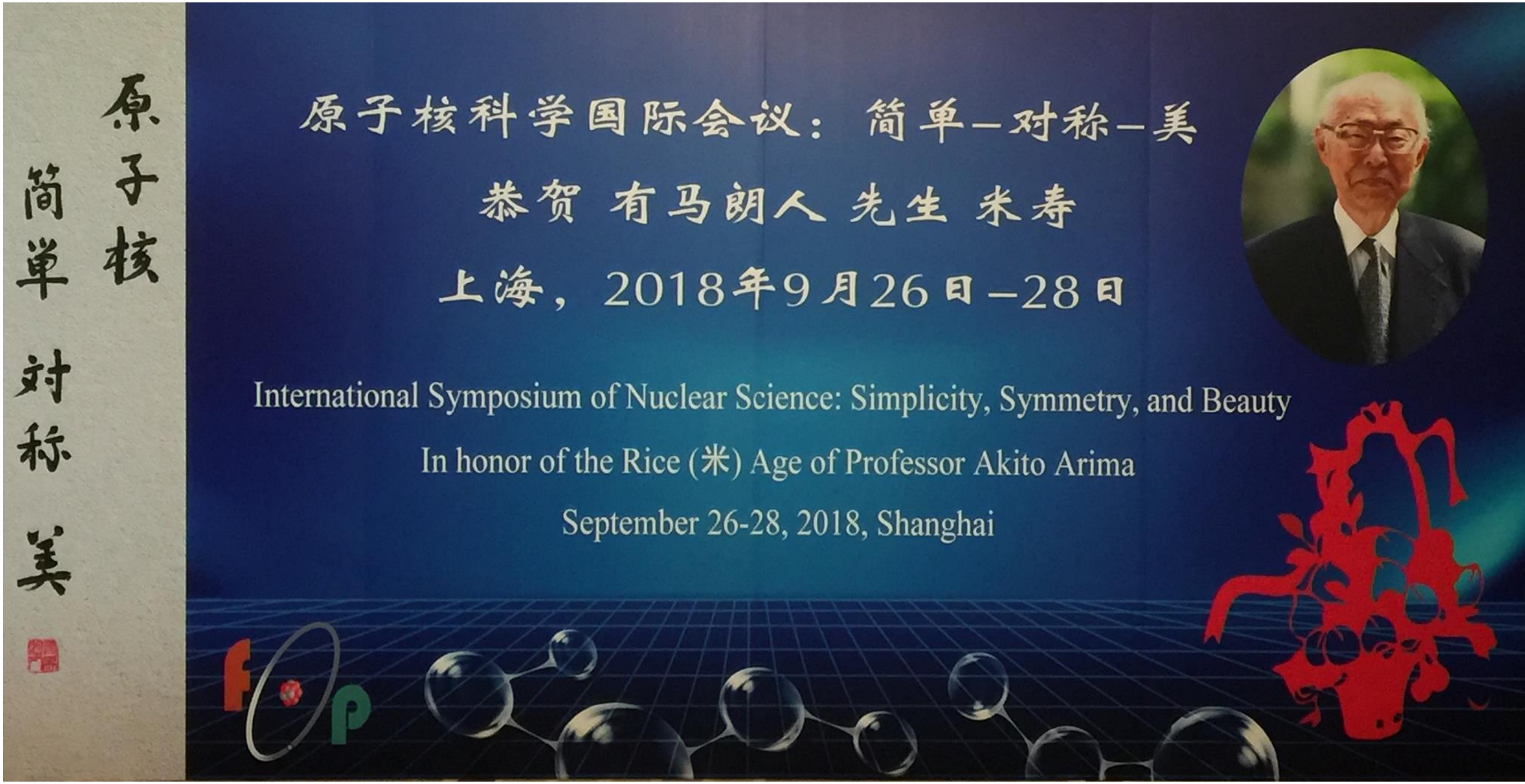
上海交通大學 SHANGHAI JIAO TONG UNIVERSITY

Happy 88th birthday to Professor Akito Arima!



“福如東海，壽比南山！”

(may your fortune be as boundless as the East Sea and may you live a long and happy life)

上海交通大学 SHANGHAI JIAO TONG UNIVERSITY

Happy 88th birthday to Professor Akito Arima!

PHYSICAL REVIEW C **90**, 064303 (2014)

I^4 dependence in nuclear symmetry energy

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[3] *Center of Theoretic*

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PHYSICAL REVIEW C **91**, 054302 (2015)

Model dependence of the I^4 term in the symmetry energy for finite nuclei

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PHYSICAL REVIEW C **94**, 064301 (2016)

Robustness of the I^4 symmetry energy coefficient

H. Jiang,[1,*] Y. Y. Cheng,[2] N. Wang,[3,4] Lie-Wen Chen,[2,5] Y. M. Zhao,[2,5,6,†] and A. Arima[2,7]

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Nuclear Matter Equation of State and Neutron Star Properties

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(lwchen@sjtu.edu.cn)

- **Nuclear matter EOS and the symmetry energy (Esym)**
- **High density nuclear matter from neutron star largest mass + tidal deformability from GW170817**
- **Summary and outlook**

“International Symposium on Simplicity, Symmetry and Beauty of Atomic Nuclei, in honor of Professor Akito Arima’s 88 year-old birthday (米寿)”, September 26-28, 2018, Shanghai, China

Outline

- Nuclear matter EOS and the symmetry energy (Esym)
- High density nuclear matter from neutron star largest mass + tidal deformability from GW170817
- Summary and outlook

Nuclear Mass Formula

Liquid-drop model: **Bethe-Weizsäcker mass formula (1935)**

$$a_{\rm v}A - a_{\rm s}A^{2/3} - a_4\frac{(N-Z)^2}{A} - a_{\rm c}\frac{Z(Z-1)}{A^{1/3}} + a_{\rm p}\frac{\Delta(N,Z)}{A^{1/2}}$$

Symmetry energy term (对称能项)

$$S_{\rm v}\frac{(N_{\rm v}-Z_{\rm v})^2}{A} + S_{\rm s}\frac{(N_{\rm s}-Z_{\rm s})^2}{A^{2/3}}$$

$$a_{\rm v}A - a_{\rm s}A^{2/3} - \frac{S_{\rm v}}{1+y_{\rm s}A^{-1/3}}\frac{(N-Z)^2}{A} - a_{\rm c}\frac{Z(Z-1)}{A^{1/3}} + a_{\rm p}\frac{\Delta(N,Z)}{A^{1/2}}$$

Symmetry energy including surface diffusion effects ($y_s=S_v/S_s$

W. D. Myers, W.J. Swiatecki, P. Danielewicz, P. Van Isacker, A. E. L. Dieperink,……

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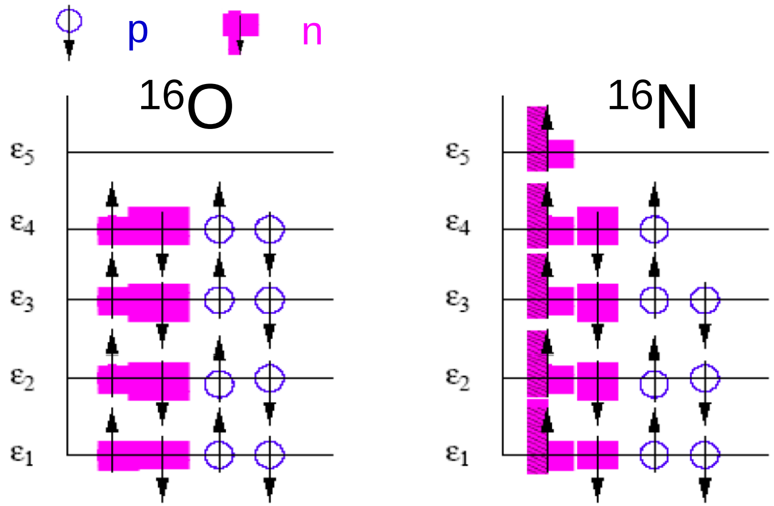
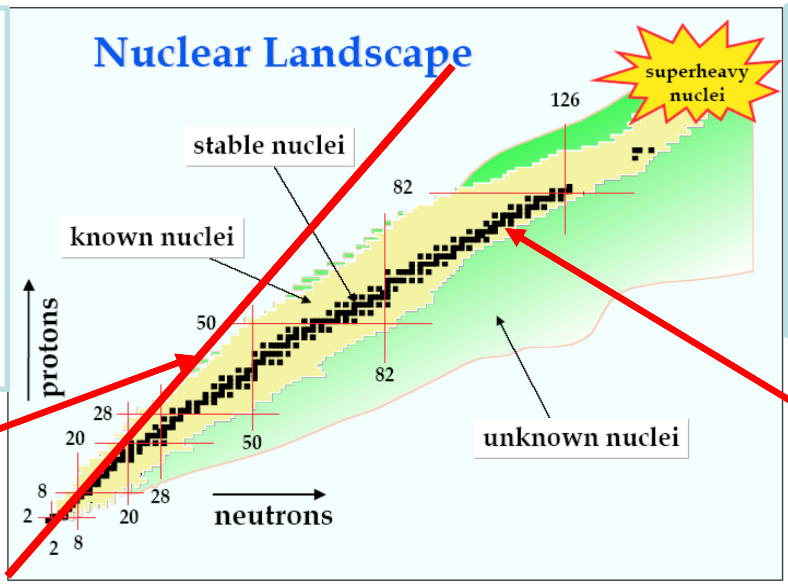
The Symmetry Energy of Finite Nuclei

$a_4(N-Z)^2/A$

Pauli Exclusion Principle



Symmetry Energy: Tends to symmetrize the n and p numbers in the nuclei (isospin symmetry)



Coulomb Energy: Tends to make the nuclei have more neutrons

N = Z

N > Z

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The Symmetry Energy of Nuclear Matter

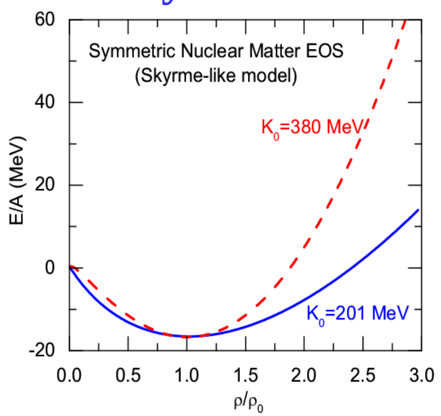
EOS of Isospin Asymmetric Nuclear Matter (Parabolic law)

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

Symmetric Nuclear Matter (relatively well-determined)

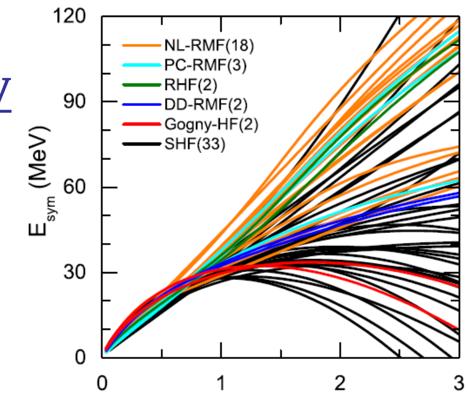
Symmetry energy term (poorly known)

Isospin asymmetry

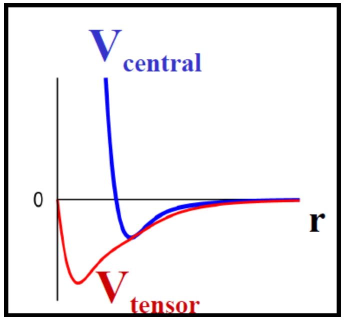


Nuclear Matter Symmetry Energy

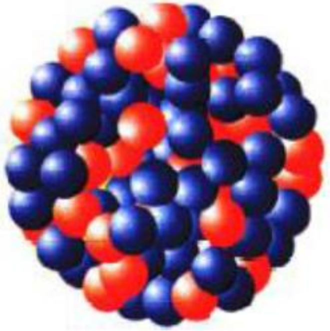
$$E_{\text{sym}}(\rho) \equiv \frac{1}{2}\frac{\partial^2 E(\rho,\delta)}{\partial \delta^2}$$



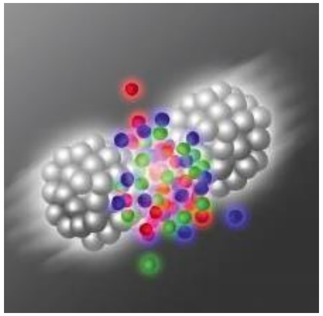
LWC, EPJ Web of Conf. 88, 00017 (2015)



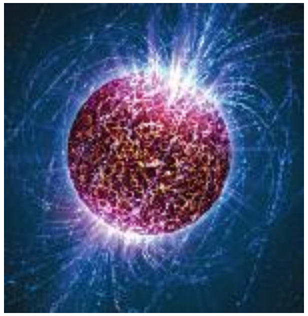
Nature of the nuclear force?



Structure and stability of nuclei?



Dynamics of heavy ion collisions?

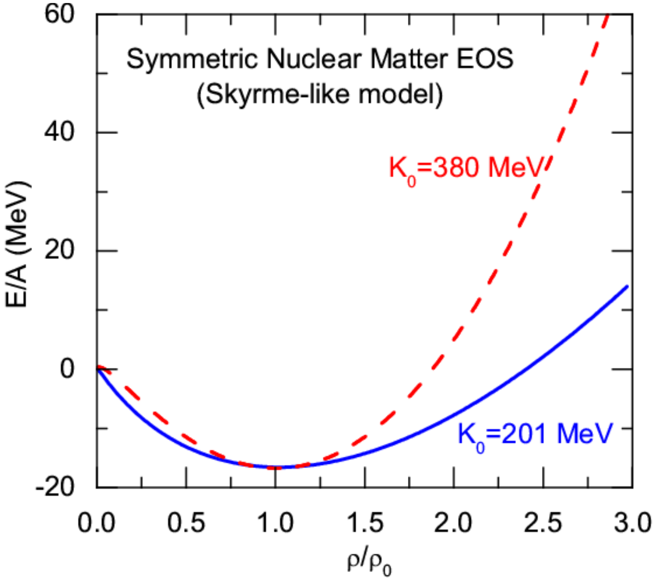


Nature of compact stars and dense nuclear matter?

EOS of Symmetric Nuclear Matter

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

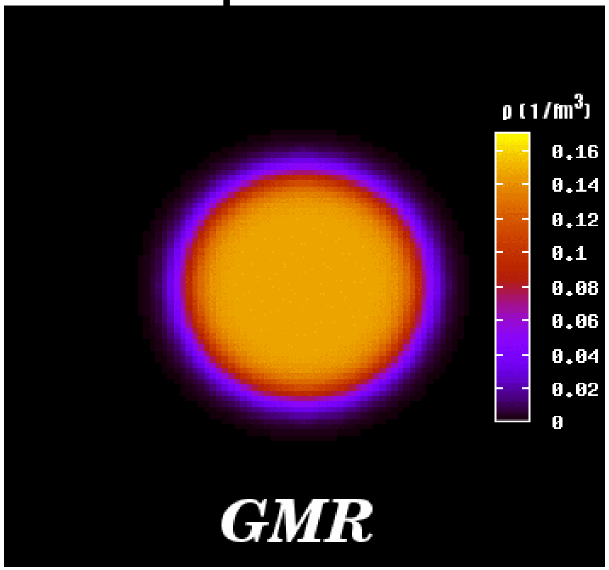
$$E_0(\rho) = E_0(\rho_0) + \frac{K_0}{2!}\chi^2 + \frac{J_0}{3!}\chi^3 + \mathcal{O}(\chi^4) \quad \chi = \frac{\rho - \rho_0}{3\rho_0}$$



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

U. Garg et al.

S. Shlomo et al.

G. Colo et al.

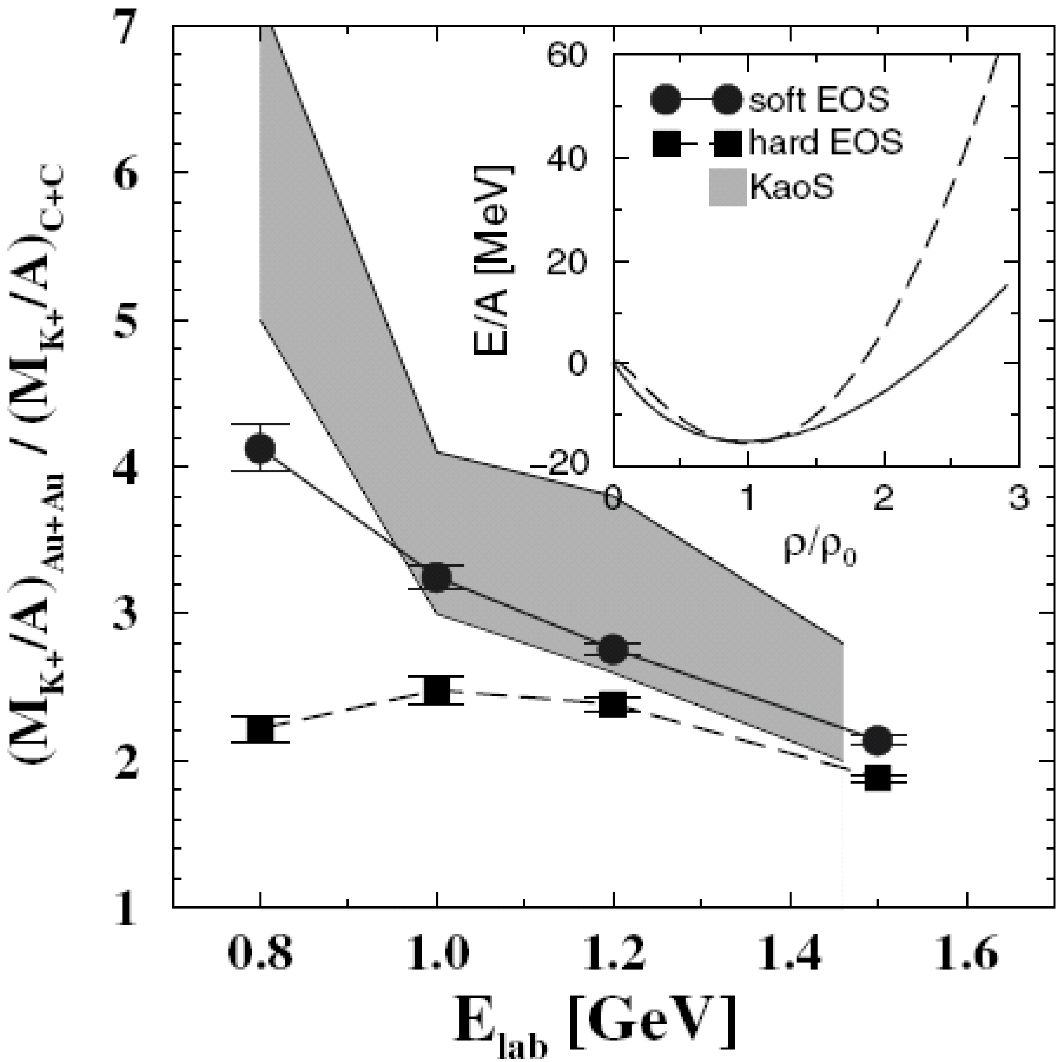
J. Piekarewicz et al.

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

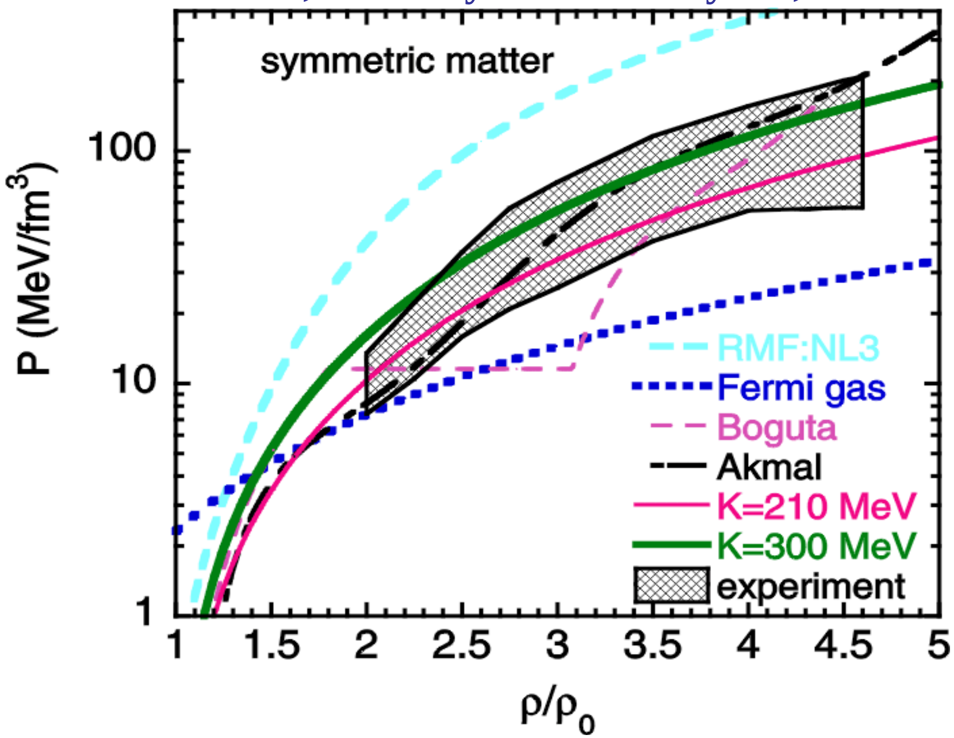
Transport calculations indicate that "results for the K^+ excitation function in Au + Au over C + C reactions as measured by the KaoS Collaboration strongly support the scenario with a **soft EOS**."

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

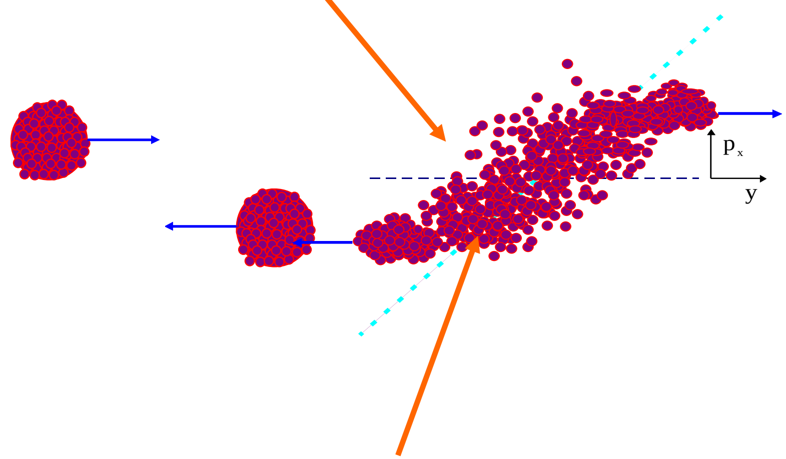
EOS of Symmetric Nuclear Matter

(3) Present 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 $5\rho_0$

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

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

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/^{3}He 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)

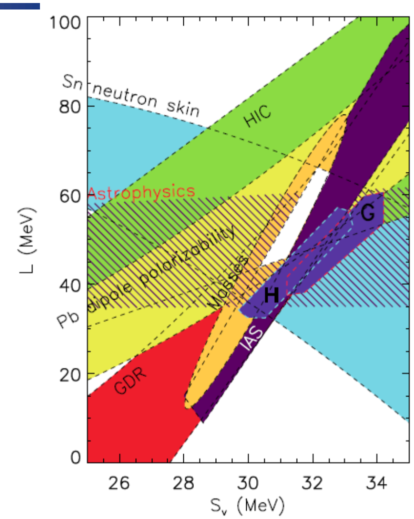
- π^-/π^+ ratio, K^+/K^0 ratio?
- Neutron-proton differential transverse flow
- n/p ratio at mid-rapidity
- Nucleon elliptical flow at high transverse momenta
- n/p ratio of squeeze-out emission

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

E_{sym}: Current Status

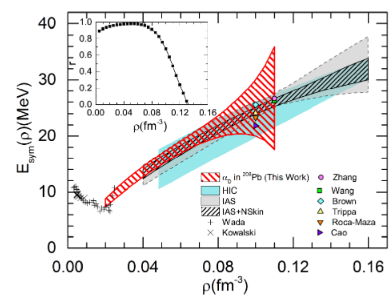
- There are MANY constraints on $E_{sym}(\rho_0)$ and L, essentially all the constraints seem to agree with:

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



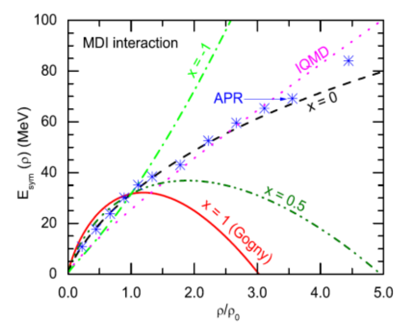
Lattimer/Steiner, EPJA50, 40 (2014)

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



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

- Essentially all the constraints on the high density Esym come from HIC's (FOPI), and all of them are based on transport models. The constraints on the high density Esym are still elusive and controversial for the moment !!!



Xiao/Li/Chen/Yong/Zhang, PRL102, 062502 (2009)

Characteristic Parameters of NM EOS

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

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

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(Received 27 May 2009; published 30 July 2009)

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

$$\delta = (n_{\rm n} - n_{\rm p})/n$$

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

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

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

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

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: I_0, $K_{sym}(\rho_0)$, $E_{sym,4}(\rho_0)$

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Characteristic Parameters of NM EOS

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: I_0, $K_{sym}(\rho_0)$, $E_{sym,4}(\rho_0)$

Order-0 ⇒ $E_0(\rho_0) = -16 \pm 1$ MeV

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

Order-3 ⇒ $L = 55 \pm 25$ MeV, J_0=???

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

- **$J_0 \approx [-464, -342]$ MeV and $K_{sym} \approx [-175, -36]$ MeV:**
  Data of finite nuclei + Flow Data in HIC + Neutron Star Mass + Tidal Deformability of Neutron Star (from recent GW170817 signal)

Outline

- **Nuclear matter EOS and the symmetry energy (Esym)**
- **High density nuclear matter from neutron star largest mass + tidal deformability from GW170817**
- **Summary**

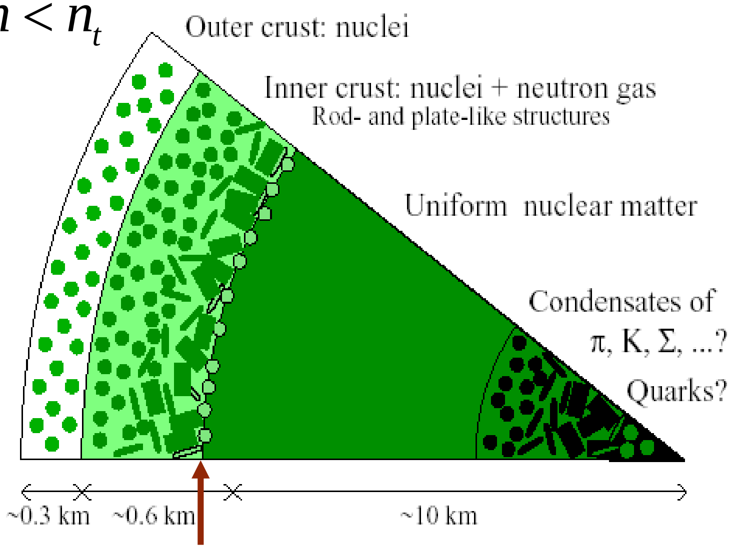
EOS of Neutron Star Matter

- Core of the neutron stars consist of infinite β-equilibrium npeμ matter with charge neutrality. Its EoS is determined by nuclear calculations, e.g., the Skyrme-Hartree-Fock(SHF)/Relativistic Mean Field(RMF) approach

- The inner crust $2.46\times10^{-4}\,\mathrm{fm}^{-3} = n_{\mathrm{out}} < n < n_t$

$$P = a + b\epsilon^{4/3}$$

$$a = \frac{P_{\mathrm{out}}\epsilon_t^{4/3} - P_t\epsilon_{\mathrm{out}}^{4/3}}{\epsilon_t^{4/3} - \epsilon_{\mathrm{out}}^{4/3}} \qquad b = \frac{P_t - P_{\mathrm{out}}}{\epsilon_t^{4/3} - \epsilon_{\mathrm{out}}^{4/3}}$$



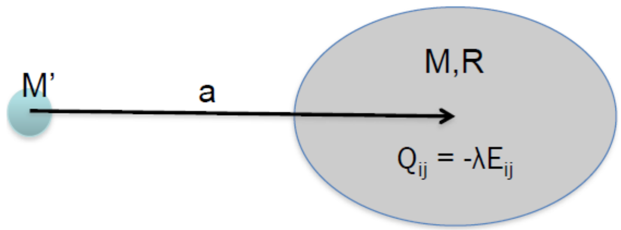
- The outer crust

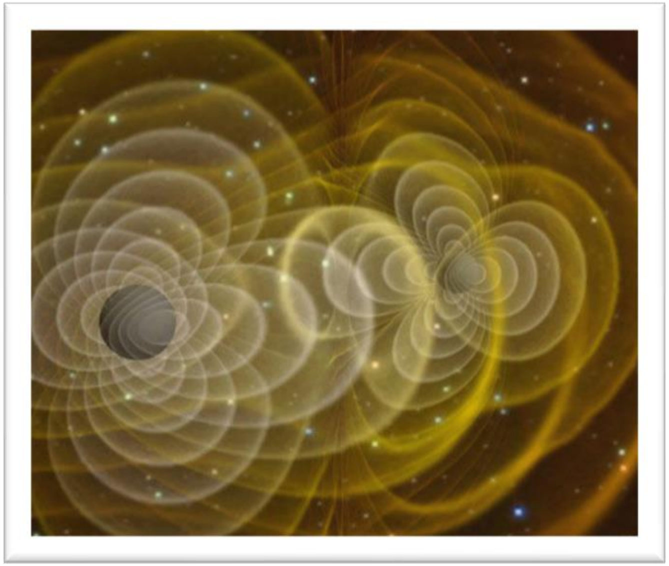
$6.93\times10^{-13}\,\mathrm{fm}^{-3} < n < n_{\mathrm{out}}$ (EOS of BPS)

$4.73\times10^{-15}\,\mathrm{fm}^{-3} < n < 6.93\times10^{-13}\,\mathrm{fm}^{-3}$ (EOS of Feynman-Metropolis-Teller)

Tidal Deformability

Tidal Deformability (Polarizability) (oscillation response coefficient λ)





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

Q_{ij}: Quadrupole moment

ε_{ij}: Tidal field of companion

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

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)

Tidal Deformability

EOS +

$$\frac{dy}{dr} = -\frac{1}{r}[y^2 + yF(p,\varepsilon) + r^2 Q(p,\varepsilon)]$$

$$\frac{dp}{dr} = -\frac{(\varepsilon + p)(m + 4\pi r^3 p)}{r(r-2m)}$$

$$\frac{dm}{dr} = 4\pi r^2 \varepsilon$$

$\Rightarrow$

M

R

$y_R \equiv y(R)$

$$k_2 = \frac{1}{20}\left(\frac{R_s}{R}\right)^5 \left(1-\frac{R_s}{R}\right)^2 \left[2-y_R+(y_R-1)\frac{R_s}{R}\right] \left\{\frac{R_s}{R}\left(6-3y_R+\frac{3R_s}{2R}(5y_R-8)\right)\right.$$
$$+\frac{1}{4}\left(\frac{R_s}{R}\right)^3\left[26-22y_R+\frac{R_s}{R}(3y_R-2)+\left(\frac{R_s}{R}\right)^2(y_R+1)\right]$$
$$\left.+3\left(1-\frac{R_s}{R}\right)^2\left[2-y_R+(y_R-1)\frac{R_s}{R}\right]\ln\left(1-\frac{R_s}{R}\right)\right\}^{-1}$$

$$F(r) = \frac{r - 4\pi r^3[\mathcal{E}(r) - P(r)]}{r - 2M(r)},$$

$$Q(r) = \frac{4\pi r\left[5\mathcal{E}(r) + 9P(r) + \frac{\mathcal{E}(r)+P(r)}{c_s^2} - \frac{6}{4\pi r^2}\right]}{r - 2M(r)} - 4\left\{\frac{M(r) + 4\pi r^3 P(r)}{r[r - 2M(r)]}\right\}^2.$$

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

The Skyrme HF Energy Density Functional

Extended Skyrme Interaction:

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

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

Momentum-dependence of many-body forces

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

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

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

13 macroscopic nuclear properties:

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

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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**
- **Other lower-order parameters are calibrated to fit data of finite nuclei**

Minimizing the Chi-square χ^2(p) :

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

Nstar maximum 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 ($M_\odot$)

PRL 119, 161101 (2017) Selected for a Viewpoint in *Physics* 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)

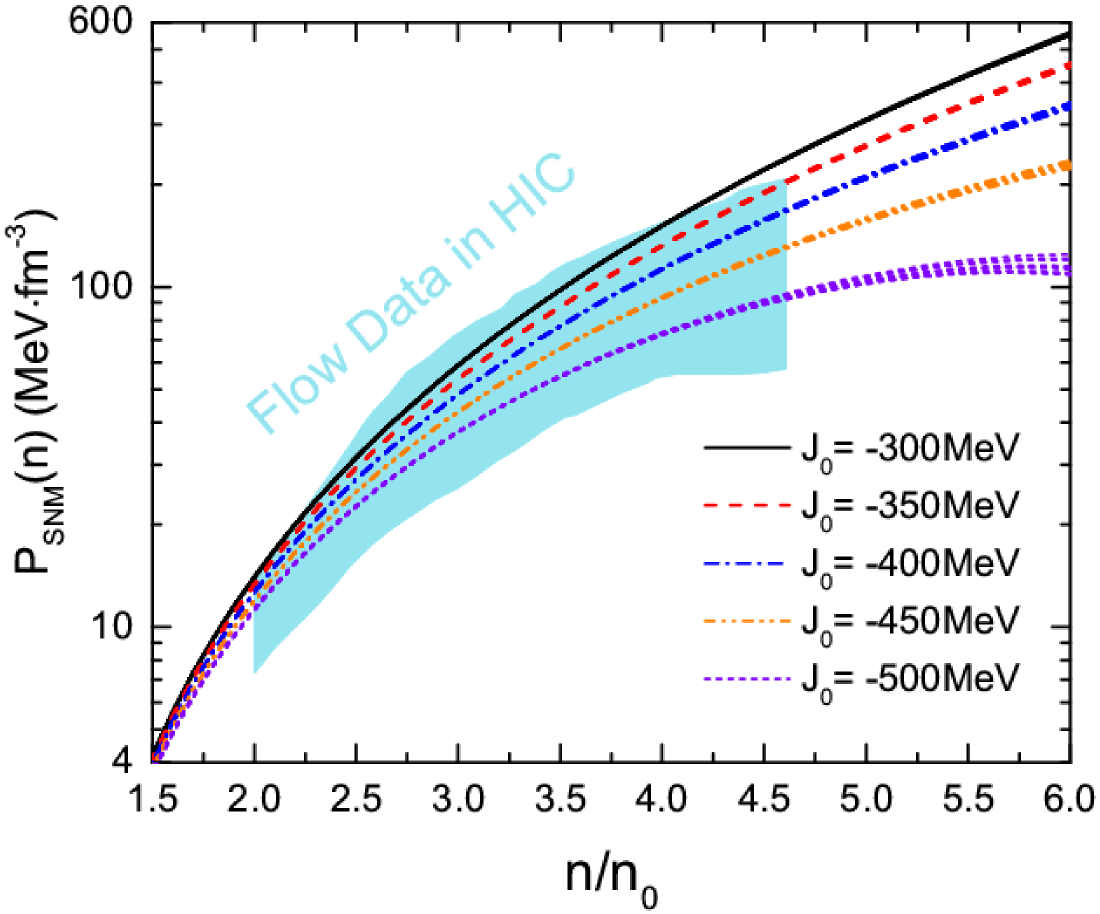
arXiv:1805.11581

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):
$\Lambda_{1.4} < 580$

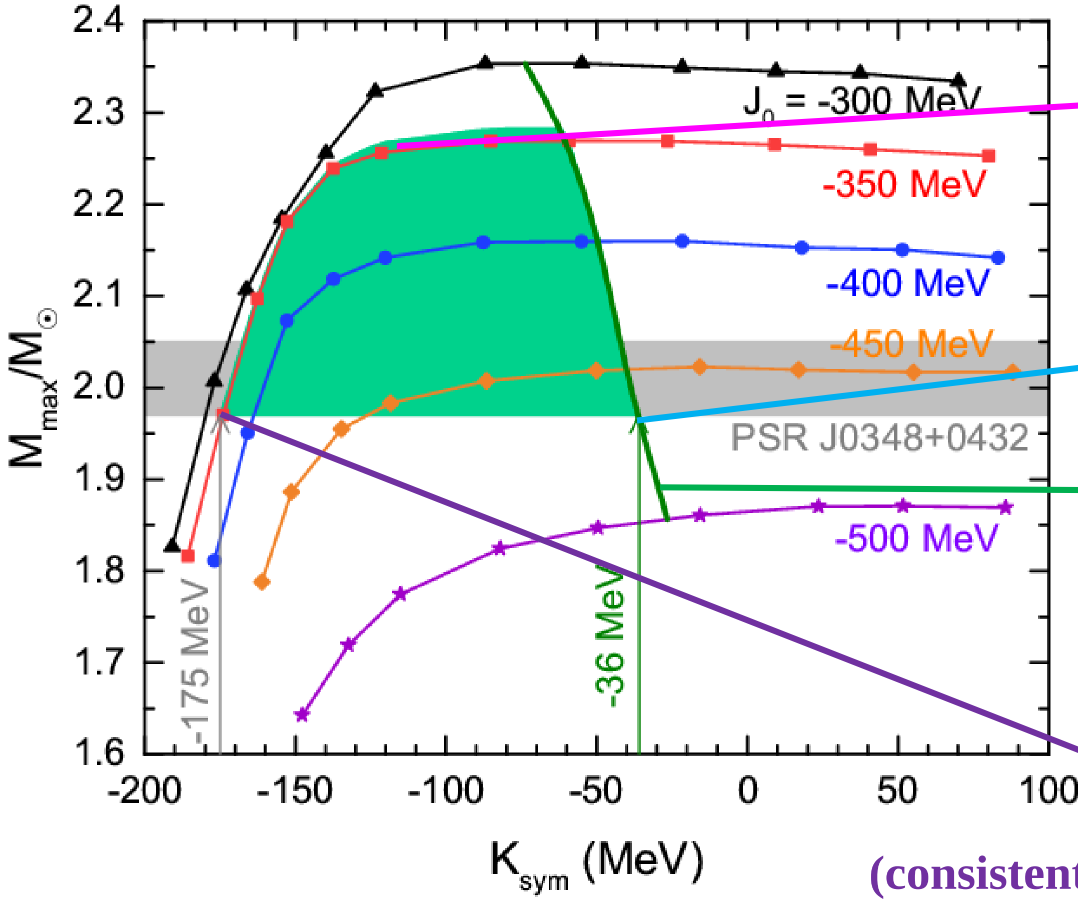
J0: Flow data



For various J0
Ksym:[-200, 100] MeV

-550 MeV < J_0 < -342 MeV: Flow Data in HIC

J0 and Ksym: Flow data, NStar Mass, Λ



J0 = -342 MeV

J0 = -464 MeV

$\Lambda_{1.4} = 580$

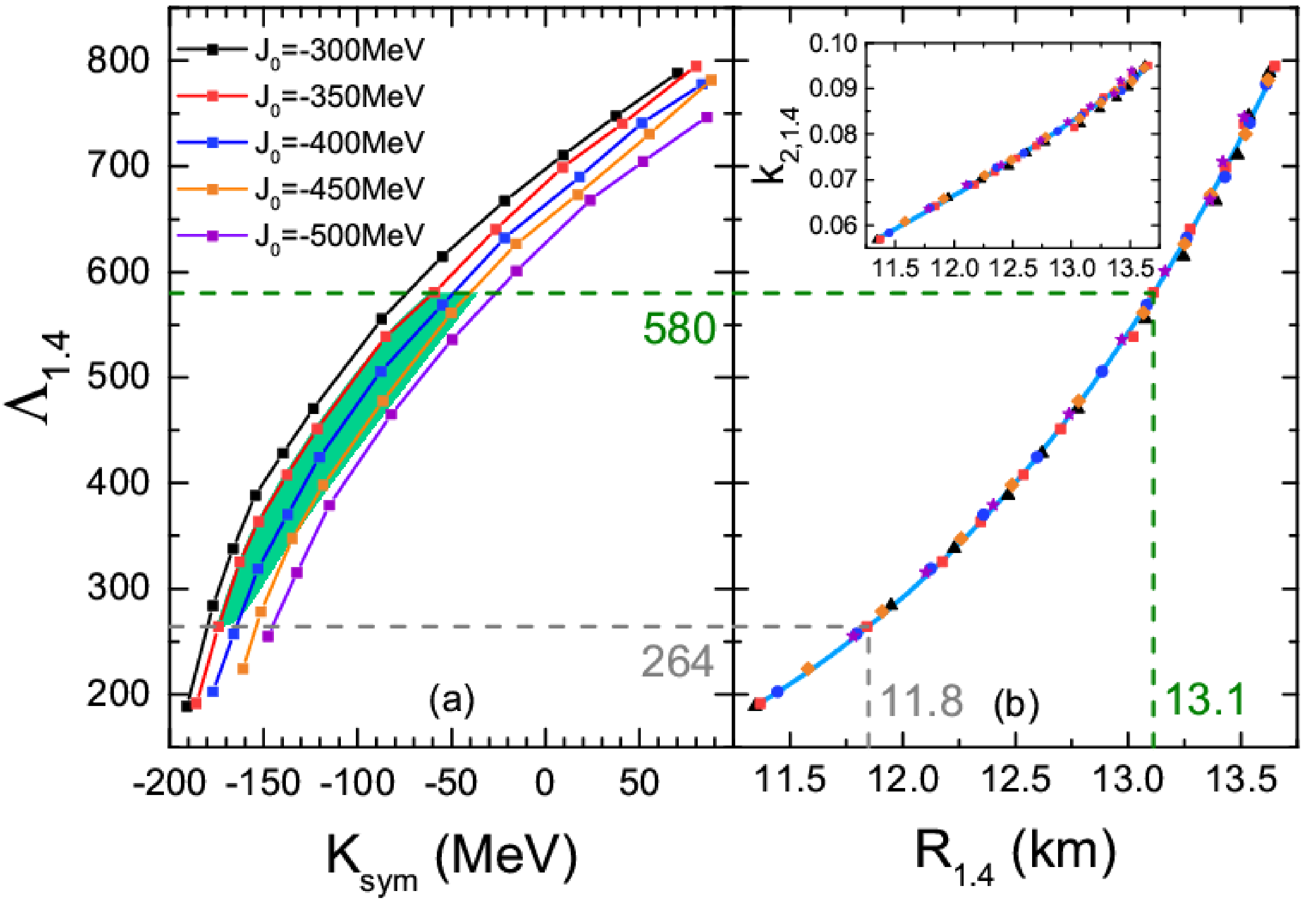
GW170817 (LIGO/Virgo):
$\Lambda_{1.4} < 580$

$\Lambda_{1.4} = 264$
(consistent with EM counterpart of GW170817)

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:

R1.4: Flow data, Nstar Mass, Λ



$R_{1.4}$: 11.8-13.1 km !

$$\Lambda_{1.4} = (1.24 \pm 0.12) \times 10^{-6} \cdot R_{1.4}^{(7.76\pm0.04)}$$
$$k_{2,1.4} = (7.62 \pm 0.53) \times 10^{-5} \cdot R_{1.4}^{(2.73\pm0.03)}$$

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

Outline

- **Nuclear matter EOS and the symmetry energy (Esym)**
- **High density nuclear matter from neutron star largest mass + tidal deformability from GW170817**
- **Summary**

上海交通大学 SHANGHAI JIAO TONG UNIVERSITY

Summary

- A lower limit of $\Lambda_{1.4}$ >264 for the tidal deformability of 1.4 solar mass neutron star can be obtained by using the flow data in HIC and the observed largest maximum mass of neutron stars
- The skewness coefficient J0 of symmetric nuclear matter can be constrained to be J0 = [-464, -342] MeV by using the flow data in HIC, the observed largest maximum mass of neutron stars, and the tidal deformability from GW170817
- The density curvature parameter Ksym of the symmetry energy can be constrained to be Ksym = [-175, -36] MeV by using the flow data in HIC, the observed largest maximum mass of neutron stars, and the tidal deformability from GW170817, ruling out the stiff high density behaviors of symmetry energy.

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Happy 88th birthday to Professor Akito Arima!