Crust breaking and limiting rotation rate of NS

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Why don’t NS spin faster?

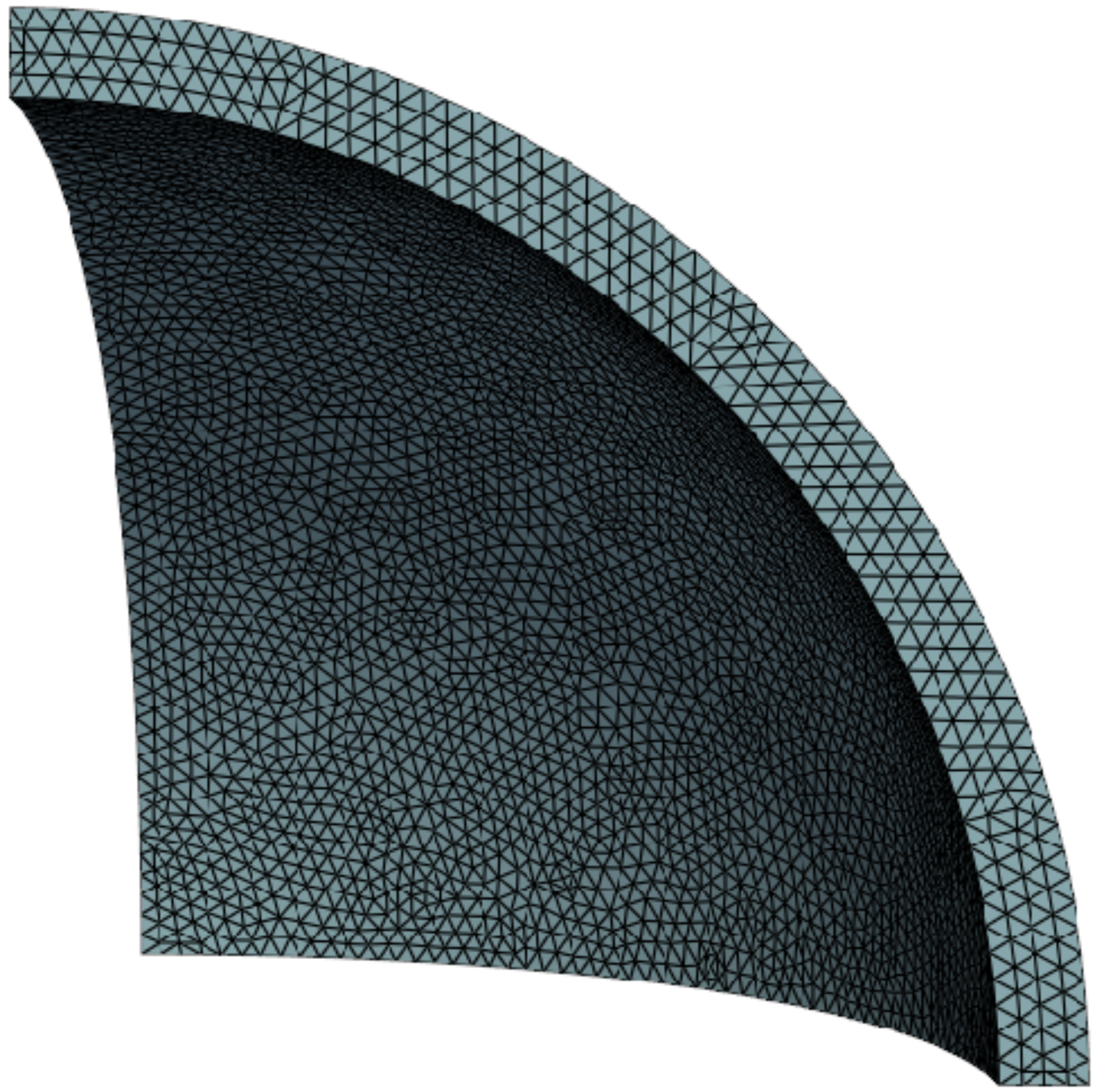
- Fastest observed star spins at 716 Hz. This is about 1/2 of Kepler frequency (where centrifugal force balances gravity).

- Hypothesis: Accretion spins up neutron stars until the crust *breaks*. This broken crust is *deformed* with a nonzero quadrupole moment so gravitational wave radiation prevents the star from spinning up further. arXiv:2410.19111 with **Jorge Morales**.

- Note Lars Bildsten suggested GW radiation limits spin but said quadrupole moment is from asymmetric electron capture layers. [Need very deep electron capture layers in inner crust.]

Finite element simulations

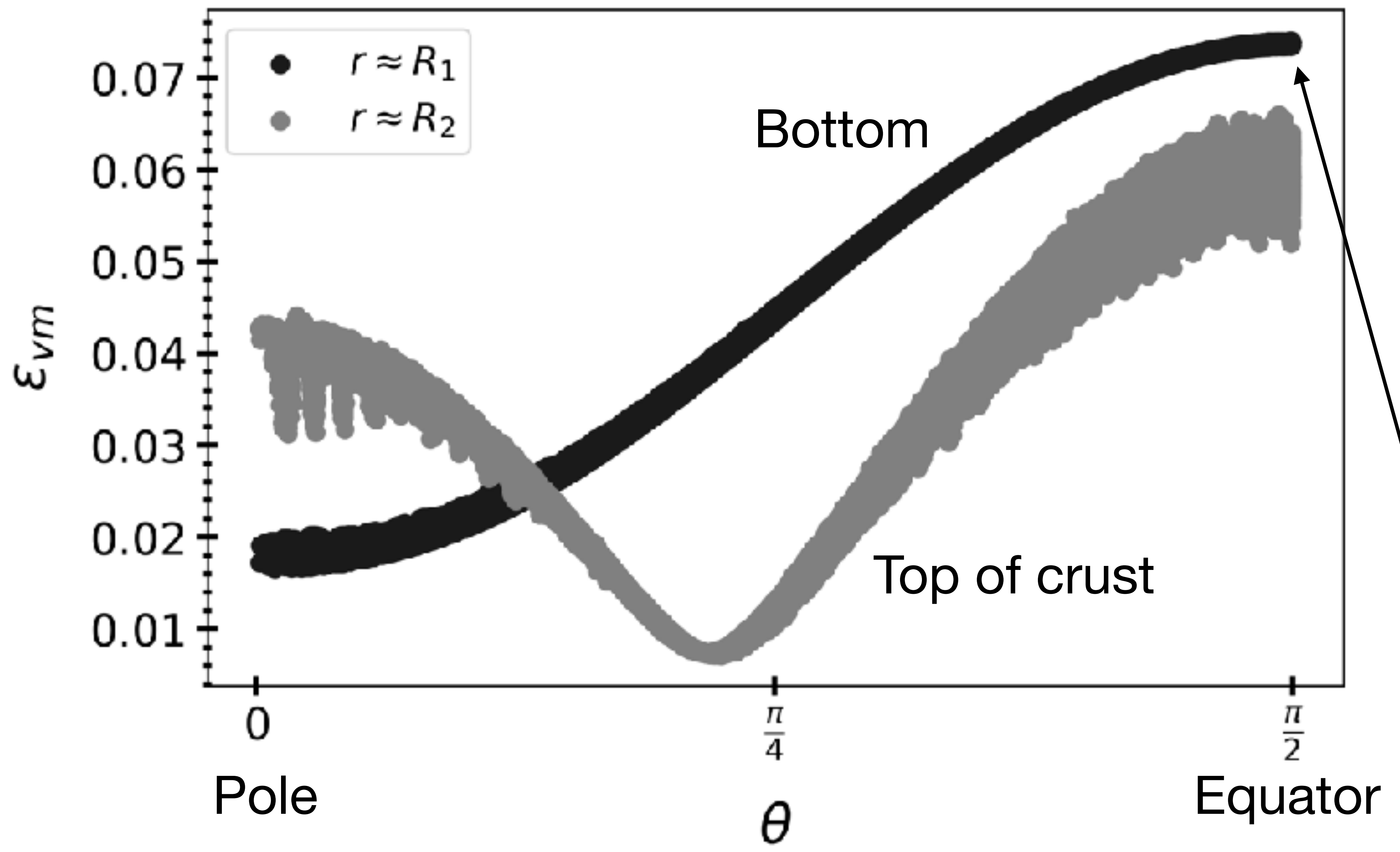
- Finite element simulation models crust as lots of tetrahedrons and satisfies all boundary conditions at crust core and crust ocean/ surface interfaces.
- Elements are of order 100m in size.
- Stress crust with increasing centrifugal forces.
- Nonrel. star with polytope EOS.
- Also compare to fully relativistic calculations of shape of rapidly rotating fluid stars.

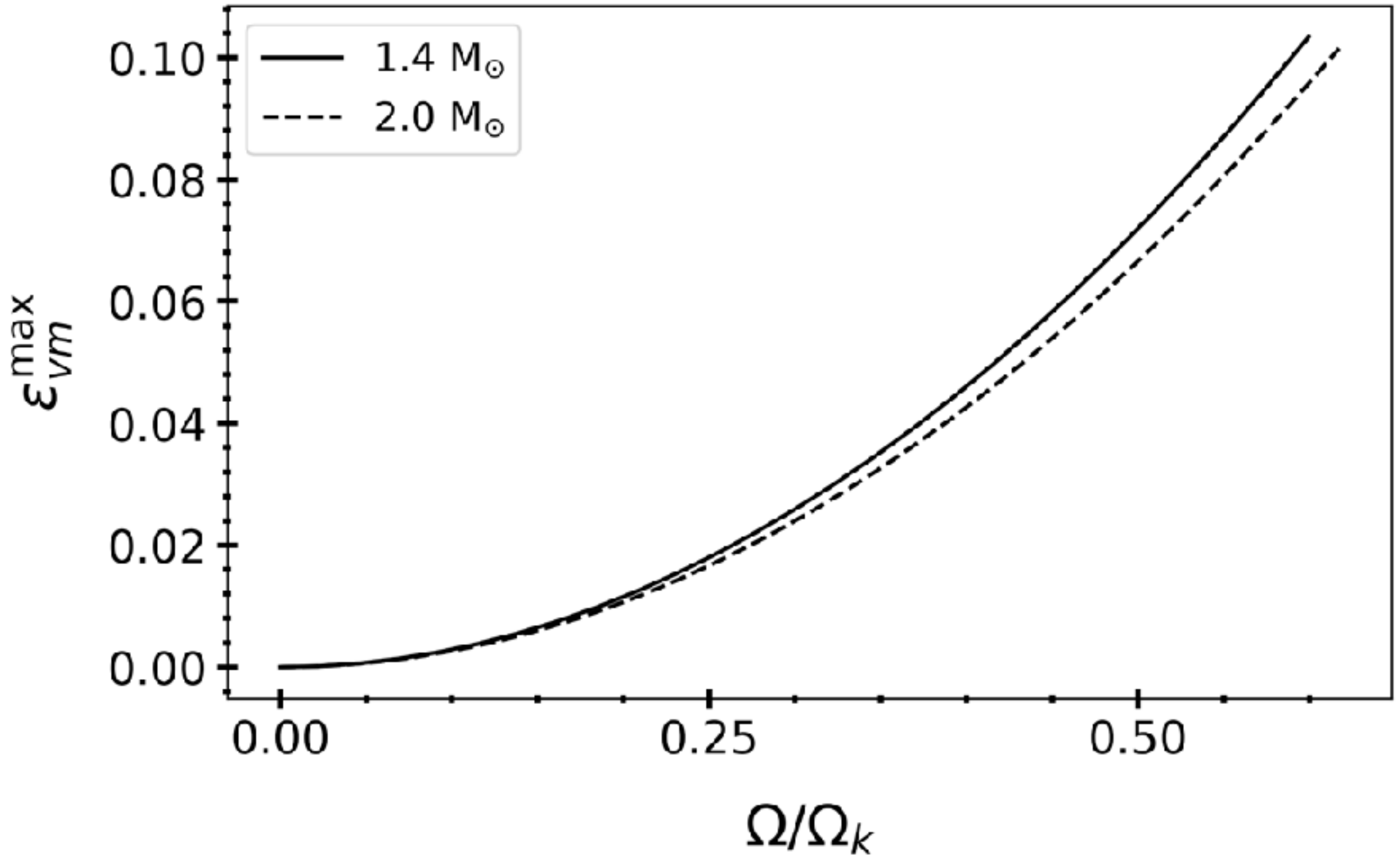


Simulation Mesh

Maximum crust strain

- Crust breaks first at crust/core interface (bottom) and at equator.
- A breaking strain of 0.1 (suggested by molecular dynamics simulations) is reached at rotation rates 0.6 of Kepler.





Crust breaks first here

Rotational frequency when crust breaks

- Example, for a breaking strain of 0.05 crust breaks at 700 +/- 100 Hz depending on radius. Compare to 716 Hz observed.

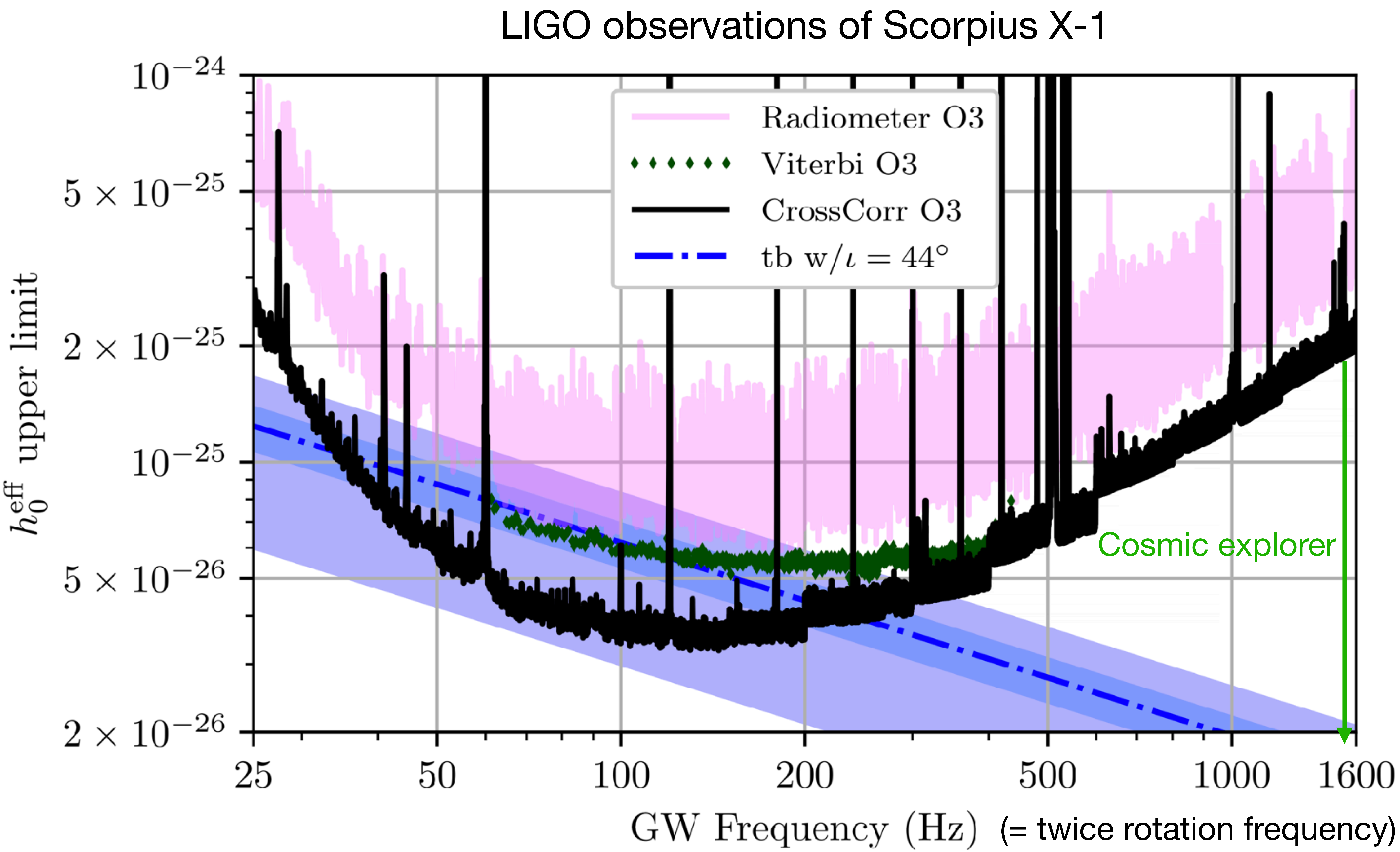
- Qualitatively expect crust to break when change in equatorial radius ΔR/R ~ breaking strain. Relativistic fluid calculations of Konstantinou & Morsink find similar rotational speeds of ~ 600+/- 100.

- Still significant uncertainty from incompletely known breaking strain.

R	Ω_K	Ω_K^r	$\Delta R_e/R$		$\varepsilon_{\rm vm}^{\rm max}$	
(km)	(Hz)	(Hz)	0.05	0.1	0.05	0.1
11	1890	1300	690	940	790	1100
12	1650	1130	600	810	690	960
13	1470	1000	530	720	620	850

- Deformation of crust could be large when it breaks because crust has large strain and the crust breaks at base where density is high.

- Maximum ellipticity $e=(I_1-I_2)/I_3$ crust can support ~ 10^{-6}. Only need ~10^{-8} for torque balance.



LIGO observations of Scorpius X-1
Radiometer O3
Viterbi O3
CrossCorr O3
tb w/$\iota = 44°$
Cosmic explorer
h_0^{eff} upper limit
10^{-24}
5×10^{-25}
2×10^{-25}
10^{-25}
5×10^{-26}
2×10^{-26}
25
50
100
200
500
1000
1600
GW Frequency (Hz)
(= twice rotation frequency)

Gravitational waves from accreting NS

- Finite element simulations find crust breaks at about 700 Hz (depending on crust breaking strain and NS radius).

- Broken crust may have a large quadrupole moment because (1) crust was strained near maximum (2) breaking happens at large densities and (3) strong NS crust can support large quadrupole moment.

- Only need about 1% of maximum quadrupole moment for GW torque to balance accretion torque.

- Can probe scenario with present and next generation GW observations.

- ArXiv:2410.19111 with **Jorge Morales**.