Compact Objects and Dense Matter: Probing Neutron Star Interiors

Devarshi Choudhury

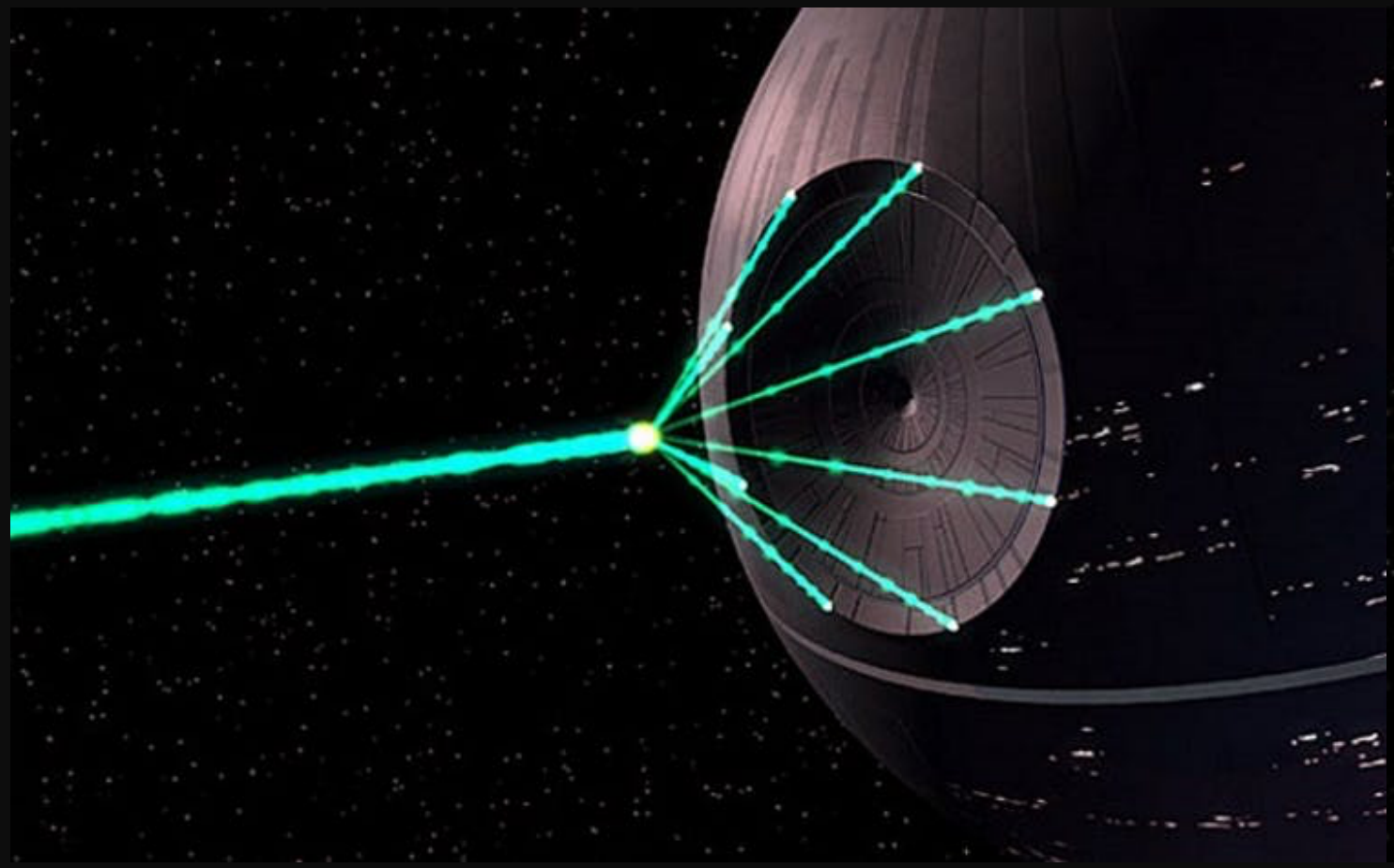
PhD Candidate

D.Choudhury@uva.nl

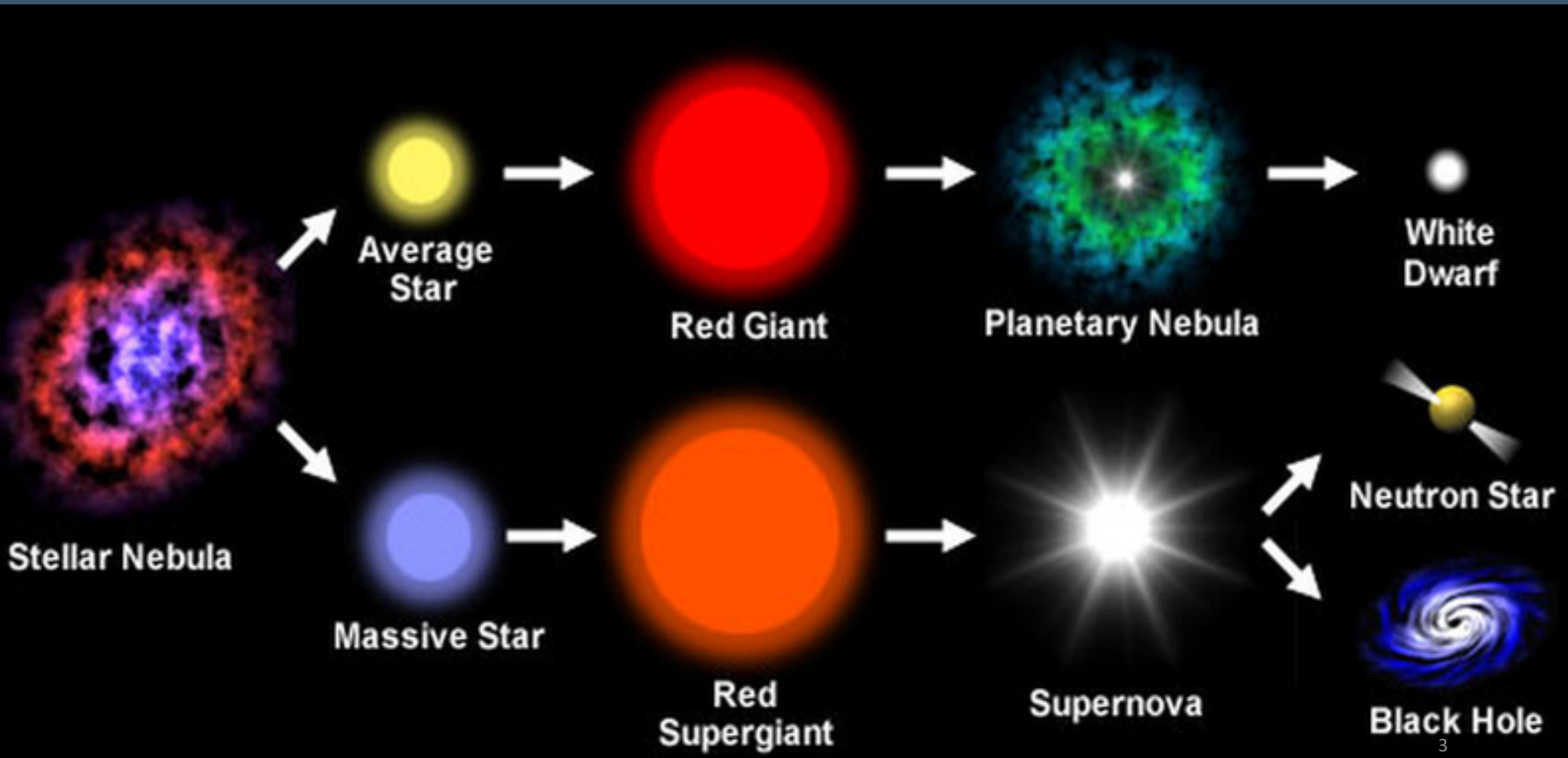
UNIVERSITY OF AMSTERDAM

ANTON PANNEKOEK INSTITUTE

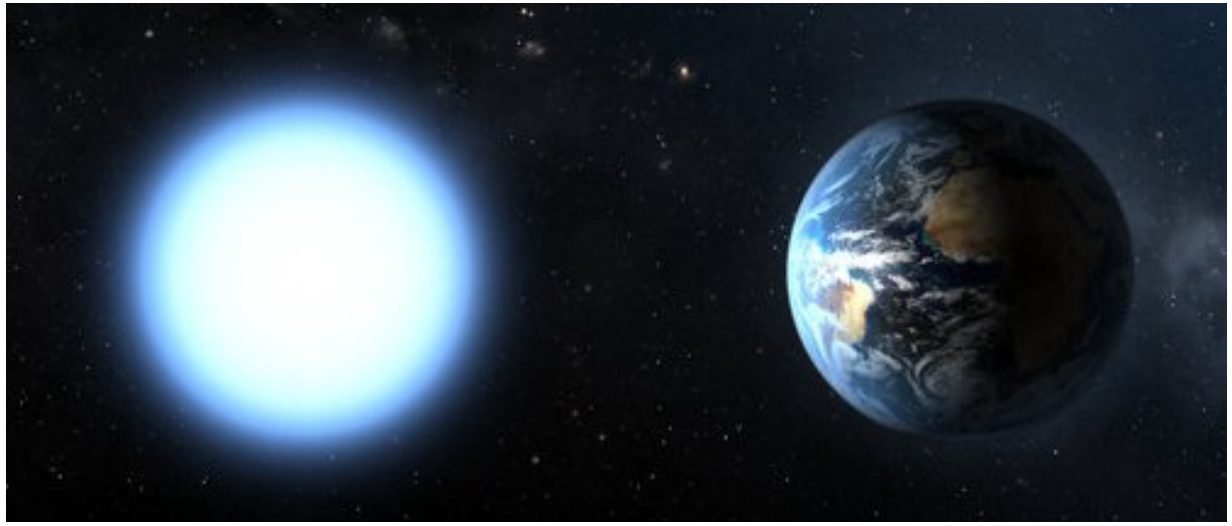
Death Stars



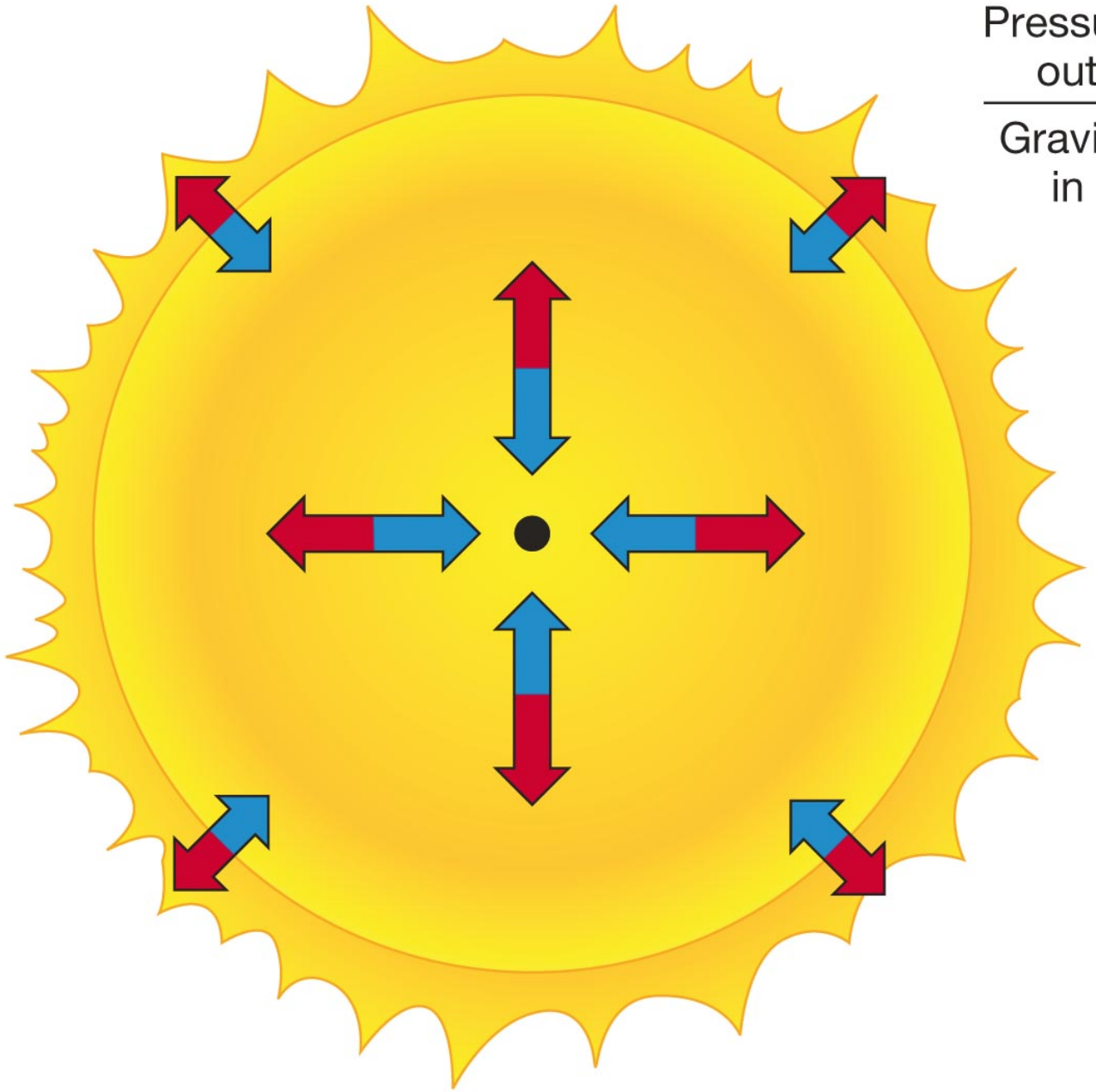
Death of Stars

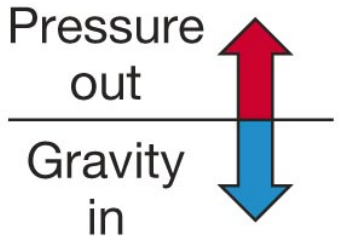


Compact Objects



Hydrostatic Equilibrium





$P_{\text{rad}} + P_{\text{gas}}$

- Fuel Depletion – gravity begins to dominate
- Core contracts and heats up
- Core material begins fusion

Low Mass Regime (< 8 $M_\odot$)

Heisenberg's Uncertainty Principle:

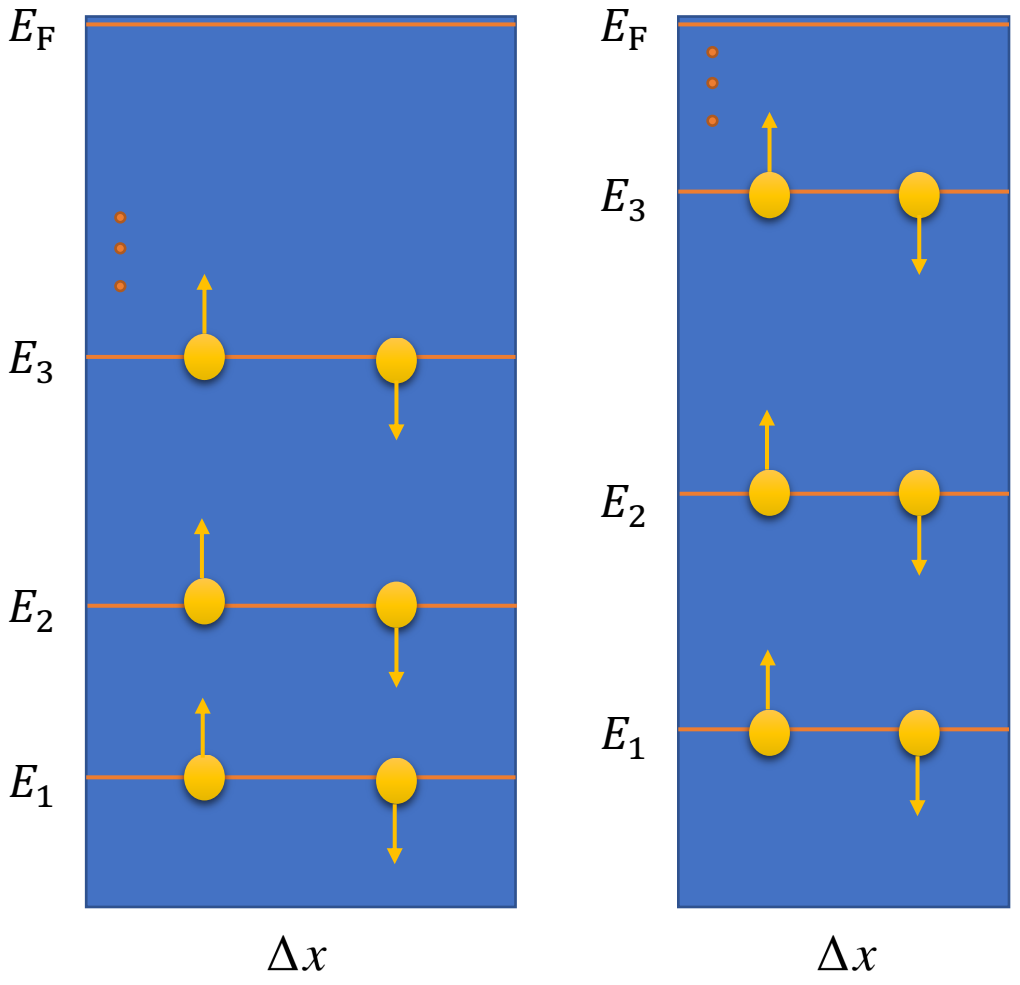
$$\Delta p \Delta x \geqslant \frac{\hbar}{2}$$

- Space between e^- decreases
- p increases ➔ E_F increases
- e^- become degenerate, i.e.,

$$E_F >> kT$$

Pauli's Exclusion Principle:

- No two fermions can exist in the same state.
- Electron degeneracy pressure



Degenerate Equation of State (EOS)

Non-relativistic:

1. $E_F = \frac{p_F^2}{2m_0}$
2. $p_F \propto \left(\frac{N}{V}\right)^{\frac{1}{3}} \rightarrow E_F \propto \left(\frac{N}{V}\right)^{\frac{2}{3}}$
3. $E_{int} = N \times E_F$
4. $P_{deg} \propto \frac{E_{int}}{V} \rightarrow P_{deg} \propto \left(\frac{N}{V}\right)^{\frac{5}{3}}$

Ultra-relativistic:

1. $E_F = p_F c$
2. $p_F \propto \left(\frac{N}{V}\right)^{\frac{1}{3}} \rightarrow E_F \propto \left(\frac{N}{V}\right)^{\frac{1}{3}}$
3. $E_{int} = N \times E_F$
4. $P_{deg} \propto \frac{E_{int}}{V} \rightarrow P_{deg} \propto \left(\frac{N}{V}\right)^{\frac{4}{3}}$

Chandrasekhar Limit

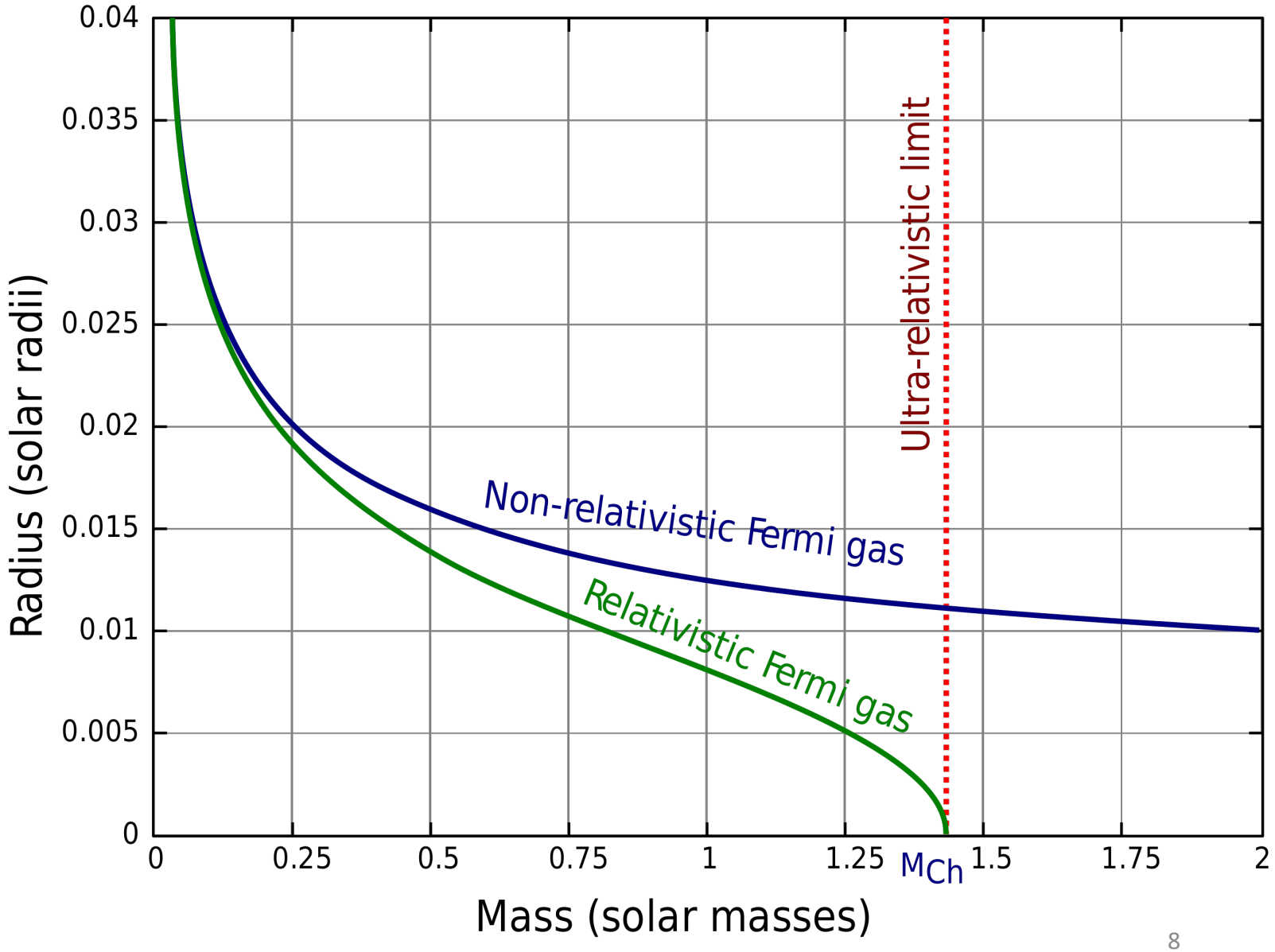
$$\frac{dP}{dr} = -\frac{GM\rho}{r^2}$$

Non-relativistic scenario:

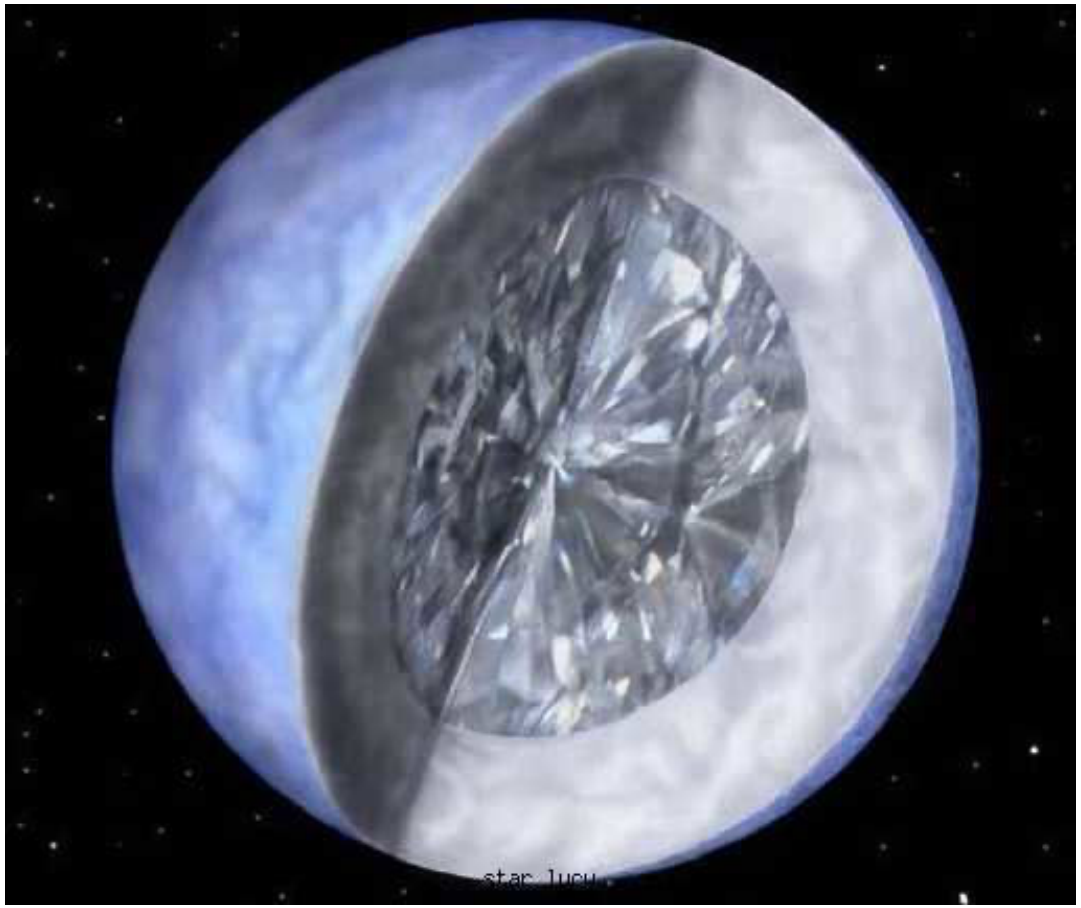
$$R \propto M^{-\frac{1}{3}}$$

Ultra-relativistic scenario:

$$M_{\mathrm{Ch}} = 1.4 M_{\odot}$$



Lucy in the Sky with Diamonds



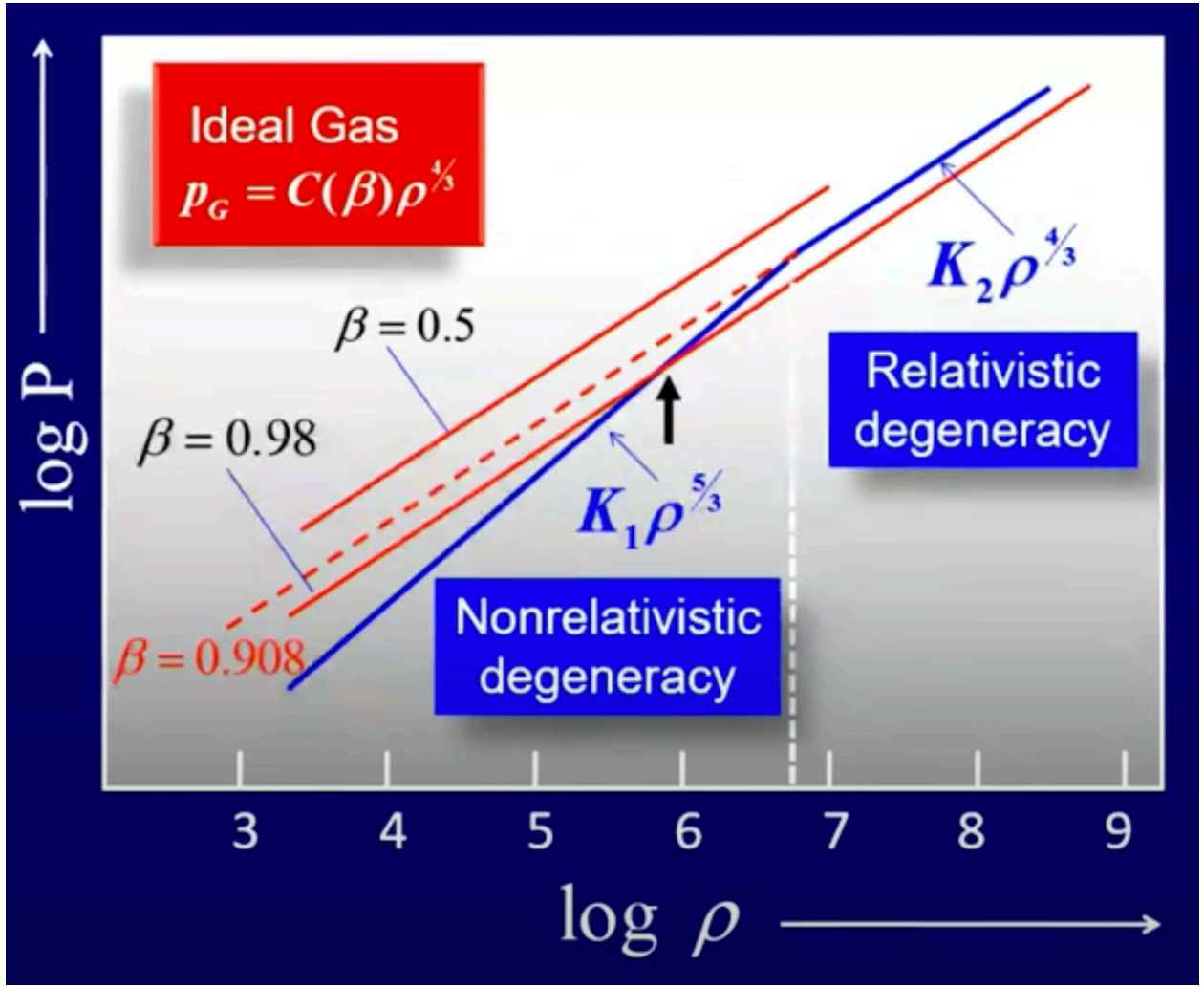
BPM 37093 aka Lucy

- Degenrate core with $T \sim 10^7$K
- Cools over billions of years to $\sim 10^3$ K
- Interiors likely solidify
- Crystalline form expected under high pressure
- Evidenced by astroseismic osbervations

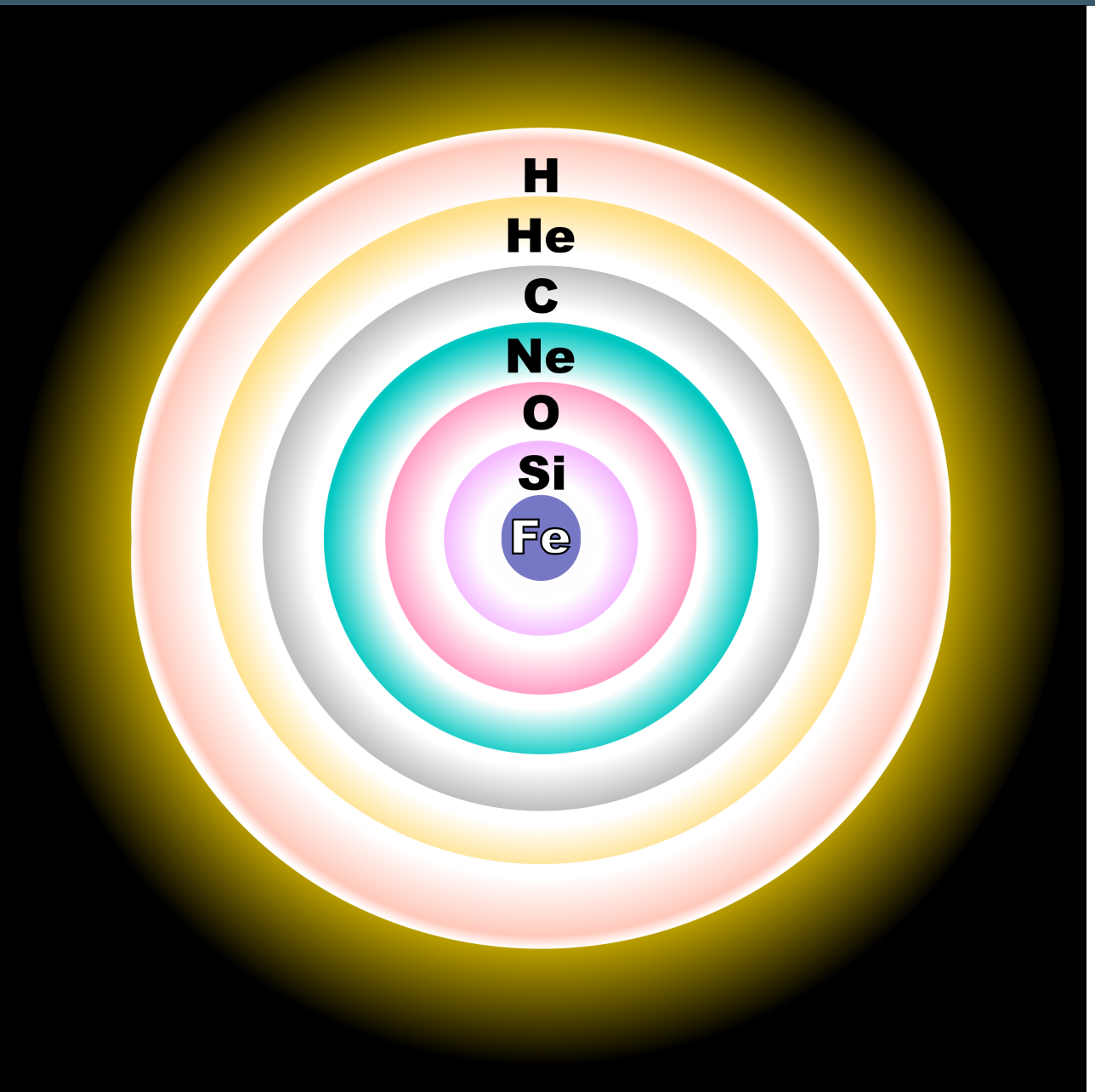
High Mass Regime

- More mass = increased interaction by photon with matter
- $P_{\text{rad}} \propto T^4$
- β = P_{gas} fraction

  1 - β = P_{rad} fraction
- If 1 - β > 9.2%,
  P_{rad} dominates & gas remains classical, i.e., kT rises quicker than E_{F}



High Mass Regime



- Fusion stops when it reaches Fe
- $T \sim 10\text{^}10$ K, flood of neutrinos via weak interactions – neutrino cooling – Degenerate Fe
- Fe photo-disintegration:

$$^{56}\mathrm{Fe} + \gamma \leftrightarrow 13\,^{4}\mathrm{He} + 4\,\mathrm{n}$$

- $\rho > 10^{7}\,\mathrm{g\,cm^{-3}}$, electron capture:

$$\mathrm{p} + \mathrm{e}^{-} \longrightarrow \mathrm{n} + \nu_{\mathrm{e}}$$

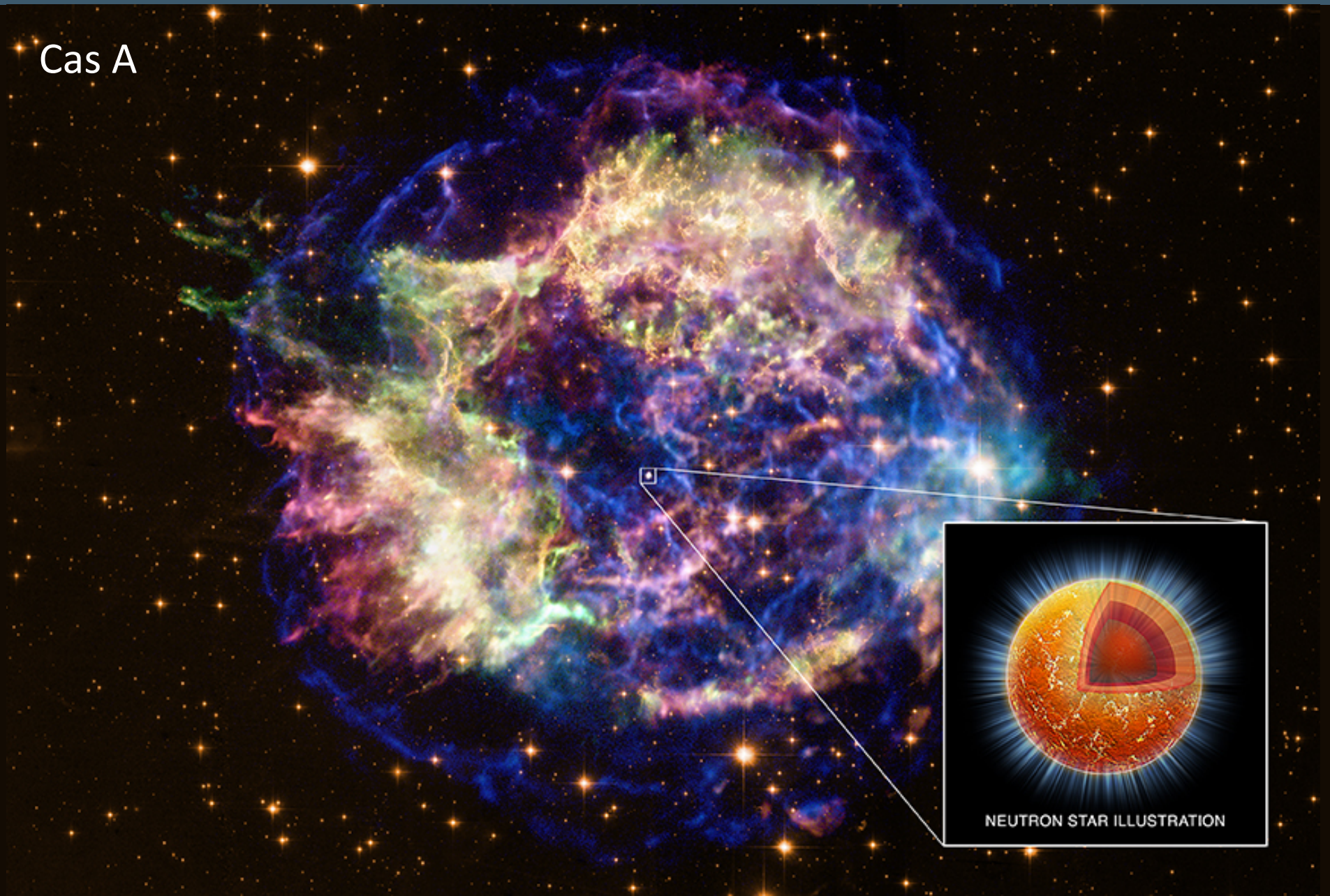
- Decrease in effective M_{Ch}
- Pair-production (extremely massive):

$$\gamma \longrightarrow \mathrm{e}^{-} + \mathrm{e}^{+}$$

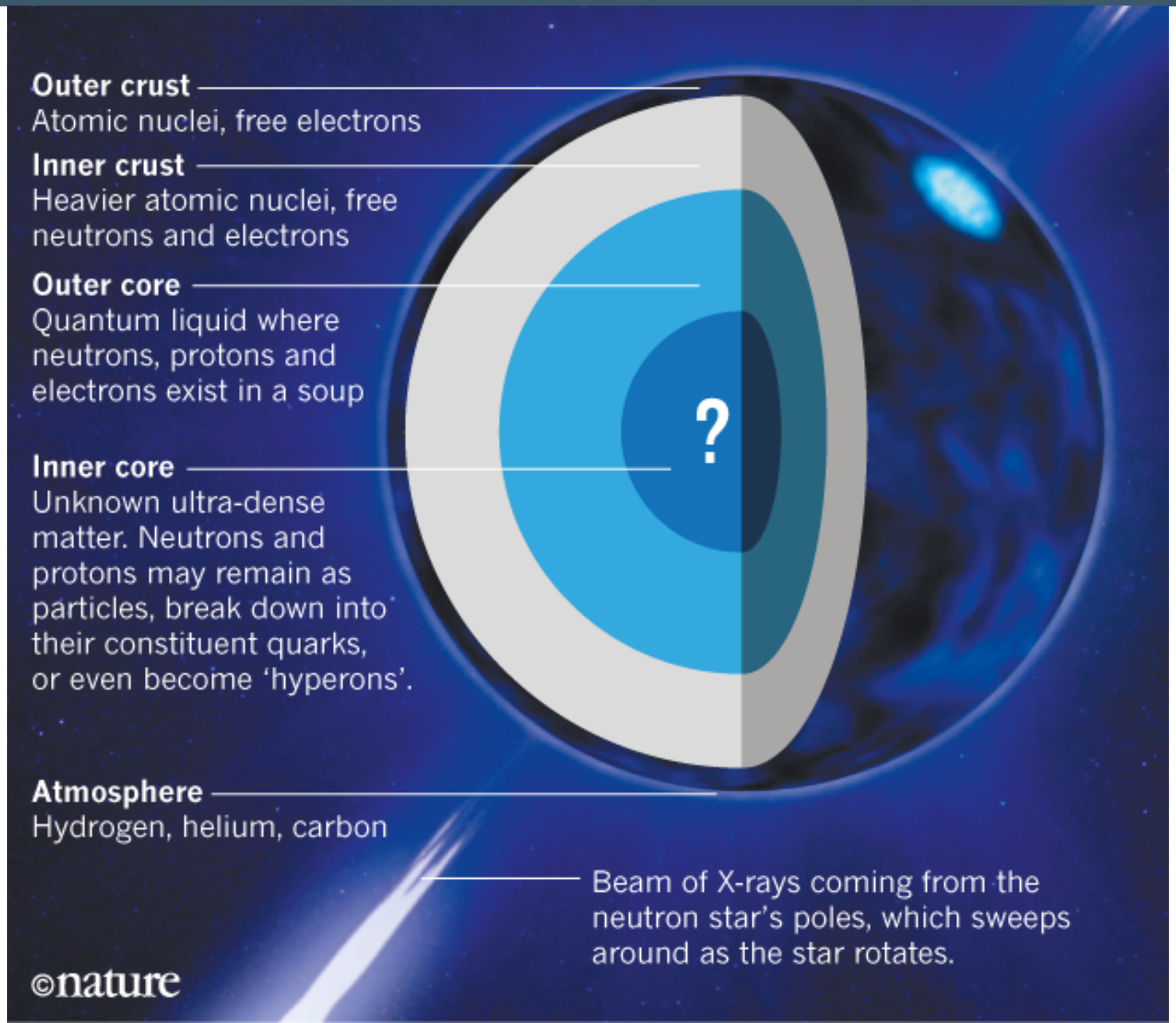
Supernova

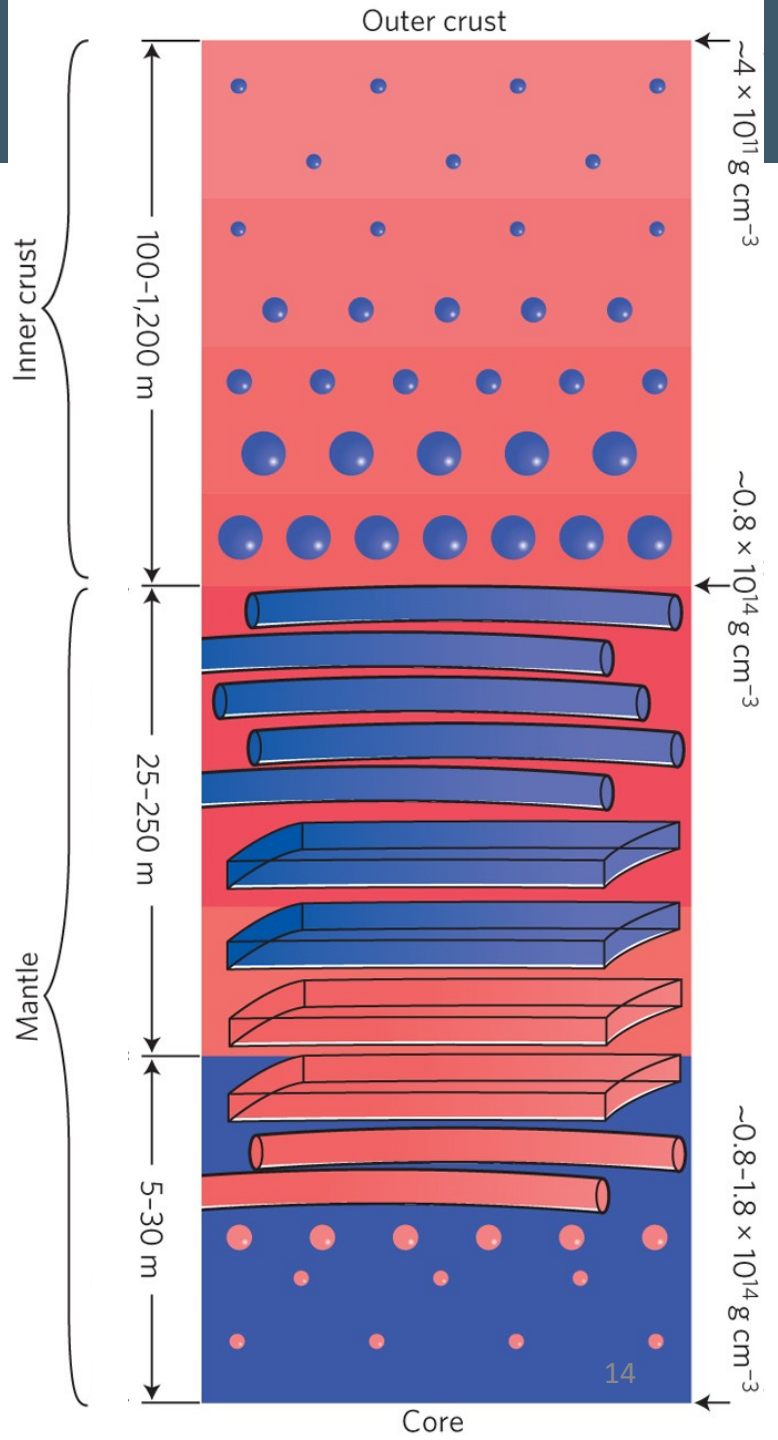
- Dynamical core collapse, $t_{\mathrm{inf}} \sim \mathrm{ms}$
- Inner core contracts quicker
- $\rho > 10^{14} \mathrm{g\ cm^{-3}}$, neutron degeneracy + strong force repulsion
- Core bounce and shock
- Shock stalls due to increased photo-disintegration + $\mathrm{e^-}$ capture
- ν produced inside contracting core are trapped – neutrinosphere
- ν diffuse into shock front, refuel it and BOOM!!

Neutron Stars

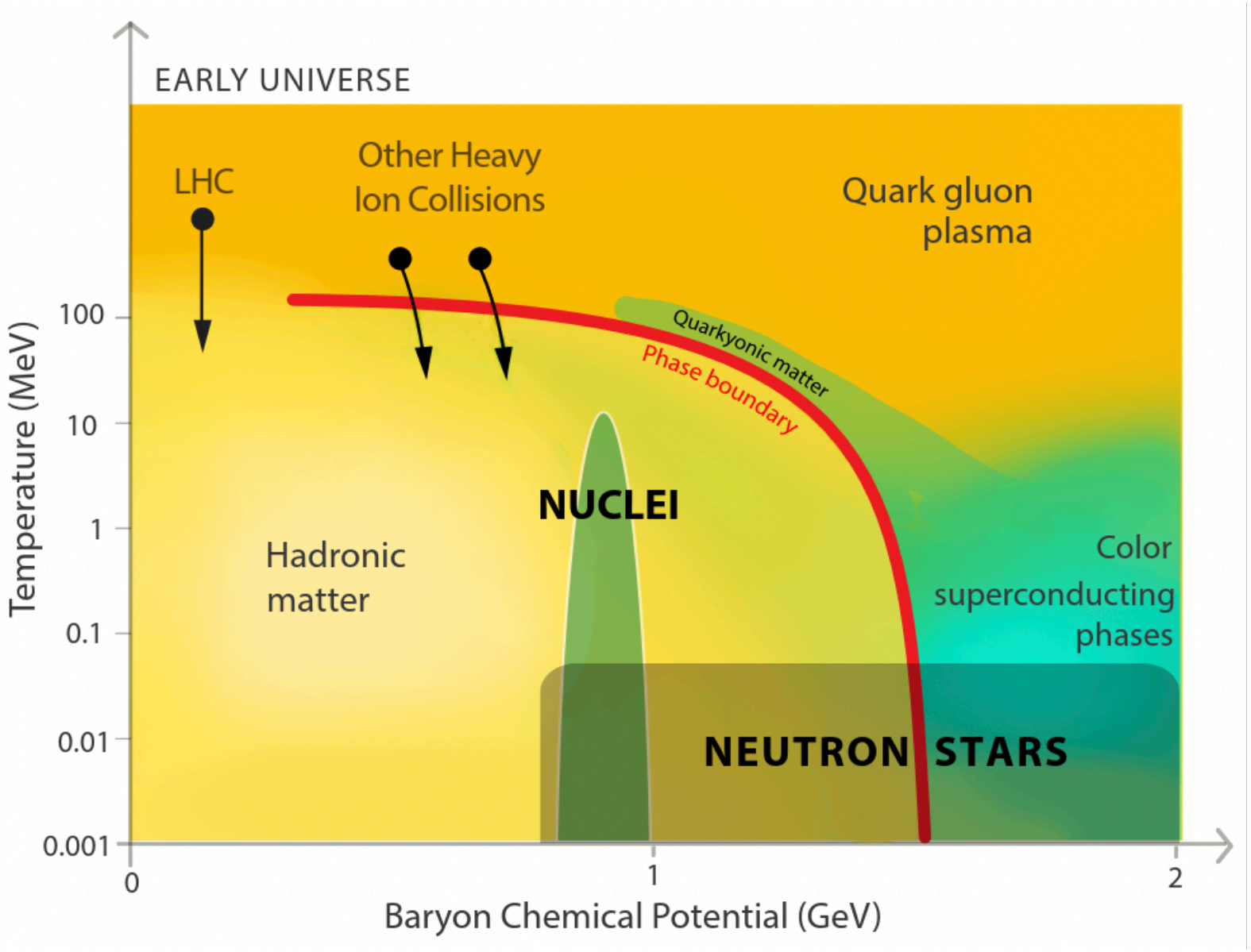


Neutron Star Structure





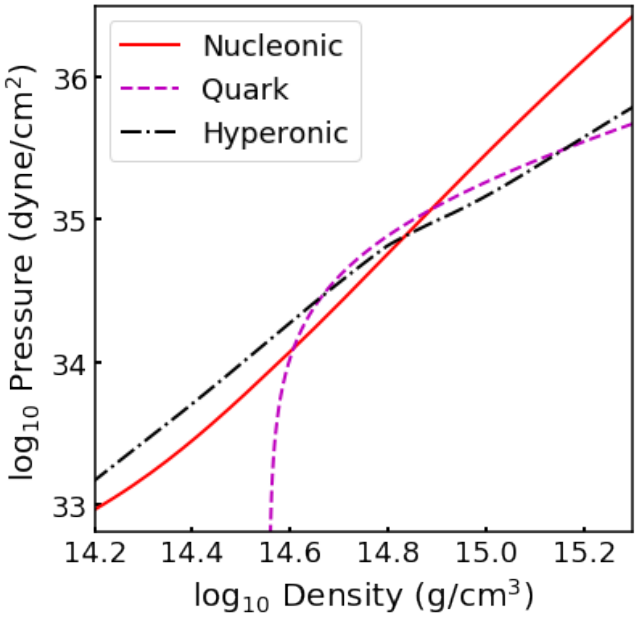
Cold Dense Matter



Watts et al. 2016

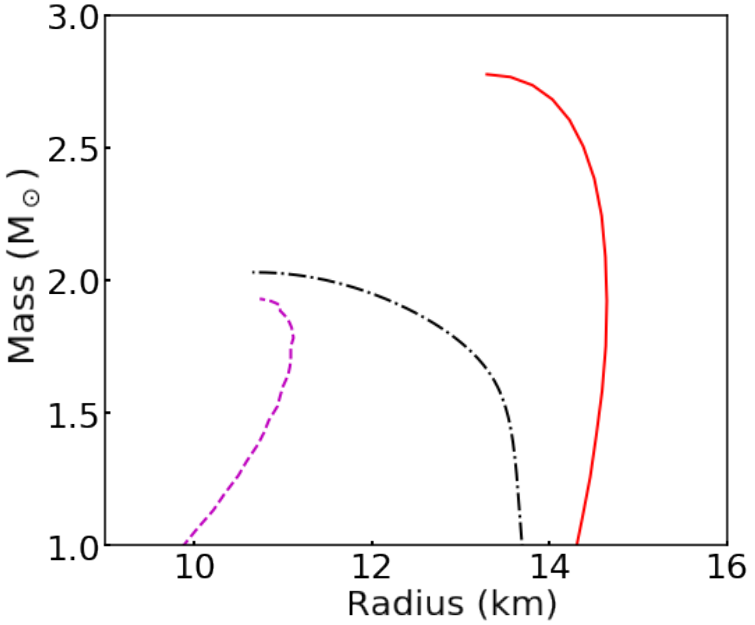
Nuclear Physics ⇔ Spacetime

Equation of state

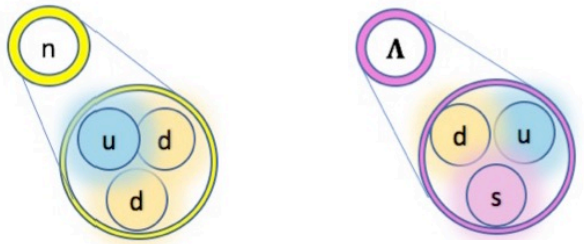


TOV equation

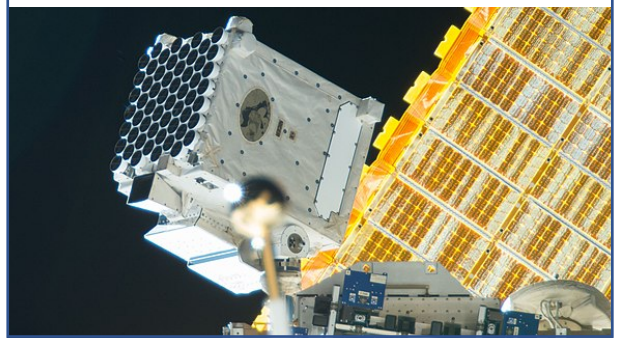
Mass–radius



Dense matter physics

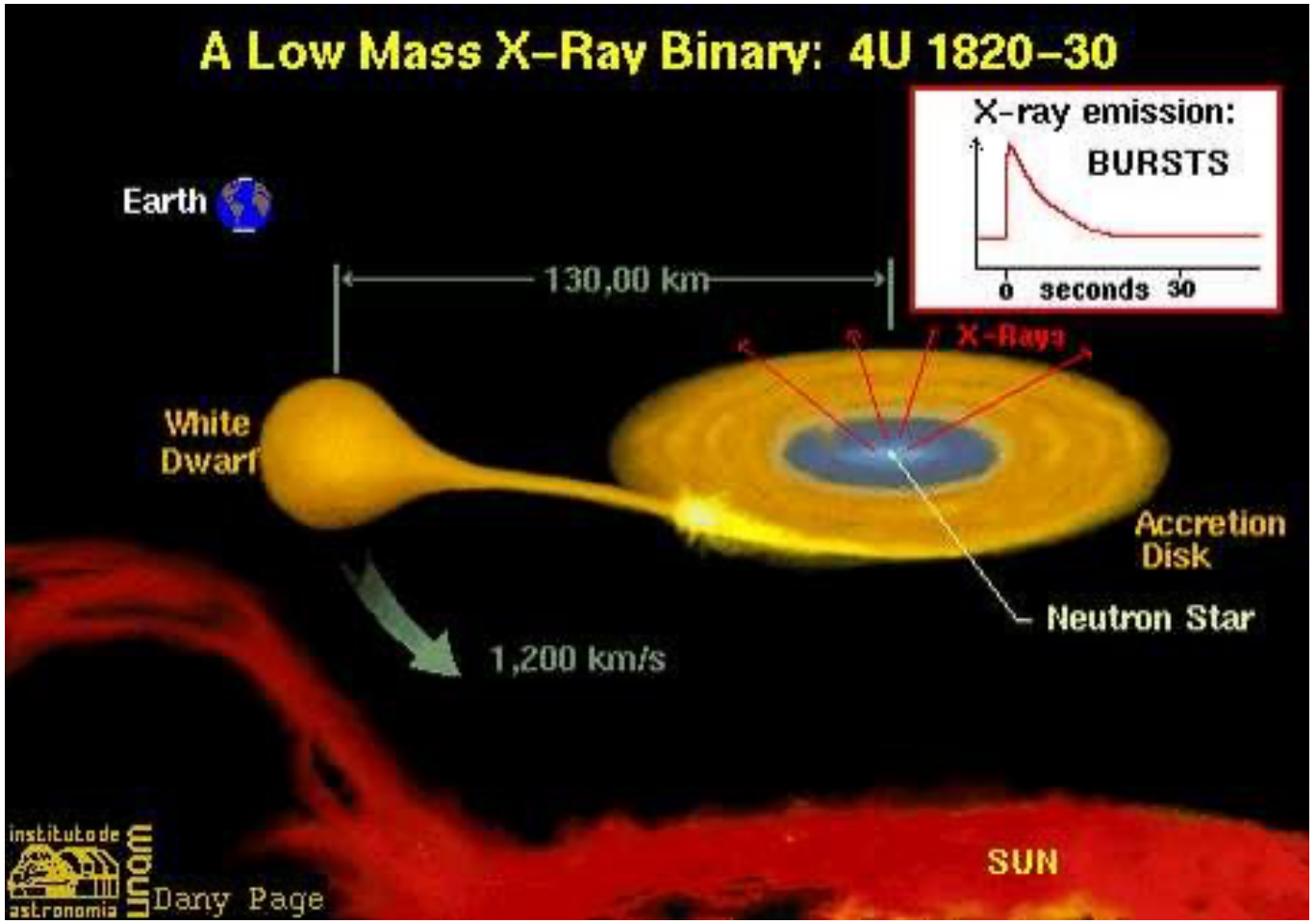


X-Ray data



Previous Mass and Radius Measurements

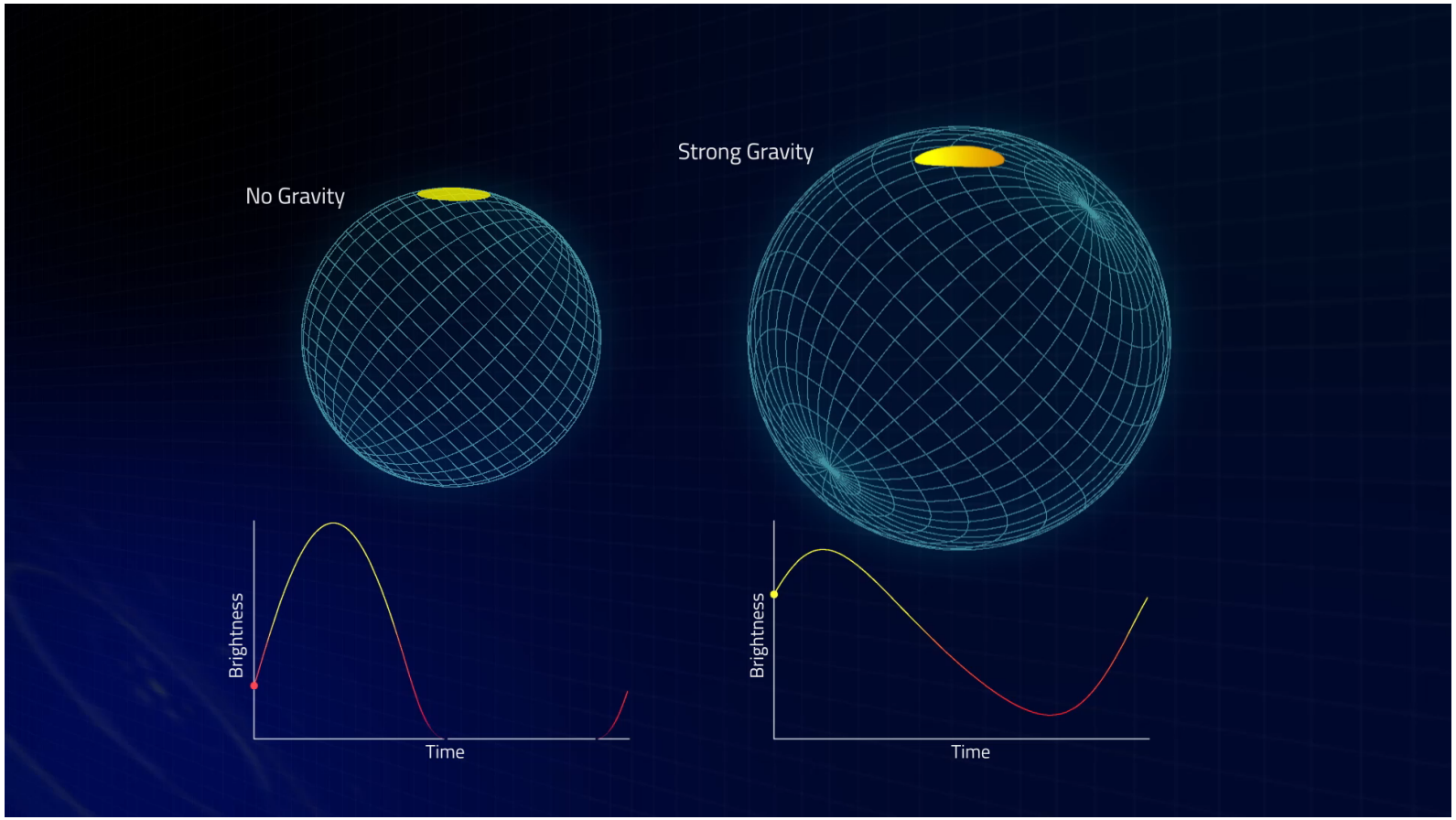
- Mass from orbital dynamics
- Radius trickier to obtain – spectral modelling during quiescence and outburst



Pulse Profile Modelling

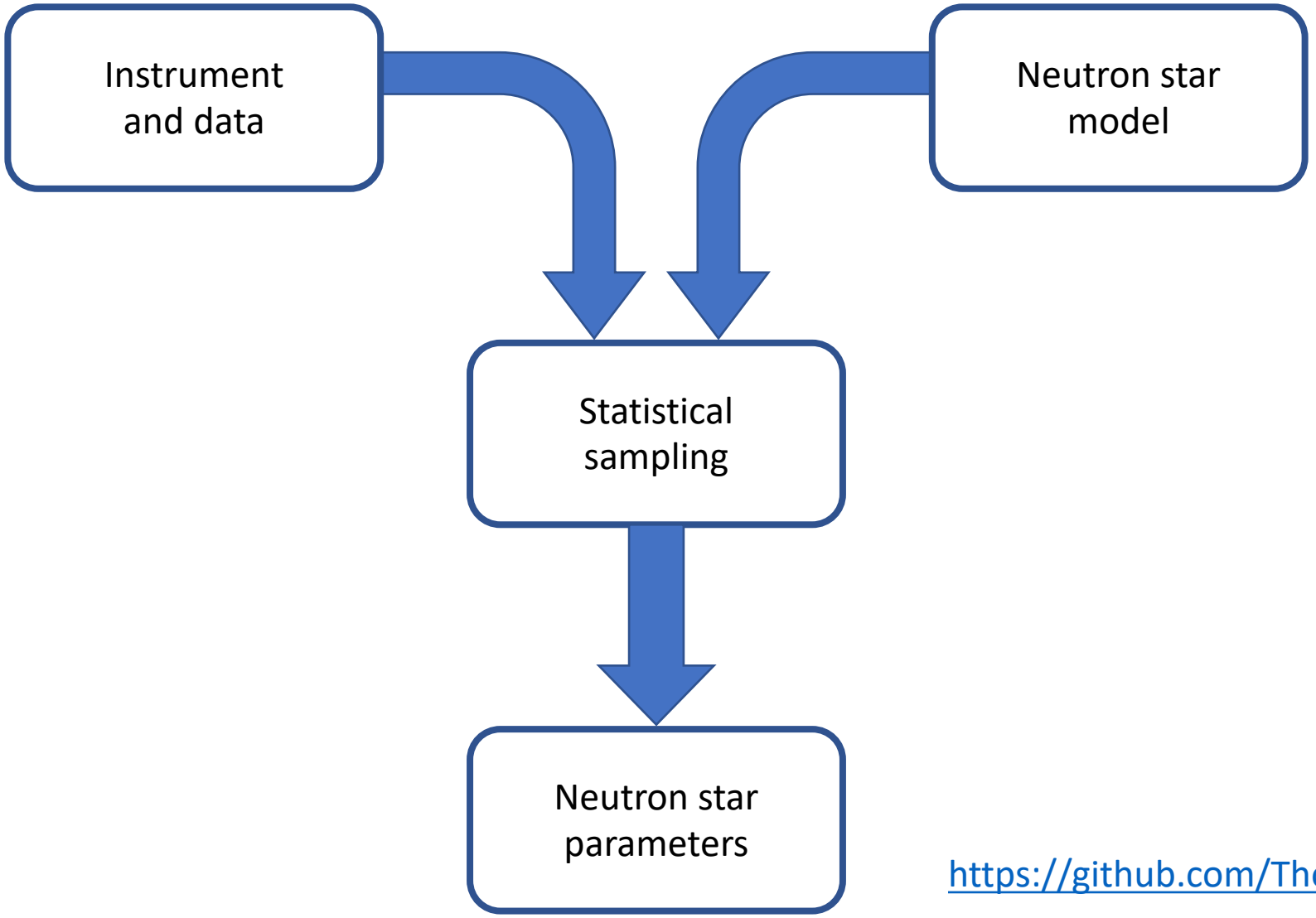
- Relativistic effects
  - Light bending
  - Doppler boosting

- Higher M/R, spin ➔ More modulation



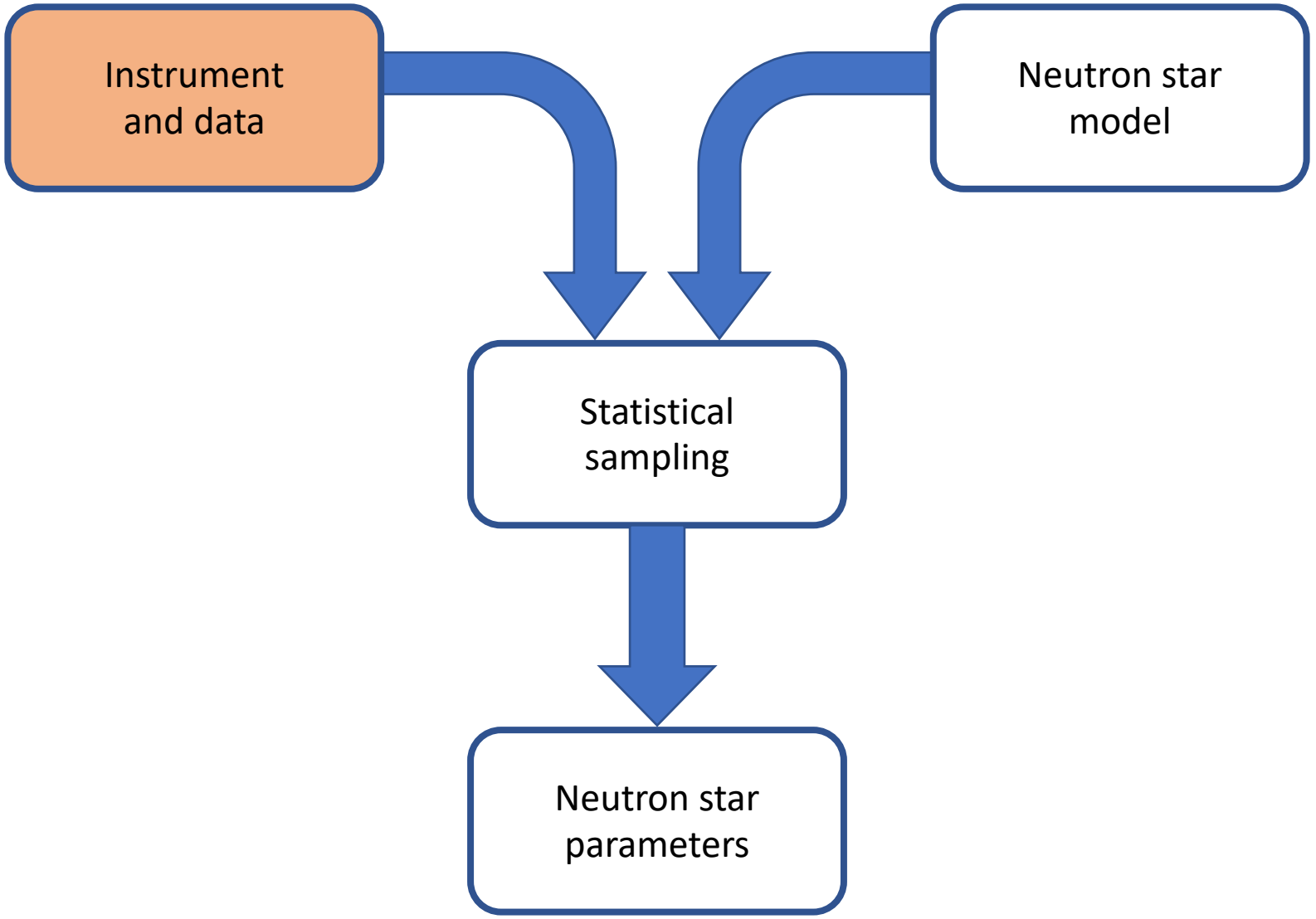
Morsink/Moir/Arzoumanian/NASA

X-ray Pulse Simulation and Inference (X-PSI)



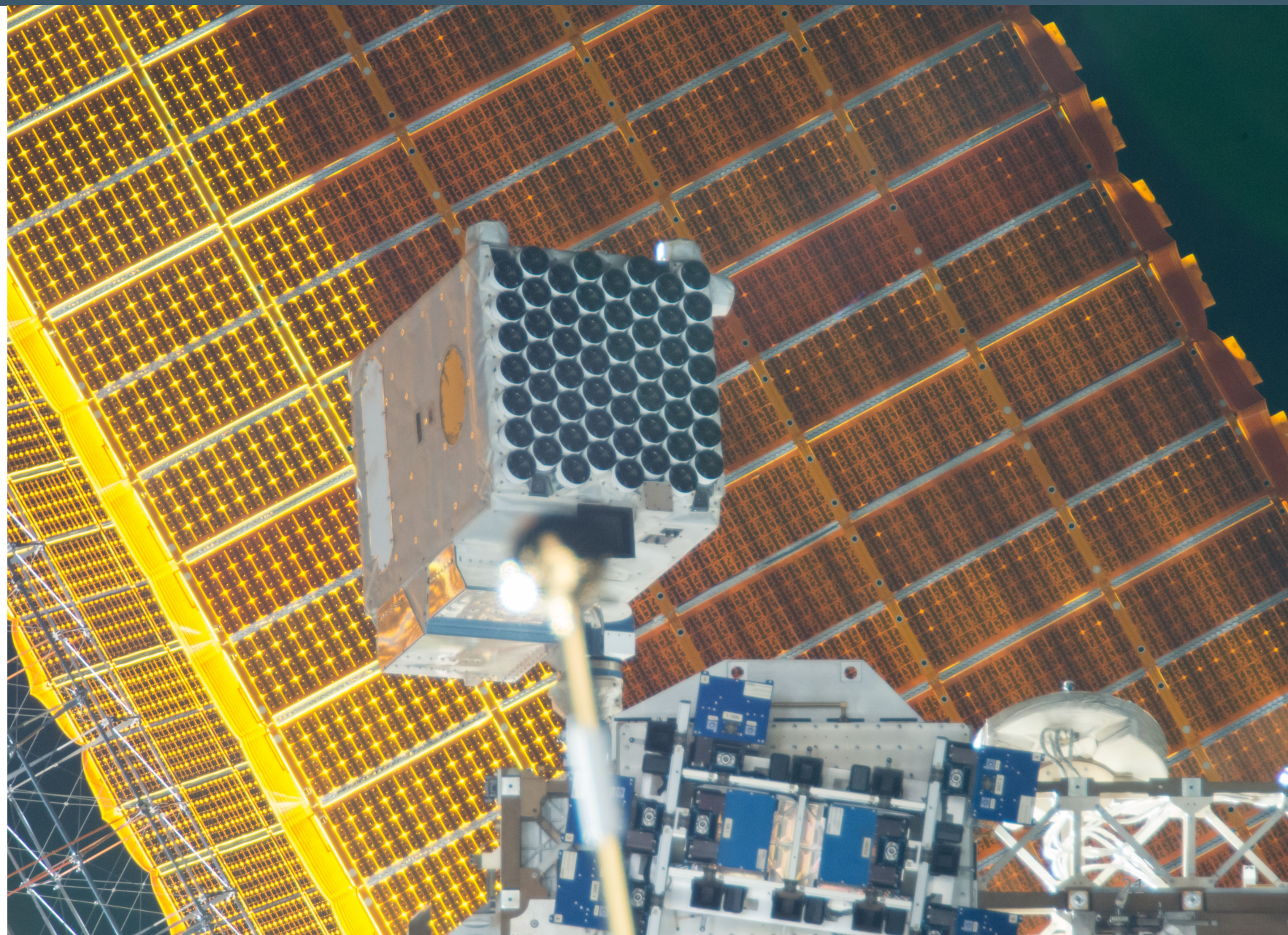
https://github.com/ThomasEdwardRiley/xpsi

X-PSI

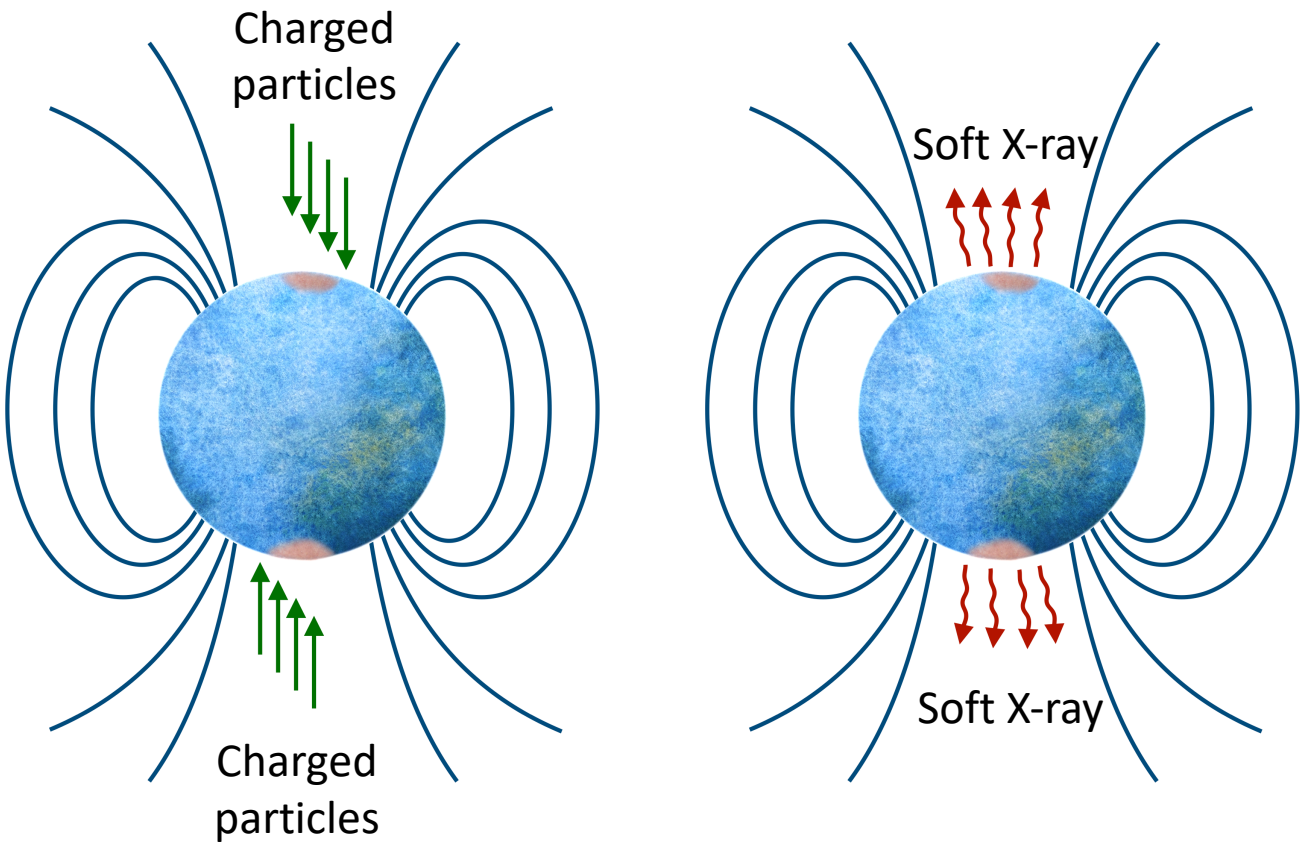

Instrument and data
Neutron star model
Statistical sampling
Neutron star parameters

Neutron Star Interior Composition Explorer (NICER)

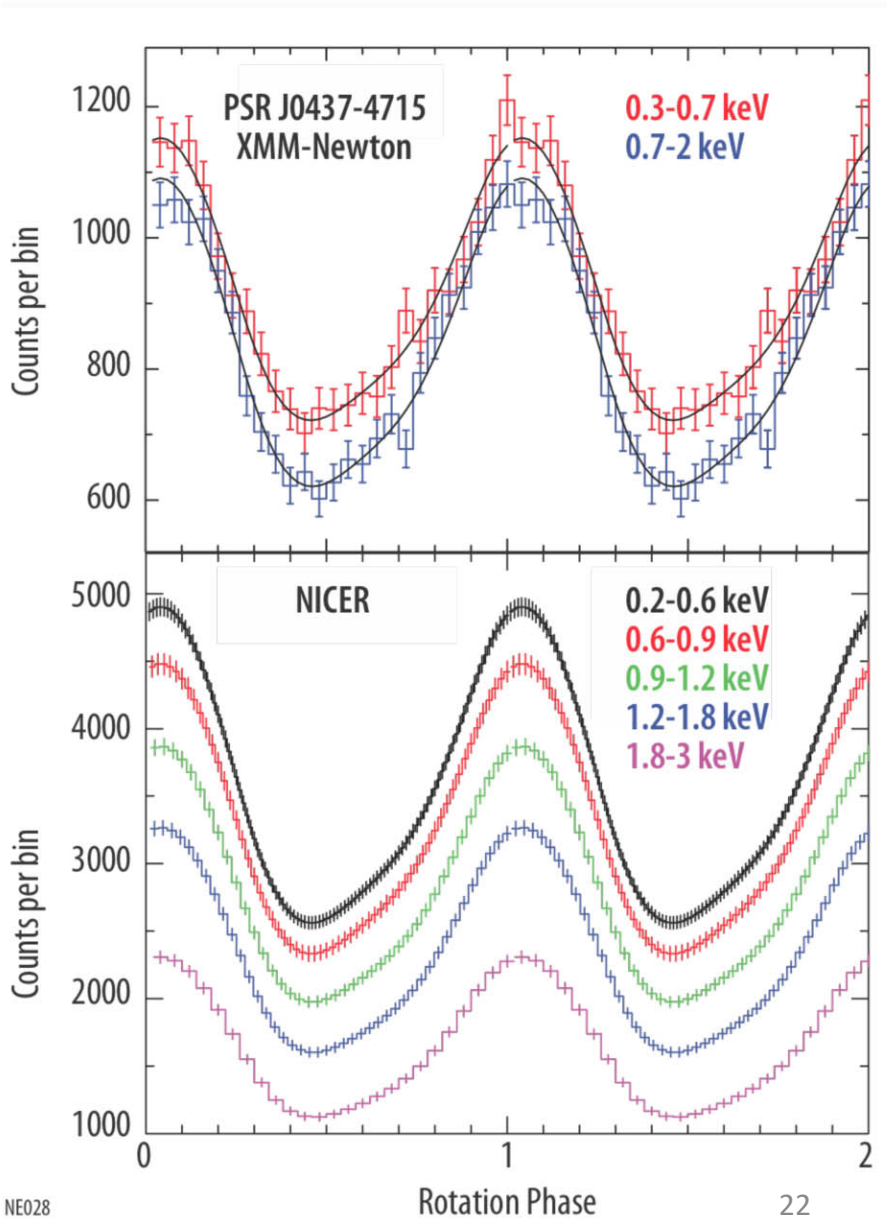
- High sensitivity in soft X-ray band for observing rotation-powered pulsars.
- High time and energy resolution



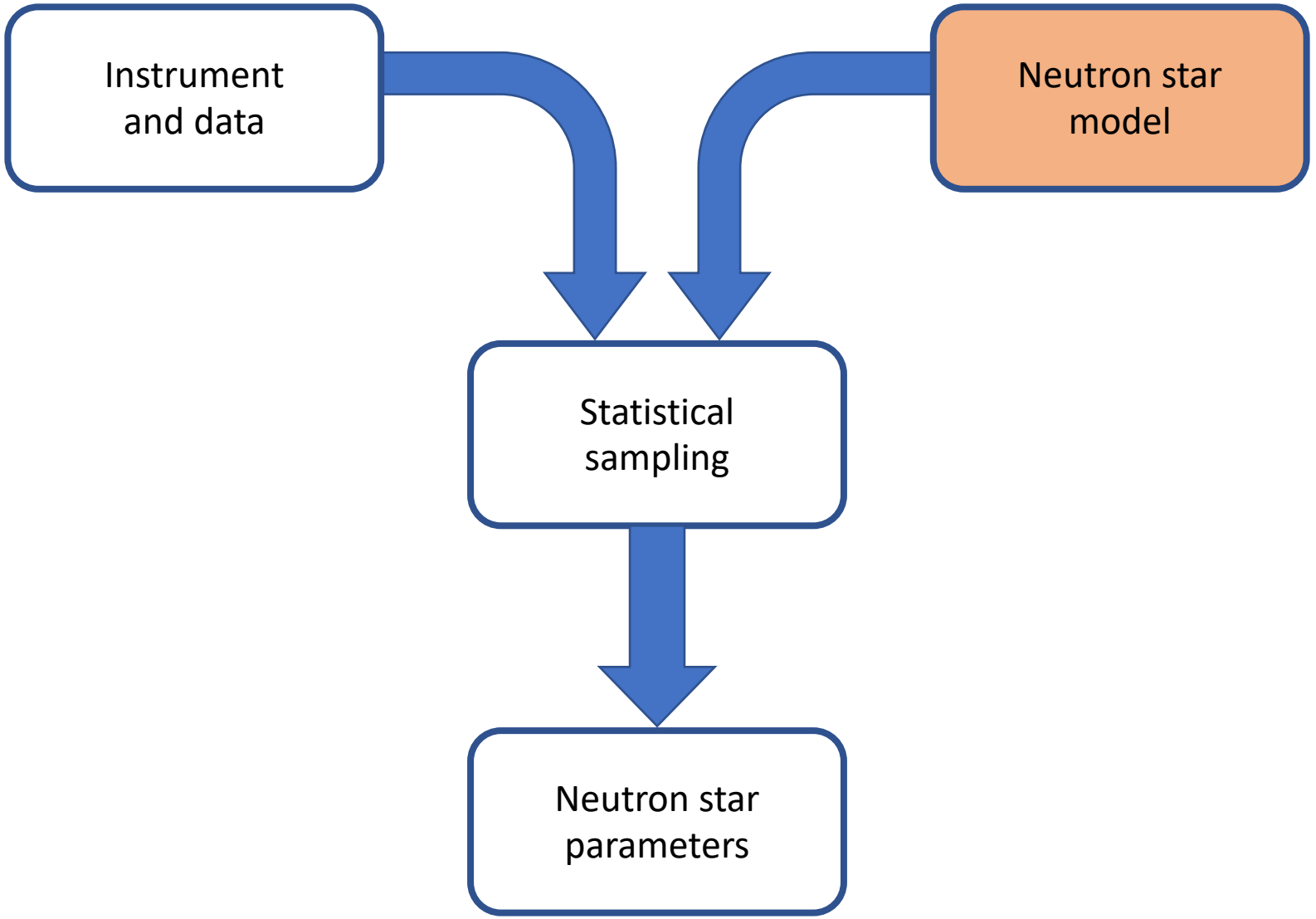
NICER data



Rotation-powered pulsars

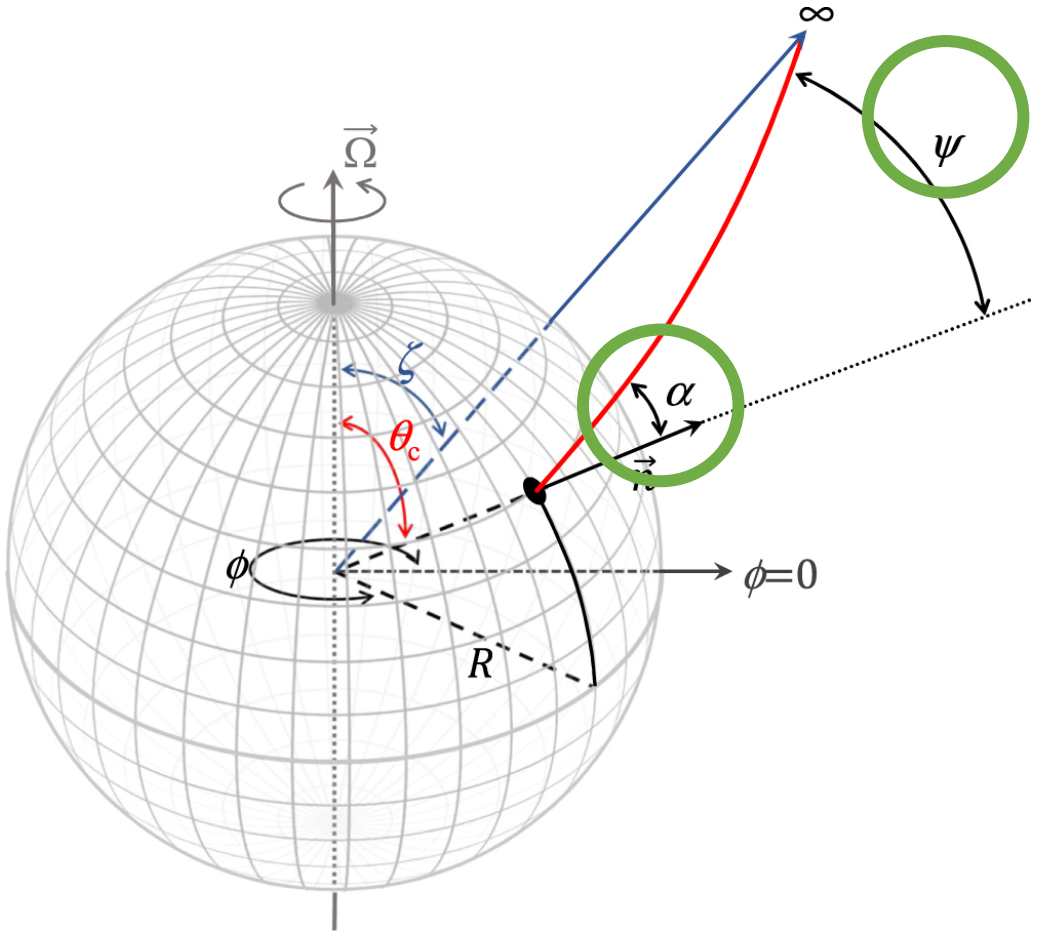


X-PSI


Instrument and data
Neutron star model
Statistical sampling
Neutron star parameters

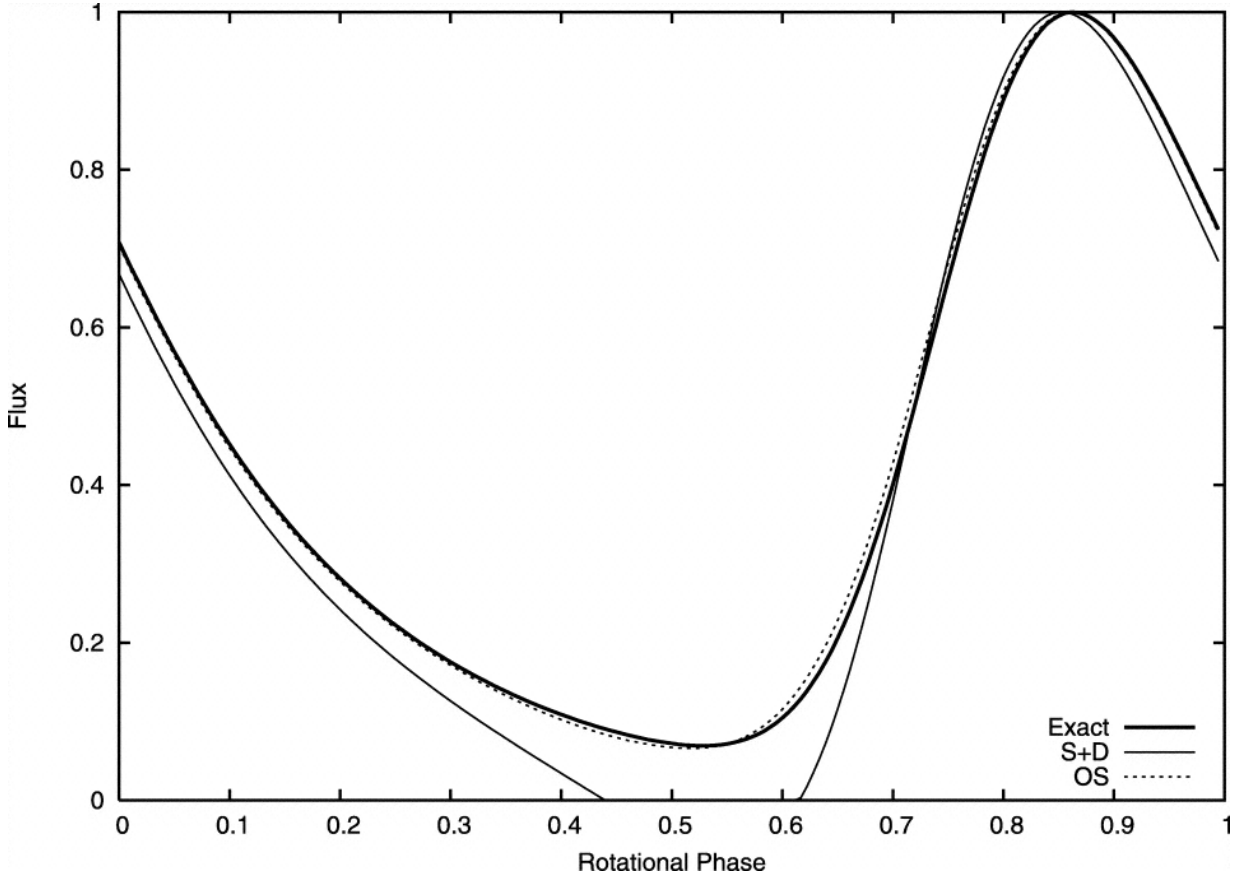
Modelling – Relativistic Ray-tracing

Bogdanov et al. 2019b



- Emission geometry – inclination, emission angle and deflection angle

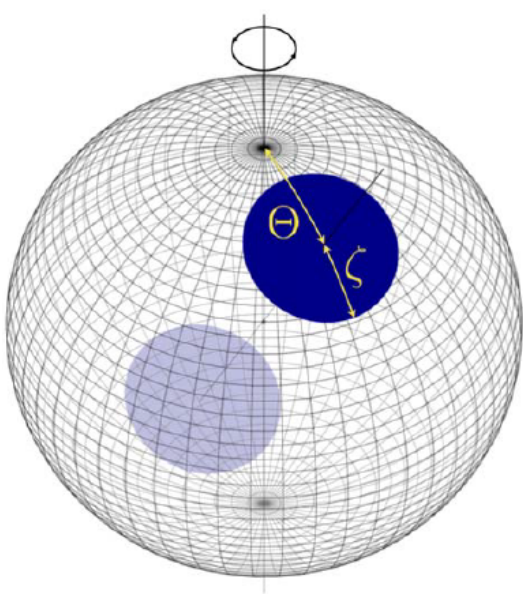
Morsink et al. 2007



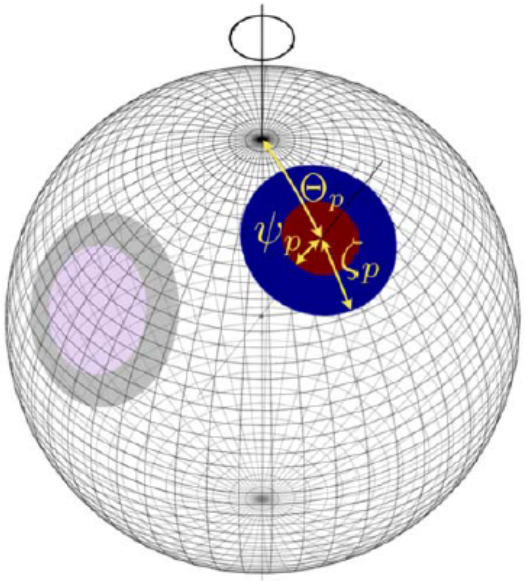
- Deflection angle dependent on exterior spacetime
- Oblate Schwarzschild + Doppler approximation

Modelling – Spot Geometry

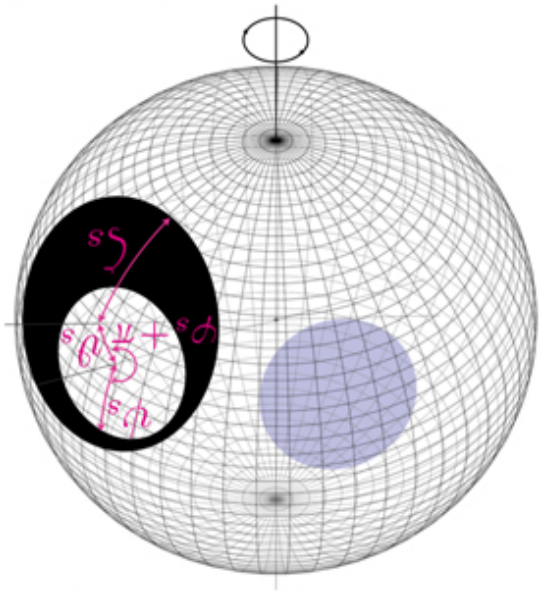
Riley et al. 2019



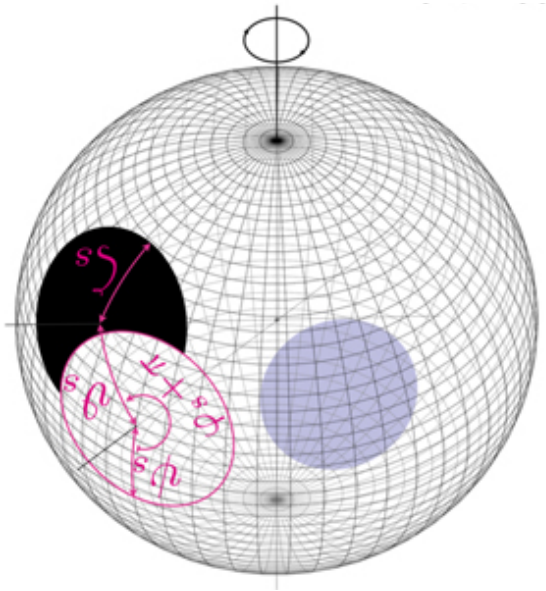
Single-temperature



Dual-temperature

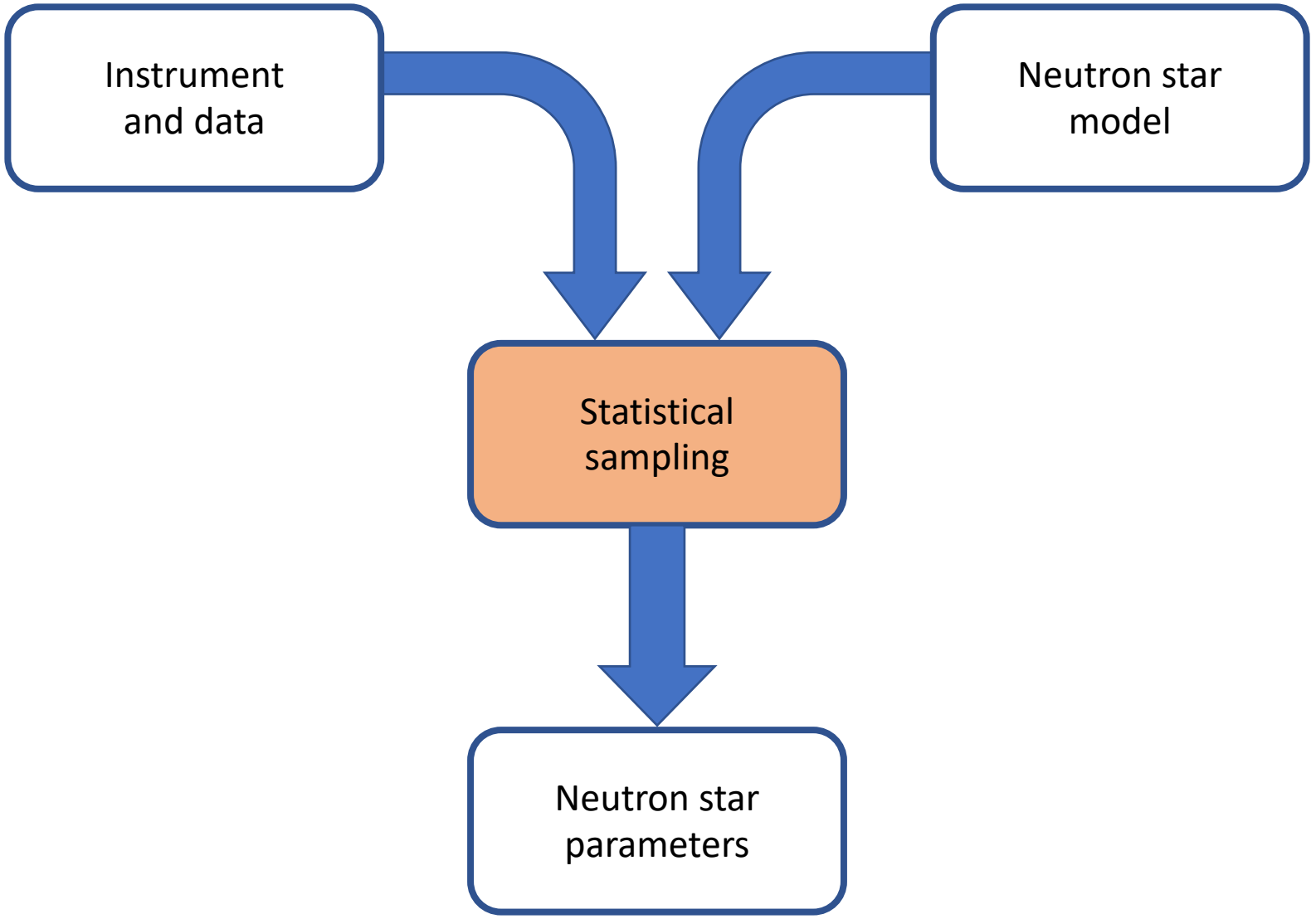


Ring



Crescent

X-PSI


Instrument and data
Neutron star model
Statistical sampling
Neutron star parameters

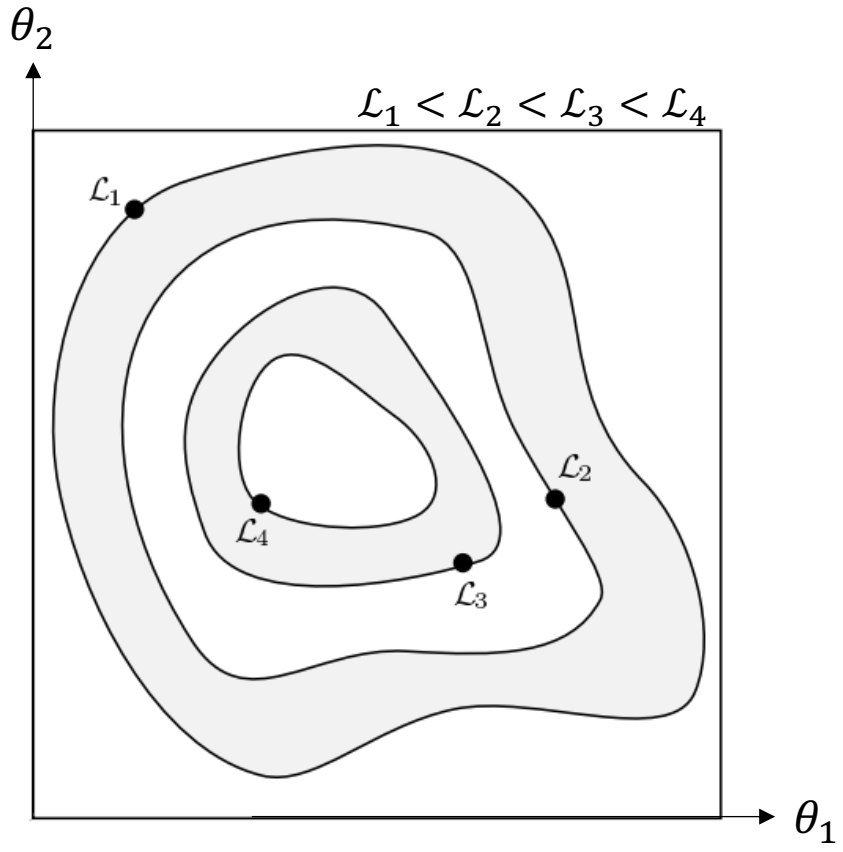
Baye's Theorem

$$\pi(\theta|D,M)\,p(D|M) = p(D|\theta,M)\,p(\theta|M)$$

posterior evidence likelihood prior

- Prior $p(\theta|M)$: Educated guess, probability that our model is going to have certain parameters
- Likelihood $p(D|\theta,M)$: How likely is it to observe the data with such a parameterised model
- Evidence $p(D|M)$: Normalization term – probability of the data given all sets of parameterization
- Posterior $p(\theta|D,M)$: Probability distribution of parameters given our data and model

Nested Sampling

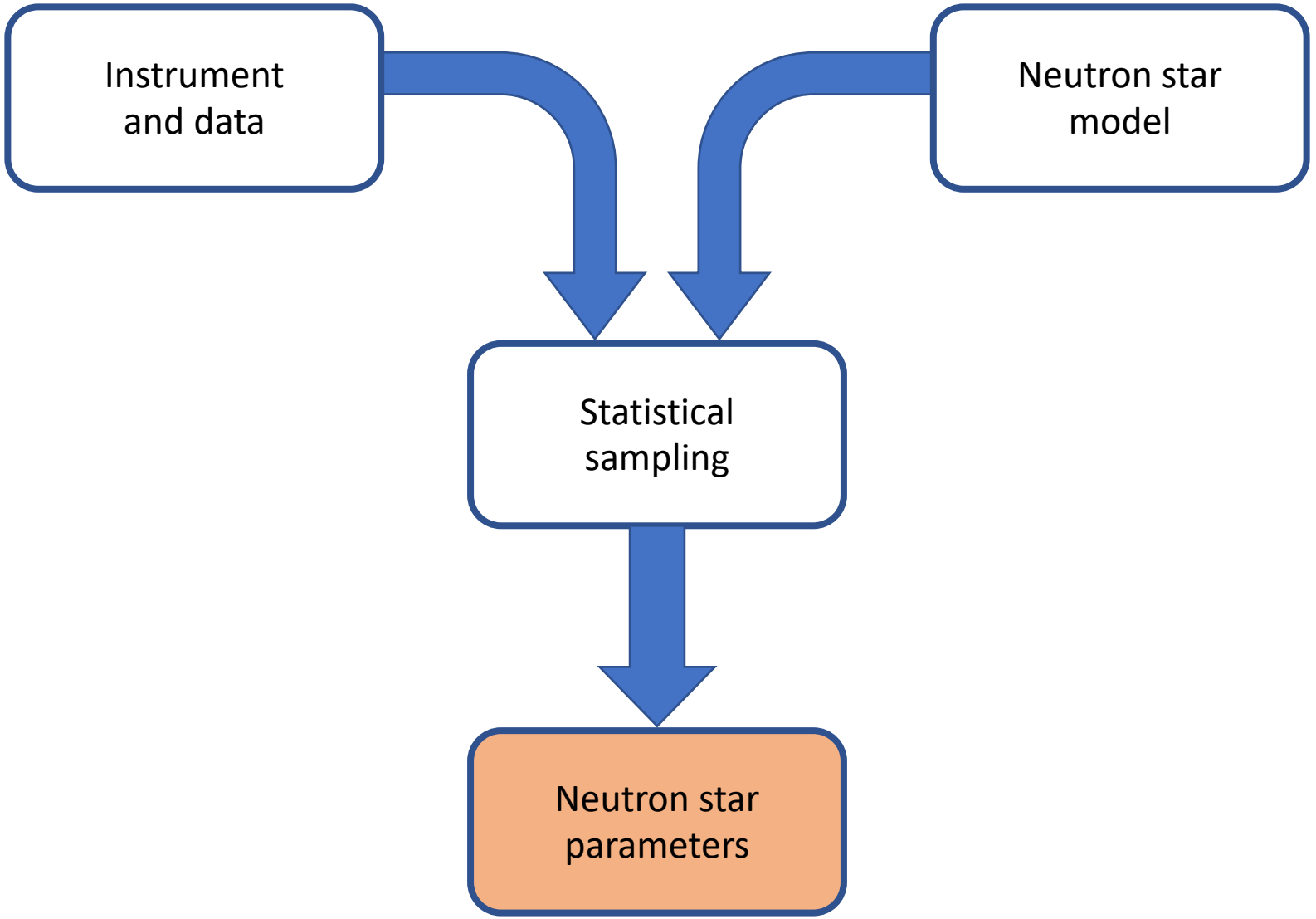


F. Feroz, M.P. Hobson & M. Bridges 2009

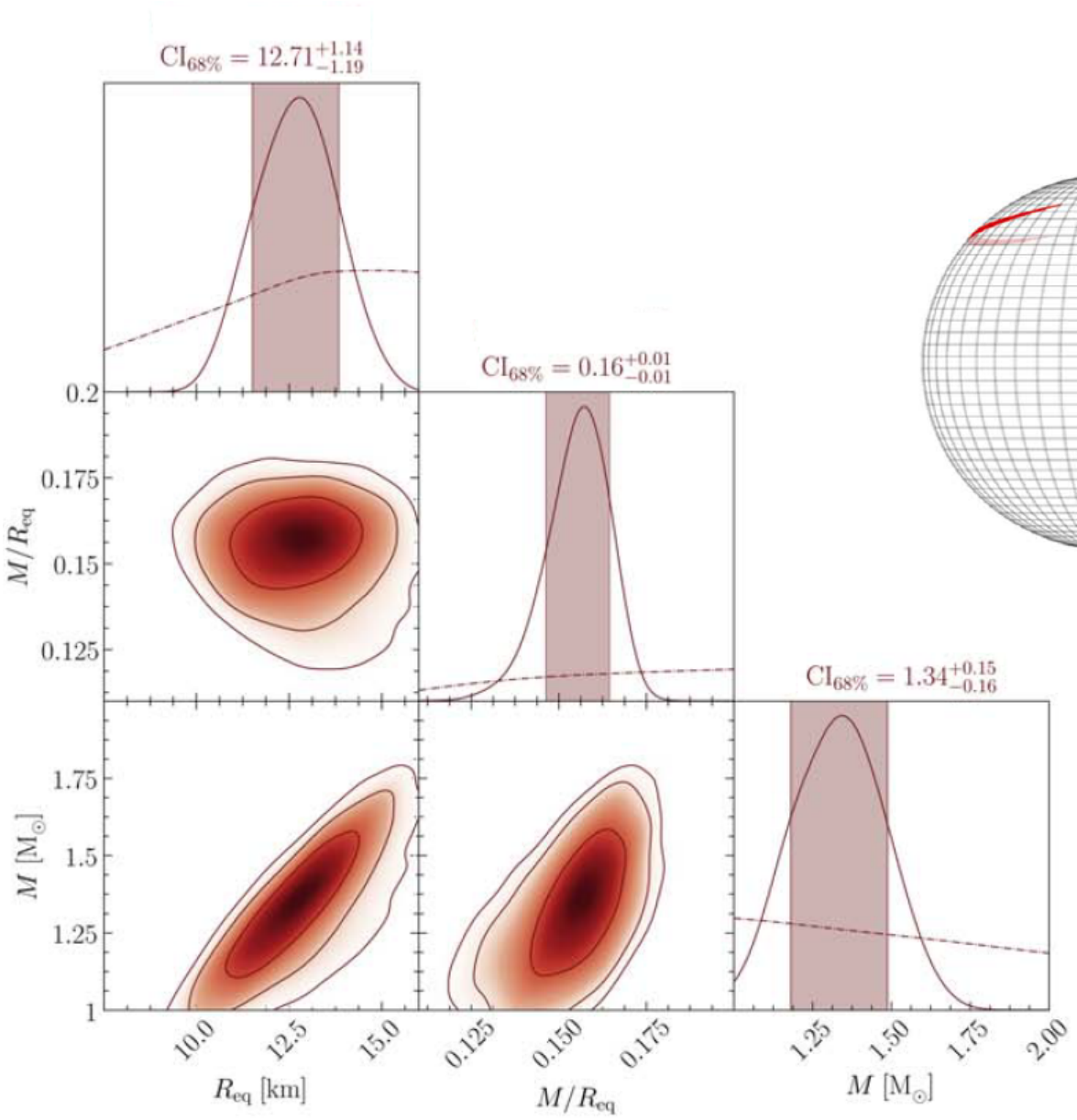
Cartesius Supercomputer

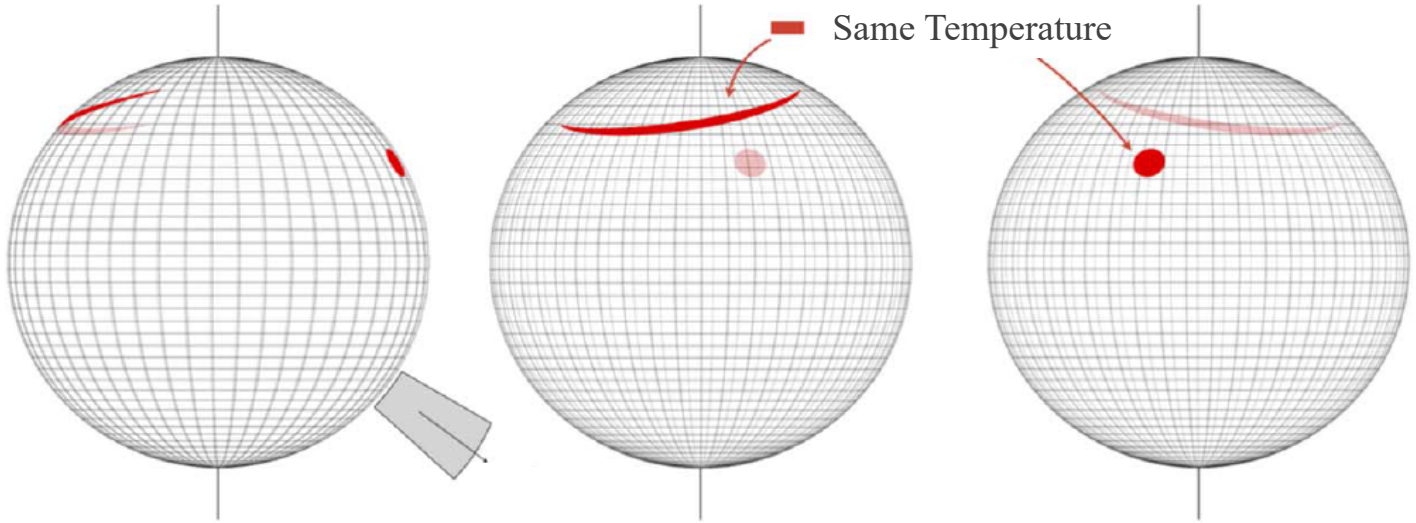
- Computationally expensive
- High Performance Computing

X-PSI


Instrument and data
Neutron star model
Statistical sampling
Neutron star parameters

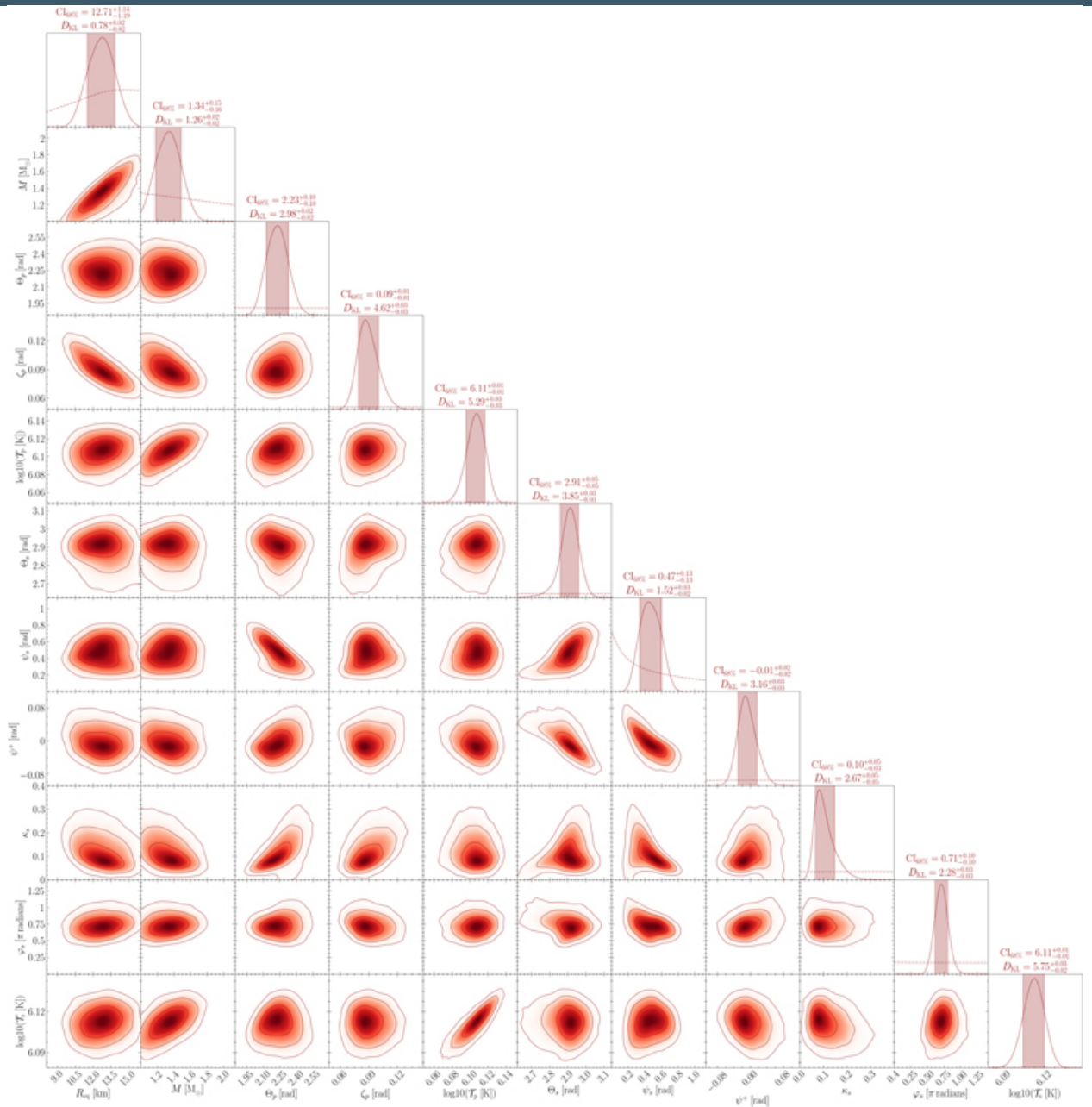
Inference - PSR J0030+0451

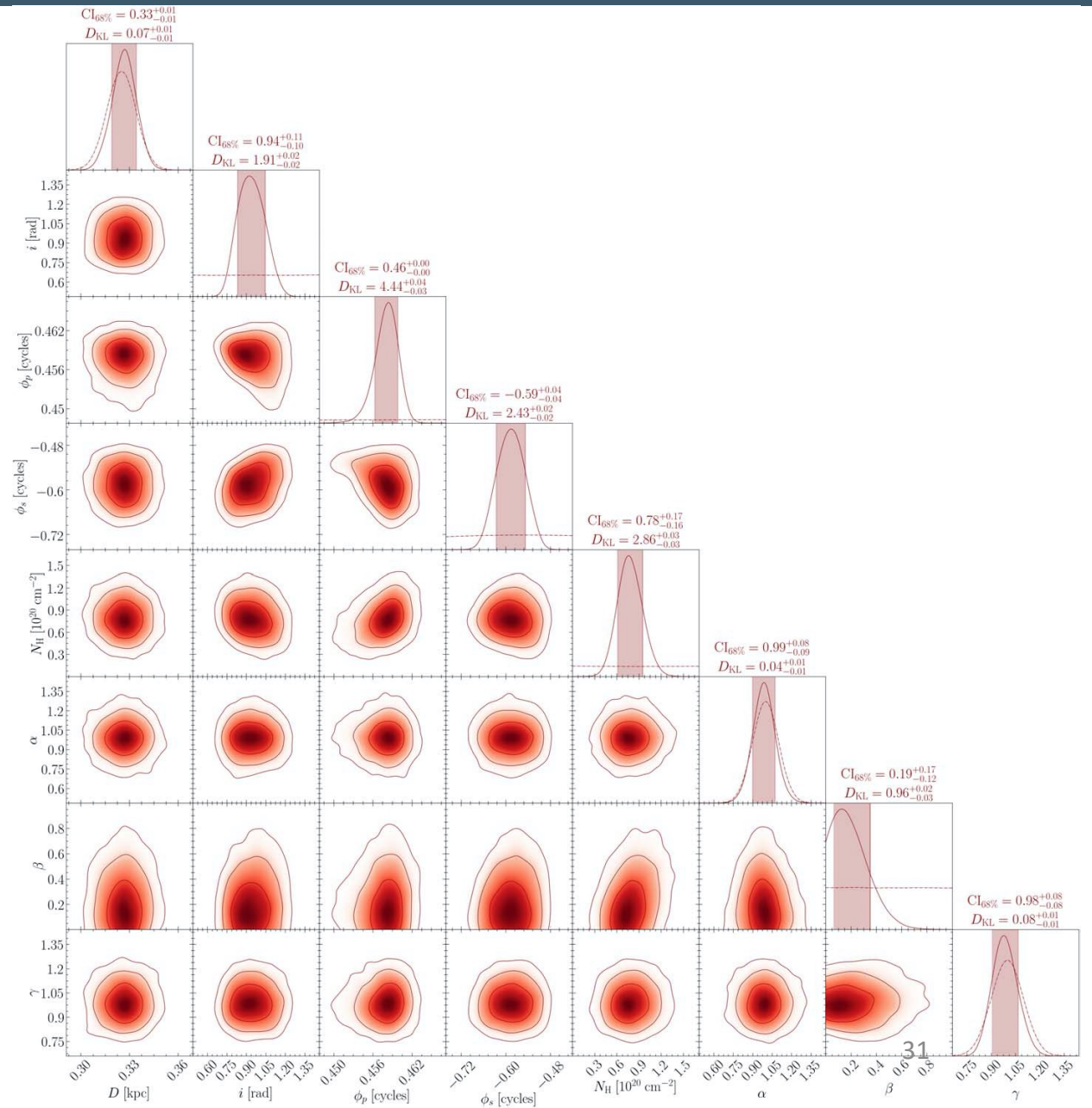




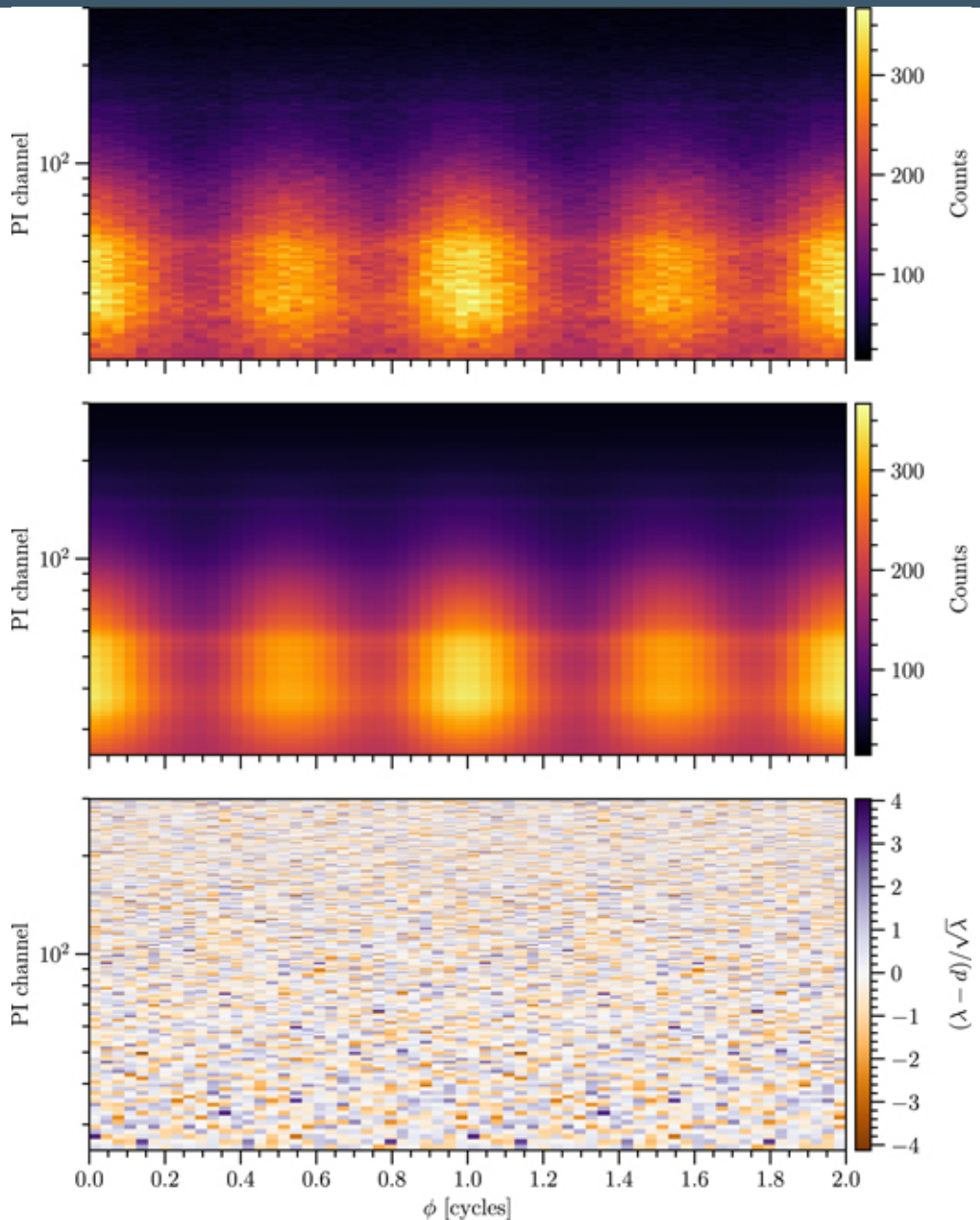
Riley et al. 2019

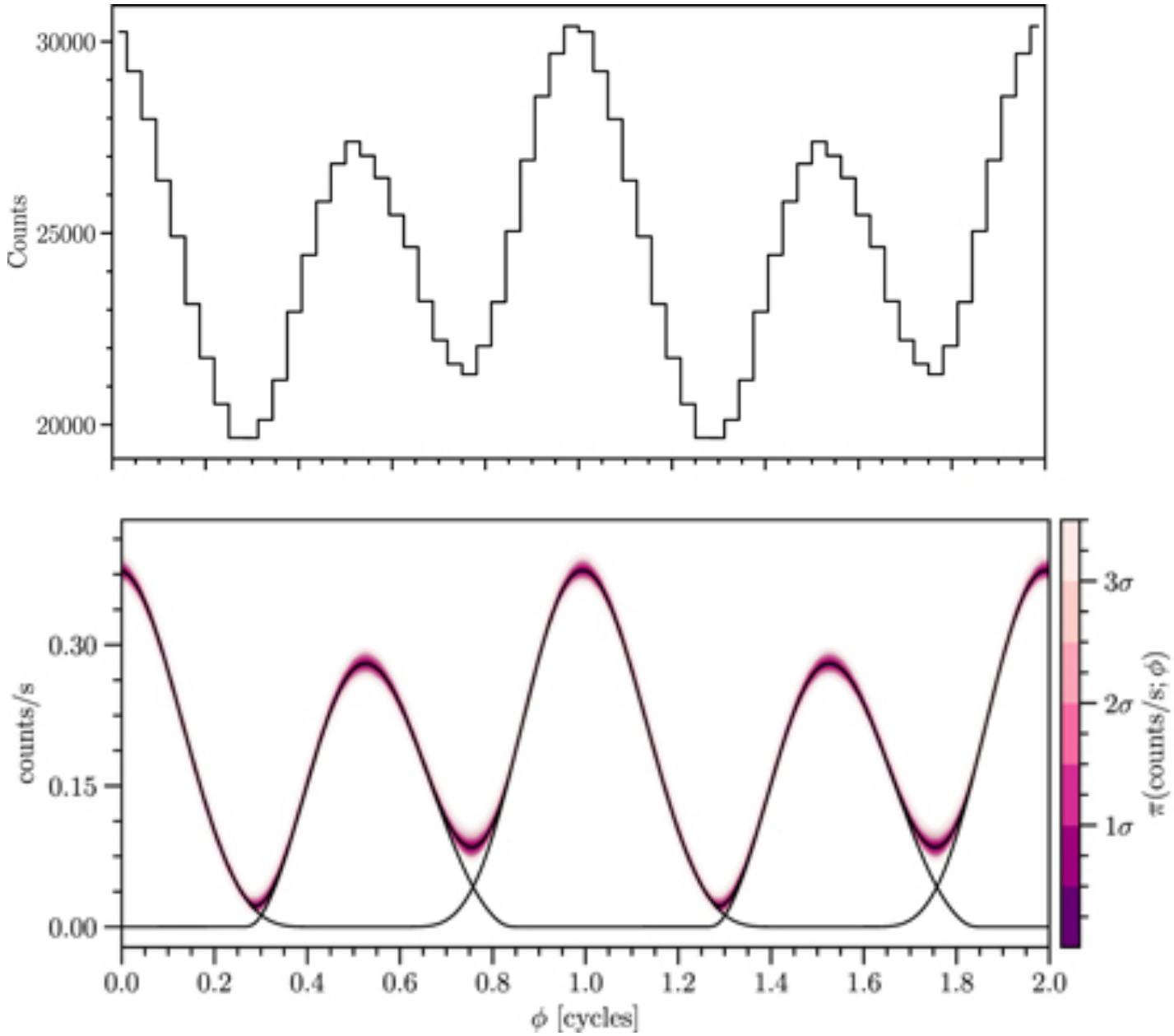
Inference - PSR J0030+0451



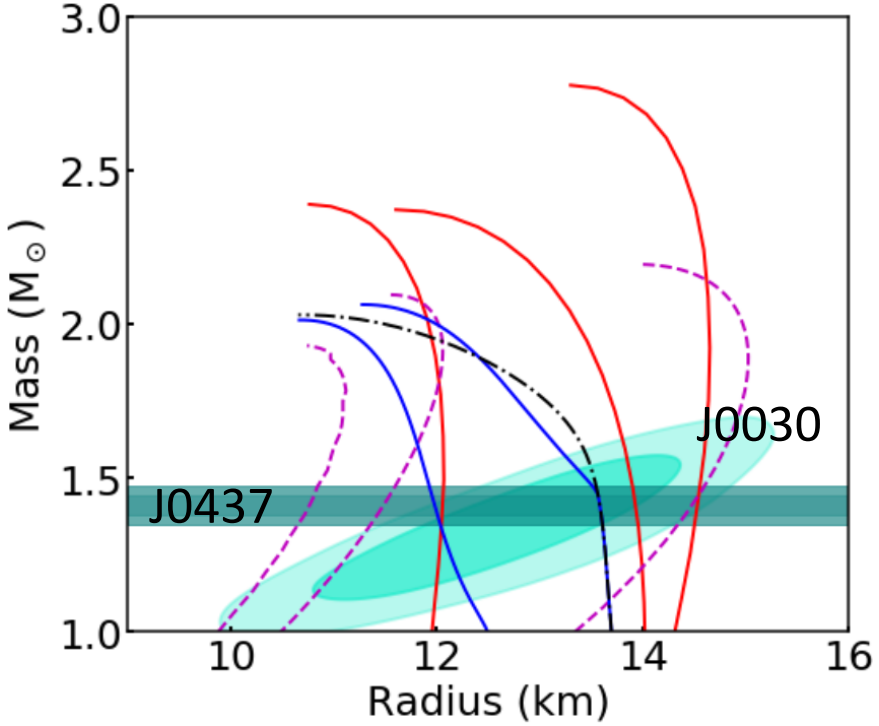


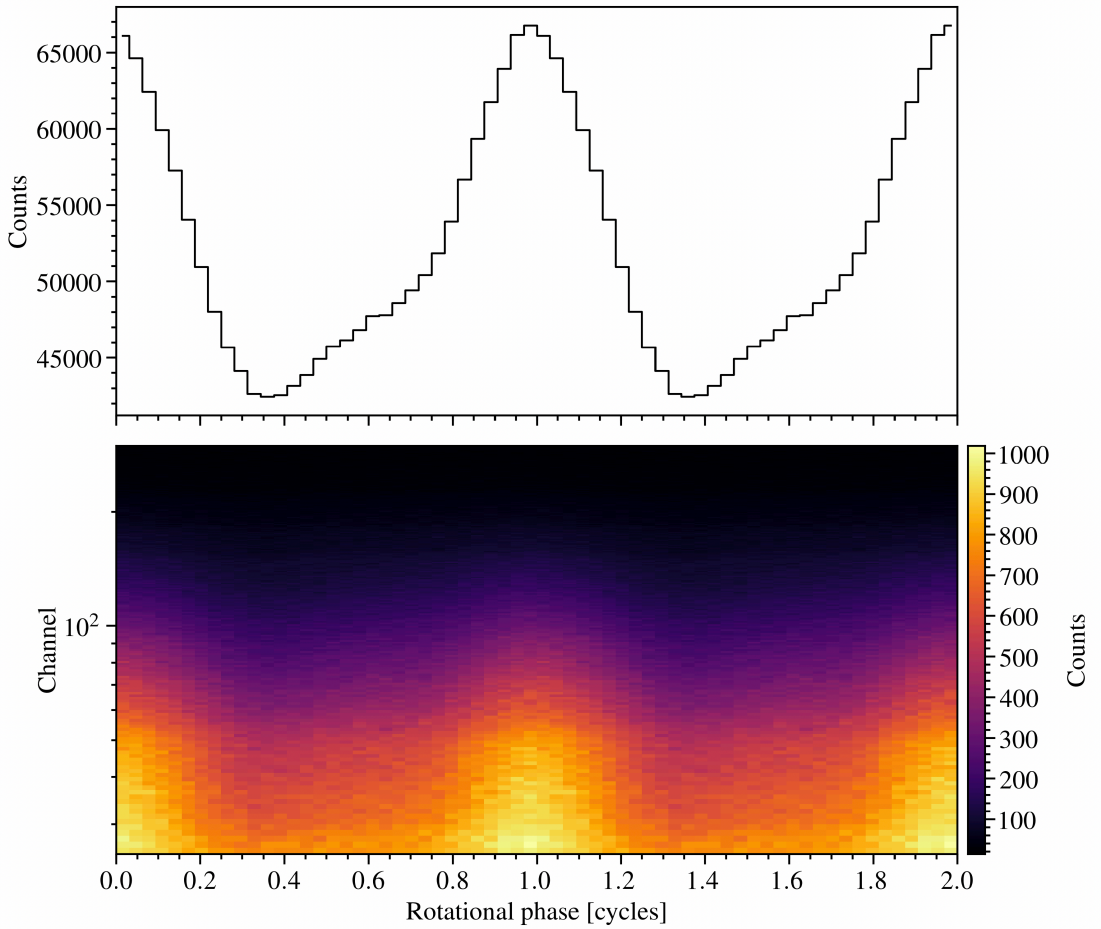
Inference - PSR J0030+0451





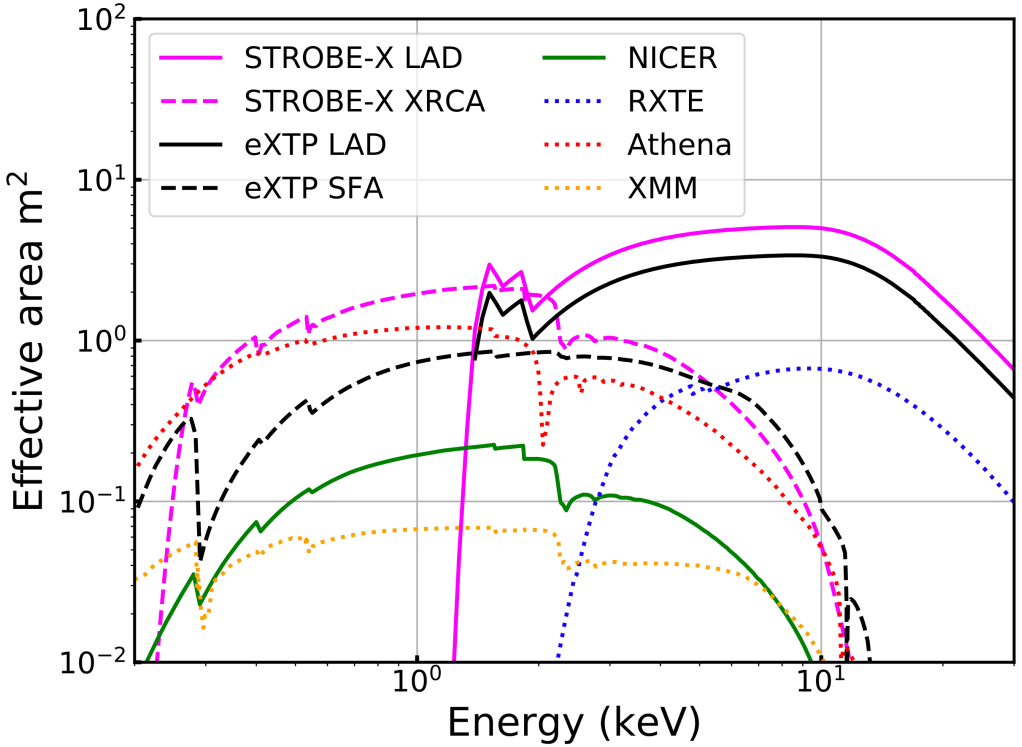
Present Work – PSR J0437-4715





- Nearest observed MSP – tight distance prior, improved counts
- Present in a binary – tight mass and inclination prior
- Expected radius constraint ~ $\pm$ 2.5 %

Scope of Future



- PSR J0740+6620 – highest mass neutron star discovered
- Accreting source observation by eXTP and STROBE-X
- Combining GW data of NS merger to constrain EOS