Delineating effects of nuclear symmetry energy on the radii and tidal deformabilities of neutron stars

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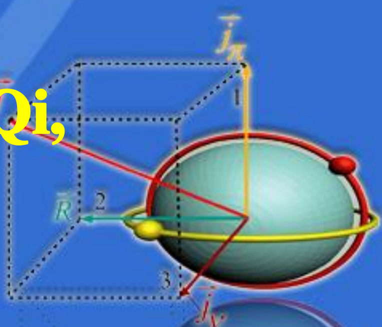

Xiamen-CUSTIPEN Workshop, 2019.01.06

Outline

- Introduction
- Parameterized equation of state
- Relation between the radii and tidal deformabilities
- Constraints on symmetry energy
- Summary

A series of related work: APJ 859, 90 (2018);
JPG 46, 014002 (2019); arXiv:1807.07698;

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Introduction

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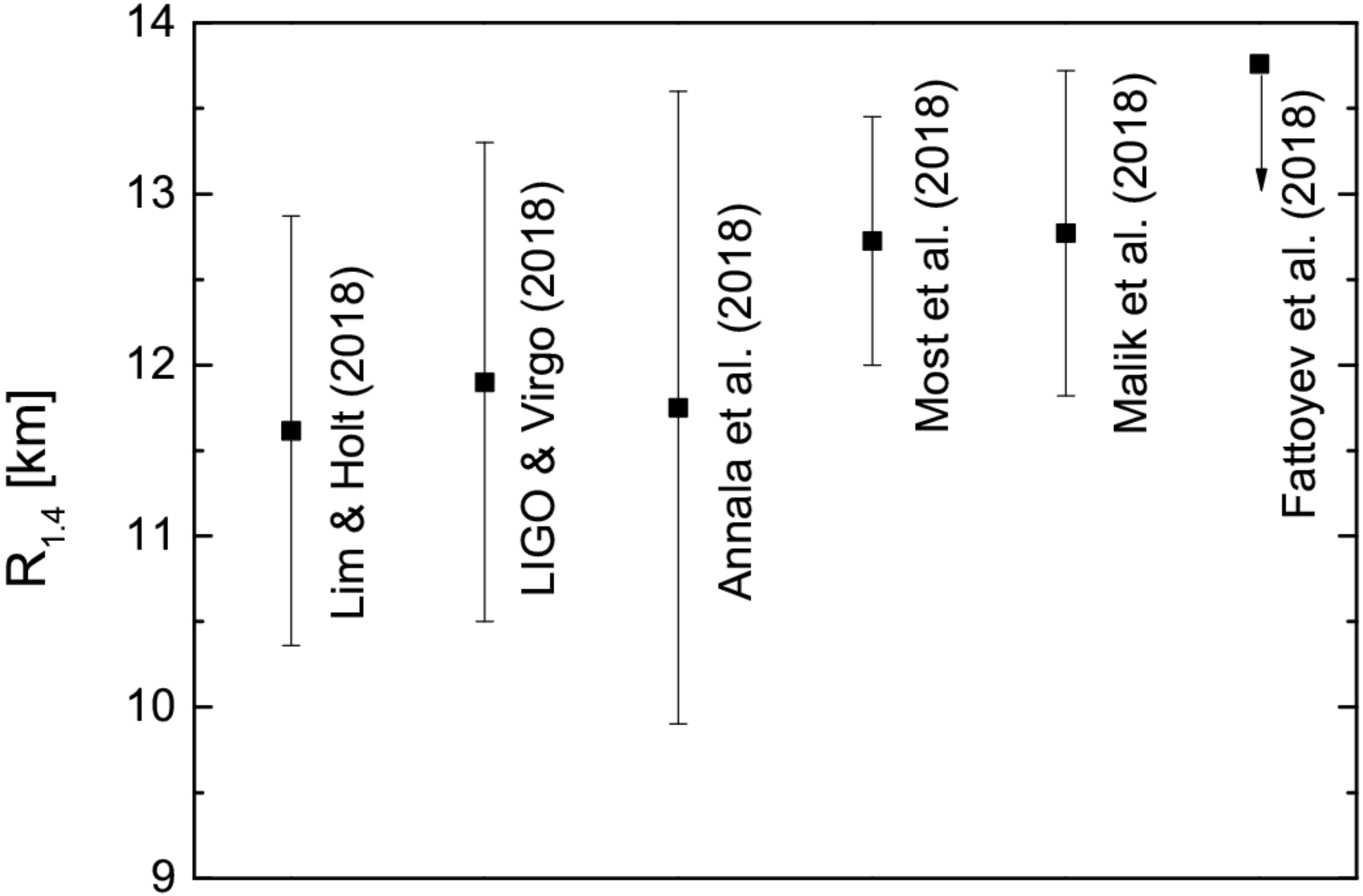

Introduction

Ongoing efforts have been devoted to constrain details of the EOS and reveal possibly interesting new physics from the tidal deformability;

- ✓ What is actually the relationship between the $\Lambda_{1.4}$ and $R_{1.4}$?

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

For M=1.4 M_{sun}, $\Lambda \propto R^5$?

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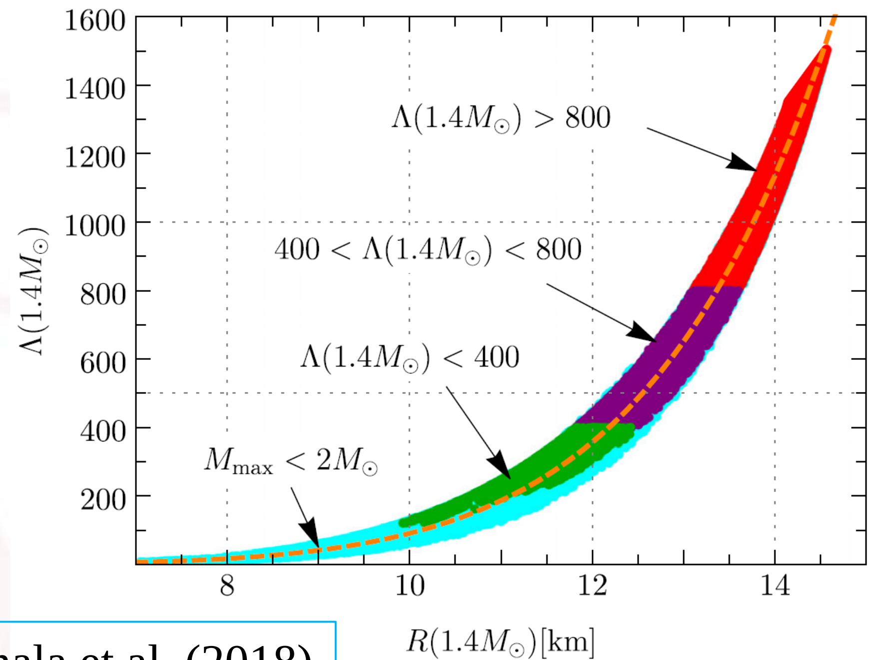
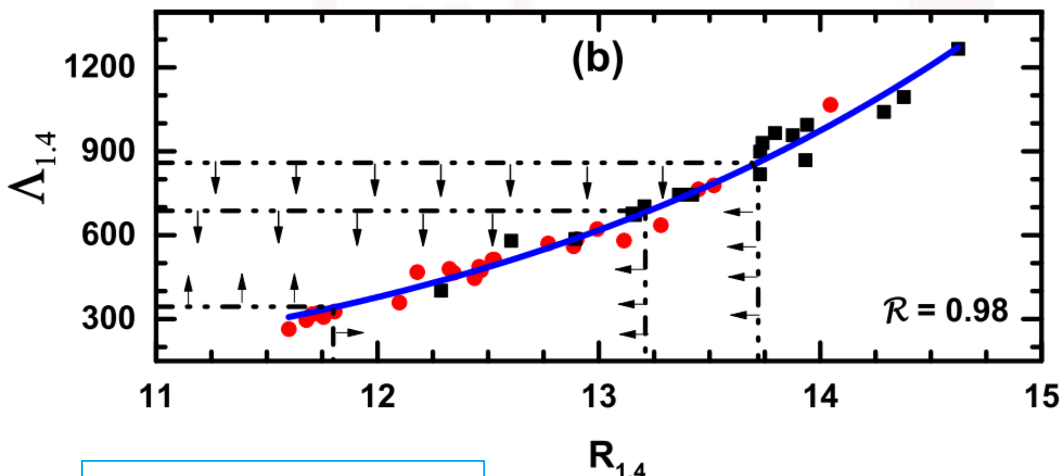
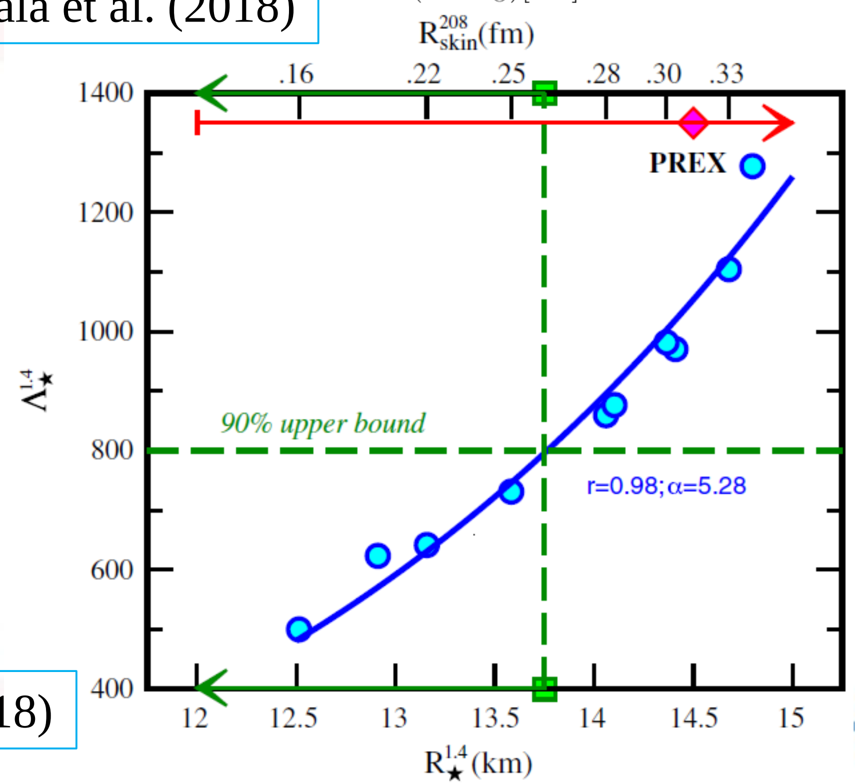


Annala et al. (2018)



Malik et al. (2018)



Fattoyev et al. (2018)

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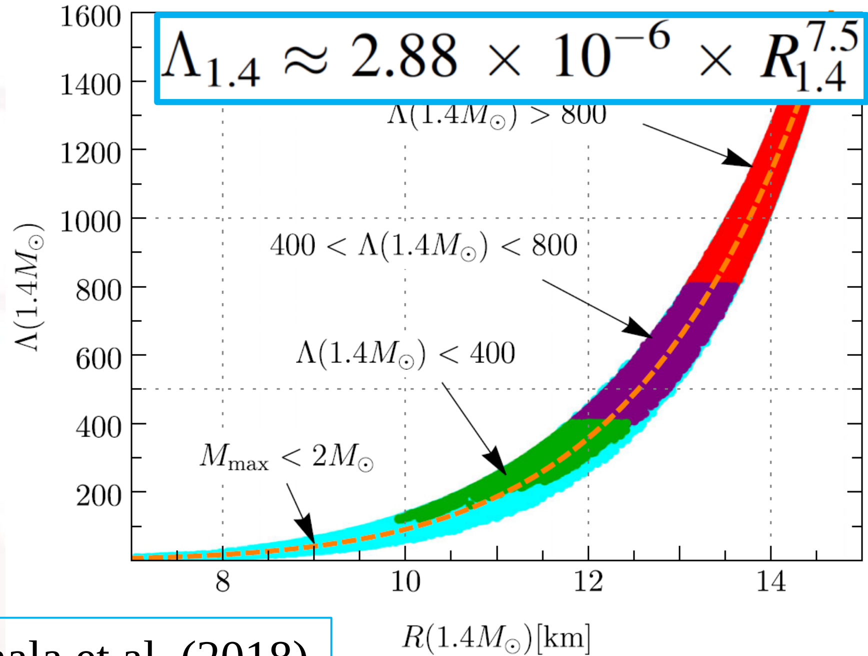
For M=1.4 M_{sun}, $\Lambda \propto R^5$?



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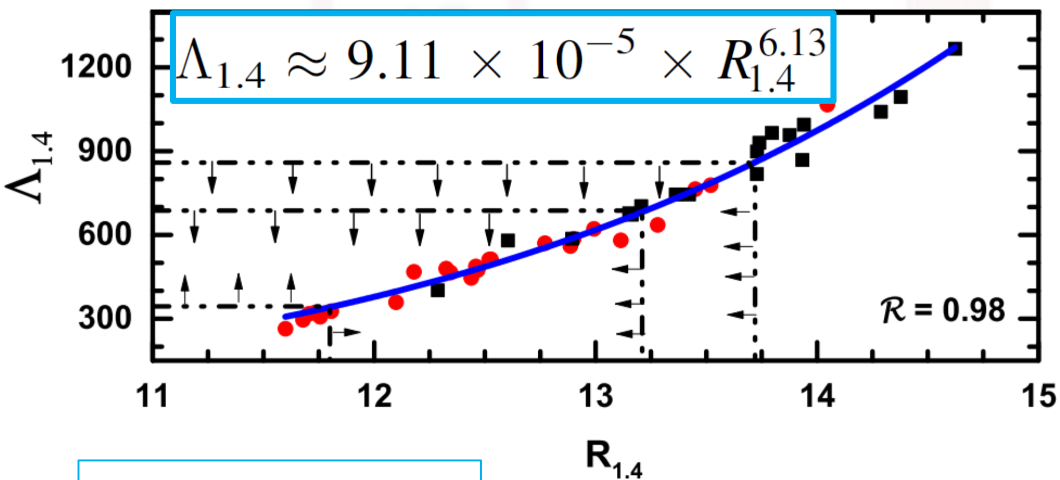

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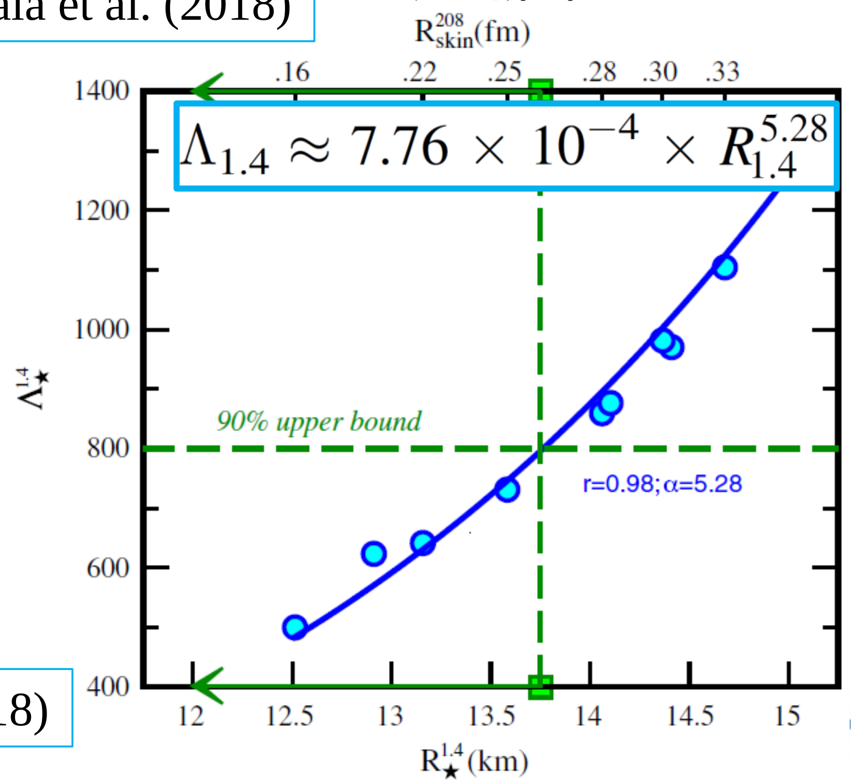

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Introduction

Ongoing efforts have been devoted to constrain details of the EOS and reveal possibly interesting new physics from the tidal deformability;

- ✓ What is actually the relationship between the $\Lambda_{1.4}$ and $R_{1.4}$?
- ✓ What aspects of the EOS of dense neutron-rich matter can be accurately determined by the $\Lambda_{1.4}$?

Introduction

Ongoing efforts have been devoted to constrain details of the EOS and reveal possibly interesting new physics from the tidal deformability;

- ✓ What is actually the relationship between the $\Lambda_{1.4}$ and $R_{1.4}$?
- ✓ What information about the EOS can be extracted from the radii of neutron stars?

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Parameterized equation of state

Details about the construction of the parameterized EOS have been introduced by Prof. Bao-An Li or our paper below:

Zhang et al. APJ 859, 90 (2018)

Parameterized equation of state

We parameterize the symmetry energy as a function of density:

$$E_{\mathrm{sym}}(\rho) = E_{\mathrm{sym}}(\rho_0) + L\left(\frac{\rho-\rho_0}{3\rho_0}\right) + \frac{K_{\mathrm{sym}}}{2}\left(\frac{\rho-\rho_0}{3\rho_0}\right)^2 + \frac{J_{\mathrm{sym}}}{6}\left(\frac{\rho-\rho_0}{3\rho_0}\right)^3$$

- ✓$E_{sym}(\rho_0)=31.7\pm3.2$ MeV;
- ✓$L=58.7\pm28.1$ MeV;
- ✓$-400 \le K_{sym} \le 100$ MeV;
- ✓$-200 \le J_{sym} \le 800$ MeV;

Details about the construction of the parameterized EOS have been introduced by Prof. Bao-An Li or our paper below:

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Tews et al. (2017); Zhang et al. (2017); Oertel et al. (2017); Li & Han (2013)

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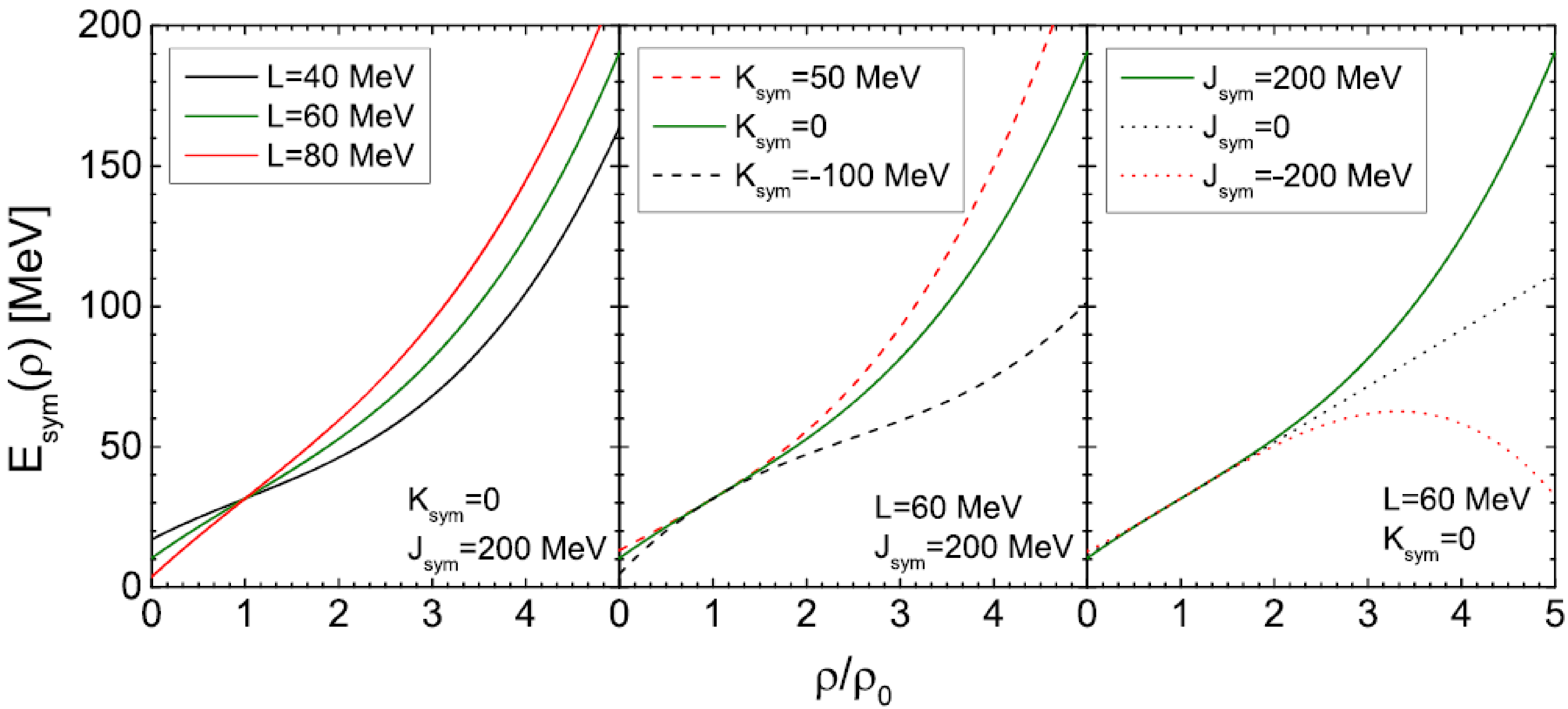
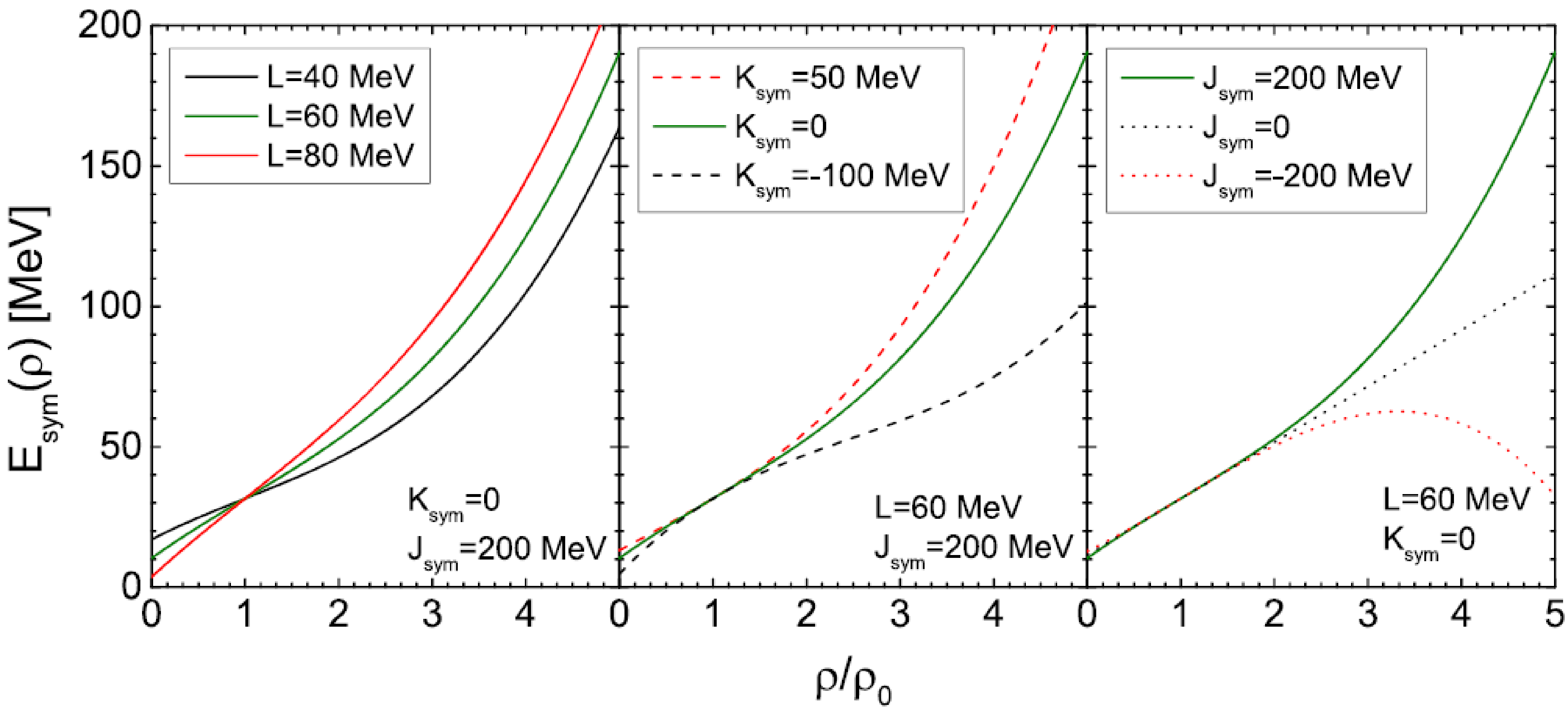
Effects of symmetry energy



Examples illustrating effects of the L (left), K_{sym} (middle) and J_{sym} (right), respectively, on the density dependence of nuclear symmetry energy Esym(ρ)

$$E_{\rm sym}(\rho) = E_{\rm sym}(\rho_0) + L\left(\frac{\rho-\rho_0}{3\rho_0}\right) + \frac{K_{\rm sym}}{2}\left(\frac{\rho-\rho_0}{3\rho_0}\right)^2 + \frac{J_{\rm sym}}{6}\left(\frac{\rho-\rho_0}{3\rho_0}\right)^3$$

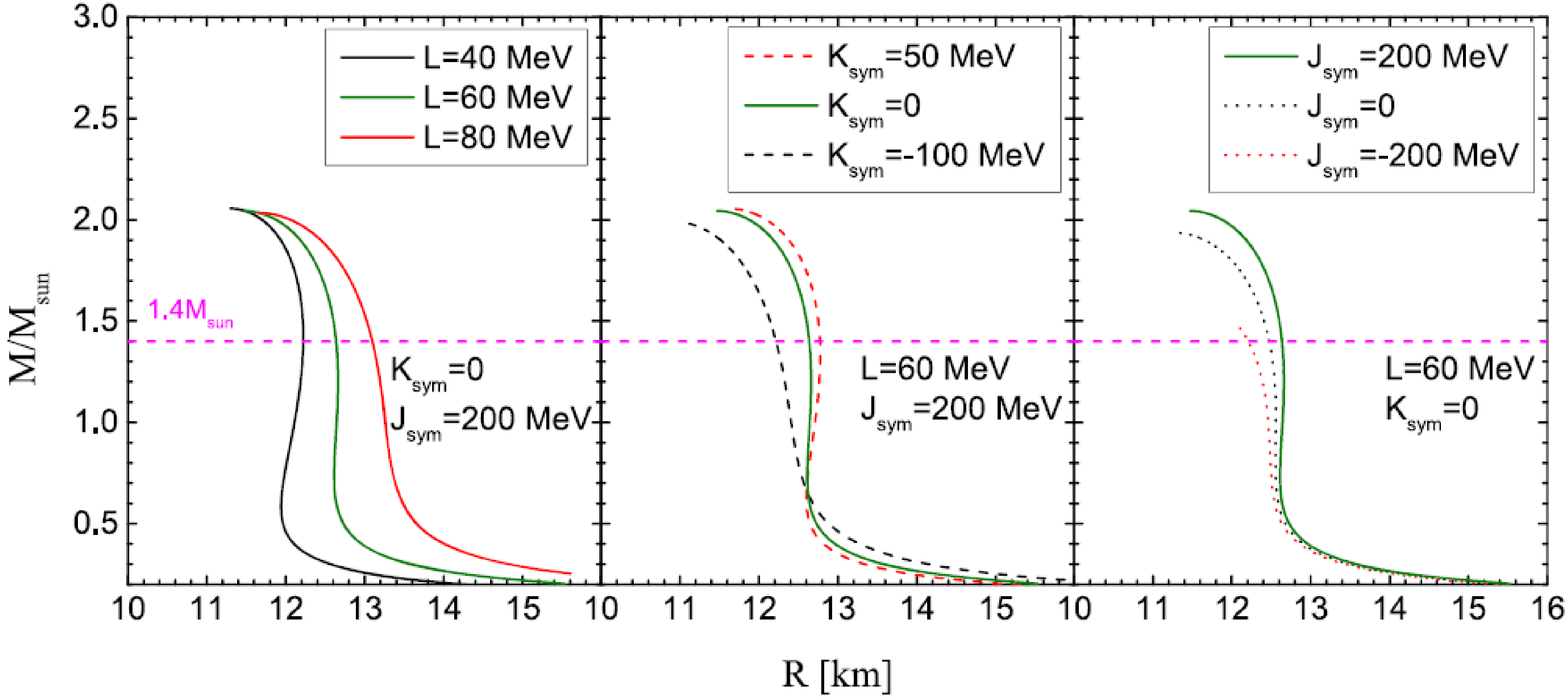
Effects of symmetry energy



Examples illustrating effects of the L (left), K_{sym} (middle) and J_{sym} (right), respectively, on the density dependence of nuclear symmetry energy Esym(ρ).

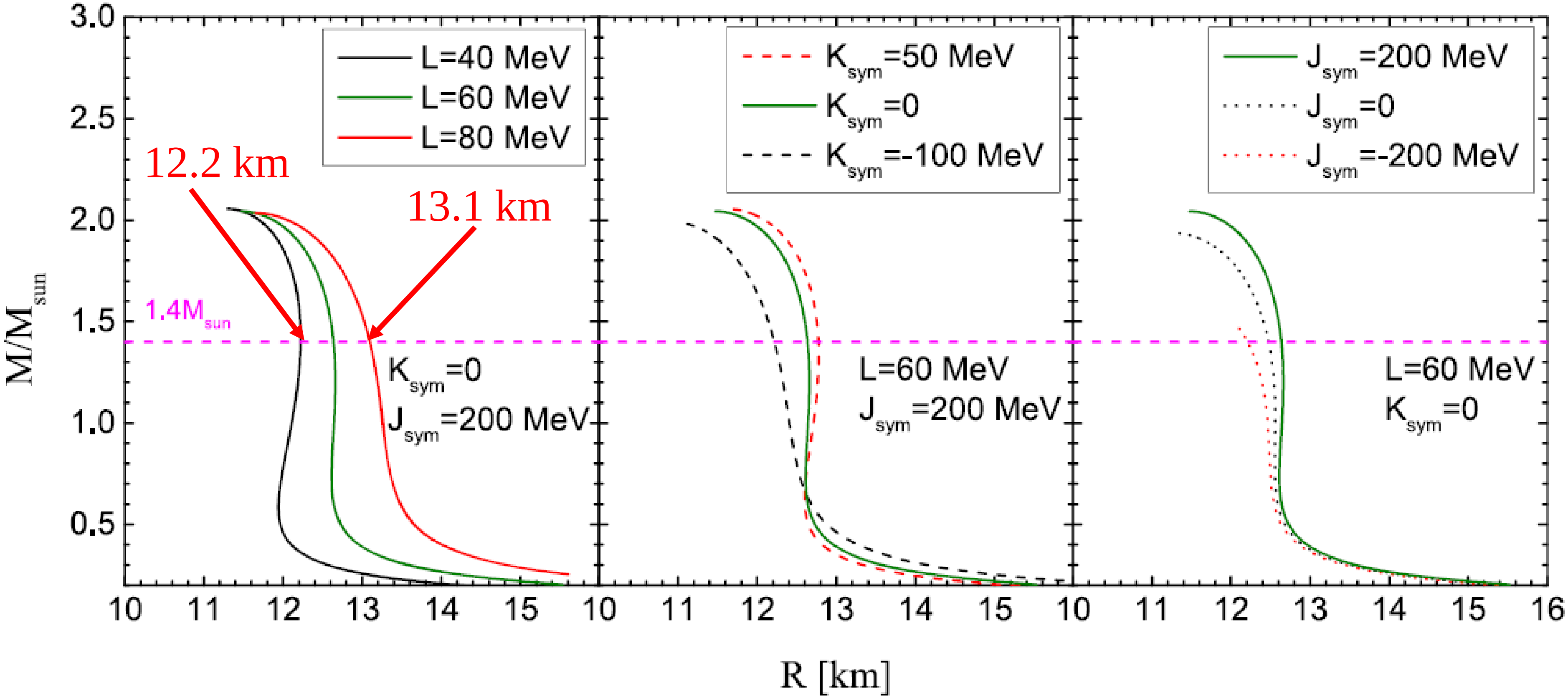
$L \sim \rho_0$ $K_{sym} \sim 2\rho_0$ $J_{sym} \sim 3\rho_0$

Effects of symmetry energy



Examples illustrating effects of the L, K_{sym} and J_{sym}, respectively, on the mass-radius correlation of neutron stars.

Effects of symmetry energy

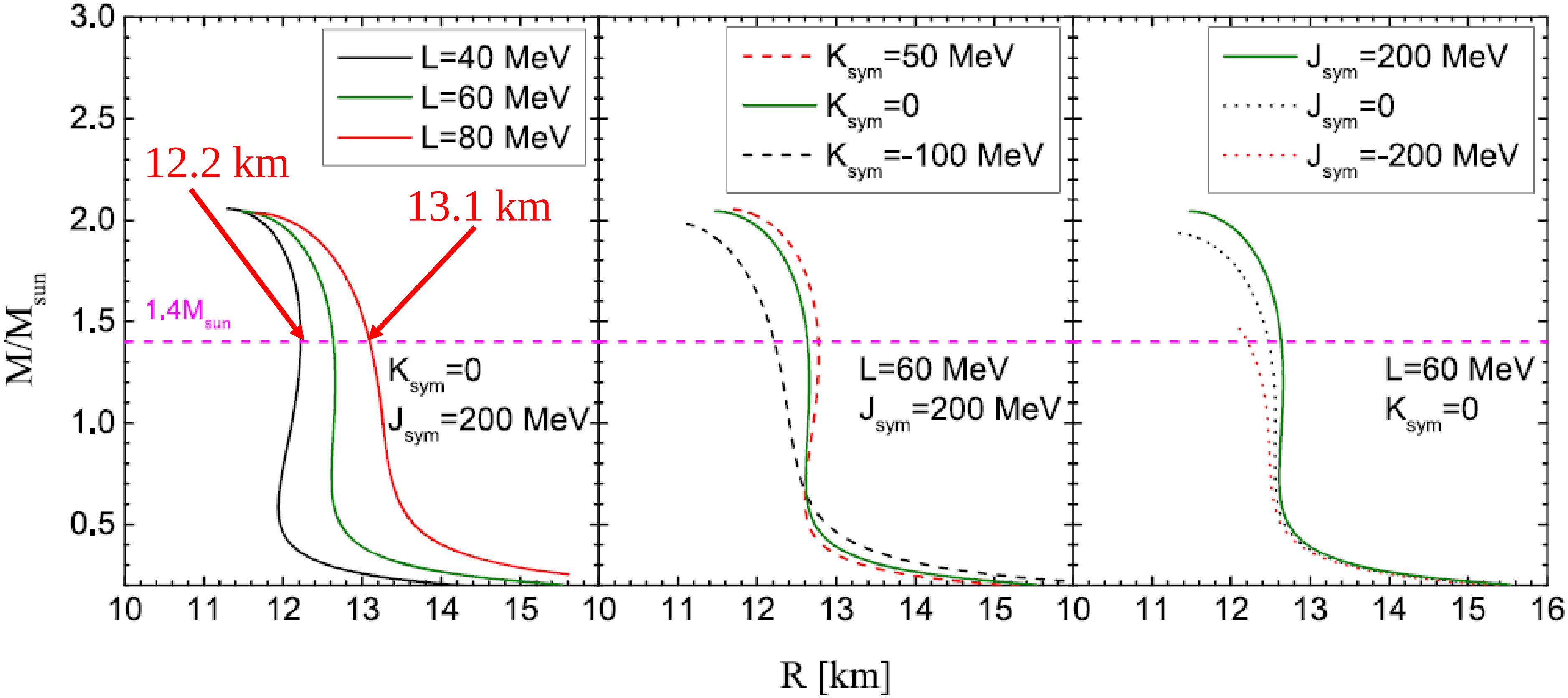


Examples illustrating effects of the L, K_{sym} and J_{sym}, respectively, on the mass-radius correlation of neutron stars.

L changes 50%

$R_{1.4}$ changes 7%

Effects of symmetry energy



Examples illustrating effects of the L, K_{sym} and J_{sym}, respectively, on the mass-radius correlation of neutron stars.

L changes 50%

$R_{1.4}$ changes 7%

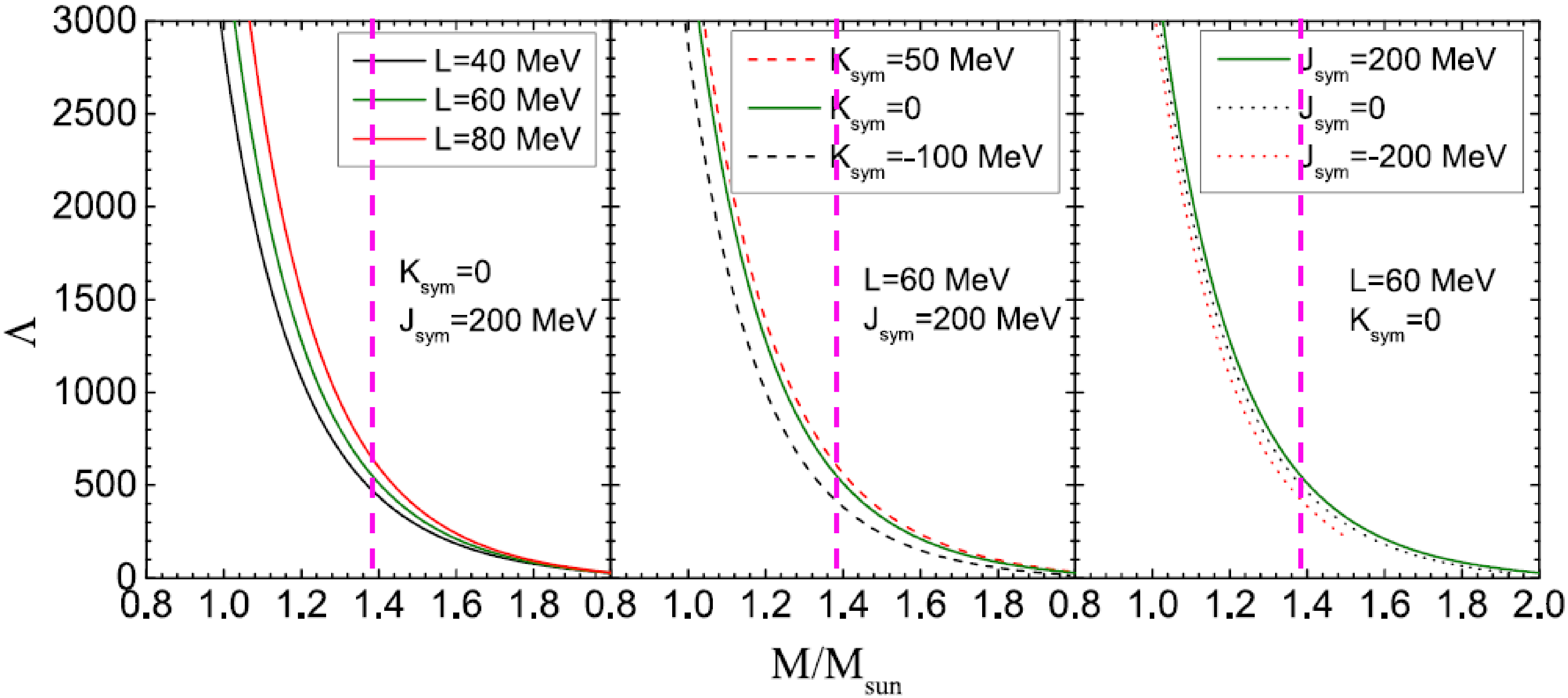
K_{sym} changes 150%

$R_{1.4}$ changes 5%

J_{sym} changes 200%

$R_{1.4}$ changes 3%

Effects of symmetry energy



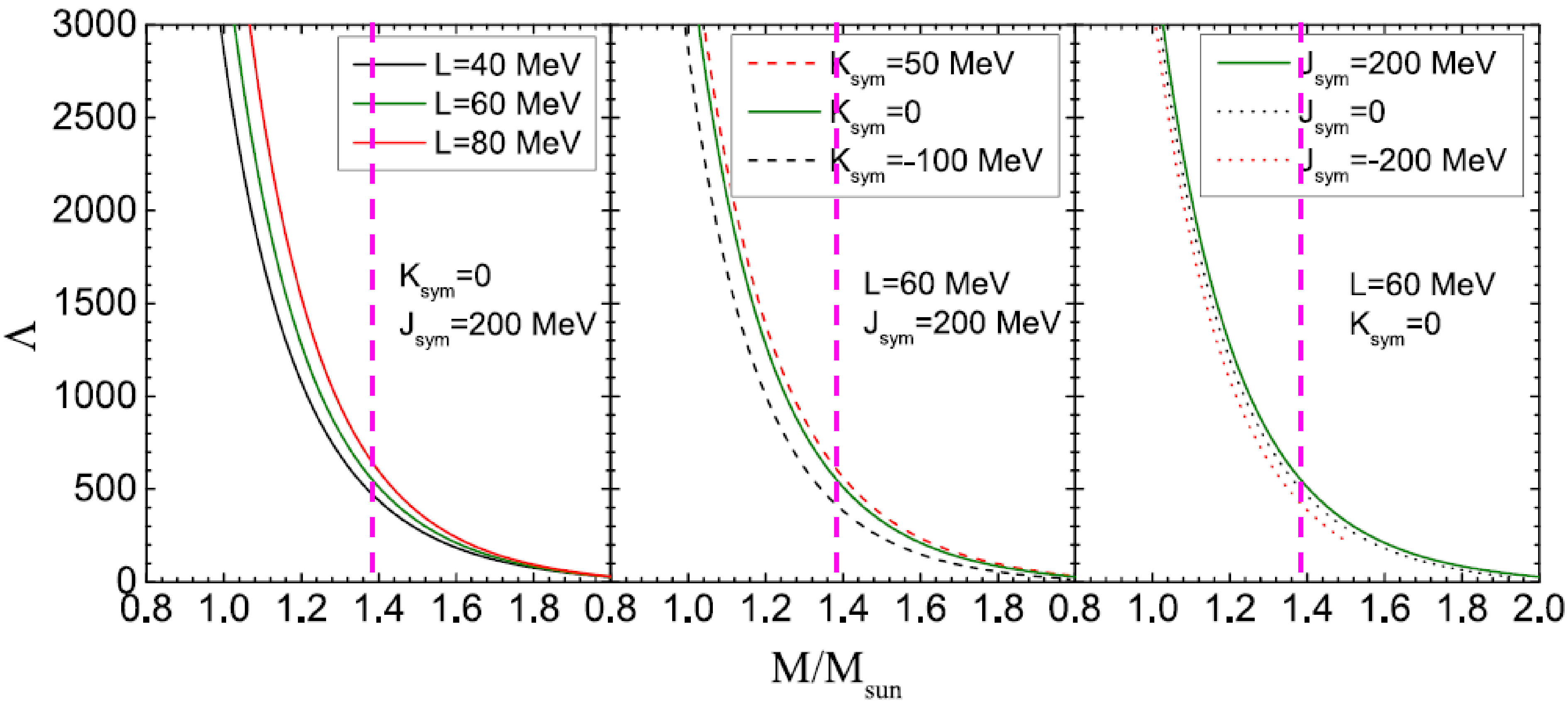
Examples illustrating effects of the L, K_{sym} and J_{sym}, respectively, on the mass-tidal deformability correlation of neutron stars.

L changes 50% $\Lambda_{1.4}$ changes 36%

K_{sym} changes 150% $\Lambda_{1.4}$ changes 47%

J_{sym} changes 200% $\Lambda_{1.4}$ changes 33%

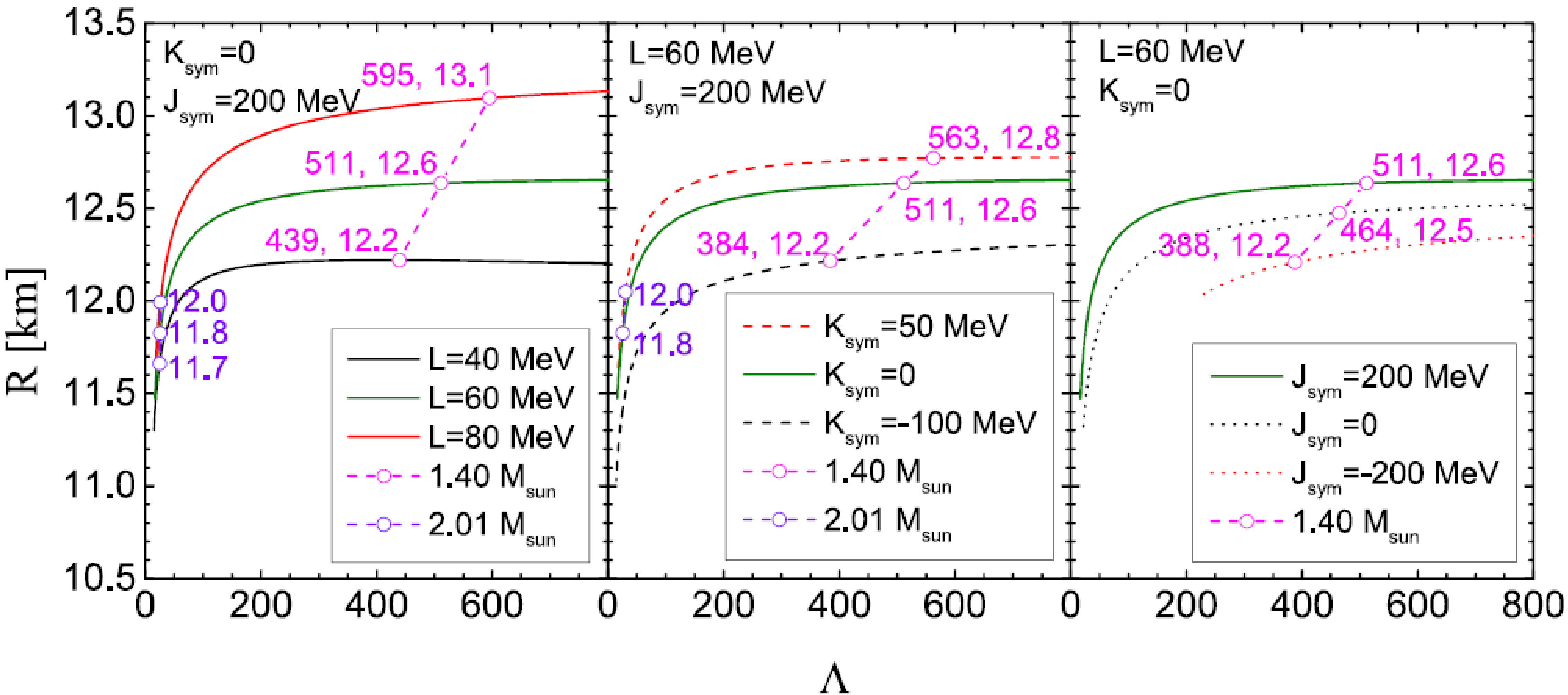
Effects of symmetry energy



Examples illustrating effects of the L, K_{sym} and J_{sym}, respectively, on the mass-tidal deformability correlation of neutron stars.

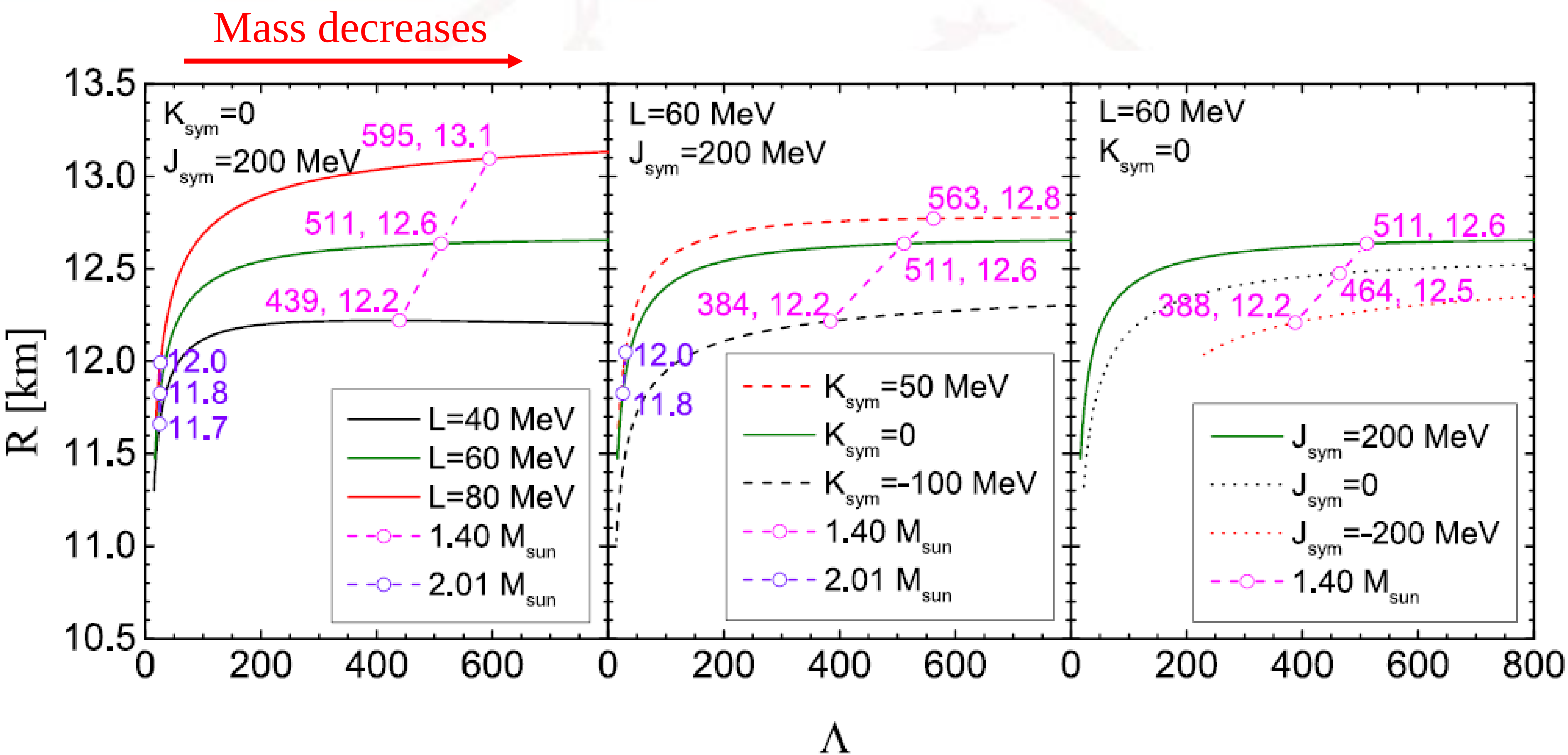
Λ is more sensitive to the variation of $E_{sym}(\rho)$ than the radius;

Effects of symmetry energy



Examples illustrating effects of the L, K_{sym} and J_{sym}, respectively, on the radius-tidal deformability correlation of neutron stars.

Effects of symmetry energy



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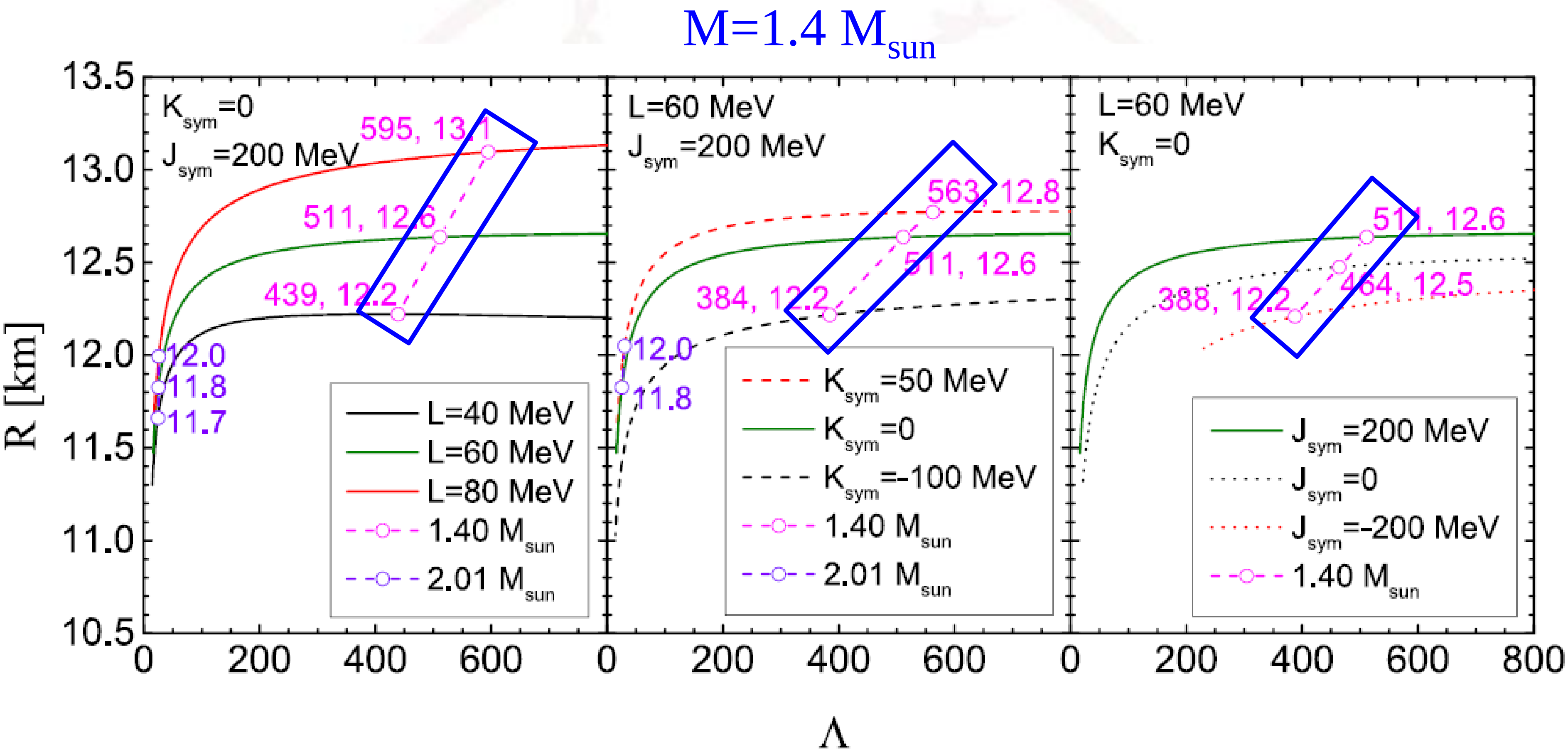
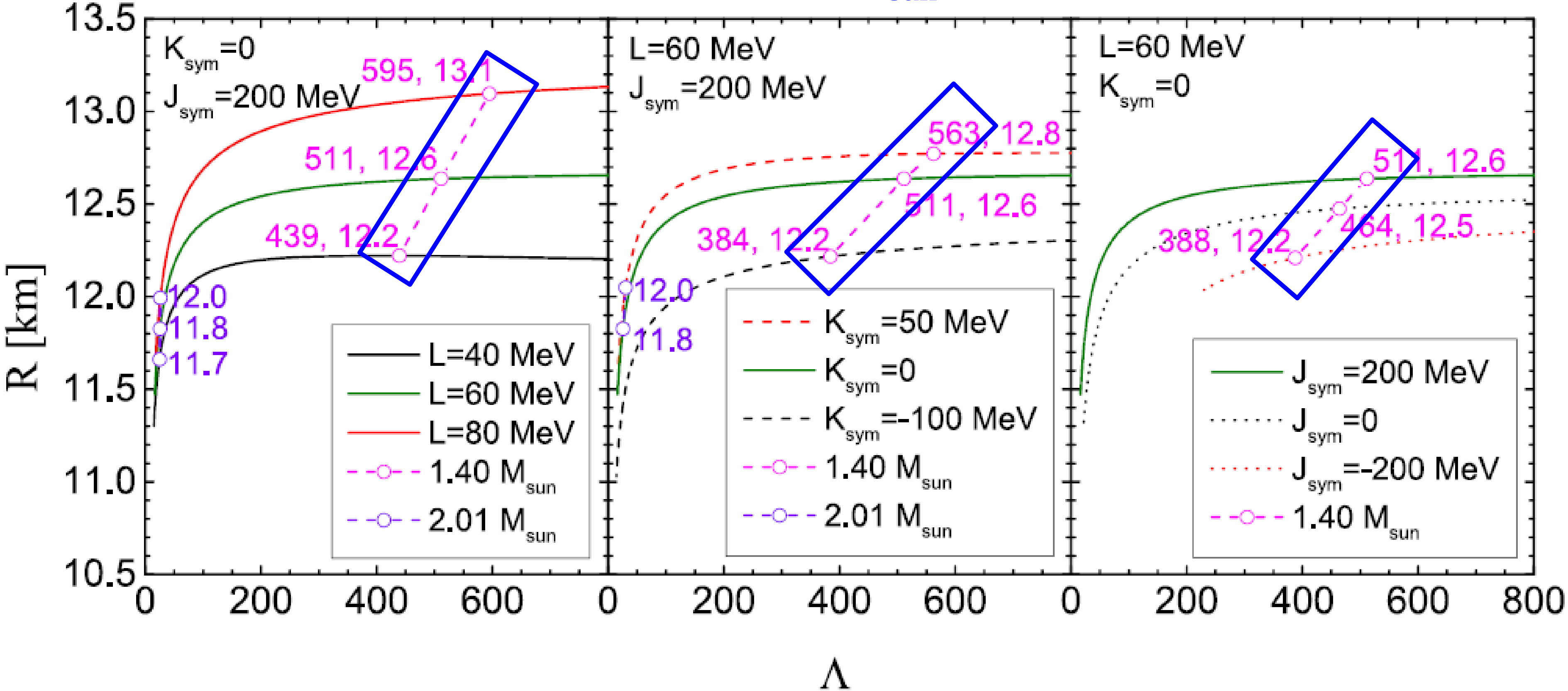


Examples illustrating effects of the L, K_{sym} and J_{sym}, respectively, on the radius-tidal deformability correlation of neutron stars.

$R_{1.4}$ increases approximately linearly with $\Lambda_{1.4}$;

Effects of symmetry energy

$M=1.4\ M_{sun}$



Examples illustrating effects of the L, K_{sym} and J_{sym}, respectively, on the radius-tidal deformability correlation of neutron stars.

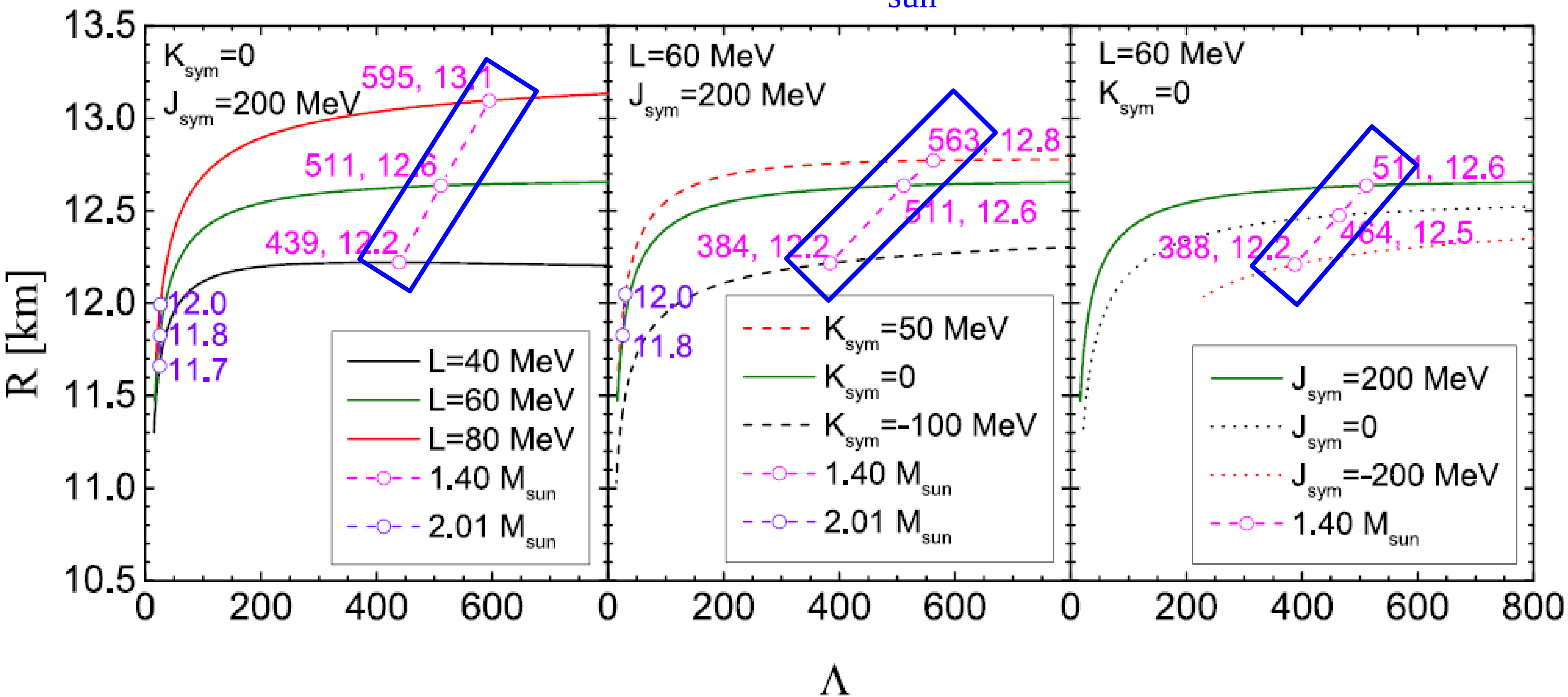
$$\Lambda_{1.4} \approx 2.88 \times 10^{-6} \times R_{1.4}^{7.5}$$

$$\Lambda_{1.4} \approx 9.11 \times 10^{-5} \times R_{1.4}^{6.13}$$

$$\Lambda_{1.4} \approx 7.76 \times 10^{-4} \times R_{1.4}^{5.28}$$

Effects of symmetry energy

M=1.4 M_{sun}



Examples illustrating effects of the L, K_{sym} and J_{sym}, respectively, on the radius-tidal deformability correlation of neutron stars.

$R_{1.4}$=7.0–14.7 km, $\Lambda_{1.4}$=0–1600

Effects of symmetry energy

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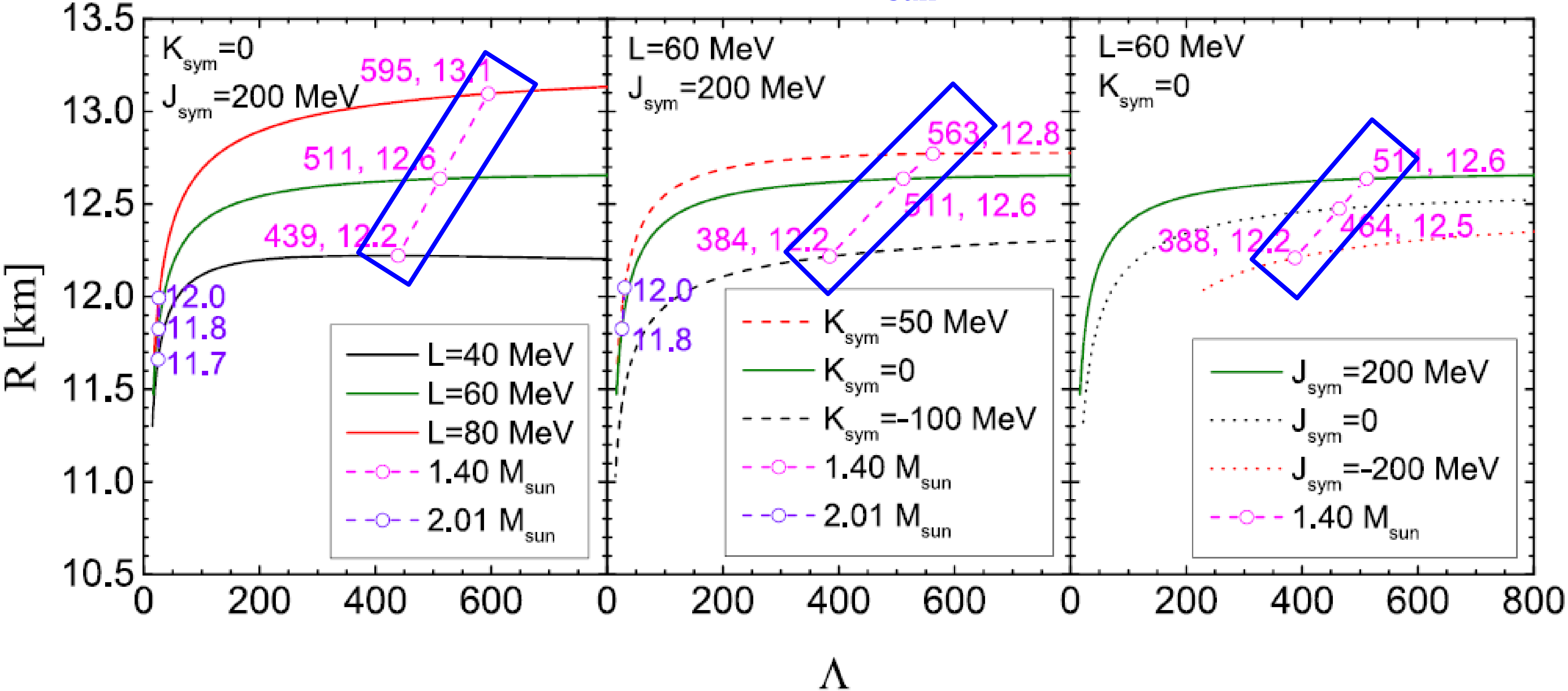

Examples illustrating effects of the L, K_{sym} and J_{sym}, respectively, on the radius-tidal deformability correlation of neutron stars.

$R_{1.4}$=7.0–14.7 km, $\Lambda_{1.4}$=0–1600

$R_{1.4}\sim\Lambda_{1.4}$ needs further studies

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Density dependence of symmetry energy

$$E_{\rm sym}(\rho) = E_{\rm sym}(\rho_0) + L\left(\frac{\rho-\rho_0}{3\rho_0}\right) + \frac{K_{\rm sym}}{2}\left(\frac{\rho-\rho_0}{3\rho_0}\right)^2 + \frac{J_{\rm sym}}{6}\left(\frac{\rho-\rho_0}{3\rho_0}\right)^3$$

$E_{sym}(\rho_0)$=31.7 MeV;

✓ $60 \le L \le 90$ MeV;

✓ $-400 \le K_{sym} \le 100$ MeV;

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✓ $60 \le L \le 90$ MeV;

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Fix L, and K_{sym}, vary J_{sym}

TOV

Mass, radius……

Density dependence of symmetry energy

$$E_{sym}(\rho) = E_{sym}(\rho_0) + L\left(\frac{\rho - \rho_0}{3\rho_0}\right) + \frac{K_{sym}}{2}\left(\frac{\rho - \rho_0}{3\rho_0}\right)^2 + \frac{J_{sym}}{6}\left(\frac{\rho - \rho_0}{3\rho_0}\right)^3$$

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✓$60 \leq L \leq 90$ MeV;

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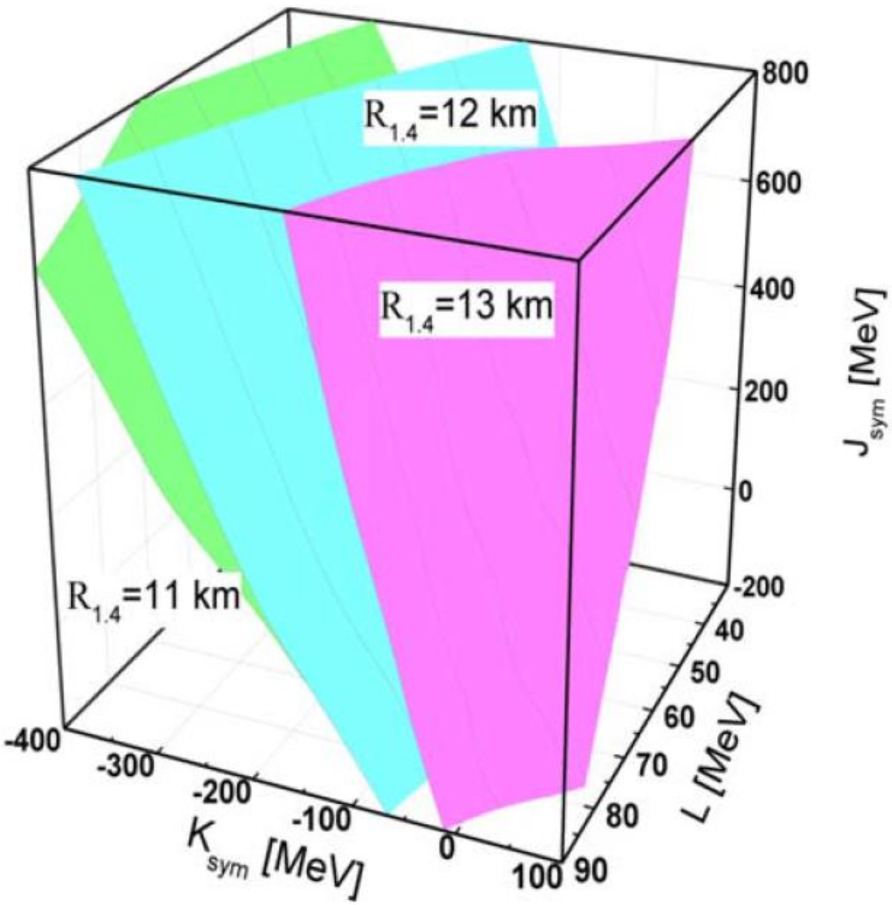
✓$-200 \leq J_{sym} \leq 800$ MeV;

Fix L=60
and K_{sym}=100
set J_{sym}=474

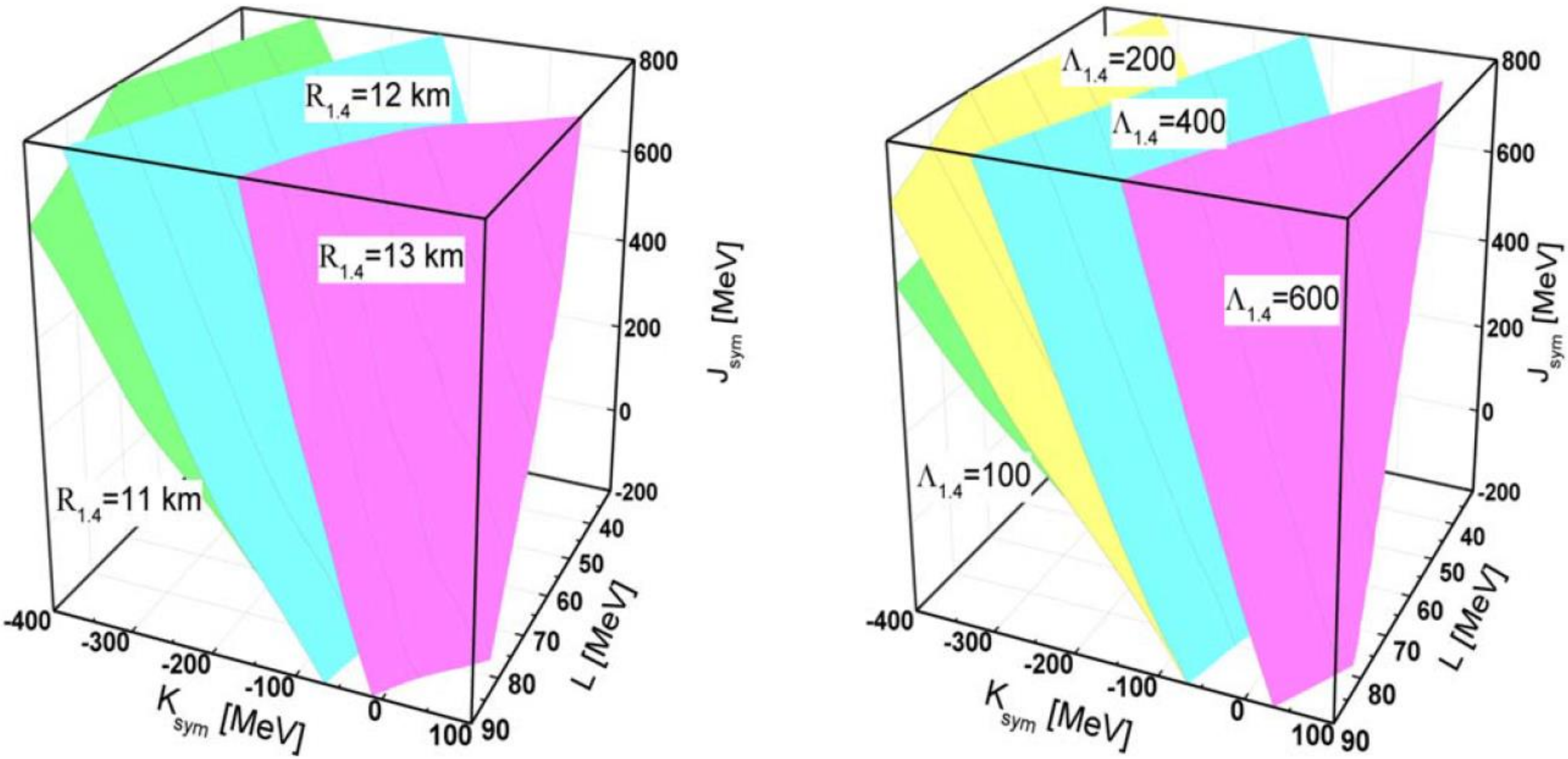
TOV

$R_{1.4}$=13 km

Density dependence of symmetry energy

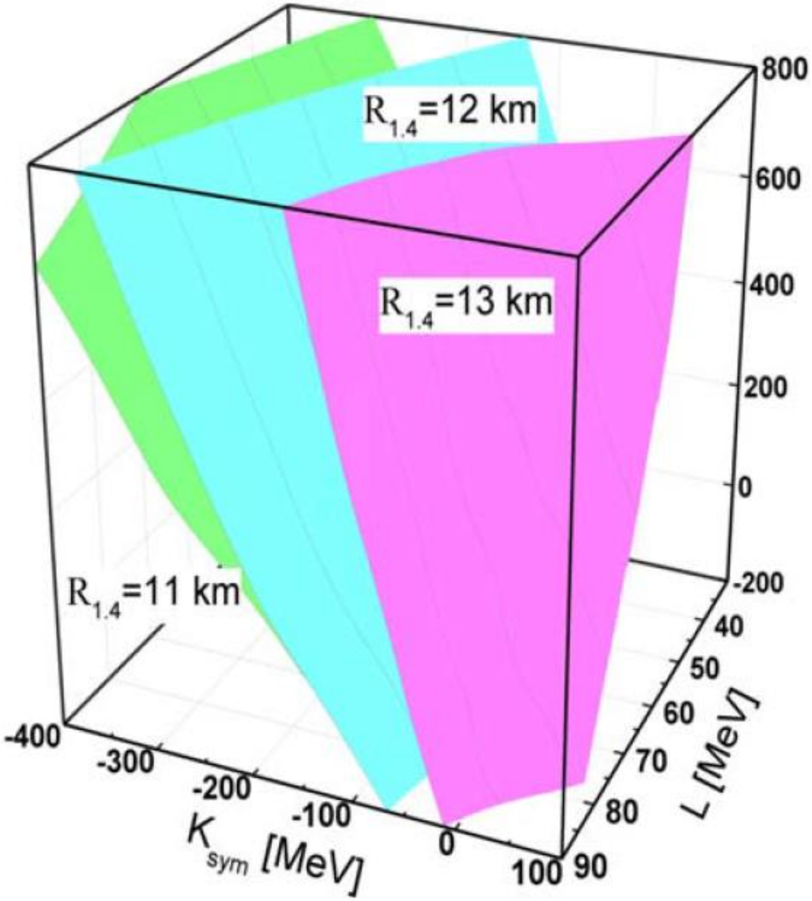


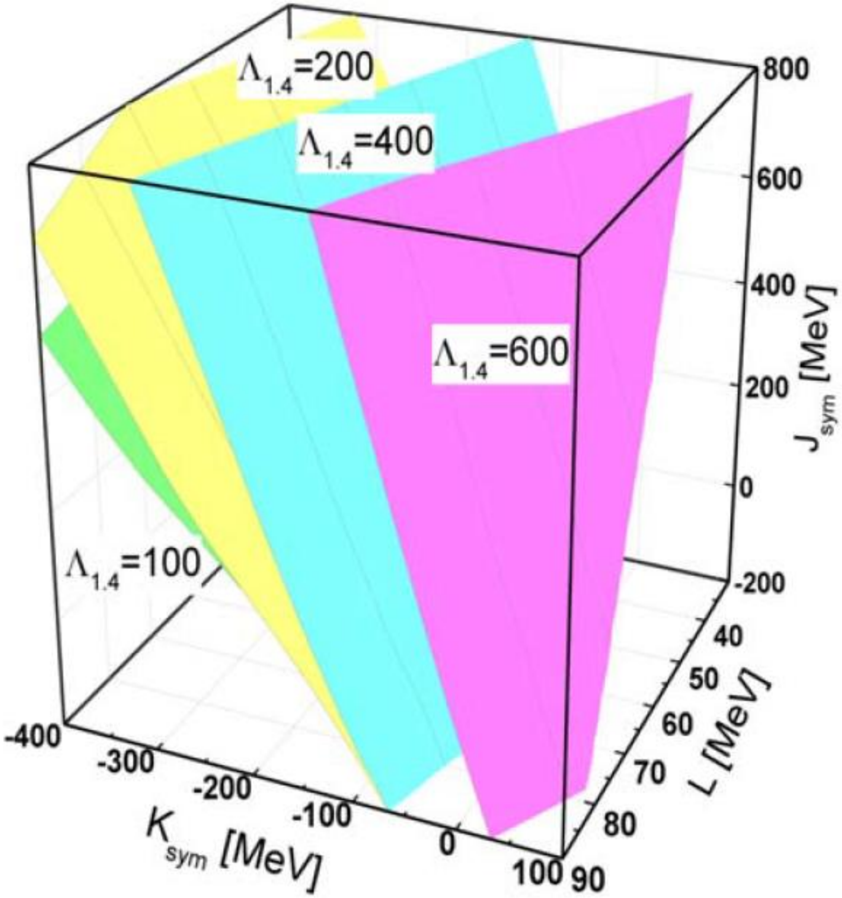
Density dependence of symmetry energy



Surfaces of constant radius (left) and tidal polarizability (right) in the symmetry energy parameter space of L, K_{sym}, and J_{sym}, respectively.

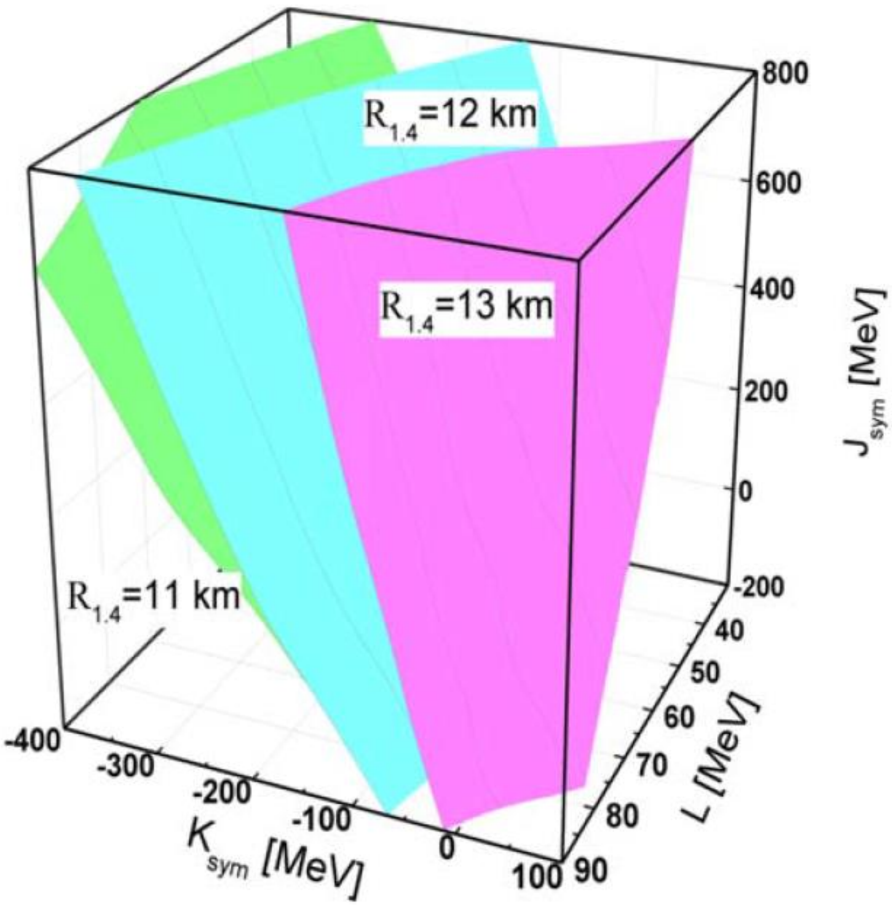
Density dependence of symmetry energy

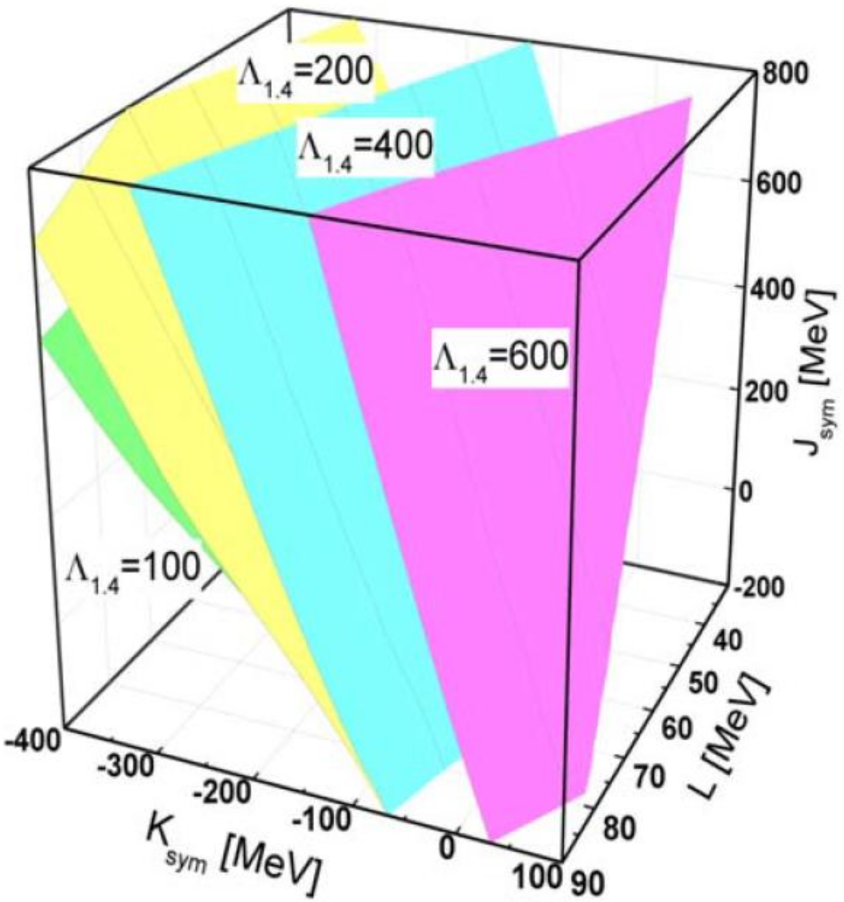




- J_{sym} can be essentially any value;

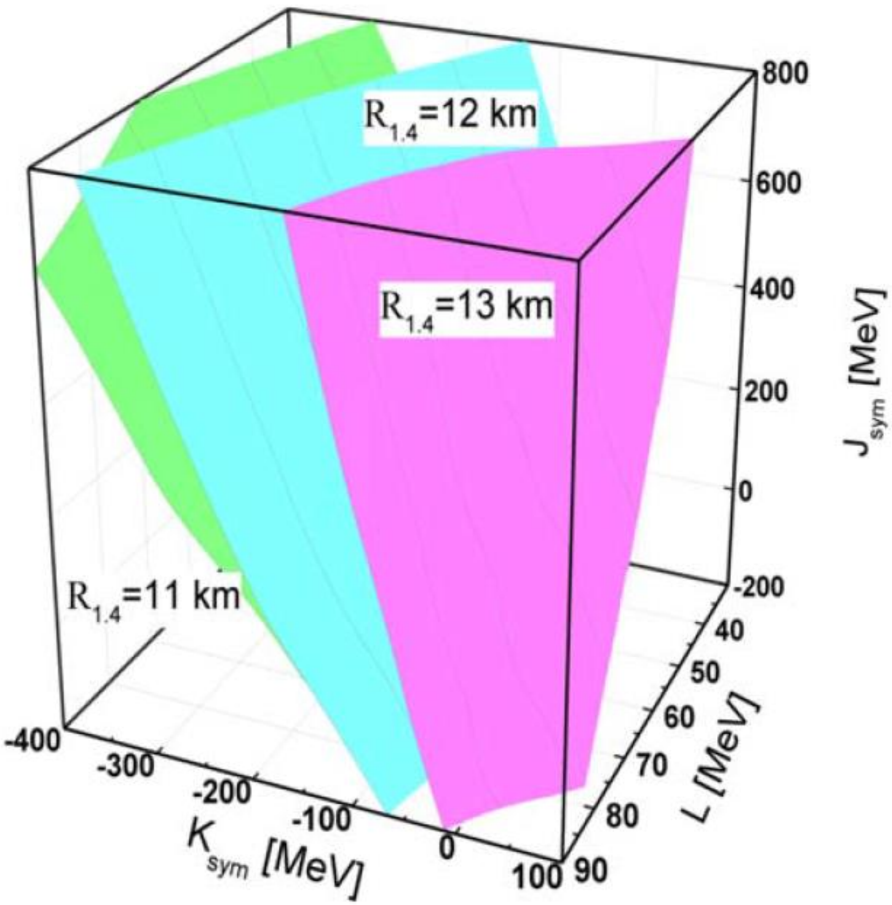
Density dependence of symmetry energy

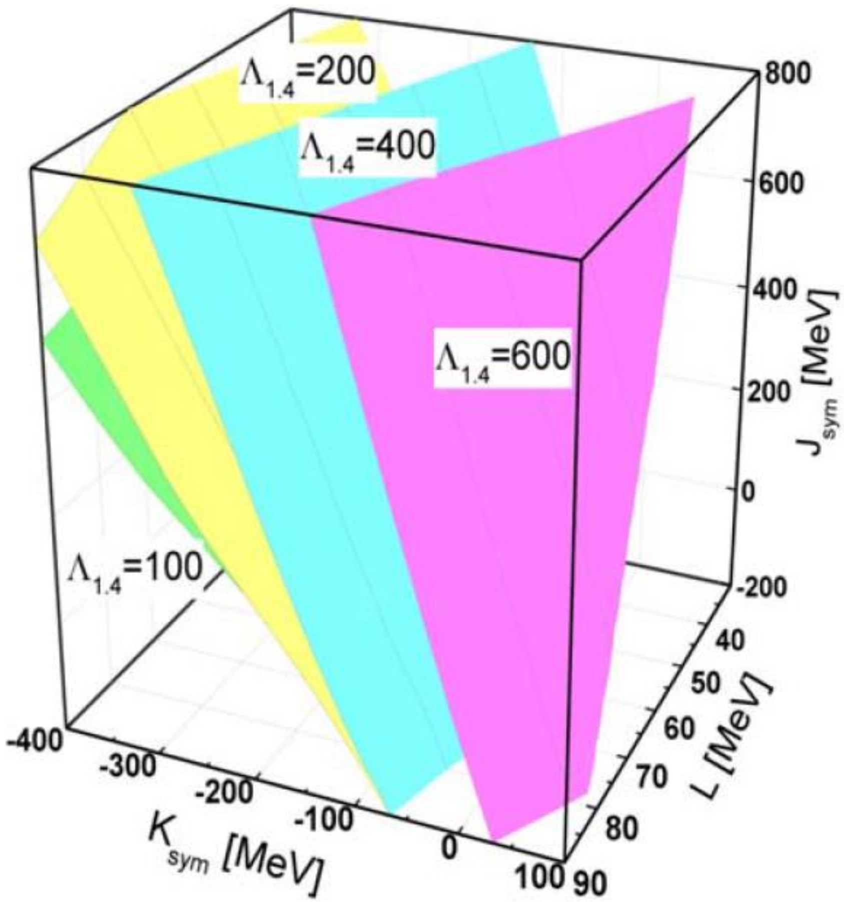




- J_{sym} can be essentially any value;
- K_{sym} has an appreciable role in determining the radius;

Density dependence of symmetry energy





- ➢ L alone cannot uniquely determine the radii of neutron stars;
- ➢ High-density behavior of $E_{sym}(\rho)$ is also important;

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- ➢Constraints on symmetry energy
- ➢Summary

Summary

- Using an explicitly isospin-dependent EOS, we first investigated effects of parameters on the radius and tidal deformability;
- While both the $R_{1.4}$ and $\Lambda_{1.4}$ depend strongly on L, the high density parameters K_{sym} and J_{sym} play appreciable roles;
- The $R_{1.4}$ and $\Lambda_{1.4}$ are approximately linearly correlated and Λ is found to be more sensitive to $E_{sym}(\rho)$ than the radius;
- The individual measurements of $\Lambda_{1.4}$ and $R_{1.4}$ can stringent constrain the high density behavior of symmetry energy;
- Additional observables and nuclear experiments are necessary to break this degeneracy in order to completely determine the density dependence of $E_{sym}(\rho)$.

Thanks for your attention!

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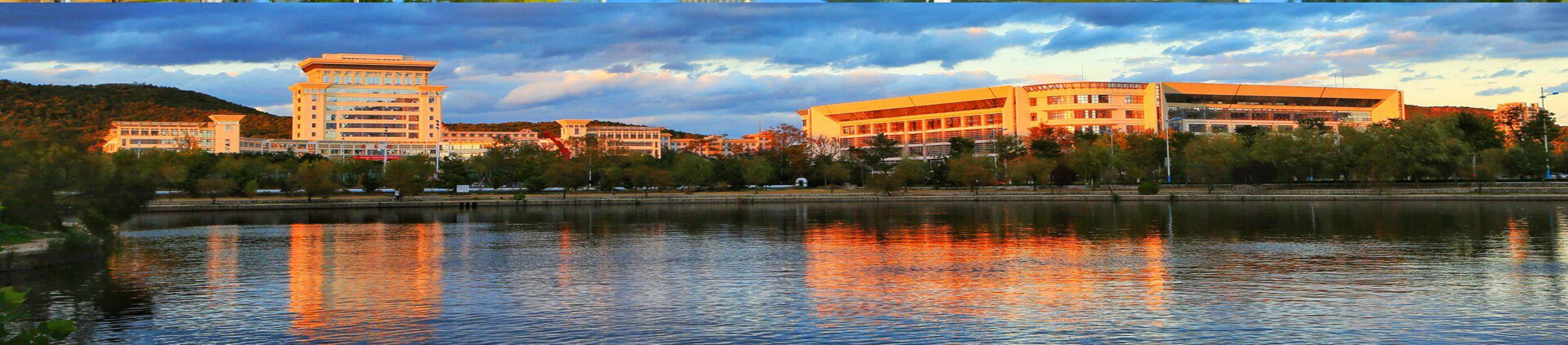
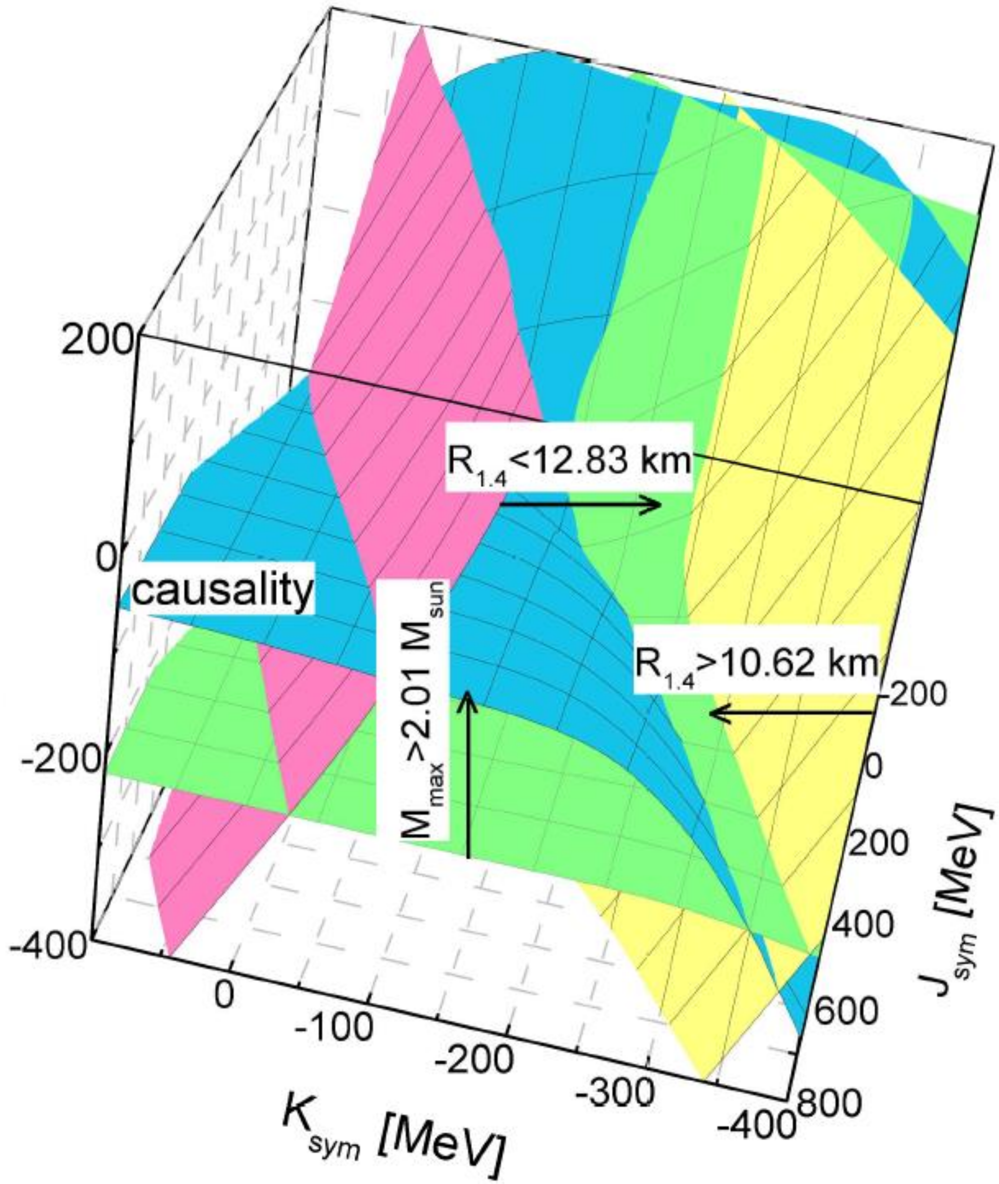
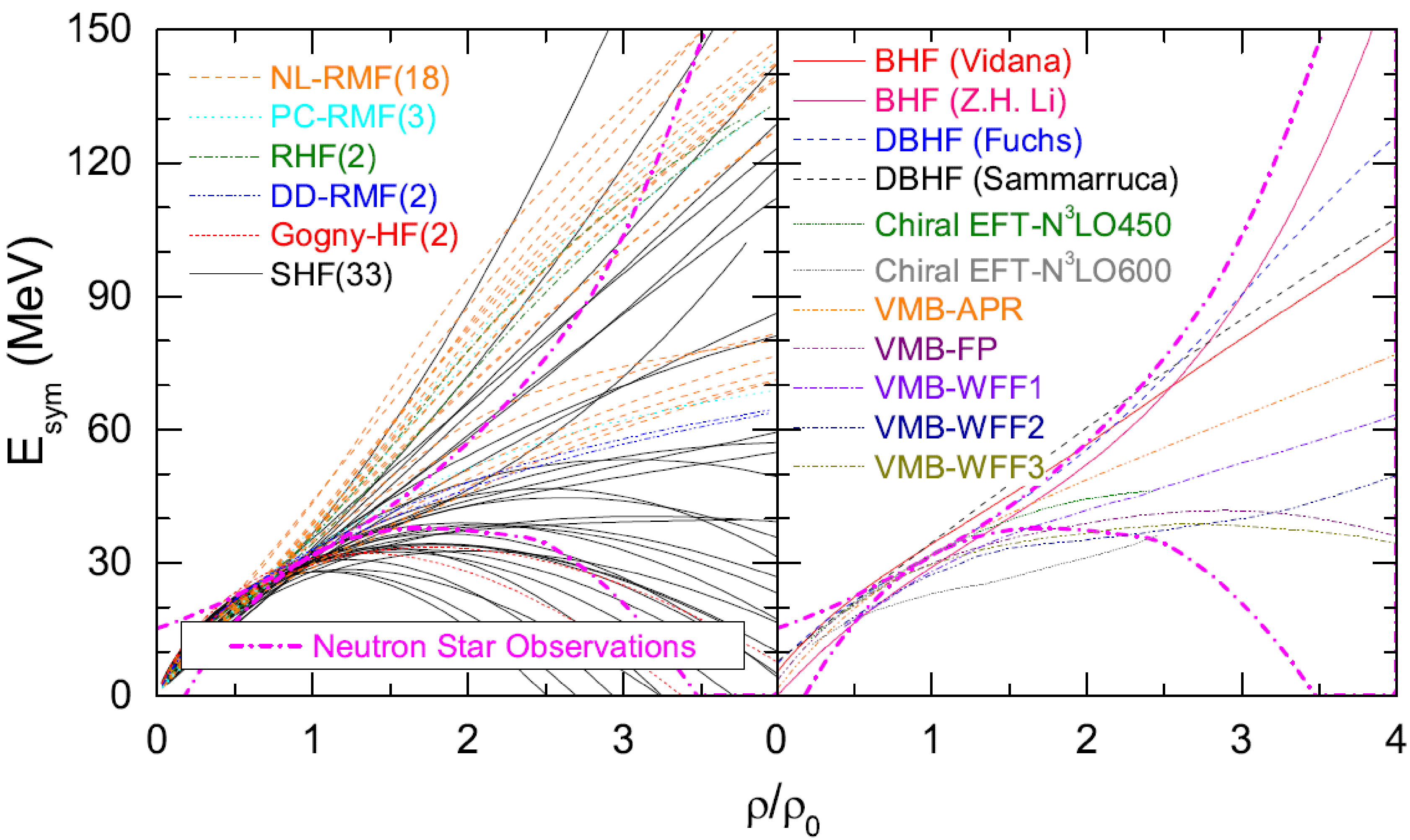


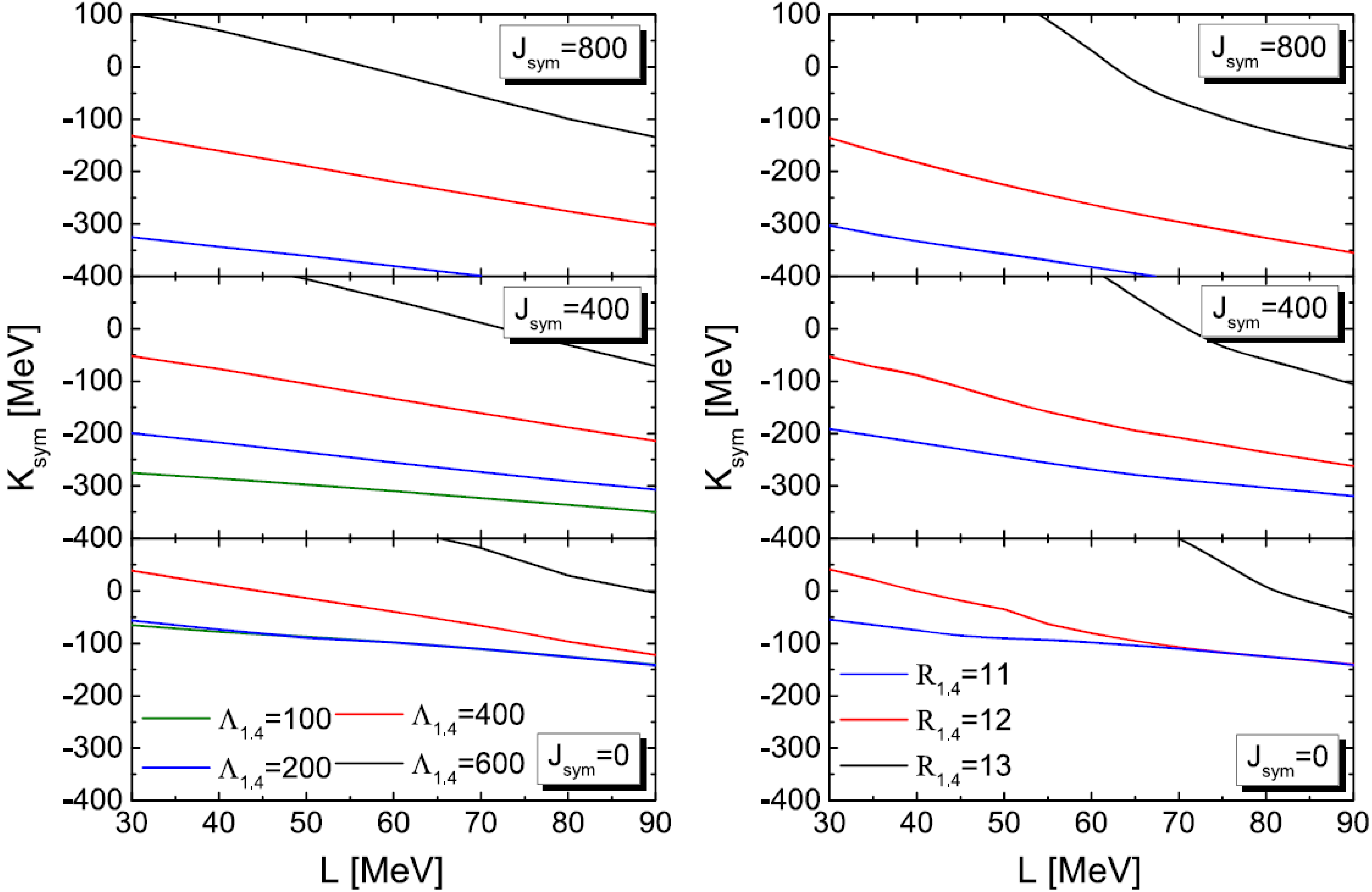
3D parameter space



Symmetry energy



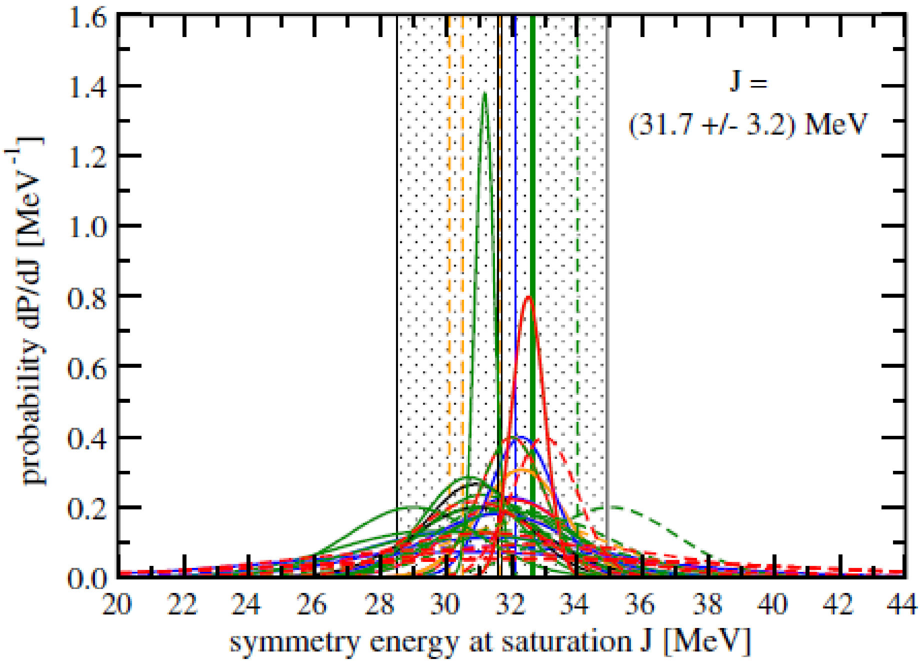
2D constraints on E_{sym}



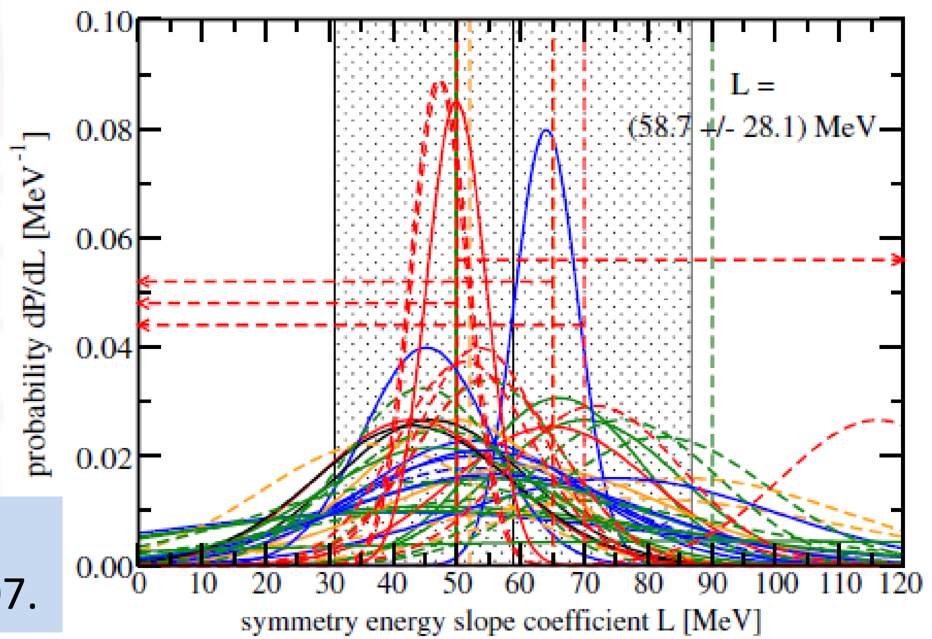
Equation of state

$$E_0(\rho) = E_0(\rho_0) + \frac{K_0}{2}\left(\frac{\rho-\rho_0}{3\rho_0}\right)^2 + \cdots$$

$$E_{sym}(\rho) = \boxed{E_{sym}(\rho_0)} + \boxed{L}\left(\frac{\rho-\rho_0}{3\rho_0}\right) + \frac{K}{\cdots}\cdots$$



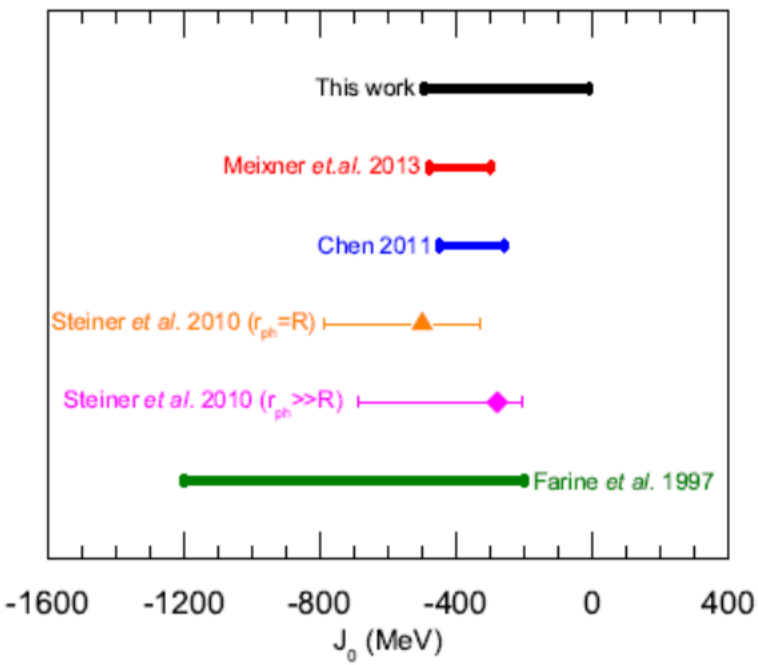
- ➢Surveys of 53 analyses of different kinds of terrestrial and astrophysical data have constrained $E_{sym}(\rho_0)$=31.7 ± 3.2 MeV and L=58.7 ± 28.1 MeV;



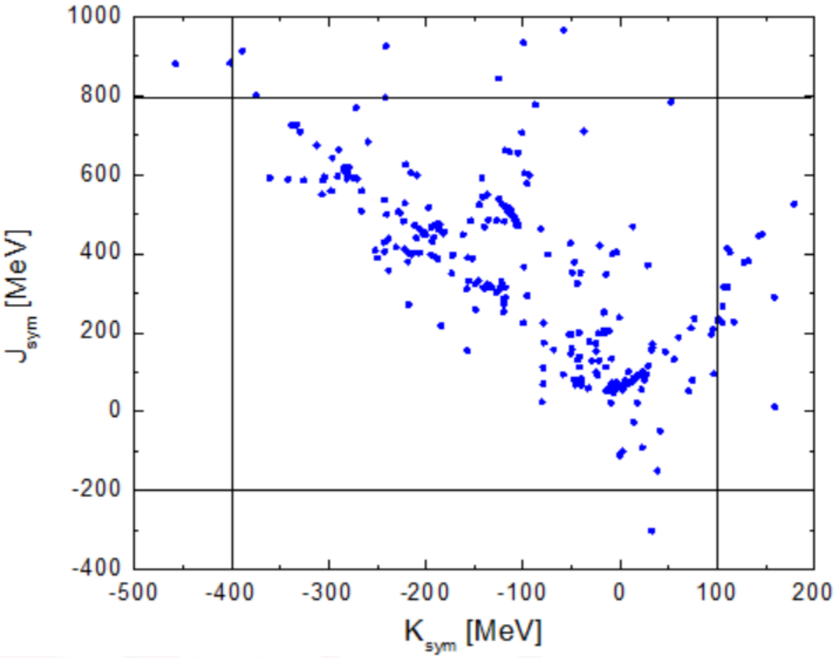
Li, B. A., & Han, X. 2013, Phys. Lett. B, 727, 276;
Oertel, M., et al. 2017, Rev. Mod. Phys., 89, 015007.

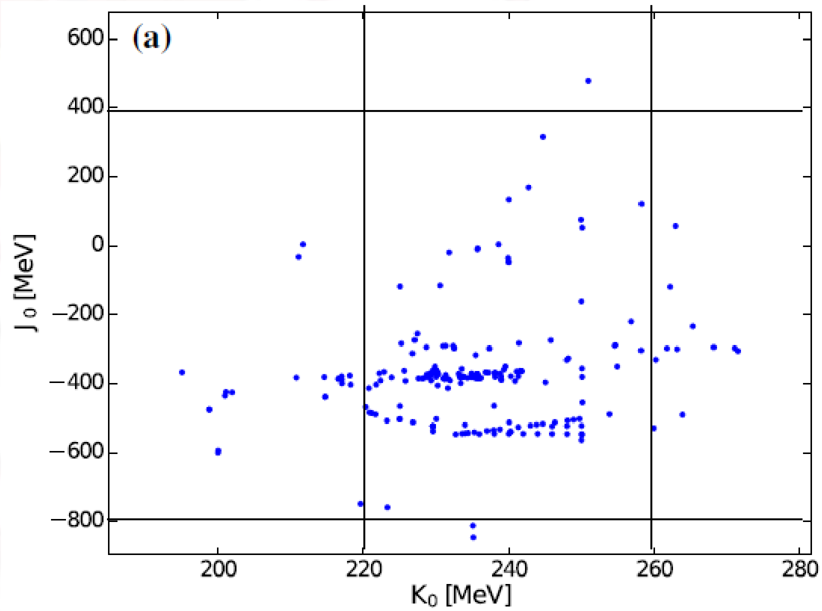
Equation of state

- ➢The high order coefficients：
  - ✓$-400 \le K_{sym} \le 100$ MeV,
  - ✓$-200 \le J_{sym} \le 800$ MeV
  - ✓$-800 \le J_0 \le 400$ MeV



Cai, B. J., & Chen, L. W. 2017, NST, 28, 185.





Zhang, N. B., et al. 2017, NST, 28, 181