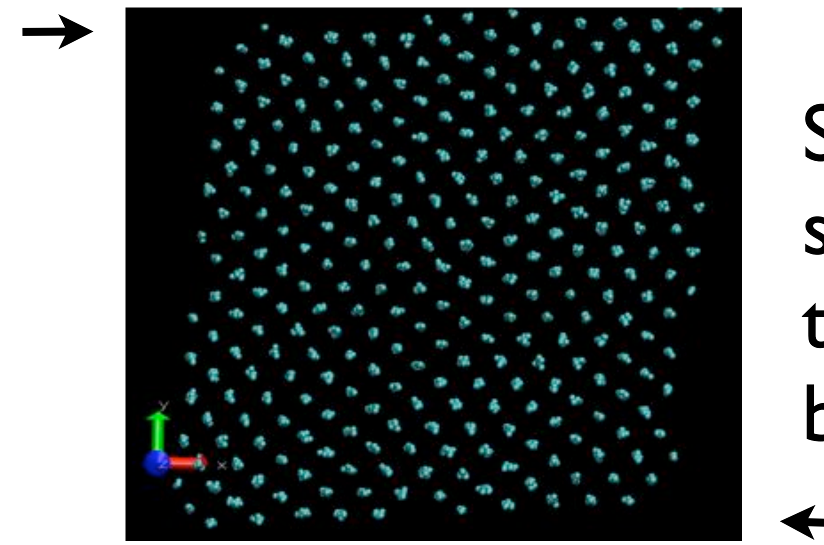
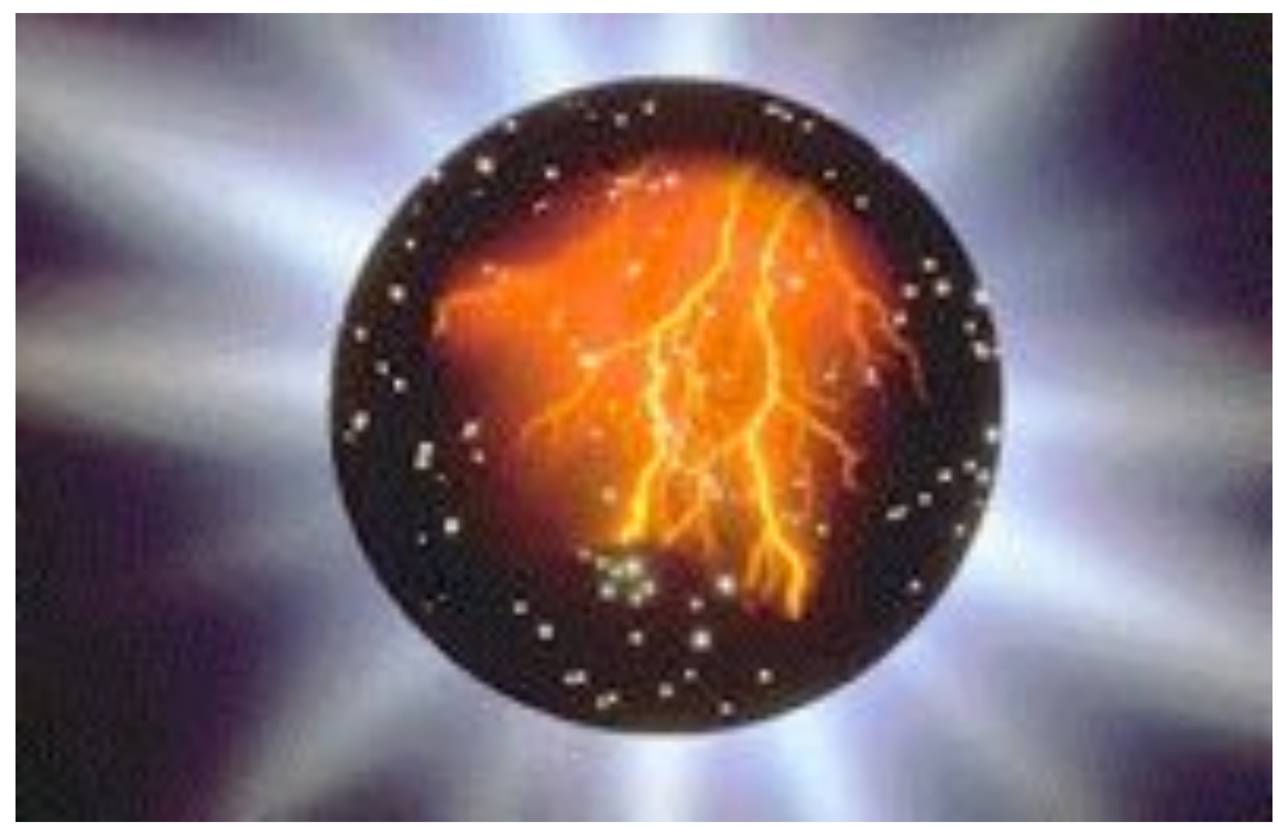
Neutron star crust and crust breaking

- Plasma crystals in lab., white dwarfs, and neutron stars.
- MD simulations find ***breaking strain of crust is very large***, even including effects of defects, impurities, and grain boundaries.
- Possible applications of crust breaking: glitches, magnetar flares, mountains and gravitational waves ...



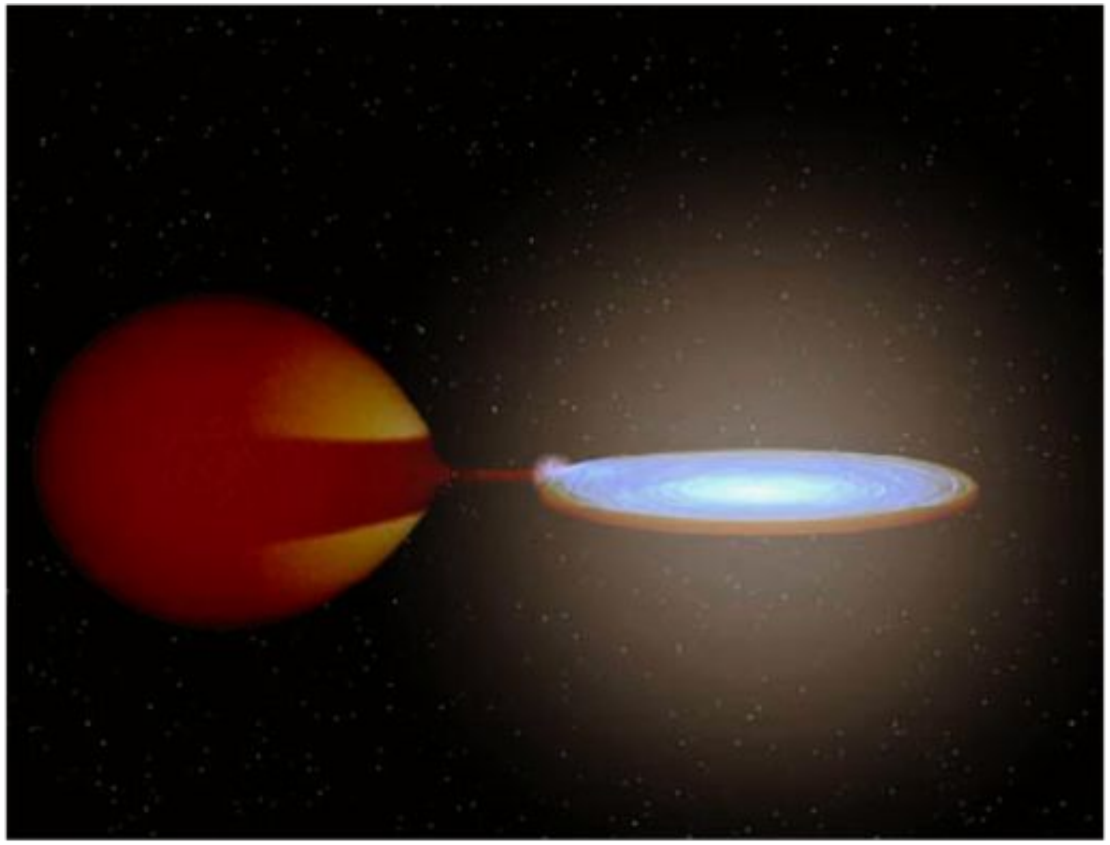
Stress MD simulation till it breaks



C. J. Horowitz, Indiana University
Transients Workshop, INT, Jul., 2011

Layers of an Accreting NS

- Matter falls on NS from companion, radiates X-rays.
- Atmosphere: very thin layer (10s of cm) determines spectrum
- Envelope: thin layer important for surface T.
- **Ocean:** liquid layer that freezes near 10^{10} g/cm^3.
- **Outer crust:** Coulomb lattice of nuclei plus degenerate e. elec capture drives n rich.
- **Inner crust:** Lattice of nuclei+ electrons + free neutrons. Near ~10^{14} g/cc nuclei start to touch.

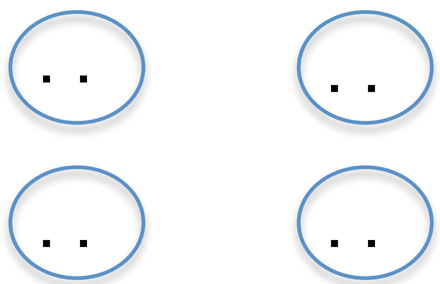


- **Pasta:** competition between Coulomb repulsion and nuc attraction → complex shapes.
- Core: uniform liquid of n, p, e.
- Inner core??: exotics

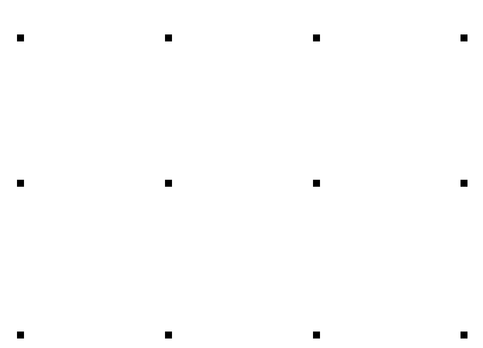
<< Layer of maximum strength >>

Coulomb Plasma and Pressure Ionization

- In sun, high T ionizes atoms.
- In NS high P ionizes. With density H_2 liquid goes to molecular H_2 solid with e localized



- Further P converts molecular H_2 to metallic H, e delocalized → metal



- NS crust is so dense that e Fermi E is largest E in system → Nearly free Fermi gas with very small Coulomb corrections. NS have very simple electronic structure.

Electron Fermi Screening

Fermi gas $P=(3\pi^2)^{1/3}n^{4/3}/4$

$-(1/n)\nabla P=eE$

$-\nabla\cdot(1/n)\nabla P=e\nabla\cdot E=$

$4\pi e^2[Z\delta(x)-(n-n_0)]$

$\nabla P=(\pi/3)^{2/3}n^{1/3}\nabla\delta n$

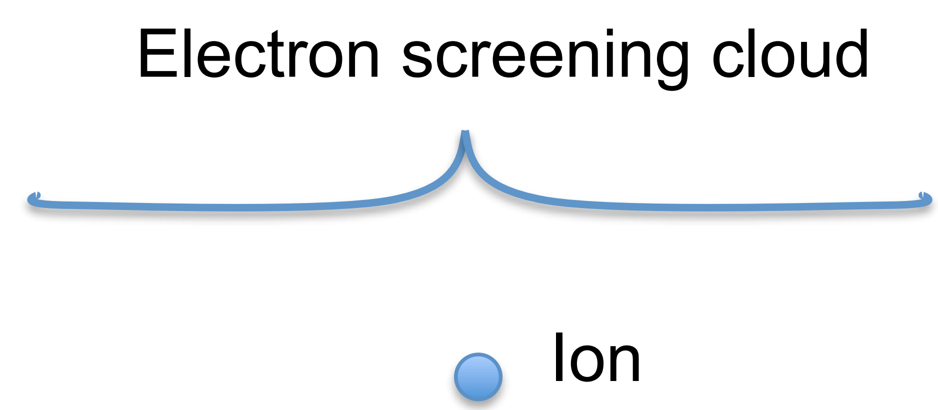
$-(\pi/3)^{2/3}\, n^{-2/3}\nabla^2\delta n= 4\pi e$

$(Z\delta(x)-\delta n)$

$[1-\lambda^2\nabla^2]\,\delta n=Z\delta(x)$

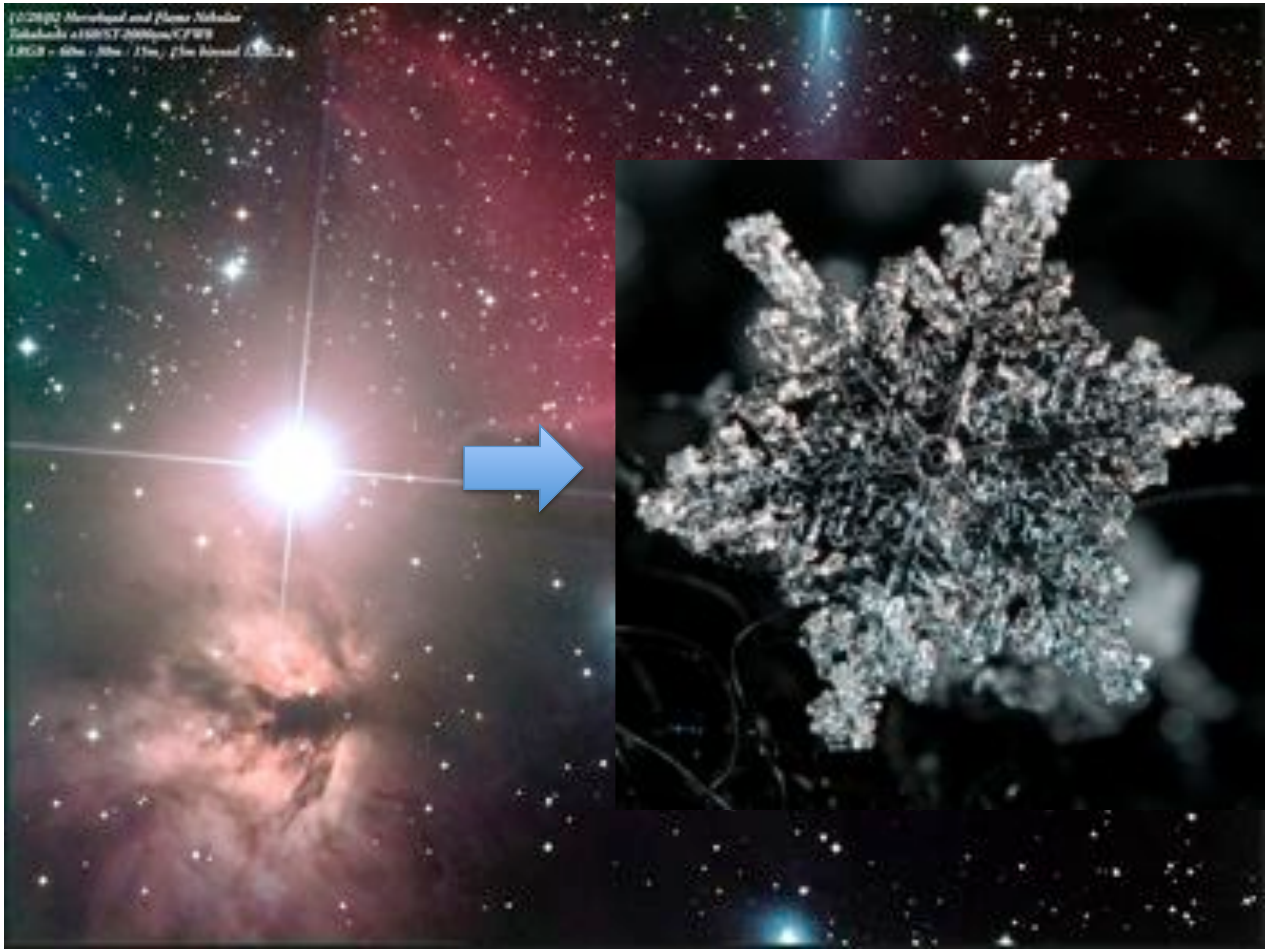
Screening length

$\lambda=(\pi/2\alpha)^{1/2}1/k_F$



- Screening cloud $\delta n(r)=-Ze^{-r/\lambda}/(4\pi\lambda^2 r)$
- Coulomb pot between ions is screened $v(r)=Z^2e^2e^{-r/\lambda}/r$

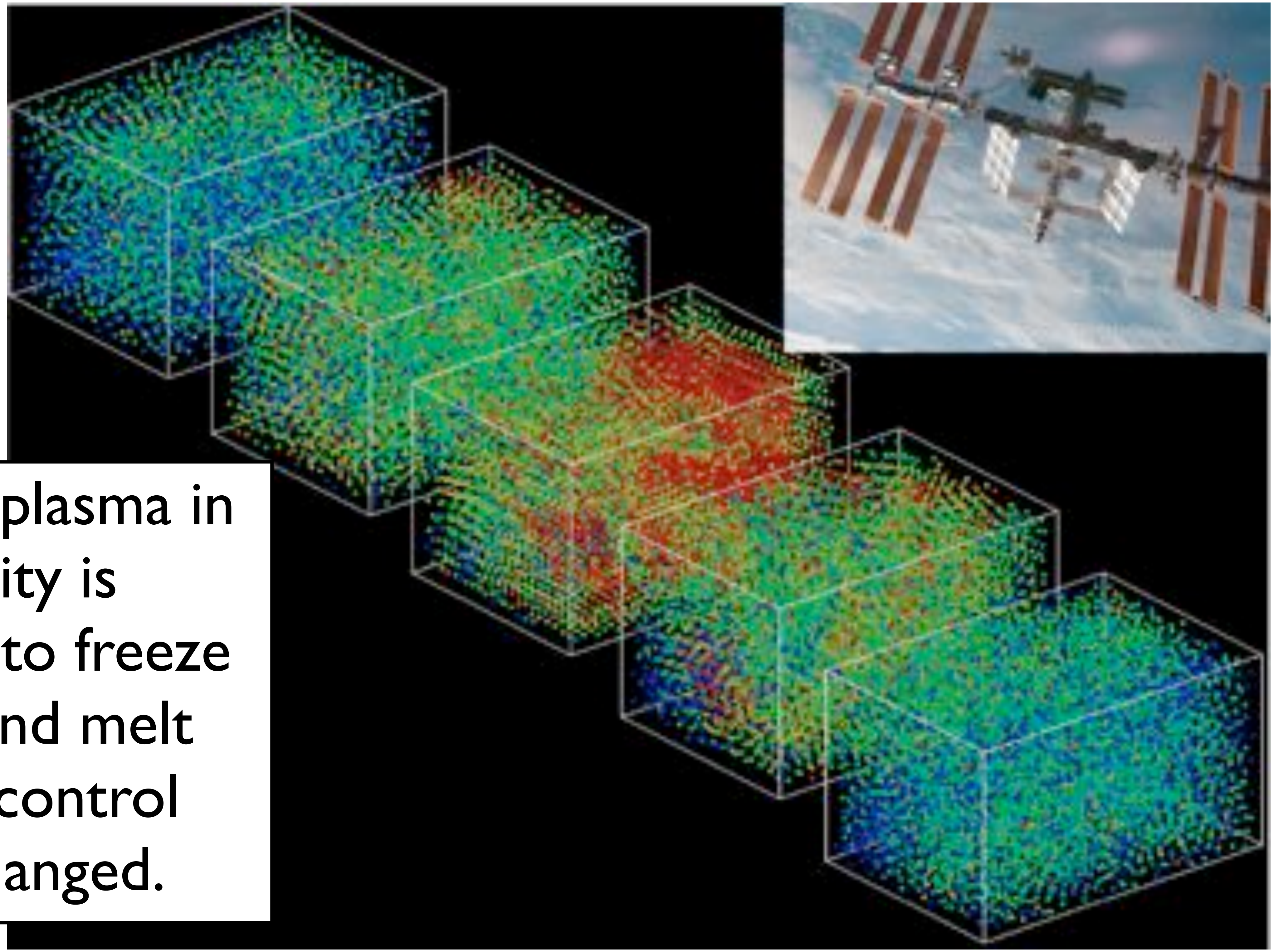
How Stars Freeze



Plasma Crystals

- Stars are plasmas, however interior of white dwarfs and crust of neutron stars are so dense that they can freeze.
- Plasma crystals first observed in lab in 1994.
- In **stars**: plasma consists of ions plus very degenerate (relativistic) electron gas. Electrons slightly screen ion-ion interactions: $V(r) = Z^2e^2/r \exp(-r/\lambda)$. Electrons give large Thomas Fermi screening length λ.
- **Complex (or dusty) plasma** can have micron sized microparticles in weakly ionizing gas. Particles acquire large negative charge. Compared to a star:
  - λ is shorter (fcc or hcp instead of bcc lattice)
  - Also have fluctuating and friction interactions with background gas. In stars, e-ion interactions small because of very large Fermi energy.
  - Overall confining potential.

Plasma Crystal on Space Station



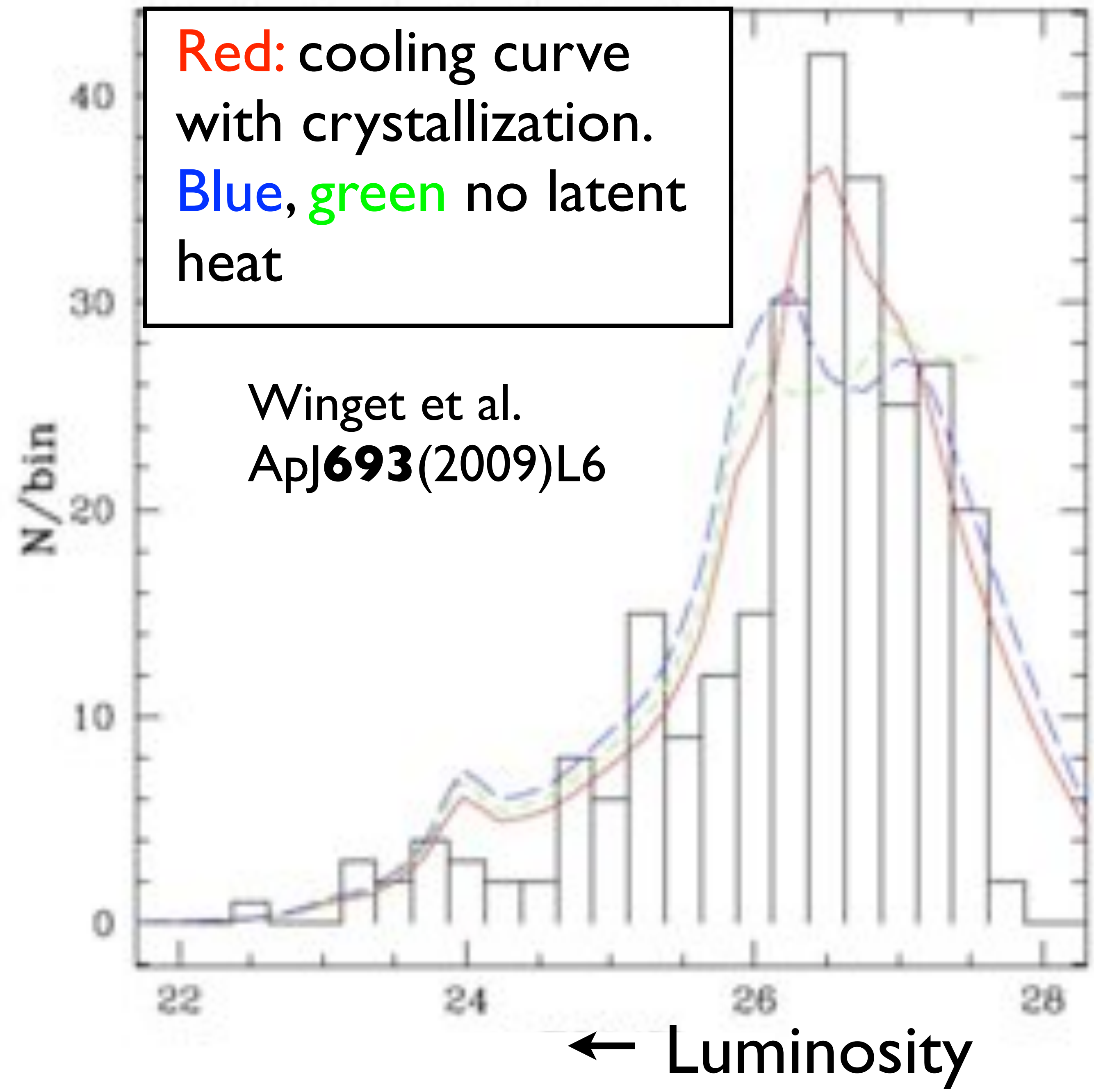
Complex plasma in microgravity is observed to freeze (center) and melt (right) as control voltage changed.

B. A. Klumov, Physics-Uspekhi, 53, 1053 (2010)

Light colors (red, orange) indicate large bond angle metric (fcc, hcp lattice) while blue, green indicate small metric (amorphous)

White Dwarf Crystallization

- As core of WD freezes, release of latent heat slows cooling and leads to peak in luminosity function (# of WD stars with given luminosity).
- Freezing T can give info on C/O ratio in core, Phys. Rev. Let. **104**, 231101 (2010)



Globular cluster NGC 6397 (Hubble)

Neutron star crust microphysics

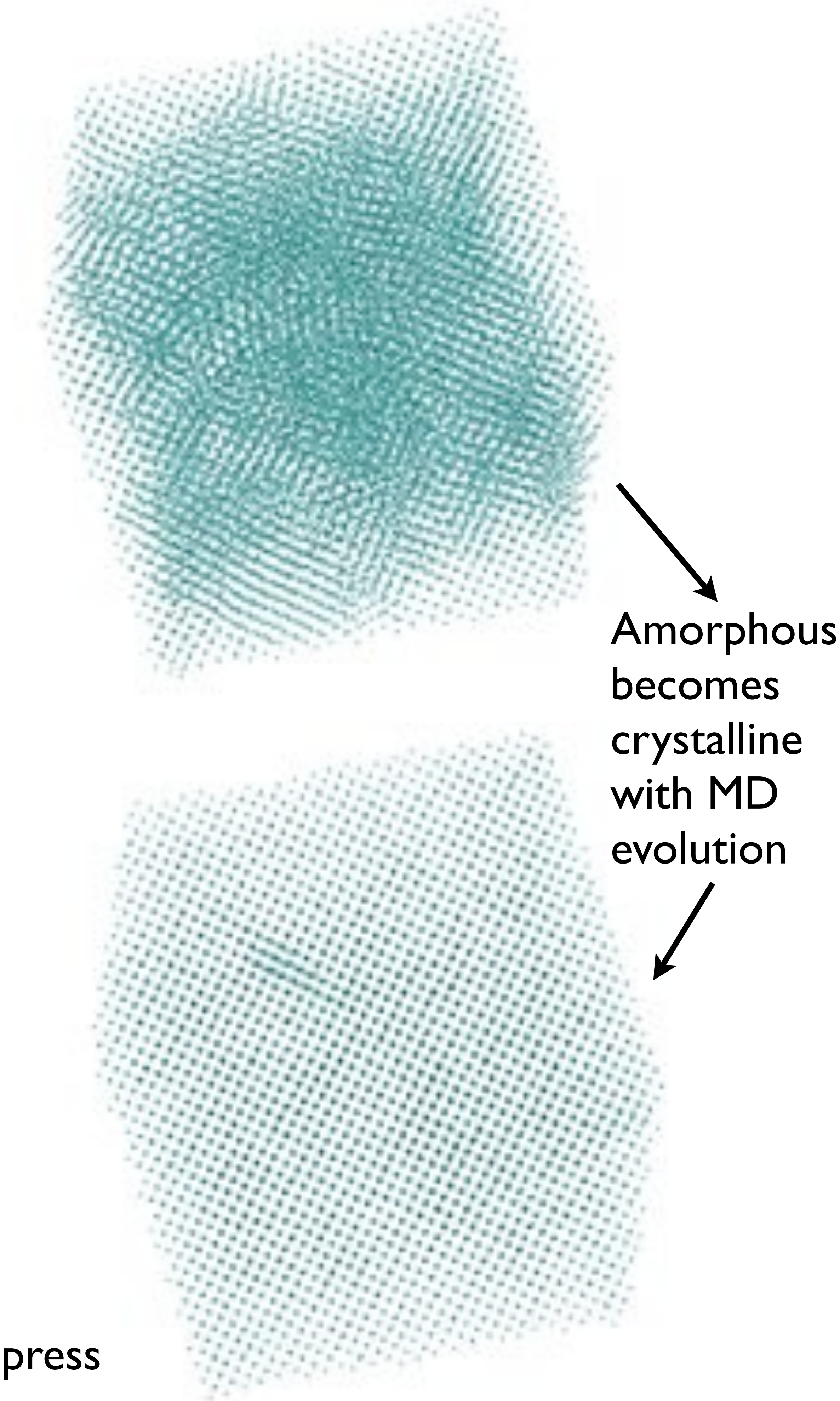
- Shear modulus, shear speed
- Breaking strain (strength)
- Bulk modulus
- Shear viscosity
- Thermal conductivity
- Electrical conductivity
- Diffusion coefficients
- Heat capacity
- Pycnonuclear and electron capture reaction rates
- Phase diagram (melting point and chemical separation)
- ...

Hypothesis

- Neutron star crust is an extremely good crystal that is remarkably free of defects such as vacancies, dislocations, and grain boundaries.
- Because imperfections diffuse very quickly.
- Neutron star crust is a “nearly perfect solid”.

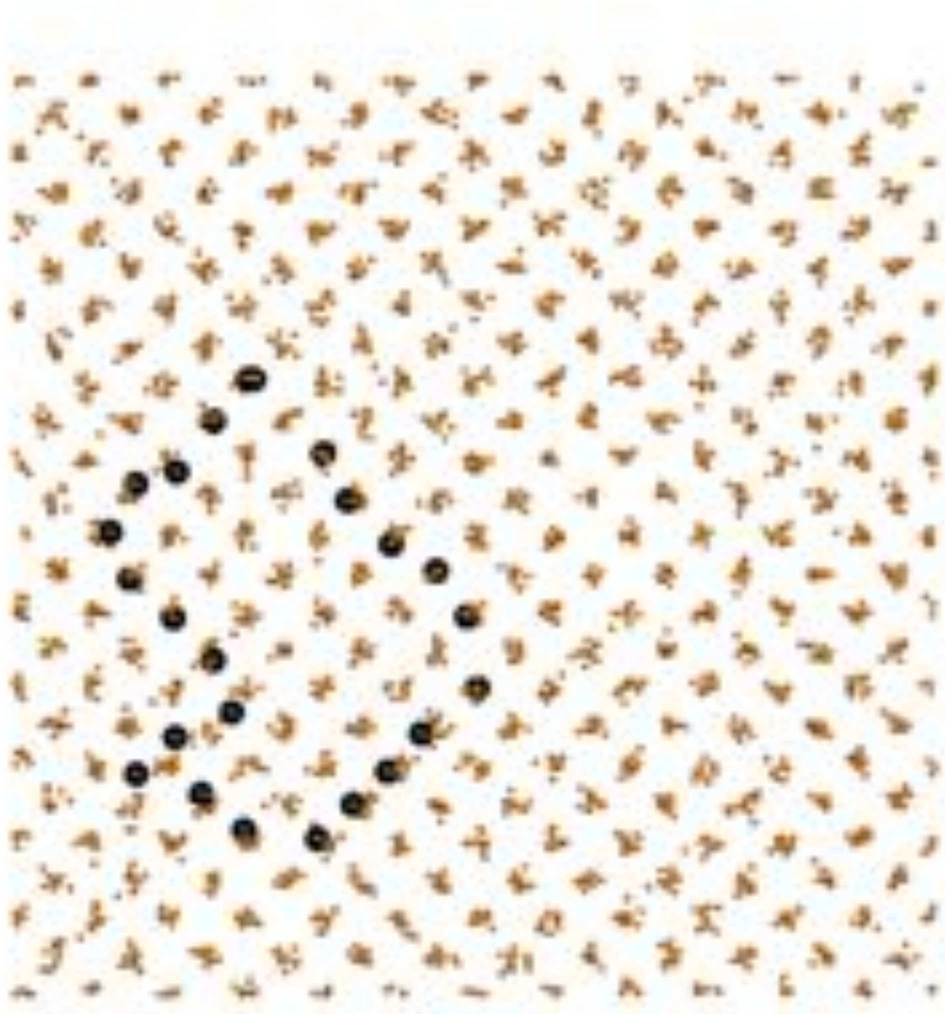
Diffusion in Coulomb Crystals

- Ions in a star are completely pressure ionized. They have soft 1/r interactions. There are no hard cores!
- Diffusion may be much faster than in conventional materials because ions can get by one another.
- Example: quench a liquid configuration of 27648 ions by reducing T by a factor of 2.9. Then evolve amorphous system with MD for long time. System spontaneously crystallizes.
- Fast diffusion suggests *WD interiors and neutron star crust are remarkably perfect crystals with few defects*.

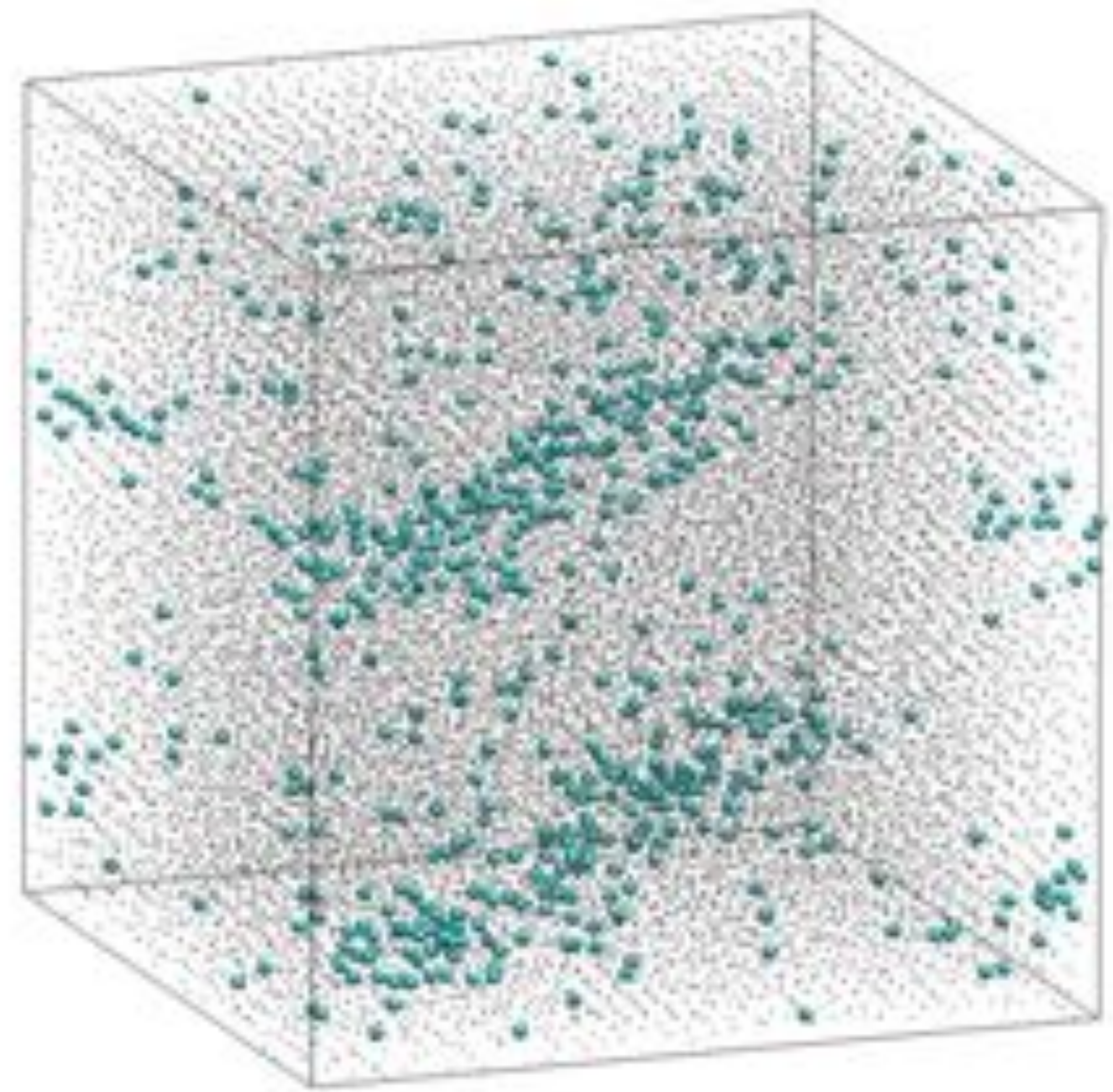


arXiv:1104.4822, Phys. Rev. E in press

Diffusion examples



Diffusion in nearly perfect 3456 ion bcc lattice. Large disks are ions that have move more than 1.34a in time 250/plasma frequency



Liquid 27648 ion sample frozen into two micro-crystals. Diffusion mostly along grain boundaries.

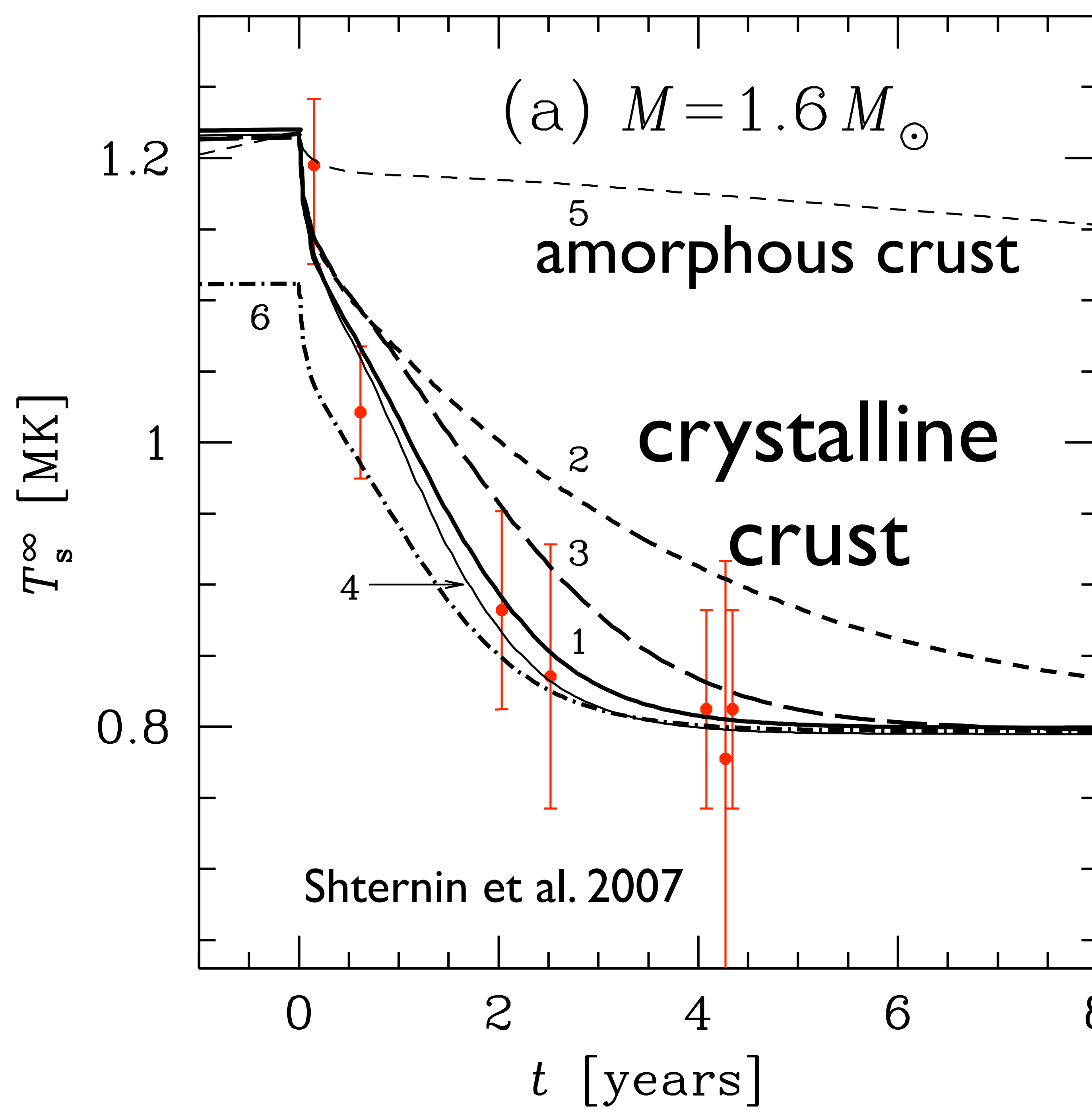
Cooling of KS 1730-260 Surface After Extended Outburst

Observe cooling of NS crust after heating from accretion stops.

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 thermal conductivity crystalline crust.



Gravitational Waves from Mountains

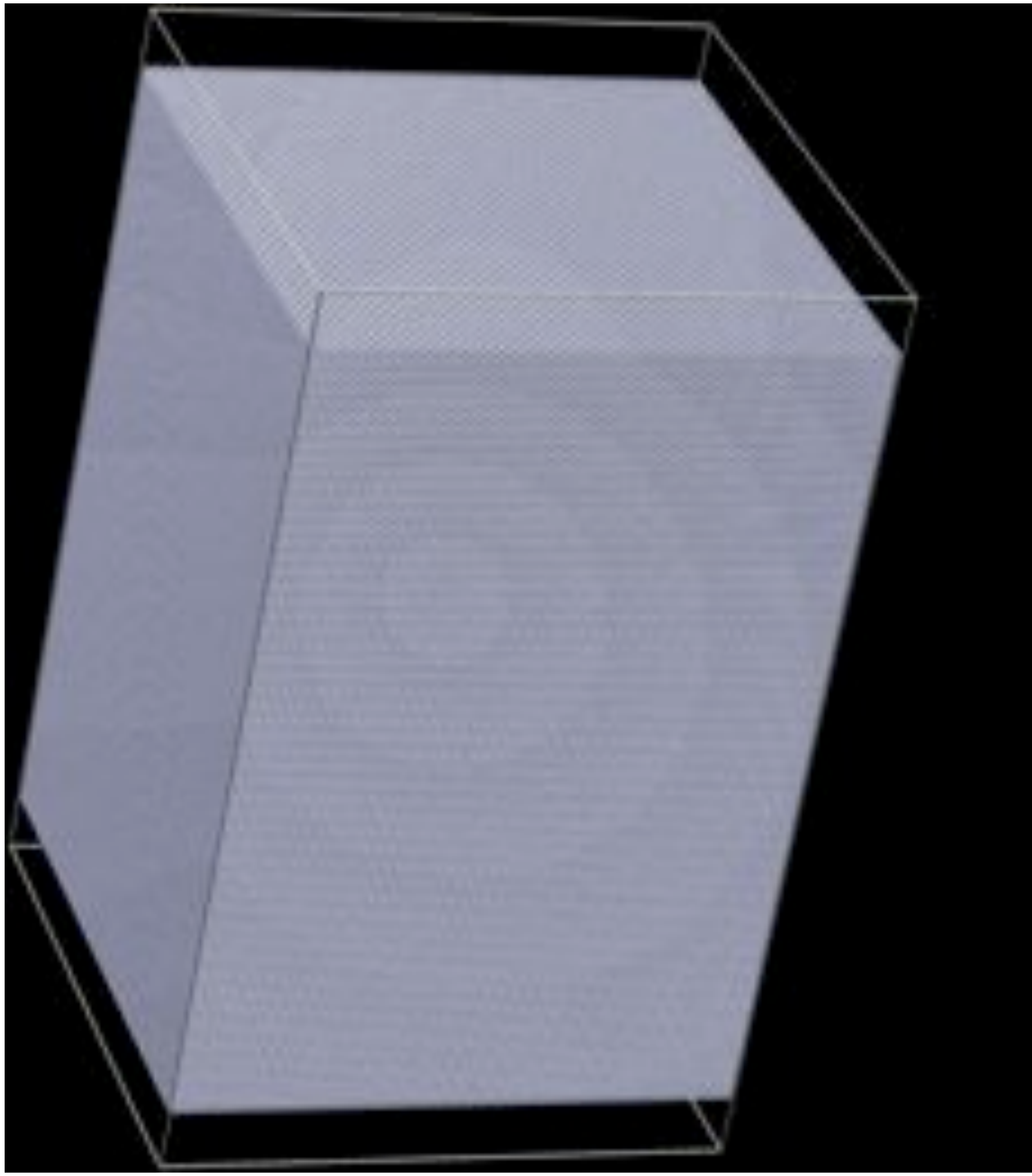
- Strong continuous GW sources (at LIGO frequencies) place extraordinary demands on neutron rich matter and stress it to the limit.
  - Place a mass on a stick and shake vigorously.
  - May need both a large mass and a strong stick.
  - Let me talk about the strong stick.
- Example: consider a large mountain (red) on a rapidly rotating neutron star. Gravity from the mountain causes space-time to oscillate, radiating gravitational waves. How do you hold the mountain up?

Mountain (red) on rotating neutron star.

Also GW from r modes that depend on damping (shear / bulk viscosity)

Neutron Star Quadrupole Moments and Gravitational Waves

- A solid crust can support a mass quadrupole moment, that on a rapidly rotating NS, efficiently radiates GW.
- Very active ongoing/ future searches for continuous GW at LIGO, Virgo ...
- How big can the quad. moment be? This depends on the strength of the crust (before mountain collapses under extreme gravity of a NS).
- We perform large scale MD simulations of the crust breaking including effects of defects, impurities, and grain boundaries...
- We find neutron star crust is the strongest material known. *It is 10 billion times stronger than steel.* Very promising for GW searches.



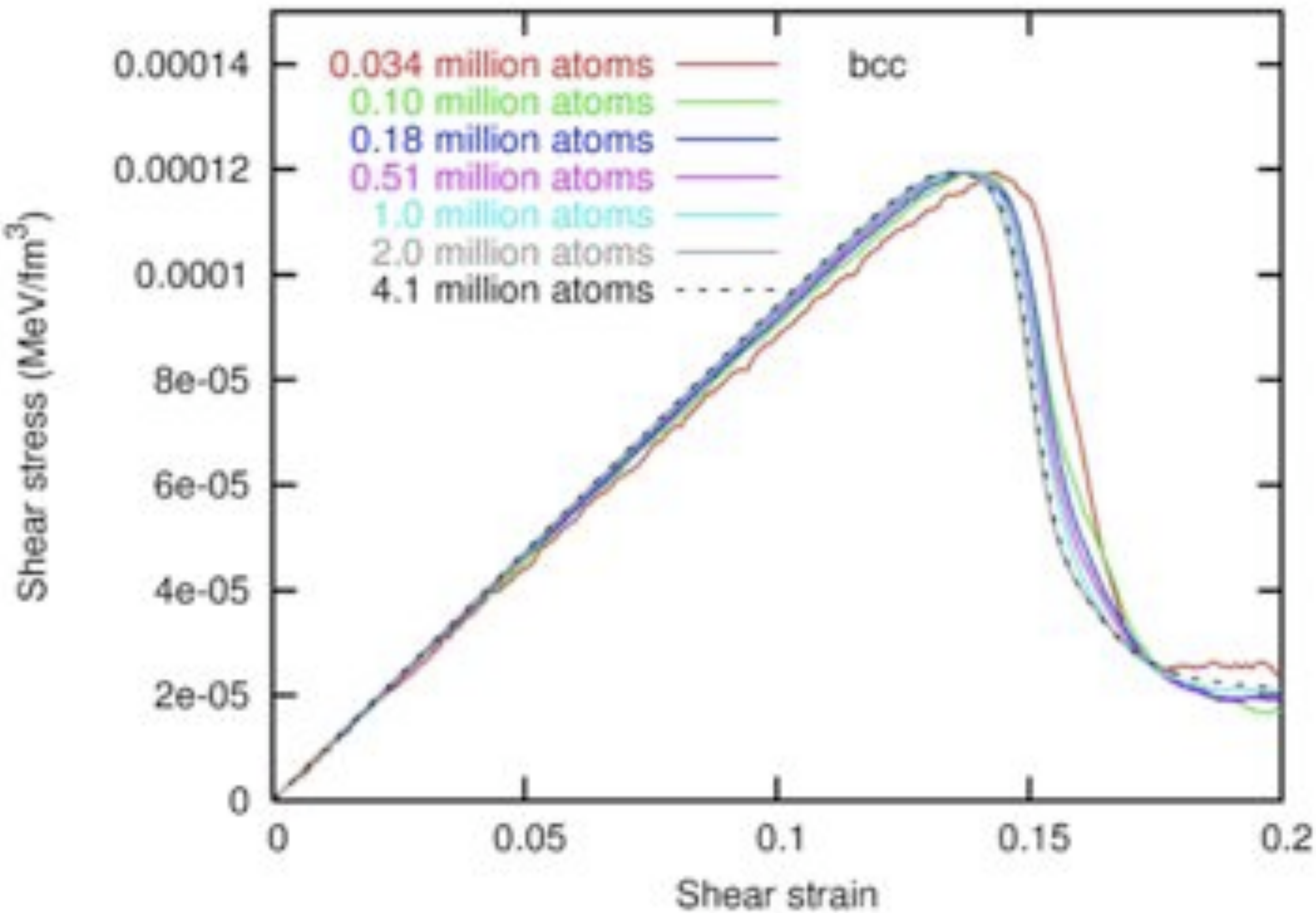
Movie of breaking of 1.7 million ion crystal. Red indicates deformation of lattice.

CJH, Kai Kadau, Phys Rev Let. **102**,191102 (2009)

MD Simulation of Stress vs Strain

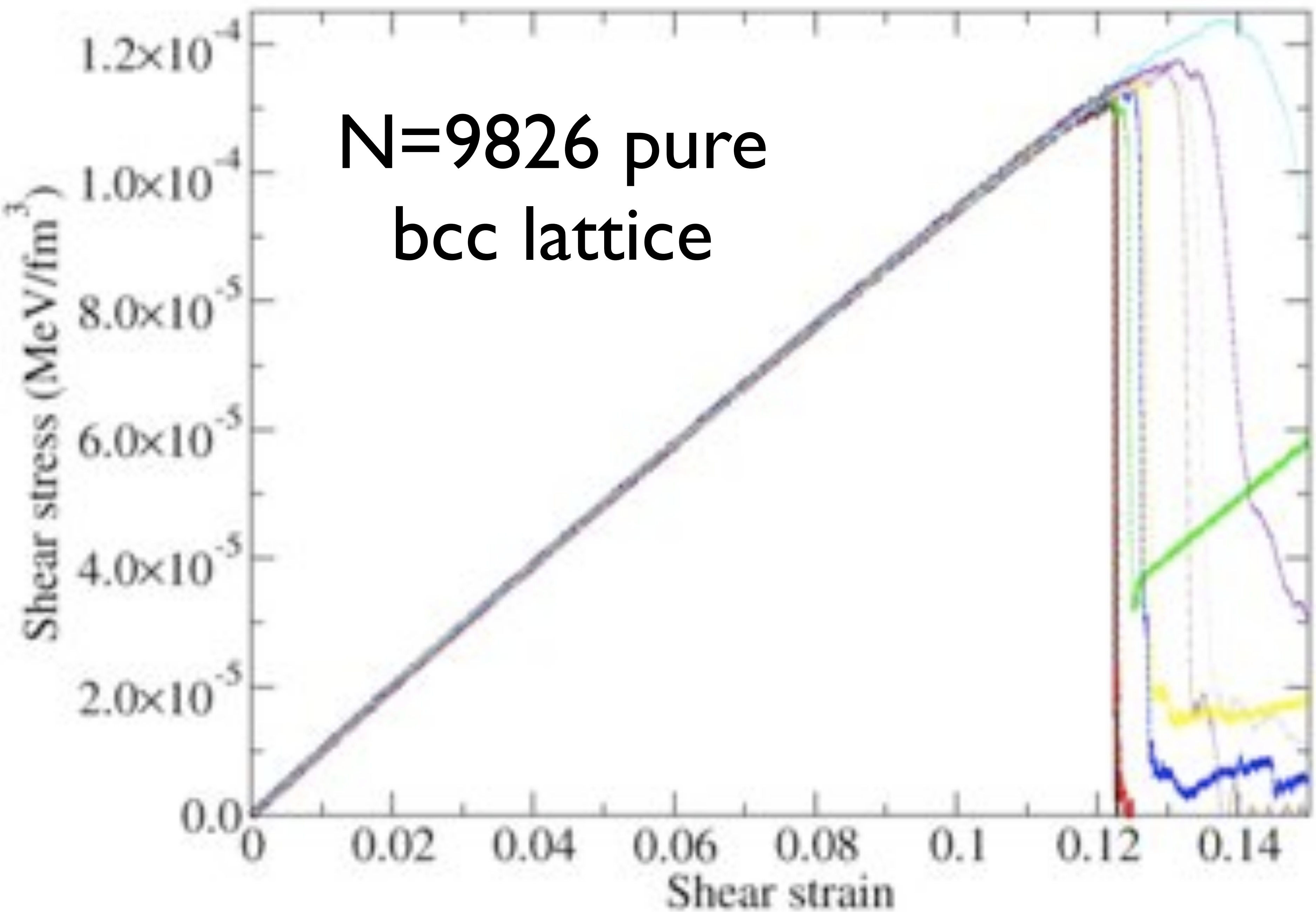
- Stress tensor is force per unit area resisting strain (fractional deformation).
- Very long ranged tails of screened coulomb interactions between ions important for strength.

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



- Shear stress 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.

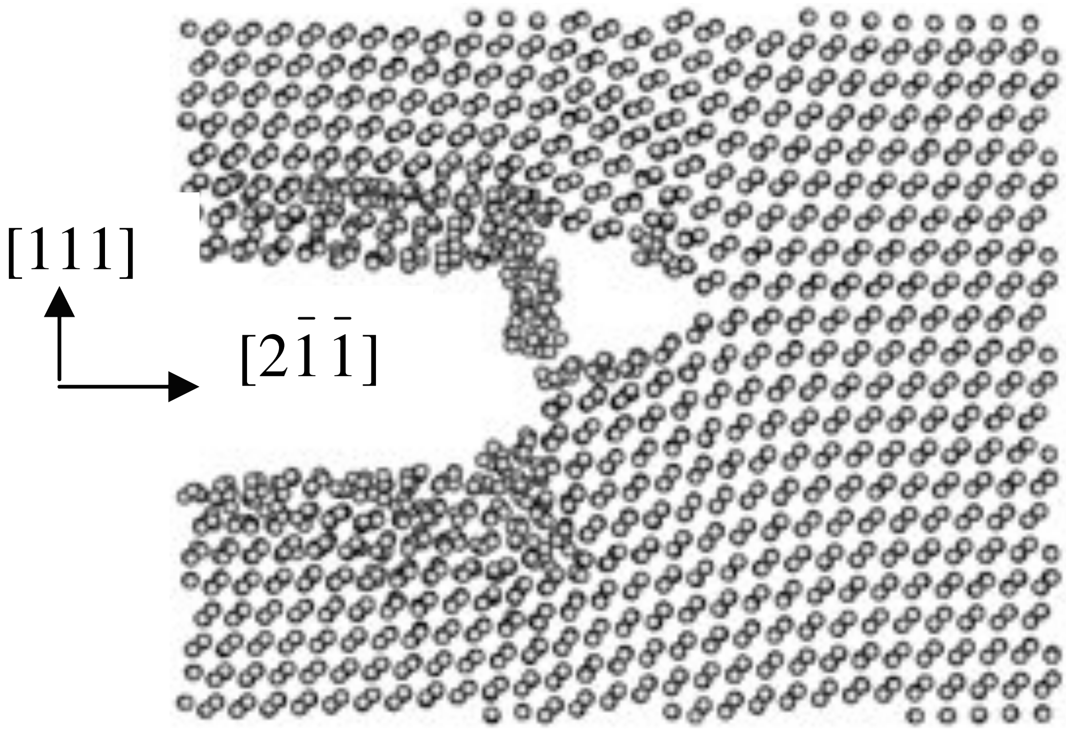
Shear Stress vs Strain



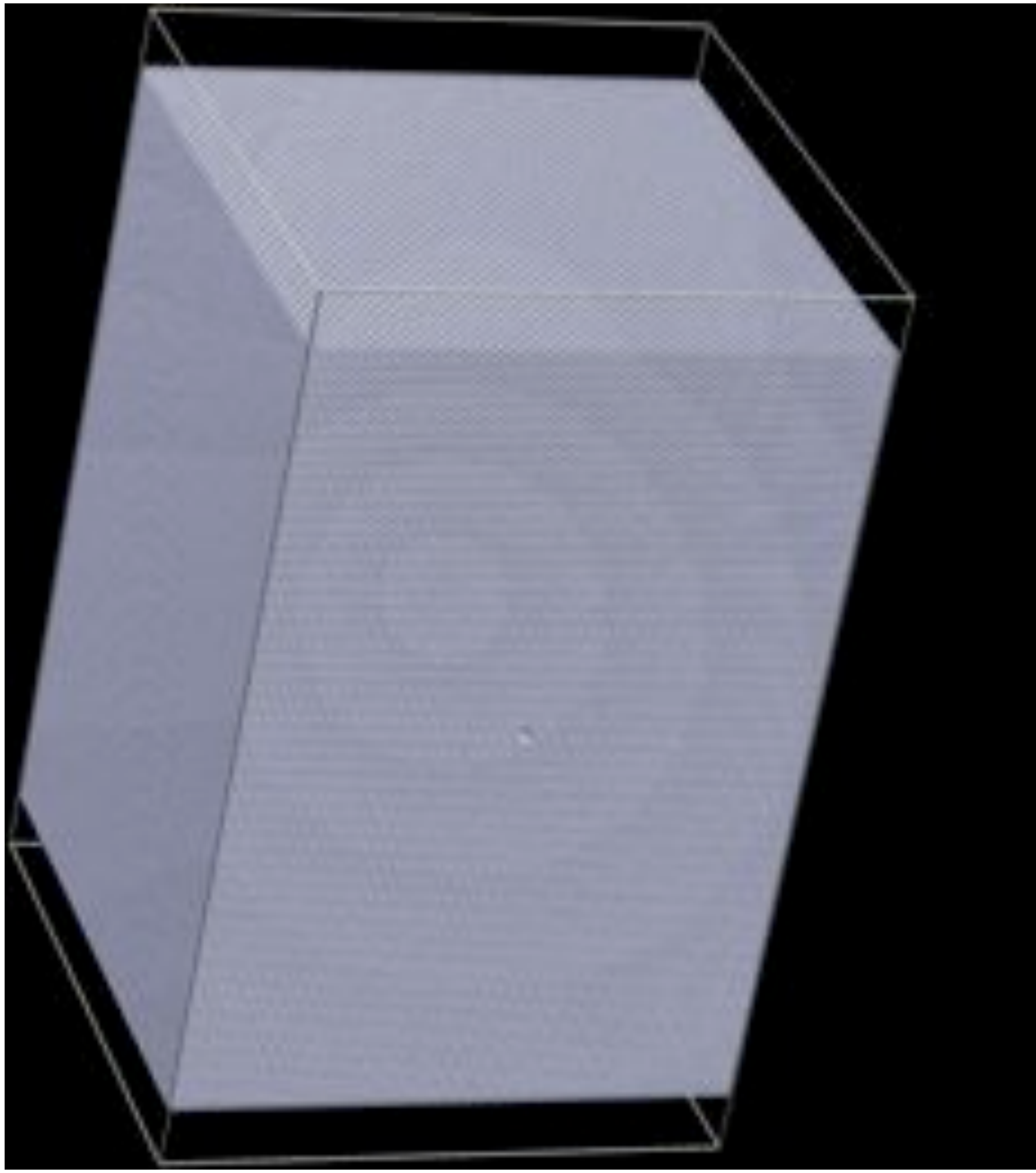
- Shear stress versus strain for strain rates of (left to right) 0.125 (black), 0.25 (red), 0.5(green), 1(blue), 2(yellow), 4 (brown), 8(gray), 16(violet), and 32(cyan) $X10^{-8}$ c/fm.

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.

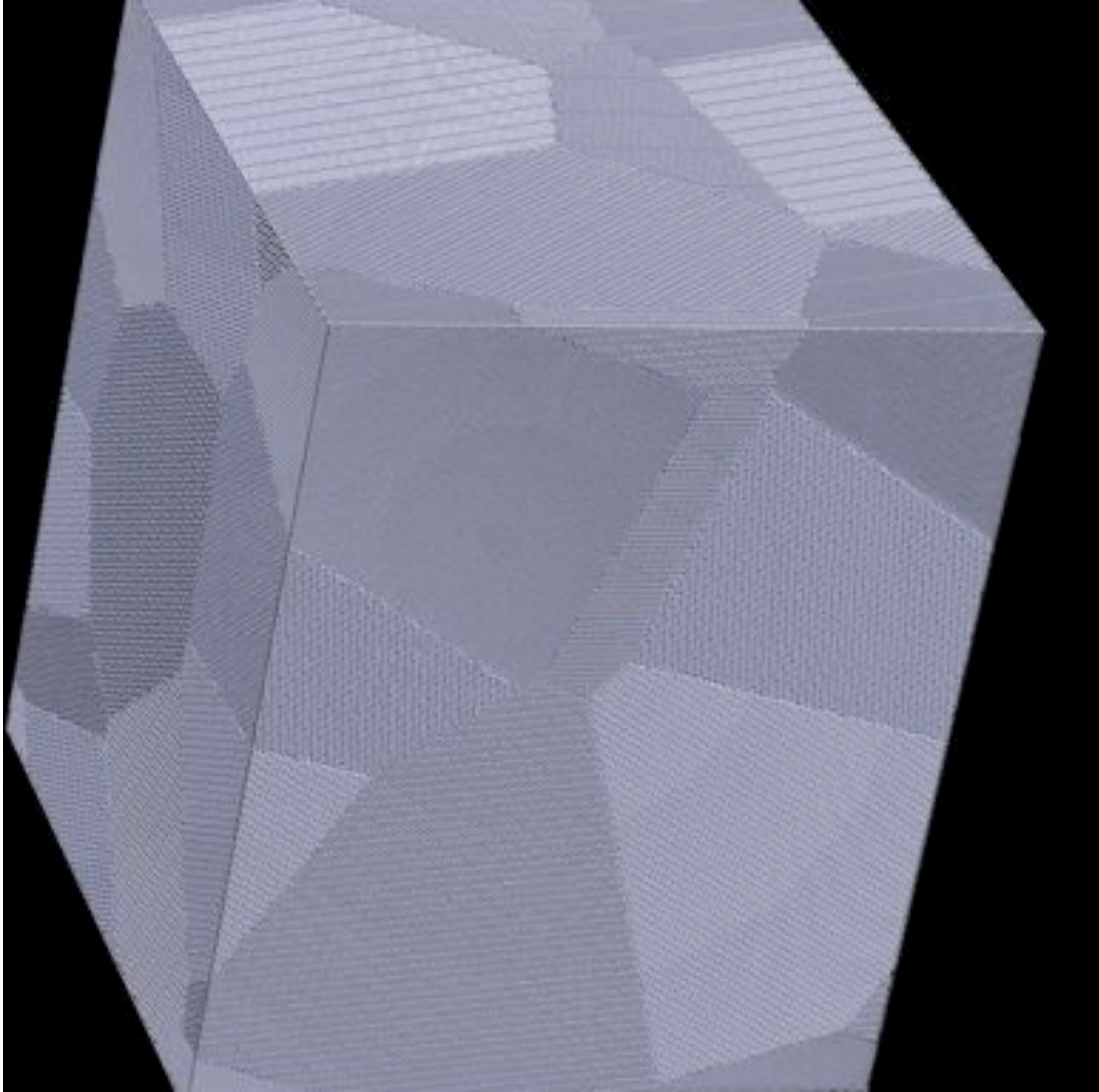


- Neutron star crust is under great pressure which prevents formation of voids. Crust does not fracture.

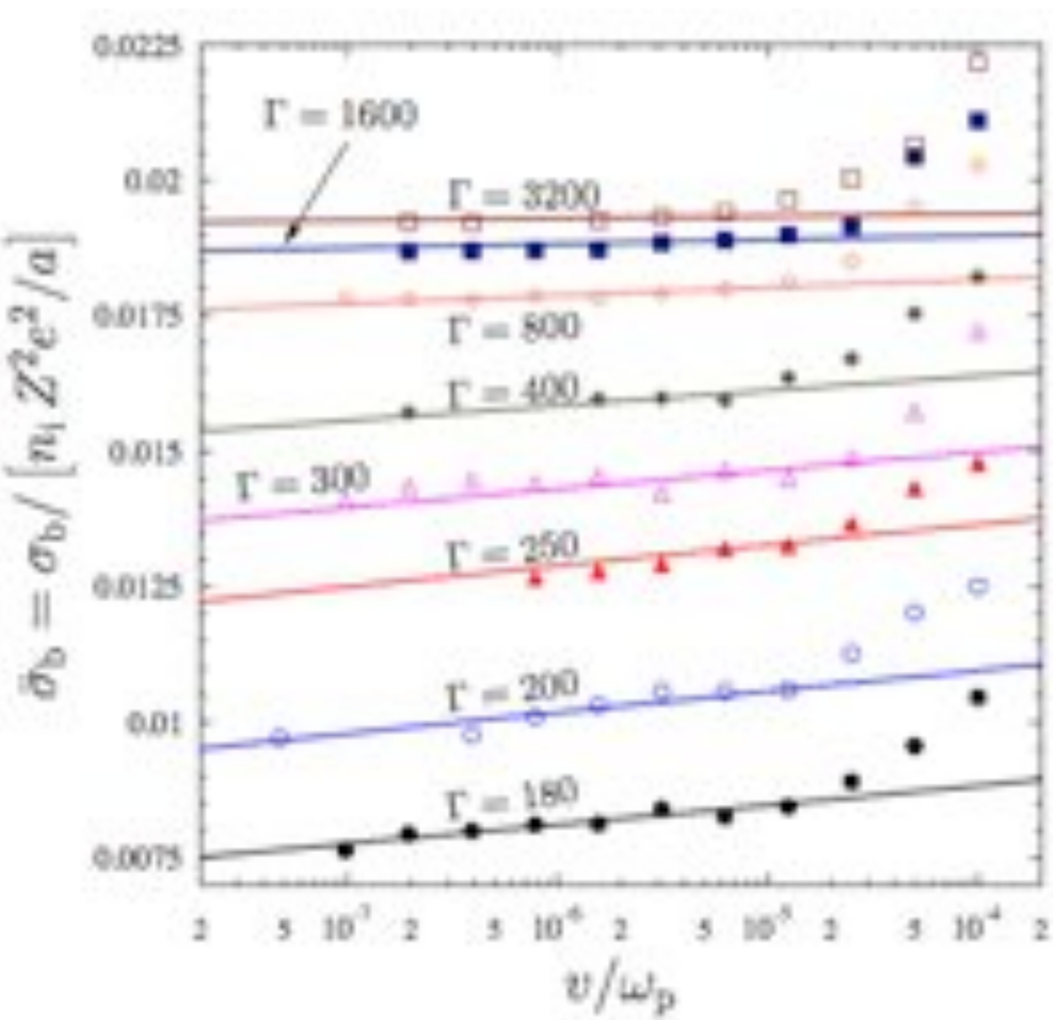


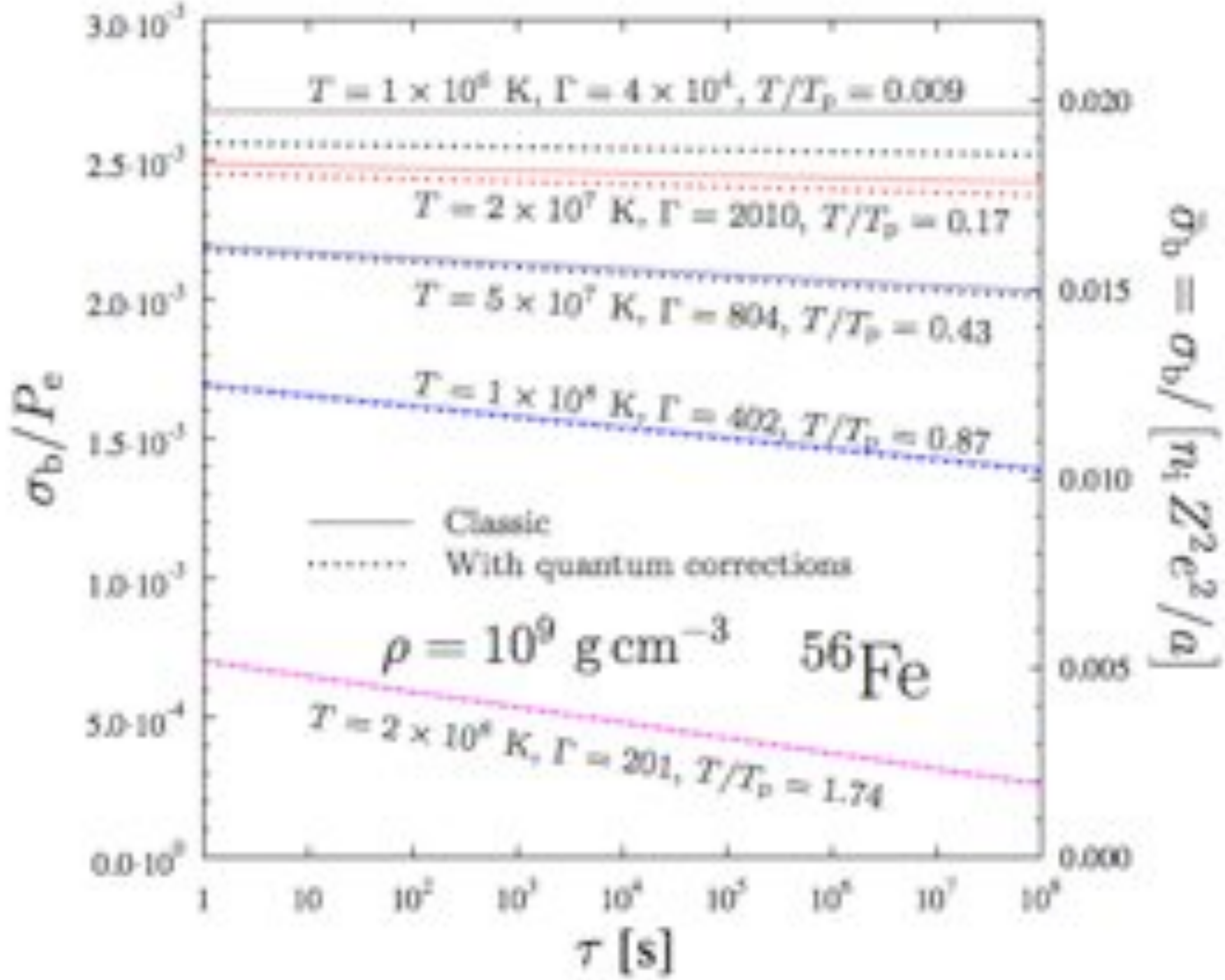
Simulation of neutron star crust with central defect using 1.7 million ions

Polycrystalline sample (bcc) with 12.8 million ions consisting of 8 differently oriented grains.



Extrapolation to long times





Fit MD results of breaking stress vs strain rate on left to phenomenological model of an activation energy and critical volume for breaking. Extrapolate model to very long times on right.

A. Chugunov, CJH, MNRAS **407**, L54 (2010).

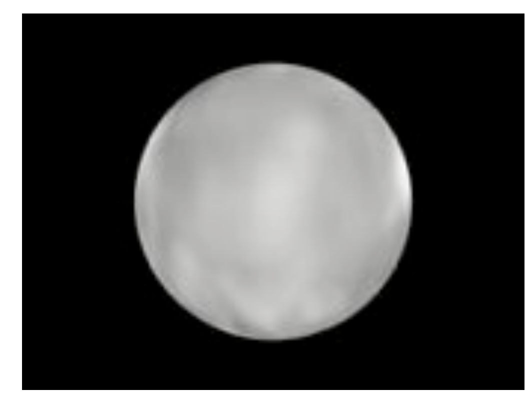
Breaking Strain is Large ~0.1

- Often conventional materials fail as strain causes defects to migrate and then collection of defects leads to fracture.
- Plasma crystals in neutron star crust
  - Large pressure suppresses formation of vacancies and prevents fracture.
  - Most defects diffuse rapidly away.
  - Very few remaining defects and these have only a very small impact on the strength.
  - Each ion has long range coulomb interactions with thousands of neighbors and is insensitive to a few out of place neighbors. --> *Many redundant bounds give great strength.*

Gravitational Wave Searches

- Can gain sensitivity to weak continuous GW signals by coherently integrating for long times. *Searches are very computationally intensive!* Must search over many parameter values: period, period derivative, location on sky...
- Einstein@home uses large # of volunteer computers. Sign up at http://einstein.phys.uwm.edu/
- Interesting neutron stars:
  - **Fast rotating**: GW power rapidly increases with frequency.
  - **Large accretion**: angular momentum gained from accretion could be radiated in GW. Explains why fastest NS only spin at about half of breakup rate.
  - **Young and radio bright**: example, direct limit on Crab, GW radiation is less than few % of observed rotational power.
  - **Unknown**: vast majority of NS in galaxy are unknown but potentially observable in GW.
  - **Unexpected**: Low mass NS can have large deformations and be uniquely strong GW sources. Solid quark matter could be even stronger and also support large deformations.
  - ...

Near Shoemaker images of asteroid 433 Eros



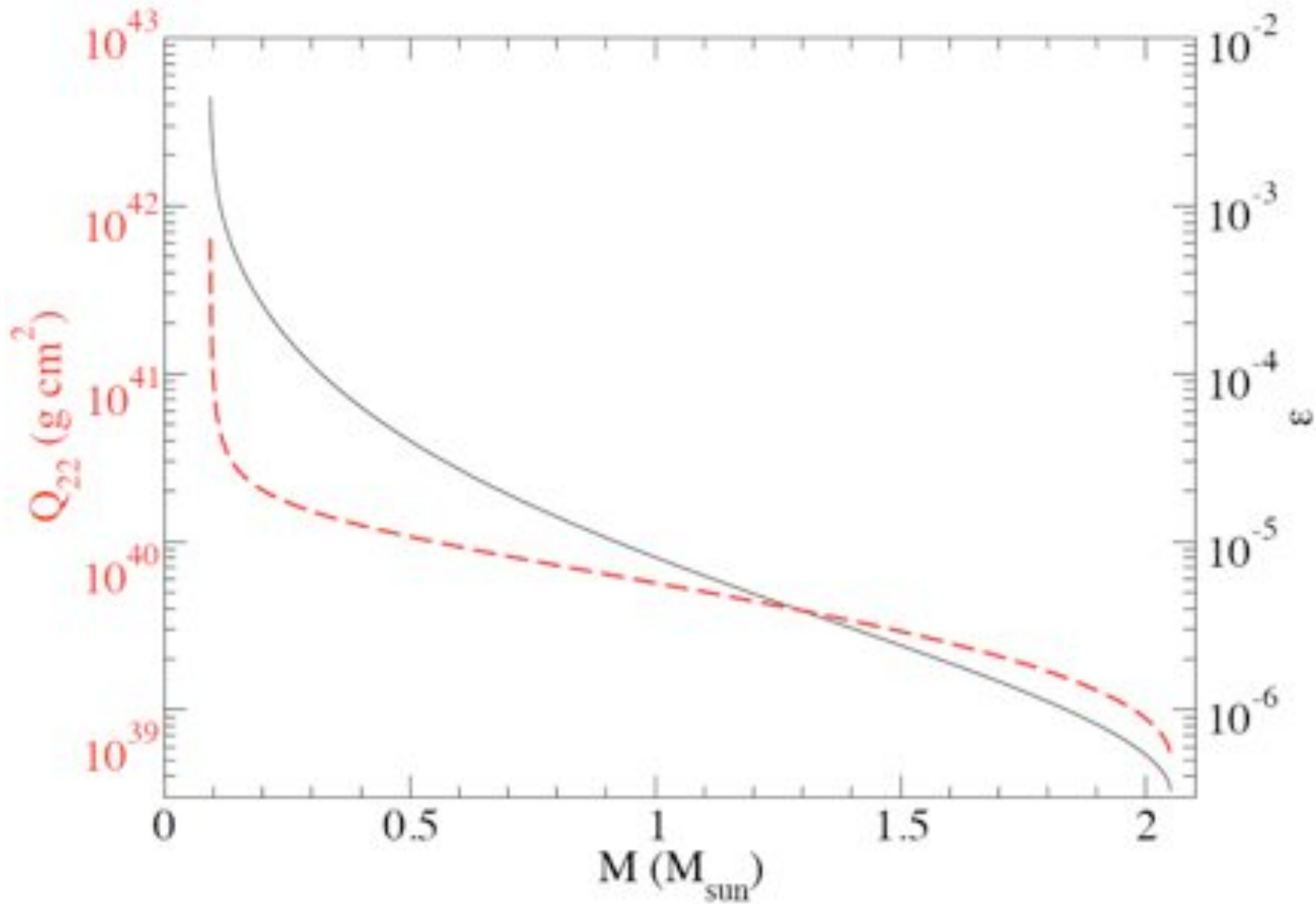
Hubble images of dwarf planet Ceres

Low Mass Neutron Stars

- Low mass neutron stars (maximally deformed) are the answer to the following astro-engineering question: given material with the strength of neutron star crust, construct the strongest possible continuous gravitational wave source (at LIGO frequencies).

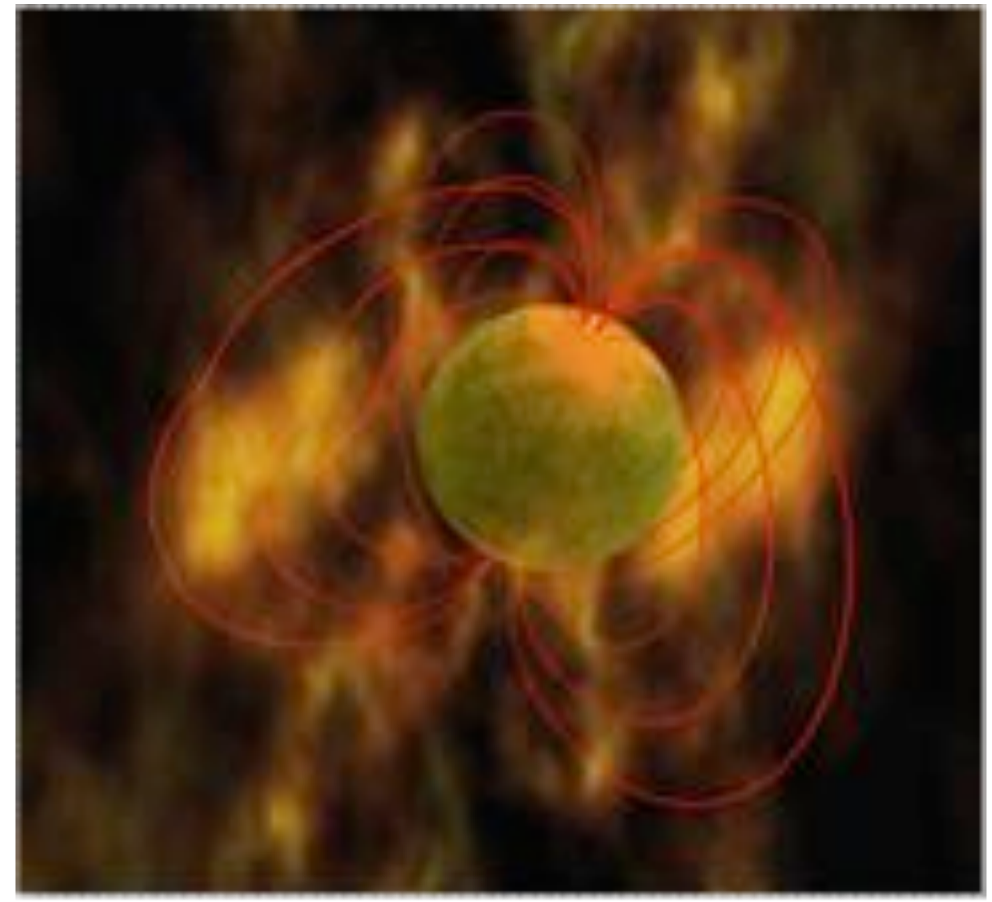
Ok, hot Jupiters can't be formed, but doppler shift planet searches are most sensitive to them, so you should search anyway.

Maximum deformation and quadruple moment vs NS mass



Magnetar Giant Flares and Star Quakes

- Magnetars are neutron stars with 10^{15} G fields [normal pulsars 10^{12} G]
- Giant flares are rare, extraordinarily energetic gamma ray bursts from magnetars that are thought to involve crust breaking.
- 27 Dec 2004 flare from SGR 1806-20, 30,000+ light years away.

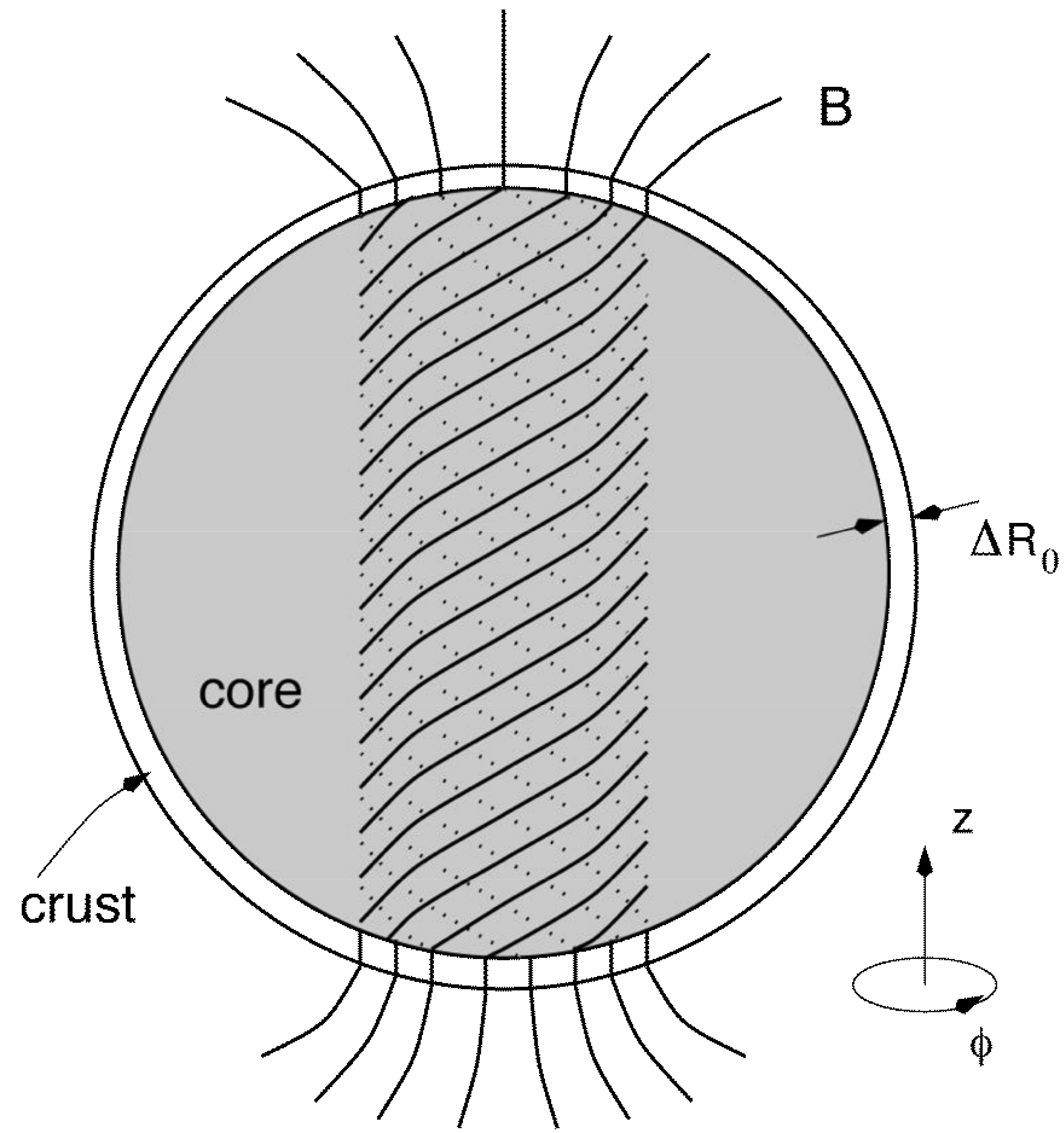


Robert S. Mallozzi, UAH / NASA MSFC

- 0.2 sec spike of γ-rays
  - $L_{peak} \sim 2 \times 10^{47}$ erg/s $\sim 1000 \times L_{MW}$
  - $E_{bol} \sim 4 \times 10^{46}$ erg ~ 300 kyr $\times L_{\odot}$
  - fluence at Earth ~ 1 erg cm^{-2}
  - saturated all but particle detectors
  - created detectable disturbance in ionosphere (Campbell et al. 2005)
  - echo detected off Moon (Mazets et al. 2005)

Curst Breaking Mechanism for Giant Flares

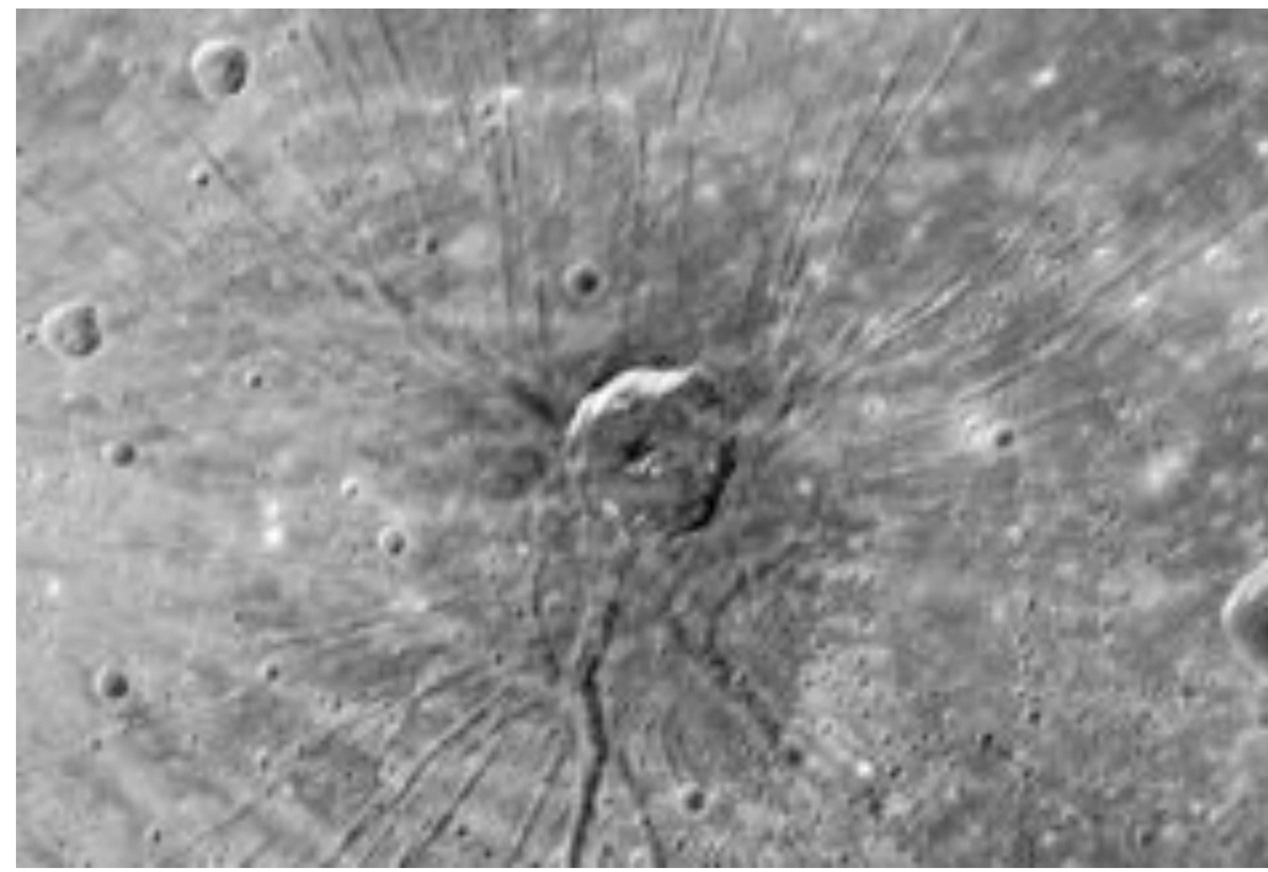
- Twisted magnetic field diffuses and stresses crust.
- Crust breaks and moves allowing magnetic field to reconnect, releasing huge energy observed in giant flares.
- We find the crust is very strong and can control large energy in the magnetic field.
- Possibilities: 1) crust breaks allowing field to reconnect 2) field reconnects and breaks crust 3) field reconnects and does not break crust.



Thompson + Duncan

Glitches and crust breaking

- As star spins down, crust must break.
- What role does breaking of strong crust play in glitches?
- Perhaps some "classical glitches" just from crust breaking? Large but rare because crust so strong??
- Perhaps crust breaking leads to vortex unpinning?



Cracks on planet mercury.

Neutron Star Crust and crust breaking

- We performed large scale MD simulations of solids in white dwarfs and NS. Coulomb crystals are likely nearly perfect with few defects.
- We find breaking strain of neutron star crust is very large ~ 0.1 even including the effects of dislocations, impurities, and grain boundaries.
- This large strength can support large mountains that on a rapidly rotating stars will radiate strong gravitational waves.
- Large breaking strain has implications for glitches and magnetar flares.
- Collaborators D. Berry, E. Brown, A. Chugunov, ***K. Kadau***, J. Piekarewicz. Students: L. Caballero, H. Dussan, J. Hughto, J. Mason, A. Schneider, and G. Shen.
- Supported in part by DOE.