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Clusters in Heavy-Ion Collisions and its Effects on the Symmetry Energy

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- Nuclear Matter EOS and the Symmetry Energy (Esym)
- Clustering Effects on Esym
- Coalescence Production of Clusters in Heavy-Ion Collisions as a Probe of Density Fluctuations
- Summary

International Workshop on "Challenges to Transport Theory for Heavy-Ion Collisions", ECT*/Trento, Italy, May 10-24, 2019

Outline

- Nuclear Matter EOS and the Symmetry Energy (Esym)
- Clustering Effects on Esym
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The Symmetry Energy of Nuclear Matter

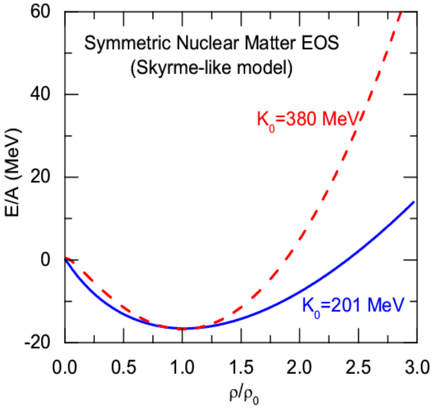
EOS of Isospin Asymmetric Nuclear Matter (Parabolic law)

$$E(\rho,\delta) = E(\rho,0) + E_{\rm sym}(\rho)\delta^2 + O(\delta^4), \quad \delta = (\rho_n - \rho_p)/\rho$$

Symmetric Nuclear Matter (relatively well-determined)

Symmetry energy term (largely uncertain)

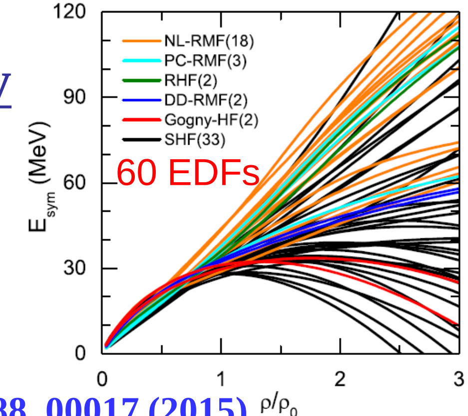
Isospin asymmetry



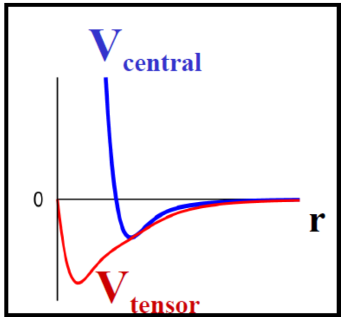
Nuclear Matter Symmetry Energy

$$\boxed{E_{\rm sym}(\rho) \equiv \frac{1}{2}\frac{\partial^2 E(\rho,\delta)}{\partial \delta^2}}$$

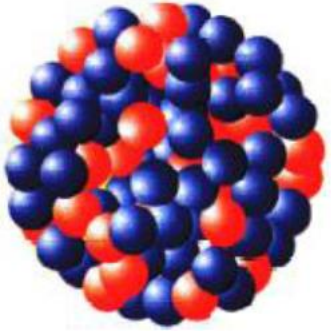
Saturation: $\rho_0 \approx 0.16\ \mathrm{fm}^{-3}$



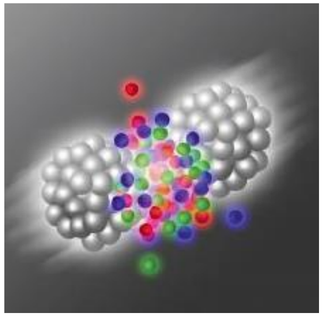
LWC, EPJ Web of Conf. 88, 00017 (2015)



Nature of the nuclear force?



Structure and stability of nuclei?



Dynamics of heavy ion collisions?

Nature of compact stars and dense nuclear matter?

Characteristic Parameters of Nuclear Matter

PHYSICAL REVIEW C **80**, 014322 (2009)

Higher-order effects on the incompressibility of isospin asymmetric nuclear matter

Lie-Wen Chen,[1,2] Bao-Jun Cai,[1] Che Ming Ko,[3] Bao-An Li,[4] Chun Shen,[1] and Jun Xu[3]
[1] *Department of Physics, Shanghai Jiao Tong University, Shanghai 200240, People's Republic of China*
[2] *Center of Theoretical Nuclear Physics, National Laboratory of Heavy Ion Accelerator, Lanzhou 730000, People's Republic of China*
[3] *Cyclotron Institute and Physics Department, Texas A&M University, College Station, Texas 77843-3366, USA*
[4] *Department of Physics, Texas A&M University-Commerce, Commerce, Texas 75429-3011, USA*
(Received 27 May 2009; published 30 July 2009)

$$E(\rho,\delta) = E_0(\rho) + E_{\rm sym}(\rho)\delta^2 + E_{{\rm sym},4}(\rho)\delta^4 + O(\delta^6)$$

$$E_0(\rho) = E_0(\rho_0) + \frac{K_0}{2!}\chi^2 + \frac{J_0}{3!}\chi^3 + \frac{I_0}{4!}\chi^4 + O(\chi^5)$$

$$\chi = \frac{\rho-\rho_0}{3\rho_0}$$

$$E_{\rm sym}(\rho) = E_{\rm sym}(\rho_0) + L\chi + \frac{K_{\rm sym}}{2!}\chi^2 + \frac{J_{\rm sym}}{3!}\chi^3 + \frac{I_{\rm sym}}{4!}\chi^4 + O(\chi^5)$$

$$E_{{\rm sym},4}(\rho) = E_{{\rm sym},4}(\rho_0) + L_{{\rm sym},4}\chi + \frac{K_{{\rm sym},4}}{2}\chi^2 + \frac{J_{{\rm sym},4}}{3!}\chi^3 + \frac{I_{{\rm sym},4}}{4!}\chi^4 + O(\chi^5)$$

Order of the characteristic parameters according to the expansion with χ and δ:

Order-0: $E_0(\rho_0)$; Order-2: K_0, $E_{sym}(\rho_0)$;

Order-3: J_0, L; Order-4: $K_{sym}(\rho_0)$, I_0, $E_{sym,4}(\rho_0)$

Characteristic Parameters of Nuclear Matter

Order of the characteristic parameters according to the expansion with χ and δ:

Order-0: $E_0(\rho_0)$; Order-2: K_0, $E_{sym}(\rho_0)$;

Order-3: J_0, L; Order-4: $K_{sym}(\rho_0)$, I_0, $E_{sym,4}(\rho_0)$

Order-0 → $E_0(\rho_0)$ = -16±1 MeV

Order-2 → K_0 = 230±20 MeV, $E_{sym}(\rho_0)$ = 32.5±2.5 MeV

Order-3 → L = 55±25 MeV, J_0=???

Order-4 → $K_{sym}(\rho_0)$=???, I_0=???, $E_{sym,4}(\rho_0)$ =???

Order-5 → ??????

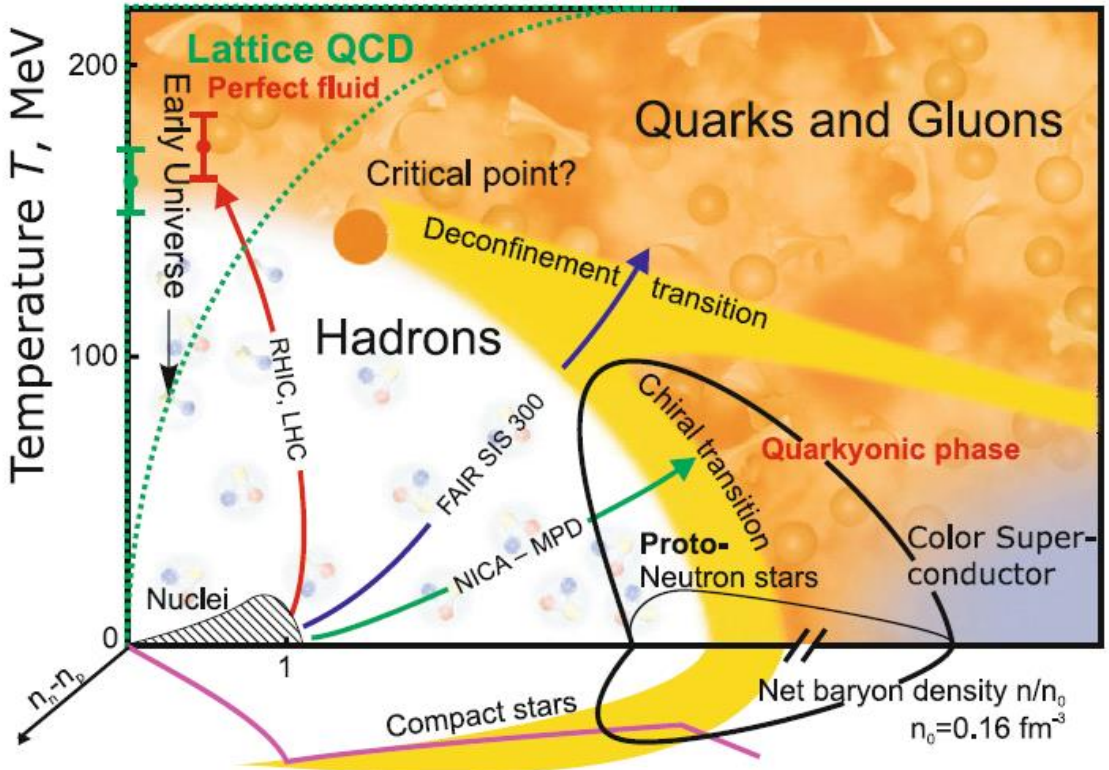
……

- **$J_0 \approx$ -408.5 +/- 66.5 MeV and $K_{sym} \approx$ -118.5 +/- 84.5 MeV:**
  Data of finite nuclei + Flow Data in HIC + Observed NStar Largest Mass + Tidal Deformability of Neutron Star (from recent GW170817 signal) analyzed simultaneously within the same EDF – extended SHF
  (Y. Zhou/LWC/Z. Zhang, arXiv:1901.11364, PRD(RC), in press)

Phase Diagram of Strong Interaction Matter

QCD Phase Diagram in 3D: density, temperature, and isospin

V.E. Fortov, Extreme States of Matter – on Earth and in the Cosmos, Springer-Verlag Berlin Heidelberg 2011



Esym: Important for understanding the EOS of strong interaction matter and QCD phase transitions at extreme isospin conditions

1. Heavy Ion Collisions (Terrestrial Lab);
2. Compact Stars(In Heaven); …

Quark Matter Symmetry Energy ?

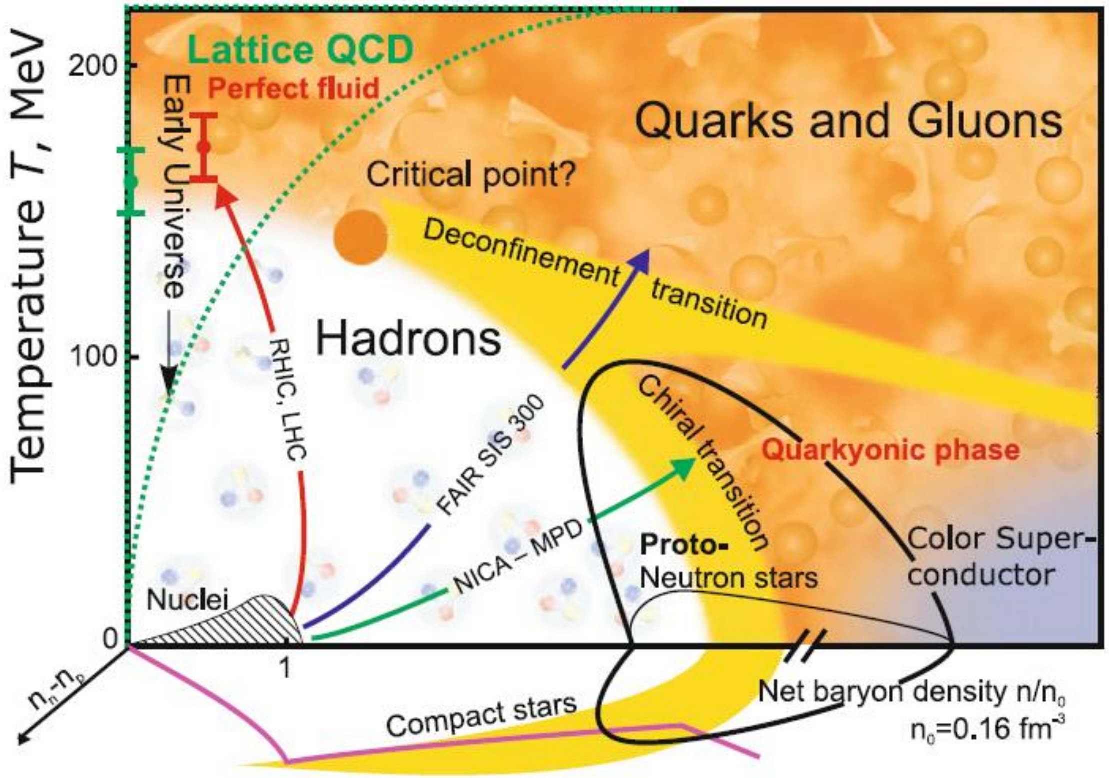
M. Di Toro et al., NPA775 (2006); Pagliara/Schaffner-Bielich, PRD81, (2010); Shao et al., PRD85,(2012); Chu/Chen, ApJ780 (2014); H. Liu et al., PRD94 (2016); Xia/Xu/Zong, (2016); LWC, arXiv:1708.04433

At extremely high baryon density, the matter could be the deconfined quark matter, and there we should consider quark matter symmetry energy (isospin symmetry is still satisfied). The isopsin asymmetric quark matter could be produced/exist in HIC/Compact Stars

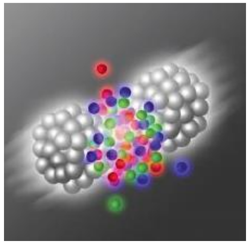
Phase Diagram of Strong Interaction Matter

QCD Phase Diagram in 3D: density, temperature, and isospin

V.E. Fortov, Extreme States of Matter – on Earth and in the Cosmos, Springer-Verlag Berlin Heidelberg 2011

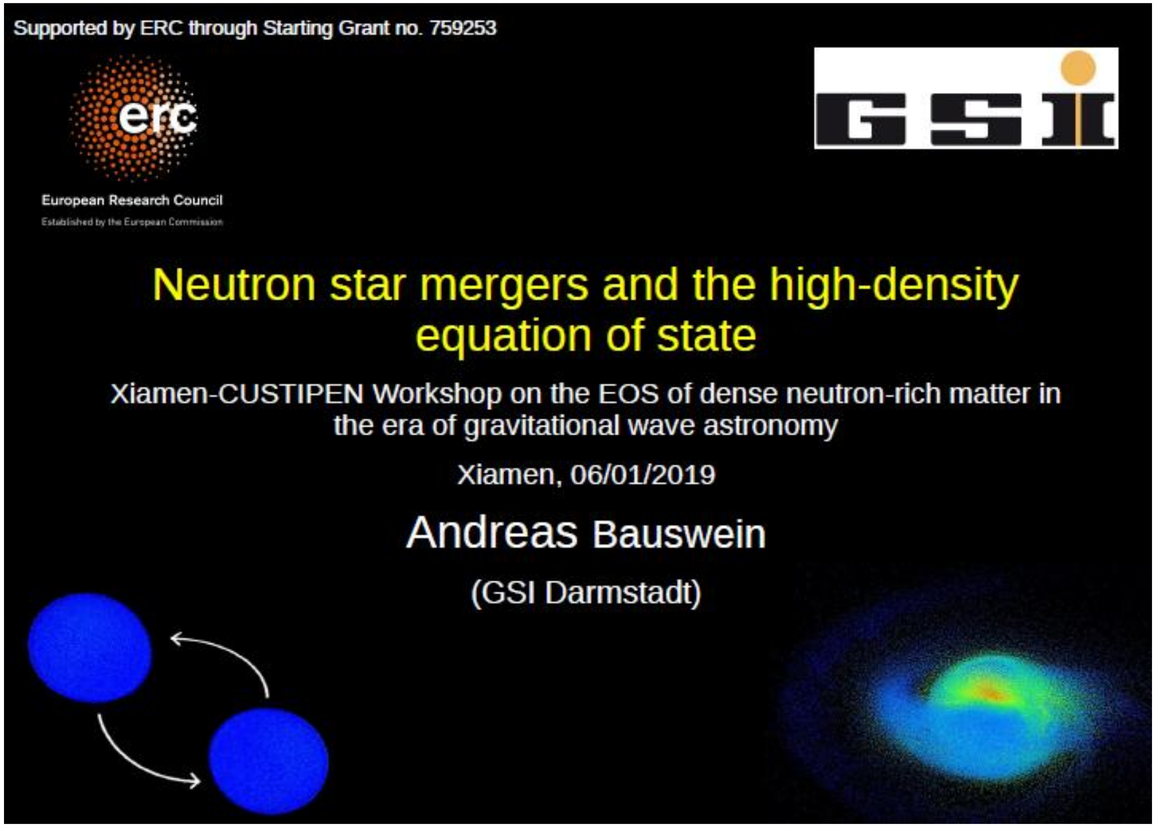


Probing QCD phase diagram in Heavy Ion Collisions in terrestrial labs and in NStar-NStar Collisions (Merger) in heaven?



- **Small baryon chemical potential: Smooth Crossover Transition**
- **Large baryon chemical potential: First-order Phase Transition**
- **QCD Critical Endpoint: where the first-order phase transition ends**

n_B and T in binary neutron star merger



The maximum baryon density in binary neutron star merger could reach more than ~$10\rho_0$ and temperature ~50 MeV but with large isospin density!

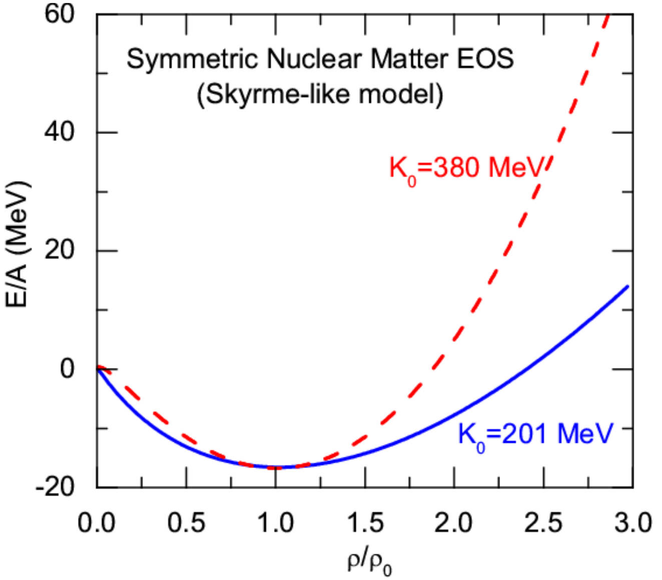
See also: Elias R. Most et al., PRL122, 061101 (2019)
Andreas Bauswein et al., PRL122, 061102 (2019)

The high density Esym of nuclear/quark matter is particularly important for NS mergers!

EOS of Symmetric Nuclear Matter

(1) EOS of symmetric matter around the saturation density ρ_0

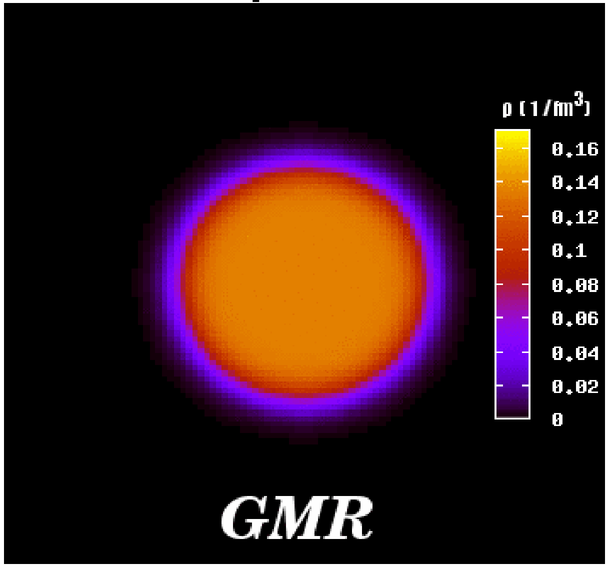
$$E_0(\rho) = E_0(\rho_0) + \frac{K_0}{2!}\chi^2 + \frac{J_0}{3!}\chi^3 + \mathcal{O}(\chi^4) \quad \chi = \frac{\rho - \rho_0}{3\rho_0}$$



Incompressibility:

$$K_0 = 9\rho_0^2 \left(\frac{d^2E}{d\rho^2}\right)_{\rho_0}$$

Giant Monopole Resonance



Frequency $f_{GMR} \propto \sqrt{K_0}$

K_0=231±5 MeV
Youngblood/Clark/Lui, PRL82, 691 (1999)

Recent results:

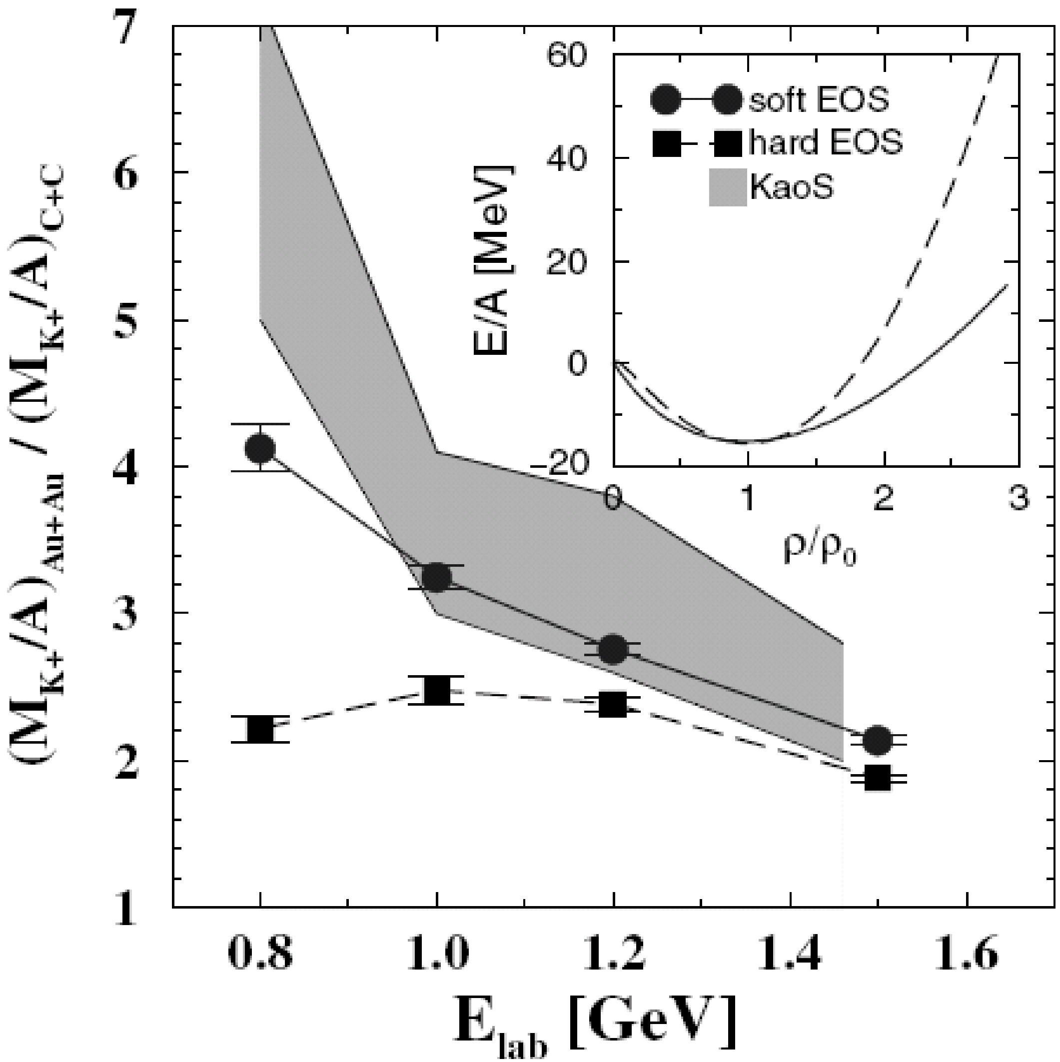
K_0=230±20 MeV

G. Colo, U. Garg,
J. Margueron,
J. Piekarewicz,
H. Sagawa, S. Shlomo et al.

Uncertainty of the extracted K_0 is mainly due to the uncertainty of *L* (slope parameter of the symmetry energy) and m^*_0 (isoscalar nucleon effective mass)
(See, e.g., LWC/J.Z. Gu, JPG39, 035104(2012))

EOS of Symmetric Nuclear Matter

(2) EOS of symmetric matter for $1\rho_0 < \rho < 3\rho_0$ from K^+ production in HIC's



J. Aichelin and C.M. Ko, PRL55, (1985) 2661

C. Fuchs, Prog. Part. Nucl. Phys. 56, (2006) 1

C. Fuchs et al, PRL86, (2001) 1974

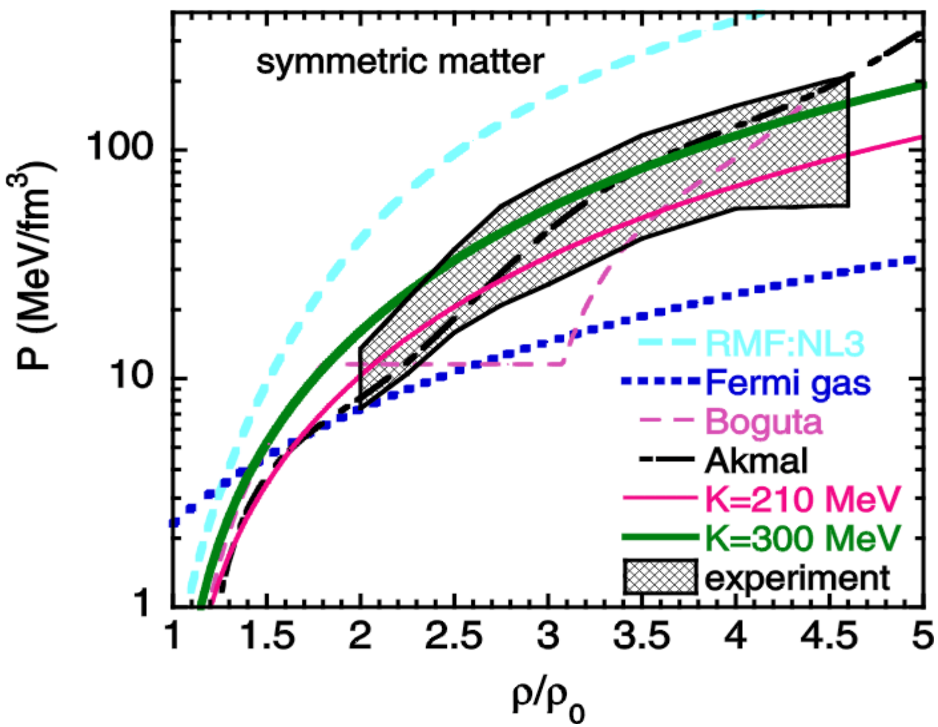
Transport calculations indicate that "results for the K^+ excitation function in Au + Au over C + C reactions as measured by the KaoS Collaboration strongly support the scenario with a soft EOS."

See also: C. Hartnack, H. Oeschler, and J. Aichelin, PRL96, 012302 (2006)

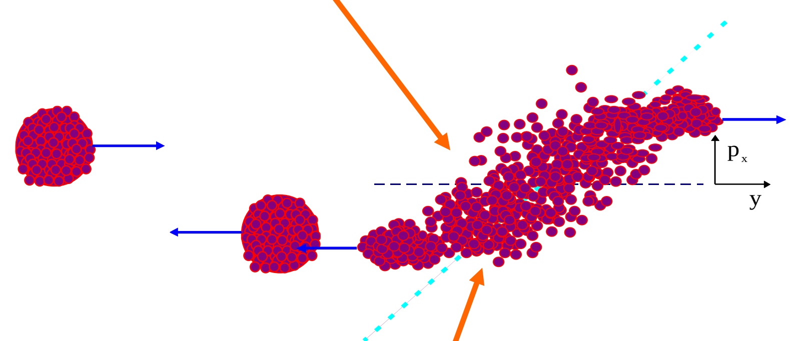
EOS of Symmetric Nuclear Matter

(3) Constraints on the EOS of symmetric nuclear matter for $2\rho_0 < \rho < 5\rho_0$ using flow data from BEVALAC, SIS/GSI and AGS

P. Danielewicz, R. Lacey and W.G. Lynch, Science 298, 1592 (2002)



The highest pressure recorded under laboratory controlled conditions in nucleus-nucleus collisions



High density nuclear matter 2 to $5\rho_0$

$$\text{Pressure } P(\rho) = \rho^2 \left(\frac{\partial E}{\partial \rho} \right)_s$$

- Use constrained mean fields to predict the EOS for symmetric matter
  - Width of pressure domain reflects uncertainties in comparison and of assumed momentum dependence.

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Esym: Experimental Probes

Promising Probes of the $E_{sym}(\rho)$ (an incomplete list !)

At sub-saturation densities (亚饱和密度行为)

- Sizes of n-skins of unstable nuclei from total reaction cross sections
- Proton-nucleus elastic scattering in inverse kinematics
- Parity violating electron scattering studies of the n-skin in ^{208}Pb
- n/p ratio of FAST, pre-equilibrium nucleons
- Isospin fractionation and isoscaling in nuclear multifragmentation
- Isospin diffusion/transport
- Neutron-proton differential flow
- Neutron-proton correlation functions at low relative momenta
- $t/^3He$ ratio
- Hard photon production
- Pigmy/Giant resonances
- Nucleon optical potential

Towards high densities reachable at CSR/Lanzhou, FAIR/GSI, RIKEN, GANIL and, FRIB/MSU (高密度行为)

- π^-/π^+ ratio, K^+/K^0 ratio?
- Neutron-proton differential transverse flow
- n/p ratio at mid-rapidity
- Nucleon elliptical flow at high transverse momenta
- n/p ratio of squeeze-out emission

B.A. Li, L.W. Chen, C.M. Ko Phys. Rep. 464, 113(2008)

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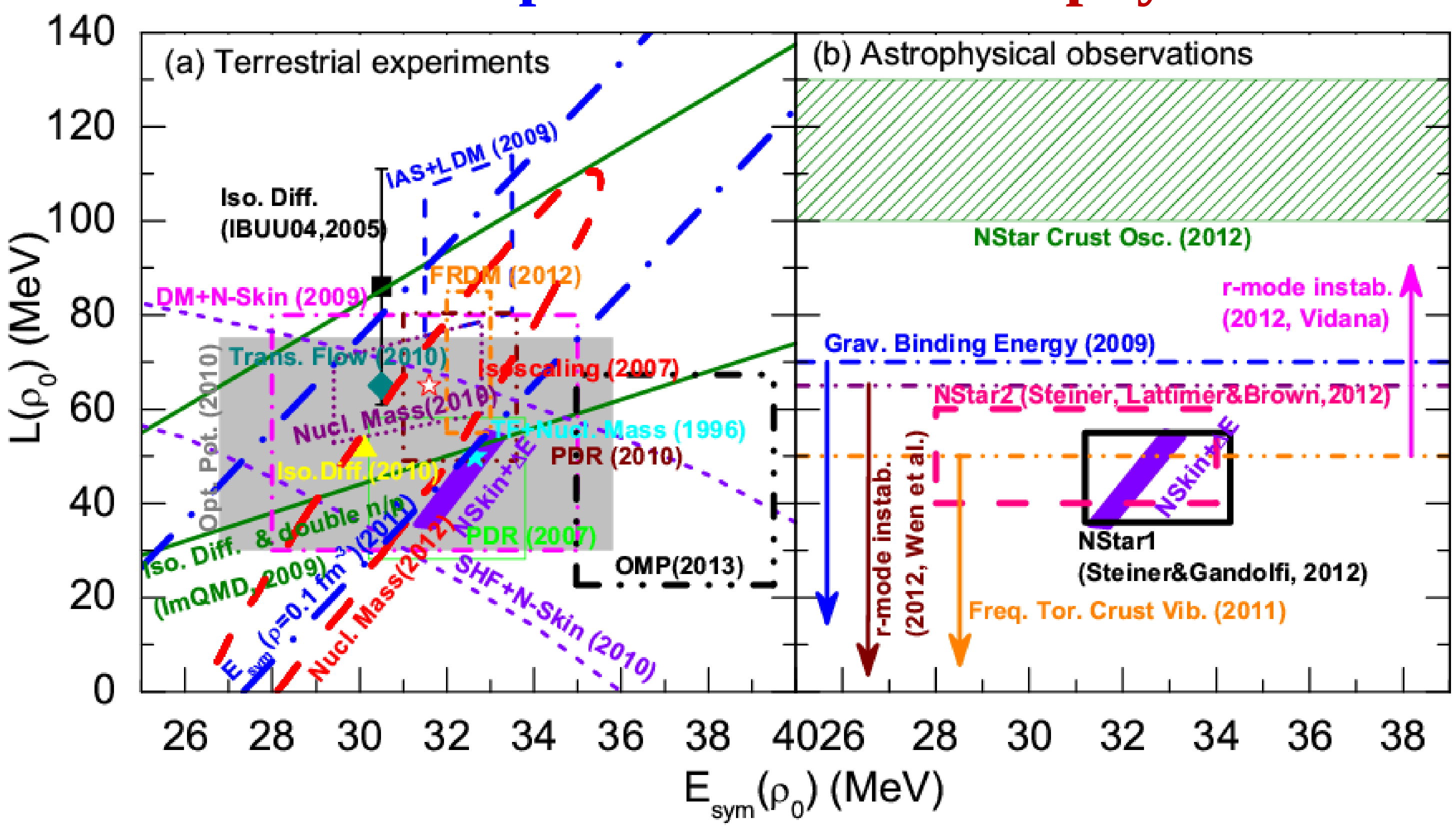
E_{sym}: Around saturation density

Current constraints (An incomplete list) on E_{sym} (ρ_0) and L from terrestrial experiments and astrophysical observations



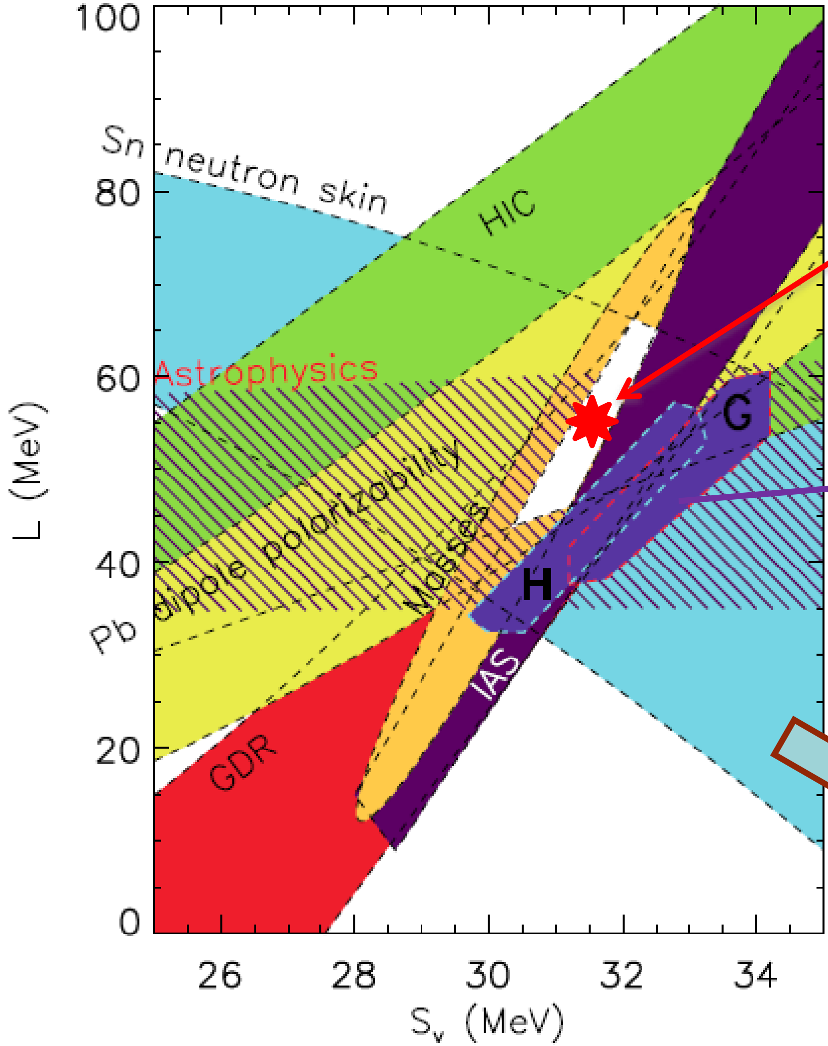
L and $E_{sym}(\rho_0)$ are usually correlated because the observables are usually probing the Esym NOT at saturation density !!!

$E_{sym}(\rho_0)$ = 32.5±2.5 MeV, L = 55±25 MeV

L.W. Chen, Nucl. Phys. Rev. (原子核物理评论) 31, 273 (2014) [arXiv:1212.0284]
B.A. Li, L.W. Chen, F.J. Fattoyev, W.G. Newton, and C. Xu, arXiv:1212.1178

E_{sym}: Around saturation density

Jim Lattimer and Andrew Steiner using 6 out of approximately 30 available constraints



The centroid is around
S_v=31MeV and L=55 MeV

Microscopic calculations (H/G) do not include higher-order contribution? EOS of SNM?

Chen/Ko/Li/Xu, PRC82, 024321 (2010)

Why? Zhang/Chen, PLB726, 234 (2013)

Neutron skin is actually determined by L(0.11 fm^{-3}) rather than L(0.16 fm^{-3})

0.11 fm^{-3} ~ Average density of Heavy Nuclei

J.M. Lattimer and A.W. Steiner, EPJA50, (2014) 40

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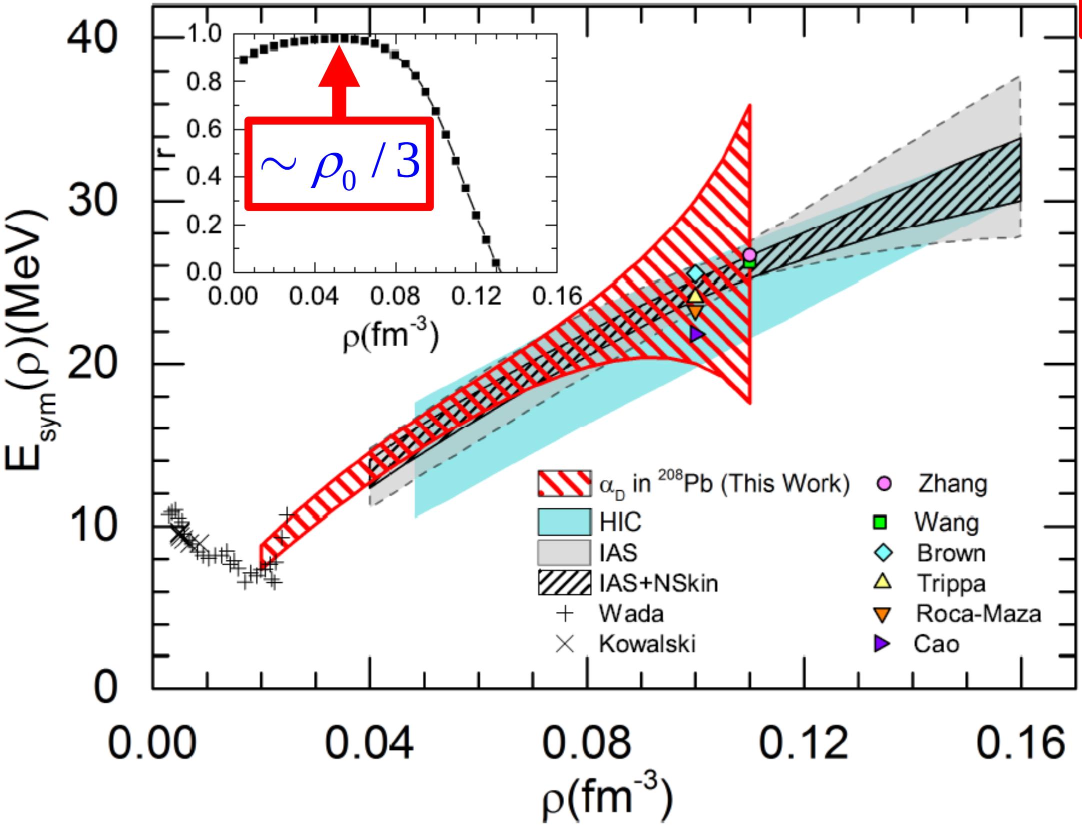
E_{sym}: Subsaturation densities

Z. Zhang and LWC, PRC92, 031301(R) (2015)

$\bullet\Delta E(A\sim 208)\propto E_{sym}(\rho_{A=208}),\ \rho_{A=208}\approx 2/3\rho_0$

$\bullet 1/\alpha_D(A=208)\propto E_{sym}(\rho_{A=45}),\ \rho_{A=45}\approx 1/3\rho_0$



- HIC: Sn+Sn
  M.B. Tsang *et al.*, Phys. Rev. Lett.**102**, 122701(2009)
- IAS and IAS+NSkin
  P. Danielewicz and J. Lee, Nucl. Phys. **A922**, 1 (2014)
- Zhang: Isotope binding energy difference
  Z. Zhang and L.W. Chen, Phys. Lett. **B726**, 234 (2013)
- Wang: Fermi energy difference
  N. Wang *et al.*, Phys. Rev. C **87**, 034327 (2013)
- Brown: Doubly magic nuclei
  B.A. Brown, Phys. Rev. Lett. **11**, 232502 (2013)
- Trippa: Giant dipole resonance
  L. Trippa *et al.*, Phys. Rev. C **77**
- Roca-Maza: Giant quadrupole resonance
  X. Roca-Maza *et al.*, Phys. Rev. C **87**, 034301 (2013)
- Cao: Pygmy dipole resonance
  L.G. Cao and Z.Y. Ma, Chin. Phys. Lett. **25**, 1625 (2008)

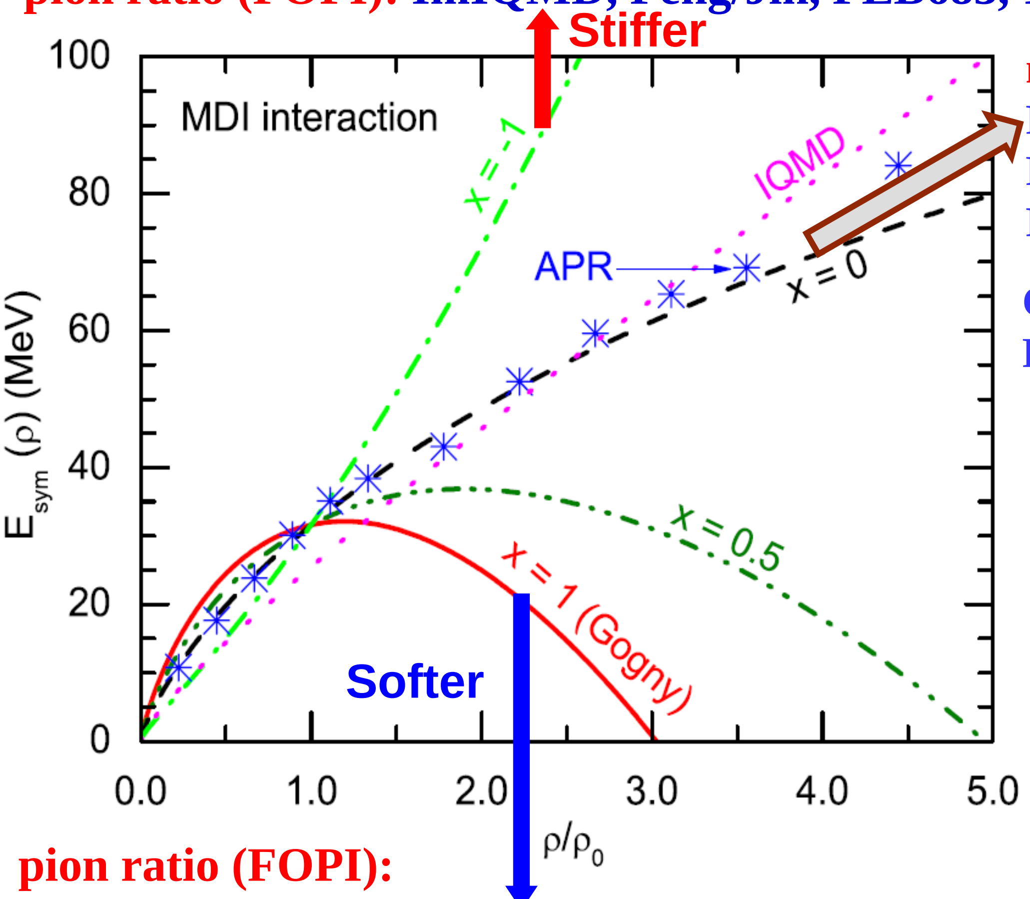
Wada and Kowalski: experimental results of the symmetry energies at densities below $0.2\rho_0$ and temperatures in the range 3 ~11 MeV from the analysis of cluster formation in heavy ion collisions.

Wada et al., Phys. Rev. C85, (2012) 064618; Kowlski et al., Phys. Rev. C75, (2007) 014601.
Natowitz et al., Phys. Rev. Lett. 104, (2010) 202501.

E_{sym}: Supra-saturation density

A Soft or Stiff Esym at supra-saturation densities ???

pion ratio (FOPI): ImIQMD, Feng/Jin, PLB683, 140(2010)



n/p v2 (FOPI): $\boxed{(\rho/\rho_0)^\gamma \text{ with } \gamma = 0.9 \pm 0.4}$

Russotto/Trauntmann/Li et al.,
PLB697, 471(2011) (UrQMD)
PRC94, 034608 (2016) $\boxed{\gamma = 0.72 \pm 0.19}$

Cozma/Trauntmann/Li et al.,
PRC88, 044912 (2013) (Tubingen QMD - MDI)

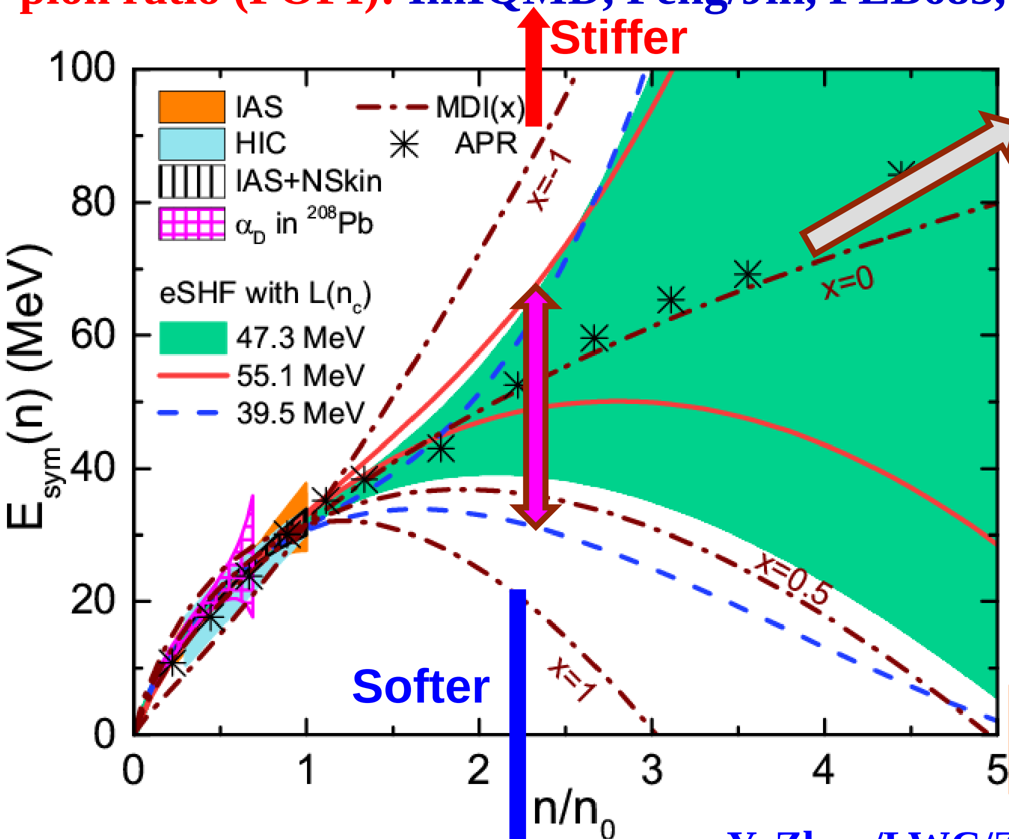
pion ratio (FOPI):
IBUU04, Xiao/Li/Chen/Yong/Zhang, PRL102,062502(2009)
ImIBLE, Xie/Su/Zhu/Zhang, PLB718,1510(2013)

Pion Medium Effects?
Threshold effects?
Δ resonances?
……
Xu/Ko/Oh
PRC81, 024910(2010)
Xu/Chen/Ko/Li/Ma
PRC87, 067601(2013)
Hong/Danielewicz,
PRC90, 024605 (2014)
Song/Ko, PRC91, 014901 (2015)

E_{sym}: Supra-saturation density

A Soft or Stiff Esym at supra-saturation densities ???

pion ratio (FOPI): ImIQMD, Feng/Jin, PLB683, 140(2010)



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Data of finite nuclei + Flow Data in HIC + Observed NStar Largest Mass +Tidal Deformability of Neutron Star (from recent GW170817 signal) analyzed simultaneously within the same EDF – extended SHF

Equation of state of dense matter in the multimessenger era

Ying Zhou,[1] Lie-Wen Chen,[1,*] and Zhen Zhang[2]

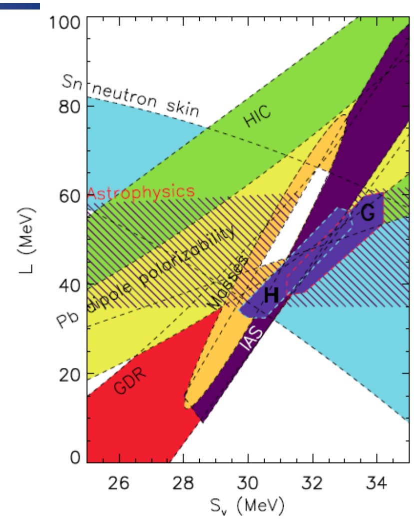
Y. Zhou/LWC/Z. Zhang, arXiv:1901.11364, PRD(RC), in press

pion ratio (FOPI):
IBUU04, Xiao/Li/Chen/Yong/Zhang, PRL102,062502(2009)
ImIBLE, Xie/Su/Zhu/Zhang, PLB718,1510(2013)

E_{sym}: Current Status

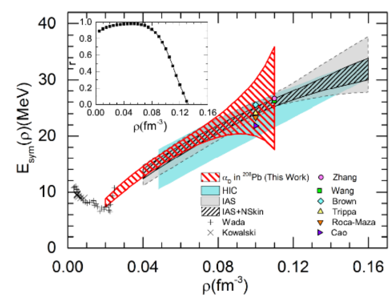
● There are MANY constraints on E_{sym} (ρ_0) and L, essentially all the constraints seem to agree with:

$$E_{sym}(\rho_0) = 32.5 \pm 2.5 \text{ MeV}$$
$$L = 55 \pm 25 \text{ MeV}$$



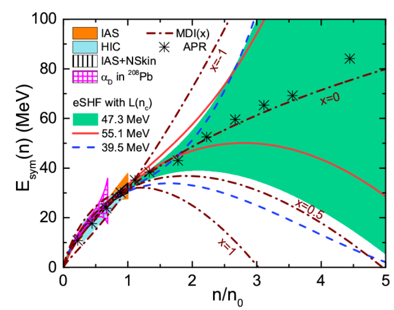
Lattimer/Steiner, EPJA50, 40 (2014)

● The symmetry energy at subsaturation densities have been relatively well-constrained



Z. Zhang/LWC, PLB726, 234 (2013); PRC92, 031301(R)(2015)

●Based on the multimessenger measurements, the high density Esym cannot be too stiff or too soft but still with large uncertainty!!!



Y. Zhou/LWC/Z. Zhang, arXiv:1901.11364, PRD(RC), in press

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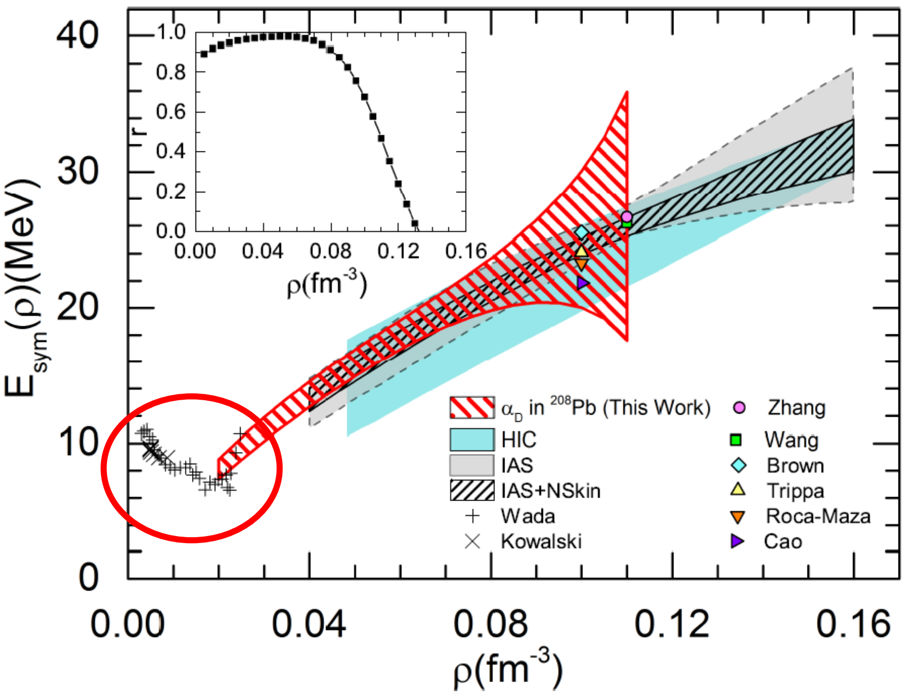
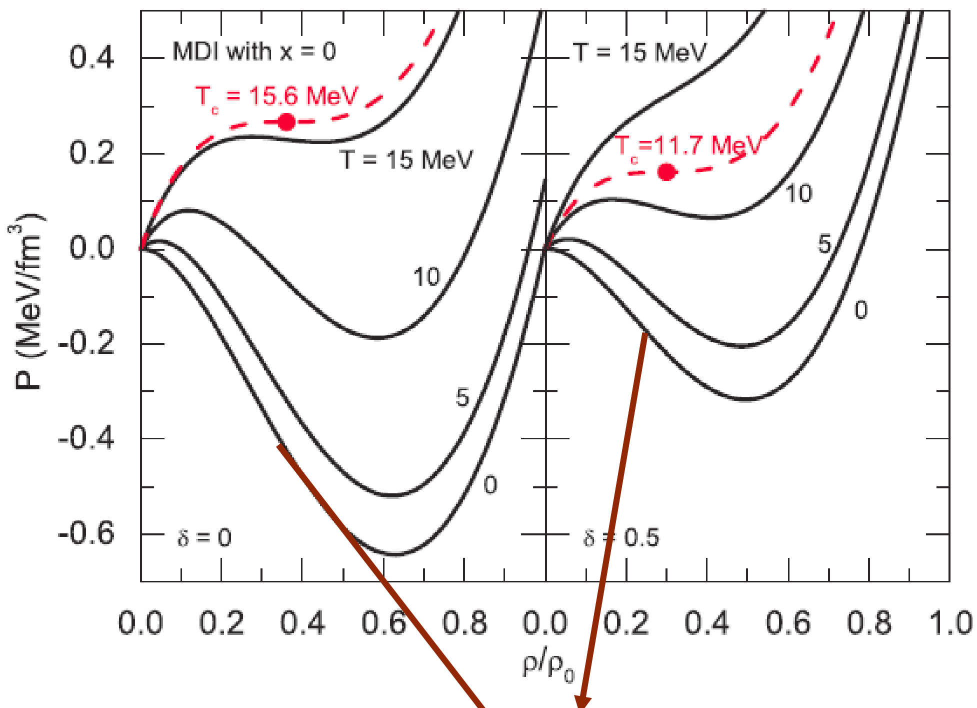
Clustering Effects on E_{sym}

Z. Zhang/LWC, PRC92, 031301(R)(2015)



Xu/Chen/Li/Ma, PRC77, 014302(2008)



All constraints are based on mean-field models without considering clustering which could be important for symmetric nuclear matter at low densities!

Spinodal instability

⇩

Clustering

⇩

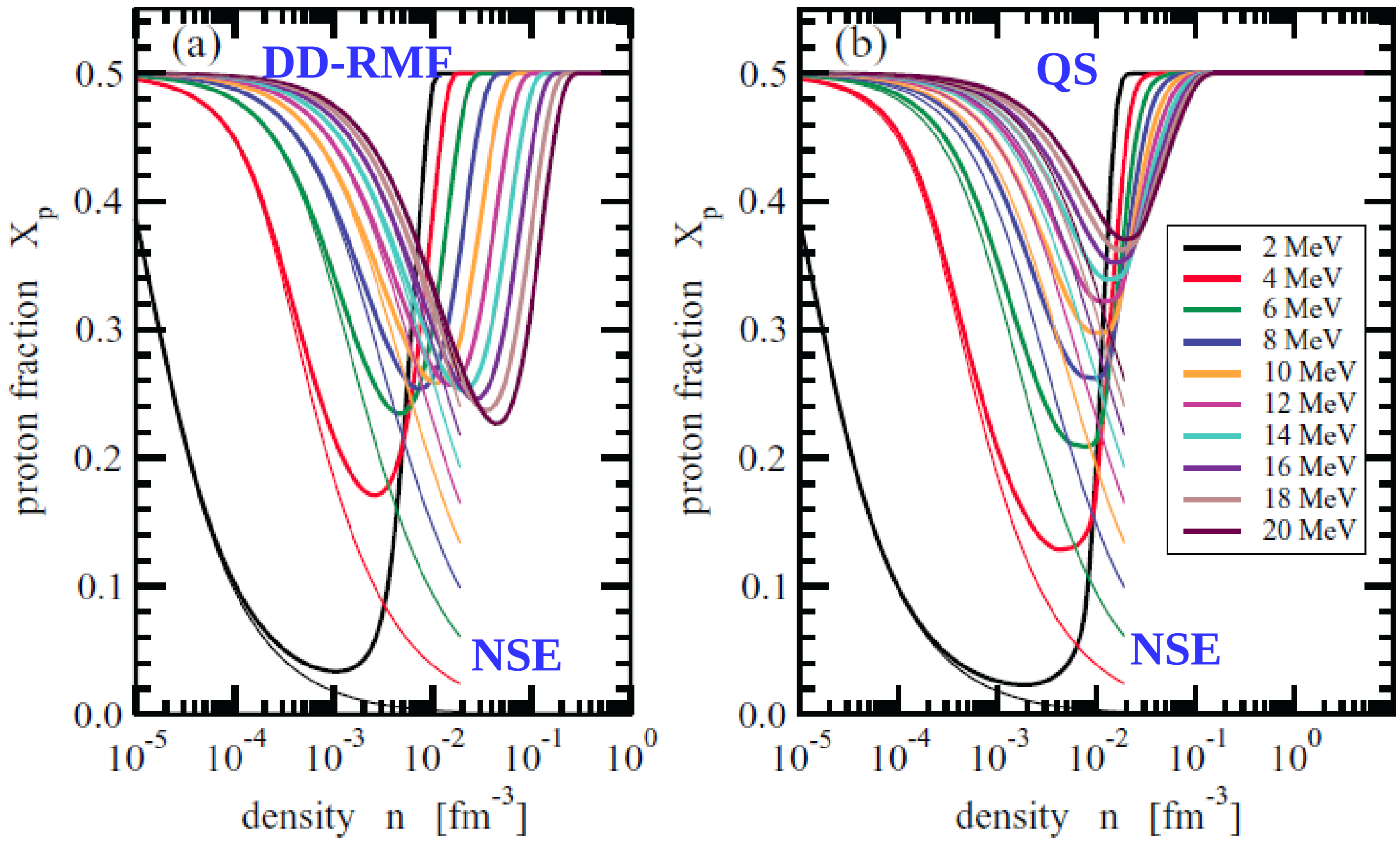
The critical density depends on the temperature and isospin asymmetry

Clustering Effects in Nuclear Matter

PHYSICAL REVIEW C **81**, 015803 (2010)

Composition and thermodynamics of nuclear matter with light clusters

S. Typel,[1,2,*] G. Röpke,[3,†] T. Klähn,[4,5,‡] D. Blaschke,[5,6,§] and H. H. Wolter[7,‖]



- **The clustering effects depend on the temperature and densities**
- **At low temperature (T<2 MeV), the clustering is essential only at very low densities (<0.02 fm^{-3})**

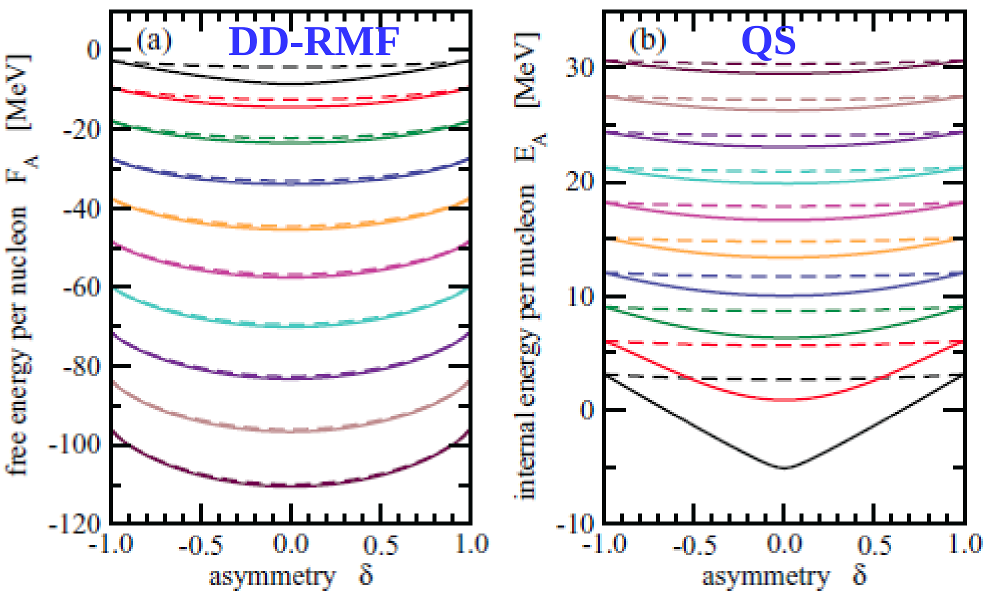
Clustering Effects on E_{sym}

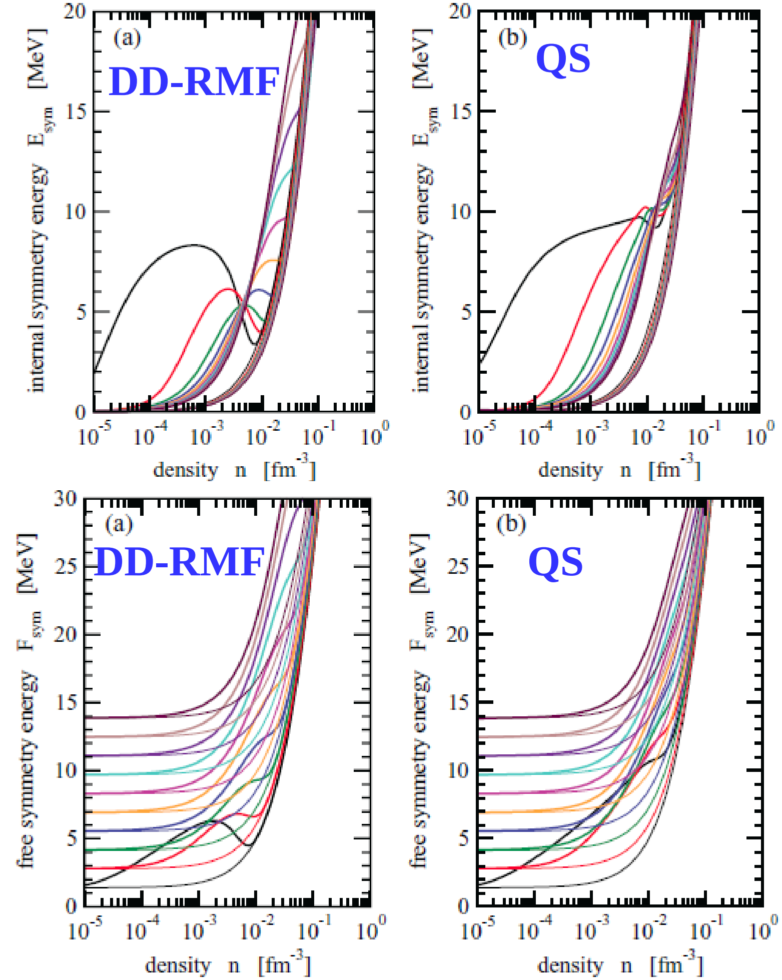
PHYSICAL REVIEW C **81**, 015803 (2010)

Composition and thermodynamics of nuclear matter with light clusters

S. Typel,[1,2,*] G. Röpke,[3,†] T. Klähn,[4,5,‡] D. Blaschke,[5,6,§] and H. H. Wolter[7,‖]

0.001 fm^{-3}





- **The parabolic approximation is bad (the δ expansion is NOT convergent) at low T**

$$E_{sym}(n,T) = \frac{1}{2}[E_A(n,1,T) - 2E_A(n,0,T) + E_A(n,-1,T)],$$

Clustering Effects in Nuclear Matter

Generalized Nonlinear RMF (gNL-RMF) for nuclear matter with light clusters

$$\mathcal{L} = \sum_{j=p,n,t,h} \mathcal{L}_j + \mathcal{L}_\alpha + \mathcal{L}_d + \mathcal{L}_\sigma + \mathcal{L}_\omega + \mathcal{L}_\rho + \mathcal{L}_{\omega\rho},$$

Zhao-Wen Zhang and LWC, PRC95, 064330 (2017)

where the fermions are described as

$$\mathcal{L}_j = \bar{\Psi}_j \left[\gamma_\mu i D_j^\mu - M_j^*\right] \Psi_j,$$

the α particles and the deuterons Lagrangian densities are

$$\mathcal{L}_\alpha = \frac{1}{2}\left(iD_\alpha^\mu \phi_\alpha\right)^* \left(iD_{\mu\alpha}\phi_\alpha\right) - \frac{1}{2}\phi_\alpha^* \left(M_\alpha^*\right)^2 \phi_\alpha,$$

$$\mathcal{L}_d = \frac{1}{4}\left(iD_d^\mu \phi_d^\nu - iD_d^\nu \phi_d^\mu\right)^* \left(iD_{d\mu}\phi_{d\mu} - iD_{d\nu}\phi_{d\nu}\right) - \frac{1}{2}\phi_d^{\mu *} \left(M_d^*\right)^2 \phi_{d\mu},$$

with

$$iD_j^\mu = i\partial^\mu - g_\omega^j \omega^\mu - \frac{g_\rho^j}{2}\vec{\tau} \cdot \vec{\rho}^\mu,$$

$$M_j^* = M_j - g_\sigma^j \sigma, \quad j = p, n, \alpha, d, t, h.$$

The effective mass of clusters are related by the binding energy by

$$M_i = A_i m - B_i,$$

DD-RMF (S. Typel et al.)

⇓

NL-RMF

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Binding energy of clusters:

- binding energy

$$M_i = A_i m - B_i^0 - \Delta B_i$$

- dependence of density

$$\Delta B_i(n,T) = -\tilde{n}_i\left(1+\frac{\tilde{n}_i}{2\tilde{n}_i^0}\right)\delta B_i(T), \qquad \tilde{n}_i = \frac{2}{A_i}\left[Z_i n_p^{tot} + N_i n_n^{tot}\right]$$

- dependence of temperature

$$\tilde{n}_i^0(T) = \frac{B_i^0}{\delta B_i(T)}$$

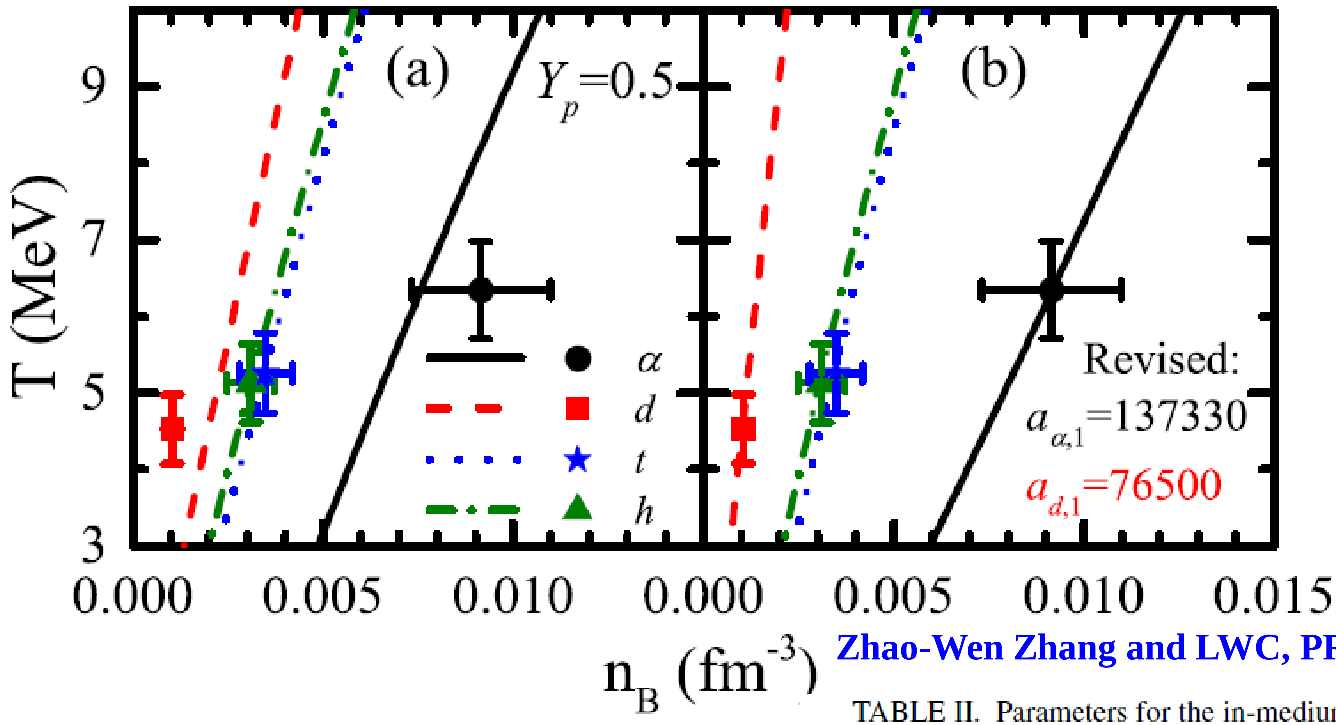
- Jastrow approach

$$\delta B_d(T) = \frac{a_{d,1}}{T^{3/2}}\left[\frac{1}{\sqrt{y_d}} - \sqrt{\pi}a_{d,3}\exp\left(a_{d,3}^2 y_d\right)\mathrm{erfc}\left(a_{d,3}\sqrt{y_d}\right)\right], \qquad y_d = 1 + a_{d,2}/T$$

- Gaussian approach

$$\delta B_i(T) = \frac{a_{i,1}}{\left(T+a_{i,2}\right)^{3/2}}, \qquad i = \alpha, t, h$$

Mott points



Zhao-Wen Zhang and LWC, PRC95, 064330 (2017)

TABLE II. Parameters for the in-medium cluster binding energy shifts. The values are taken from Ref. [11] and the values of $a_{\alpha,1}$ and $a_{d,1}$ in the parentheses are the revised values in the present work to fit the experimental Mott densities [47].

Cluster i	$a_{i,1}$ (MeV$^{5/2}$ fm^3)	$a_{i,2}$ (MeV)	$a_{i,3}$ (MeV)	B_i^0 (MeV)
α	164371 (137330)	10.6701		28.29566
d	38386.4 (76500)	22.5204	0.2223	2.224566
t	69516.2	7.49232		8.481798
h	58442.5	6.07718		7.718043

The binding energy of clusters depend on T and n_B

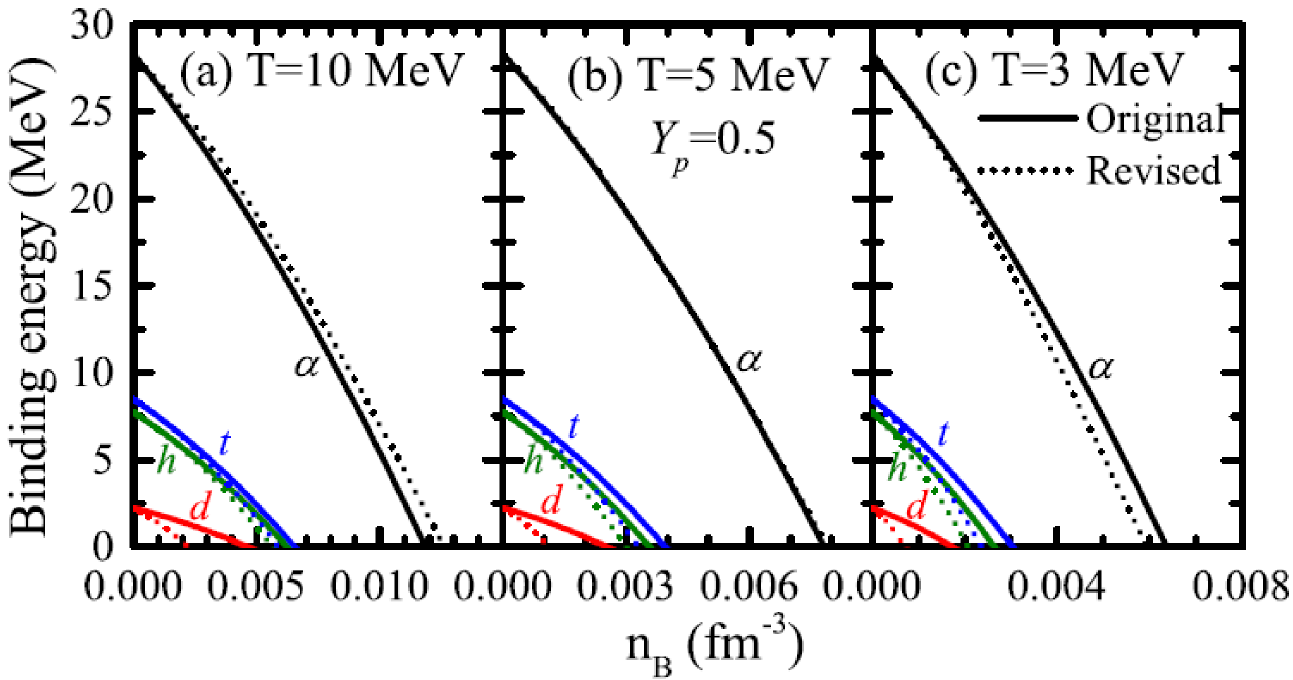
Mott Point: Binding energy vanish

Data of Mott points:

K. Hagel et al., Phys. Rev. Lett. 108, 062702 (2012)

Mott points

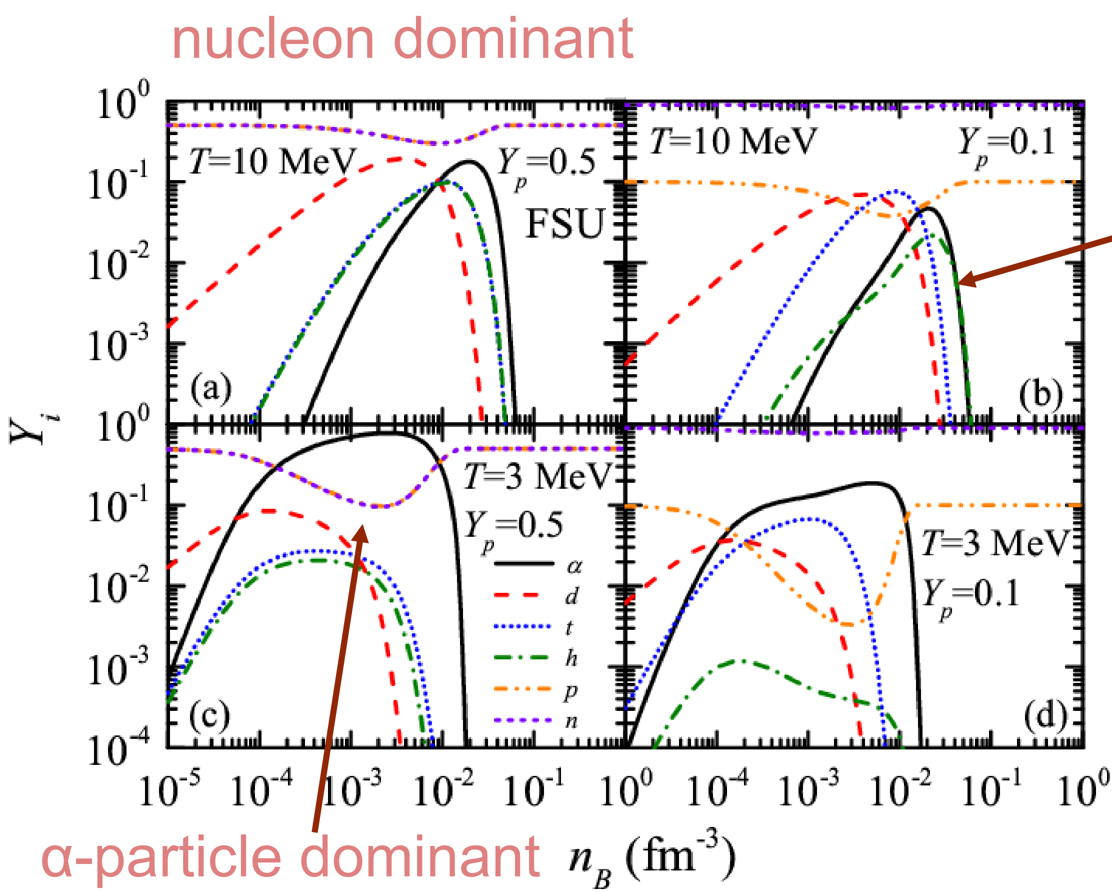
Zhao-Wen Zhang and LWC, PRC95, 064330 (2017)



The binding energy of clusters depend on T and n_B

Mott Point: Binding energy vanish

Fraction of clusters

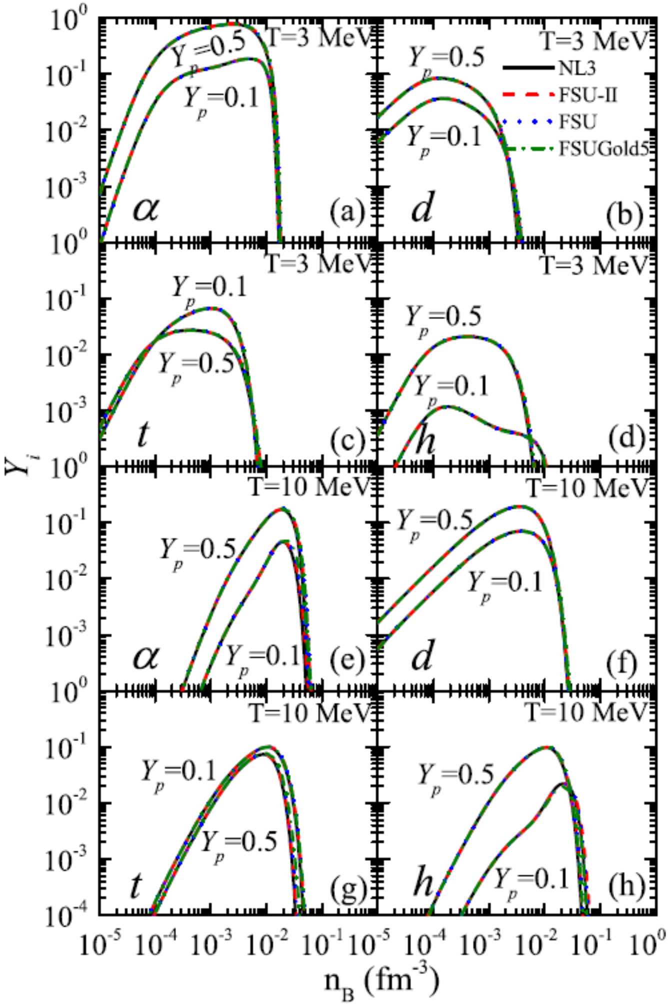


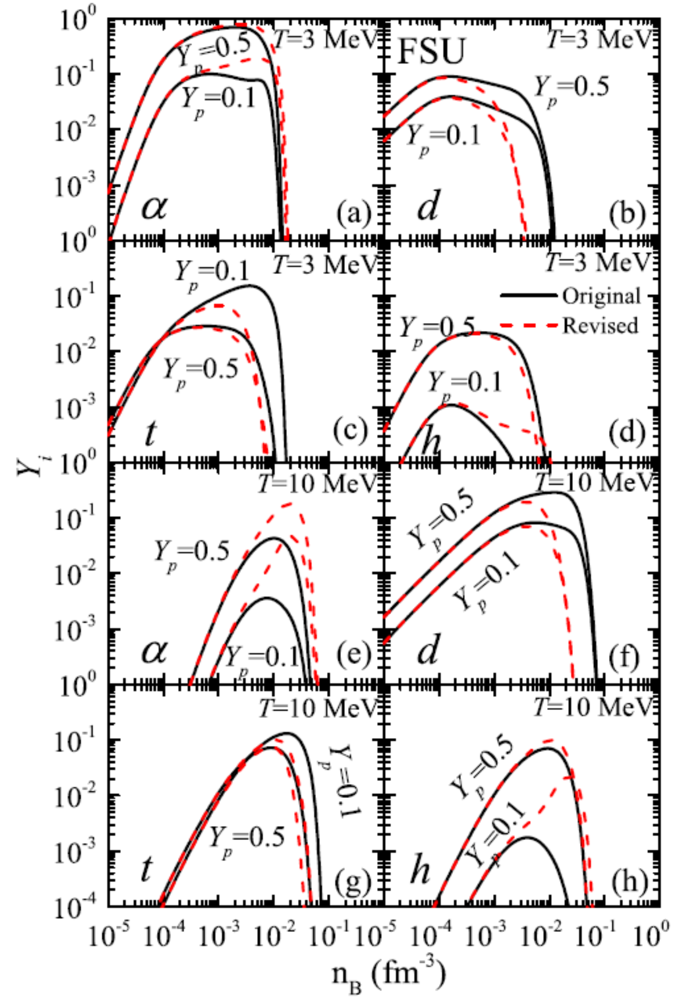
binding energies of triton and helium 3 are isospin-dependent

- **The clustering is still significant even for nuclear matter with large isospin**
- **At low T, the alpha-clustering becomes particularly important**
- **T is smaller, the critical density where the clustering starts to work is lower**

Zhao-Wen Zhang and LWC, PRC95, 064330 (2017)

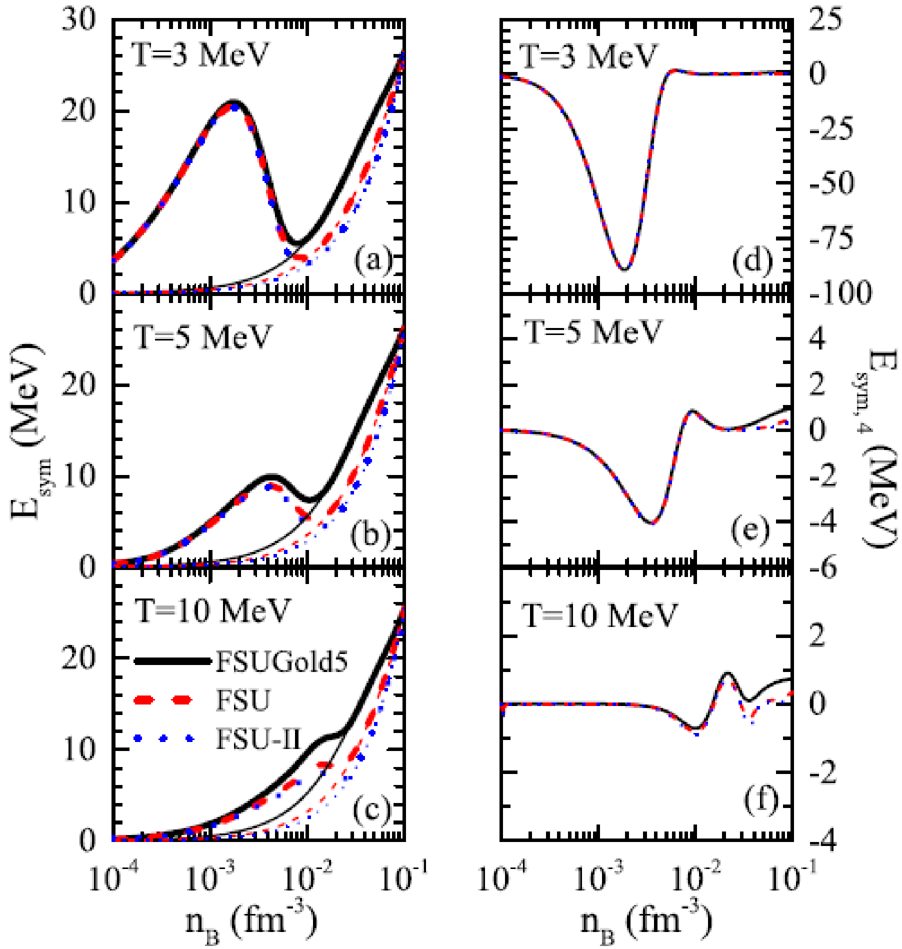
Fraction of clusters

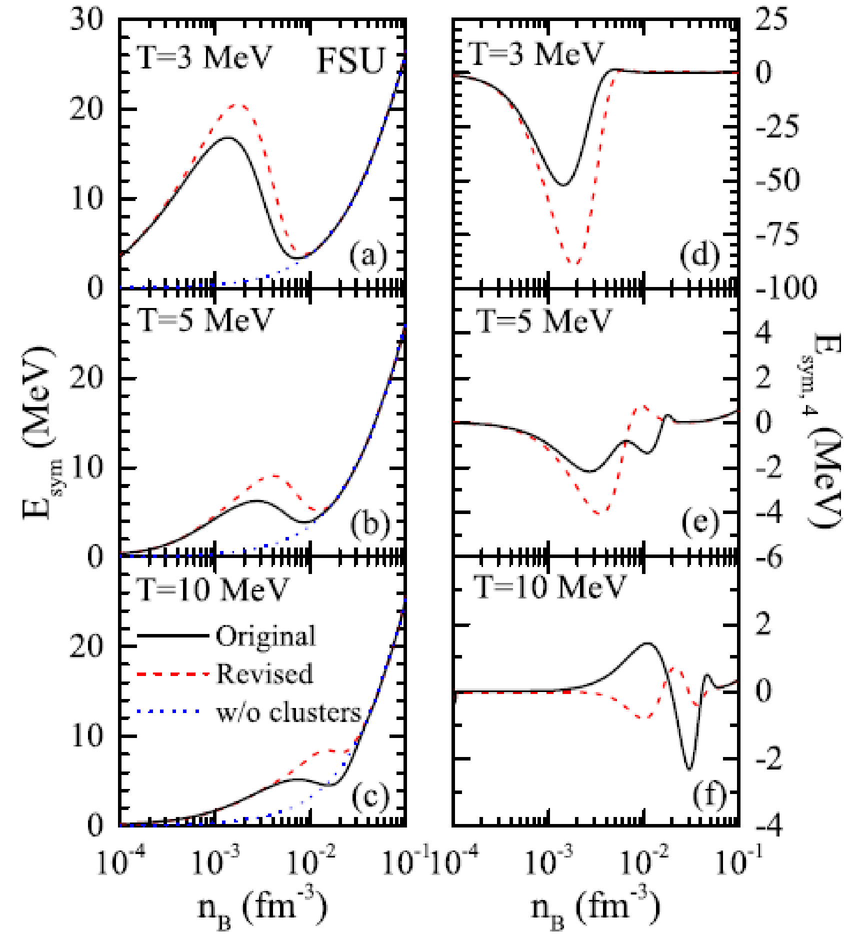




- **The clustering effects are insensitive to the RMF interactions (At very low densities, the fields effects are weak?)**
- **The modification of the in-medium binding energy changes significantly the fraction**

Interaction-dependence of E_{sym}

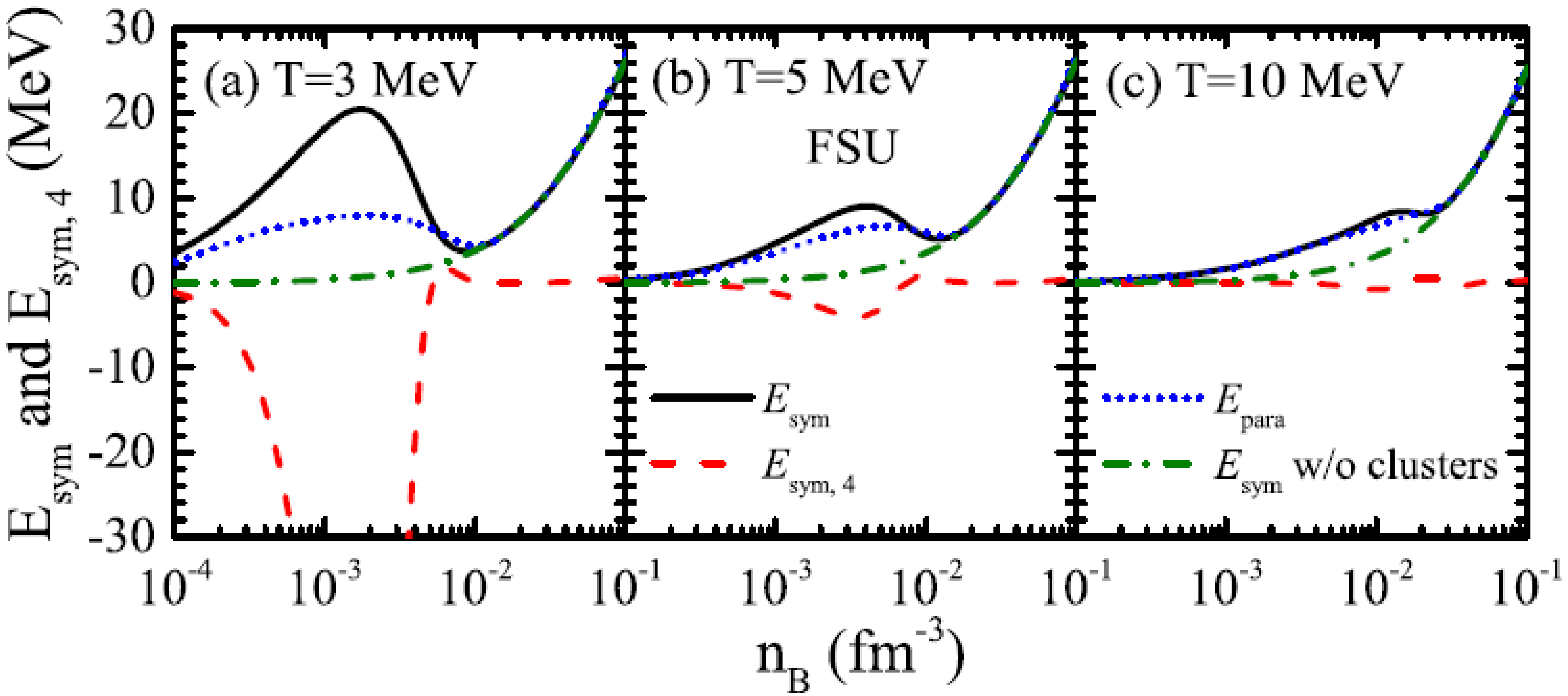




$$E_{\mathrm{sym}}(n,T)=\frac{1}{2}\frac{\partial^2 E_{\mathrm{int}}}{\partial\delta^2}\bigg|_{\delta=0} \qquad E_{sym,4}(n,T)=\frac{1}{24}\frac{\partial^4 E_{\mathrm{int}}}{\partial\delta^4}\bigg|_{\delta=0}$$

Symmetry energy: Parabolic Appr.

$$E_{\text{para}}(n,T) = E_{\text{int}}(n,T)\big|_{\delta=1} - E_{\text{int}}(n,T)\big|_{\delta=0}$$



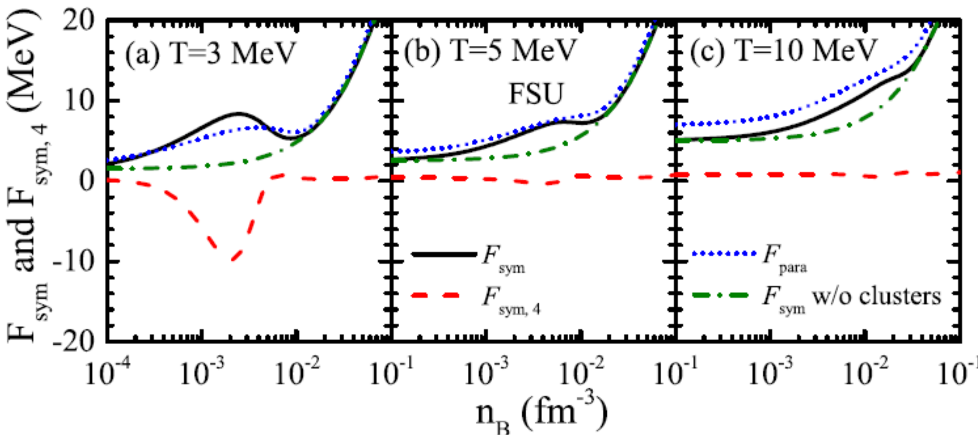
- **The expansion of binding energy in isospin asymmetry is not convergent at low T.**

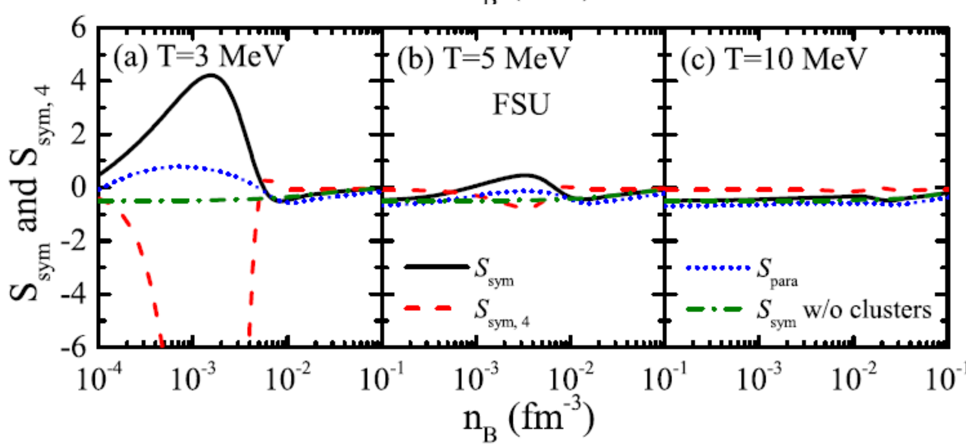
Zhao-Wen Zhang and LWC, PRC95, 064330 (2017)

Symmetry free energy and entropy

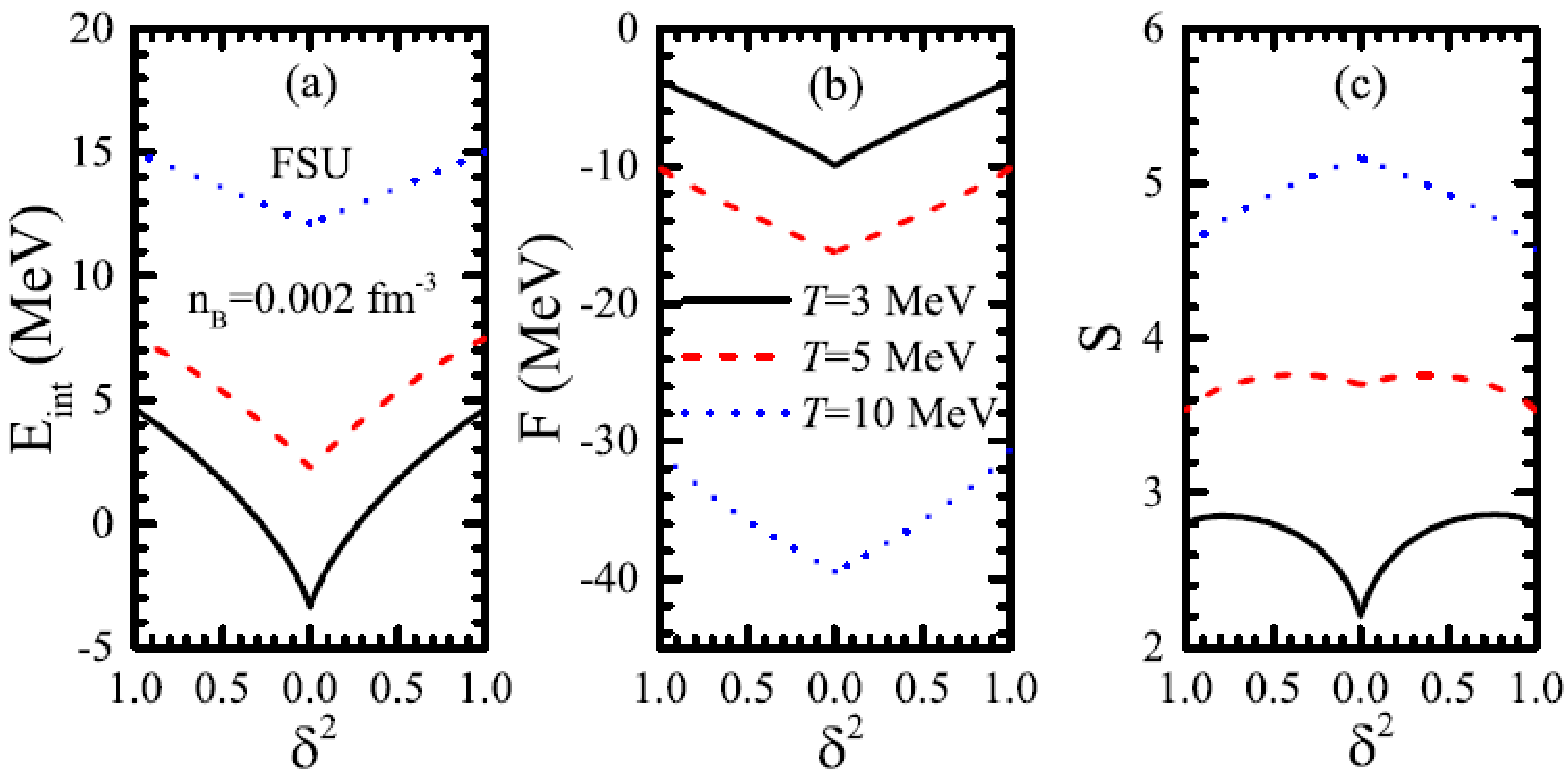
$$F_{\rm sym}(n,T)=\frac{1}{2}\frac{\partial^2 F}{\partial\delta^2}\bigg|_{\delta=0}\qquad F_{sym,4}(n,T)=\frac{1}{24}\frac{\partial^4 F}{\partial\delta^4}\bigg|_{\delta=0}\qquad S_{\rm sym}(n,T)=\frac{1}{2}\frac{\partial^2 S}{\partial\delta^2}\bigg|_{\delta=0}\qquad S_{sym,4}(n,T)=\frac{1}{24}\frac{\partial^4 S}{\partial\delta^4}\bigg|_{\delta=0}$$

$$F_{\rm para}(n,T)=F(n,T)\big|_{\delta=1}-F(n,T)\big|_{\delta=0}\qquad S_{\rm para}(n,T)=S(n,T)\big|_{\delta=1}-S(n,T)\big|_{\delta=0}$$





Parabolic approach

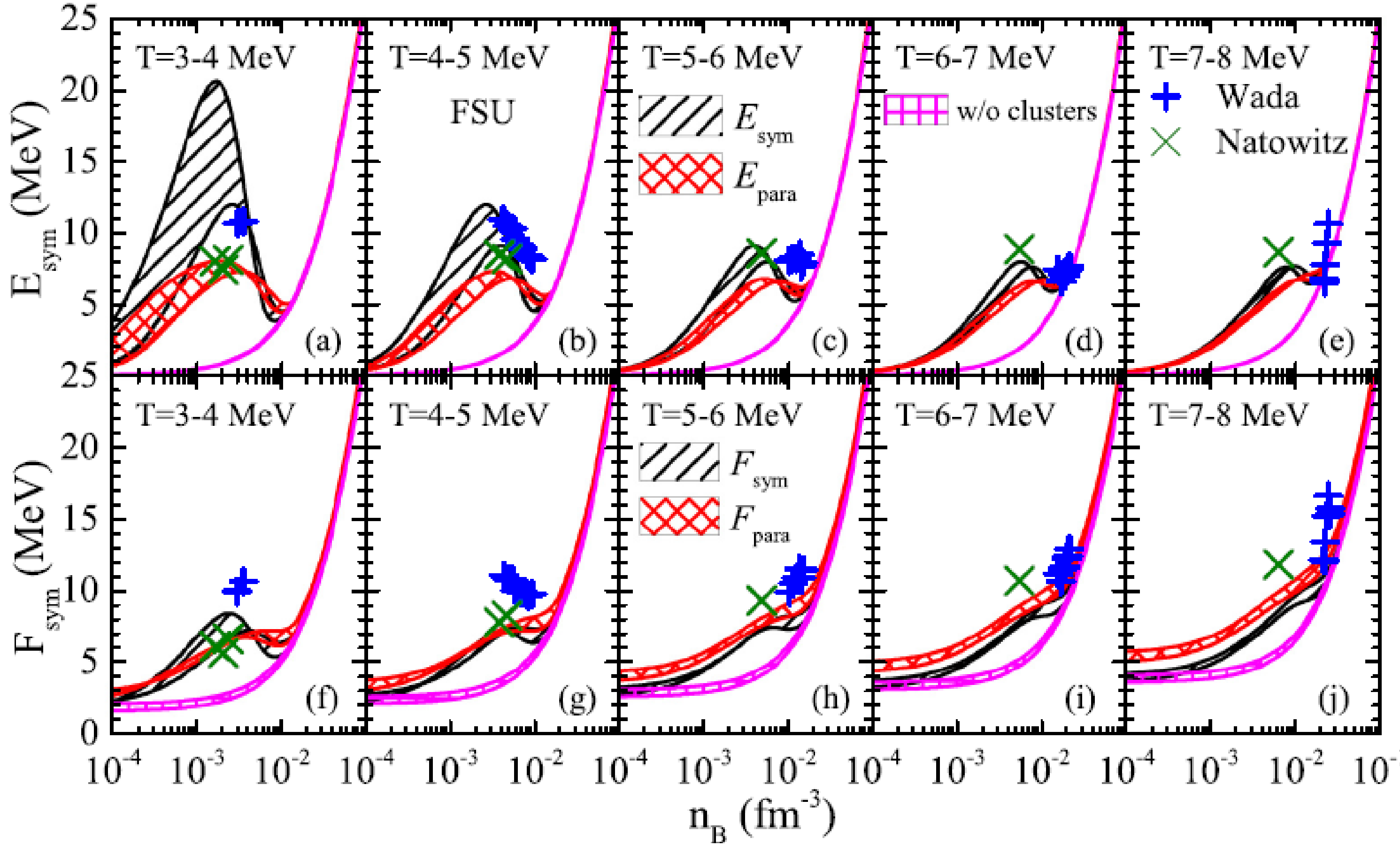


- Parabolic approach is broken for **Eint and S** by clustering effect at low T

Zhao-Wen Zhang and LWC, PRC95, 064330 (2017)

Compared with data

Zhao-Wen Zhang and LWC, PRC95, 064330 (2017)



- **Experimental data can be reasonably reproduced**

Data:

J.B. Natowitz, *et al*. Phys. Rev. Lett., 104, 202501 (2010), R. Wada *et al*., Phys. Rev. C 85, 064618 (2012)

Outline

- Nuclear Matter EOS and the Symmetry Energy (Esym)
- Clustering Effects on Esym
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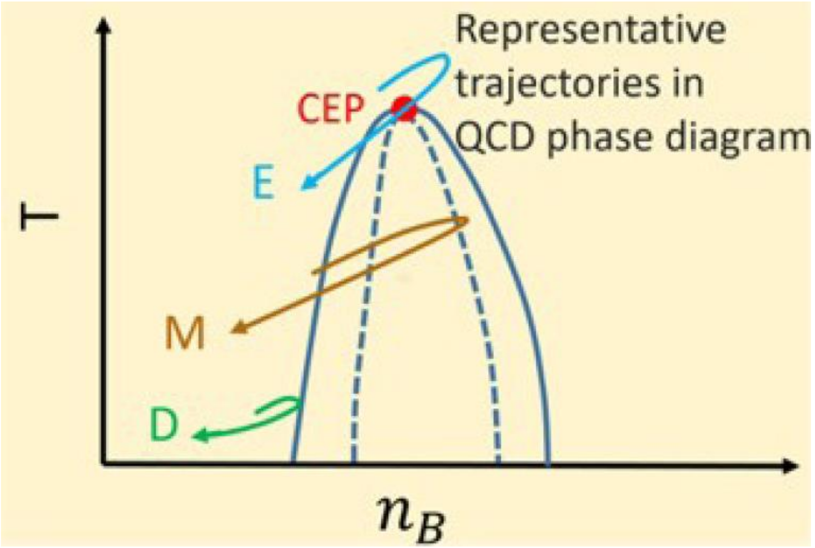
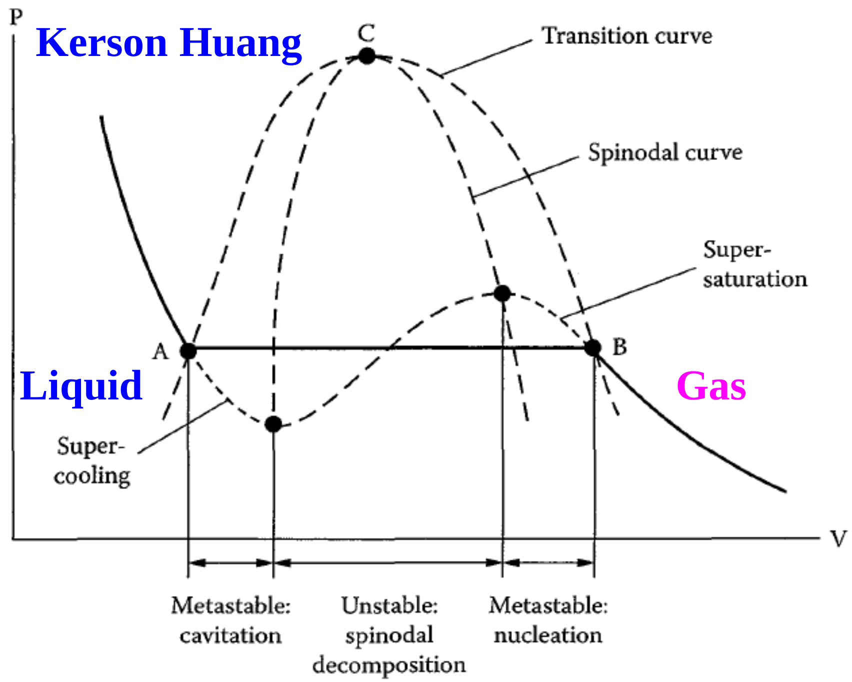
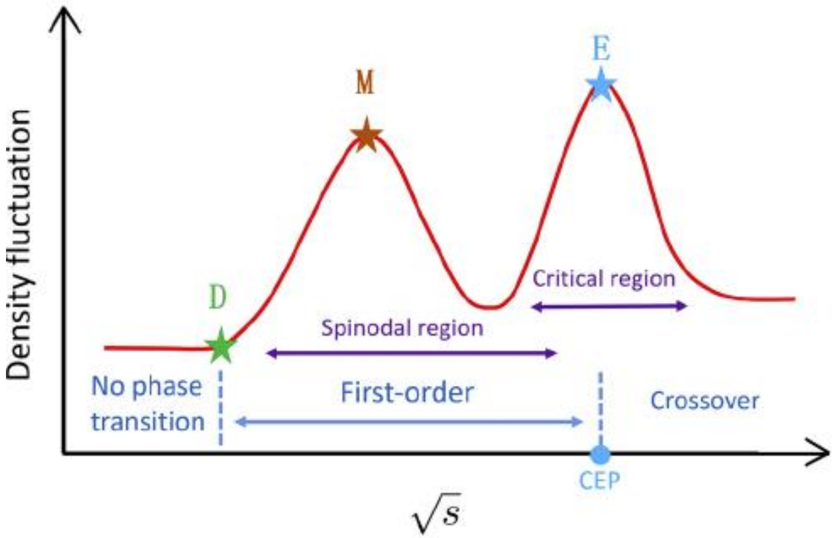
Peak structure and CEP





$$(\Delta M)^2 \propto N(V)\int d\mathbf{r}\, G(r) \propto N(V)\xi^2(t)$$

Fluc. Corr. Func. Corr. Length



Critical point: Largest density fluctuation (e.g., critical opalescence)

First-order phase transition: Large density fluctuations due to spinodal instability (but take time to build)

Steinheimer/Randrup/Koch(12,14); Herold et al.(14); Li/Ko (16)

K. J. Sun, LWC, C.M. Ko, J. Pu, and Z. Xu, PLB781, 499(2018) [arXiv:1801.09382]

Basic idea

Baryon density fluctuation vs light nuclei production

Baryon density fluctuation
is closely related to
the correlation between nucleons.

The correlation between nucleons
determines
the production of light nuclei

Baryon density fluctuation in vicinity of
first-order phase transition/CEP
could be deciphered from
the production of light nuclei

Cluster Production: Coalescence?

Coalescence model provides a useful approach to describe light cluster production in HIC

- Coalescence model provides a useful tool to describe light nuclei production in HIC
- Coalescence model also provides a useful tool to describe hadron production from partonic matter (hadronization)
- ……

Butler, Pearson, Sato, Yazaki, Gyulassy, Frankel, Remler, Dove, Scheibl, Heinz, Schnedermann, Mattiello, Nagle, Polleri, …
Biro, Zimanyi, Levai, Csizmadia, Hwa, Yang, Ko, Lin , Greco, Chen, Fries, Muller, Nonaka, Bass, Voloshin, Molnar, Xie, Shao, …

Deuteron production in HIC

The correlation between neutron and proton with small relative momentum and deuteron formation both appear due to the final state interaction (S. Mrowczynsky, PLB248 (1990), P. Danielewicz et al., PLB274 (1992))

The n-p pair in a scattering state with small relative momentum and deuteron (n-p pair in a bound state) should provide the same space-time information about the size of an emission source

Using stiff symmetry energy will produce more deuterons than using soft symmetry energy?

Similarly to the n-p correlation function (HBT), deuteron yield in HIC's induced by neutron-rich nuclei is also a sensitive probe of the nuclear symmetry energy!!!

n-p HBT: Chen/Greco/Ko/Li, PRL90, 162701(2003); PRC68, 014605 (2003)

Deuteron: Chen/Ko/Li, PRC68, 017601 (2003); NPA729, 809 (2003)

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Cluster Yields w/o density fluctuation

$$\boxed{\begin{aligned} N_{\mathrm{d}} &= \frac{3}{2^{1/2}}\left(\frac{2\pi}{m_0 T_{\mathrm{eff}}}\right)^{3/2}\frac{N_p N_n}{V}, \\ N_{^3\mathrm{H}} &= \frac{3^{3/2}}{4}\left(\frac{2\pi}{m_0 T_{\mathrm{eff}}}\right)^{3}\frac{N_p N_n^2}{V^2}. \end{aligned}}$$

K. J. Sun/LWC, PRC95, 044905 (2017)

The above equations are consistent with conventional thermal model:

$$N^{\mathrm{th}} = \frac{gV}{(2\pi)^3}4\pi T m^2 K_2\left(\frac{m}{T}\right)\mathrm{e}^{\frac{\mu}{T}}$$

$$T = T_{\mathrm{eff}}$$

K_2 is the modified Bessel function

$$\boxed{\begin{aligned} N_p^{\mathrm{th}} &= \frac{g_p V}{(2\pi)^3}(2\pi m_0 T)^{\frac{3}{2}}\mathrm{e}^{\frac{\mu_p - m_0}{T}}, \\ N_d^{\mathrm{th}} &= \frac{g_d V}{(2\pi)^3}(4\pi m_0 T)^{\frac{3}{2}}\mathrm{e}^{\frac{2\mu_p - 2m_0}{T}}, \\ N_{^3\mathrm{He}}^{\mathrm{th}} &= \frac{g_{^3\mathrm{He}} V}{(2\pi)^3}(6\pi m_0 T)^{\frac{3}{2}}\mathrm{e}^{\frac{3\mu_p - 3m_0}{T}}, \end{aligned}}$$

$$K_\nu(x) \to \sqrt{\frac{\pi}{2x}}e^{-x}\left(1 + \frac{4\nu^2 - 1}{8x} + \mathcal{O}\left(\frac{1}{x^2}\right)\right)$$

K. J. Sun, LWC, C.M. Ko, and Z. Xu, PLB774, 103 (2017) [arXiv:1702.07620 (2017)}

Cluster Yields with density fluctuation

Density fluctuation over space:

Neutron: $$\rho_n(\mathbf{x}) = \frac{1}{V}\int \rho_n(\mathbf{x})d^3\mathbf{x} + \delta\rho_n(\mathbf{x}) = \langle\rho_n\rangle + \delta\rho_n(\mathbf{x}) \qquad \langle\delta\rho_n\rangle = 0$$

Proton: $$\rho_p(\mathbf{x}) = \frac{1}{V}\int \rho_p(\mathbf{x})d^3\mathbf{x} + \delta\rho_p(\mathbf{x}) = \langle\rho_p\rangle + \delta\rho_p(\mathbf{x}) \qquad \langle\delta\rho_p\rangle = 0$$

$$N_d \approx \frac{3}{2^{1/2}}\left(\frac{2\pi}{mT}\right)^{3/2}\int d^3\mathbf{x}\,\rho_n(\mathbf{x})\rho_p(\mathbf{x})$$

$$N_{^3H} \approx \frac{3^{3/2}}{4}\left(\frac{2\pi}{mT}\right)^{3}\int d^3\mathbf{x}\,\rho_n^2(\mathbf{x})\rho_p(\mathbf{x})$$

$$\boxed{N_d \approx \frac{3}{2^{1/2}}\left(\frac{2\pi}{mT}\right)^{3/2} N_p\langle\rho_n\rangle(1 + C_{np})}$$

$$\boxed{N_{^3H} \approx \frac{3^{3/2}}{4}\left(\frac{2\pi}{mT}\right)^{3} N_p\langle\rho_n\rangle^2(1 + \Delta\rho_n + 2C_{np})}$$

d yield ~ Cnp; ^{3}H yield ~ the relative density fluctuation +Cnp!

n and p density correlation function: $$C_{np} = \langle\delta\rho_n\delta\rho_p\rangle/(\langle\rho_n\rangle\langle\rho_p\rangle)$$

n relative density fluctuation: $$\Delta\rho_n = \langle(\delta\rho_n)^2\rangle/\langle\rho_n\rangle^2$$

Isospin relative density fluctuation: $$\Delta\rho_I = \frac{\langle(\delta\rho_n - \delta\rho_p)^2\rangle}{(\langle\rho_n\rangle + \langle\rho_p\rangle)^2} = \frac{R_{np}^2\Delta\rho_p - 2R_{np}C_{np} + \Delta\rho_n}{(1 + R_{np})^2}$$

$$R_{np} = N_p/N_n = \langle\rho_p\rangle/\langle\rho_n\rangle$$

K. J. Sun, LWC, C.M. Ko, J. Pu, and Z. Xu, PLB781, 499(2018) [arXiv:1801.09382]

Cluster Yields with density fluctuation

K. J. Sun, LWC, C.M. Ko, J. Pu, and Z. Xu, PLB781, 499(2018) [arXiv:1801.09382]

$$\boxed{\begin{aligned} C_{np} &\approx g_{\text{p-d}} R_{np} V_{\text{ph}} \mathcal{O}_{\text{p-d}} - 1, \\ \Delta\rho_n &\approx g_{\text{p-d-t}} (1 + C_{np})^2 \mathcal{O}_{\text{p-d-t}} - 2C_{np} - 1 \end{aligned}}$$

$$g_{\text{p-d}} = \frac{2^{1/2}}{3(2\pi)^3}$$

$$g_{\text{p-d-t}} = 9/4 \times (4/3)^{3/2}$$

$$R_{np} = N_p/N_n = \langle\rho_p\rangle/\langle\rho_n\rangle \qquad N_p/N_n = (\pi^+/\pi^-)^{1/2}$$

$$\mathcal{O}_{\text{p-d}} = N_{\text{d}}/N_{\text{p}}^2 \qquad \mathcal{O}_{\text{p-d-t}} = N_{\text{p}} N_{^3\text{H}}/N_{\text{d}}^2$$

- Effective Phase Space Volume:

There exists a constant between chemical and kinetic freeze-out

$$V_{\text{ph}} = (2\pi m T)^{3/2} V \qquad T^{3/2} V = \lambda T_{\text{ch}}^{3/2} V_{\text{ch}} \qquad \lambda = 1.6$$

J. Xu, C.M. Ko, PLB 772, 290 (2017).

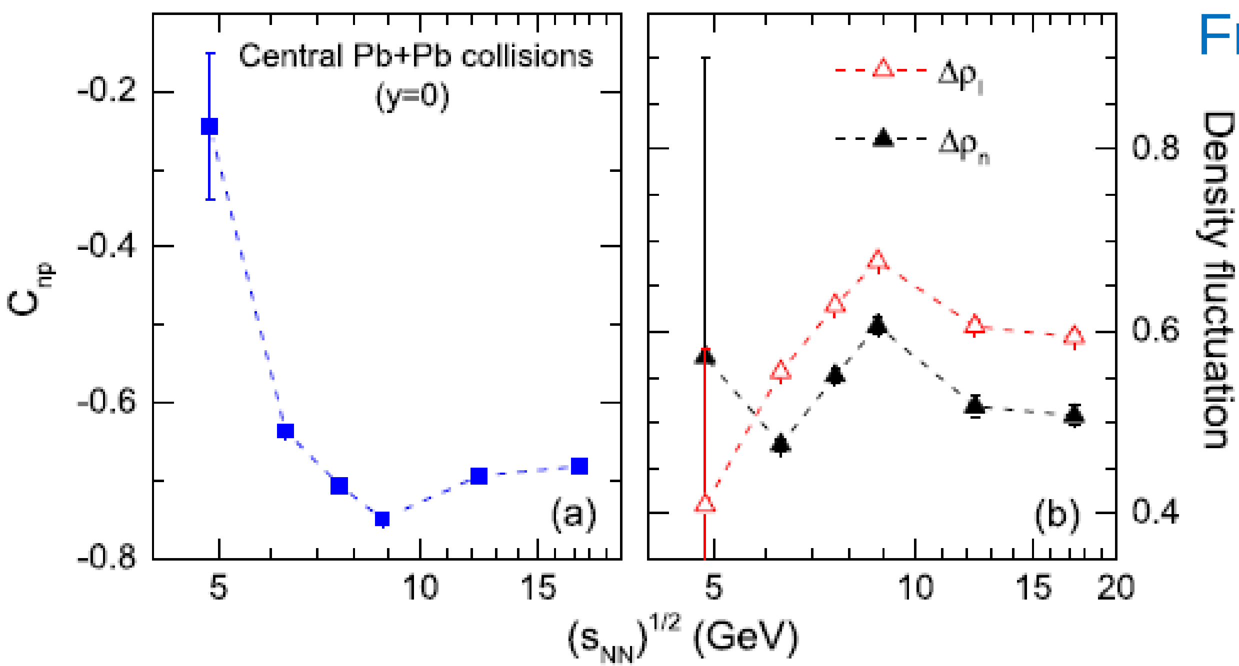
- Chemical freeze-out Tch and Vch can be obtained from statistic model

J. Cleymans et al., PRC 73, 034905 (2006); A. Andronic, IJMPE29, 1430047 (2014)

Circumstantial evidence of peak structure

Yields dN/dy of p, d and ^{3}H at midrapidity, together with the yield ratio π^+/π^- measured in central Pb+Pb collisions at 20 AGeV ($0-7\%$ centrality, $\sqrt{s_{NN}}=6.3$ GeV), 30 AGeV ($0-7\%$ centrality, $\sqrt{s_{NN}}=7.6$ GeV), 40 AGeV ($0-7\%$ centrality, $\sqrt{s_{NN}}=8.8$ GeV), 80 AGeV ($0-7\%$ centrality, $\sqrt{s_{NN}}=12.3$ GeV), and 158 AGeV ($0-12\%$ centrality, $\sqrt{s_{NN}}=17.3$ GeV) by the NA49 Collaboration [31,41,42]. Also given are the chemical freeze-out temperature $T_{\rm ch}$ (GeV) and volume $V_{\rm ch}$ (fm^3), the derived yield ratios $\mathcal{O}_{\text{p-d}}$ and $\mathcal{O}_{\text{p-d-t}}$, and the extracted $C_{\rm np}$, $\Delta\rho_n$ and $\Delta\rho_l$. In obtaining $\mathcal{O}_{\text{p-d}}$ and $\mathcal{O}_{\text{p-d-t}}$, the weak decay contributions to the yield of proton from hyperons are corrected by using results from the statistical model (see text for details).

$\sqrt{s_{NN}}$	p	d	^{3}H(10^{-3})	π^+/π^-	$T_{\rm ch}$	$V_{\rm ch}$	$\mathcal{O}_{\text{p-d}}(10^{-4})$	$\mathcal{O}_{\text{p-d-t}}$	$C_{\rm np}$	$\Delta\rho_n$	$\Delta\rho_l$
6.3	46.1 ± 2.1	2.094 ± 0.168	$43.7(\pm6.4)$	0.86	0.131	1389	10.5 ± 0.11	0.444 ± 0.014	-0.636 ± 0.004	0.475 ± 0.007	0.556 ± 0.004
7.6	42.1 ± 2.0	1.379 ± 0.111	$22.3(\pm3.4)$	0.88	0.139	1212	8.78 ± 0.13	0.465 ± 0.019	-0.707 ± 0.004	0.551 ± 0.007	0.629 ± 0.004
8.8	41.3 ± 1.1	1.065 ± 0.086	$14.8(\pm2.6)$	0.90	0.144	1166	7.32 ± 0.20	0.500 ± 0.020	-0.749 ± 0.007	0.606 ± 0.045	0.677 ± 0.006
12.3	30.1 ± 1.0	0.543 ± 0.044	$4.49(\pm0.94)$	0.91	0.153	1231	7.70 ± 0.11	0.404 ± 0.034	-0.693 ± 0.004	0.518 ± 0.012	0.605 ± 0.006
17.3	23.9 ± 1.0	0.279 ± 0.023	$1.58(\pm0.31)$	0.93	0.159	1389	6.66 ± 0.01	0.415 ± 0.032	-0.681 ± 0.0004	0.507 ± 0.011	0.594 ± 0.006



From NA49 Collaboration

T. Anticic et al. (NA49 Collaboration), Phys. Rev. C 94, 044906 (2016).

For $\Delta\rho_n$:

- **A peak is observed at 8.8 GeV;**
- **There is another possible peak below 6.3 GeV**

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Circumstantial evidence of peak structure

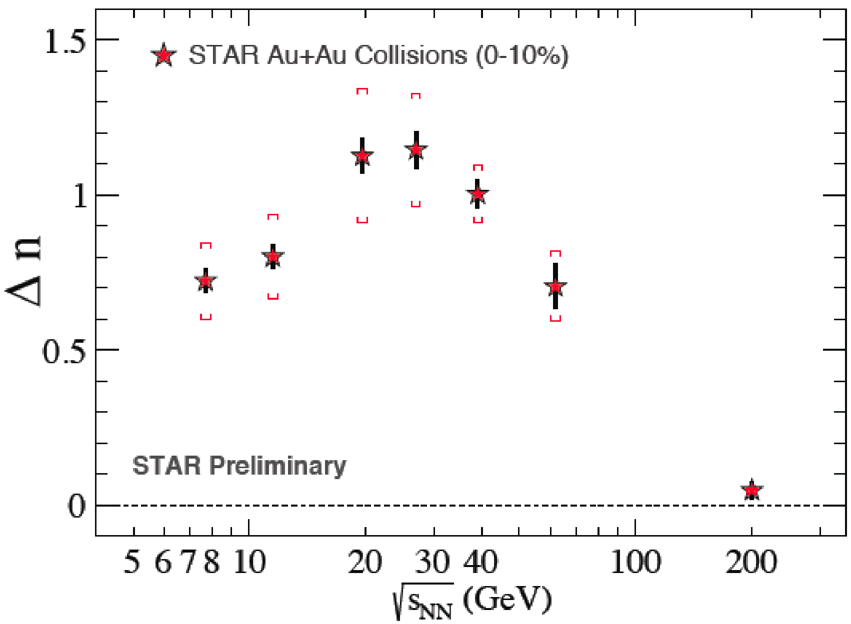
Collision energy and centrality dependence of light nuclei(triton) production at STAR

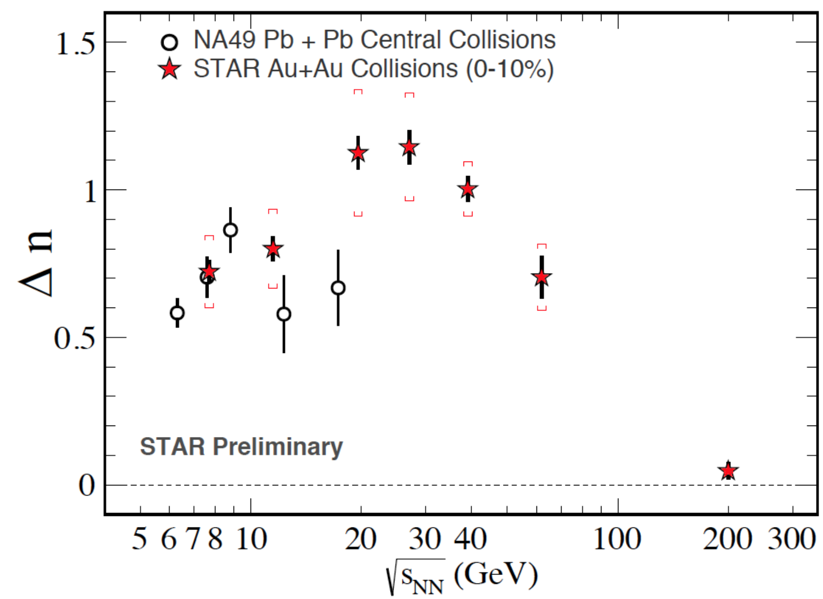
Dingwei Zhang, *for the STAR Collaboration*

Central China Normal University

STAR

2018 Quark Matter Venezia





Δn shows a non-monotonic energy dependence with a peak around 20 – 27 GeV. Proton [4] and deuteron [5] measured by STAR.

NA49 and STAR-BES seems to indeed suggest double peak structure!

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Summary

- **Significant progress has been made on the constraints on Esym from subsaturation to suprasaturation density, especially due to the multimessenger measurements**
- **Clustering effects play minor effects on the obtained constraints of Esym above 0.02 fm^{-3} but are very important at lower densities and low temperature – the δ expansion is actually divergent!**
- **The coalescence production of light nuclei in heavy-ion collisions provides a potentially useful probe of the nucleon density fluctuations in the collisions**
- **Transport model + generalized RMF with light nuclei?**

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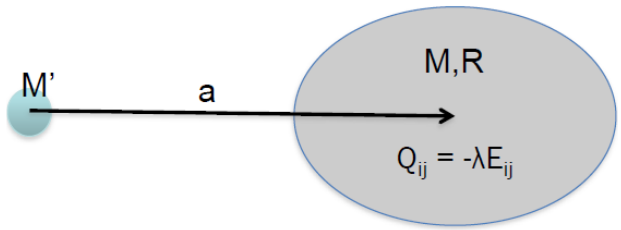
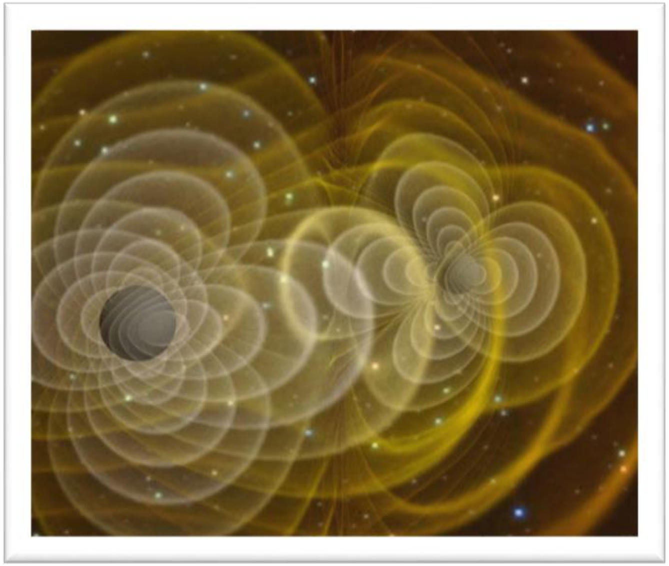
谢 谢！

Thanks！

Tidal Deformability

Tidal Deformability (Polarizability)
(oscillation response coefficient λ)





$$Q_{ij} = \lambda \varepsilon_{ij}$$

Q_{ij}: Quadrupole moment

ε_{ij}: Tidal field of companion

$$\boxed{\lambda = \frac{2}{3} k_2 R^5}$$

k_2: Love number
R: Radius
M: Mass

Dimensionless Tidal Deformability

$$\Lambda = \frac{2}{3} k_2 (R/M)^5$$

Éanna É. Flanagan and Tanja Hinderer, Phys.Rev.D 77, 021502(R) (2008)
F.J. Fattoyev, J. Carvajal, W.G. Newton, and Bao-An Li, Phys. Rev. C 87, 015806 (2013)

The extended SHF Energy Density Functional

Extended Skyrme Interaction:

$$
\begin{aligned}
v_{i,j} = & \; t_0(1+x_0P_\sigma)\delta(\boldsymbol{r}) \\
& + \frac{1}{2}t_1(1+x_1P_\sigma)[\boldsymbol{K}'^2\delta(\boldsymbol{r}) + \delta(\boldsymbol{r})\boldsymbol{K}^2] \\
& + t_2(1+x_2P_\sigma)\boldsymbol{K}'\cdot\delta(\boldsymbol{r})\boldsymbol{K} \\
& + \frac{1}{6}t_3(1+x_3P_\sigma)n(\boldsymbol{R})^\alpha\delta(\boldsymbol{r}) \\
& + iW_0(\boldsymbol{\sigma}_i+\boldsymbol{\sigma}_j)\boldsymbol{K}'\cdot\delta(\boldsymbol{r})\boldsymbol{K} \\
& + \frac{1}{2}t_4(1+x_4P_\sigma)[\boldsymbol{K}'^2 n(\boldsymbol{R})^\beta\delta(\boldsymbol{r}) + \delta(\boldsymbol{r})n(\boldsymbol{R})^\beta\boldsymbol{K}^2] \\
& + t_5(1+x_5P_\sigma)\boldsymbol{K}'\cdot n(\boldsymbol{R})^\gamma\delta(\boldsymbol{r})\boldsymbol{K}
\end{aligned}
$$

N. Chamel, S. Goriely, and J.M. Pearson, PRC80, 065804 (2009)

Z. Zhang/LWC, PRC94, 064326 (2016)

Momentum-dependence of many-body forces

LWC/Ko/Li/Xu, PRC82, 024321(2010)

13 Skyrme parameters: $\boxed{\alpha,\ t_0 \sim t_5,\ x_0 \sim x_5}$

$$
\mathcal{H} = \mathcal{K} + \mathcal{H}_0 + \mathcal{H}_3 + \mathcal{H}_{\rm eff} + \frac{G_S}{2}(\nabla\rho)^2 - \frac{G_V}{2}(\nabla\rho_1)^2 - \frac{G_{SV}}{2}\delta\nabla\rho\nabla\rho_1 + \mathcal{H}_{\rm Coul} + \mathcal{H}_{\rm SO} + \mathcal{H}_{\rm sg},
$$

13 macroscopic nuclear properties:

$$\boxed{n_0,\ E_0,\ K_0,\ J_0,\ E_{\rm sym},\ L,\ K_{\rm sym},\ m^*_{s,0},\ m^*_{v,0},\ G_S,\ G_V,\ G_{SV},\ G'_0}$$

Why extended SHF EDF?

PHYSICAL REVIEW C **94**, 064326 (2016)

Extended Skyrme interactions for nuclear matter, finite nuclei, and neutron stars

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[2]*Center of Theoretical Nuclear Physics, National Laboratory of Heavy Ion Accelerator, Lanzhou 730000, China*

symmetry energy softer at subsaturation densities (favored by experimental constraints and theoretical predictions) but stiffer at higher densities (favored by the observation of $2M_{\odot}$ neutron stars) challenges the SHF model with the conventional Skyrme interactions. For example, the Skyrme interaction TOV-min [28], which is built by fitting properties of both finite nuclei and neutron stars, can successfully support $2M_{\odot}$ neutron stars but predicts a neutron matter EOS significantly deviating from the ChEFT calculations [14] as well as the constraint extracted from analyzing the electric-dipole polarizability in ^{208}Pb [49] at densities below about $0.5\rho_0$.

Furthermore, it is well known that a notorious shortcoming of the conventional standard Skyrme interactions is that they predict various instabilities of nuclear matter around saturation density or at supra-saturation densities, which in principle hinders the application of the Skyrme interactions in the study of dense nuclear matter as well as neutron stars. For instance, most of the conventional standard Skyrme interactions predict spin or spin-isospin polarization in the density region of about $(1 \sim 3.5)\rho_0$ [25,51], including the famous SLy4 interaction [19] which has been widely used in both nuclear physics and neutron star studies and leads to spin-isospin instability of symmetric nuclear matter at densities beyond about $2\rho_0$ [52]. On the other hand, the calculations

- **The eSHF provides a nice approach that can describe simultaneously nuclear matter, finite nuclei, and neutron stars!**
- **The eSHF EDF is very flexible to mimic various density behaviors for EOS (13 parameters)**

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Extended Skyrme forces with fixed J_0 and K_{sym}

$$n_0,\ E_0,\ K_0,\ J_0,\ E_{\rm sym},\ L,\ K_{\rm sym},\ m^*_{s,0},\ m^*_{v,0},\ G_S,\ G_V,\ G_{SV},\ G'_0$$

TABLE I. Experimental data for 12 spherical even-even nuclei binding energies $E_{\rm B}$ [27], charge r.m.s. radii $r_{\rm c}$ [28–30], ISGMR energies $E_{\rm GMR}$ and its exprimental error [31], and spin-orbit energy level splittings $\epsilon^A_{\rm ls}$ [32].

${}^A_Z$X	$E_{\rm B}$(MeV)	$r_{\rm c}$(fm)	$E_{\rm GMR}$(MeV)	$\epsilon^A_{\rm ls}$(MeV)
^{16}O	−127.619	2.6991	···	6.30(1pν)
				6.10(1pπ)
^{40}Ca	−342.052	3.4776	···	···
^{48}Ca	−416.001	3.4771	···	···
^{56}Ni	−483.995	3.7760	···	···
^{68}Ni	−590.408	···	···	···
^{88}Sr	−768.468	4.2240	···	···
^{90}Zr	−783.898	4.2694	17.81±0.35	···
^{100}Sn	−825.300	···	···	···
^{116}Sn	−988.681	4.6250	15.90±0.07	···
^{132}Sn	−1102.84	···	···	···
^{144}Sm	−1195.73	4.9524	15.25±0.11	···
^{208}Pb	−1636.43	5.5012	14.18±0.11	1.32(2dπ)
				0.89(3pν)
				1.77(2fν)

Our Strategy:

- Higher-order **J0** and **Ksym** are fixed at various values
- $E_{sym}(\rho_c)$ and $L(\rho_c)$ at ρ_c =0.11 fm^{-3} are fixed at $E_{sym}(\rho_c)$=26.65 MeV and $L(\rho_c)$=47.3+/-7.8 MeV using heavy isotope binding energy difference and α_D of ^{208}Pb (Z. Zhang/LWC, PLB726, 234(2013); PRC90, 064317(2014))
- Other 9 lower-order parameters and W_0 are calibrated to fit data of finite nuclei
- Causality

Minimizing the Chi-square χ^2(p) :

$$\chi^2(P)=\sum_{n=1}^{N}\left(\frac{\mathcal{O}_n^{(\rm th)}(P)-\mathcal{O}_n^{(\rm exp)}}{\Delta\mathcal{O}_n}\right)^2$$

Observed Nstar max. mass and Tidal def.

28 OCTOBER 2010 | VOL 467 | NATURE | 1081

LETTER

doi:10.1038/nature09466

A two-solar-mass neutron star measured using Shapiro delay

P. B. Demorest[1], T. Pennucci[2], S. M. Ransom[1], M. S. E. Roberts[3] & J. W. T. Hessels[4,5]

Observed heaviest Nstar so far:

A Massive Pulsar in a Compact Relativistic Binary

John Antoniadis *et al.*

Science **340**, (2013);

DOI: 10.1126/science.1233232

Science AAAS

PSR J0348+0432

2.01 ± 0.04 solar mass ($M_\odot$)

Selected for a Viewpoint in *Physics*

PRL **119**, 161101 (2017) PHYSICAL REVIEW LETTERS week ending 20 OCTOBER 2017

GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral

B. P. Abbott *et al.**

(LIGO Scientific Collaboration and Virgo Collaboration)

PRL121, 161101 (2018)

GW170817: Measurements of neutron star radii and equation of state

The LIGO Scientific Collaboration and The Virgo Collaboration

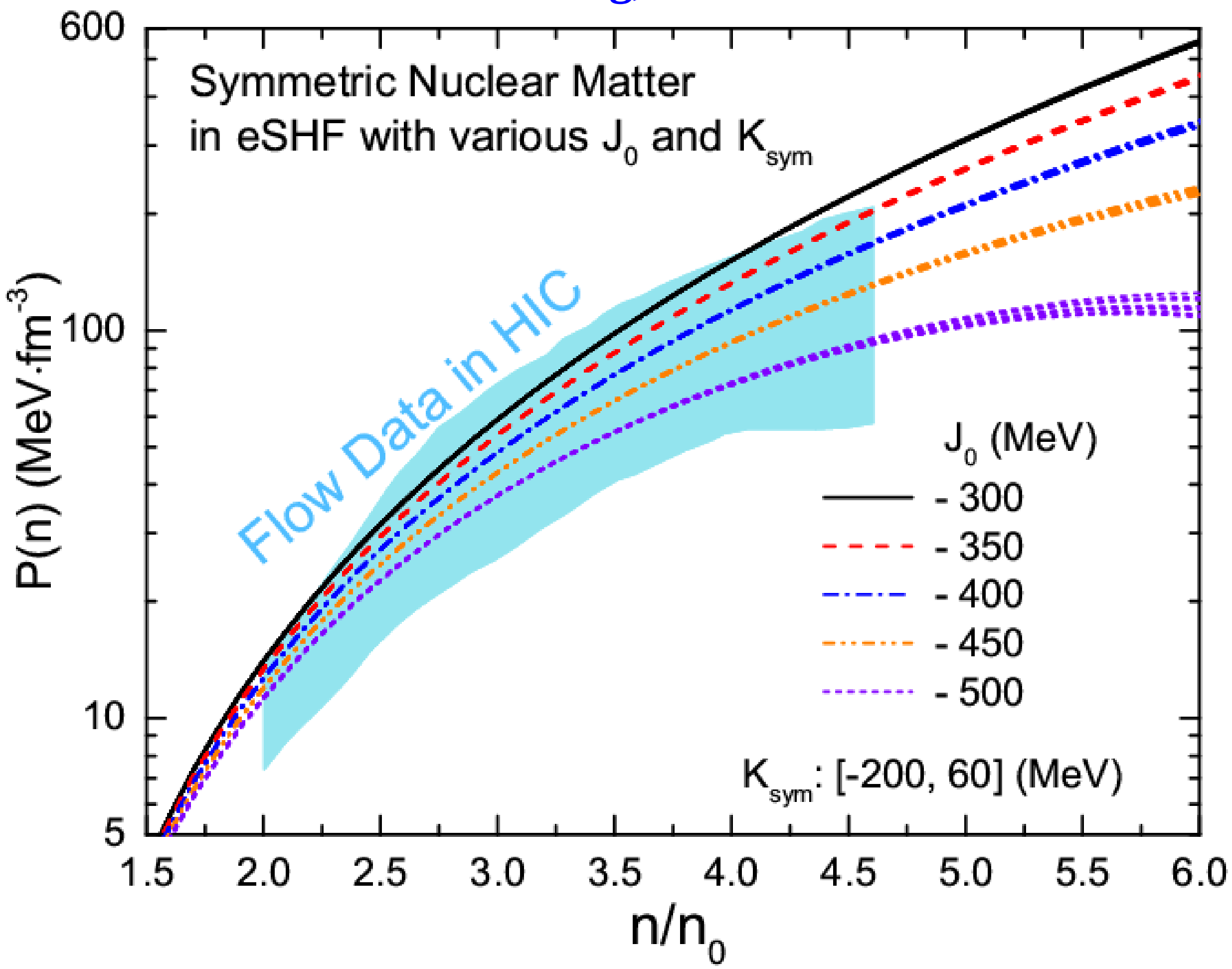
(compiled 30 May 2018)

GW170817 (LIGO/Virgo):

$\Lambda_{1.4} < 580$

J0: Flow data in HIC's

Y. Zhou/LWC/Z. Zhang, to be submitted



For various J0 and Ksym:[-200, 60] MeV

$E_{sym}(\rho_c)$= 26.65 MeV
$L(\rho_c)$= 47.3 MeV

Pressure of SNM is very sensitive to J0 but essentially independent of Ksym

-550 MeV ~ < J_0 < -342 MeV: Flow Data in HIC's

J0 and Ksym: Flow data, NStar Mass, Λ

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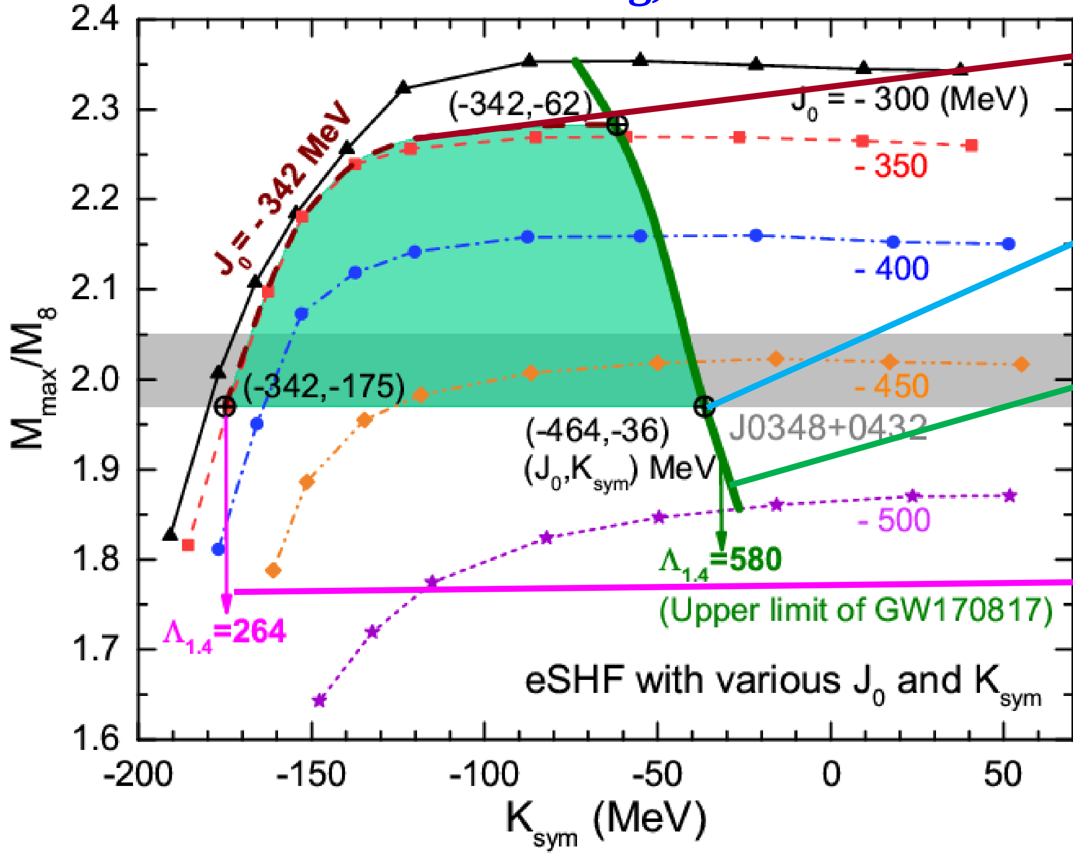
Y. Zhou/LWC/Z. Zhang, to be submitted



J0 = -342 MeV

J0 = -464 MeV
Ksym < - 36 MeV

$\Lambda_{1.4}$ < 580

GW170817 (LIGO/Virgo)

$\Lambda_{1.4}$ > 264

Consistent with EM counterpart of GW170817, see, e.g.,
D. Radice et al., ApJL852, L29(2018);
M.W. Coughlin et al., MNRAS 480, 3871(2018)

K_{sym} affects strongly M_{max} for K_{sym} < - 100 MeV

Flow Data in HIC +Mmax:
K_{sym} > -175 MeV, $\Lambda_{1.4}$ >264

Flow Data in HIC+Mmax+ $\Lambda_{1.4}$:
-464 MeV < J_0 < -342 MeV:
-175 MeV < K_{sym} < -36 MeV:

Esym: alpha BEC

Z.W. Zhang/LWC/, arXiv:1903.14108