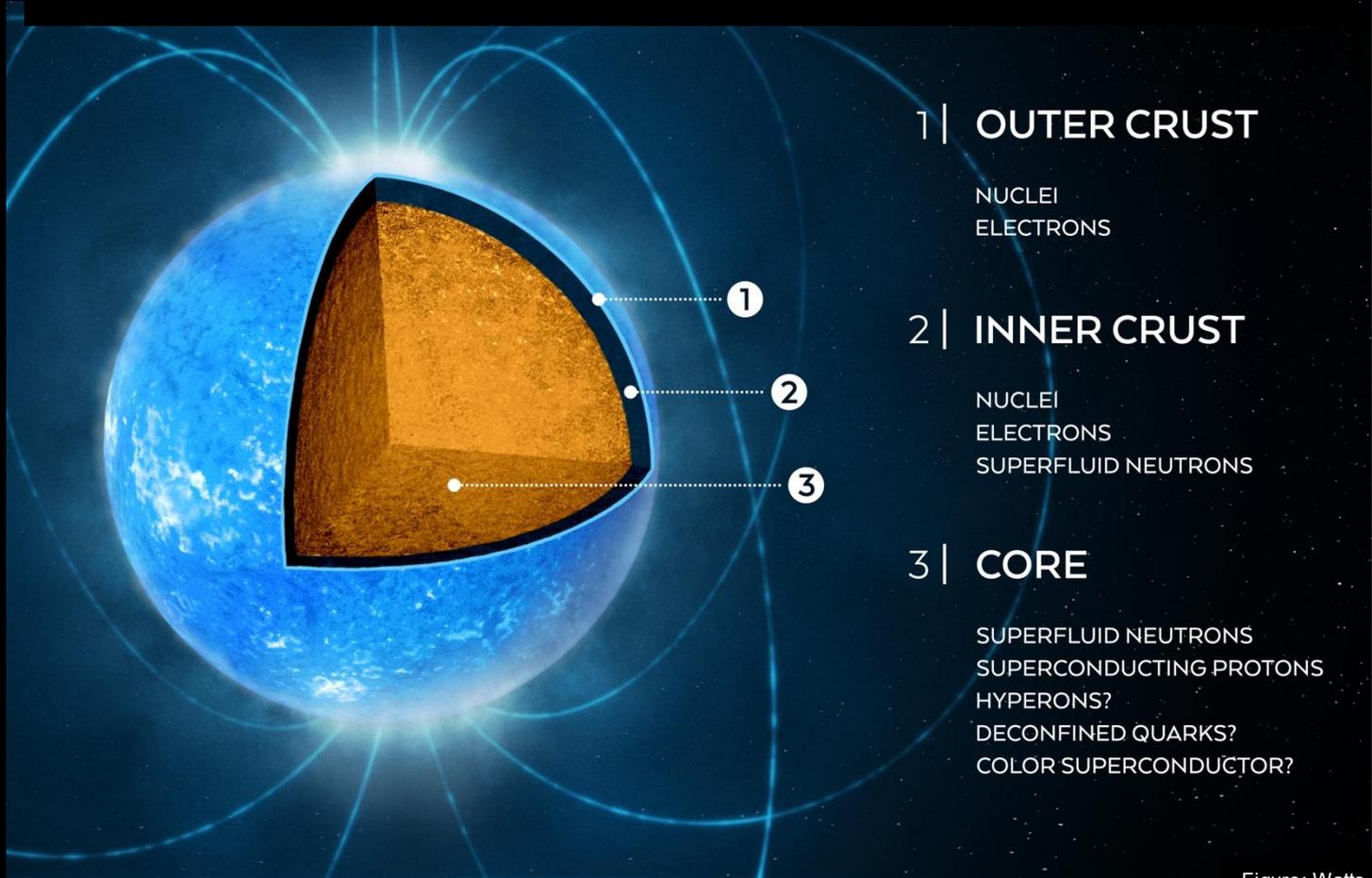
FROM NUCLEAR PHYSICS TO TELESCOPE (AND BACK)

Figure: Adapted from Ray et al. 2019

NICER

Image: NASA

THE PULSE PROFILE MODELING TECHNIQUE

Rotation-powered millisecond pulsars
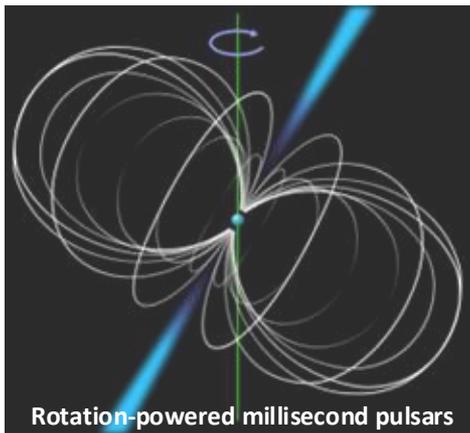
Physics and priors

- 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
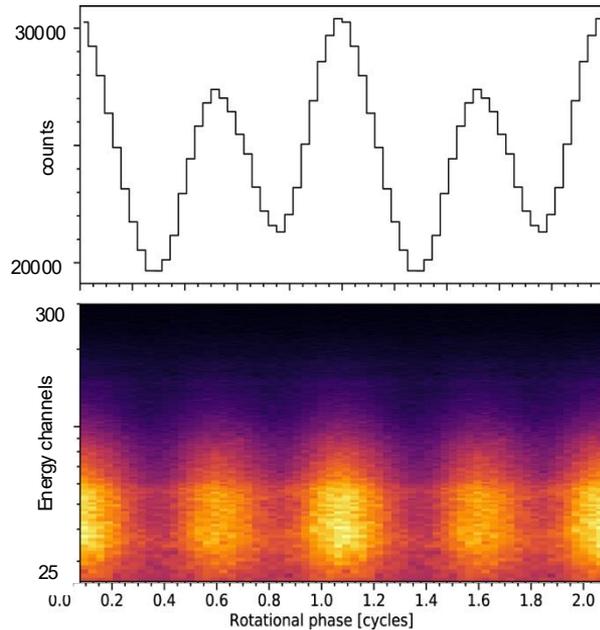- 'EOS-agnostic' priors on radius

Pulse profile data: Phase, Energy

Lightcurve model: the (astro)physics
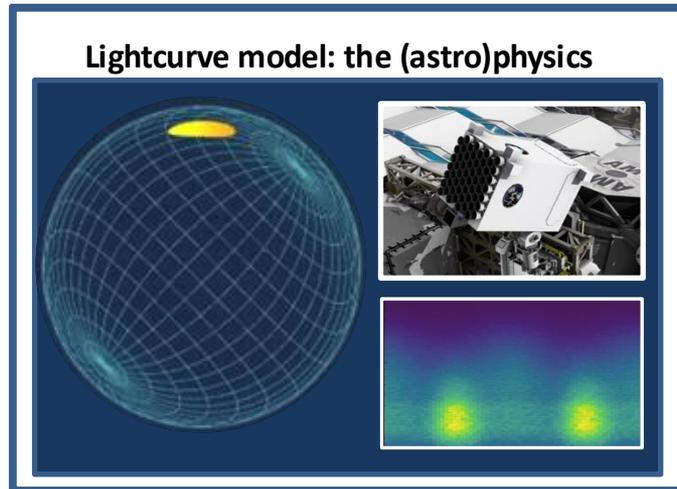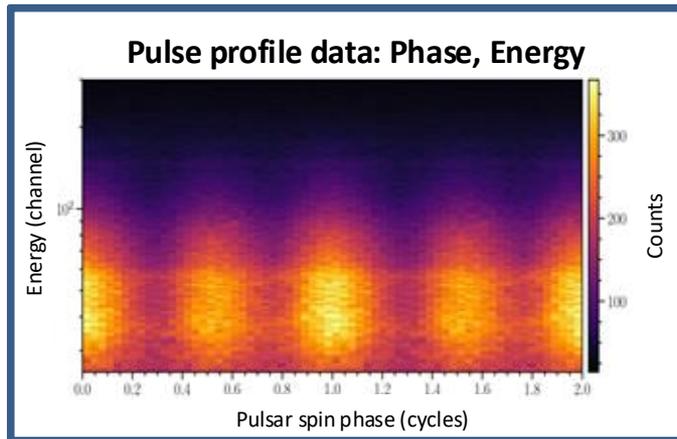
Bayesian inference of model parameters (statistical sampling)

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

PULSE PROFILE DATA SETS

PSR J0030+0451
- Bright source
- Isolated system

PSR J0740+6620
- Faint source
- Binary - mass 2.1M$_\odot$

PSR J0437−4715
- Closest and brightest source
- Binary: mass 1.4M$_\odot$

Riley et al. 2019, *Miller et al. 2019*
Salmi et al. 2023, Vinciguerra et al. 2023, 2024
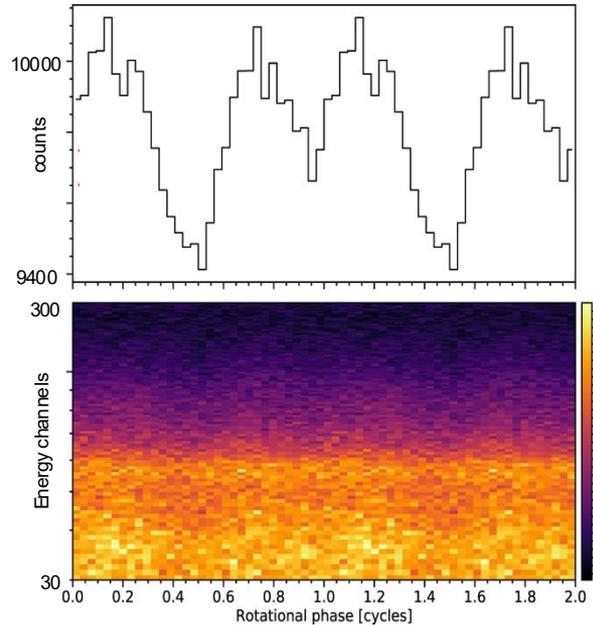
Riley et al. 2021, *Miller et al. 2021*
Salmi et al. 2022, 2023, 2024a,
Dittmann et al. 2024, Hoogkamer et al. 2025
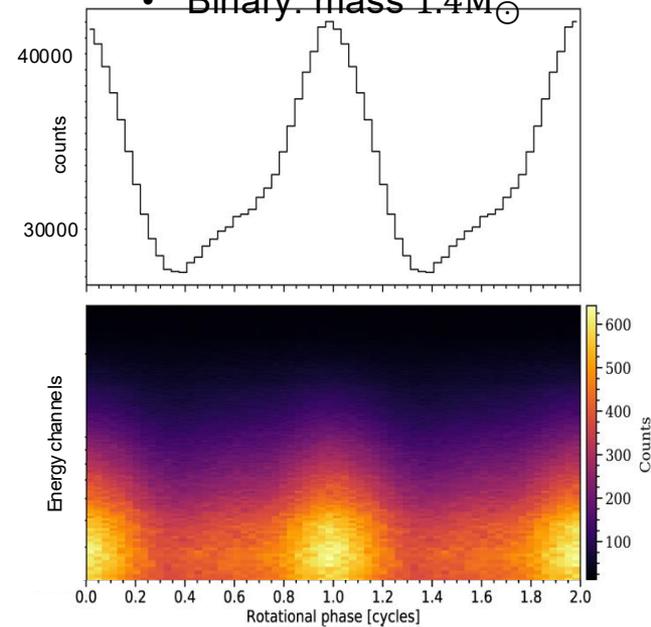
Choudhury et al. 2024

MAPPING THE HOT MAGNETIC POLES
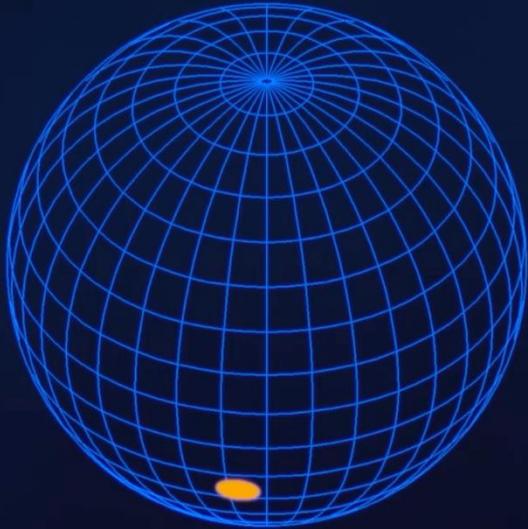
PSR J0030+0451   PSR J0740+6620   PSR J0437-4715
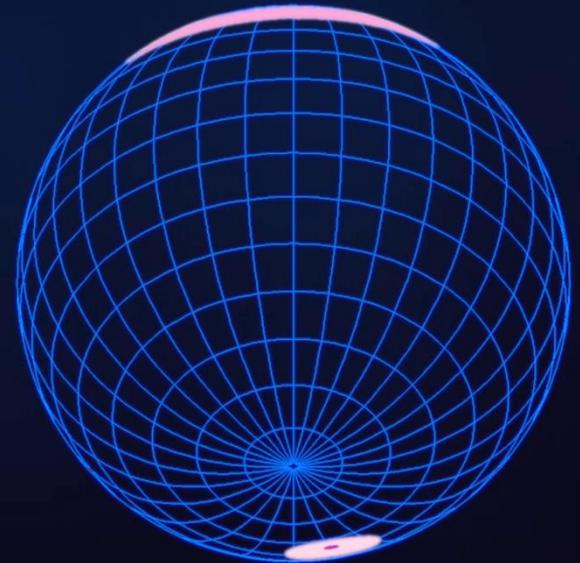
As seen from Earth
Results from the X-PSI pipeline (https://github.com/xpsi-group/xpsi, also Riley et al. 2023 JOSS)
Maps from Riley et al. 2019, Riley et al. 2021, Choudhury et al. 2024 + Morsink/NASA

NON-DIPOLAR MAGNETIC FIELD?
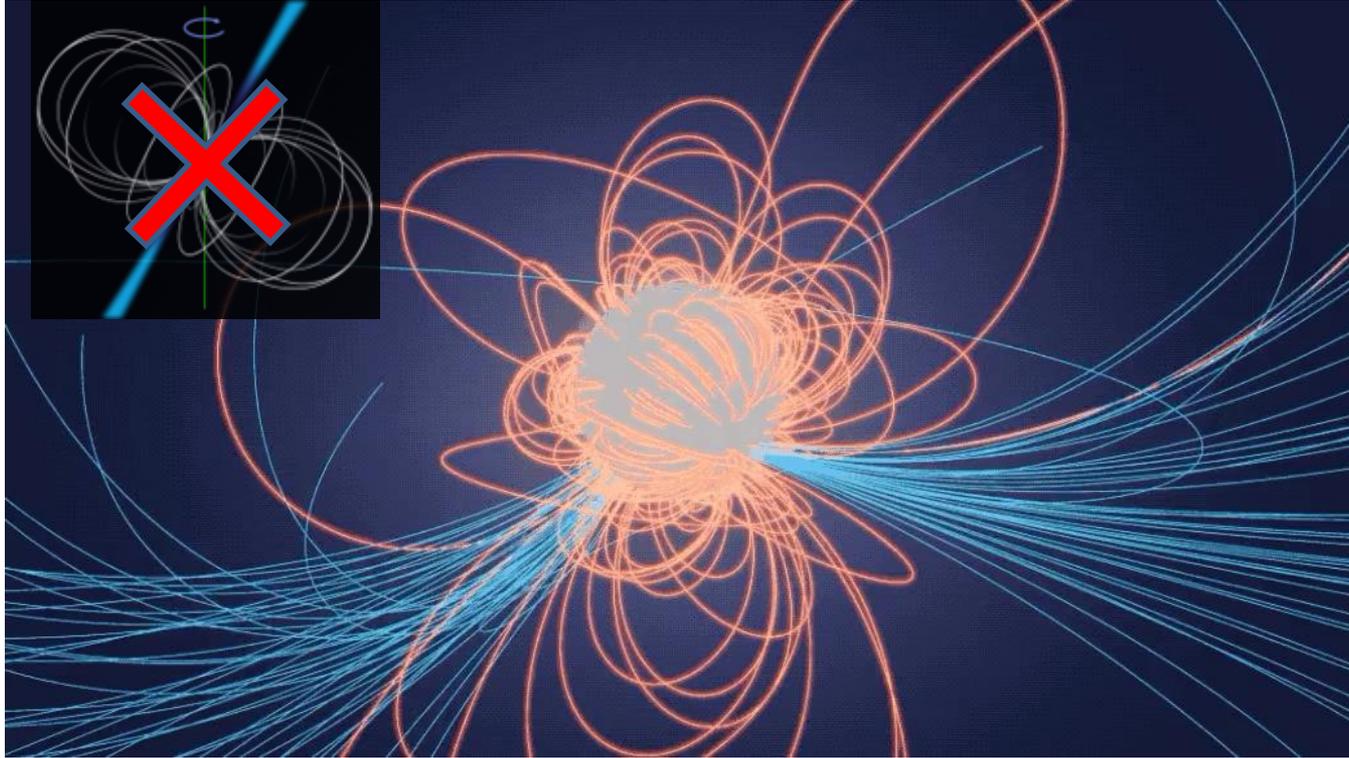
Credit: NASA's Goddard Space Flight Center/Harding, Kalapotharakos, Wadiasingh.

MASSES AND RADII
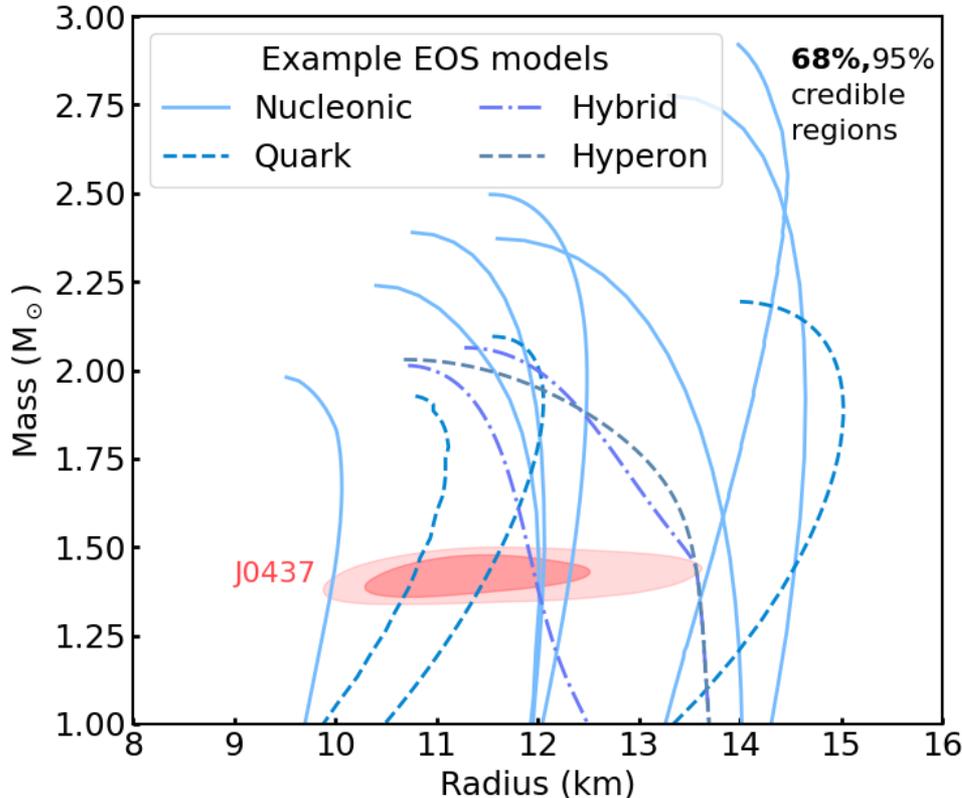
PSR J0437-4715

- Very well-constrained mass (Reardon et al. 2024)
- AGN in field of view ⇒ complex background
- PPM analyses to date
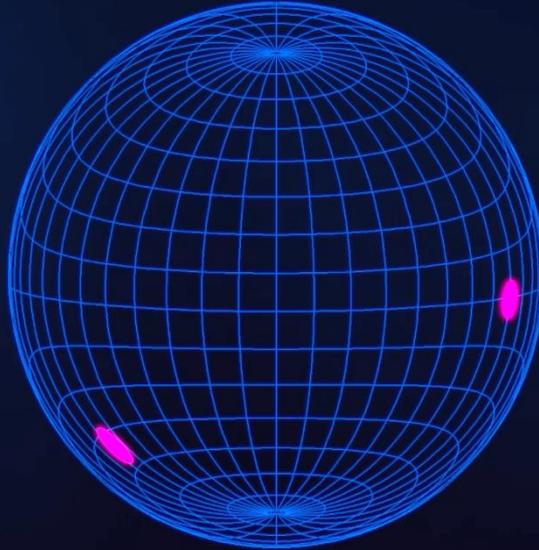 - 2017-2021 data set (Choudhury et al. 2024)
- Consistent with softer EOS, and with GW170817

- Hoogkamer et al. 2026 (PRD in press, arXiv:2510.27619) studied this data set with EOS-informed priors. Found new narrow geometric mode. Higher likelihood, but physically less likely since inconsistent with multi-wavelength pulsar data/models.

- In progress: analysis of extended data set (Choudhury++, Stammler++)

- *Miller et al 2025, arXiv:2512.08790: analysis including additional model component*

MASSES AND RADII
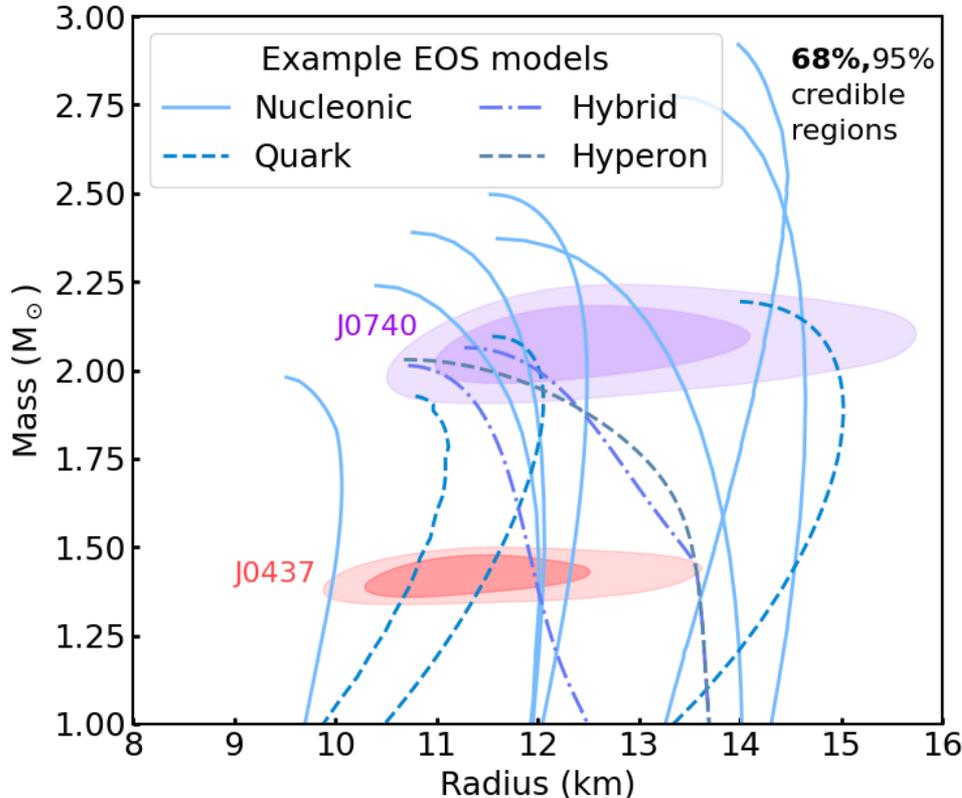
PSR J0437-4715

PSR J0740+6620

- Well-constrained, high mass (Cromartie et al. 2020, Fonseca et al. 2021)
- PPM analyses to date:
  - 2018-2020 data set (Riley et al. 2021, *Miller et al. 2021*)
  - 2018-2021 data set, cross-testing background treatments (Salmi et al. 2022)
  - 2018-2022 data set (Salmi et al. 2024a, *Dittmann et al. 2024*)
- Very softest EOS disfavored

- Hoogkamer et al. 2025 (PRD) tested sampler dependence/confirmed convergence of results from Salmi et al. 2024a
- Hoogkamer et al. 2026 (PRD in press) tested same data set with EOS-informed priors.

MASSES AND RADII
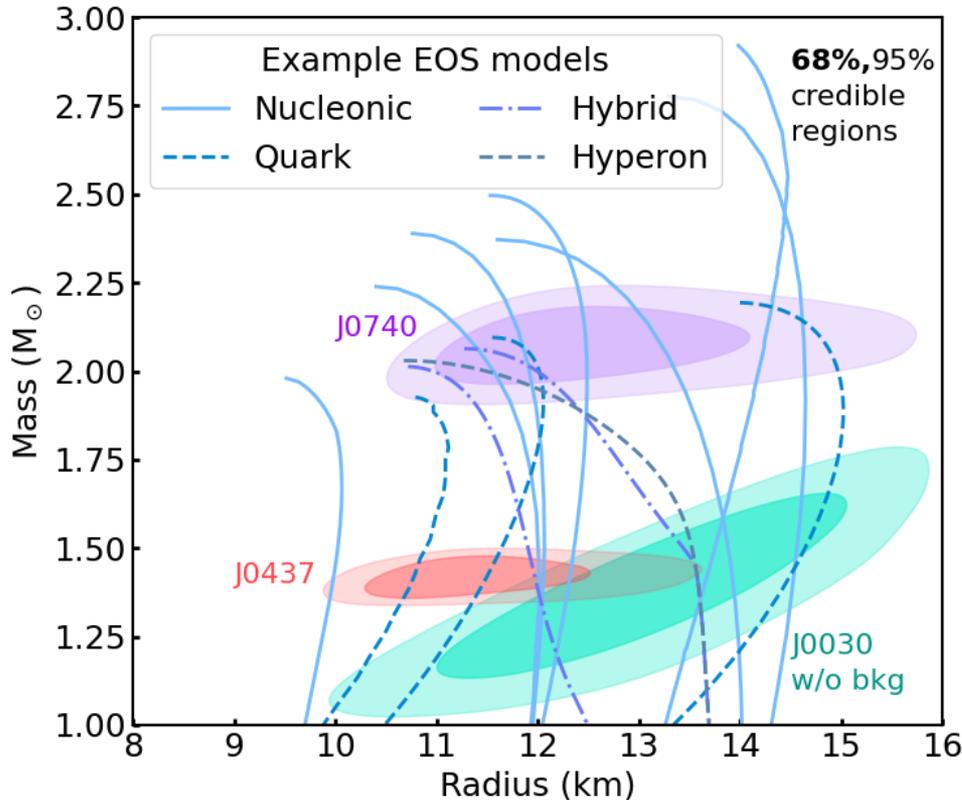
PSR J0437-4715

PSR J0740+6620

PSR J0030+0451

- No mass prior (not in a binary)
- PPM analyses to date:
  - 2017-2018 data set, no background constraints (Riley et al. 2019, *Miller et al. 2019)*
  - Replication of X-PSI analysis by Afle et al. (2023)
  - 2017-2018 data set, with background constraints and improved sampler settings (Vinciguerra et al. 2024)
- Shown here is solution from V24 without background constraints.

MASSES AND RADII

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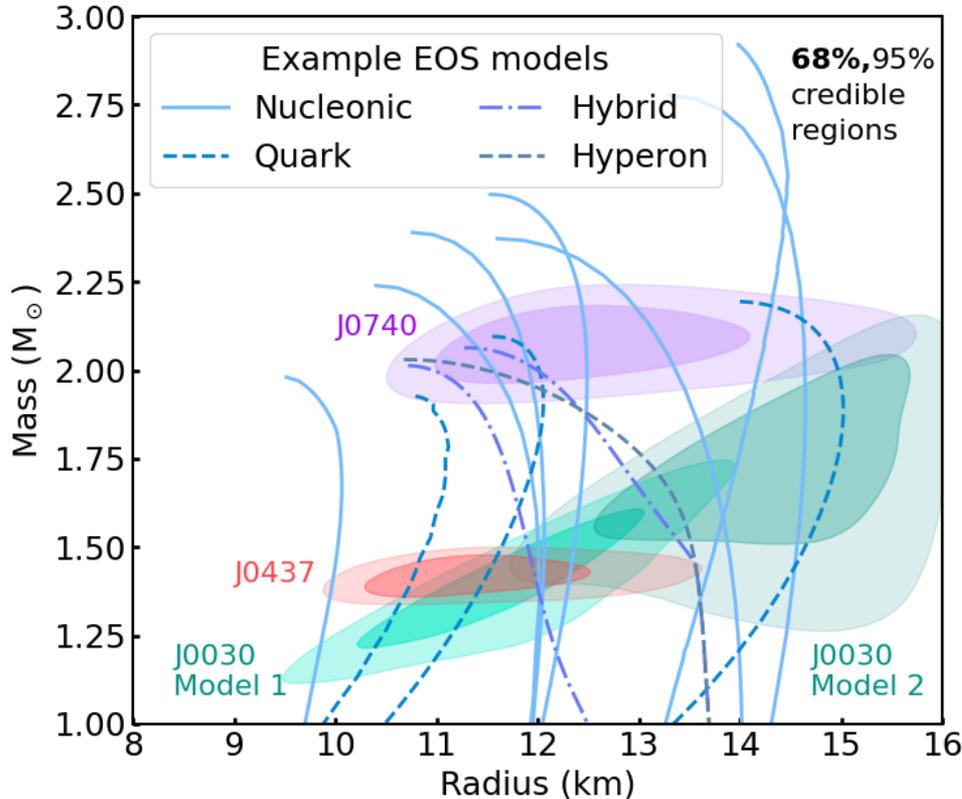
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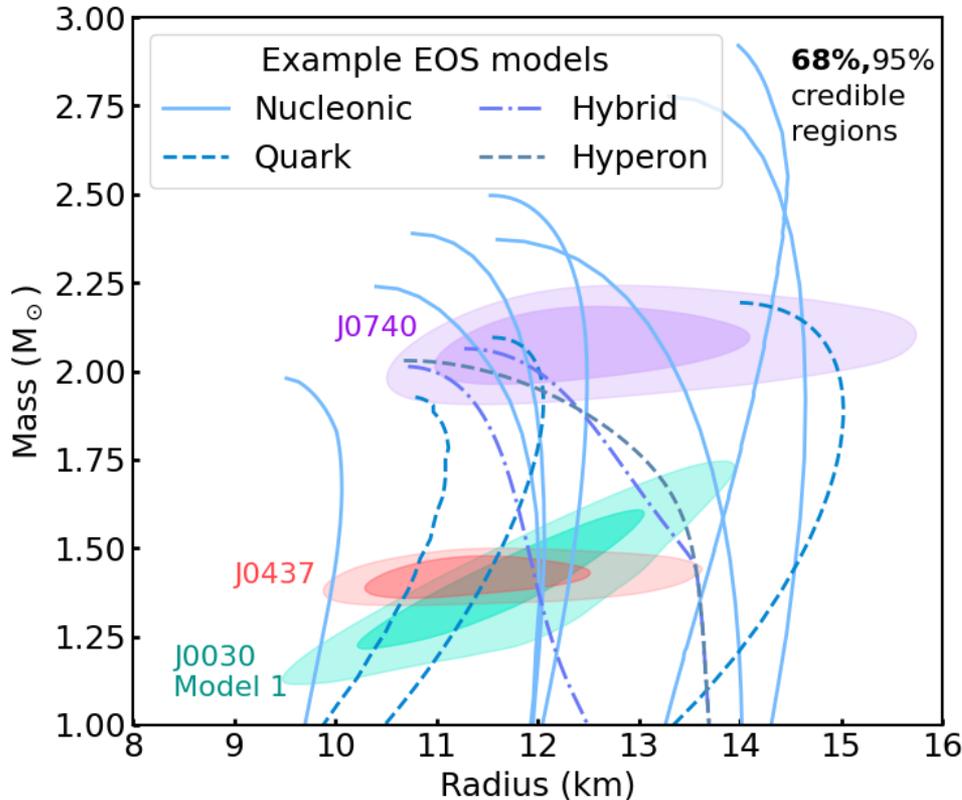
MASSES AND RADII

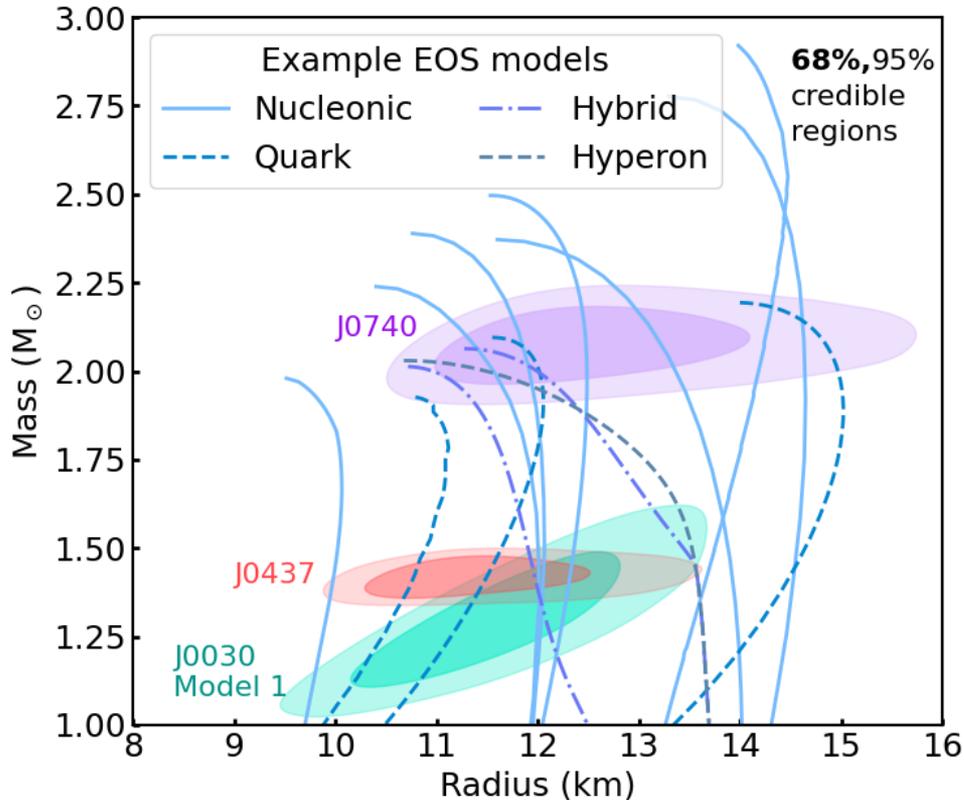
PSR J0437-4715

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MASSES AND RADII

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PSR J0740+6620
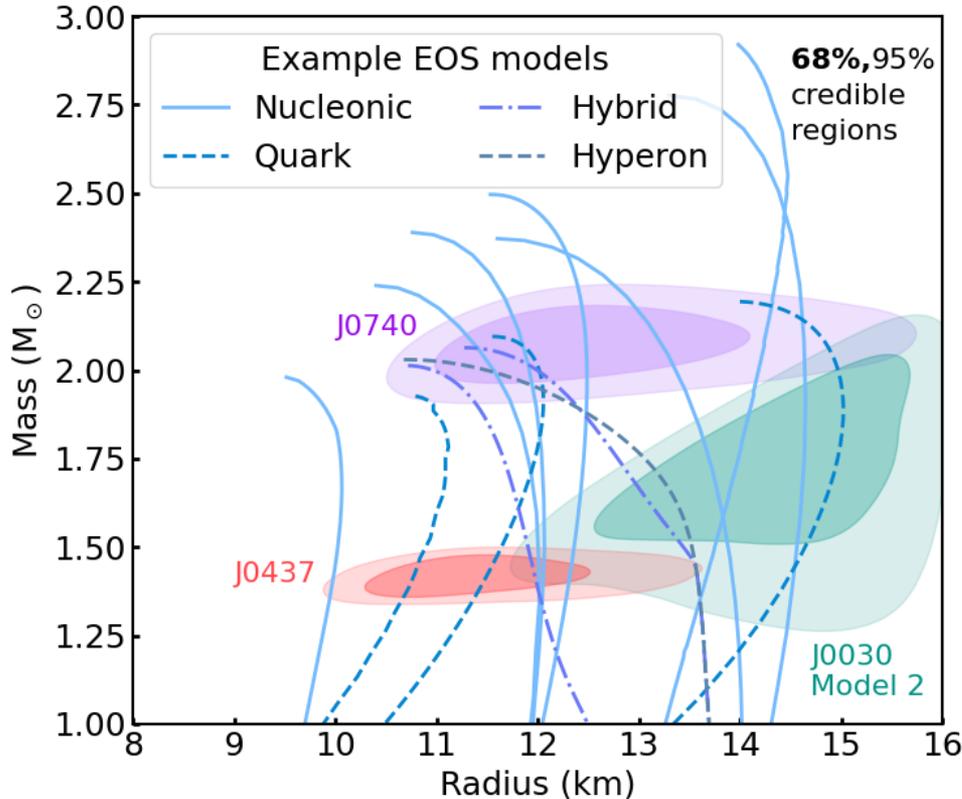
PSR J0030+0451

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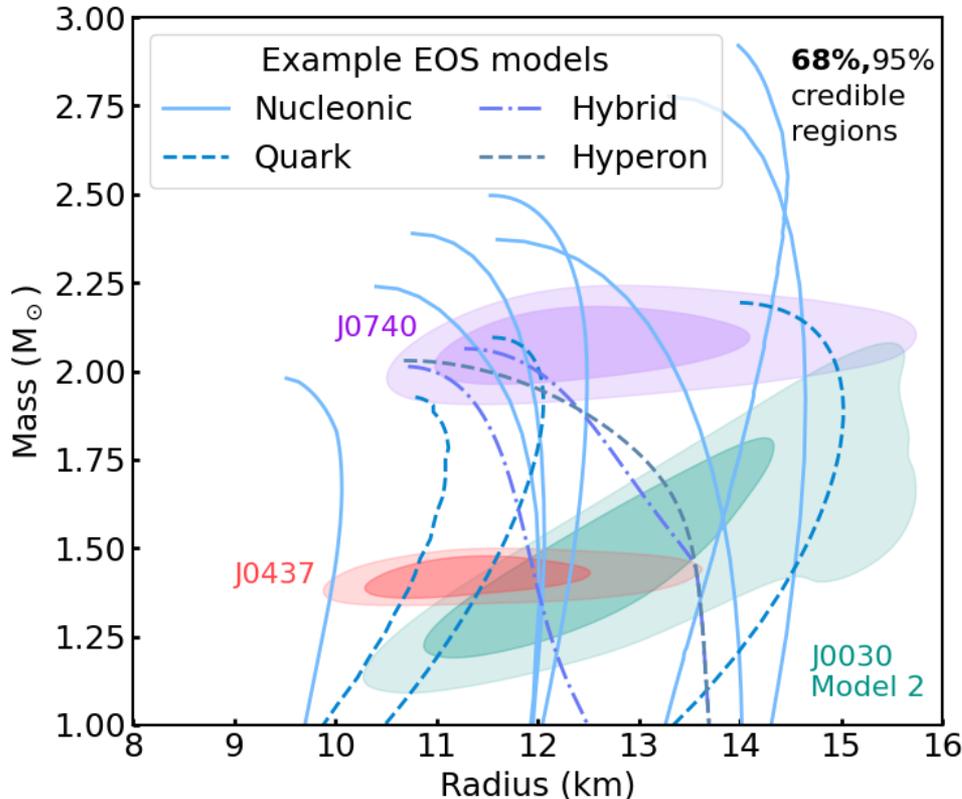
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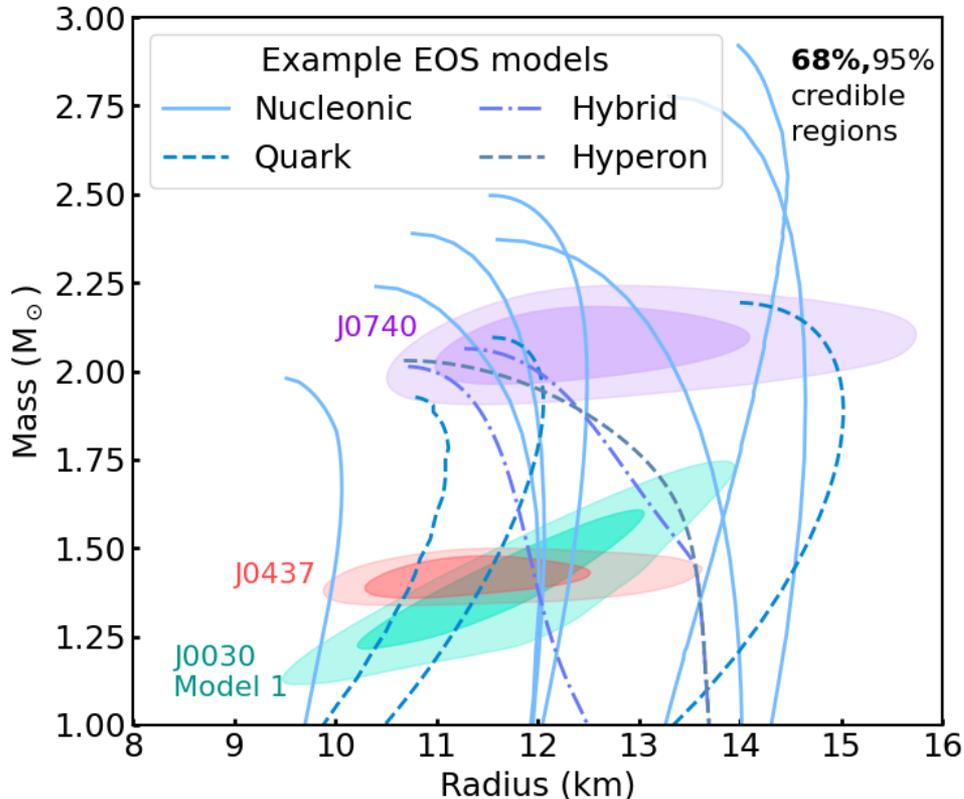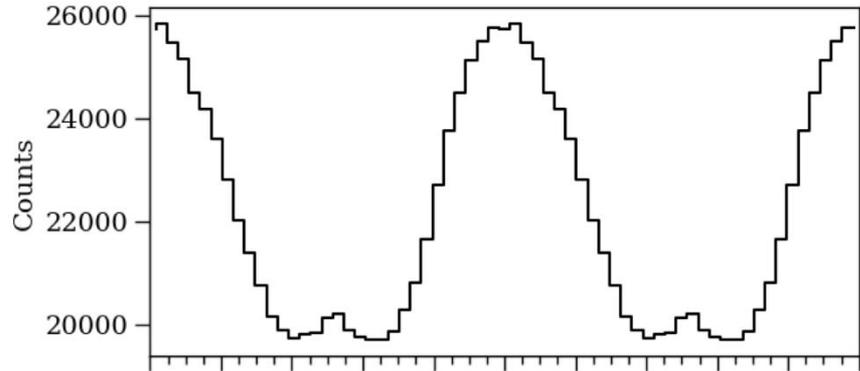
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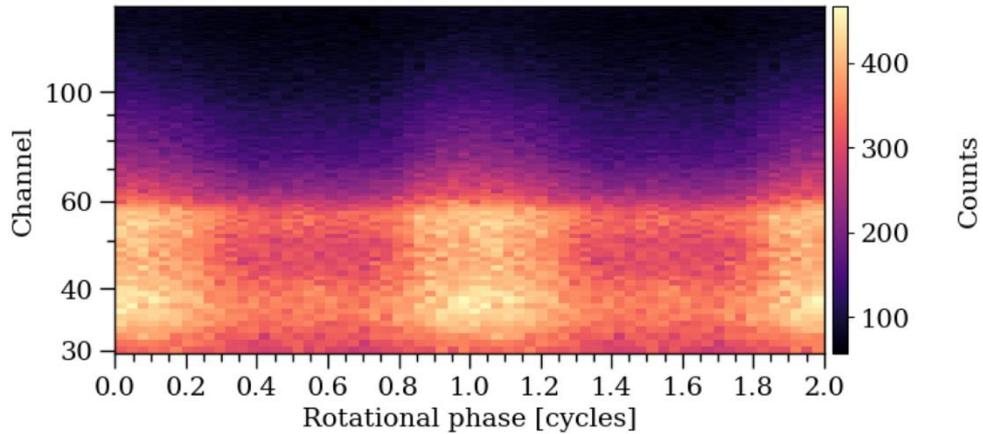
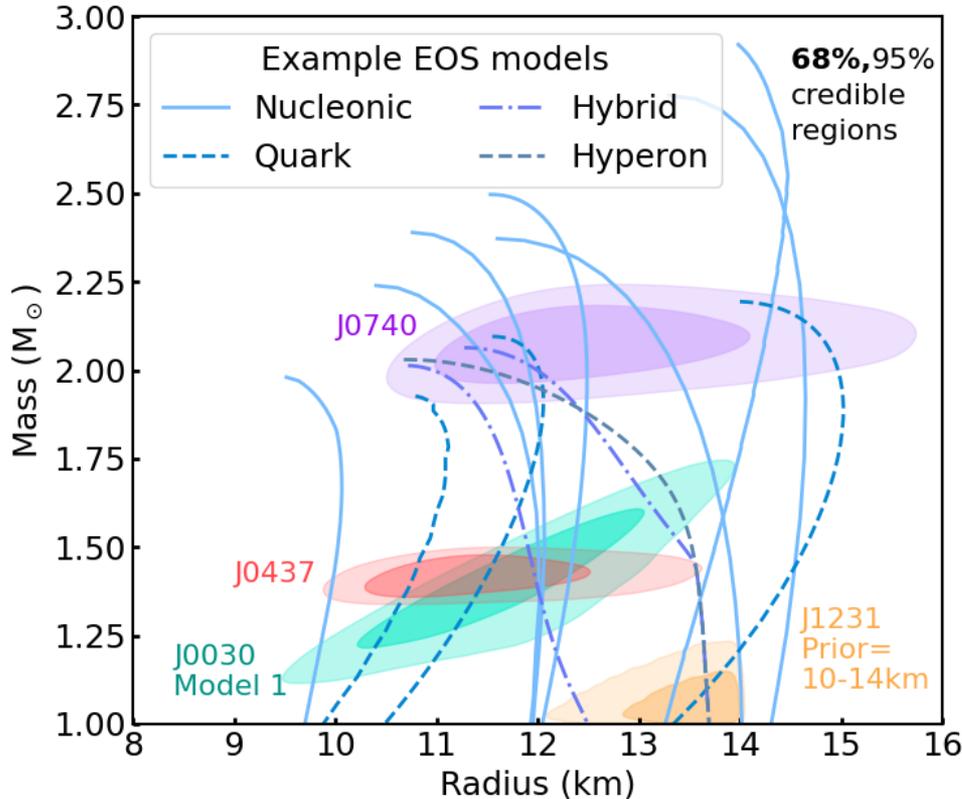# MASSES AND RADII

PSR J0437-4715

PSR J0740+6620

PSR J0030+0451

PSR J1231-1411

- Unusual pulse profile (very weak 2nd pulse)

MASSES AND RADII

PSR J0437-4715

PSR J0740+6620

PSR J0030+0451

PSR J1231-1411

- Unusual pulse profile (very weak 2nd pulse)
- Weakly-constrained mass prior
- PPM analysis to date:
  - 2017-2023 data set (Salmi et al. 2024b)
- Restricted radius prior required for convergence (so be careful using this in EOS analyses!)
- We can find good solutions that are consistent with EOS inferred from the other sources

- Work underway to determine why this source is so challenging (*see also Qi et al. 2025*)

MASSES AND RADII

PSR J0437-4715

PSR J0740+6620

PSR J0030+0451

PSR J1231-1411 (not shown)
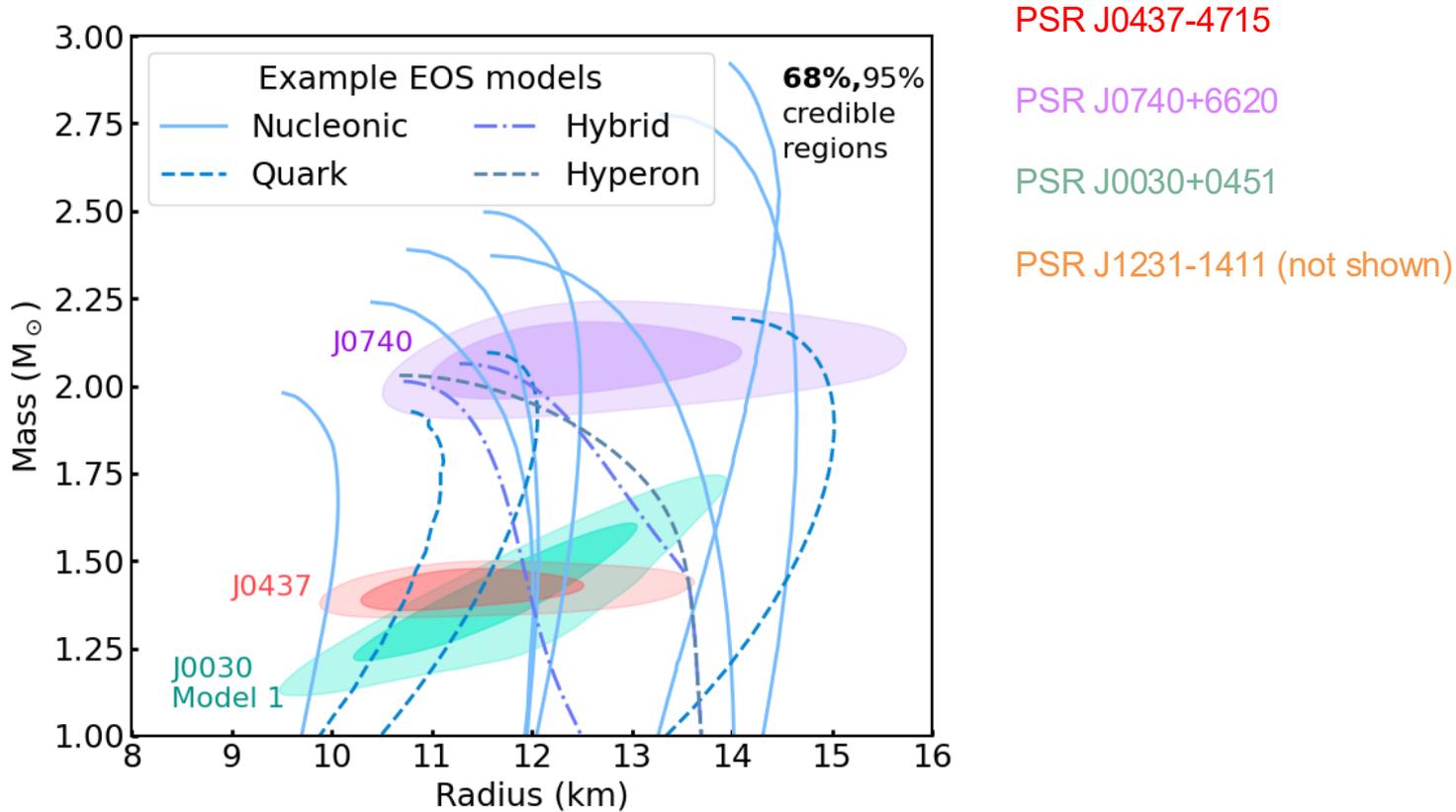
MASSES AND RADII
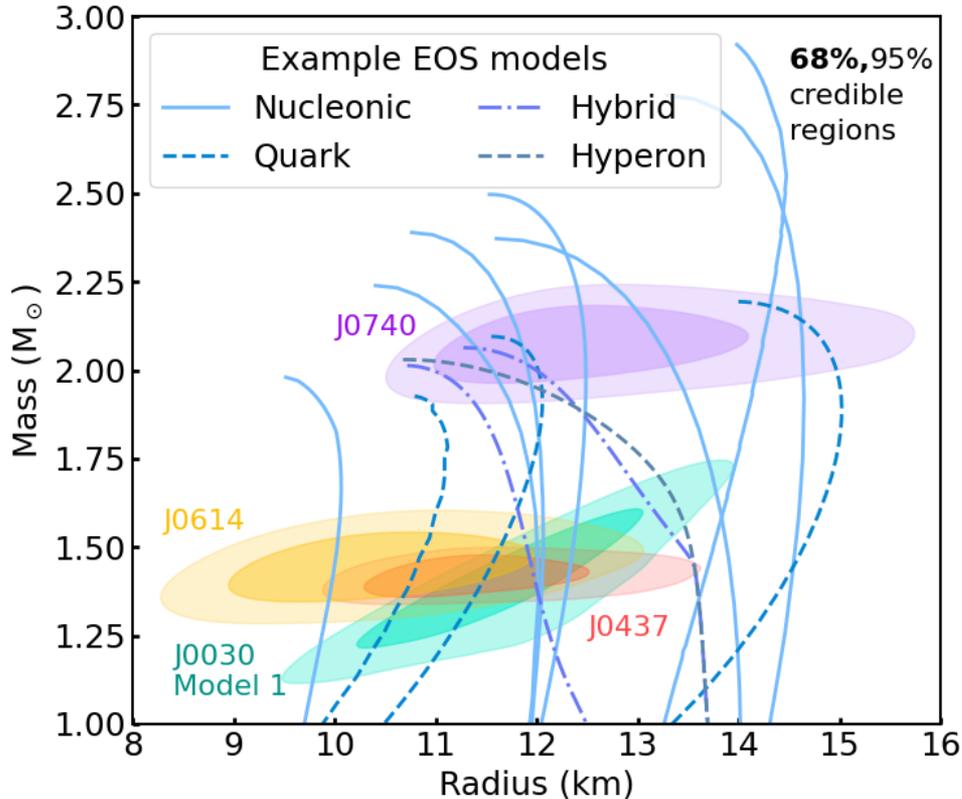
PSR J0437-4715

PSR J0740+6620

PSR J0030+0451

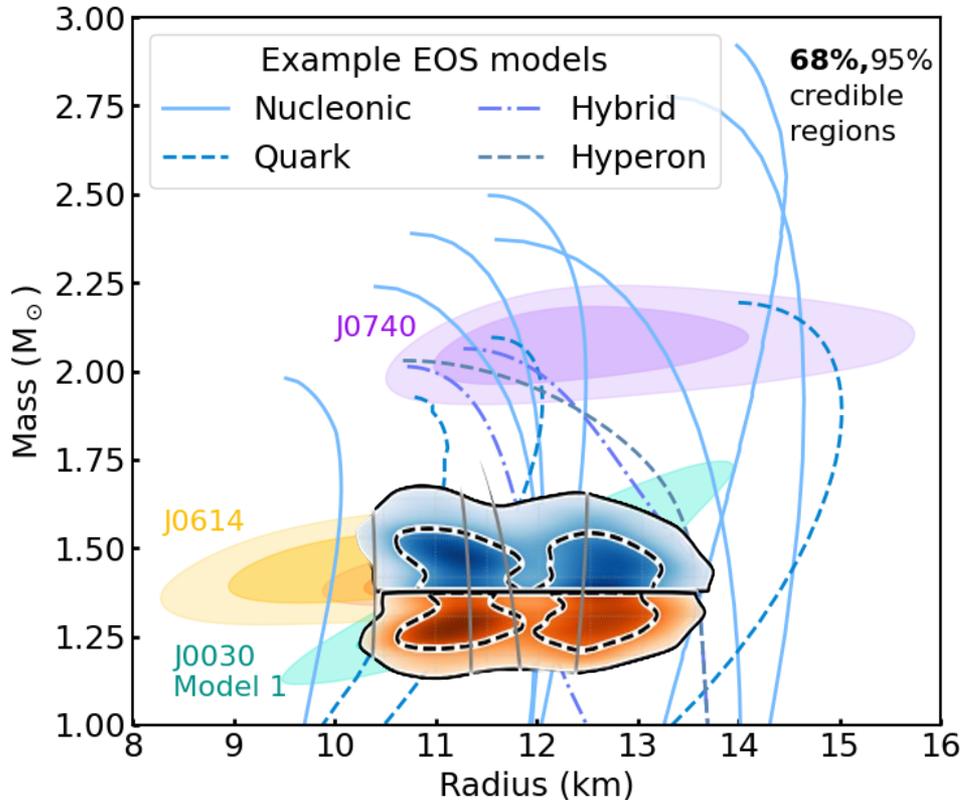PSR J1231-1411

PSR J0614-3329

- Constrained mass prior from MeerKAT PTA (Miles et al. 2025)
- PPM analysis to date
  - 2017 – 2023 data set (Mauviard et al. 2025)
- Geometry – 1 polar, 1 equatorial hotspot
- All (geometric) models favor median radii in 9 - 11km range

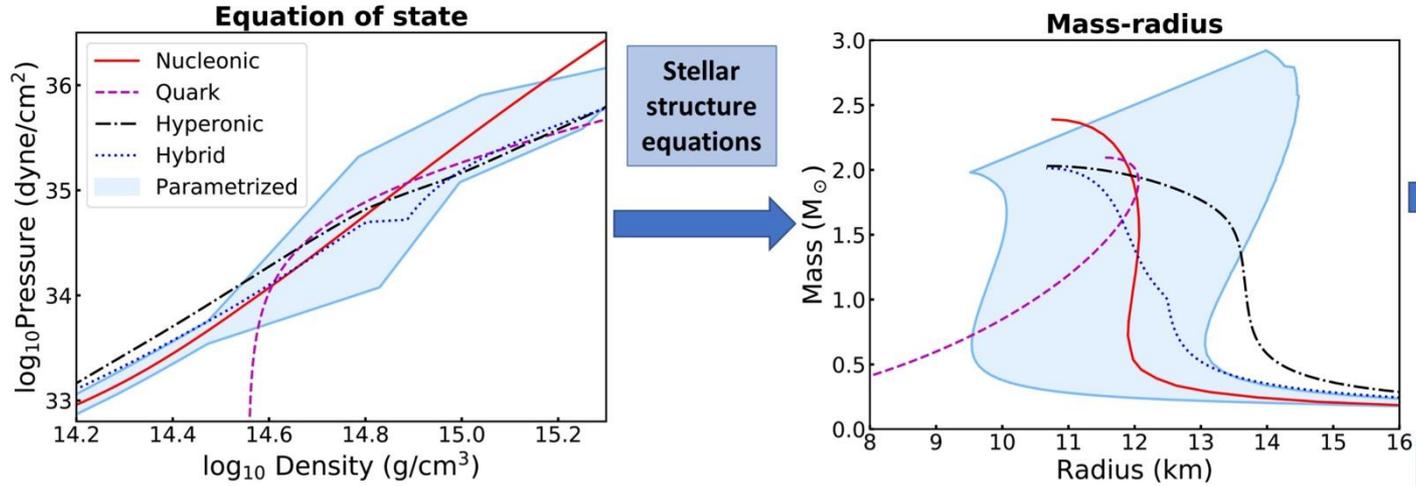# CONSISTENCY WITH GW?

PSR J0437-4715

PSR J0740+6620

PSR J0030+0451

PSR J1231-1411

PSR J0614-3329

GW170817: LSC and VSC 2018

EQUATION OF STATE INFERENCE

Equation of state

Nucleonic
Quark
Hyperonic
Hybrid
Parametrized

$\log_{10}$Pressure (dyne/cm^2)

$\log_{10}$ Density (g/cm^3)

Stellar structure equations

Mass-radius

Mass (M$_\odot$)

Radius (km)

- 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**

EOS INFERENCE (EXAMPLE)
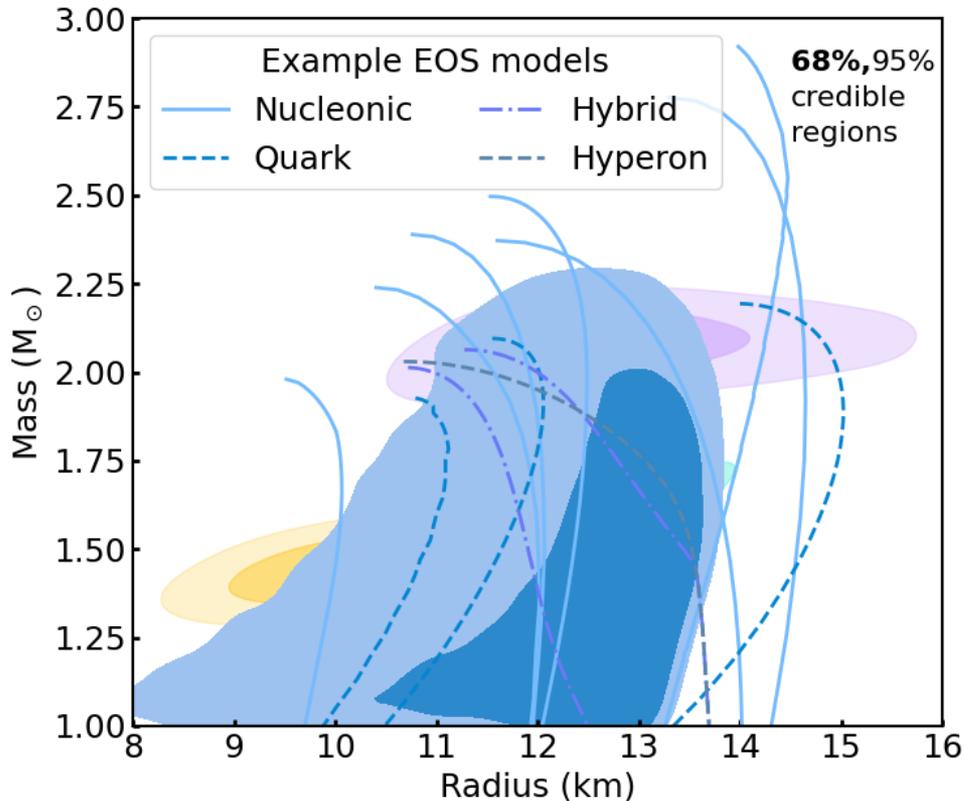
EOS model

- BPS outer crust
- cEFT up to 1.5 saturation density (Keller et al. 2023)
- Piecewise polytrope extensions at high density
- Full description and alternative models in Rutherford et al. 2024, see also Mauviard et al. 2025.

- Prior space for this model excludes high radii, favours radii around 12-13km.
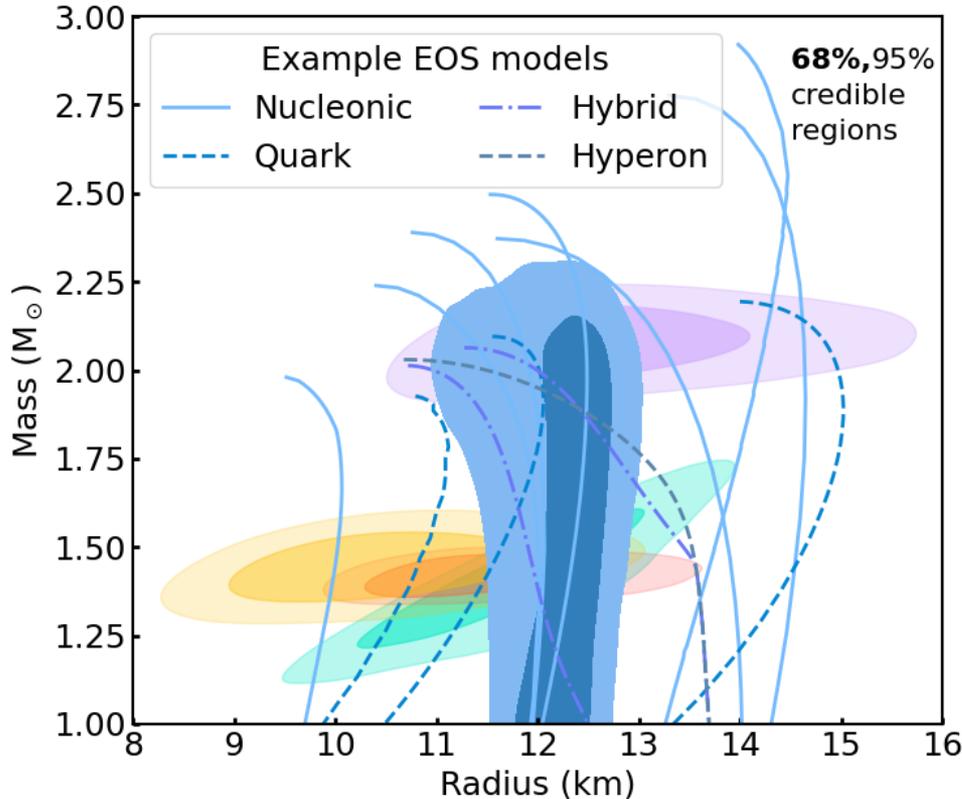
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EOS model

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- Prior space for this model excludes high radii, favours radii around 12-13km.

- Posteriors once NICER and GW data are included (Rutherford et al. 2024, see Mauviard et al. 2025 for an update that includes J0614).

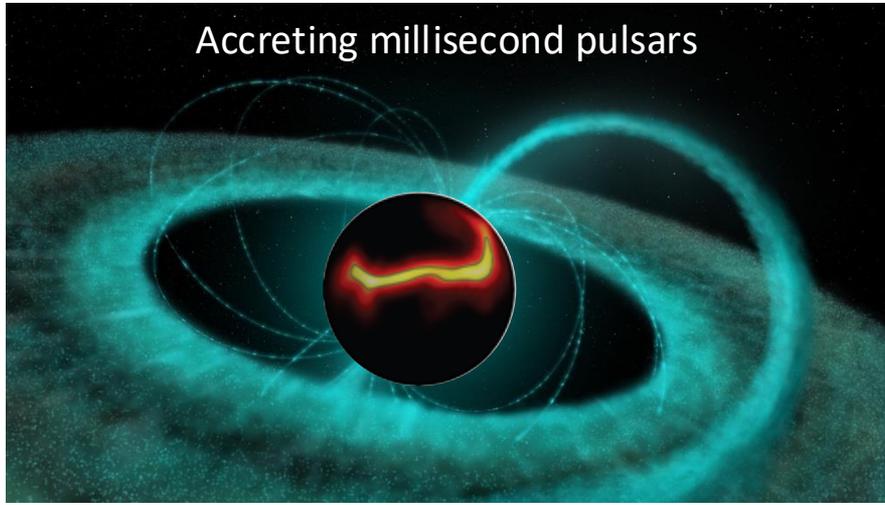NICER REPAIR – EVA 91, 16 JAN 2025

Image: NASA

June 2025: NICER operations suspended

Image: NASA

PPM FOR ACCRETING/BURSTING NEUTRON STARS

Accreting millisecond pulsars

Burst oscillations

- Spots are complex (Das et al. 24, 25).
- Understanding the disk is important (Dorsman et al. 25, 26)
- Polarimetry can help! (Salmi et al. 2025)
- Joint NICER/IXPE analysis for SGRA J1444 underway (Dorsman, Salmi + in prep)
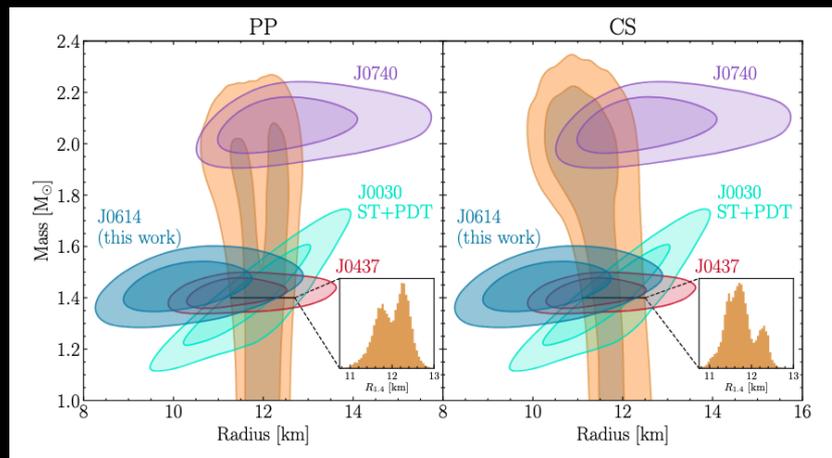
Variability a major challenge, but solvable (Kini et al. 23,24a)
First results find small R (Kini et al. 24b) – but model needs work.

AMPs a major target for eXTP (launch 2030)

Improved surface pattern models for all source types
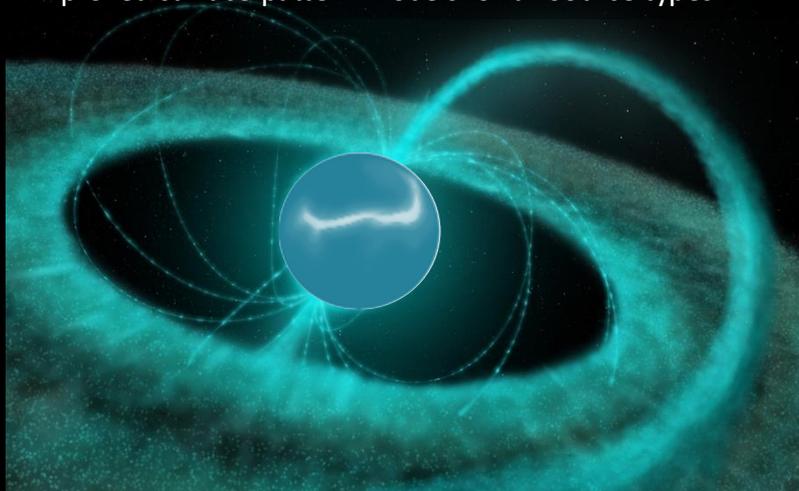
EOS analysis: follow on (e.g. Rutherford et al. 2024, Mauviard et al. 2025) and now more integrated in PPM (Hoogkamer et al. 2026)

NICER legacy - 8 yrs of amazing data!   New X-ray telescopes: eXTP (2030), NewAthena   Better priors from radio pulsar timing

SUMMARY

- **Results to date for rotation-powered millisecond pulsars point to a soft to medium stiffness EOS, and non-dipolar fields.**

- **More data and sources to come.**

- **PPM pipelines are evolving e.g more physical surface patterns, EOS informed priors……**

- **PPM is now being applied to accreting neutron stars, and we are preparing for new telescopes (eXTP, NewAthena)**

X-PSI results shown here: Vinciguerra et al. 2024, Salmi et al. 2024, Choudhury et al. 2025, Mauviard-Haag et al. 2025