多信使时代核物质的状态方程

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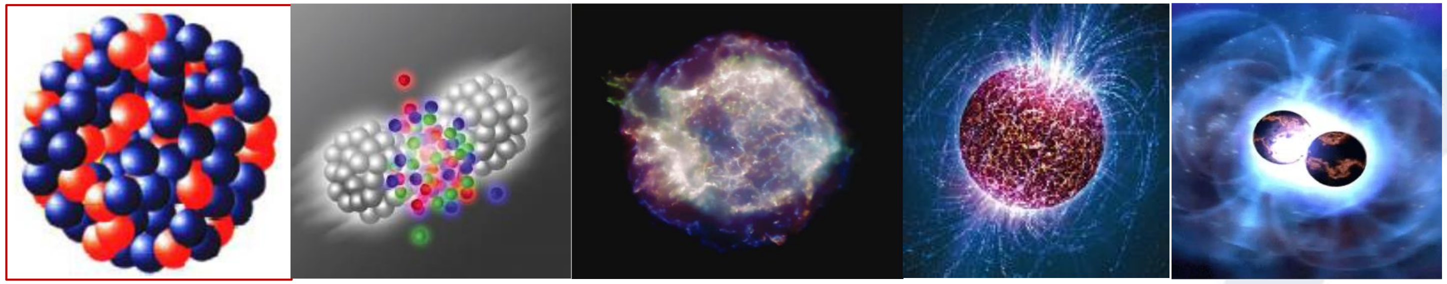
- **Where does the dense nuclear matter exist?**



Nucleus HIC SN NStar NS Merger

- **Can we build a unified Energy Density Functional to describe these dense systems?**

复旦大学 核科学与技术系/现代物理研究所 (online)
2022年4月29日

Outline

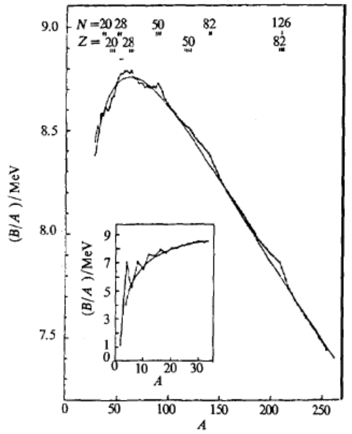
- Nuclear matter EOS and the symmetry energy (Esym)
- Dense nuclear matter from *Nuclear experiments + Neutron star mass and radius +Tidal deformability from GW170817*
- Summary and outlook

The Symmetry Energy of Finite Nuclei

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

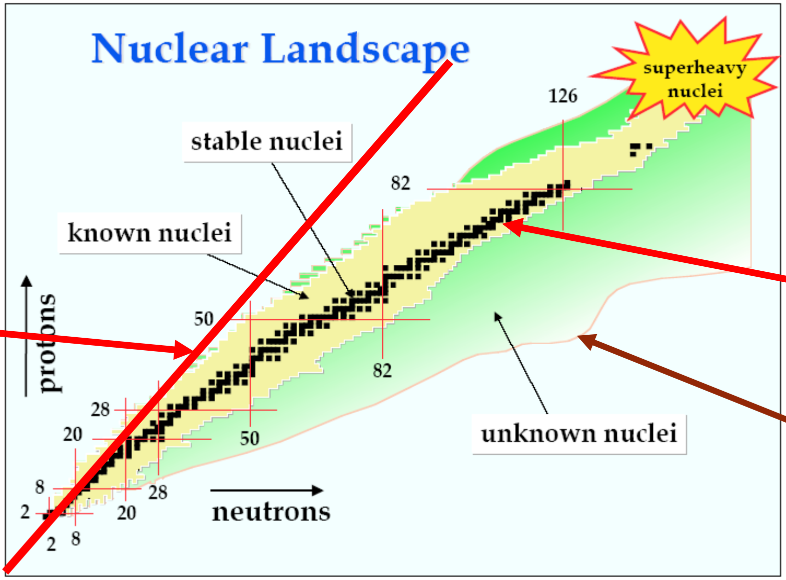
$$a_V A - a_s A^{2/3} - a_4 \frac{(N-Z)^2}{A} - a_c \frac{Z(Z-1)}{A^{1/3}} + a_p \frac{\Delta(N,Z)}{A^{1/2}}$$

Symmetry energy term
(对称能项)



对称能:
使中子数和质子数
趋于对称

N = Z



库仑能:
使中子数和质子数
偏离对称

N > Z

The Esym(2/3ρ_0) is very important for the global behaviors of N/P driplines!

R. Wang (王睿) /LWC, PRC92, 031303(R) (2015)

The Symmetry Energy of Nuclear Matter

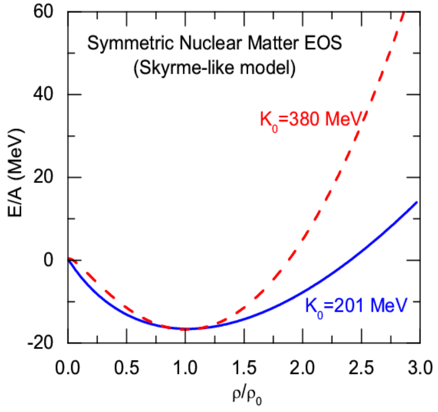
EOS of Isospin Asymmetric Nuclear Matter (Parabolic law)

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

Symmetric Nuclear Matter (relatively well-determined)

Isospin asymmetry

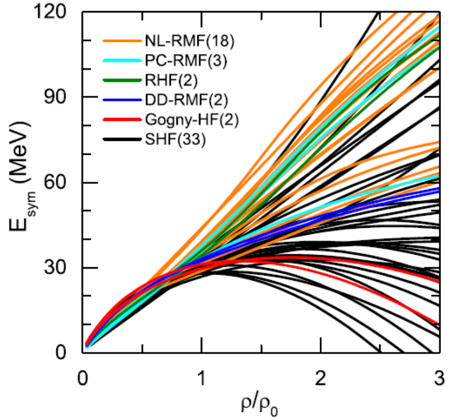
Symmetry energy term (largely uncertain)



Saturation: $\rho_0 \approx 0.16\ \text{fm}^{-3} \approx 2.7\times10^{14}\text{g/cm}^3$

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)

对称能是回答以下两个重大科学问题的关键量

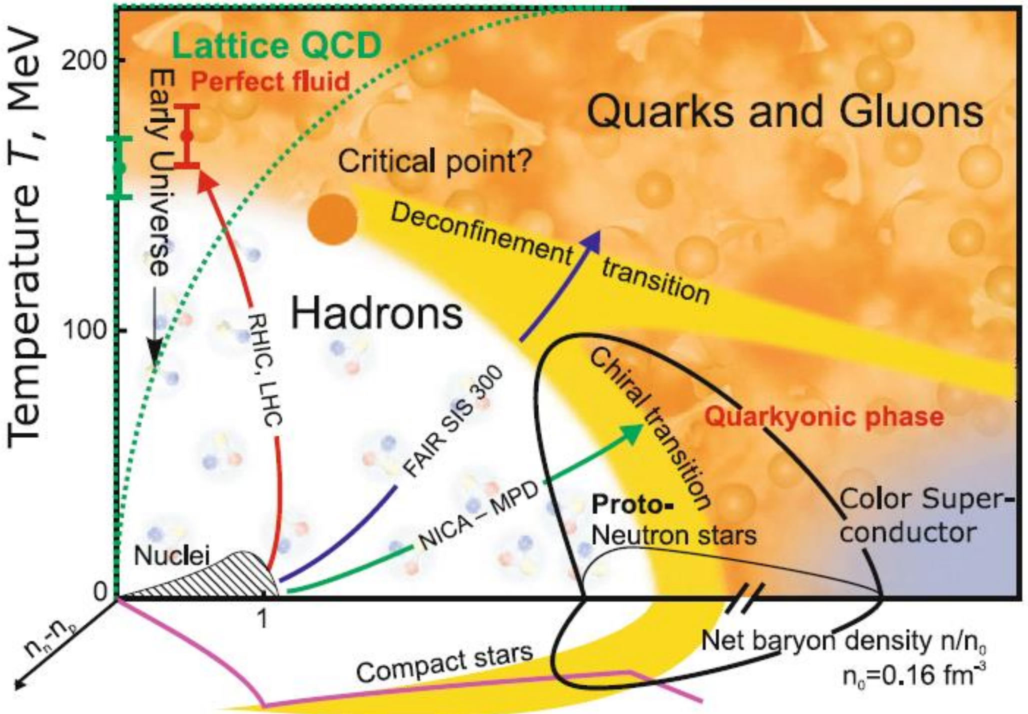
- 中子星和致密核物质的性质是什么?
- 宇宙中的元素是怎样产生的?

The Frontiers of Nuclear Science
A LONG RANGE PLAN
《美国核科学前沿长期规划》
The Nuclear Science Advisory Committee

◆ **确定对称能**已成为一些核物理大科学装置的重要物理目标，比如：中国兰州CSR/惠州HIAF、日本RIBF/RIKEN、美国FRIB/MSU和德国FAIR/GSI

QCD Phase Diagram

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

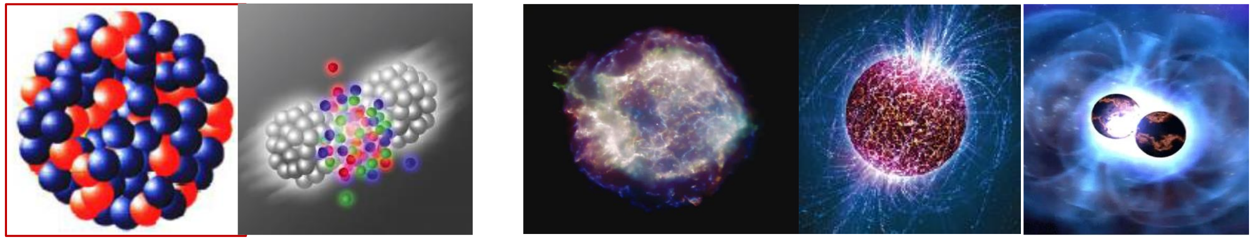


- Small baryon chemical potential: **Smooth Crossover Transition**
- Large baryon chemical potential: **First-order Phase Transition**
- QCD **Critical Endpoint (CEP)**: where the first-order phase transition ends

Holy Grail of Nuclear Physics

Probing QCD phase diagram in Nuclei and Heavy Ion Collisions in terrestrial labs

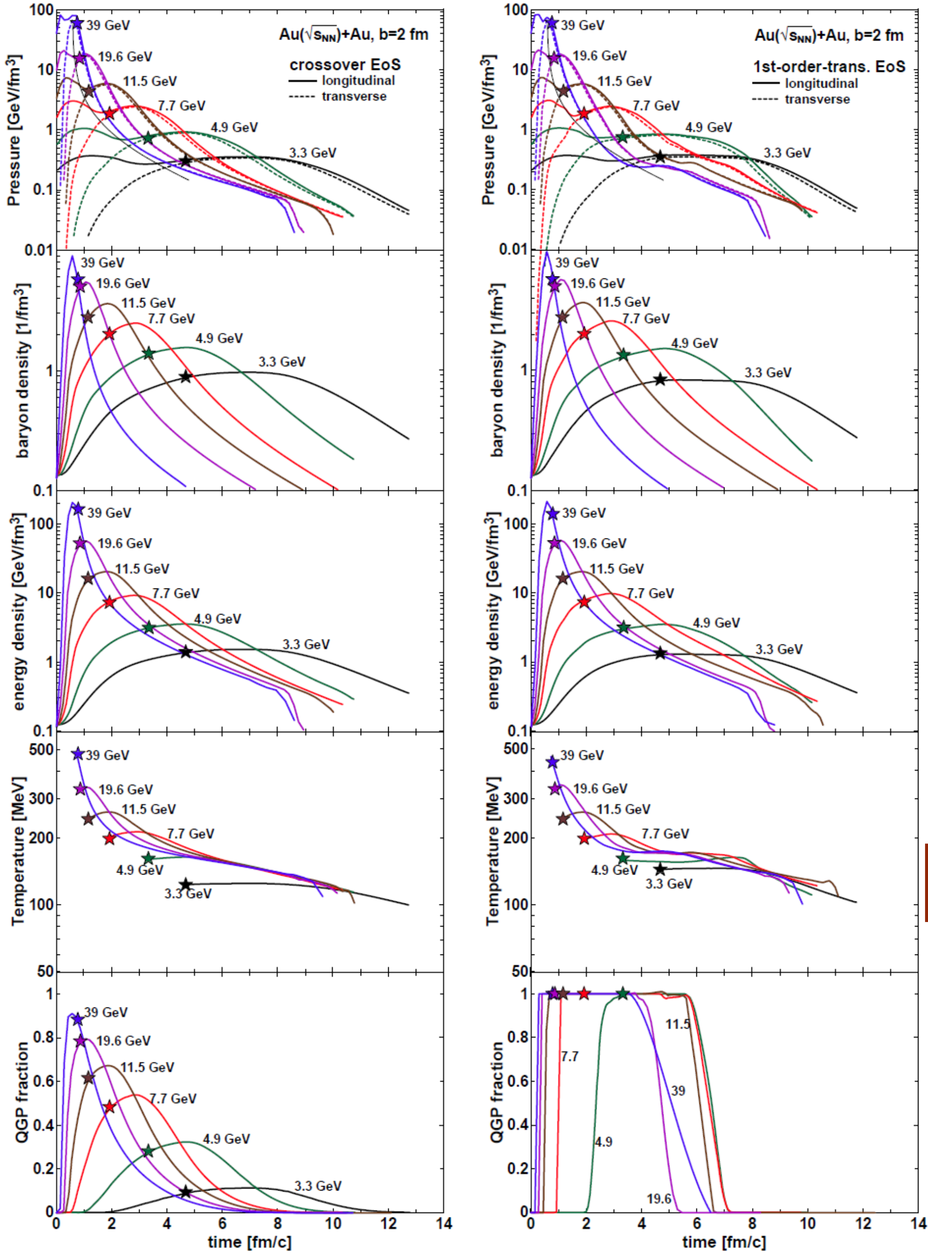
and in NS Merger, SN, and Nstar in heaven?



NS Mergers/NStar/CCSNe:
Ideal and unique site to probe QCD phase diagram at low T and high densities (and large isospin)!
Quark Matter Symmetry Energy?

M. Di Toro et al., NPA775 (2006); P.C. Chu (初鹏程)/LWC, ApJ780 (2014); LWC,《原子核物理评论》34, 20 (2017) [arXiv:1708.04433]

n_B and T in relativistic heavy-ion collisions



Head on Au+Au collisions (3-fluid dynamics)

Yu. B. Ivanov and A. A. Soldatov,
PRC 101, 024915 (2020) [arXiv:1911.10872]

The maximum baryon density could reach about ~ $4\rho_0$ ($30\rho_0$) in head on AuAu collisions at sqrt(s_NN) = 3.3 (39) GeV

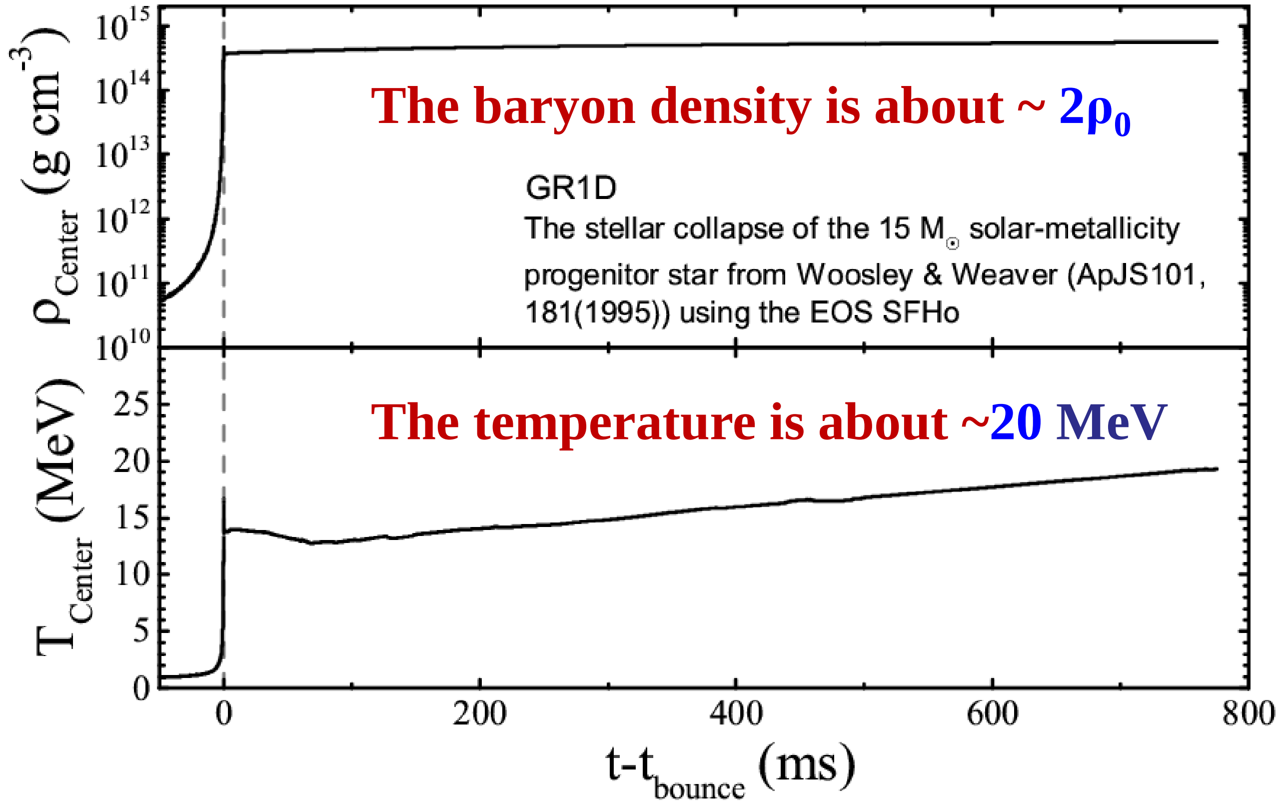
The temperature could reach about ~110 (500-110) MeV in head on AuAu collisions at sqrt(s_NN) = 3.3 (39) GeV

See also:
I.C. Arsene et al., PRC75, 034902(2007)

n_B and T in core-collapse SN and NStar

A typical Core-Collapse Supernova Explosion

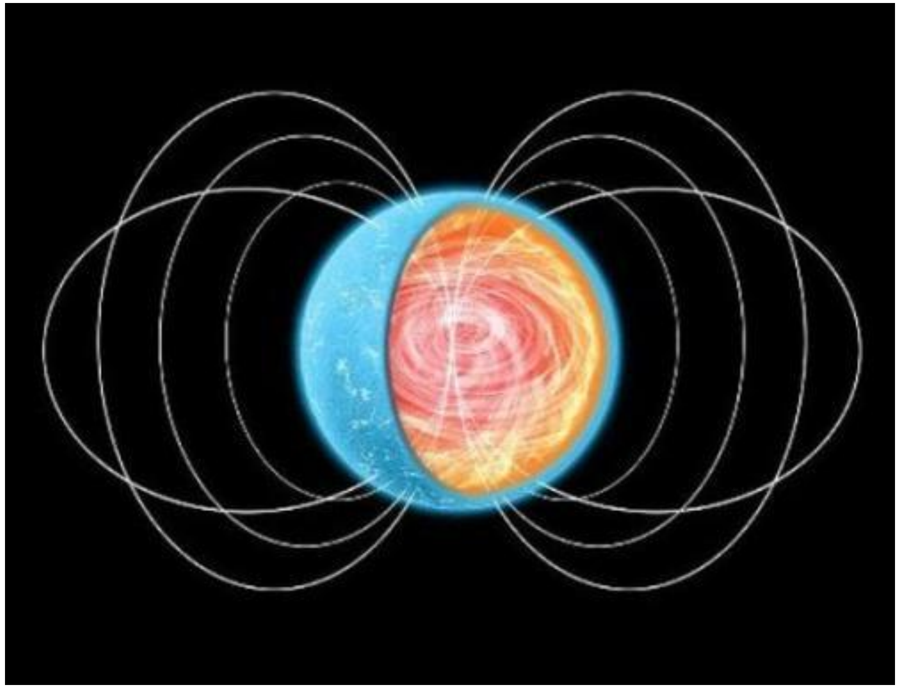
Xu-Run Huang (黄旭润), Shuai Zhao, and LWC, ApJL923, L26 (2021)



Density at the center: ~ $2\rho_0$

Temperature at the center: ~ 20 MeV (~50 MeV around the shock wave)

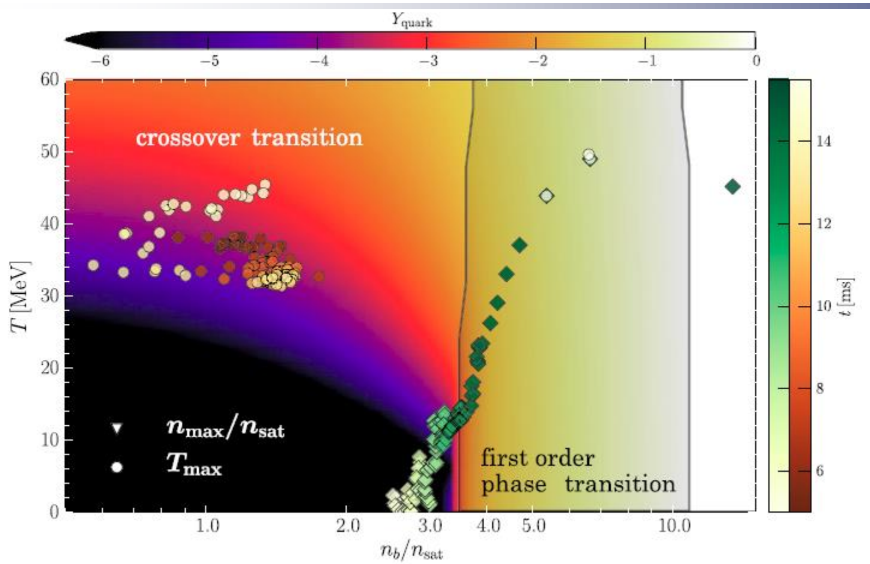
Neutron stars



Center density: ~ $6\rho_0$; Average density: ~ $2.5\rho_0$

Temperature ~ 0

n_B and T in binary neutron star merger

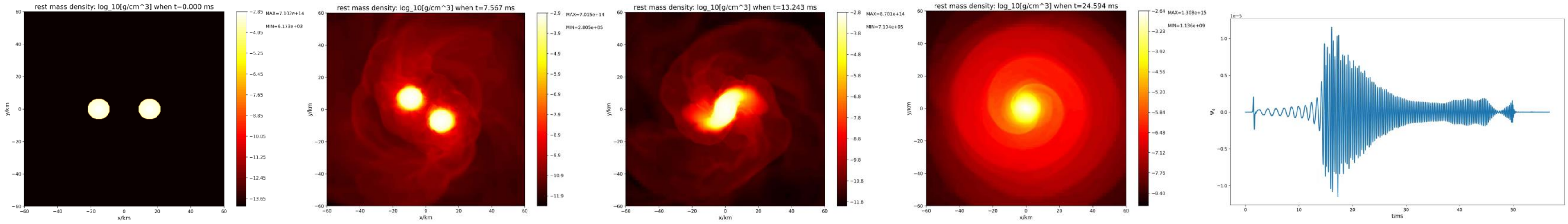


The overall evolution during and after the merger of the low-mass binary with total mass 2.8 $M_\odot$

The baryon density in binary neutron star merger could reach more than ~15ρ_0 and the temperature could reach ~0-50 MeV but with large isospin density!

Elias R. Most et al., PRL122, 061101 (2019)

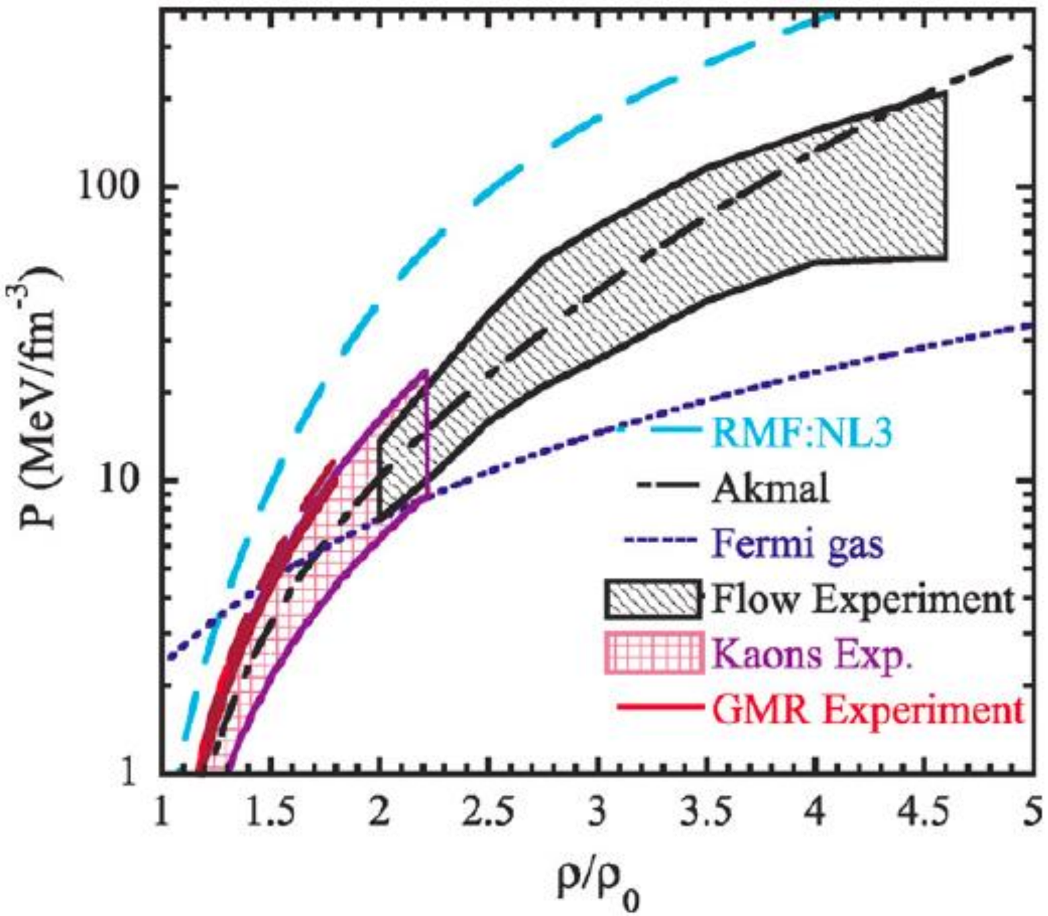
Matter density evolution of BNS mergers with equal mass 1.364$M_\odot$ (LS220 EOS, Ji-Min Bai(白济民) et al., preliminary)



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

EOS of Symmetric Nuclear Matter

W.G. Lynch et al., PPNP62, 427 (2009)



Curent status of the EOS of SNM:

- **Around $\rho_{0:}$ K_0=240±20 MeV from GMR [U. Garg and G. Colo, PPNP101, 55 (2018)]**
- **$1\rho_0 < \rho < 3\rho_0$ from K^+ production in HIC's. The range of densities for the kaon constraint represents an educated guess (有根据的推测☹) based on available calculations [C. Fuchs, PPNP 56, 1 (2006)]**
- **$2\rho_0 < \rho < 5\rho_0$ using flow data from BEVALAC, SIS/GSI and AGS [P. Danielewicz, R. Lacey and W.G. Lynch, Science 298, 1592 (2002)]**

The EOS of Symmetric NM has been relatively well constrained!

(~Soft EOS of SNM at high densities)

Esym: Many-Body Approaches

The nuclear matter EOS cannot be measured experimentally, its determination thus depends on theoretical approaches

- **Microscopic Many-Body Approaches**

  Non-relativistic Brueckner-Bethe-Goldstone (BBG) Theory
  Relativistic Dirac-Brueckner-Hartree-Fock (DBHF) approach
  Self-Consistent Green's Function (SCGF) Theory
  Variational Many-Body (VMB) approach
  Green's Function Monte Carlo Calculation
  V_{lowk} + Renormalization Group
  Nuclear Lattice Approach

- **Effective Field Theory**

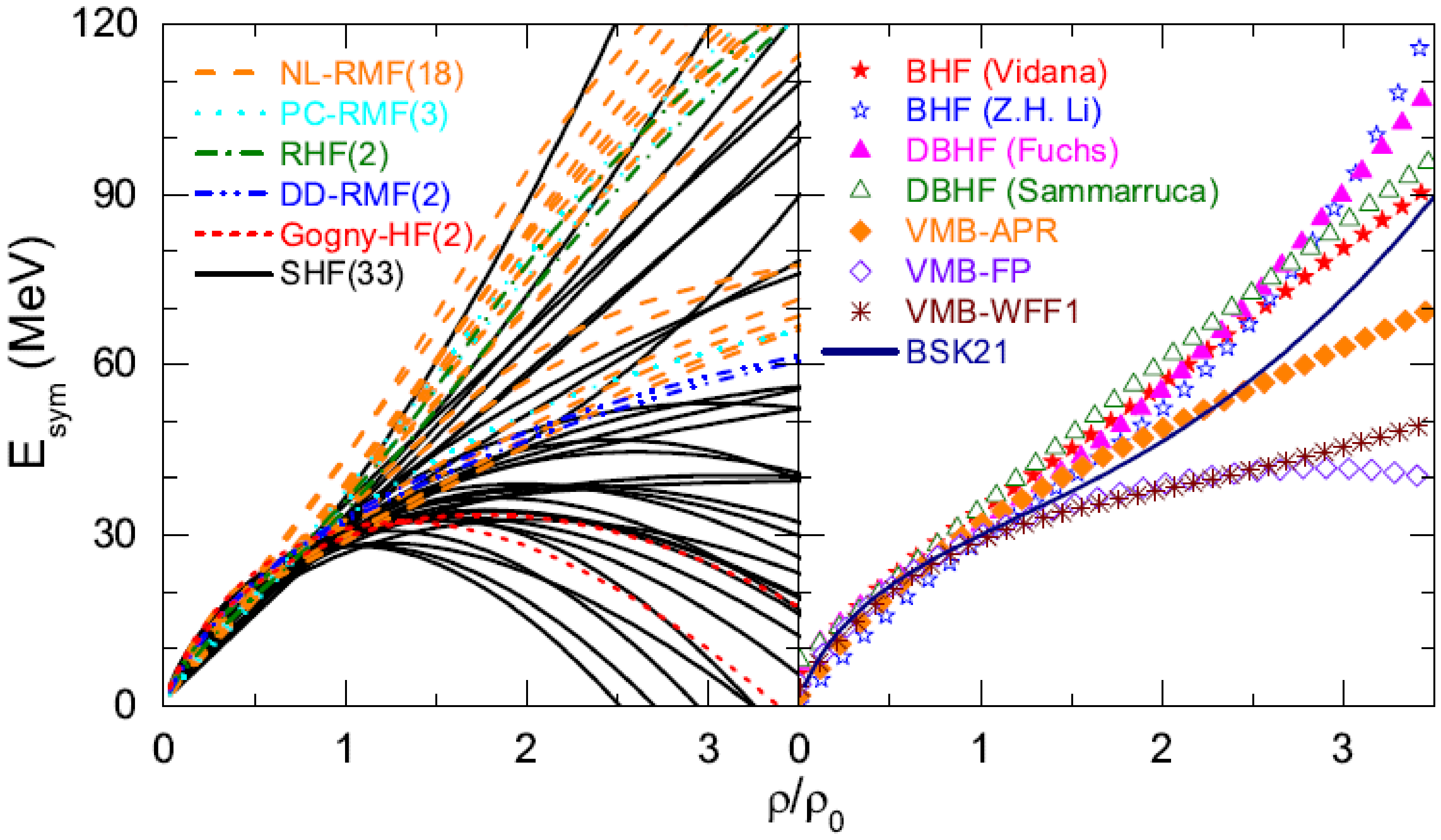
  Density Functional Theory (DFT)
  Chiral Perturbation Theory (ChPT)
  QCD-based theory

- **Phenomenological Approaches**

  Relativistic mean-field (RMF) theory
  Quark Meson Coupling (QMC) Model
  Relativistic Hartree-Fock (RHF)
  Non-relativistic Hartree-Fock (Skyrme-Hartree-Fock)
  Thomas-Fermi (TF) approximations

Esym: Many-Body Approaches

L.W. Chen, Nucl. Phys. Rev. (原子核物理评论) 34, 20 (2017)
[arXiv:1708.04433]



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)
[arXiv:0804.3580] (Citations: 1082+)

Facilities of Radioactive Ion Beams

An incomplete list

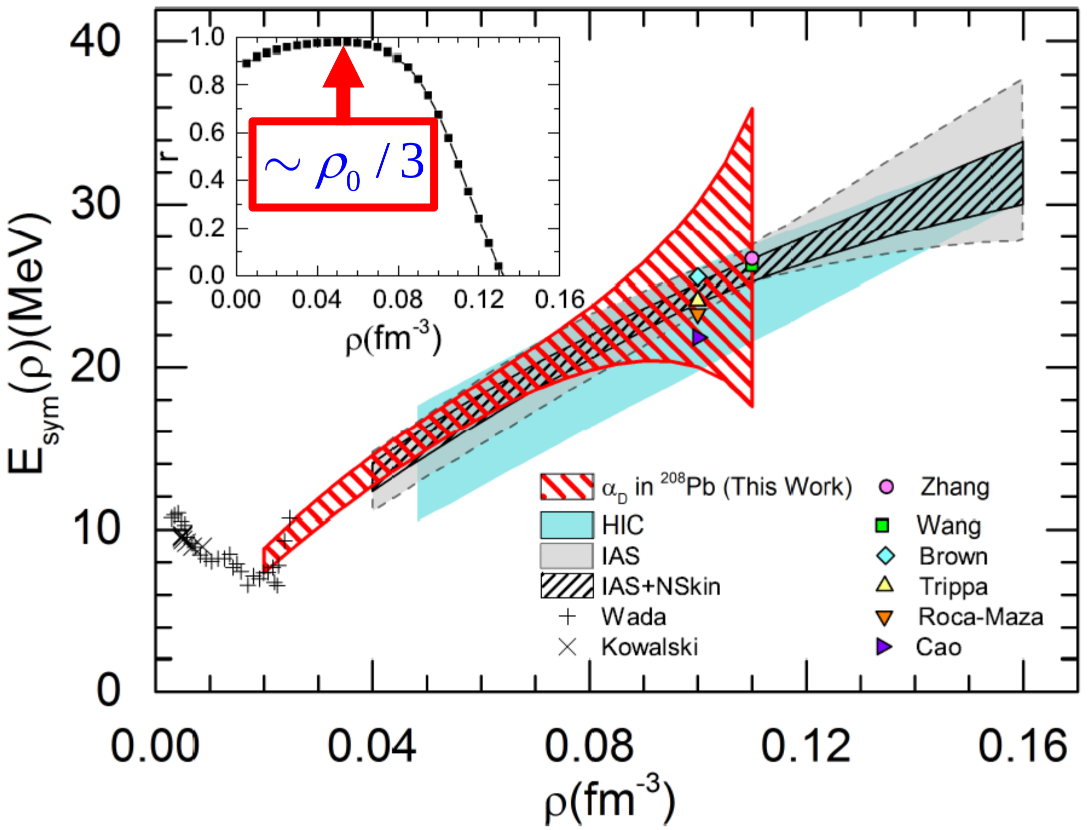
- Cooling Storage Ring (CSR) Facility at HIRFL/Lanzhou in China (2008)
  up to 500 MeV/A for ^{238}U (~1GeV/A for C)
  http://www.impcas.ac.cn/zhuye/en/htm/247.htm
- Radioactive Ion Beam Factory (RIBF) at RIKEN in Japan (2007)
  http://www.riken.jp/engn/index.html
- Texas A&M Facility for Rare Exotic Beams -T-REX (2013)
  http://cyclotron.tamu.edu
- Facility for Antiproton and Ion Research (FAIR)/GSI in Germany (2022?)
  up to 2 GeV/A for ^{132}Sn (NUSTAR - NUclear STructure, Astrophysics and Reactions)
  http://www.gsi.de/fair/index_e.html
- SPIRAL2/GANIL in France (2013)
  http://pro.ganil-spiral2.eu/spiral2
- Selective Production of Exotic Species (SPES)/INFN in Italy (2015)
  http://web.infn.it/spes
- Facility for Rare Isotope Beams (FRIB)/MSU in USA (2022?)
  up to 400(200) MeV/A for ^{132}Sn
  http://www.frib.msu.edu/
- The Korean Rare Isotope Accelerator (KoRIA-RAON(RISP Accelerator Complex) (2021?)
  up to 250 MeV/A for ^{132}Sn, up to 109 pps

……(NICA, J-PARC-HI)

SHANGHAI JIAO TONG UNIVERSITY 上海交通大學

E_{sym}: Subsaturation densities

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



- $\Delta E(A\sim 208) \propto E_{sym}(\rho_{A=208}),\ \rho_{A=208} \approx 2/3\rho_0$
- $1/\alpha_D(A=208) \propto E_{sym}(\rho_{A=45}),\ \rho_{A=45} \approx 1/3\rho_0$

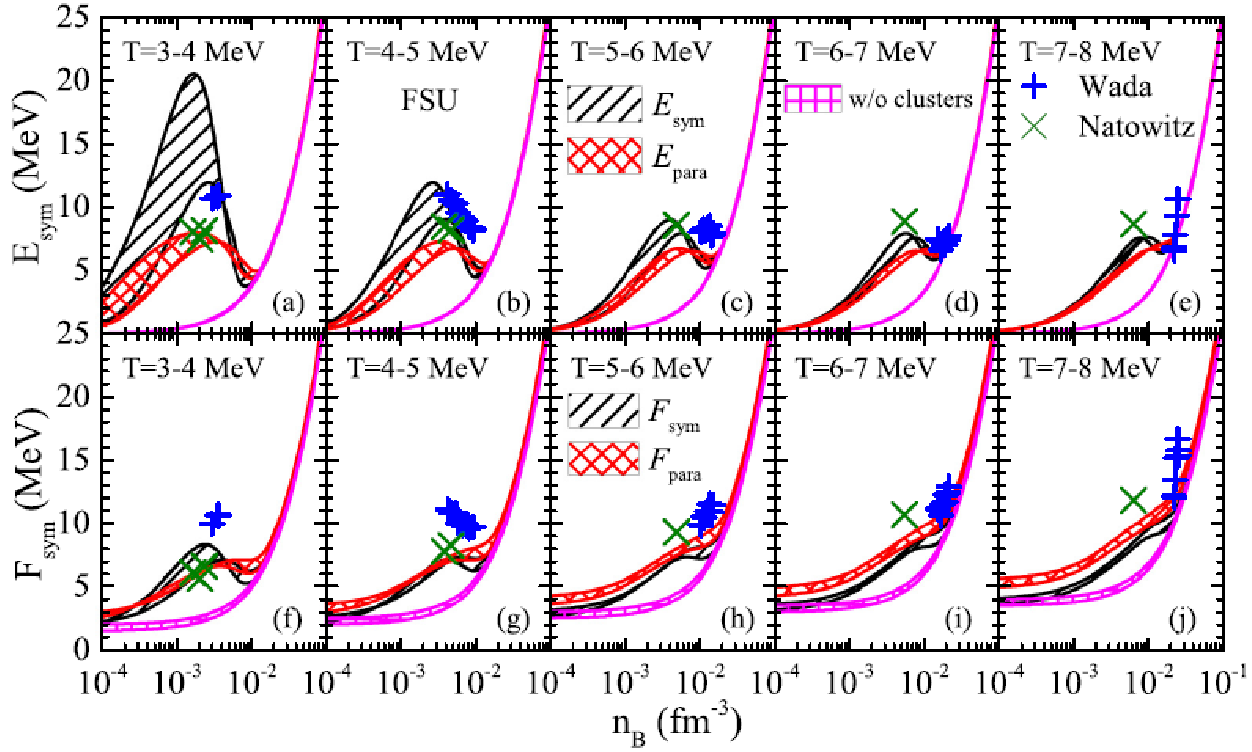
- HIC: Sn+Sn
  M.B. Tsang *et al.*, Phys. Rev. Lett. **102**, 122701(2009)
- IAS and IAS+NSkin
  P. Danielewicz and J. Lee, Nucl. Phys. **A922**, 1 (2014)
- Zhang: Isotope binding energy difference
  Z. Zhang and L.W. Chen, Phys. Lett. **B726**, 234 (2013)
- Wang: Fermi energy difference
  N. Wang *et 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.

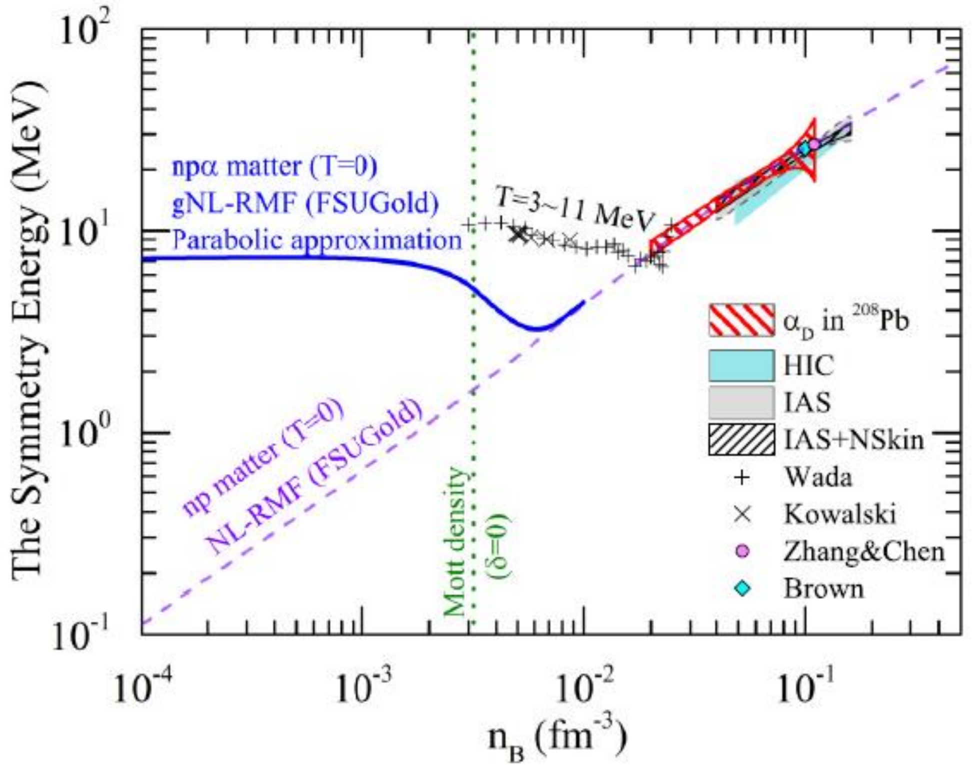
E_{sym}: Subsaturation densities

Clustering effects on Esym within NL-RMF for n, p, t, h, α matter



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

Alpha BEC effects on Esym within NL-RMF for cold npα matter



Zhao-Wen Zhang (张肇文) and LWC, PRC100, 054304 (2019)

See also: S. Typel, G. Röpke, T. Klähn, D. Blaschke, and H. H. Wolter, Phys. Rev. C 81, 015803 (2010).

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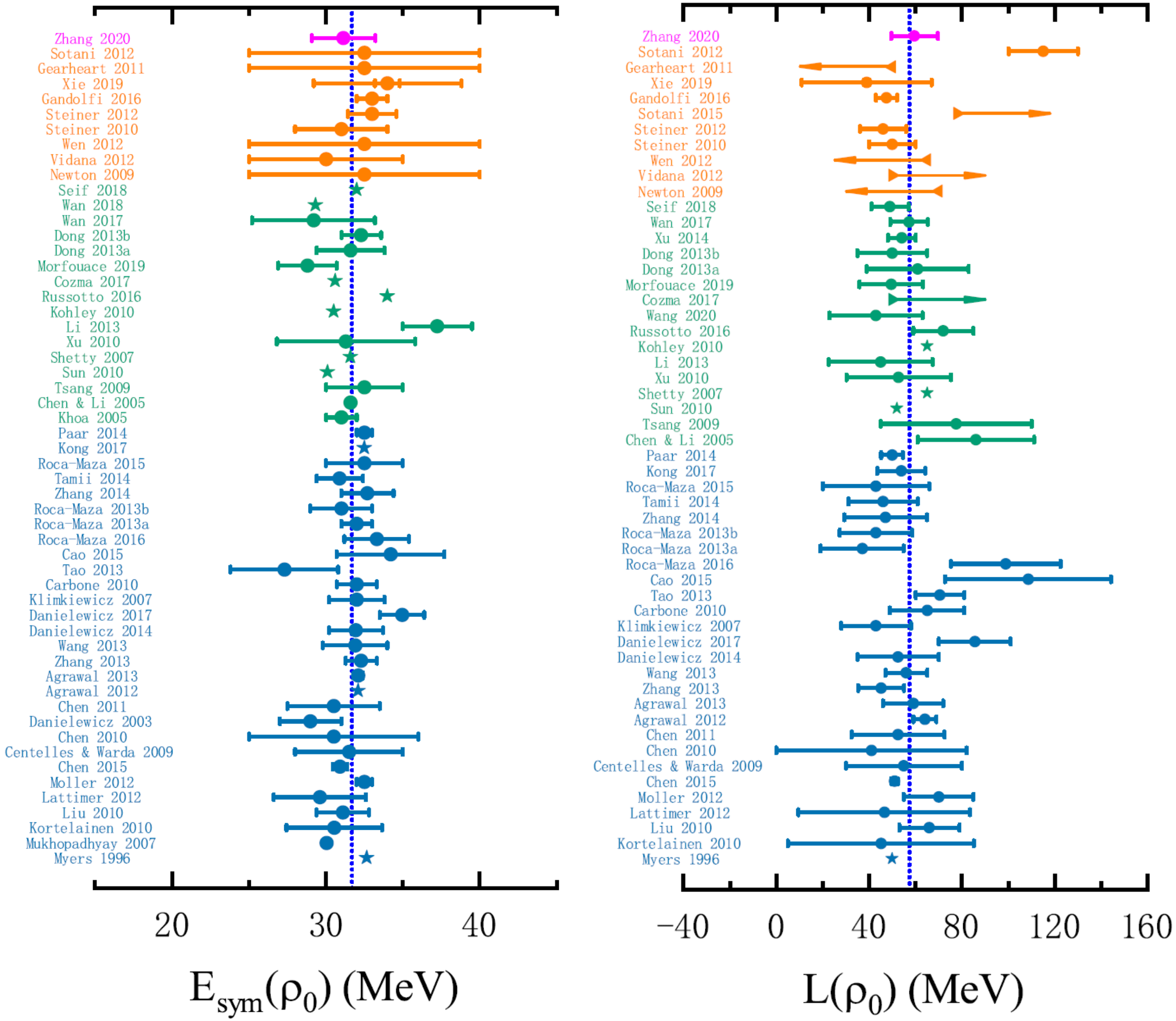
E_{sym}: Around saturation density



LWC et al., Invited Review/PPNP

58 analyses of terrestrial nuclear experiments and astrophysical observations

$E_{sym}(\rho_0) = 31.7 \pm 3.1$

$L = 57.5 \pm 24.5$ MeV

Similar conclusion has been obtained in:

B. A. Li and X. Han, Phys. Lett. B727, 276 (2013); M. Oertel, M. Hempel, T. Klahn, and S. Typel, Rev. Mod. Phys. 89, 015007 (2017).

Assuming all the constraints are equally reliable !!!

Very recent PREX-II data suggest stiff Esym around saturation density!

E_{sym}: Around saturation density

PHYSICAL REVIEW LETTERS 125, 222301 (2020)

Probing the Neutron Skin with Ultrarelativistic Isobaric Collisions

Hanlin Li,[1] Hao-jie Xu,[2,*] Ying Zhou,[3] Xiaobao Wang,[2] Jie Zhao,[4] Lie-Wen Chen,[3,†] and Fuqiang Wang[2,4,‡]

H.-j. Xu et al., arXiv:2111.14812

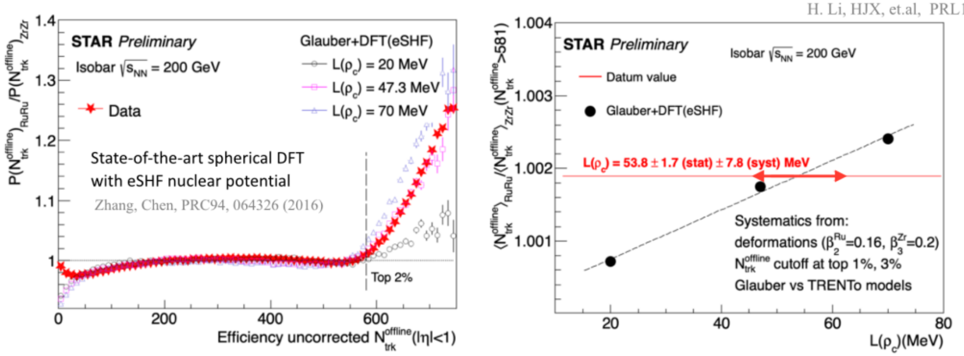
Probing nuclear structure with mean transverse momentum in relativistic isobar collisions

Hao-jie Xu,[1] Wenbin Zhao,[2] Hanlin Li,[3] Ying Zhou,[4] Lie-Wen Chen,[4] and Fuqiang Wang[1,5]

Multiplicity ratio to probe symmetry energy

15

H. Li, HJX, et.al, PRL125, 222301 (2020)



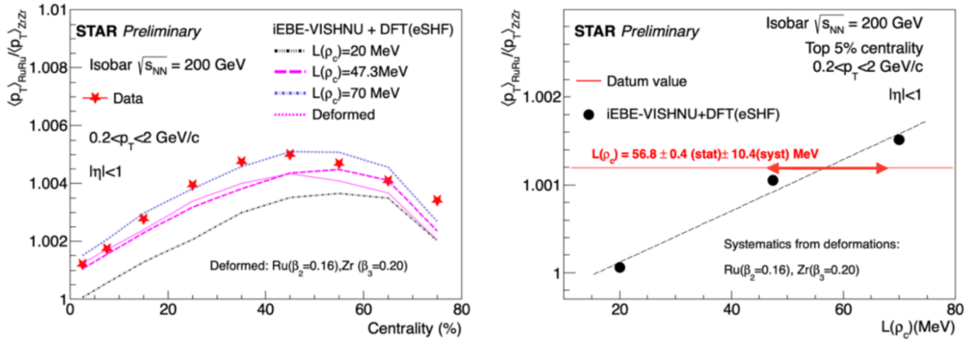
- Mean multiplicity ratio in central collisions to extract neutron skin thickness and symmetry energy
- Uncertainties can be improved with deformed (more difficult) DFT calculations

$L(\rho_c) = 53.8 \pm 1.7 \pm 7.8$ MeV
$L(\rho) = 65.4 \pm 2.1 \pm 12.1$ MeV
$\Delta r_{np,Zr} = 0.195 \pm 0.019$ fm
$\Delta r_{np,Ru} = 0.051 \pm 0.009$ fm

Haojie Xu

$\langle p_T \rangle$ ratio to probe symmetry energy

16



- The values at top 5% are used to extract neutron skin
- The centrality dependence needs further investigation (nuclei size vs collision geometry)

$L(\rho_c) = 56.8 \pm 0.4 \pm 10.4$ MeV
$L(\rho) = 69.8 \pm 0.7 \pm 16.0$ MeV
$\Delta r_{np,Zr} = 0.202 \pm 0.024$ fm
$\Delta r_{np,Ru} = 0.052 \pm 0.012$ fm

HJX, et.al arXiv:2111.14812

Consistent with the measurement from multiplicity ratio

Haojie Xu

Multiplicity ratio: Lc=53.8±1.7±7.8 MeV
L=65.4±2.1±12.1 MeV

<pT> ratio: Lc=56.8±0.4±10.4 MeV
L=69.8±0.7±16.0 MeV

RHIC-STAR isobaric collisions data favor stiff Esym around saturation density!

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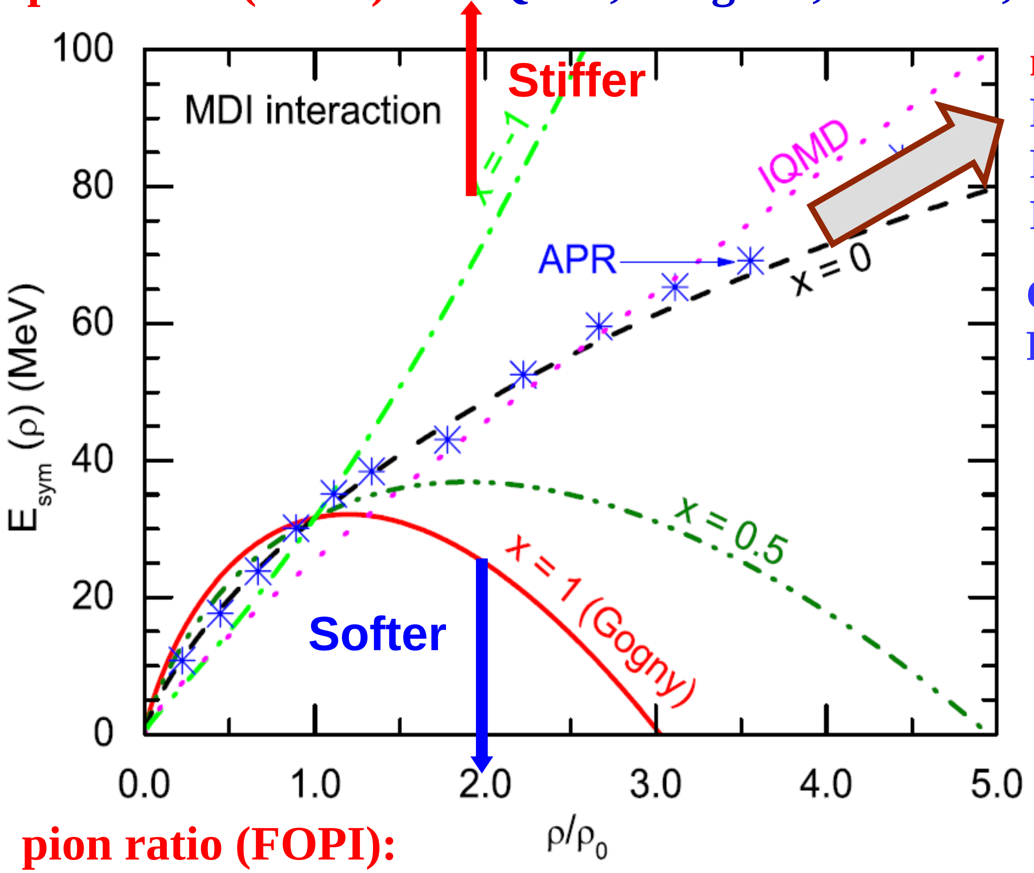
E_{sym}: Supra-saturation density

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

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



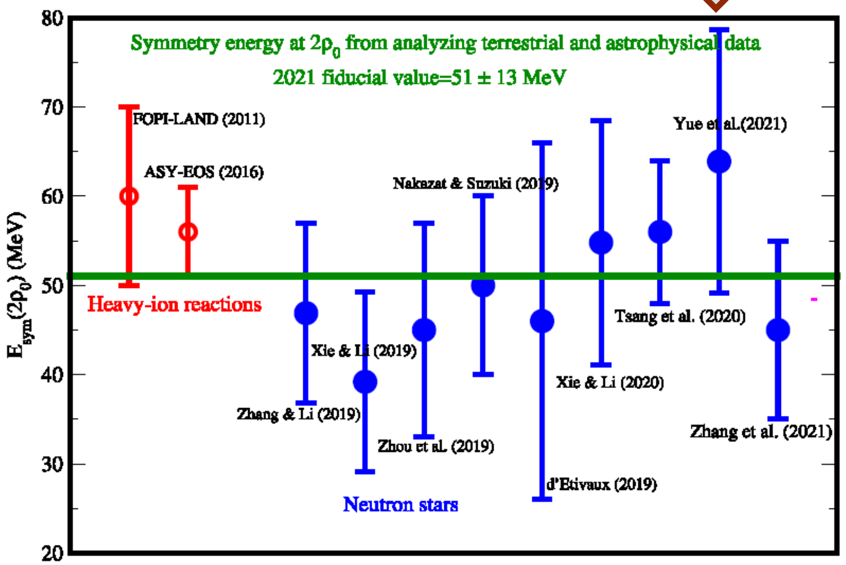
pion ratio (FOPI):
IBUU04, Xiao/Li/Chen/Yong/Zhang, PRL102,062502(2009)
ImIBLE, Xie/Su/Zhu/Zhang, PLB718,1510(2013)

n/p v2 (FOPI): $(\rho/\rho_0)^\gamma$ with $\gamma = 0.9 \pm 0.4$
Russotto/Trauntmann/Li et al., PLB697, 471(2011) (UrQMD)
PRC94, 034608 (2016) $\gamma = 0.72 \pm 0.19$

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

Tong-Gang Yue (岳侗钢), LWC, Z. Zhang (张振), and Y. Zhou (周颖), arXiv:2102.05267

PREX-II



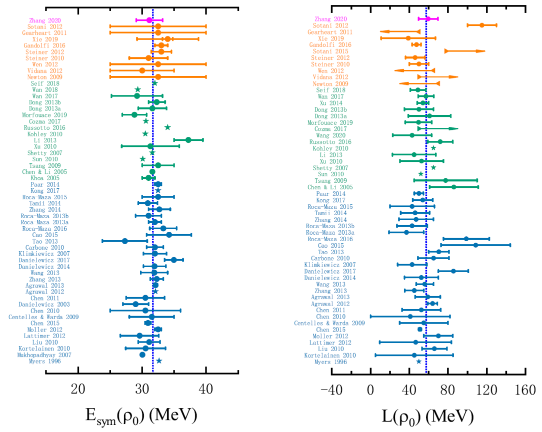
B.A.Li, B.J. Cai, W.J. Xie, and N.B. Zhang, Universe 7, 187 (2021)

E_{sym}: Current Status

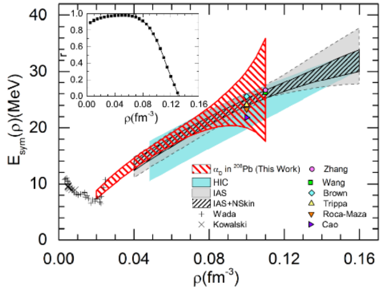
● There are MANY constraints on $E_{sym}(\rho_0)$ and L, and the world average values are:

$$E_{sym}(\rho_0) = 31.7 \pm 3.1 \text{ MeV}$$
$$L = 57.5 \pm 24.5 \text{ MeV}$$

Very recent PREX-II makes the situation elusive !!! (This Talk)

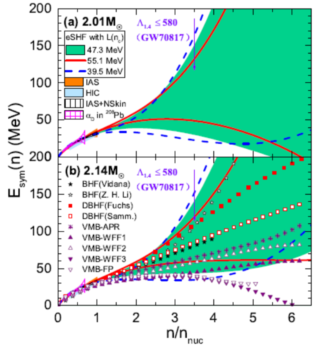


● The symmetry energy at subsaturation densities have been relatively well-constrained



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

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



Y. Zhou (周颖), LWC, ApJ886, 52(2019) [arXiv:1907.12284]

Outline

- **Nuclear matter EOS and the symmetry energy (Esym)**
- **Dense nuclear matter from *Nuclear experiments + Neutron star mass and radius +Tidal deformability from GW170817***
- **Summary and outlook**

Characteristic Parameters of NM EOS

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)

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

$$\delta = (\rho_n - \rho_p)/\rho$$

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

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

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

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

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

Jie Pu (普洁) et al., to be Submiited

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 → $K_0 = 240 \pm 20$ MeV, $E_{sym}(\rho_0) = 32.5 \pm 2.5$ MeV???

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

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

- **$J_0 \approx$? and $K_{sym} \approx$? High Density Behaviors?**
  Data of finite nuclei + Flow Data in HIC + Observed NStar Largest Mass + NStar M-R from NICER + Tidal Deformability of Neutron Star (from GW170817) analyzed simultaneously within a unified Nuclear Energy Density Functional

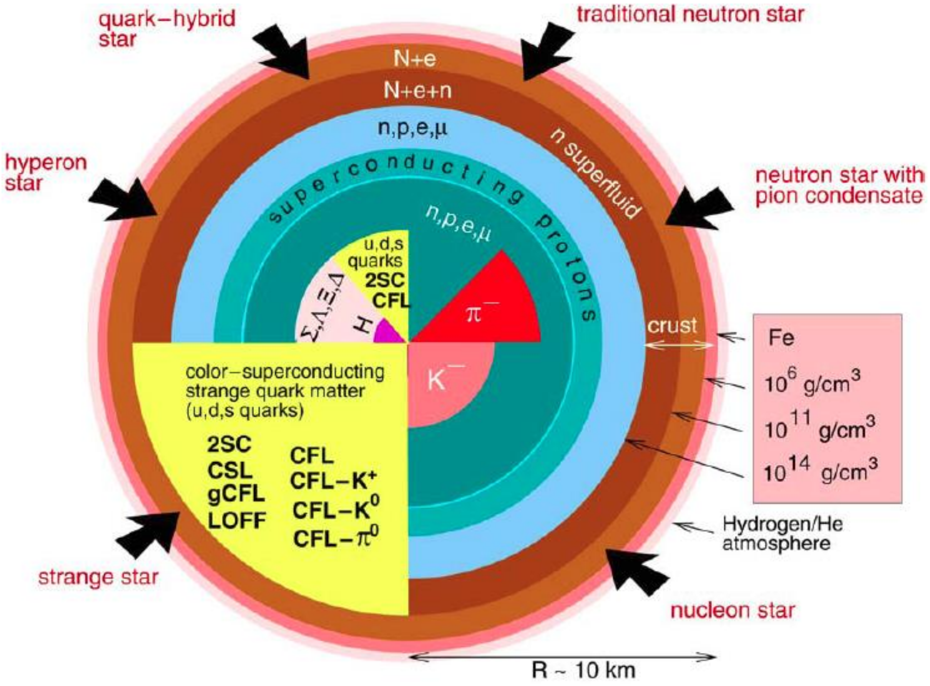
Why a unified Nuclear Energy Density Functional?

The nuclear energy density functional theory (e.g., SHF/RMF) is still the only realistic framework to simultaneously investigate the physics of heavy nuclei and neutron stars as well as heavy-ion collisions !!!

Composition of Neutron Star Matter

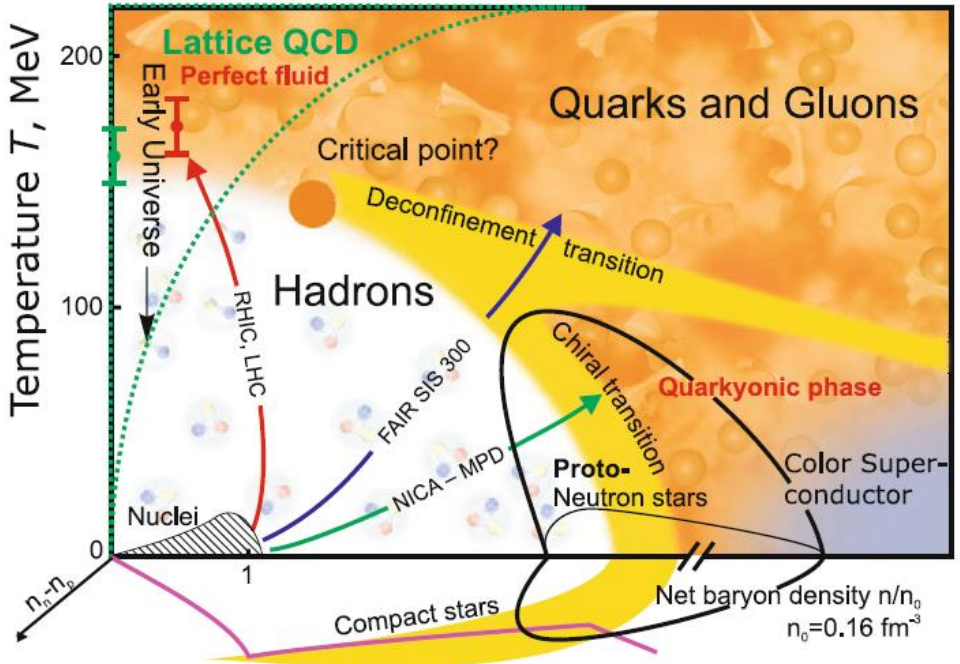
Pulsars: Neutron Stars? Quark Stars? Hybrid Stars? Others?

F. Weber, PPNP54, 193 (2005)



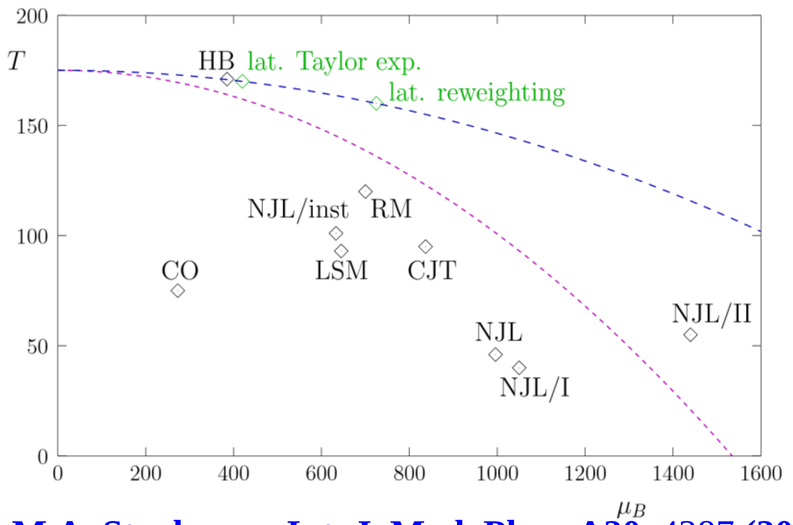
Mass: ~ 1.4 $M_{\odot}$, Radius: ~ 10 km
Extremely neutron-rich matter
Density at the center: ~ $6\rho_0$
Average density: ~ $2.5\rho_0$

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

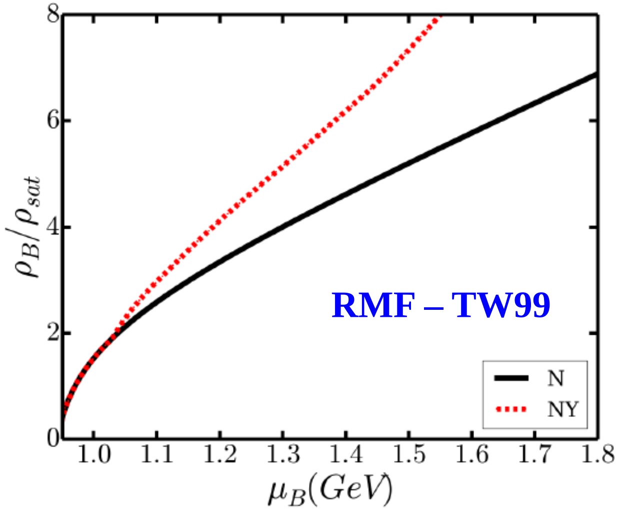


The mass of ud Quark Star can be 2.77$M_{\odot}$, Z. Cao (曹政), LWC, P.C. Chu (初鹏程), and Y. Zhou (周颖), arXiv:2009.00942.

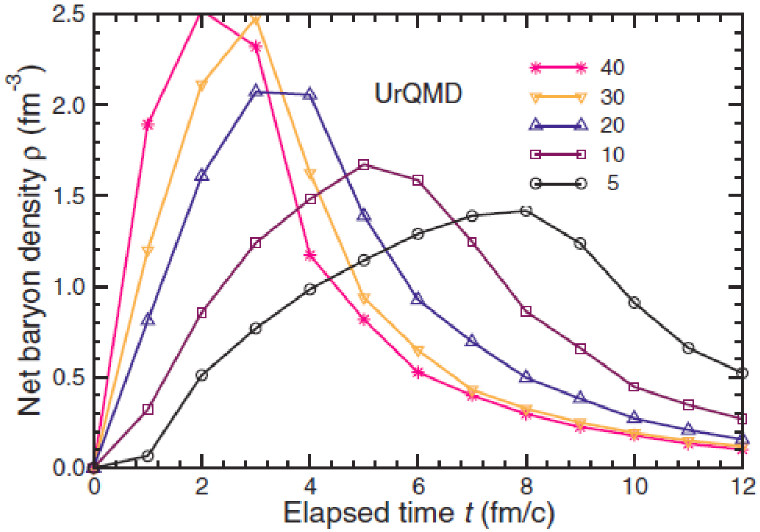
Composition of Neutron Star Matter



M.A. Stephanov, Int. J. Mod. Phys. A20, 4387 (2005).



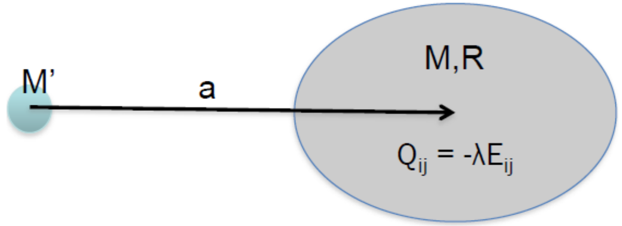
Z. Bai/Y.X. Liu, arXiv:1904.01978

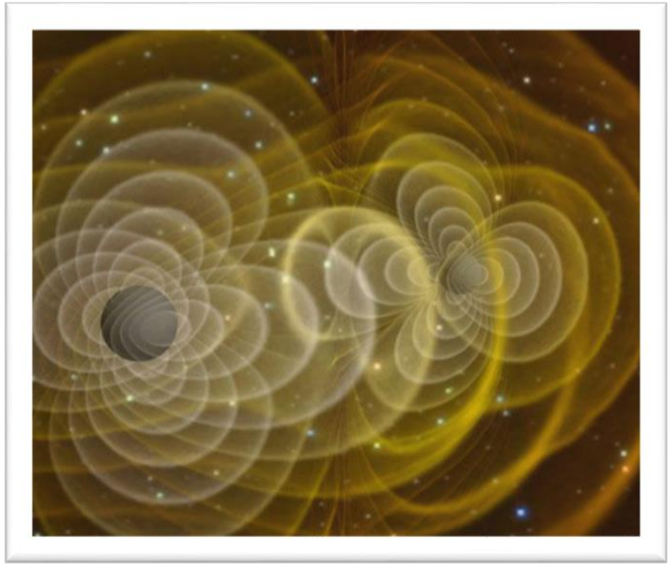


I.C. Arsene et al., PRC75, 034902(2007)

- **The maximum baryon density could reach about $30\rho_0$ in heavy ion collisions at but with high temperature (>110 MeV)**
- **The critical density for deconfinement/chiral symmetry restoration at T = 0 could be $>>6\rho_0$ (μ_B~1.6 GeV)!**
- **Quark phase exists inside Nstars??? (E. Annala et al., Nature Physics (2020))**

Tidal Deformability (Polarizability)
(oscillation response coefficient λ)





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

Q_{ij}: Quadrupole moment

ε_{ij}: Tidal field of companion

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

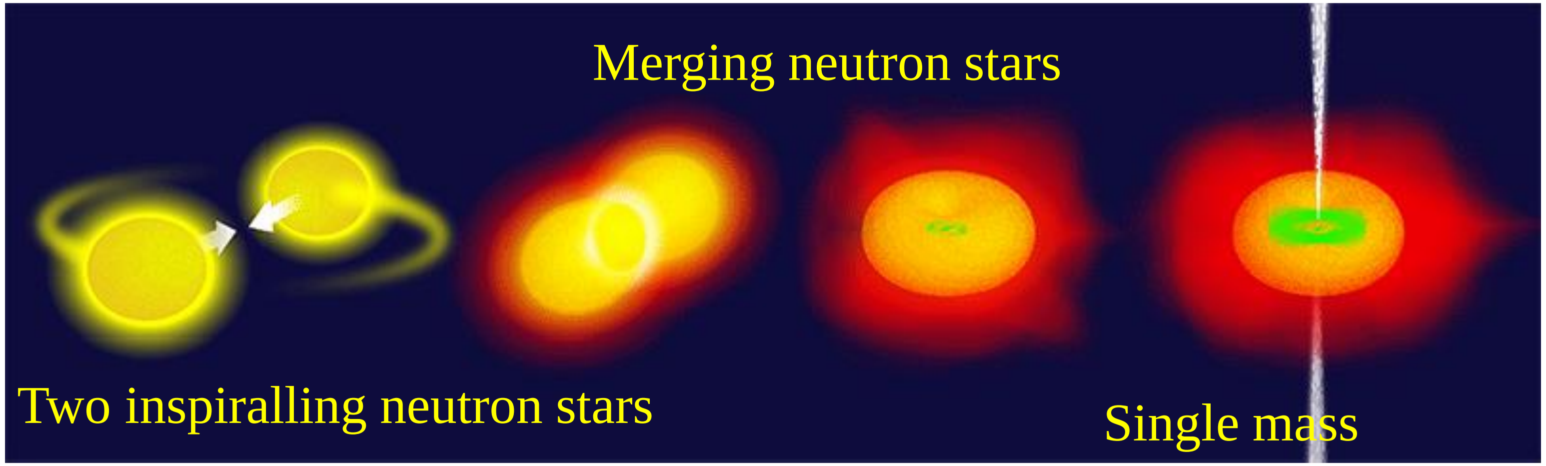
k_2: Love number
R: Radius
M: Mass

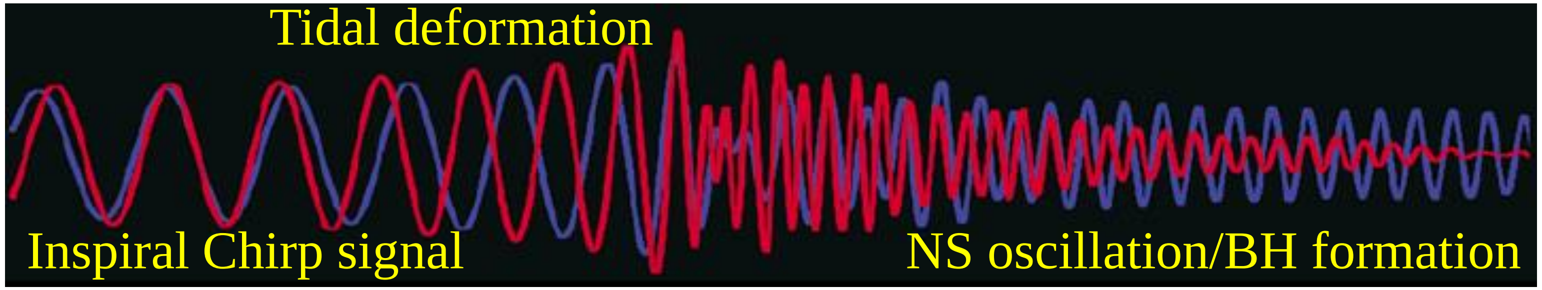
Dimensionless Tidal Deformability

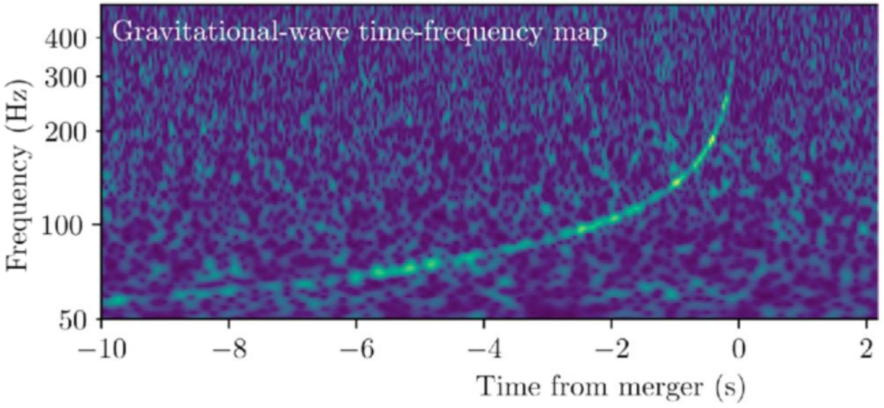
$$\Lambda = \frac{2}{3} k_2 (R/M)^5$$

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)

Binary Neutron Star Merger







LIGO is sensitive to increase in orbital frequency as system loses energy to both gravitational waves and internal excitation of neutron stars. GW170817 data place limits on polarizability (deformability) Λ of NS and hence limits on NS radius.

Multimessenger era: GW170817

Selected for a Viewpoint in *Physics*
PRL **119,** 161101 (2017) PHYSICAL REVIEW LETTERS week ending 20 OCTOBER 2017

arXiv:1710.05832

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

B. P. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)

Citations: 5669+

- **On August 17, 2017, the merger of two neutron stars was observed with gravitational waves (GW) by the LIGO and Virgo detectors.**
- **The Fermi and Integral spacecrafts independently detected a short gamma ray burst.**
- **Extensive follow up observations detected this event at X-ray, ultra-violet, visible, infrared, and radio wavelengths.**
- **No ultra-high-energy gamma-rays and no neutrino candidates consistent with the source were found in follow-up searches. These observations support the hypothesis that GW170817 was produced by the merger of two neutron stars in NGC 4993 followed by a short gamma-ray burst (GRB 170817A) and a kilonova/macronova powered by the radioactive decay of *r*-process nuclei synthesized in the ejecta**

EOS of Neutron Star Matter

Our assumptions

- Core of the neutron stars consist of **infinite β-equilibrium npeμ matter with charge neutrality**. Its EOS is determined by **the Nuclear Energy Density Functionals**

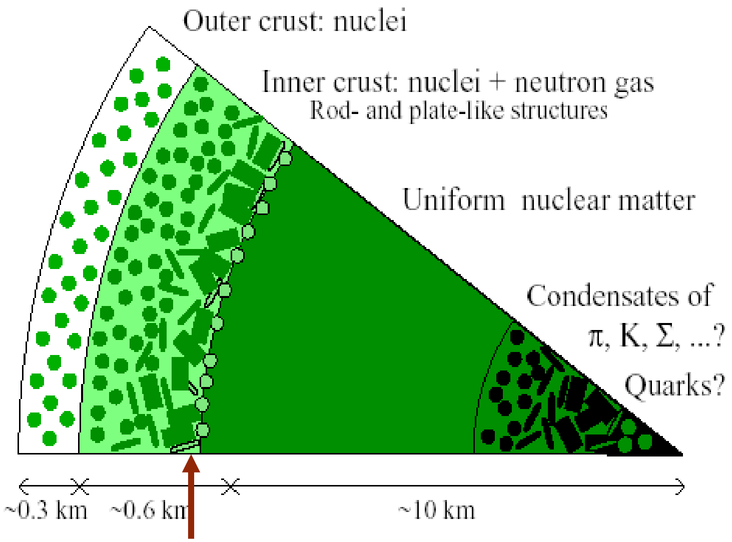
- The inner crust $2.46\times10^{-4}\,\mathrm{fm}^{-3} = n_{\mathrm{out}} < n < n_t$

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

n_t is determined self-consistently by using dynamical method

(J Xu(徐骏)/LWC/Li/Ma, ApJ697,1549(2009))

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



Core-Crust edge

- 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)

The extended SHF Energy Density Functional

SHANGHAI JIAO TONG UNIVERSITY 上海交通大學

Extended Skyrme Interaction:

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

Momentum-dependence of many-body forces

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

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

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:

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

SHANGHAI JIAO TONG UNIVERSITY 上海交通大学

Why extended SHF EDF?

PHYSICAL REVIEW C 94, 064326 (2016)

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

(张振，中山大学) Zhen Zhang[1] and Lie-Wen Chen[1,2,*]

[1]*Department of Physics and Astronomy and Shanghai Key Laboratory for Particle Physics and Cosmology, Shanghai Jiao Tong University, Shanghai 200240, China*

[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

Momentum-dependence of many-body forces plays an important role for the high-density behaviors of EOS!

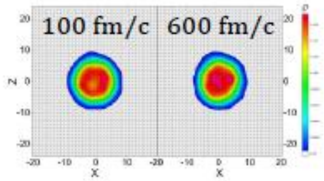
- **The eSHF can describe simultaneously nuclear matter, finite nuclei, and neutron stars!**
- **The eSHF EDF is very flexible to mimic various density behaviors for EOS (13 parameters)**

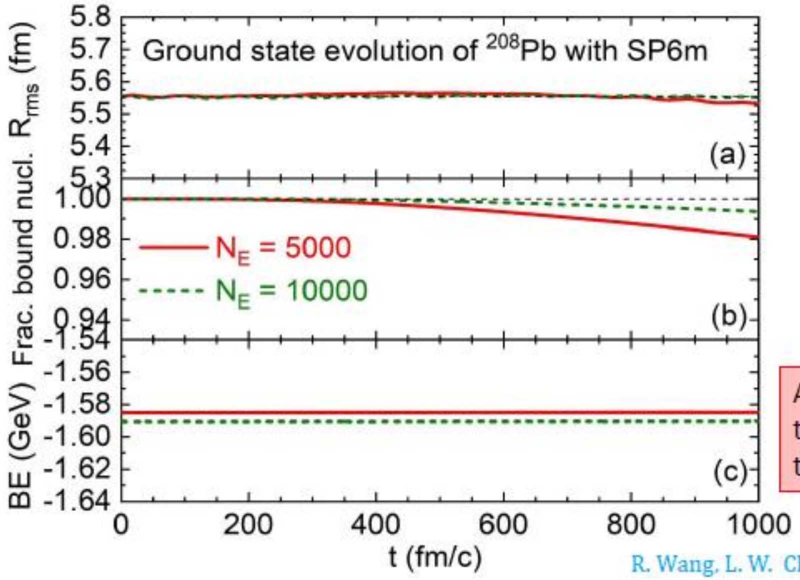
$$E_0(\rho) = a_2\rho^{2/3} + a_3\rho^{3/3} + a_4\rho^{(\alpha+3/3)} + a_5\rho^{5/3} + a_6\rho^{(\beta+5/3)} + a_7\rho^{(\gamma+5/3)}$$

The extended Skyrme force for HIC

Ground state LHV Calculations

The rms radius, fraction of bound nucleons, binding energy of ground state evolution





Free test nucleons are those whose form factor do not overlap with that of other test nucleons

$$\langle r^2 \rangle = N_{\rm nucl}^{-1} \int_{\rm bound} d^3 r^2 \rho(r)$$

At 1000 fm/c, only about 2% of test nucleons evaporated from the nucleus for $N_E = 5000$ case

R. Wang, L. W. Chen, and Z. Zhang, PRC99, 044609 (2019)

Very stable ground state of the initialized nuclei!

R. Wang (王睿), LWC, and Z. Zhang (张振), PRC99, 044607 (2019)

The GPU parallel computing with large enough test particle number (up to ~100000 !)

Physics Letters B 807 (2020) 135532

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Constraining the in-medium nucleon-nucleon cross section from the width of nuclear giant dipole resonance

Rui Wang [a,b], Zhen Zhang [c], Lie-Wen Chen [d], Che Ming Ko [e], Yu-Gang Ma [a,b]

基于格点Hamiltonian方法和随机碰撞方法，发展了完整的格点Boltzmann-Uehling-Uhlenbeck(BUU)输运模型并成功用于描述原子核的集体运动

Invited Review

frontiers in Physics

REVIEW
published: 06 October 2020
doi: 10.3389/fphy.2020.00330

Nuclear Collective Dynamics in Transport Model With the Lattice Hamiltonian Method

Rui Wang [1,2], Zhen Zhang [3], Lie-Wen Chen [4] and Yu-Gang Ma [1,2]*

王睿, 张振, LWC, and Y.G.Ma

上海交通大学 SHANGHAI JIAO TONG UNIVERSITY

Extended Skyrme forces with fixed J_0&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_ZX	$E_{\rm B}$(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(张振)/LWC, PLB726, 234(2013); PRC90, 064317(2014))
- Other 9 lower-order parameters and W_0 are calibrated to fit data of finite nuclei
- Causality

Lower-order parameters are basically fixed by nuclear properties, while higher-order parameters are not important for nuclei

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 (before 2019):

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)

PRL121, 161101 (2018)

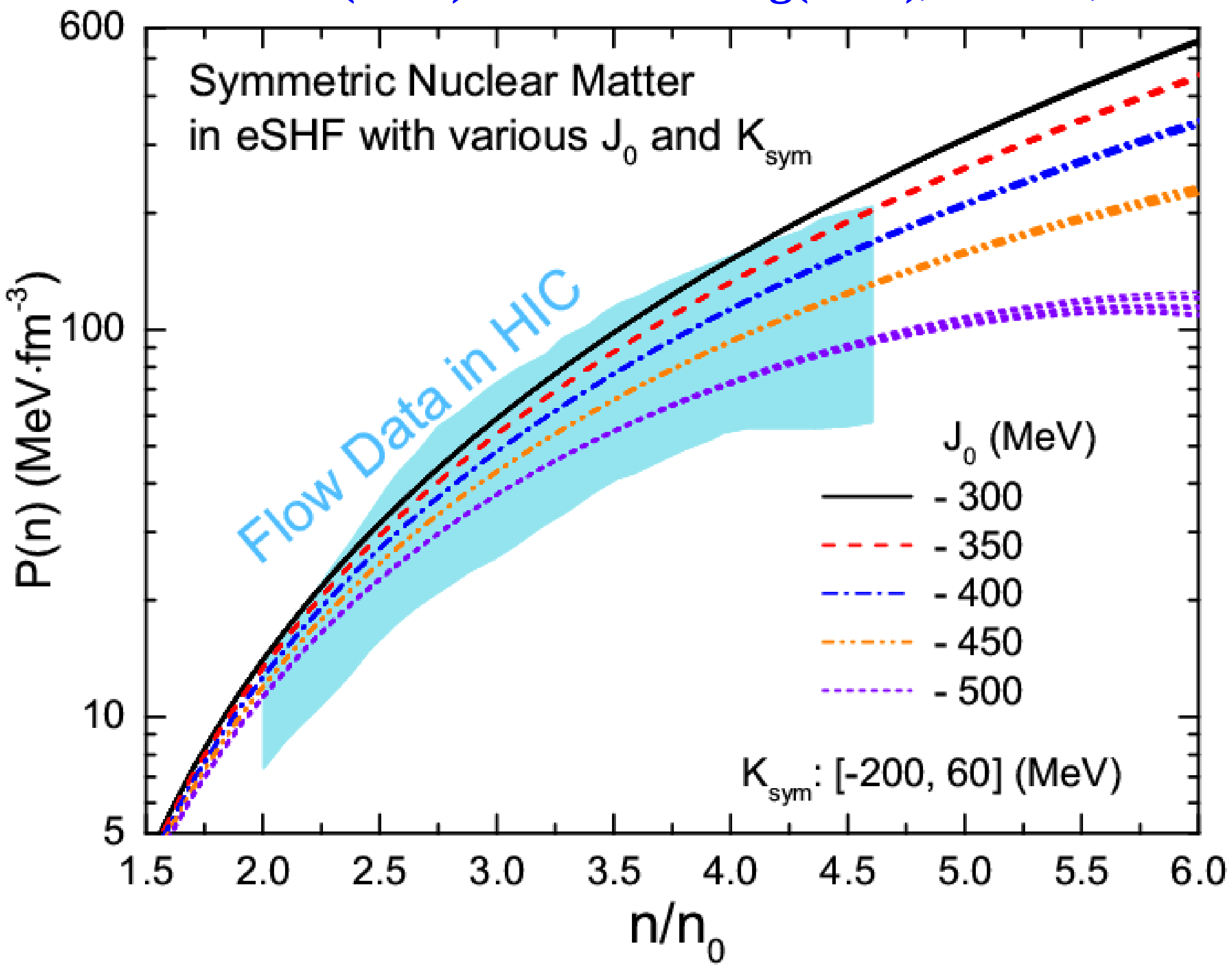
GW170817: Measurements of neutron star radii and equation of state

The LIGO Scientific Collaboration and The Virgo Collaboration
(compiled 30 May 2018)

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

J0: Flow data in HIC's

Y. Zhou(周颖)/LWC/Z. Zhang(张振), PRD99, 121301(R) (2019) [arXiv:1901.11364]



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

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

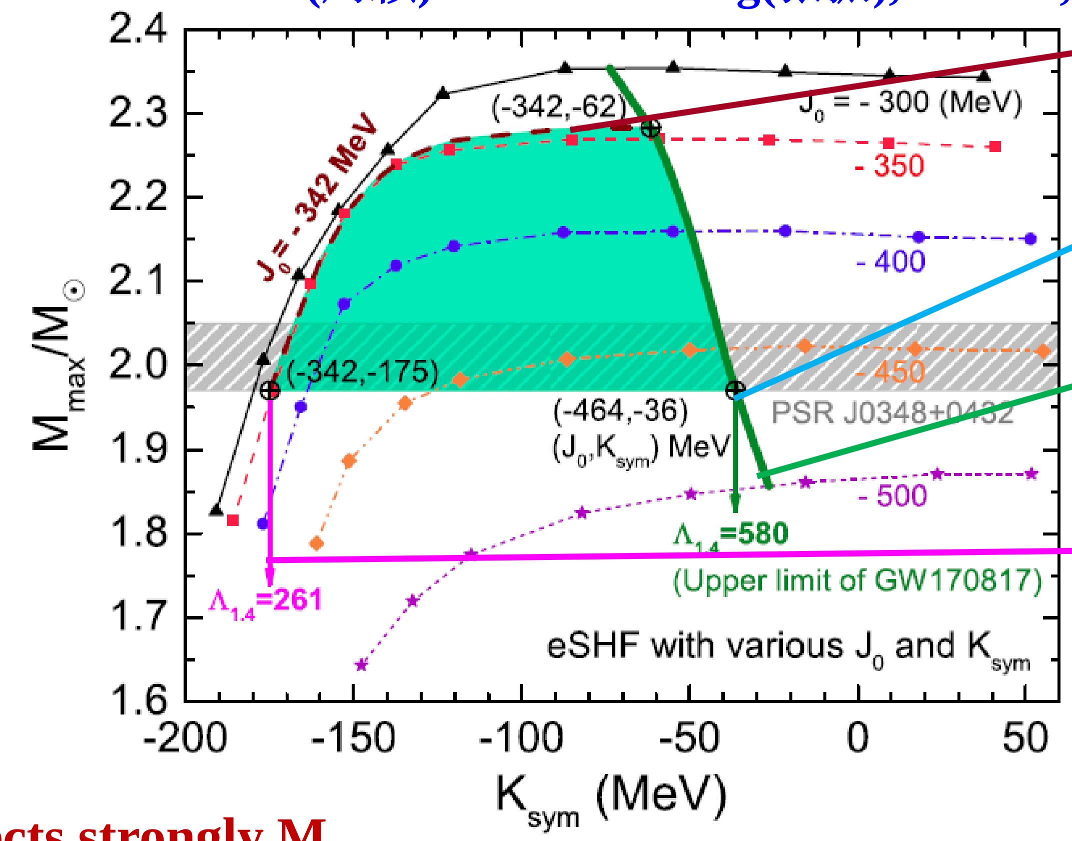
$E_{sym}(\rho_c)$= 26.65 MeV
$L(\rho_c)$= 47.3 MeV

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

Lower-order parameters are basically fixed by nuclear properties

J0 and Ksym: Flow data, NStar Mass, Λ

Y. Zhou(周颖)/LWC/Z. Zhang(张振), PRD99, 121301(R) (2019) [arXiv:1901.11364]



J0 = -342 MeV (from flow data)

J0 = -464 MeV
Ksym < - 36 MeV

$\Lambda_{1.4}$ < 580

GW170817 (LIGO/Virgo)

$\Lambda_{1.4}$ > 261

Lower-order parameters are basically fixed by nuclear properties

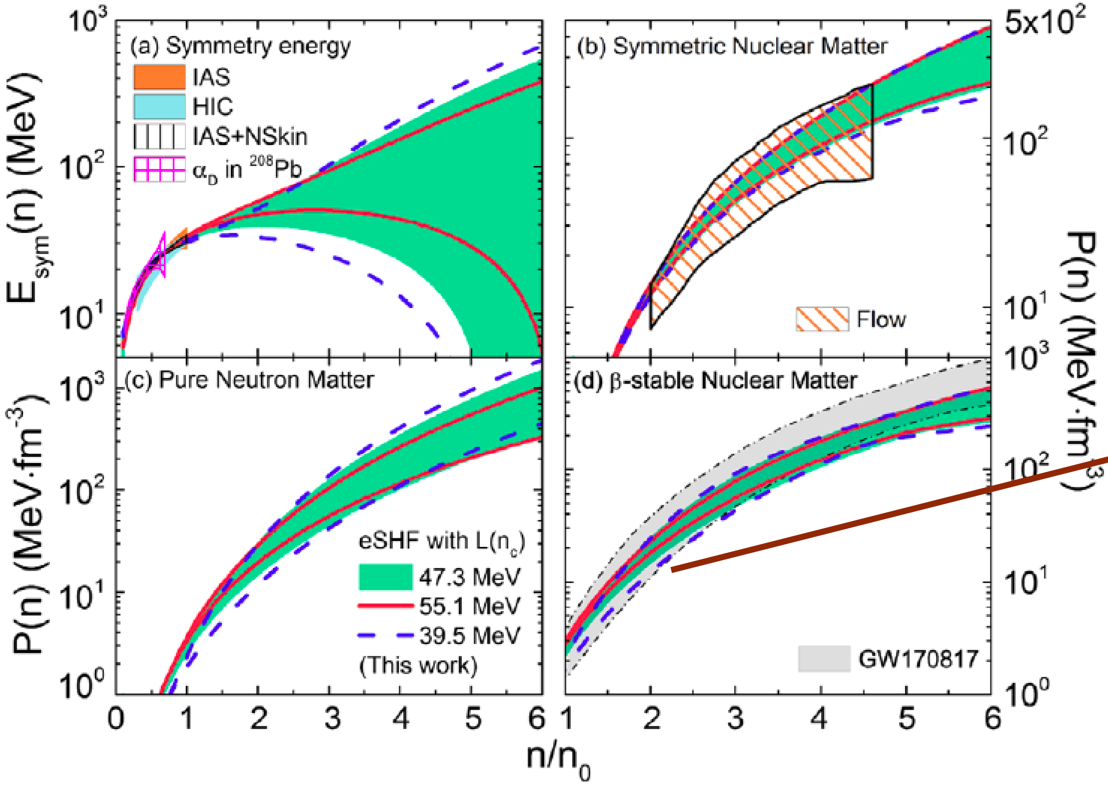
K_{sym} affects strongly M_{max} for K_{sym}< - 100 MeV

Flow Data in HIC +Mmax:
K_{sym} > -175 MeV, $\Lambda_{1.4}$ >261

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

EOS: Flow data, NStar Mass, Λ

Y. Zhou(周颖)/LWC/Z. Zhang(张振), PRD99, 121301(R) (2019) [arXiv:1901.11364]



$L(\rho_c)$=47.3+/-7.8 MeV using α_D of ^{208}Pb (Z. Zhang(张振), LWC, PRC90, 064317(2014))

$L(\rho_c)$ indeed affects the extraction of Esym at high densities but does not change much the NStar matter EOS!

Consistent with LIGO/Virgo constraints (see, e.g., D. Radice et al., ApJL852, L29(2018)) but more stringent due to nuclear data added

$L(\rho_c)$=47.3 MeV:
J0:[-464,-342] MeV,
K_{sym}:[-175,-36] MeV
$E_{sym}(2\rho_0)$:[39.4, 54.5] MeV

$L(\rho_c)$=39.5 MeV:
J0:[-475,-342] MeV,
K_{sym}:[-203,-34] MeV
$E_{sym}(2\rho_0)$:[33.0, 51.3] MeV

$L(\rho_c)$=55.1 MeV:
J0:[-455,-342] MeV,
K_{sym}:[-138,-38] MeV
$E_{sym}(2\rho_0)$:[46.9, 57.6] MeV

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New Observed Heaviest NStar

nature astronomy LETTERS
https://doi.org/10.1038/s41550-019-0880-2

Relativistic Shapiro delay measurements of an extremely massive millisecond pulsar

H. T. Cromartie[1*], E. Fonseca[2], S. M. Ransom[3], P. B. Demorest[4], Z. Arzoumanian[5], H. Blumer[6,7], P. R. Brook[6,7], M. E. DeCesar[8], T. Dolch[9], J. A. Ellis[10], R. D. Ferdman[11], E. C. Ferrara[12,13], N. Garver-Daniels[6,7], P. A. Gentile[6,7], M. L. Jones[6,7], M. T. Lam[6,7], D. R. Lorimer[6,7], R. S. Lynch[14], M. A. McLaughlin[6,7], C. Ng[15,16], D. J. Nice[8], T. T. Pennucci[17], R. Spiewak[18], I. H. Stairs[15], K. Stovall[4], J. K. Swiggum[19] and W. W. Zhu[20]

edge-on) binary pulsar systems. By combining data from the North American Nanohertz Observatory for Gravitational Waves (NANOGrav) 12.5-yr data set with recent orbital-phase-specific observations using the Green Bank Telescope, we have measured the mass of the MSP J0740+6620 to be $2.14^{+0.10}_{-0.09}$ $M_\odot$ (68.3% credibility interval; the 95.4% credibility interval is $2.14^{+0.20}_{-0.18}$ $M_\odot$). It is highly likely to be the most massive neutron star yet observed, and serves as a strong constraint on the neutron star interior EoS.

The Astrophysical Journal Letters, 915:L12 (15pp), 2021 July 1 https://doi.org/10.3847/2041-8213/ac03b8

CrossMark

Refined Mass and Geometric Measurements of the High-mass PSR J0740+6620

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ABSTRACT

We report results from continued timing observations of PSR J0740+6620, a high-mass, 2.8-ms radio pulsar in orbit with a likely ultra-cool white dwarf companion. Our data set consists of combined pulse arrival-time measurements made with the 100-m Green Bank Telescope and the Canadian Hydrogen Intensity Mapping Experiment telescope. We explore the significance of timing-based phenomena arising from general-relativistic dynamics and variations in pulse dispersion. When using various statistical methods, we find that combining ~ 1.5 years of additional, high-cadence timing data with previous measurements confirms and improves upon previous estimates of relativistic effects within the PSR J0740+6620 system, with the pulsar mass $m_p = 2.08^{+0.07}_{-0.07}$ $M_\odot$ (68.3% credibility) determined by the relativistic Shapiro time delay. For the first time, we measure secular variation in the orbital period and argue that this effect arises from apparent acceleration due to significant transverse motion. After incorporating contributions from Galactic differential rotation and off-plane acceleration in the Galactic potential, we obtain a model-dependent distance of $d = 1.14^{+0.17}_{-0.15}$ kpc (68.3% credibility). This improved distance confirms the ultra-cool nature of the white dwarf companion determined from recent optical observations. We discuss the prospects for future observations with next-generation facilities, which will likely improve the precision on m_p for J0740+6620 by an order of magnitude within the next few years.

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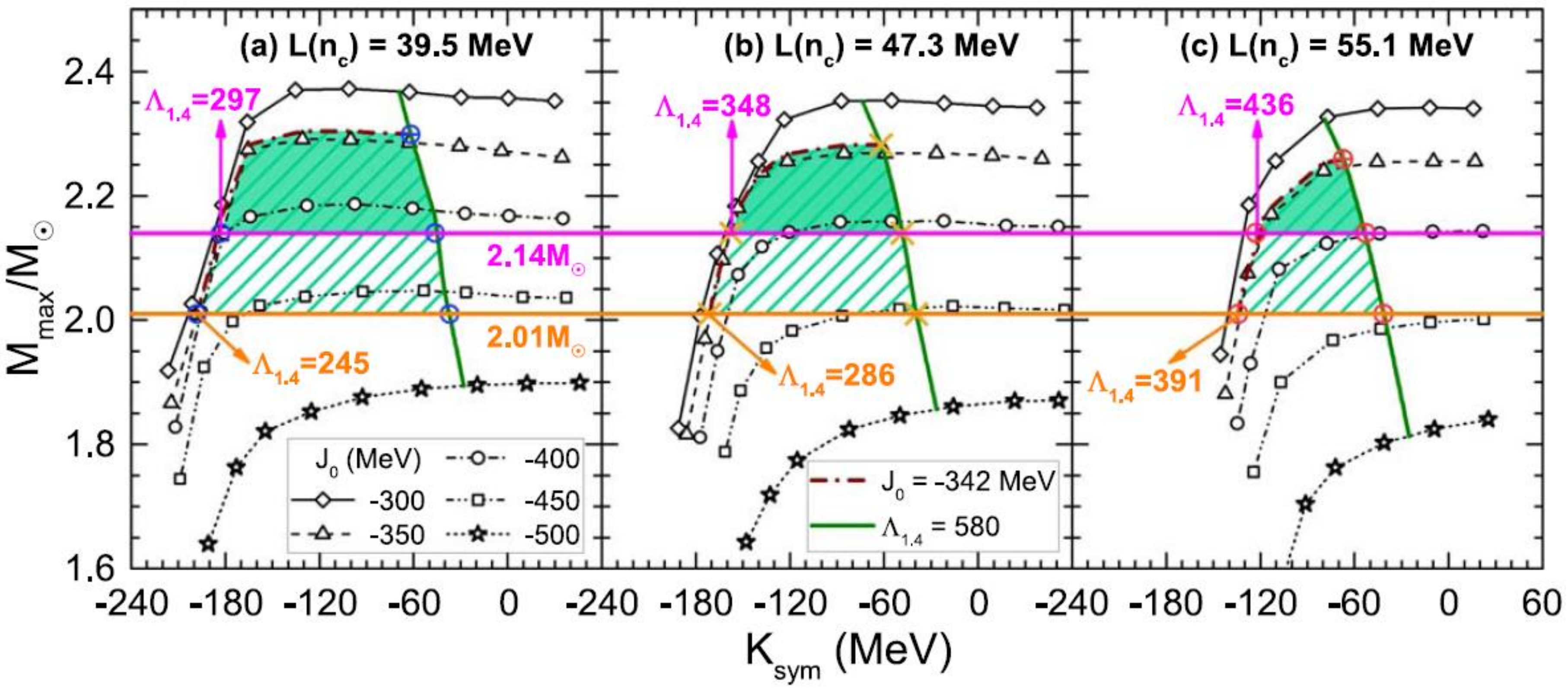
New Observed Heaviest NStar

Y. Zhou(周颖), L.W. Chen*, ApJ886, 52(2019)
[arXiv:1907.12284]

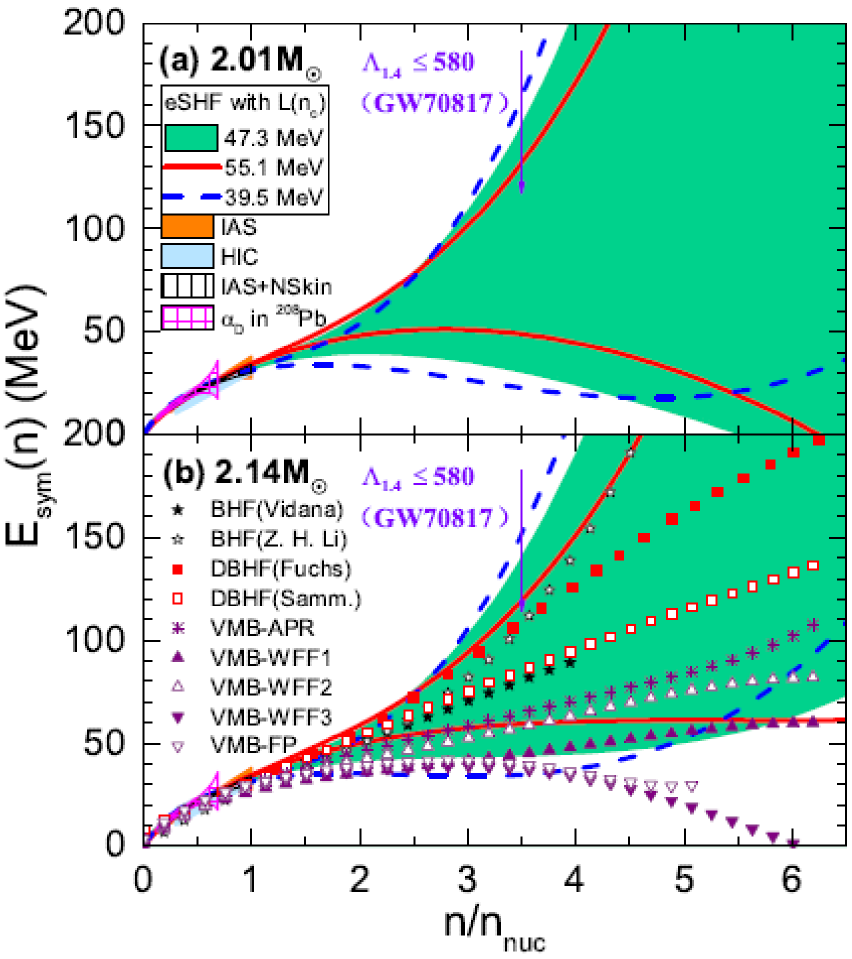


$\Lambda_{1.4}$ >297

The maximum mass of static NS is about **2.3M$_\odot$!**

Ruling out the “supersoft” Esym

Y. Zhou (周颖), L.W. Chen*, ApJ886, 52(2019) [arXiv:1907.12284]



$$\frac{\hbar^2 k_F^2}{3m_s^*}(1+F_0') = \frac{\partial^2 \mathcal{E}(\rho,\rho_1,s_0,s_1)}{\partial(\rho_1)^2}\Big|_{\rho_1=s_0=s_1=0}$$

$$E_{\rm sym}(\rho) = \frac{\hbar^2 k_F^2}{6m_s^*}(1+F_0')$$

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

The Landau stability conditions,

$$F_l > -(2l+1),$$
$$F_l' > -(2l+1),$$
$$G_l > -(2l+1),$$
$$G_l' > -(2l+1),$$

$$\mu_e = \mu_n - \mu_p = 4\delta E_{\rm sym}(\rho)$$

Negative Esym leads to isospin instability:
Pure Neutron Matter will appear

Ruling out the “supersoft” Esym means the pure neutron matter cannot appear inside NStars

Nskin in ^{208}Pb : PREX-II

PHYSICAL REVIEW LETTERS **126,** 172502 (2021)

Editors' Suggestion | Featured in Physics

PREX:
The Lead (Pb) Radius EXperiment

Accurate Determination of the Neutron Skin Thickness of ^{208}Pb through Parity-Violation in Electron Scattering

D. Adhikari,[1] H. Albataineh,[2] D. Androic,[3] K. Aniol,[4] D. S. Armstrong,[5] T. Averett,[5] C. Ayerbe Gayoso,[5] S. Barcus,[6]

$$R_n - R_p = 0.283 \pm 0.071\ \text{fm}$$

PREX-II: Rskin = [0.212, 0.354] fm for Pb208

Huge Nskin!

In PREX, the neutron density distribution in 208Pb is determined by measuring the parity-violating electroweak asymmetry in the elastic scattering of polarized electrons off 208Pb and thus is free from the strong interaction uncertainties

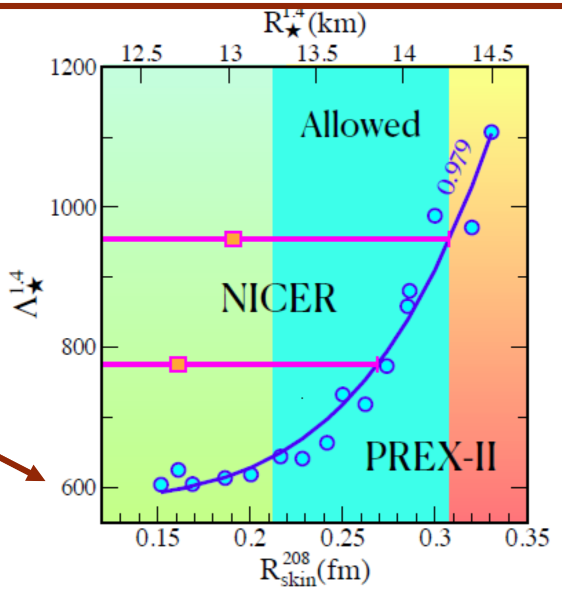
PHYSICAL REVIEW LETTERS **126,** 172503 (2021)

Editors' Suggestion

Implications of PREX-2 on the Equation of State of Neutron-Rich Matter

Brendan T. Reed,[1,2,*] F. J. Fattoyev,[3,†] C. J. Horowitz,[2,‡] and J. Piekarewicz[4,§]

RMF: Inconsistent with GW170817: $\Lambda_{1.4}$ <580 !!!



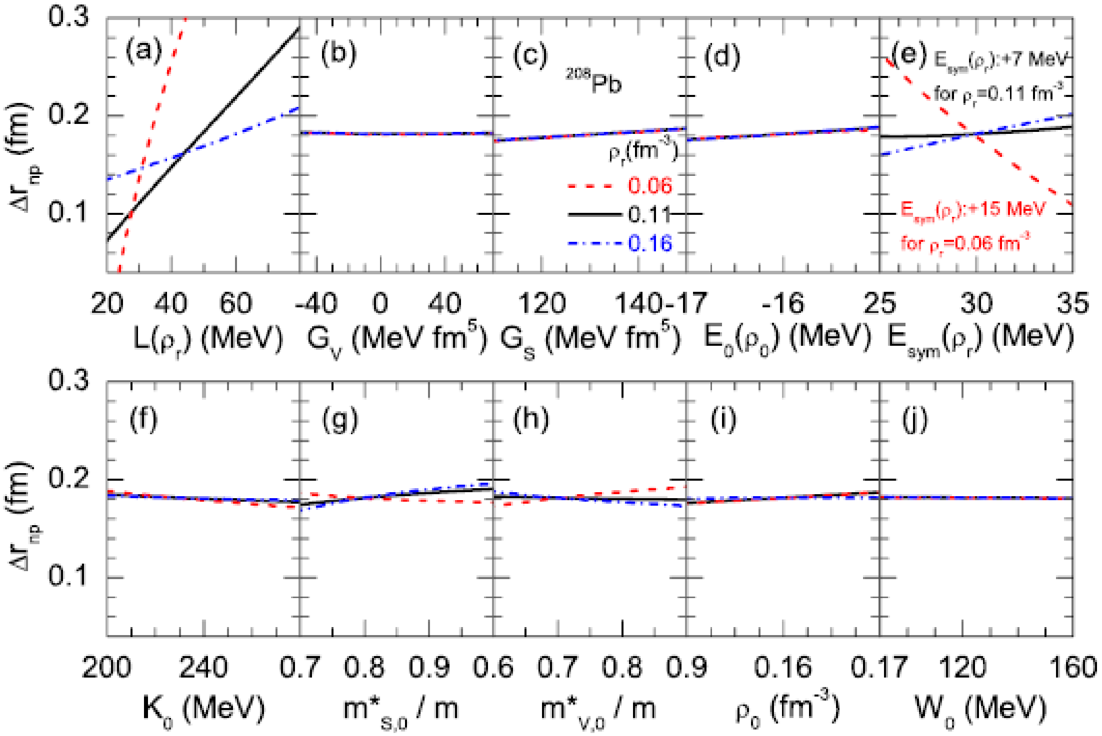
δ meson may be important in the RMF model !!!
Fan Li (李帆)/Cai/Zhou/Jiang/LWC, ApJ 929, 183 (2022)

Nskin in ^{208}Pb : PREX-II

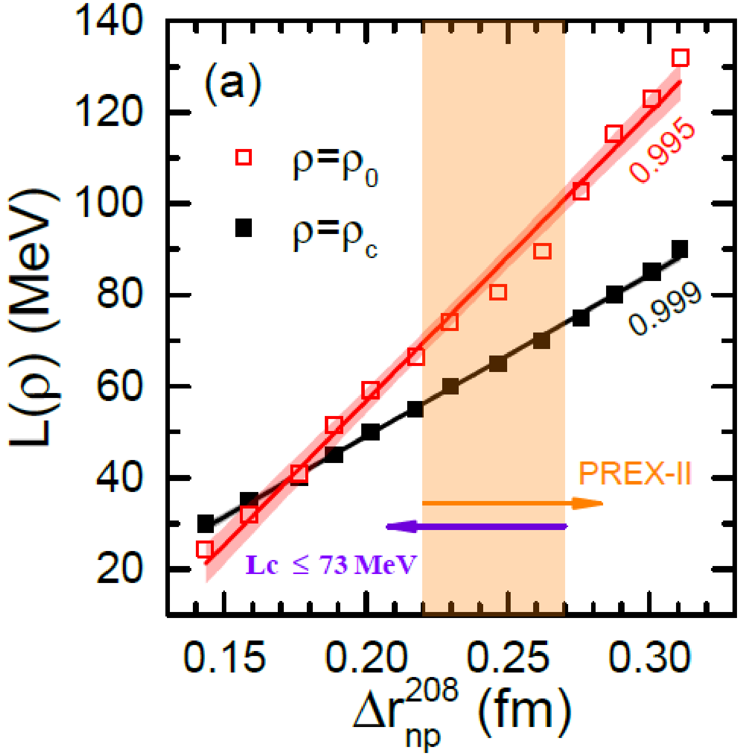
What determines the Nskin thickness? ---The density slope parameter L, especially Lc at $\rho_c \sim 2\rho_0/3$ (average density of nuclei)!!!

B. A. Brown, PRL85, 5296 (2000); R. J. Furnstahl, NPA706, 85 (2002); L.W. Chen et al., PRC72, 064309 (2005); M. Centelles et al., PRL102, 122502 (2009); L. W. Chen et al., PRC 82, 024321 (2010); X. Roca-Maza et al.,PRL106, 252501 (2011), ……

SHF



eSHF



Nskin is determined by Lc !!!

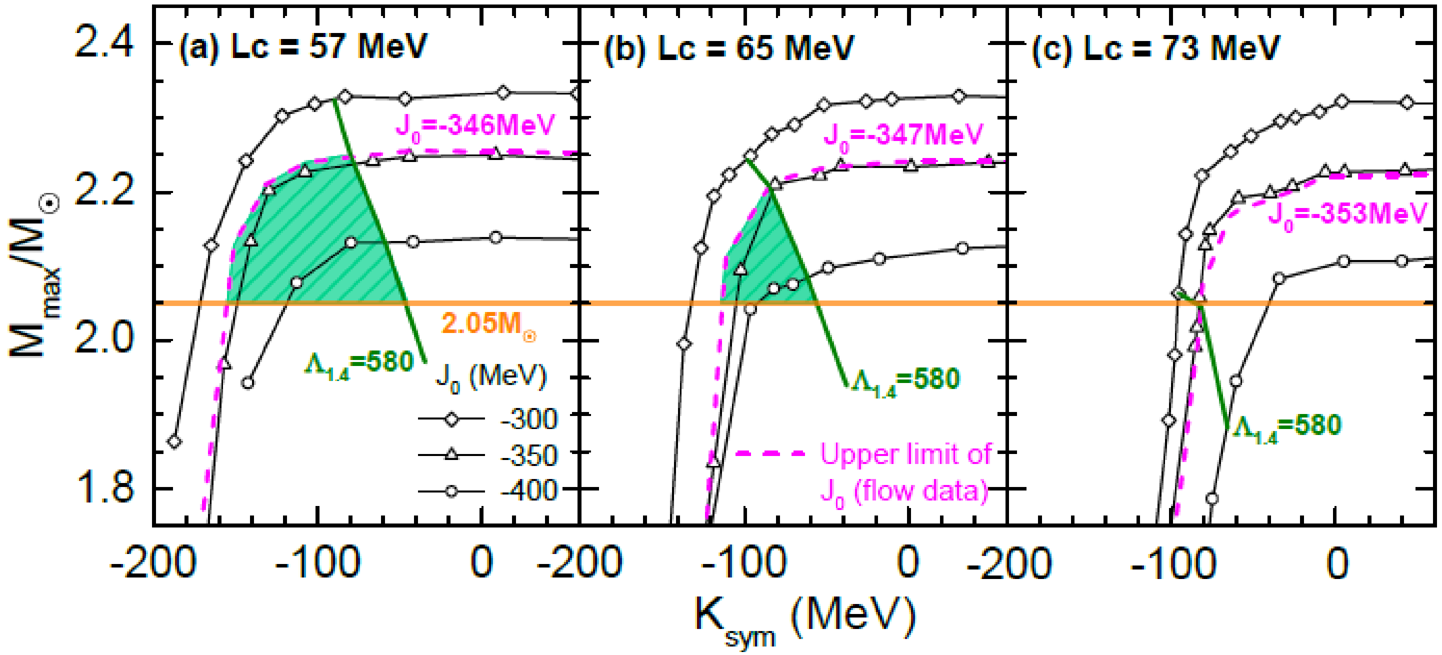
Z. Zhang (张振) and LWC*, PLB726, 234 (2013) (Citations: 146+)

T.G. Yue (岳侗钢), , LWC*, Z. Zhang (张振), and Y. Zhou (周颖), arXiv:2102.05267

Nskin in ^{208}Pb : PREX-II

Implications of Rskin from PREX-II

T.G. Yue (岳侗钢), , LWC*, Z. Zhang (张振), and Y. Zhou (周颖), arXiv:2102.05267



Lc cannot be too big!!! Lc < 73 MeV and then set an upper limit on Rskin: <0.27 fm for Pb208

eSHF provides a single unified framework to simultaneously describe the finite nuclei (Eb, Rc, GMR, Nskin-PREX-II) + Flow data in HIC+NStar (e.g., NICER)+GW170817

$E_{sym}(\rho_0)$ =34.5±1.5 MeV and L=85.5±22.2 MeV

Nskin in ^{208}Pb : PREX-II

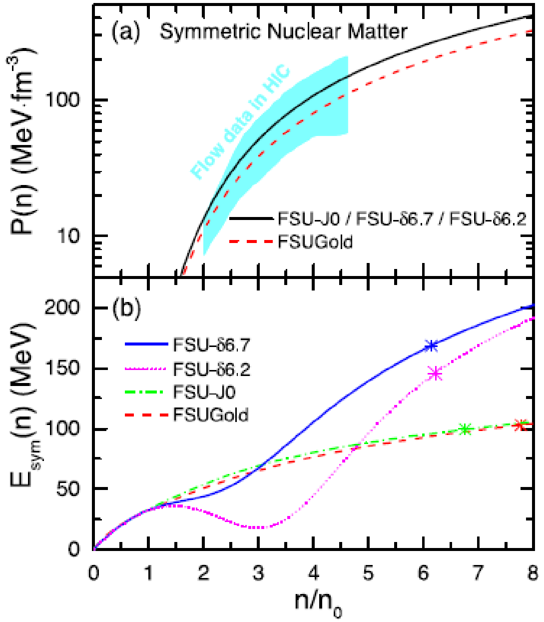
THE ASTROPHYSICAL JOURNAL, 929:183 (7pp), 2022 April 20 https://doi.org/10.3847/1538-4357/ac5e2a

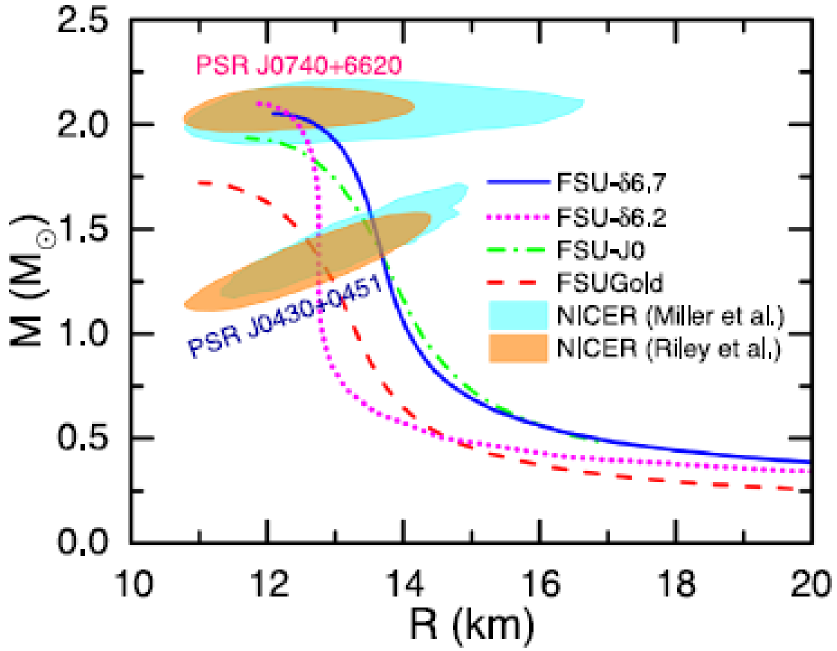
Effects of Isoscalar- and Isovector-scalar Meson Mixing on Neutron Star Structure

Fan Li[1], Bao-Jun Cai[2], Ying Zhou[2], Wei-Zhou Jiang[3], and Lie-Wen Chen[1,4]

Fan Li (李帆), B.J. Cai, Y. Zhou, W.Z. Jiang, and LWC, ApJ 929, 183 (2022)

$$
\begin{aligned}
\mathcal{L} = {} & \overline{\psi}(i\partial_\mu\gamma^\mu - m)\psi \\
& + g_\sigma\sigma\overline{\psi}\psi - g_\omega\omega_\mu\overline{\psi}\gamma^\mu\psi - g_\rho\rho_\mu\overline{\psi}\gamma^\mu\tau\psi + g_\delta\delta\overline{\psi}\tau\psi \\
& + \frac{1}{2}(\partial_\mu\sigma\partial^\mu\sigma - m_\sigma^2\sigma^2) - \frac{1}{3}b_\sigma m(g_\sigma\sigma)^3 - \frac{1}{4}c_\sigma(g_\sigma\sigma)^4 \\
& - \frac{1}{4}\omega_{\mu\nu}\omega^{\mu\nu} + \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu + \frac{1}{4}c_\omega(g_\omega^2\omega_\mu\omega^\mu)^2 \\
& - \frac{1}{4}\rho_{\mu\nu}\rho^{\mu\nu} + \frac{1}{2}m_\rho^2\rho_\mu\rho^\mu + \frac{1}{2}\Lambda_V(g_\rho^2\rho_\mu\rho^\mu)(g_\omega^2\omega_\mu\omega^\mu) \\
& + \frac{1}{2}(\partial_\mu\delta\partial^\mu\delta - m_\delta^2\delta^2) + \boxed{\frac{1}{2}C_{\delta\sigma}(g_\sigma^2\sigma^2)(g_\delta^2\delta^2)},
\end{aligned}
$$





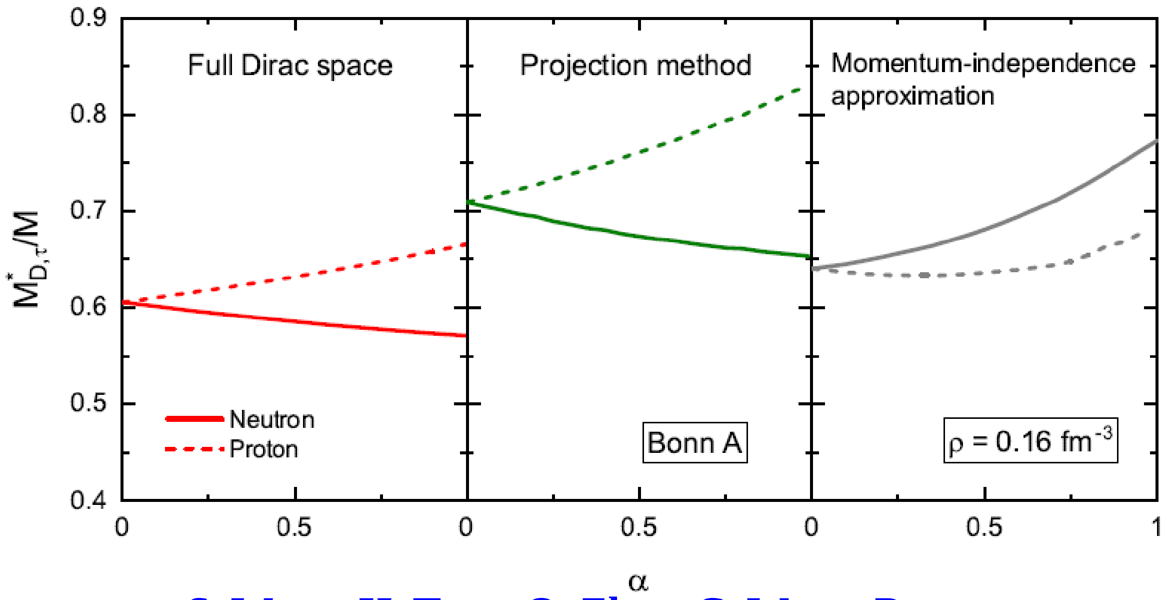
δ meson and its coupling to σ meson may play an important role in the RMF model !!!

FSUGold + δ-σ mixing provides a single unified framework to simultaneously describe the finite nuclei (Eb, Rc, GMR, Nskin-PREX-II) + Flow data in HIC+NStar (e.g., NICER)+GW170817

Nskin in ^{208}Pb : PREX-II

Asymmetric Nuclear Matter and Neutron Star Properties in Relativistic *ab initio* Theory in the Full Dirac Space

Sibo Wang,[1] Hui Tong,[2,3] Qiang Zhao,[4] Chencan Wang,[5] Peter Ring,[6] and Jie Meng[7,8,*]



S. Wang, H. Tong, Q. Zhao, C. Wang, P. Ring, and J. Meng, arXiv:2203.05397

Table 2

Nuclear Matter Bulk Parameters, NS Properties, and Ground-state Properties of ^{208}Pb and ^{48}Ca in FSUGold, FSU-J0, FSU-δ6.7, and FSU-δ6.2

Quantity	FSUGold	FSU-J0	FSU-δ6.7	FSU-δ6.2
n_0(fm^{-3})	0.148	0.148	0.148	0.148
e_0(MeV)	−16.31	−16.31	−16.31	−16.31
K_0(MeV)	229.2	229.2	229.2	229.2
J_0(MeV)	−521.6	−322.0	−322.0	−322.0
m^*_{Dirac}	0.610	0.610	0.610	0.610
$m^*_{\mathrm{Dirac},n,0.5}$	0.610	0.610	0.576	0.578
$m^*_{\mathrm{Dirac},p,0.5}$	0.610	0.610	0.643	0.640

Fan Li (李帆), B.J. Cai, Y. Zhou, W.Z. Jiang, and LWC, ApJ 929, 183 (2022)

The isospin splitting of the nucleon Dirac mass in FSUGold + δ-σ mixing framework is in surprisingly good agreement with the microscopic RBHF calculations in the Full Dirac Space !!!

Outline

- **Nuclear matter EOS and the symmetry energy (Esym)**
- **Dense nuclear matter from *Nuclear experiments + Neutron star mass and radius +Tidal deformability from GW170817***
- **Summary and outlook**

Summary and Outlook

- 通过重离子碰撞，原子核结构性质(mass, neutron skin, GR/PG…), 以及核子光学势的研究，我们已经对亚饱和密度以及饱和密度附近核物质对称能有了比较好的认识：
  - ➢ 亚饱和密度区的核物质对称能 – 比较精确
  - ➢ 饱和密度附近的核物质对称能:

  World Average: $E_{sym}(\rho_0)$ =31.7±3.1 MeV and L=57.5±24.5 MeV

  But REX-II data make the situation quite elusive!!!

  更精确的约束需要更精确的实验数据和更可靠的理论方法!

- GW170817给出了对称能高密行为的上限，2.14倍太阳质量的存在排除了“超软”的高密对称能，意味着中子星内部不存在纯中子物质
- 决定核物质状态方程的高密行为依然是一个巨大的, 丰中子核引起的重离子碰撞的实验数据以及中子星/引力波观测数据将变得非常重要!
- 单个(相对论和非相对论)能量密度泛函能成功描述核实验数据和天文学观测数据(高密核物质中超子自由度、介子凝聚、夸克自由度？？？)

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