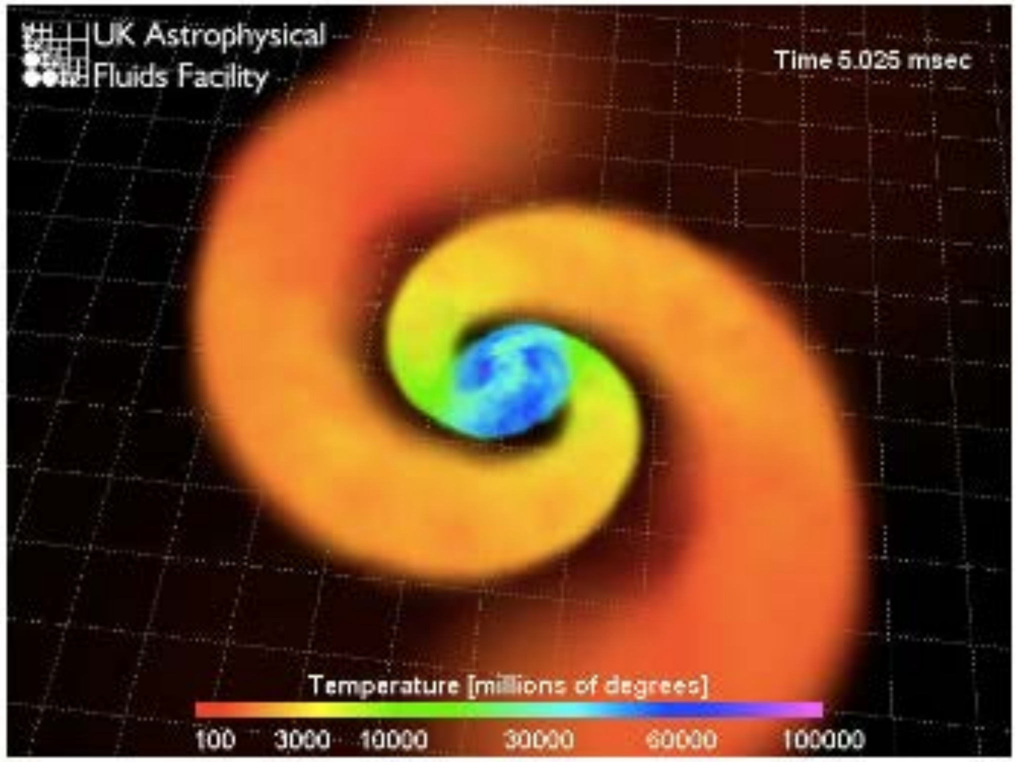
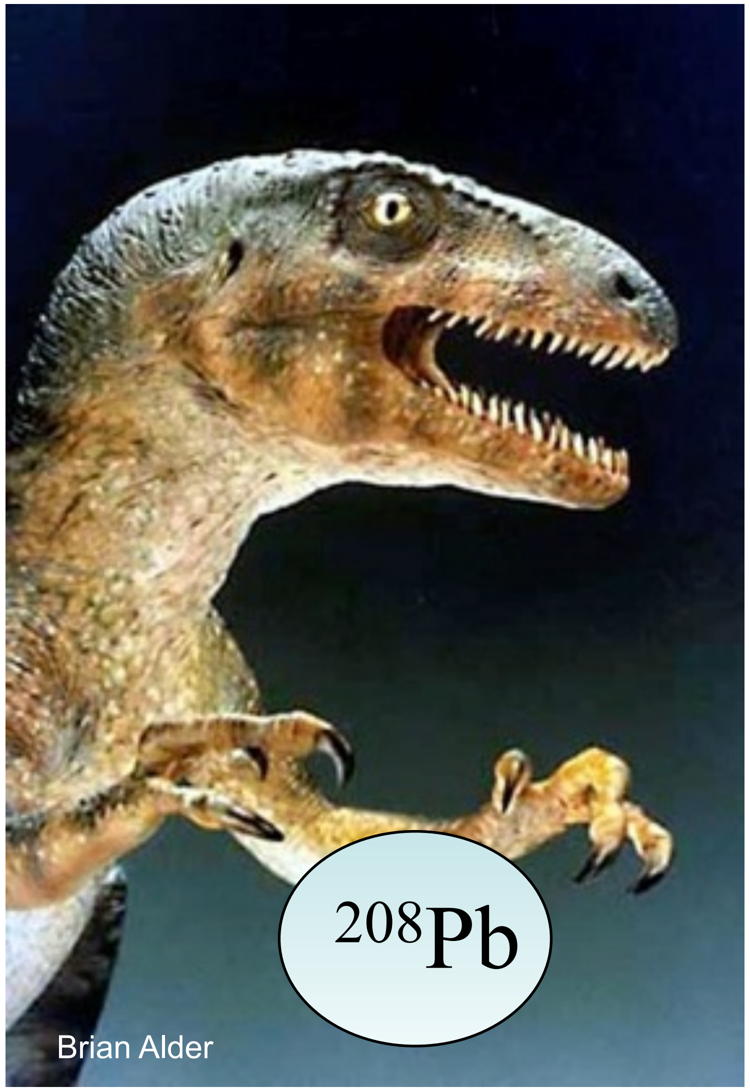
The Crust of Merging Neutron Stars



- C. J. Horowitz, Indiana University
- INT, July 2014

The crust of merging neutron stars



- **PREX** uses parity violating electron scattering to accurately measure the neutron radius of ^{208}Pb.
- Merger nucleosynthesys and nuclear pasta.
- MD simulations of nuclear pasta.
- MD simulations of ions and strength of neutron star (outer) crust.

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

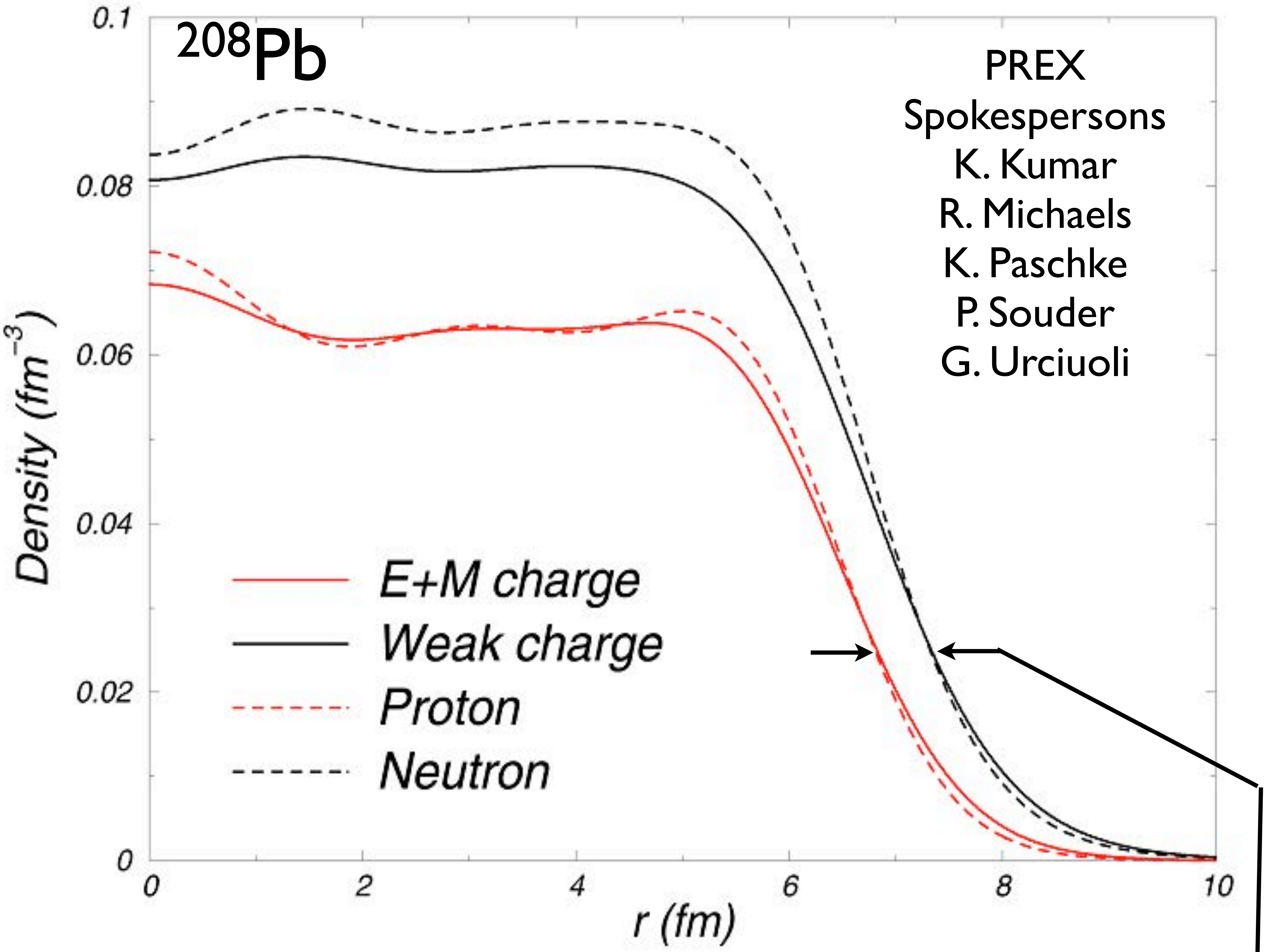
$$A_{pv} = \frac{d\sigma/d\Omega_+ - d\sigma/d\Omega_-}{d\sigma/d\Omega_+ + d\sigma/d\Omega_-}$$

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

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

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

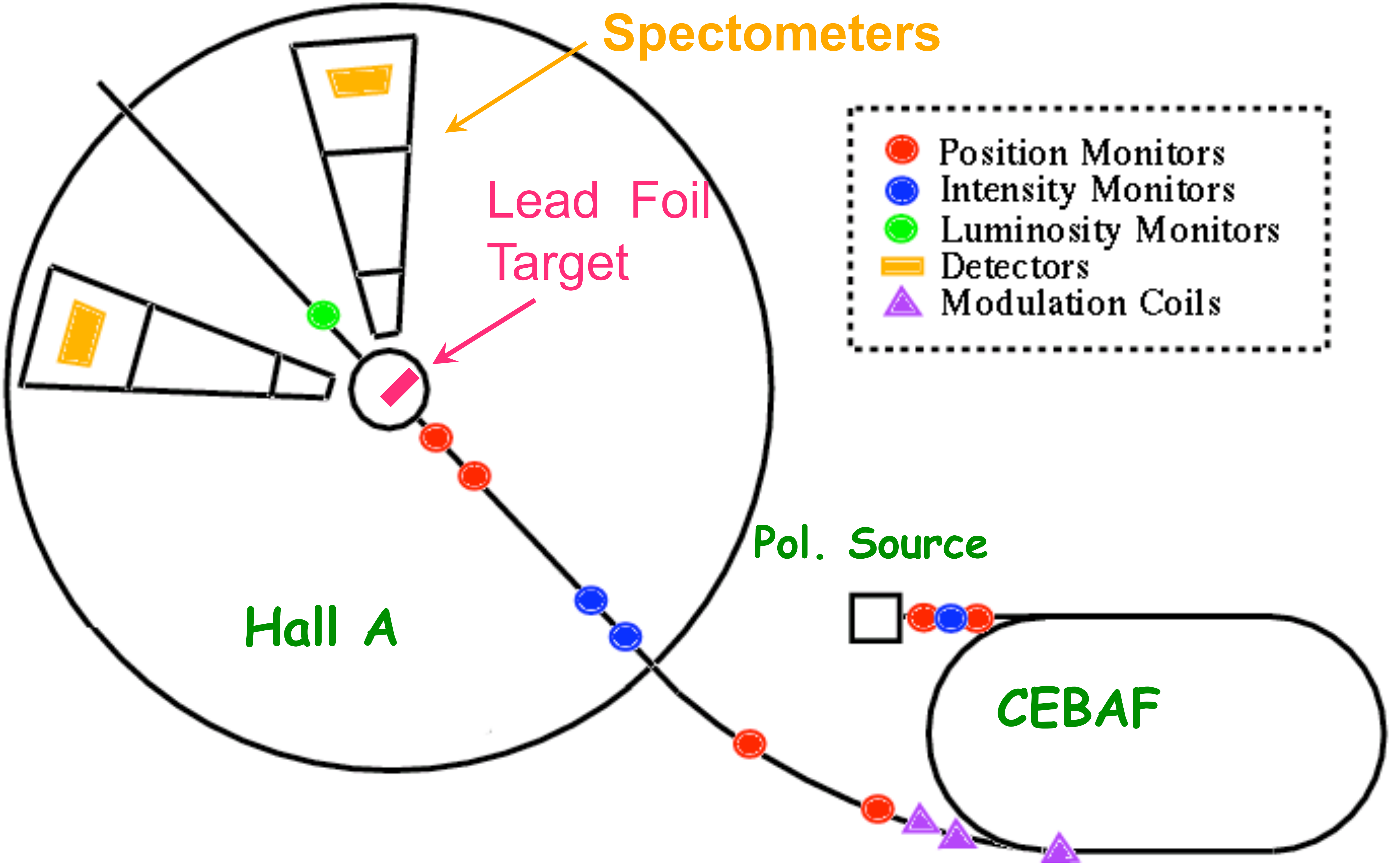
- Model independently map out distribution of weak charge in a nucleus.
- **Electroweak reaction free from most strong interaction uncertainties.**
  - Donnelly, Dubach, Sick first suggested PV to measure neutrons.



PREX
Spokespersons
K. Kumar
R. Michaels
K. Paschke
P. Souder
G. Urciuoli

- PREX measures how much neutrons stick out past protons (neutron skin).

PREX in Hall A at JLab



Spectometers

Lead Foil Target

- 🔴 Position Monitors
- 🔵 Intensity Monitors
- 🟢 Luminosity Monitors
- 🟧 Detectors
- △ Modulation Coils

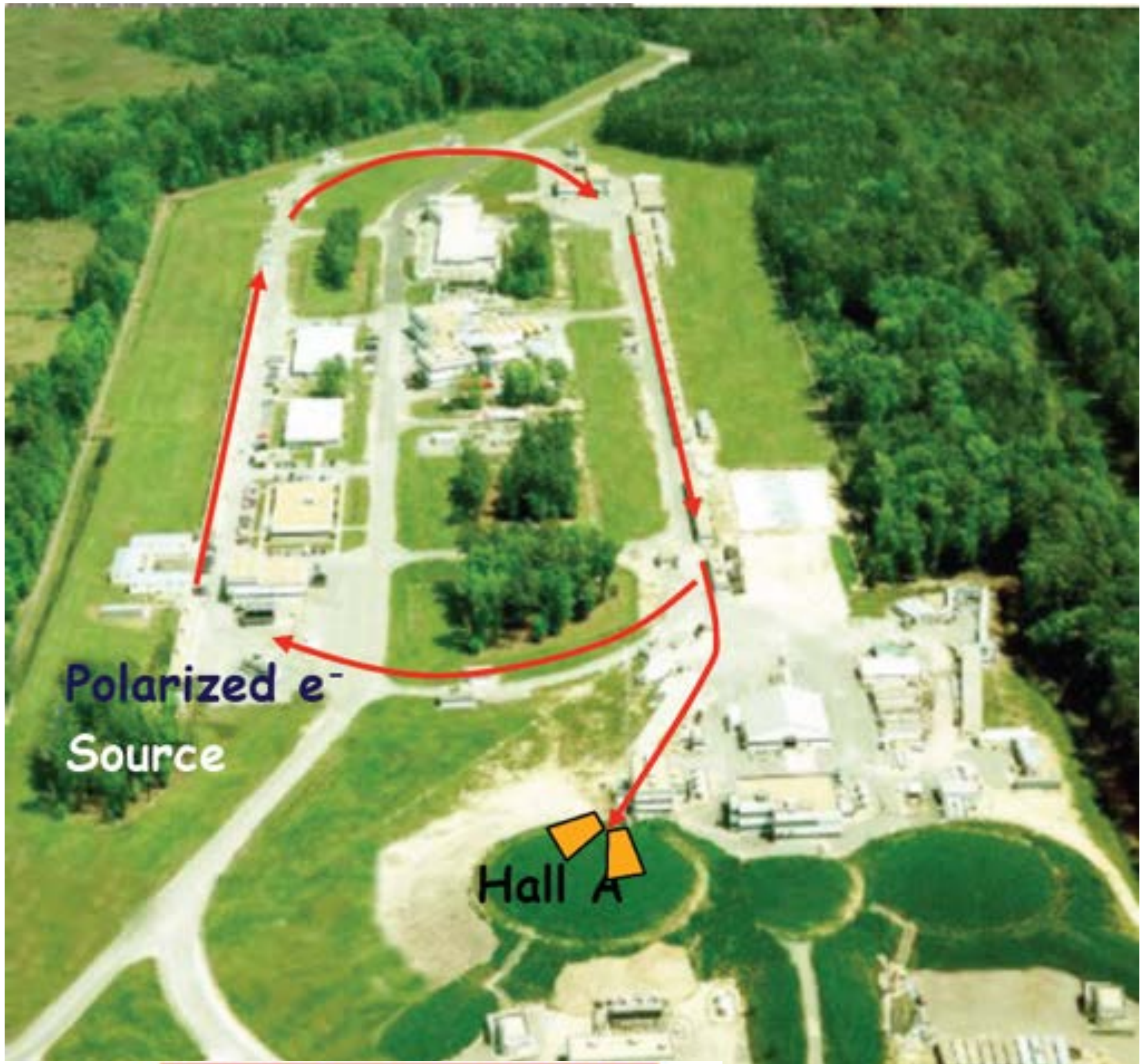
Pol. Source

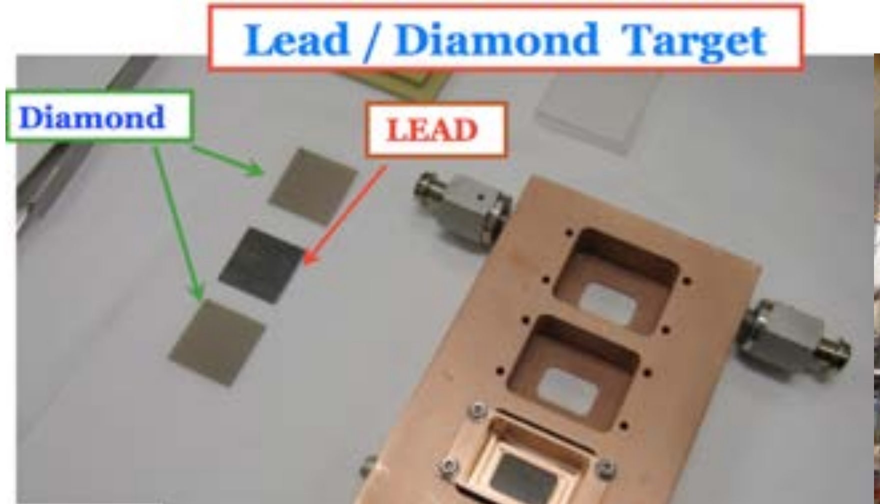
Hall A

CEBAF

First PREX result and future plans

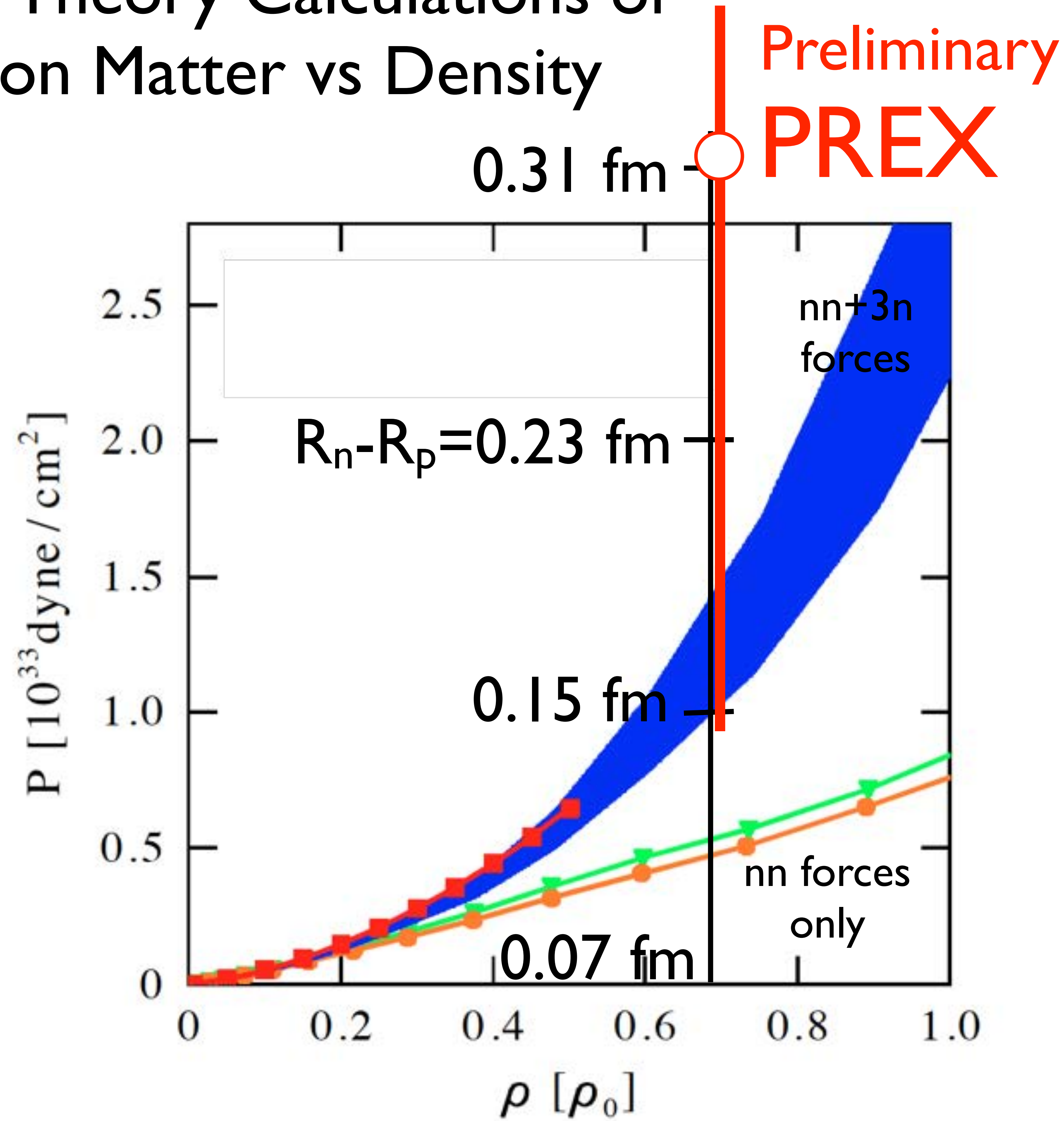
- At Jefferson Laboratory, 1.05 GeV electrons elastically scattered from thick ^{208}Pb foil. PRL **108**, 112502, PRC **85**, 032501
- A_{PV}=0.66 ±0.06(stat) ±0.014(sym) ppm
- Neutron skin thickness: R_n-R_p=$0.33^{+0.16}_{-0.18}$ fm
- Experiment achieved systematic error goals.
- Future plans: **PREX-II** (approved 25 days) Run ^{208}Pb again to accumulate more statistics. Goal: R_n to ±0.06 fm.
- **CREX**: Approved follow on for ^{48}Ca with goal: R_n to ±0.02 fm.





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

- Chiral EFT calc. of pressure P of neutron matter by Hebeler et al. including three *neutron* forces (blue band) PRL**105**, 161102 (2010)
- Their calculated P and Typel-Brown correlation --> R_n-R_p=0.14 to 0.2 fm
- PREX agrees with results including 3n forces. Three *neutron* forces are very interesting, unconstrained. Some information on 3 *nucleon* forces in ^{3}H, ^{3}He...



Galileo’s Crime

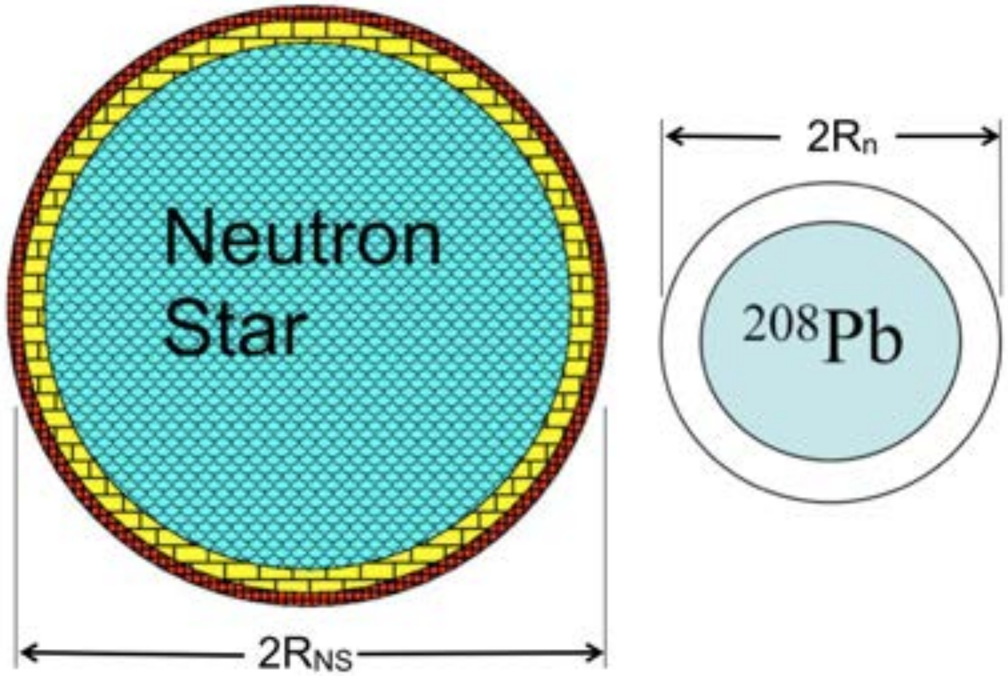
- Both the laboratory and the heavens are made of the same material.
- Newton said gravity acted same on apple and moon.
- In 19th century the observation that spectral lines are the same in lab and in stars created astrophysics.
- In 20th century we have astro-particle physics.
- While 21st century begins to address if life is the same in the heavens as on earth.

- For this talk, material is neutron rich matter. In astrophysics and in the laboratory it has the same neutrons, the same strong interactions, and the same equation of state.
- A measurement in one domain (astronomy or the lab) has important implications in the other domain.

Density Dependence of EOS

- Pressure of neutron matter pushes neutrons out against surface tension ==> R_n-R_p of ^{208}Pb determines P at low densities of about 2/3ρ_0 (average of surface and interior ρ).
- Radius of (~1.4M_{sun}) NS depends on P at medium densities of ρ_0 and above.
- Maximum mass of NS depends on P at high densities.

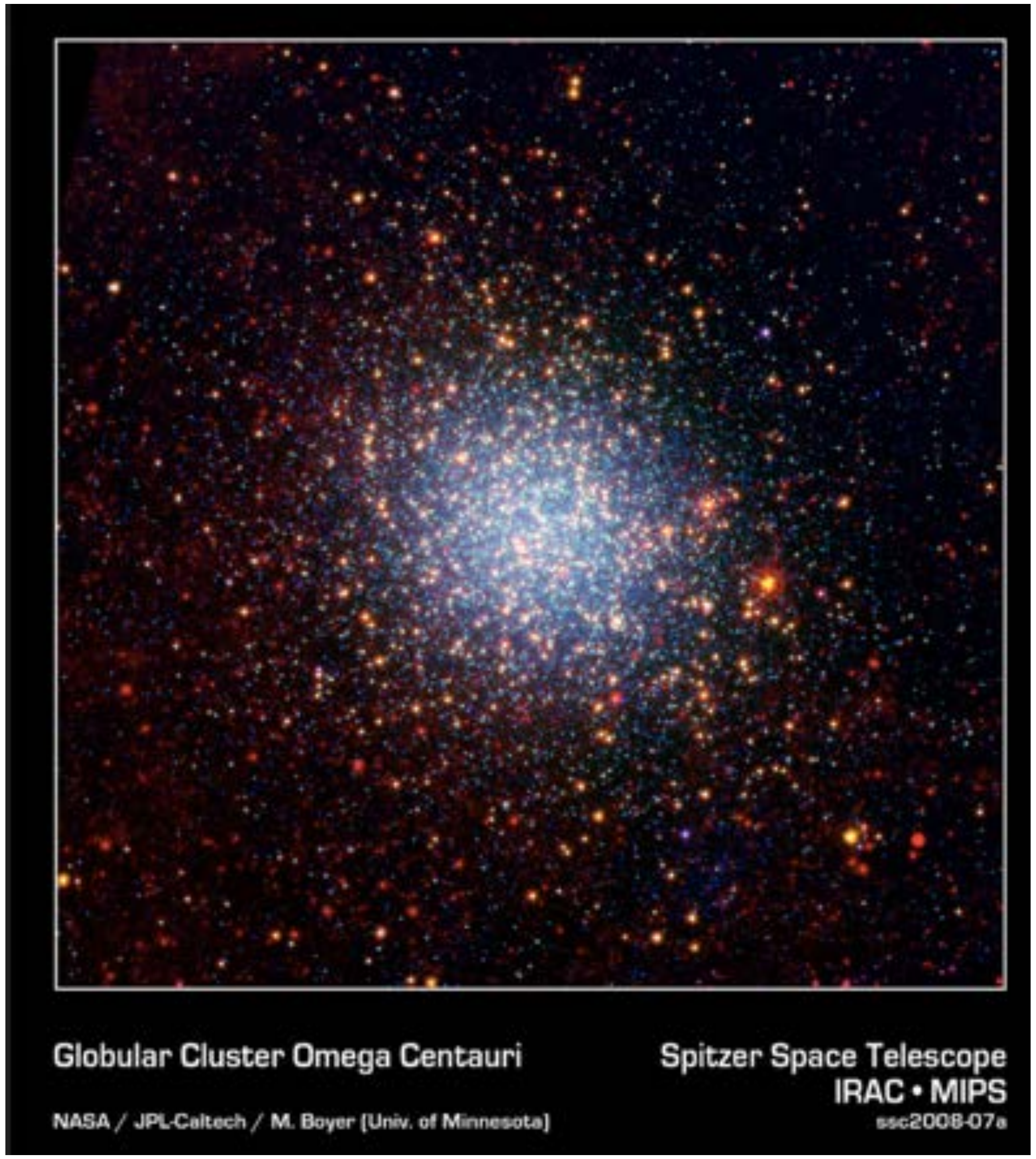
Neutron Star radius versus ^{208}Pb Radius



- These three measurements constrain density dependence of EOS and possible pressure changes from phase transitions.

Quiescent NS in Globular Clusters: Guillot et al., arXiv:1302.0023

- Considers five LMXB in M13, M28, NGC6304, NGC6397, Omega Cen.
- Simple assumptions:
    - Nonmagnetic hydrogen atmospheres: no evidence for B field, heavier elements should rapidly sink, one companion star observed to have H envelope.
    - Spherically symmetric: no observed pulsations.
    - All observed stars have approximately the same radius (independent of mass): consistent with most EOS, greatly improves statistics.
    - Distance to stars known: Globular cluster distances good but perhaps not perfect, *Gaia should give ~ perfect distances soon.*
    - Interstellar absorption from X-ray data.
- Result $R= 9.1^{+1.3}_{-1.5}$ km (90%-confidence).



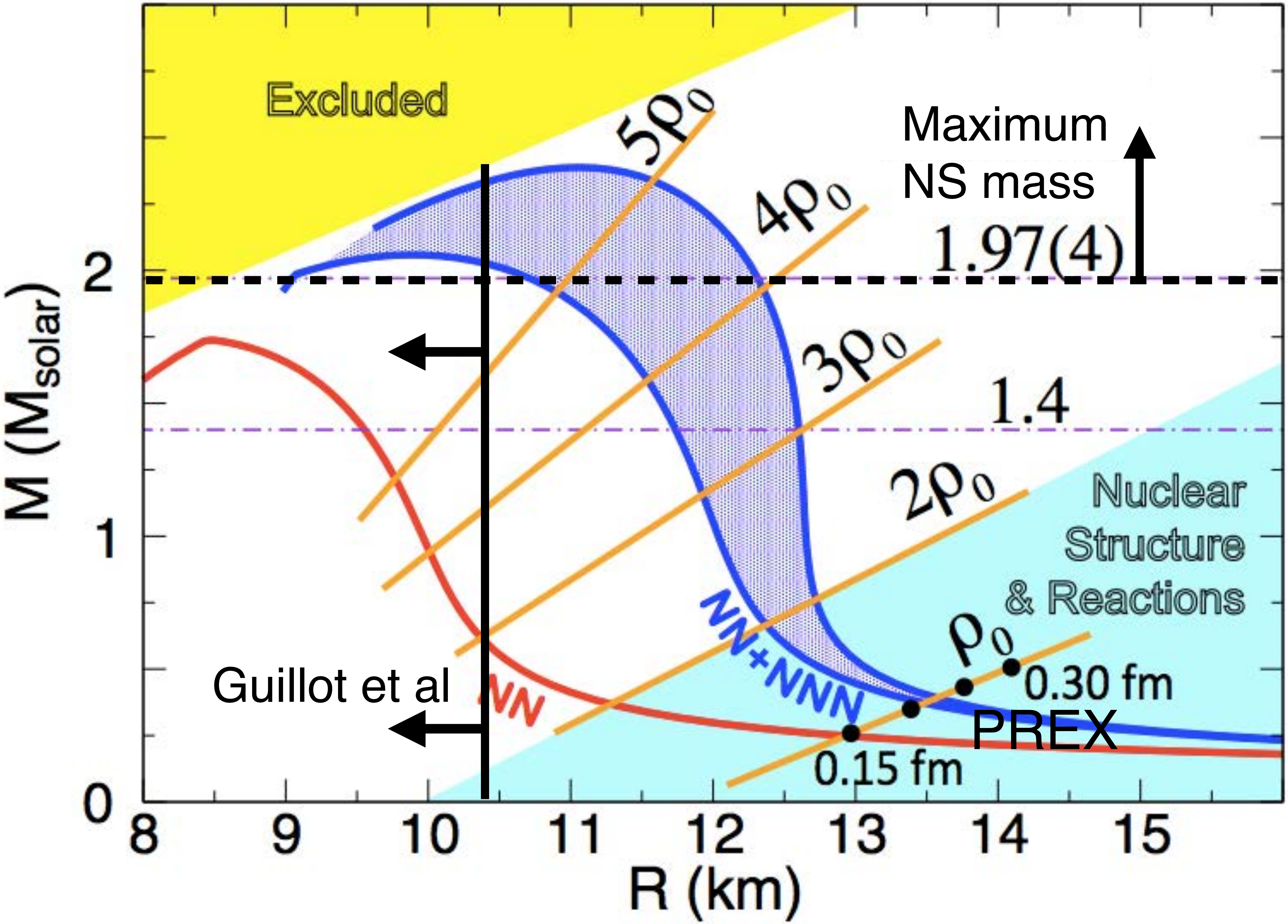
Globular Cluster Omega Centauri

Spitzer Space Telescope
IRAC • MIPS

NASA / JPL-Caltech / M. Boyer (Univ. of Minnesota)

ssc2008-07a

Gandolfi et al. PRC85, 032801 (2012)

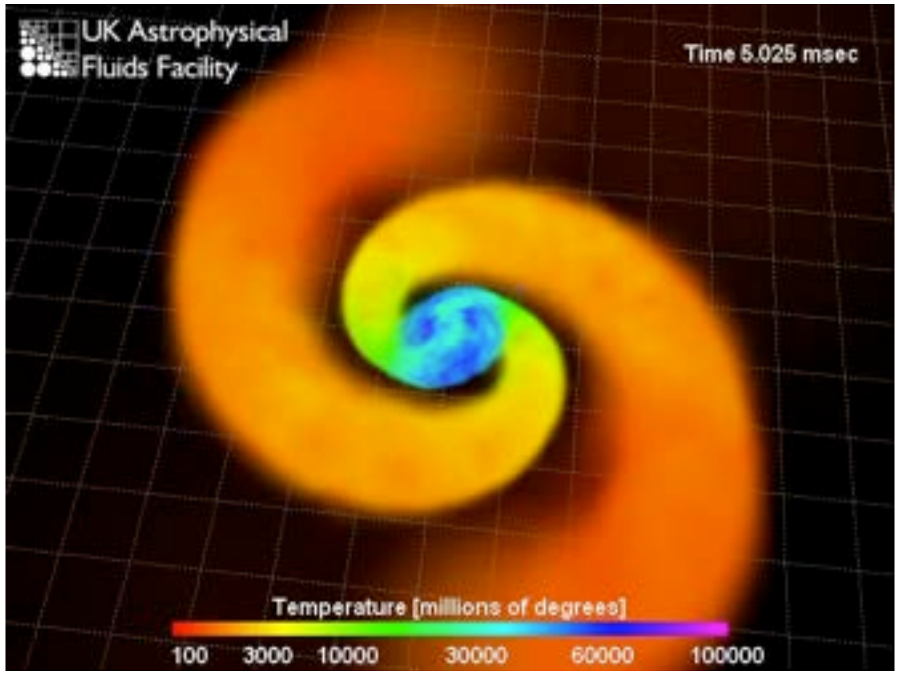


Paul Souder's 70th Birthday

- Plan A: give him a gold watch (but I'm too cheap).
- Plan B: help Paul locate the source of all the gold in the galaxy.

Site of the r-process

- Half of heavy elements (including gold) made in r-process.
- **What makes all of the neutrons?**
  - **Neutrinos:** ratio of n/p in supernova ν driven wind set by rates of ν capture.
  - **Gravity:** compresses matter until electron capture drives it n rich. Tidal forces during NS mergers can eject n-rich material.
- Follow fluid element in tidal tail as it decompresses (next pages).
- Matter ejecta so n rich that it undergoes robust r-process!



- r-process yield depends on:
  - How much material is ejected in a merger? Better numerical relativity simulations.
  - What is merger rate? Advanced LIGO will soon directly measure rate.

Simulation by Stephan Rosswog, University of Leicester. Visualisation by Richard West, UKAFF.

Nuclear Pasta Formation

- During a NS merger tidal excitation decreases density: uniform nuclear matter -> nuclear pasta -> nuclei + n -> r-process.

- Nuclear matter, at somewhat below ρ_0, forms complex shapes because of competition between short range nuclear attraction and long range Coulomb repulsion —> "Coulomb frustration".

- Semiclassical model for n,p interaction: $v(r)=a\, e^{-r^2/\Lambda} + b_{ij}\, e^{-r^2/2\Lambda} + e_i e_j\, e^{-r/\lambda}/r$

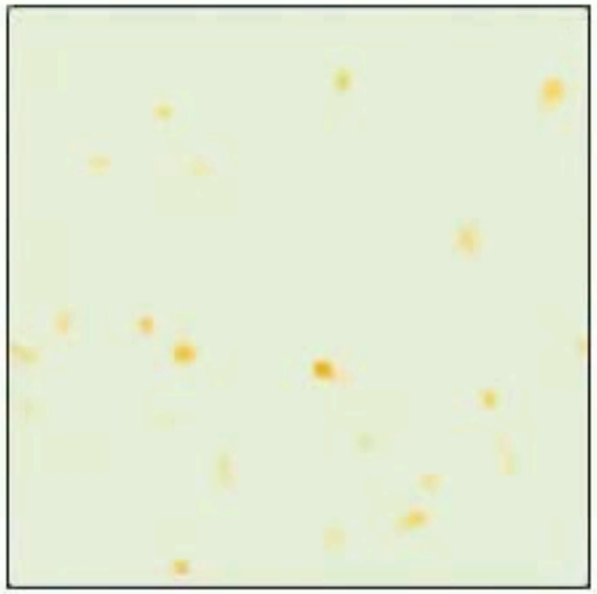
- Parameters of short range interaction fit to binding E and saturation density of nuclear matter.

- Simple model allows MD simulations with 300,000+ nucleons, for long times 10^7 + fm/c.

Simulation of pasta formation. ArXiv:1307.1678

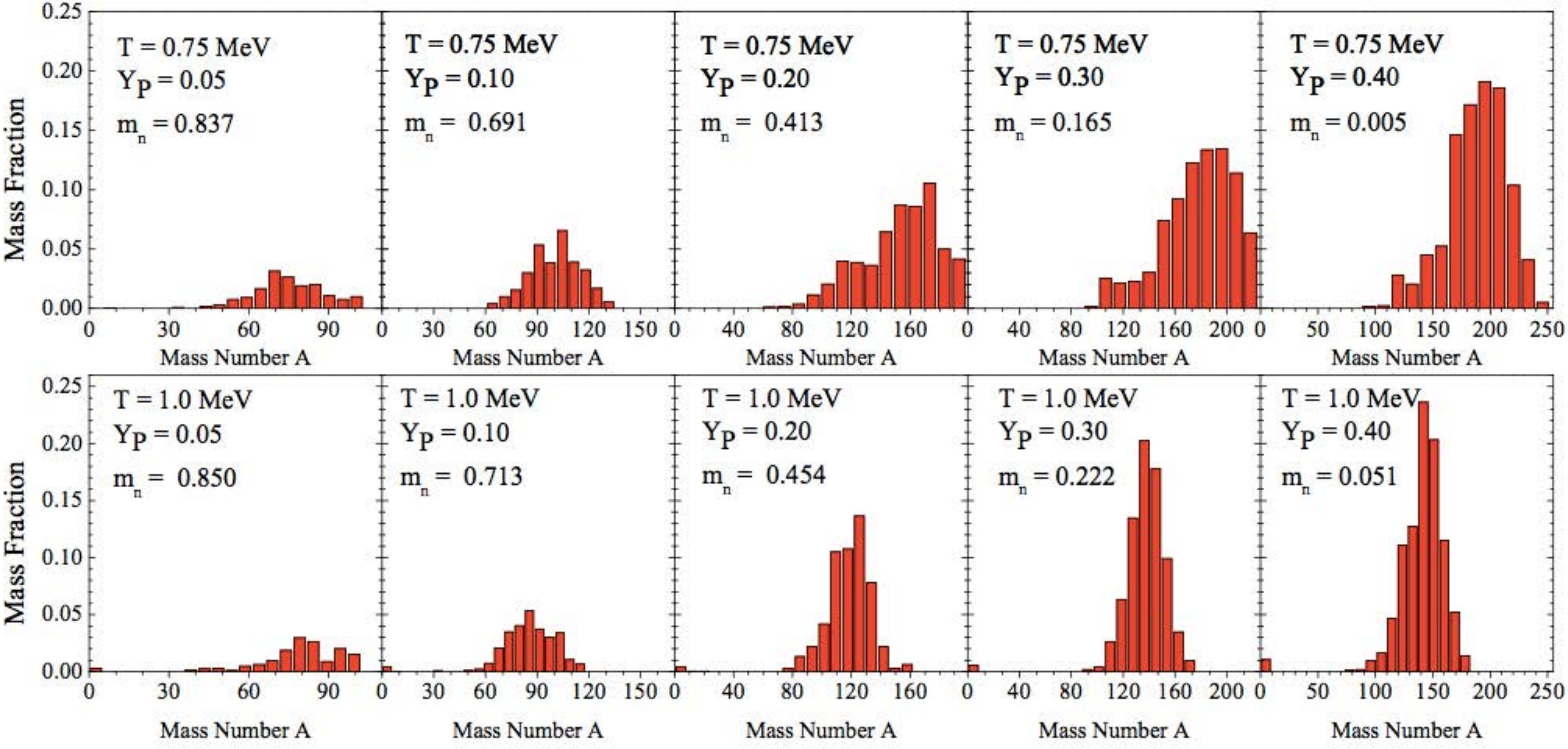
51200 nucleons,
$Y_p=0.4$,
T=1 MeV,
$\lambda=10$ fm,
$\xi=2\times10^{-8}$ c/fm,
$L_0=80$ fm
$L=(1+\xi t)L_0$

Few thousand core weeks of CPU time



$n=0.1200\mathrm{fm}^{-3}$

Andre Schneider


T = 0.75 MeV
$Y_P = 0.05$
$m_n = 0.837$
T = 0.75 MeV
$Y_P = 0.10$
$m_n = 0.691$
T = 0.75 MeV
$Y_P = 0.20$
$m_n = 0.413$
T = 0.75 MeV
$Y_P = 0.30$
$m_n = 0.165$
T = 0.75 MeV
$Y_P = 0.40$
$m_n = 0.005$
T = 1.0 MeV
$Y_P = 0.05$
$m_n = 0.850$
T = 1.0 MeV
$Y_P = 0.10$
$m_n = 0.713$
T = 1.0 MeV
$Y_P = 0.20$
$m_n = 0.454$
T = 1.0 MeV
$Y_P = 0.30$
$m_n = 0.222$
T = 1.0 MeV
$Y_P = 0.40$
$m_n = 0.051$
Mass Fraction
0.00
0.05
0.10
0.15
0.20
0.25
Mass Number A
0
30
60
90
120
150
0
40
80
120
160
200
0
50
100
150
200
250

Matt Caplan

Average mass and charge at T=1 MeV

Y	<A>	<Z>	<A> NSE	<Z> NSE
0.2	136	43	179	54
0.3	167	58	184	58
0.4	190	77	194	78

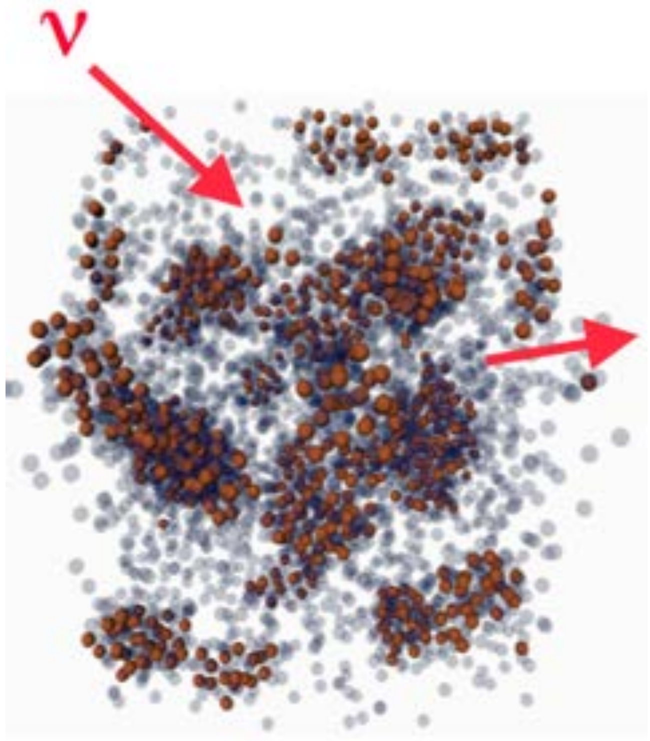
Nuclear statistical equilibrium for FRDM mass model

Microscopic model

- Also works at higher densities where NSE models may have big corrections from interactions between nuclei.
- Can calculate initial conditions for nucleosynthesis.
  - Initial temperature
  - Initial proton fraction and how this is perhaps somewhat increased by weak interactions as matter expands.

How to smell the pasta?

Observables sensitive to pasta shapes



- Coherent *ν*-pasta scattering gives *ν* **opacity** for supernova simulations. Depends on static structure factor $S_n(q)=<\rho_n(q)^*\rho_n(q)>$ or dynamical response function $S_n(q,w)$ [Classical MD -> dynamical response]
- Coherent electron-pasta scattering gives **shear viscosity**, **thermal conductivity**, and **electrical conductivity** of pasta in NS crusts.
- Hysteresis in pasta shapes with density changes gives **bulk viscosity**. Could be important for damping of neutron star r-mode oscillations.
- Response to small deformations of simulation volume gives **shear modulus** -- determines neutron star oscillation frequencies.
- Response to large deformations gives **breaking strain**. Pasta strength important for star quakes (crust breaking), magnetar giant flares, and mountain heights. Deform simulation volume and look at stress vs strain.

Disordered Pasta

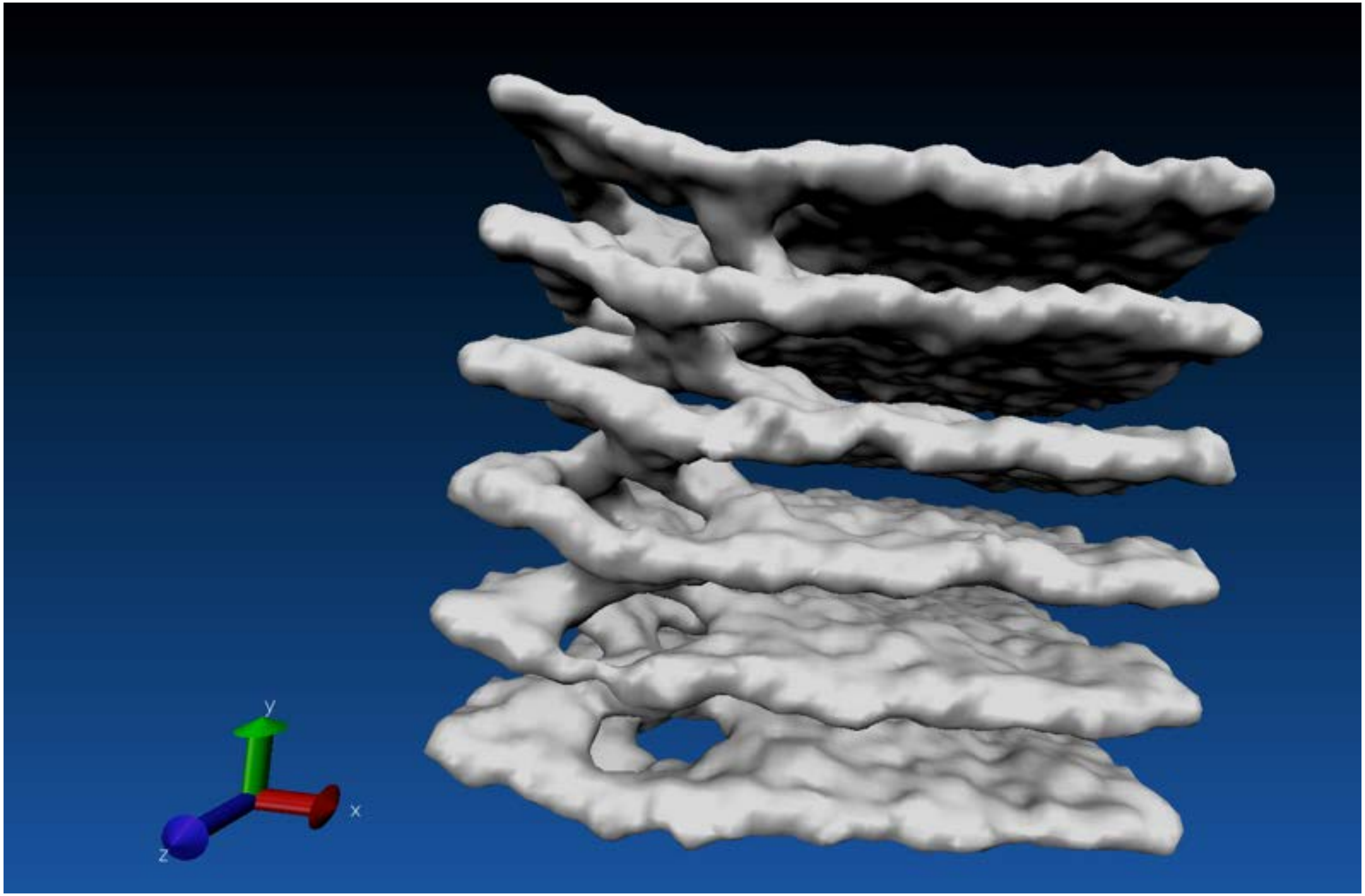
- Jose Pons *et al* speculate [Nature Physics, **9**, 431 (2013)] that an "impure" pasta layer with a low electrical conductivity leads to magnetic field decay (in of order a million years) in neutron stars. This could explain why no X-ray pulsars are observed with rotation periods longer than 20 sec.
- They assumed a crystal lattice of some average charge with random **impurities** of different charges and required a significant spread in charges to produce enough election-pasta scattering for a low conductivity.
- Note this likely also decreases the thermal conductivity which should be observable in X-ray light curves of crust cooling.
- How to describe the amount of disorder in pasta, and could it be large enough to give low electrical and thermal conductivities?

Pasta Defects

- How to describe pasta imperfections?
  - Impurities—unlikely because nucleons may be free to flow and equal out composition.
  - Topological defects— could be very long lived excitations that increase electron-pasta scattering.
  - Grain boundaries between different pasta phases and or orientations.
- Need pasta molding over larger length scales to find elementary excitations and there impact on transport.

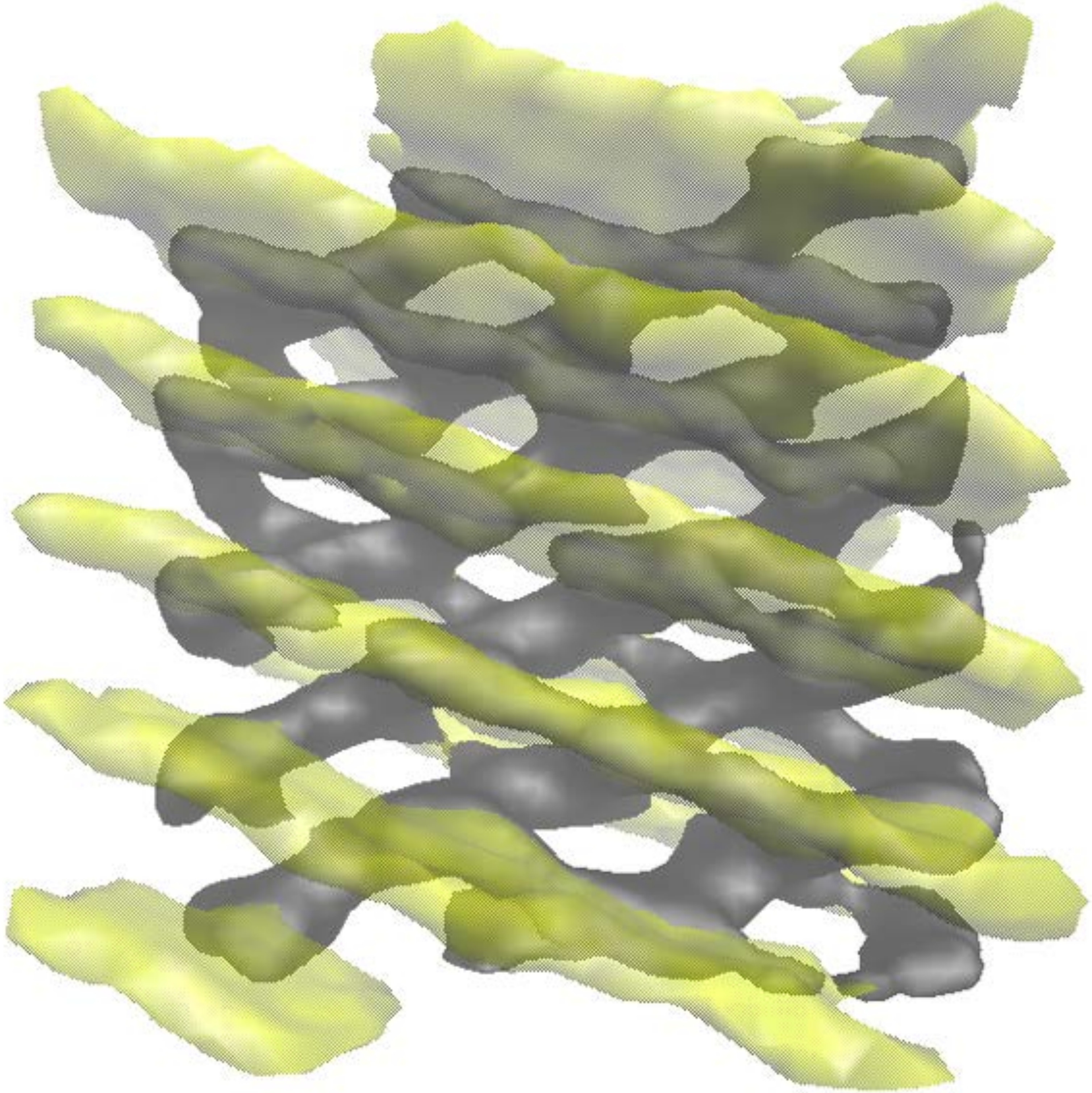
Screw dislocations in nuclear pasta?

Screw defect in Lasagne

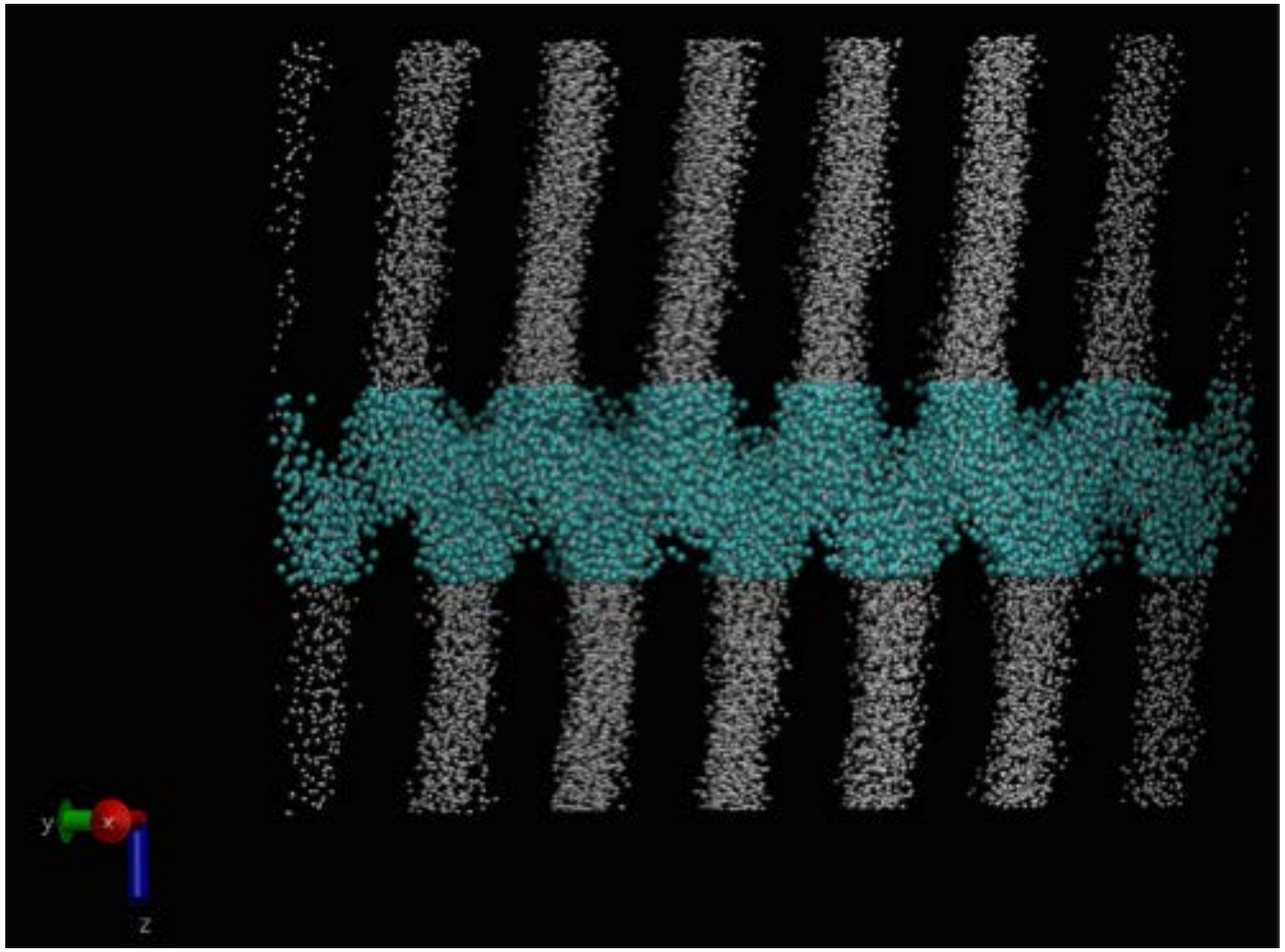


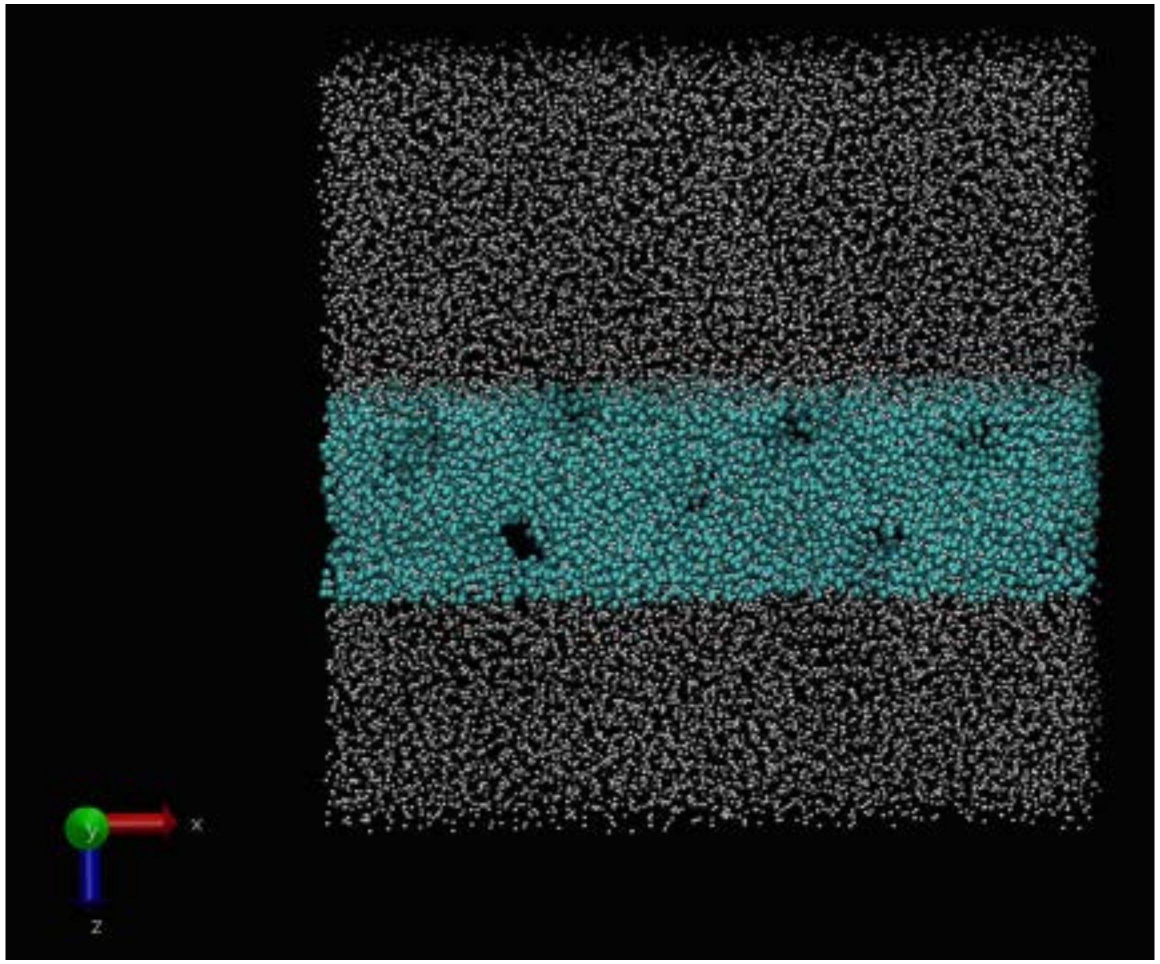
75,000 nucleon configuration (Y_p=0.4, T=1 MeV, ρ=0.05 fm^{-3}) that was started from random positions and quickly formed screw defect. Defect then stable for over 10 million MD time steps.

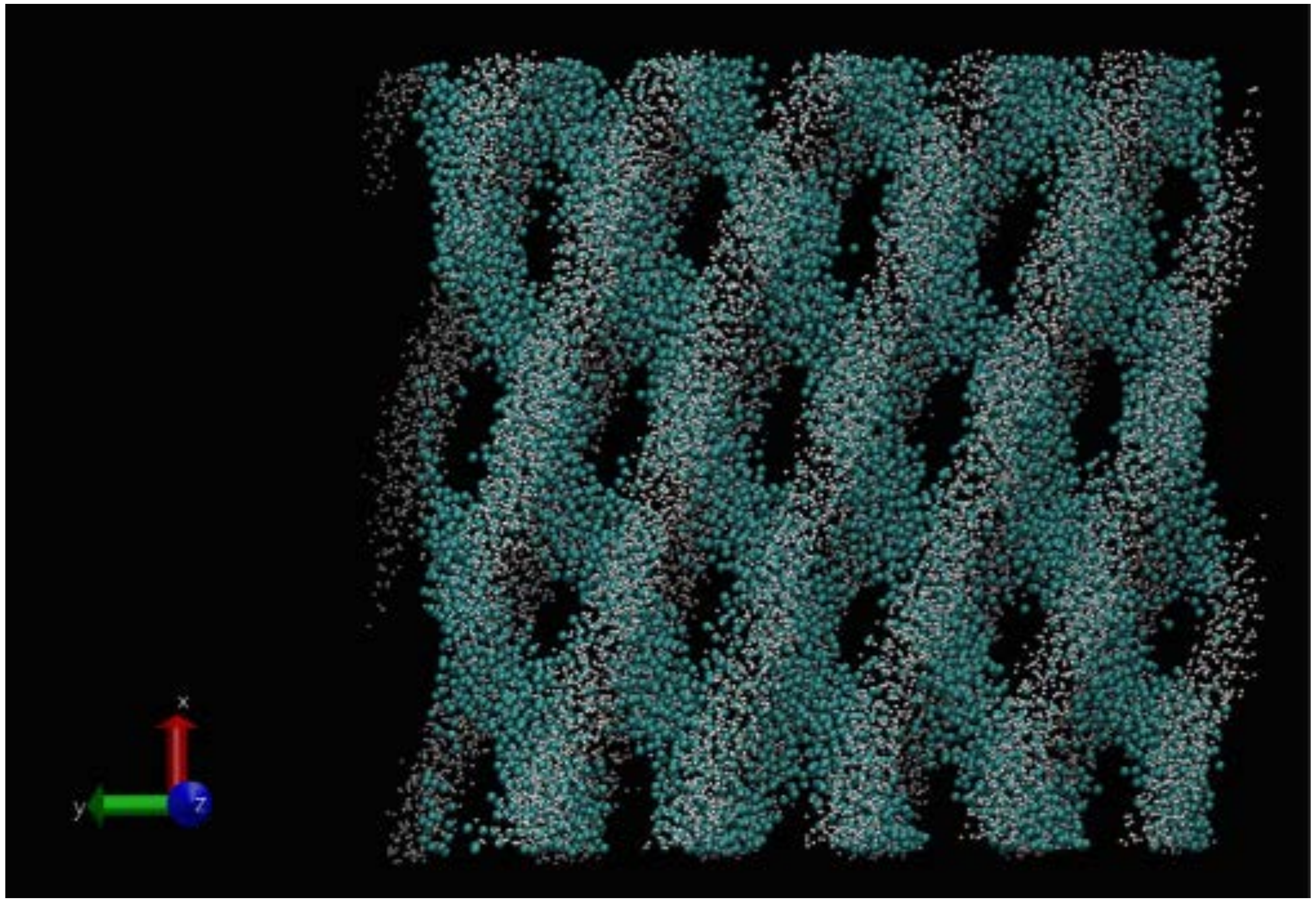
Plane of screw defects



50,000 nucleon configuration of lasagne planes (yellow) with a 2D array of screw defects (gray)



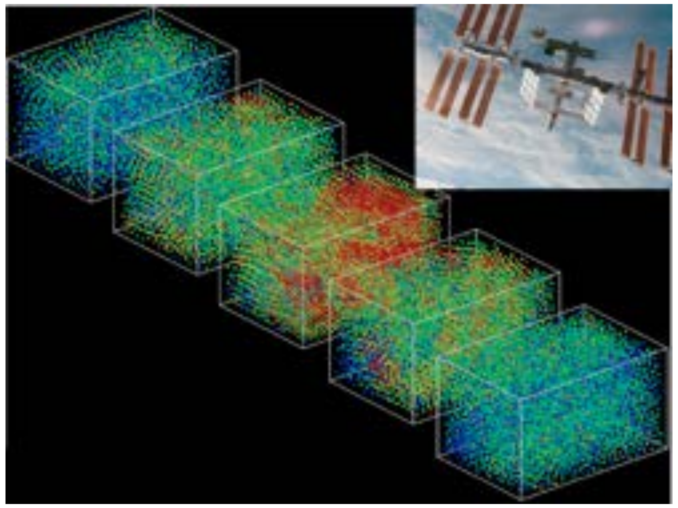




Try and characterize possible nuclear pasta defects. Then calculate effects of defects on electron transport.

Neutron Star Outer Crust and Plasma Crystals

- Stars are plasmas, however interior of white dwarfs and crust of neutron stars are so dense that they freeze.
- 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 Fermi screening length λ.
- **Complex (or dusty) plasma** can have micron sized microparticles in weakly ionizing gas. Particles acquire large negative charge. Plasma crystals first observed in lab in 1994. Now study crystallization in microgravity on International Space Station.
- **White Dwarfs** crystallize from the center out, and release of latent heat delays cooling. Recent measurements of WD in NGC 6397 may observe melting temperature (depends on central composition).



Plasma crystals on International Space Station

Globular cluster NGC 6397 (Hubble)

Hypothesis

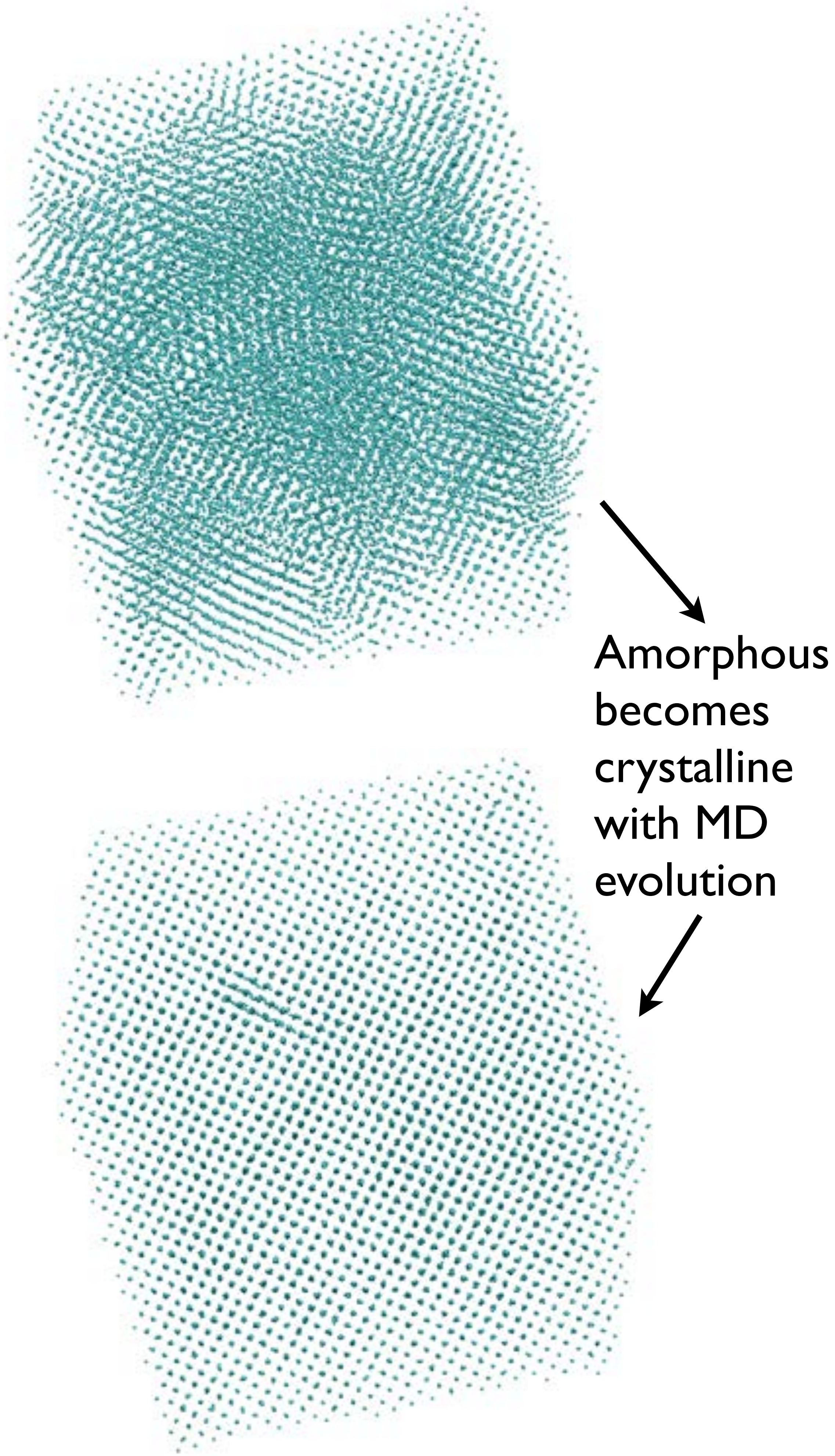
- Neutron star crust is an extremely good crystal that is remarkably free of defects such as vacancies, dislocations, and grain boundaries.
- Because imperfections diffuse very quickly.
- Neutron star crust is a “nearly perfect solid” that is very strong.

Neutron star crust of nearly perfect crystals

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*.

Phys. Rev. E **84**, 016401 (2011)



Amorphous becomes crystalline with MD evolution

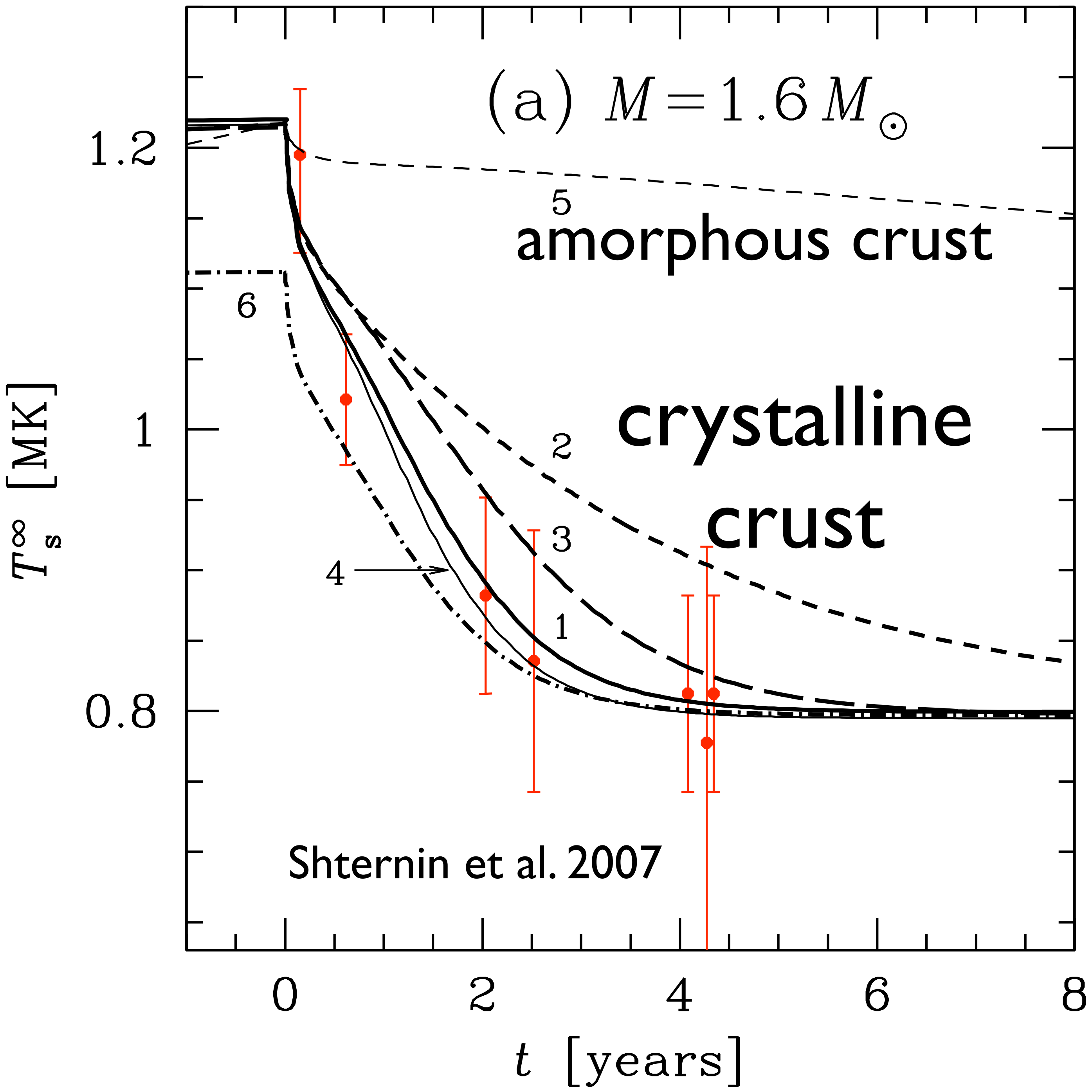
Cooling of KS 1730-260 Surface After Extended Outburst

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

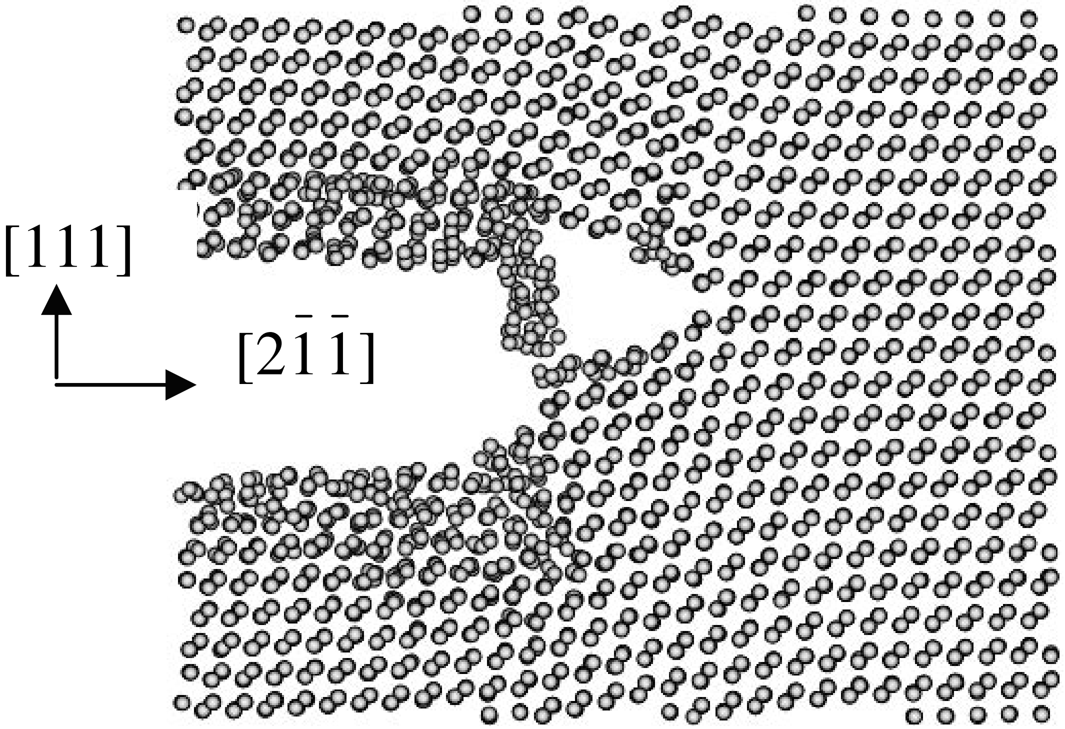
- Strong continuous GW sources (at LIGO frequencies) place extraordinary demands on neutron rich matter and stress it to the limit.
  - Place a mass on a stick and shake vigorously.
  - May need both a large mass and a strong stick.
  - Let me talk about the strong stick.
- Example: consider a large 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.

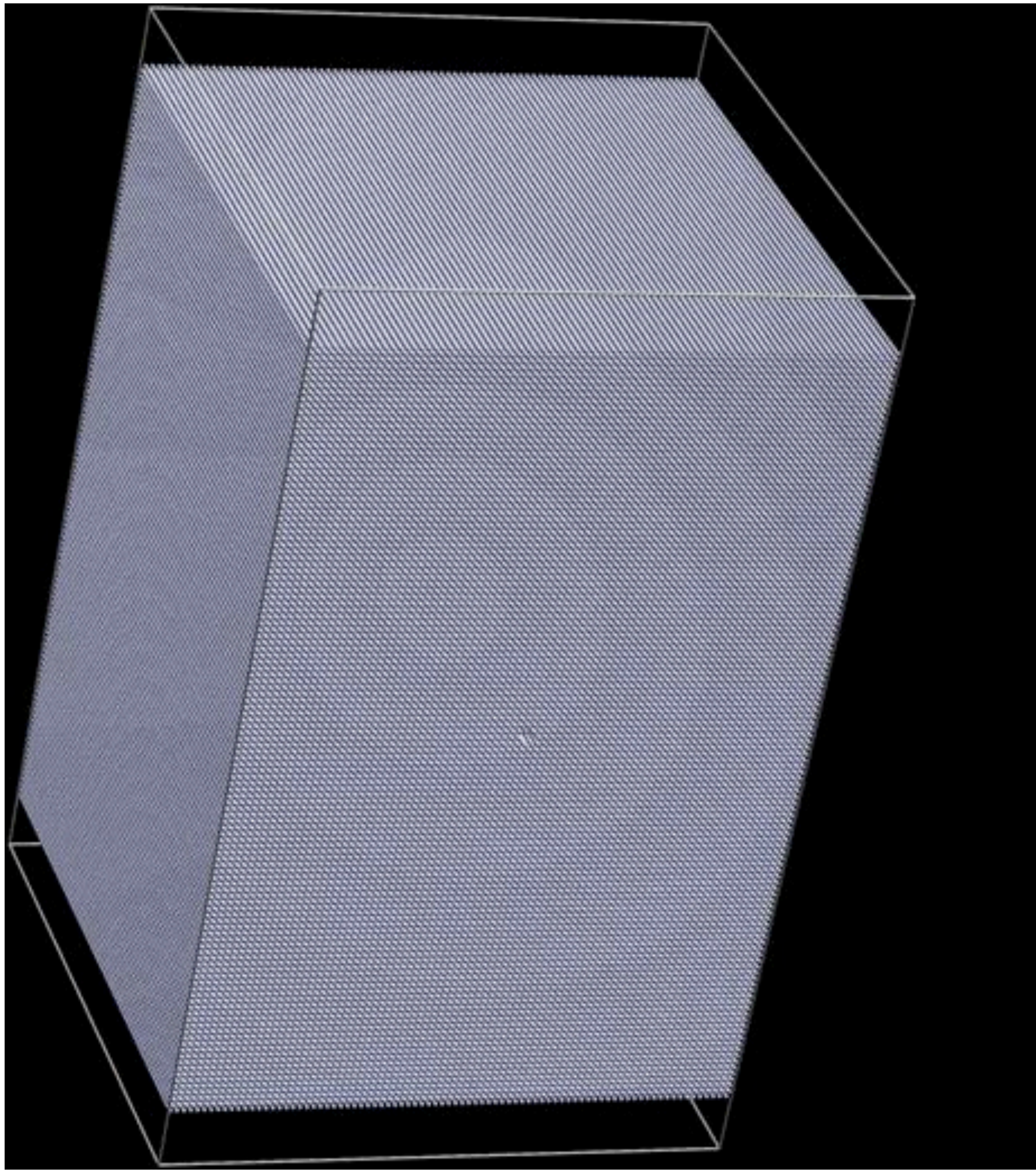
Also GW from r modes that depend on damping (shear / bulk viscosity)

MD simulation of Crust Failure

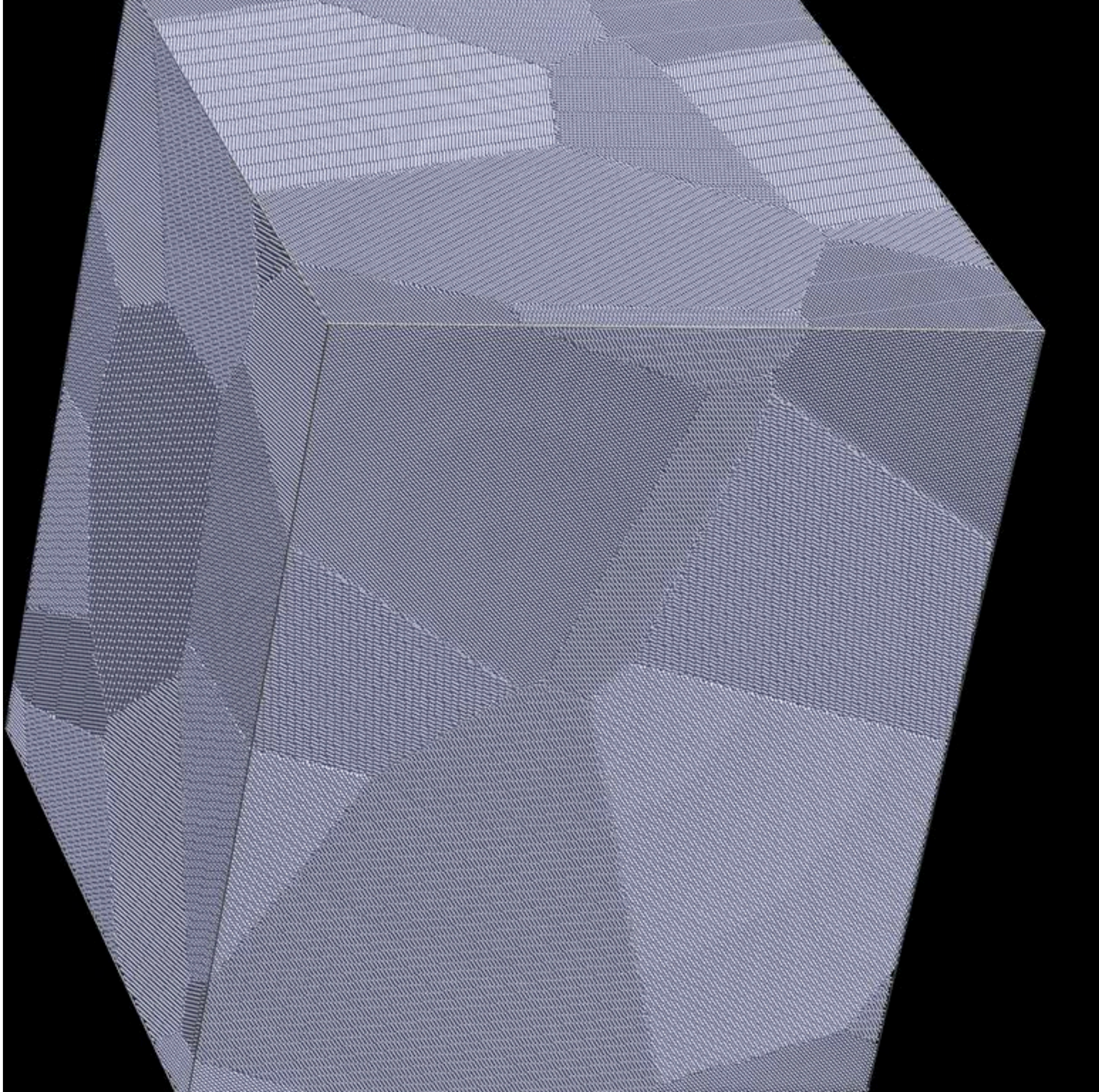
- Fracture in brittle material such as silicon involves propagation of cracks that open voids.
- Crack propagating in MD simulation of Silicon. Swadener et al., PRL**89** (2002) 085503.



- 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



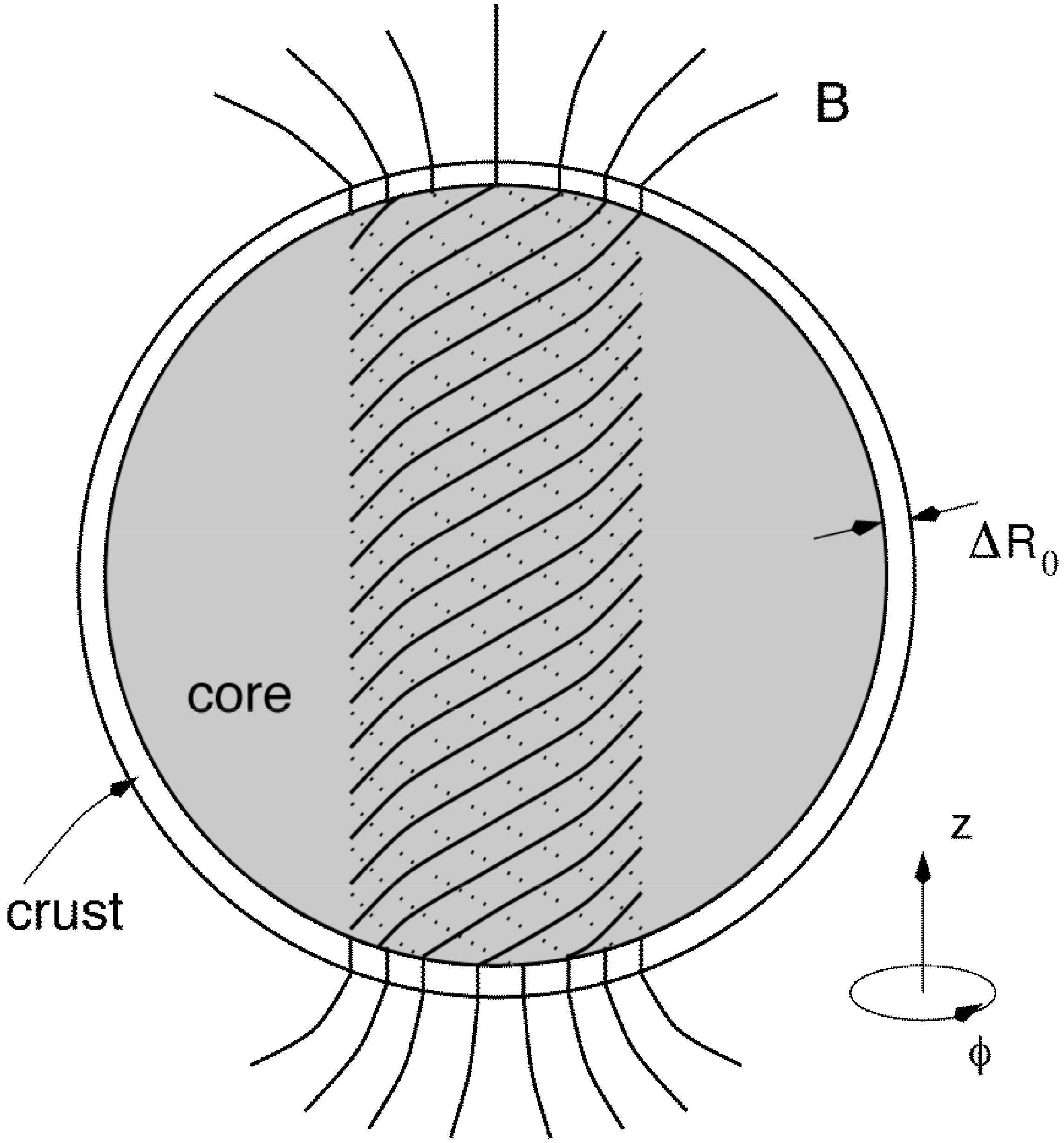
Polycrystalline sample (bcc) with 12.8 million ions consisting of 8 differently oriented grains.

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.*
- *Our strong crust can support ellipticities* $\epsilon=(I_1-I_2)/I_3$ *up to about* 10^{-5}.

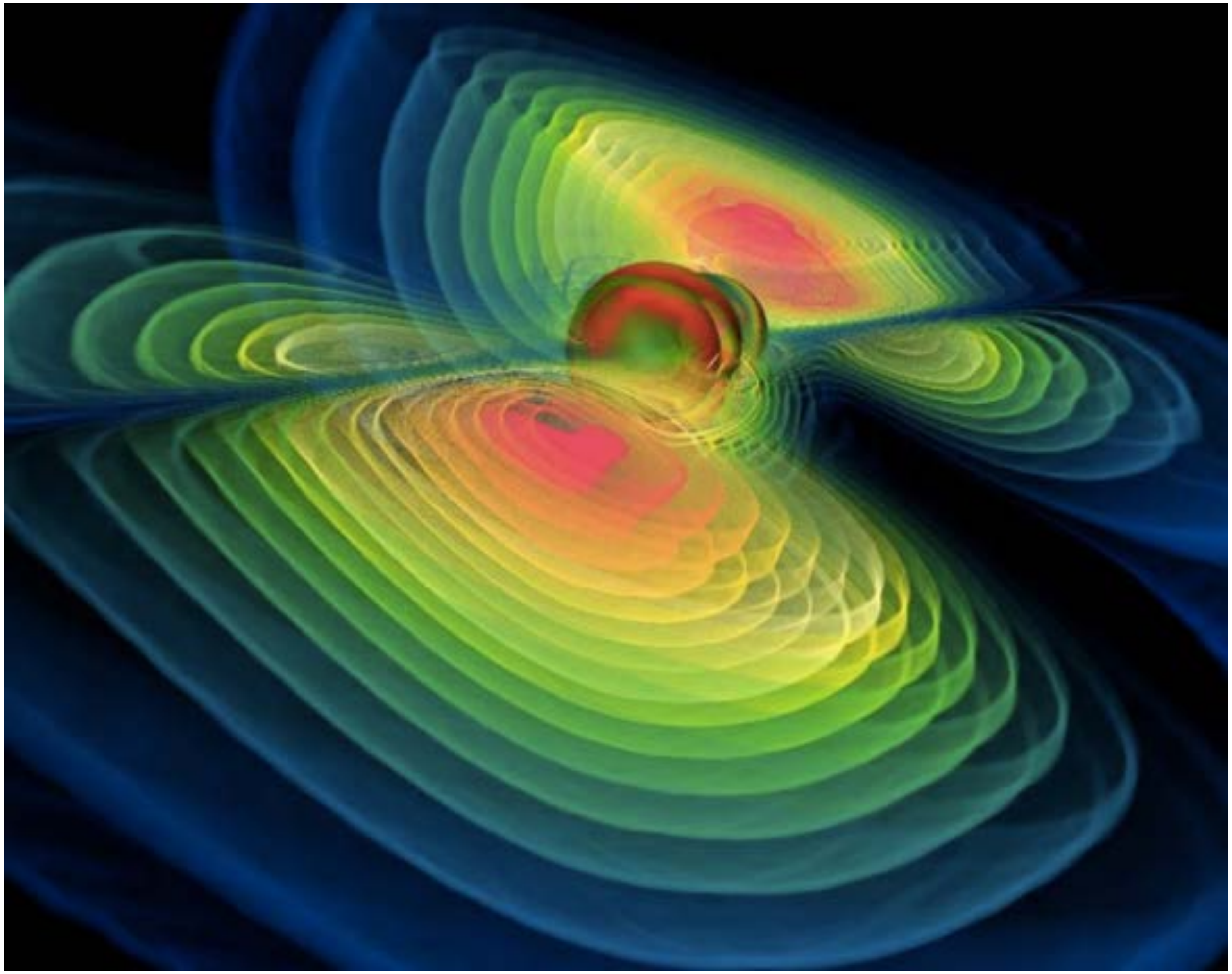
Curst Breaking Mechanism for Magnetar Giant Flares

- 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. Helps explain large10^{46} erg energy of 2004 flare from SGR1806.



Thompson + Duncan

Continuous Gravitational Waves



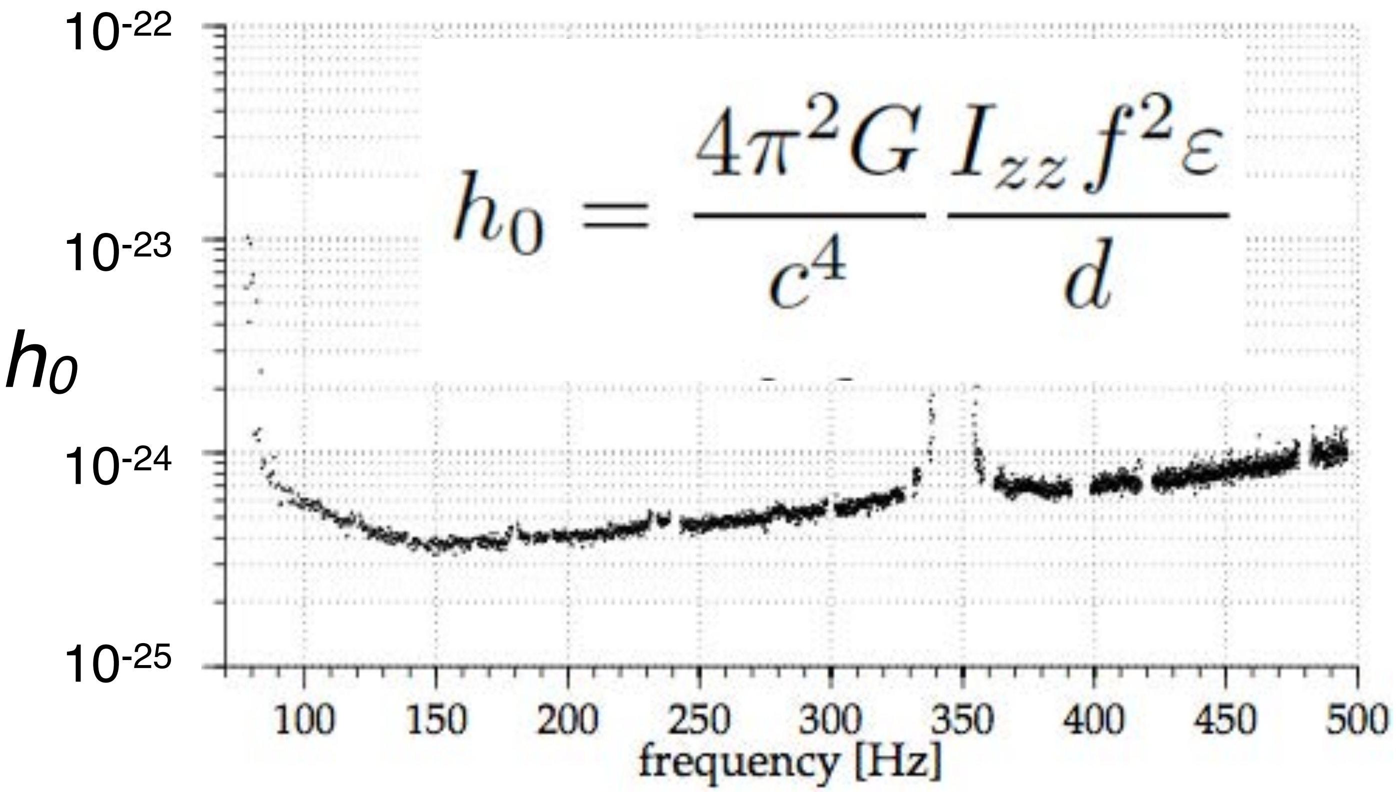
- Continuous GW sources at LIGO frequencies **need strong sticks** to accelerate masses.

Searches for Continuous Gravitational Waves

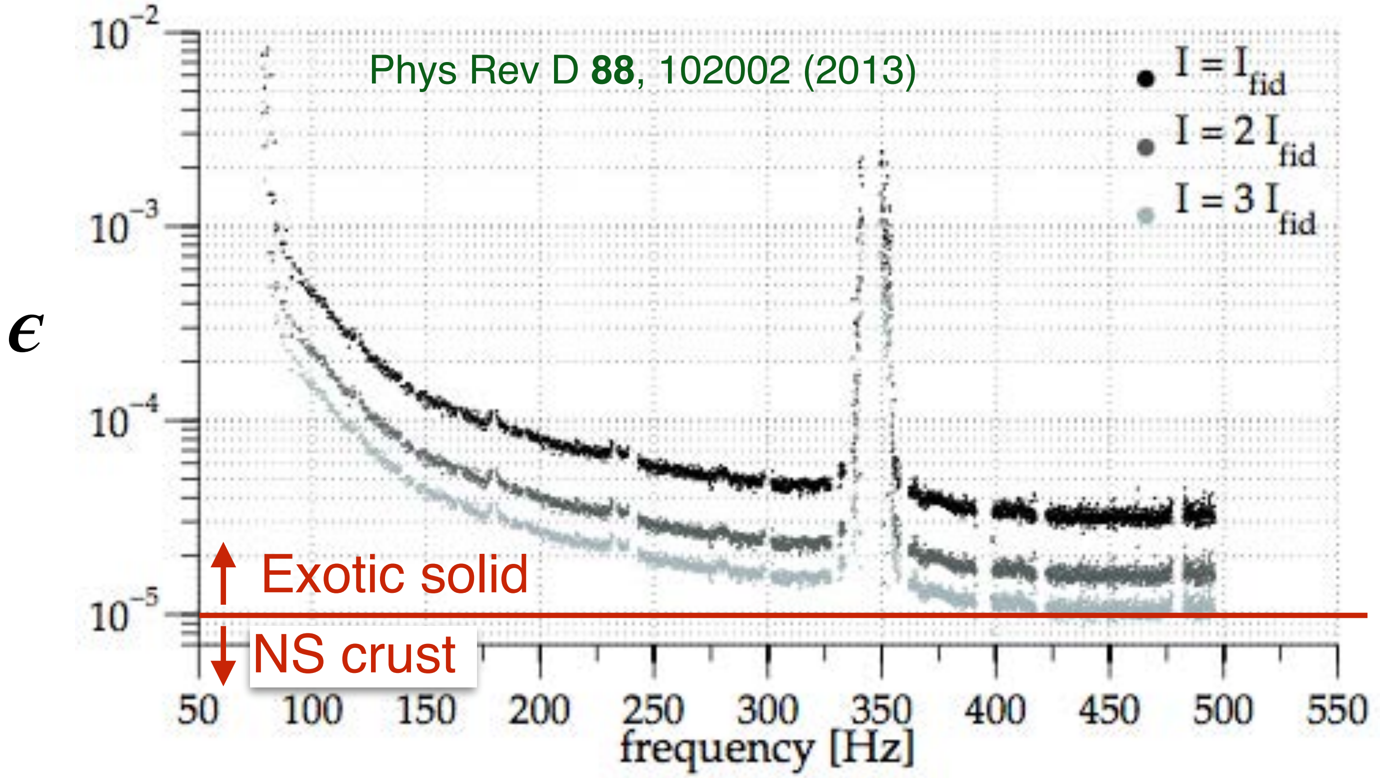
- *Searches are very computationally intensive.* Must search over many parameter values: period, period derivative, location on sky...
- Which neutron stars are interesting?:
  - **Fast rotating**: GW power rapidly increases with frequency.
  - **Large accretion**: angular momentum gained from accretion 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.
  - ...

Continuous GW from Galactic Center

- Search for GW, from isolated neutron stars near the galactic center, using LIGO S5 data.
- Sensitive to strain $h_0 < 10^{-24}$.
- At distance d=8.3 kpc corresponds to ellipticity ϵ of 10^{-5} to 10^{-4}.
- Near but slightly above maximum for NS crust.
- High density solid phase (if it exists) likely supports larger ϵ.
- Example: color superconducting phase with strange quarks paired to up or down quarks of different Fermi momenta by forming a nonuniform crystal lattice.
- Advanced LIGO will improve by x10 and be sensitive to maximally deformed conventional NS crust.

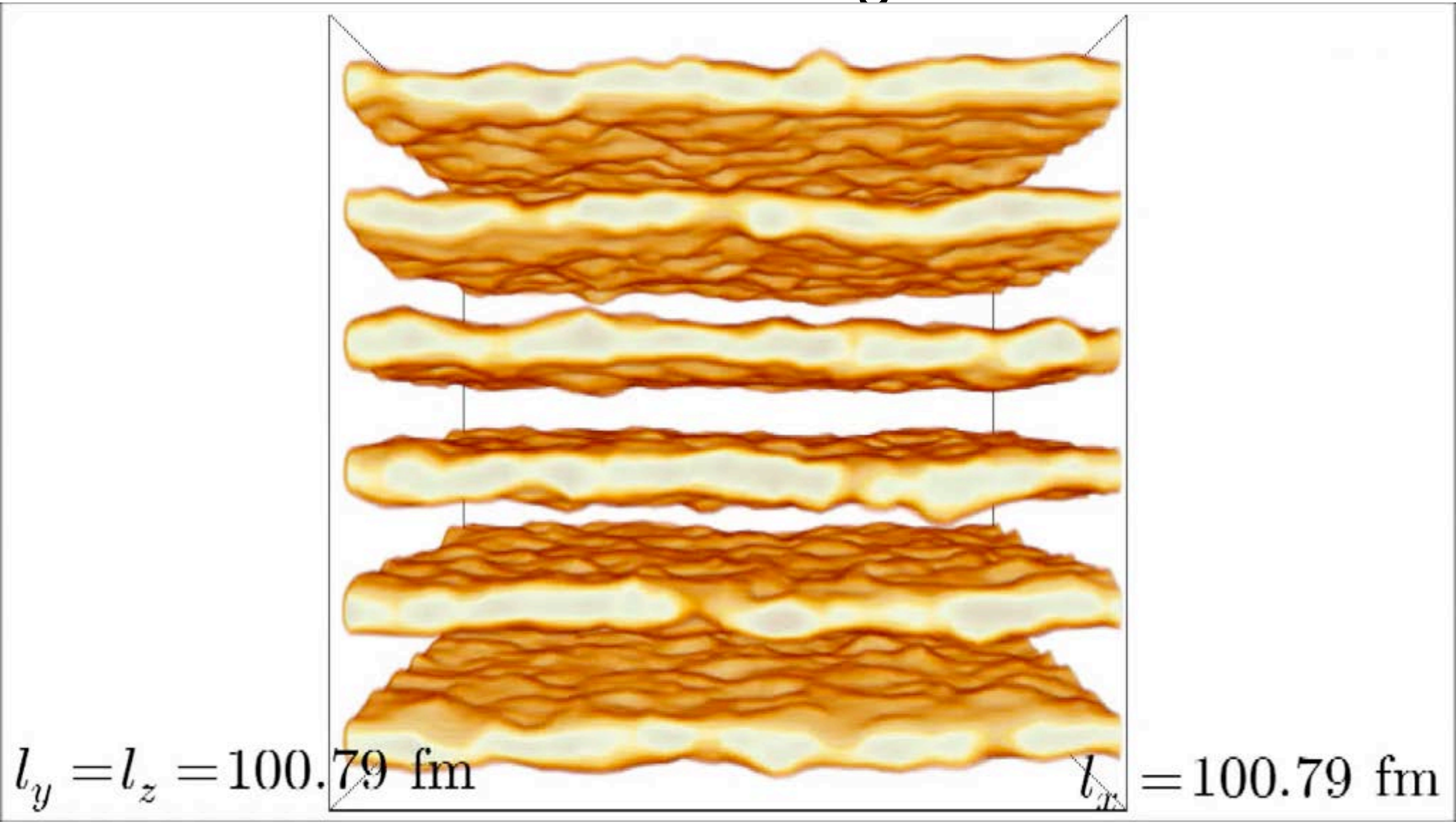


$$h_0 = \frac{4\pi^2 G}{c^4}\frac{I_{zz} f^2 \varepsilon}{d}$$



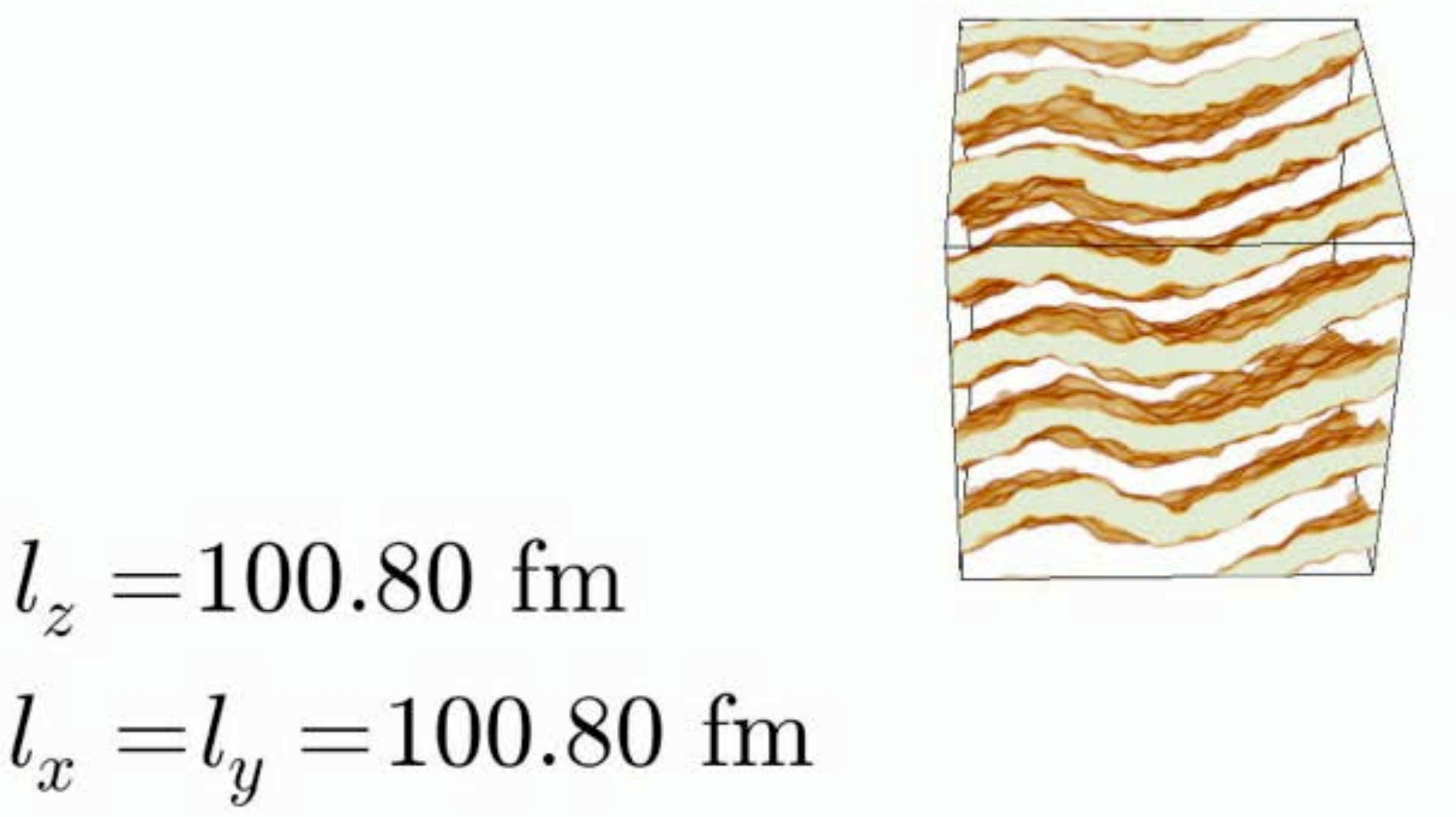
Phys Rev D **88**, 102002 (2013)

Pasta Strength



- Sound track from Emily Clark. Stereo left is density of small region near center while stereo right is density of small region near one corner.

Pasta stretching

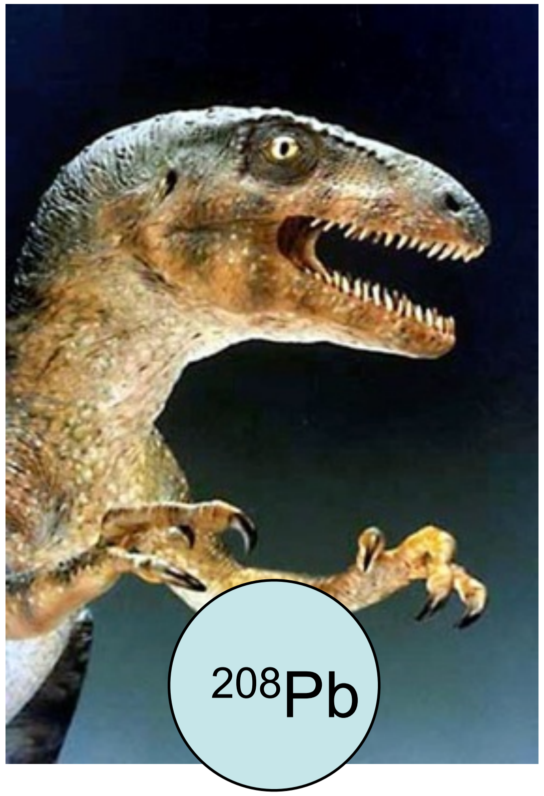


$l_z = 100.80$ fm

$l_x = l_y = 100.80$ fm

Preliminary 51200 nucleon simulation where the volume was stretched in z direction (and compressed in x and y directions to conserve volume) to calculate shear modulus and breaking strain. —Matt Caplan

The Crust of Merging Neutron Stars



- PREX with many people S. Ban, R. Michaels, J. Piekarewicz, M. Gorschtein,…
- Neutron star crust: K. Kadau, D. Berry, A. Chugunov, A. Schneider, M. Caplan, E. Clark,
- Support from DOE, SCIDAC

- C. J. Horowitz, Indiana University, horowit@indiana.edu

- INT, July 2014