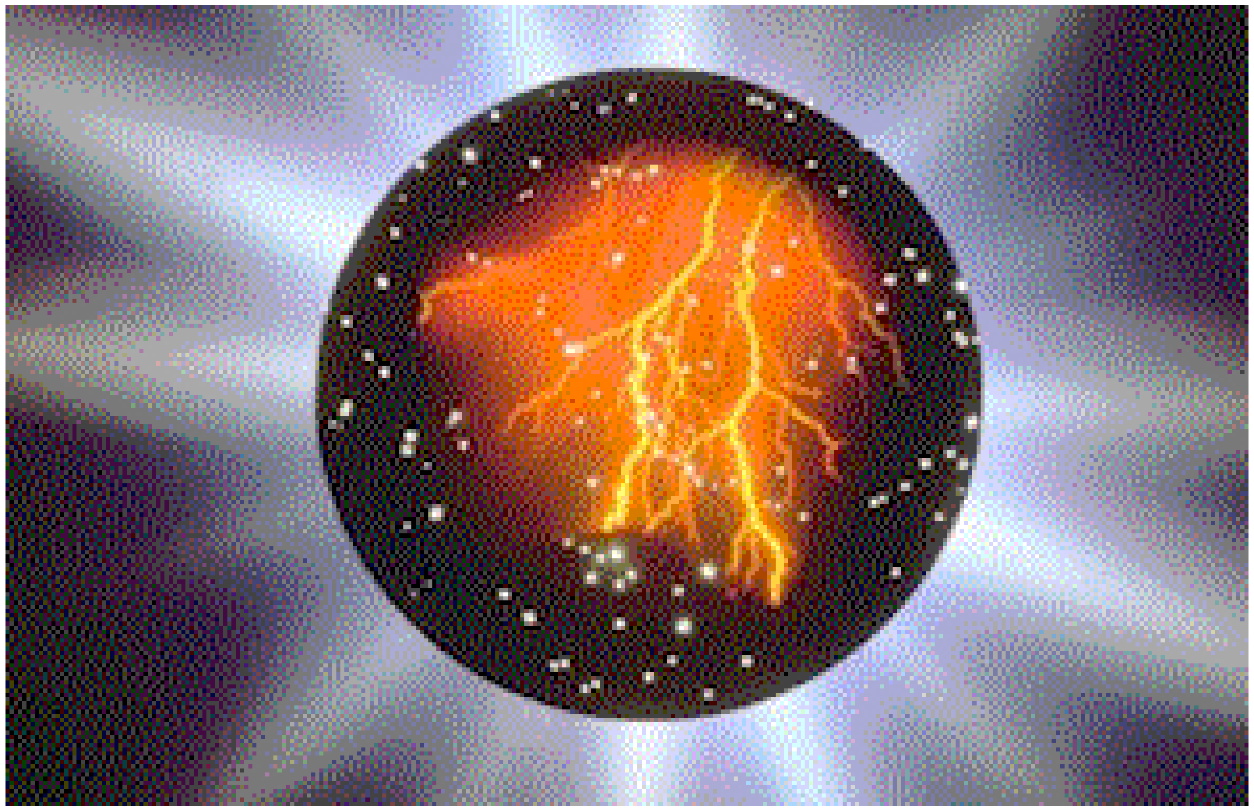
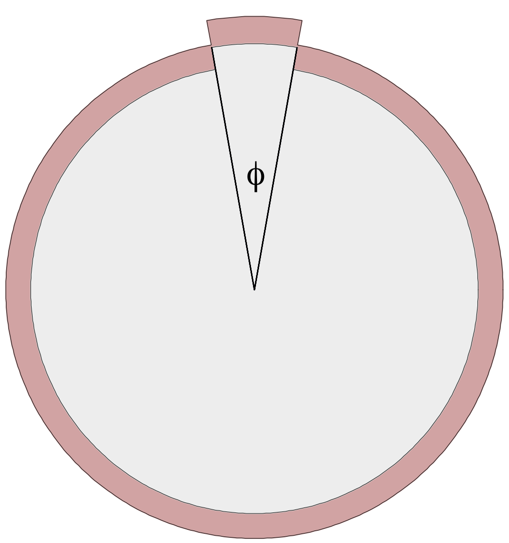
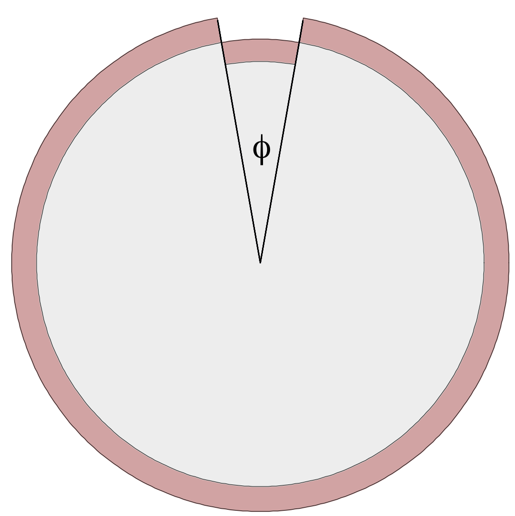
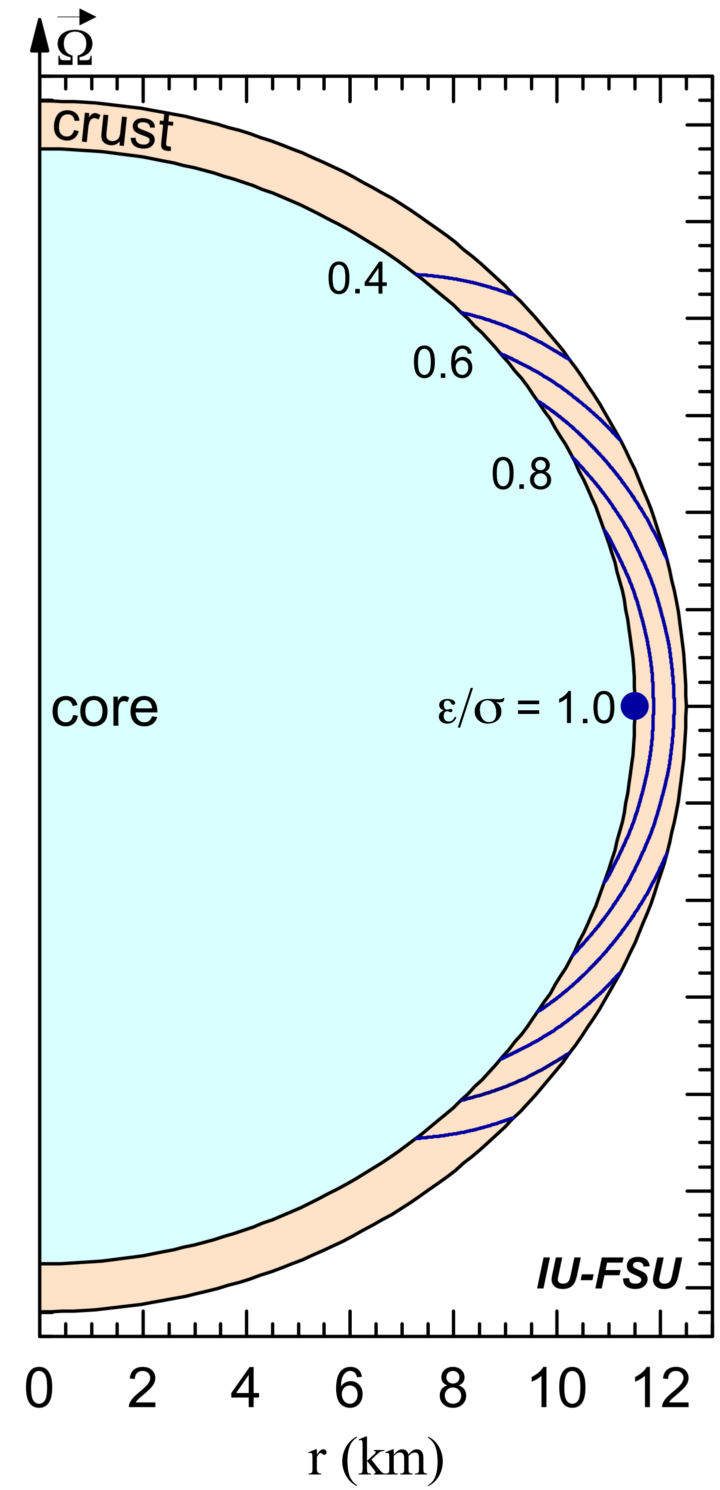
Crust breaking on accreting stars







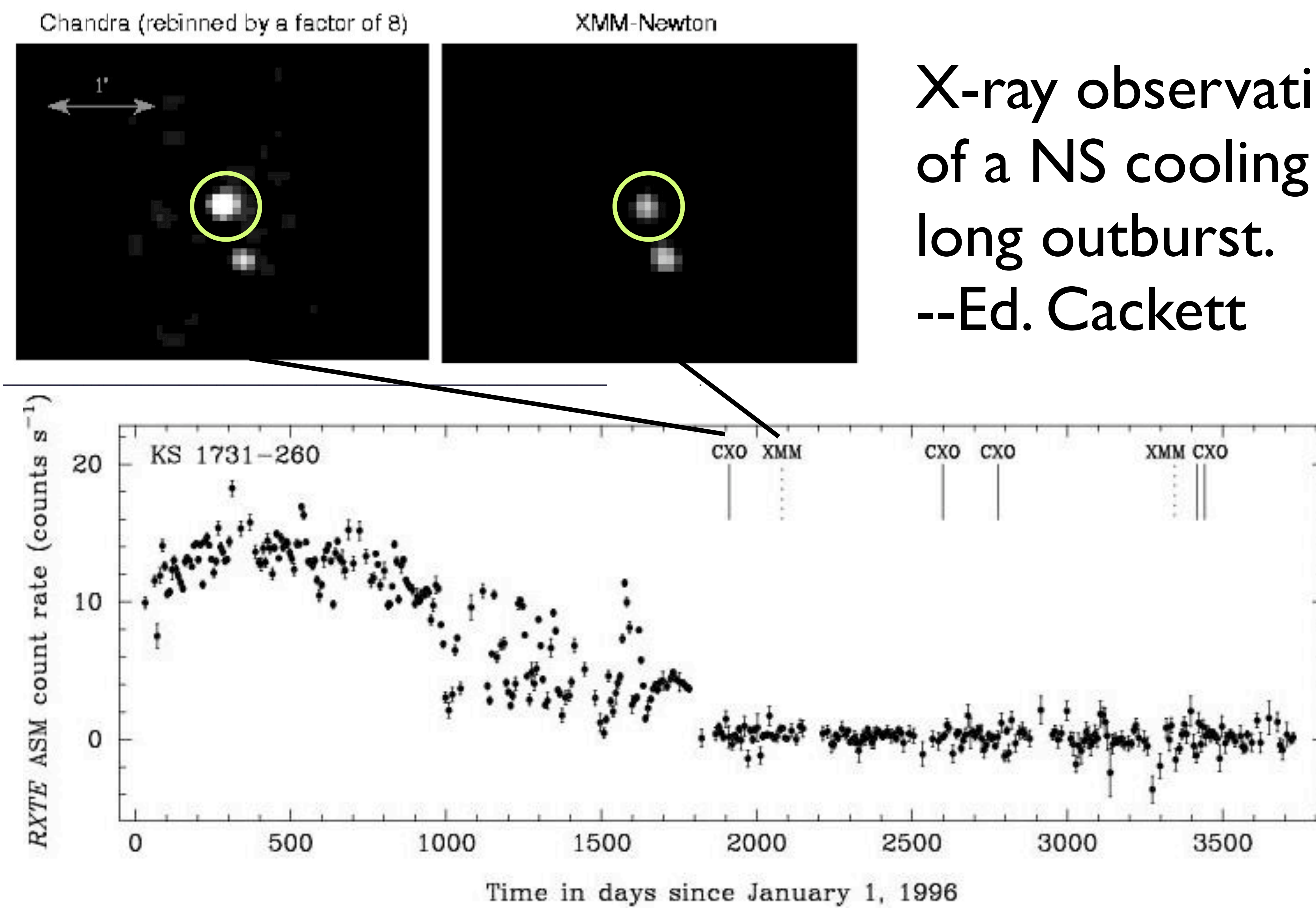


C. J. Horowitz, Indiana U, Astro-solids, INT, Apr. 2018

Crust Breaking on Accreting stars

- Review MD simulations of crust breaking. —> Crust is very strong!
- Crust breaking as a star spins down.
- Crust breaking as a star spins up.

Cooling of crust of KS 1731-260



X-ray observations of a NS cooling after long outburst.

--Ed. Cackett

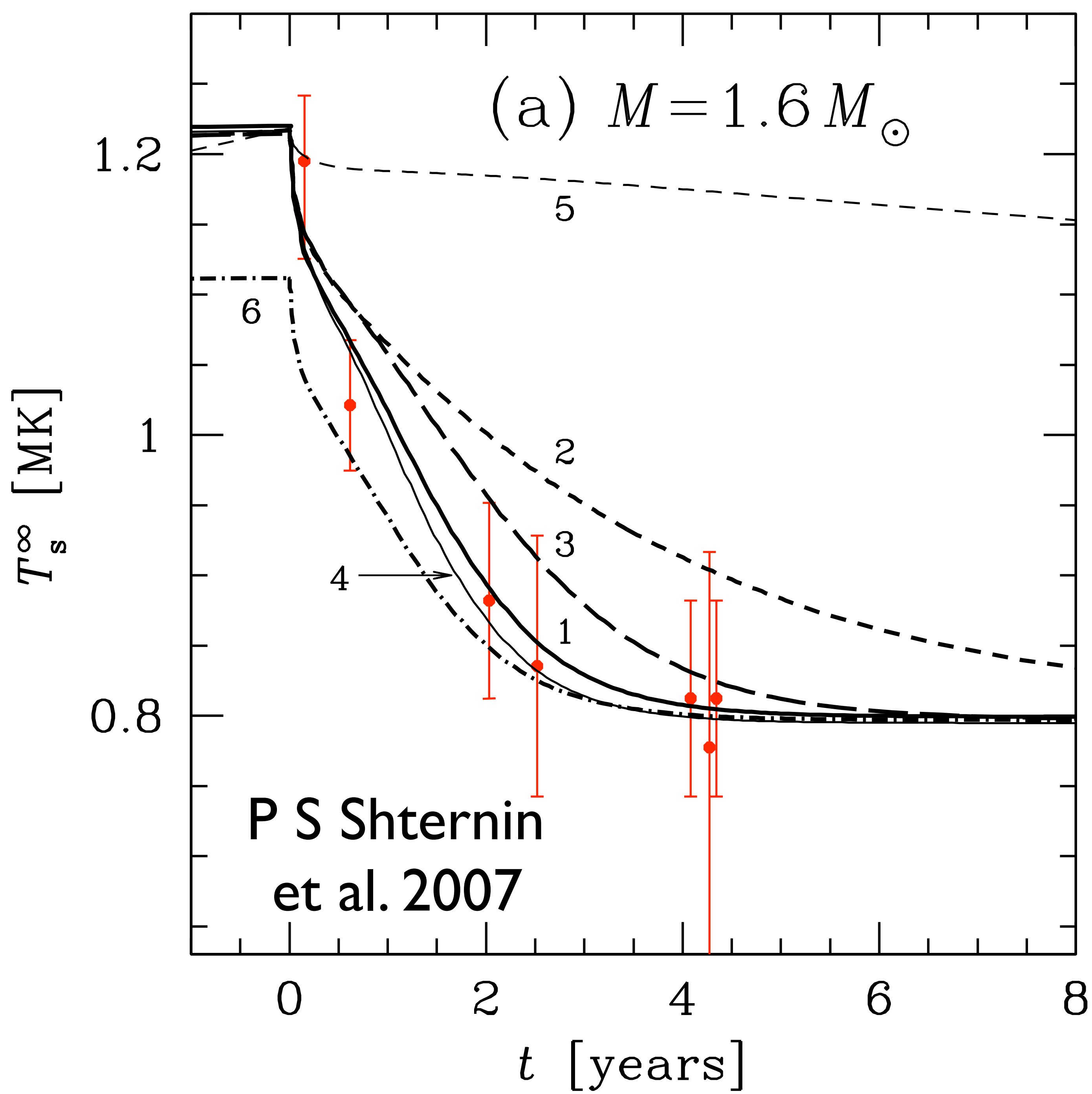
Cooling of KS 1730-260 Surface After Extended Outburst

Rutledge et al. suggested cooling would measure crust properties.

Also calculations by E. Brown and A. Cumming.

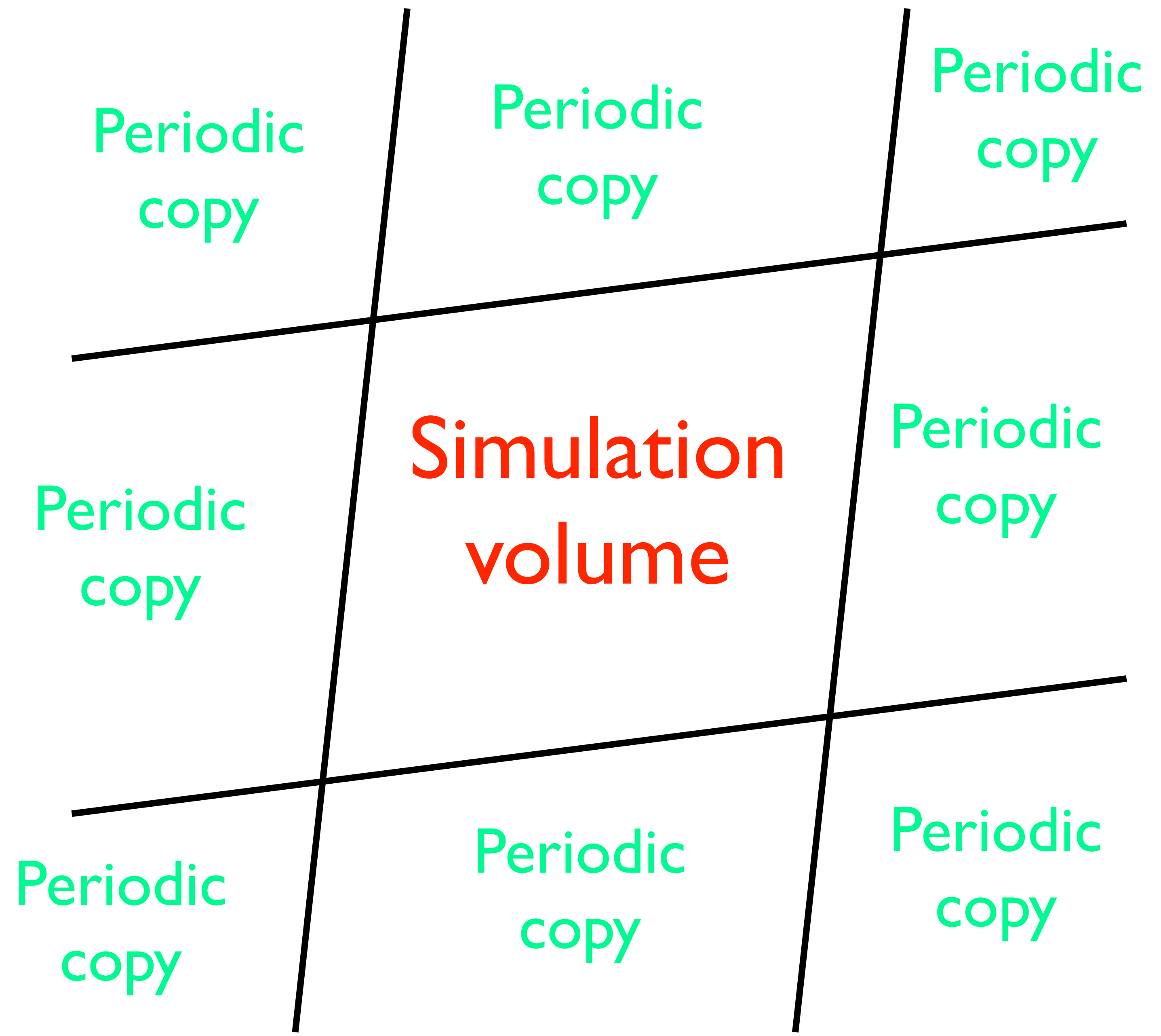
Curves 1-4 use high crust thermal conductivity (regular lattice) while 5 uses low conductivity (amorphous)

Data favor high conductivity!
Crust is observed to be crystalline with few impurities.



MD Simulation of Breaking Strain

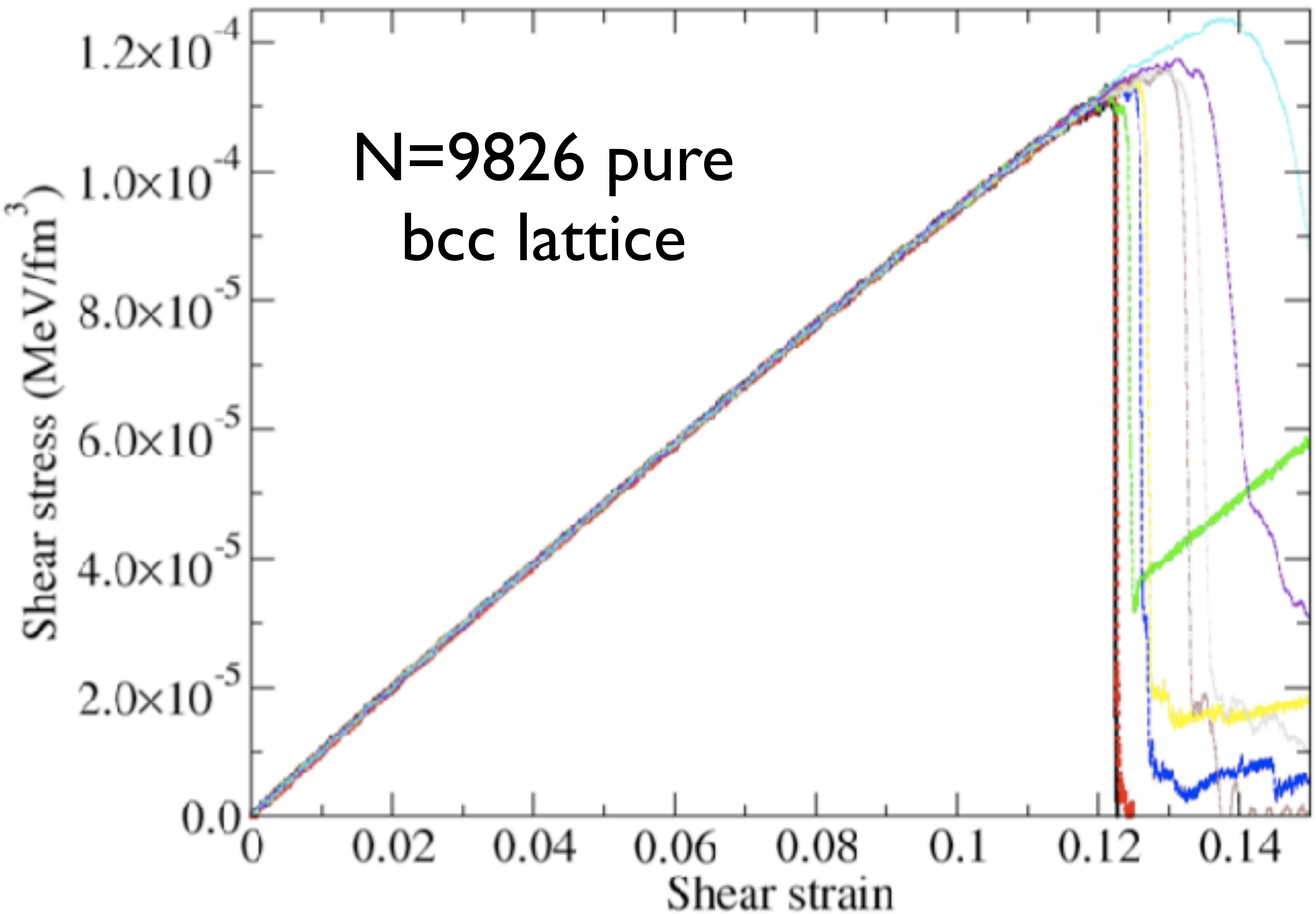
- Slowly shear square simulation volume with time.
- Calculate force from nearest periodic image.
- If particle leaves simulation volume have it enter simulation volume from other side.
- CJH, Kai Kadau, PRL **102**, 191102



Shear Stress vs Strain

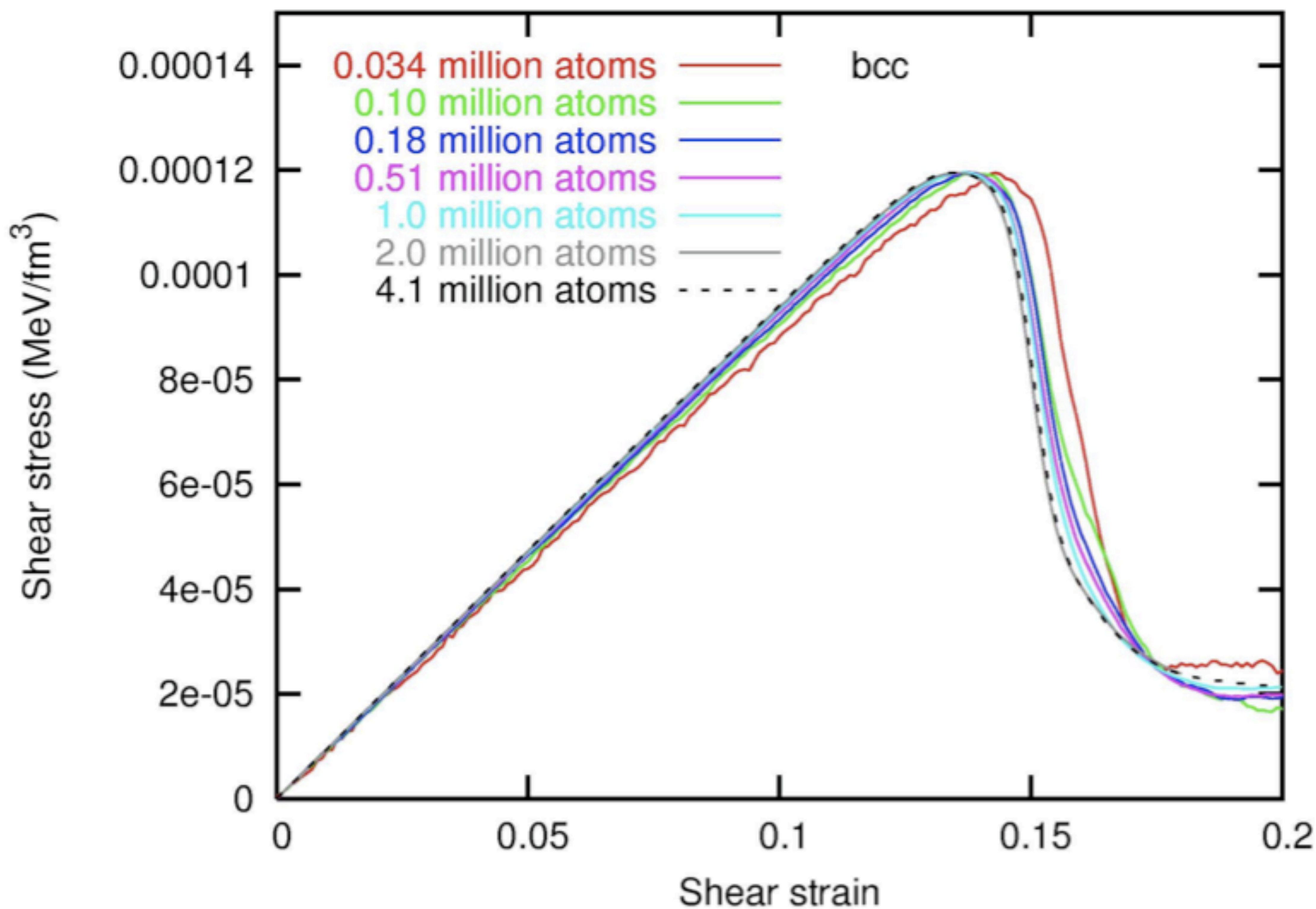
- Stress tensor is force per unit area resisting strain (fractional deformation).
- Hook's law: slope of stress vs strain is shear modulus.
- Very long ranged tails of screened coulomb interactions between ions important for strength.

$$V(r) = \frac{Z^2 e^2}{r} e^{-r/\lambda}$$



- Shear stress versus strain for strain rates of (left to right) 0.125 (black), 0.25 (red), 0.5(green), 1(blue), 2(yellow), 4(brown), 8(gray), 16(violet), and 32(cyan) X10^{-8} c/fm.

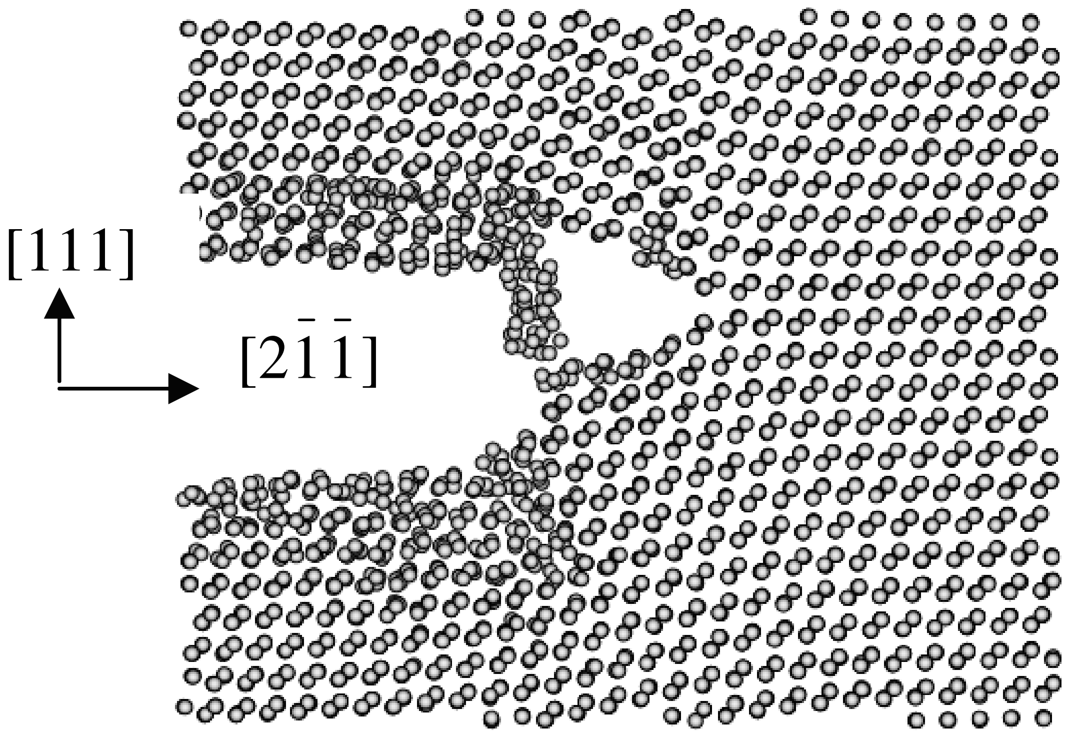
Size dependence of Stress vs Strain



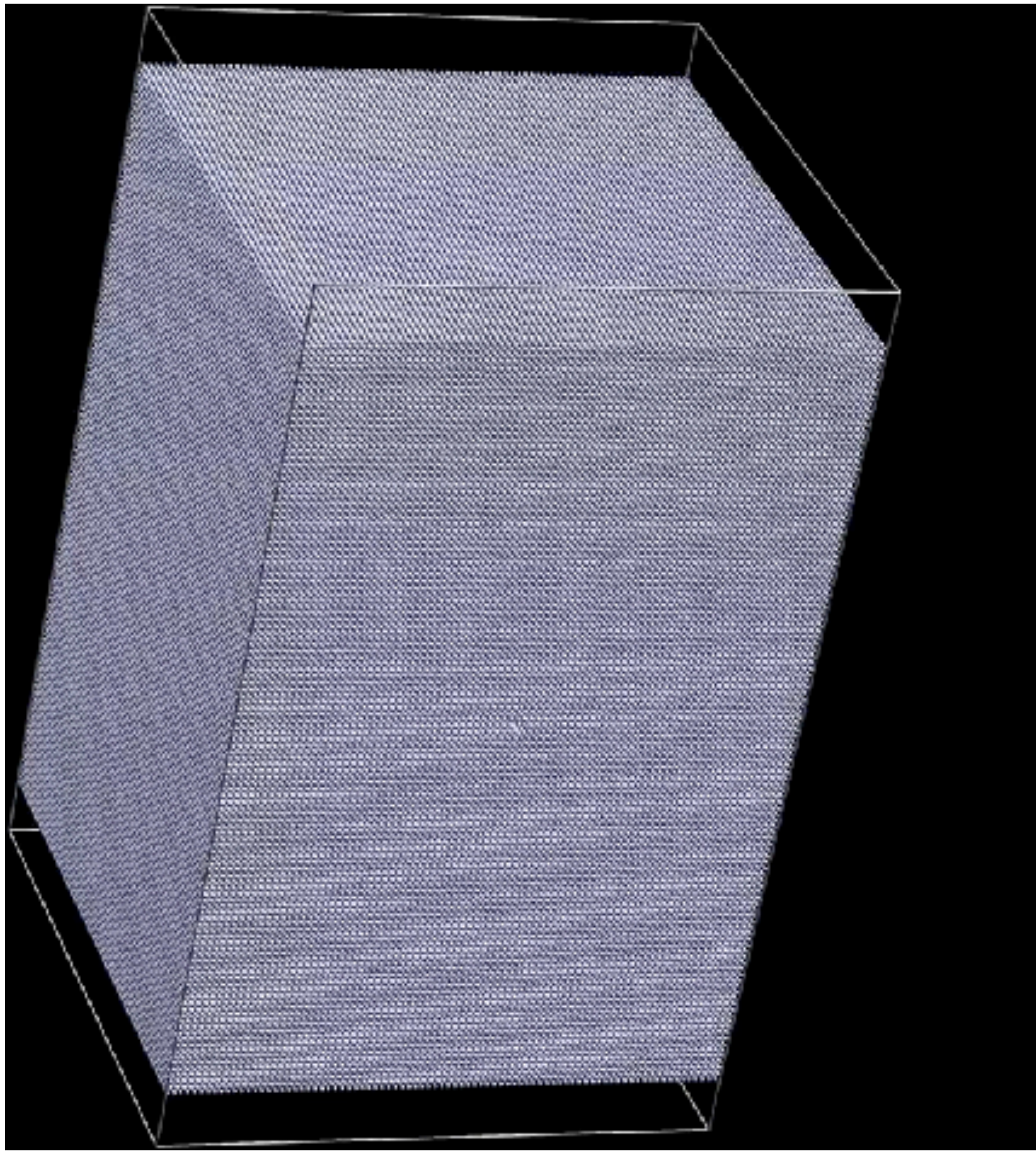
- Shear stress vs. system size at a rate of 4 X 10^{-7} c/fm as calculated with the Scalable Parallel Short ranged Molecular dynamics (SPaSM) code on up to 512 processors.

Breaking of NS Crust

- Fracture in brittle material such as silicon involves propagation of cracks that open voids.
- Crack propagating in MD simulation of Silicon. Swadener et al., PRL**89** (2002) 085503.

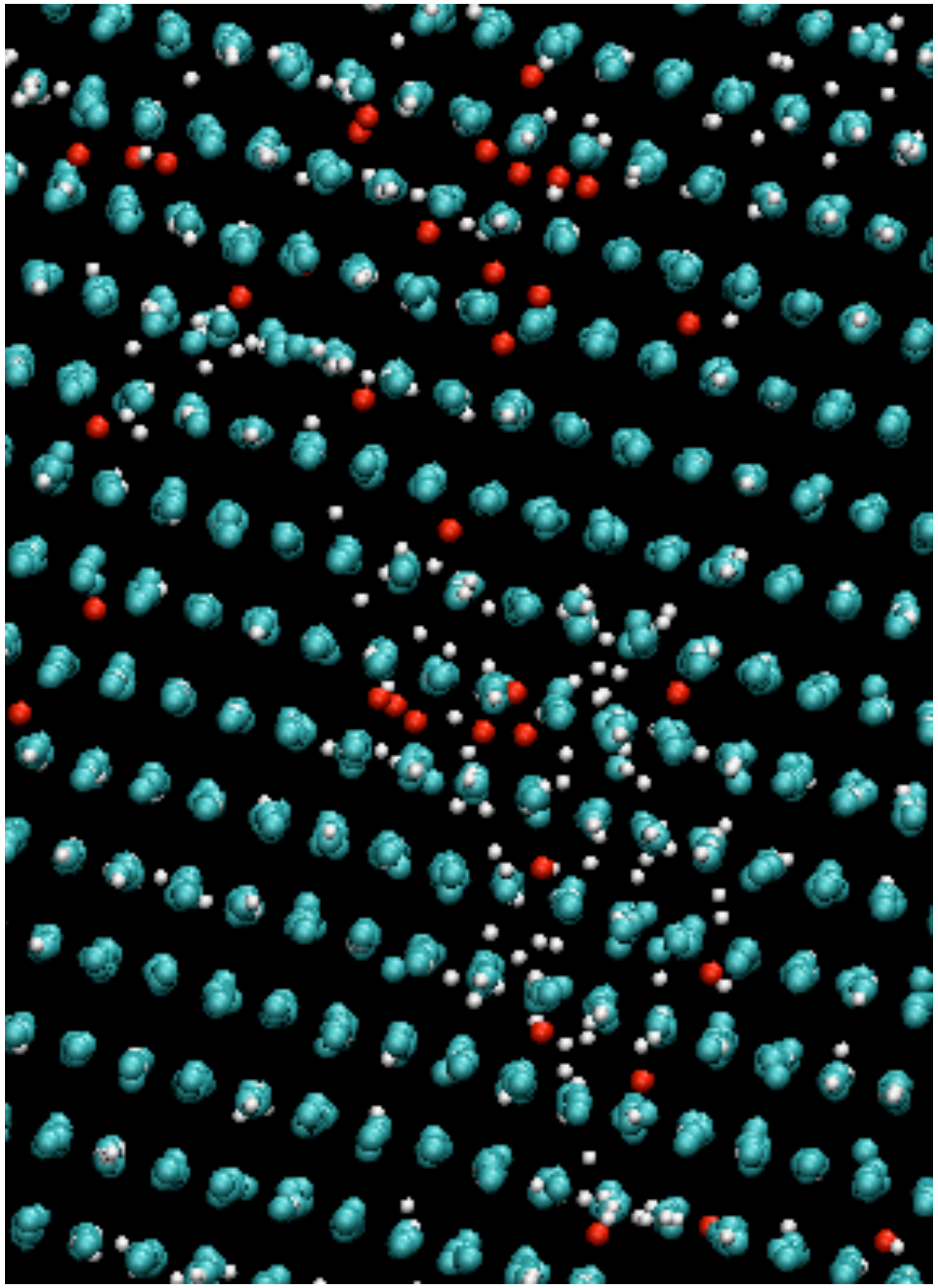


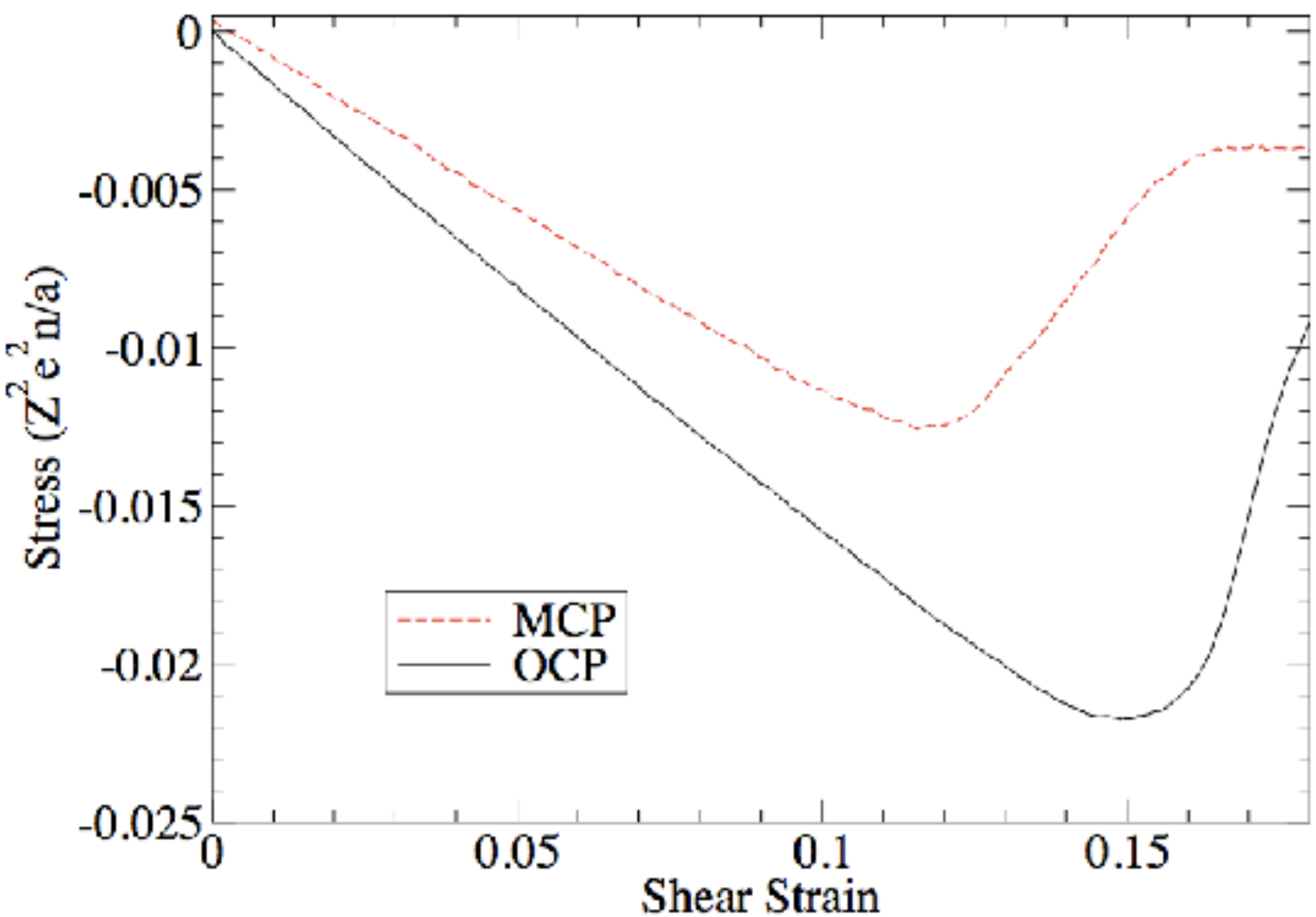
- Neutron star crust is under great pressure which prevents formation of voids. **Crust does not fracture!**



1.7 million ion crystal with cylindrical defect in center. Red color indicates deformation.

Effects of impurities

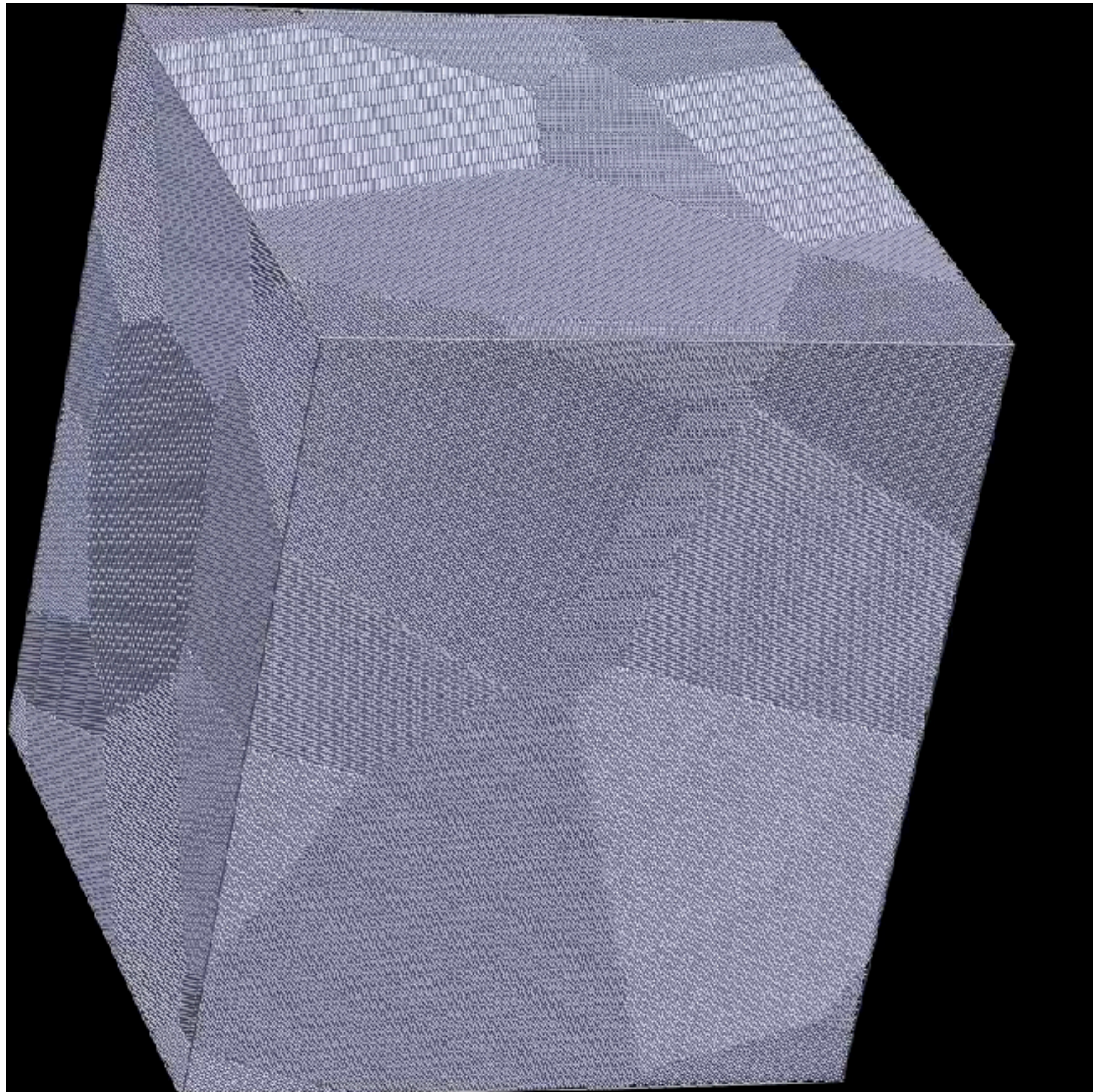




27648 ion simulation with complex rp ash composition (MCP) that includes many impurities is only slightly weaker than pure crystal (OCP).

Role of Grain Boundaries

- Grain boundaries may weaken crust.
- Expect grain size to be larger than we can simulate.
- However we find strength only grows with grain size.
- Example of poly-crystalline sample with 8 grains and 13 million ions.



Neutron Star Crust is Very Strong

- Each ion has long range Coulomb interactions with thousands of neighbors. The system is still strong even if several of these redundant bonds are broken.
- The great pressure suppresses the formation of dislocations, voids, and fractures. This inhibits many failure mechanisms.
- **We find neutron star crust is the strongest material known. It is ten billion times stronger than steel (has 10^{10} the breaking stress)!**
- The breaking strain σ (fractional deformation at failure) is very large, of order σ=0.1 even including the effects of impurities, defects, and grain boundaries.
- Ushomirsky et al. speculate on implications of σ=0.01, but this is a guess. Our σ is ten times bigger. But more importantly, our result is based on detailed MD simulations.

Star quakes and glitches

- Crust is stressed as isolated NS spins down, reducing centrifugal support of equatorial bulge. When crust breaks, moment of inertia changes producing glitch.
- Not enough angular momentum in deformation of crust for star quakes to explain all glitches.
- Strong crust could increase time between star quakes and size of produced glitch.
- Strain tensor $u_{ij} = 1/2(du_i/dr_j + du_j/dr_i)$ where $\mathbf{u}$ is displacement field of crust.
- Strain angle is difference between largest and smallest eigenvalue of strain tensor. Crust fails when strain angle exceeds breaking strain.

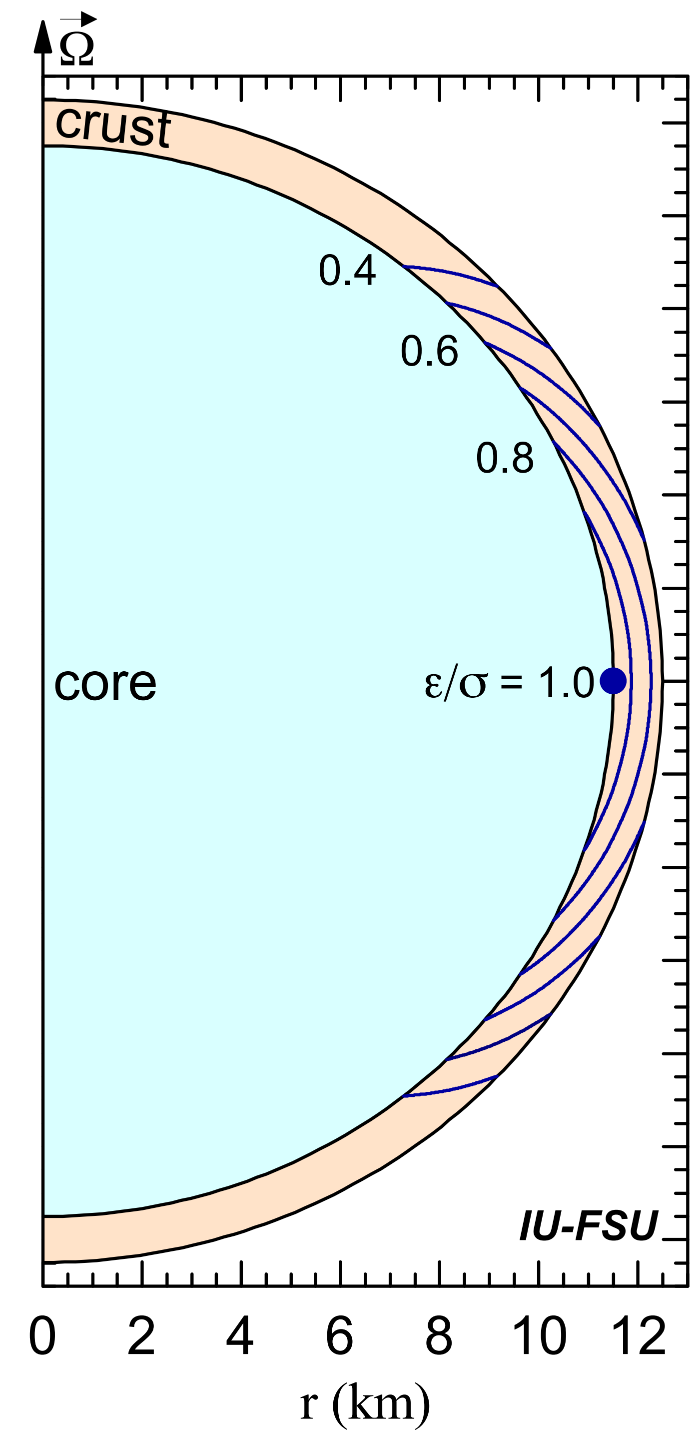
Strain in crust

- Assume uniform density crust over incompressible core [L. M. Franco, B. Link, and R. I. Epstein, ApJ. **543**, 987 (2000)]. Strain tensor is

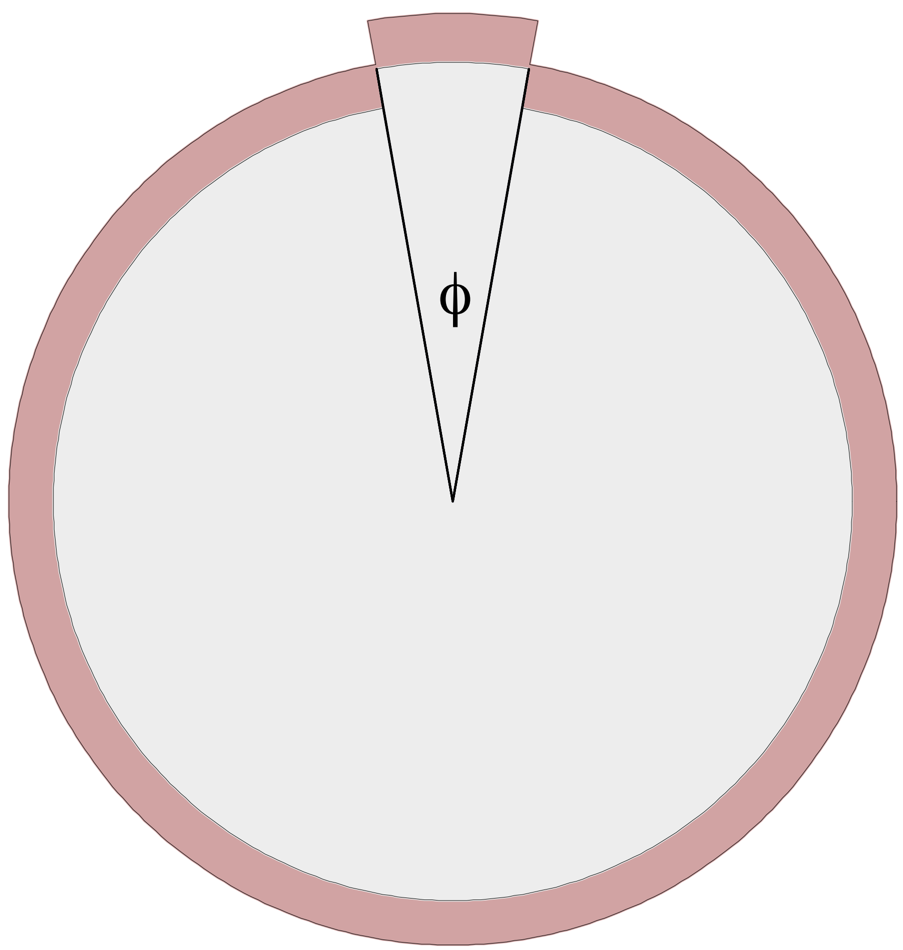
$$u_r(r,\theta) = \left(ar - \frac{A}{7}r^3 - \frac{B}{2r^2} + \frac{b}{r^4}\right) P_2(\theta)$$
$$u_\theta(r,\theta) = \left(\frac{ar}{2} - \frac{5}{42}Ar^3 - \frac{b}{3r^4}\right) \frac{dP_2(\theta)}{d\theta}$$

- Boundary conditions at surface R and crust core interface R'.

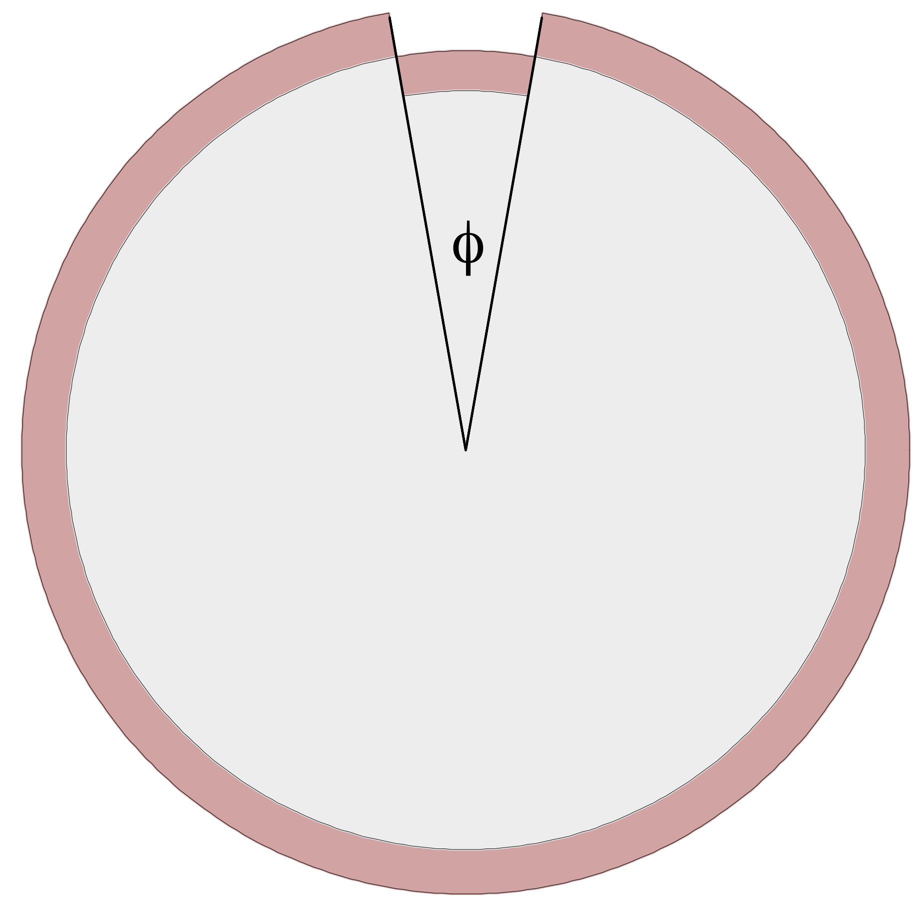
$$\begin{aligned}
a - \frac{8}{21}AR^2 - \frac{B}{2R^3} + \frac{8}{3}\frac{b}{R^5} &= 0\ , \\
a - \frac{8}{21}AR'^2 - \frac{B}{2R'^3} + \frac{8}{3}\frac{b}{R'^5} &= 0\ , \\
-2f'(R) - \frac{2}{5}\frac{v_{\rm K}^2}{c_{\rm t}^2}\frac{f(R)}{R} + \frac{R^2}{3}\frac{\Omega_{\rm i}^2 - \Omega_{\rm f}^2}{c_{\rm t}^2} &= AR^2 + \frac{B}{R^3} \\
-\frac{1}{2}\left[AR'^2 + \frac{B}{R'^3}\right] &= f'(R')\ .
\end{aligned}$$



Crust breaking in region ϕ

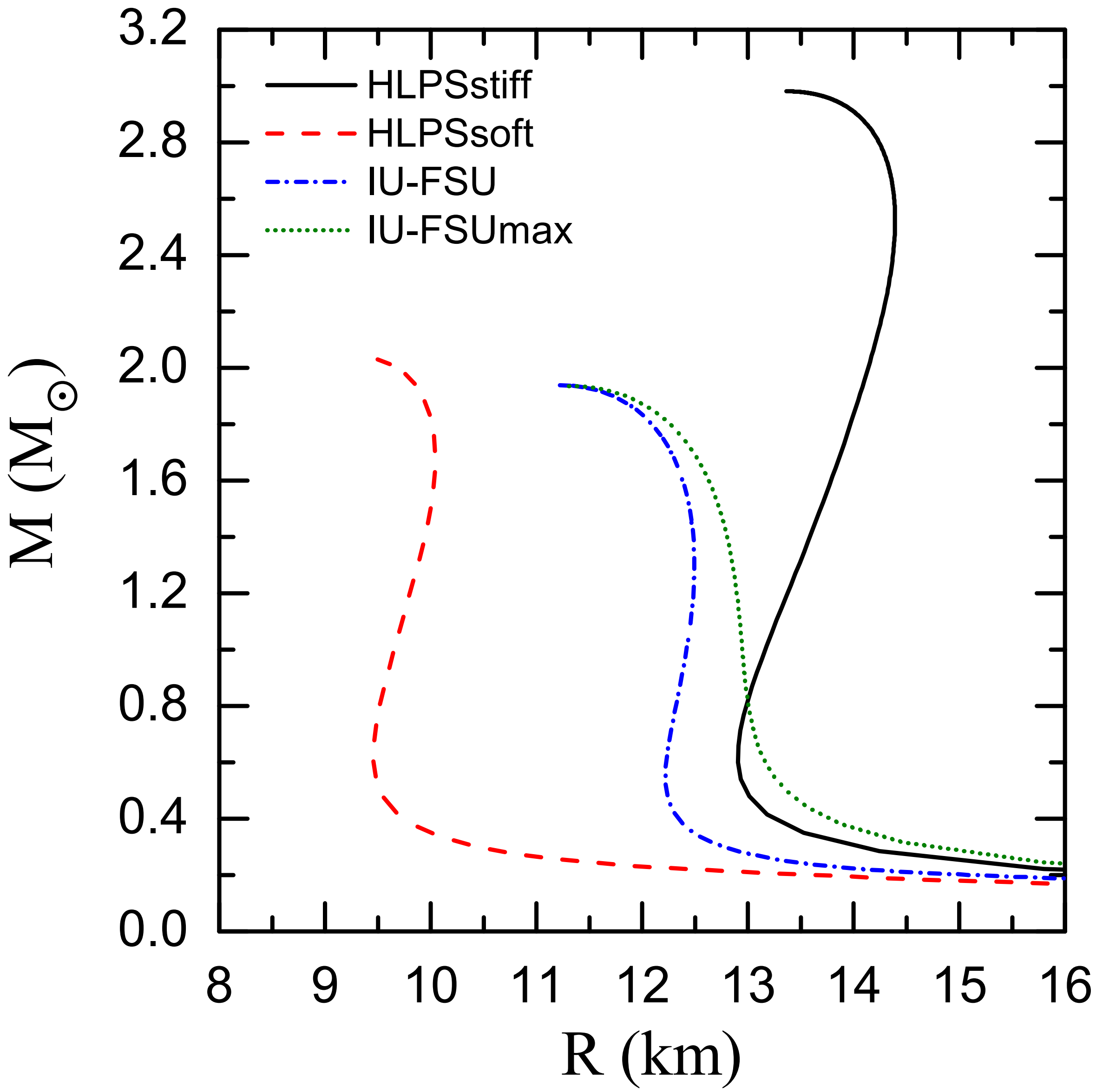


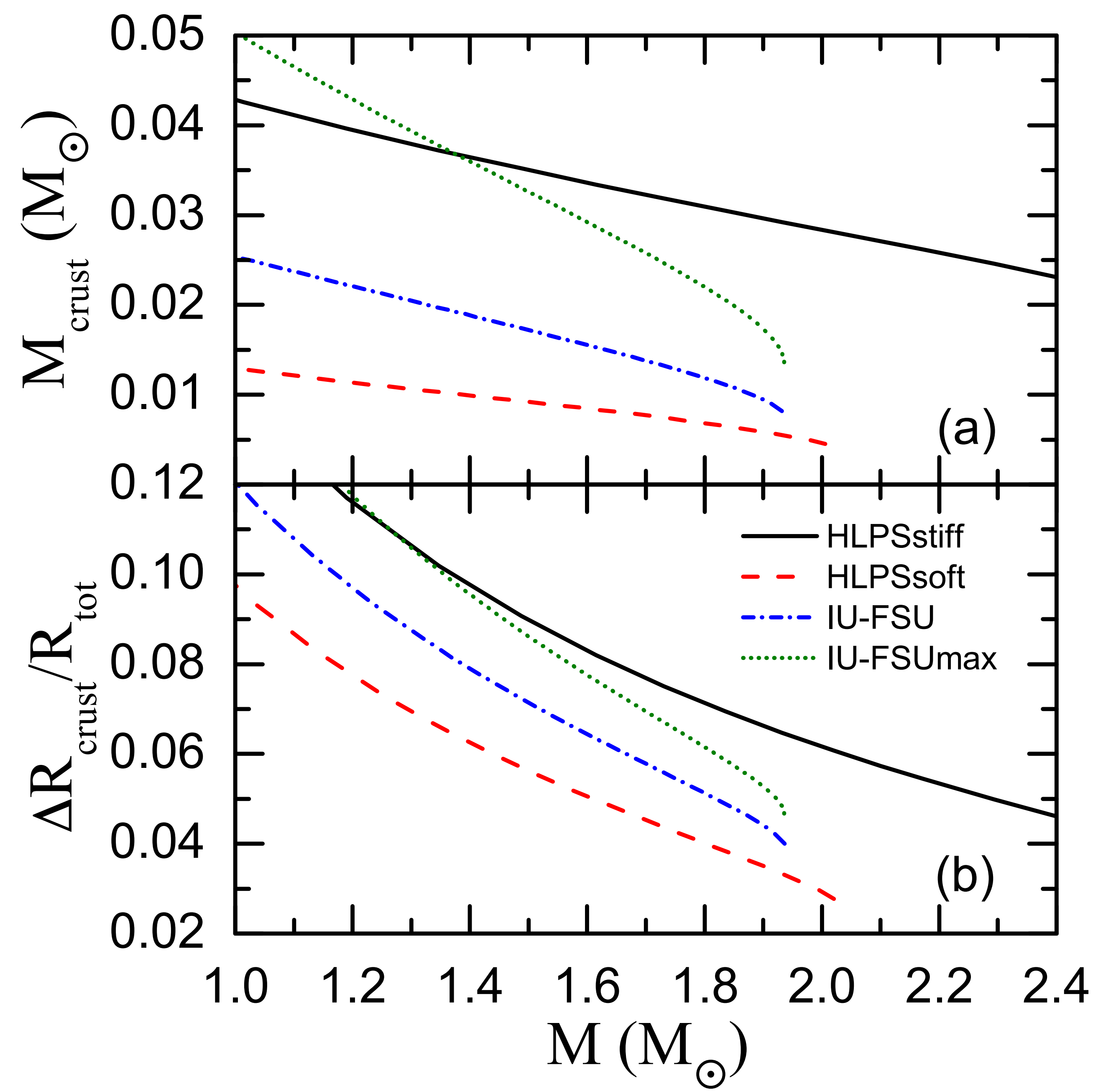
Spinning up accreting star



Spinning down star

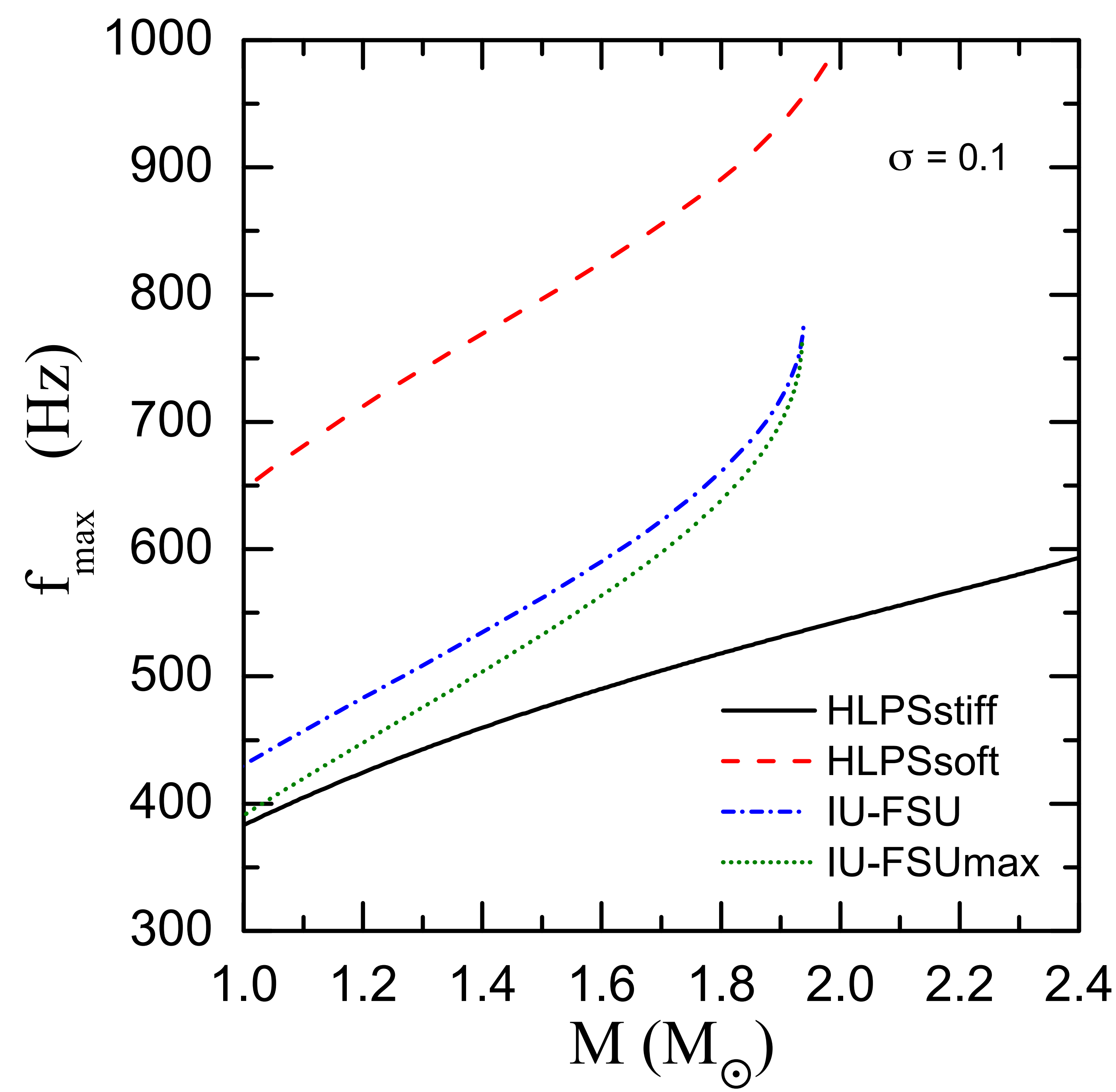
EOS and crust thickness





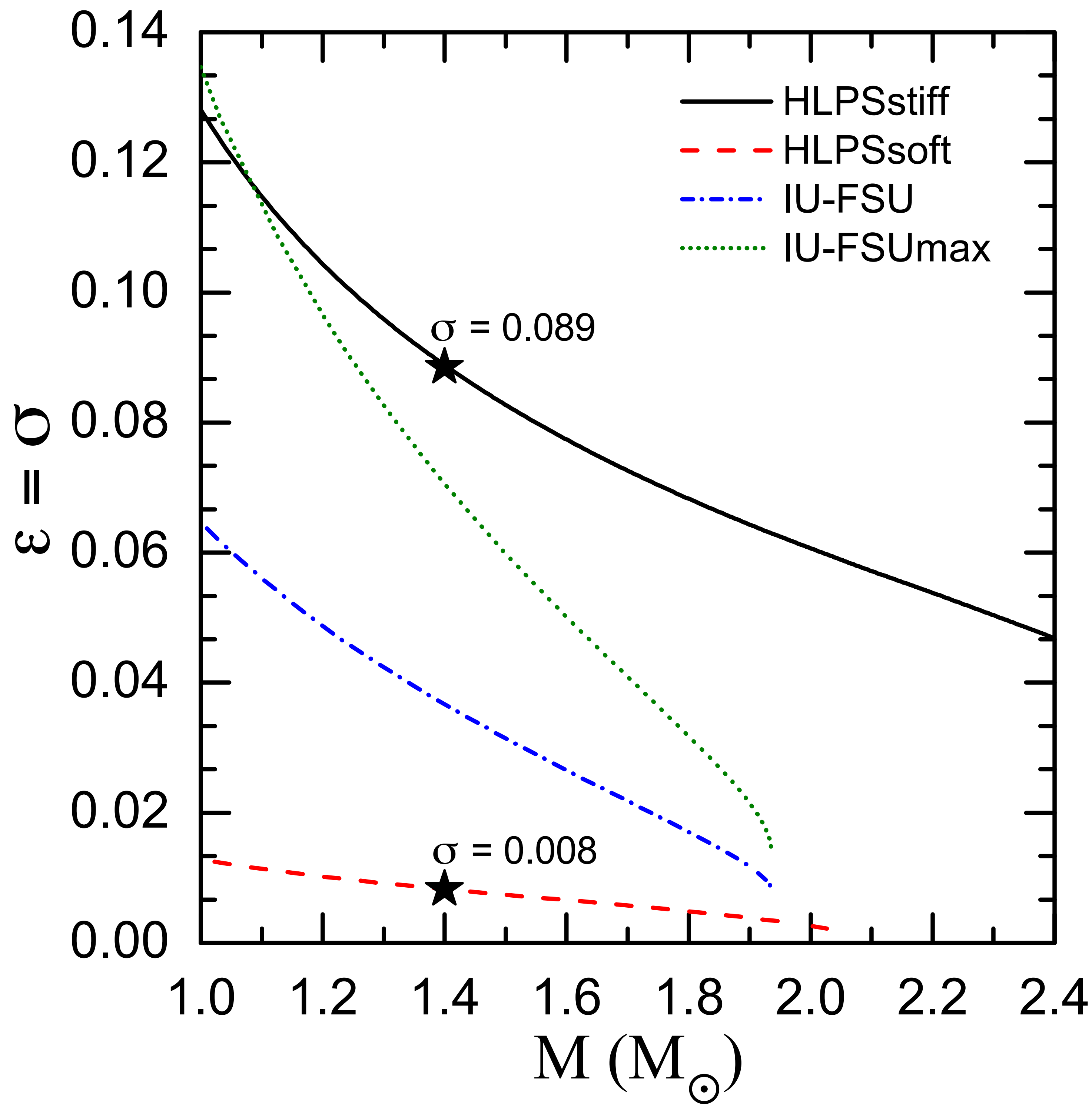
Crust breaking on spinning down NS

- If breaking strain is 0.1 there is a minimum initial rotational frequency for crust to break before it stops spinning.
- *Most isolated NS likely born spinning too slowly for crust ever to brake.*
- If star born spinning very fast then asymmetric breaking of crust can produce significant ellipticity.



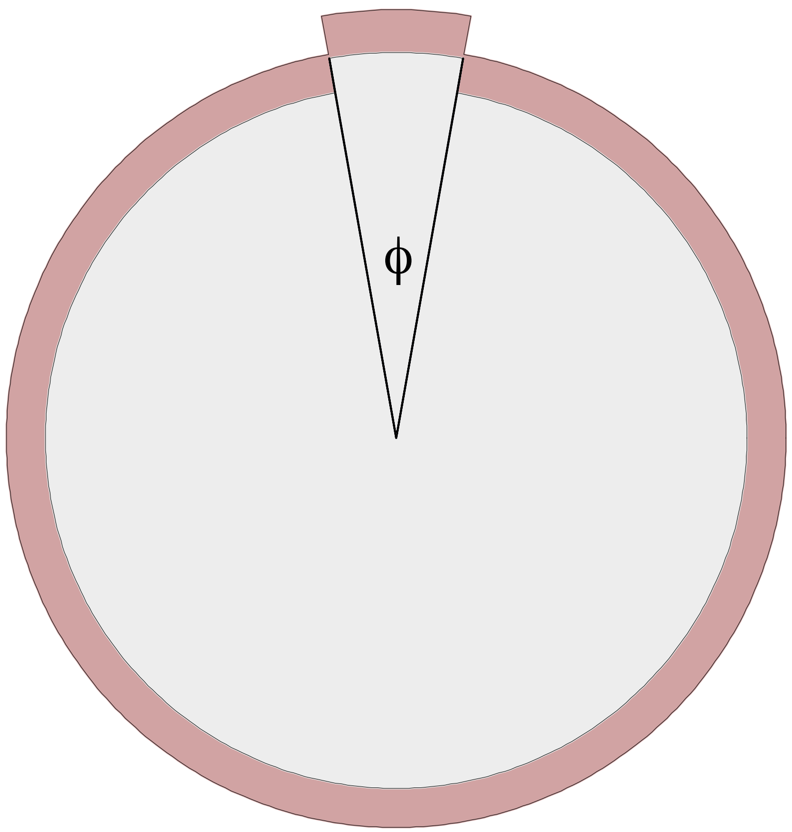
Spinning up accreting NS: Strength so crust breaks at 716 Hz

- Assume crust starts at 0 strain at a frequency so that it reaches 716 Hz by time crust is replaced.
- What is breaking strain so that crust then fails?



Limiting rotational freq. of NS

- ***May be set by the strength of the crust.***
- If crust breaks asymmetrically —> get nonzero ellipticity ϵ and GW radiation.
- Crust breaking gives an ϵ related to maximum ϵ [10^{-6} to 10^{-5}] because crust is maximally stressed when it breaks.
- Very roughly, ϵ is maximum ϵ times fraction of crust that breaks. ~1% break could give torque balance.
- F. J. Fattoyev, C. J. H., and Hao Lu, ArXiv:1804.04952

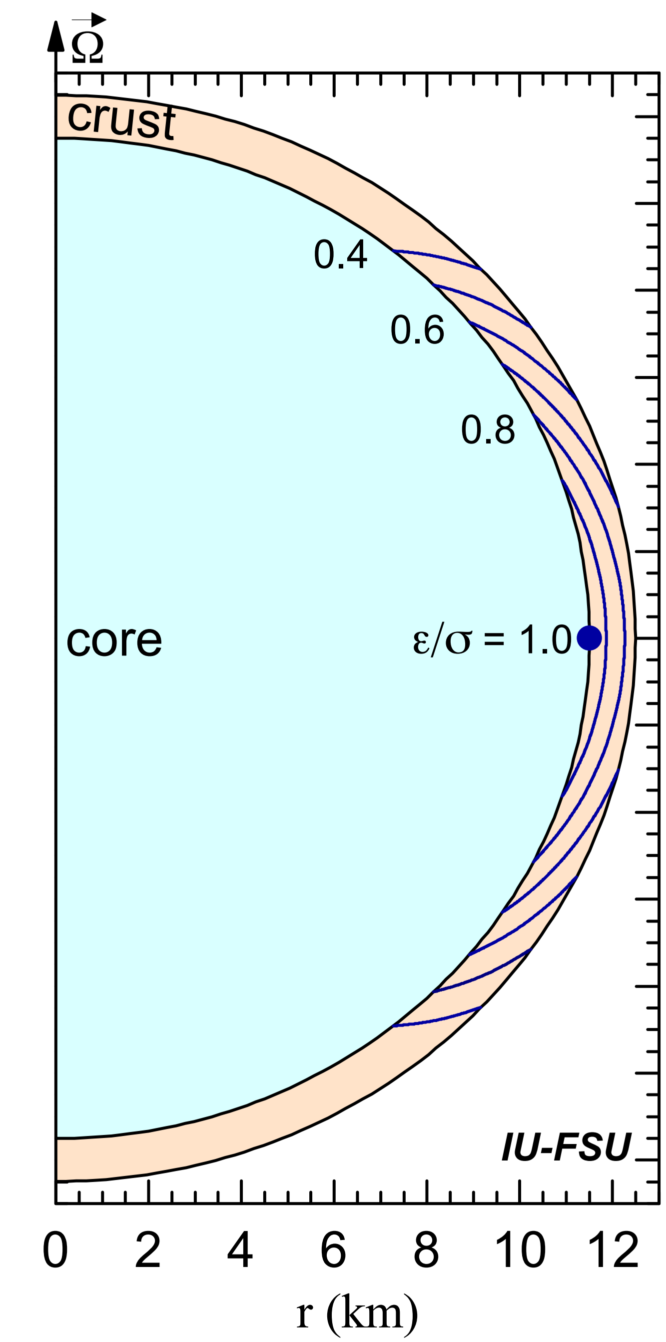


Some open questions

- What happens after the crust breaks?
- Shear modulus, breaking strain of pasta?
- Crust breaking in nonuniform crust?
- Role of strong magnetic fields for shear modulus, breaking strain, mode of crust failure…?
- Can there be hybrid crust / magnetic mountains? Can strong B field lines act as “rebar” to reinforce crust?

Crust breaking on accreting stars

- *Limiting rotational speed of NS may be set by strength of the crust, ArXiv:1804.04952.*
- Kai Kadau, Andrey Chugunov, **Farrukh Fattoyev**
- Graduate students: Joe Hughto, Andre Schneider, Matt Caplan, Hao Lu
- Support from DOE DE-FG02-87ER40365 (Indiana University) and DE-SC0018083 (NUCLEI SciDAC-4 Collaboration).



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