Neutron rich matter, the symmetry energy, and nuclear pasta

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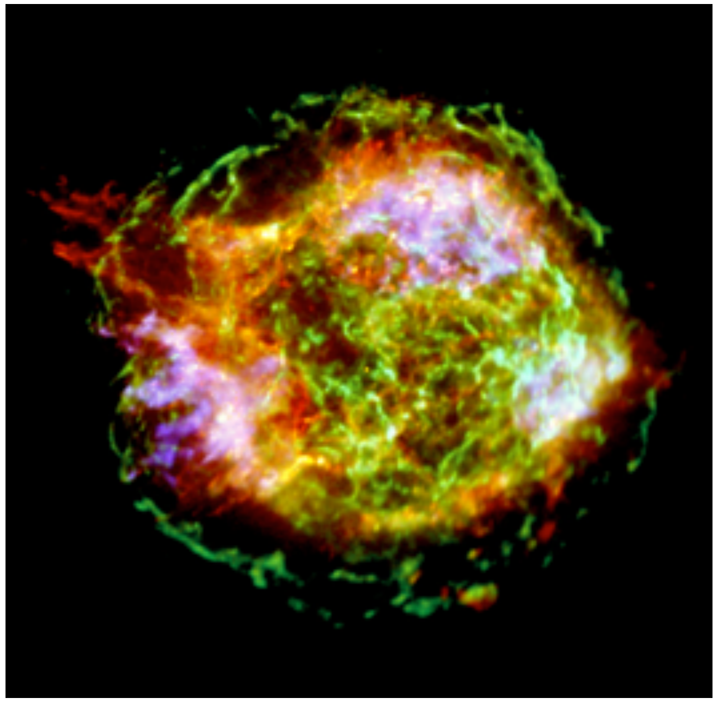
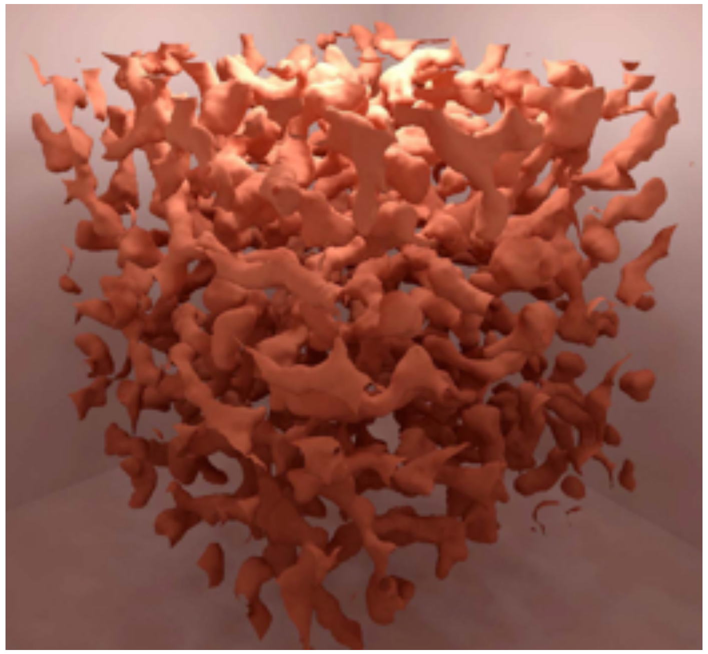
Compact Stars and Gravitational Waves, Kyoto, Nov. 2016

Neutron Rich Matter

- Compress almost anything to 10^{11}+ g/cm^3 and electrons react with protons to make neutron rich matter. This material is at the heart of many fundamental questions in nuclear physics and astrophysics.
  - What are the high density phases of QCD?
  - Where did the chemical elements come from?
  - What is the structure of many compact and energetic objects in the heavens, and what determines their electromagnetic, neutrino, and gravitational-wave radiations?
- Interested in neutron rich matter over a tremendous range of density and temperature were it can be a *gas, liquid, solid, plasma, liquid crystal (nuclear pasta), superconductor, superfluid, color superconductor...*



Supernova remanent Cassiopea A in X-rays



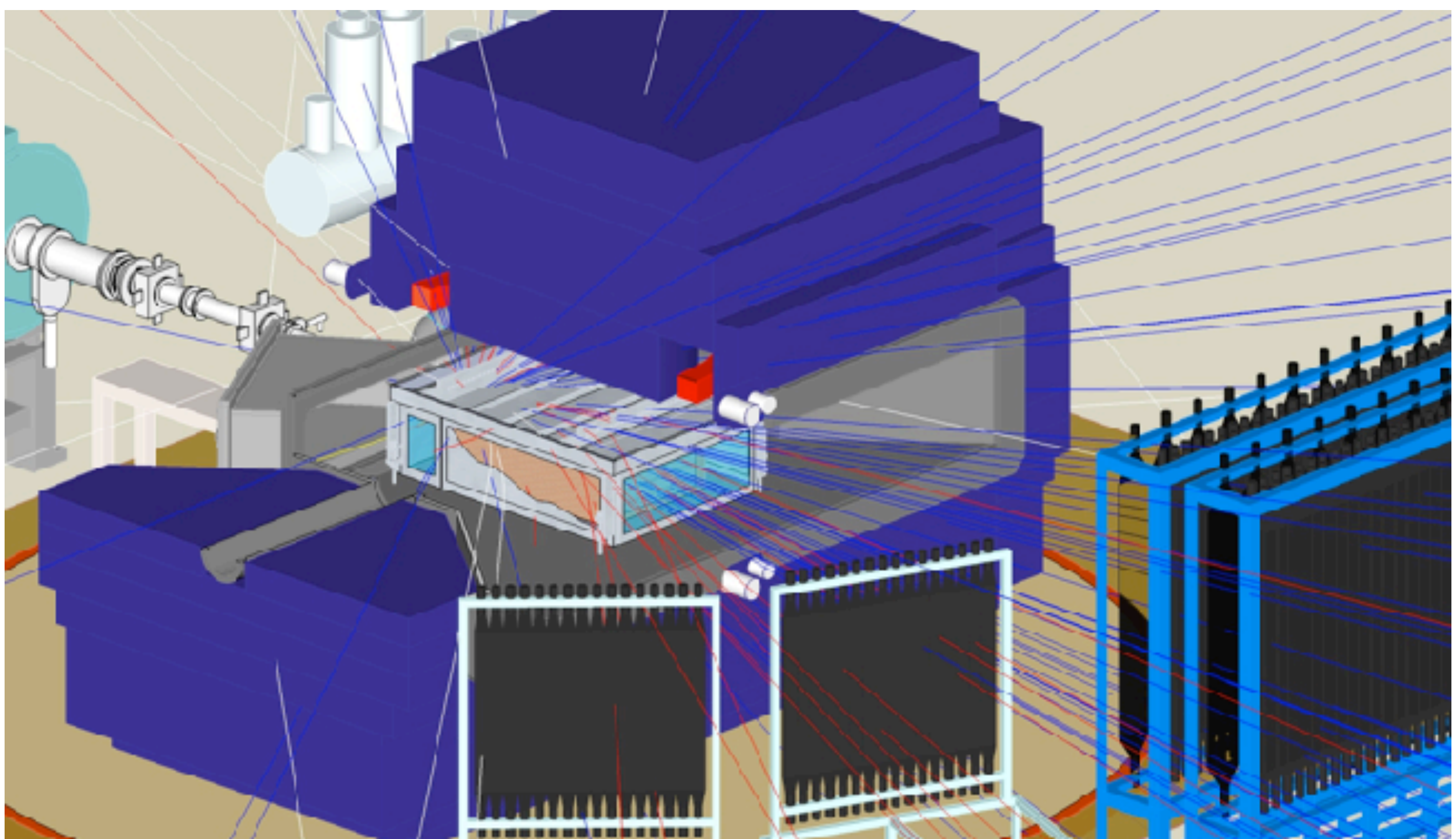
MD simulation of Nuclear Pasta with 100,000 nucleons

Symmetry Energy $S(\rho)$

- Describes how energy of nuclear matter rises with increasing neutron excess.
- Important for extrapolating laboratory measurements to very neutron rich systems in astrophysics.
- *$S(\rho)$ at high densities ($\rho>\rho_0$) is the single laboratory observable most closely related to the structure of neutron stars.*
- Heavy ion collisions, with radioactive beams, can produce high density n rich matter in the laboratory.

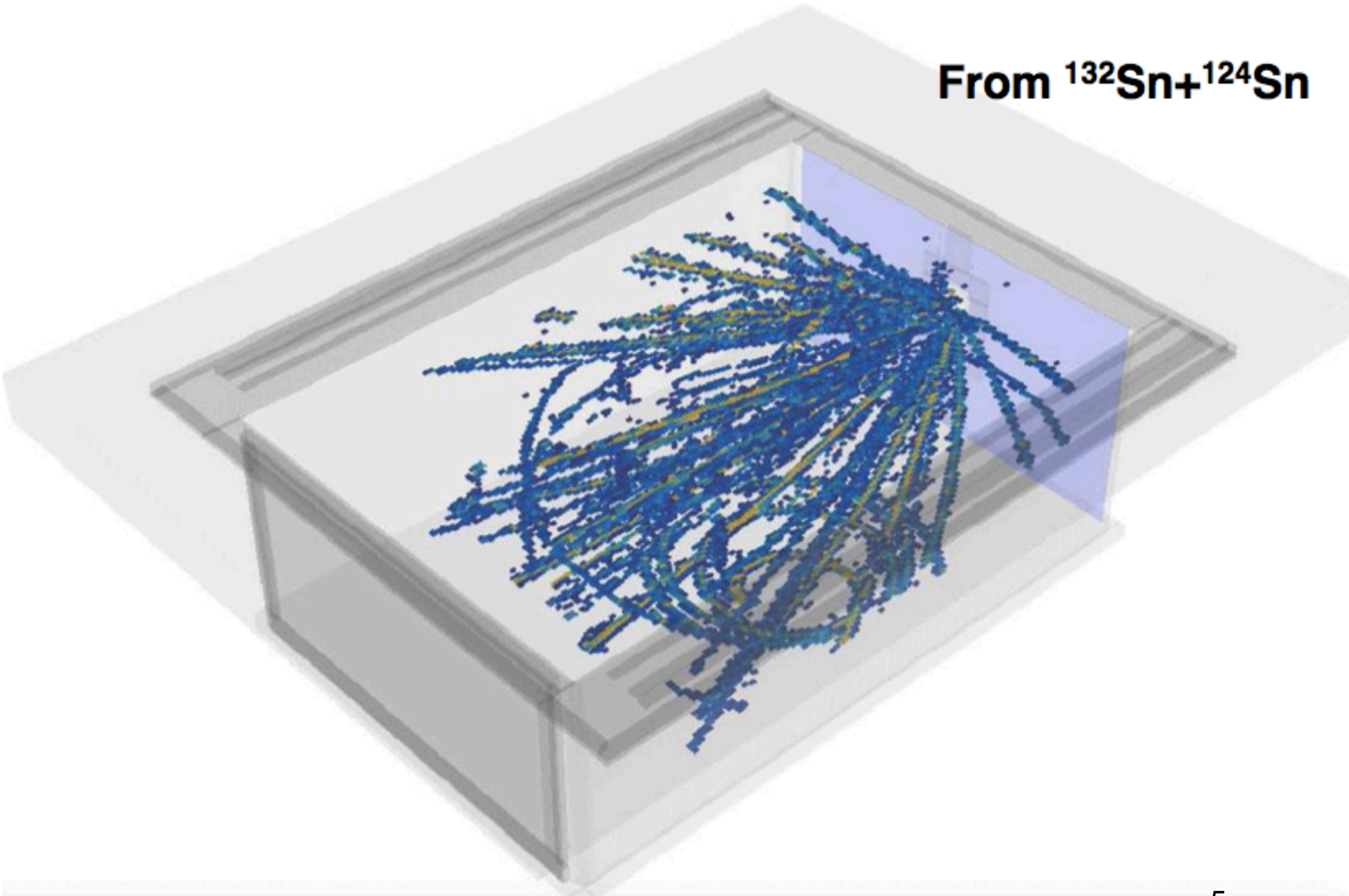
Samurai TPC and S(ρ) at $\rho > \rho_0$

- Determining S(ρ) from HI exp. may depend on transport models. Look at pion production and π^+/π^- ratios, n/p flow…
- Experimental program underway at RIKEN RIBF using SAMURAI magnet and



time projection chamber (TPC).
Exp. with ^{108}Sn, ^{132}Sn beams 2016

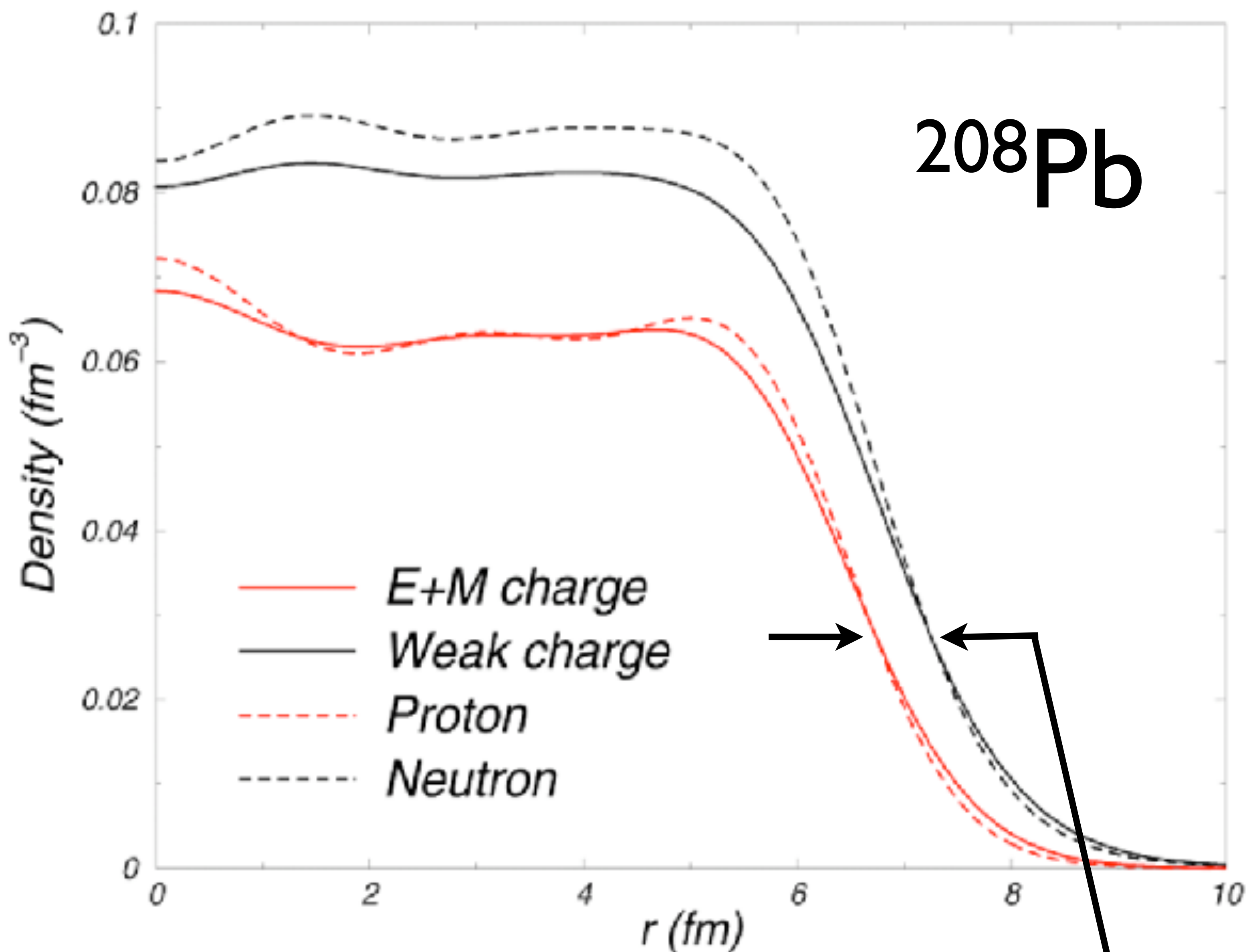
First results in a year



Event from Tetsuya MURAKAMI talk

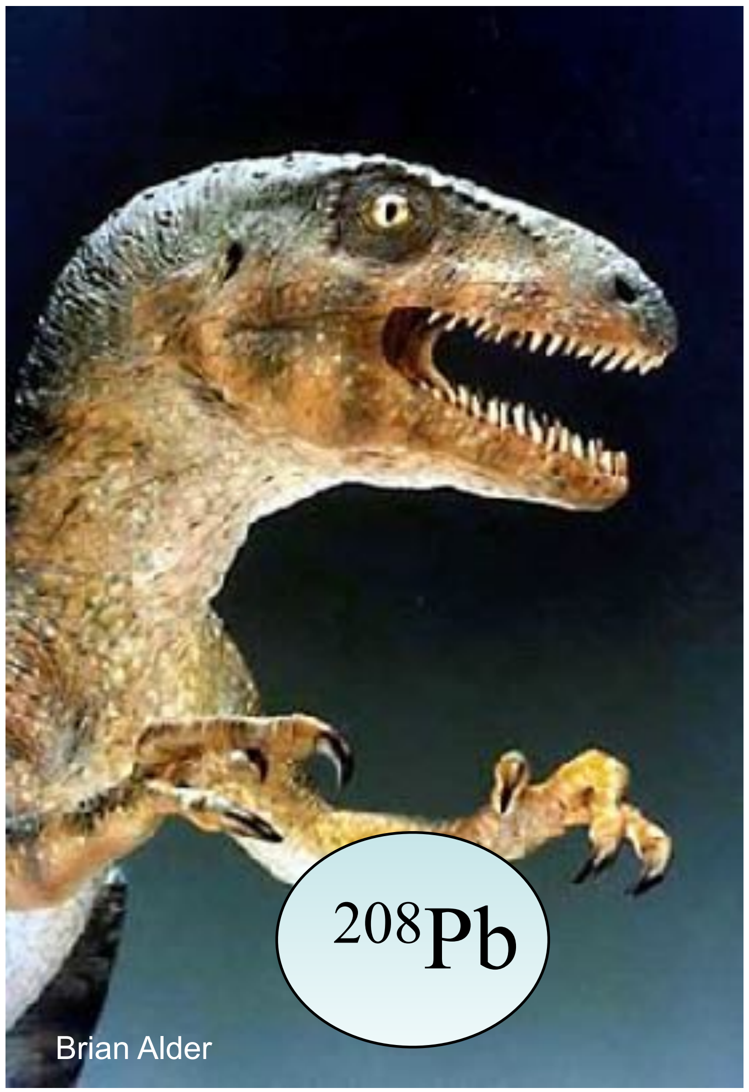
Neutron skins and dS/dρ

- Cleanest way to get dS/dρ is to measure neutron skin thickness.
- ^{208}Pb has 44 more n than p. If extra n are in the center they will cost S(ρ) at relatively high ρ. But if extra n are in the surface they will only cost S(ρ) at low surface densities.
- The density dependence of S (dS/dρ) will push n out to the surface and give a thick n skin.



Measure how much neutrons stick out past protons

Laboratory probe of neutron rich matter



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

This has important implications for neutron rich matter and astrophysics.

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

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

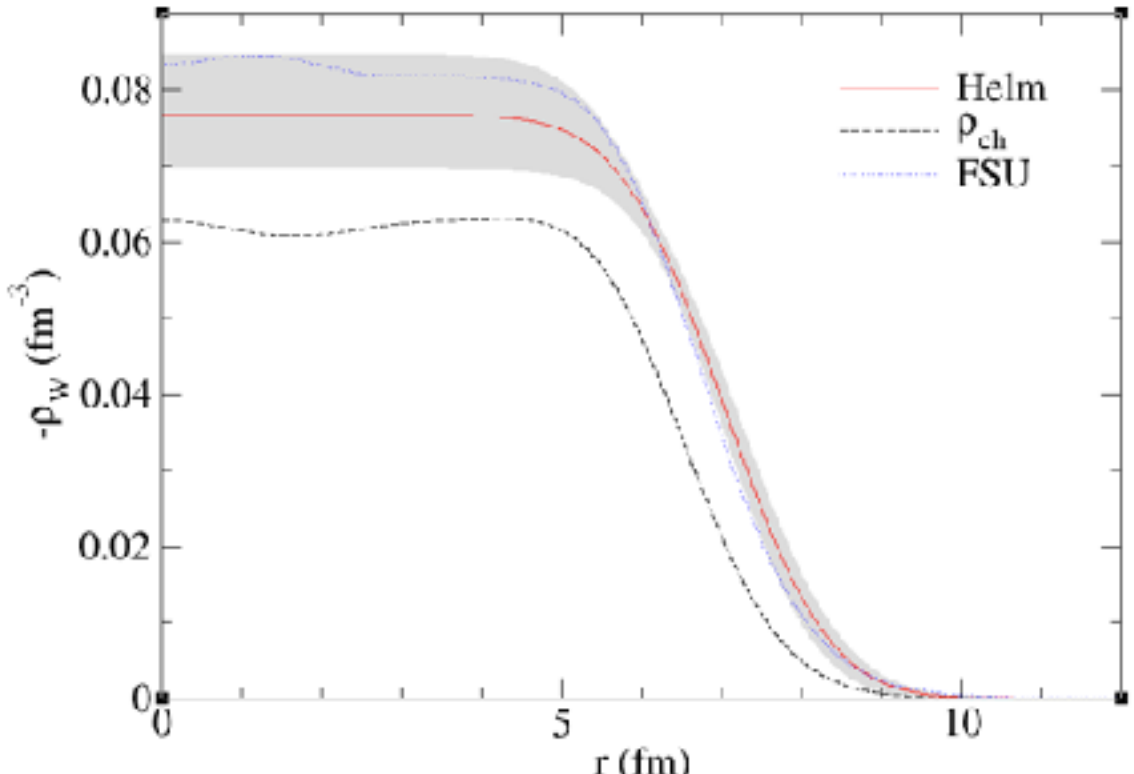
$$F_W(Q^2) = \int d^3r \frac{\sin(Qr)}{Qr} \rho_W(r)$$

- Model independently map out distribution of weak charge in a nucleus.
- **Electroweak reaction free from most strong interaction uncertainties.**

–Donnelly, Dubach, Sick

First PREX results

- 1.05 GeV electrons elastically scattering at ~5 deg. from ^{208}Pb
- **A_{PV} = 0.657 ± 0.060(stat) ± 0.014 (sym) ppm**
- Weak form factor at q=0.475 fm^{-1}: $F_W(q) = 0.204 \pm 0.028$
- Radius of weak charge distr. $R_W = 5.83 \pm 0.18 \pm 0.03$ fm
- Compare to charge radius R_{ch}=5.503 fm --> Electroweak skin: $R_W - R_{ch} = 0.32 \pm 0.18$ fm
- First observation that weak charge density more extended than (E+M) charge density --> weak skin.
- Unfold nucleon ff--> neutron skin: $R_n - R_p = 0.33^{+0.16}_{-0.18}$ fm
- Phys Rev Let. **108**, 112502 (2012), Phys. Rev. C **85**, 032501(R) (2012)



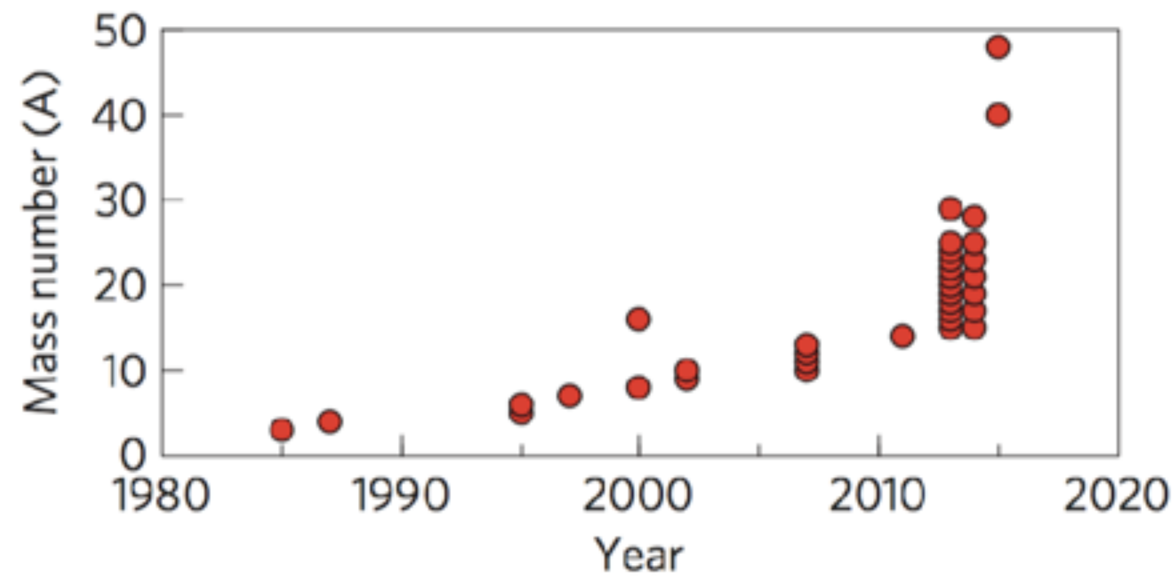
Helm model weak charge density (gray area) consistent with PREX results.

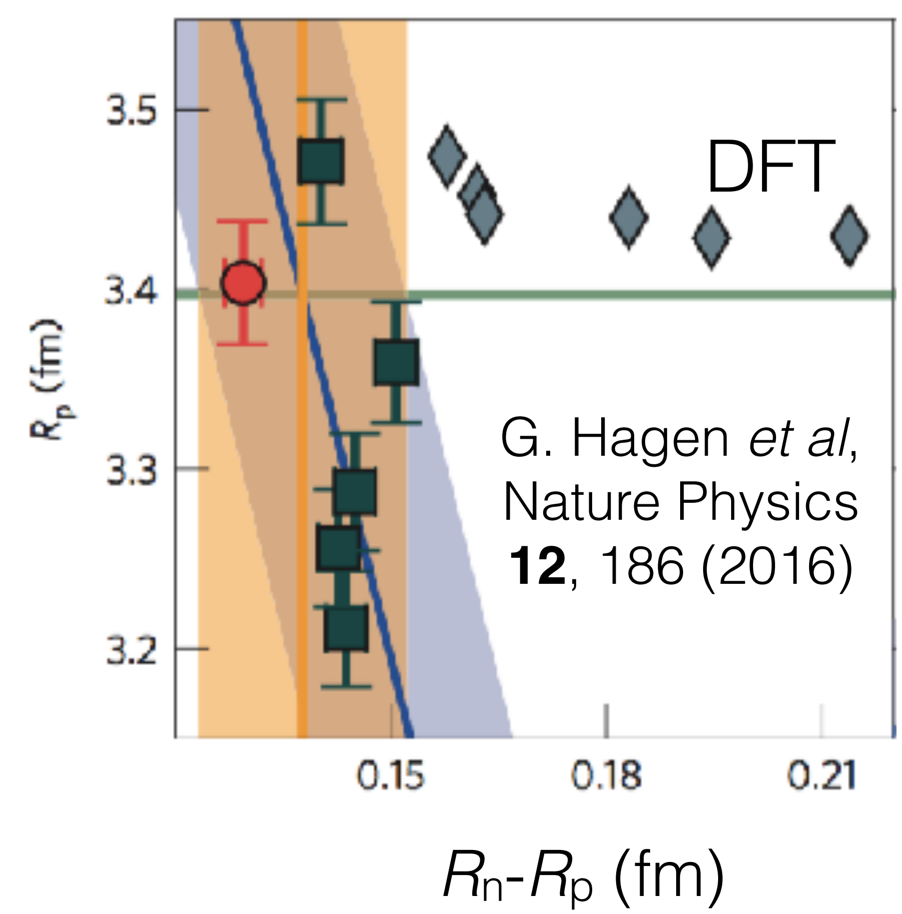
Next Steps

- PREX-II: ^{208}Pb with more statistics. Goal: R_n to ±0.06 fm. Will large R_n-R_p be confirmed?
- CREX: Measure R_n of ^{48}Ca to ±0.02 fm. Microscopic calculations feasible for light n rich ^{48}Ca (but not ^{208}Pb) to relate R_n to three neutron forces.

Study 3 neutron forces in ^{48}Ca

- Large computational advances allow microscopic calculations of structure of medium mass (A=48) nuclei using realistic two nucleon and three nucleon forces from Chiral EFT.
- Coupled cluster calculations by G. Hagen *et al* make sharp prediction R_n-R_p(^{48}Ca) = 0.135 ±0.015 fm.
- Three neutron forces play an important role. Many DFT models predict larger neutron skin.
- Prediction will be directly tested by CREX with goal of R_n to ±0.02 fm.

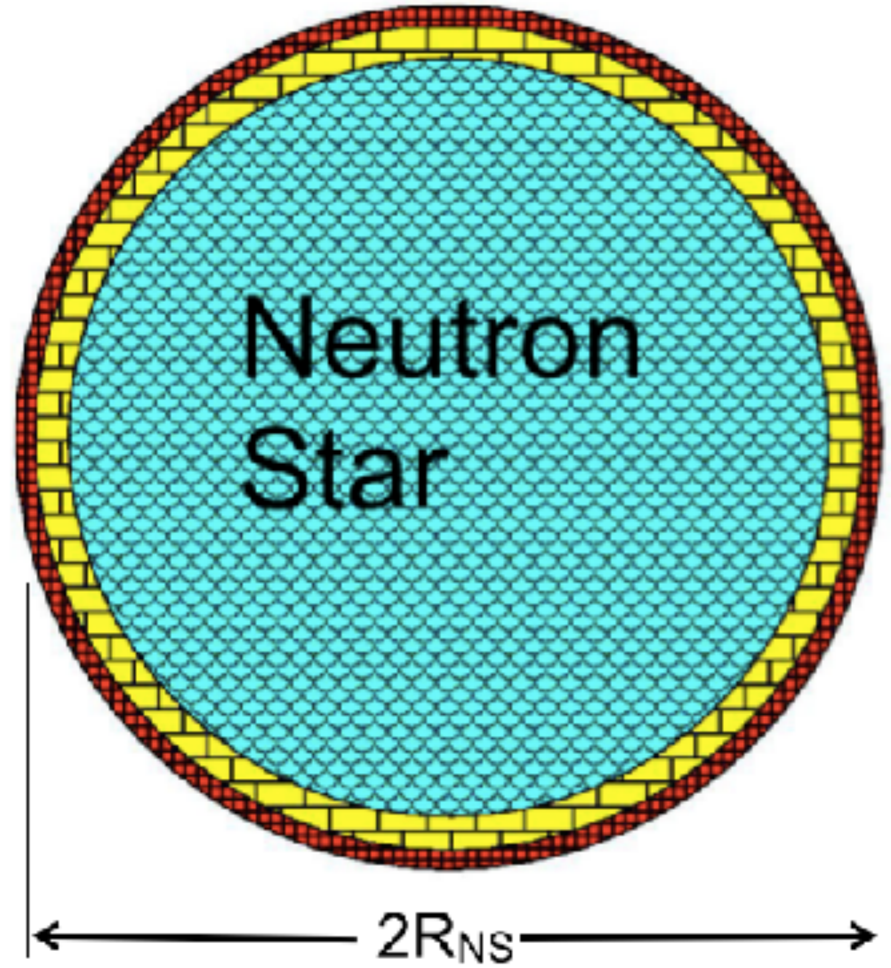


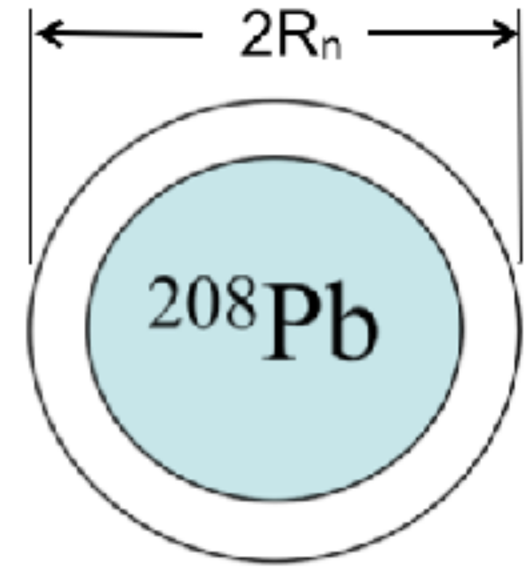


G. Hagen *et al*, Nature Physics **12**, 186 (2016)

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 near ρ_0
- Radius of (~1.4M_{sun}) NS depends on P at medium densities > ρ_0.
- Maximum mass of NS depends on P at high densities.
- These three measurements constrain density dependence of EOS.





R_{NS} ~ $3L_{LIGO}$

Neutron star is 18 orders of magnitude larger than Pb nucleus but has same neutrons, strong interactions, and equation of state.

PREX II: $R_n(^{208}Pb)$ to ±0.06 fm
CREX: $R_n(^{48}Ca)$ to ±0.02 fm or ~ $5\Delta L_{LIGO}$

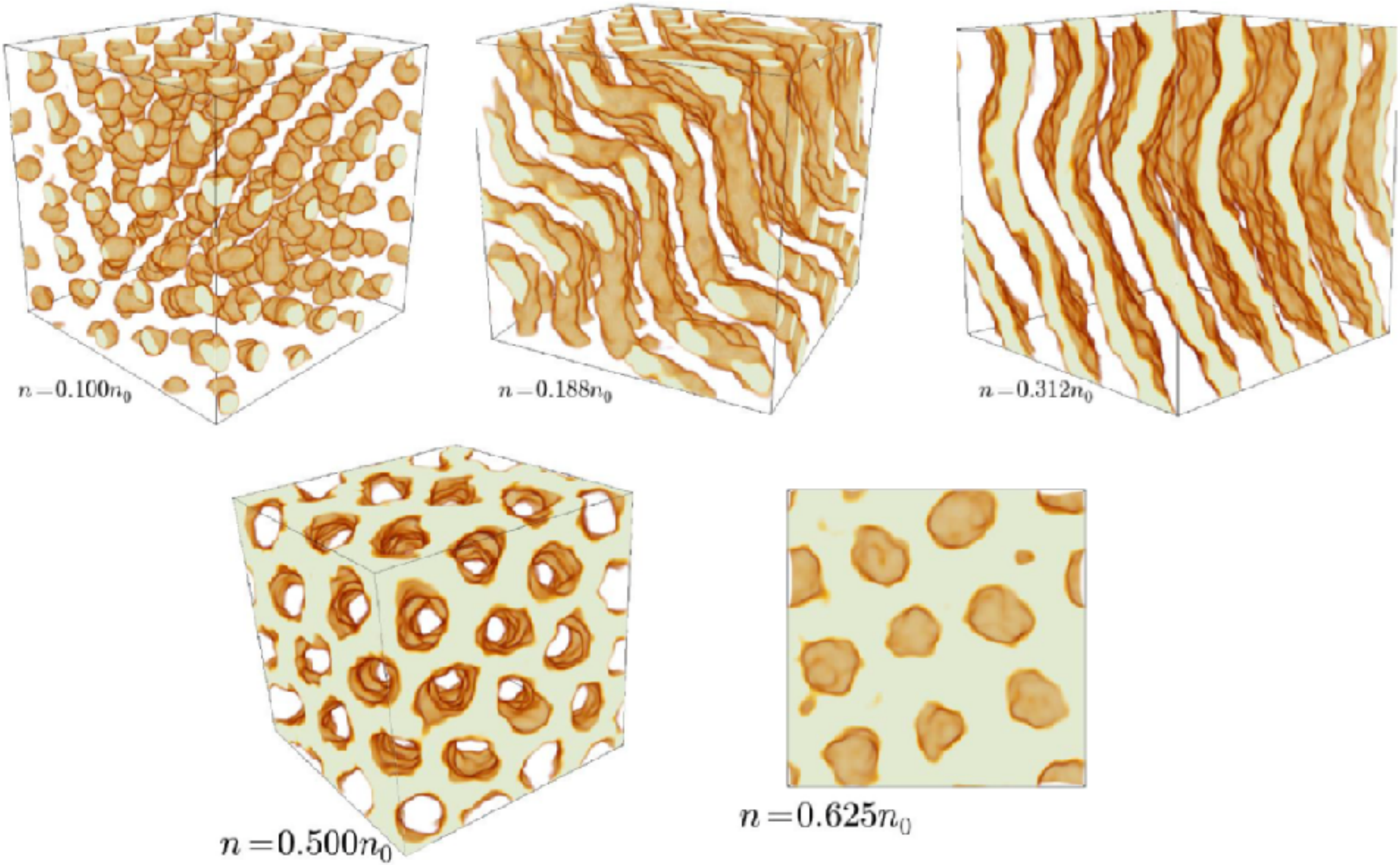
Nuclear Pasta

- 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".

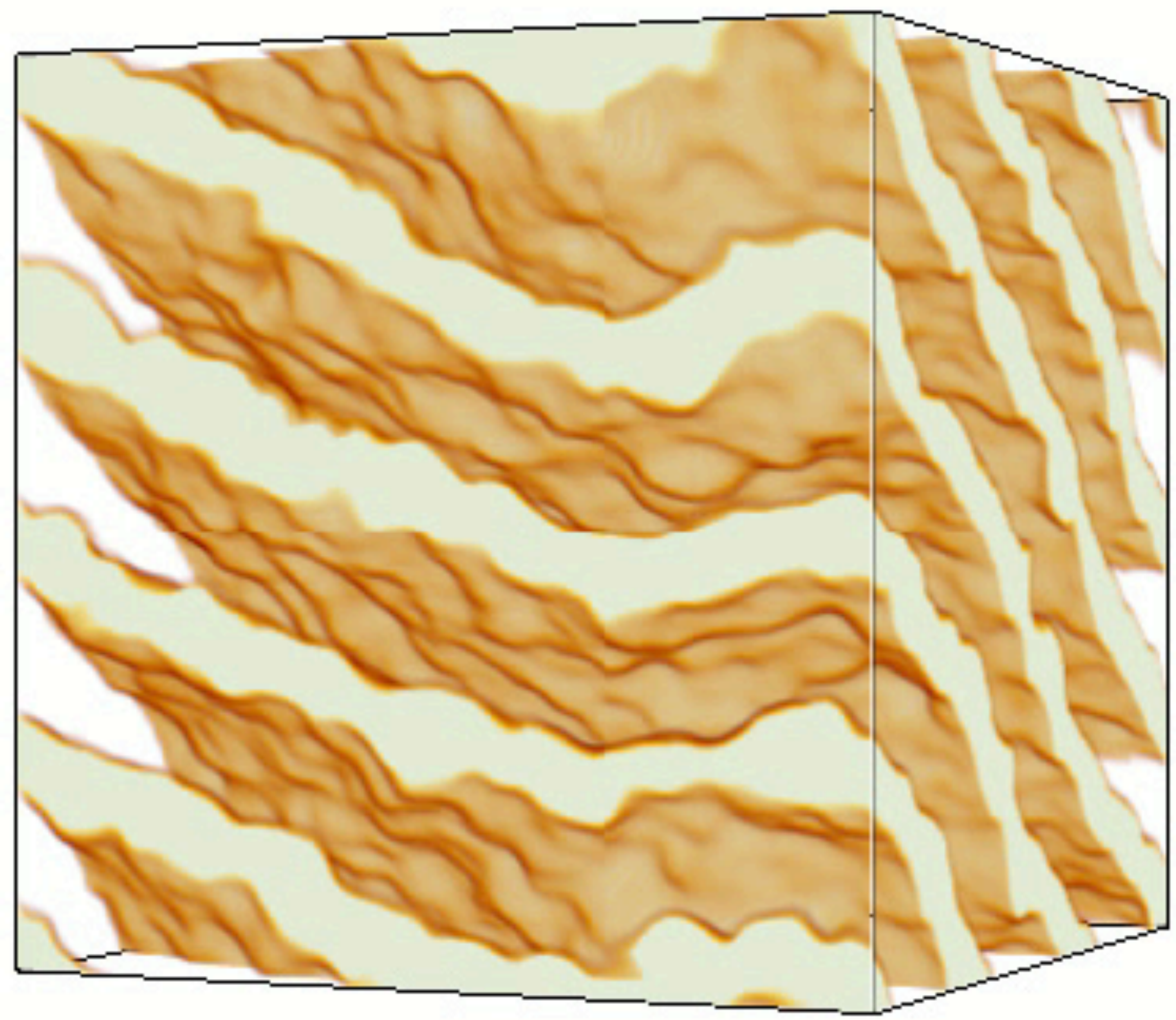
- Nuclear pasta expected in neutron stars at base of crust about 1 km below surface at $\sim 1/3\rho_0$.

- **Semiclassical MD model**: $v(r) = a\, e^{-r^2/\Lambda} + b_{ij}\, e^{-r^2/2\Lambda} + e_i e_j\, e^{-r/\lambda}/r$ Parameters of short range interaction fit to binding E and density of nuclear matter.

Nuclear Pasta Shapes



MD simulation with slowly increasing volume



Andre Schneider

$n = 0.0585 \mathrm{fm}^{-3}$

51200 nucleons, T=1 MeV, Y_p=0.4

Excited Pasta

Al Feldstein's cover for Weird Science # 8

Excited pasta

- Complex pasta shapes from Coulomb frustration. This implies many different shapes could be within as little as a few keV/nucleon.

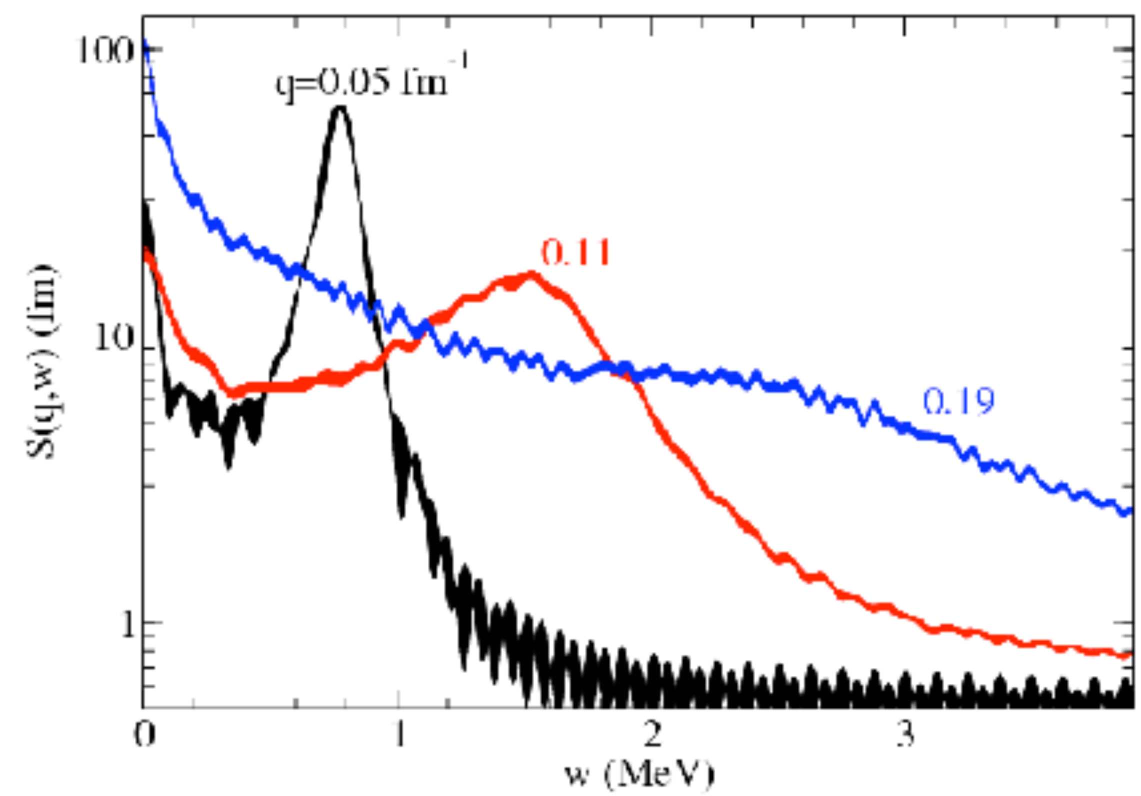
- Large density of states will increase the heat capacity and could increase the energy transferred when ν_μ or ν_τ scatter in a supernova.

- Possible excitation modes: low energy “giant resonances”, or coherent shape oscillations, plasma oscillations… Or ??

Dynamical response function

- Response of system when a probe transfers momentum q and energy w.
- Can be calculated directly from MD trajectories in (semi) classical approx.
- $S(q,w)=\int dt \cos(wt)\, S(q,t)$,
- $S(q,t)=\langle \rho(q,t)^* \rho(q,0)\rangle$
- $\rho(q,t)=\sum_j \exp[i q_j \cdot r_j(t)]$

Phys.Rev. C72 (2005) 035801

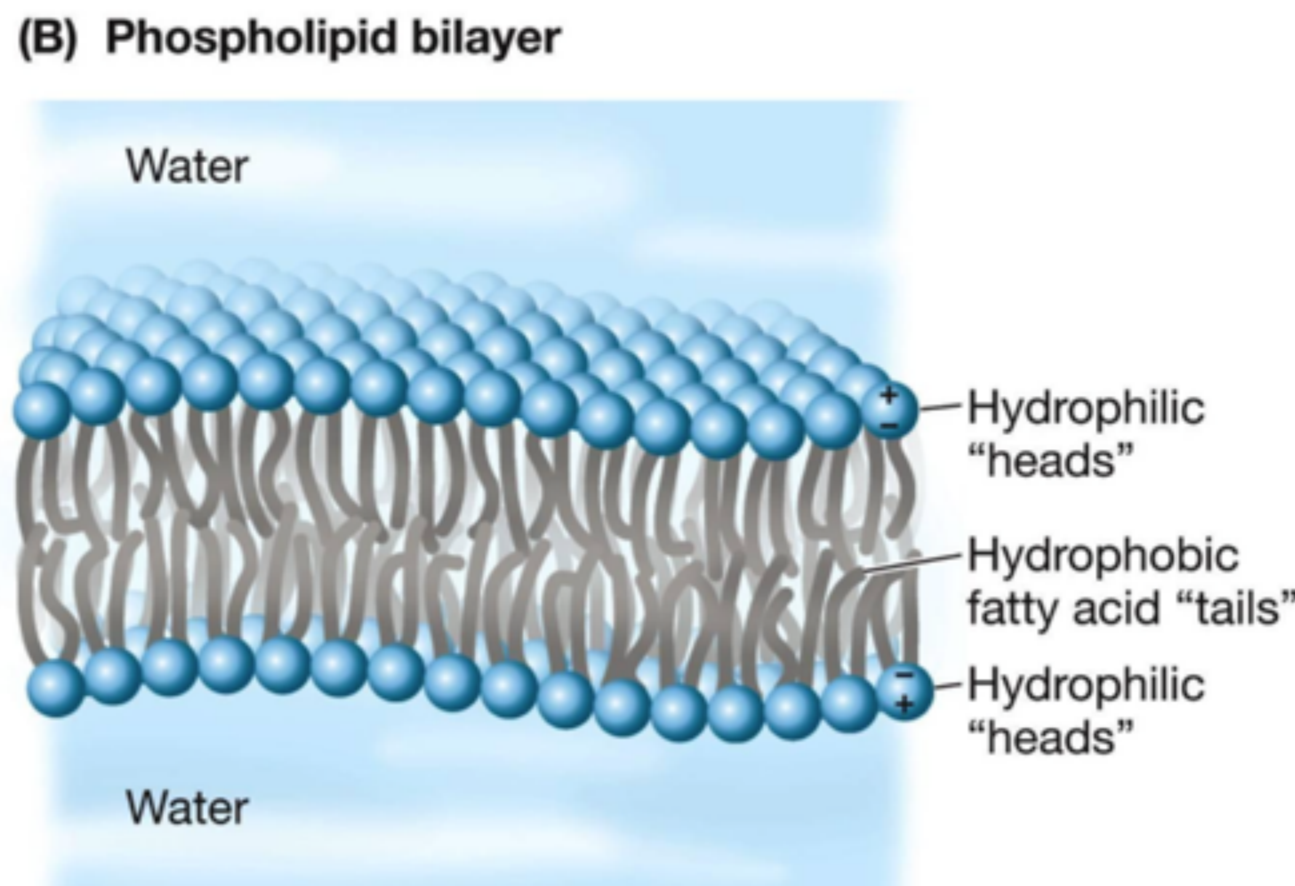


- Simulation at $\rho=0.05$ fm^{-3}, T=1 MeV and $Y_p=0.2$ with 100,000 nucleons.
- $q=0.05$ fm^{-1} curve shows plasma oscillation peak.

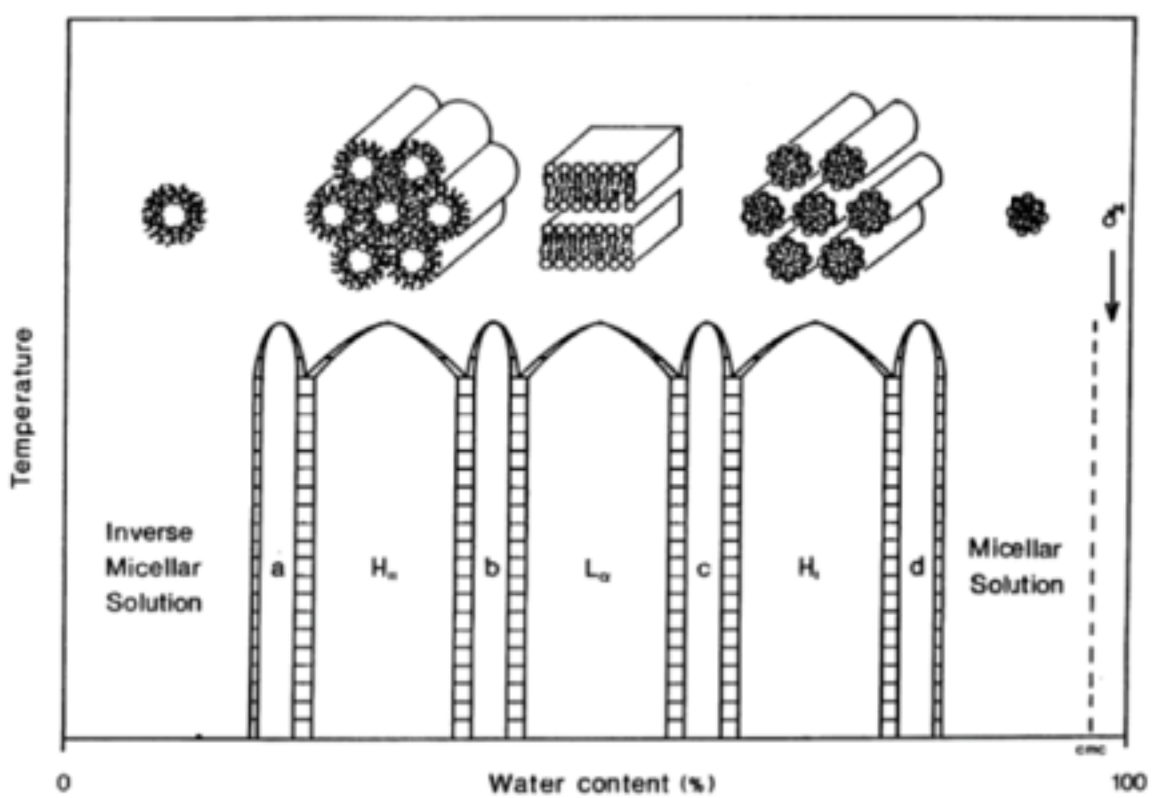
Spiral Pasta

Nuclear Pasta vs Biological

- Biological membranes can form similar shapes to nuclear pasta.
- Note even the names nucleus, nuclear fission and fusion are from biology.



LIFE 8e, Figure 3.20 (Part 2)



Shape of Nuclei in the Crust of Neutron Star

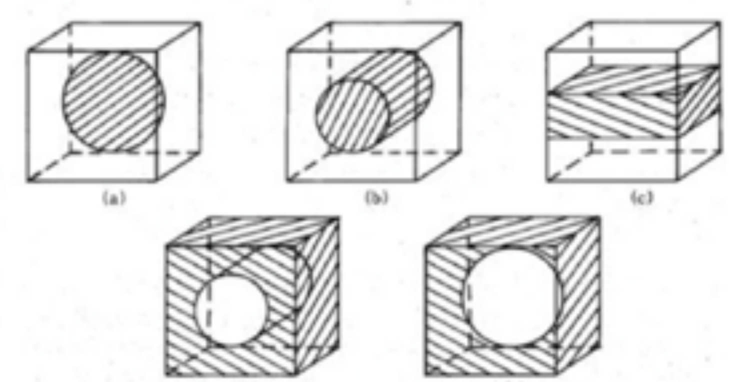


Fig. 1. Candidates for nuclear shapes. Protons are confined in the hatched regions, which we call nuclei. Then the shapes are, (a) sphere, (b) cylinder, (c) board or plank, (d) cylindrical hole and (e) spherical hole. Note that many cells of the same shape and orientation are piled up to form the whole space, and thereby the nuclei are joined to each other except for the spherical nuclei (a).

Shape Fluctuations

- Semi empirical mass formula

$$BE = a_v A - a_s A^{2/3} - a_c Z^2/A^{1/3} ...$$

- Higher order terms such as curvature energy $\sim A^{1/3}$ require very large systems to isolate.

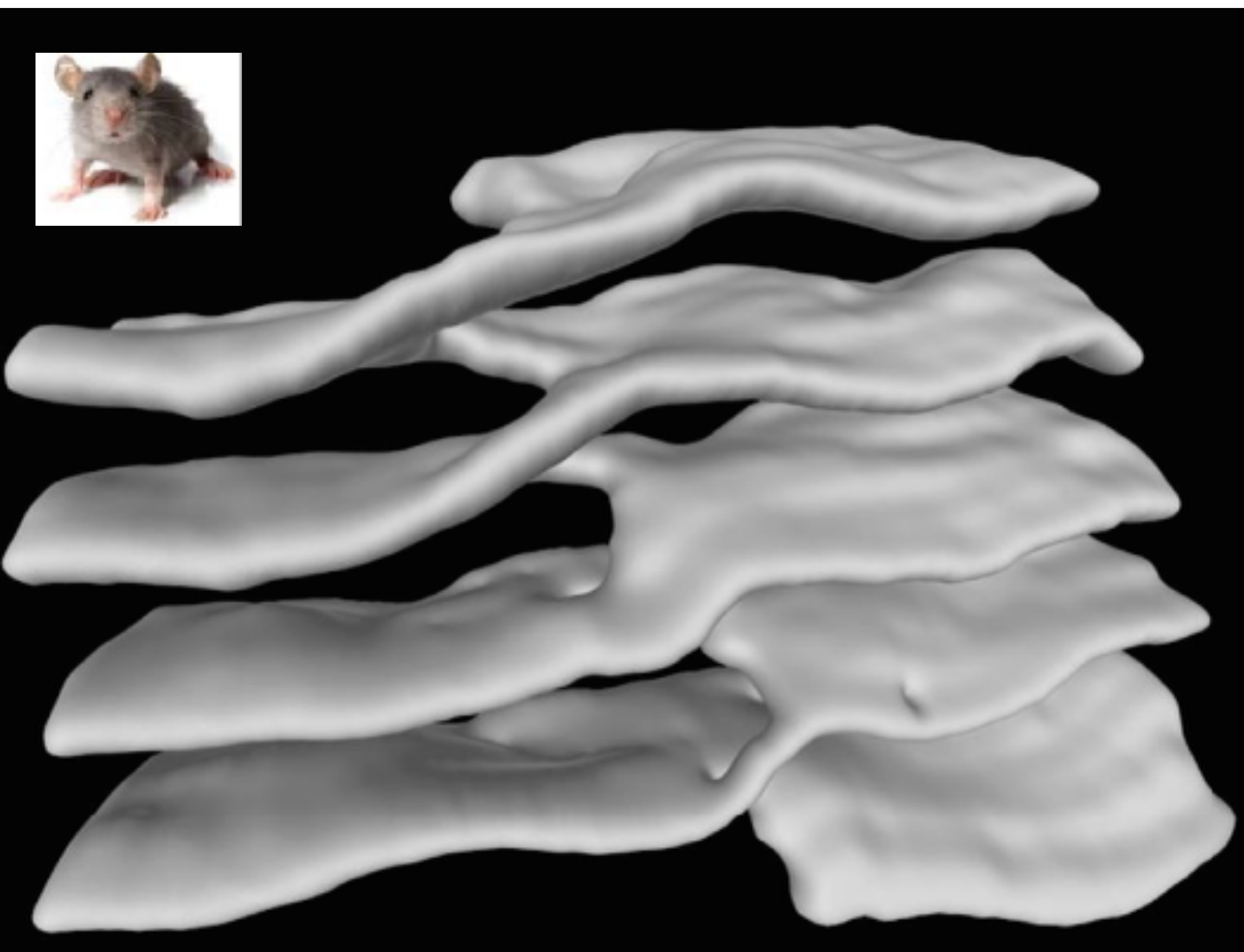
- Curvature Hamiltonian suggested for biological systems.

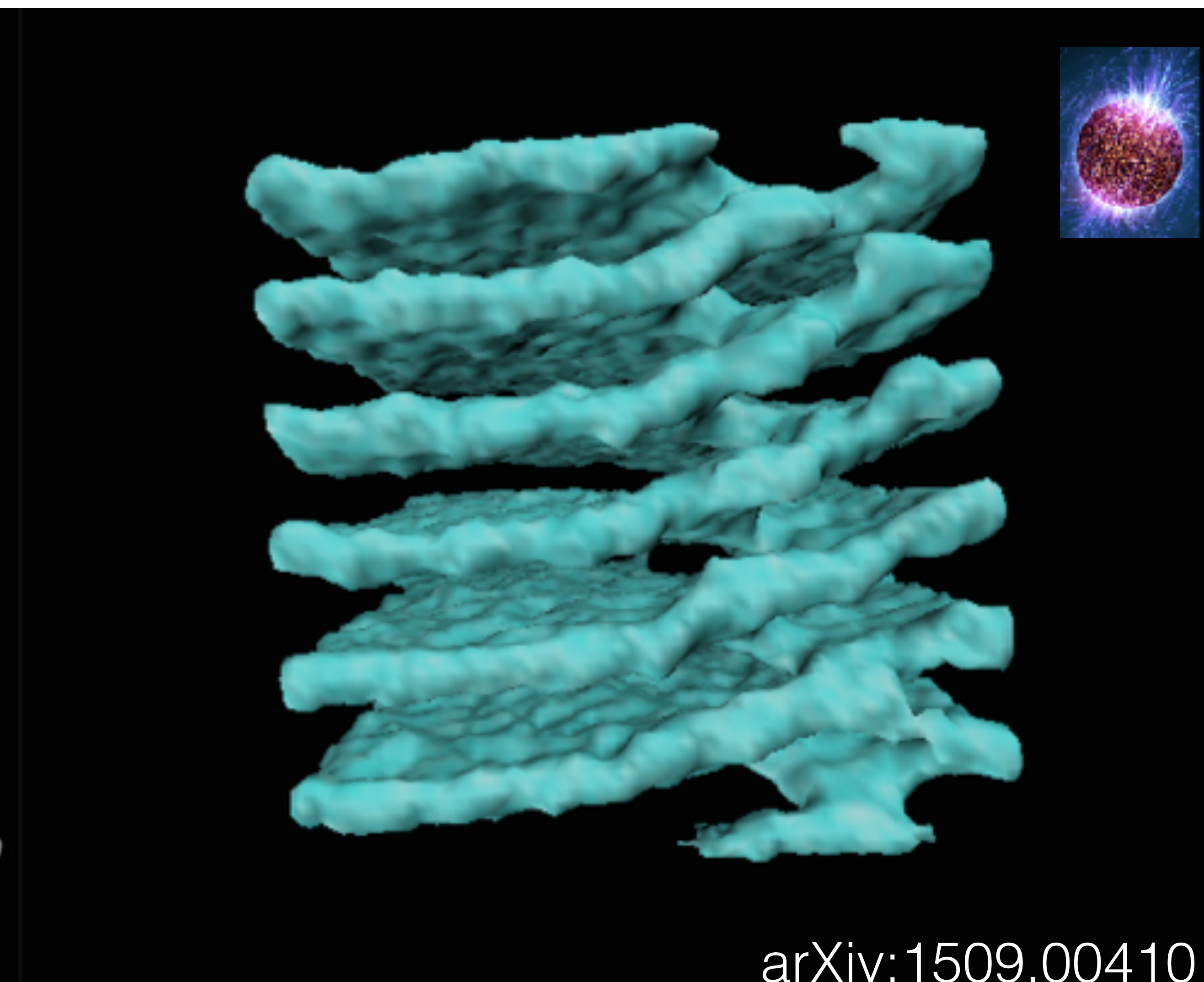
$$H_0 = \frac{1}{2} B \int dS (C_1 + C_2)^2 + \bar{B} \int dS C_1 C_2$$

- Integral over surface area dS, where C_1, C_2 are principle curvatures. One solution: $C_1 = C_2 = 0$ —> Flat sheets. Another solution: $C_1 = -C_2$ —> Spiral ramps.

Spiral ramps in biology and nuc. pasta

- Endoplasmic reticulum (ER) is an organelle present in cells where proteins are synthesized with the help of the large surface area. Recently its 3D structure was determined (left) [Cell 154 (2013) 285].

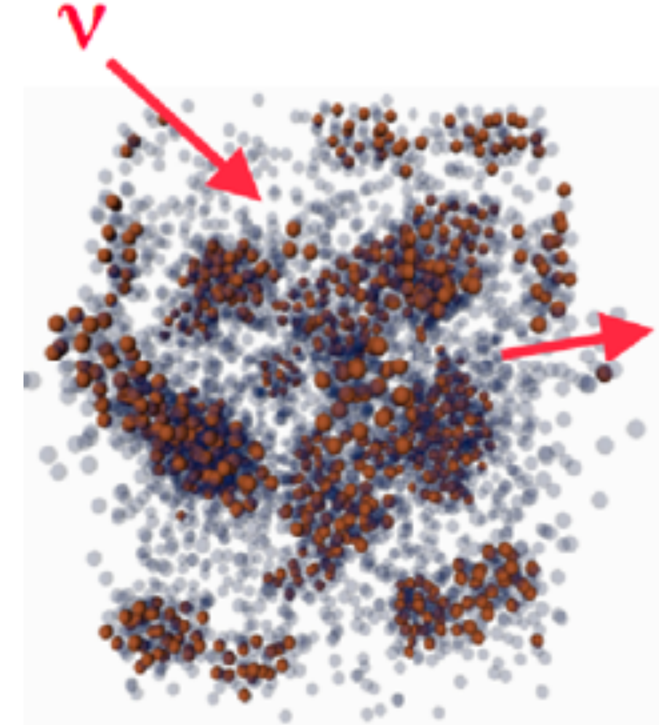




- Electron micrograph of endoplasmic reticulum at 1 g/cm^3.
- MD simulation with 75000 nucleons of nuclear pasta at 10^{14} g/cm^3.


How to
“smell”
pasta?

"Smelling nuclear pasta": observables sensitive to complex shapes

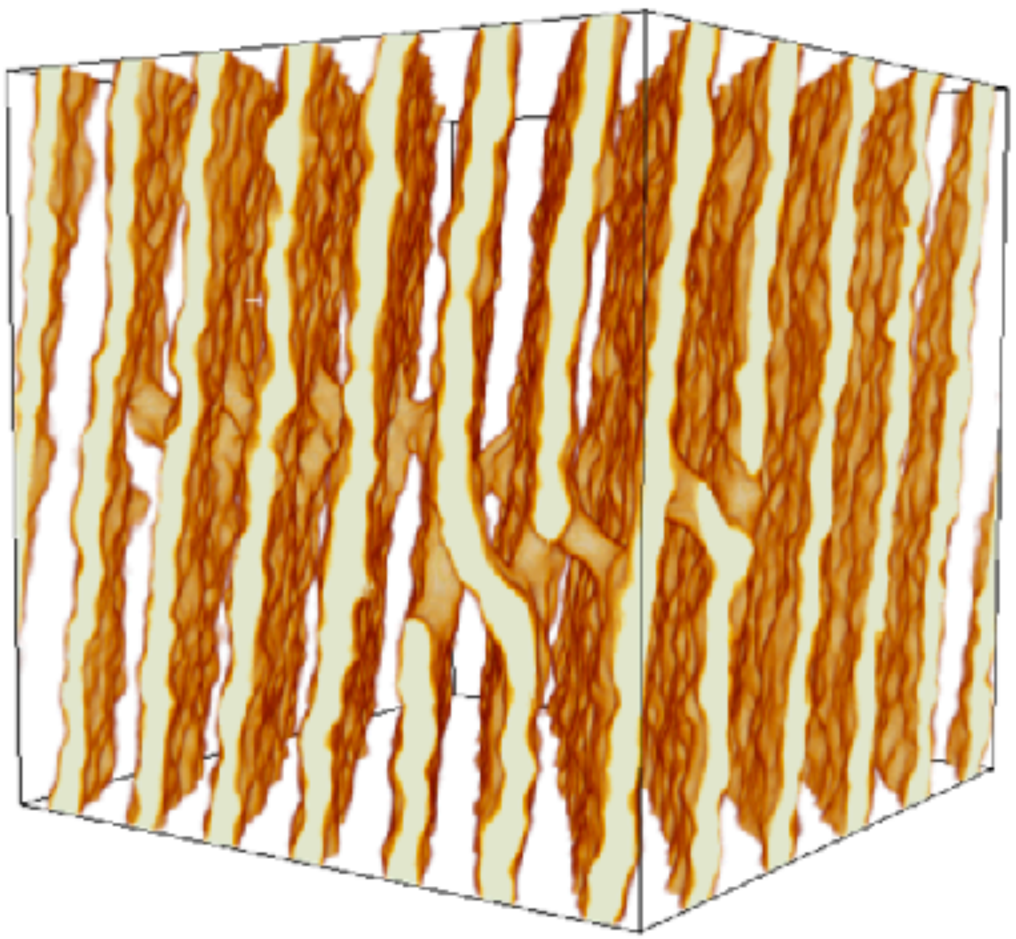


- Coherent ***ν***-pasta scattering gives ***ν* opacity** for supernova simulations. Depends on static structure factor $S_n(q)=\langle\rho_n(q)^*\rho_n(q)\rangle$ or dynamical response function $S_n(q,w)$
- Coherent electron-pasta scattering gives **shear viscosity**, **thermal conductivity**, and **electrical 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.

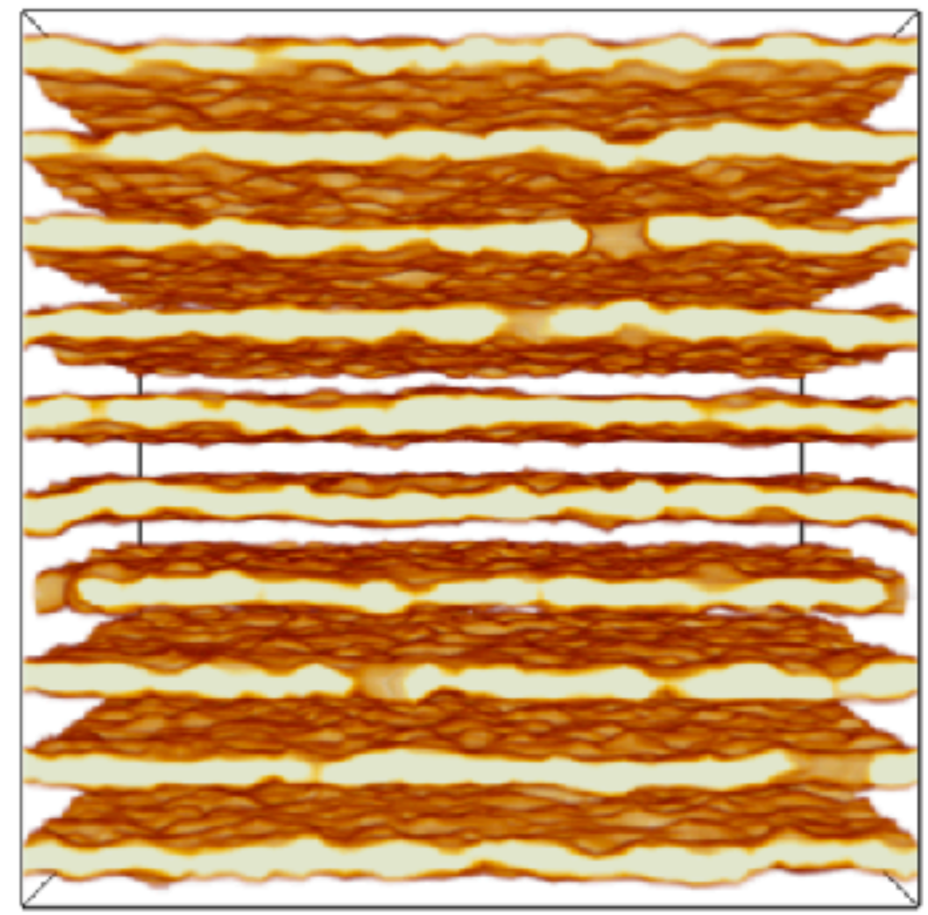
Disordered Pasta

- 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 isolated X-ray pulsars are observed with rotation periods longer than 20 sec.
- Assumed a lattice of some average charge with **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 (Wiedemann-Franz law relates electrical / 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 with and without defects



MD simulation from random start has defects (n=204,800)

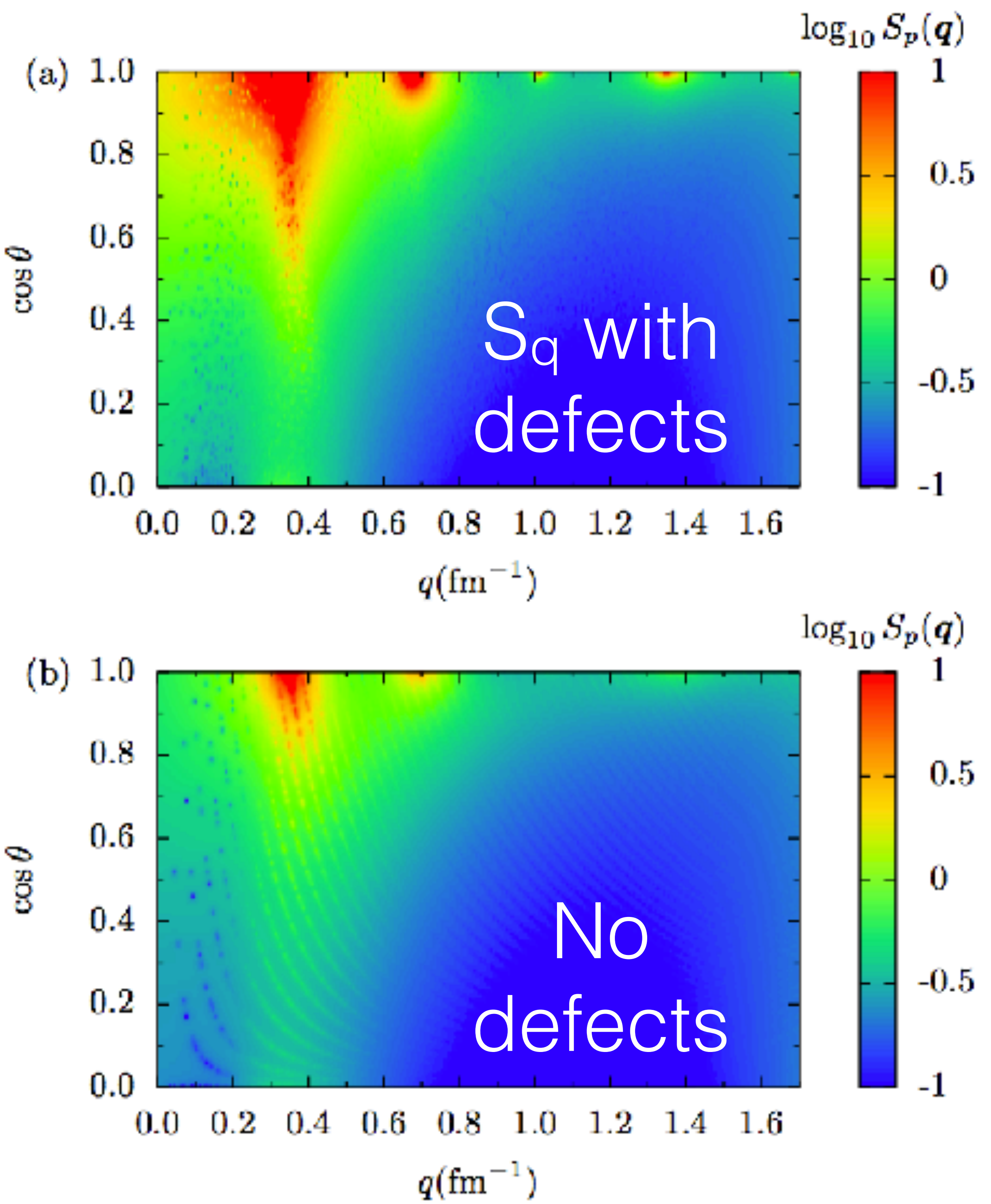


Pasta biased with small potential to form perfect plates

A. S. Schneider et al, Phys. Rev. C **93**, 065806 (2016)

Structure factor S_q and impurity parameter Q_{imp}

- Static structure factor: $S_{\mathbf{q}} = \langle \rho(\mathbf{q})^* \rho(\mathbf{q}) \rangle$, with $\rho = \sum_j \exp(i\mathbf{q} \cdot \mathbf{r}_j)$.
- Extra scattering from defects can be described by an impurity parameter: $Q_{imp} = \langle Z^2 \rangle - \langle Z \rangle^2 \approx 30$
- Reduces electron mean free path so thermal conductivity scales with Q_{imp}^{-1}.



409600 nucleons, ρ=0.05 fm^{-3}, T=1 MeV, Yp=0.4

Phys. Rev. C 93, 065806 (2016)

Cooking Pasta

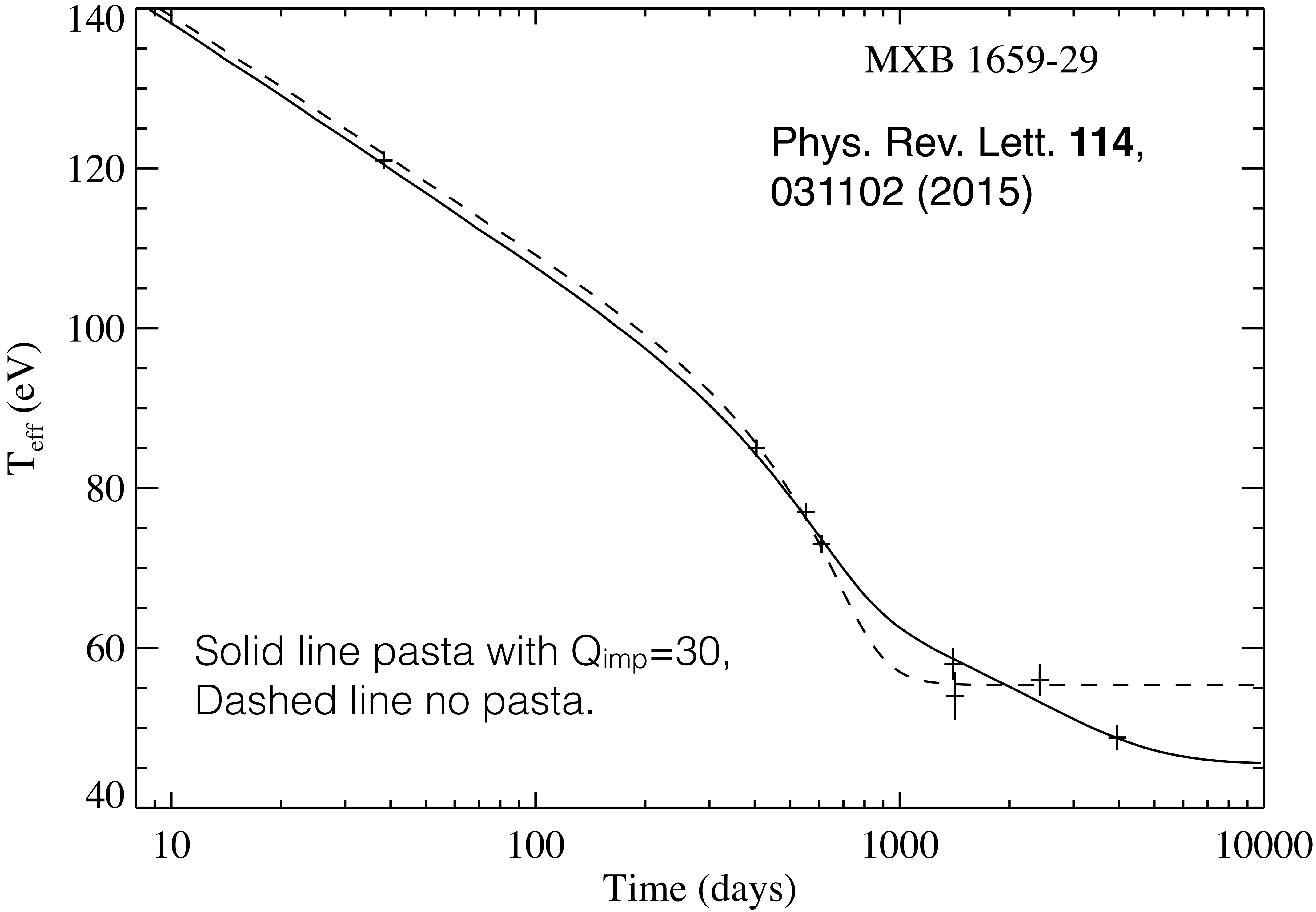
Crust cooling in transiently accreting LMXBs

- Extended accretion for ~10 y heats the crust of a NS out of equilibrium with the core. Crust then cools when accretion stops.

- Surface temperature T, at later times t after accretion stops, probes thermal conductivity and heat capacity of the crust at increasing densities. Light curve, T vs t, maps out crust thermal properties vs density.

- T at t>1000 days into quiescence, probes thermal conductivity deep in the inner crust where we expect pasta.

- Continued late time cooling of MXB 1659-29 requires a layer with a low thermal conductivity, and a high heat capacity, with $Q_{imp} \gtrsim 20$ at $\rho \gtrsim 8\times10^{13}$ g/cm^3 [A. Deibel et al., arXiv:1609.07155].



Surface temperature of transiently accreting MXB 1659 versus time since accretion stopped. Solid curve shows results for disordered pasta while ordered pasta yields the dashed curve.

Pasta Scattering

Neutrino pasta scattering

- Supernova neutrinos have wavelengths comparable to pasta sizes and can scatter coherently from the many neutrons in a single piece of pasta.

- Just like neutrino-nucleus elastic scattering, the coherent cross section is proportional to the square of an effective number of neutrons in a piece of pasta.

- This could significantly increase the neutrino opacity and slow neutrino diffusion when pasta is present.

Opacity valves

- An ionized plasma has a high photon opacity that may become much smaller when the medium cools and recombines. This can lead to oscillations and variable stars.

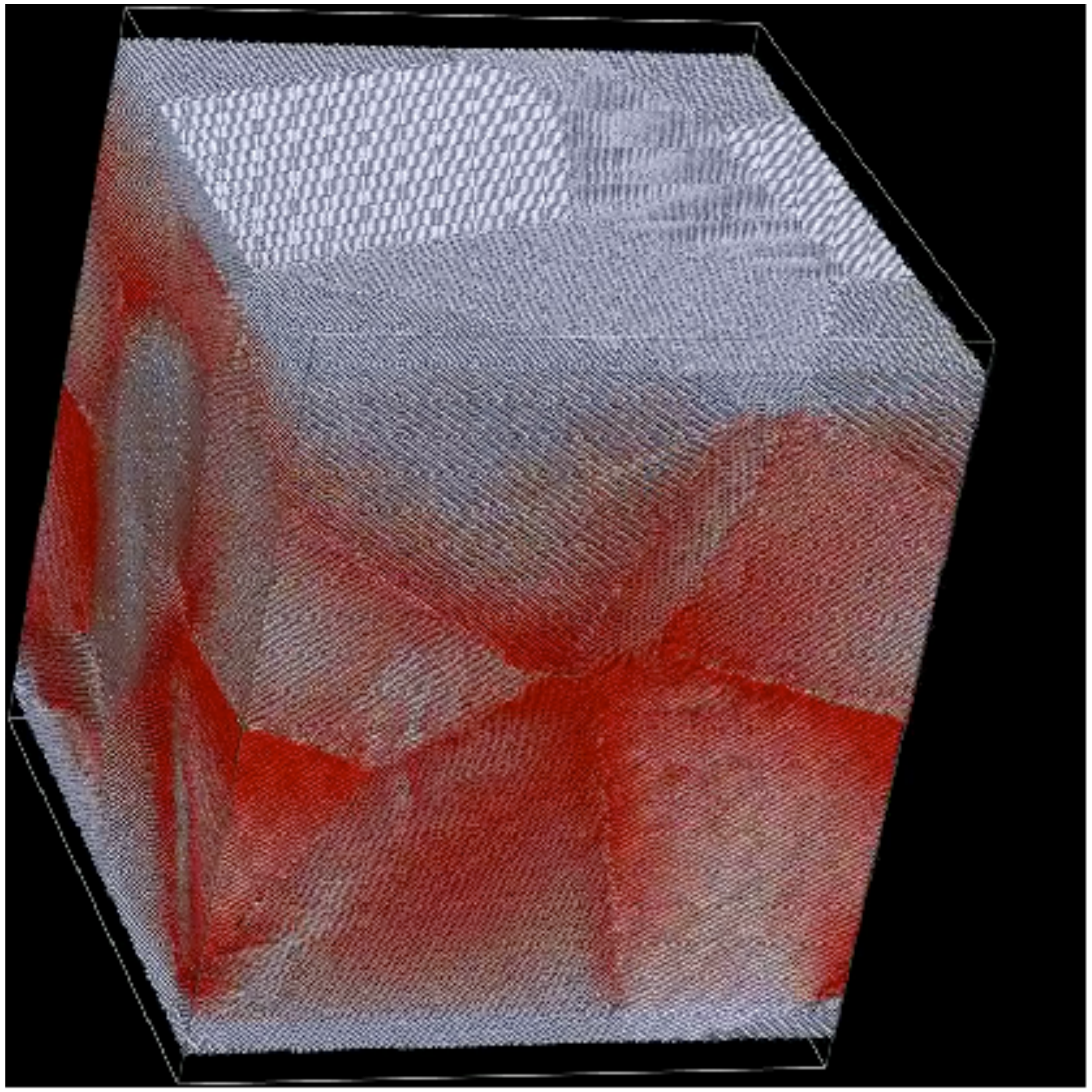
- The neutrino opacity may be low at high temperatures where medium is dissociated into nucleons and high at lower temperatures where nucleons cluster into pasta or heavy nuclei.

- Pasta formation may impact neutrino diffusion in protoneutron star cooling. Work in progress with L. Roberts, E. O'Connor, T. Fischer, W. Newton.

Mountains of Pasta

Crust mountains and gravitational waves(GW)

- A “mountain” on a rapidly rotating NS efficiently radiates GW because a large mass undergoes large accelerations.
- What is maximum size of a mountain? This depends on strength of NS crust.
- We find NS crust is strongest material known: 10^{10} times stronger than steel. It can support few cm tall mountains!
- Our crust can support ellipticities $\epsilon=(I_1-I_2)/I_3$ up to about 10^{-5}.



MD simulation of 13 million ions including the effects of defects, impurities, and grain boundaries... Red indicates deformation.

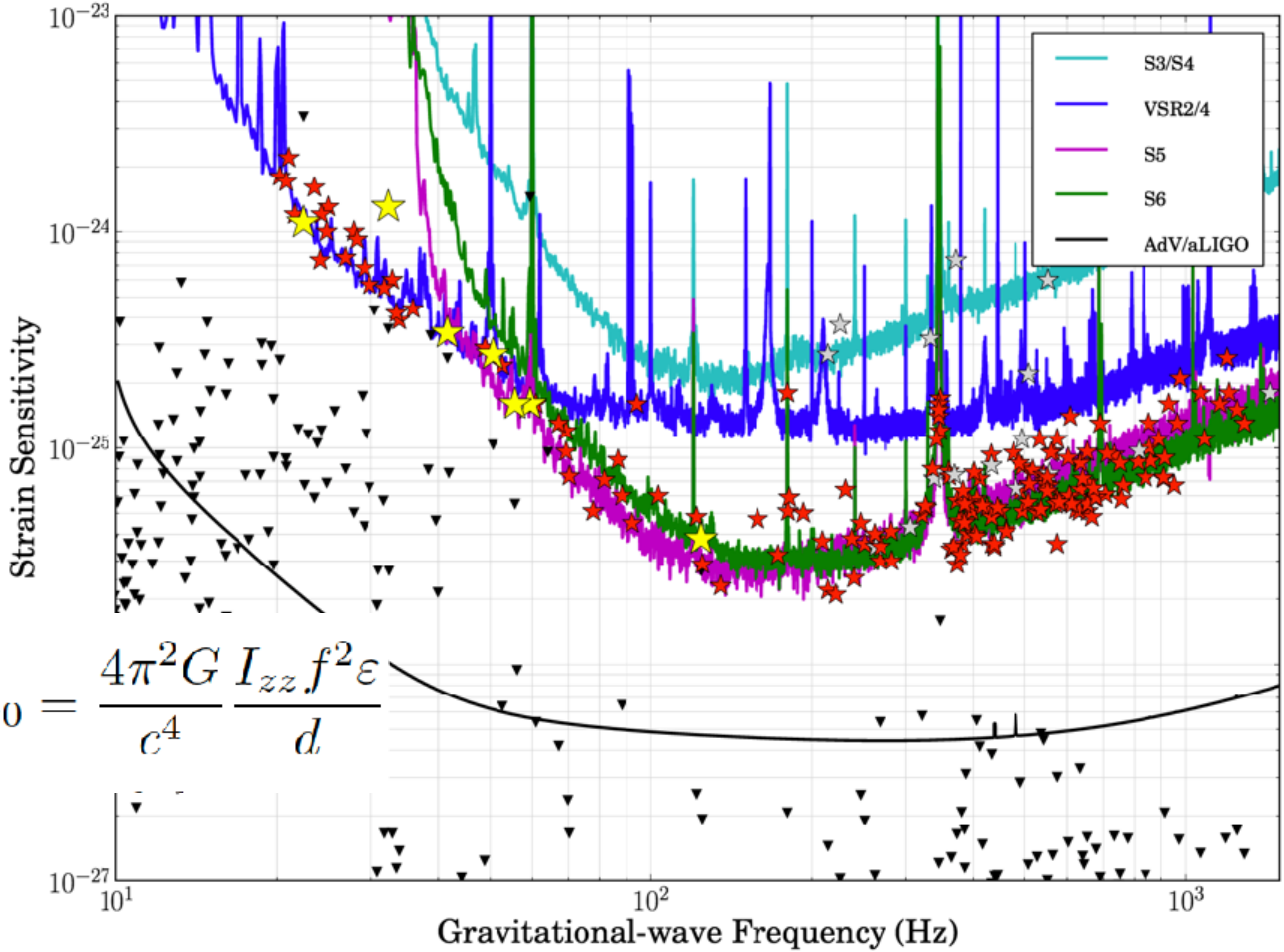
Phys. Rev. Let. **102**, 191102 (2009)

Breaking strain of nuclear pasta

- We assumed only coulomb interactions and have so far neglected neutron gas and formation of nuclear pasta.
- Strength of crust grows with density and pasta in densest part of crust.
- Unknown strength of nuclear pasta could significantly modify results.
- How do actual mountains compare to maximum possible?

- Mountain formation mechanisms are largely unknown:
  - Asymmetric accretion.
  - Temperature gradients and electron captures.
- Strong coulomb crust is promising for GW searches.

GW from known pulsars: results form the initial detector era



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

ApJ **785**, 119 (2014)

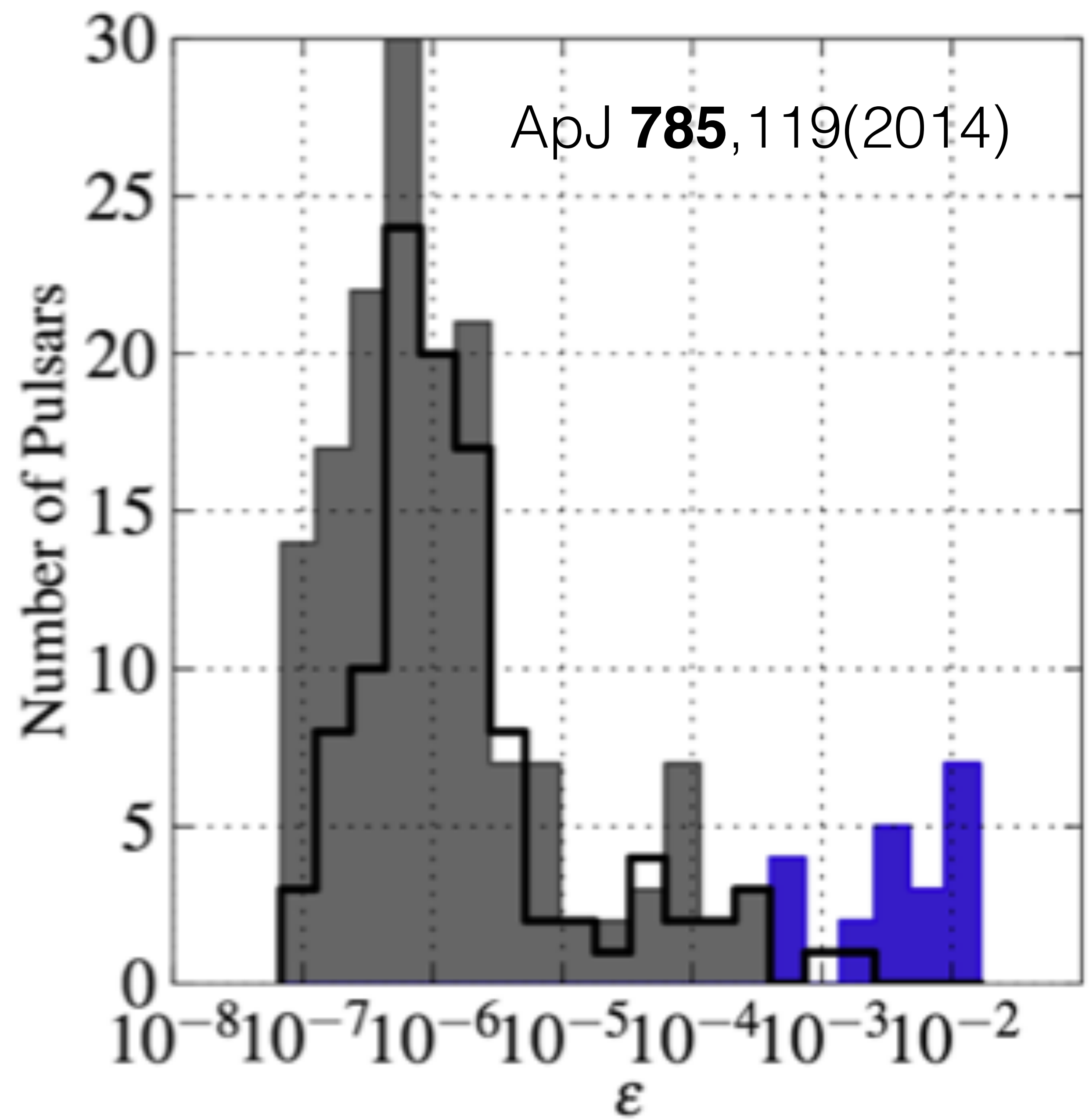
GW upper limits on ellipticity

- From negative GW searches one can set upper limits on the ellipticity of several known pulsars.

- The best present limits are: $\epsilon=(I_1-I_2)/I_3<10^{-7}$.

- A maximum crust mountain of $\epsilon=10^{-6}$ to 10^{-5}, if present, would have been seen.

- These limits will likely improve significantly with Advanced LIGO. -> *Motivates more work on the strength of pasta and on mountain formation on neutron stars.*



Upper limit on ellipticity

Neutron rich matter, the symmetry energy, and pasta

- Parity violating PREX and CREX measure neutron skin of ^{208}Pb, ^{48}Ca and constrain pressure, symmetry energy, and three neutron forces.
- PREX collaboration, Zidu Lin, S. Ban, J. Piekarewicz, R. Michaels, …
- MD simulations of nuclear pasta: **Matt Caplan, Zidu Lin**, Don Berry, Farrukh Fattoyev, Andre Schneider…
- Crust cooling: Andrew Cumming…
- Neutrino pasta scattering: Luke Roberts, Evan O'Connor, Tobias Fischer,W. Newton…
- Supported in part by DOE

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Compact Stars and Gravitational Waves, Kyoto, Nov. 2016