When do the pulsar upper limits get interesting?

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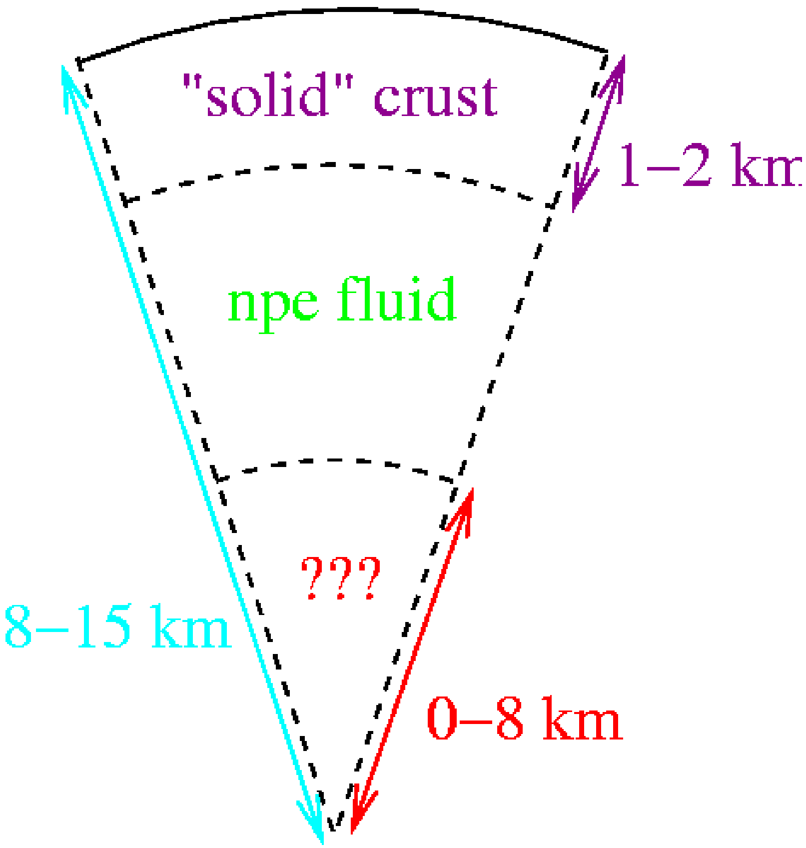
How bumpy can neutron stars be?

- Conventional neutron stars with solid crusts
  - » Conservative target bump size (known decades, e.g. Jones 2001)
  - » Physics is well understood and laboratory tested
- Solid strange quark stars
  - » Largest bump size (new)
  - » Very far-out physics (limit of what ApJL will publish)
- Stars with hybrid baryon-quark cores
  - » Larger bumps than pure neutron stars (new)
  - » Physics is untested in laboratory but not too far out
- (Stars with color superconducting quark cores)

Conventional neutron stars

- Superfluid core and mantle
- Solid crust
  - » Density $\rho < 1.5 \times 10^{14}$ g/cm^3
  - » Temperature $T < 10^{10}$ K
- Outer crust
  - » Density $\rho <$ few x 10^{11} g/cm^3
  - » Neutron-rich nuclei in crystal
  - » "Accessible" in lab
- Inner crust (neutron drip)
  - » Neutron-rich nuclei in crystal
  - » Free neutron fluid coexists
  - » Modest extrapolation from lab



Conventional neutron stars

- Define "bump": ellipticity $\varepsilon = (I_{xx} - I_{yy}) / I_{zz}$
- Minimize deformation energy $E_0 + A\,\varepsilon^2 + B\,(\varepsilon - \varepsilon_0)^2$
  - » A ~ gravitational potential energy, B ~ Coulomb energy
  - » Strained deformation $\varepsilon = B / (A + B)\ \varepsilon_0 = 10^{-5}\ \varepsilon_0$
  - » Strain $\xi = |\varepsilon - \varepsilon_0| \sim |\varepsilon_0|$
- Breaking strain $\xi <$ few x 10^{-3} for terrestrial materials
- Bottom line $\varepsilon < 10^{-8}$ (conservative)
  - » (Not for magnetars and Ruderman/Cutler mechanism, but they'll slow down too fast for LIGO)

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Solid strange stars

- Strange stars (Witten 1981, …)
  - » Mix of u/d/s quarks, tiny normal solid crust on top
  - » Almost uniform density few x 10^{14} g/cm^3, radius 5 – 8 km
  - » Generally thought to be fluid
- Latest solid incarnation (Xu 2003)
  - » Motivated by X-ray burst oscillations as t-modes (fishy)
  - » Need quark clusters & van der Waals interaction
- Shear modulus (in B) up to 100x neutron star crust
- Gain almost 10x since whole star is solid
- Bottom line $\varepsilon < 10^{-5}$ (largest of any model?)
  - » Rough estimate done

Hybrid stars

- Gradual phase transition (Glendenning 1992)
  - » Baryons yield to quark matter at asymptotically high density
  - » Quark blobs and baryon fluid coexist over a range of densities
  - » Why not abrupt (constant pressure)? Two conserved numbers
  - » Electric charge separates, so you get crystal lattice
- Solid core up to 8 km thick! (varies wildly)
- Shear modulus?
  - » Coulomb force/area indicates few times that of crust
  - » Pasta structure?
- Bottom line: $\varepsilon < \text{few} \times 10^{-7}$ (large but not crazy)
  - » Looking at this more closely since it's somewhat realistic

Color superconductivity

- State of quark matter at asymptotically high density (Wilczek & Rajagopal 1990s)
- ???

Conclusions

- No upper limit on ε will ever rule out any theory of dense matter – any star could just be flat, or even groups of stars (old, isolated pulsars)
- But we can say "We're observing at a level where we might expect to see something in X theory" – if there is no competition from a spindown upper limit
- Limits on $\varepsilon < 10^{-5}$ are already (mildly) interesting
- Limits on $\varepsilon <$ few x 10^{-7} get us to the level where we might see something in a reasonable theory