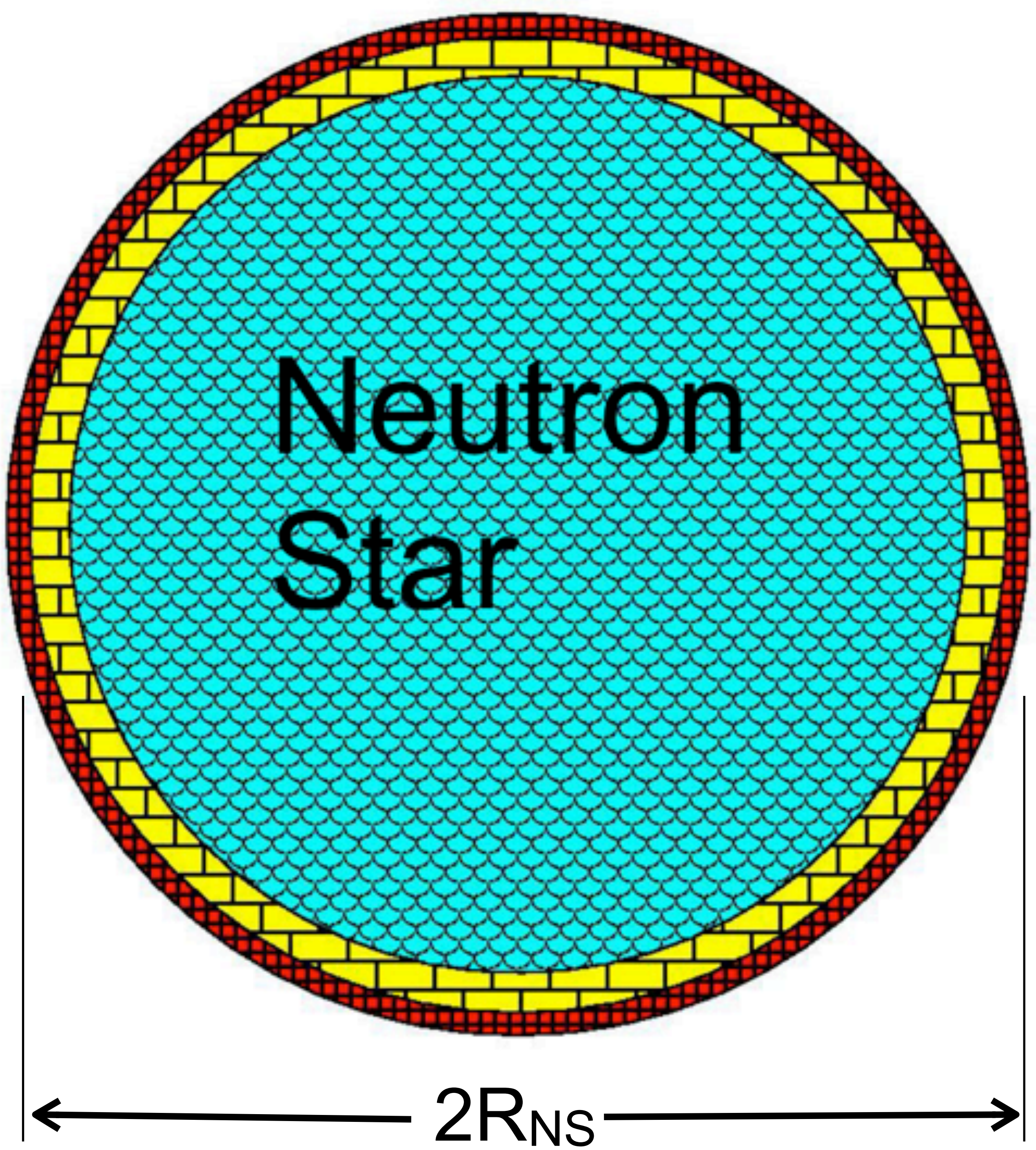
Equation of State in Astrophysics and Symmetry Energy

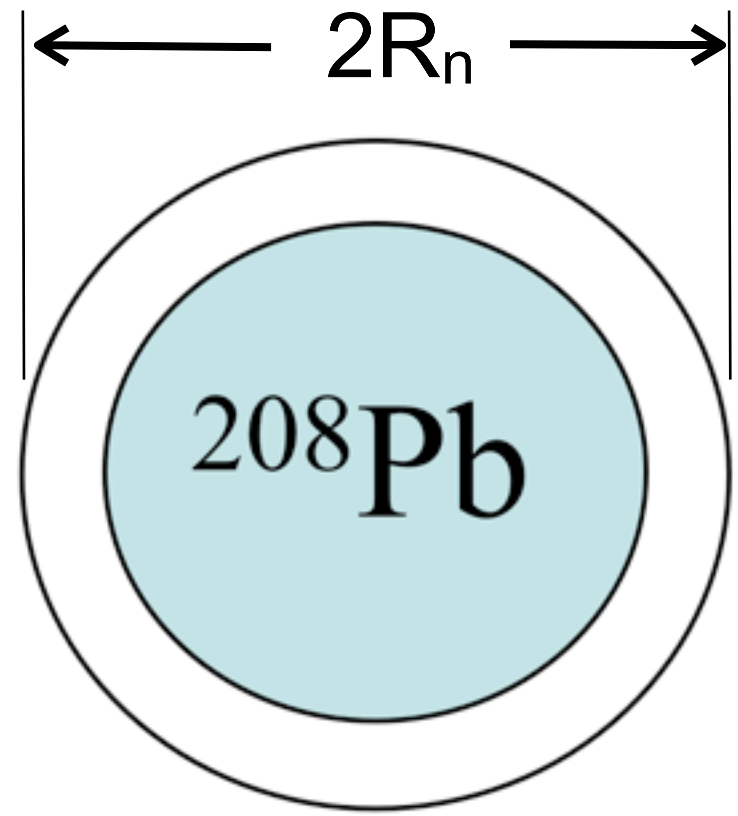
- **Density dependence of symmetry E, *L*** (Betty)
  - X-ray observations of neutron star (NS) radii.
  - Energy functional for stable nuclei, NS, and drip line.
- **Symmetry E at high density** (Hermann)
  - NS cooling by neutrino emission.
  - Composition of dense QCD.
- **Symmetry E at very low density**, cluster formation, and supernovae.

C. J. Horowitz, IU and MSU, WCU/Hanyang-APCTP Focus Program, “Effective field theories, halos, drip-lines and EoS for compact stars”, Pohang, Korea, Apr. 2012

I) X-ray observations of NS radii and density dependence of symmetry energy

Neutron Star radius versus ^{208}Pb Radius





PREX uses parity violation to measure R_n.

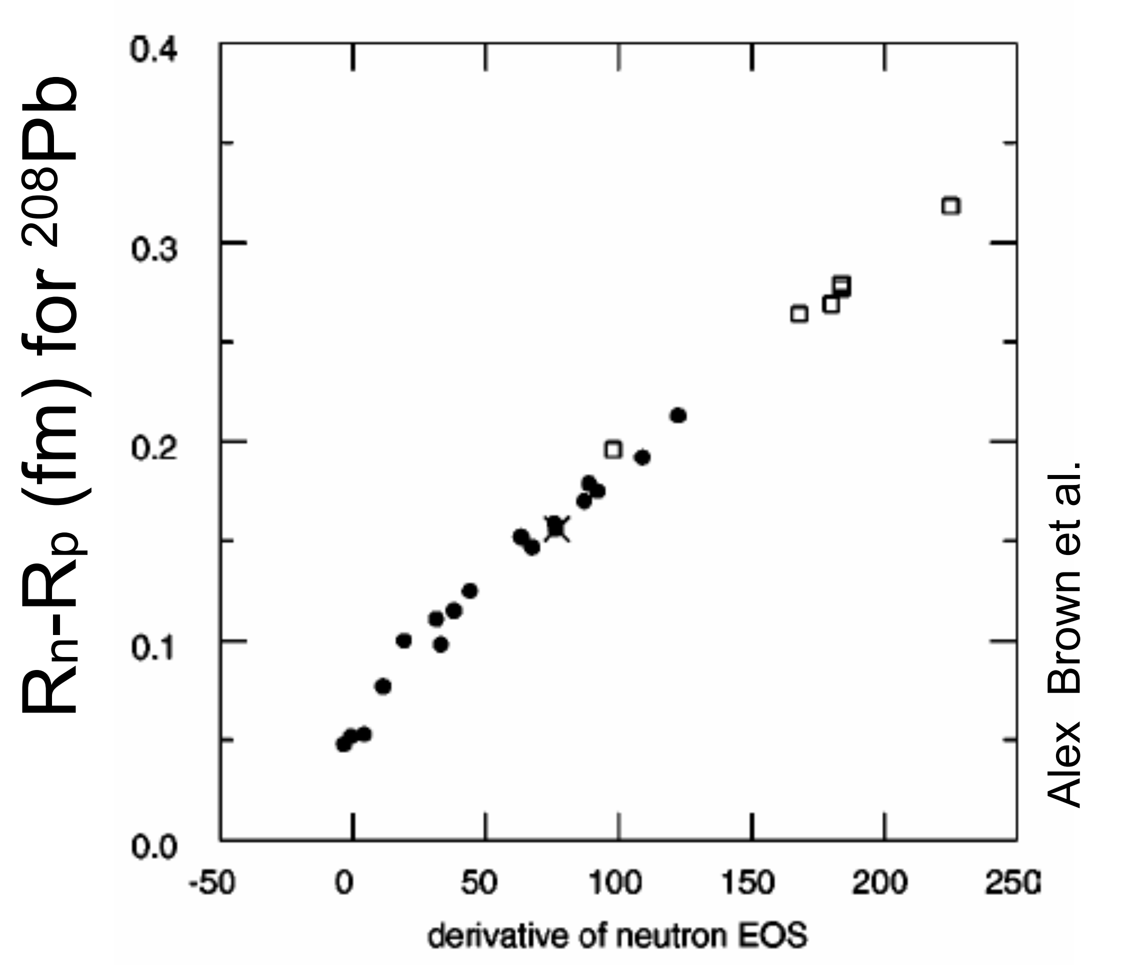
Pb Radius Measurement

- Pressure forces neutrons out against surface tension. Large pressure gives large neutron radius.
- Pressure depends on derivative of energy with respect to density.
- Energy of neutron matter is E of nuc. matter plus symmetry energy.

$$E_{neutron} = E_{nuclear} + S(\rho)$$

$$P \rightarrow dE/d\rho \rightarrow dS/d\rho$$

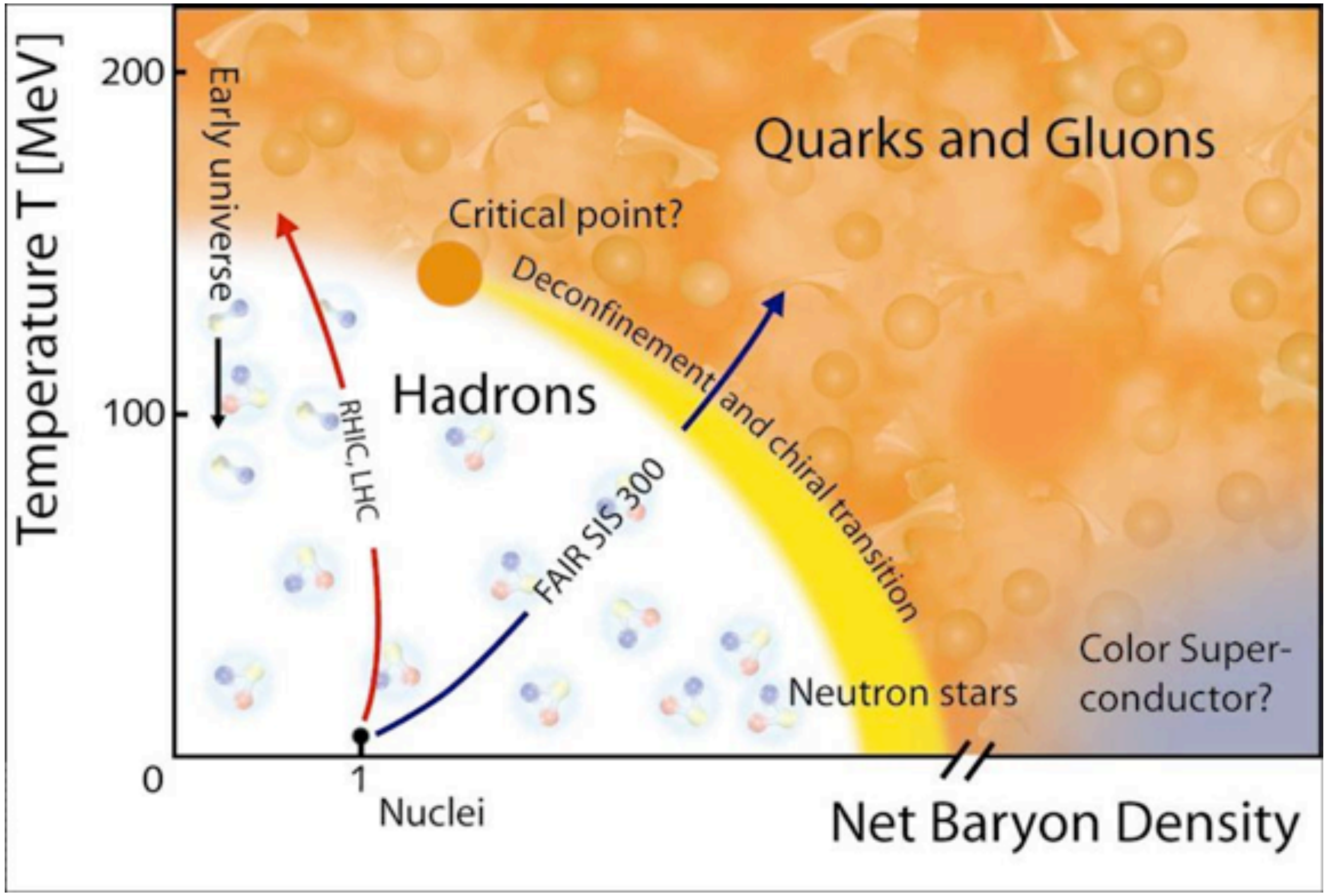
- **Neutron radius determines P of neutron matter at ≈ 0.1 fm^{-3} and the density dependence of the symmetry energy dS/dρ.**



Neutron minus proton rms radius of Pb versus pressure of pure neutron matter at ρ=0.1 fm^{-3}.

Pb Radius vs Neutron Star Radius

- The ^{208}Pb radius constrains the pressure of neutron matter at subnuclear densities.
- The NS radius depends on the pressure at nuclear density and above. Central density of NS few to 10 x nuclear density.
- Also, observations of massive neutron stars constrain the maximum mass the EOS can support before collapse to a black hole. This is sensitive to the EOS at high densities.
- *Pb radius probes low density, NS radius medium density, and maximum NS mass probes high density equation of state.*



An observed softening of EOS with density (smaller increase in pressure) could strongly suggest a transition to an exotic high density phase such as quark matter, strange matter, or a color superconductor…

J. Piekarewicz, CJH

Observing Neutron Star Radii, Masses

- Deduce surface area from luminosity, temperature from X-ray spectrum.

$$L_\gamma = 4\pi R^2 \sigma_{SB}\, T^4$$

- Complications:
  - Need distance (parallax for nearby isolated NS...)
  - Non-blackbody corrections from atmosphere models can depend on composition and B field.
  - Curvature of space: measure combination of radius and mass.
- Steiner, Lattimer, Brown [ArXiv: 1005.0811] combine observations of 6 NS in 2 classes: X-Ray bursts and NS in globular clusters.

Find EOS that is somewhat soft at medium densities so 1.4 M_{sun} star has 12 km radius.

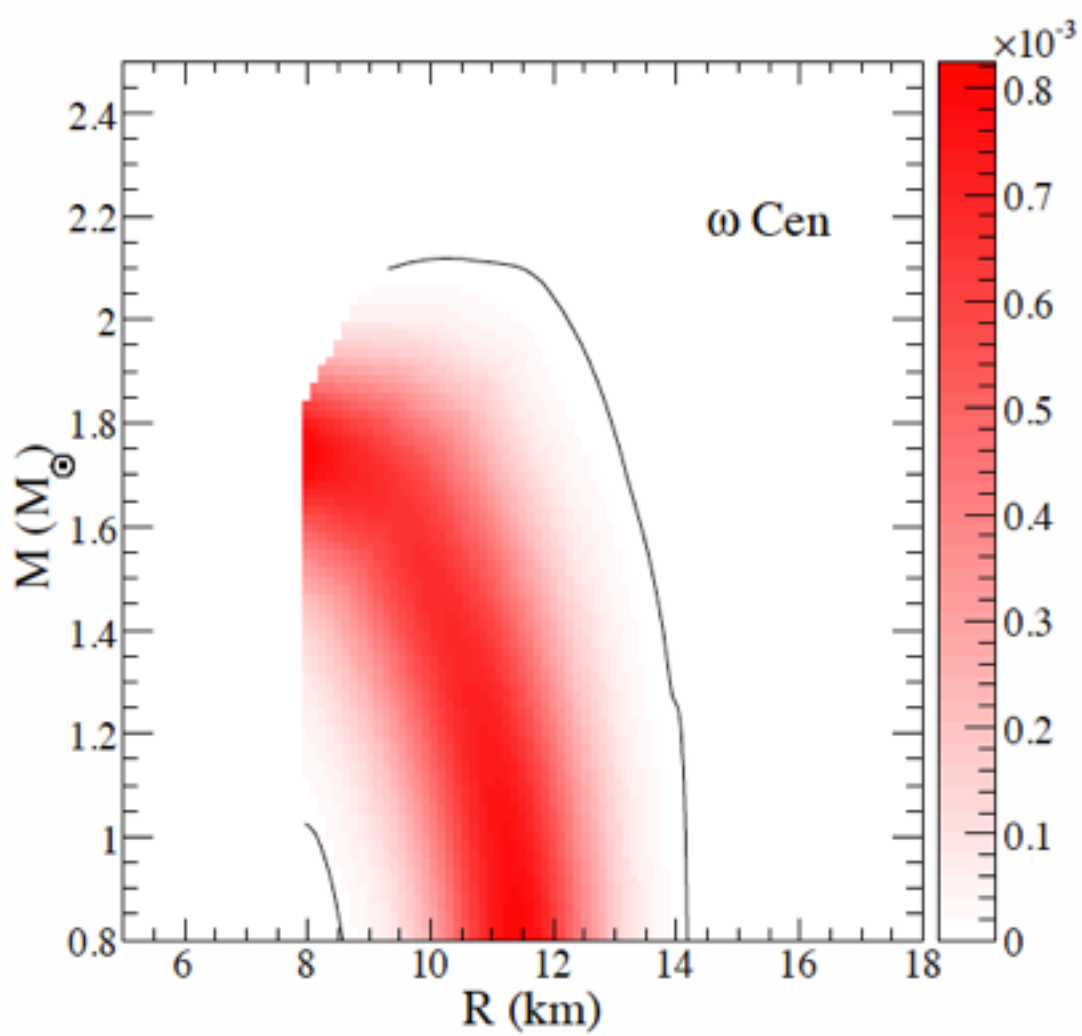
* Predict ^{208}Pb neutron skin: R_n-R_p=0.15+/- 0.02 fm.

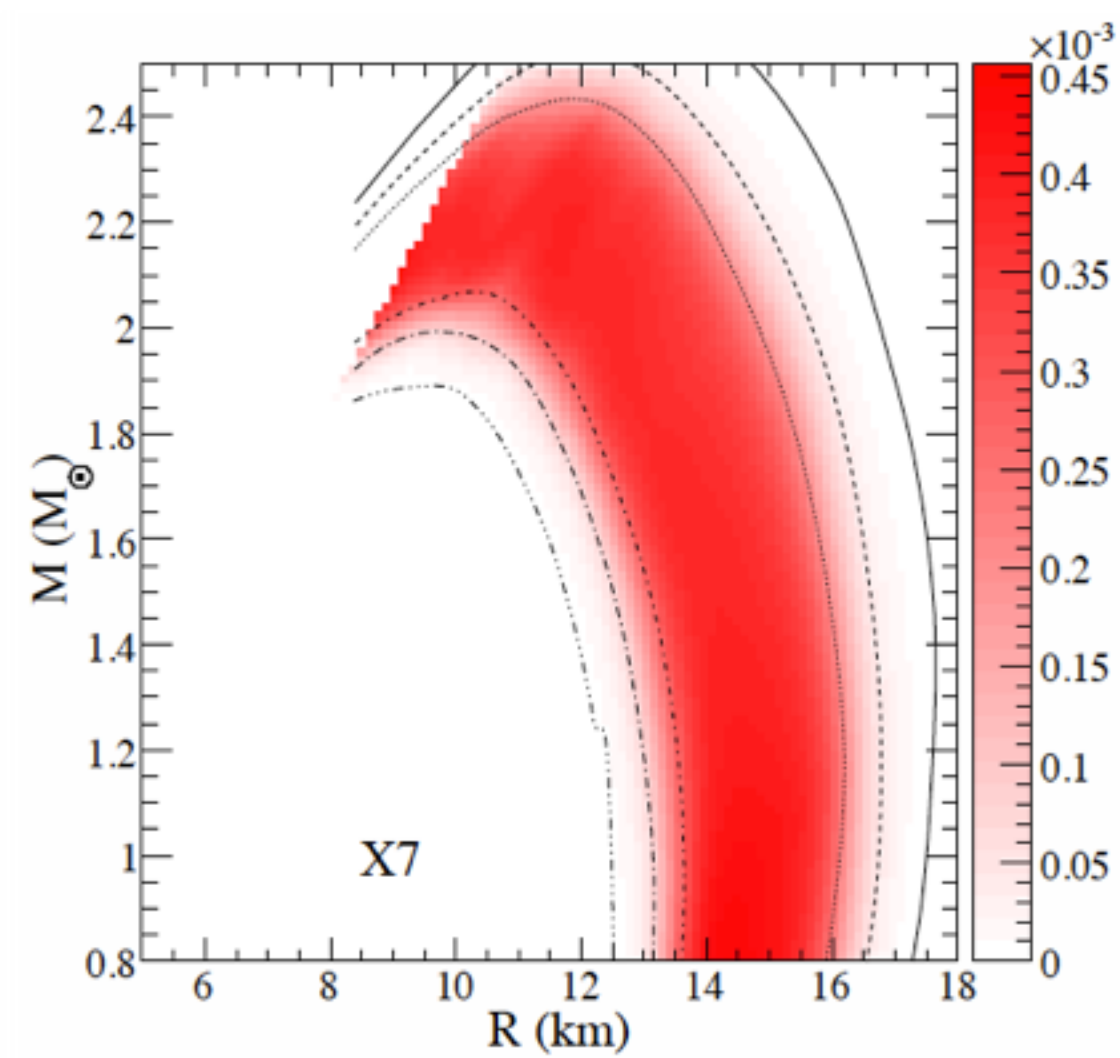
* F. Ozel et al. get smaller radii.

- Radio observations of PSR J1614 find M=1.97+/-0.04 M_{sun} from binary with 0.5 M_{sun} WD. Demorest et al., Nature **467** (2010) 1081.
- Some tension between big PREX skin and small NS radii.
- If PREX continues to find large R_n-R_p and 1.4 M_{sun} NS has small radius near 10 km (Ozel et al) then EOS is stiff, soft, stiff with density --> Phase transition to exotic phase.

NS in Globular Clusters

- Know distance to cluster from observing other stars.
- Crowded cluster environment -> NS have companions from which they accrete material.
- Accretion likely buried most magnetic field and contained some hydrogen, that rises to top in strong gravity. Star has simple nonmagnetic hydrogen atmosphere.

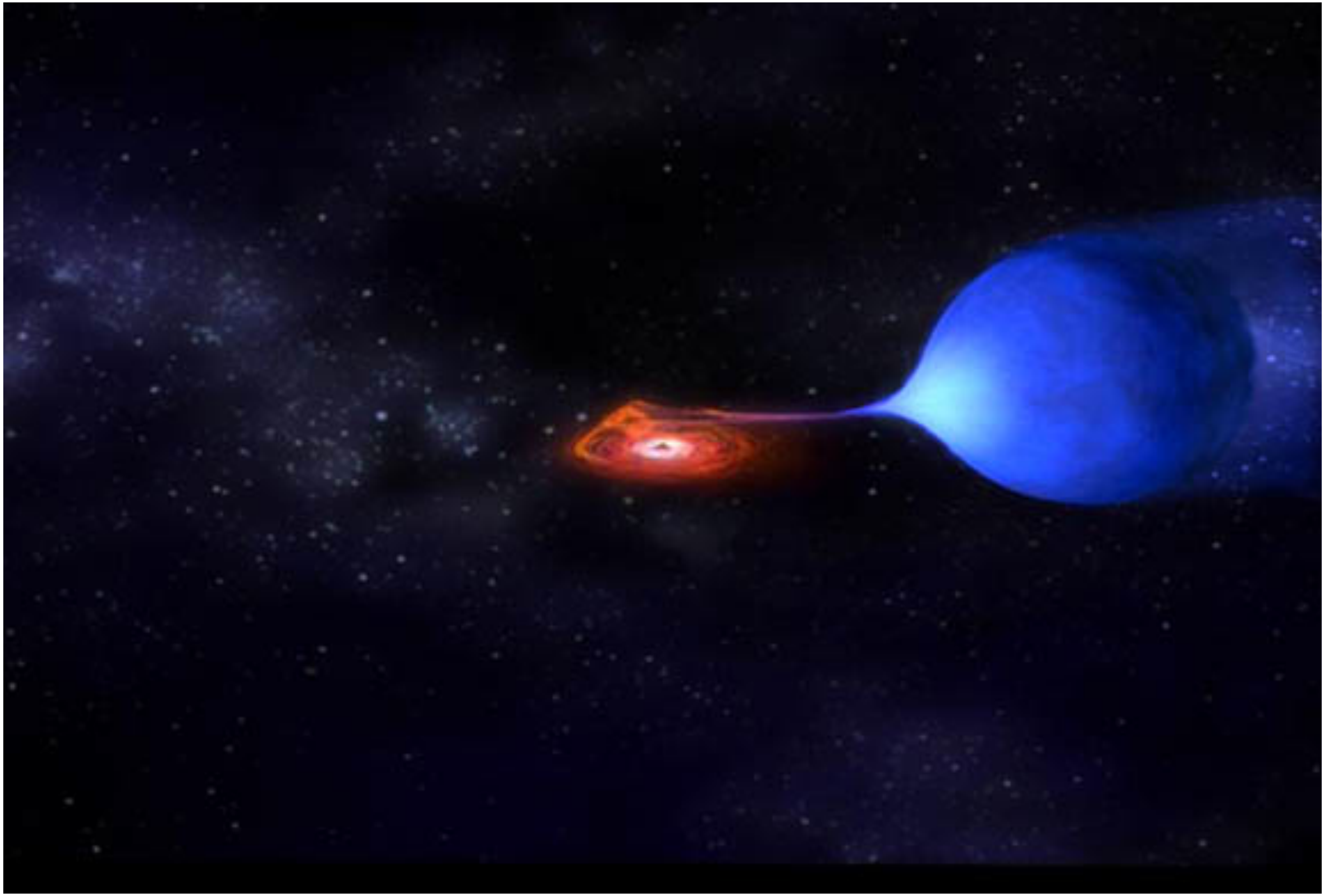




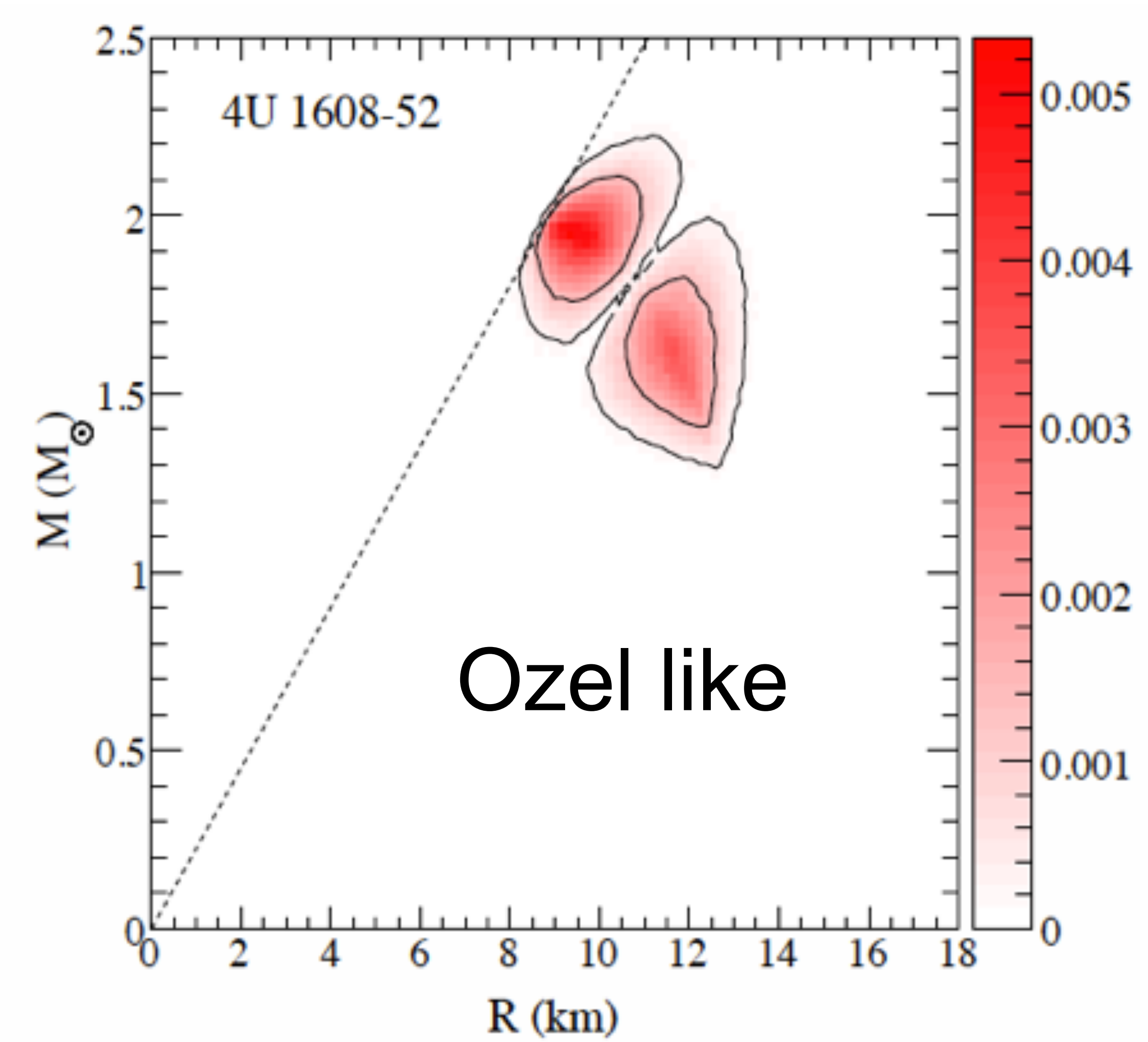

Ngc 5139 Omega Centuri

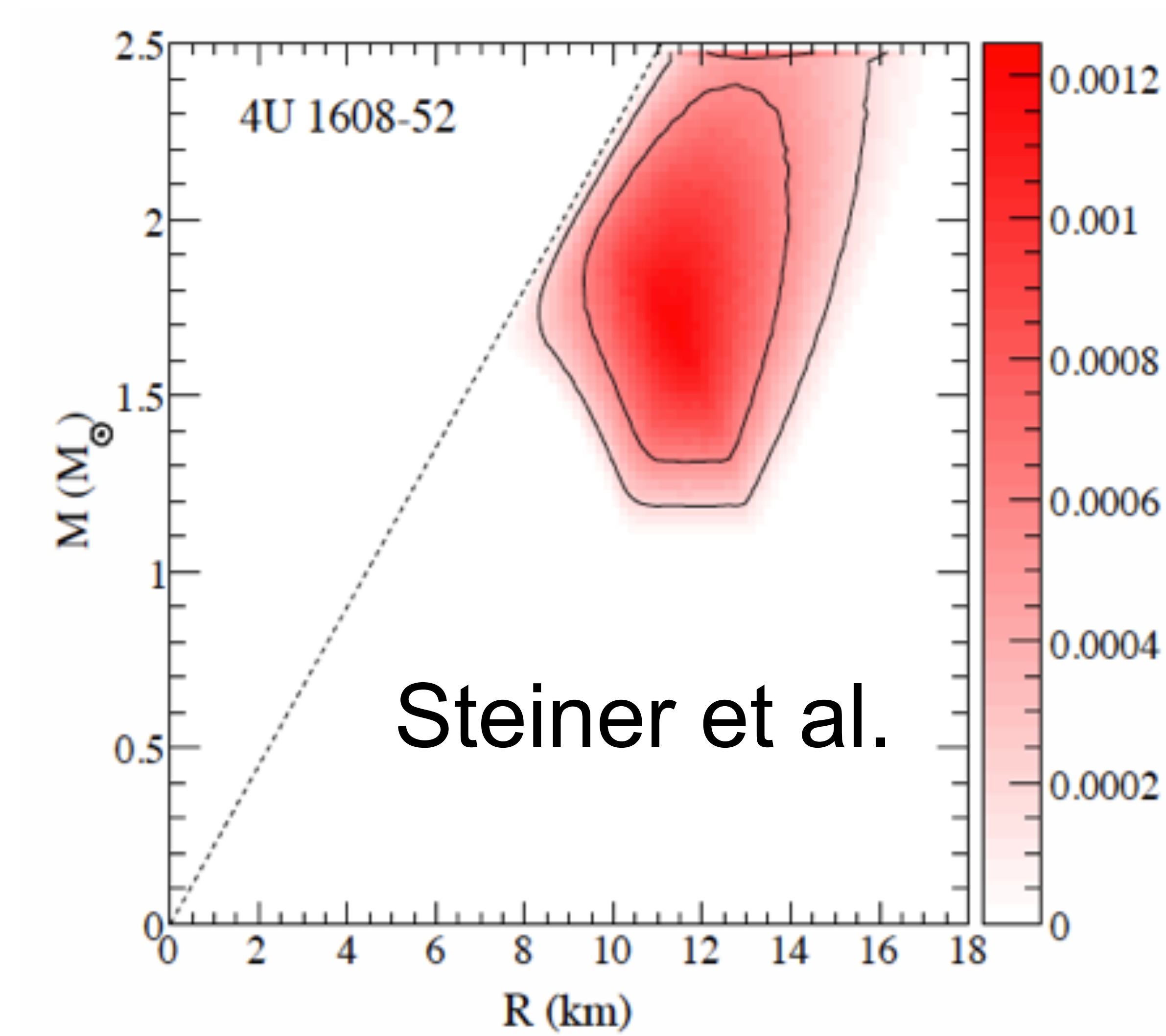
X-ray bursts

- NS accretes material from companion that ignites a runaway thermonuclear burst.
- **Eddington luminosity**: when radiation pressure balances gravity. Observe luminosity, calculate radiation pressure, and infer surface gravity (another combination of mass and radius). This additional relation gives both mass and radius separately!
- Complications: when during the burst does radiation pressure balance gravity? Uncertain non-black body NS atmosphere. Bust may be aspherical. Different bursts may have different behaviors. Which are good systems to use?



Ozel et al. vs Steiner, Lattimer, Brown

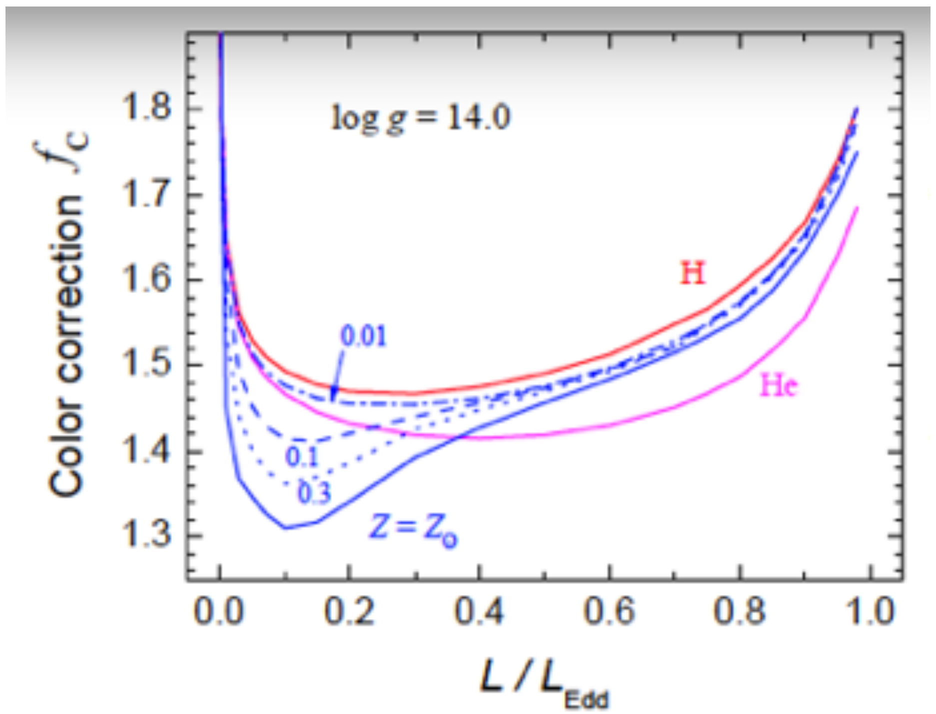




- Ozel assume photosphere radius = NS radius while Steiner et al assume it is much larger. Steiner et al. assume color correction factor (from NS atmosphere) is independent of luminosity.

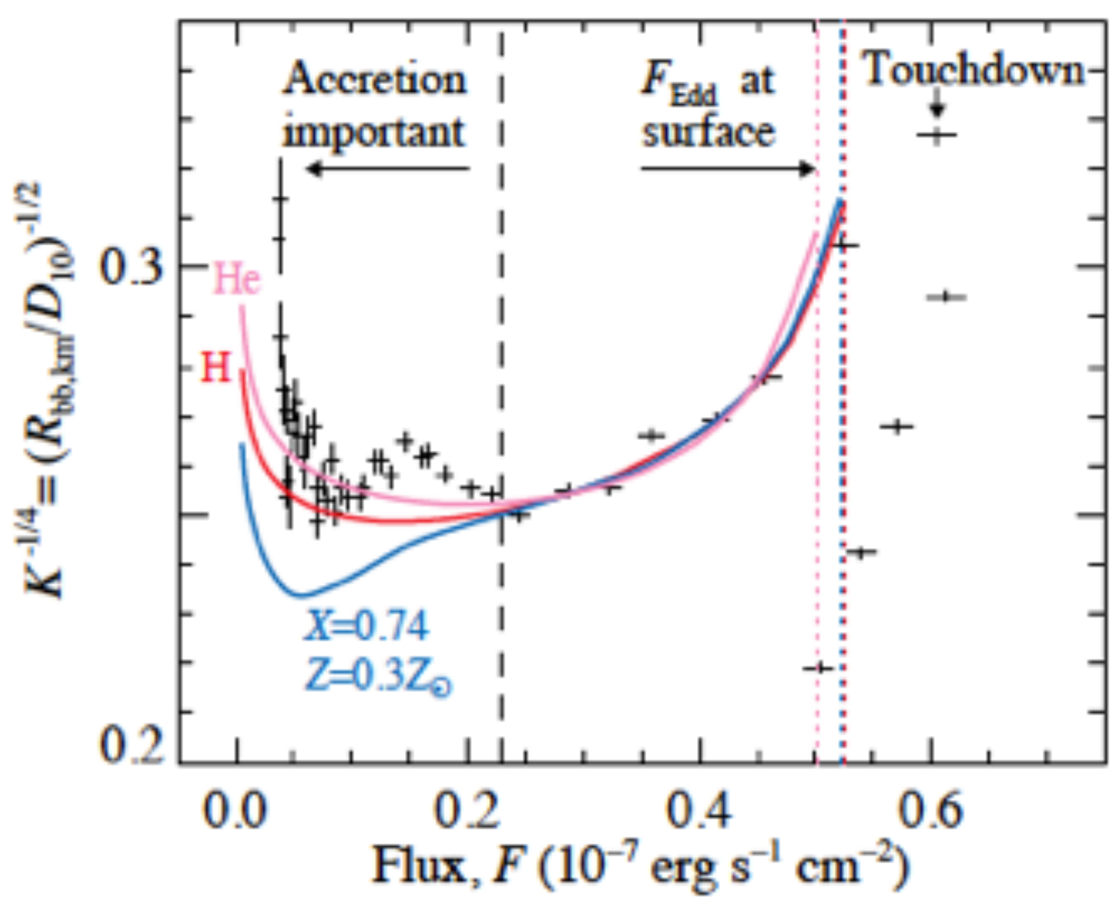
Model atmospheres of X-ray bursting neutron stars

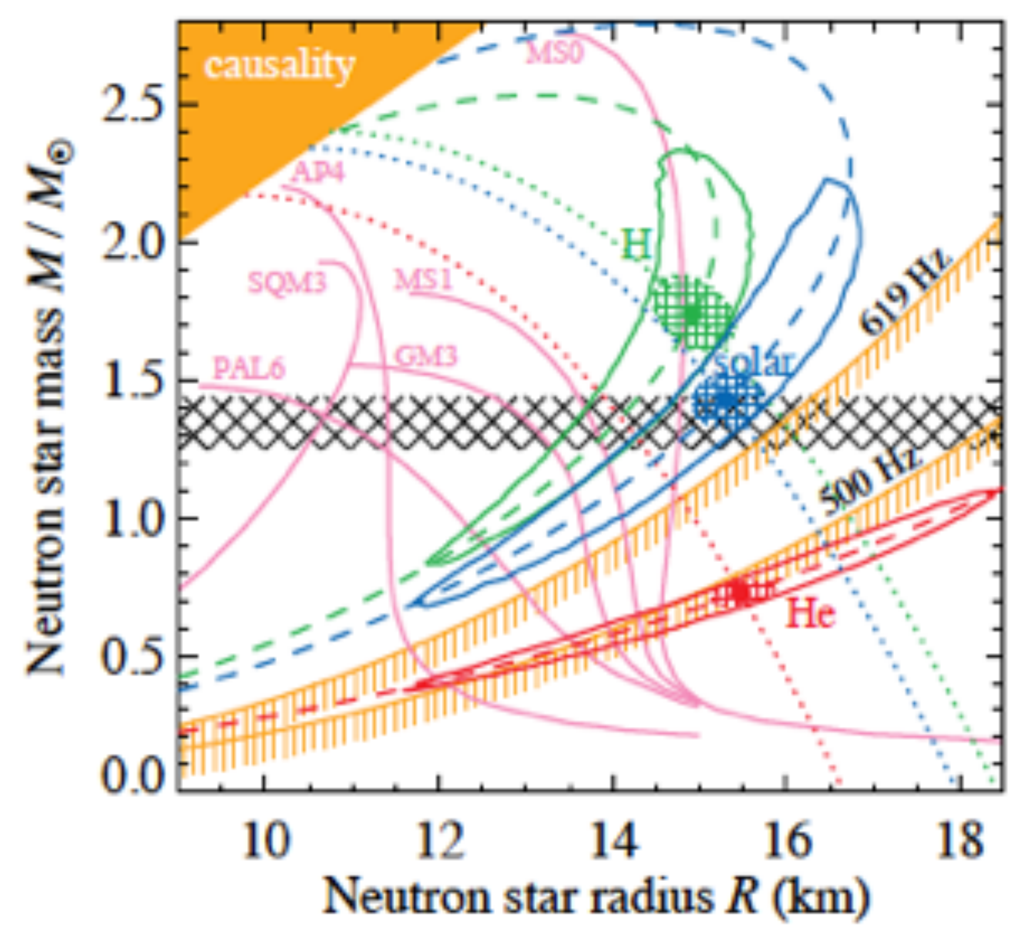
V. Suleimanov*,†, J. Poutanen**, M. Revnivtsev‡ and K. Werner*



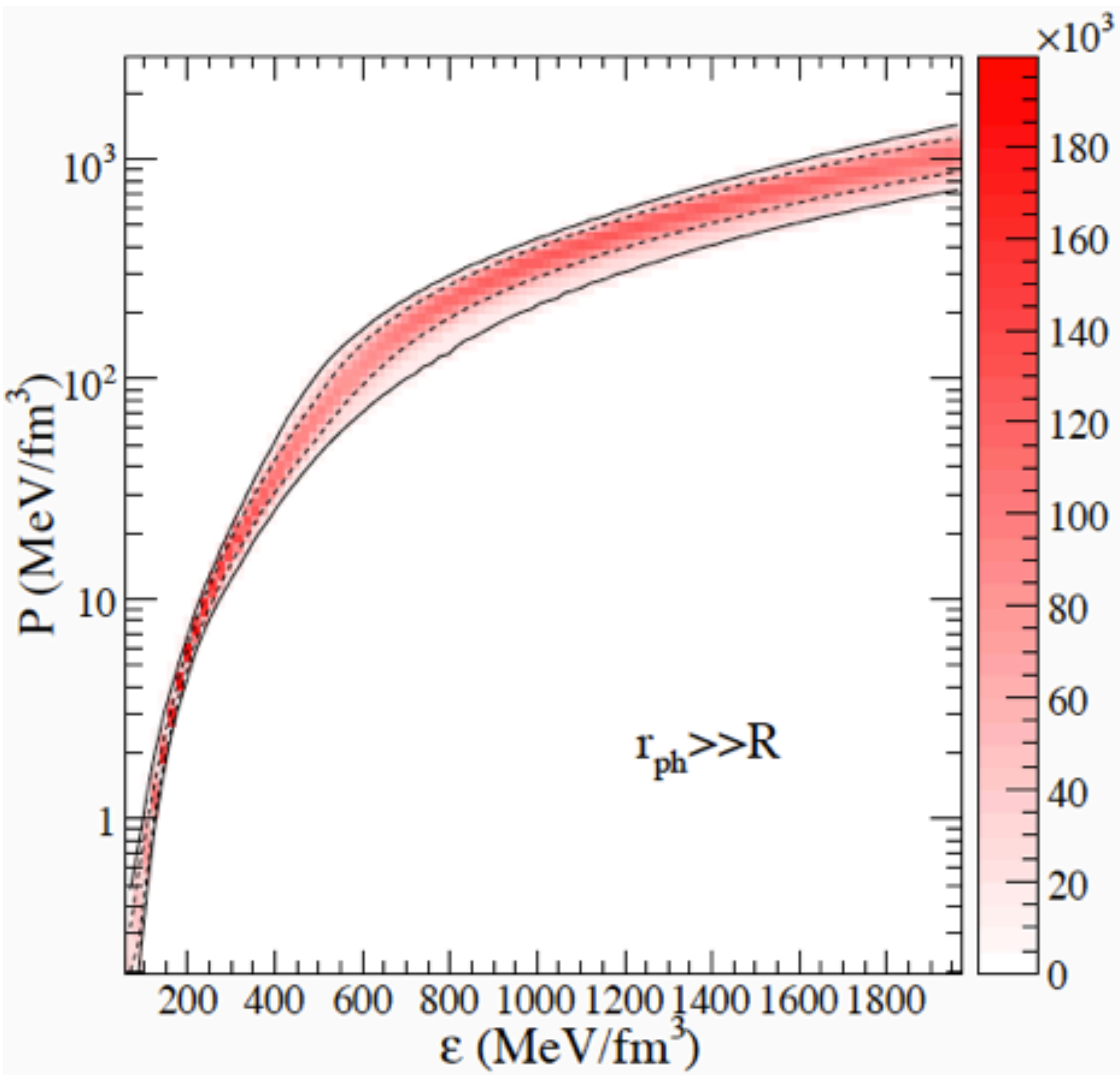
Model atmospheres determine non-black body correction f_C. This depends on luminosity and composition. Apply to 4U 1724-307 and find large ~15 km radius.

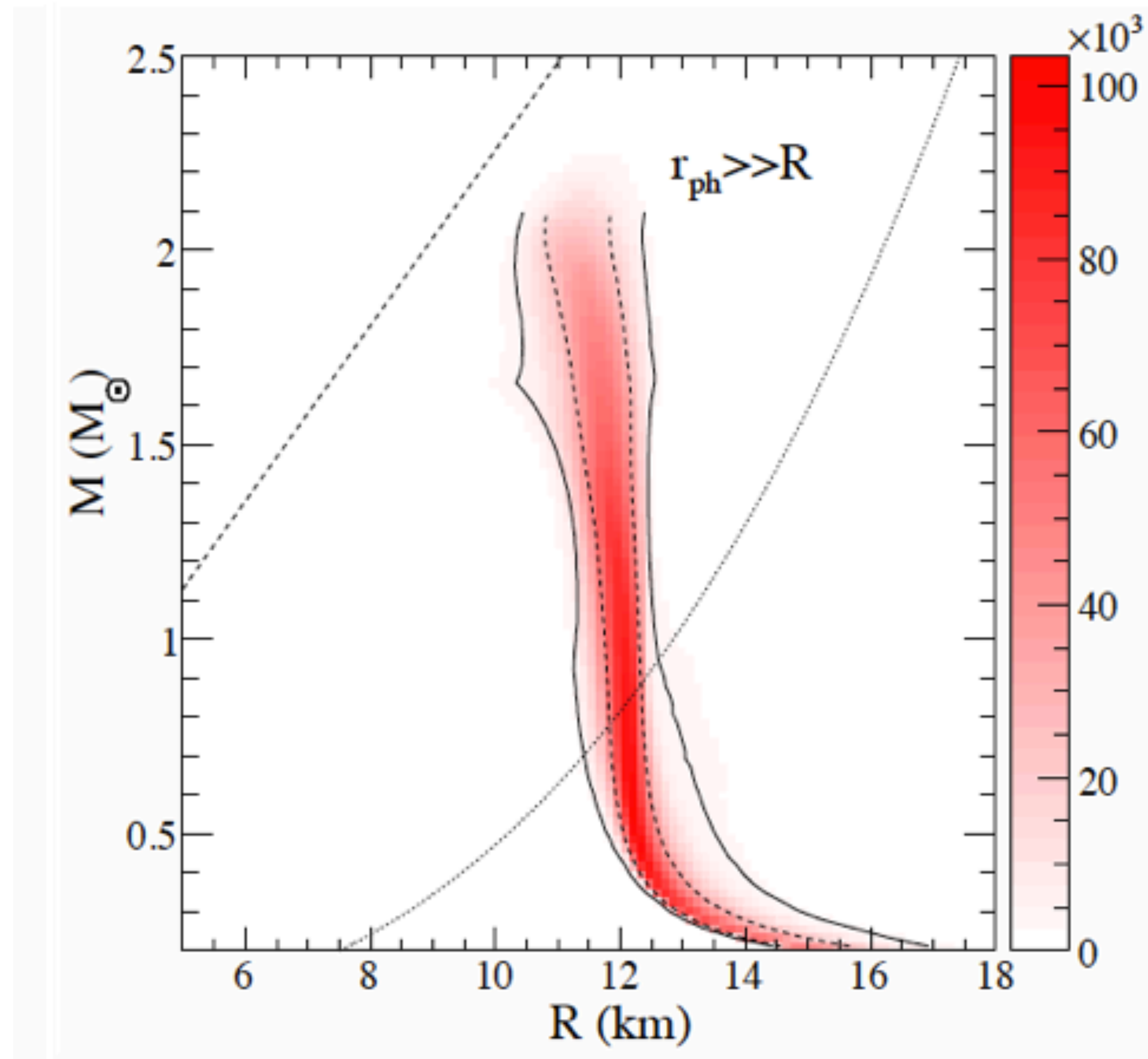
- arXiv:1010.0151



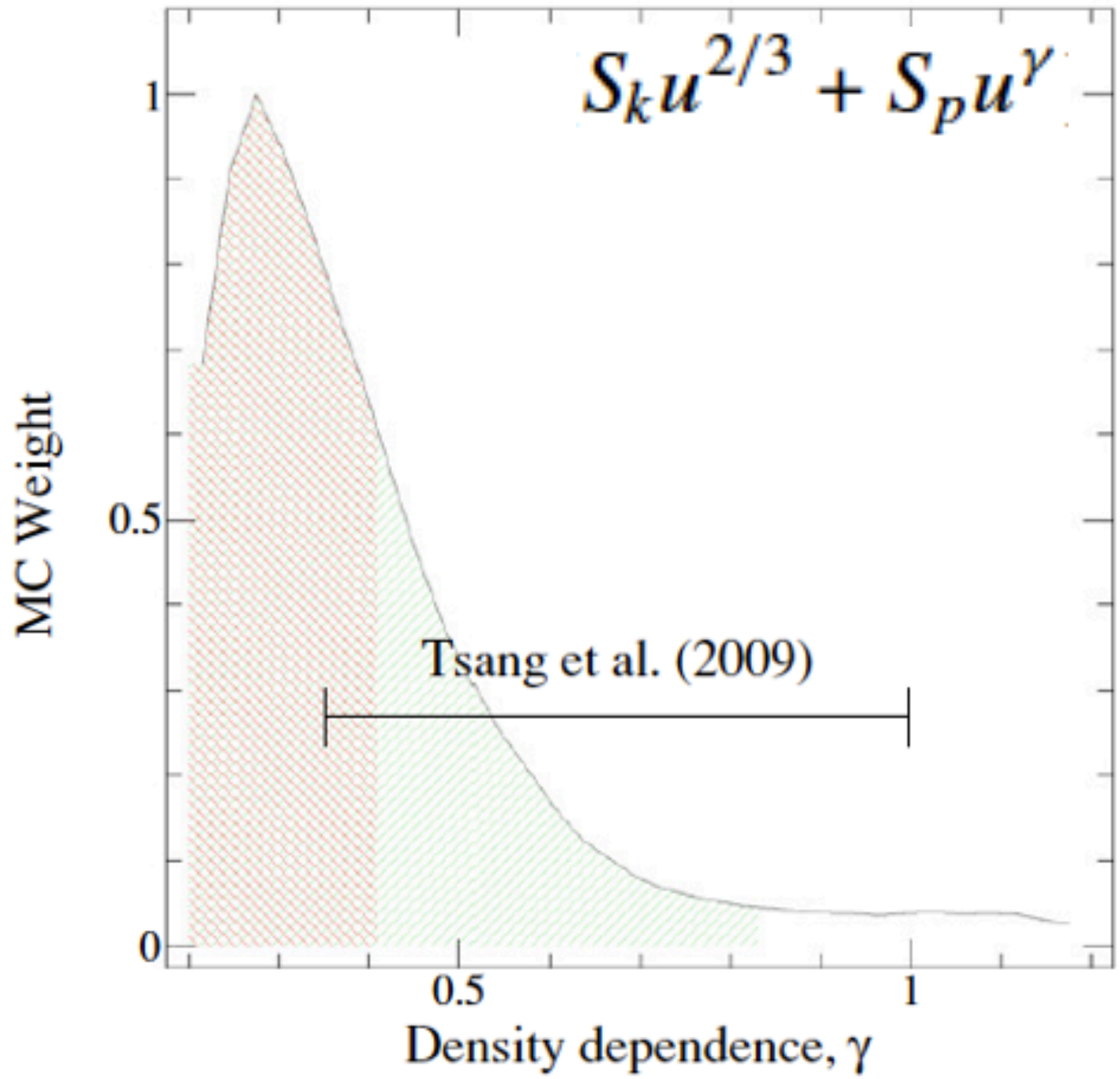


Steiner et al find common EOS to fit 3 globular cluster, 3 x-ray bursts





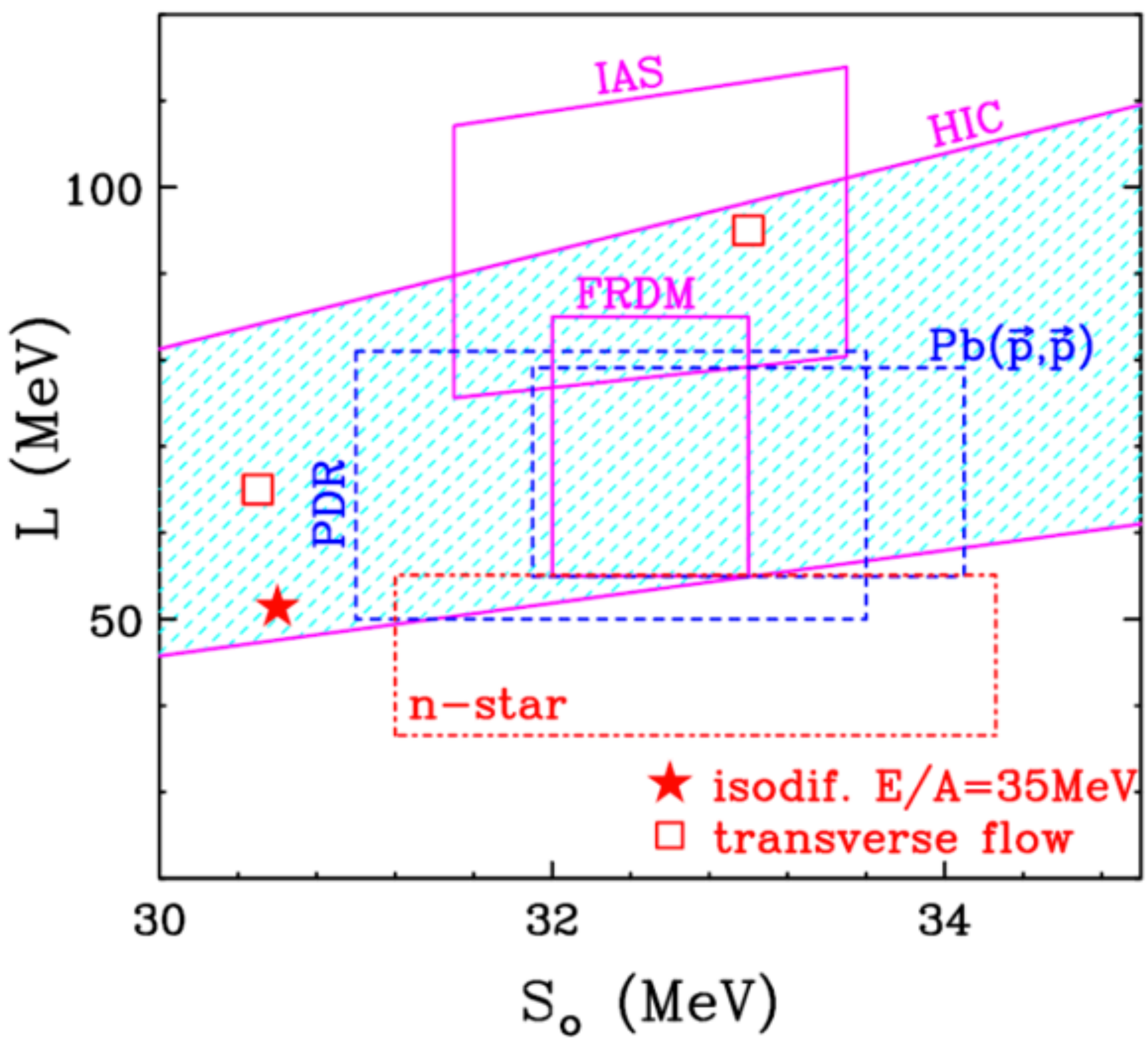
Extracted symmetry energy



- 12 km radius for $1.4M_{sun}$ coupled with > 2 M_{sun} max. NS mass implies soft sym E.

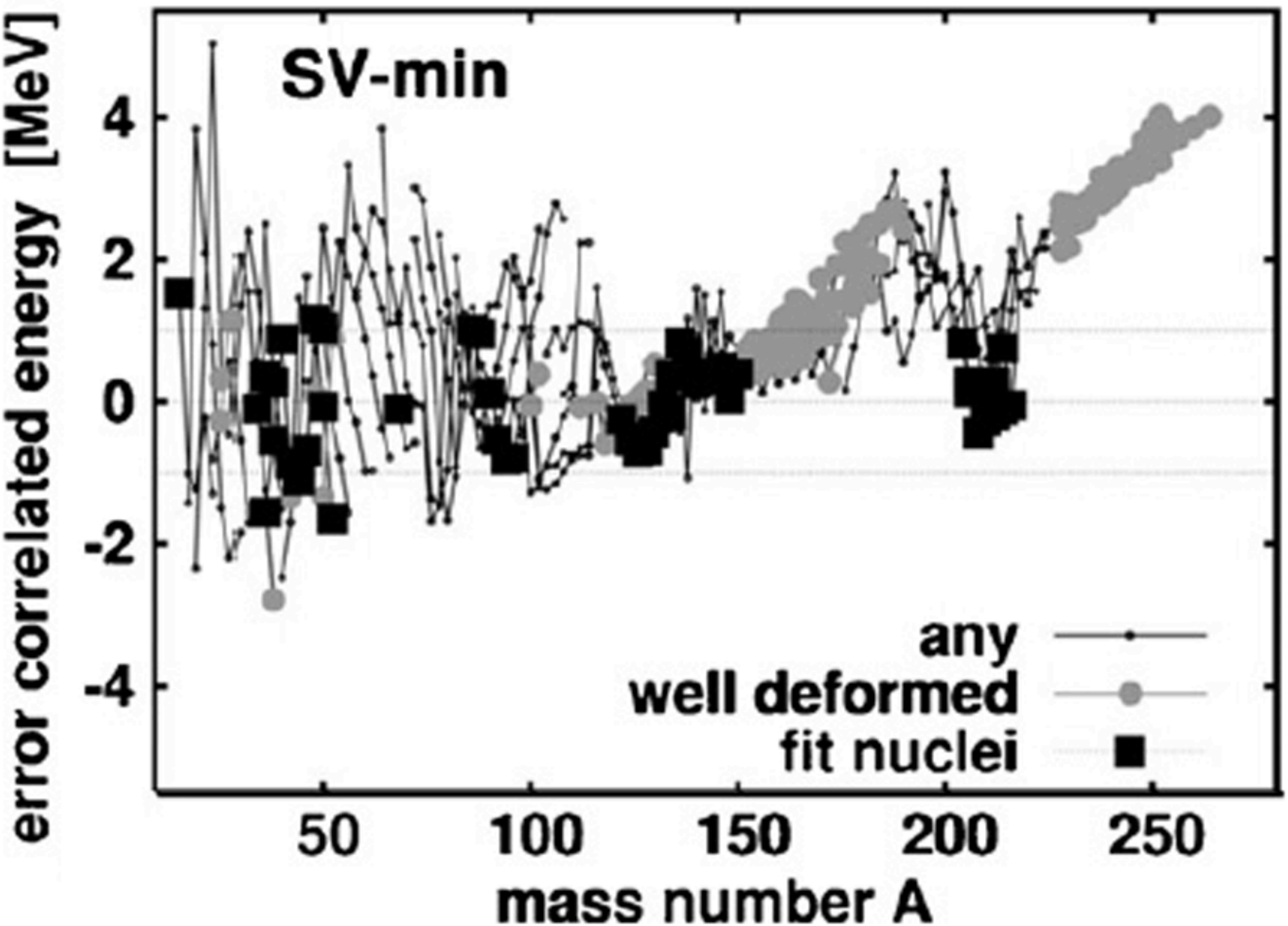
Symmetry energy review: M. B. Tsang et al, arXiv:1204.0466

- Constraints on symmetry energy at saturation density S_0 and its derivative L.
- 12 km neutron star radius (n-star) suggests small L
- Very roughly $R_{1.4}=10.8+L/30$ km. L=80 MeV -> R=13.5 km

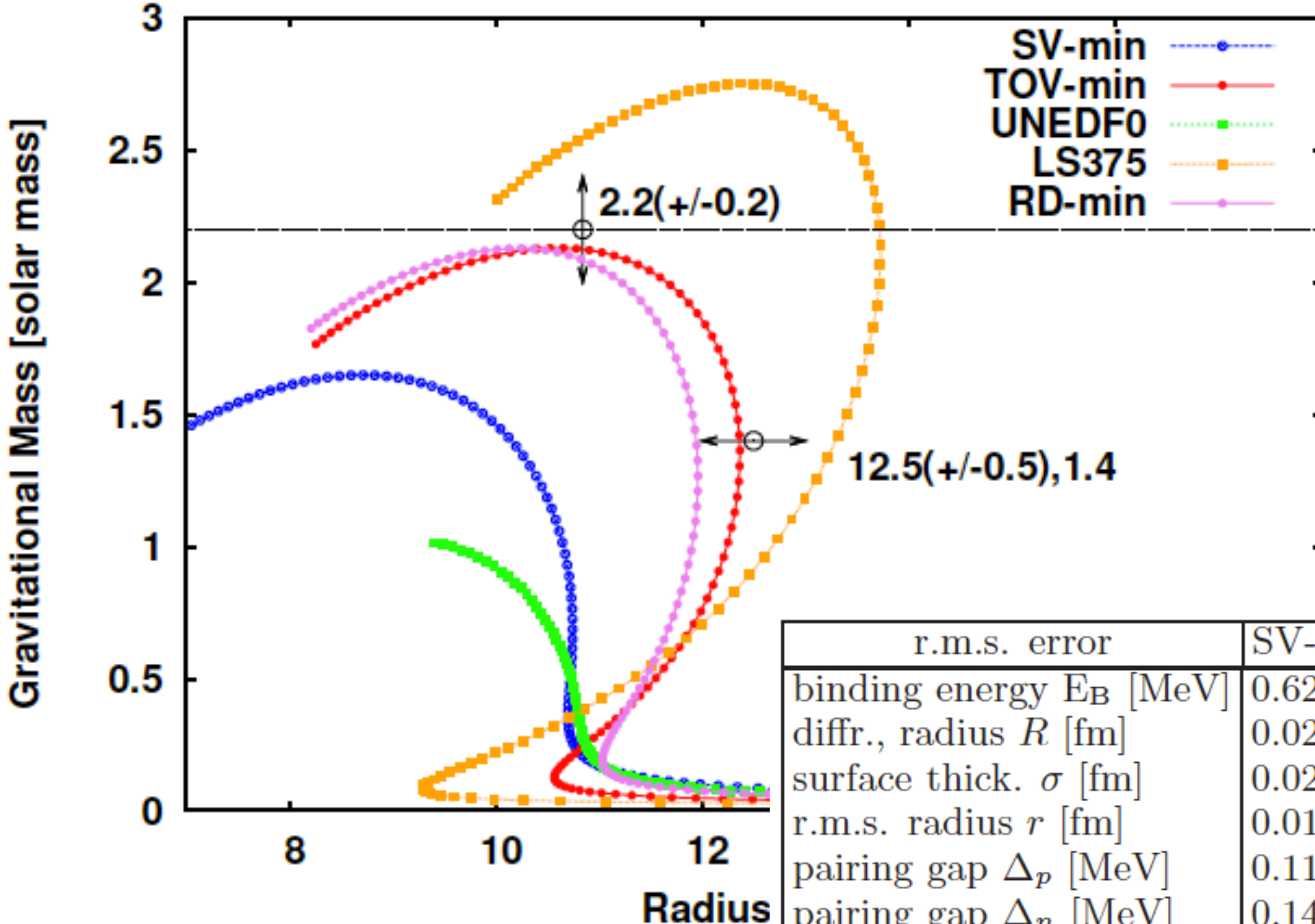


Energy functional for stable nuclei, neutron stars, and drip line nuclei.

- J. Erler, M. Rafalski, W. Nazarewicz, CJH.
- Fit new Skyrme force simultaneously to masses and charge densities of stable nuclei and masses and radii of neutron stars.
- Need TOV solver in parameter fitting routine.

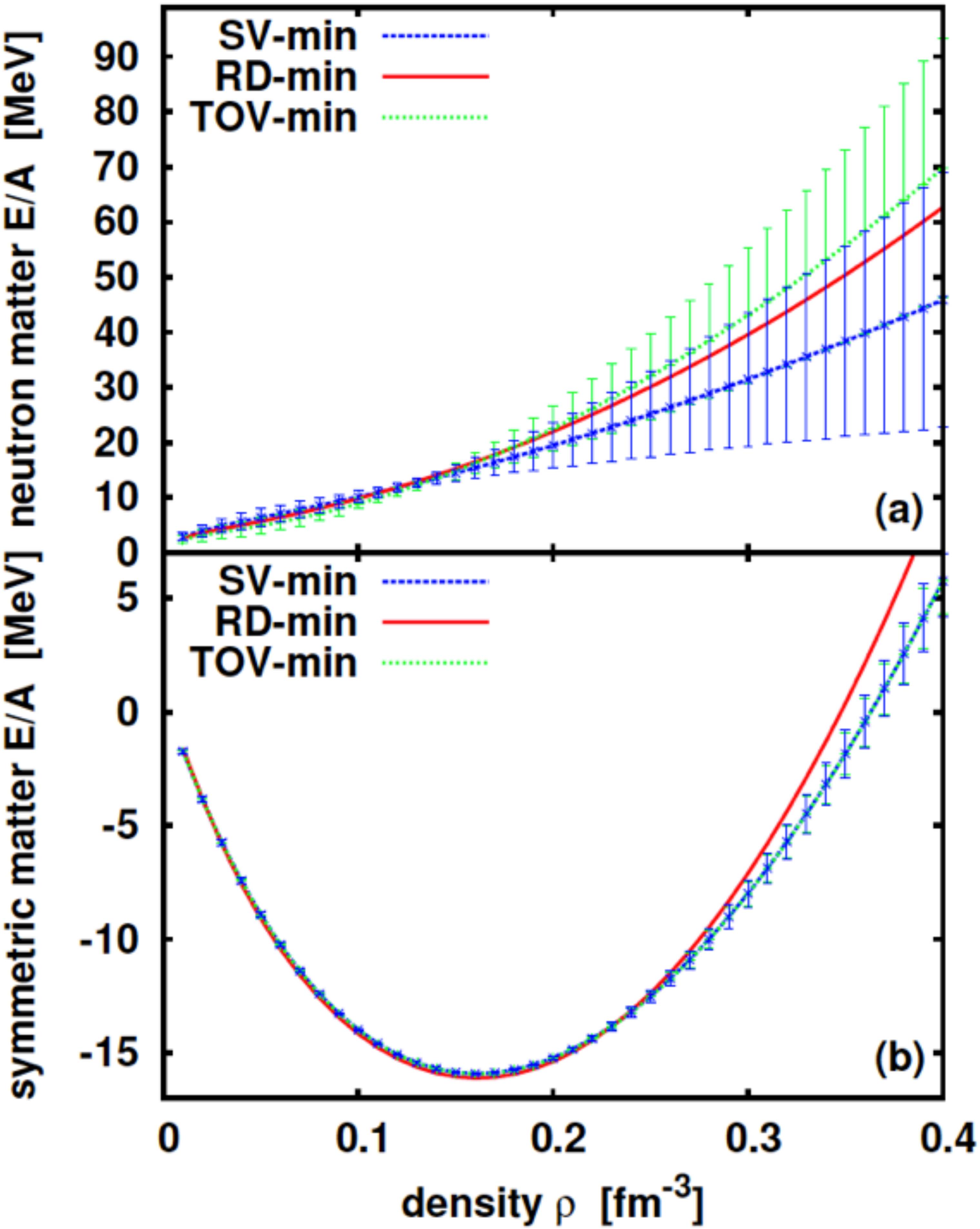


SV-min
error correlated energy [MeV]
4
2
0
-2
-4
50
100
150
200
250
mass number A
any
well deformed
fit nuclei



r.m.s. error	SV-min	TOV-min
binding energy E_B [MeV]	0.62	0.65
diffr., radius R [fm]	0.028	0.028
surface thick. σ [fm]	0.022	0.022
r.m.s. radius r [fm]	0.014	0.014
pairing gap Δ_p [MeV]	0.11	0.11
pairing gap Δ_n [MeV]	0.14	0.14
Total χ^2	53.22	53.50

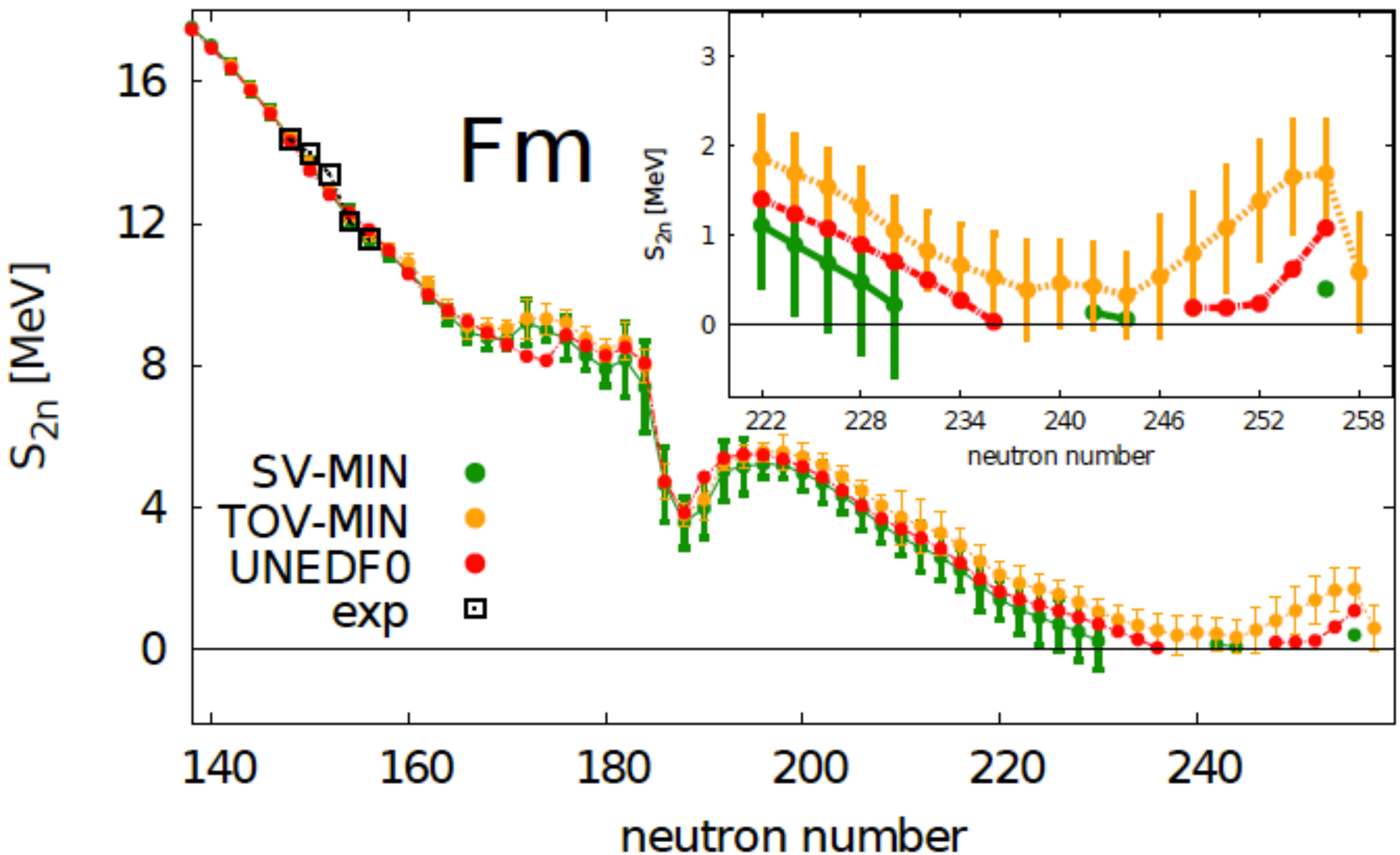
SV-min (blue) fit to only nuclei, TOV-min (red) fit to nuclei + neutron star maximum mass and radius of $1.4M_{sun}$ star.



Equation of state predicted by fit including error bars from full error matrix of fit.

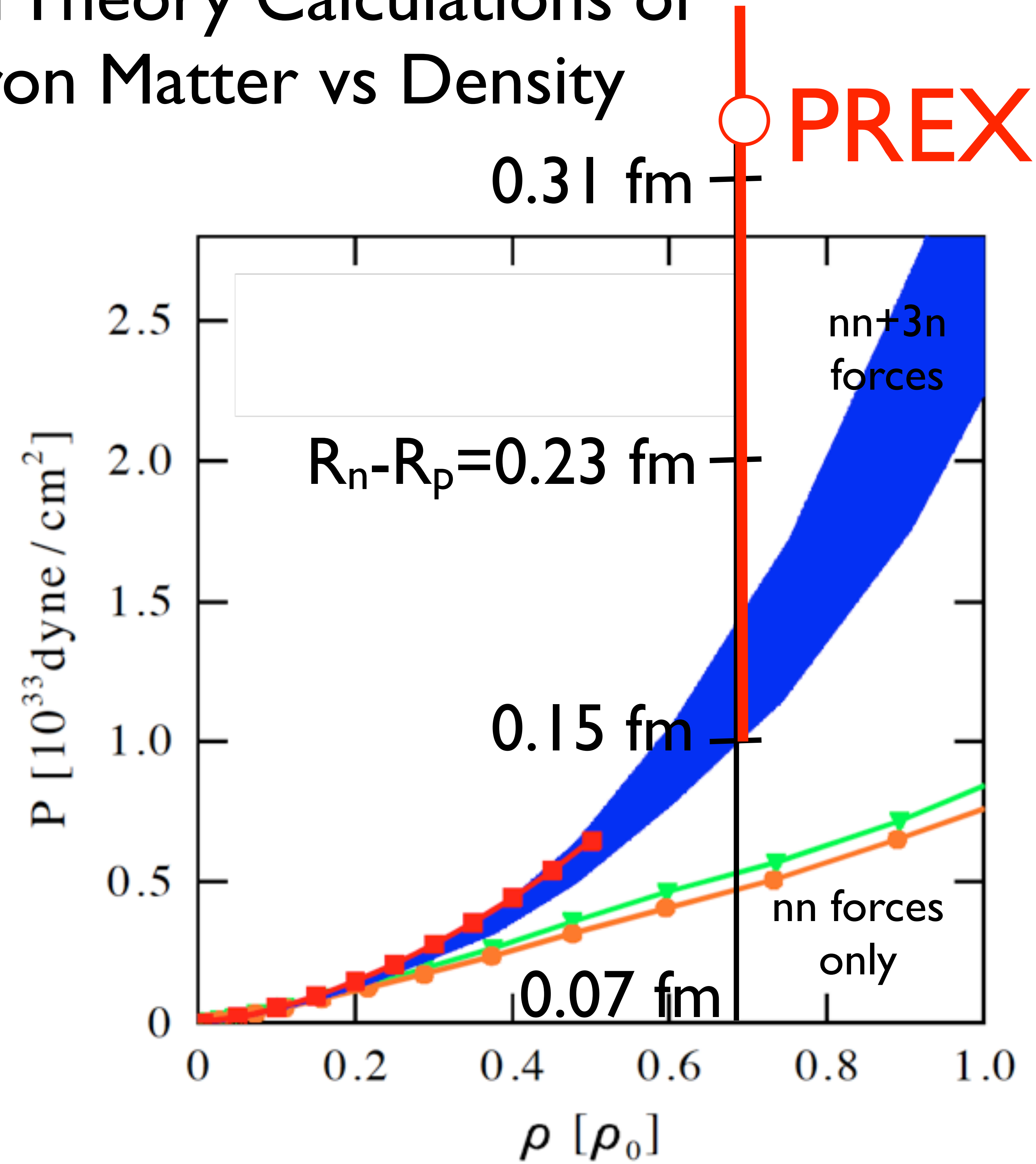
Fitting neutron stars changes neutron matter from blue to green without changing nuclear matter.

Fermium isotopes (Z=100) at drip line



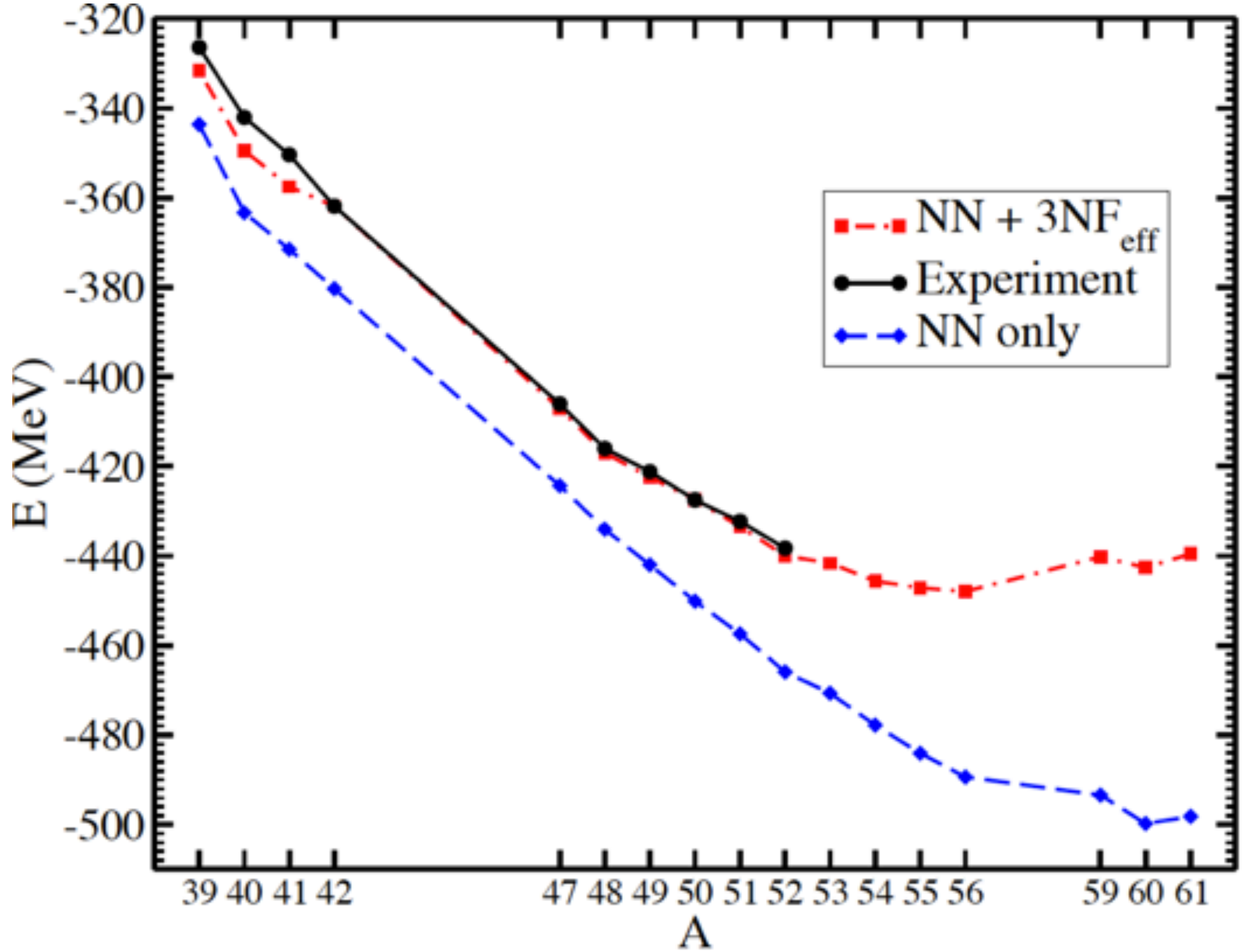
Chiral Effective Field Theory Calculations of Pressure of Neutron Matter vs Density

- 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 ^3H, ^3He...



Evolution of shell structure in neutron-rich calcium isotopes

G. Hagen,[1,2] M. Hjorth-Jensen,[3,4] G. R. Jansen,[3] R. Machleidt,[5] and T. Papenbrock[2,1]



- Coupled cluster calculations of total binding energy of Ca isotopes. Three nucleon forces change drip line from ^{70}Ca to ^{60}Ca.
- Important complementarity between precise experiments on stable nuclei and less precise radioactive beam experiments on very neutron rich nuclei.

II) Symmetry Energy at High Density, Composition of Dense QCD, and Neutron Star Cooling

Measuring the symmetry energy at high densities in Heavy Ion collisions.

- May involve observables that are hard to interpret theoretically.
- ***Is the single experimental quantity most closely related to the structure of neutron stars, indeed, to what neutron stars are made of.***

Neutron star cooling

- NS cooling probes dense matter.
- Neutron stars are born hot in supernova explosions and cool by neutrino emission from their dense interiors.
- Standard cooling (modified URCA) involves beta decay of two nucleons
  - n + n --> p + n + e + anti-nu
  - e + p + n --> n + n + nu
- Enhanced cooling involves beta decay of a single hadron.

Direct URCA

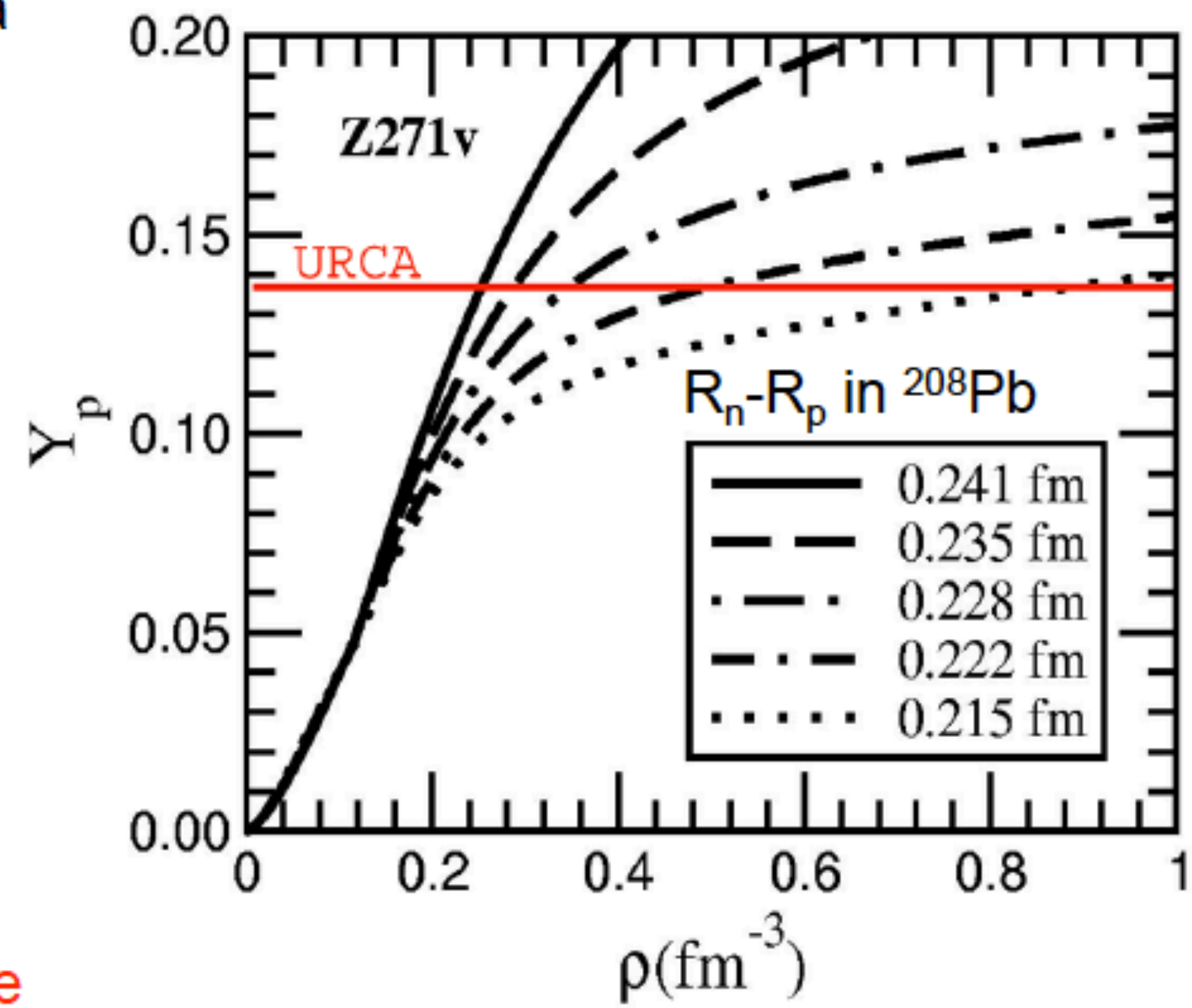
- If proton fraction, in dense matter, is large enough so that $k_{fp}+k_{fe} > k_{fn}$ than
  - n --> p + e + anti-nu
  - e + p --> n + nu
- can conserve both E and momentum and leads to rapid cooling.
- If other hadrons, for example Lambdas, are present they can also beta decay.
  - Λ --> p + e + anti-nu
  - e + p --> Λ + nu

PREX Constrains Rapid Direct URCA Cooling of Neutron Stars

- Proton fraction Y_p for matter in beta equilibrium depends on symmetry energy S(n).

$$S \approx \mu_n - \mu_p = \mu_e$$

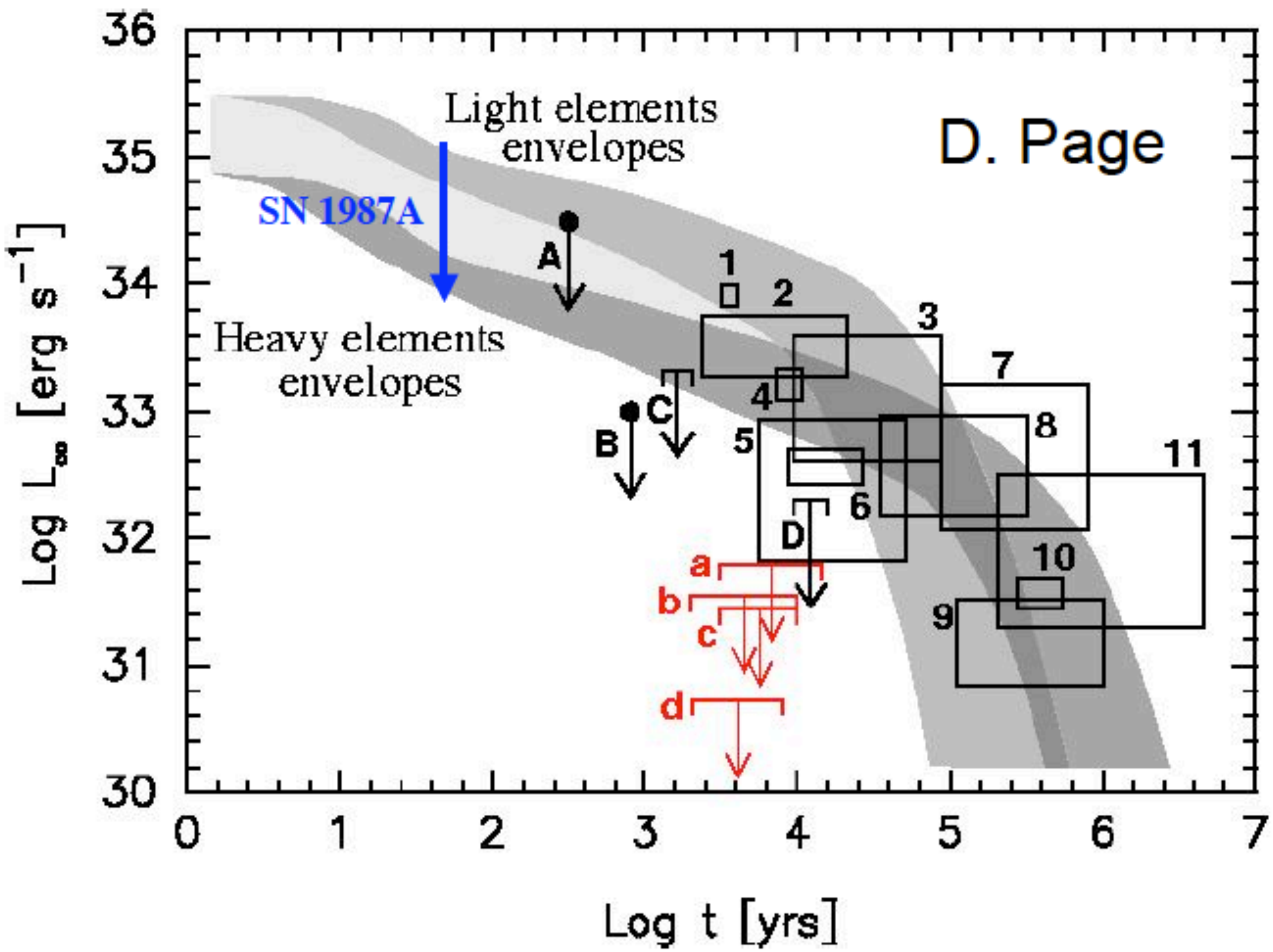
- R_n in Pb determines density dependence of S(n).
- The larger R_n in Pb the lower the threshold mass for direct URCA cooling.
- If R_n-R_p<0.2 fm all EOS models do not have direct URCA in 1.4 $M_\odot$ stars.
- If R_n-R_p>0.25 fm all models do have URCA in 1.4 $M_\odot$ stars.



If Y_p > red line NS cools quickly via direct URCA n→ p+e+ν otherwise decay can't conserver momentum.

J Piekarewicz, CJH

Neutron Star Luminosity vs Age



Mag H fits:

1) RX J0822-4247 (in Puppis A)
2) 1E 1207.4-5209 (in PKS 1209-52)
3) PSR 0538+2817
4) RX J0002+6246 (in CTB 1)
5) PSR 1706-44
6) PSR 0933-45 (in Vela)

BB fits:

7) PSR 1055-52
8) PSR 0656+14
9) PSR 0633+1748 "Geminga"
10) RX J1856.5-3754
11) RX J0720.4-3125

Upper limits:

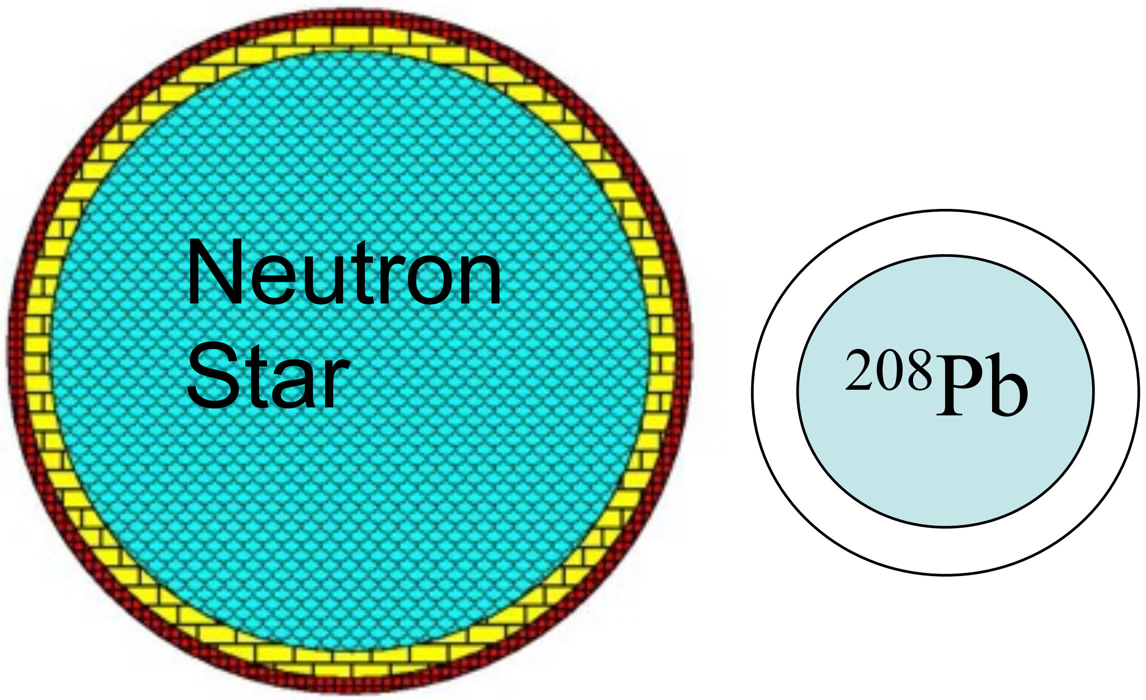
A) CXO J232327.8+584842 (in Cas A)
B) PSR J0205+6449 (in 3C58)
C) PSR J1124-5916 (in G292.0+1.8)
D) RX J0007.0+7302 (in CTA 1)

NS cooling roadmap

- Confirm observation of rapid cooling in some stars (presumably these are more massive, while less massive stars have normal cooling).
- Independently rule out (or in) direct URCA by measuring symmetry energy at high density.
- Infer that dense matter contains additional hadrons beyond n and p.

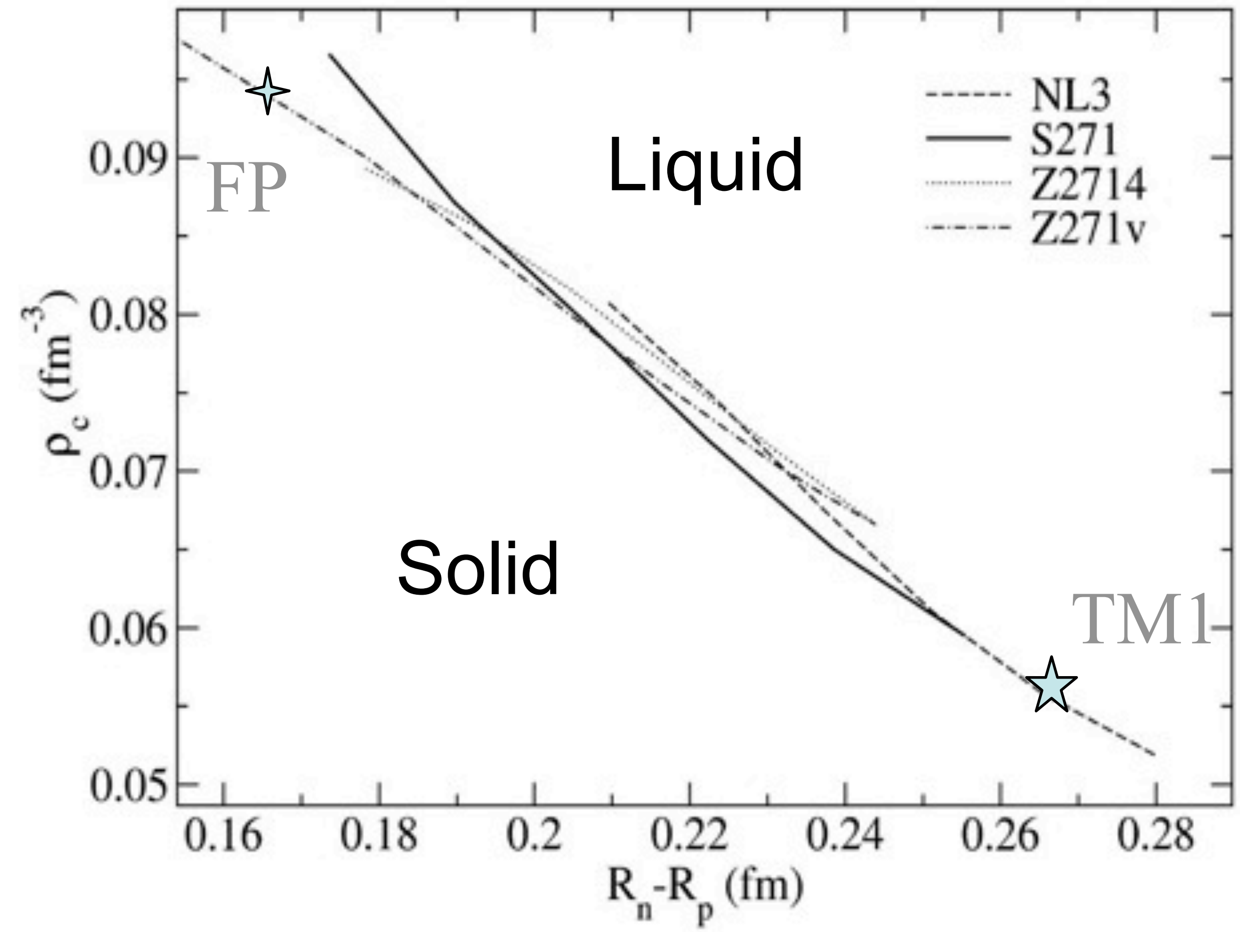
III) Symmetry E at very low density, clustering, and supernovae

Neutron Star Crust vs ^{208}Pb Neutron Skin



- Neutron star has solid crust (yellow) over liquid core (blue).
- Nucleus has neutron skin.
- Both neutron skin and NS crust are made out of neutron rich matter at similar densities.
- Common unknown is EOS at subnuclear densities.

Liquid/Solid Transition Density



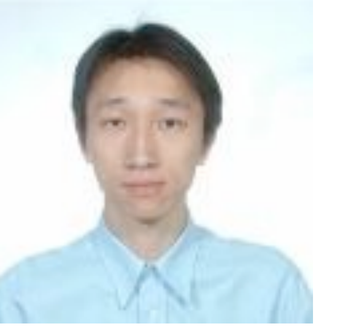
- Thicker neutron skin in Pb means energy rises rapidly with density-> Quickly favors uniform phase.
- Thick skin in Pb->low transition density in star.

CJH, J. Piekarewicz, PRL**86** (2001) 5647

Symmetry E of Clusters

- Consider collection of n, p, and alpha particles.
- At zero T, symmetric nuclear matter will be all alpha particles.
- Symmetry E is just binding E of alphas because as one goes away from N=Z fewer alphas can be formed. This is independent of density in low density limit.
- At finite T abundance of various clusters will be important to determine symm E and can be measured in HI collisions.

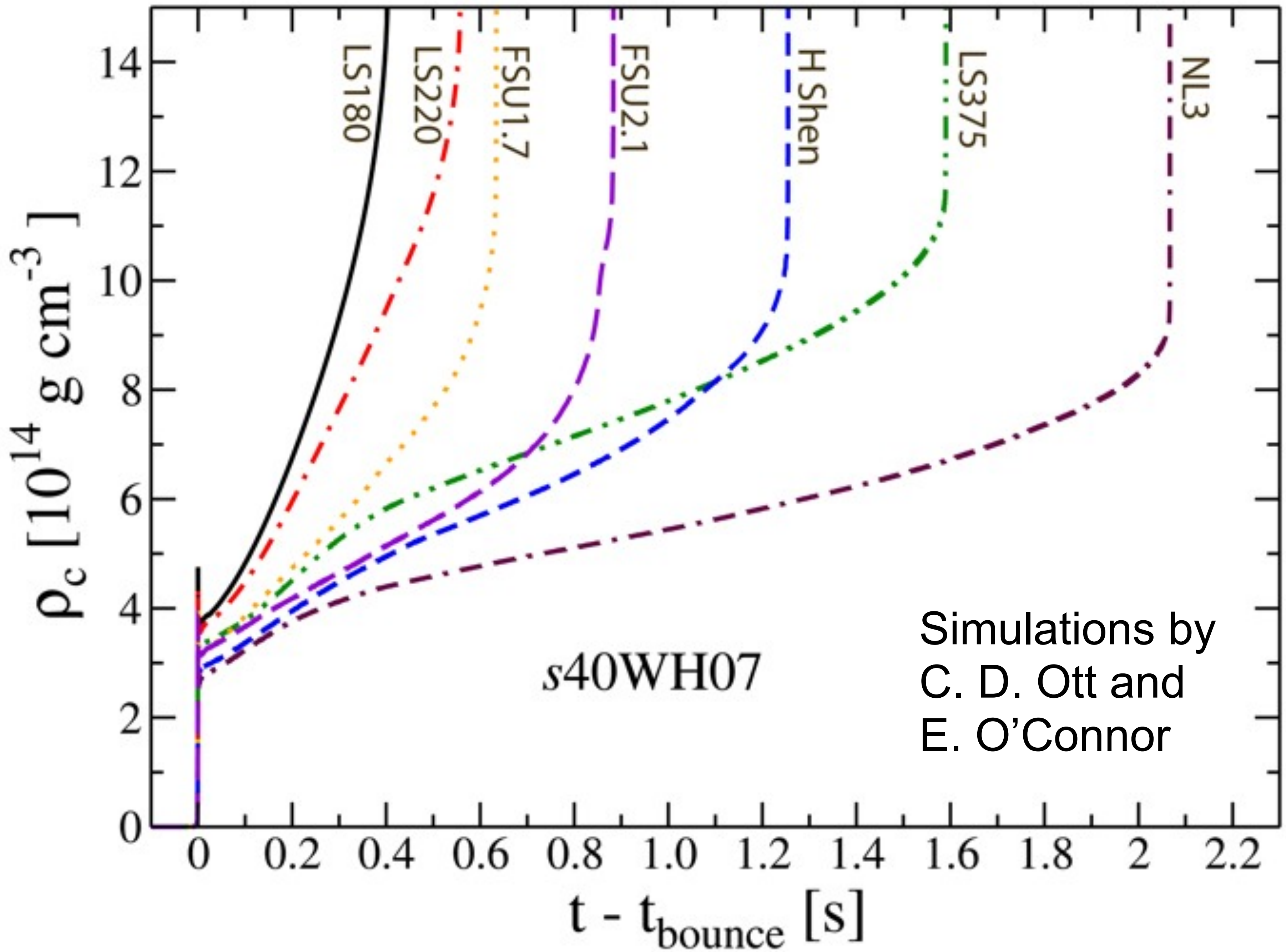
New Equations of State (EOS) for Supernova Simulations



Gang Shen

- The EOS ---pressure as a function of density, temperature, and proton fraction--- is an important ingredient for SN and neutron star merger simulations. Previously only LS and H. Shen EOS in widespread use.
- At low density we use a Virial expansion with nucleons, alphas, and thousands of heavy nuclei. At high density we use relativistic mean field calculations in a spherical Wigner-Seitz approximation. Full thermodynamically consistent EOS table took 100,000+ CPU hours.
- Our EOSs are exact at low density and contain more detailed composition information for calculating neutrino interactions than LS or H. Shen.
- Large equation of state tables are available for download to be used in simulations of supernovae, proto-neutron star evolution, neutron star mergers, black hole formation ...
  - http://cecelia.physics.indiana.edu/gang_shen_eos

Collapse of 40 solar mass star to black hole



- Central density (diverges when black hole forms) vs time after core bounce for different EOSs. Neutrino signal ends when BH forms.
- Our very stiff (NL3) and softer (FSU1.7, FSU2.1) EOSs give longer times than Lattimer Swesty (LS180) EOS.

Equation of State in Astrophysics and Symmetry Energy

- Collaborators: S. Ban, M. Gorchtein, R. Michaels, J. Piekarewicz ... Students: L. Caballero, H. Dussan, J. Hughto, A. Schneider, and G. Shen.
- Supported in part by DOE and State of Indiana.

C. J. Horowitz, IU and MSU, WCU/Hanyang-APCTP Focus Program, “Effective field theories, halos, drip-lines and EoS for compact stars”, Pohang, Korea, Apr. 2012