# The Structure of Neutron Rich Nuclei and Neutron Stars

- Introduction: relation between neutron rich nuclei and neutron stars.
- Parity Radius Experiment to determine neutron radius of $^{208}$Pb.
- Implications for neutron stars: radius, transition density of crust, electron fraction, and direct URCA cooling.

Santa Fe, July 2003

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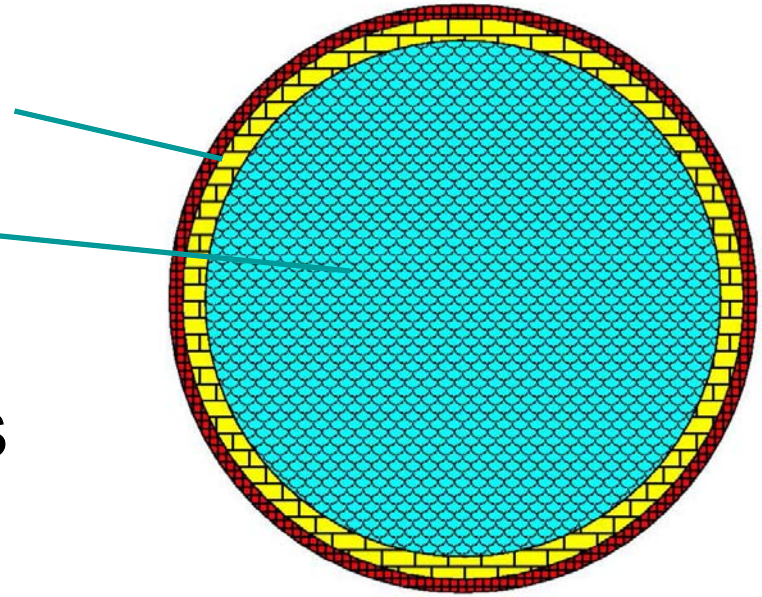
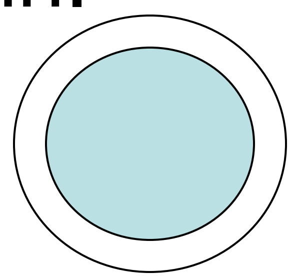
# N. Star Crust vs Neutron Skin

- Neutron star has solid crust over liquid core.
- Heavy nucleus has neutron skin.





$^{208}Pb$

Both neutron skin and solid crust are made out of neutron rich matter at similar densities.

# Density Dependence of Symmetry Energy

- Important for extrapolating nuclear observables to neutron rich matter.
- Volume and surface sym. energies

  $E = a_0 A + a_{sym} (N-Z)^2/A + a^{sur}_{sym} (N-Z)^2/A^{4/3}$.

  Or density dependence of sym E: $a_{sym}(\rho)$. Large density dependence implies large surface sym E.
- Present binding E data constrains an average of $a_{sym}(\rho)$ over $\rho \leq \rho_0$.
- Symmetry energy at high $\rho$ very important in astrophysics (neutron stars, supernovae…)
- In principle, $a_{sym}$ at high $\rho$ from heavy ion collisions but important reaction mechanism uncertainties. [Bao-An Li]

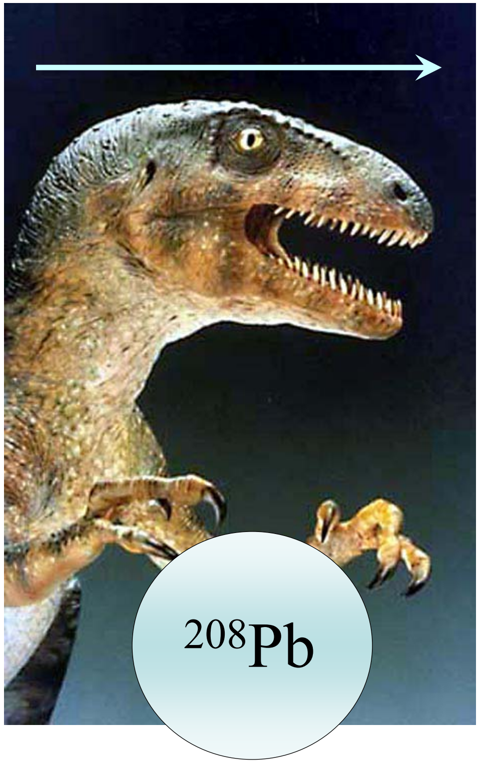
# Neutron Rich Skin

- A heavy nucleus should have a neutron rich skin because of the neutron excess and coulomb barrier which removes protons from surface.
- Thickness of skin depends on pressure of neutron rich matter as neutrons are pushed out against surface tension.
- Pressure follows from density dependence of symmetry energy.
- A high pressure $dE/d\rho$ or large $da_{sym}/d\rho$ implies a large neutron skin $R_n$-$R_p$.

# Measuring Neutron Skins

- Hadronic probes have significant errors from strong interaction uncertainties.
- Hard to resolve skin.
- Make the skin thicker: in radioactive very neutron rich nuclei so it can be resolved.
- Measure with a more precise probe.
- Precision measurements in stable nuclei are complimentary to less accurate measurements with radioactive beams.

# Parity Radius Experiment (PReX)



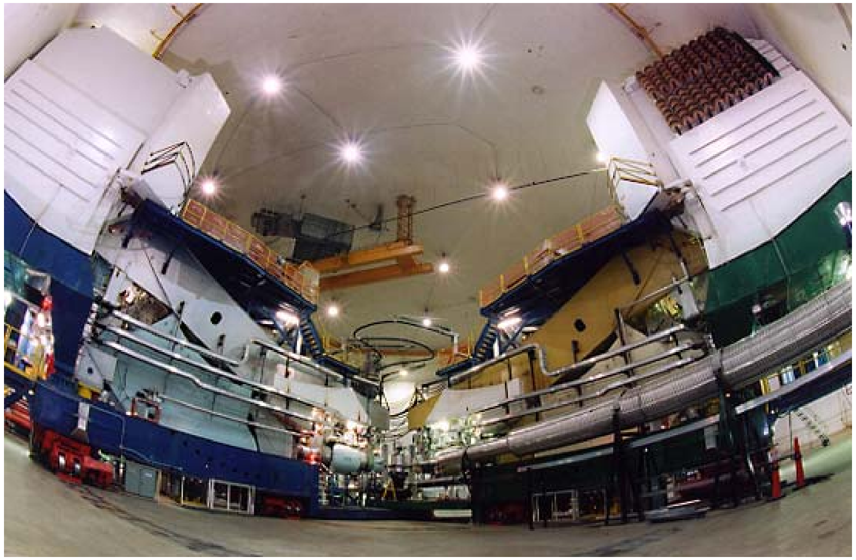
# Weak Interaction Probes Neutrons

- $Z^0$ couples to weak charge.
- Weak charge is weak isospin - $2\sin^2\Theta_W$ $Q_{em}$. Add up valence quarks:

  $Q_n$=-1/2, $Q_p = ½-2\sin^2\Theta_W \approx 0$.
- Weak charge of n $\gg$ that of p.
- Parity violating asymmetry in elastic electron scattering provides a purely electroweak probe of neutron density.

# Jefferson Lab Hall A exp.

- $A=(\sigma_+-\sigma_-)/(\sigma_++\sigma_-)$ for 850 MeV e scattering at 6 deg. from $^{208}Pb$.
- Goal: measure A $\approx$ 0.6 ppm to 3%. This gives neutron radius to 1% ($\pm$ 0.05 Fm).
- Cleanly resolves skin $R_n$-$R_p$$\approx$ 0.2 Fm



R. Michaels, P. Souder, and G. Urciuoli

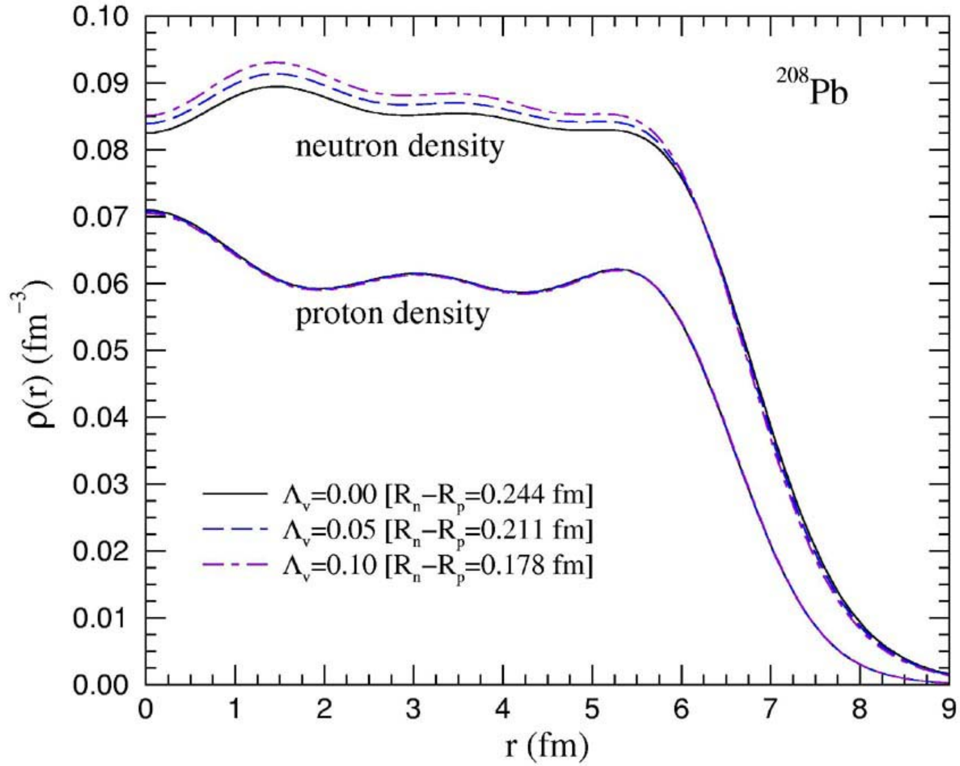
- Provides fundamental nuclear structure information because it can be both accurate and model independent.

# Rel. Effective Field Theory

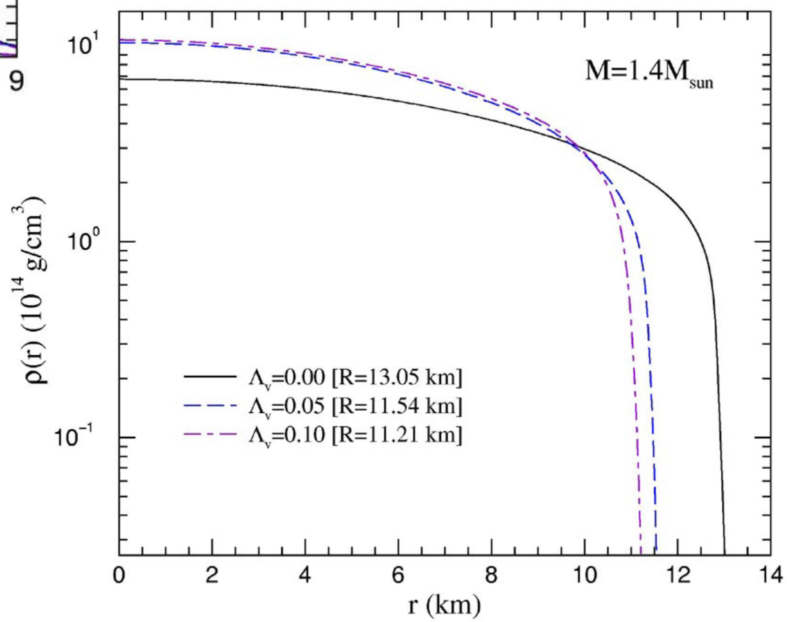
- Correlate different nuclear and neutron star observables.
- Add new couplings between isoscalar and isovector mesons.

$$\mathcal{L}_{\mathrm{int}} = \bar{\psi}\left[g_{\mathrm{s}}\phi - \left(g_{\mathrm{v}}V_\mu + \frac{g_\rho}{2}\boldsymbol{\tau}\cdot\mathbf{b}_\mu + \frac{e}{2}(1+\tau_3)A_\mu\right)\gamma^\mu\right]\psi$$
$$-\frac{\kappa}{3!}(g_{\mathrm{s}}\phi)^3 - \frac{\lambda}{4!}(g_{\mathrm{s}}\phi)^4 + \frac{\zeta}{4!}g_{\mathrm{v}}^4(V_\mu V^\mu)^2 + \frac{\xi}{4!}g_\rho^4(\mathbf{b}_\mu\cdot\mathbf{b}^\mu)^2$$
$$+g_\rho^2\,\mathbf{b}_\mu\cdot\mathbf{b}^\mu\left[\Lambda_4 g_{\mathrm{s}}^2\phi^2 + \Lambda_{\mathrm{v}} g_{\mathrm{v}}^2 V_\mu V^\mu\right]$$

- Adjust $\Lambda_4$ or $\Lambda_v$ to change $\rho$ dep. of symmetry energy.




Adjusting $\Lambda_v$ … parameters changes neutron density in $^{208}$Pb at fixed proton density and changes neutron star structure.

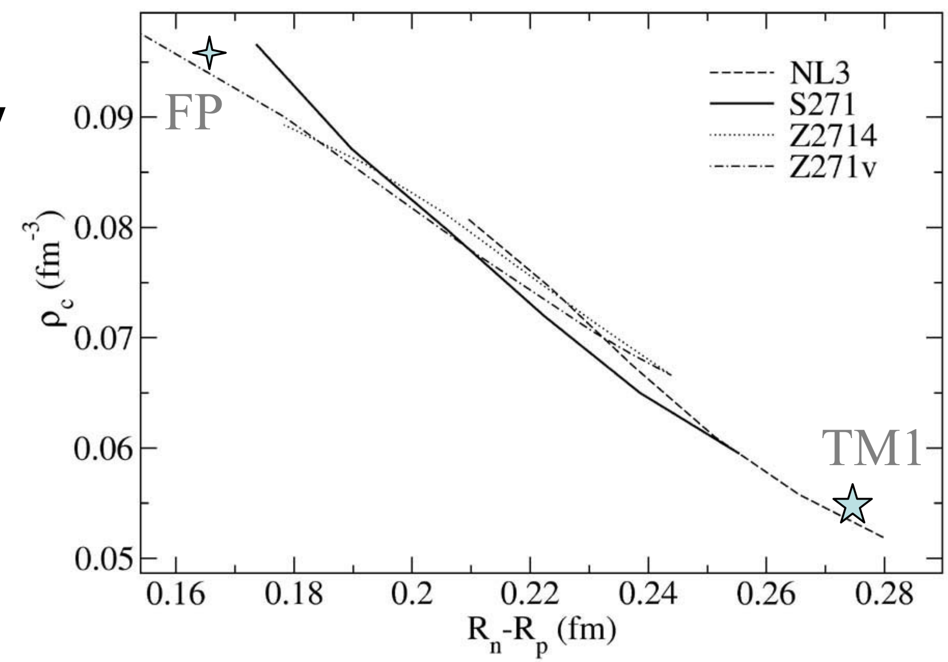


# Liquid/Solid Transition Density

- RPA stability against small amplitude density osc. Unstable if $\varepsilon_L<0$.

$$\epsilon_L(q_0=0,q)=\det\left(1-D_L\Pi_L\right)$$

- Thicker neutron skin in Pb means energy rises rapidly with density→ Quickly favors uniform phase. Thick skin in Pb→low transition density in star.



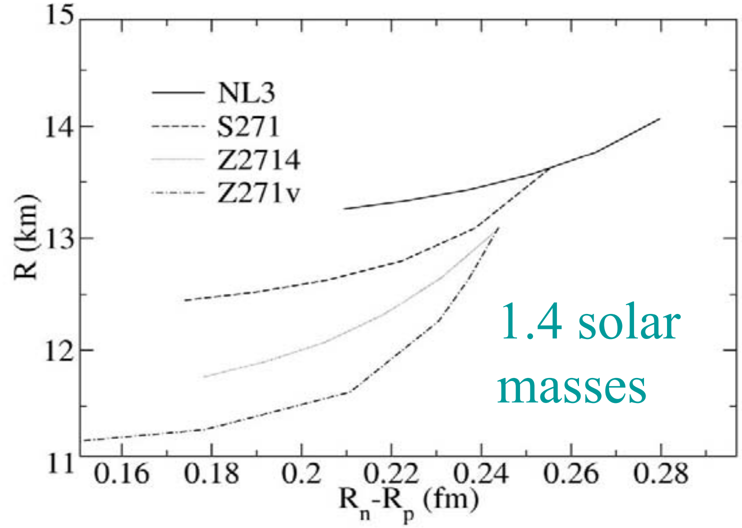

- Matter is a uniform liquid above $\rho_c$ and a nonuniform solid below.

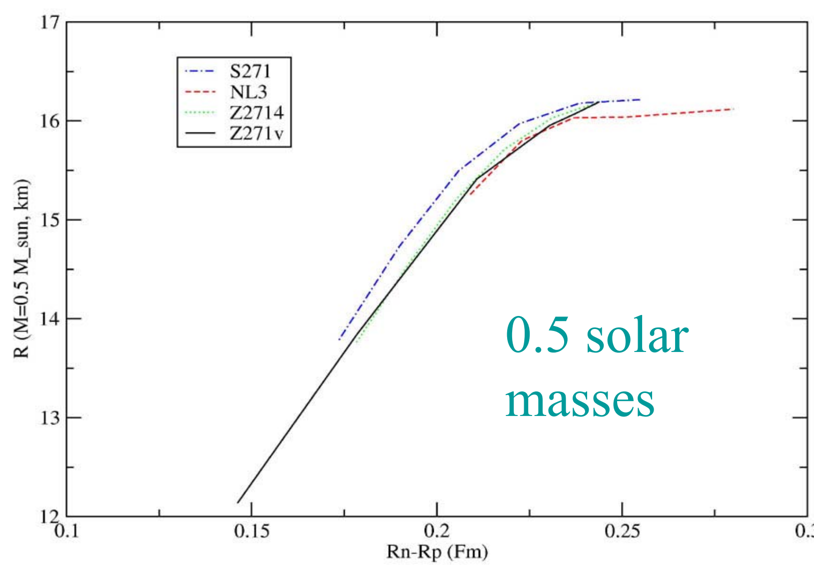
# Neutron Star Radii

- Depends only on EOS. If one has R(M) for range of M $\rightarrow$ invert and get EOS: P($\rho$)
- Problem: well measured M near 1.4 $M_\odot$ (Low mass NS hard to form)
- Central density $\rho_c$ of 1/2$M_\odot$ NS near $\rho_0$. Use Parity Radius Exp. to infer R(0.5$M_\odot$).
- Interested in density dependence of EOS. An abrupt softening with $\rho \rightarrow$ transition to an exotic phase.
- Very interesting if R(0.5$M_\odot$) big and R(1.4$M_\odot$) small.

# Star Radius vs. Pb $R_n$

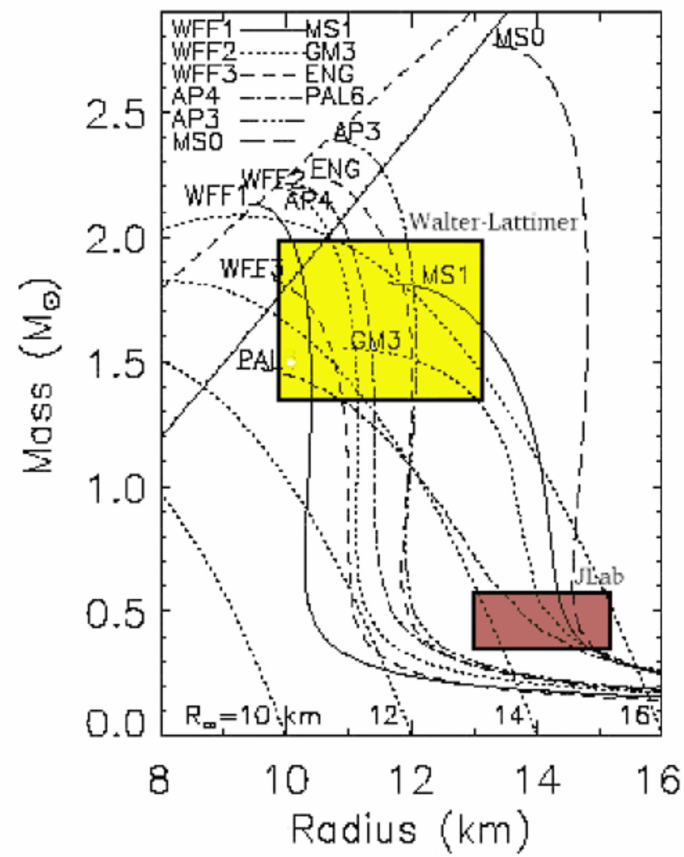
- In general expect larger $R_n$-$R_p$ to give larger radius for 1.4 solar mass neutron star.
- However $R_n$-$R_p$ only sensitive to EOS at low density. Star radius also depends on high density EOS.
- Low mass star has central density near $\rho_0$. Strong correlation between $^{208}$Pb and star radii.



# Constraints on High Mass and Low Mass Neutron Star Radii

- Assume $R_n$-$R_p$ is measured to be near 0.2 fm in Pb.
- This implies $R(0.5M_{\odot}) \approx$ 14 to 15 km. (brown box)
- RXJ18563 or other star sets limit for larger M (yellow)




EOS curves from Stony Brook


Way too Cool

# Neutron Star Cooling

- NS born hot in SN and cool by $\nu$ emission from interior.
- Cooling curve (T vs age) uniquely sensitive to properties of very dense matter.
- "Standard cooling" from: $nn \rightarrow npe^{-}\bar{\nu}_e$
- Two n needed to conserve p and E.
- "Enhanced cooling" involves beta decay of a single hadron (could be n, $\Lambda$, $\pi$, free q…)

# Goal: Use cooling observations to "prove" dense neutron rich matter contains more then just n, p and e.

- Verify surface temperatures and ages of some stars require enhanced $\nu$ cooling.
  - Uncertainties in ages and temp.
  - Vela is best case??
- Rule out enhanced cooling from pair breaking-recombination.
- Rule out (or in) direct URCA cooling.
- If program can be carried out $\rightarrow$ Exotic matter in center of N. Star is no longer exotic, it is required. This is great progress even if can't say what extra component is.

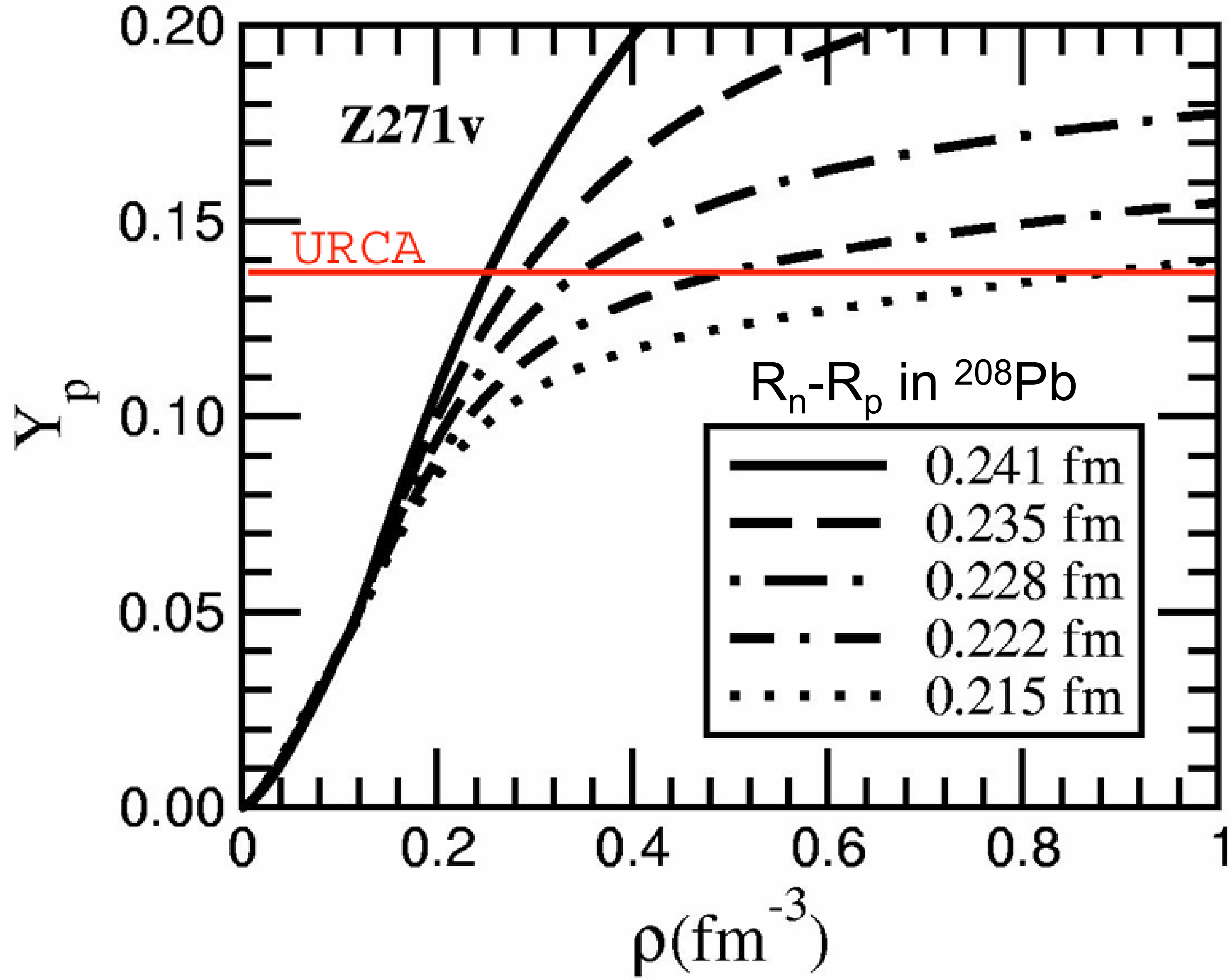
# How Large are Pairing Gaps?

- Important to have additional calculations of $\Delta$ for high density neutron rich matter. New effective field theory approaches are promising.

# URCA Process

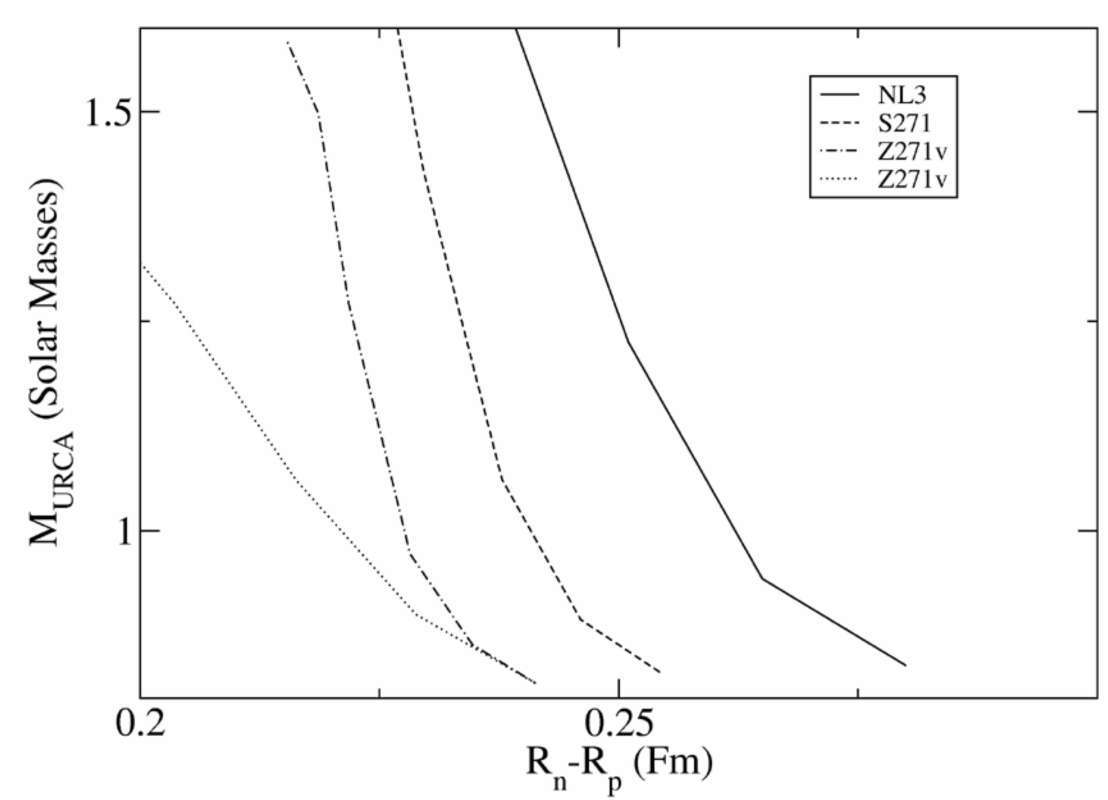
- Example of enhanced cooling: $n \rightarrow p\, e^- \bar{\nu}_e$ followed by $p+e^- \rightarrow n+\nu_e$. Rapidly produces $\nu$ pairs. Large electron Fermi mom. gives large lepton phase space and high rate.
- Conservation of p and E requires $k_{Fn} \leq k_{Fp}+k_{Fe}$
- This needs large electron fraction. In $\beta$ equil.

  $\mu_n - \mu_p = \mu_e$
- Need large sym energy at high density to get high enough electron fraction.
- $R_n$ in Pb determines density dependence of symmetry energy.




Proton fraction vs density for EOS with different neutron radii in $^{208}$Pb

# Threshold Mass for URCA




- If $R_n$-$R_p$ < 0.2 fm all models don't allow URCA in 1.4 $M_\odot$ stars.
- If $R_n$-$R_p$>0.25 fm all models allow URCA. Thus $R_n$ measurement can strongly suggest or rule out URCA process.

# Conclusions

- Parity violating electron scattering provides fundamental measurement of neutron skin in $^{208}$Pb. Can be both accurate and model indep.
- This determines density dependence of symmetry energy.
  - This fixes transition density of neutron star crust.
  - This with measured neutron star radius can rule in or out high density phase transition in neutron rich matter.
  - This should rule out (or in) direct URCA cooling of neutron stars.
- J. Piekarewicz, J. Carriere and CJH.