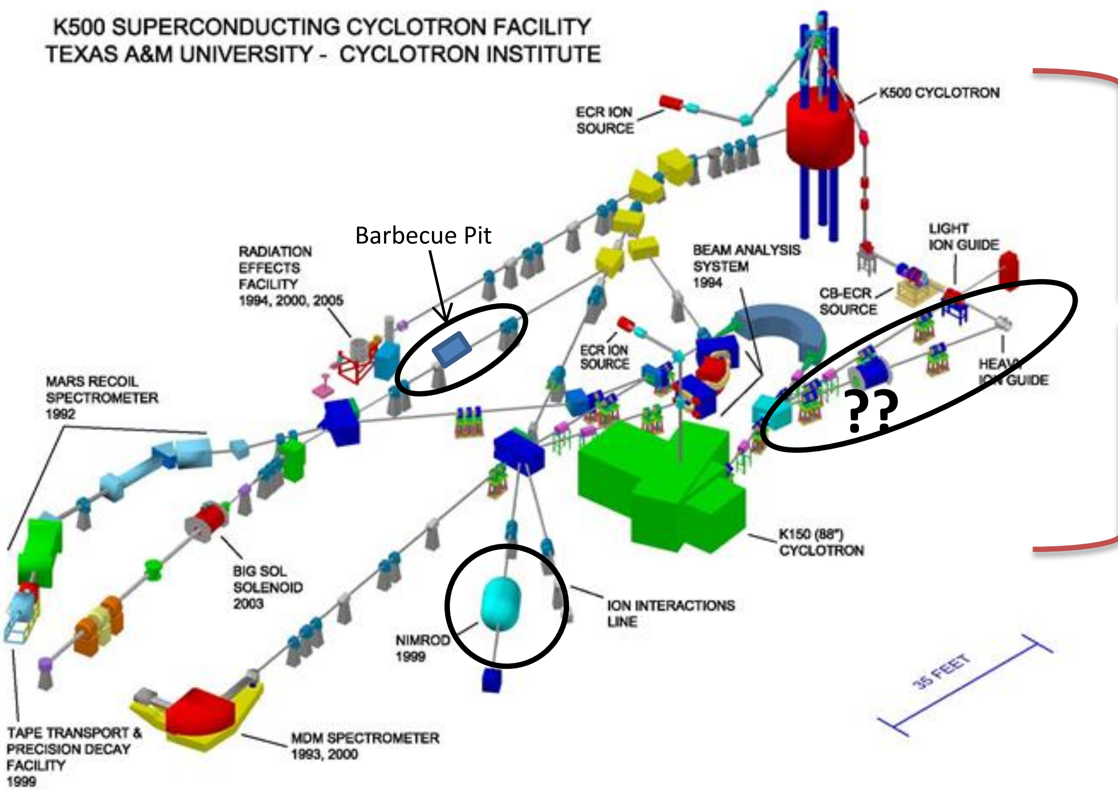
Probing the Nuclear Equation of State at Low Density Using Near Fermi-Energy Heavy Ion Collisions

al. et J. Natowitz

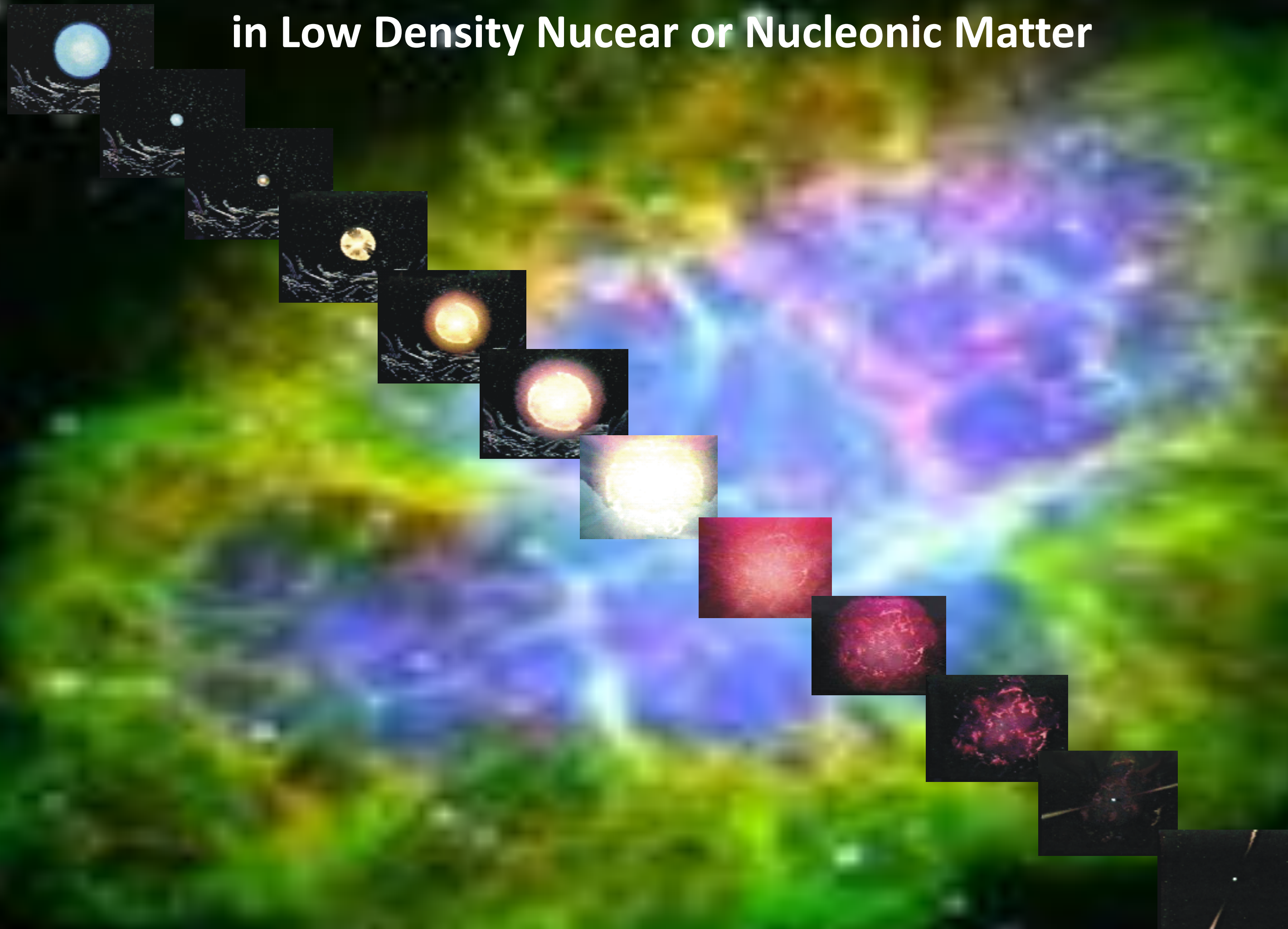


T-REX

[TAMU **Re**accelerated **EX**otics]

CYCLOTRON INSTITUTE
Texas A&M University

Laboratory Studies of Clusterization and Symmetry Energy in Low Density Nucear or Nucleonic Matter



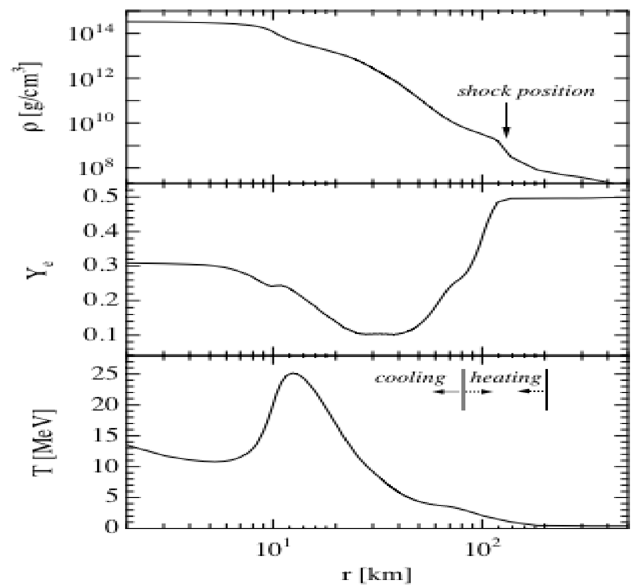
Nuclear and Astrophysical Equations of State - Relevance to Properties of The Neutrinosphere in Supernovae, Nucleosynthesis, Neutron Stars,

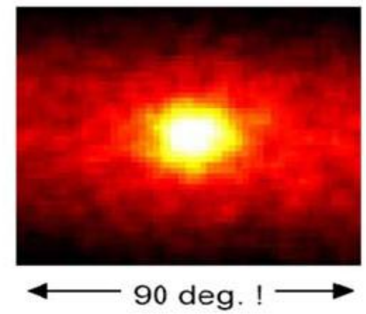
CLUSTER FORMATION Modifies Nuclear EOS

Astrophysical Implications, e.g., Core-collapse Supernovae

K.Sumiyoshi et al., Astrophys.J. **629**, 922 (2005)

Density. electron fraction, and temperature profileof a 15 solar mass supernova at 150 ms after core bounce --as function of the radius.

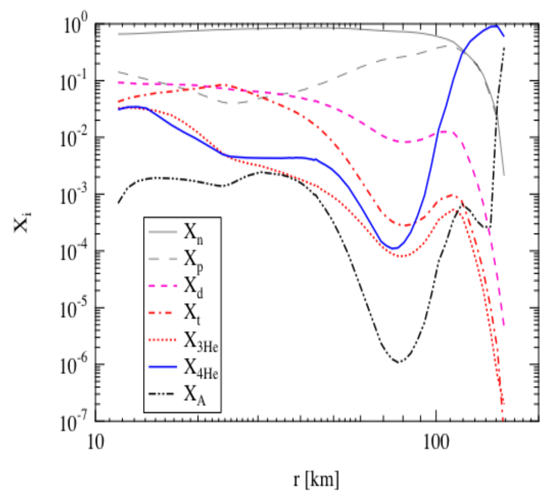




C.J. Horowitz, A. Schwenk
ArXiv nucl-th/0507033

- Conditions at neutrinosphere:
  - Temperature ~ 4 MeV crudely observed with 20 SN1987a events.
  - $\sigma \sim G_F^2 E_\nu^2$ and $E_\nu \sim 3T$
  - $\rho \sim 10^{11}$ g/cm^3 [$\sim 10^{-4}$ fm^{-3}]

K.Sumiyoshi, G. Roepke
PRC 77, 055804 (2008)



Cluster formation Influences neutrino flux
What is the composition, EOS and neutrino response of nuclear matter near the neutrinosphere?

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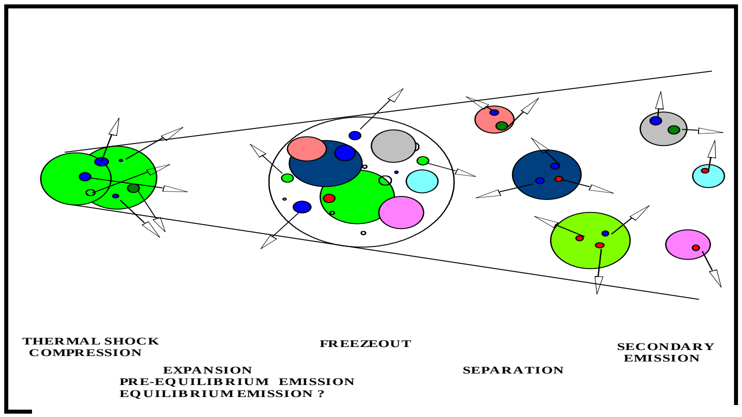
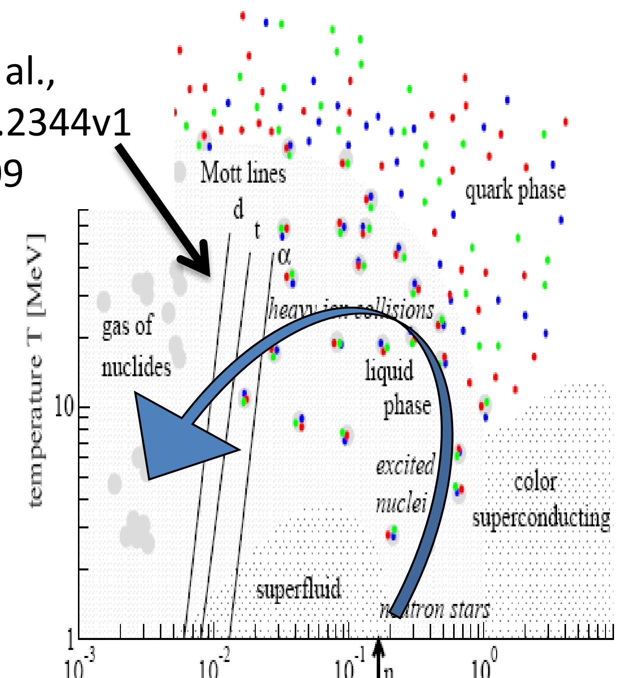
Texas A&M University

Exploring The Nuclear Matter Equation of State in the Laboratory With Collisional Heating

NEAR FERMI ENERGY HEAVY ION COLLISIONS AT LOW IMPACT PARAMETER



S. Typel, et al., ArXiv 0908.2344v1 August 2009



Time fm/c

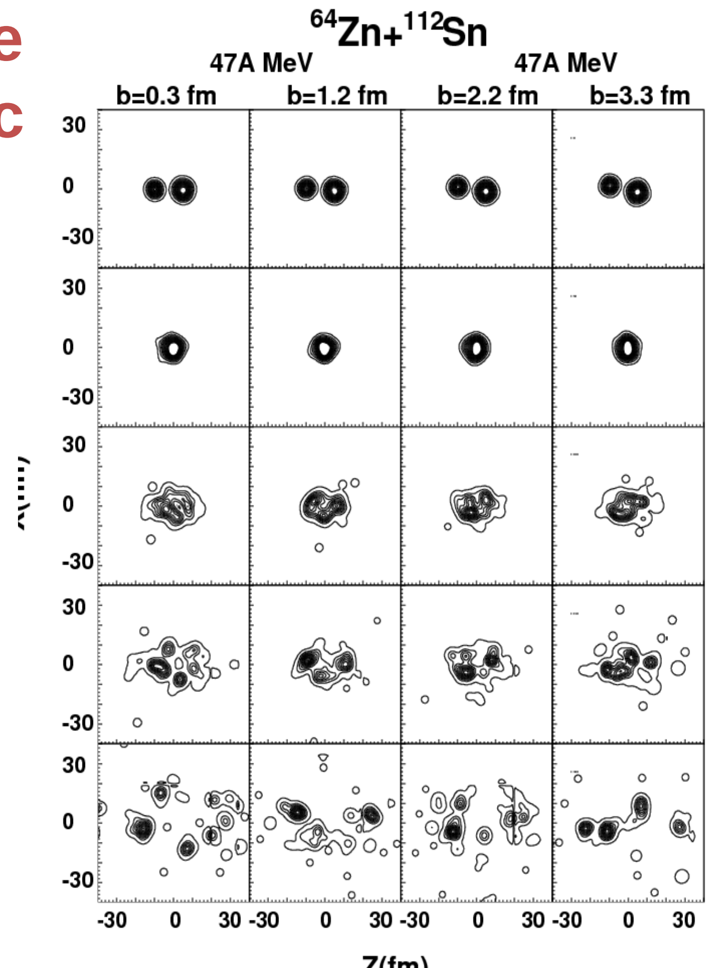
0

50

100

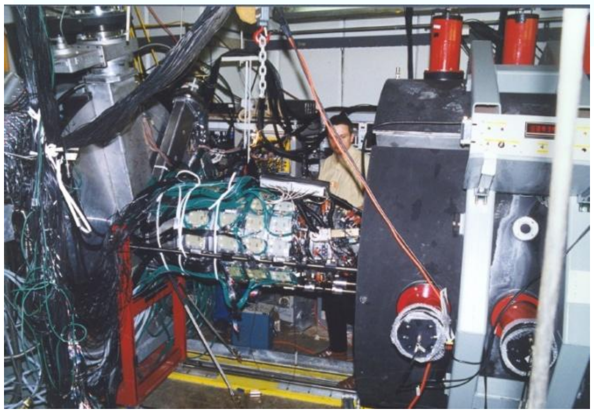
200

300



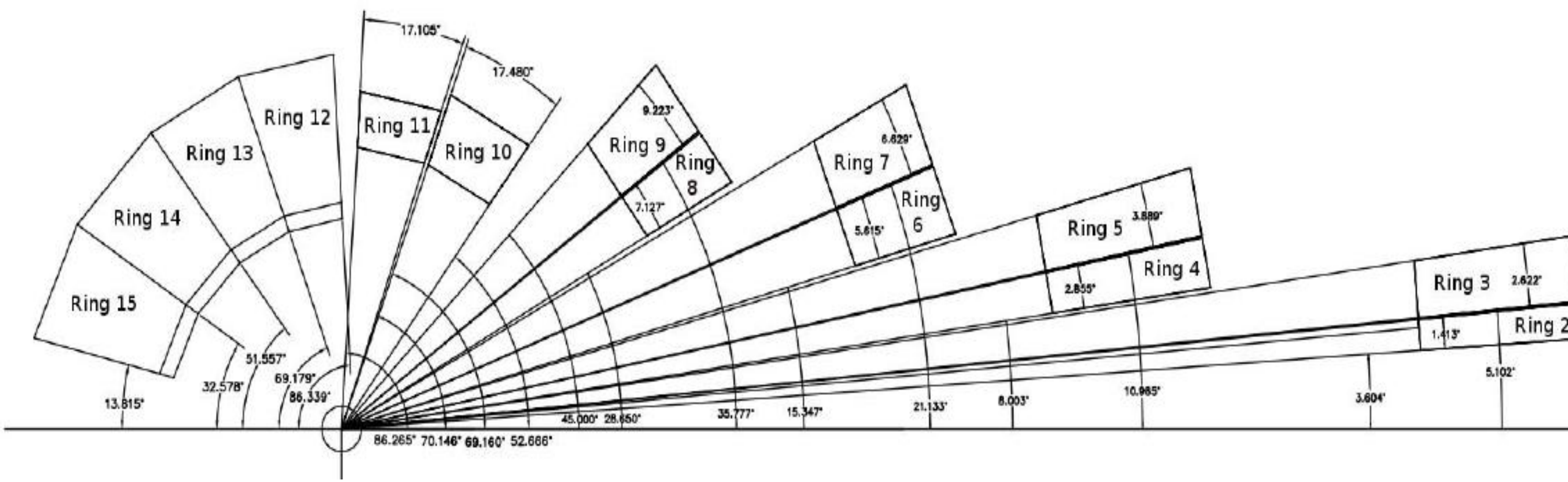
Antisymmetrized Molecular Dynamics Model* Calculations *A. Ono

NIMROD 4π Charged Particle Telescope Array and 4π Neutron Calorimeter ejectile identification, energy, angle, correlations on an event by event basis



- The charged particle detectors are composed of Ionization Chambers, silicon telescopes and CsI(Tl) scintillators covering angles between 3 and 170 degrees
- **R. Wada el al, Phys. Rev. C 69, 044610(2004)**

S. Wuenschel et al., NIM 604, 578–583 (2009).



RELEVANT RECENT PUBLICATIONS

"Laboratory Tests of Low Density Astrophysical Nuclear Equations of State"
L. Qin et al., , Phys. Rev. Lett.**108.,** 172701 (2012)

"Experimental Determination of In-Medium Cluster Binding Energies and Mott Points in Nuclear Matter"
K. Hagel et al., Phys. Rev. Lett. **108** .062702 (2012)

"The Nuclear Matter Symmetry Energy at 0.03 $\leq \rho/\rho_0 \leq 0.2$"
R. Wada et al., Phys. Rev. **C 85**, 064618 (2012)

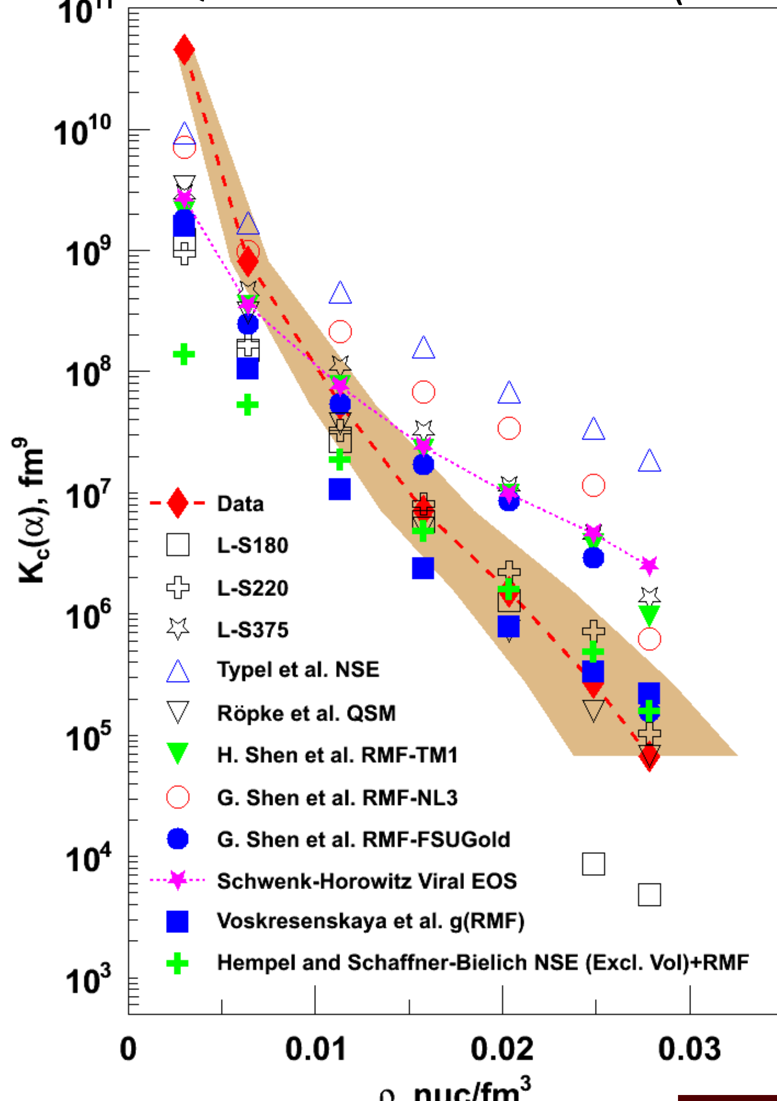
"Density determinations in heavy ion collisions"
G. Roepke et al., Phys. Rev. C**.** **88,** 024609 (2013)

Experimental reconstruction of excitation energies of primary hot isotopes in heavy ion collisions near the Fermi Energy"
M.R.D.Rodrigues et al, Phys. Rev. C, 88, 034605 (2013)

And references therein

Test of Astrophysical Equations of State
Equilibrium Constant, K_α

L. Qin et al.PRL **108** 172701 (2012).



- **Many tests of EOS are done using mass fractions. Various calculations include various different competing species., if all relevant species are not included, mass fractions are not accurate.**

- **Equilibrium constants, e.g.,**

( ) ———

should be independent of proton fraction and choice of competing species.

- **Models converge at lowest densities, but many are significantly above data at higher density**

- **Lattimer & Swesty with K=180, 220 show reasonable agreement with data**

- **QSM with in-medium binding energy shifts works well**

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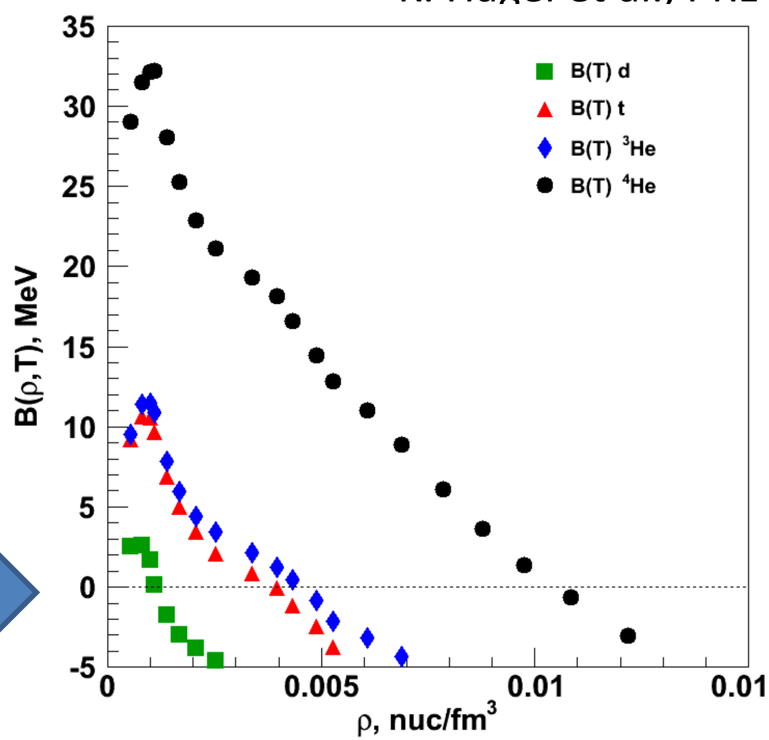
Density Dependent Binding Energies of Light Clusters – The Mott Point

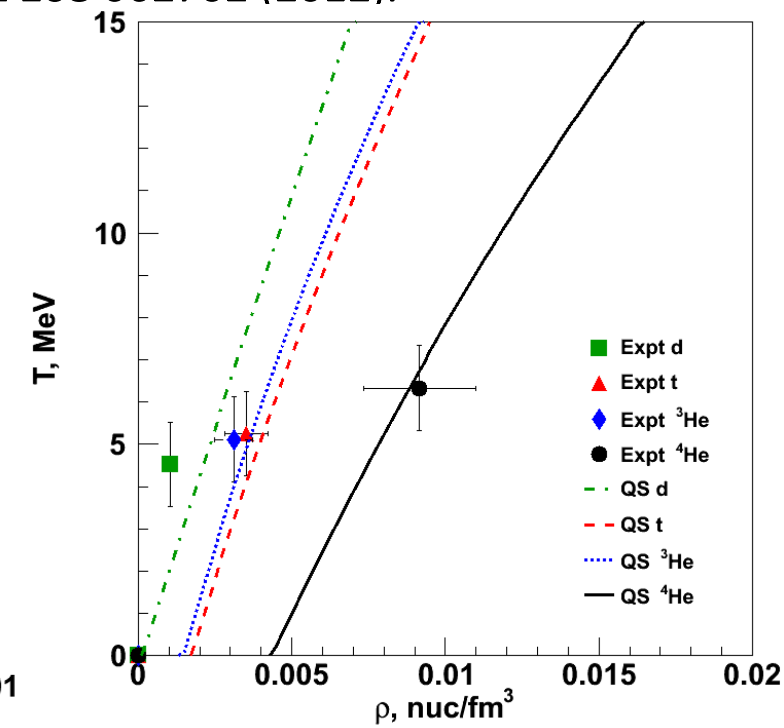
- Successful QSM Model of Roepke et al. Incorporates In-Medium modification of Cluster Binding Energies . Clusters become unbound wrt medium at the Mott Point

- Mott points determined in reactions of 47AMeV ^{40}Ar and ^{64}Zn projectiles with $^{112, 124}$Sn are in close agreement with the theoretical estimates

K. Hagel et al., PRL **108** 062702 (2012).

The Mott Point





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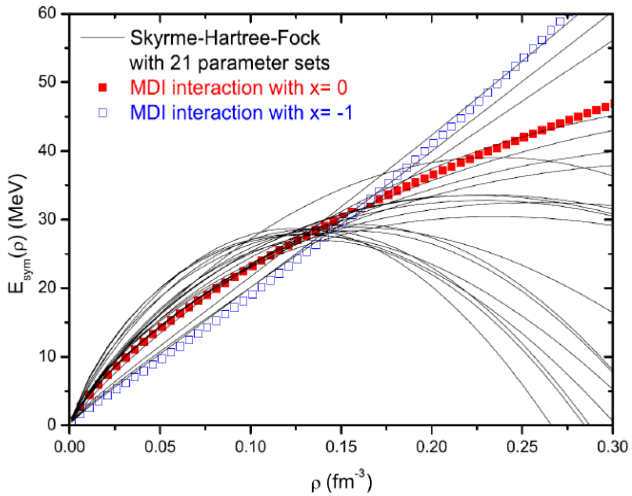
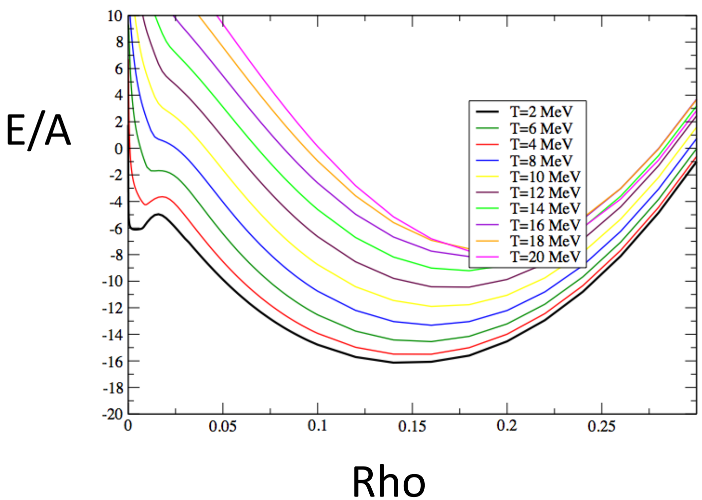
The Symmetry Energy Problem
Density Dependence ?



Experimentally or observationally constraining the density dependence of the symmetry energy over a broad range of densities is a complex problem-



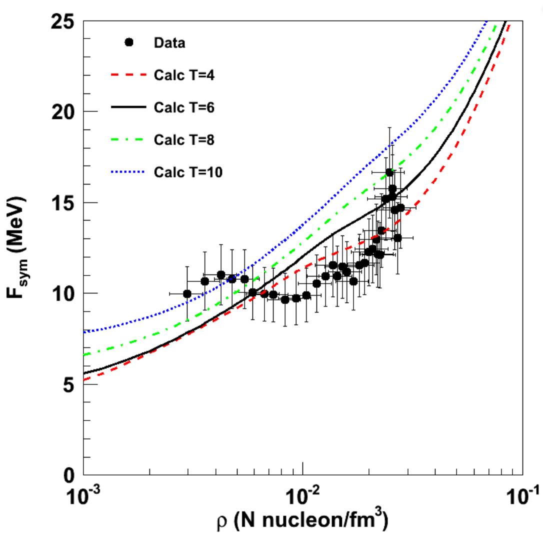
While low density situation would appear to be easier to constrain- cluster formation changes the medium This leads to additional complexity (opportunity)

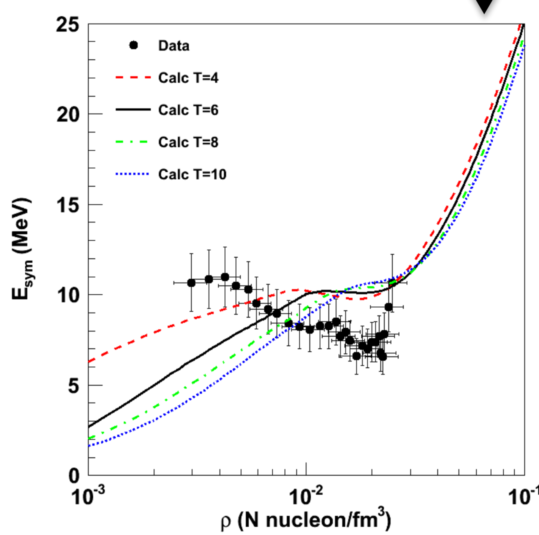
Symmetry Energy at Low Density

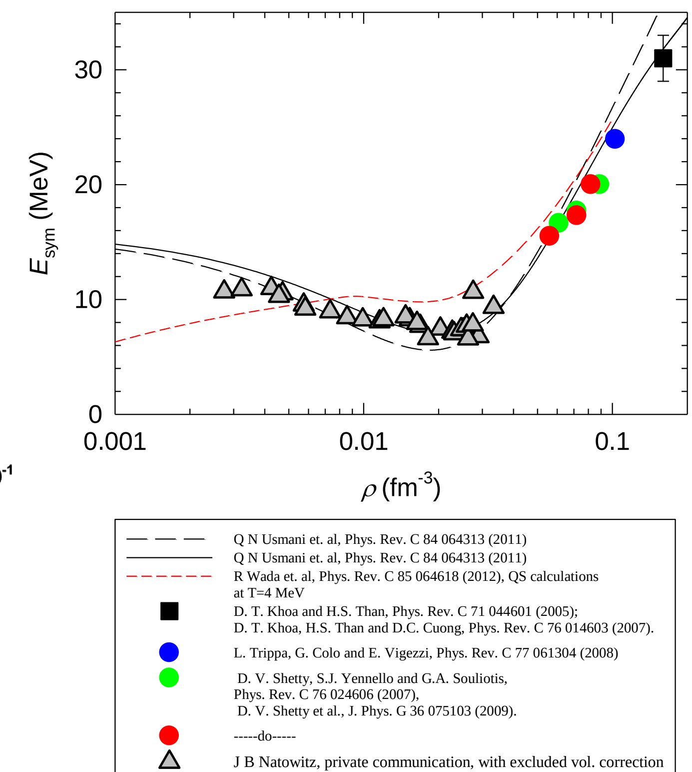
R. Wada et al.Phys. Rev. C 85, 064618 (2012)

At Low Density The Symmetry Energy is Determined by Cluster Formation. Analysis of Cluster Yield Ratios For Different N/Z Systems Allows Determination of The Symmetry Free Energy. Employment of Entropies Calculated with the QSM Model of Roepke, Typel et al (shown to be appropriate by other measured quantities) Allows Extraction of The LOW Density Symmetry Energy

$$F_{sym} + T \cdot S_{sym} = E_{sym}$$







S. Typel *et al.*, Phys. Rev. C 81, 015803 (2010).
See also
J.B. Natowitz et al., Phys.Rev.Lett.104:202501 (2010).

Symmetry Energy II: Isobaric Analog States

Paweł Danielewicz[1] and Jenny Lee[2]

arXiv:1307.4130 July 2013

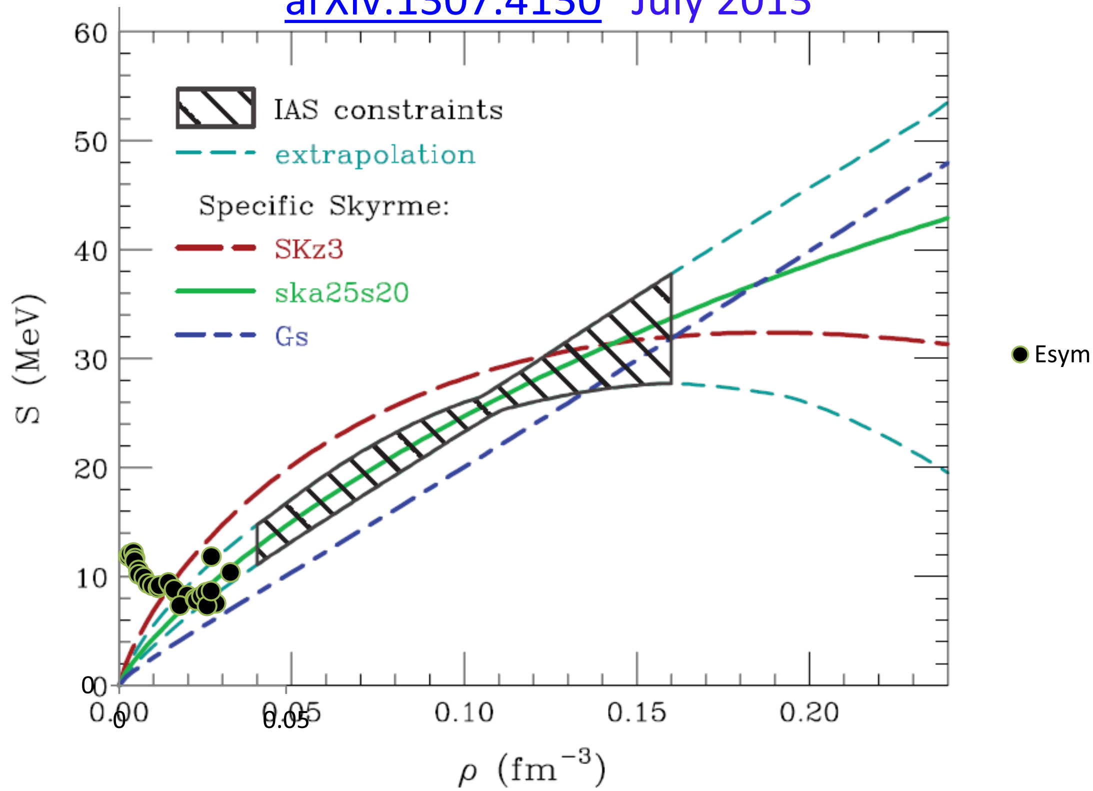
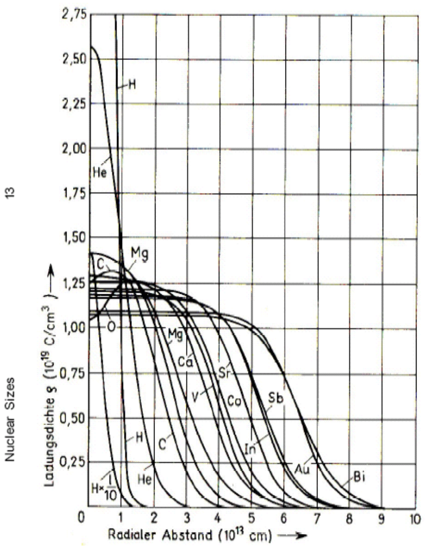


FIG. 15: Symmetry energy in uniform matter as a function of density. The hatched region represents IAS constraints. The short-dashed lines represent extrapolations of that region to supra-normal, $\rho > \rho_0$, and low, $\rho < \rho_0/4$, densities. The solid, long-dashed and short-long-dashed lines represent the symmetry energies for the three Skyrme parametrizations represented in Fig. 14 (with symmetry coefficients).

Clustering in the Skins of Leptodermous Systems

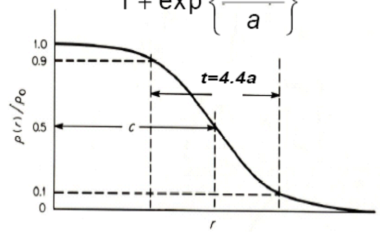
Nuclear Charge Distributions (e,e)



R. Hofstadter, Ann. Rev. Nucl. Sci. 7, 231 (1957)

Fermi Distribution

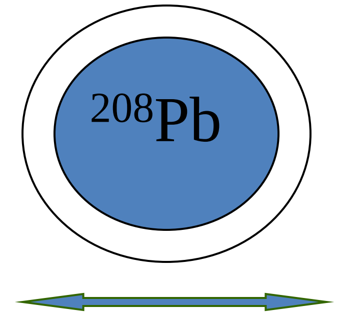
$$\rho(r) = \frac{\rho_0}{1 + \exp\left\{\frac{r - C}{a}\right\}}$$



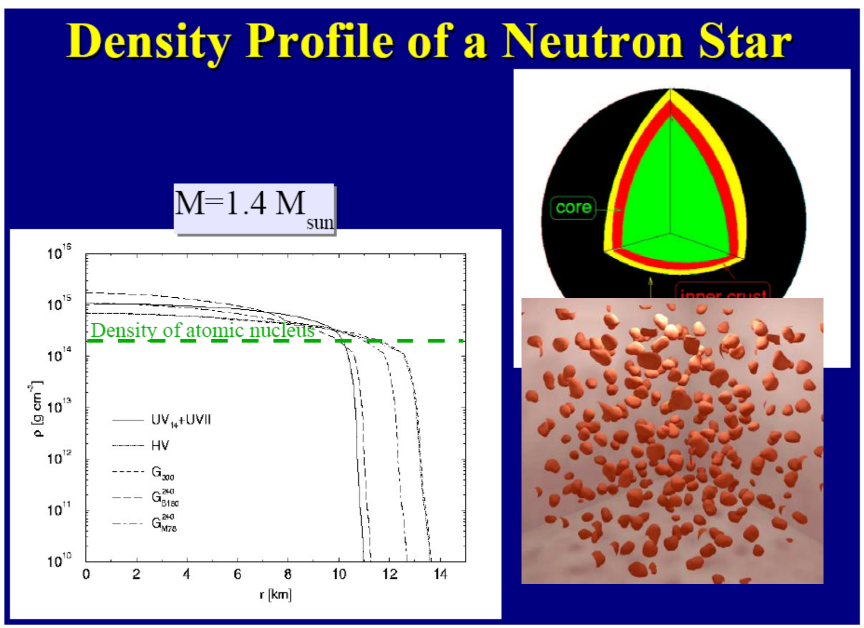
C: Half-density radius
a: Surface diffuseness
t: Surface thickness

Leptodermous: t « C

Holodermous : t ~ C



1.4 x 10 $^{-17}$ km



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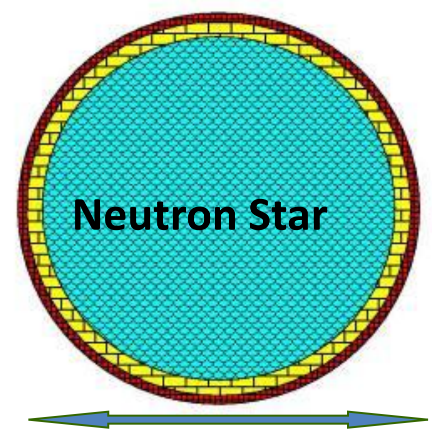
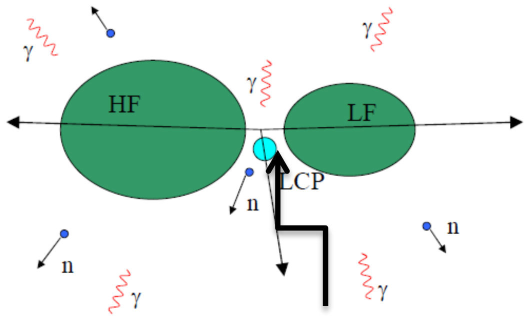


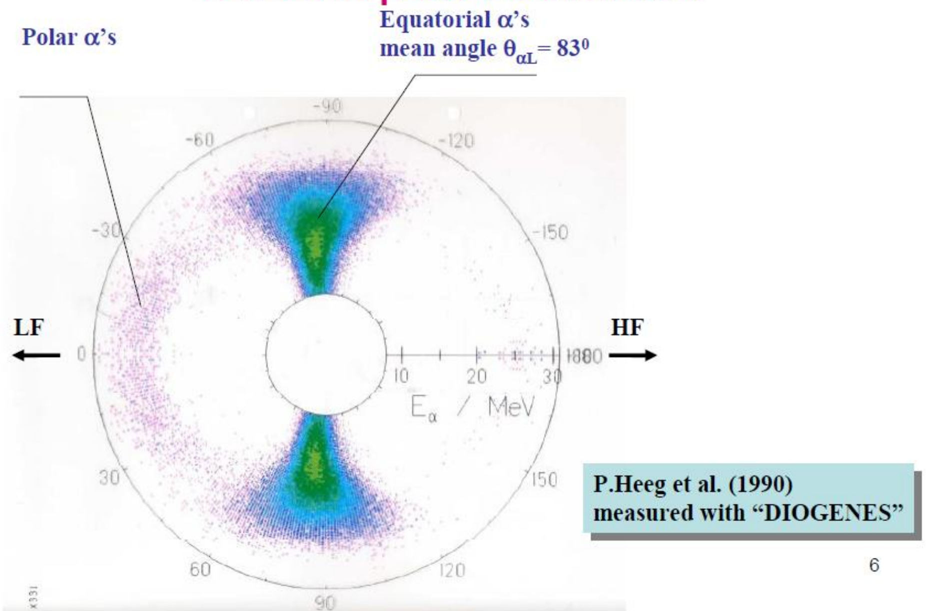
~ 20 km

Is Clusterization of Low Density Skins the Explanation for Light Particle Accompanied or "Ternary" Fission



Low Density At Scission Point

Angle-energy correlation for α-accompanied fission in polar coordinates.



252 Cf - Thesis T U Darmstadt

- LCP's are emitted nearly perpendicular to the fission axis
- > 90% of all ternary particles are α-particles
- Yields of heavier particles drastically decreases with the increase of LCP mass
- The energy distribution of LCP has nearly Gaussian shape with $\langle E_\alpha \rangle \approx 15$ MeV
- The emission of LCP slightly changes energy and mass distributions of fission fragments as well as other parameters, e.g. $\bar{\nu}$, M_γ etc.
- Ternary fission is a unique tool to study the energetics and dynamics of the fission process at scission.

Ternary fission Yields

- Thesis data of U. Koester, TU Berlin

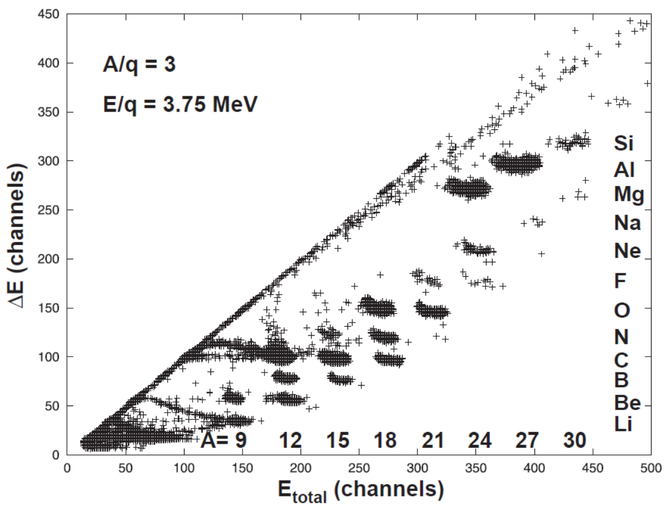
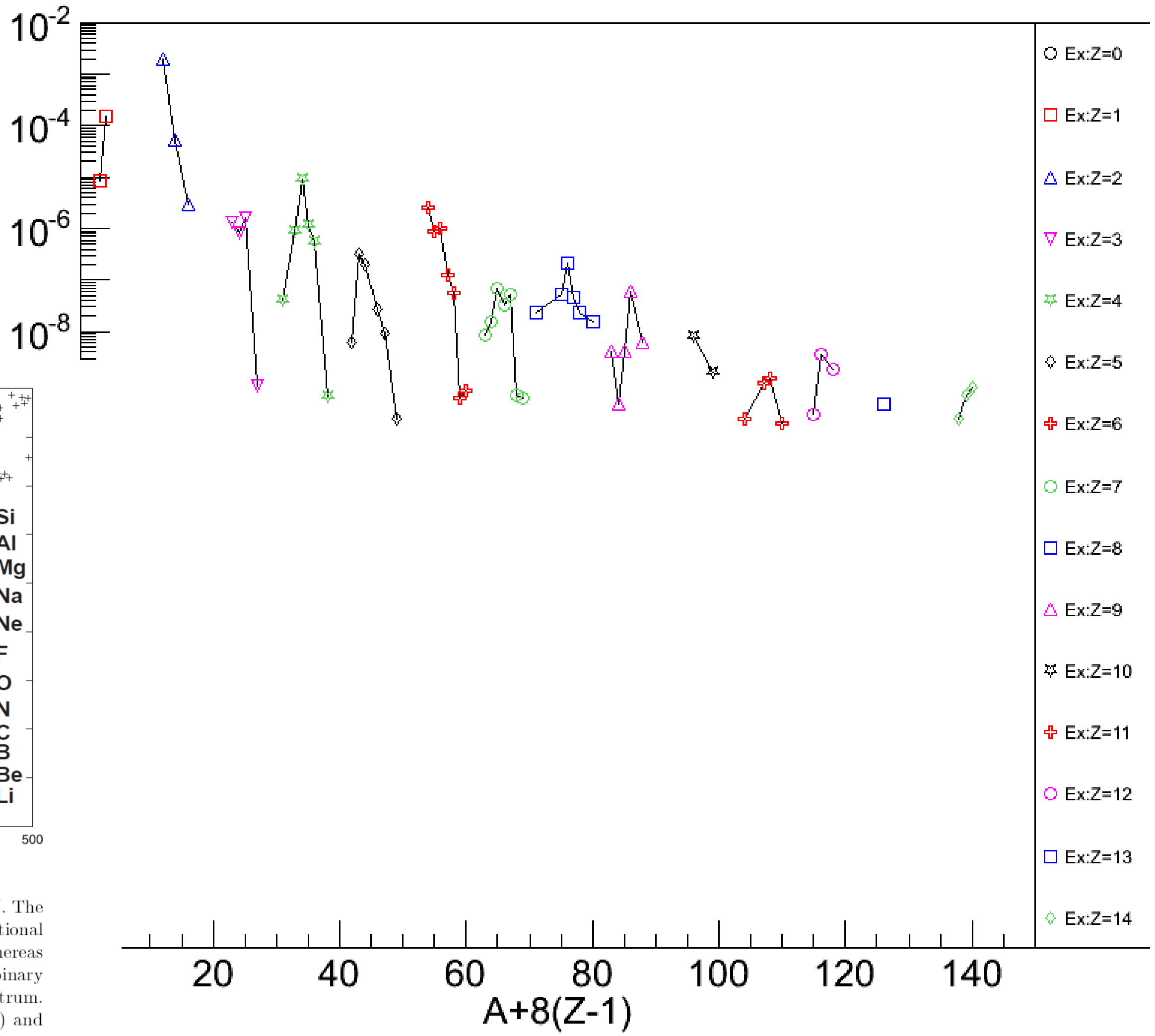
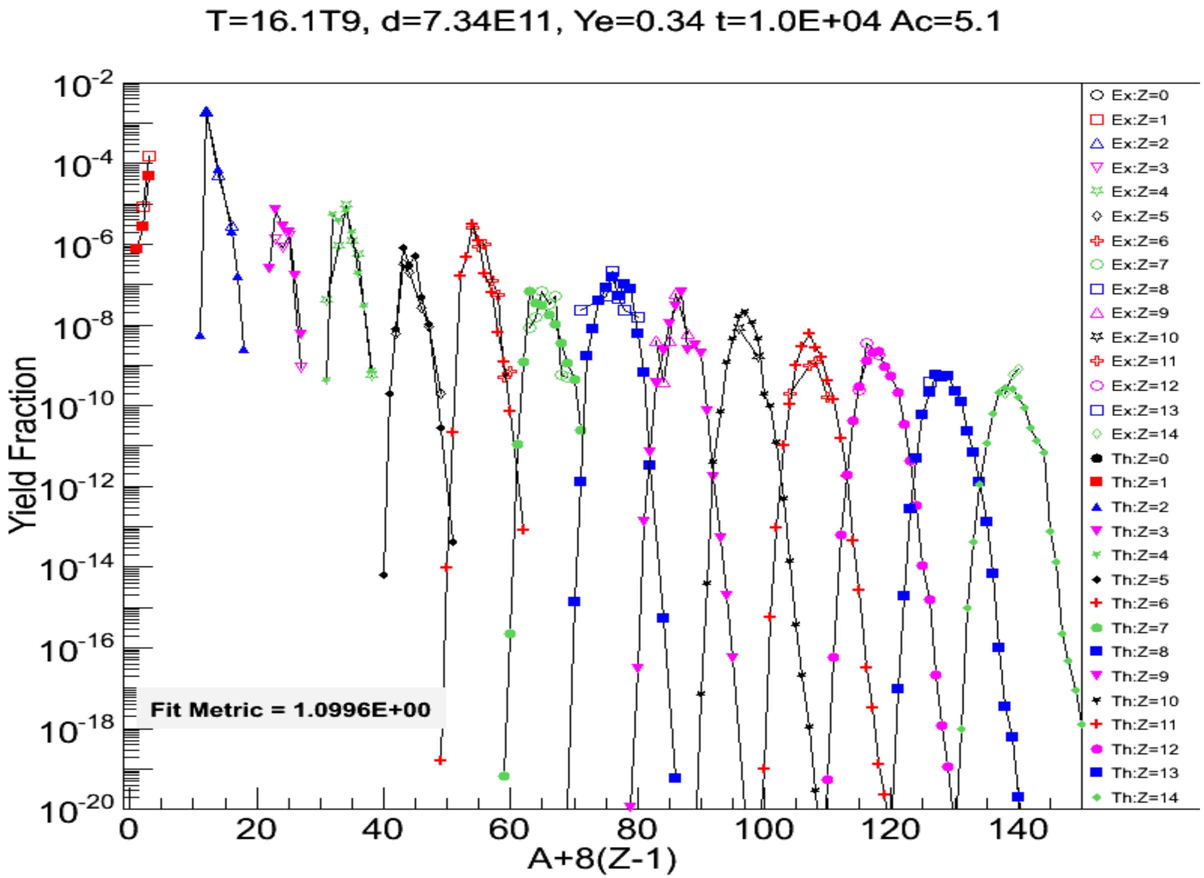


Fig. 3. ΔE-E-scatter plot with separator setting $A/q = 3$ and $E/q = 3.75$ MeV. The measurement time for this spectrum was 6.1 h. The horizontal scale is proportional to the particle energy (and due to a fixed A/E ratio also to the mass), whereas the vertical scale is roughly proportional to the nuclear charge Z. Scattered binary particles create background close to the diagonal in the upper part of the spectrum. Background in the lower part is due to pile-up (from abundant ^{3}H and ^{6}He) and particles scattered in the entrance window of the ionization chamber (tails going to the top and left which can be seen at ^{6}He, ^{9}Li and ^{12}C). One channel corresponds approximately to 75 keV.



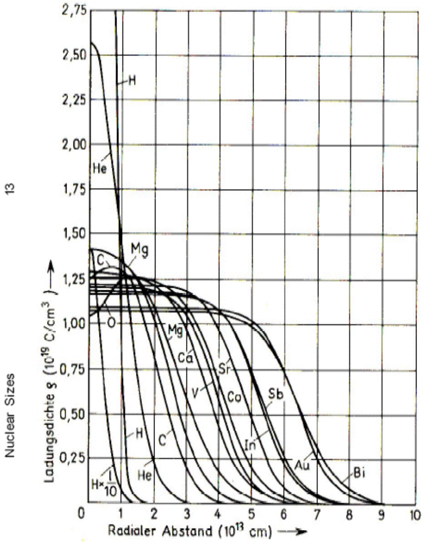
YIELD FIT
– Nuclear Statistical Equilibrium (B. Meyer, Clemson) Plus Time Dependent Nucleation (Demo et al.}



T = 1.38 MeV, Rho =4.6e-04 fm^{-3}, Yp = 0.34, t = 3 x10^{-20} sec

Clustering in the Skins of Leptodermous Systems

Nuclear Charge Distributions (e,e)



R. Hofstadter, Ann. Rev. Nucl. Sci. 7, 231 (1957)

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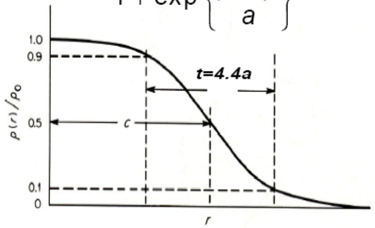
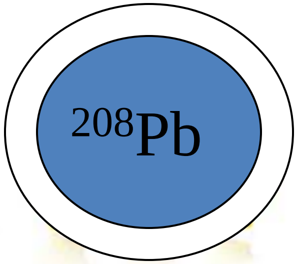


C: Half-density radius
a: Surface diffuseness
t: Surface thickness

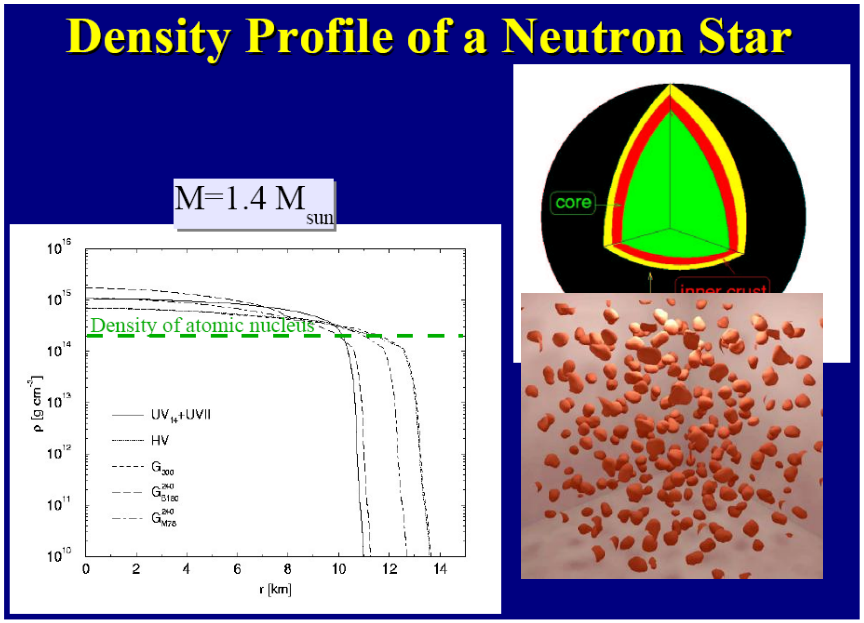
Leptodermous: t « C

Holodermous : t ~ C

PASTINA



1.4 x 10 $^{-17}$ km



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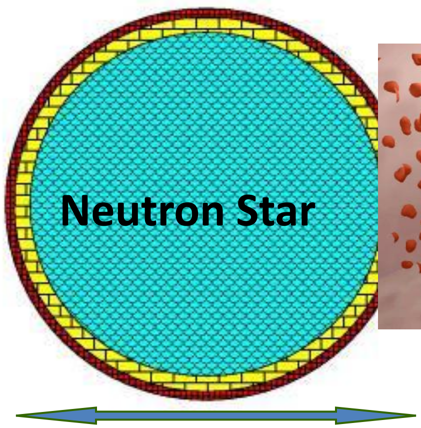
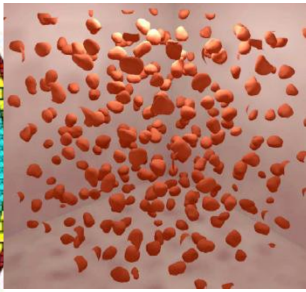




~ 20 km

A Comment -NEUTRON SKINS AND SYMMETRY ENERGY

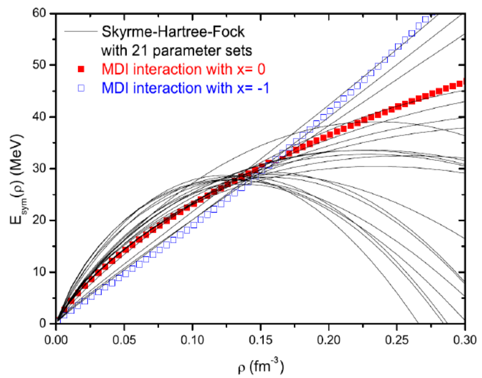
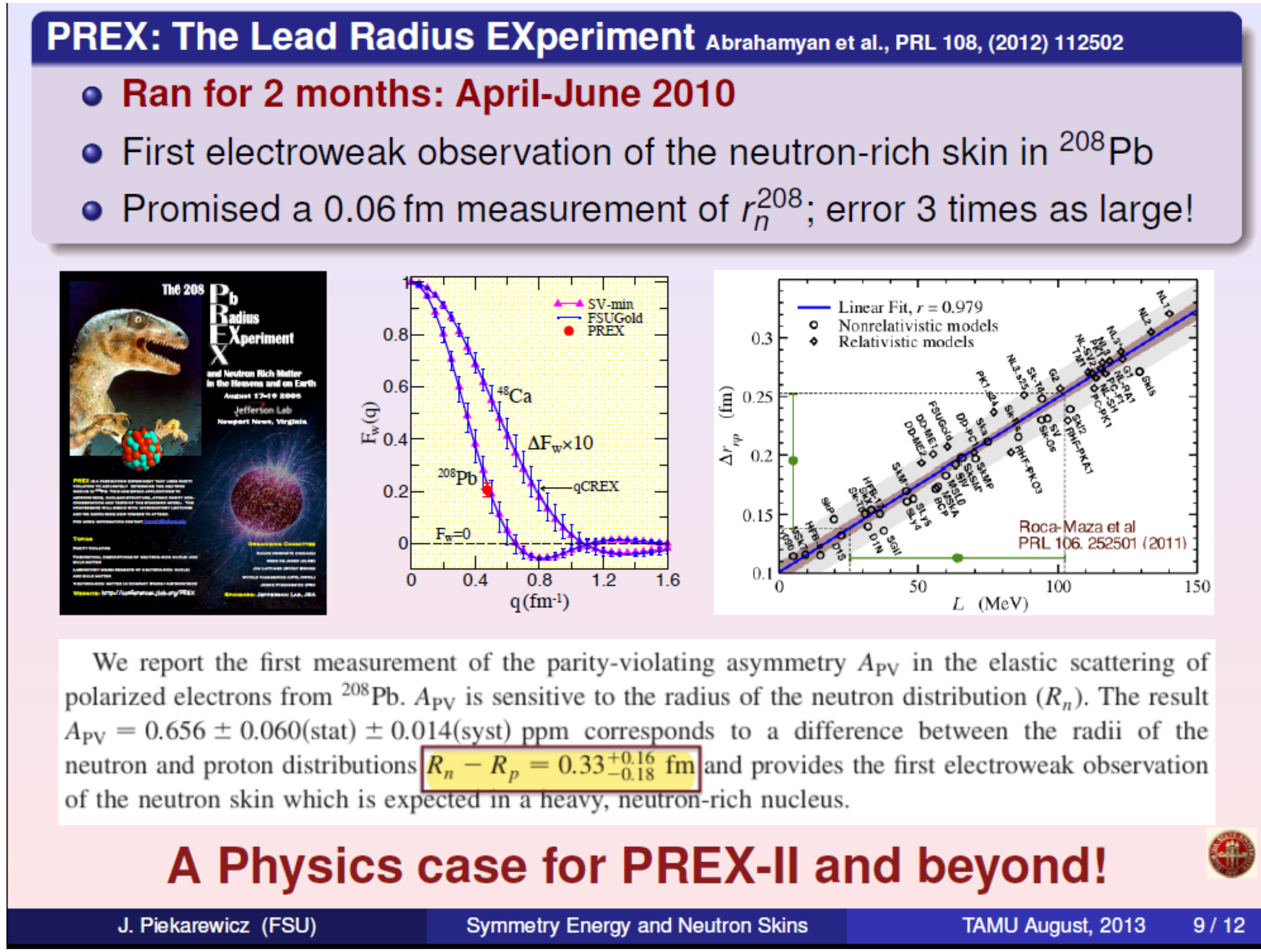


Fig. 3. Density dependence of the symmetry energy predicated by various interactions.



Does clustering affect the neutron skin thickness and Hence the determination of symmetry energy slope at normal density?

- **Summary**

For near symmetric nuclear matter at densities ~.03≤ $\rho/\rho_0 \leq 0.2$ We

- **Measured Alpha Mass Fractions, Equilibrium constants-Tested Astrophysical Equations of State**

- **Determined Density dependence of Binding energies - Extracted Mott Points**

- **Determined Symmetry Free Energies-Symmetry Energy Coefficients**

- **Found Good overall agreement with model which includes clusterization and in-medium effects on clusters.**

- **For Ternary Fission we are exploring a NSE Model Approach based on clustering in the nuclear skin- Low Density at Lower Temperature**
- **Thank You**

Collaborators

K. Hagel, R. Wada, K. Schmidt, S. Wuenschel, E. J. Kim, M. Barbui, G. Giuliani, L. Qin, S. Shlomo, A. Bonasera, G. Röpke, S. Typel, Z. Chen, M. Huang, J. Wang, H. Zheng, S. Kowalski, M. R. D. Rodrigues, D. Fabris, M. Lunardon, S. Moretto, G. Nebbia, S. Pesente, V. Rizzi, G. Viesti, M. Cinausero, G. Prete, T.Keutgen, Y. El Masri, Z. Majka, Y. G. Ma and J. B. Natowitz,