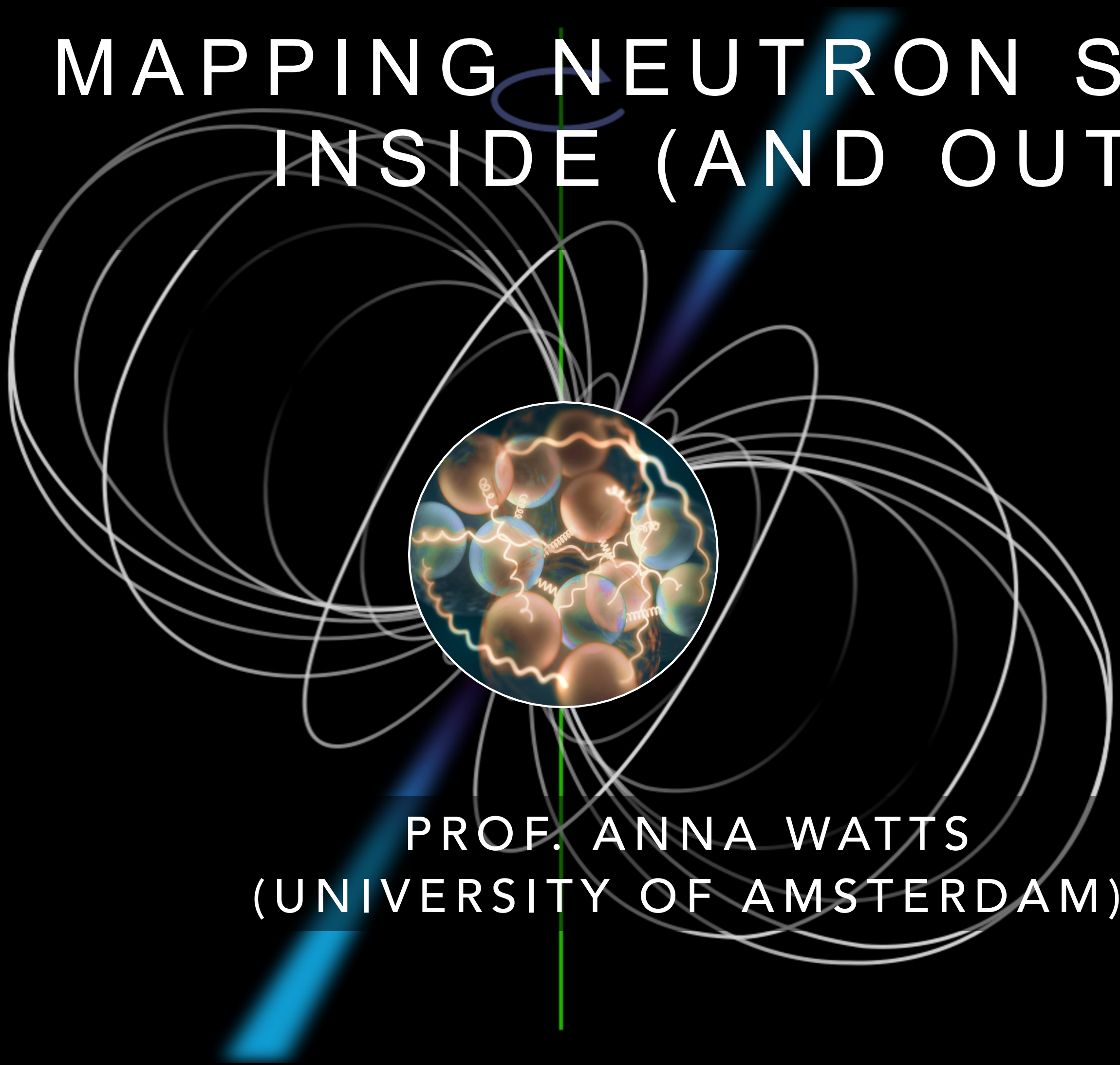
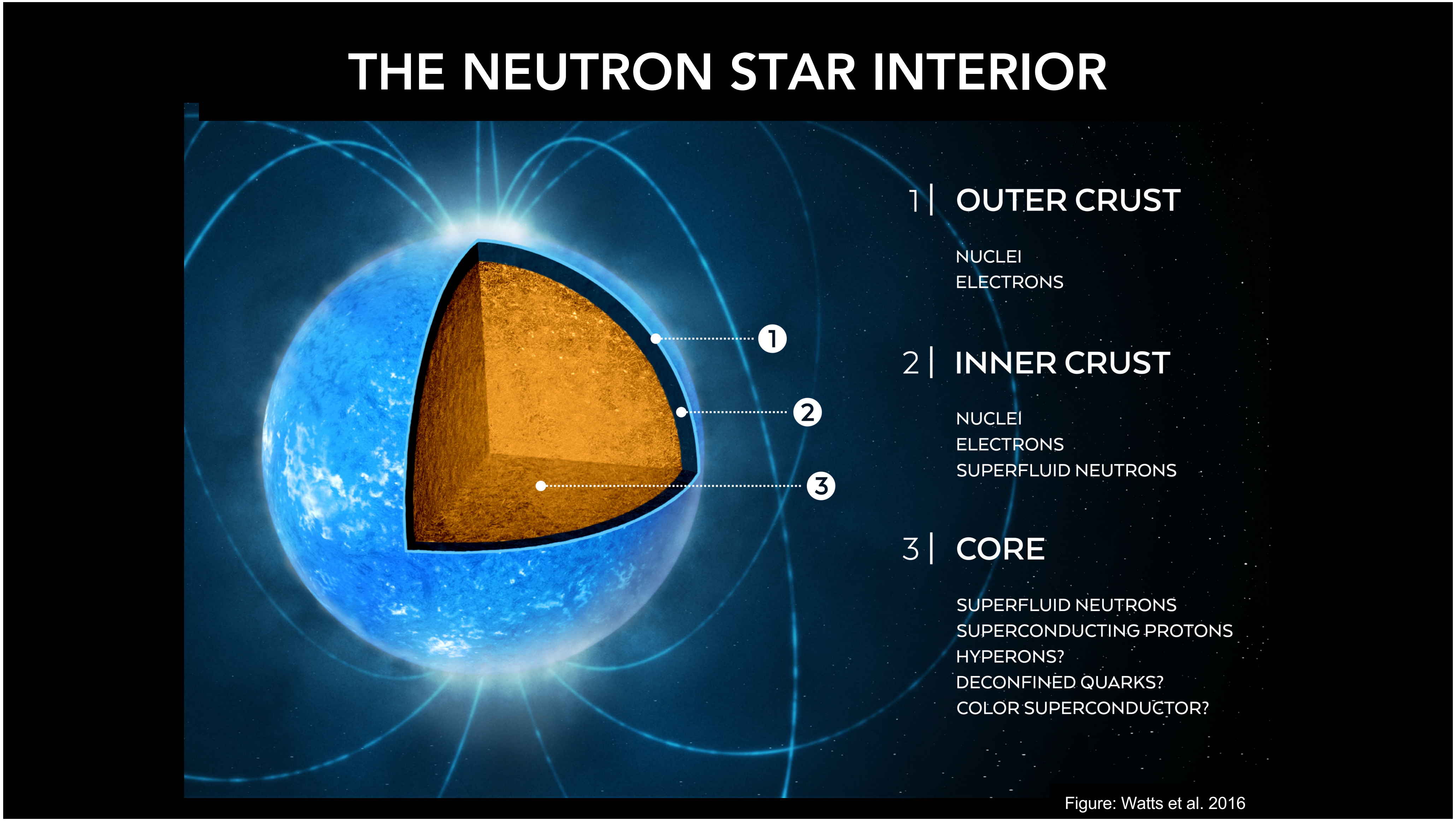
MAPPING NEUTRON STARS INSIDE (AND OUT)



PROF. ANNA WATTS
(UNIVERSITY OF AMSTERDAM)


THE NEUTRON STAR INTERIOR
1
2
3
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

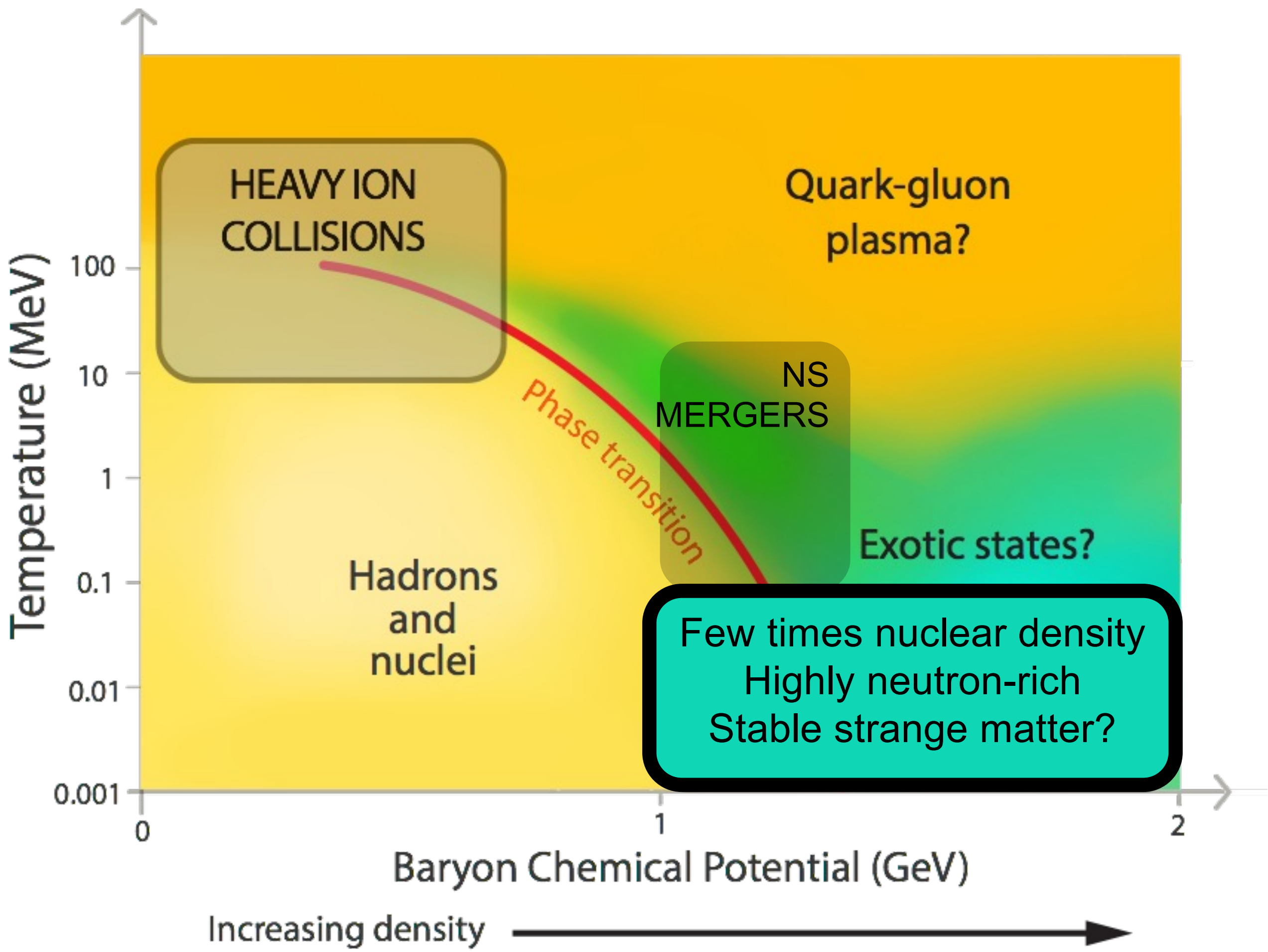


Figure: Adapted from Watts et al. 2016

FROM NUCLEAR PHYSICS TO TELESCOPE (AND BACK)

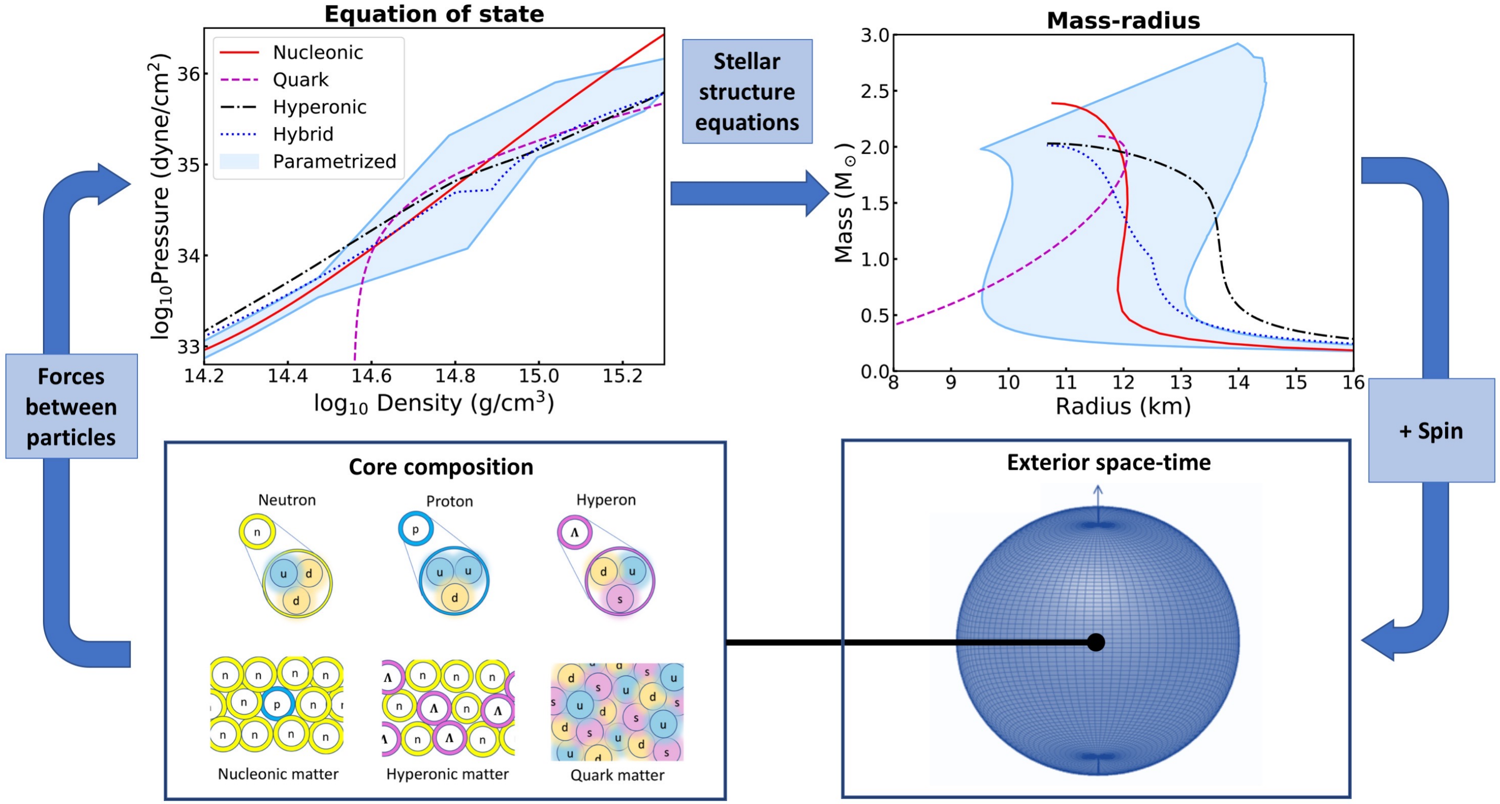
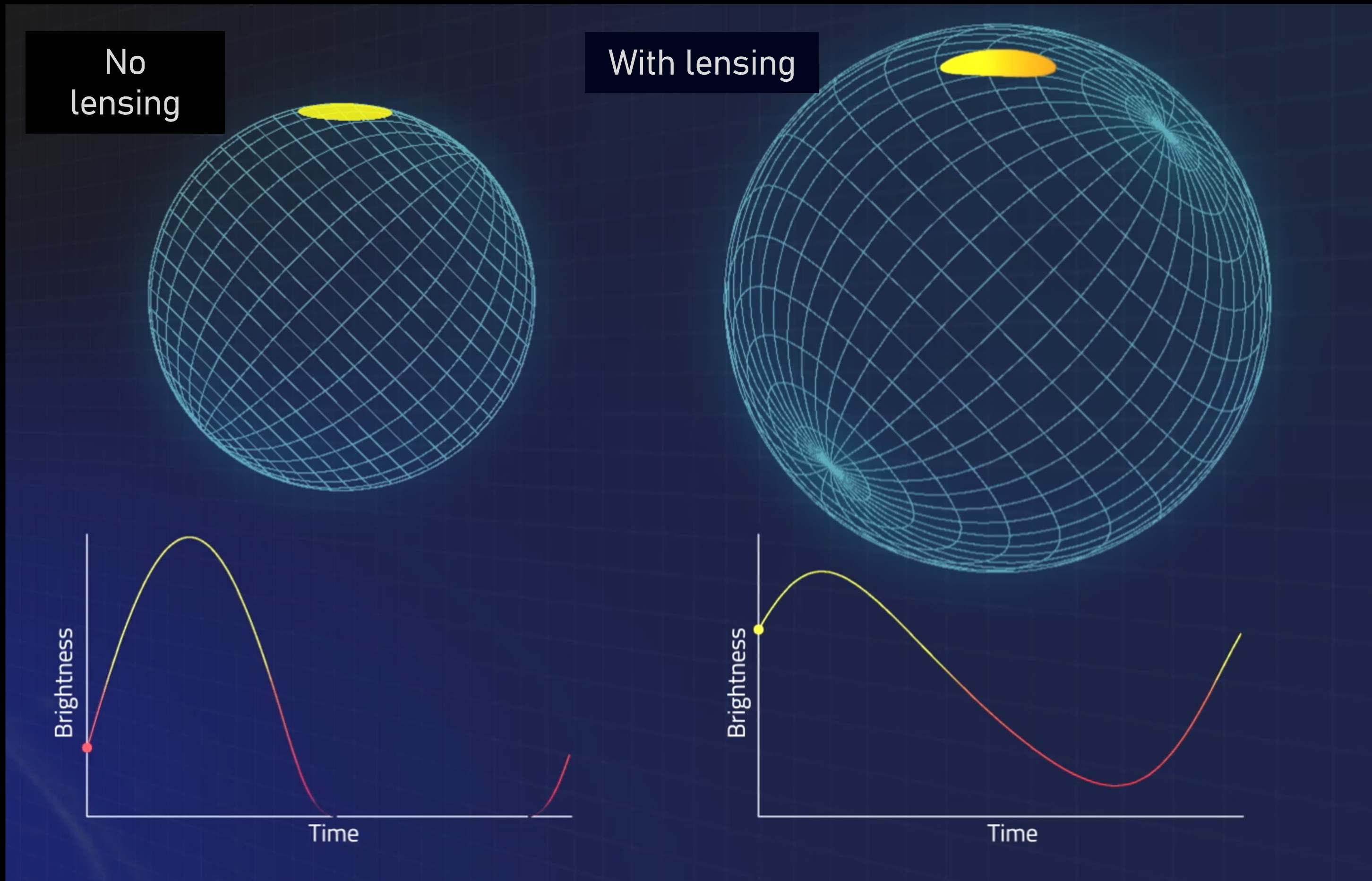


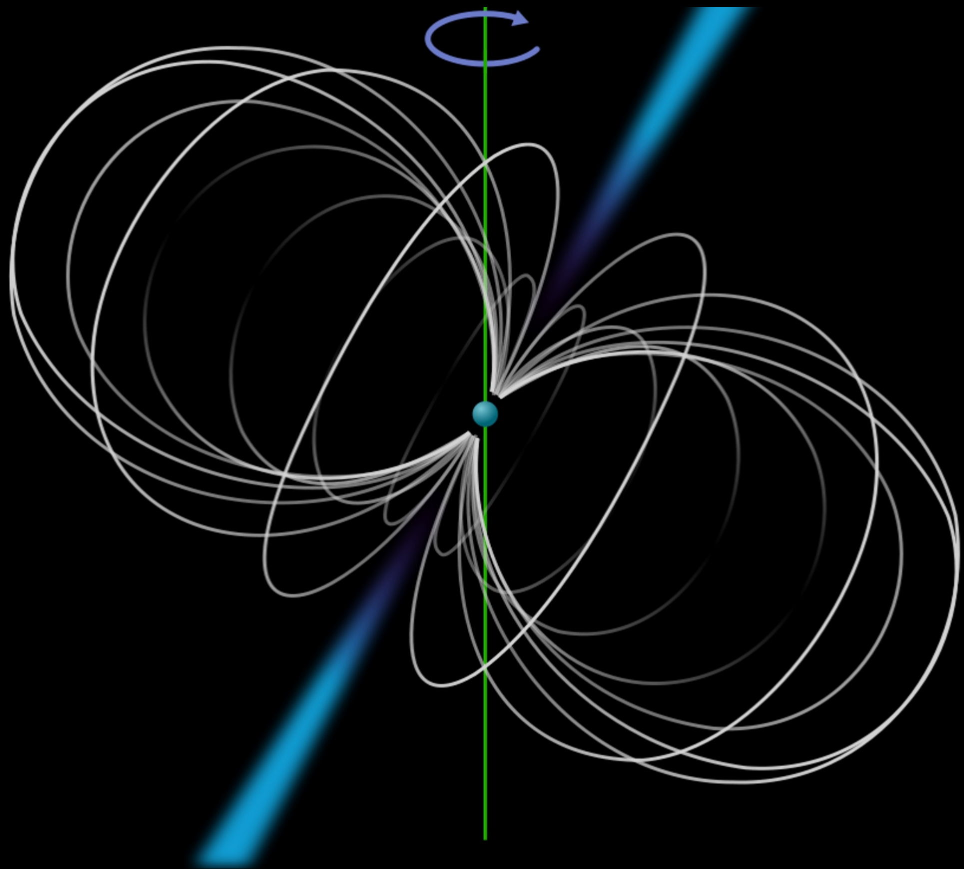
Figure: Adapted from Ray et al. 2019

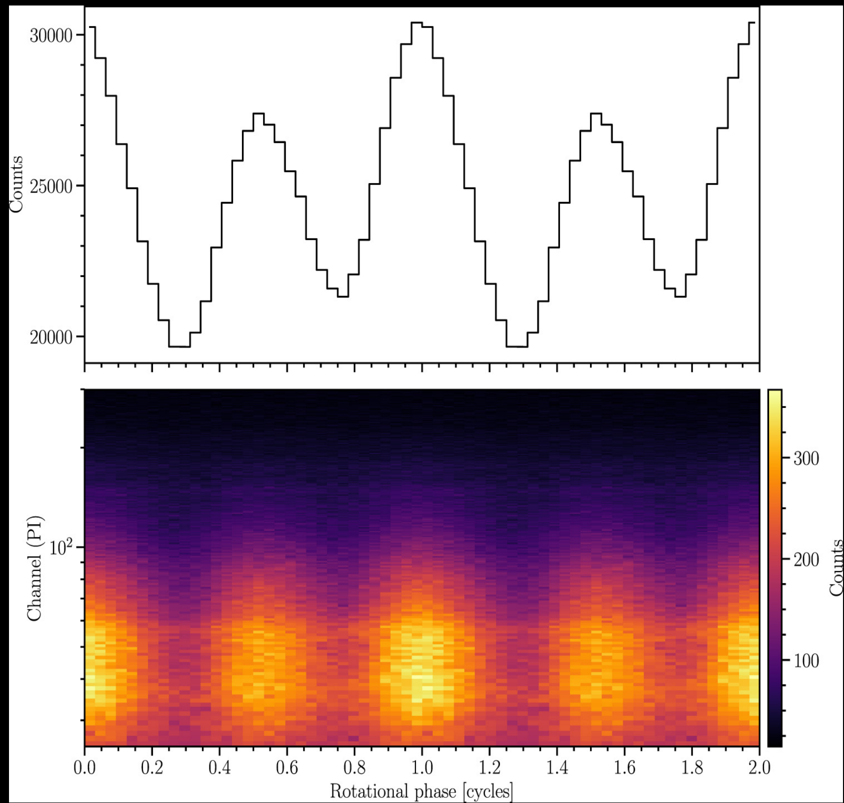
PULSE PROFILE MODELING (PPM)

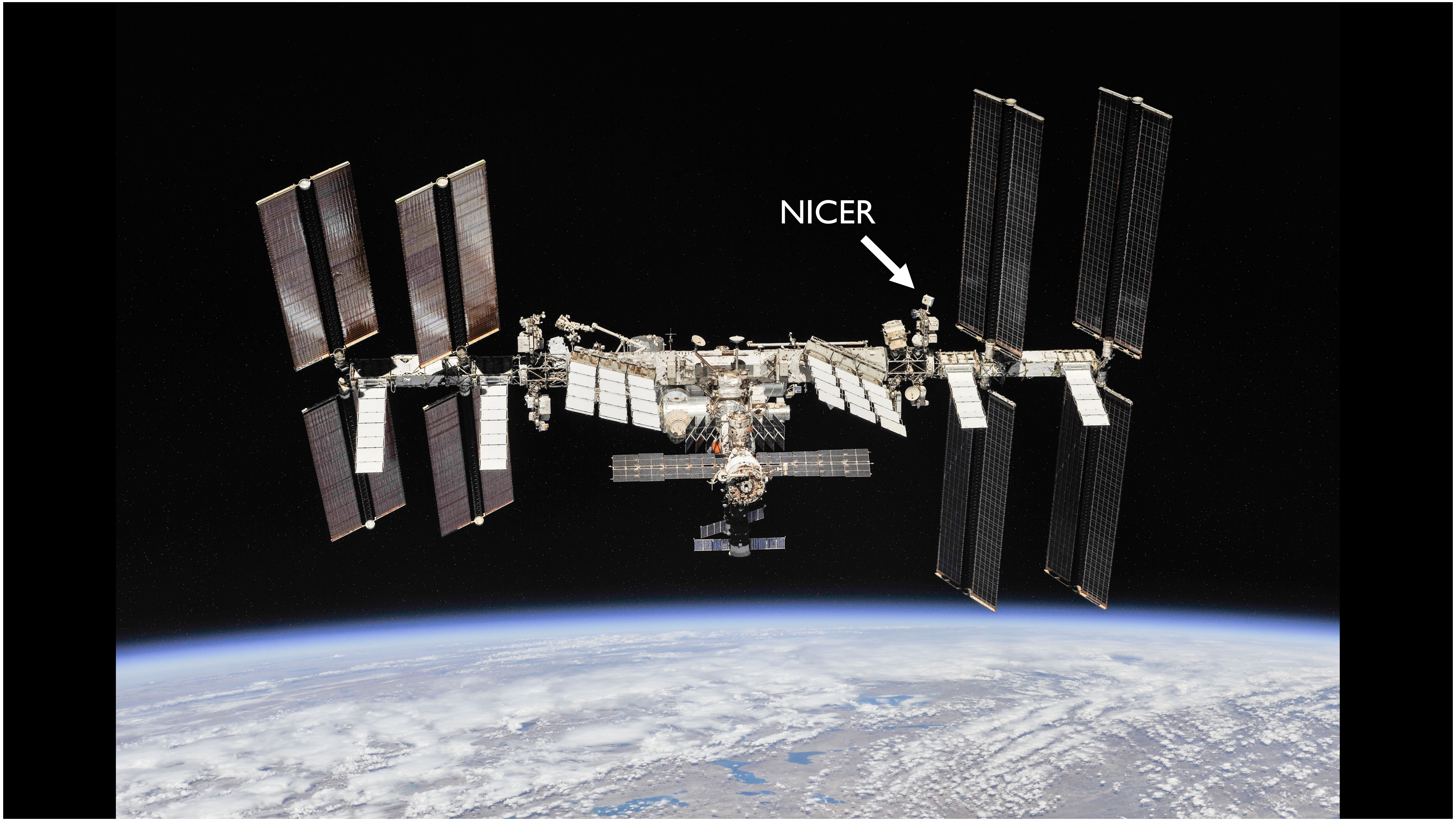


Credit: Morsink/Moir/Arzoumanian/NASA-GSFC

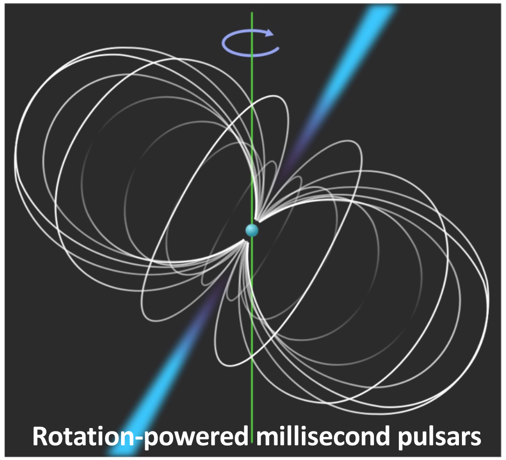
ROTATION-POWERED MILLISECOND X-RAY PULSARS






NICER

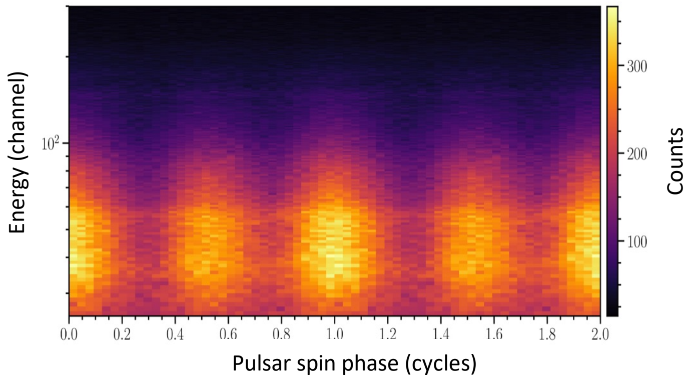
THE PULSE PROFILE MODELING TECHNIQUE



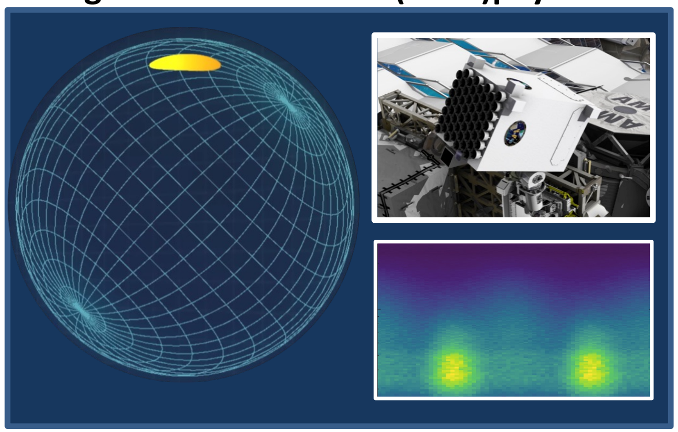
Physics and priors

- 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



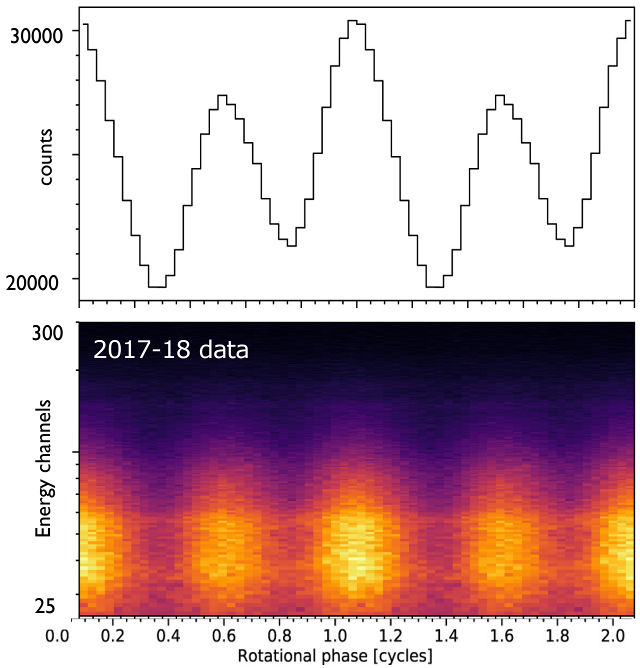
Bayesian inference of model parameters (statistical sampling)

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

EXAMPLE PULSE PROFILE DATA SETS

PSR J0030+0451

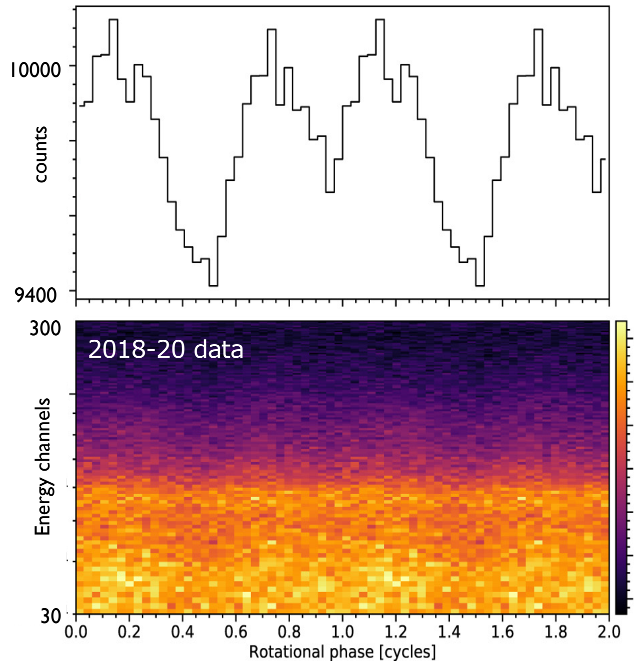
- Bright source
- Isolated system



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

PSR J0740+6620

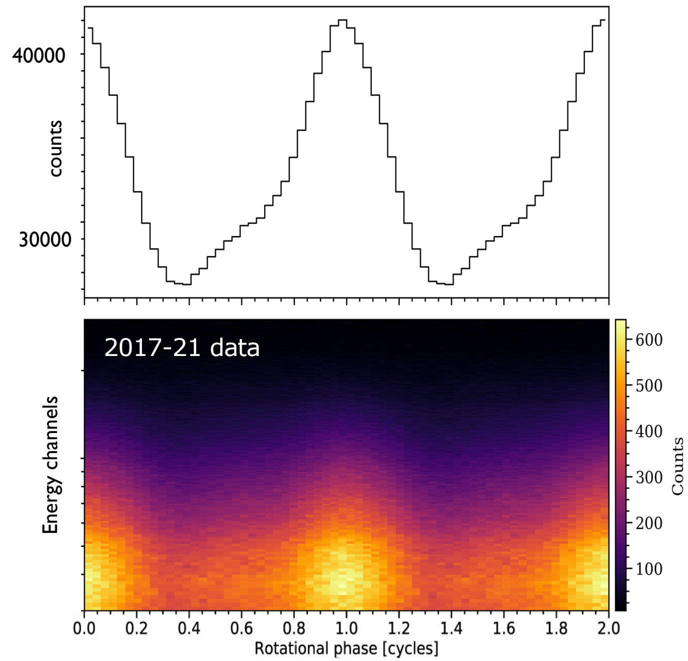
- Faint source
- Binary - mass $2.1 M_\odot$



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

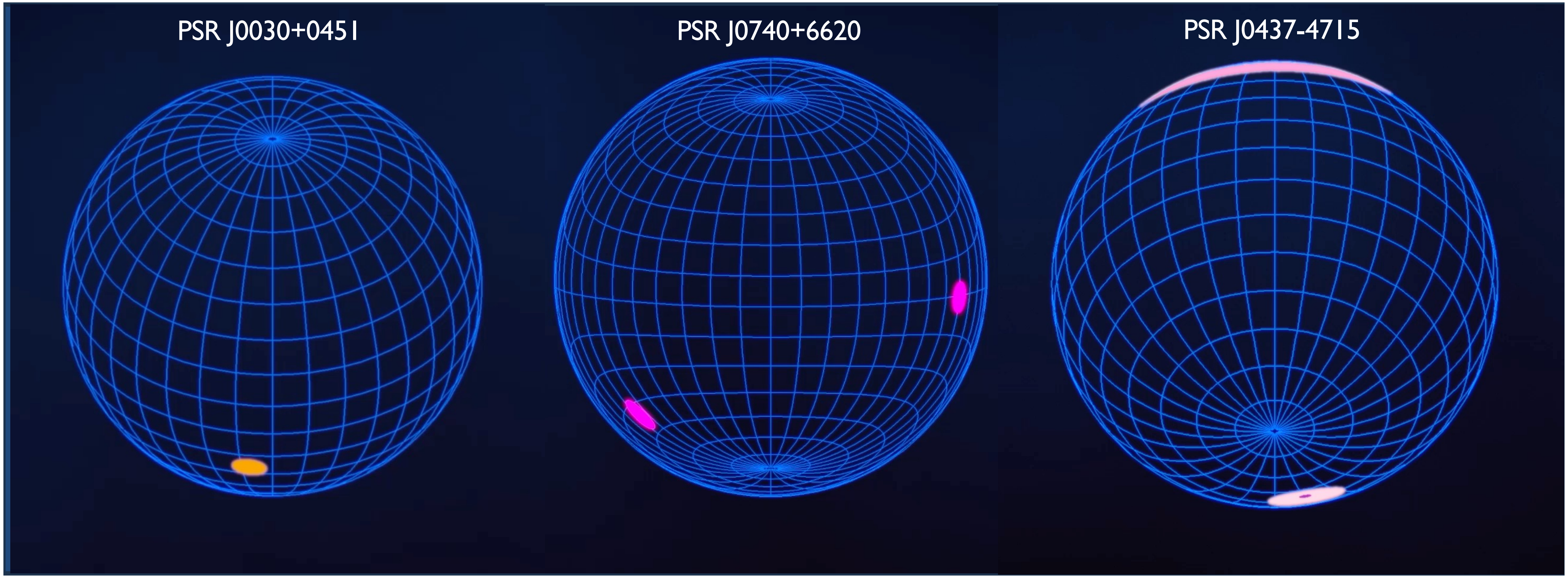
PSR J0437–4715

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



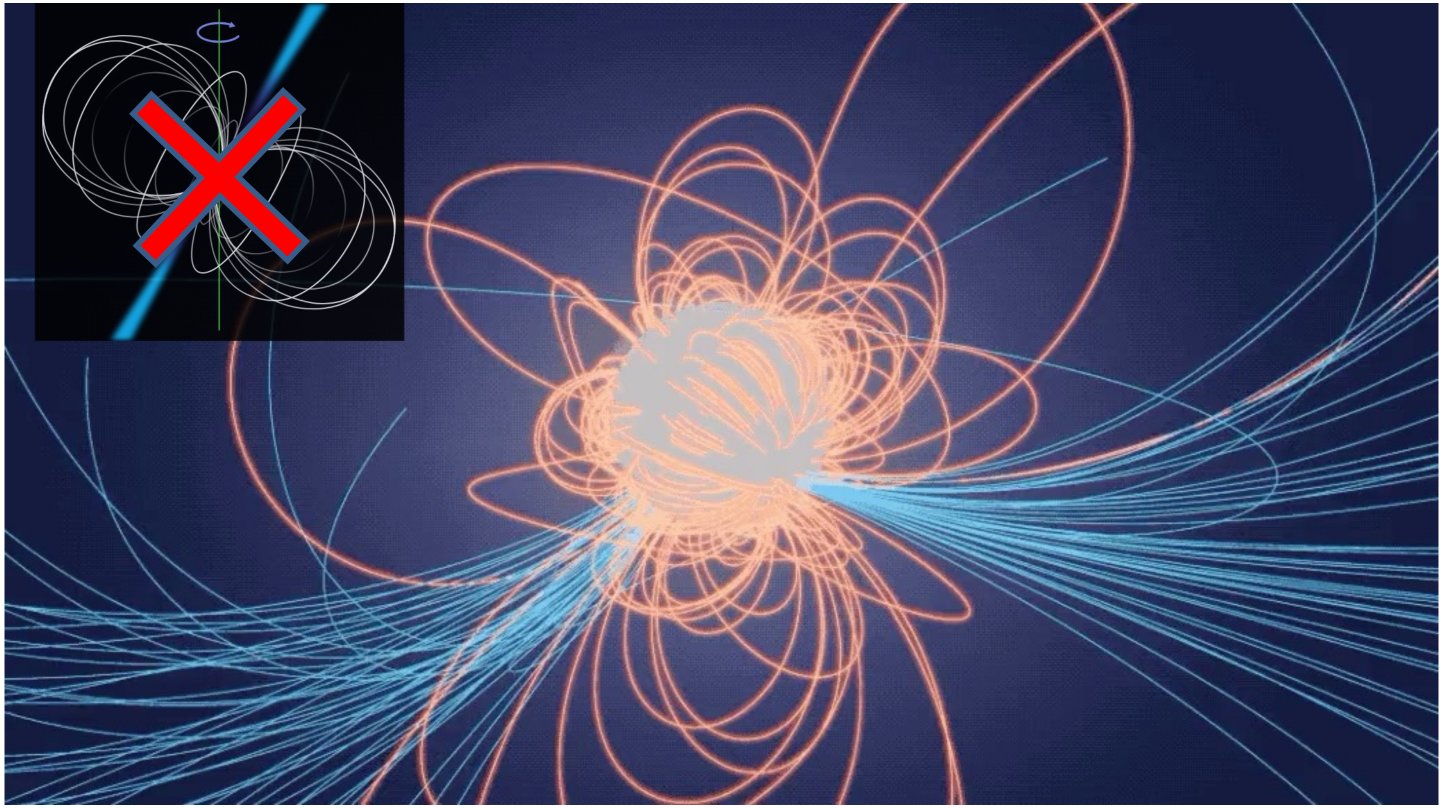
Choudhury et al. 2024, *Miller et al. 2026*

MAPPING THE HOT MAGNETIC POLES



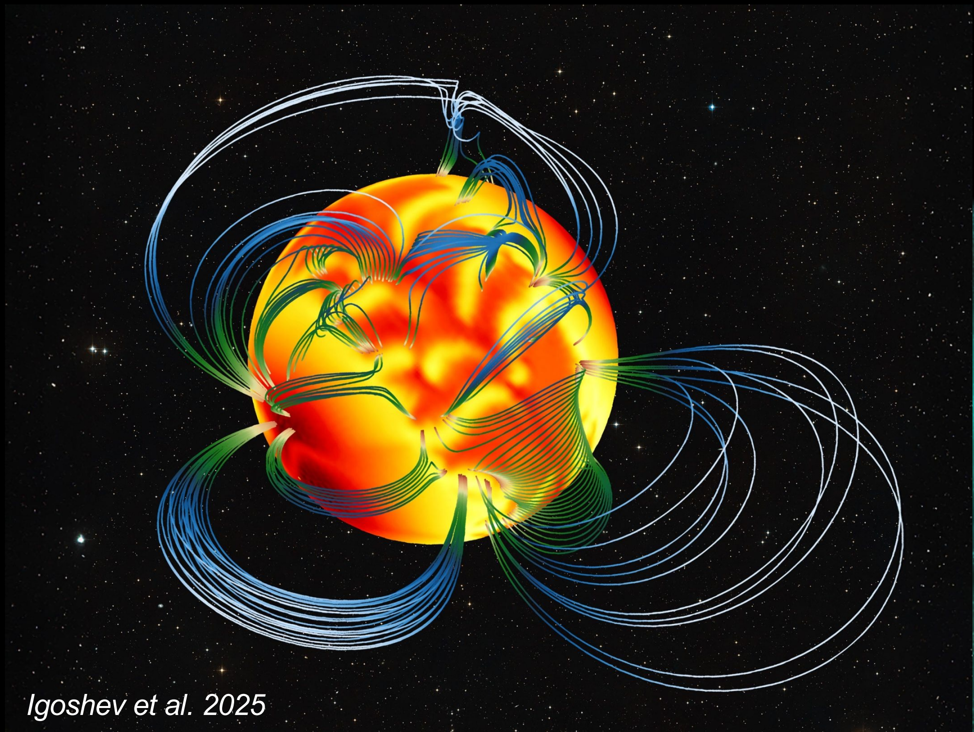
As seen from Earth
Results from the X-PSI pipeline (https://github.com/xpsi-group/xpsi, also Riley et al. 2023 JOSS)
Maps from Riley et al. 2019, Riley et al. 2021, Choudhury et al. 2024 + Morsink/NASA

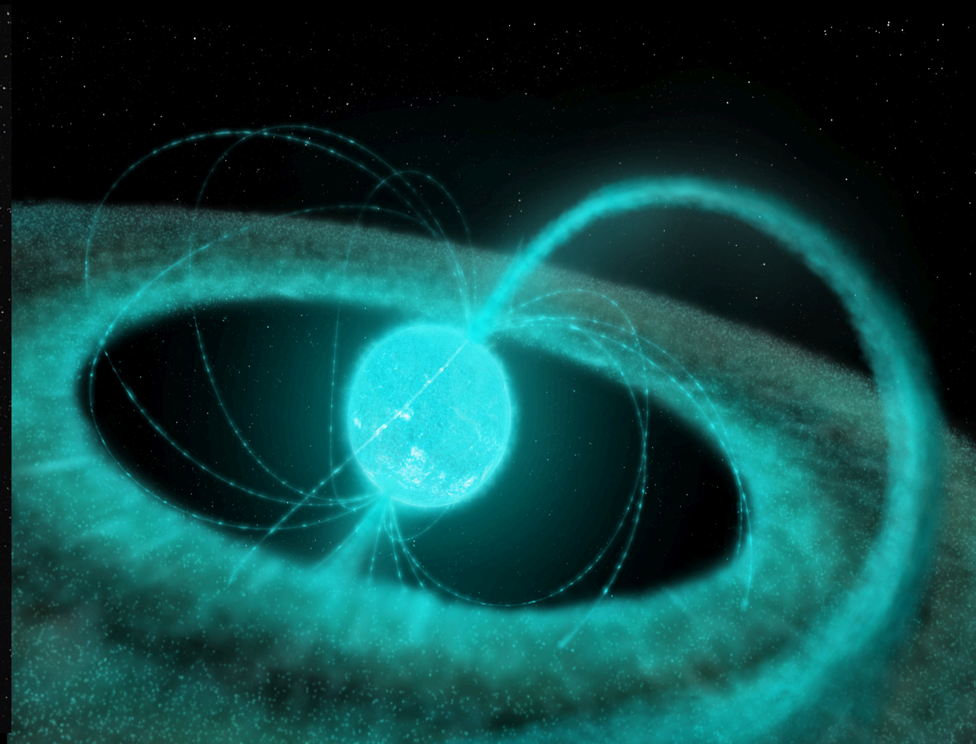
NON-DIPOLAR MAGNETIC FIELD?



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

HOW DID SUCH FIELDS FORM?

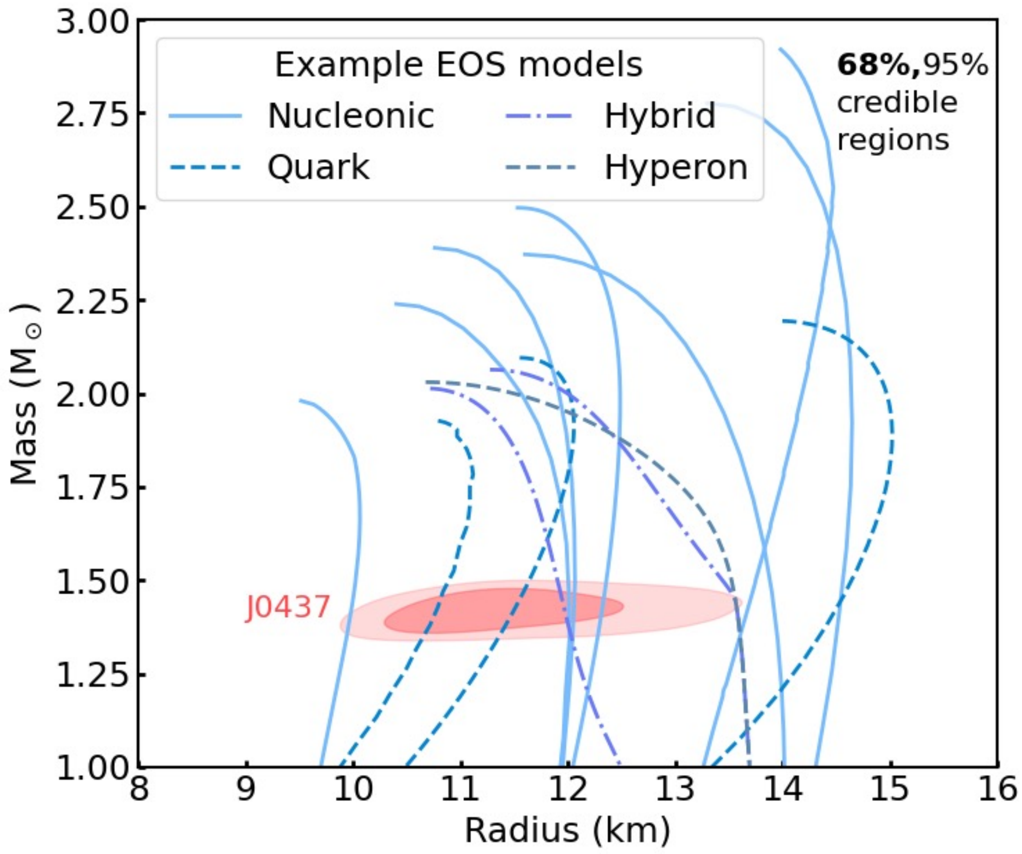




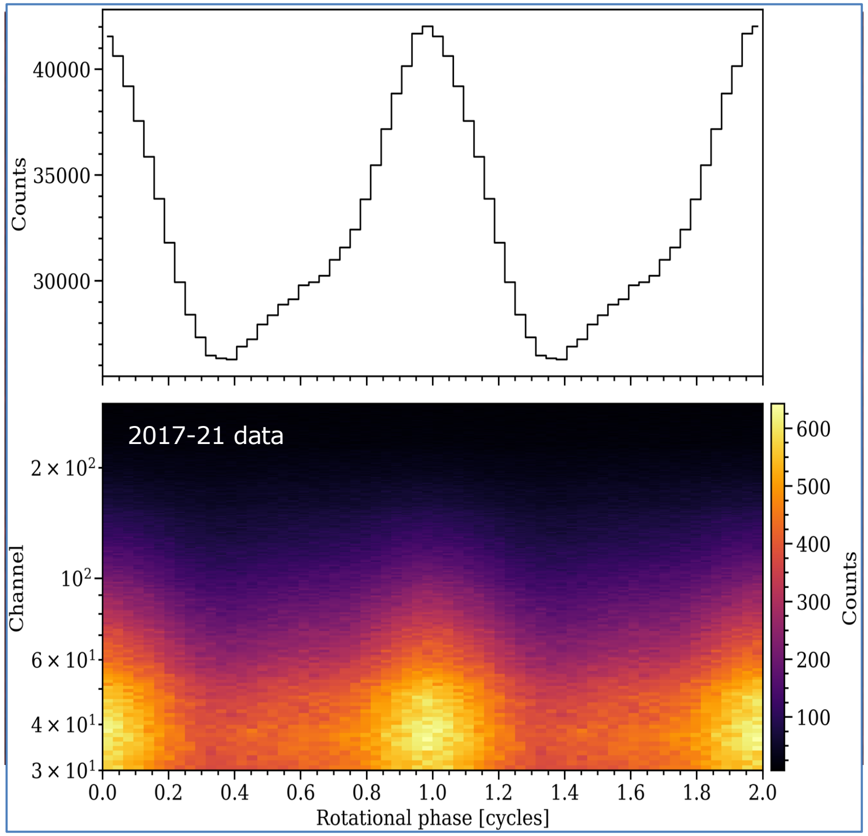
Early in life, perhaps during supernova?

During accretion phase that recycled these pulsars to millisecond periods?

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

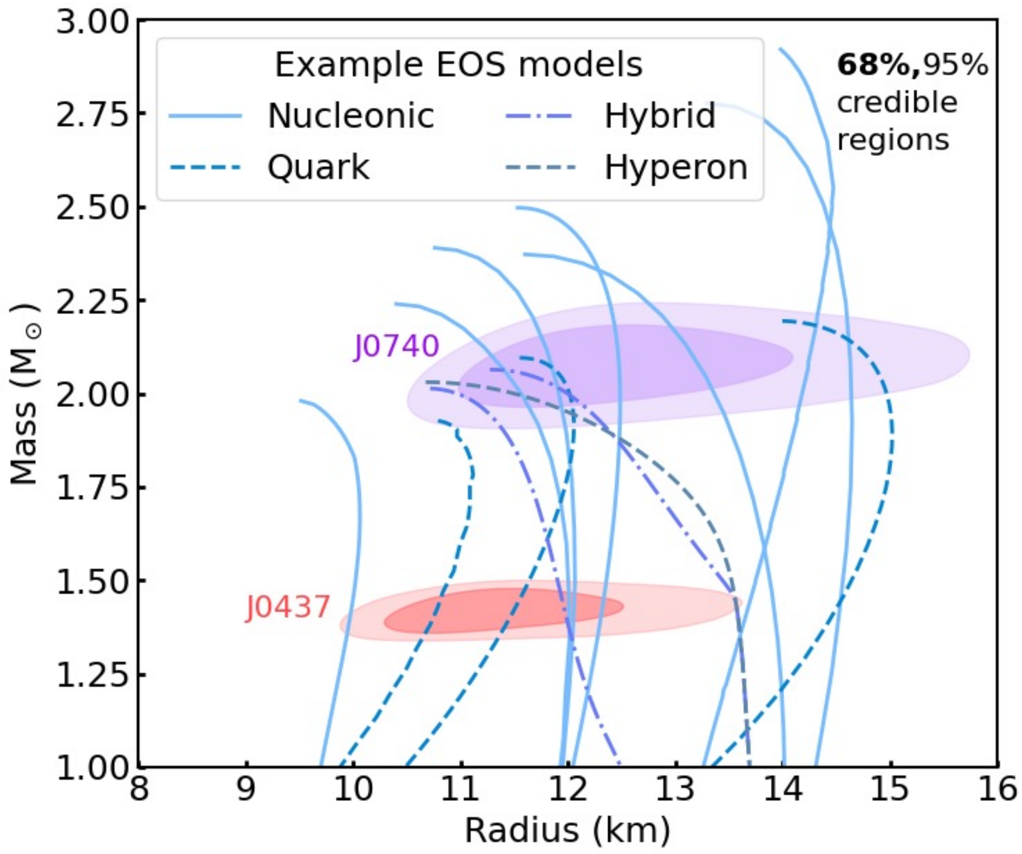


Choudhury et al. 2024, Mass prior from Reardon et al. 2024



Bogdanov et al. 2019

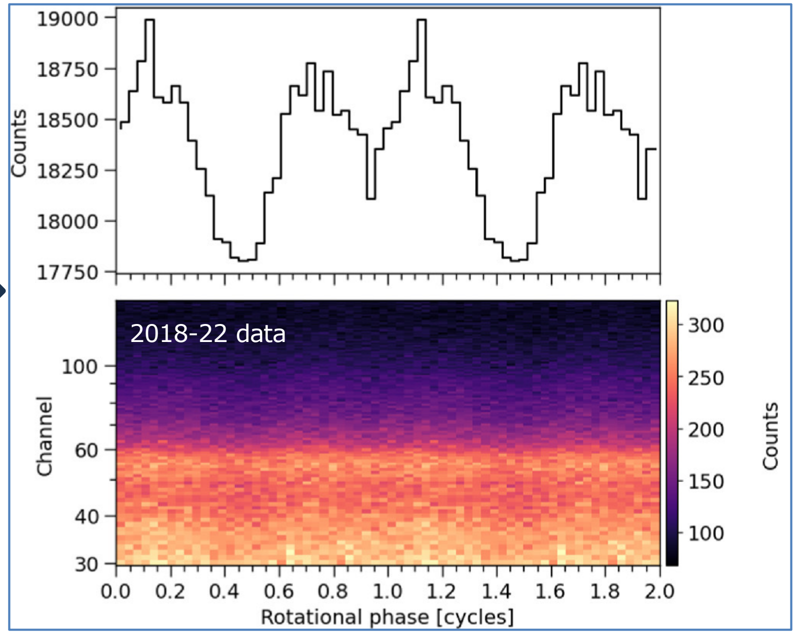
PSR J0740+6620: A FAINT 2.1 $M_\odot$ PULSAR



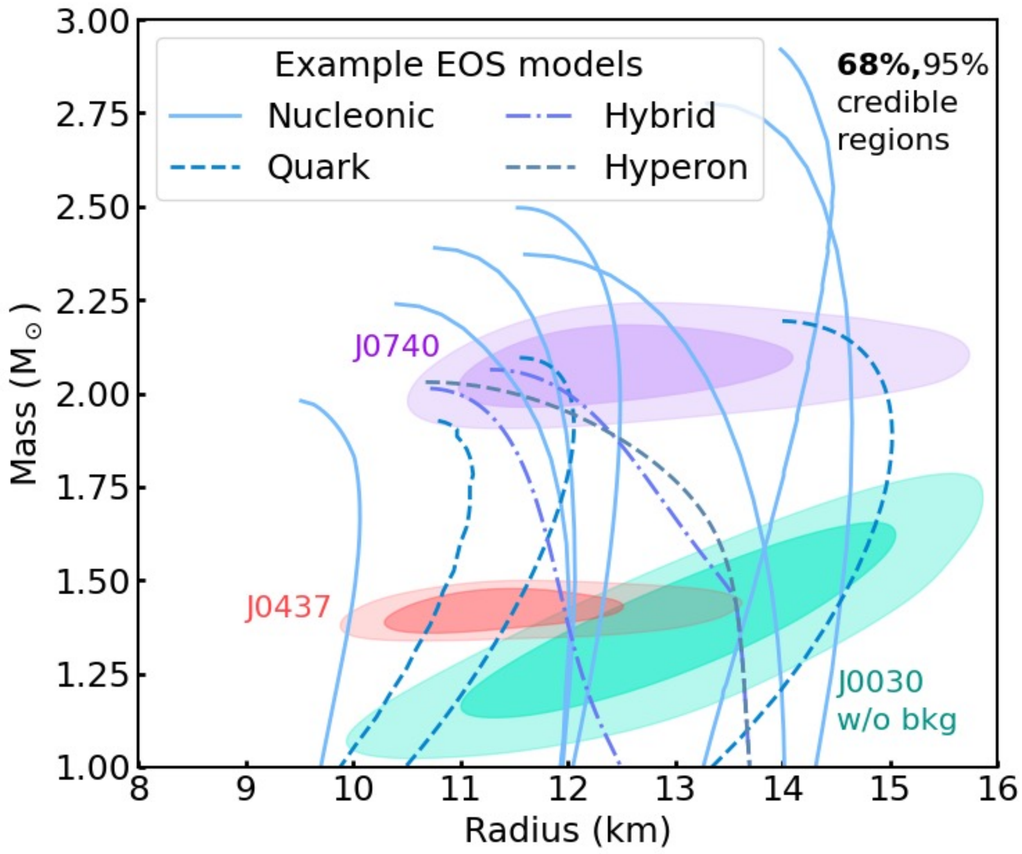
Salmi et al. 2024a, Mass prior from Fonseca et al. 2021

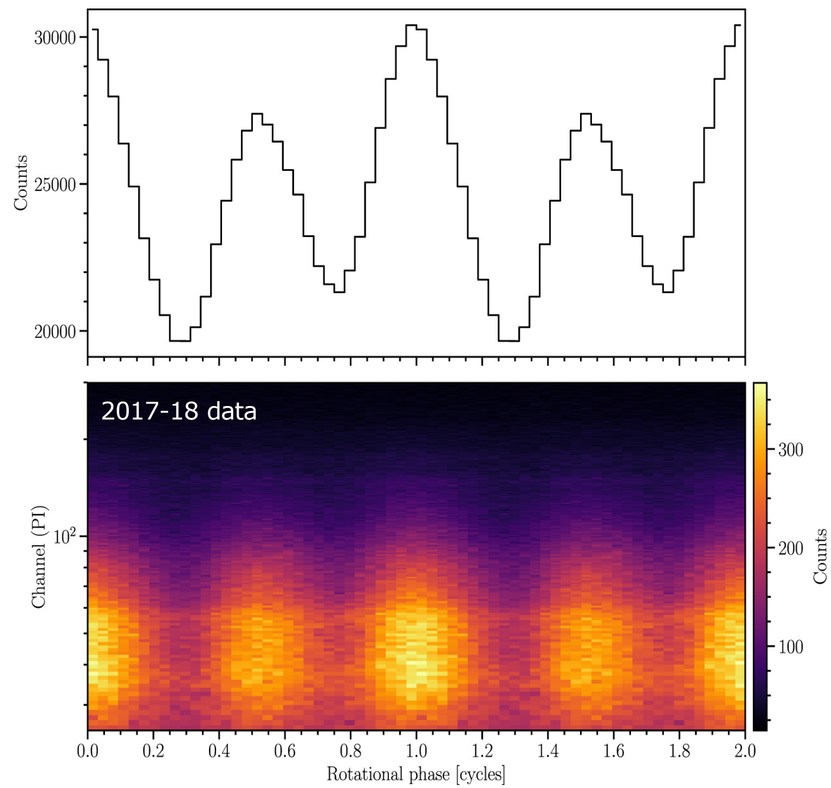
"Unpulsed" component:

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



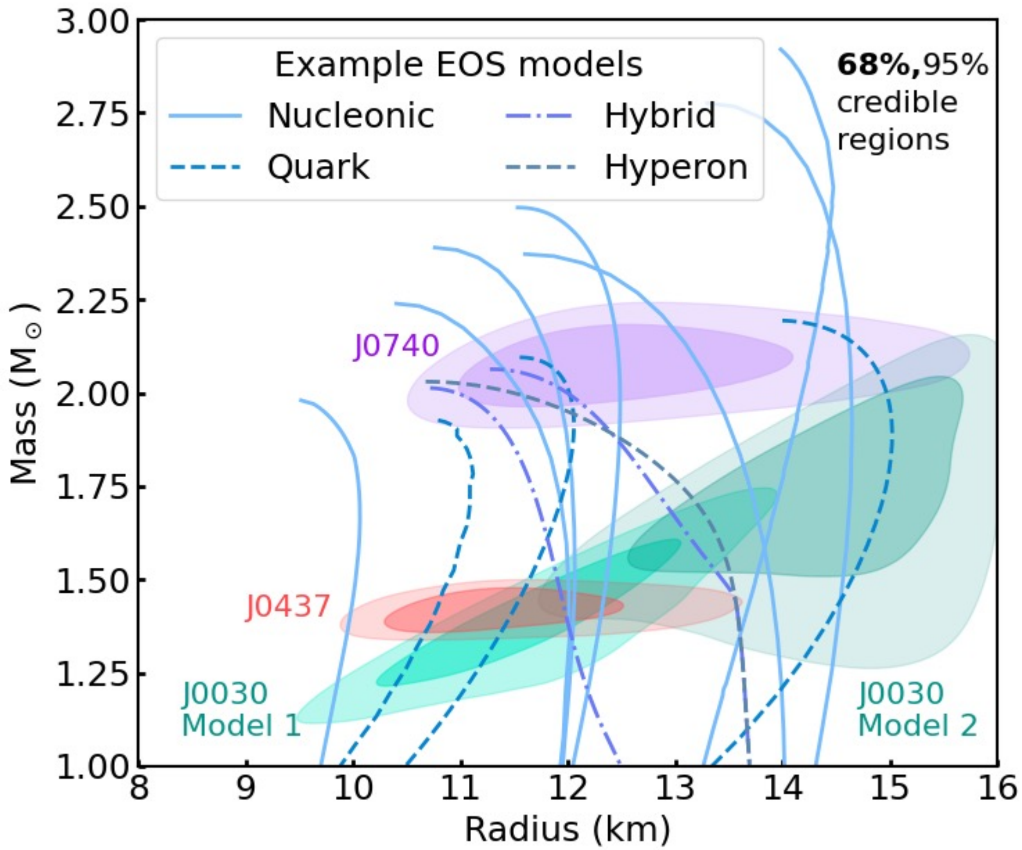
PSR J0030+0451: AN ISOLATED PULSAR

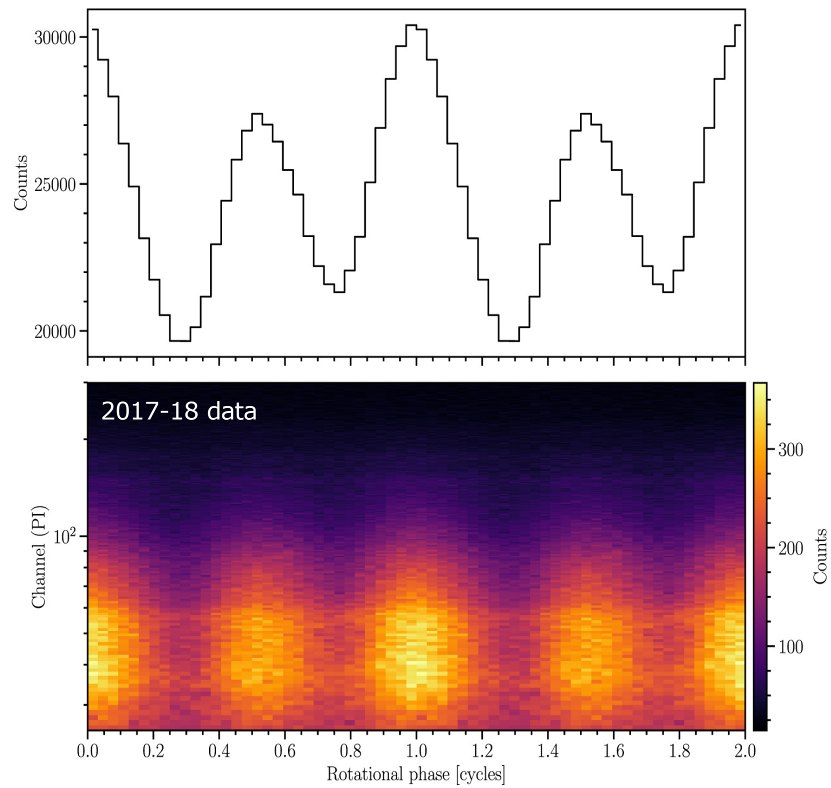




Riley et al. 2019

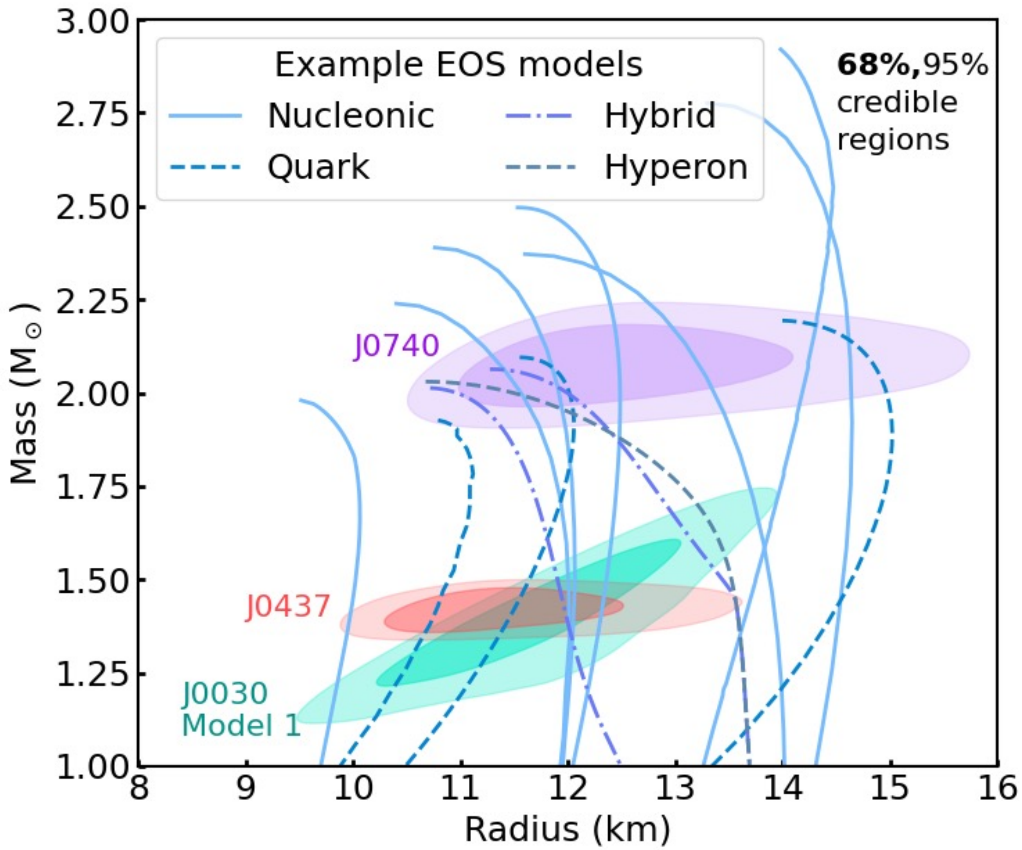
PSR J0030+0451: AN ISOLATED PULSAR

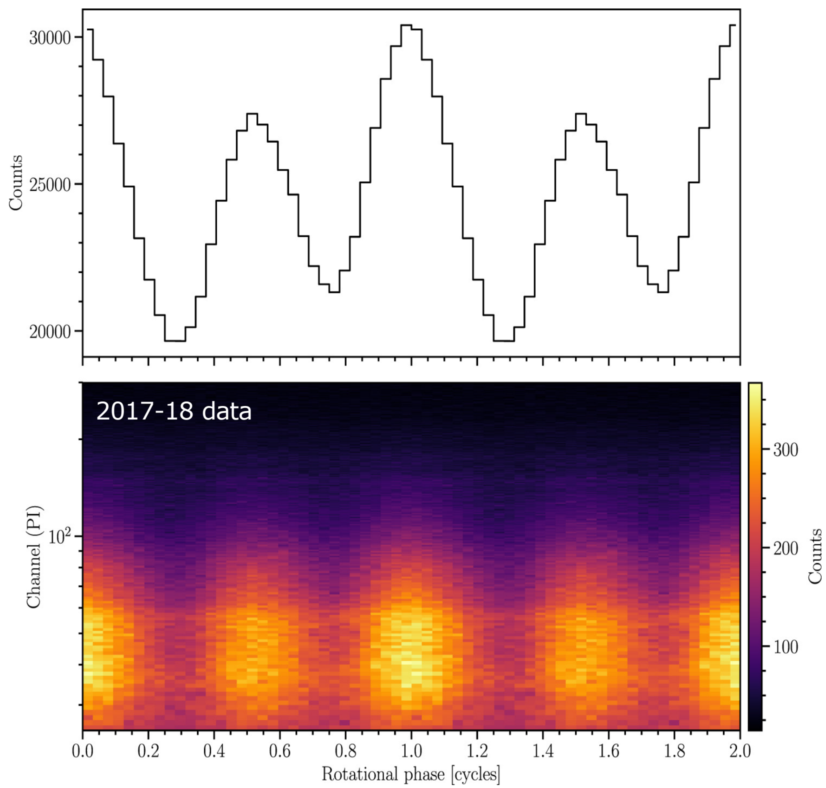




Vinciguerra et al. 2024: Include background constraints - different hotspot geometries possible.

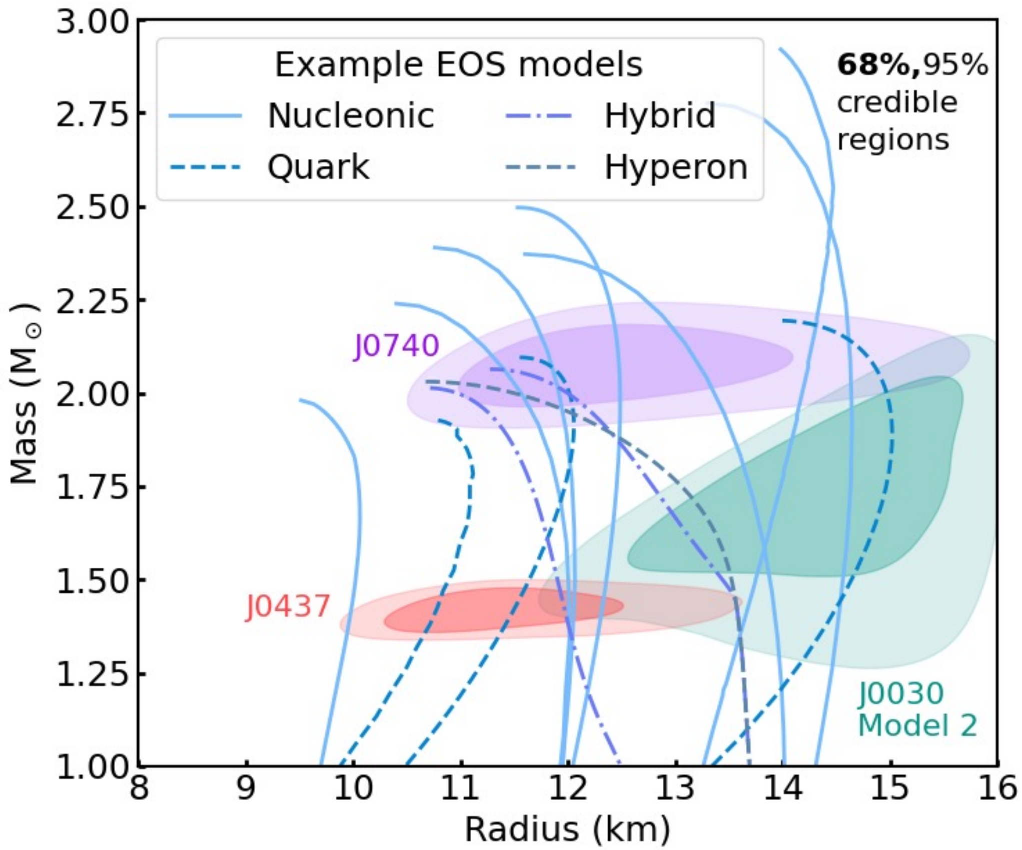
PSR J0030+0451: AN ISOLATED PULSAR

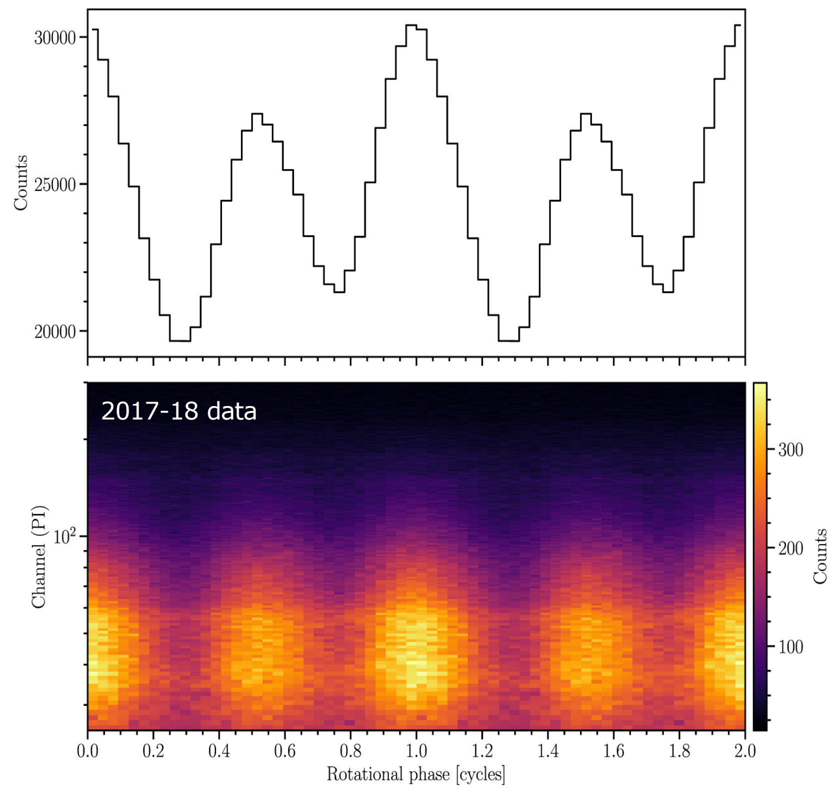




Vinciguerra et al. 2024: Include background constraints - different hotspot geometries possible.

PSR J0030+0451: AN ISOLATED PULSAR





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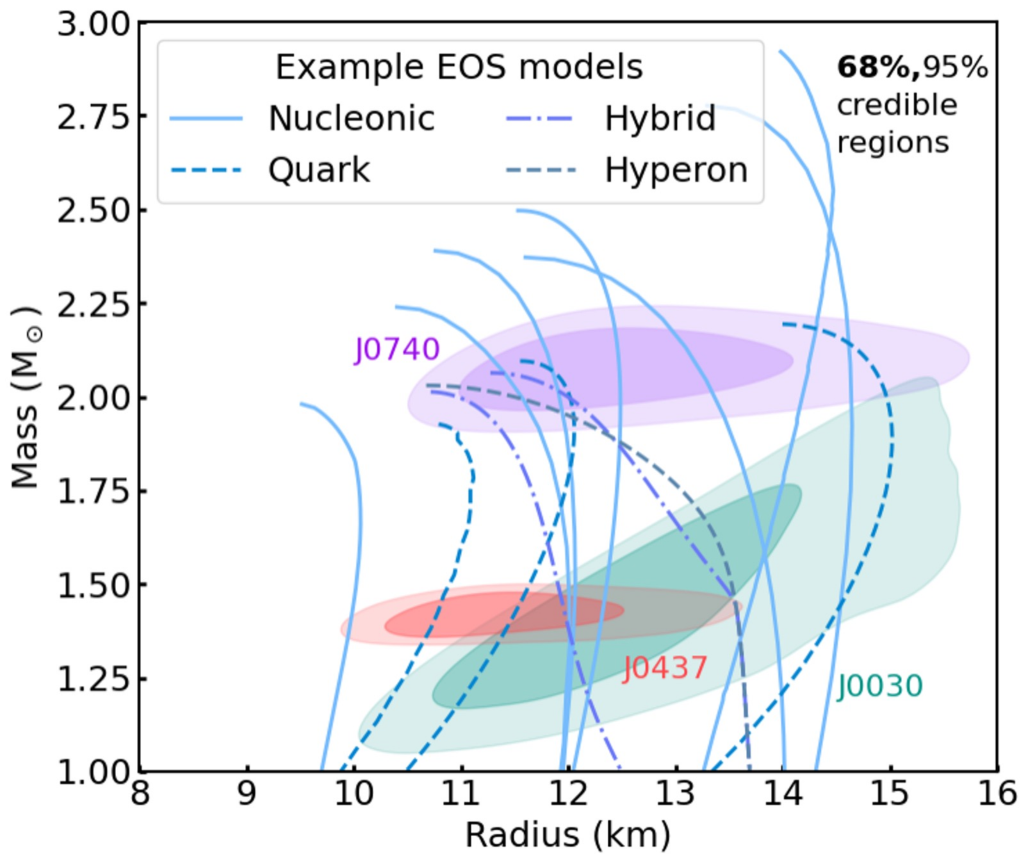
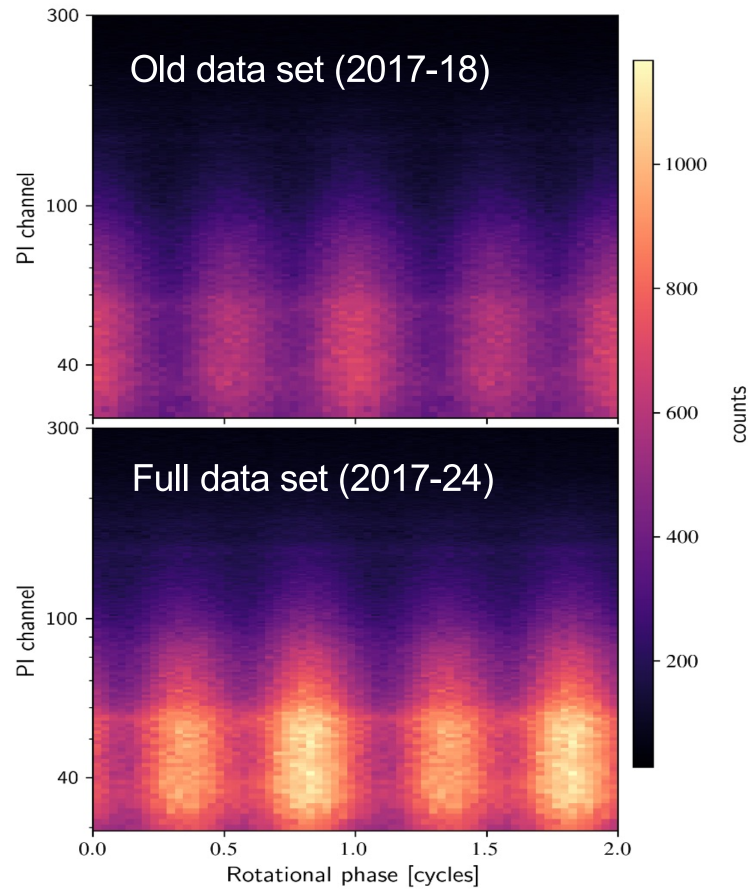
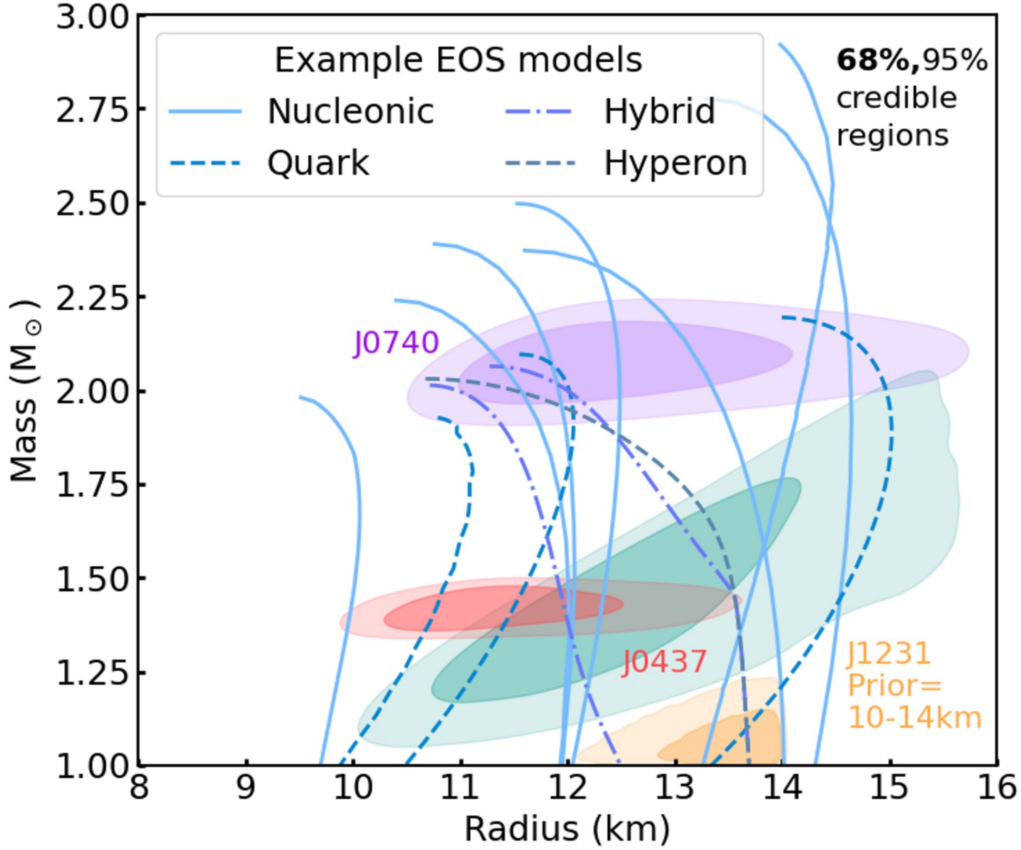
PSR J0030+0451: AN ISOLATED PULSAR



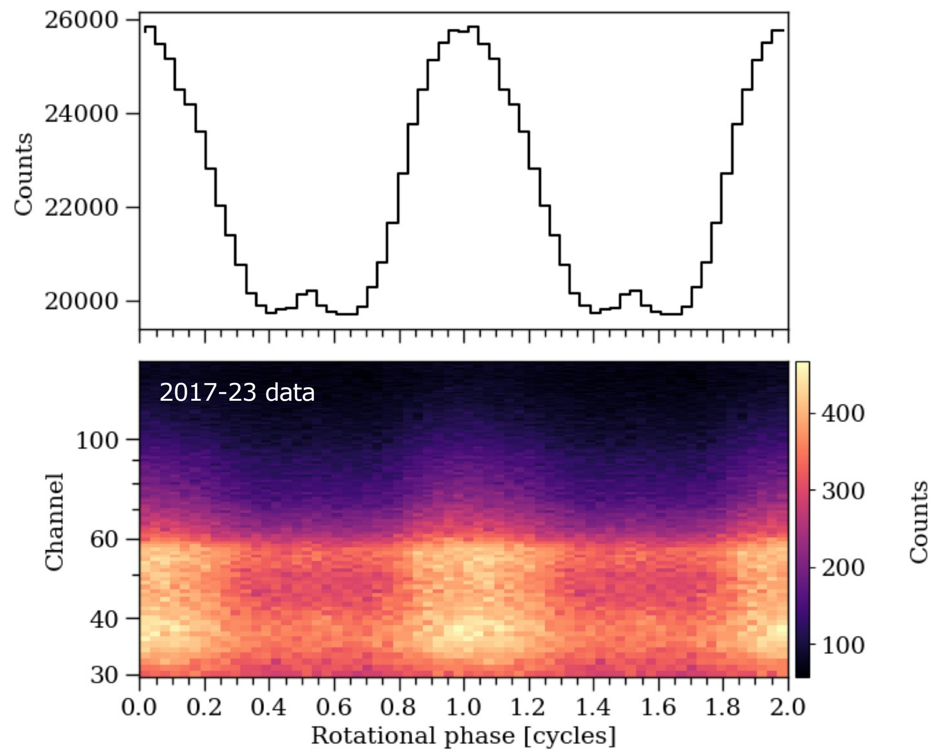


Kini et al. 2026

PSR J1231-1411: AN UNCOOPERATIVE PULSAR

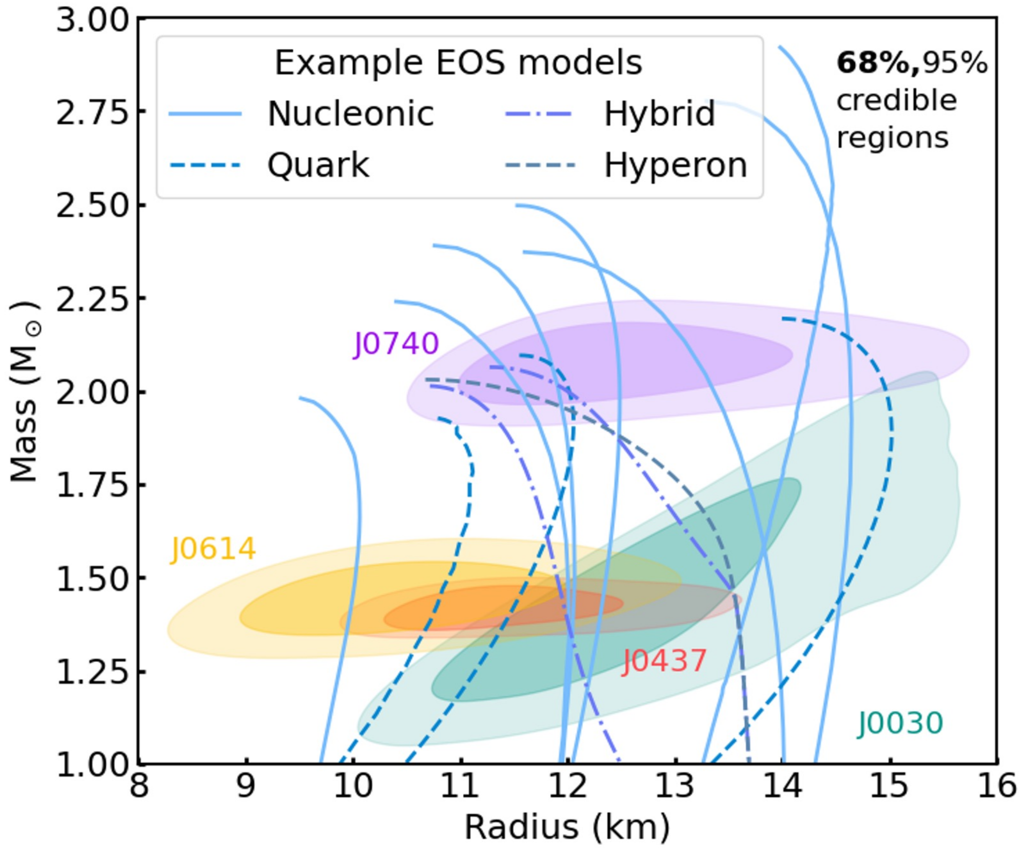


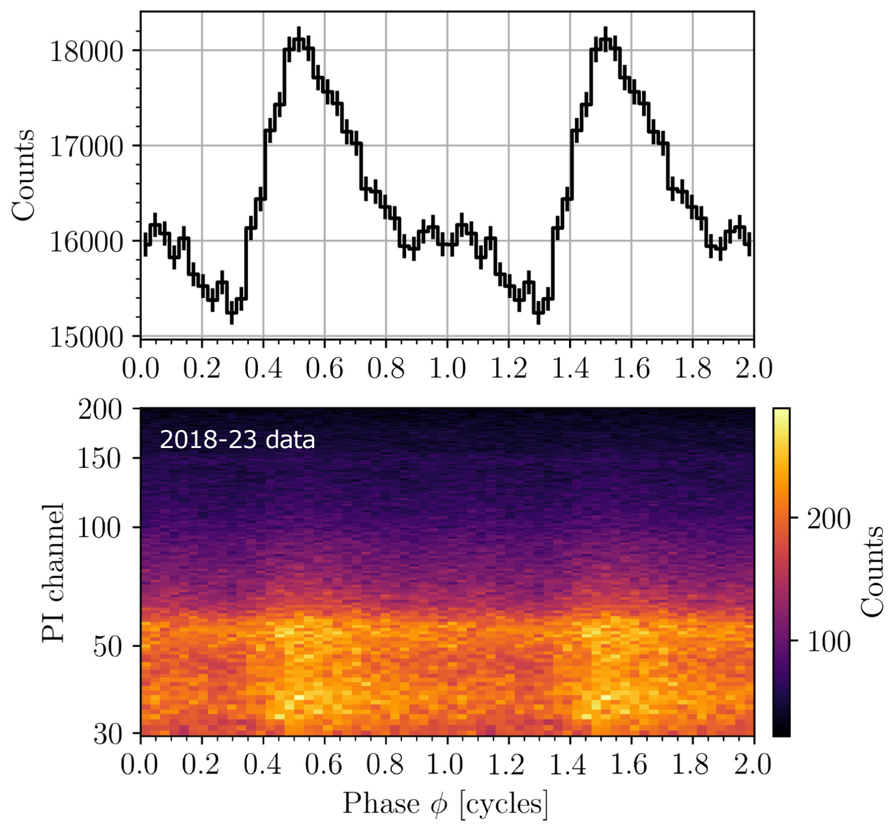
Salmi et al. 2024b, Mass prior from Cromartie et al. 2026



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

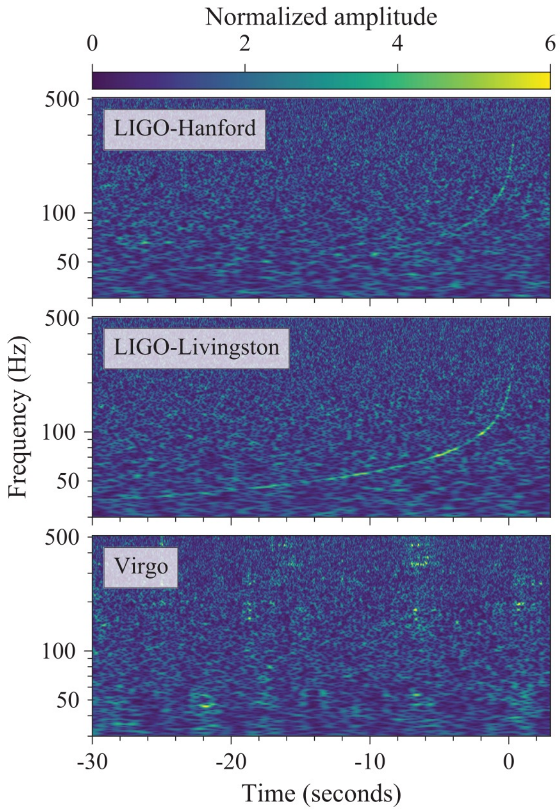
PSR J0614-3329: ANOTHER 1.4 $M_\odot$ PULSAR



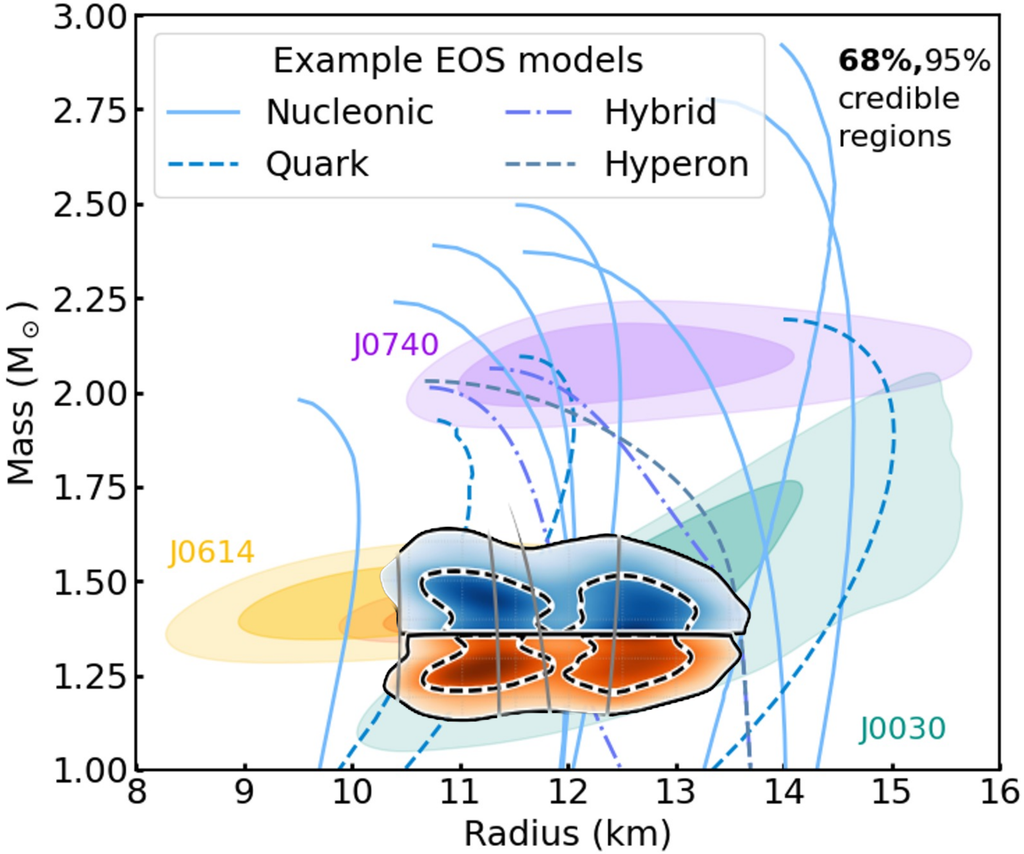


Mauviard et al. 2025

CONSISTENCY WITH GW RESULTS? YES!

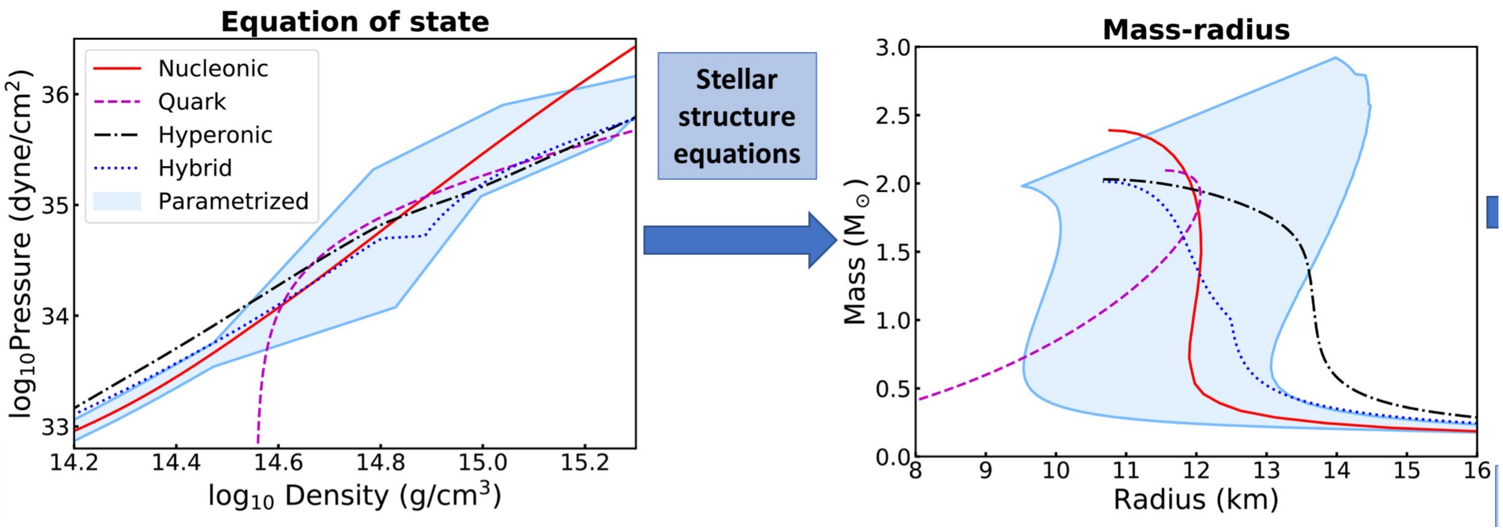


GW170817: LIGO Scientific Collaboration and Virgo Collaboration (2017, 2018)



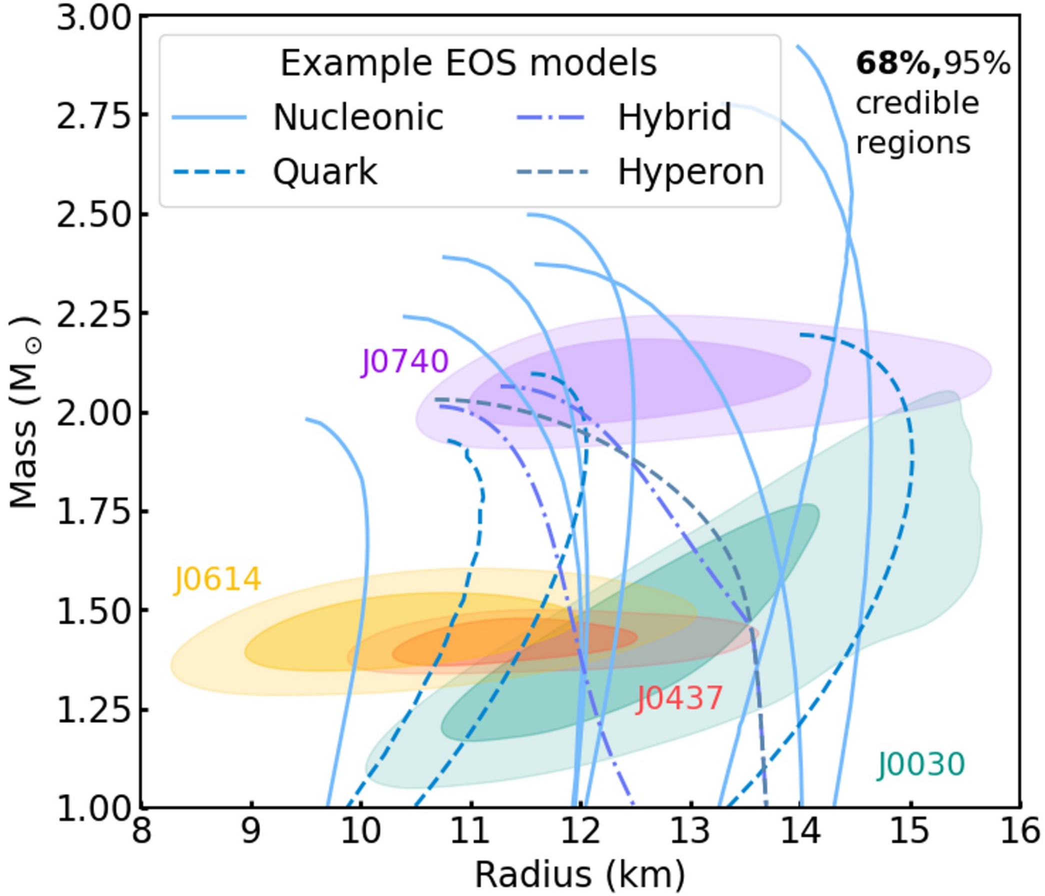
Note: GW probes mass/tidal deformability – converted to radius assuming a specific (quite generic) EOS model family

EQUATION OF STATE INFERENCE



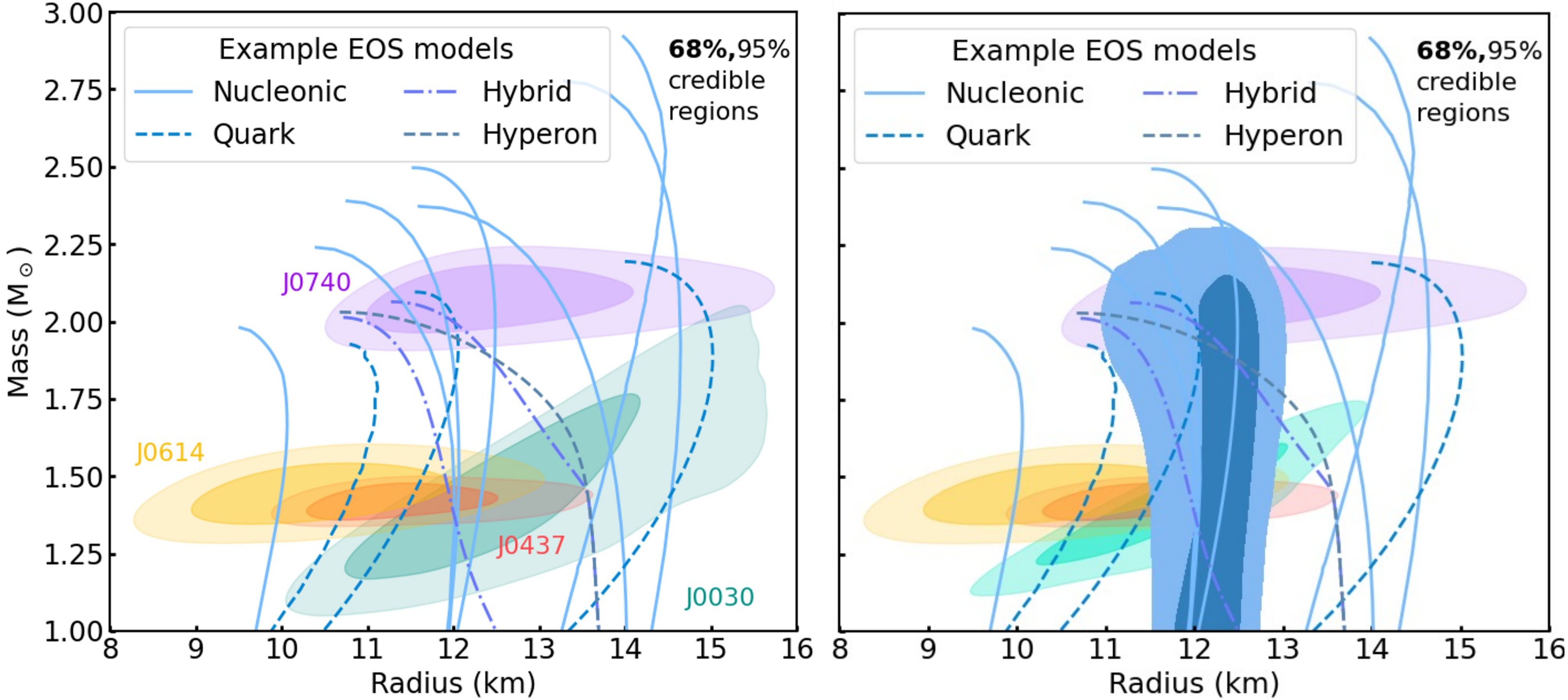
- Start with our inferred mass-radius posteriors
- Select an EOS model (with parameters and priors on those parameters)
- Infer EOS model parameters and central densities -> Inferred EOS
- This then translates into an inferred mass-radius **relation**

WHAT HAVE WE LEARNED ABOUT DENSE MATTER?



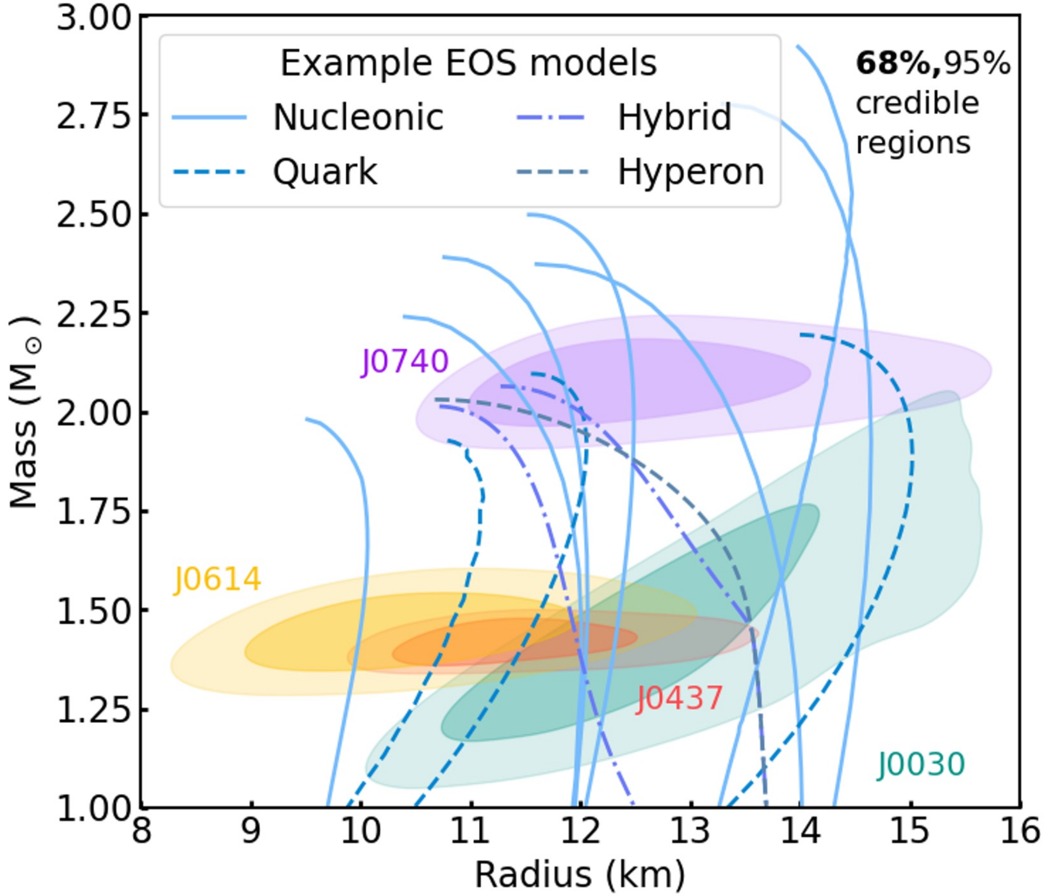
NICER results currently favour soft to medium stiffness Equations of State – extremes seem ruled out.

WHAT HAVE WE LEARNED ABOUT DENSE MATTER?

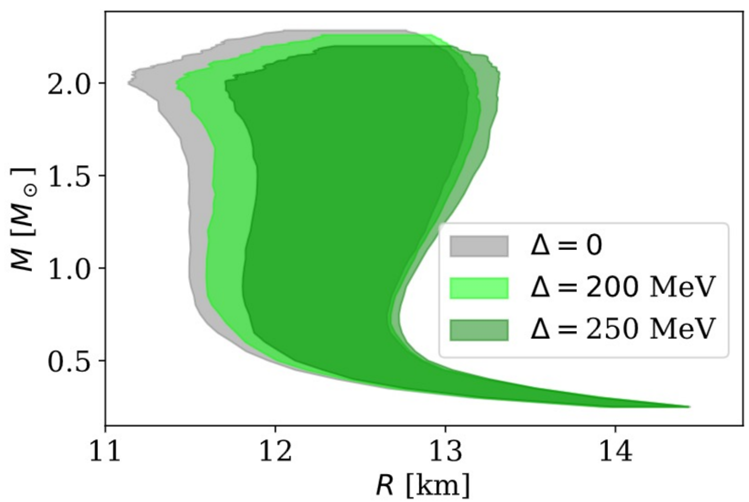


cEFT + parameterized models perform well (e.g. Rutherford et al. 24, Mendes et al. 26)

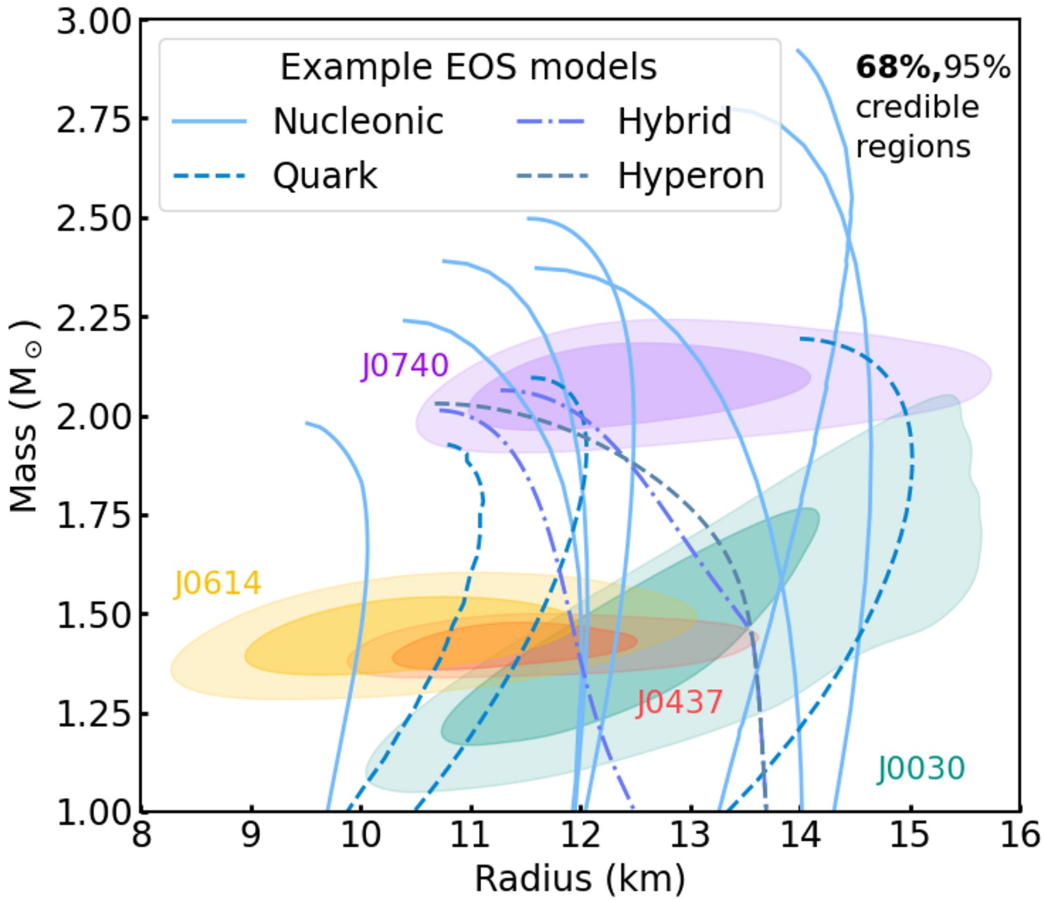
WHAT HAVE WE LEARNED ABOUT DENSE MATTER?

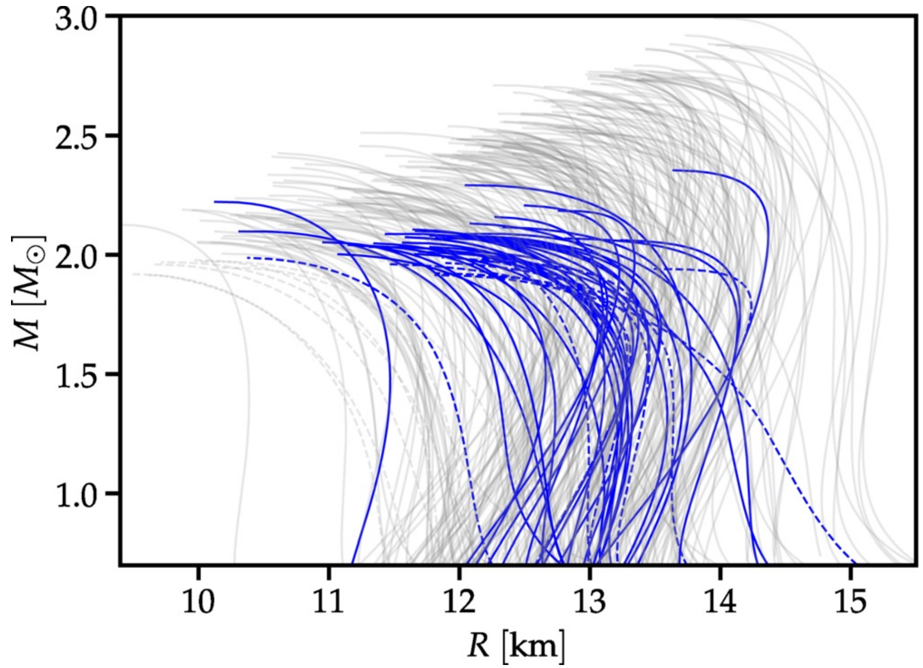


- Deconfined quark matter in NS cores remains plausible (e.g. Annala et al. 23).
- Interesting limits being placed on e.g. twin stars (Blomqvist et al. 26), color superconductivity (Kurkela et al. 2024, 25).



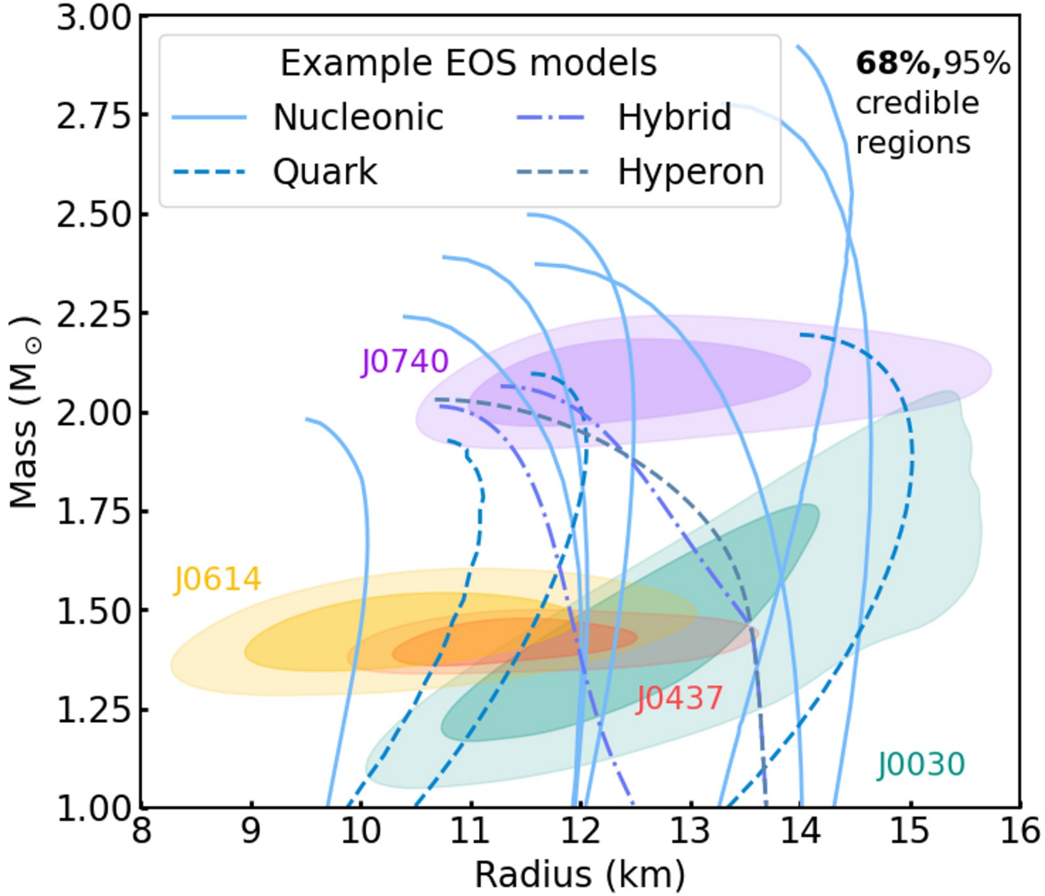
WHAT HAVE WE LEARNED ABOUT DENSE MATTER?





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**

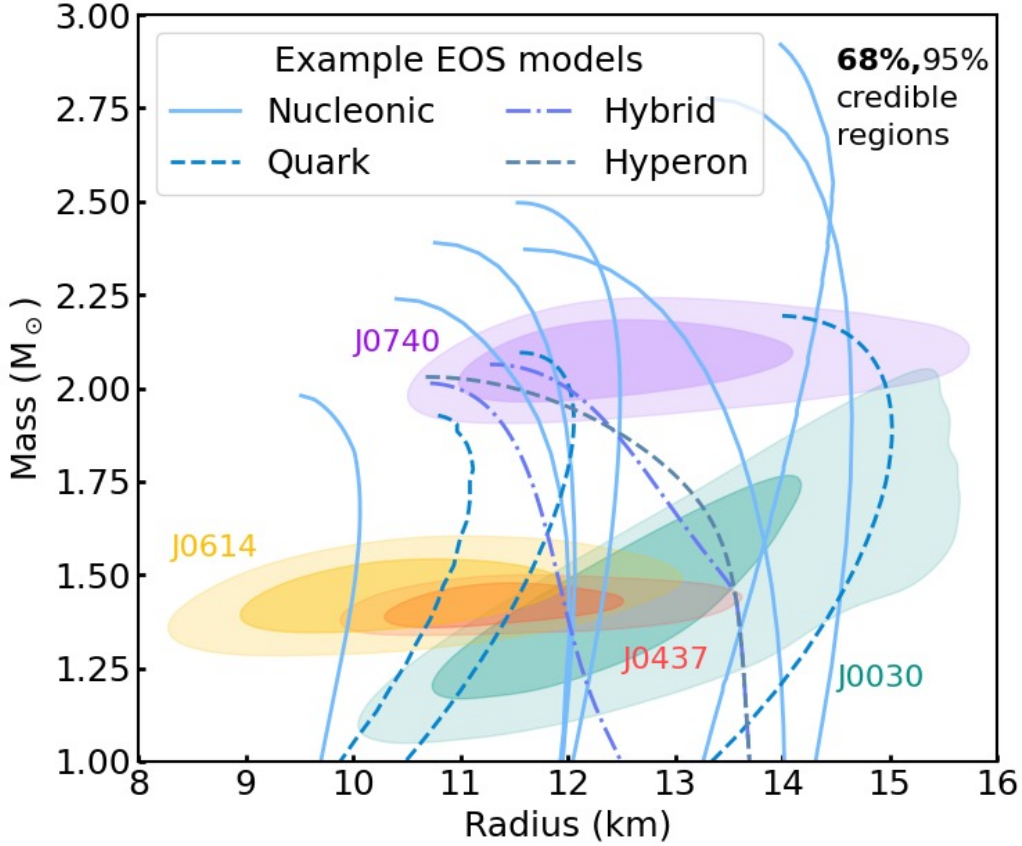
Gradient of the mass radius curve: high radius at low mass, and low radius at high mass, are disfavored by data.

Are there **deconfined quarks**? Maybe!

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

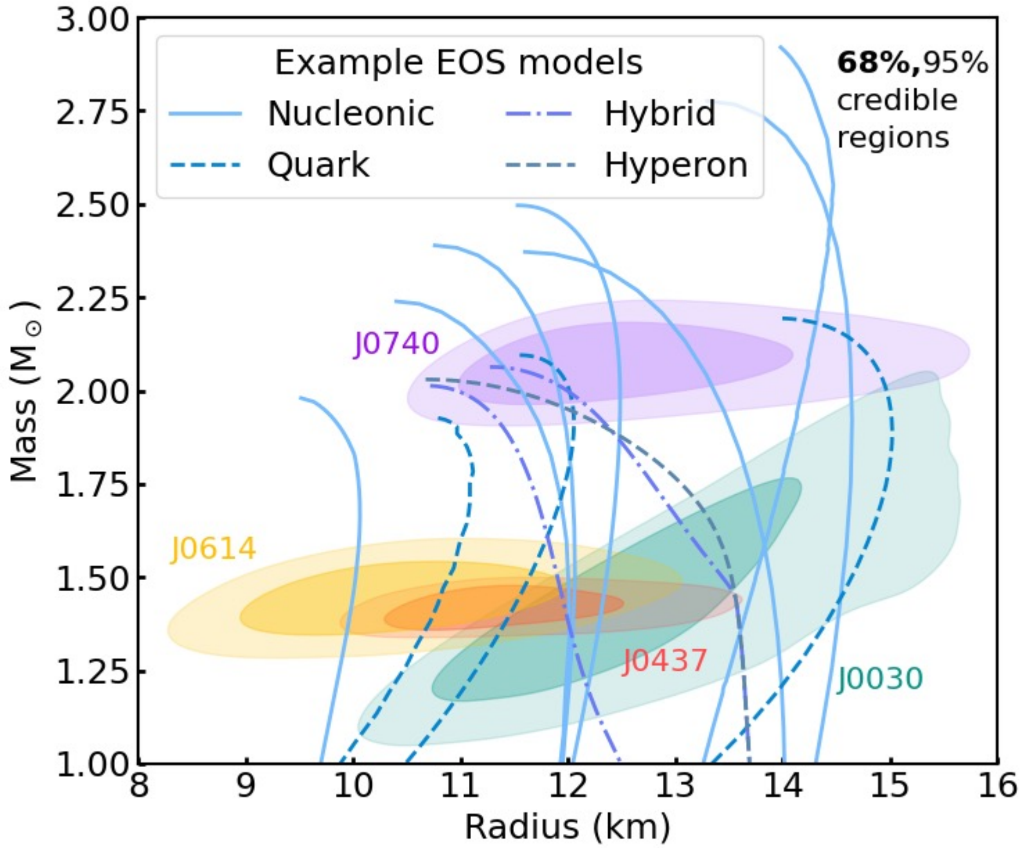
What is the **mass boundary between neutron stars and black holes**?

WHAT NEXT? NEW SOURCES



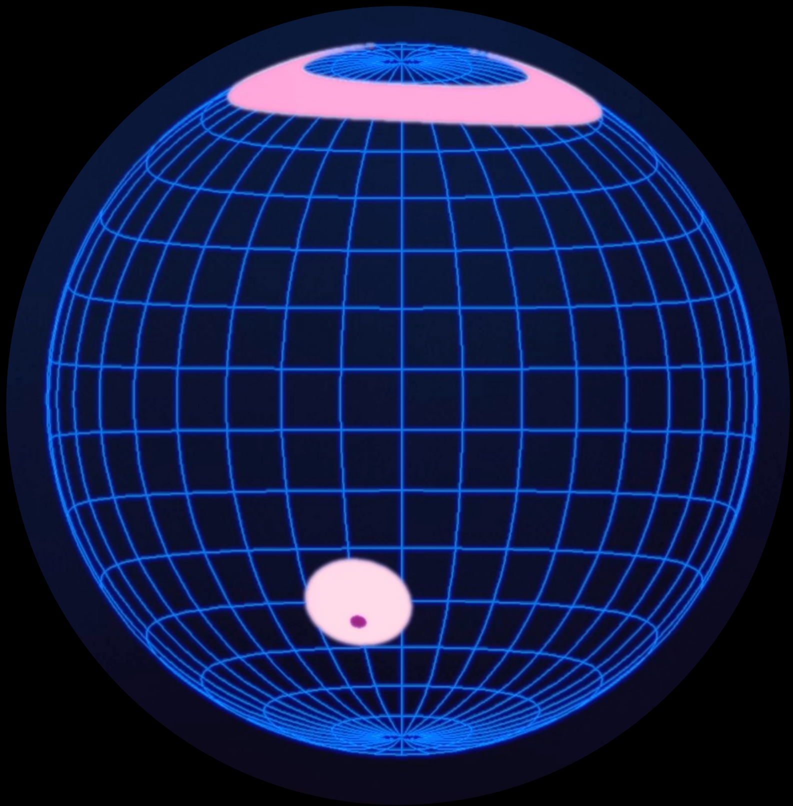
- PSR J1614-2230. In a binary, with a very tight mass prior of 1.937 ± 0.014 $M_\odot$ (Agazie et al. 2023).
- PPM results coming very soon!

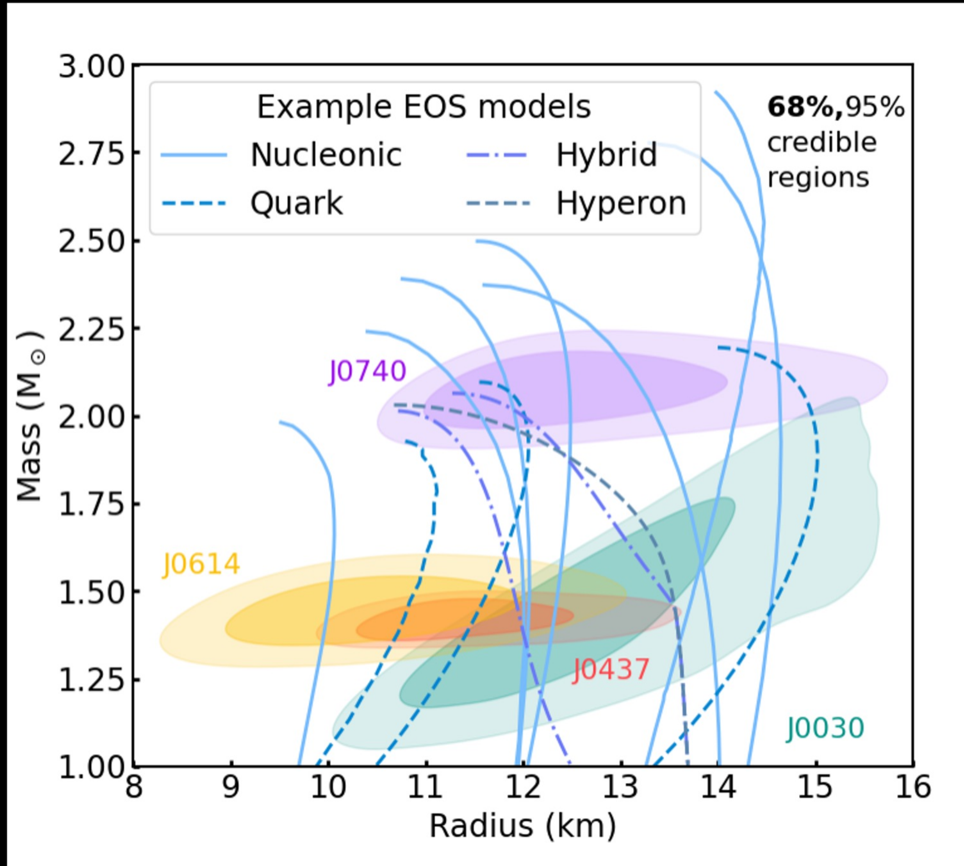
WHAT NEXT? NEW SOURCES



- PSR J1614-2230. In a binary, with a very tight mass prior of 1.937 ± 0.014 $M_\odot$ (Agazie et al. 2023).
- PPM results coming very soon! Mauviard et al. in prep.
- Other sources not shown: PSR J2124-3358 (González-Caniulef et al. 2026), qLMXB 47 Tuc (Kazantsev et al. 2026).

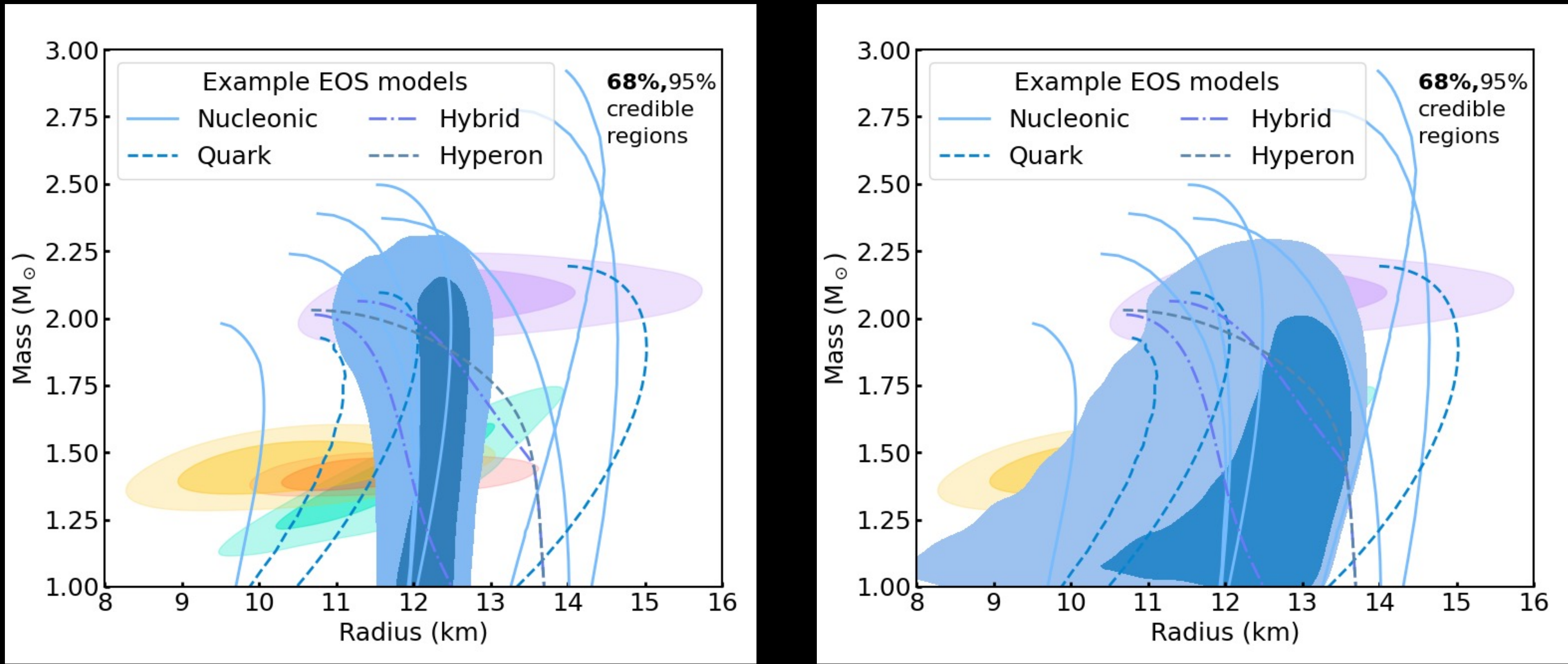
WHAT NEXT?





Better magnetosphere/multiwavelength emission modeling

WHAT NEXT?

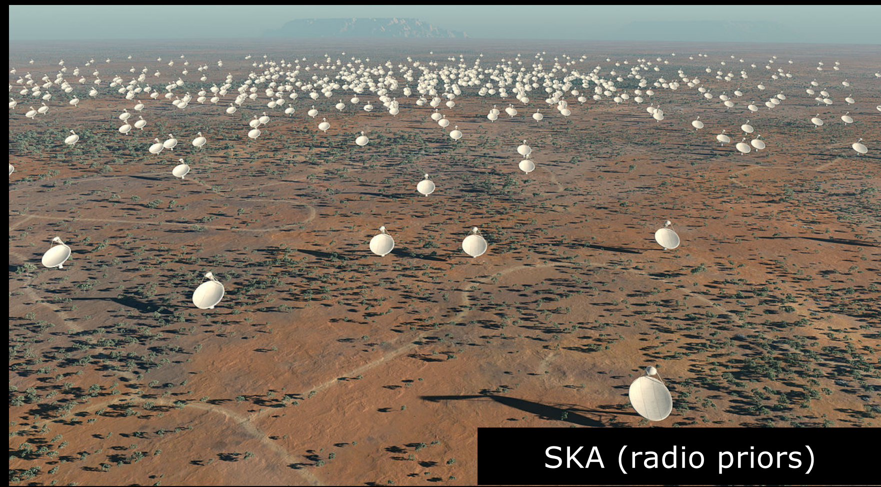


Use dense matter information earlier? (Hoogkamer et al. 2026)

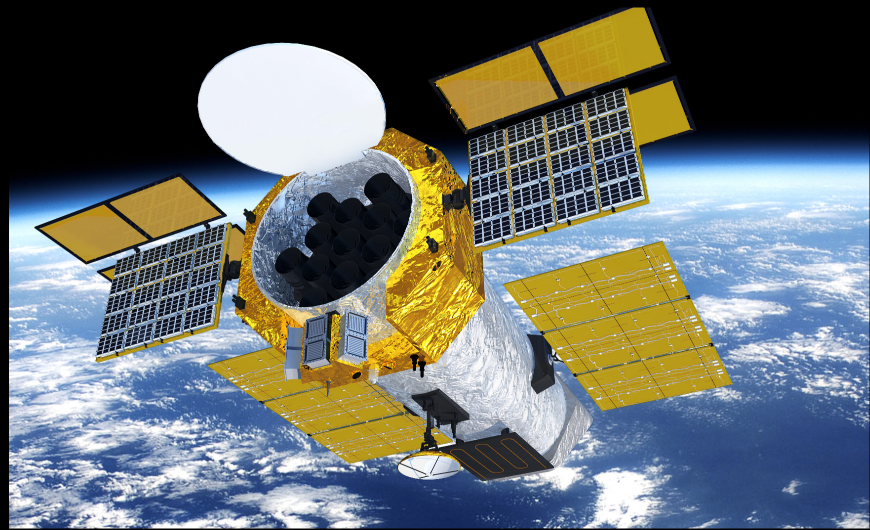
WHAT NEXT?

NewAthena (late 2030s)

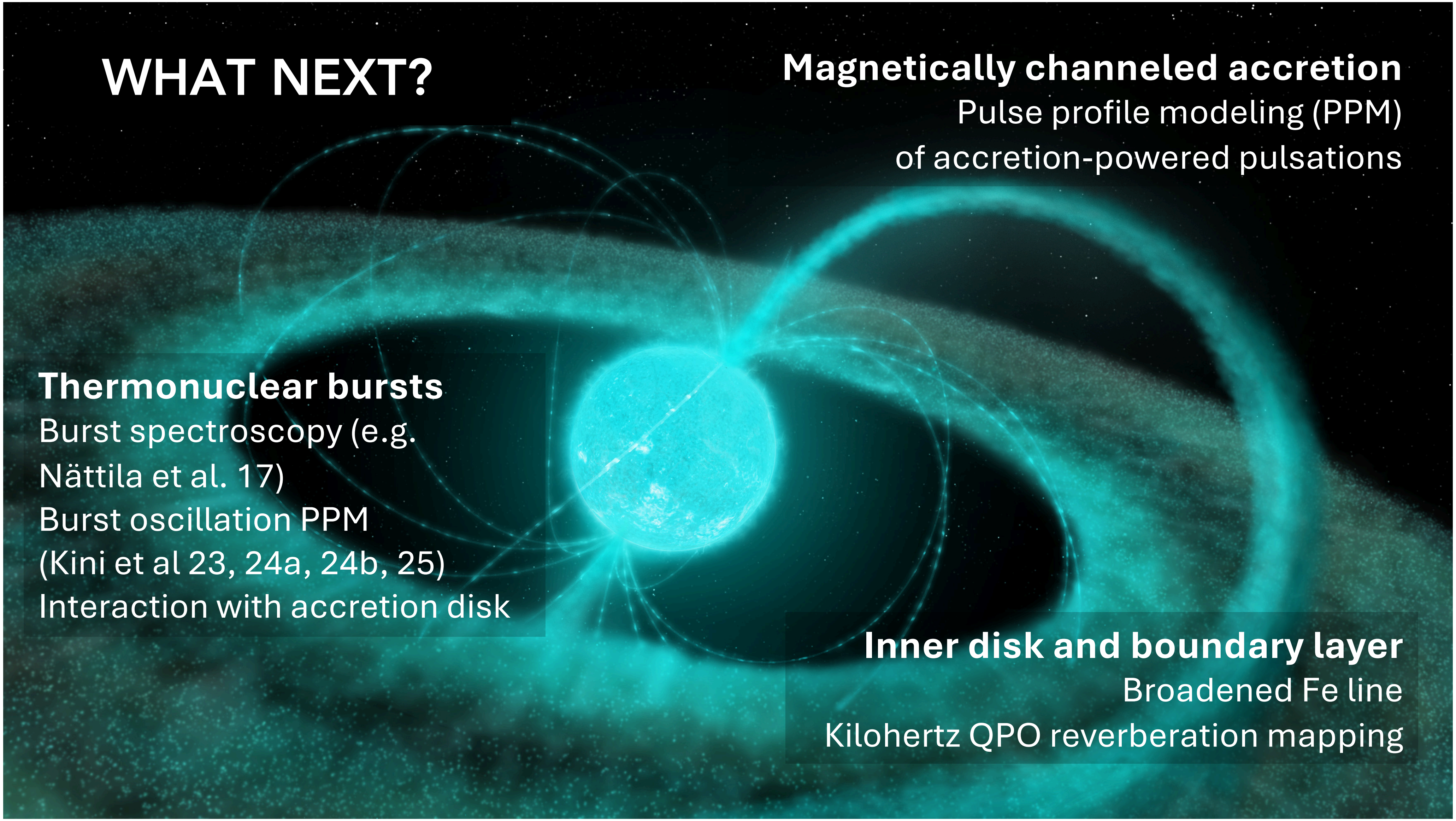
New telescopes - wider band, low/~no background, larger area



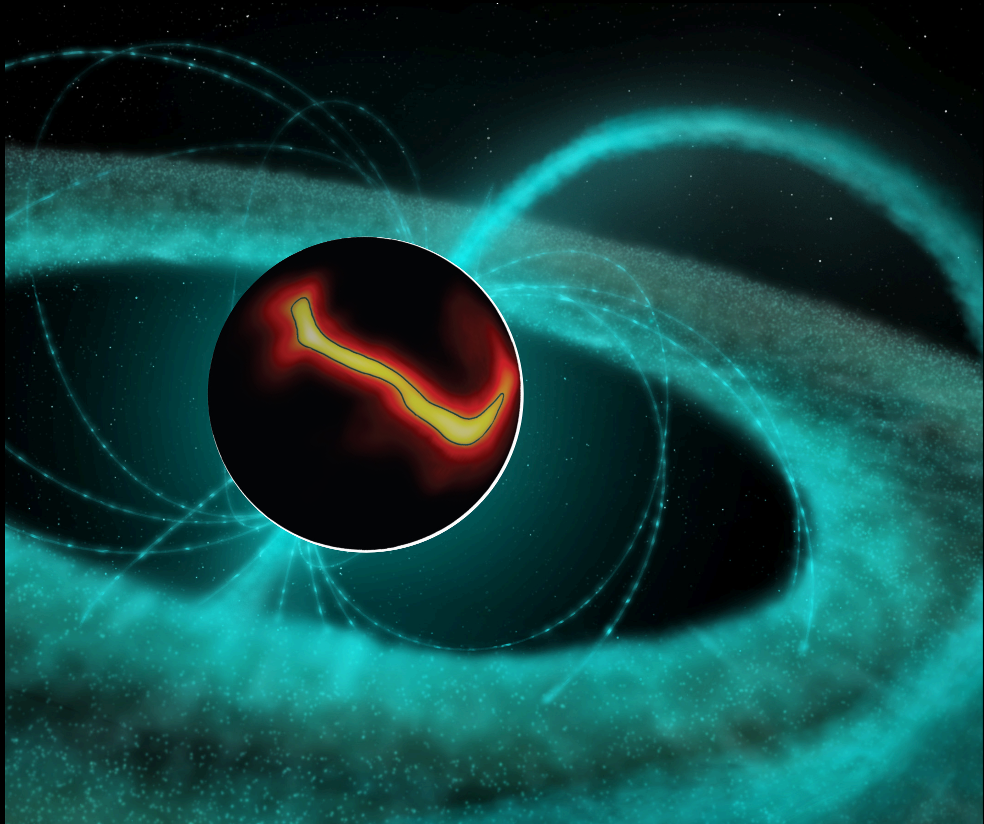
SKA (radio priors)



eXTP (2030)


WHAT NEXT?
Magnetically channeled accretion
Pulse profile modeling (PPM)
of accretion-powered pulsations
Thermonuclear bursts
Burst spectroscopy (e.g.
Nättila et al. 17)
Burst oscillation PPM
(Kini et al 23, 24a, 24b, 25)
Interaction with accretion disk
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, Mao et al. 2026.)
- 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.
- Wider band, spectral resolution, larger effective area of eXTP and NewAthena will help.

SUMMARY

- NICER has unlocked a completely new technique for determining neutron star properties.
- We have now measured the size of several 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.
- New telescopes in the 2030s offer outstanding prospects for PPM.