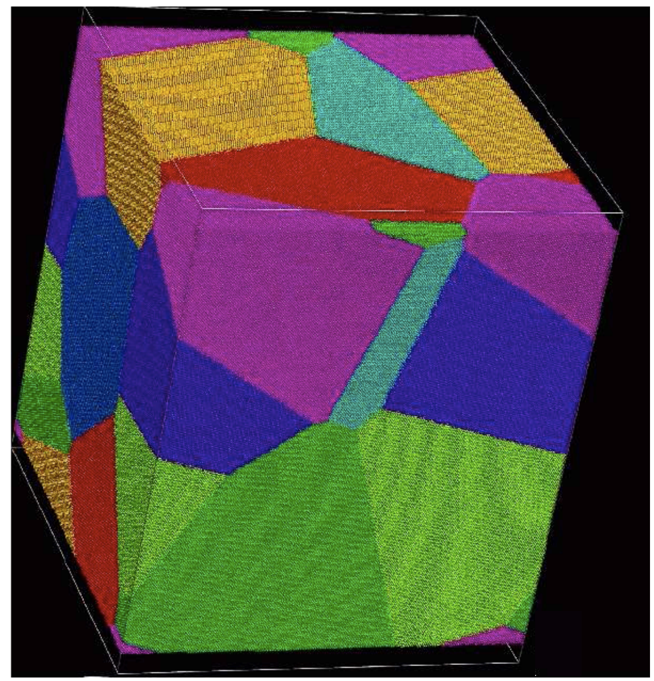
Crust Crystallography

- Introduction NS crust.
- Formation of new crust from nucleosynthesis ash.
- Thermal cond., shear modulus.
- Shear viscosity of nuclear pasta.
- Molecular dynamics simulations of breaking strain (strength) of crust.



C. J. Horowitz, Indiana University

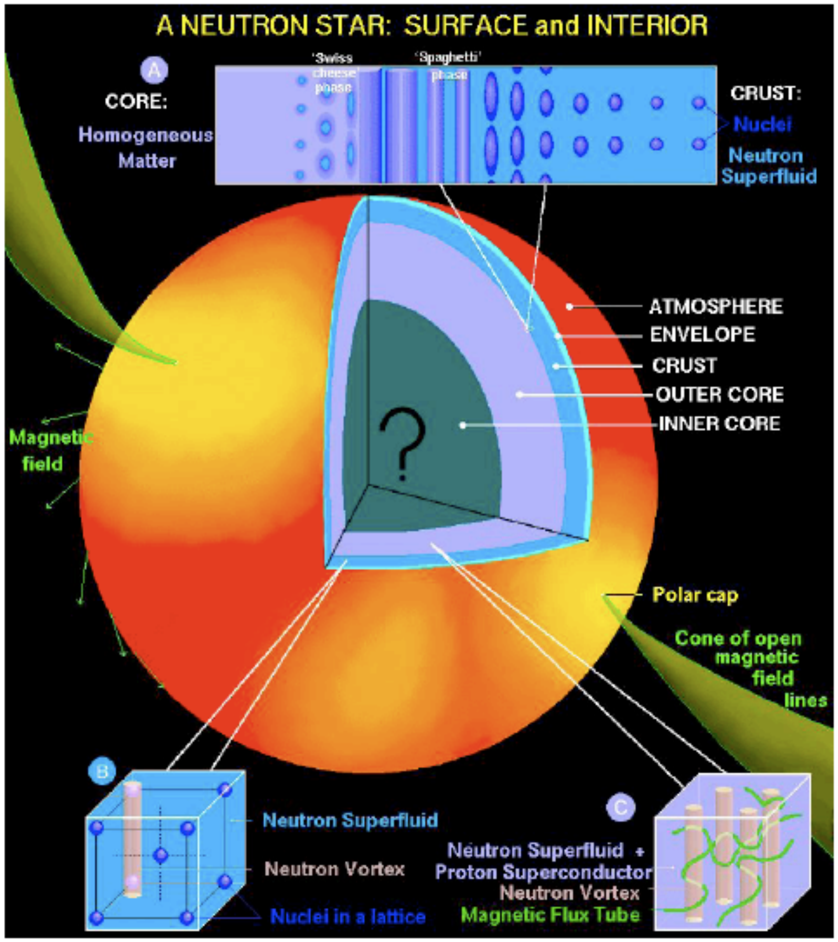
Probing NS with Gravitational Waves, Penn State, June, 2009

Layers of a Neutron Star

- Atmosphere: very thin (<1m) region important for X-ray spectrum.
- Envelope: thin region with large temperature gradient. Important for relation between surface and interior T.
- Ocean: liquid layer on accreting NS, $\rho<10^{10}$ g/cm^3.
- Outer crust: solid made of ions + gas of e. Electrons screen interaction between ions

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

- Neutron drip at ~4x10^{11} g/cm^3.
- Inner crust: solid of ions, e + n gas.
- Pasta: complex nonuniform phases near ~10^{14} g/cm^3.
- Outer core: uniform liquid of n, p, e



D. Page

- Inner core: high density QCD phase ?? quark/ strange matter, color super-conductor, meson condensates...

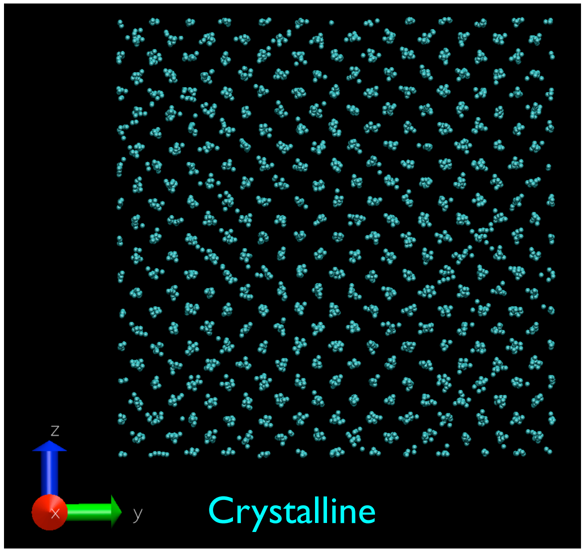
Amorphous vs Crystalline Crust

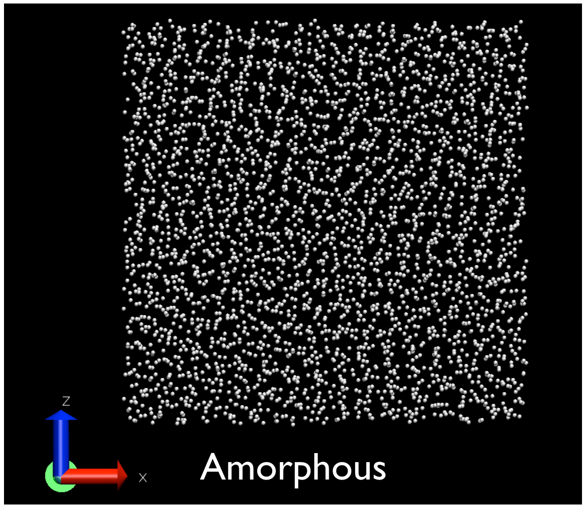
- An amorphous solid is a "frozen liquid" with a nonzero shear modulus but a disordered structure with low electrical and thermal conductivities.

- Very rapid cooling (quenching) can form an amorphous solid. Also, it was thought, many impurities would favor amorphous state.

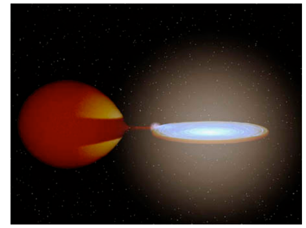
- Accreted crust forms slowly, over ~ thousands of years. And our molecular dynamics simulations find ordered crystalline states even with large #s of impurities. *Accreted crust very likely crystalline.* Agrees with observations of rapid crust cooling favoring high thermal conductivity.

- Does an isolated NS, where crust formed more quickly, have an amorphous crust? Perhaps low elec. conductivity would give too much Joule heating in a magnetar?





rp Process on Accreting NS



- Schatz et al simulate X-ray bursts with a large reaction network and predict composition of rapid proton capture ash: PRL**86**(2001)3471.

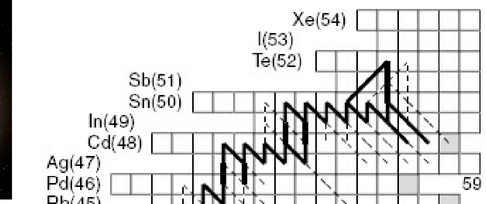
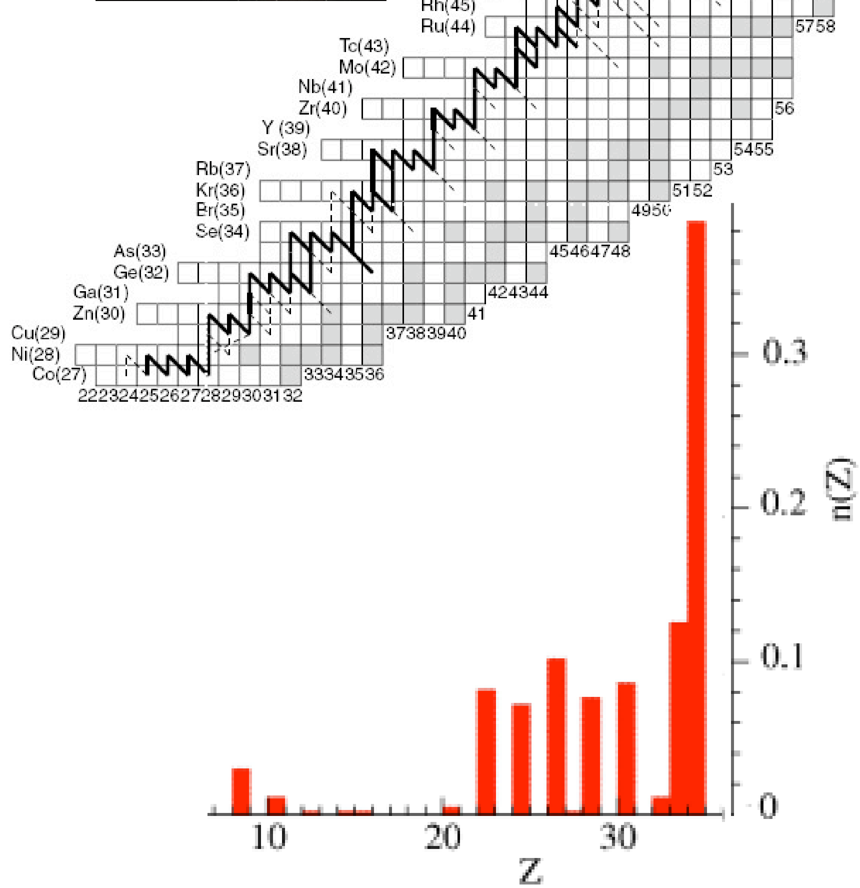
- Gupta et al includes further electron capture, light particle rxns.

- rp process ends near A~100, and e capture gives Z/A~1/3 by 10^{11} g/cm^3. Main component Z~34, Selenium.

- Important feature is large *dispersion* in Z [~50% Z=~34 and 50% 8<Z<30].

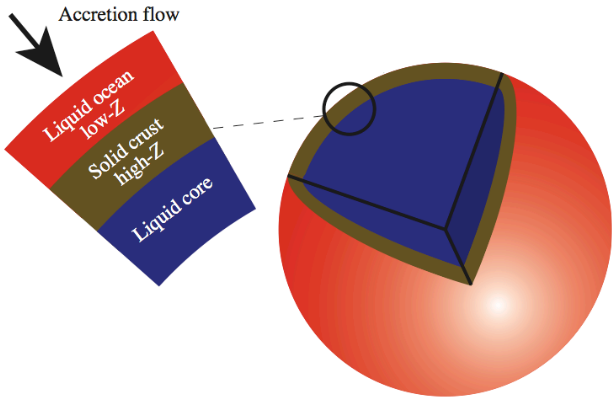
- Impurity param. $Q=\langle Z^2\rangle-\langle Z\rangle^2=39$.

- We use this complex Gupta et al composition in our MD simulations.

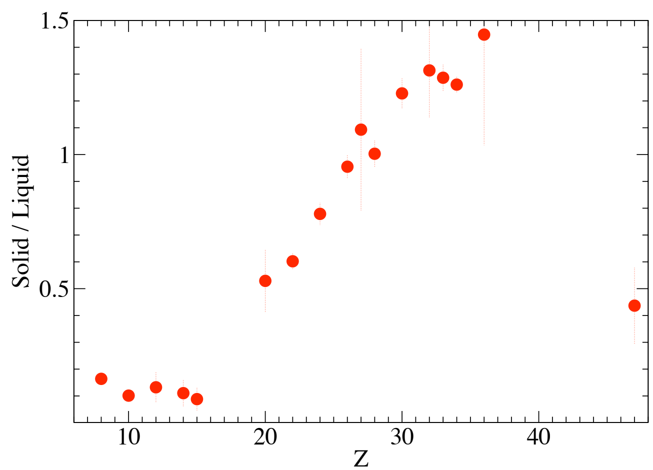



Composition or rp ash

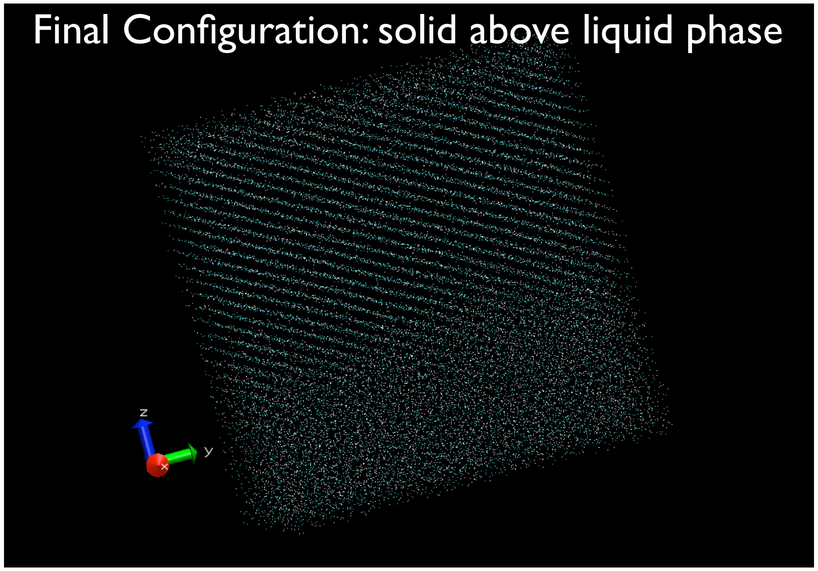
Rp Ash Freezing Simulation: 27648 ions

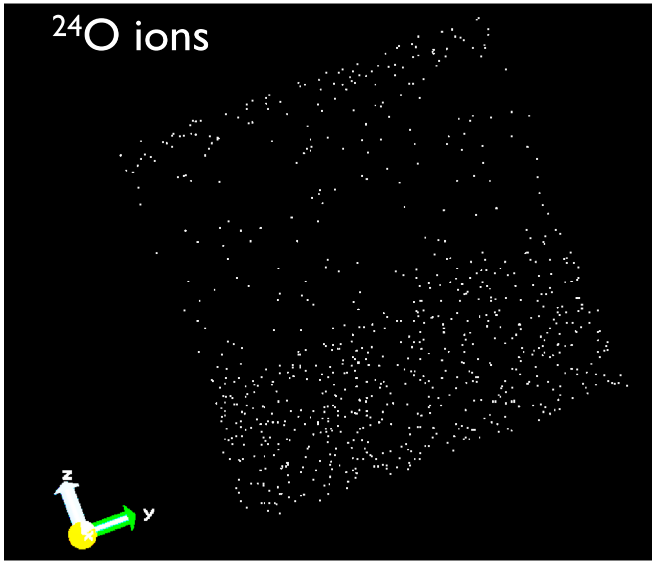


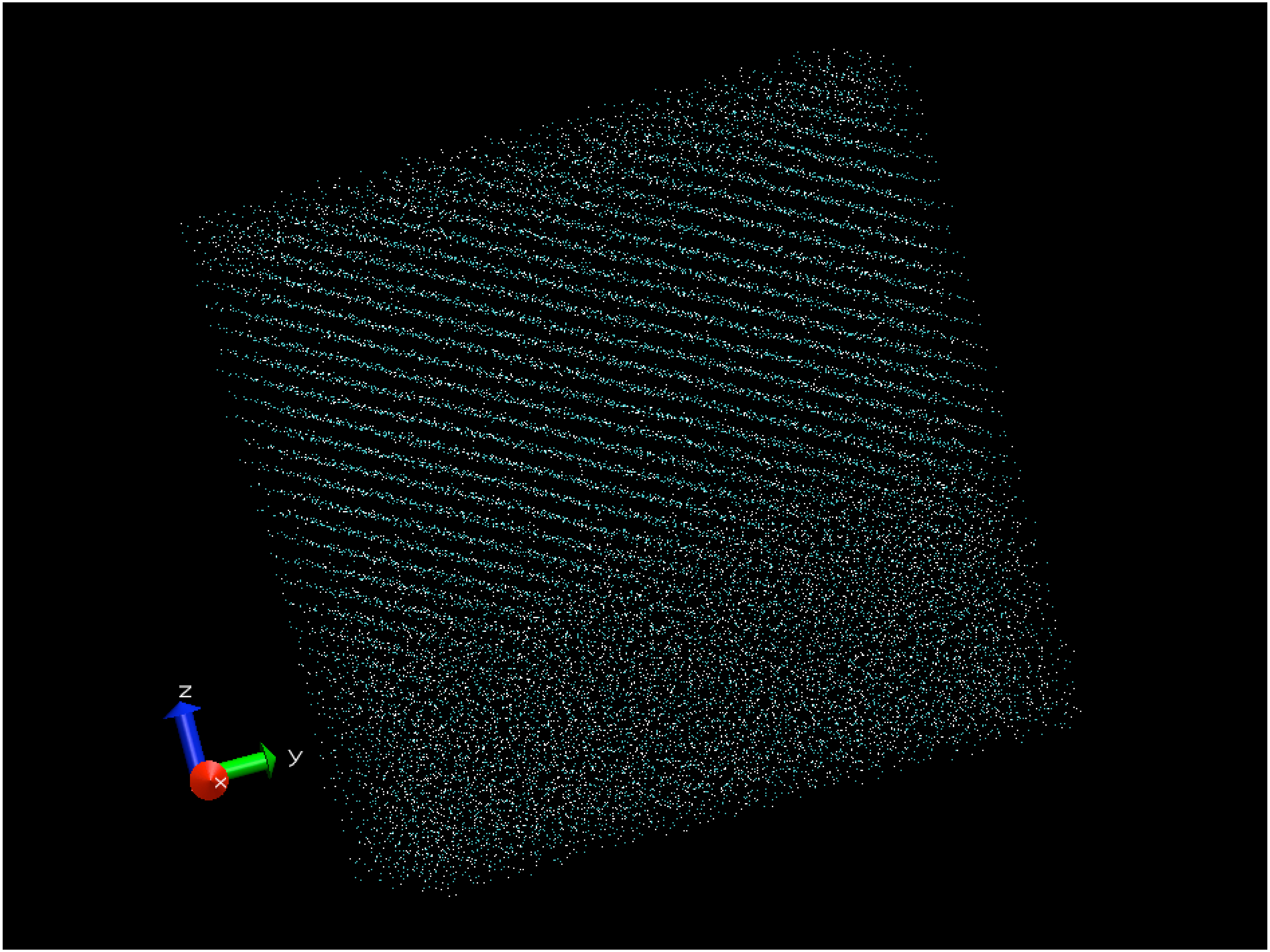
Ash accretes into liquid ocean. Chemical separation takes place as material at bottom of ocean freezes. Liquid ocean greatly enriched in low Z elements



Ratio of composition of solid to liquid.
--With E. Brown

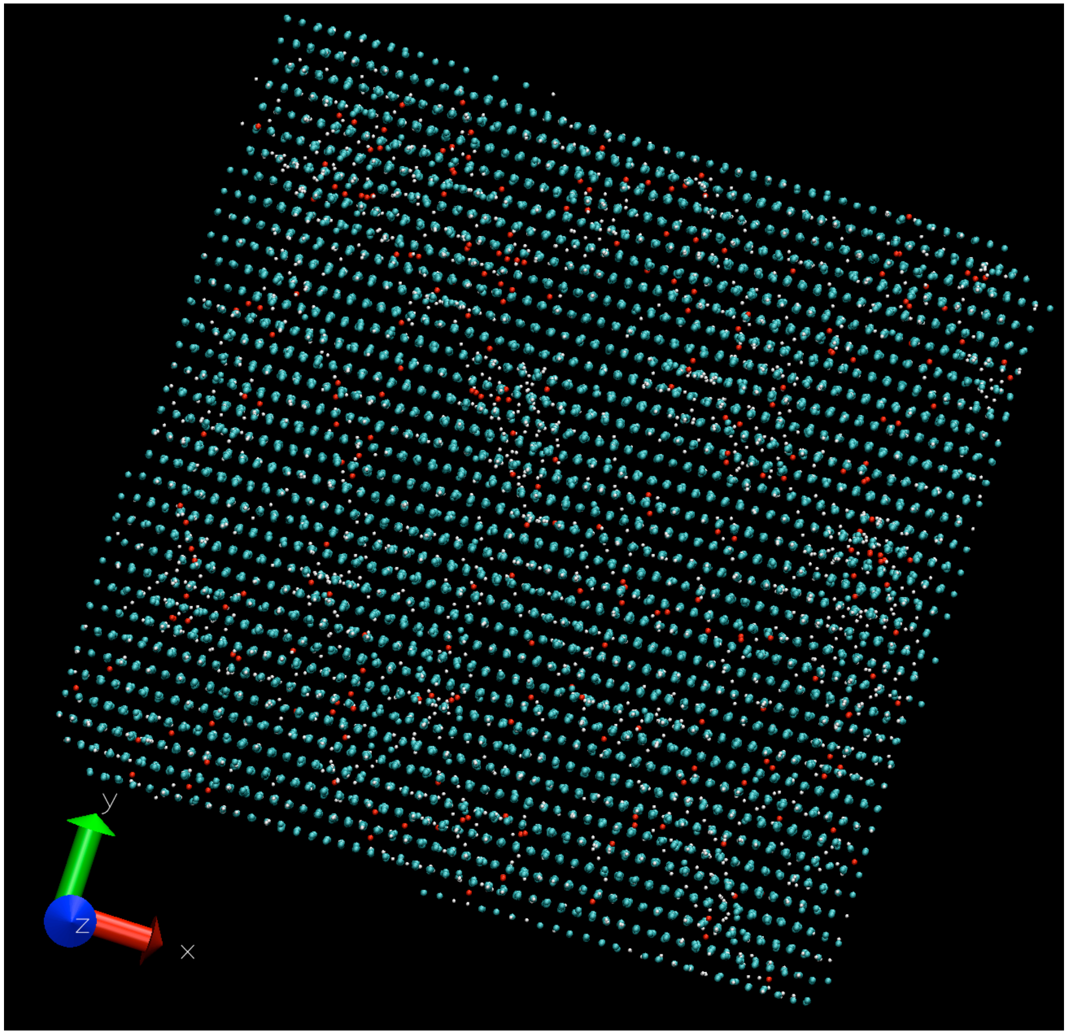


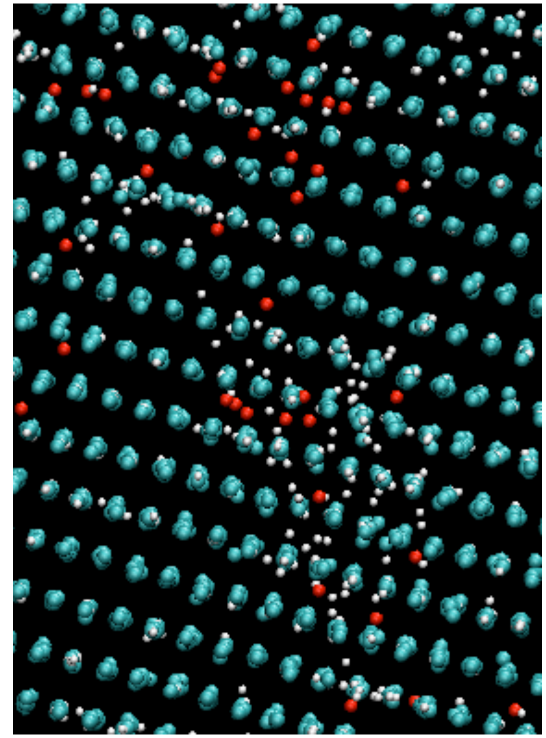




z
y
x

Structure of Accreted Crust

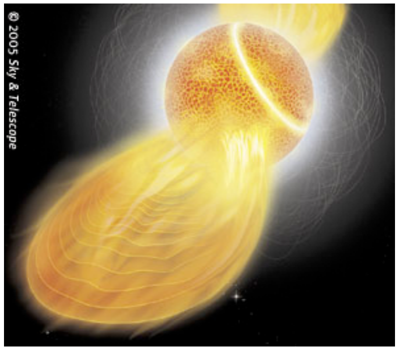


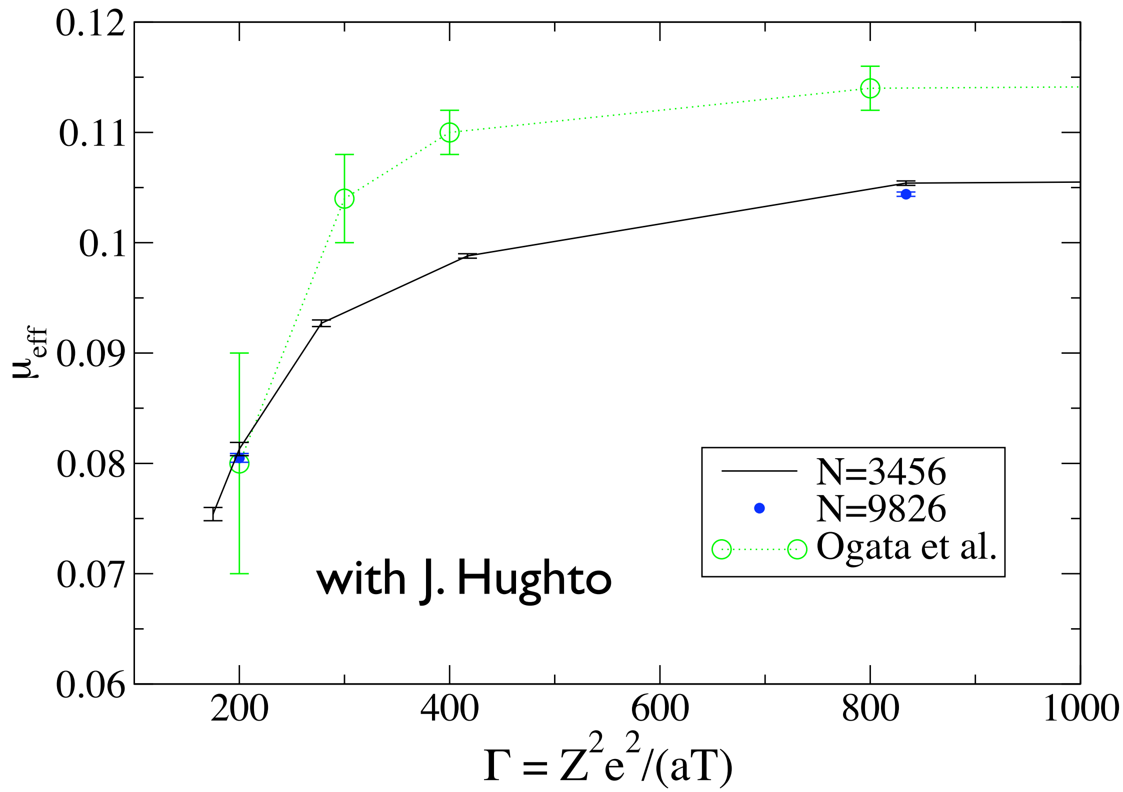


Detail showing Z=8 Oxygen ions (red) while other below average Z ions are white, and high Z ions blue. Low Z impurities are interstitial.

- 27648 ion solid with many impurities, annealed for a long time at higher T and then slowly cooled to zero T. Shows regular crystal. It is not amorphous.

Shear Modulus





- Sets speed of shear waves that may have been observed in QPOs of magnetar giant flares.
- We calculate how E rises with deformation of MD simulations.
- Scales with composition

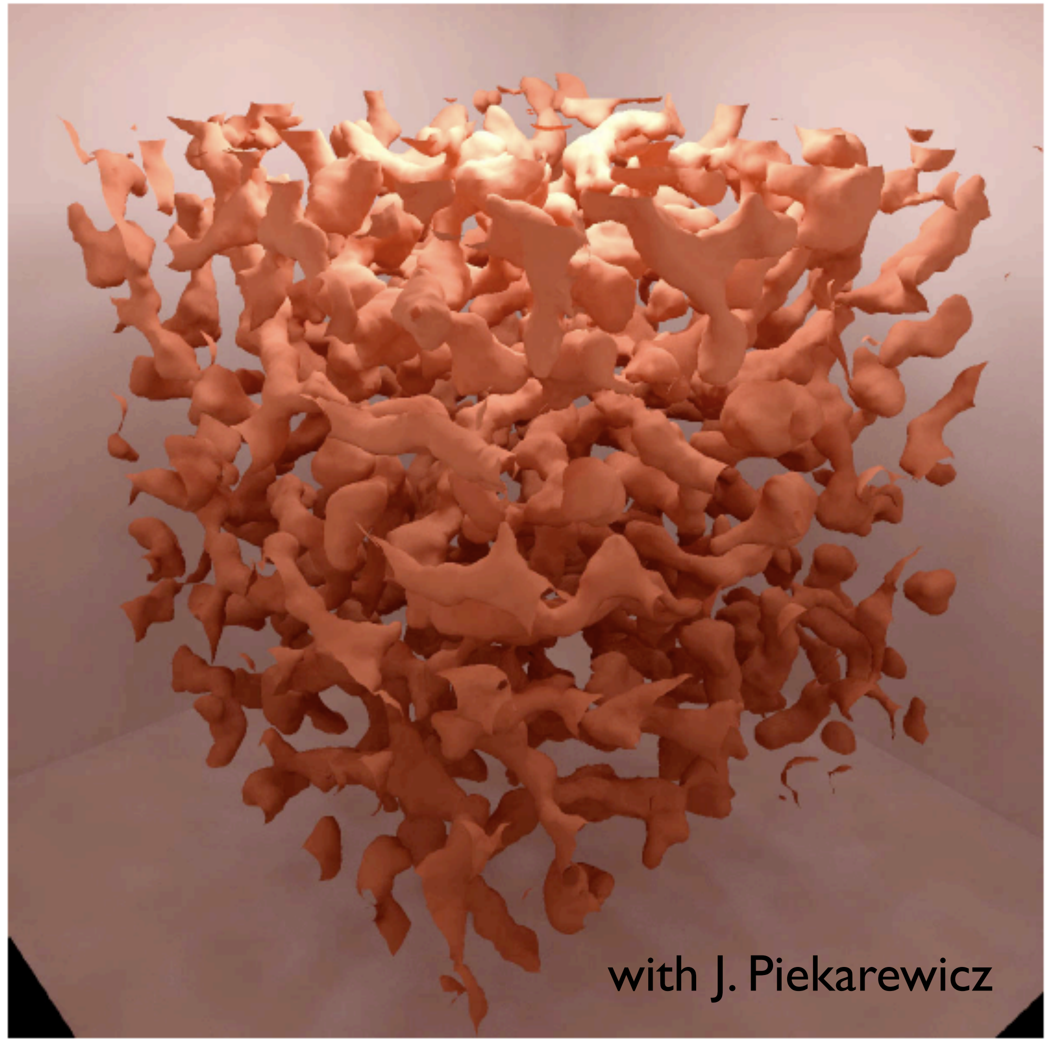
$$\mu = \mu_{\text{eff}} \frac{Z^2 e^2}{a} n$$

- μ much larger for exotic high density QCD solid phase.

- We find electron screening reduces μ by 10% compared to old Monte Carlo results of Ogata et al.
- Preliminary results show μ almost independent of impurities.

Nuclear Pasta

- **Coulomb frustration:** near nuclear density, competition between nuclear attraction and coulomb repulsion can lead to complex shapes.
- Can't directly go from symmetries of crystal lattice to uniform matter?
- Semiclassical model of nuclear pasta reproduces nuclear saturation and coulomb repulsion: p,n interacting via v(r).
- Simulation with 100,000 nucleons at Y_p=0.2, T=1MeV, ρ=0.05 fm^{-3}.



$$v(r)=a\,\mathrm{Exp}[-r^2/\Lambda]+ b_{ij}\,\mathrm{Exp}[-r^2/2\Lambda] + e_i e_j\,\mathrm{Exp}[-r/\lambda]/r$$

Shear Viscosity of Pasta

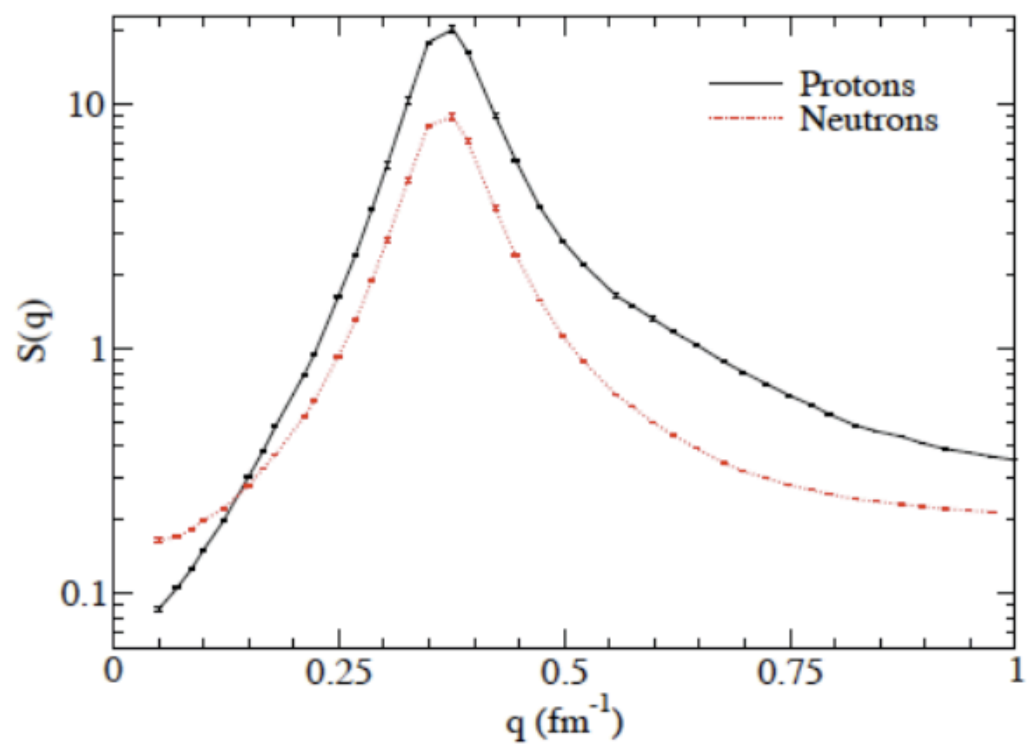
- Shear viscosity can damp oscillation modes.
- Viscosity from momentum carried by electrons and their mean free path is limited by e-pasta scattering, calculated from static structure factor $S_p(q)$.
- We find that the viscosity of pasta is not greatly enhanced by the non-spherical shapes.
- This is in contrast to conventional complex fluids where large non-spherical molecules can dramatically increase the viscosity.

$$\eta = \frac{\pi v_F^2 n_e}{20\alpha^2 \Lambda_{ep}}$$

Chugunov and Yakovlev

$$\Lambda_{ep} = \int_0^{2k_F} \frac{dq}{q} \frac{f_{sn}(q)^2}{\epsilon(q)^2} S_p(q)\left(1 - \frac{q^2}{4k_F^2}\right)\left(1 - \frac{v_F^2 q^2}{4k_F^2}\right)$$

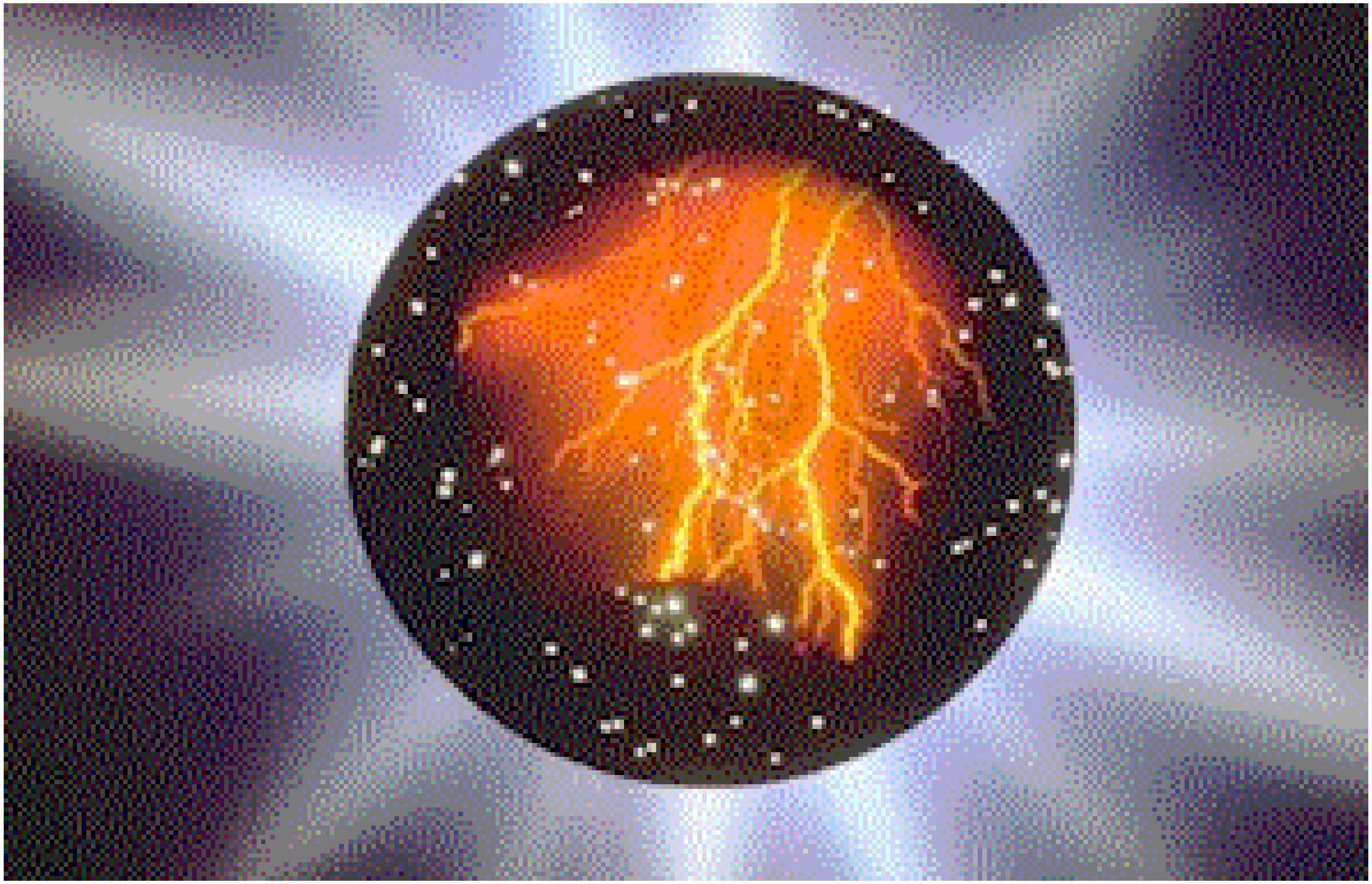
$$S_p(q) = \langle \rho_p(q)^* \rho_p(q) \rangle$$



Pasta Questions

- How to "smell the pasta"? What observable shows presence of pasta? [I think this is hard]
- How does microphysics change in going from crust, to pasta, to core? Does it change abruptly or is there a smooth transition with values for the pasta in between those for the crust and core?
- Is there large damping at crust core interface?
- How does pasta change shear modulus, shear mode frequencies, and breaking strain?
- Where is crust strongest (important for starquakes)? Is it at just sub-pasta densities?

Breaking Strain of Crust



PRL**102**, 191102 with Kai Kadau

Gravitational Waves and Mountains on NS

- A lump on a rotating NS efficiently radiates gravitational waves.
- LIGO, Geo, Virgo have all ready set limits on "mountains" on known NS. Best cases: height < few cm.
- GW radiation from mm scale mountains on accreting NS can explain observed rotation periods.
- How big can a mountain be before it collapses under its own weight? Largest uncert. is breaking strain.

Neutron star "mountain": width few km, height few cm (vertical scale exaggerated)

Laser Interferometer Gravitational Wave Observatory

Maximum Quadrupole Moment

$$Q_{\rm max} = 1.2 \times 10^{38} {\rm g\,cm}^2 \left[\frac{\bar{\sigma}_{\rm max}}{10^{-2}}\right] \frac{R_6^{6.3}}{M_{1.4}^{1.2}}$$

- Some dependence on radius, mass of star and composition Z, A of crust. Largest uncertainty is breaking strain ($\bar{\sigma}_{\rm max}$=maximum stress / shear modulus),
- If gravitational wave radiation from Q balances accretion torque, limiting rotational frequency of NS will be

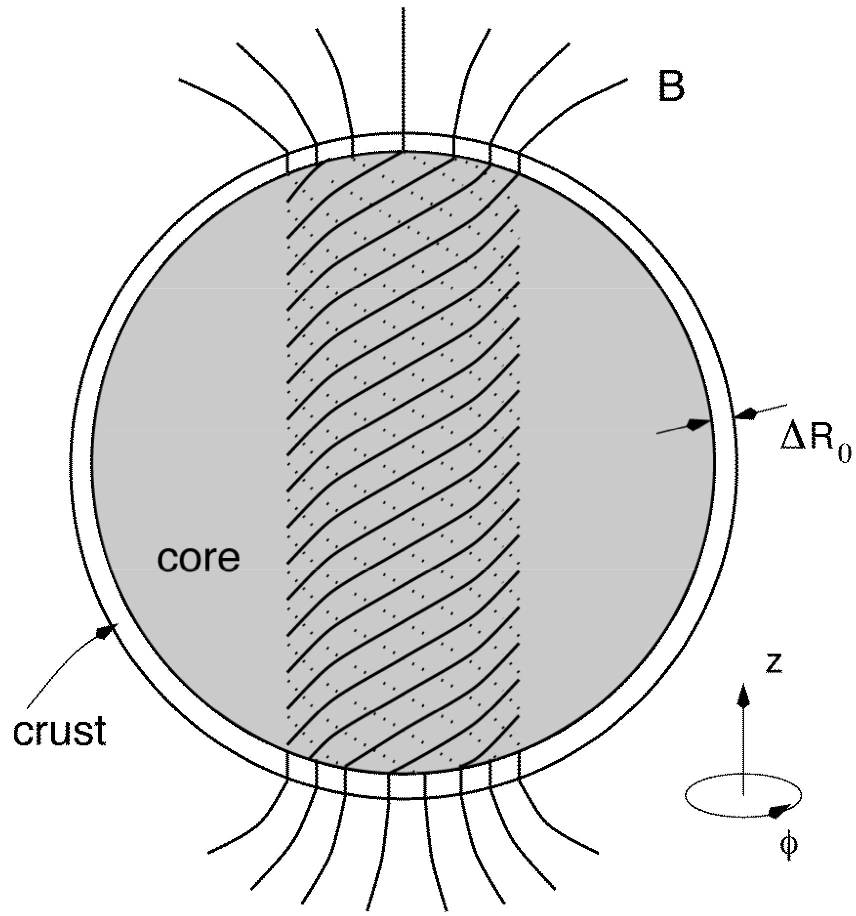
$$\nu \approx 295{\rm Hz} \left(\frac{10^{-2}}{\bar{\sigma}_{\rm max}}\right)^{2/5} \frac{M_{1.4}^{0.6}}{R_6^{2.4}} \left(\frac{\dot{M}}{10^{-8} M_\odot {\rm yr}^{-1}}\right)^{1/5}$$

- Would explain why many LMXB have a narrow range of spin frequency.

--Ushomirsky, Cutler, Bildsten 2000

Curst Breaking Mechanism for Giant Flares

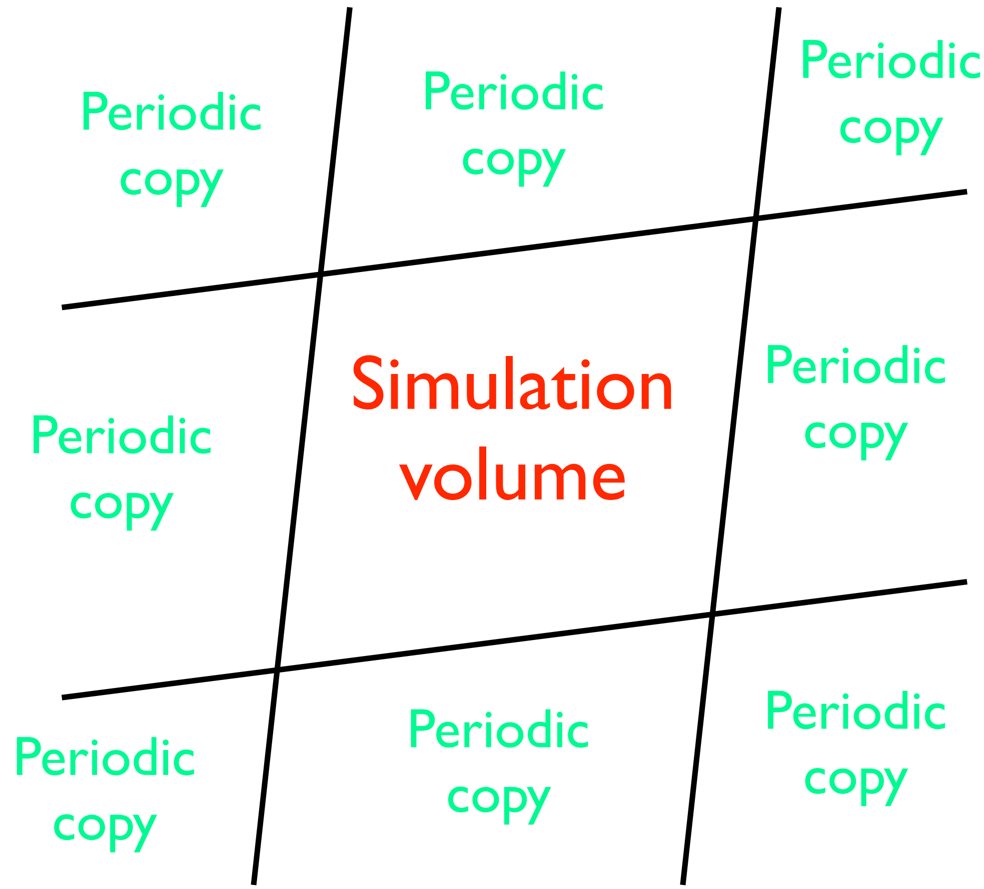
- Twisted magnetic field diffuses and stresses crust.
- Crust breaks and moves allowing magnetic field to reconnect, releasing huge energy observed in giant flares.
- Crust must be strong to control large energy in B field.



Thompson + Duncan

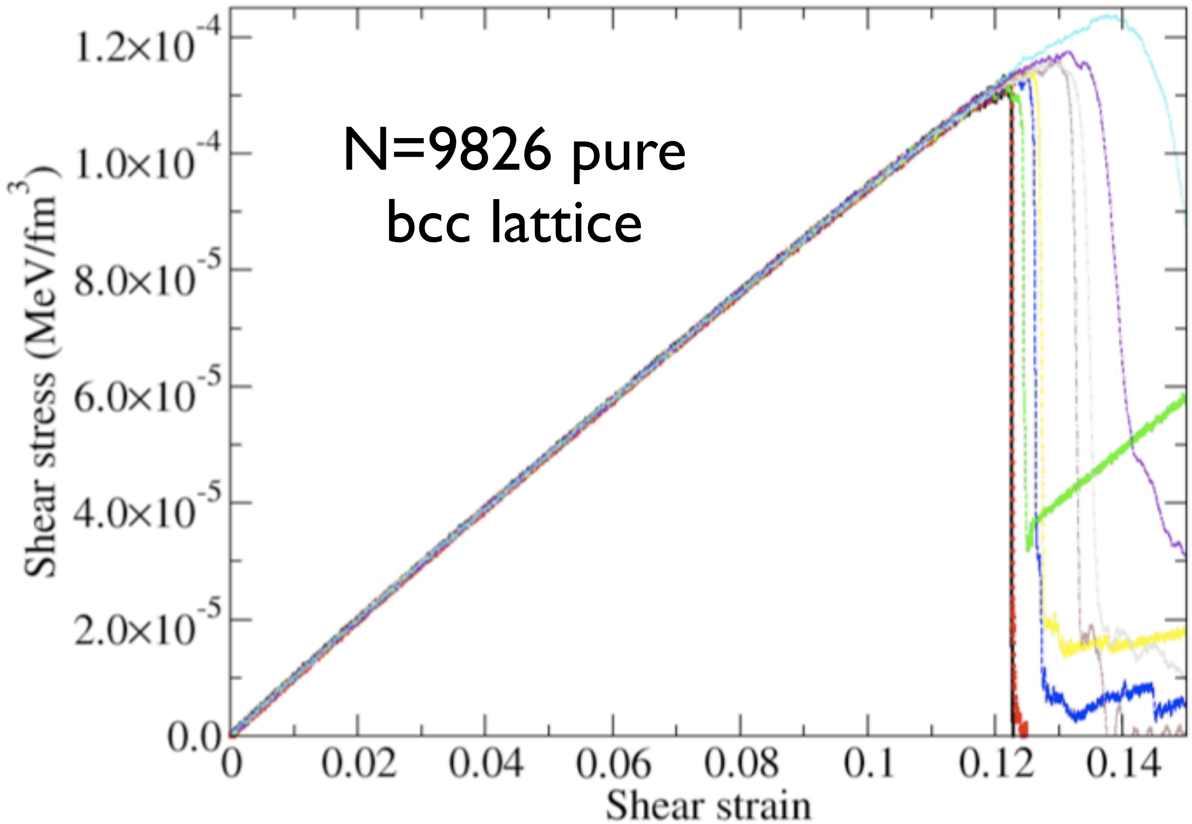
MD Simulation of Breaking Strain

- 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.



Shear Stress vs Strain

- Stress 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.

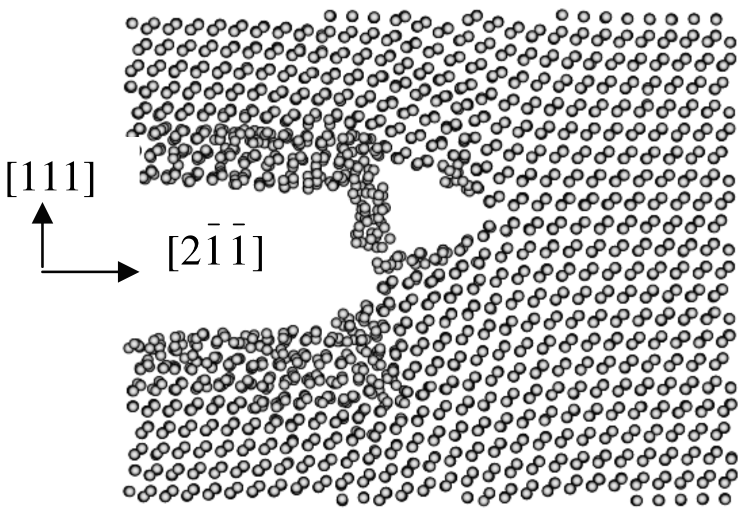


$$V(r) = \frac{Z^2 e^2}{r} \mathrm{e}^{-r/\lambda}$$

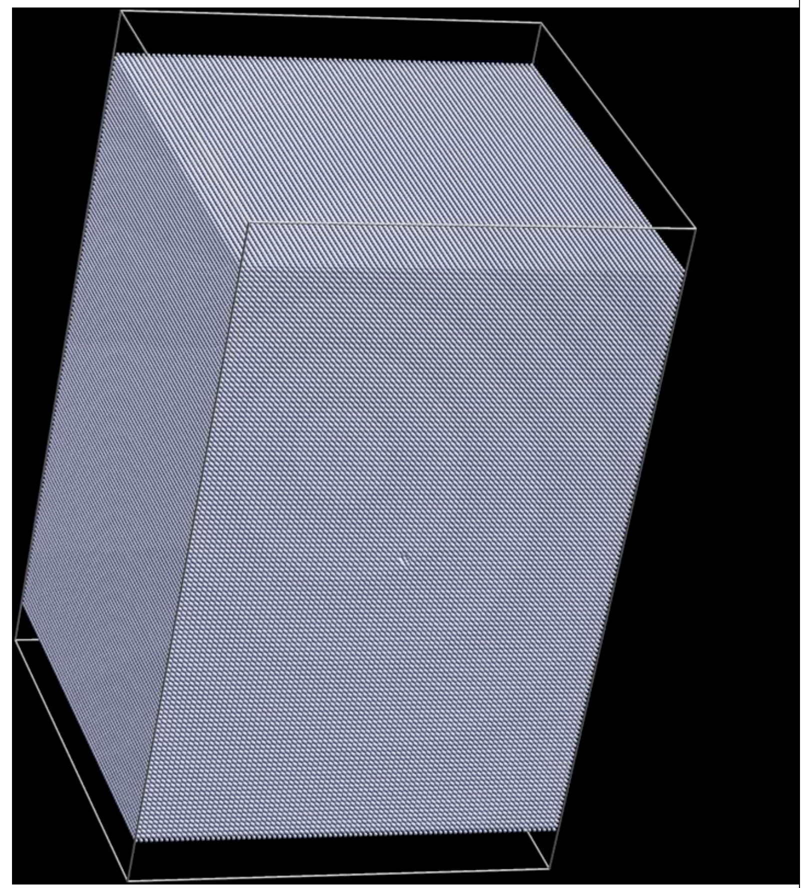
- Shear stress versus strain for strain rates of (left to right) 0.125 (black), 0.25 (red), 0.5(green), 1 (blue), 2(yellow), 4(brown), 8(gray), 16(violet), and 32(cyan) X10^{-8} c/fm.

Failure Mechanism

- 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.



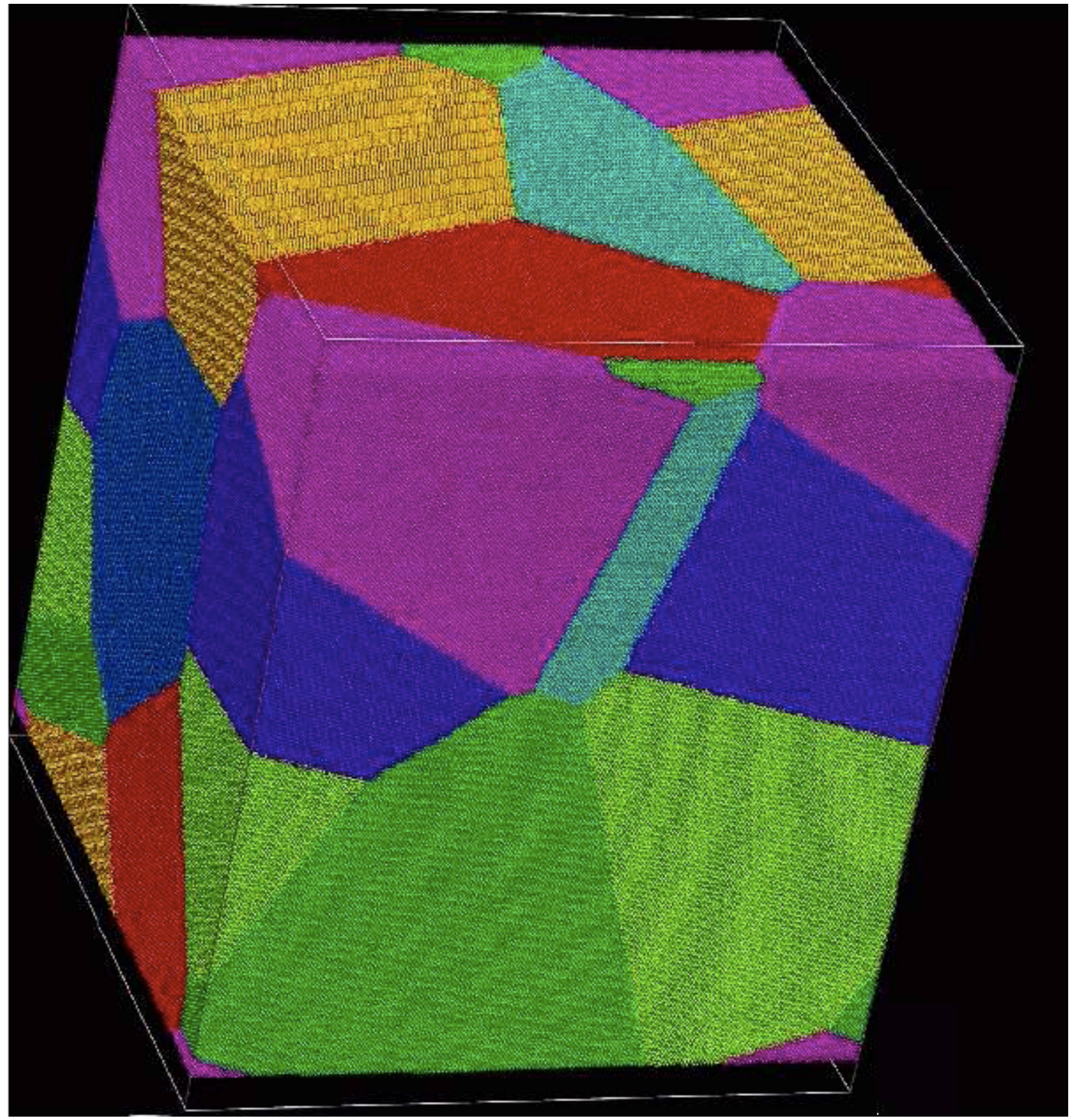
- Neutron star crust is under great pressure which prevents formation of voids. Crust does not fracture.



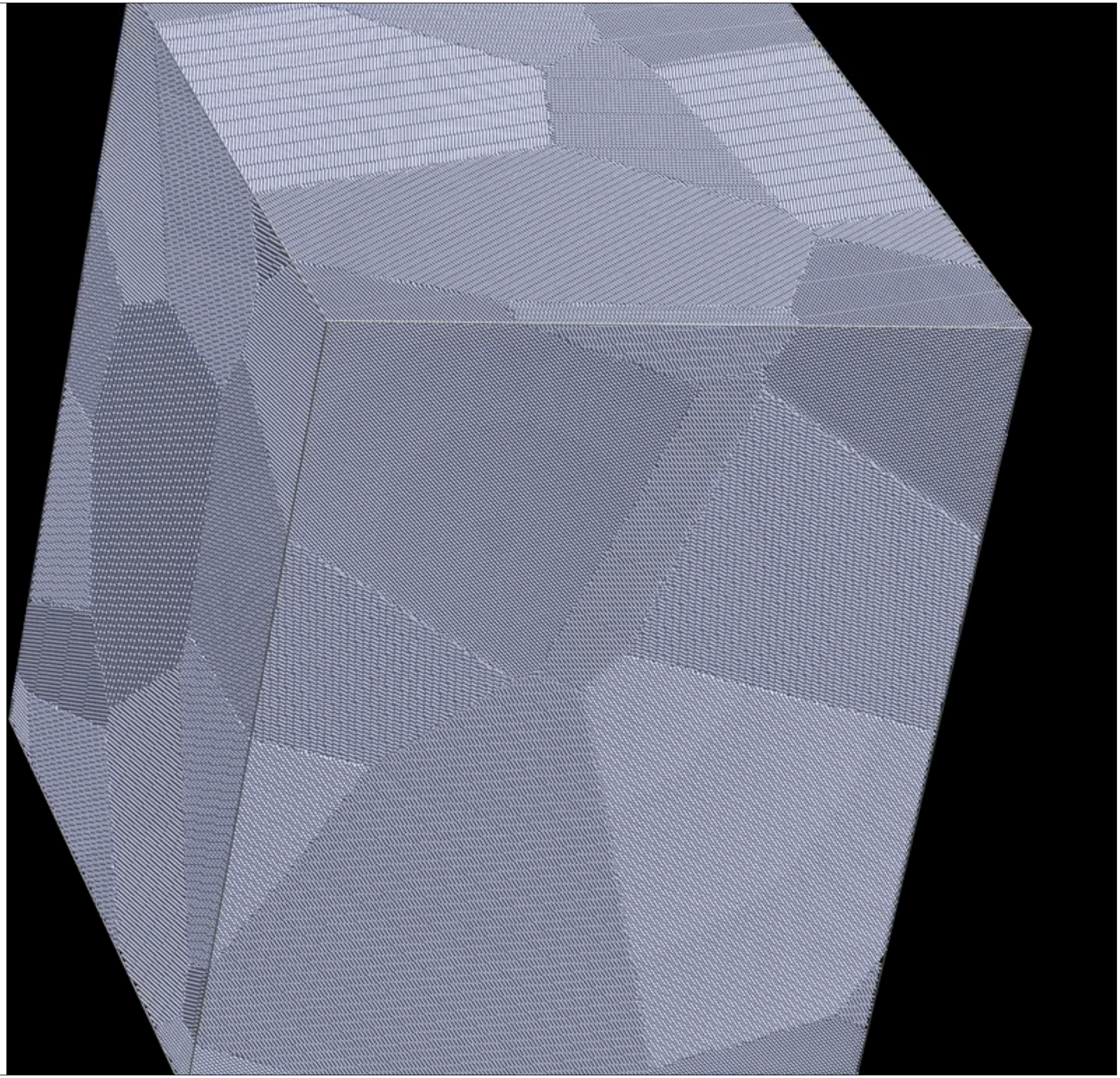
1.7 million ion crystal with cylindrical defect in center. Red color indicates deformation.

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 of different orientation.



Polycrystalline sample (bcc) with 12.8 million ions consisting of 8 differently oriented grains with an average grain diameter of 3961 fm.



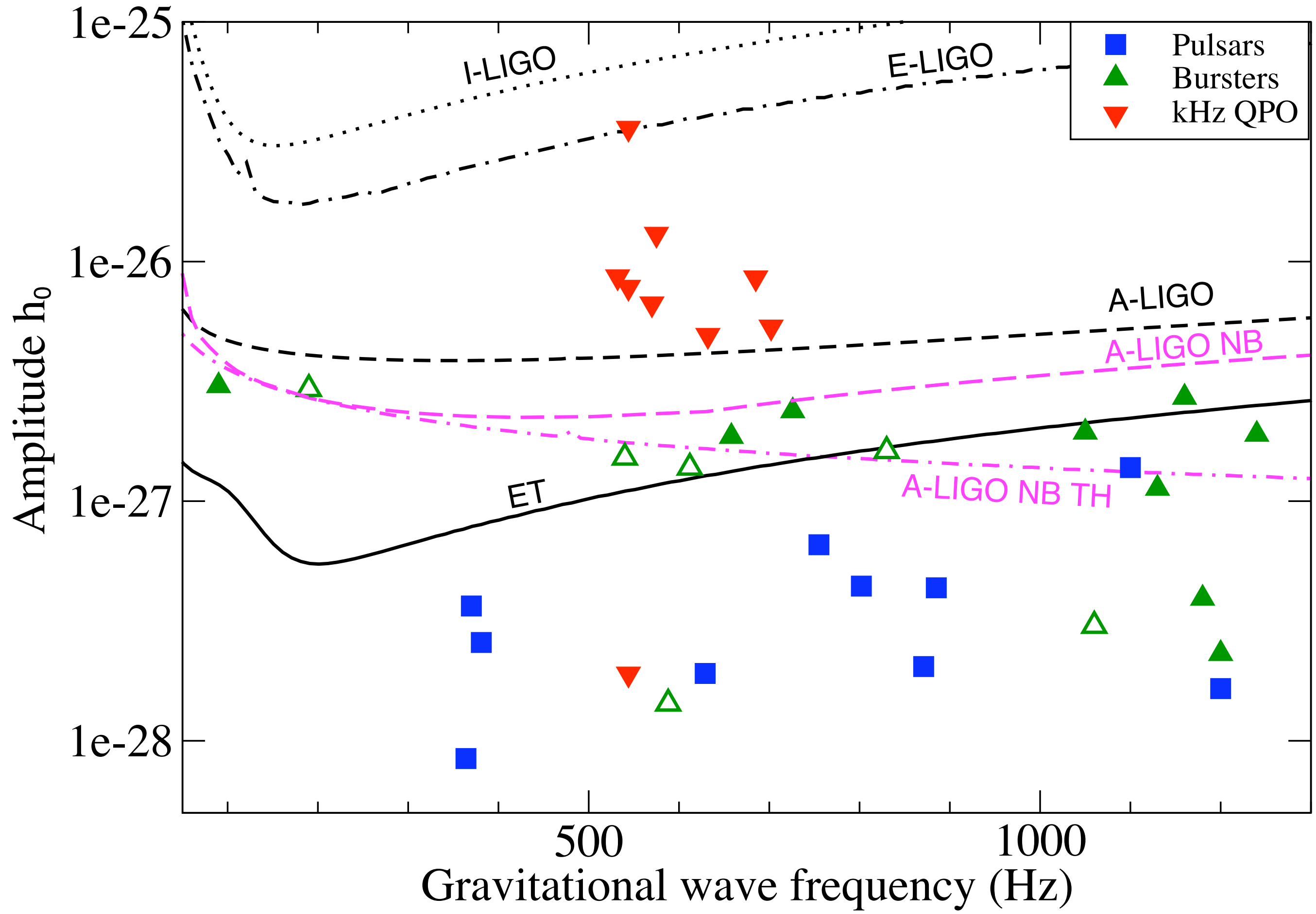
Neutron Star Crust is Very Strong

- 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 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.

Strong Crust Can Support Big Mountains

- Our breaking strain $\sigma=0.1$ can support a maximum ellipticity (fractional difference in moments of inertia) of 4×10^{-6} for a 1.4 solar mass 10 km NS.
- LIGO is all ready sensitive to GW from rapidly rotating stars with this ellipticity.
- We strongly encourage on going and future searches for continuous GW from rotating NS. **Large enough mountains could definitely be out there.**
- Perhaps most interesting targets are binaries with large accretion, that can power strong GW.
- Electromagnetic observations, X-ray, radio ..., can provide important info, such as spin period, to help GW searches.

Detectability of Continuous GW



--Watts, Krishnan, Bildsten, Schutz, 2008

- GW strain h_0 assuming GW radiation balances accretion torque. Sensitivity of Advanced LIGO (A-LIGO) and future Einstein Telescope (ET) indicated. Need breaking strains up to 10^{-2}

Neutron Star Mergers

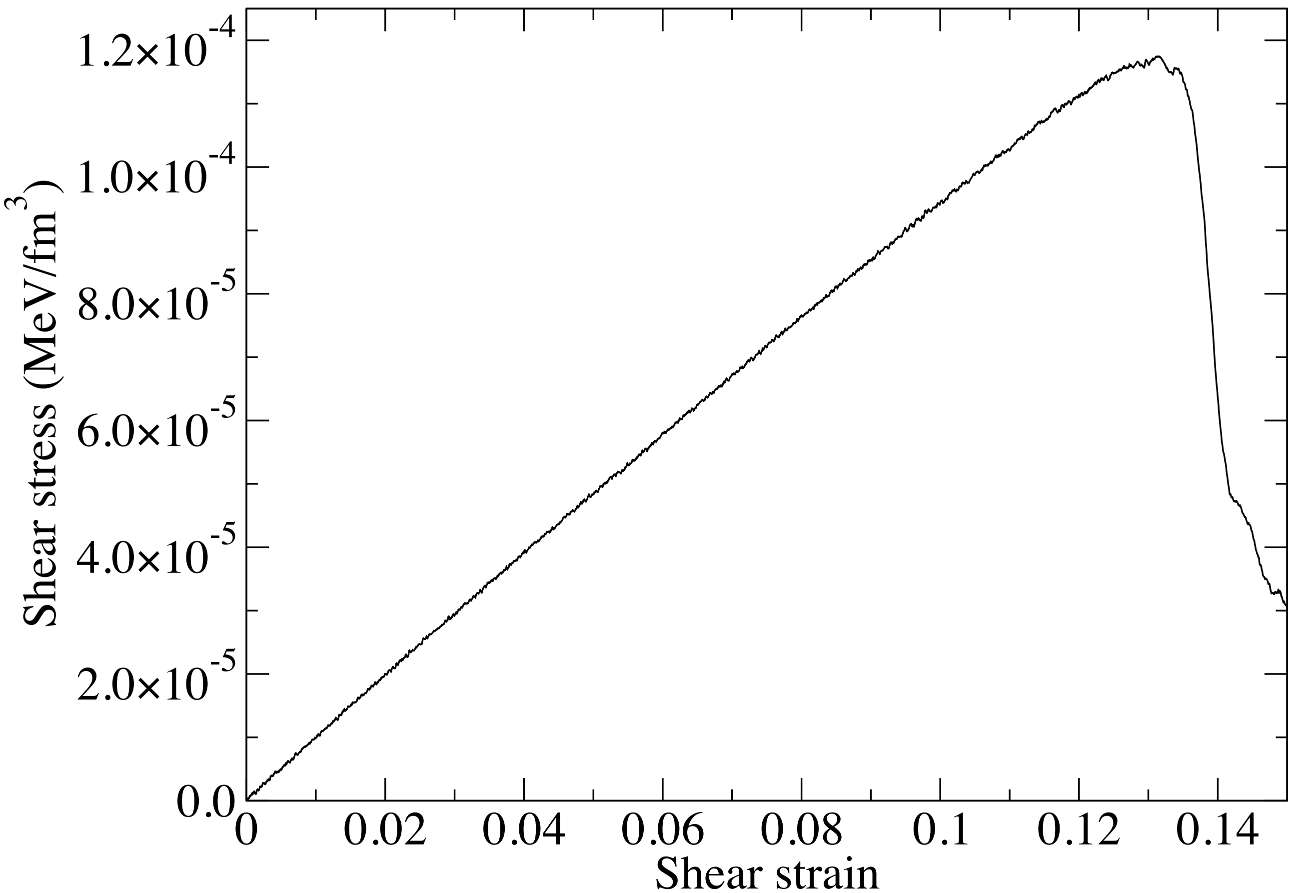
Breaking the Ice at Chirp Parties

- When do tides break the crust during NS in spirals? In principle, what is difference in waveform during early stages for stars with solid crusts vs purely liquid stars? Does perturbation theory give simple answers?

A tough nut to crack

- If core is strong exotic QCD solid, when will tides break the core during mergers? What is the difference in waveform vs liquid stars? If waveform distinguishable, can one rule out solid cores?

Magnetar Flares and Starquakes



Shear stress (MeV/fm^3)
1.2×10^{-4}
1.0×10^{-4}
8.0×10^{-5}
6.0×10^{-5}
4.0×10^{-5}
2.0×10^{-5}
0.0
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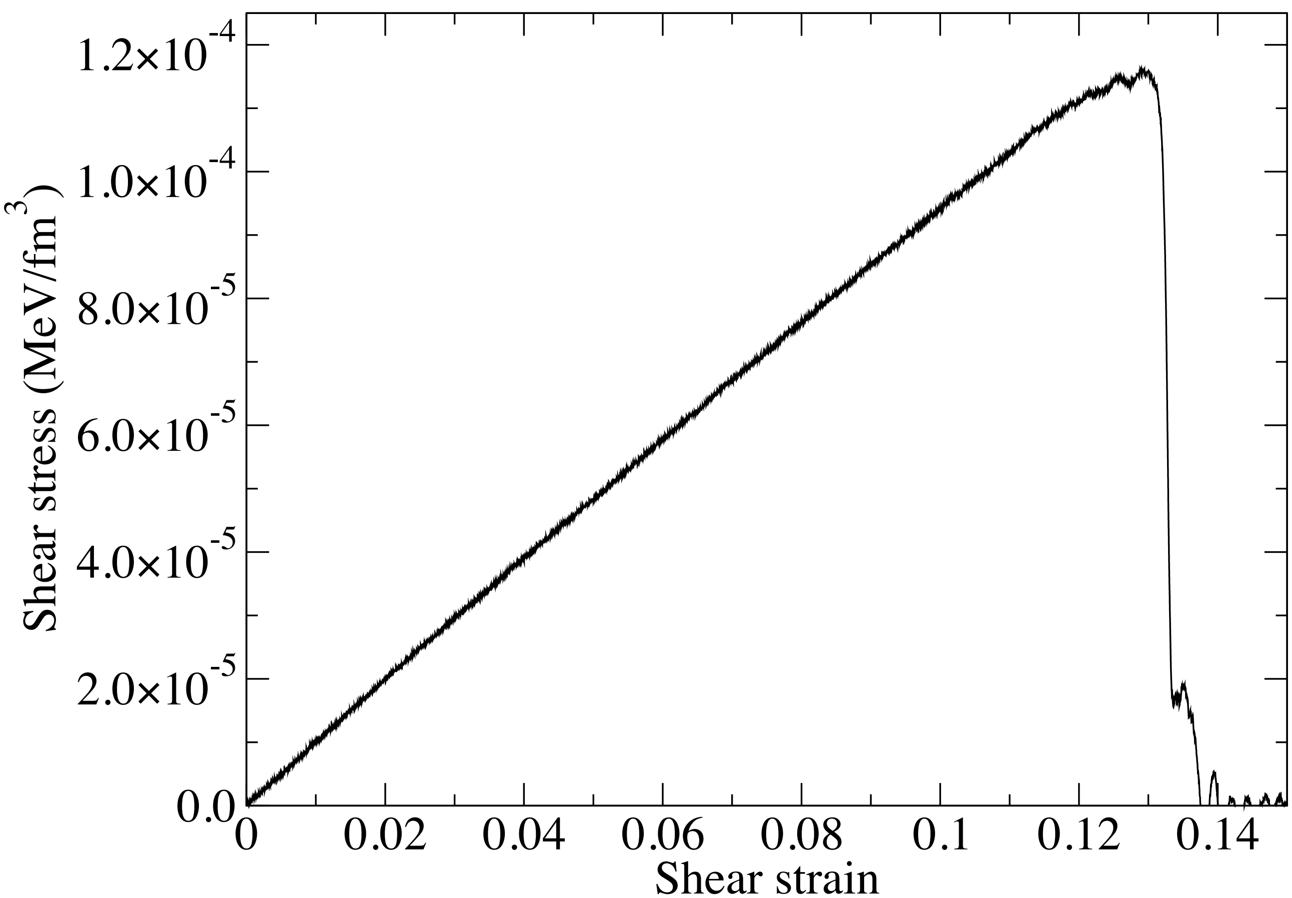
0.02
0.04
0.06
0.08
0.1
0.12
0.14
Shear strain



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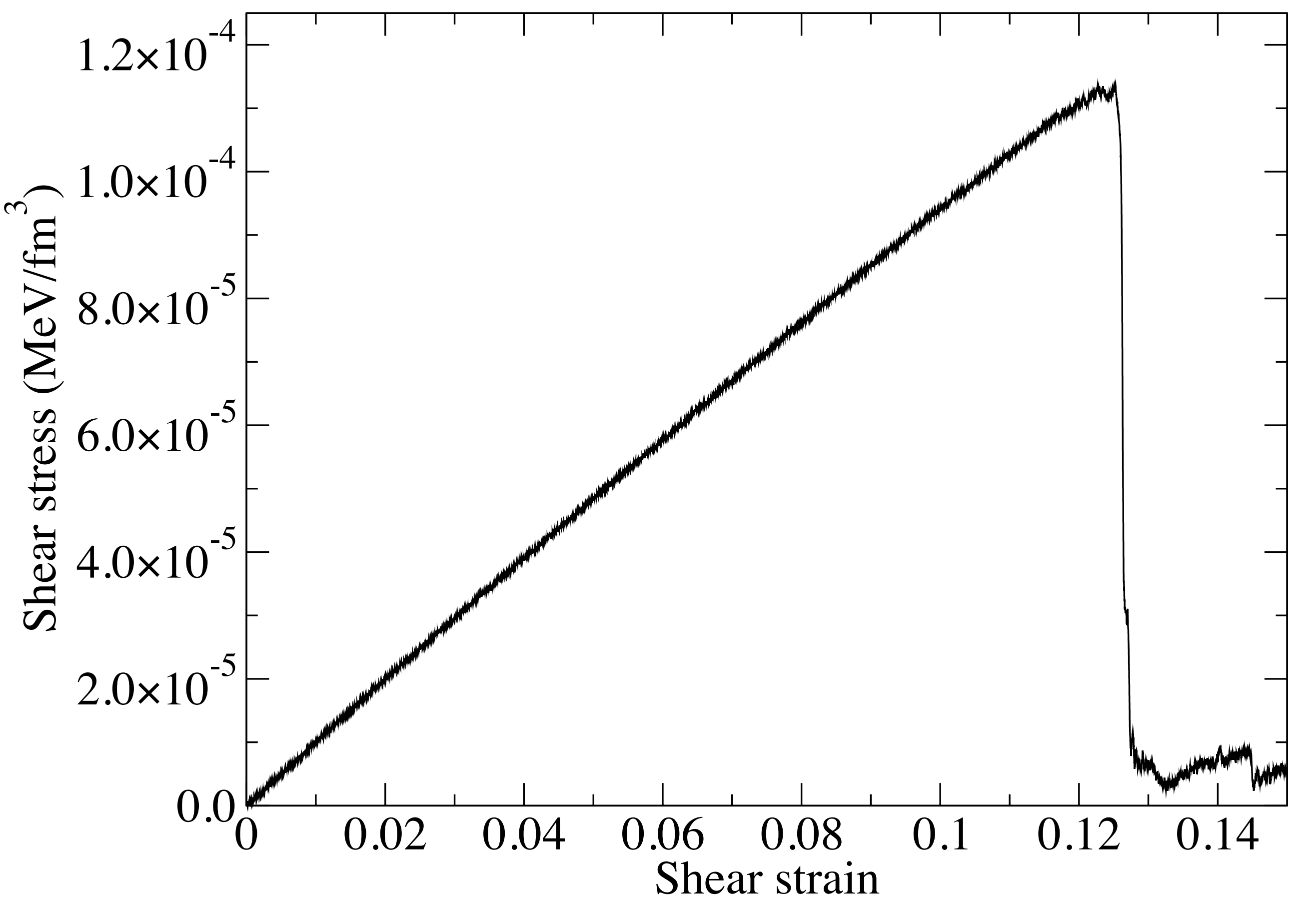
0.08
0.1
0.12
0.14
Shear strain



Shear stress (MeV/fm^3)
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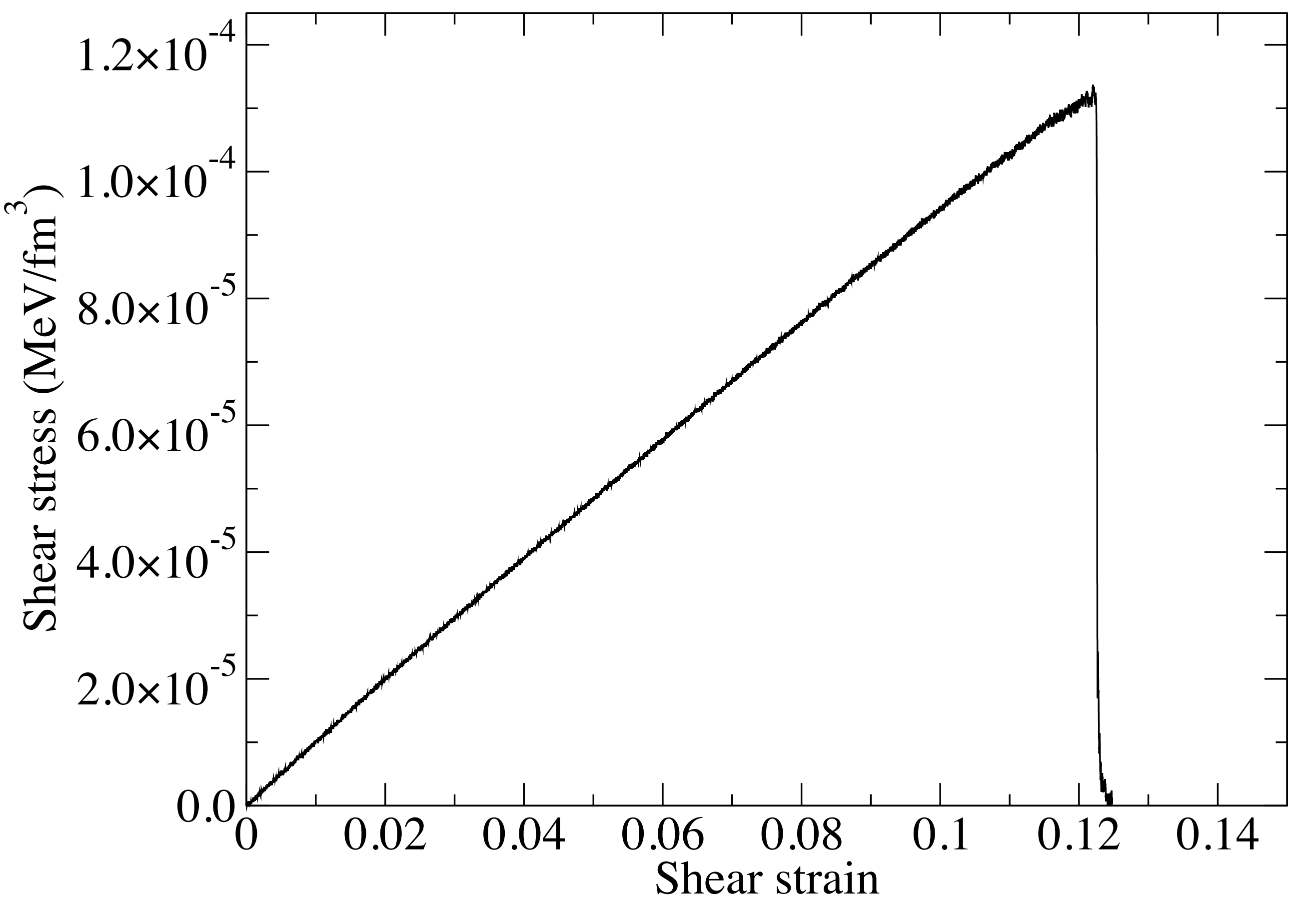
Shear strain



Shear stress (MeV/fm^3)
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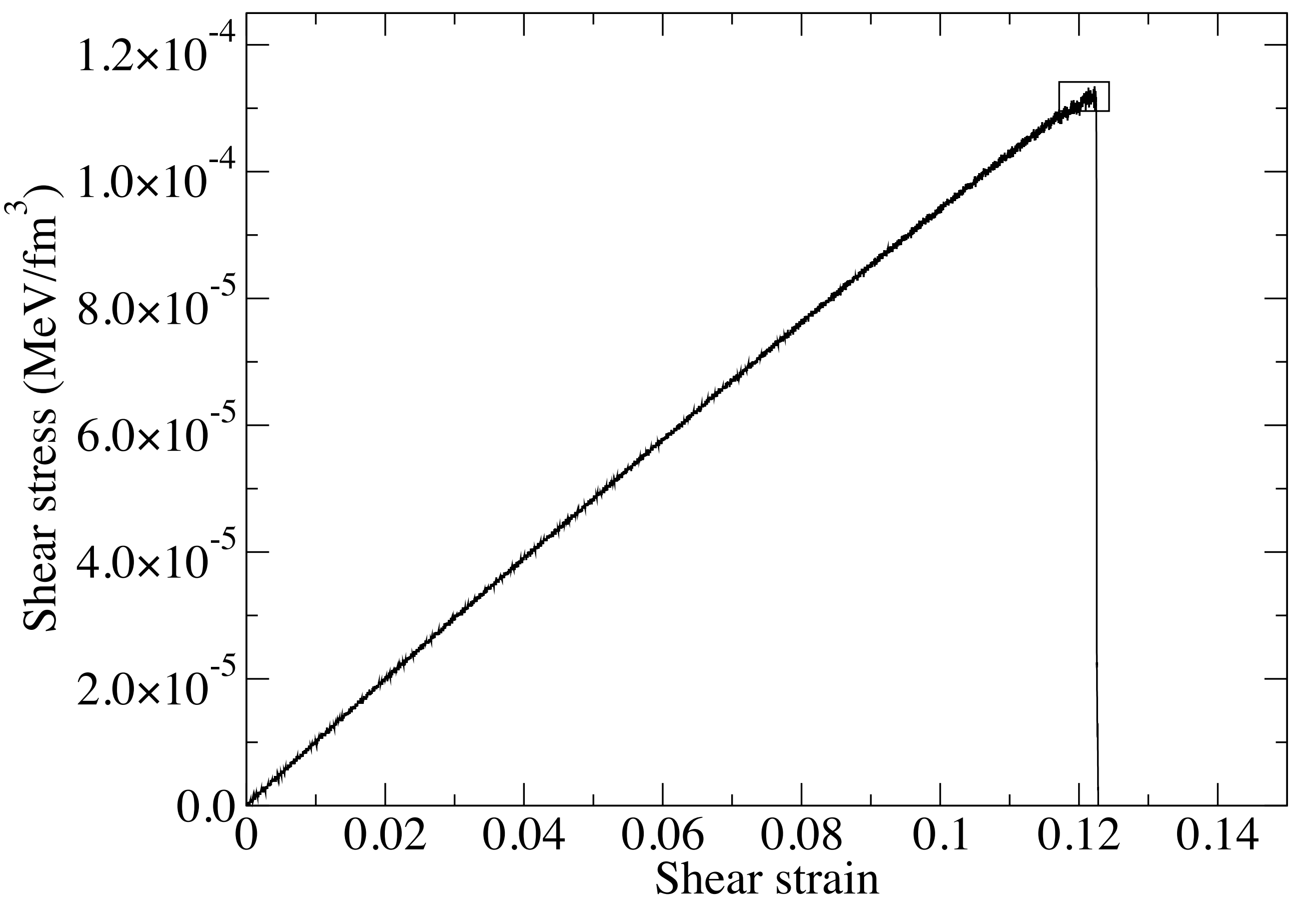
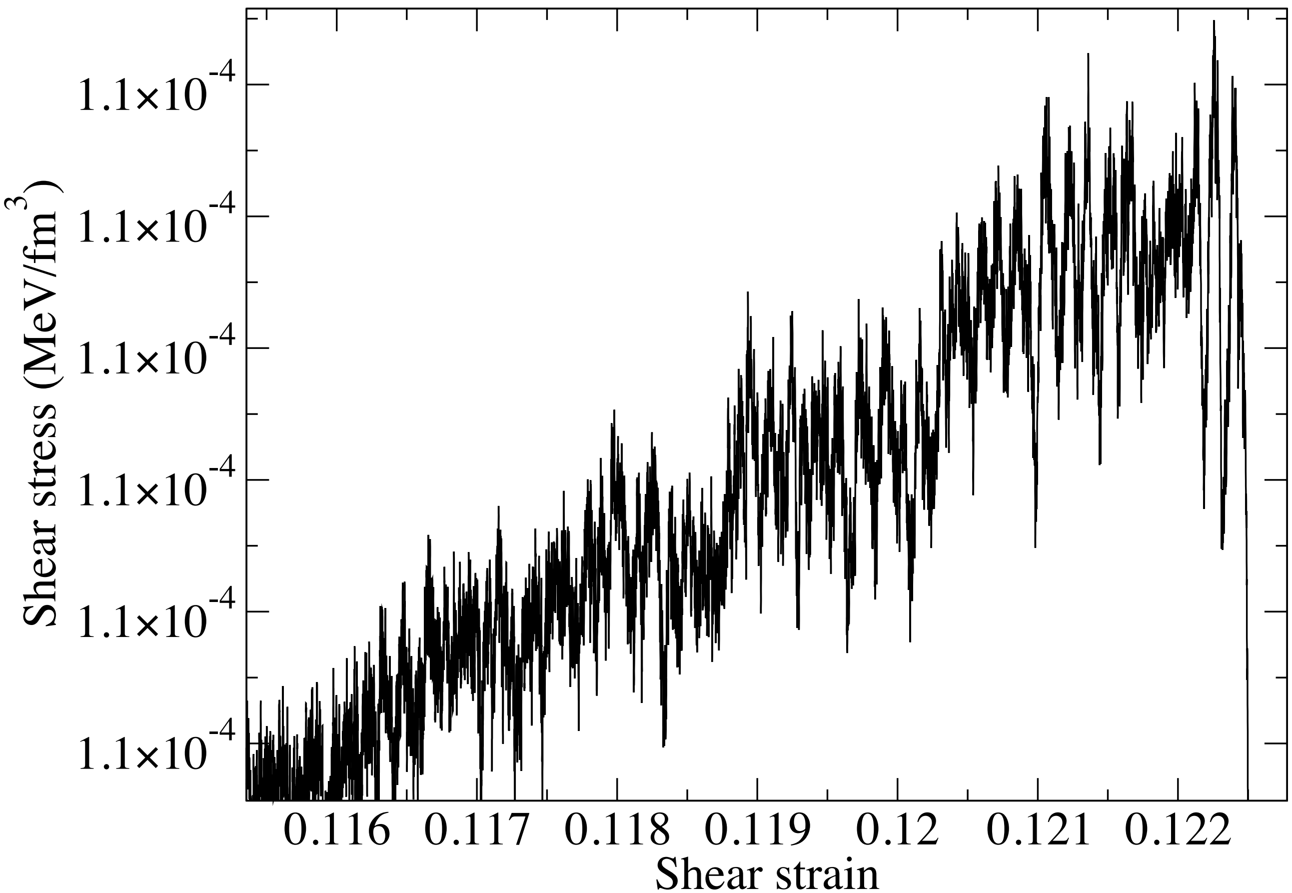
Shear strain



Shear stress (MeV/fm^3)
Shear strain
0.0
2.0×10^{-5}
4.0×10^{-5}
6.0×10^{-5}
8.0×10^{-5}
1.0×10^{-4}
1.2×10^{-4}
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14



Shear stress (MeV/fm^3)
1.1×10^{-4}
1.1×10^{-4}
1.1×10^{-4}
1.1×10^{-4}
1.1×10^{-4}
1.1×10^{-4}
0.116
0.117
0.118
0.119
0.12
0.121
0.122
Shear strain

Crust Breaking and Magnetar Giant Flares and Microflares

- We find neutron star crust breaks catastrophically.
- Very different from behavior of rocks below about 60 km in the earth where rocks expected to "flow" at high P and T.
- **Crust creaking**: Is fine structure in stress versus strain curve related to microflares?

Star Quake Questions

- Are giant flares triggered by star quakes? If so, must the crust be very strong to explain the huge E of 2004, SGR 1806 flare?
- Do flares and microflares also involve star quakes? If so how are quakes, that correspond to flares of different E, related?
- How does the crust break? and where?
  - Is it catastrophic or more gradual? In which direction and over what volume? What is role of magnetic field? Does the crust melt?
- Which oscillation modes are excited? and with what amplitudes?
- How does a first quake change the properties of future quakes?

Crust Breaking Strain Involves:

- **Nuclear physics:** sets composition, impurities and heating from nuc. reactions.
- **Astrophysics:** application to gamma / X-ray and gravitational wave astronomy.
- **Condensed matter:** role of strong B field? superfluid neutrons...?
- **Material Science:** strength of materials have important practical applications. Compare simulations to lab. data. Role of defects, grain boundaries... Unique material with long range int.
- **Planetary science/ geophysics:** how is crust breaking related to earthquakes? High pressure of crust suggests analogy with deep earthquakes??
- **Computational science:** Increasing compute power allows larger and more realistic simulations. K. Kadau ran trillion atom MD simulation (Lennard-Jones interactions) with code SPaSM.

Crust Crystallography

- Chemical separation in NS crusts with Ed Brown (MSU),
- Don Berry (IU High Performance Computing)
- Kai Kadau (LANL)
- Graduate students:
  - Liliana Caballero (now at NC State)
  - Helber Dussan
  - Joe Hughto
  - Gang Shen
- Supported by DOE, Indiana.