A NICER VIEW OF PSR J0030+0451: Implications for the dense matter EOS

Geert Raaijmakers

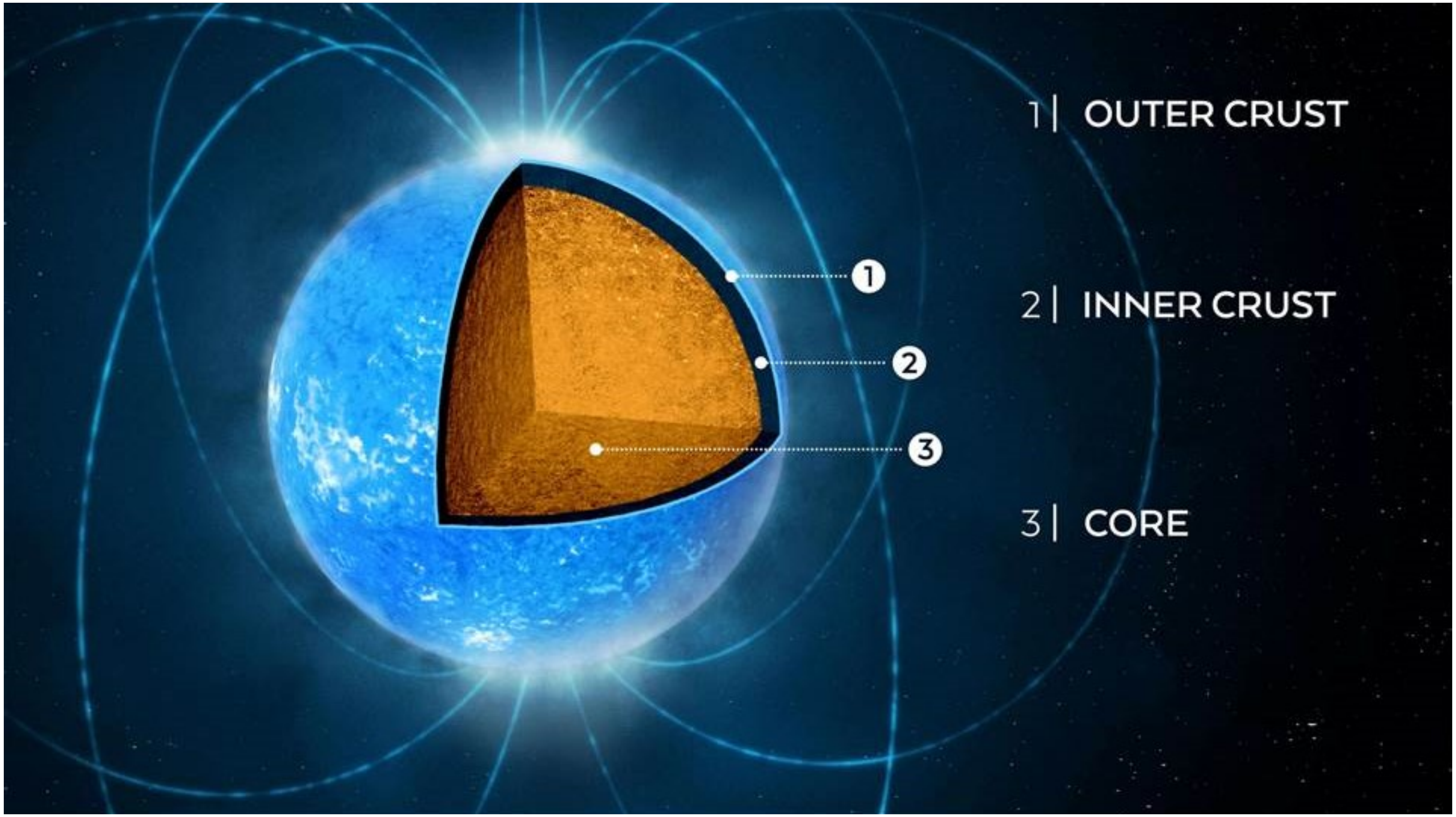
PhD Candidate at GRAPPA, University of Amsterdam
Group of Samaya Nissanke

Based on *Greif & Raaijmakers et al. '19, MNRAS*
Raaijmakers et al. '19a, ApJL
Riley et al. '19, ApJL
Bilous et al '19, ApJL
Raaijmakers et al. '19b, submitted
In collaboration with the NICER team

Overview

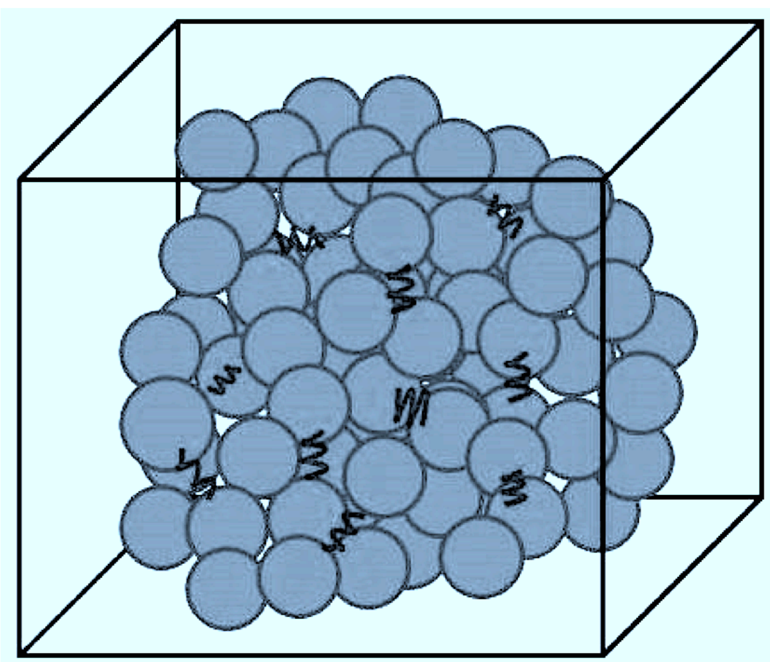
- Motivation and introduction of *NICER*
- Mass-Radius results from *NICER*
- Implications for the dense matter EOS
- Multimessenger constraints
- Future outlook

Neutron stars as dense matter probes

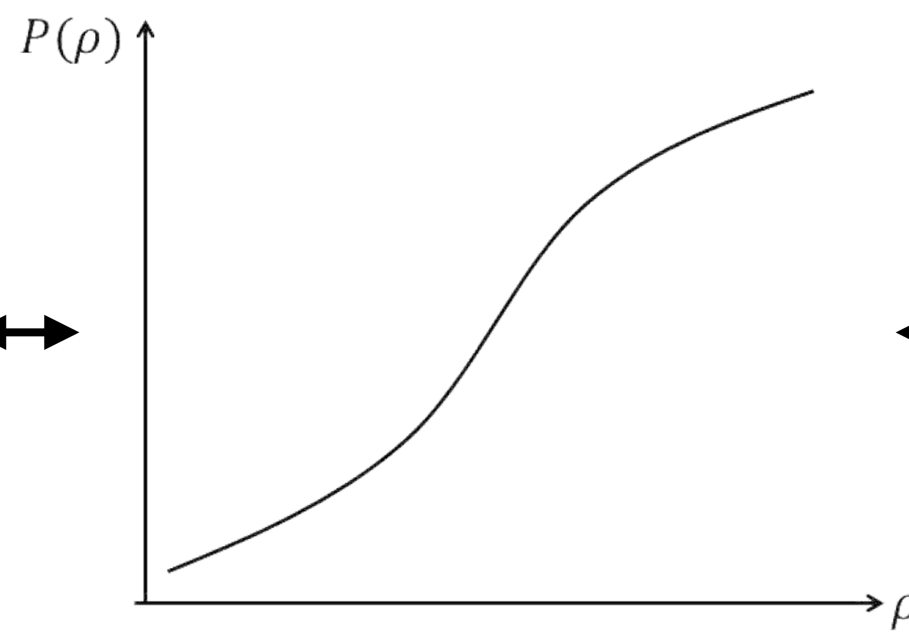


From nuclear physics to astrophysics

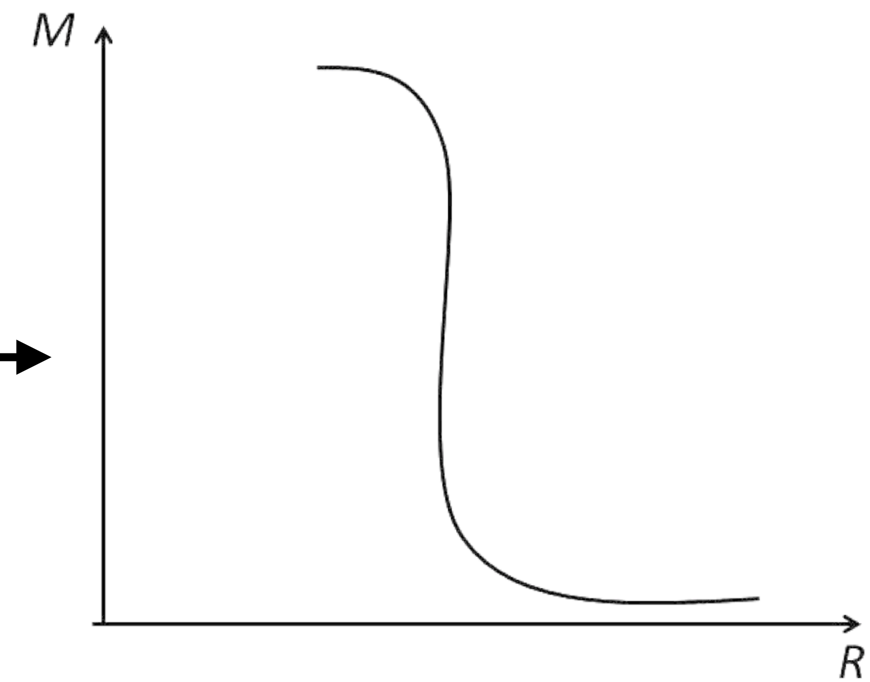
I. Dense Matter Physics

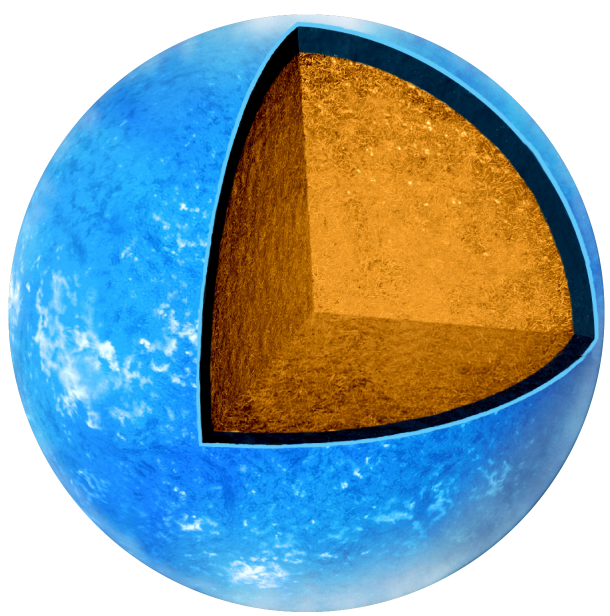


II. Equation of State



III. Mass and Radius



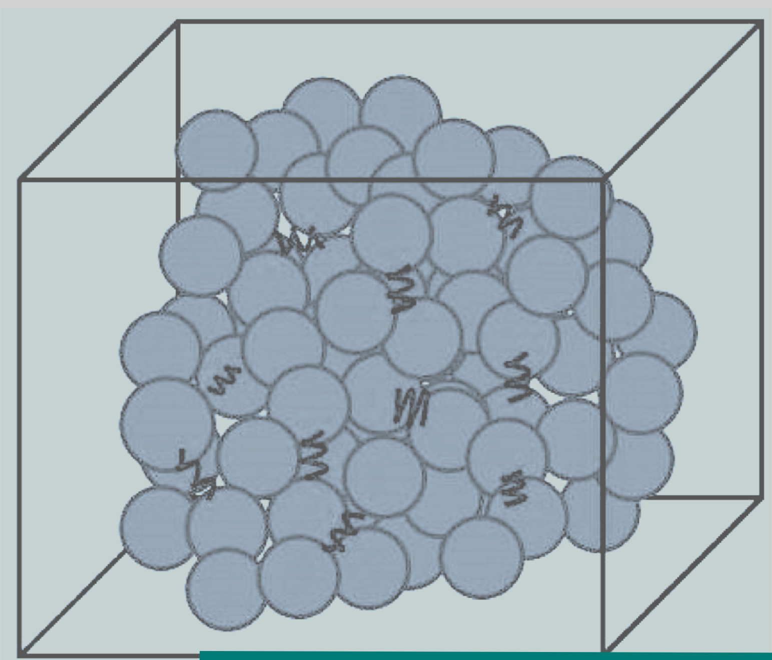


V. Neutron Star

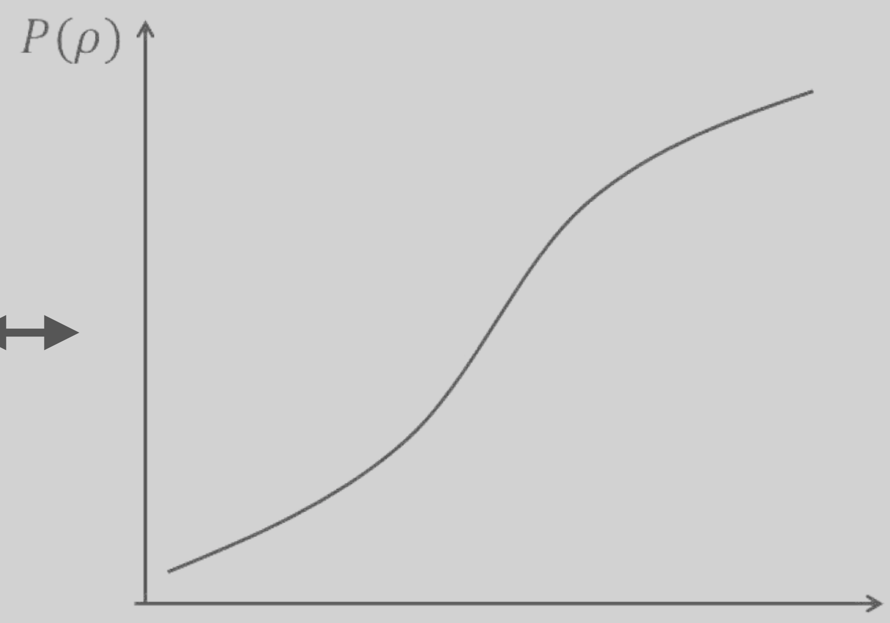
IV. Observables

From nuclear physics to astrophysics

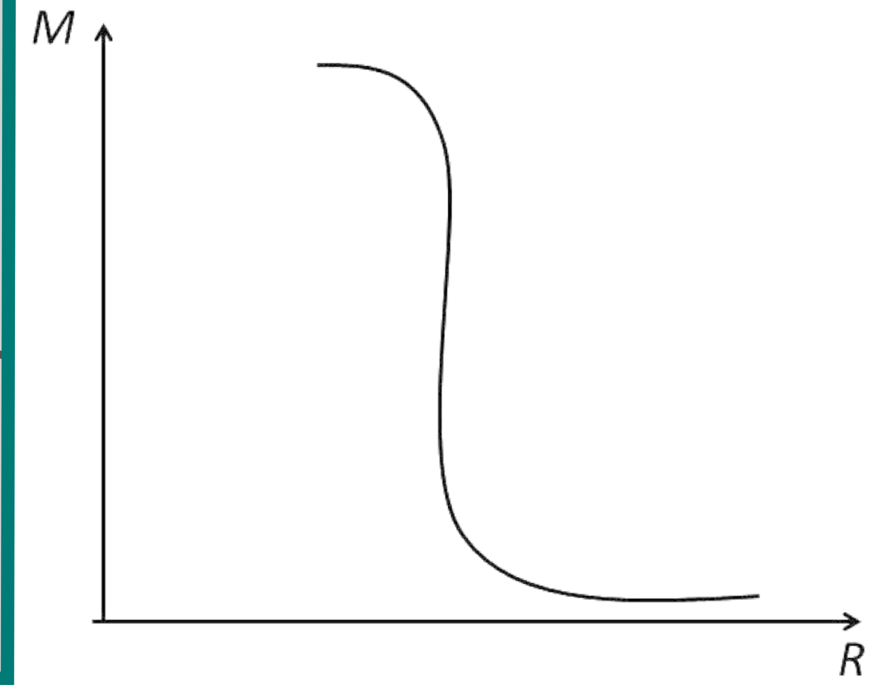
I. Dense Matter Physics

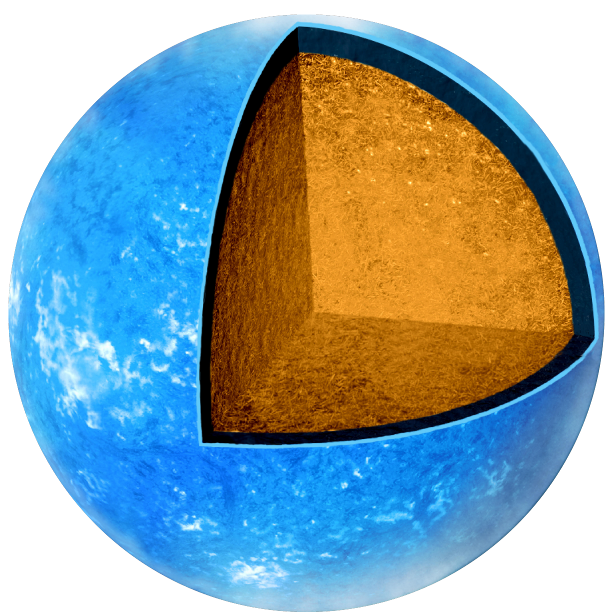


II. Equation of State

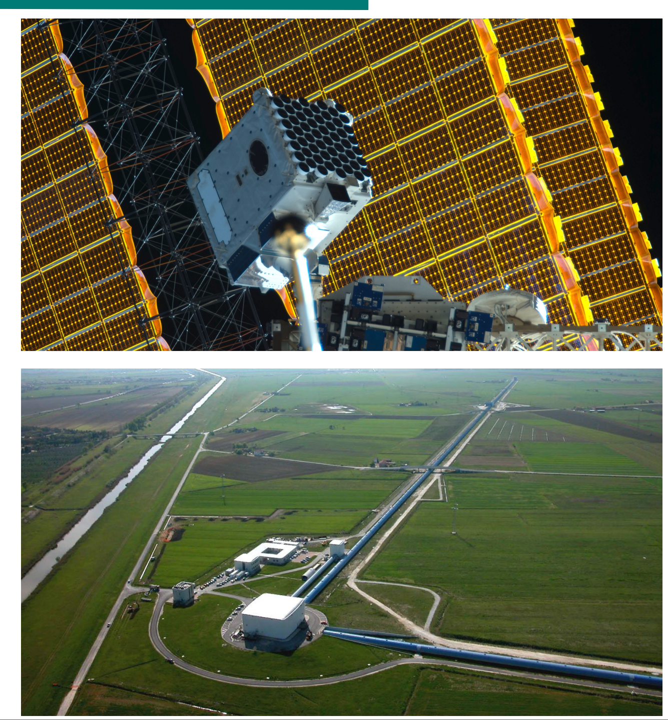


III. Mass and Radius





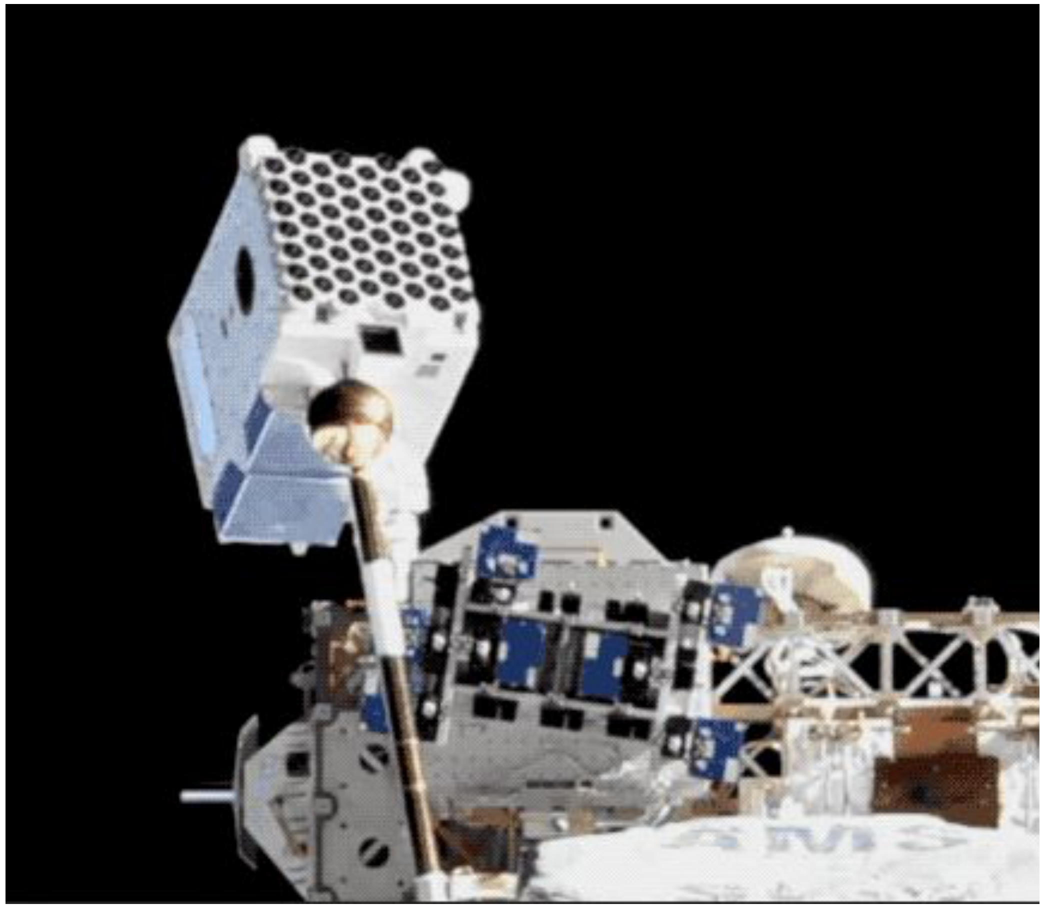
V. Neutron Star



IV. Observables

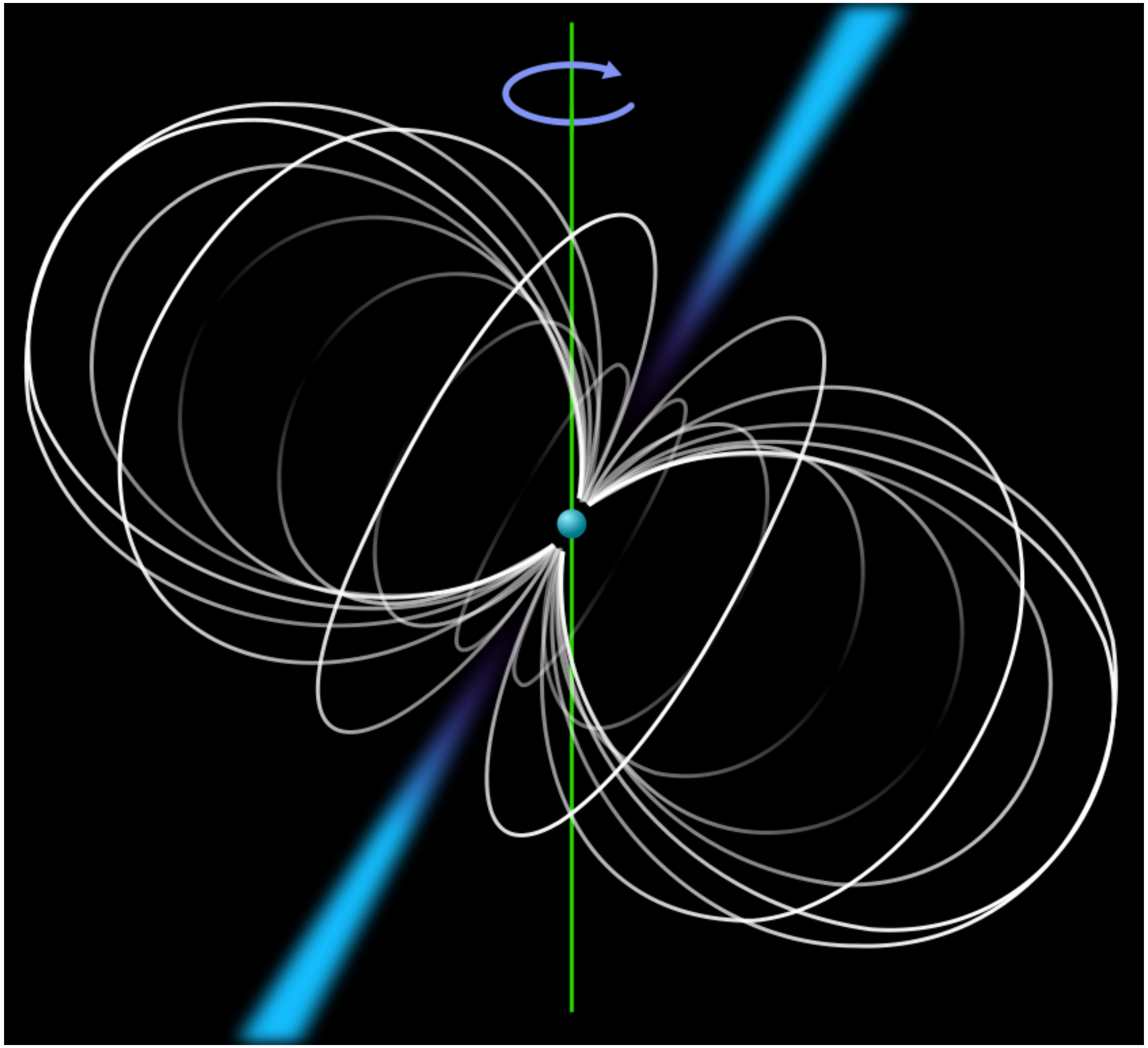
Neutron star Interior Composition ExploreR

- NASA mission launched in 2017
- Installed on board of the ISS
- 56 X-ray photon detectors, measuring both energy and time of arrival in 0.2 - 12 keV band
- Rotation-powered millisecond pulsars



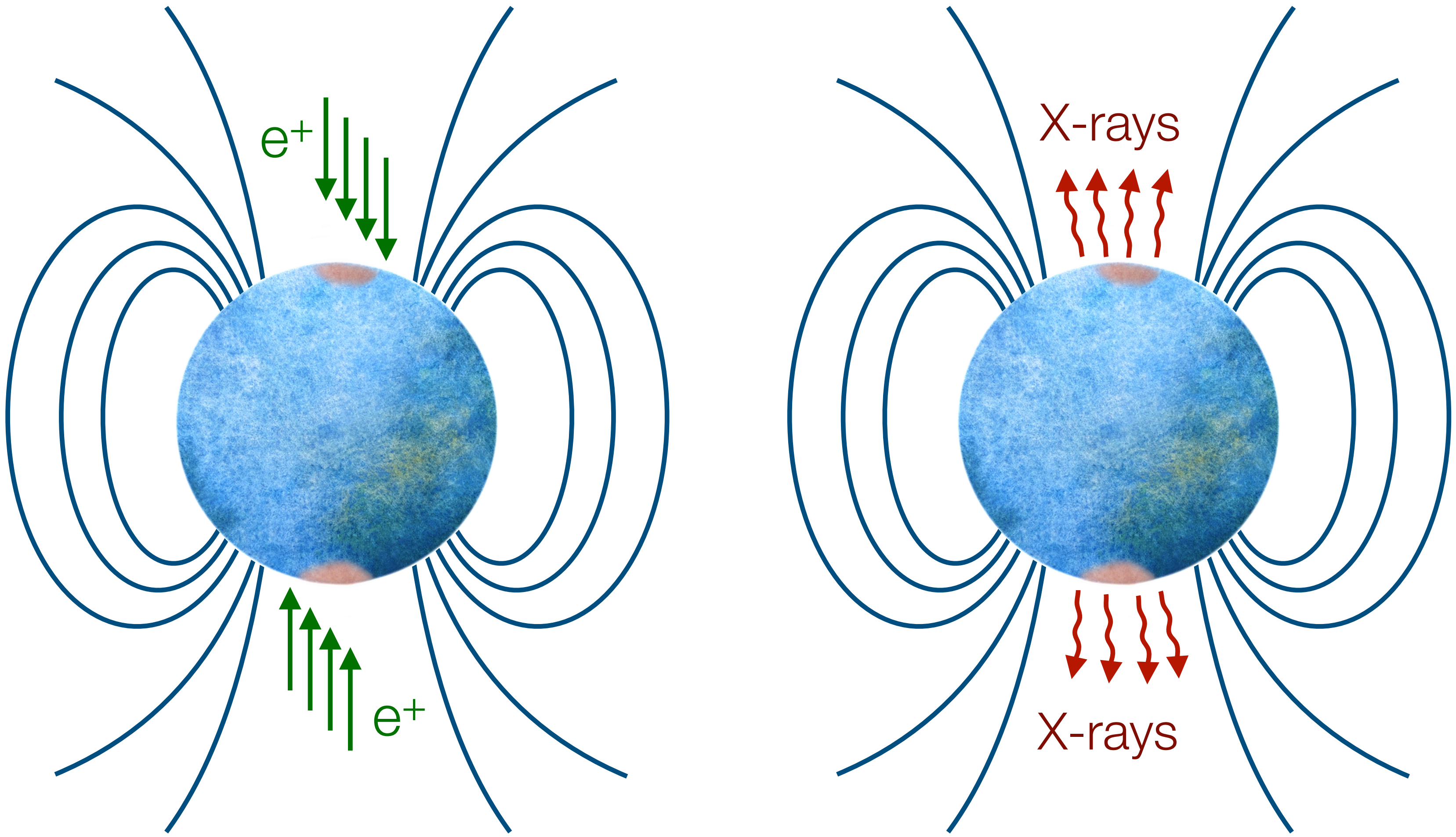
Rotation-powered millisecond pulsars

- "Recycled" pulsars through accretion
- Extremely stable orbits
- Thermal X-ray emission from return current of positrons



Rotation-powered millisecond pulsars

- "Recycled" pulsars through accretion
- Extremely stable orbits
- Thermal X-ray emission from return current of positrons



Pulse profile modeling

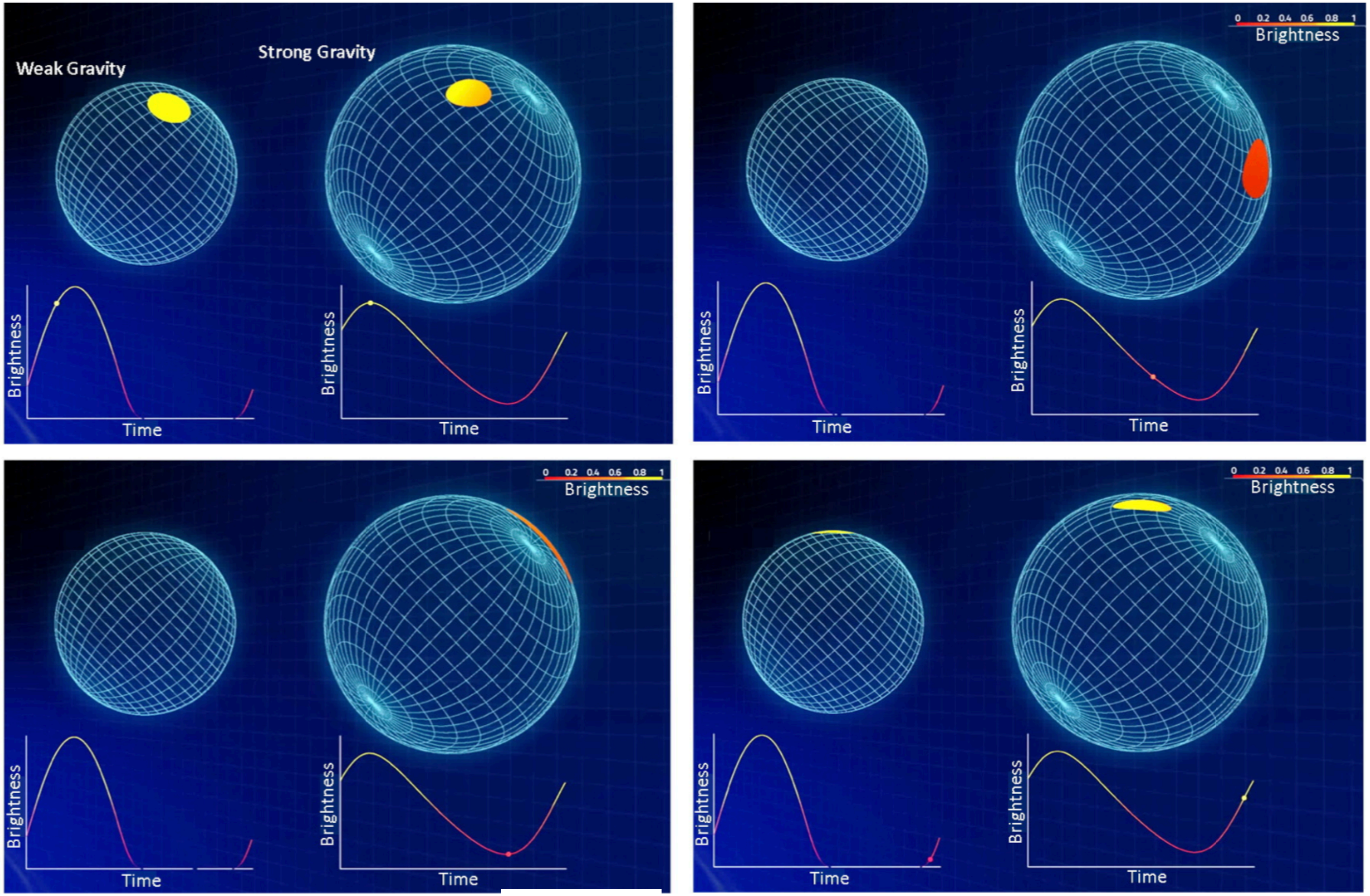
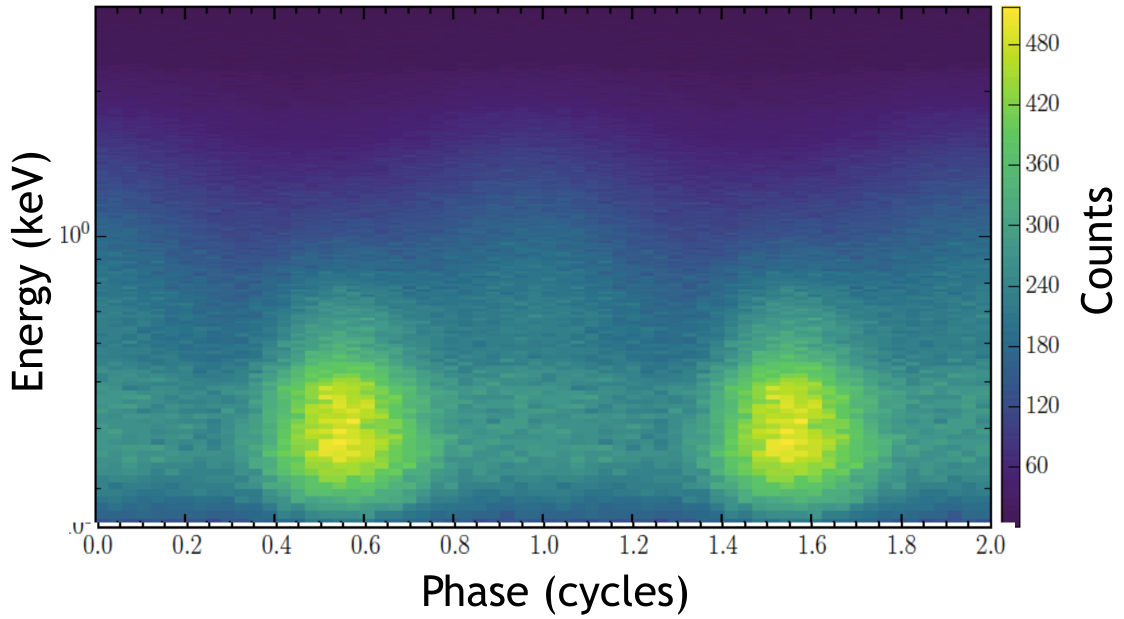


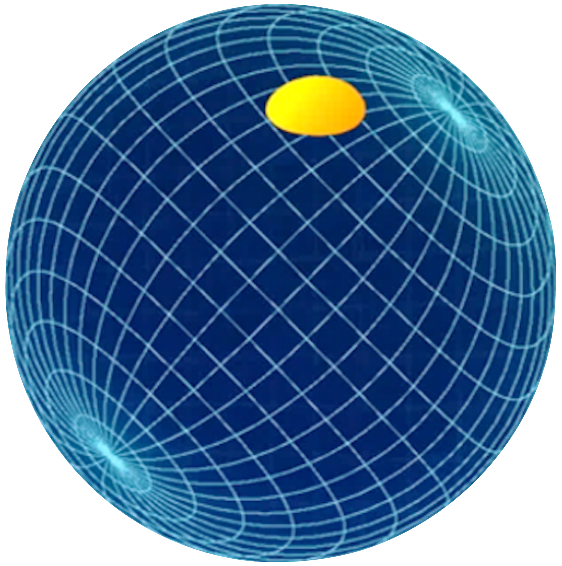
Image credit: Morsink/Moir/Arzoumanian/NASA

Pulse profile modeling

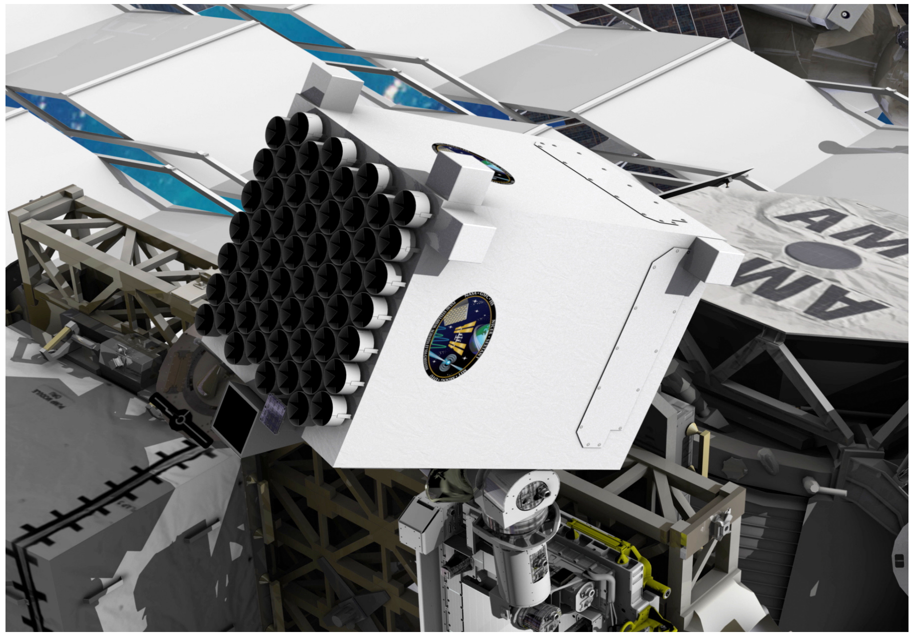
Pulse profile data: Phase, Energy



Lightcurve model:
Emission, Relativistic ray-tracing



Instrument properties

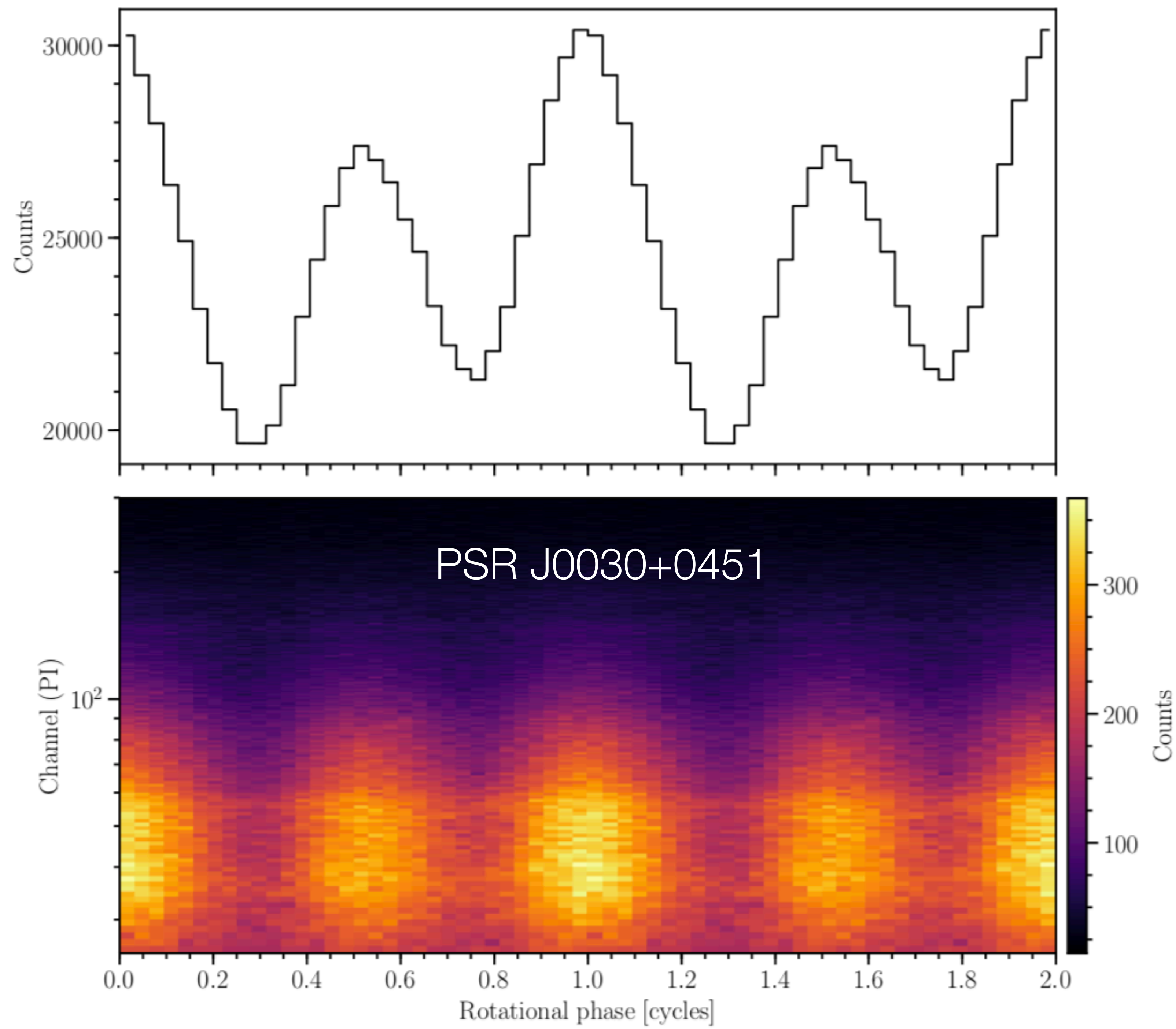


Inference code:
Likelihood calculation,
statistical sampling

Mass and Radius

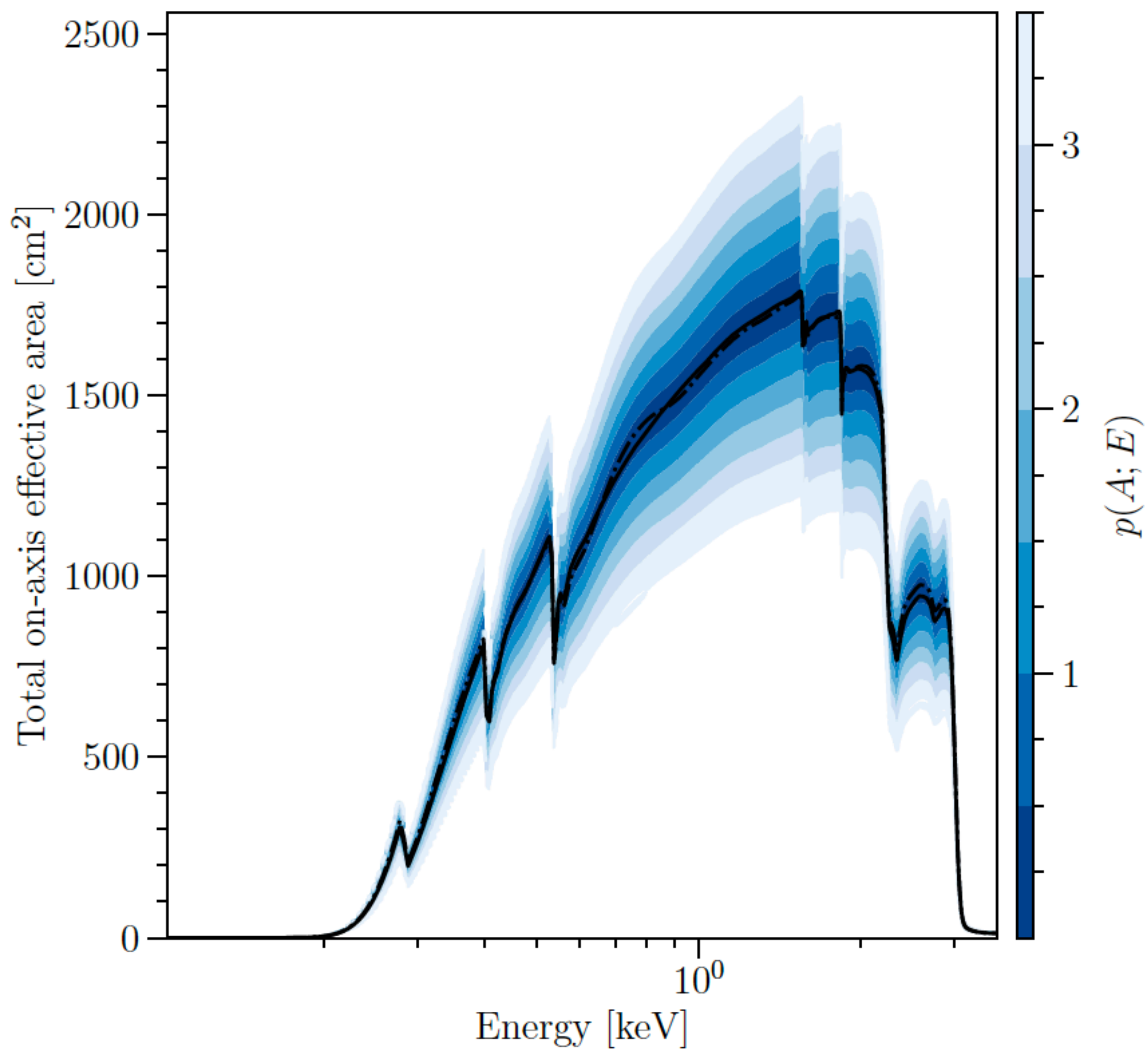
Pulse profile modeling
Data of PSR J0030+0451

- Spin period of 4.87 ms (~205 Hz)
- Distance 325(9) parsec
- Sun angle >80 degrees
- Phase-folded



Pulse profile modeling
Instrument response

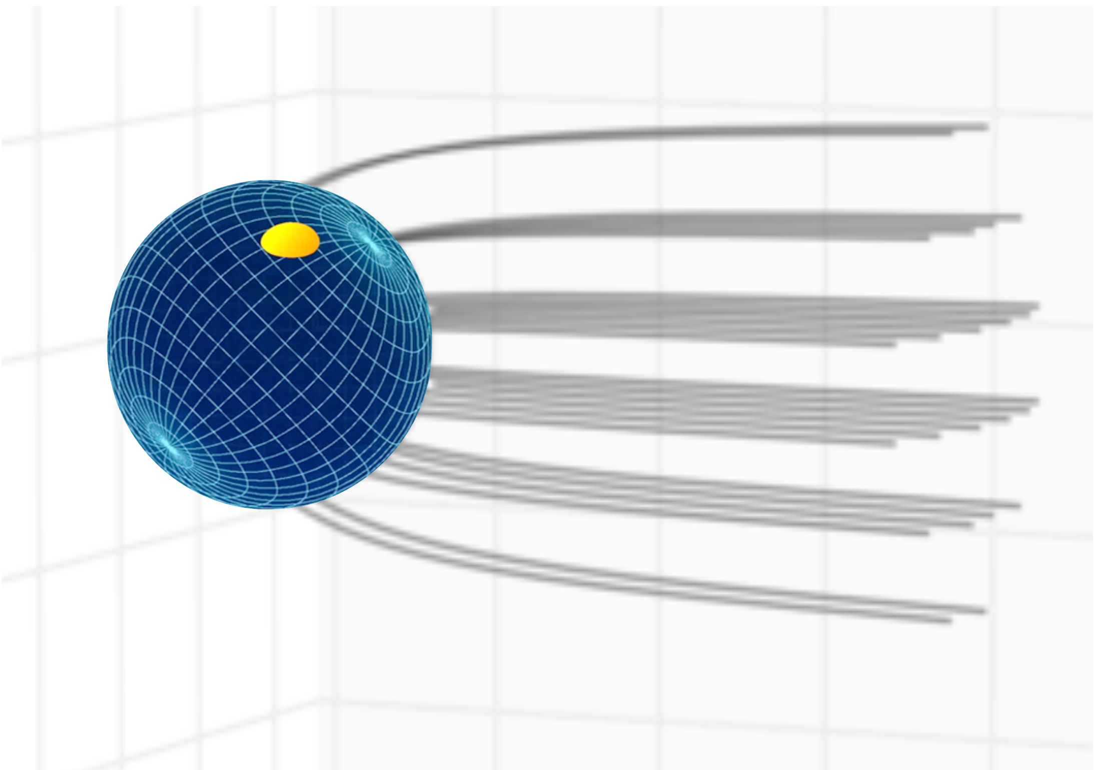
- Instrument response function calibrated to Crab
- Parameterized to capture uncertainty



Pulse profile modeling

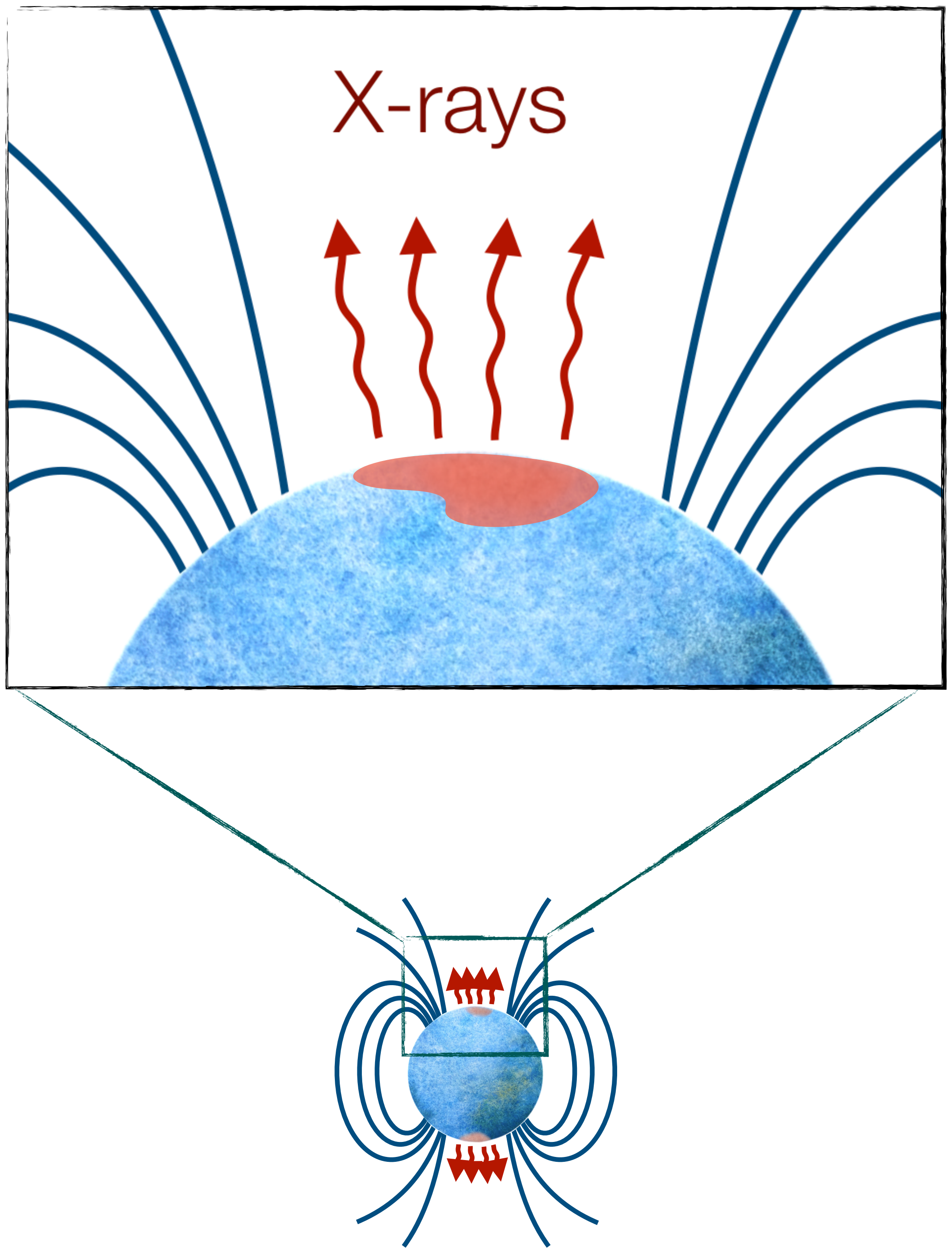
Lightcurve model

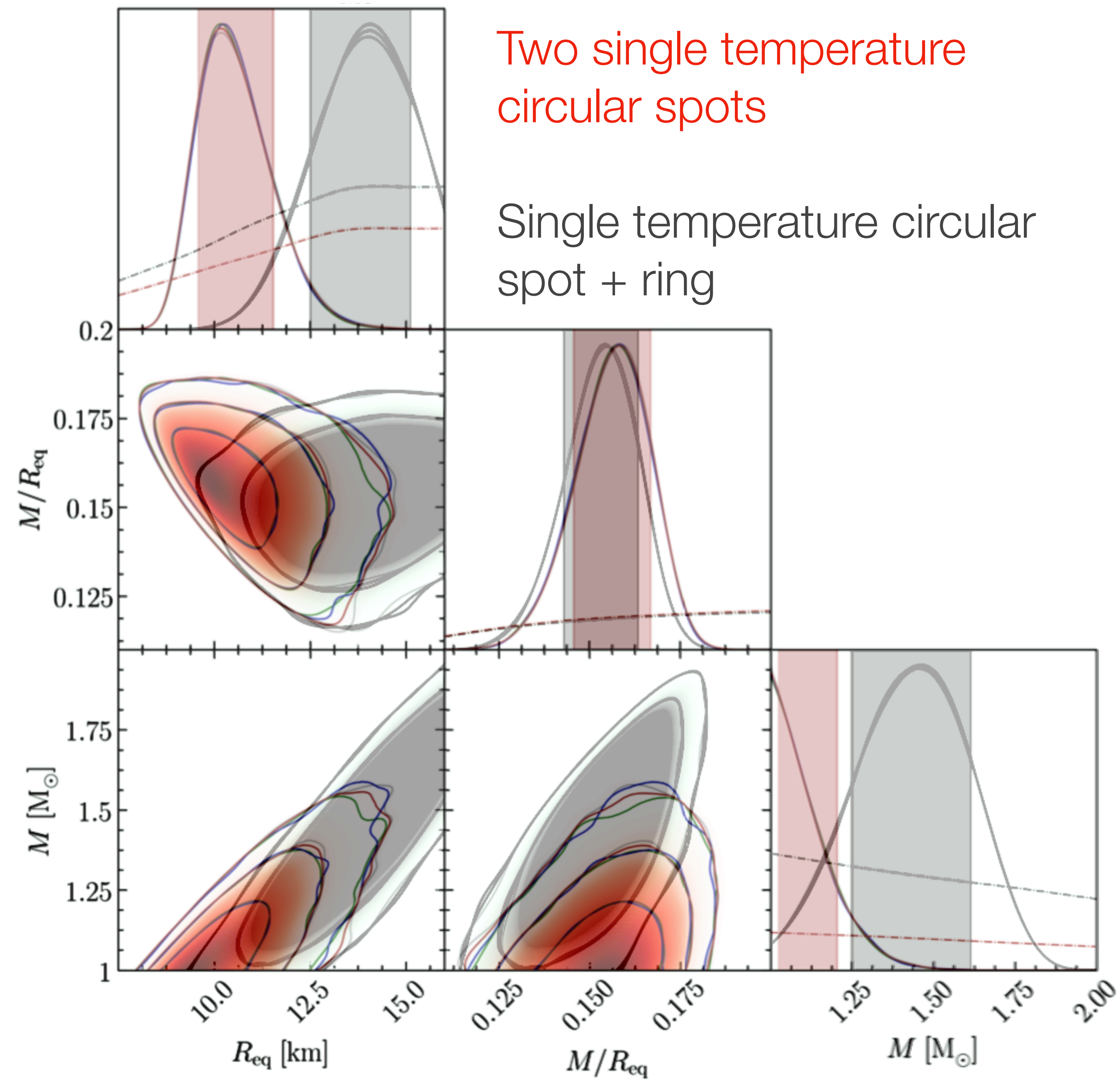
- Fully ionized hydrogen atmosphere
- Oblate Schwarzschild + Doppler approximation (Morsink et al. 2007)
- Relativistic ray-tracing and inference code X-PSI (Riley & Watts, submitted)



Pulse profile modeling

Surface emission geometry



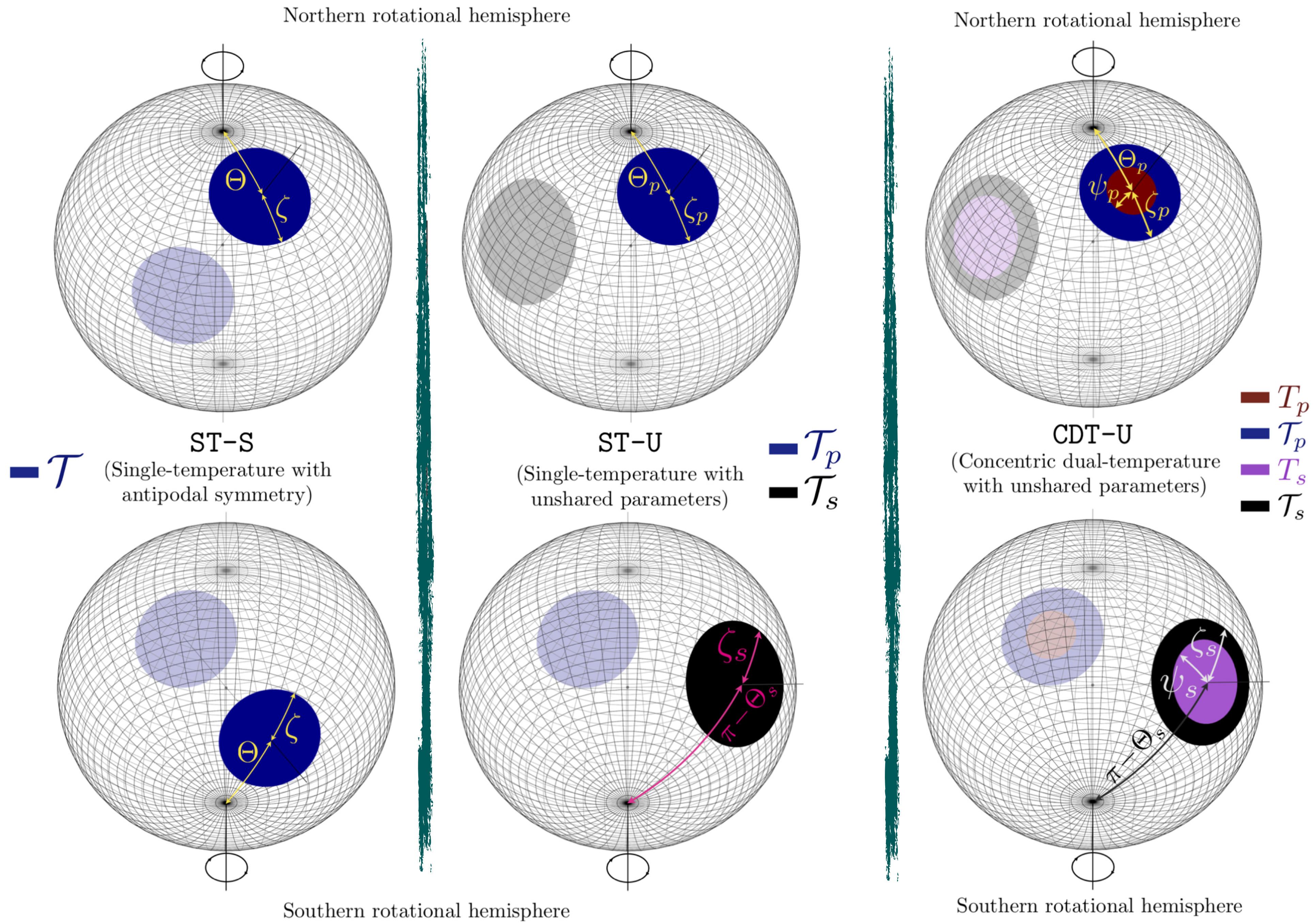


Two single temperature circular spots

Single temperature circular spot + ring

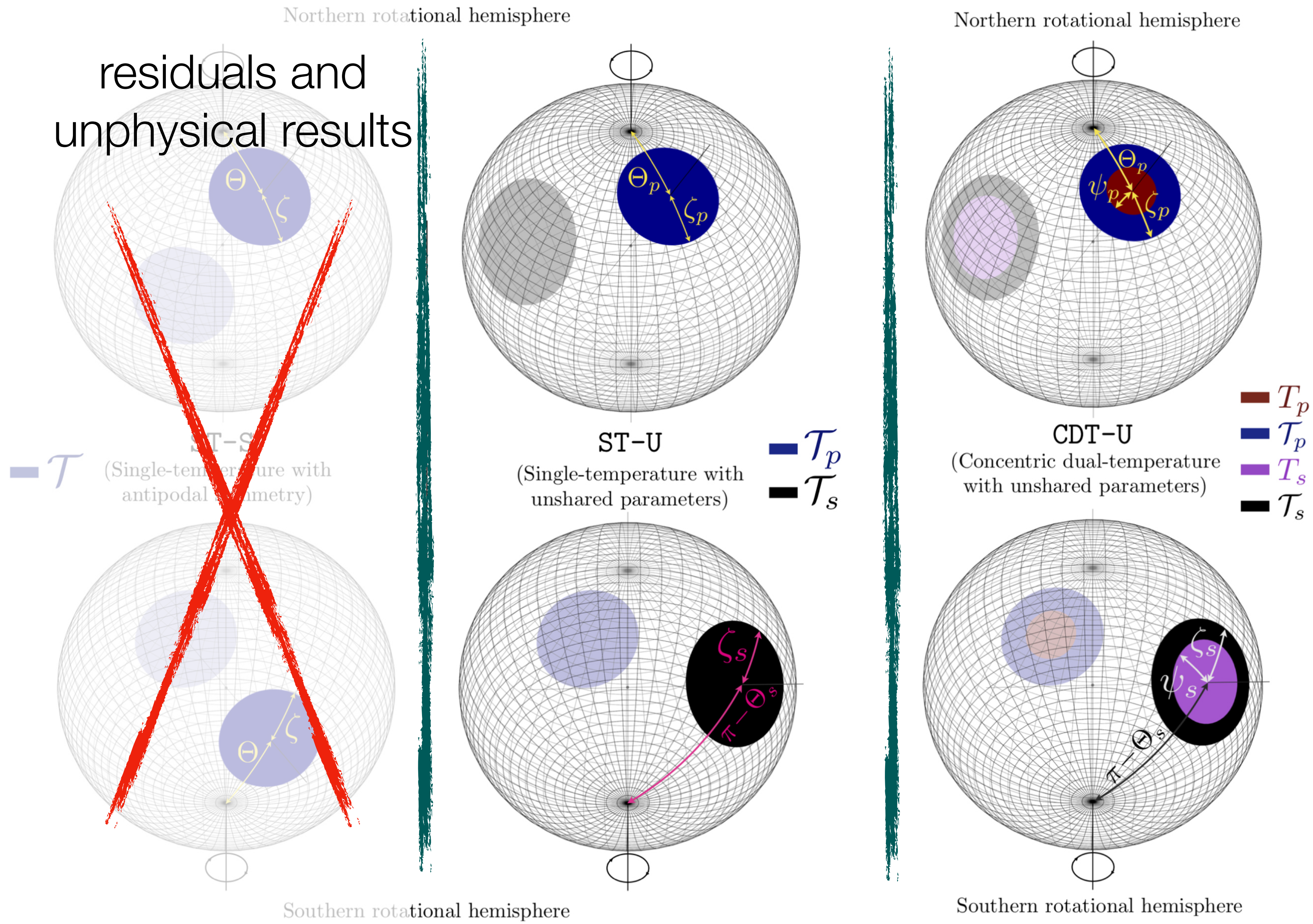
Hot region models PSR J0030+0451

- Two distinct regions
- Increasing complexity
- Both graphical comparisons and statistical



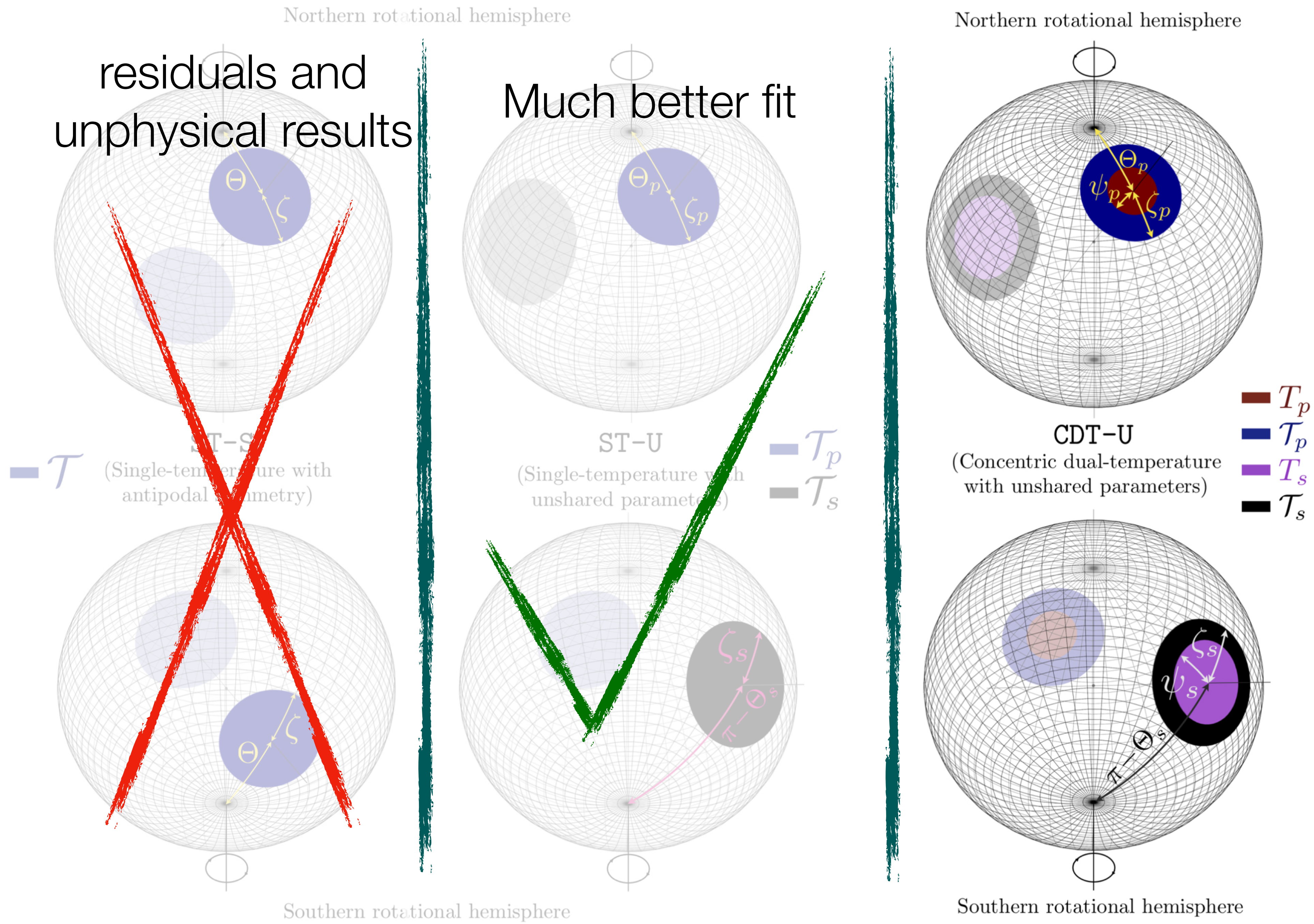
Hot region models PSR J0030+0451

- Two distinct regions
- Increasing complexity
- Both graphical comparisons and statistical



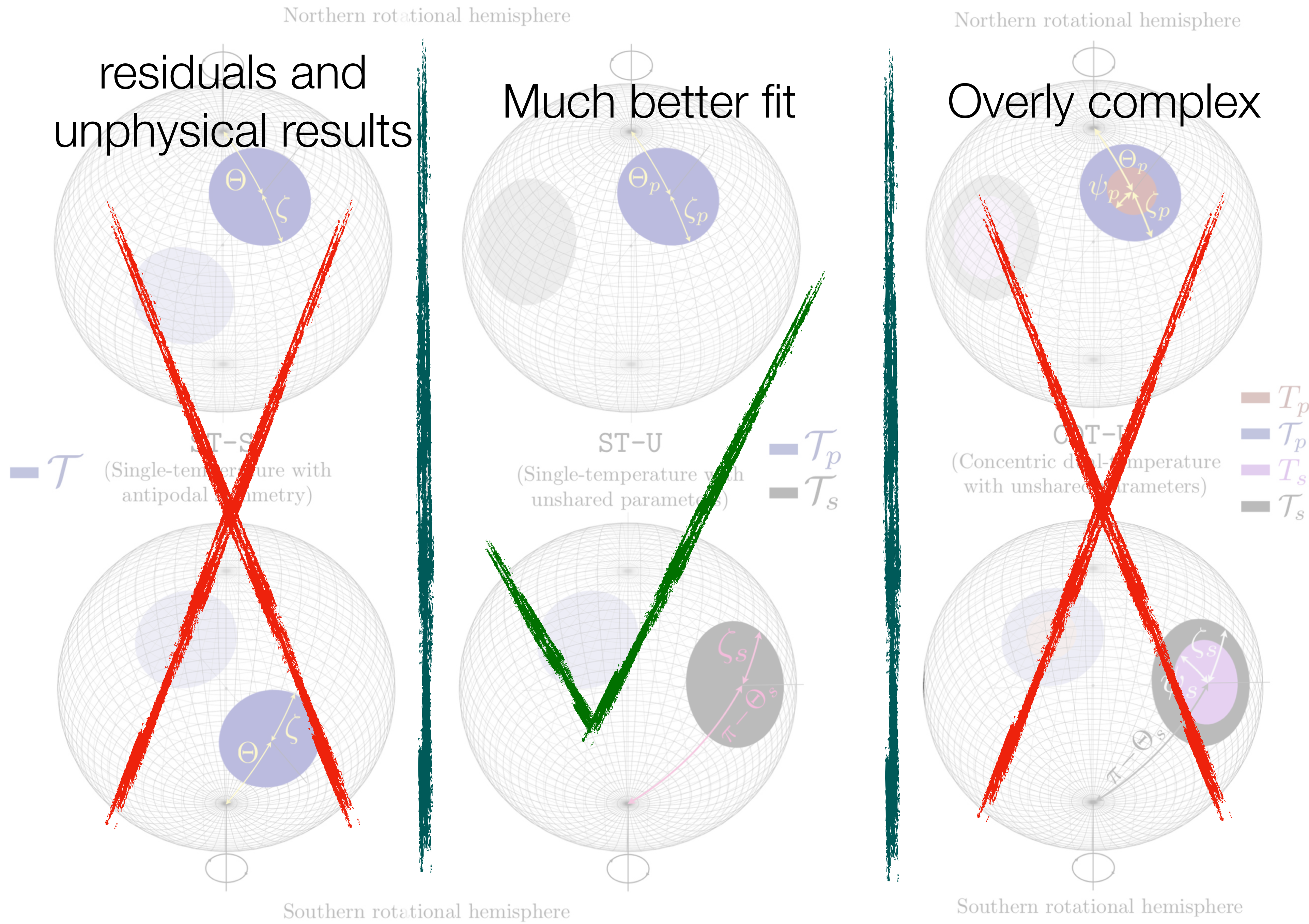
Hot region models PSR J0030+0451

- Two distinct regions
- Increasing complexity
- Both graphical comparisons and statistical

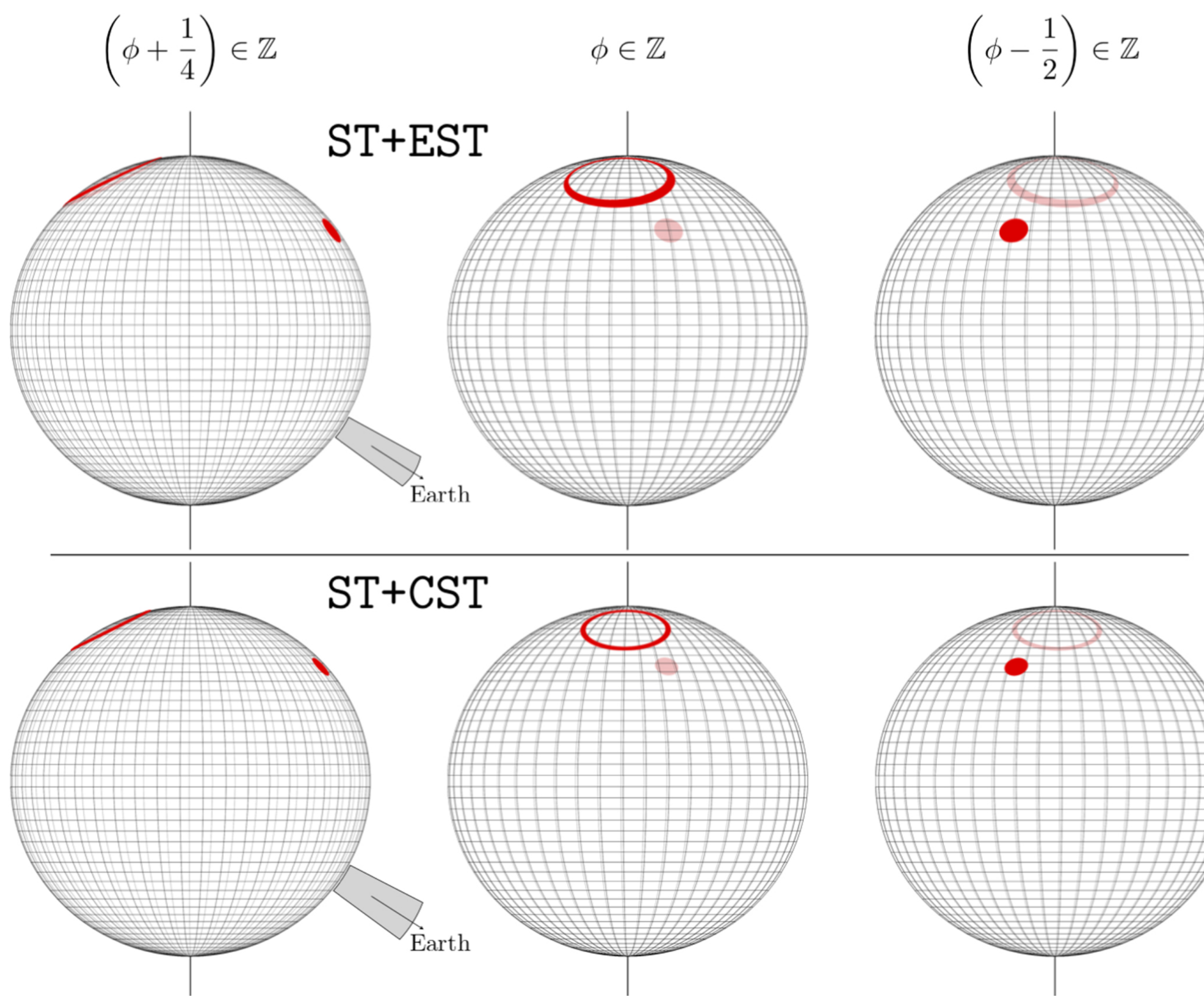


Hot region models PSR J0030+0451

- Two distinct regions
- Increasing complexity
- Both graphical comparisons and statistical

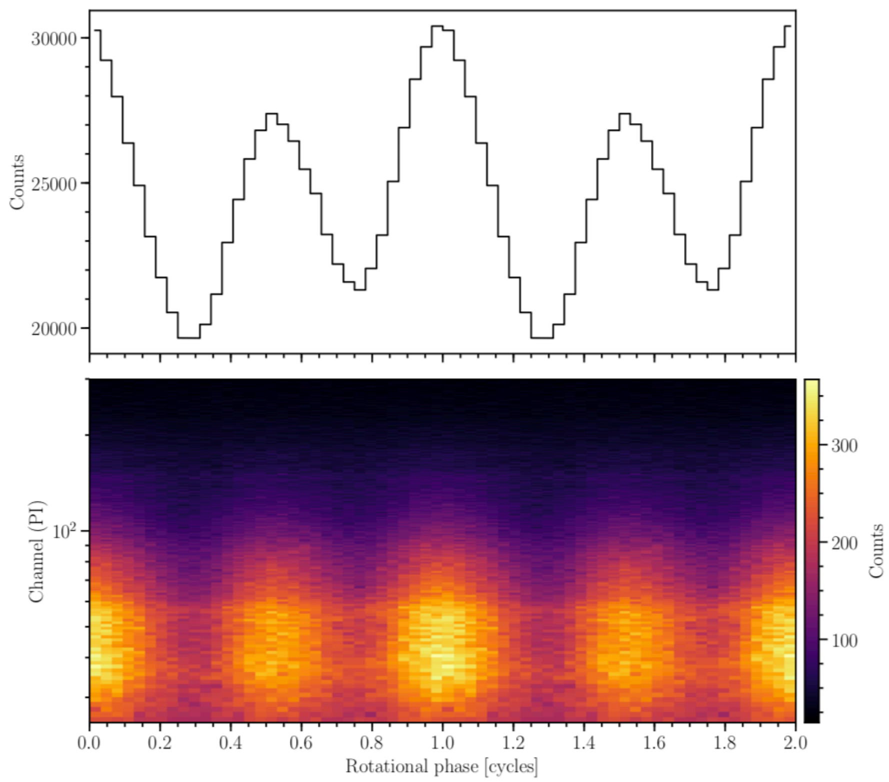


Hot region models PSR J0030+0451

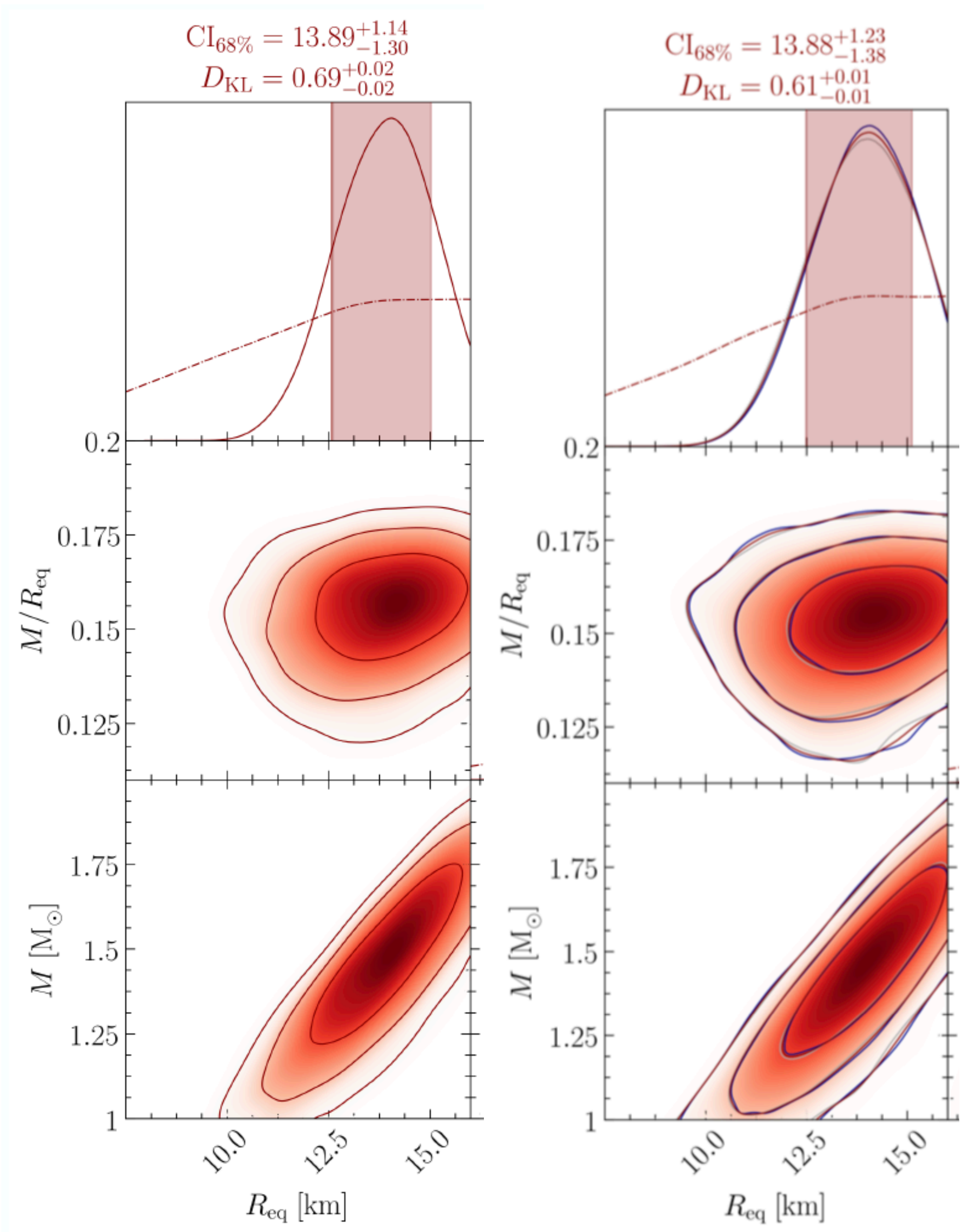


- Single temperature spot + annulus (eccentric, EST, or concentric, CST)

- Similar inferred mass and radius

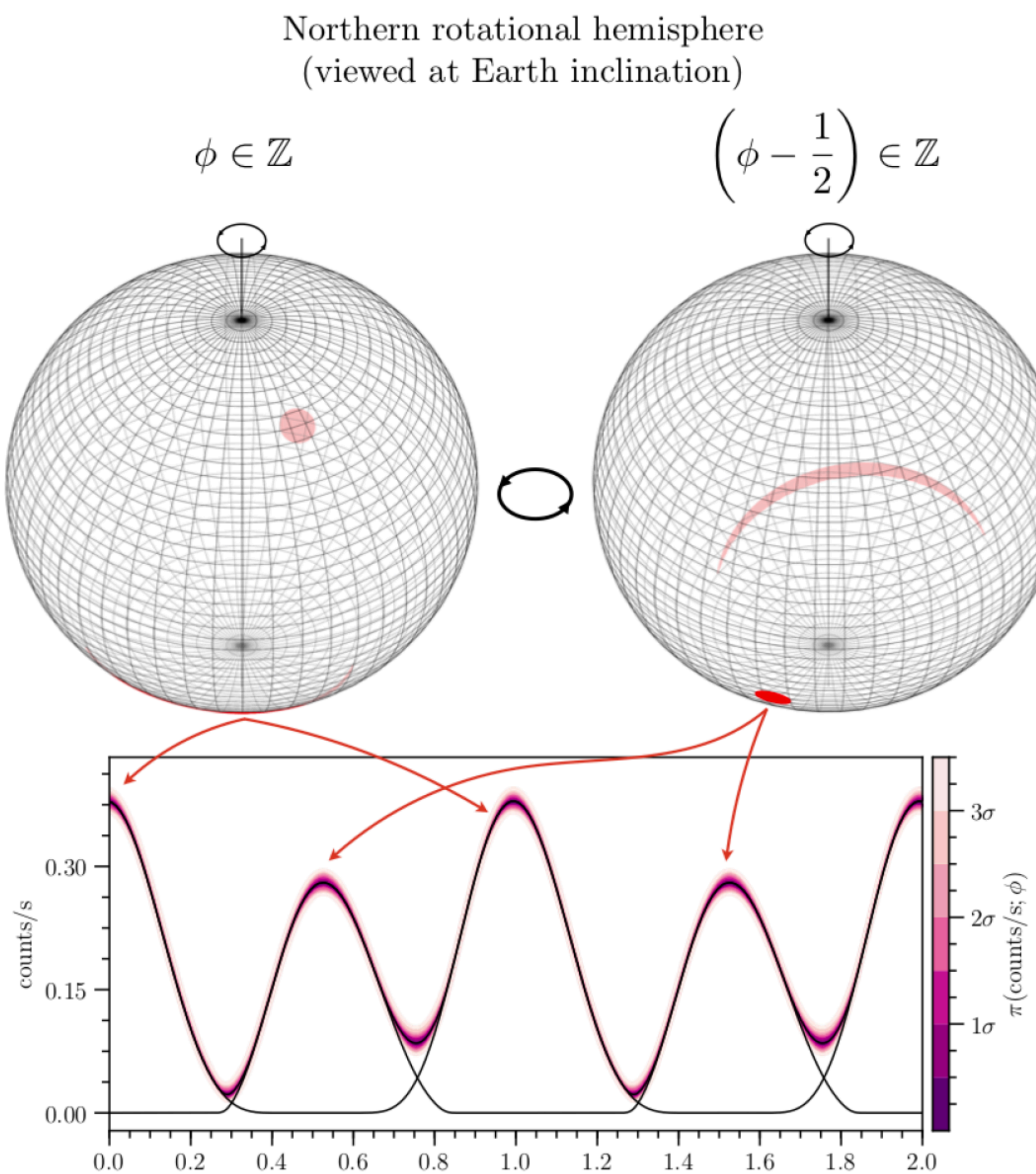


Hot region models PSR J0030+0451



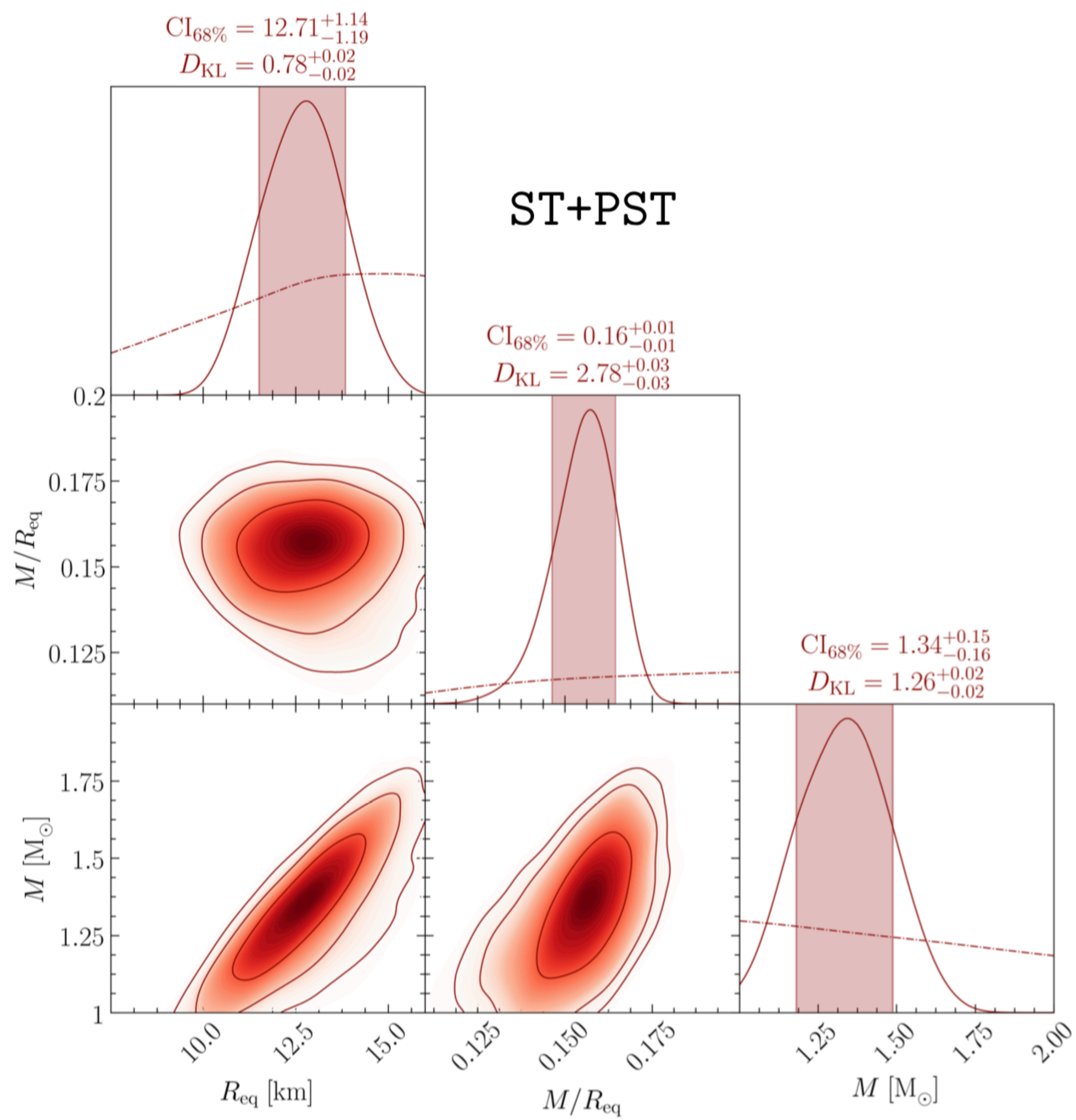
- Single temperature spot + annulus (eccentric, EST, or concentric, CST)
- Similar inferred mass and radius

Preferred model PSR J0030+0451



- ST+PST model (single temperature + crescent)
- Smaller mass and radius compared to CST/EST

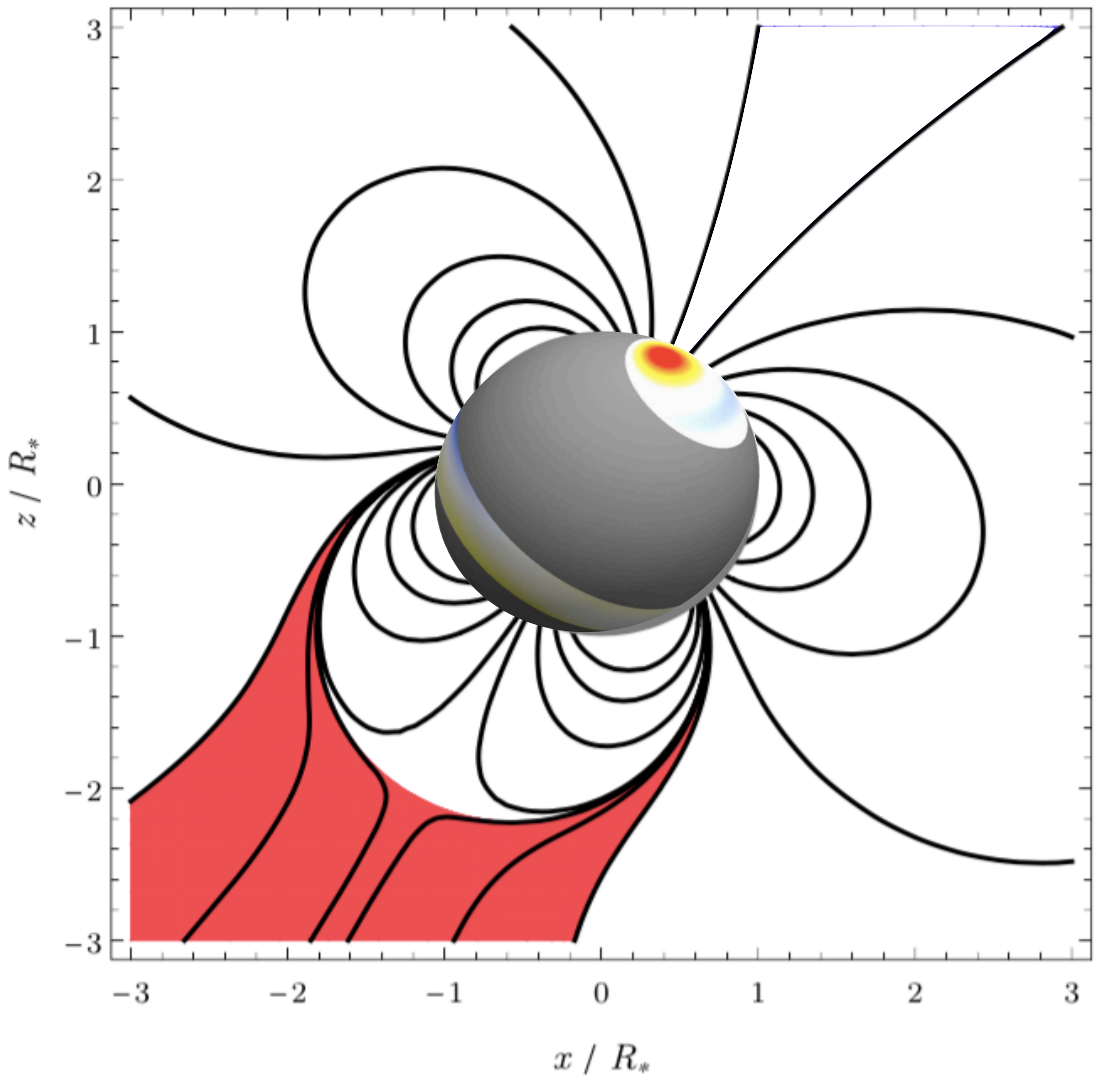
Preferred model PSR J0030+0451

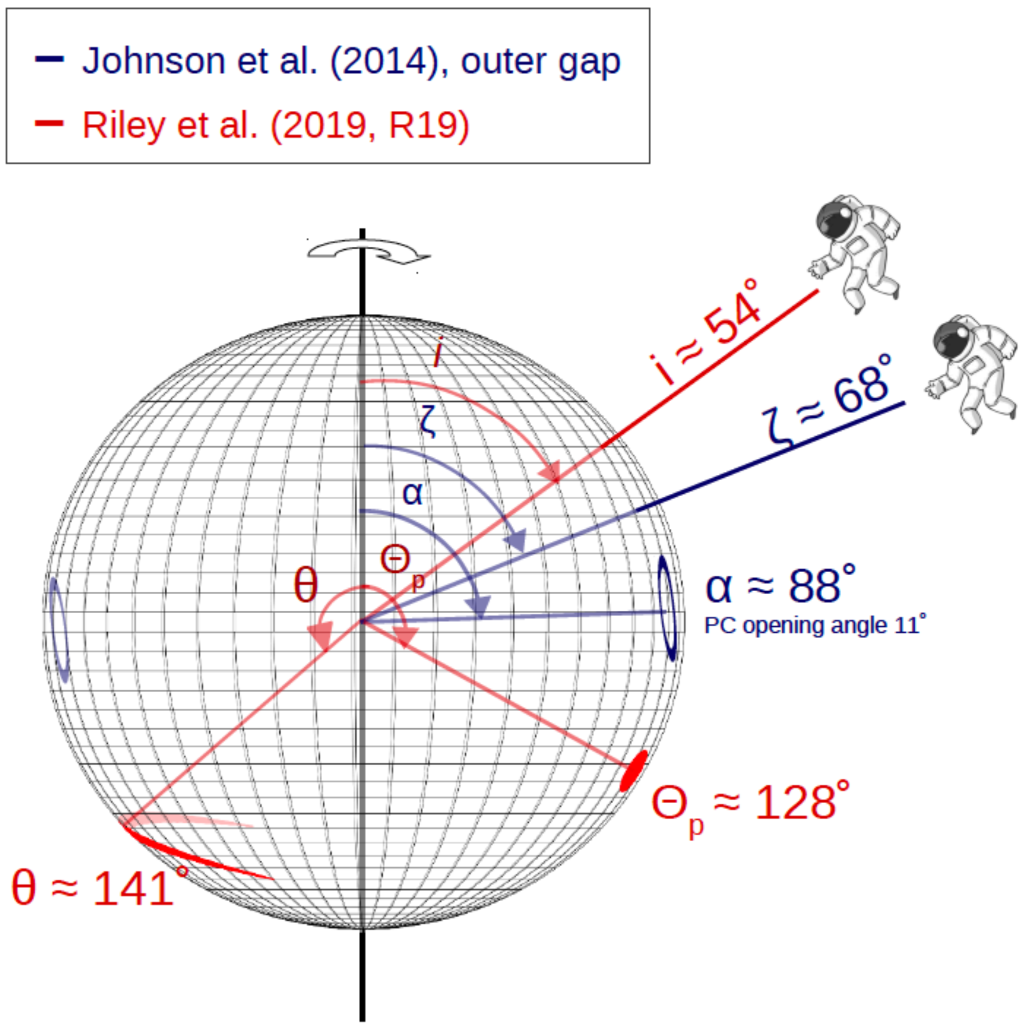


- ST+PST model (single temperature + crescent)
- Smaller mass and radius compared to CST/EST
- Similar to independent analysis of Miller et al. (2019)

Implications for pulsar magnetic fields

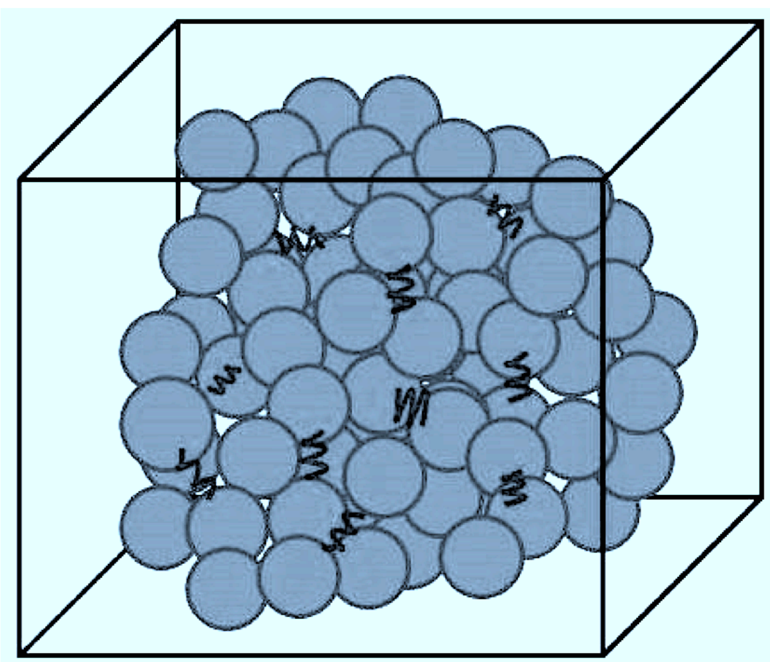
- Quadrudipole field structure? (Gralla et al. 2017)
- Need to connect to magnetic field constraints from radio and γ-rays



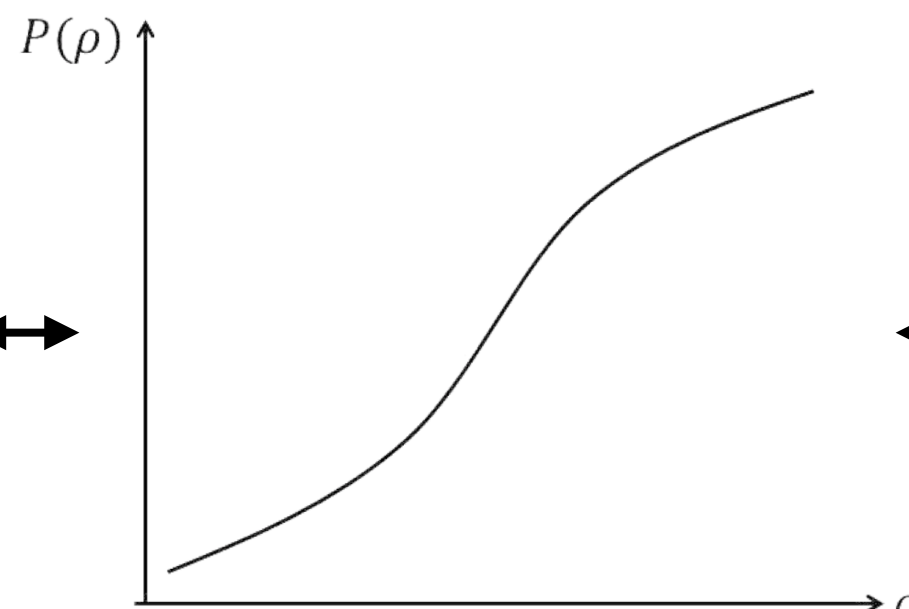


Implications for the dense matter EOS

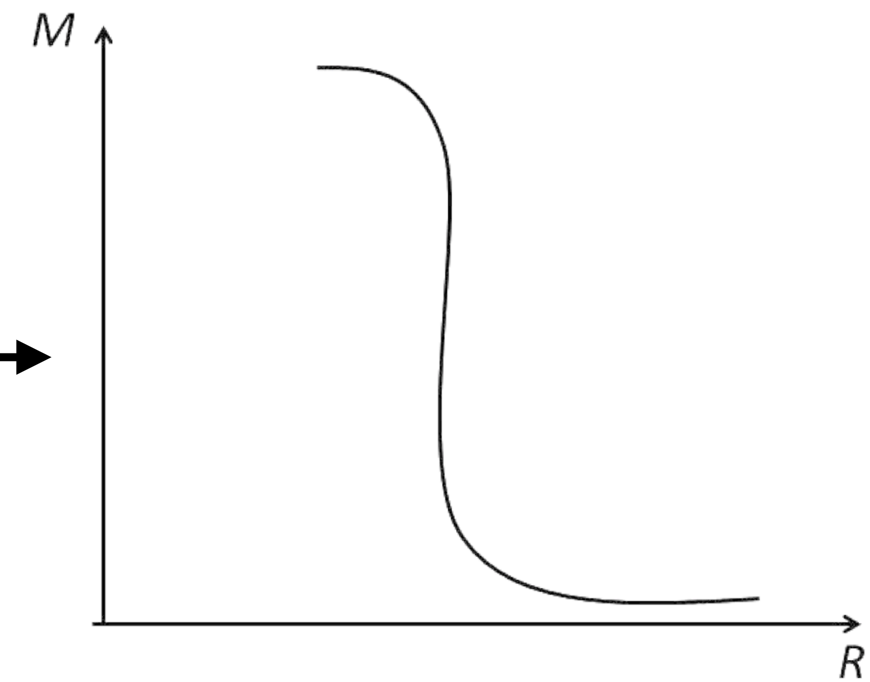
I. Dense Matter Physics

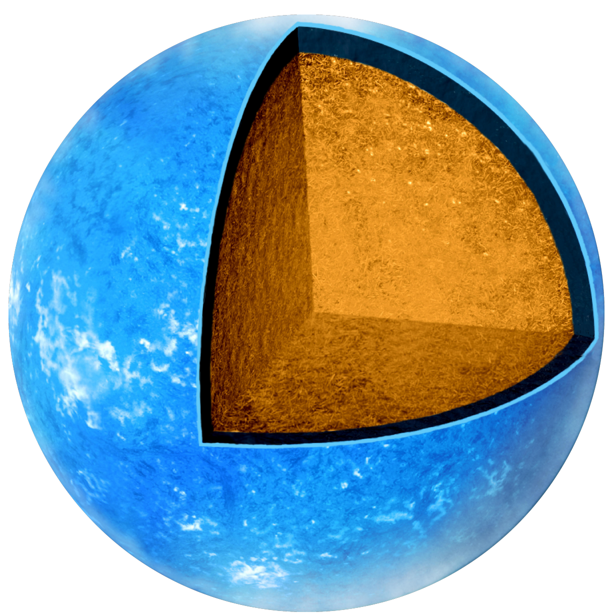


II. Equation of State

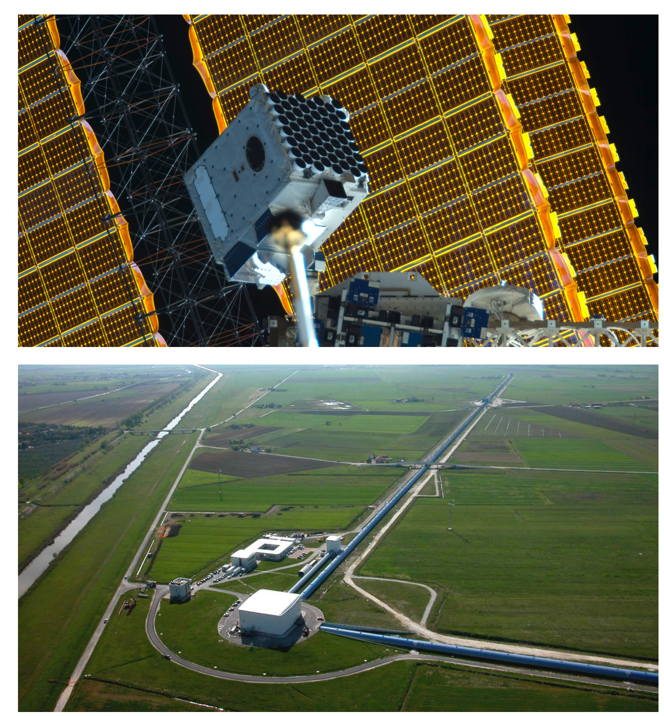


III. Mass and Radius





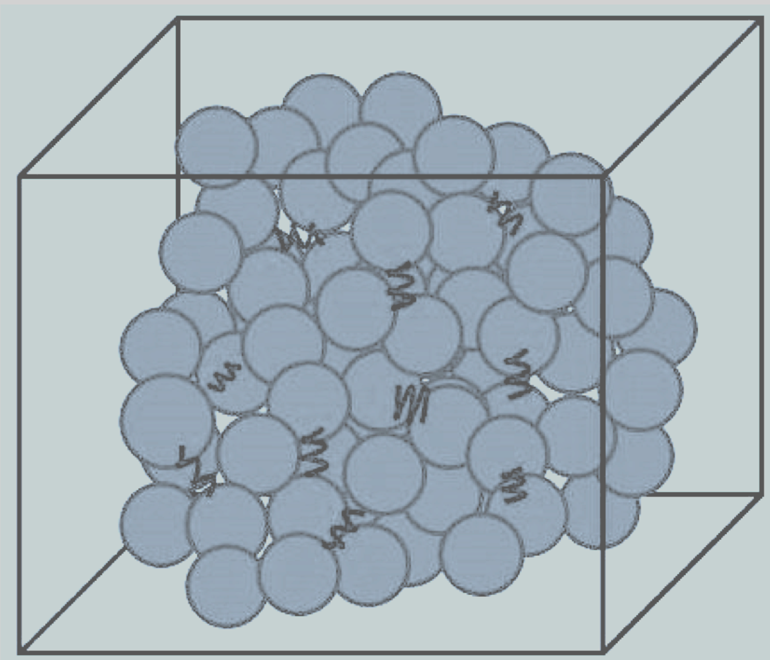
V. Neutron Star



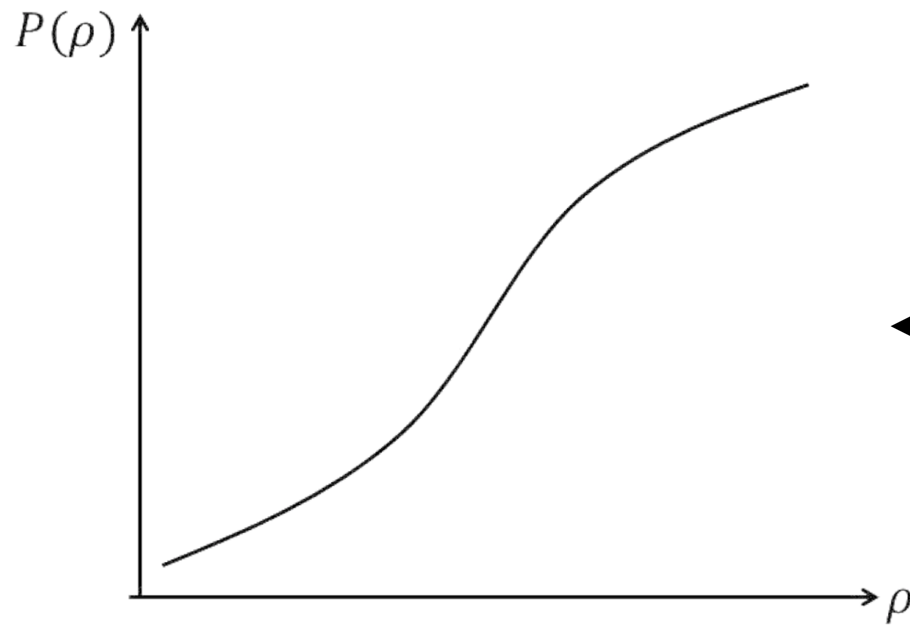
IV. Observables

Implications for the dense matter EOS

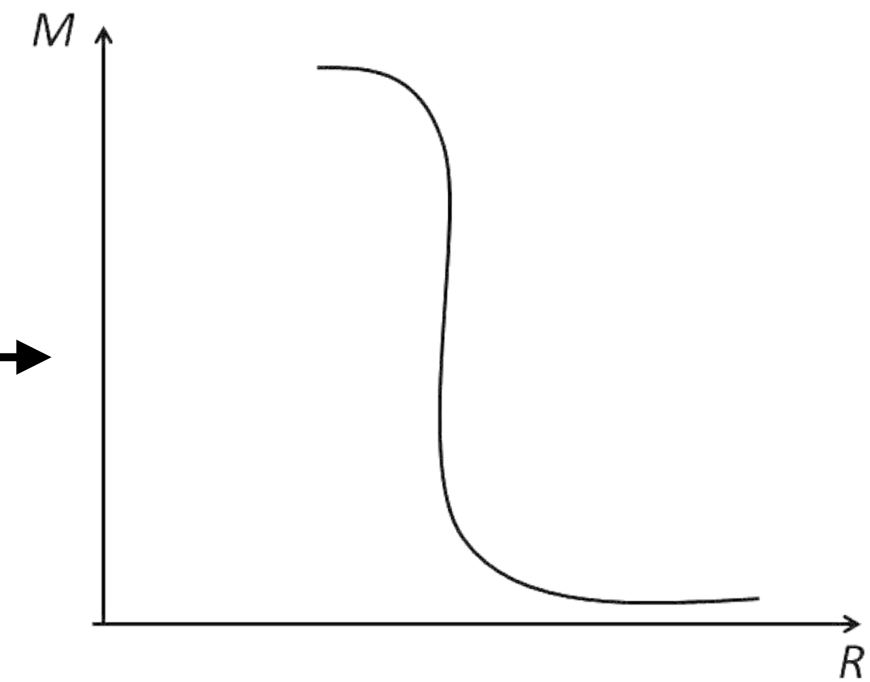
I. Dense Matter Physics

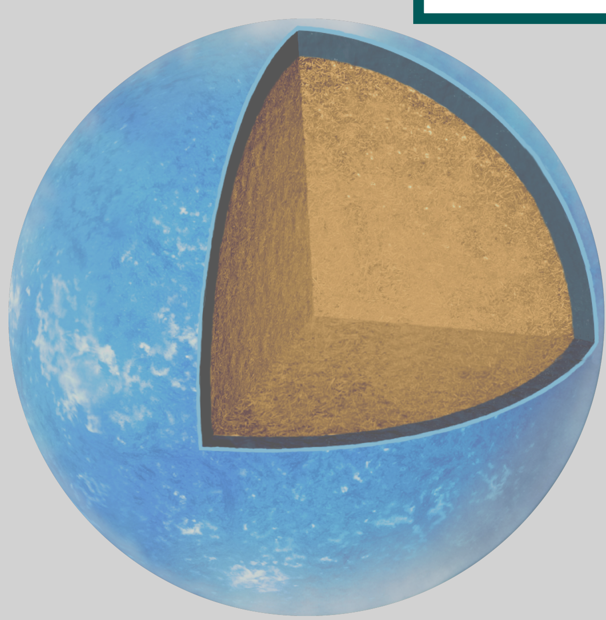


II. Equation of State



III. Mass and Radius

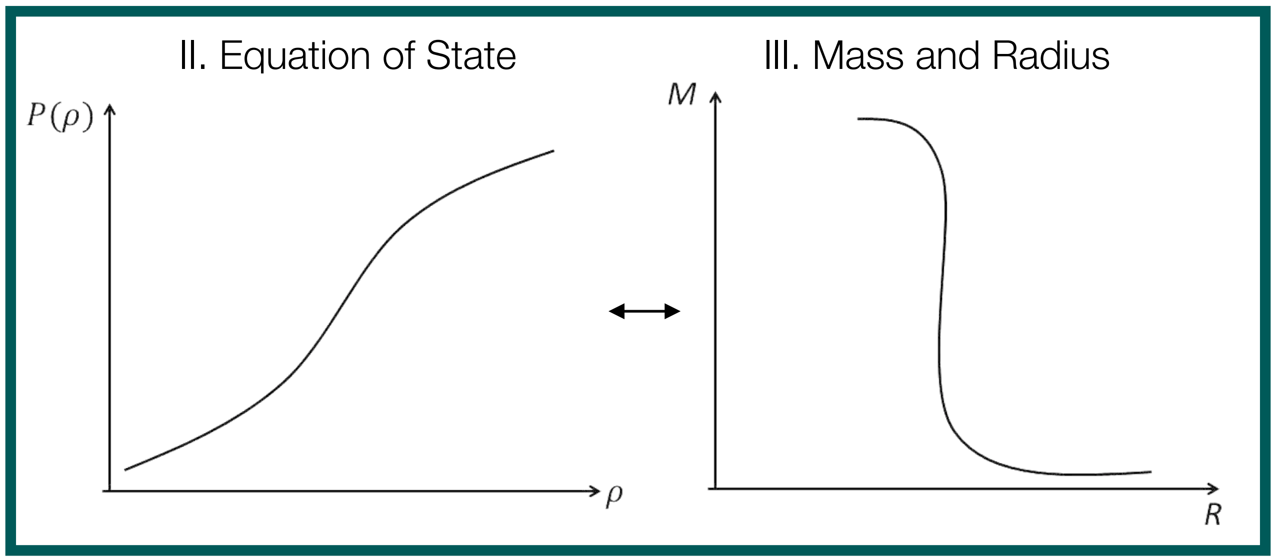




V. Neutron Star

IV. Observables

A Bayesian approach



Posterior on EOS parameters

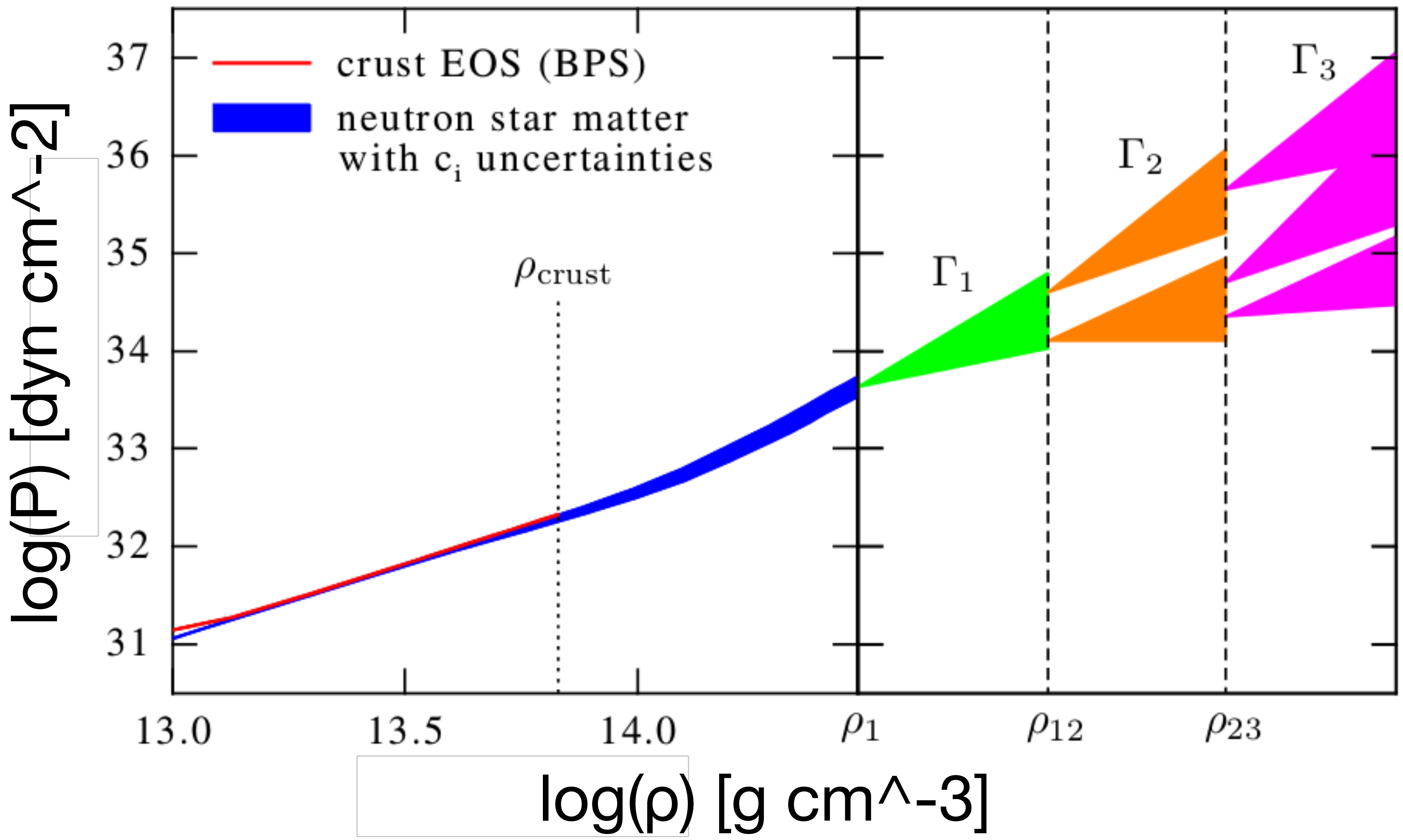
Mass-Radius likelihood

$$\mathcal{P}(\theta \mid \mathcal{D}) \propto \pi(\theta) \mathcal{P}(M, R \mid \mathcal{D})$$

Prior on EOS parameters

EOS parameterization

Piecewise polytropic model

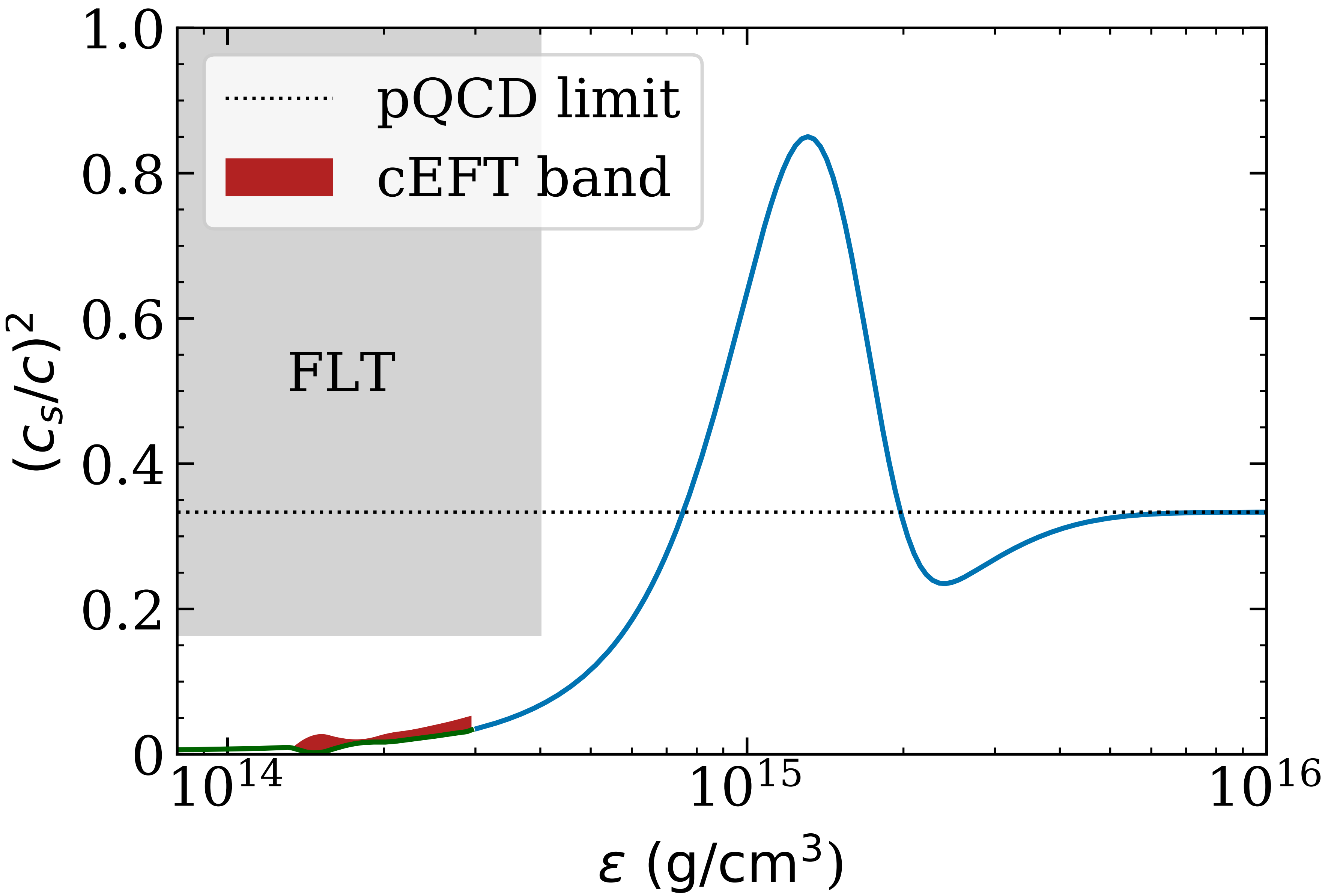


- 6 free parameters
- Continuous match to neutron matter calculations at low densities
- discontinuities in speed of sound

EOS parameterization

speed of sound model

- Converges to 1/3, as predicted by QCD
- Constrained by Fermi Liquid Theory (FML) around nuclear saturation density



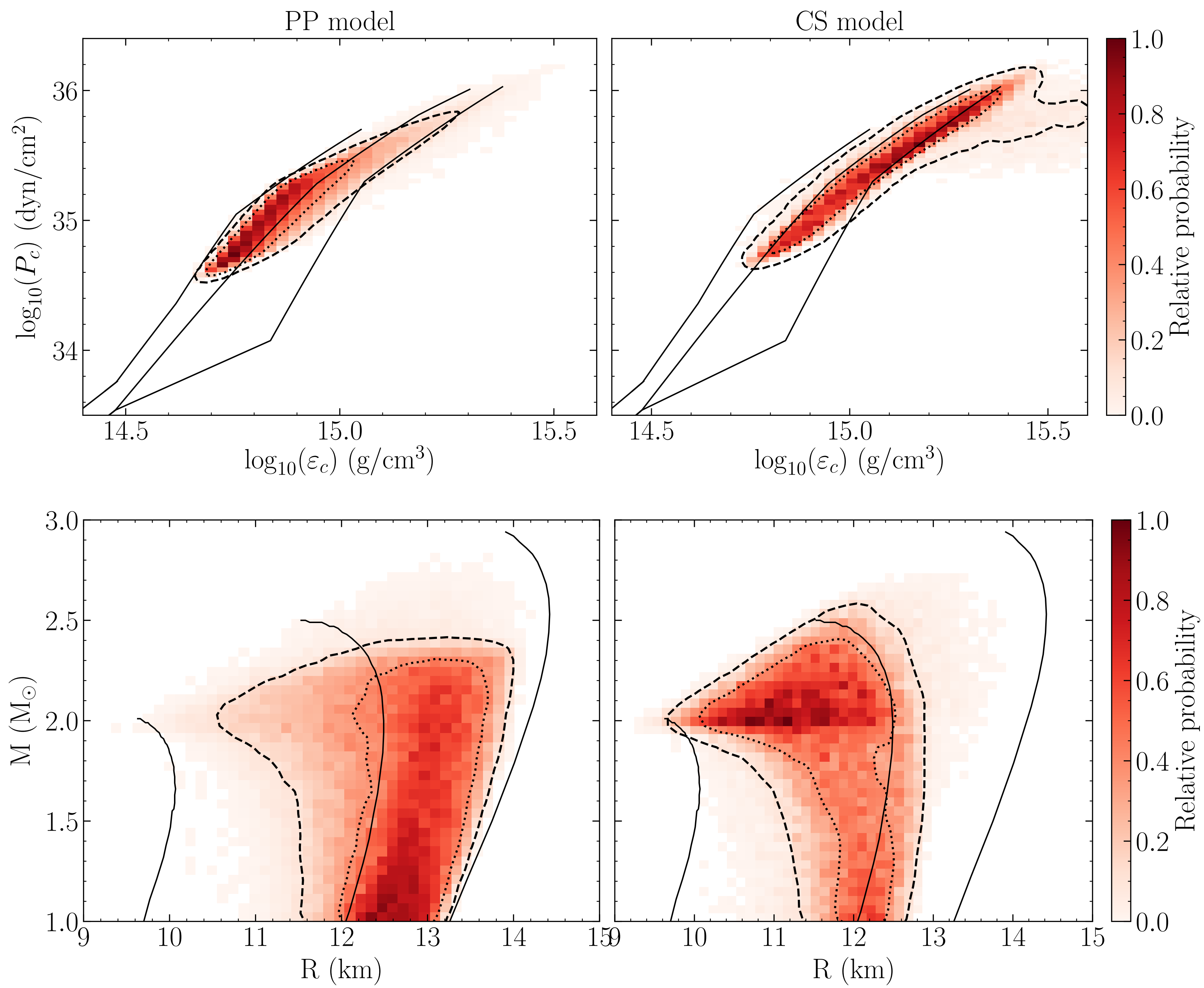
Prior choices for both models

- Reproduce PSR J0348+0432 with a mass of 2.01 solar mass (Antoniadis et al., 2013)

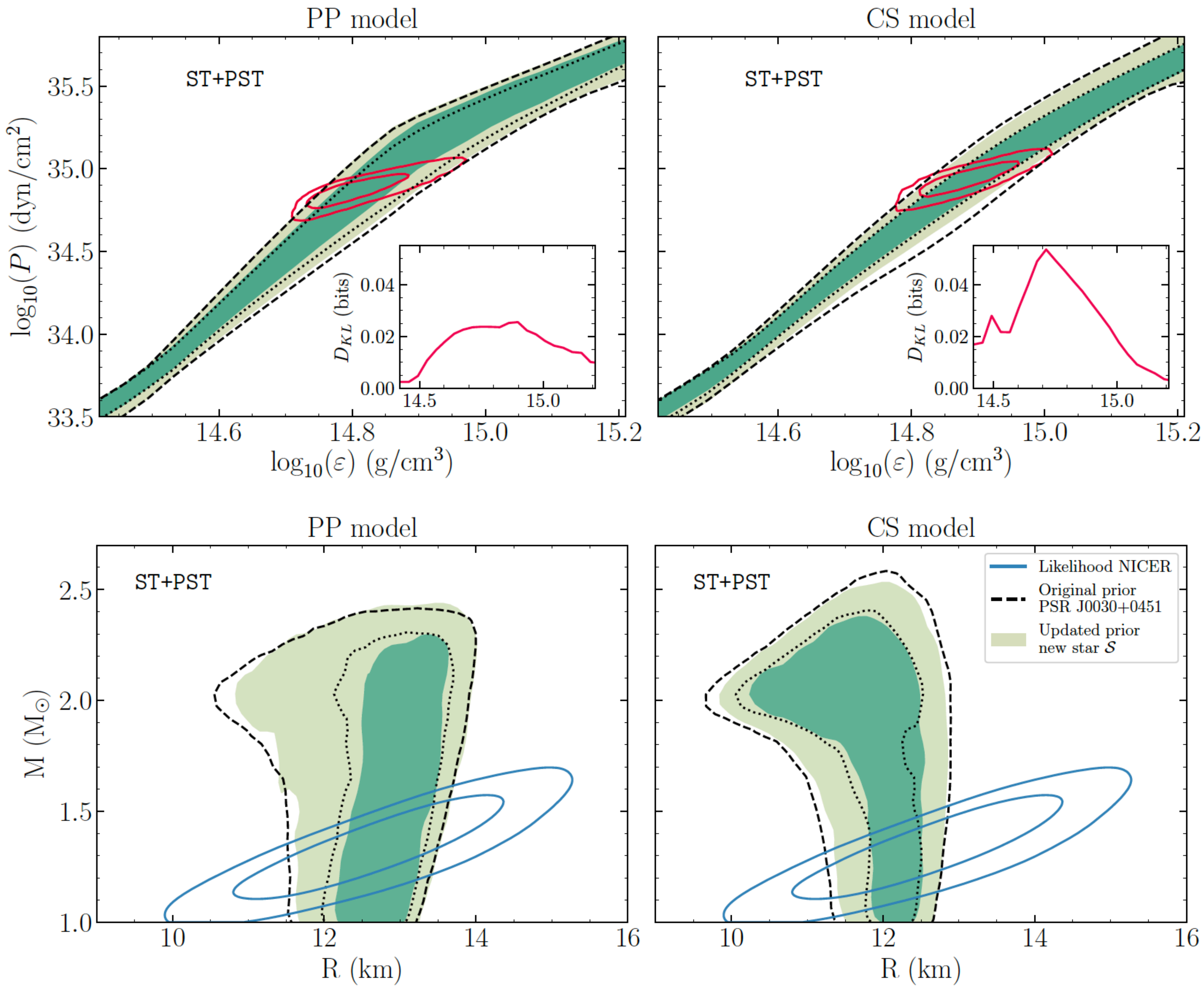
- Causal and thermodynamically stable

- Uniformly sampled EOS parameters

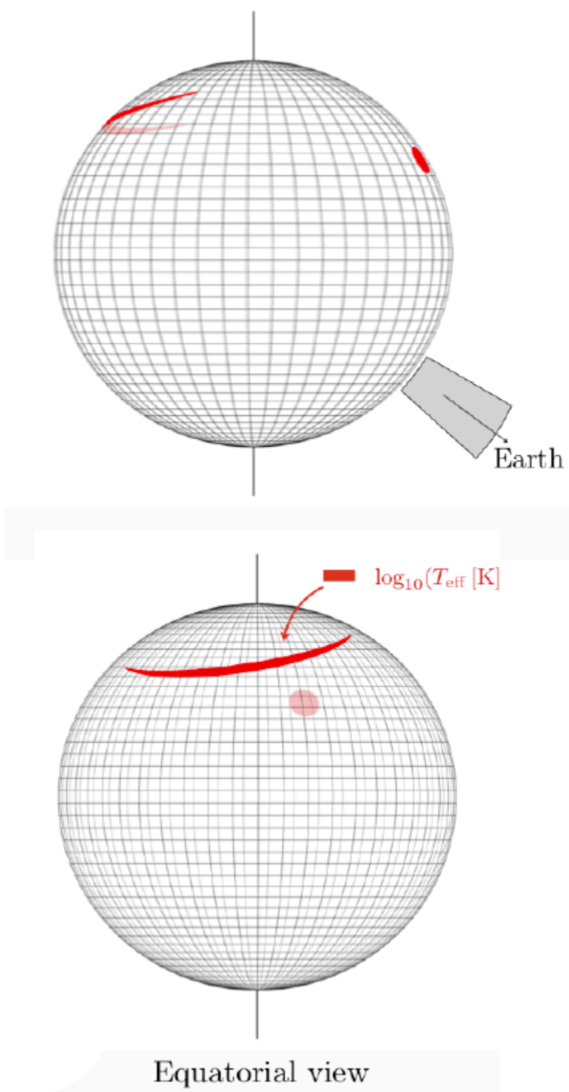
Prior distributions



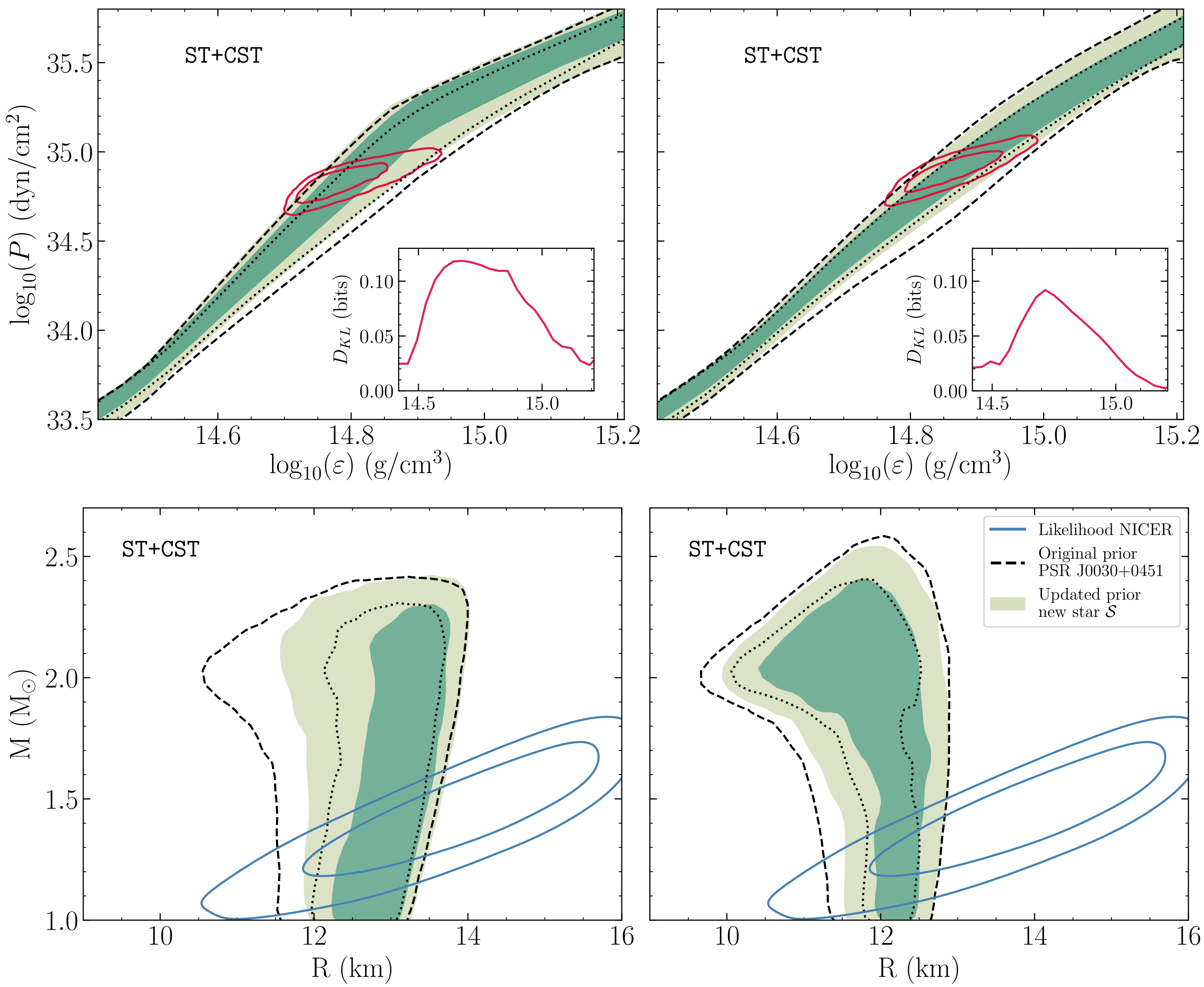
Inferred posterior distributions



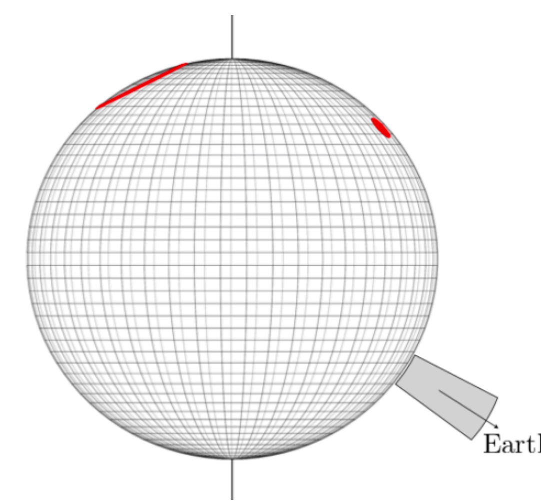
- ST + PST

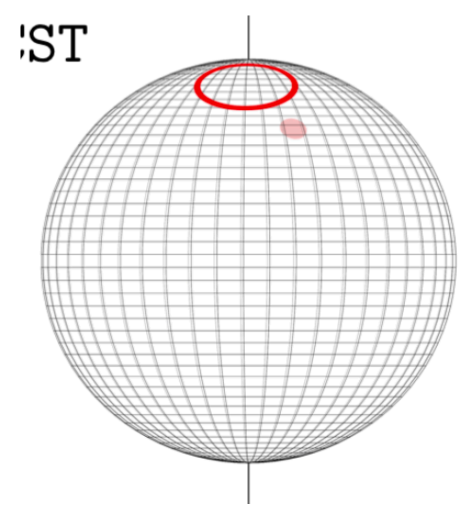


Inferred posterior distributions

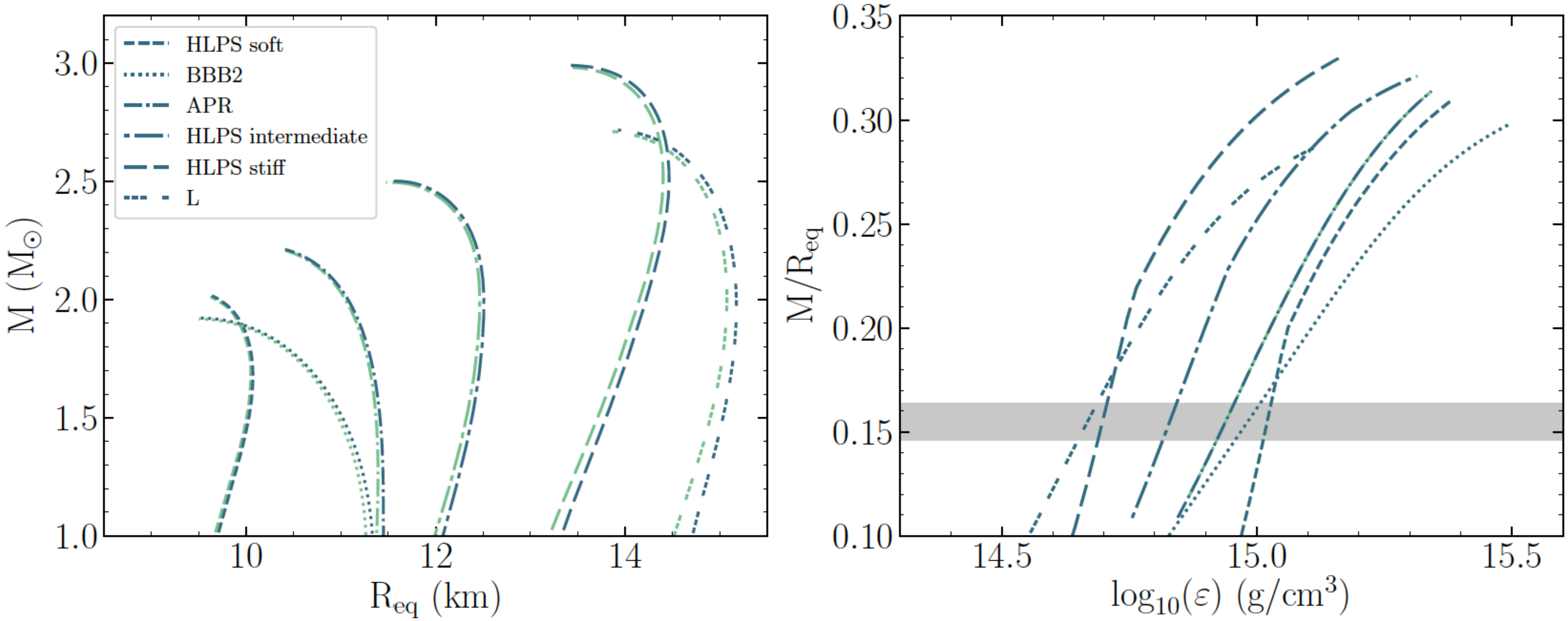


- ST + CST

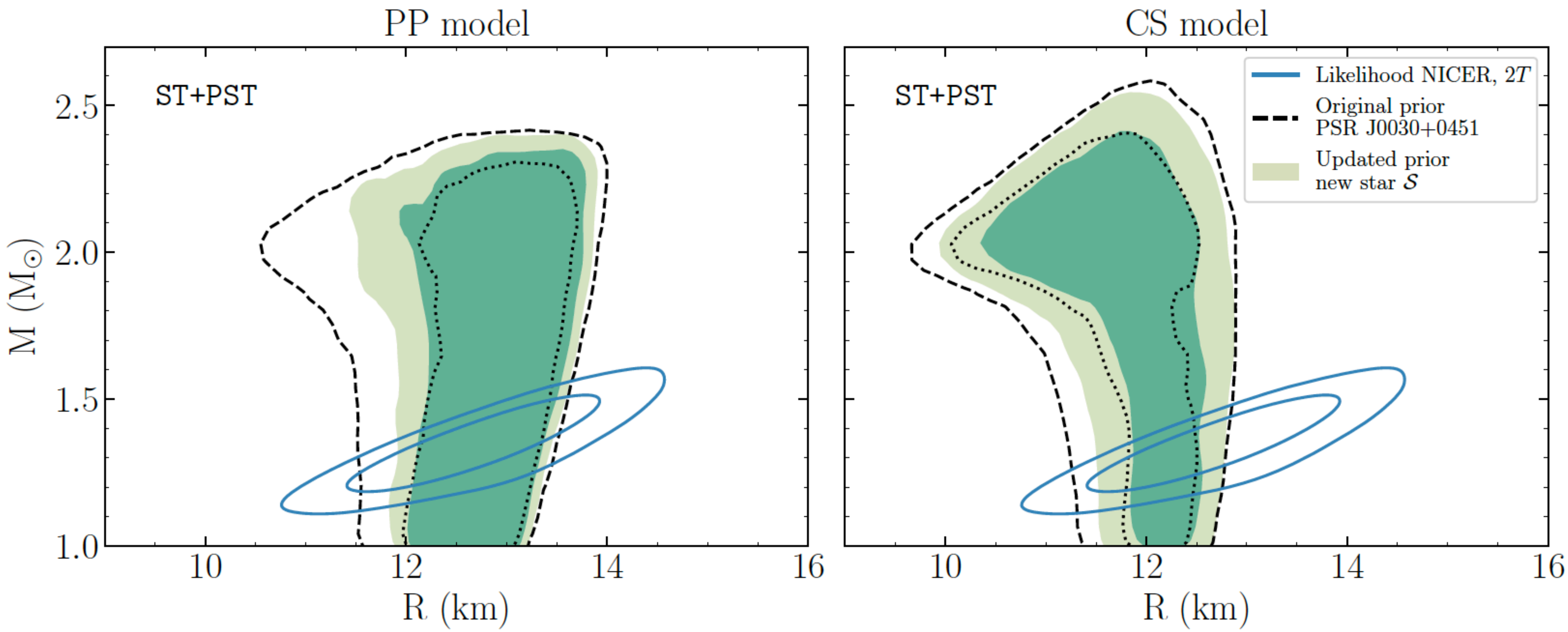




Neglecting rotation

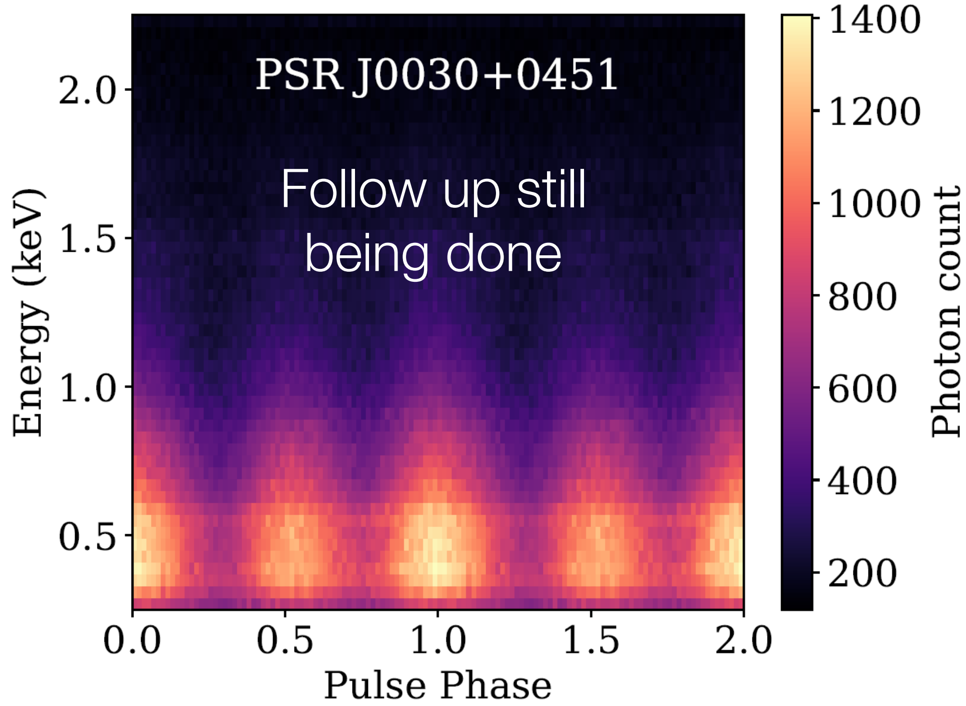


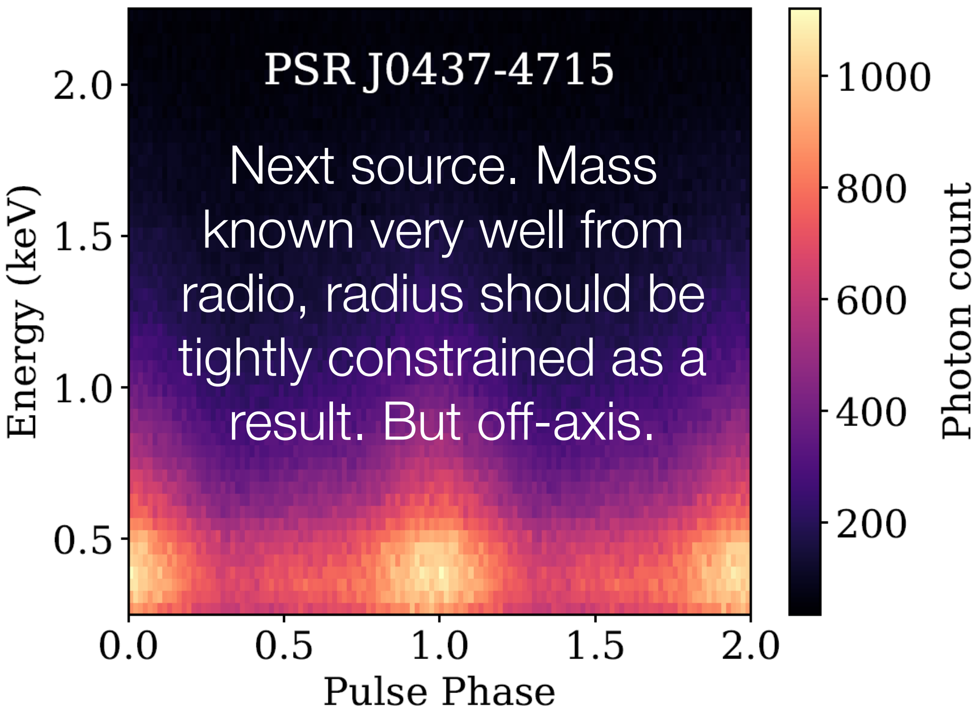
Doubling the observing time on PSR J0030+0451



Small improvements but might be better to focus on other sources

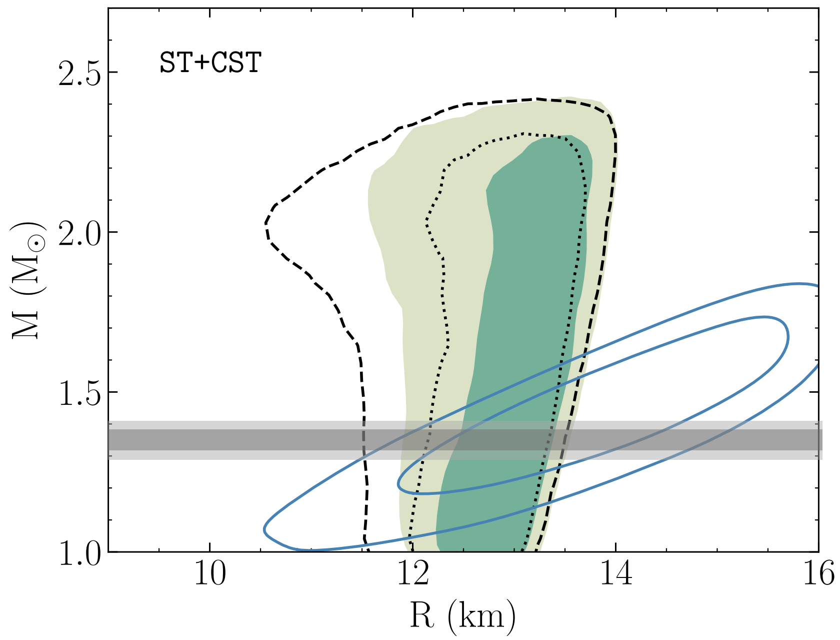
Other *NICER* sources





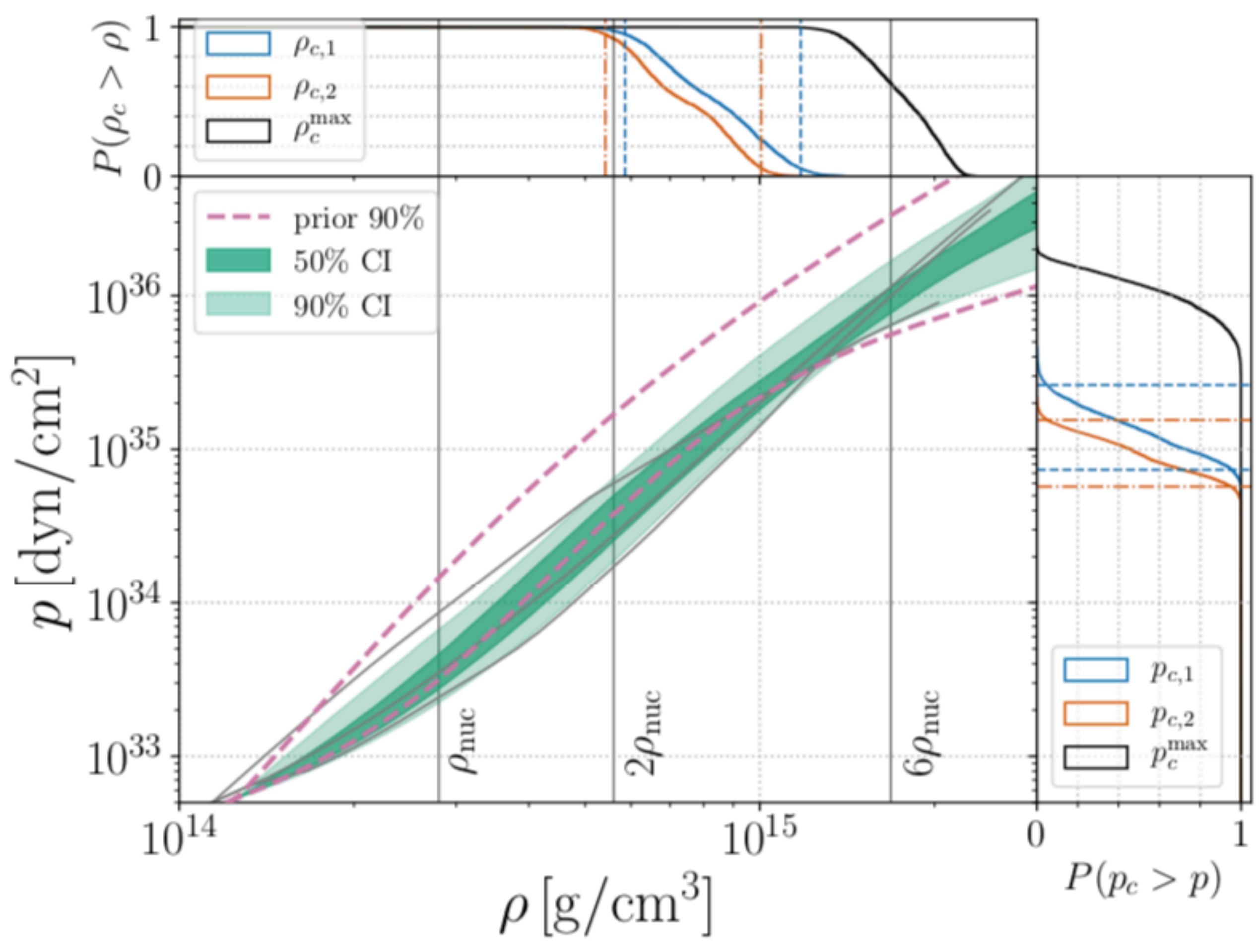
Other possibilities include:

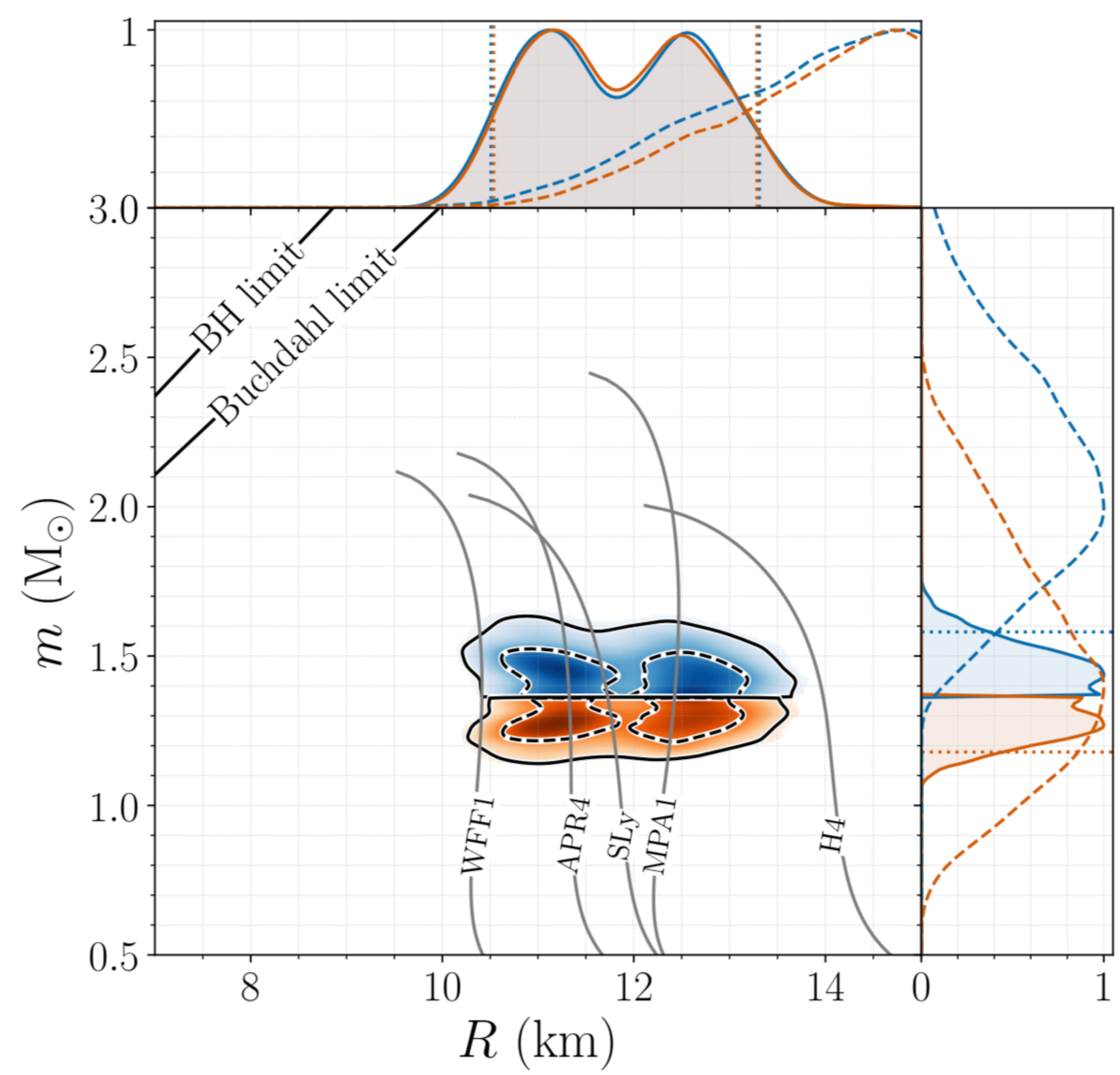
- PSR J1614-2230, a 1.9 solar mass pulsar
- PSRJ0740+6620, a 2.14 solar mass pulsar



Multimessenger constraints

- Combine data from *NICER* and GW170817 in one analysis

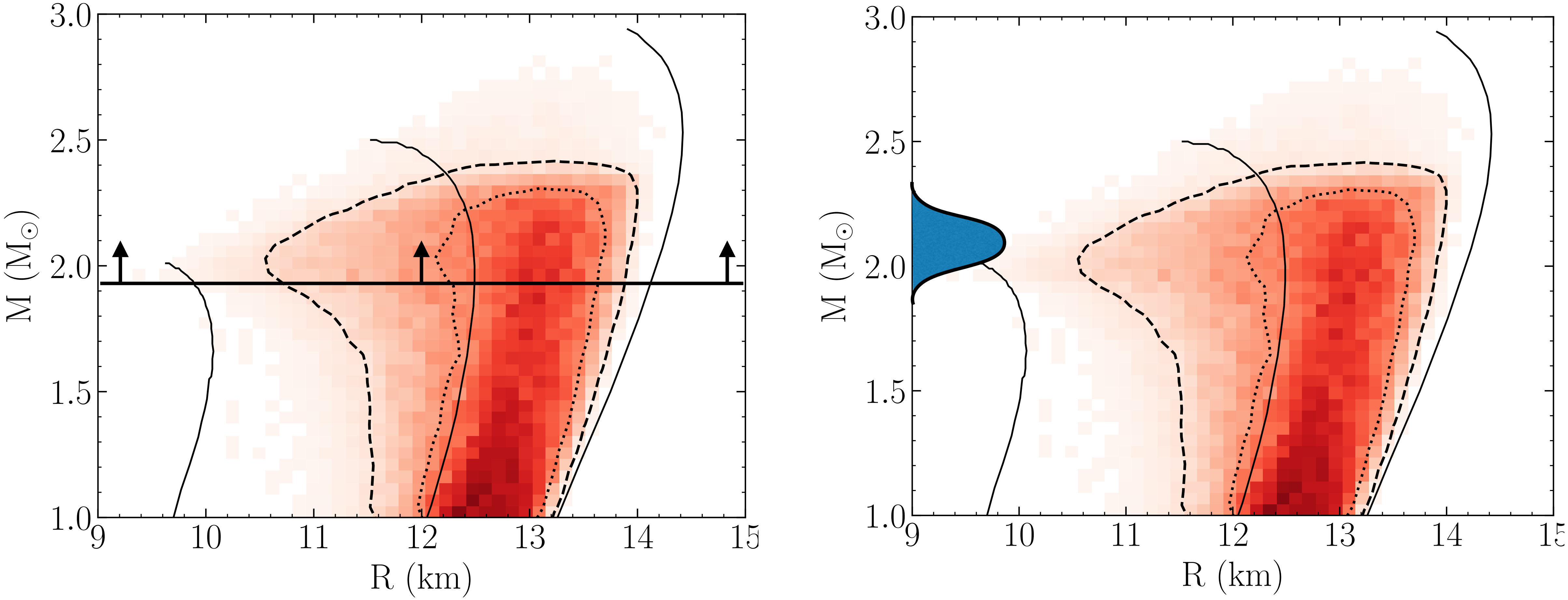




LVC (2018), 1805.11581

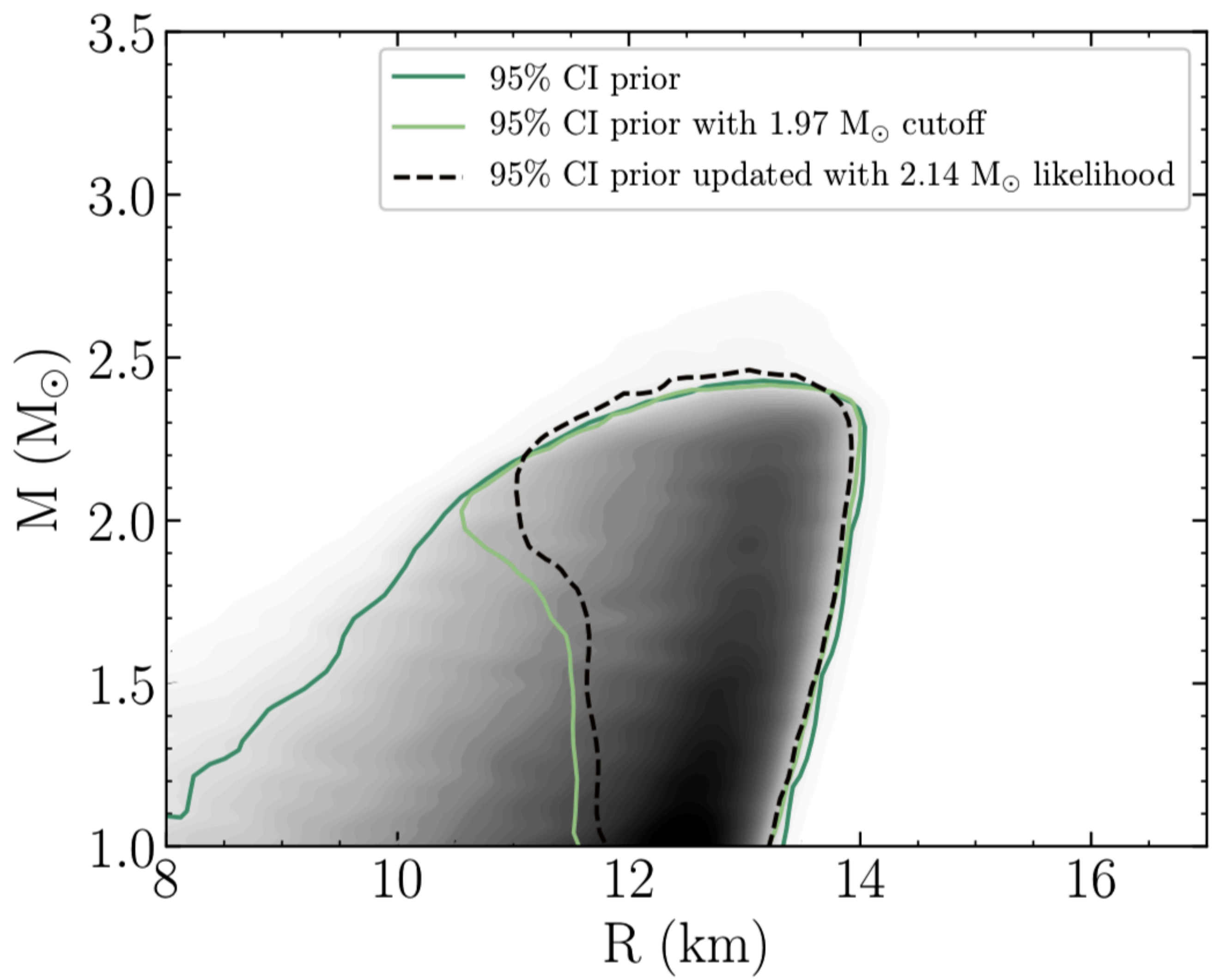
Multimessenger constraints

- Combine data from *NICER* and GW170817 in one analysis
- Similar bayesian framework except different handling of pulsar mass information

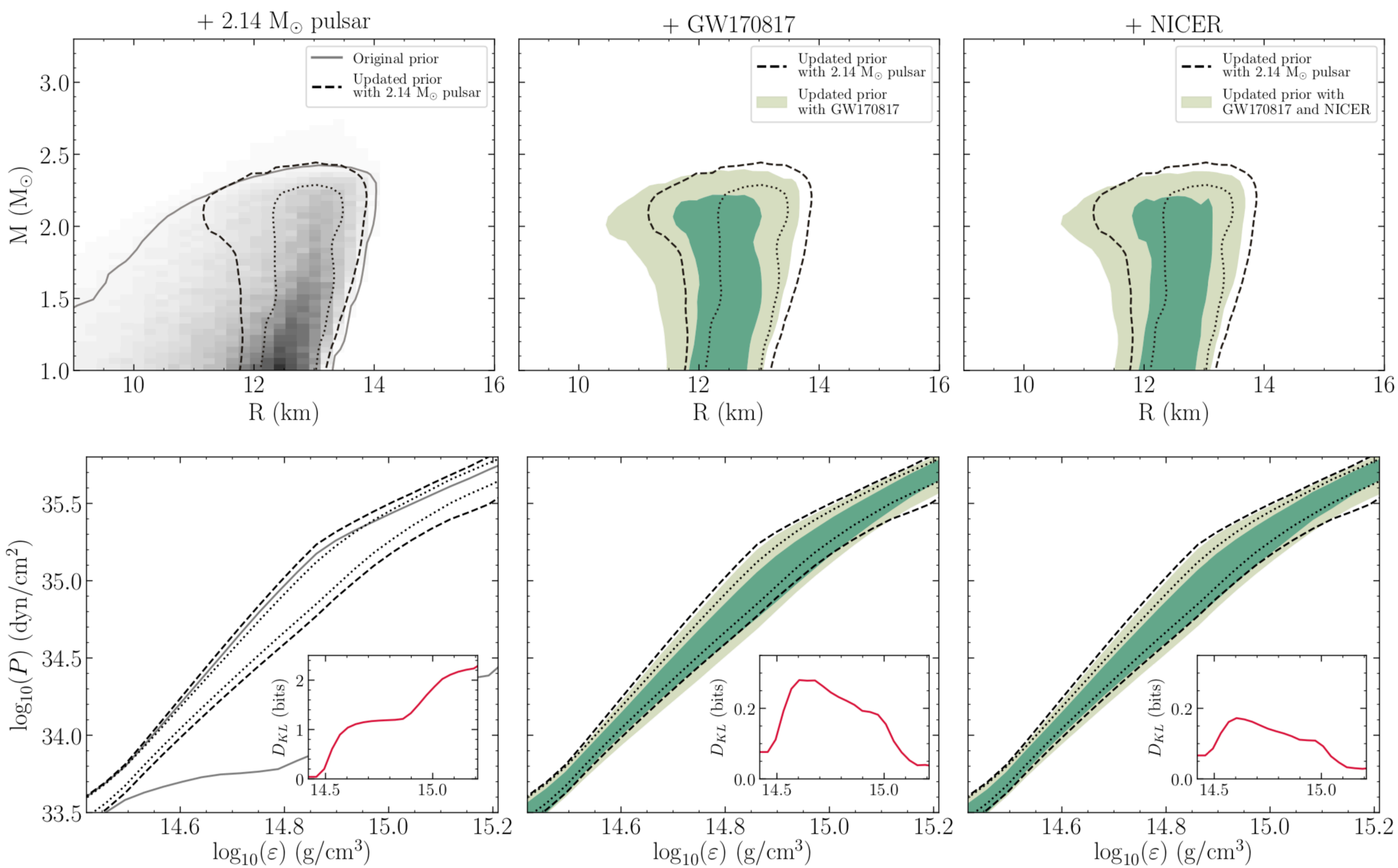


Multimessenger constraints

- Combine data from *NICER* and GW170817 in one analysis
- Similar bayesian framework except different handling of pulsar mass information
- Small differences at lower radii



Multimessenger constraints



Conclusions and outlook

- *NICER* has for the first time jointly estimated the mass and radius of a neutron star
- Constraints on the EOS so far are not very strong but expected to improve with other sources, especially with known masses
- In the future missions like eXTP and STROBE-X will provide tighter mass-radius estimates
- Further constraints can be made with a multimessenger approach