Title: Neutron Star Crust Microphysics

Date: Jun 22, 2011 02:30 PM

URL: http://pirsa.org/11060030

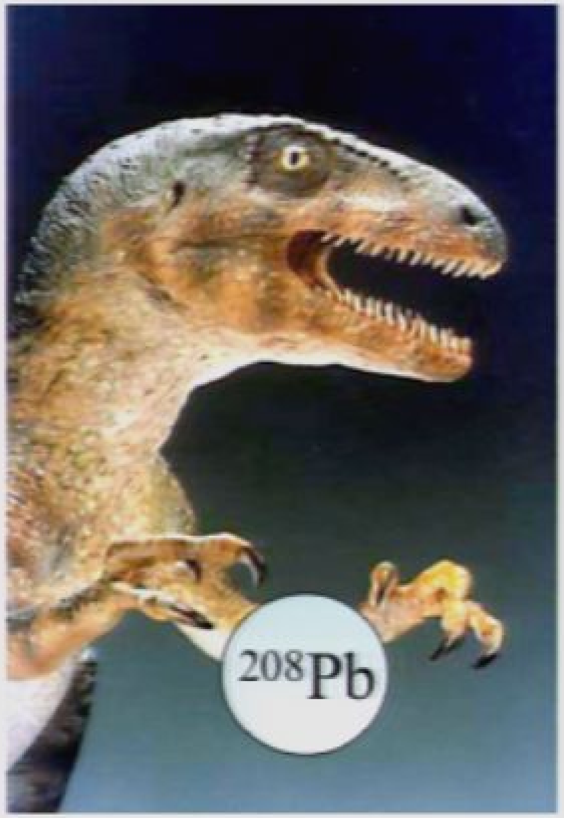
Abstract: New equations of state (EOSs) from extensive virial and relativistic mean field calculations will be presented. We construct thermodynamically consistent EOSs from slightly noisy free energy calculations, which satisfy the first law, and conserves entropy during adiabatic compression. However this requires a very careful procedure of numerically smoothing the entropy and then integrating the entropy to generate consistent free energies. We discuss various features of the EOS in different density, temperature, and proton fraction regimes. We compare the adiabatic index for our EOSs with those of the Lattimer Swesty and H. Shen et al. EOSs. We do not find a first order liquid vapor phase transition for the astrophysical EOS. Finally, we discuss neutrino interactions that are consistent with our EOSs. At low density, we present model independent neutrino responses that are based on the viral expansion .

Neutron star crust microphysics

- Pb Radius Experiment (PREX) measures neutron radius of ^{208}Pb.
- Neutron star crust microphysics
- Plasma crystals in lab., white dwarfs, neutron stars.
- Example, breaking strength of neutron star crust.
- "Observations" (benchmarking??) of microphysics are important.

C. J. Horowitz, Indiana University
MICRA, Waterloo, Jun., 2011

Pb Radius Experiment (PREX)



Provides a precise laboratory probe of neutron rich matter.

PREX uses parity violating electron scattering to accurately measure the neutron radius of ^{208}Pb.

This has many implications for nuclear structure, astrophysics, atomic parity violation, and low energy tests of the Standard Model.

Parity Violation Isolates Neutrons

- In Standard Model Z^0 boson couples to the weak charge.
- Proton weak charge is small:

$$Q_W^p = 1 - 4\sin^2\Theta_W \approx 0.05$$

- Neutron weak charge is big:

$$Q_W^n = -1$$

- Weak interactions, at low Q^2, probe neutrons.
- Parity violating asymmetry A_{pv} is cross section difference for positive and negative helicity electrons

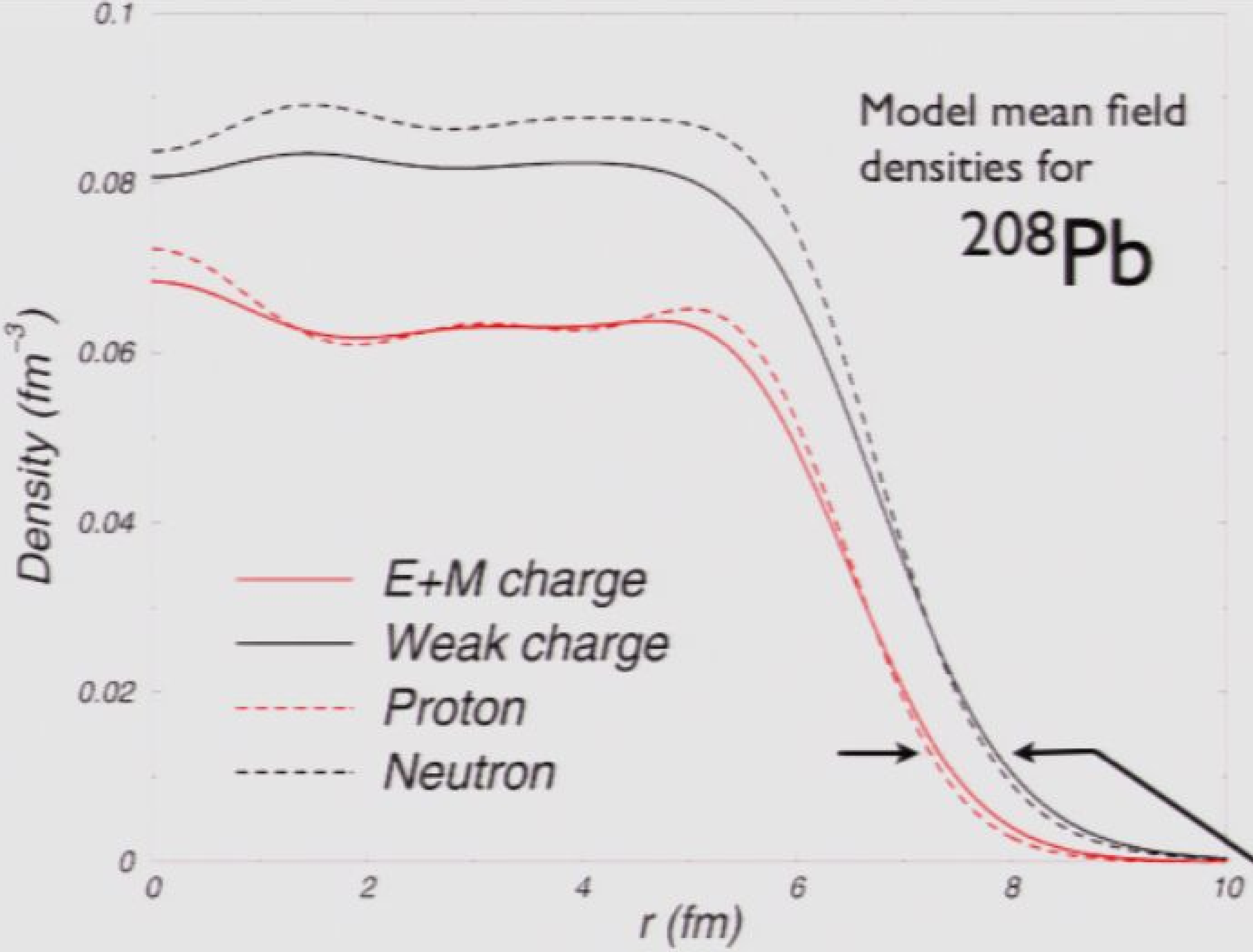
$$A_{pv} = \frac{d\sigma/d\Omega_+ - d\sigma/d\Omega_-}{d\sigma/d\Omega_+ + d\sigma/d\Omega_-}$$

- A_{pv} from interference of photon and Z^0 exchange. In Born approximation

$$A_{pv} = \frac{G_F Q^2}{2\pi\alpha\sqrt{2}} \frac{F_W(Q^2)}{F_{\mathrm{ch}}(Q^2)}$$

$$F_W(Q^2) = \int d^3r \frac{\sin(Qr)}{Qr} \rho_W(r)$$

- PREX aims to measure A_{pv} for 1.05 GeV electrons scattering from ^{208}Pb at 5 degrees to 3%. This gives neutron radius to 1% (+/- 0.05 fm).
- Note A_{pv} ~ 0.5 ppm.
  - – Donnelly, Dubach, Sick first suggested using PV to measure neutrons.



Model mean field densities for ^{208}Pb

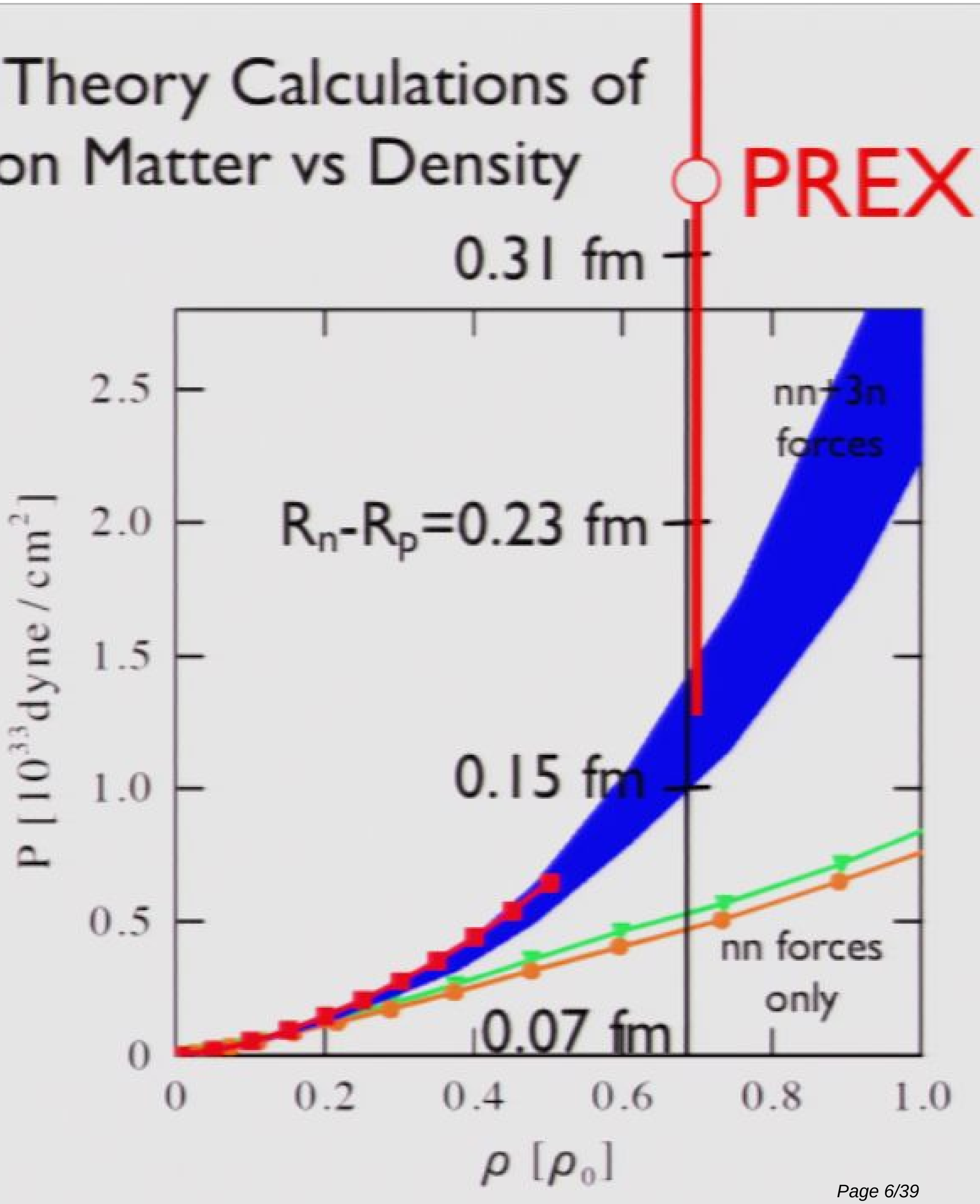
PREX

Spokespersons
K. Kumar
P. Souder
R. Michaels
G. Urchiuli

- PREX measures how much neutrons stick out past protons (neutron skin).
- First result announced April 30, 2011. Measured parity violating asymmetry: $A_{pv} = +0.6571 \pm 0.0604 \pm 0.0130$ ppm implies: $R_n\text{-}R_p = 0.34^{+0.15}_{-0.17}$ fm
- Plan to run again to obtain more statistics and reach 1% error +/- 0.05 fm for R_n, also second measurement in ^{48}Ca very attractive.

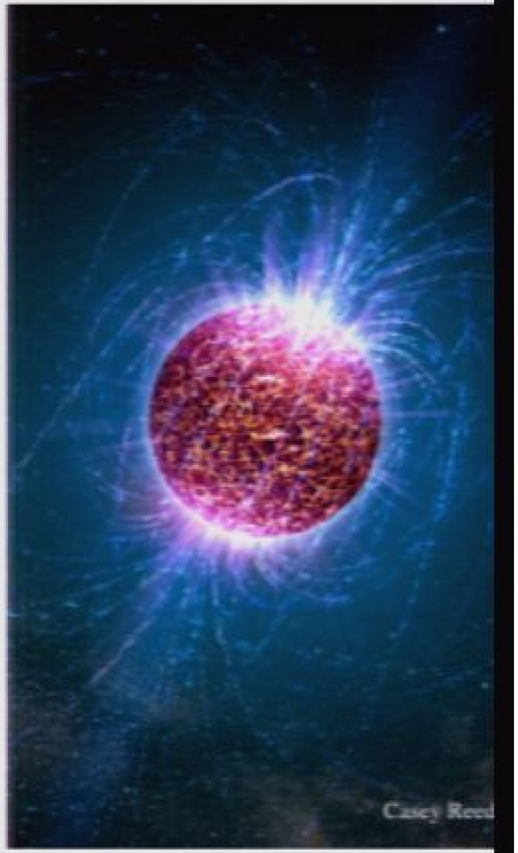
Chiral Effective Field Theory Calculations of Pressure of Neutron Matter vs Density

- A. Brown found strong correlation between pressure of neutron matter at a density of $0.66\rho_0$ and R_n-R_p in ^{208}Pb (see vertical black scale)
- Chiral EFT calc. by Hebeler et al. with only two n forces are green and brown while blue band shows results including 3 neutron forces. PRL **105**, 161102 (2010)
- PREX agrees with results including 3n forces. Hebeler et al. predict R_n-R_p=0.14 to 0.2 fm.



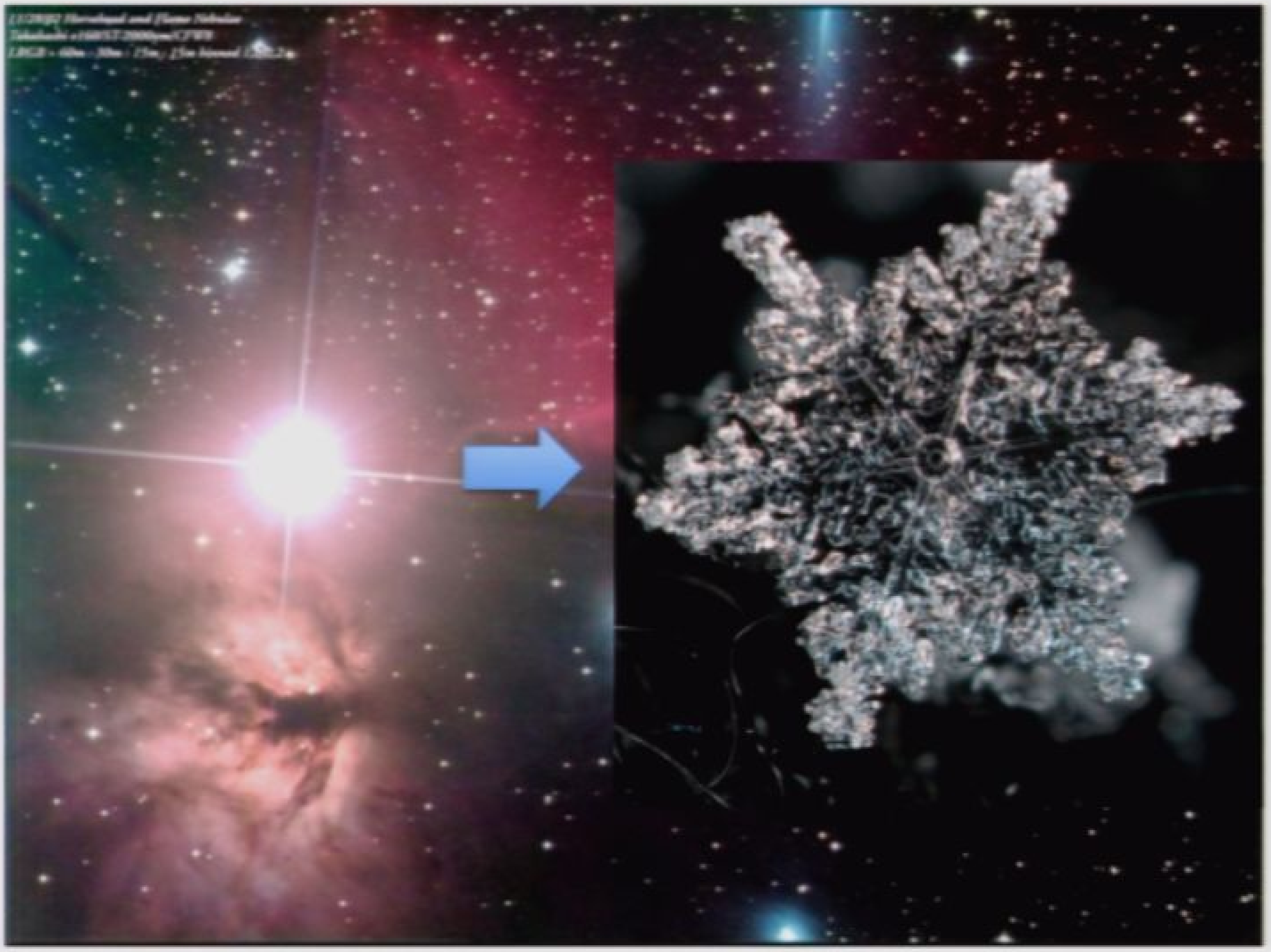
K. Hebeler, J. M. Lattimer, C. J. Pethick, A. Schwenk

Solid Microphysics


Casey Reed

- 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)
- ...

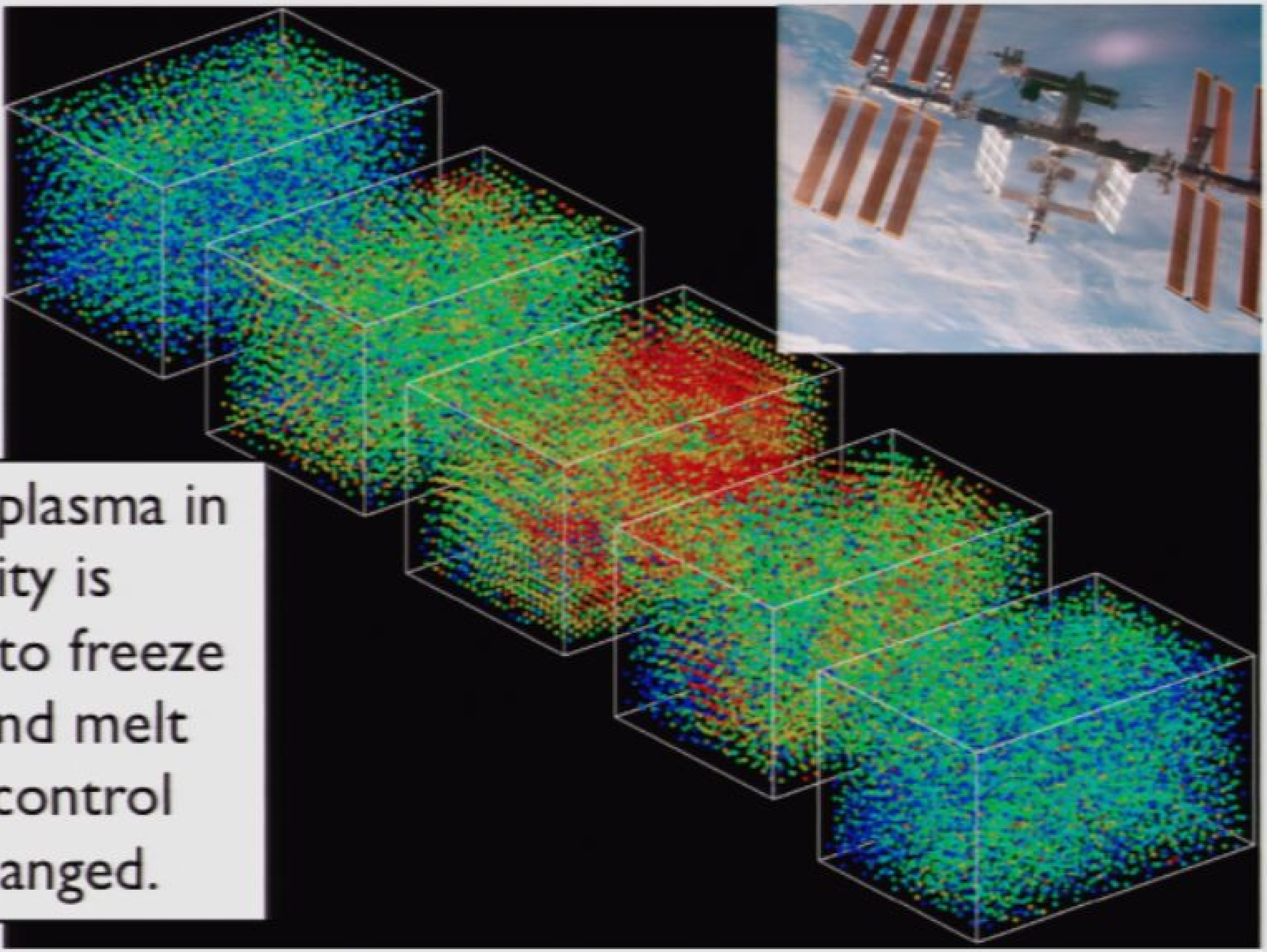
How Stars Freeze



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



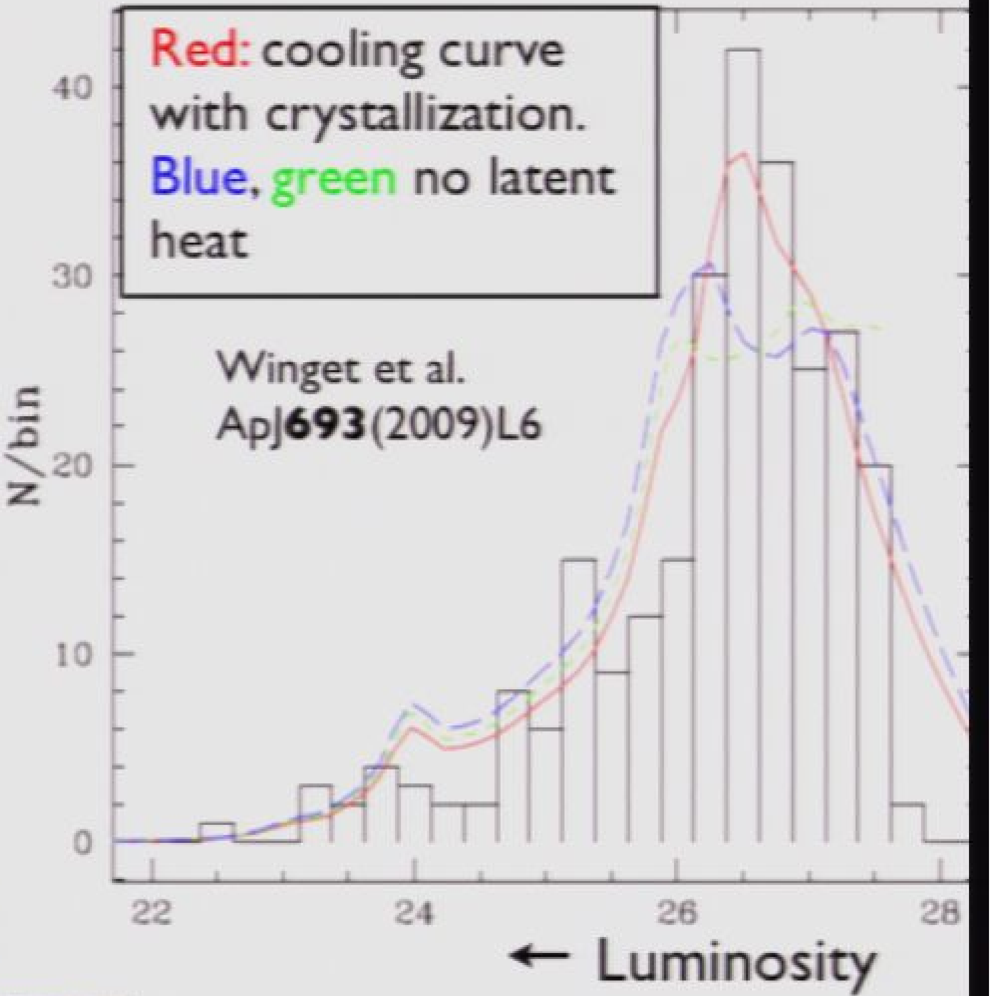
Complex plasma in microgravity is observed to freeze (center) and melt (right) as control voltage changed.

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)


Red: cooling curve with crystallization. Blue, green no latent heat

Winget et al. ApJ**693**(2009)L6

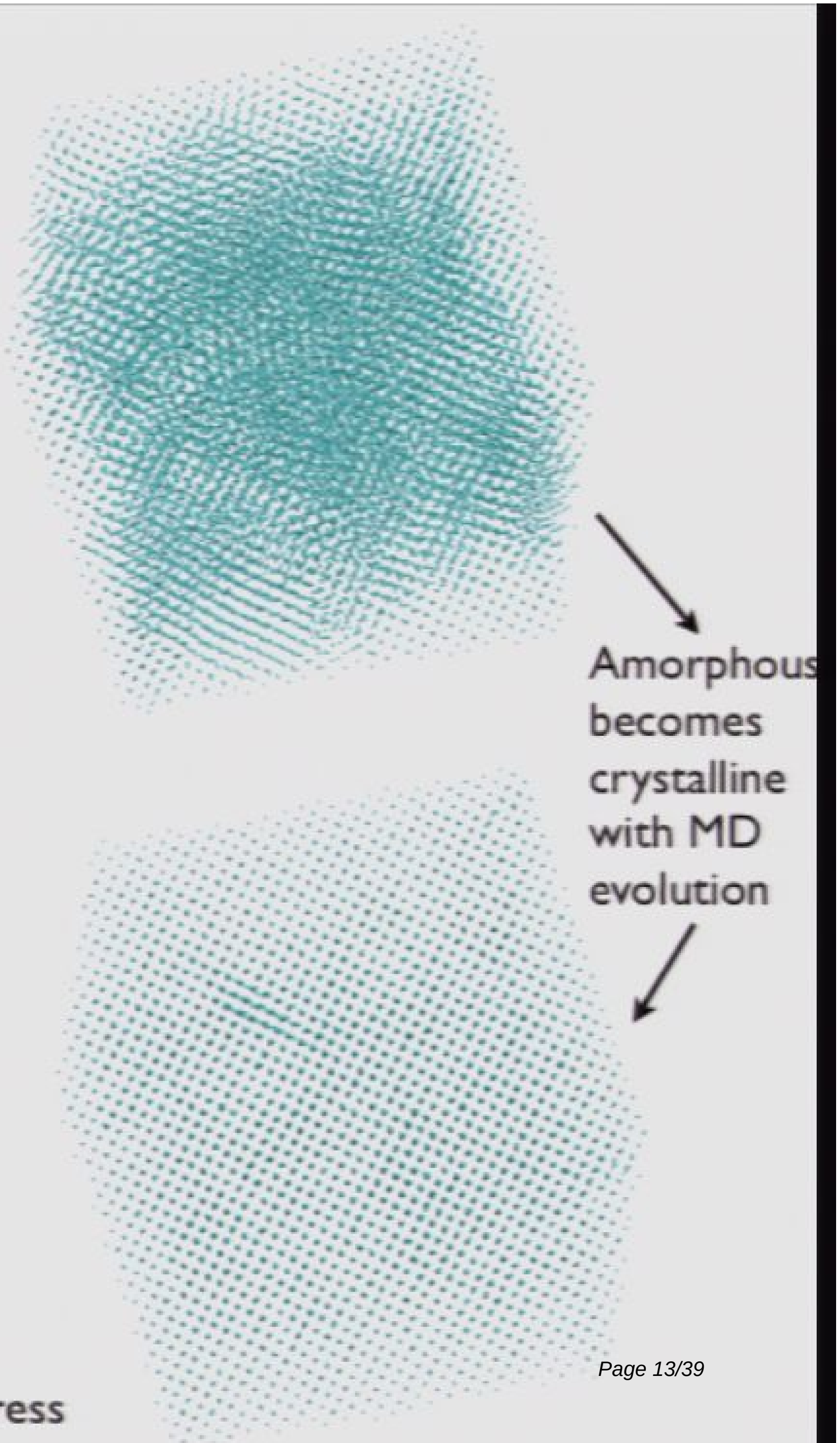
Globular cluster NGC 6397 (Hubble)

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*.



Amorphous
becomes
crystalline
with MD
evolution

arXiv:1104.4822, Phys. Rev. E in press

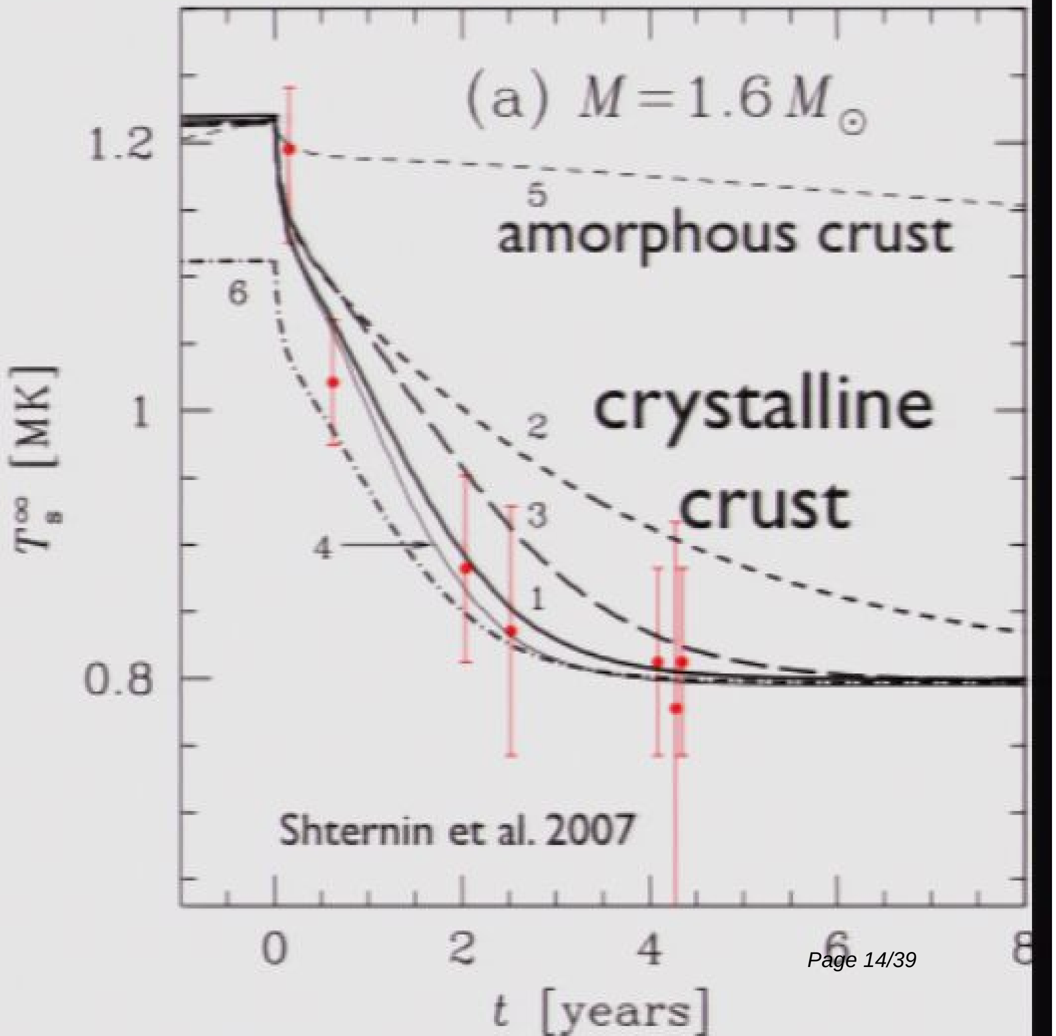
Cooling of KS 1730-260 Surface After Extended Outburst

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)

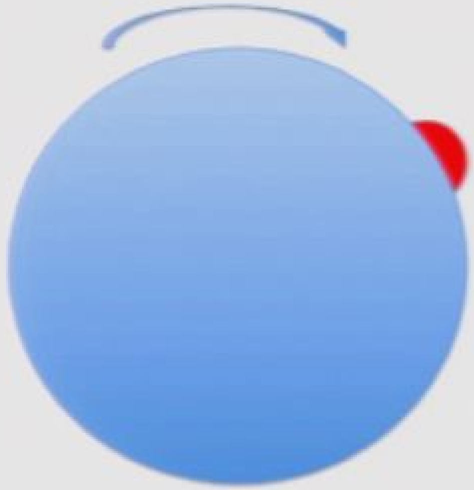
Data favor high thermal conductivity crystalline crust.



Shternin et al. 2007

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?

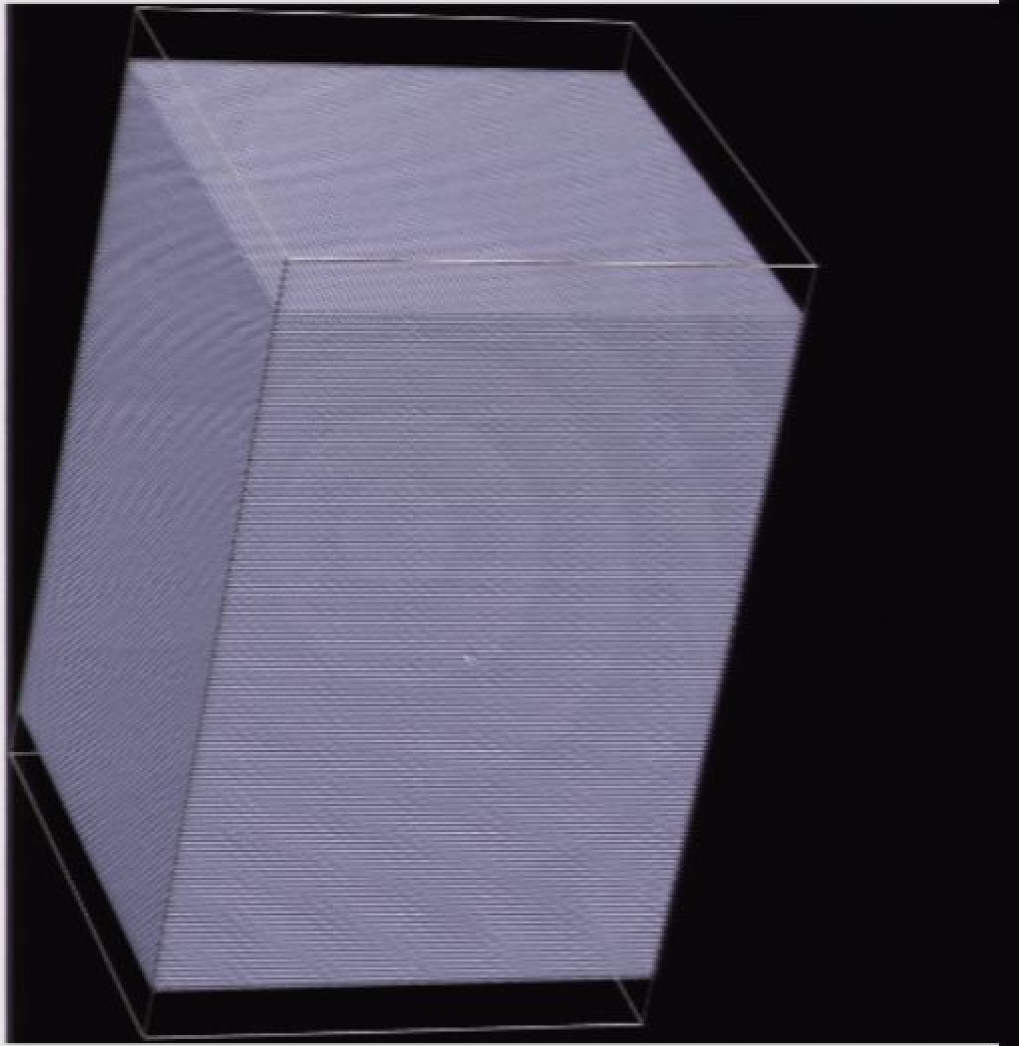


Mountain (red) on rotating neutron star.

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.

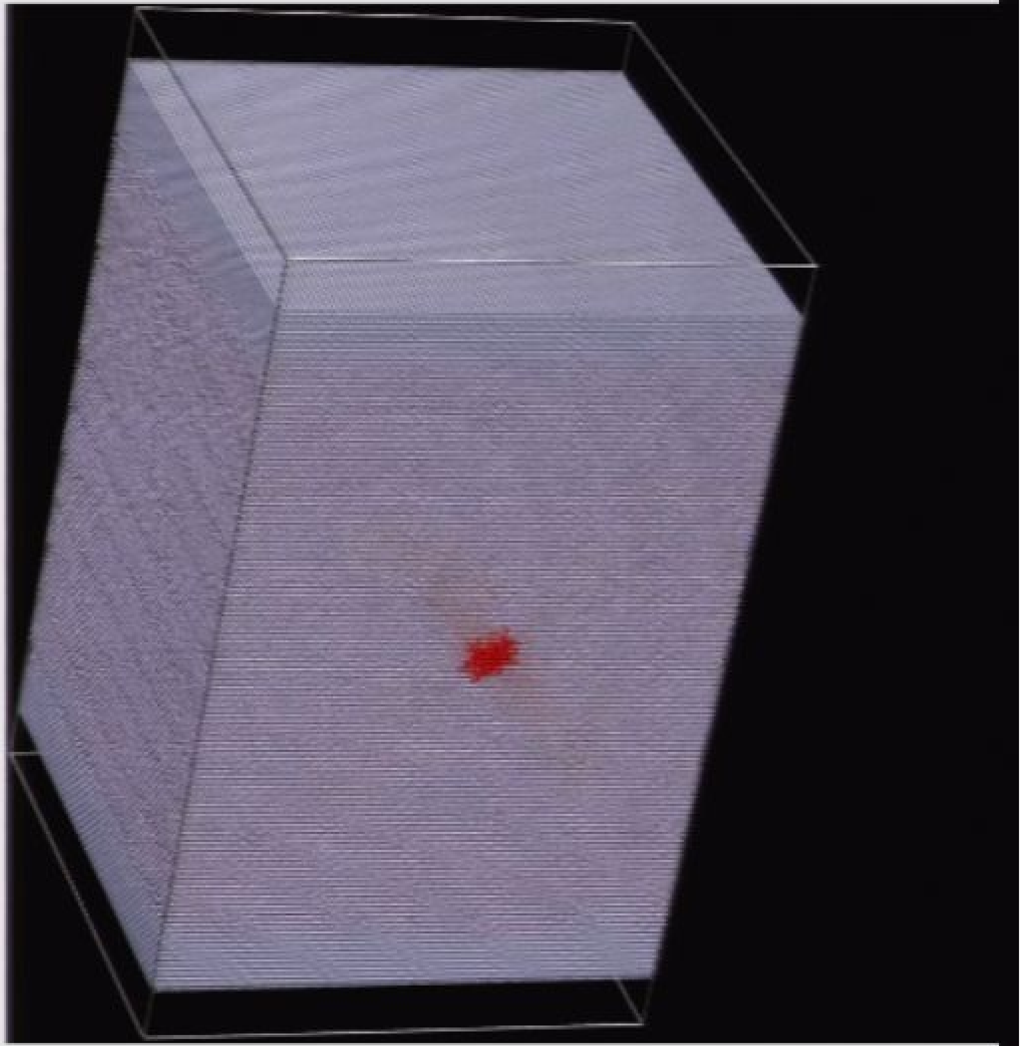


Movie of breaking of 1.7 million ion crystal with defect in center. Red indicates deformation.

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

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.

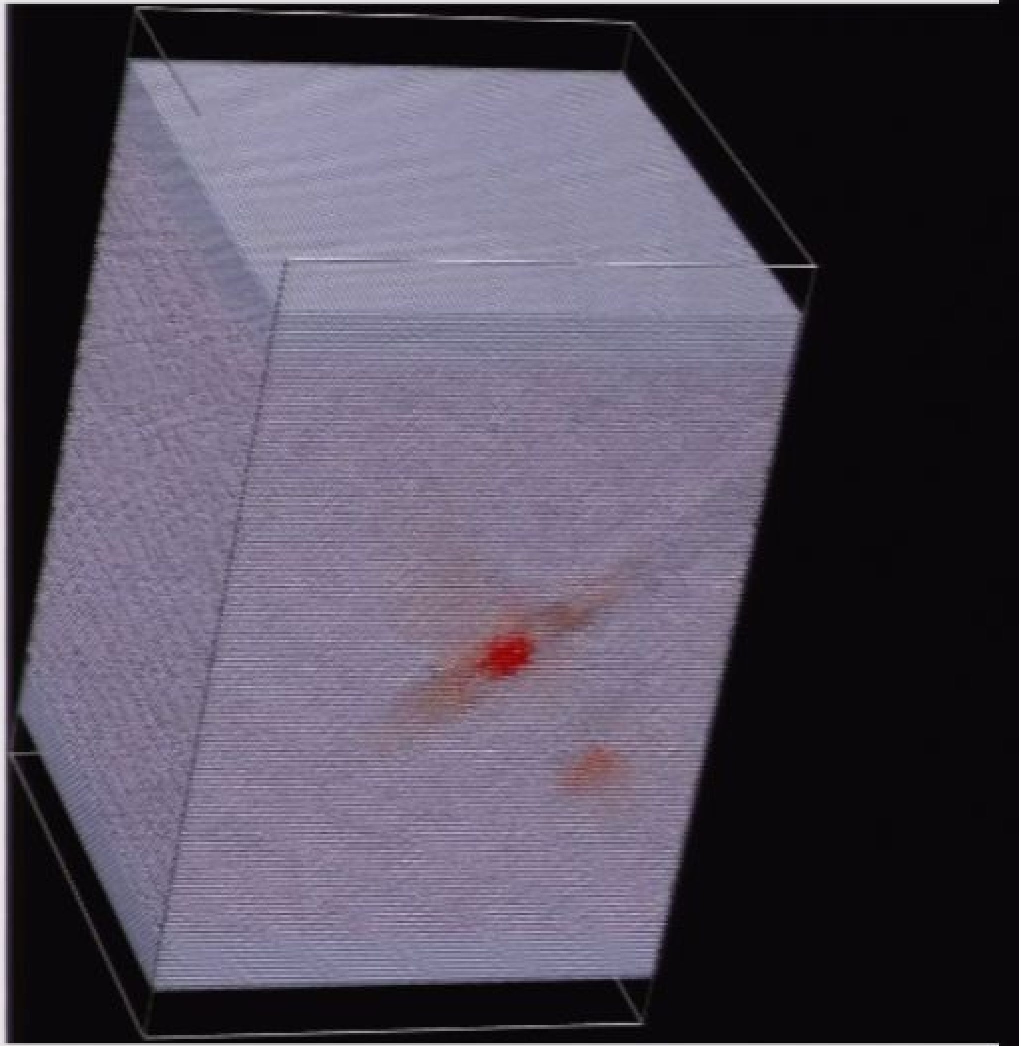


Movie of breaking of 1.7 million ion crystal with defect in center. Red indicates deformation.

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

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.

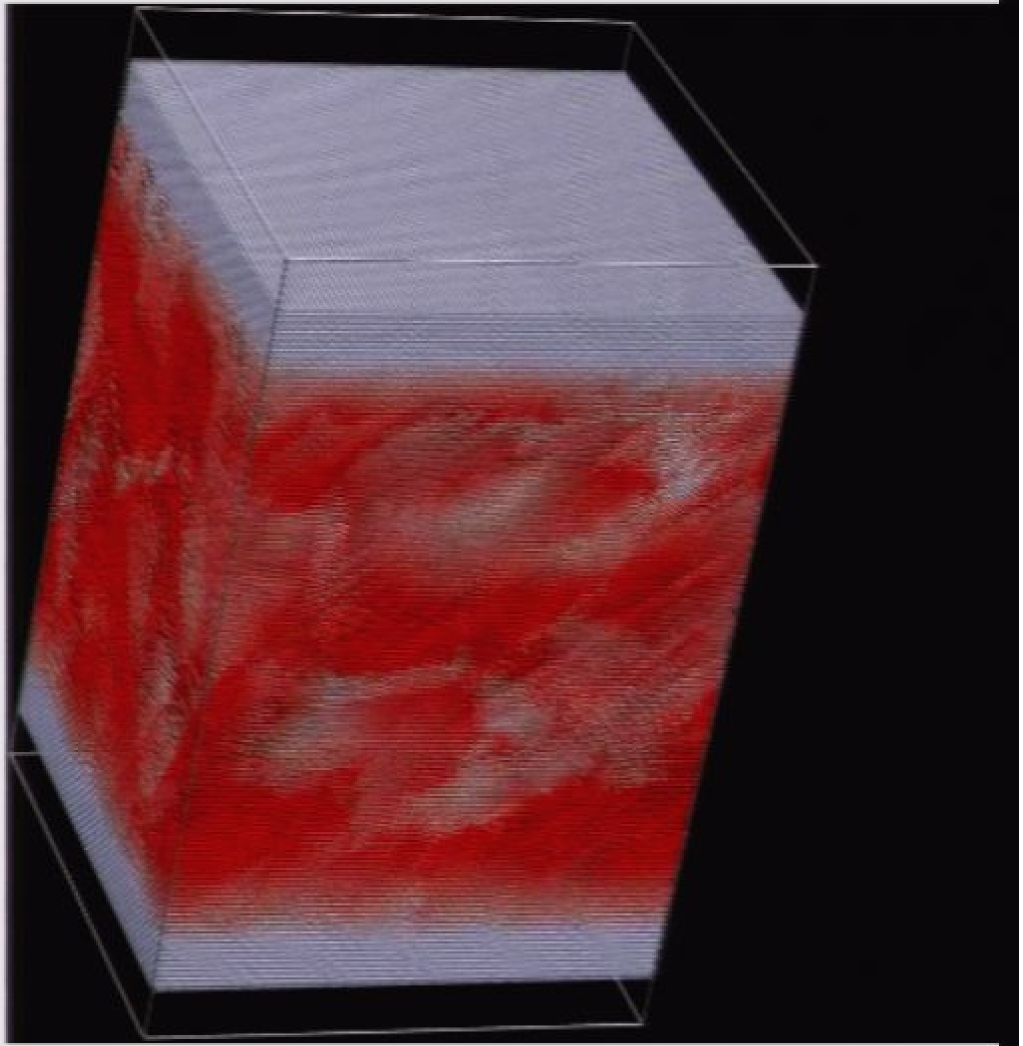


Movie of breaking of 1.7 million ion crystal with defect in center. Red indicates deformation.

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

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.

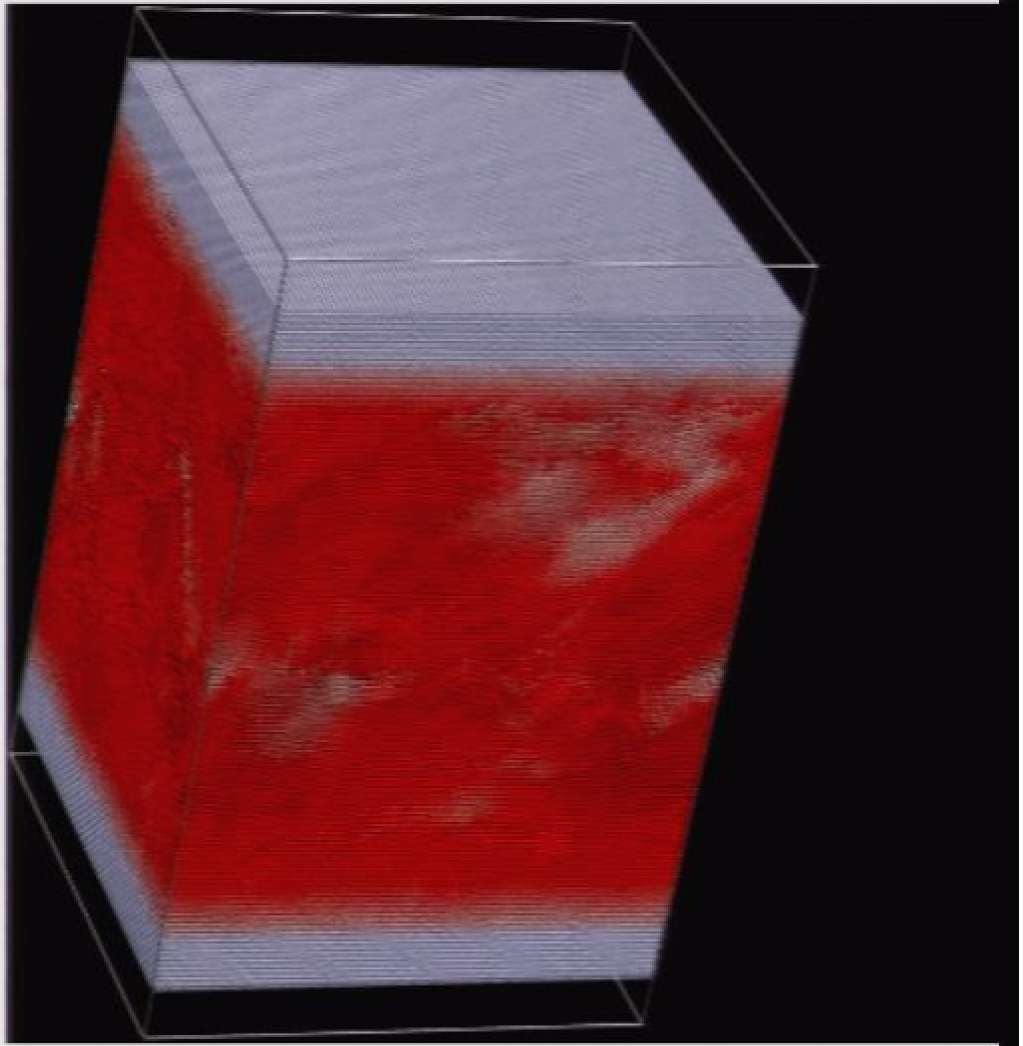


Movie of breaking of 1.7 million ion crystal with defect in center. Red indicates deformation.

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

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.

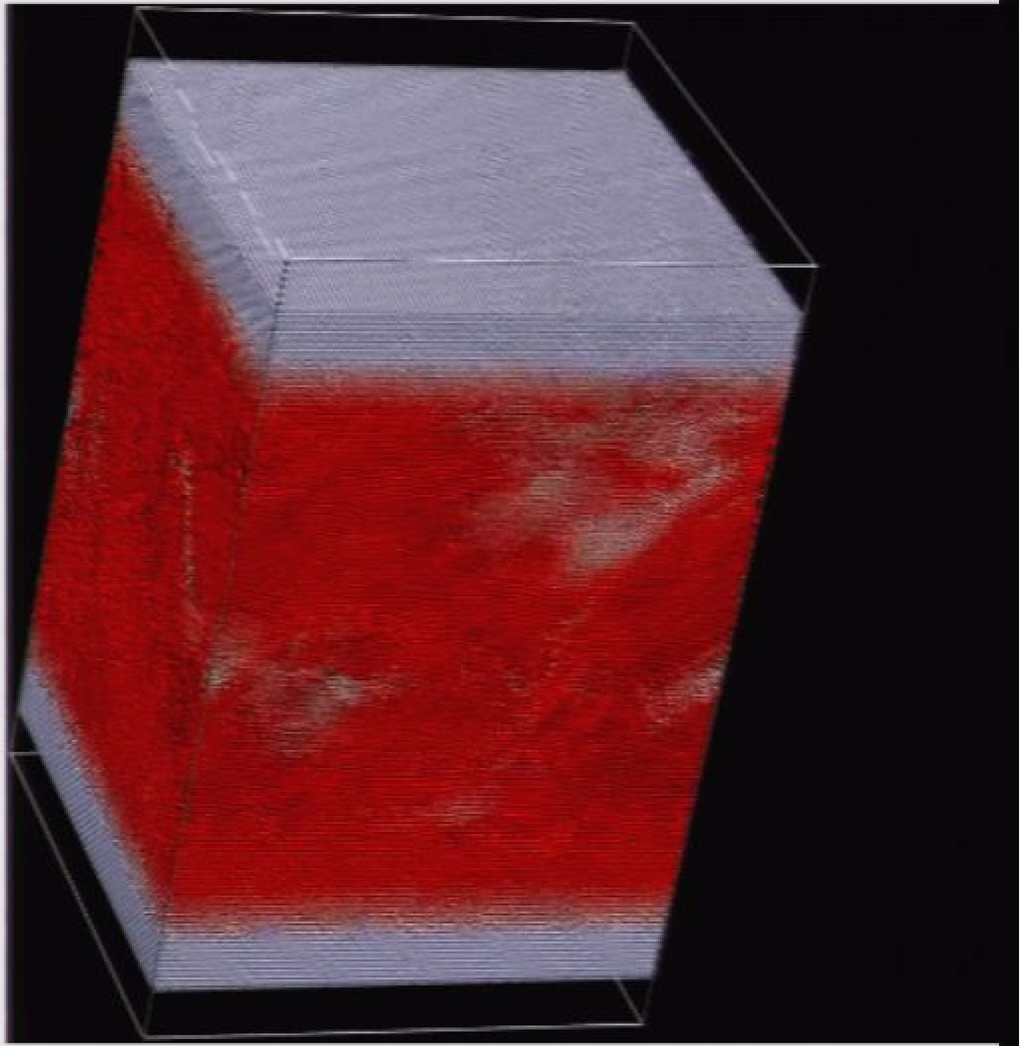


Movie of breaking of 1.7 million ion crystal with defect in center. Red indicates deformation.

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

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.

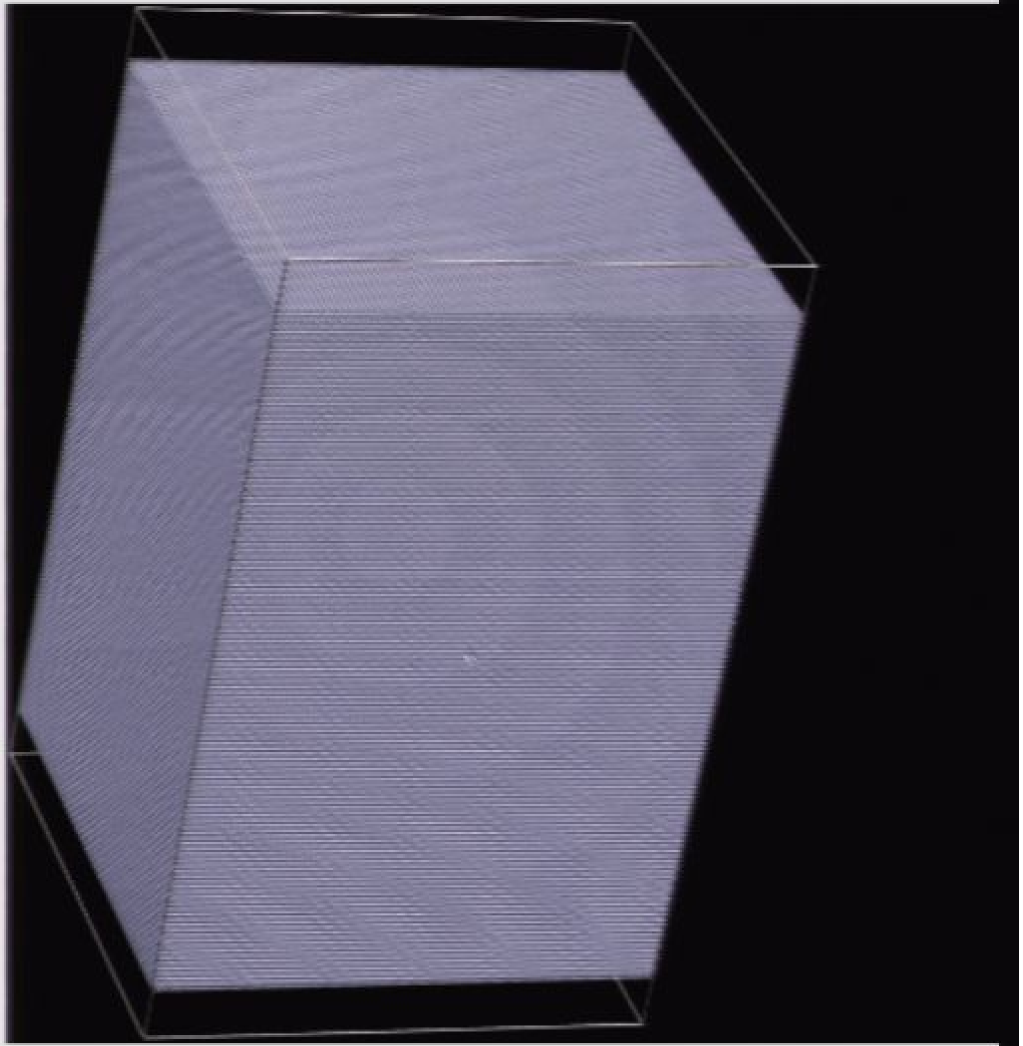


Movie of breaking of 1.7 million ion crystal with defect in center. Red indicates deformation.

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

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.

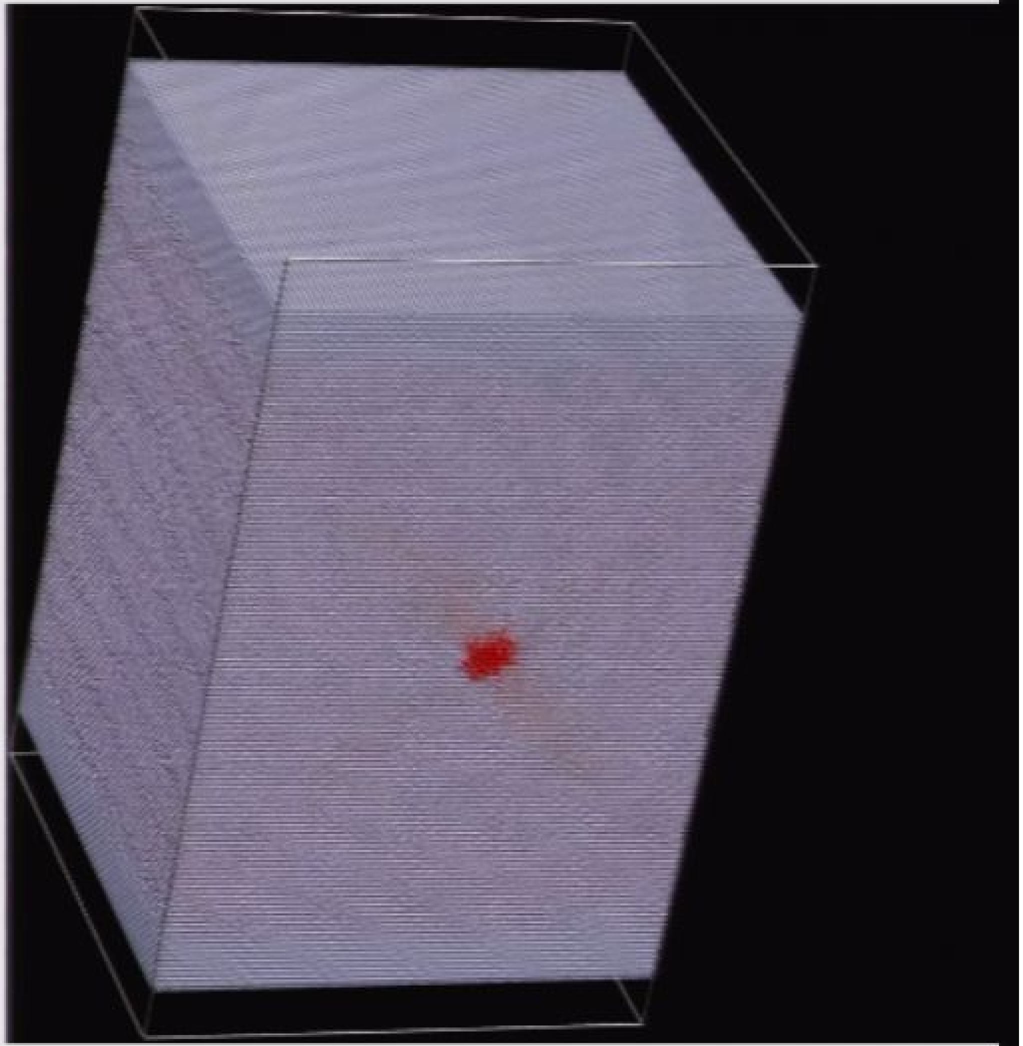


Movie of breaking of 1.7 million ion crystal with defect in center. Red indicates deformation.

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

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.

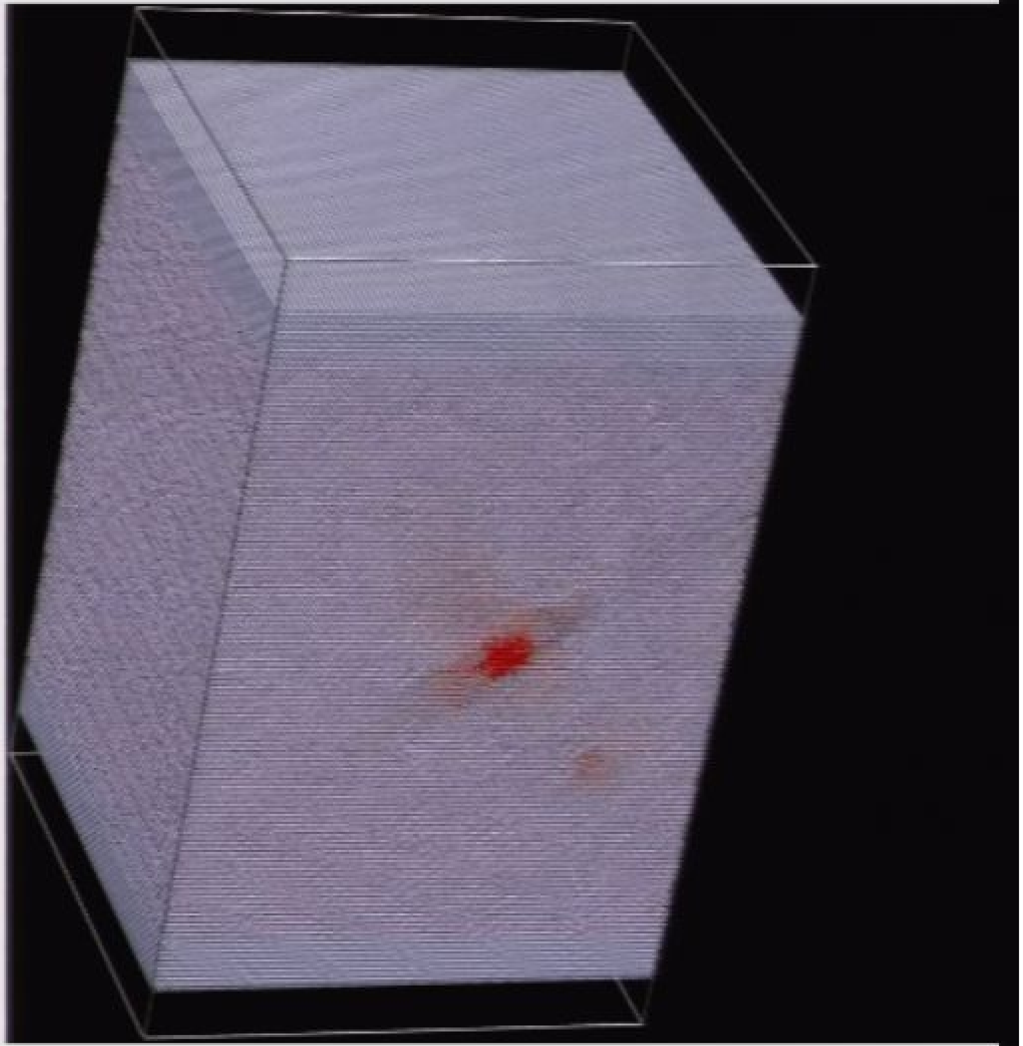


Movie of breaking of 1.7 million ion crystal with defect in center. Red indicates deformation.

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

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.

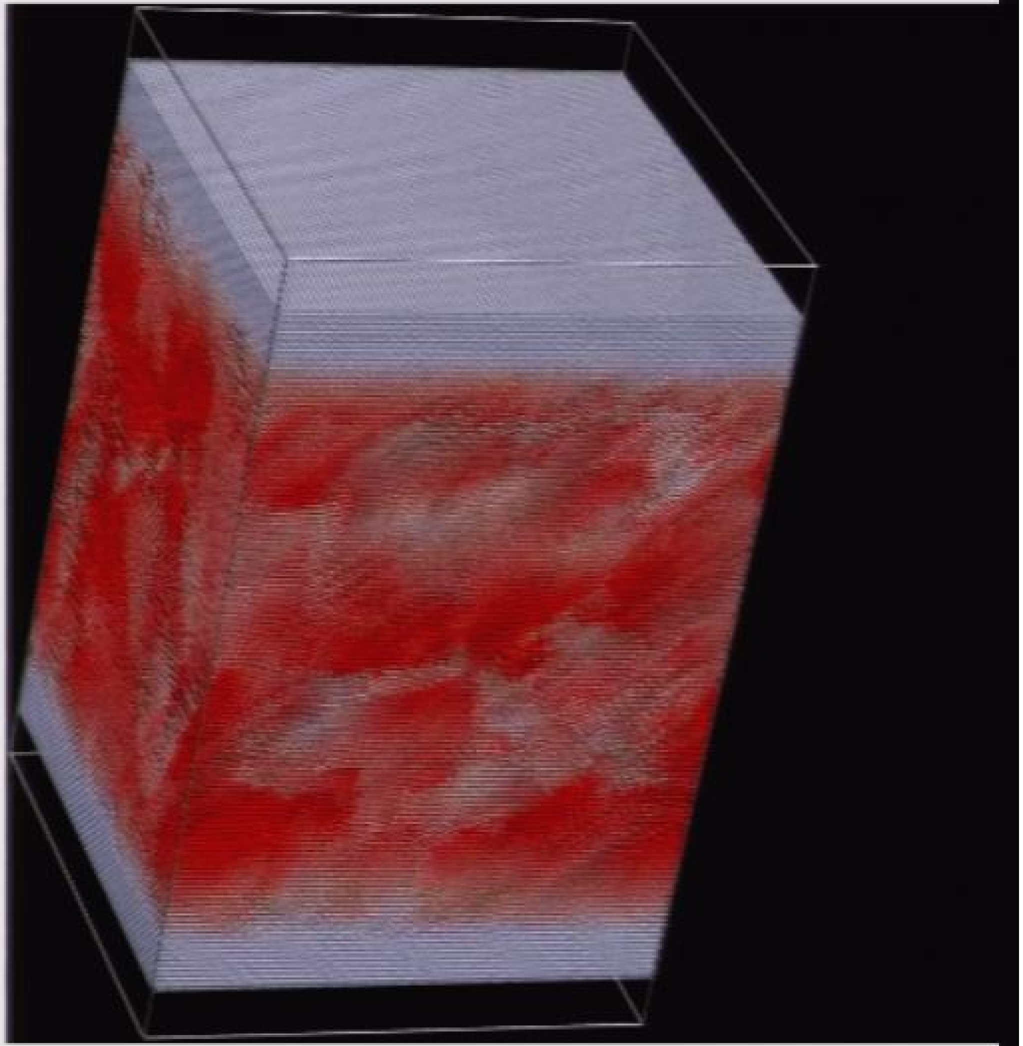


Movie of breaking of 1.7 million ion crystal with defect in center. Red indicates deformation.

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

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.

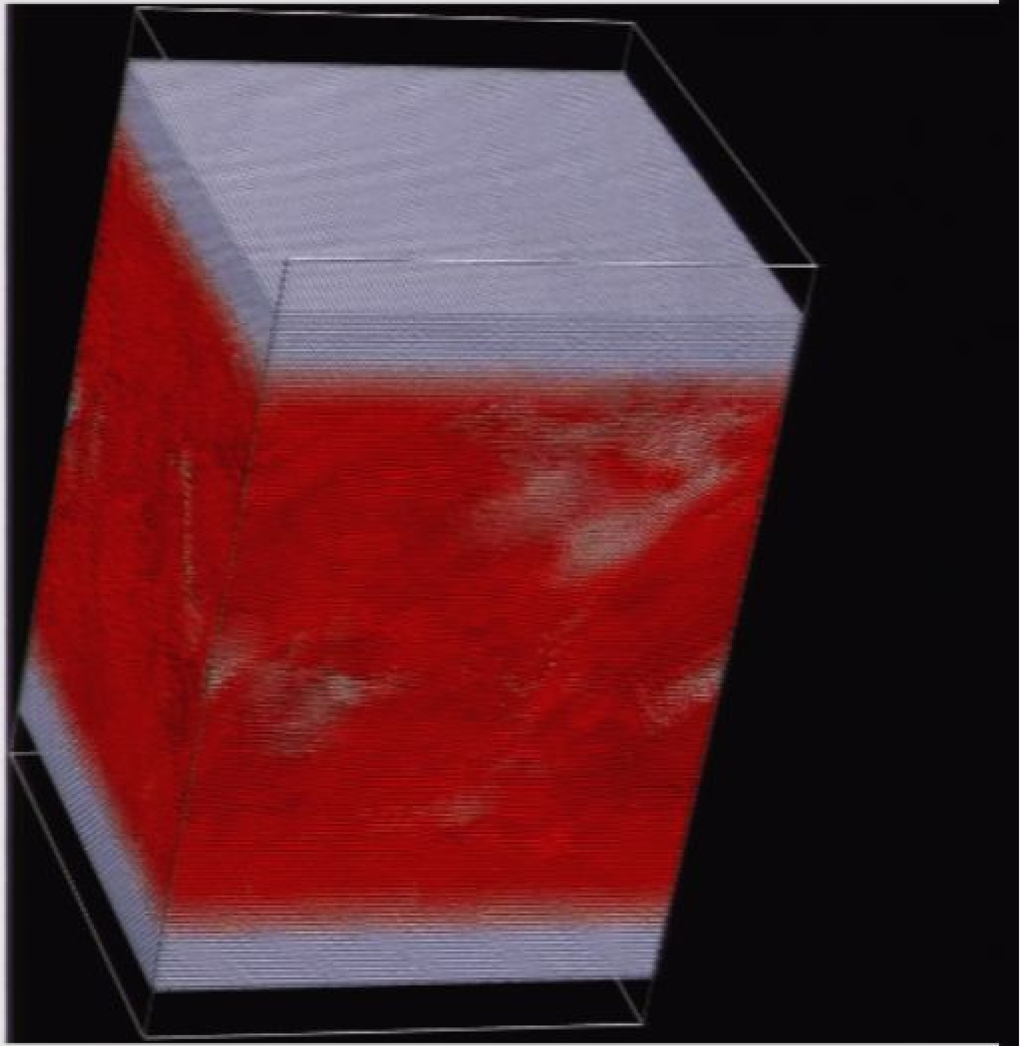


Movie of breaking of 1.7 million ion crystal with defect in center. Red indicates deformation.

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

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.

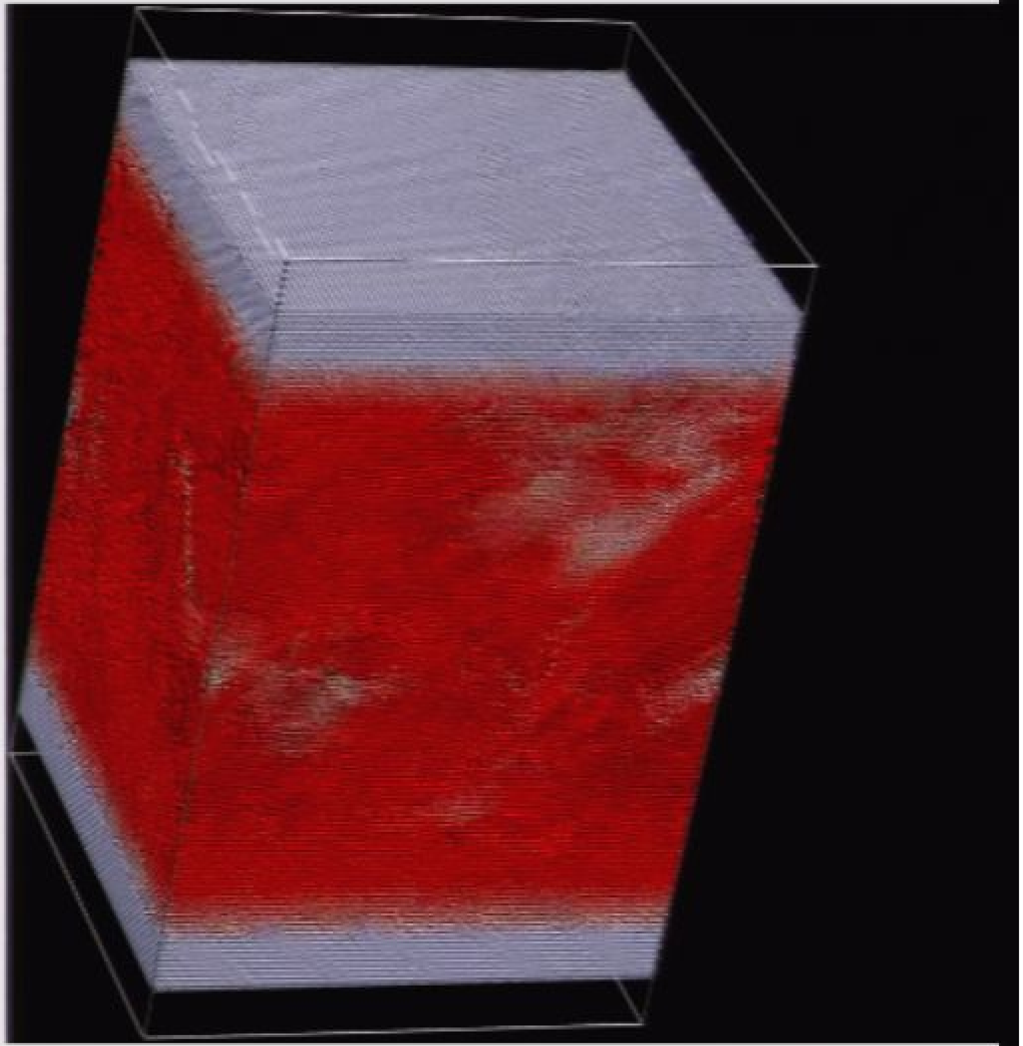


Movie of breaking of 1.7 million ion crystal with defect in center. Red indicates deformation.

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

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 with defect in center. Red indicates deformation.

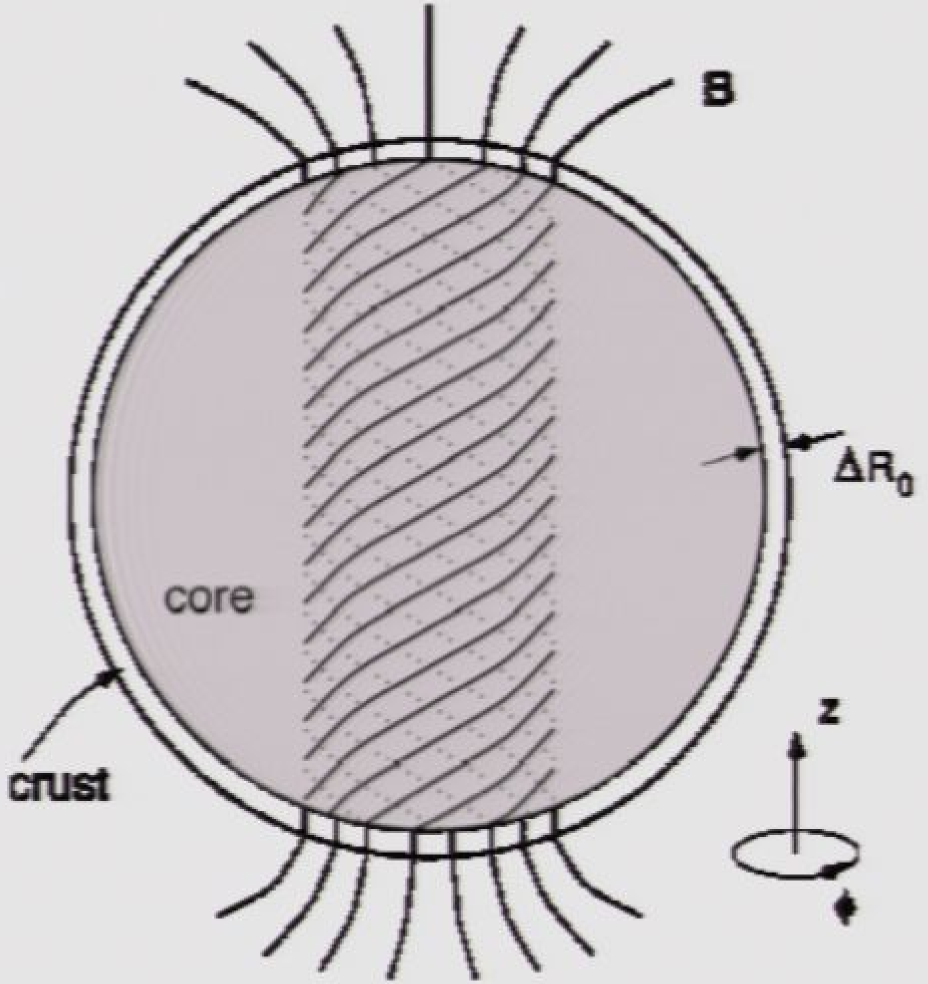
CJH, Kai Kadau, Phys Rev Let. **102**,191102 (2009)

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.*

Curst Breaking Mechanism for Giant Flares

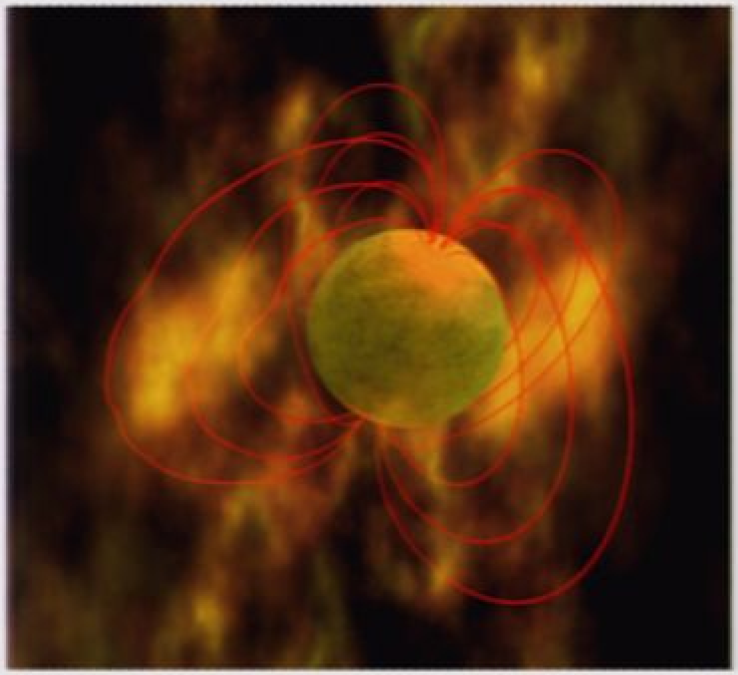
- Twisted magnetic field diffuses and stresses crust.
- Crust breaks and moves allowing magnetic field to reconnect, releasing huge energy observed in giant flares.
- We find the crust is very strong and can control large energy in the magnetic field.



Thompson + Duncan

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 ~ 1000 x L_{MW}
  - $E_{bol} \sim 4 \times 10^{46}$ erg ~ 300 kyr x $L_{\odot}$
  - 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)

Gravitational Wave Searches

EINSTEIN@HOME

EINSTEIN@HOME

Catch a Wave From Space

- 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. Cygnus X-1
  - **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

Gravitational Wave Searches

EINSTEIN@HOME

Catch a Wave From Space

- 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. Cygnus X-1
  - **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.
  - ...

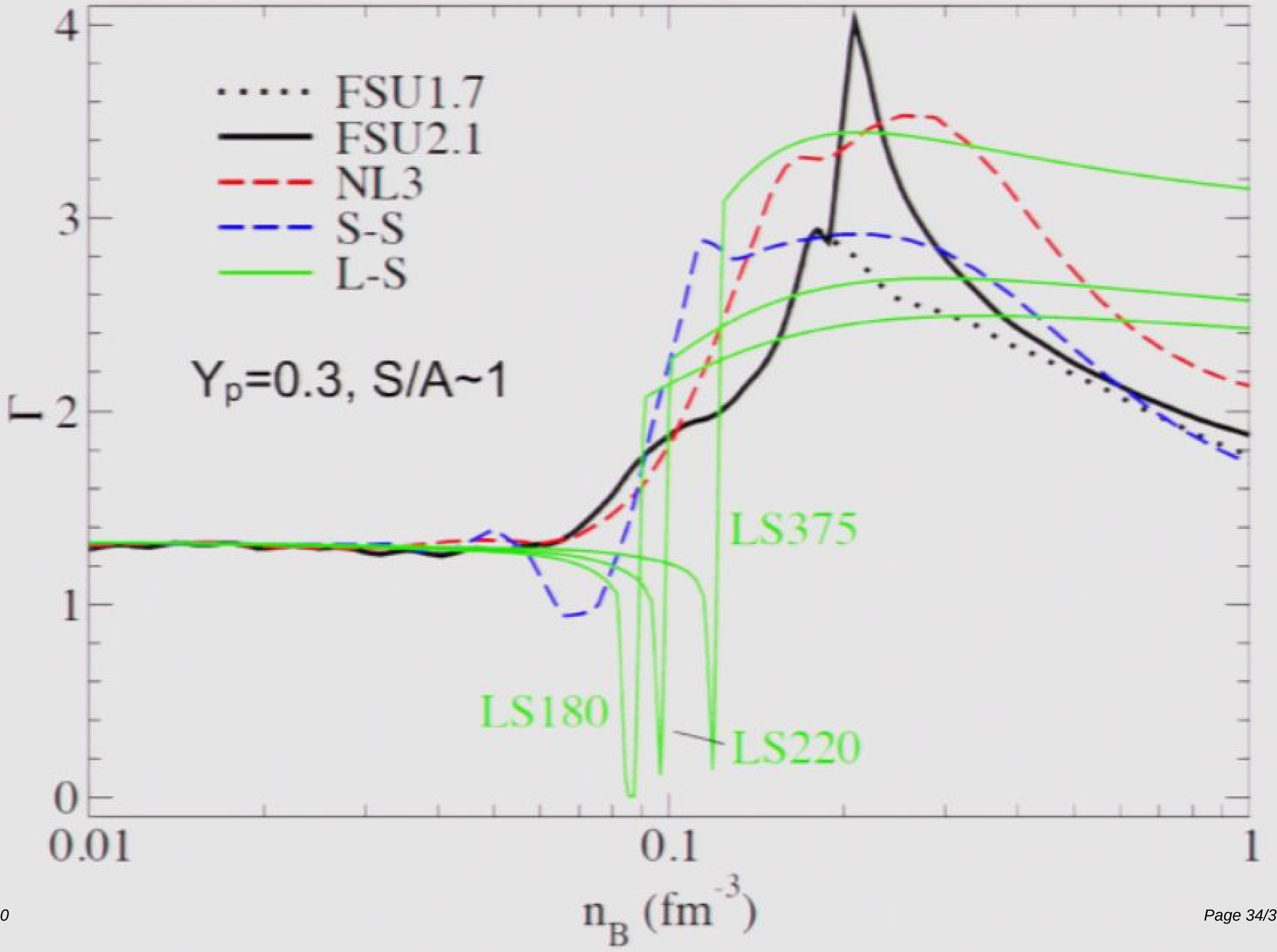
Near Shoemaker images of asteroid 433 Eros

Hubble images of dwarf planet Ceres

Open Pasta Questions

- Shear viscosity?
- Bulk viscosity (density changes drive pasta phase changes which may be slow)?
- Shear modulus, breaking strain? Strongest point in crust (important for mountains and star quakes) probably just before pasta forms.
- ...?
- How to “smell the pasta”? What observables are sensitive to pasta?

Adiabatic Index $\Gamma = d\ln P / d\ln n_B$



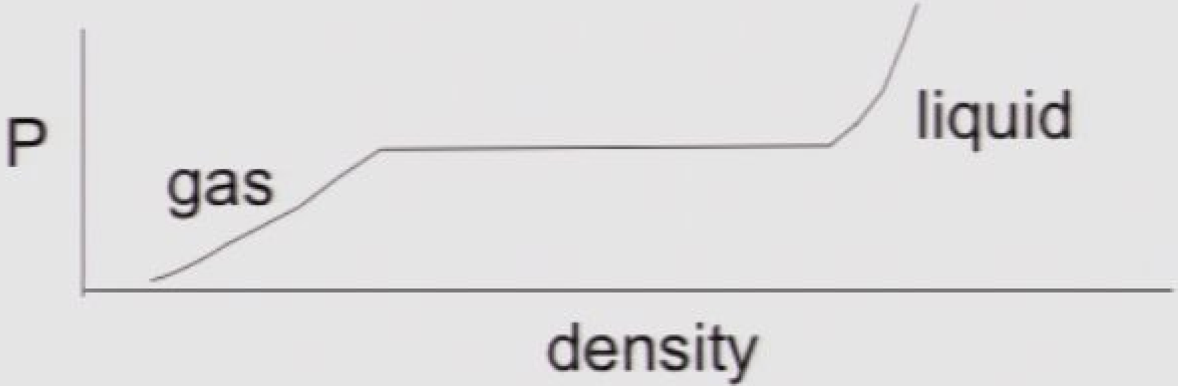
Neutron Stars Crust Microphysics

- PREX uses parity violating electron scattering to accurately measure the neutron radius of ^{208}Pb. This has implications for nuclear structure, astrophysics, and atomic parity violation.
- We performed large scale MD simulations of solids in white dwarfs and neutron stars. Coulomb crystals are likely nearly perfect with few defects. Give very large breaking strain.

- Collaborators D. Berry, E. Brown, A. Chugunov, K. Kadau, J. Piekarewicz Students: L. Caballero, H. Dussan, J. Hughto, A. Schneider, and G. Shen.
- Supported in part by DOE and State of Indiana.

Liquid-Gas Phase Transition

- In heavy ion collisions, coulomb is not dominant, and one can have a 1st order phase transition.
- In astrophysics, coulomb implies average proton density = electron density. Fraction of system that is liquid is fixed. ***NO large region with P independent of density.***
- 1st order phase transition for LS EOS is artifact of simple approximations.

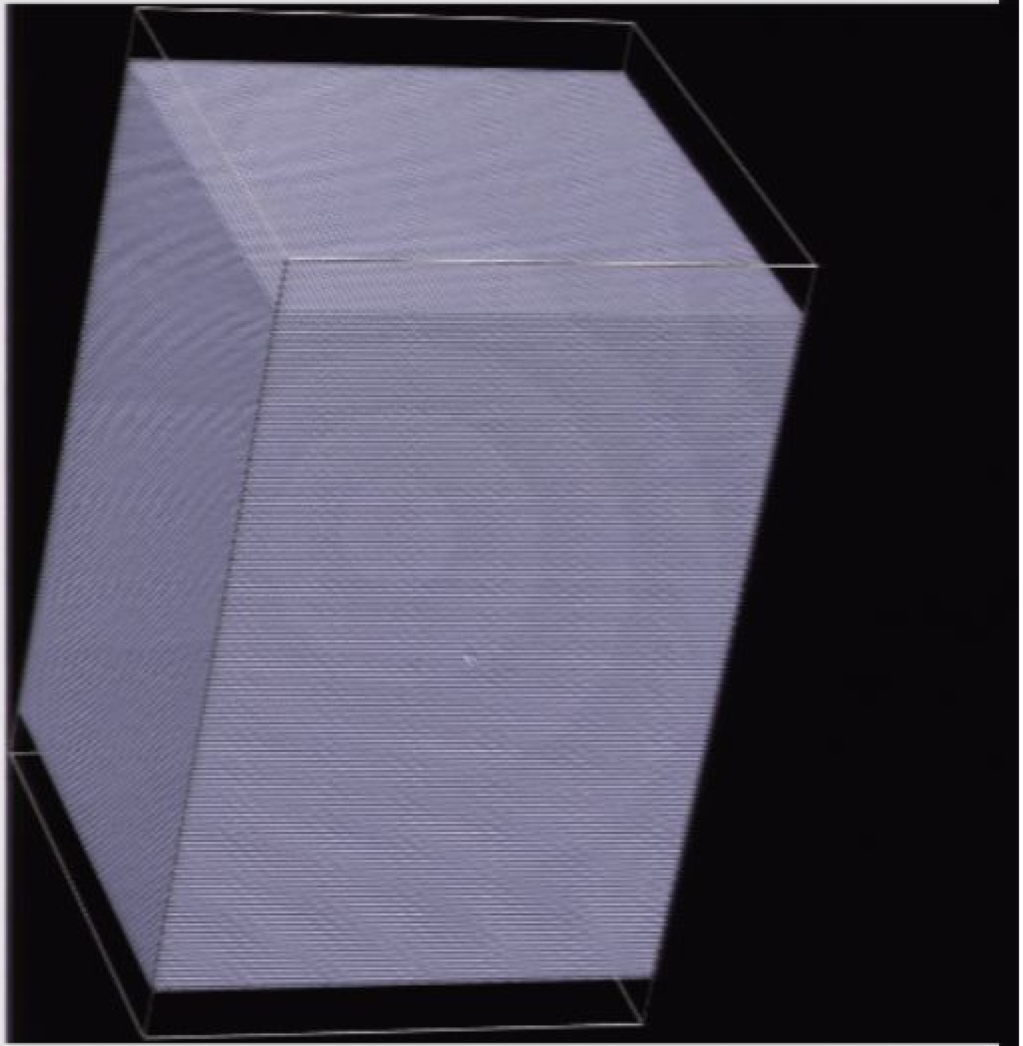


Open Pasta Questions

- Shear viscosity?
- Bulk viscosity (density changes drive pasta phase changes which may be slow)?
- Shear modulus, breaking strain? Strongest point in crust (important for mountains and star quakes) probably just before pasta forms.
- ...?
- How to “smell the pasta”? What observables are sensitive to pasta?

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 with defect in center. Red indicates deformation.

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

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.*