How the bulk properties of nuclear matter influence neutron star observables?

[1] G.G. Barnafoldi, A. Jakovac, P. Posfay, Phys. Rev. D 95, 025004

[2] G. Barnaföldi, P. Pósfay, A. Jakovác, Phys.Rev. C97 (2018) no.2, 025803

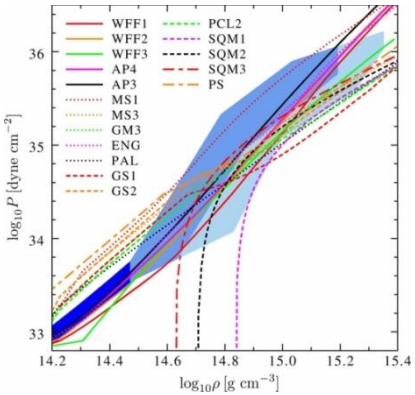
[3] Pósfay, P., Barnaföldi, G., & Jakovác, A. PASA (2018), *35*, E019.

Péter Pósfay

Supervisors: Gergely Barnaföldi, Antal Jakovác

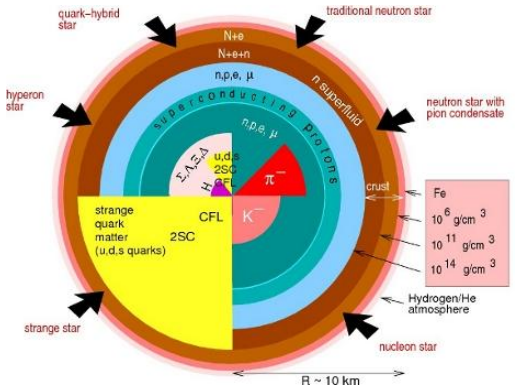
Motivation

EoS



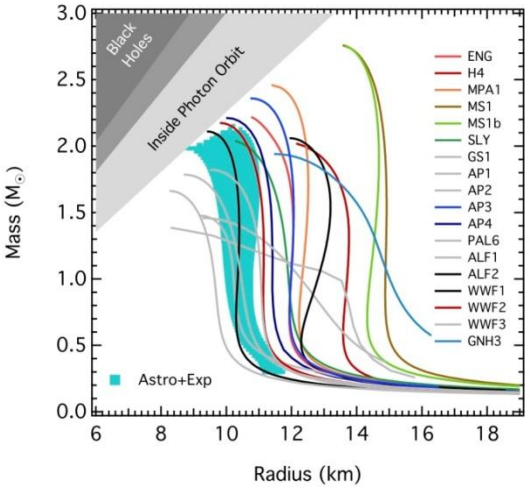
TOV equations

Star Structure



Termodynamics

M–R diagram

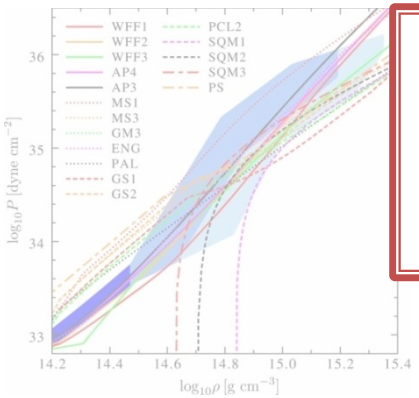


NUCLEAR MODEL

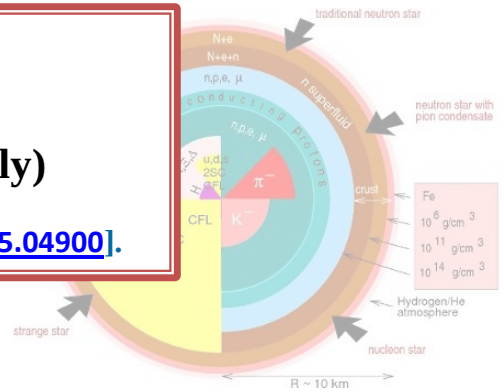
Microscopic paramaters

Motivation

EoS



Star Structure



MODEL ZOO

10 million models exist (Literally)

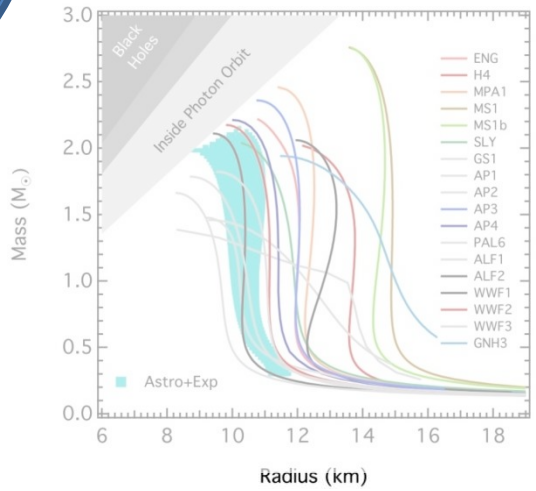
L. Rezzola & E.R. Most's recent Ref.[arXiv:1905.04900].

Termodynamics

NUCLEAR MODEL

Microscopic paramaters

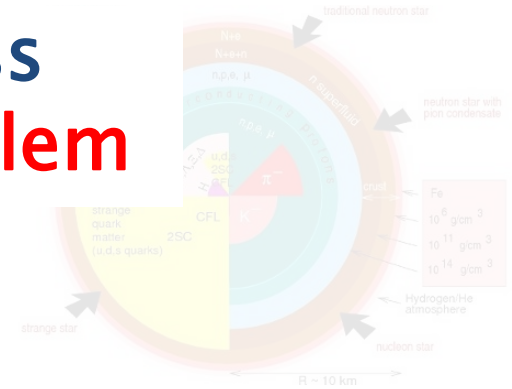
M-R diagram



Motivation

EoS

Star Structure



Information loss

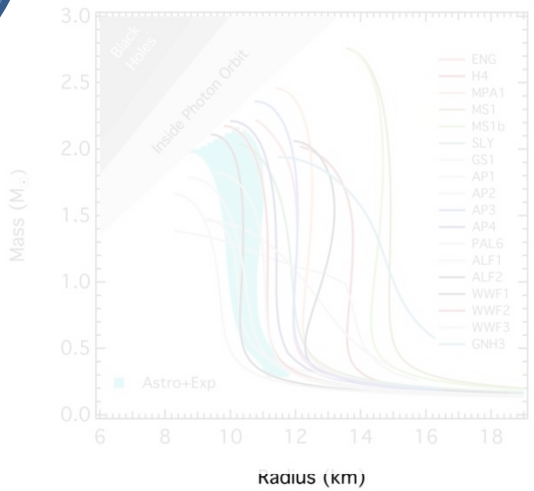
Masquarade problem

Termodynamics

NUCLEAR MODEL

Microscopic paramaters

M-R diagram



Motivation

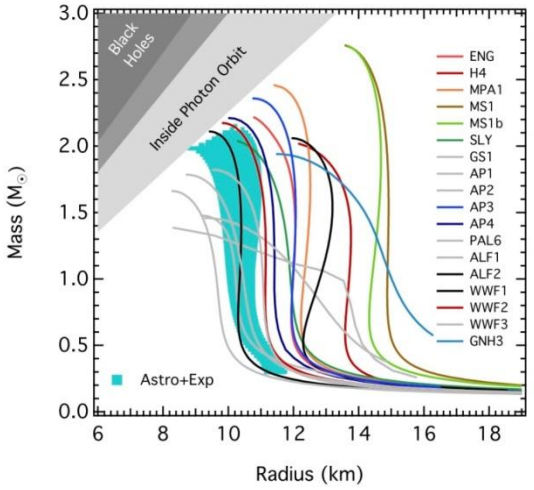
Are there **microscopic parameters** which influence the **M-R diagram** more strongly than others?

NUCLEAR MODEL
Microscopic paramaters

Large effect

Parameters influence M-R diagram

M-R diagram



Motivation

EoS

Star Structure

If YES

- **Astrophysics:** These are the most important components of the nuclear models from the compact star perspective
- **Nuclear physics:** These are the parameters which can be inferred from the M-R diagram more directly

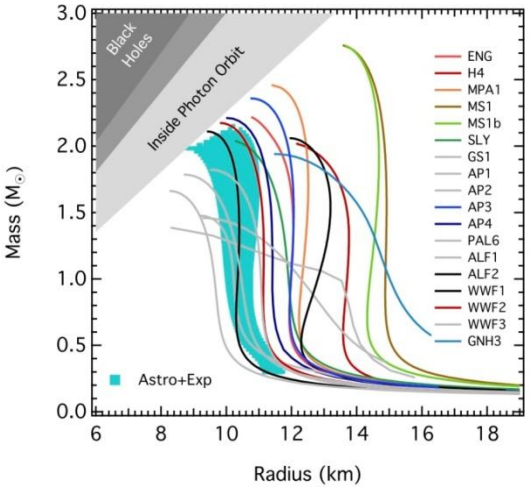
Termodynamics

NUCLEAR MODEL
Microscopic paramaters

Large effect

Parameters influence M-R diagram

M-R diagram



Fitting parameters of nuclear matter

Parameter	Value
Saturation density	0.156 1/fm^3
Binding energy	-16.3 MeV
Nucleon effective mass	0.6 M_N
Nucleon Landau mass	0.83 M_N
incompressibility	240 MeV
Asymmetry energy	32.5 MeV

Incompressibility

$$K = k_F^2 \frac{\partial^2(\epsilon/n)}{\partial k_F^2} = 9\frac{\partial p}{\partial n}$$

Landau mass

$$m_L = \frac{k_F}{v_F} \qquad v_F = \left.\frac{\partial E_k}{\partial k}\right|_{k=k_F}$$

$$m_L = \sqrt{k_F^2 + m_{N,eff}^2}$$

The effective mass and Landau mass are not independent!

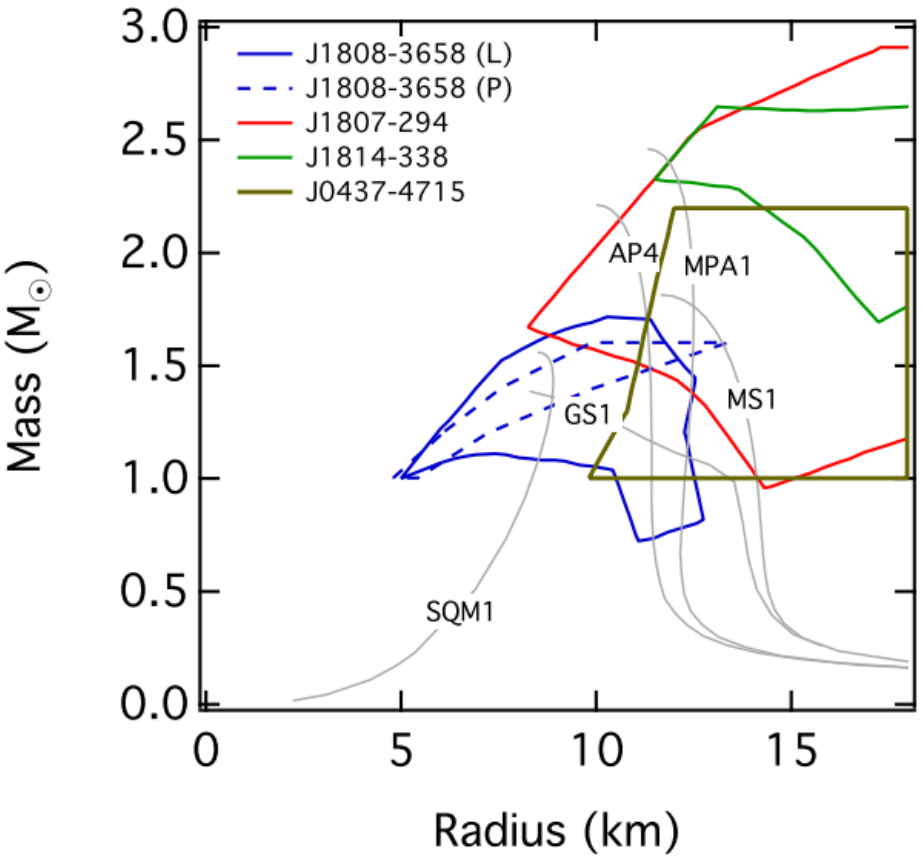
The can not be fitted simultaneously

Neutron Star Data

Maximum mass

ID	TYPE	NAME	MEAN	+ (1-SIGMA)	— (1-SIGMA)	REFERENCE
45	4	J0348+0432	2.01	0.04	-0.04	afw+13
46	4	J0437-4715	1.76	0.2	-0.2	vbs+08
47	4	J0514-4002A	1.497	0.008	-0.497	frg07
48	4	J0621+1002	1.53	0.1	-0.2	kas12
49	4	J0751+1807	1.34	0.09	-0.09	nsk08
50	4	J1012+5307	1.64	0.22	-0.16	cgk98
51	4	J1141-6545	1.27	0.01	-0.01	bbv08
52	4	B1516+02B	2.08	0.19	-0.19	fwvb+08
53	4	J1614-2230	1.97	0.04	-0.04	dpr+10
54	4	J1713+0747	1.3	0.2	-0.2	sns+05
55	4	J1738+0333	1.47	0.07	-0.06	avk+12
56	4	J1748-2021B	2.74	0.21	-0.21	frb+08
57	4	J1748-2446I	1.91	0.02	-0.1	frb+08

Radius



Modified σ–ω model in Meanfield

Nucleon effective mass

$$\mathcal{L}_{MF} = \sum_{i=1,2} \bar{\psi}_i \left(i\partial\!\!\!/ - m_N + g_\sigma \overline{\sigma} - g_\omega \gamma^0 \, \overline{\omega}_0 \right) \psi_i$$

Proton and neutron

$$-\frac{1}{2} m_\sigma^2 \overline{\sigma}^2 - \lambda_3 \, \overline{\sigma}^3 - \lambda_4 \, \overline{\sigma}^4$$

Scalar meson self interaction terms

Extra terms

$$+\frac{1}{2} m_\omega^2 \, \overline{\omega}_0^2$$

Vector meson

$$+ \frac{1}{2} m_\rho^2 \, \rho_\mu^a \, \rho^{\mu \, a}$$

Tensor meson

$$+ \overline{\Psi}_e \left(i\partial\!\!\!/ - m_e \right) \Psi_e$$

Electron in β–equilibrium

$$\mu_n = \mu_p + \mu_e$$

Modified σ–ω model in Meanfield

Nucleon effective mass

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$$+\frac{1}{2} m_\omega^2 \overline{\omega}_0^2$$

Vector meson

Extra terms

p – n Nuclear force

$$+\frac{1}{2} m_\rho^2 \rho_\mu^a \rho^{\mu a}$$

Tensor meson

$$+ \overline{\Psi}_e \left(i\partial\!\!\!/ - m_e \right) \Psi_e$$

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Proton and neutron

$$-\frac{1}{2} m_\sigma^2 \overline{\sigma}^2 - \lambda_3 \overline{\sigma}^3 - \lambda_4 \overline{\sigma}^4$$

Scalar meson self interaction terms

$$+\frac{1}{2} m_\omega^2 \overline{\omega}_0^2$$

Vector meson

$$+ \frac{1}{2} m_\rho^2 \rho_\mu^a \rho^{\mu\, a}$$

Isospin asymmetry

Tensor meson

$$+ \overline{\Psi}_e \left(i\partial\!\!\!/ - m_e \right) \Psi_e$$

Electron in β–equilibrium

$$\mu_n = \mu_p + \mu_e$$

Modified σ–ω model in Meanfield

Nucleon effective mass

$$\mathcal{L}_{MF} = \sum_{i=1,2} \bar{\psi}_i \left(i\partial\!\!\!/ - m_N + g_\sigma \overline{\sigma} - g_\omega \gamma^0 \overline{\omega}_0 \right) \psi_i$$

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Vector meson

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Tensor meson

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Modified σ–ω model in Meanfield

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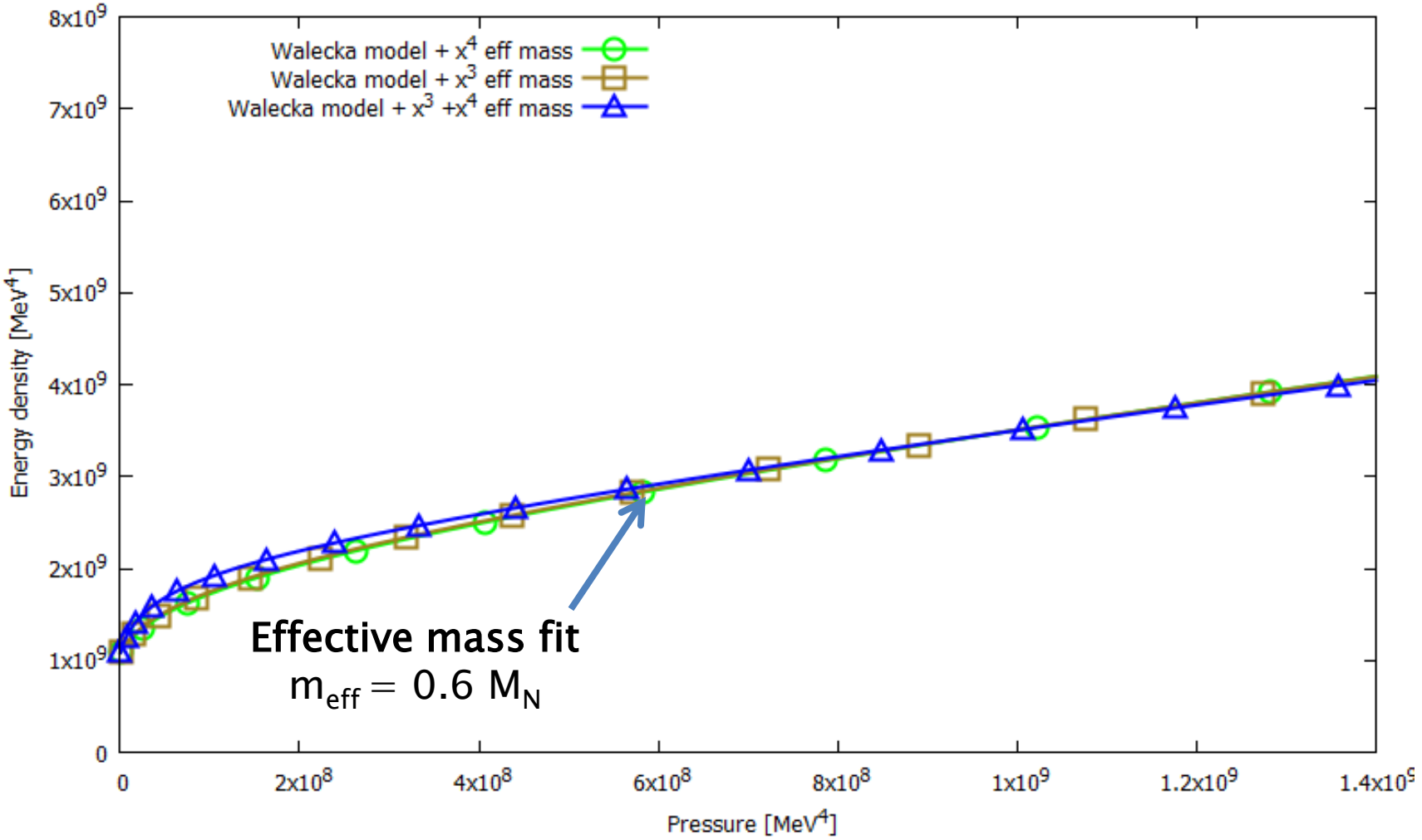
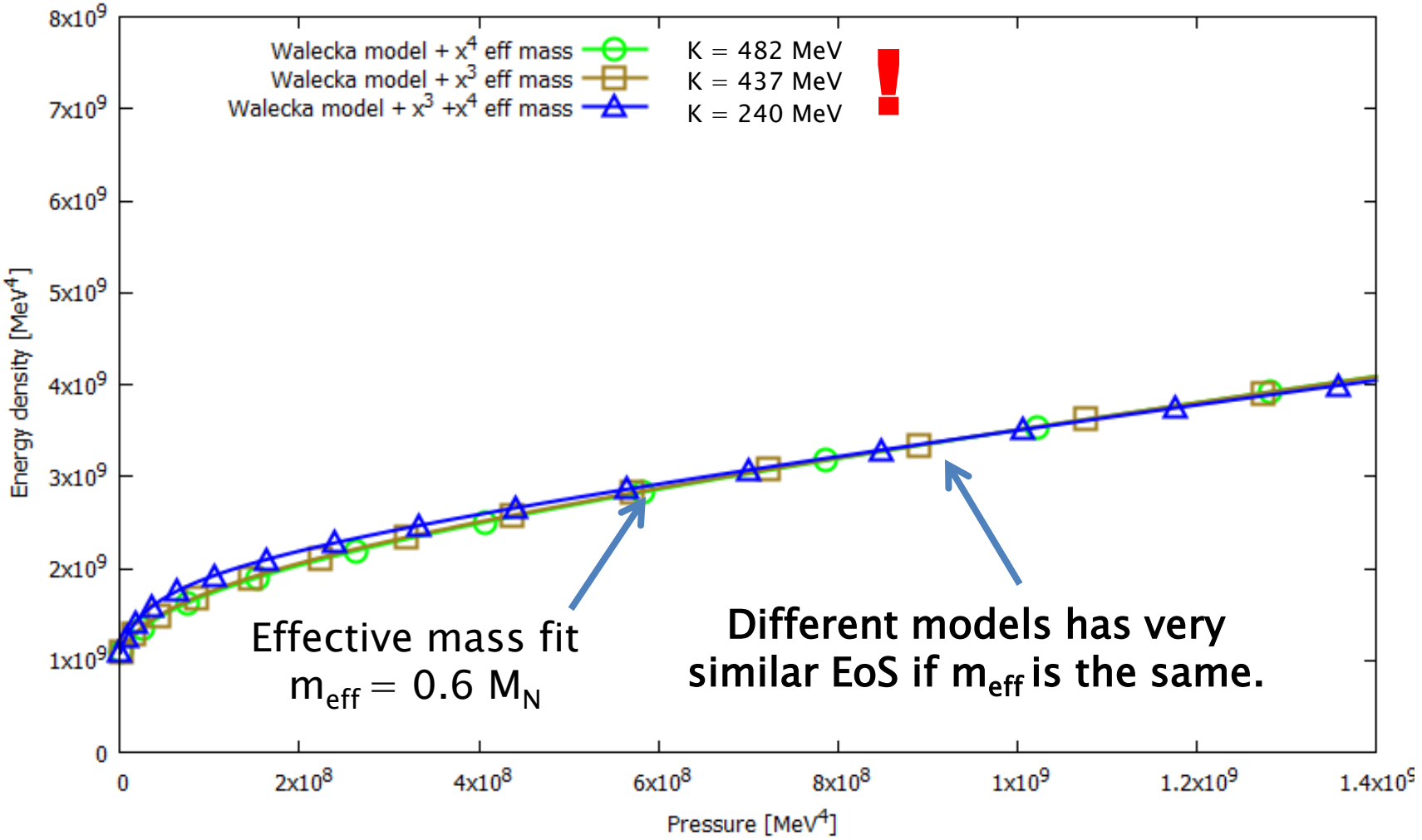
Electron in β–equilibrium

$$\mu_n = \mu_p + \mu_e$$

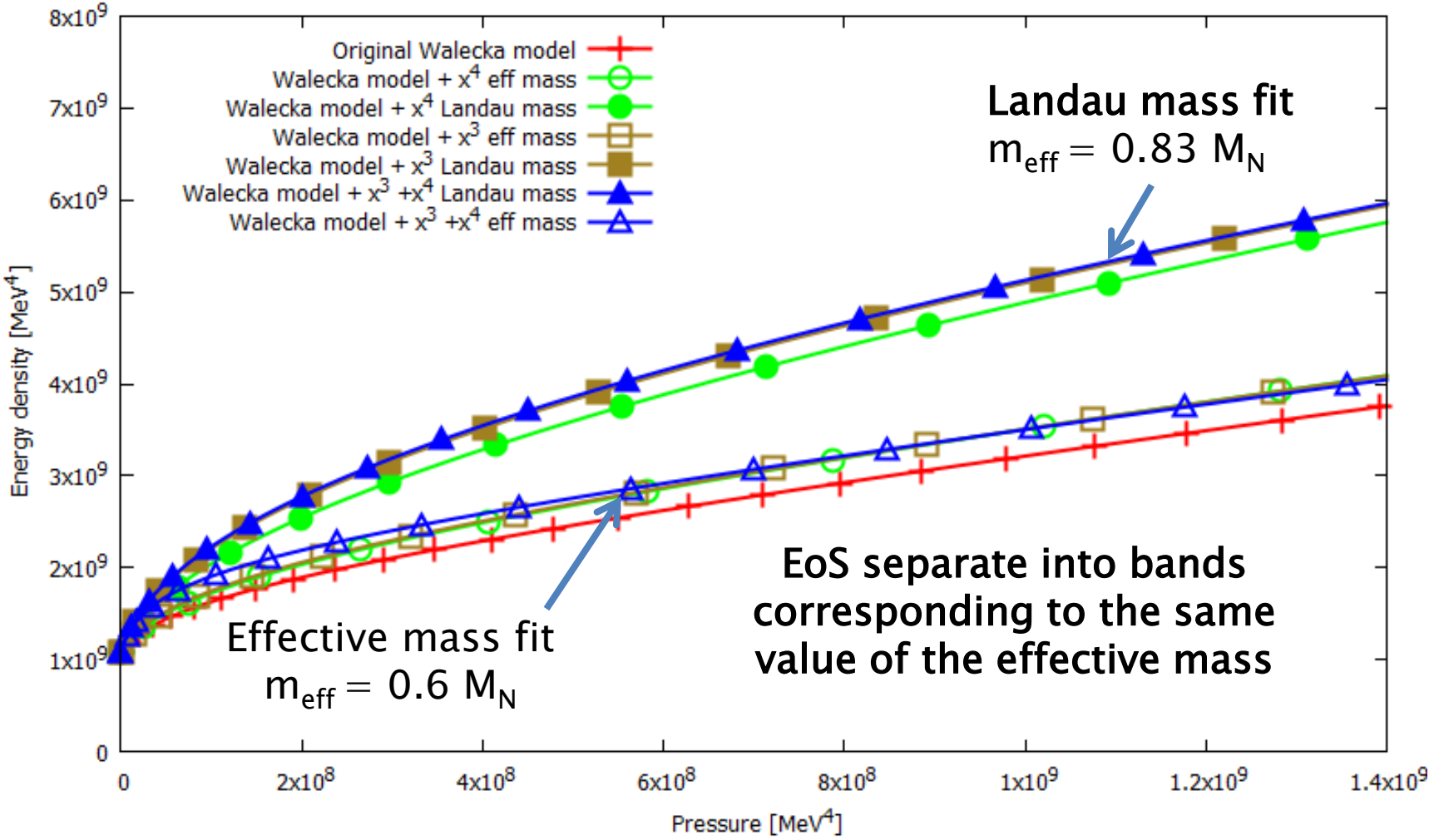
EoS of different models



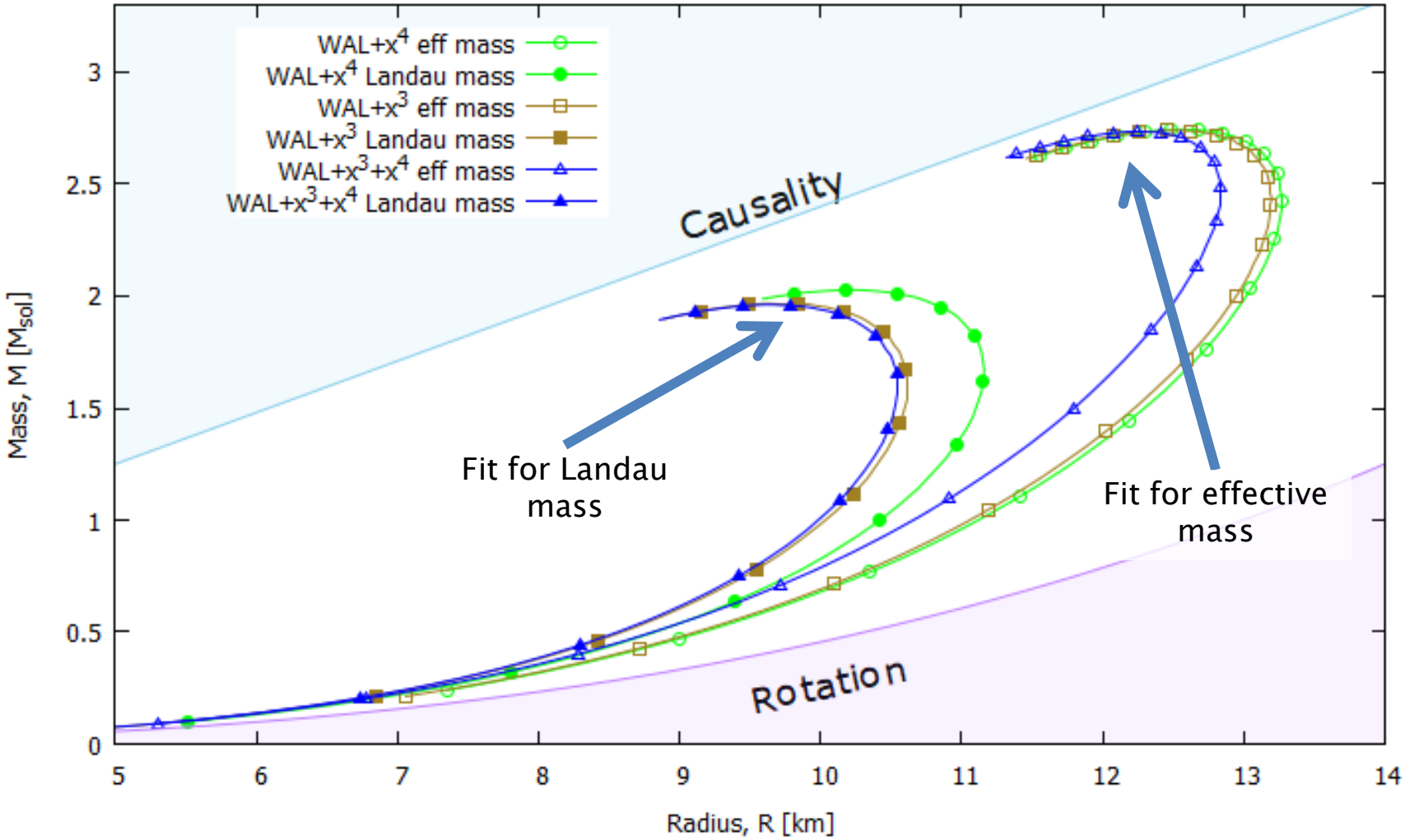
EoS of different models



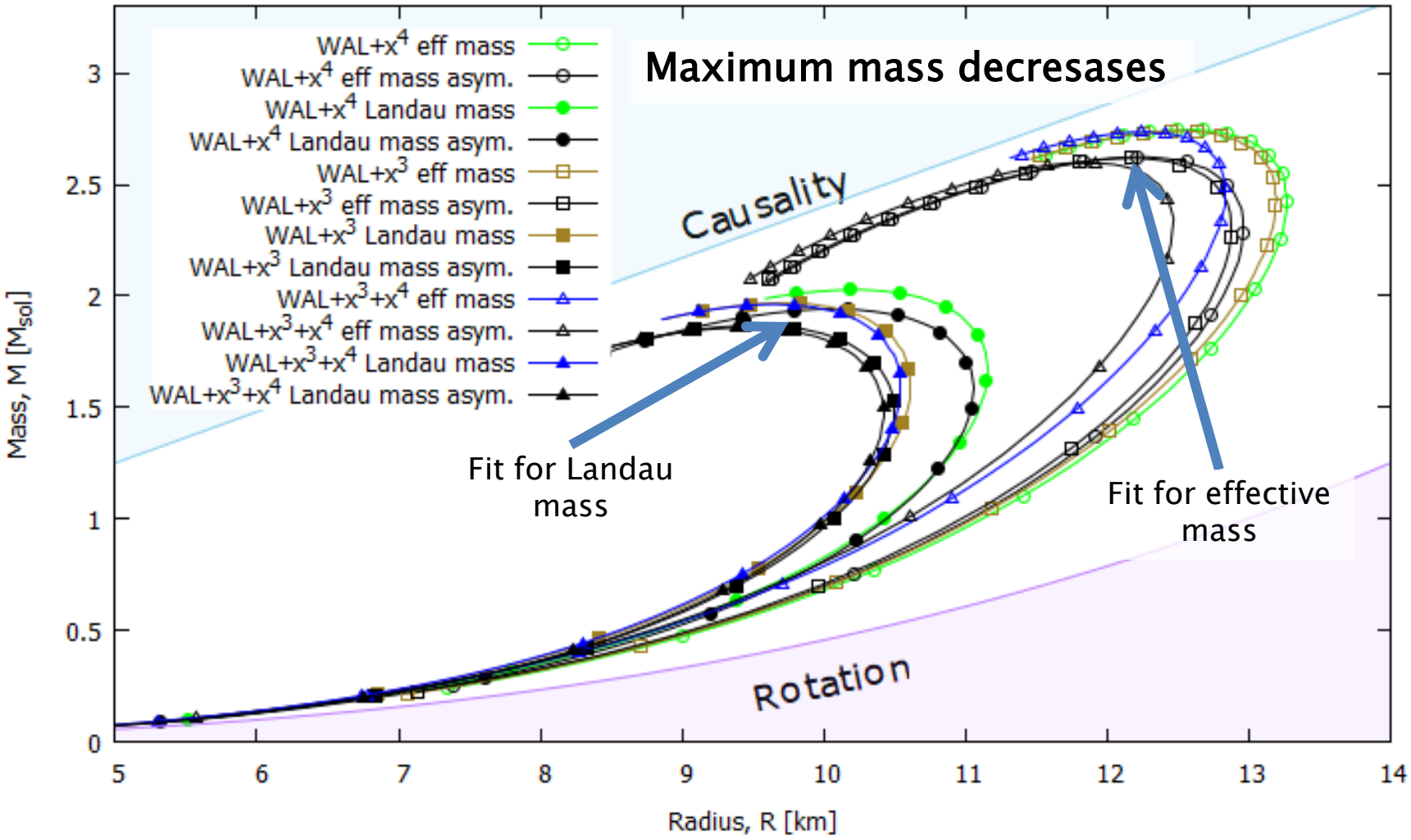
EoS of different models



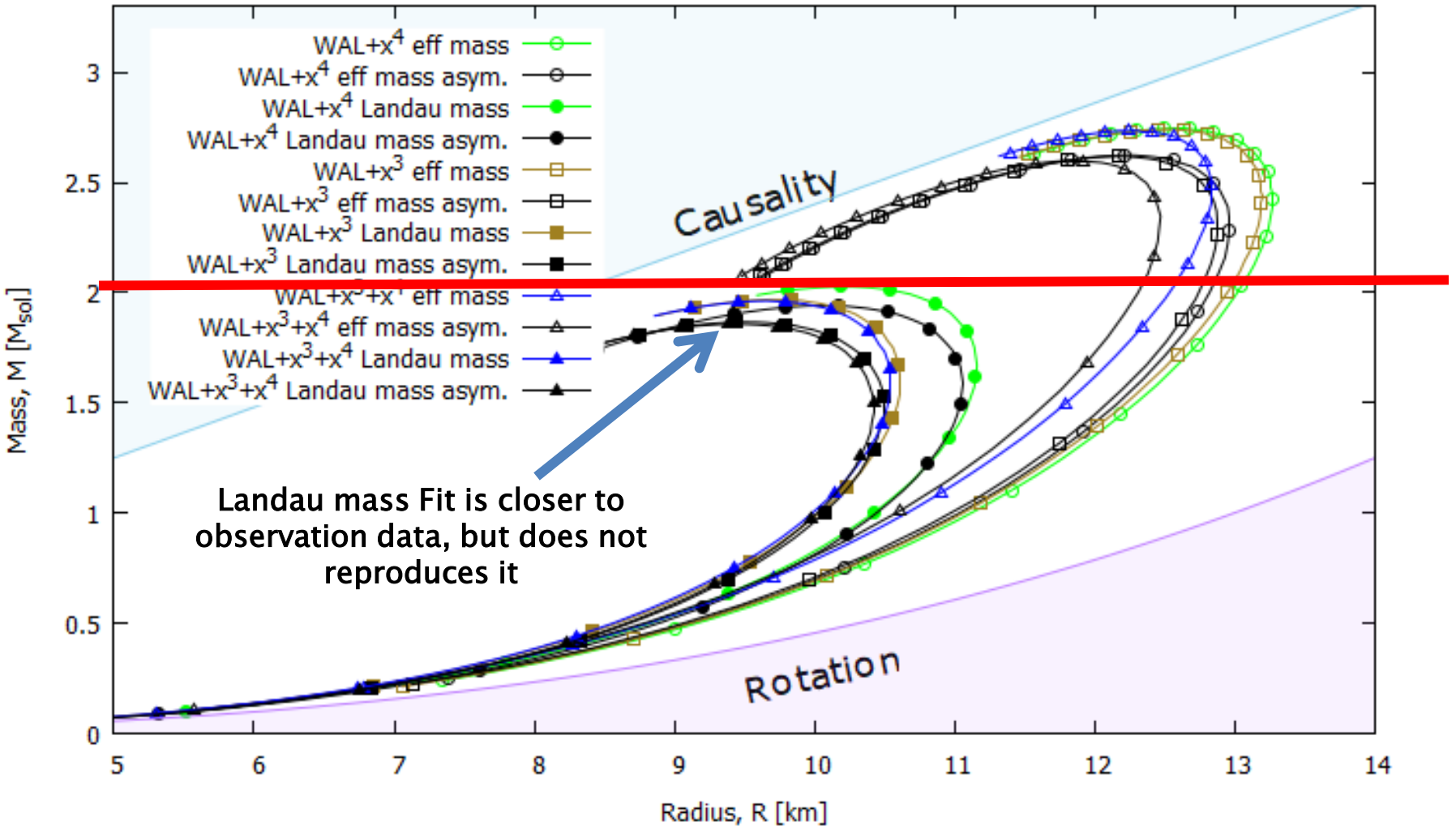
M-R diagrams Respect the EoS banding based on effective mass (symmetric case)



M-R diagrams Respect the EoS banding based on effective mass (asymmetric case)

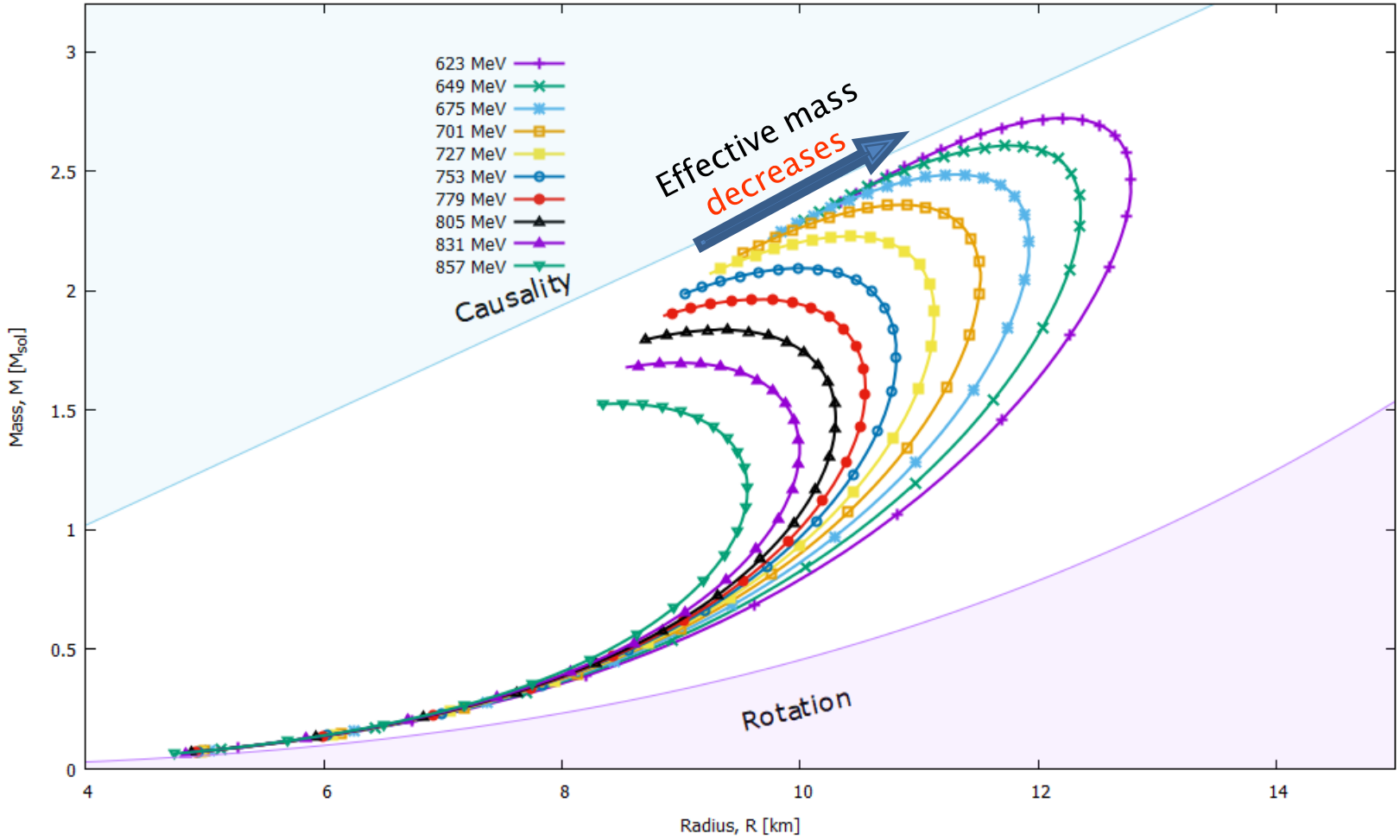


M-R diagrams Respect the EoS banding based on effective mass (asymmetric case)



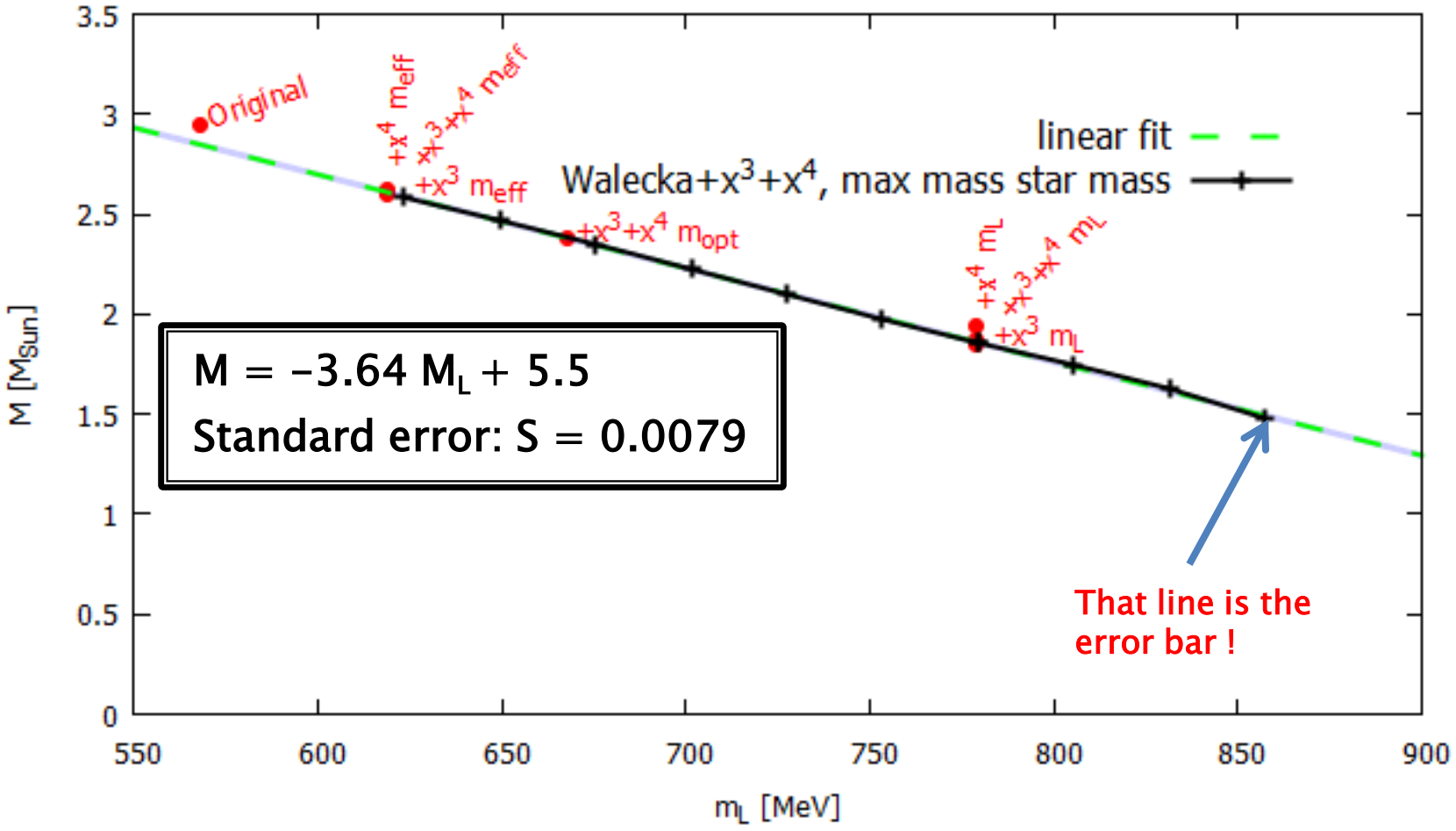
Parameter dependence of the M-R diagram

Calculate the **M-R diagrams** corresponding to the modified Walecka model fitted to different values of **Landau (effective) mass**



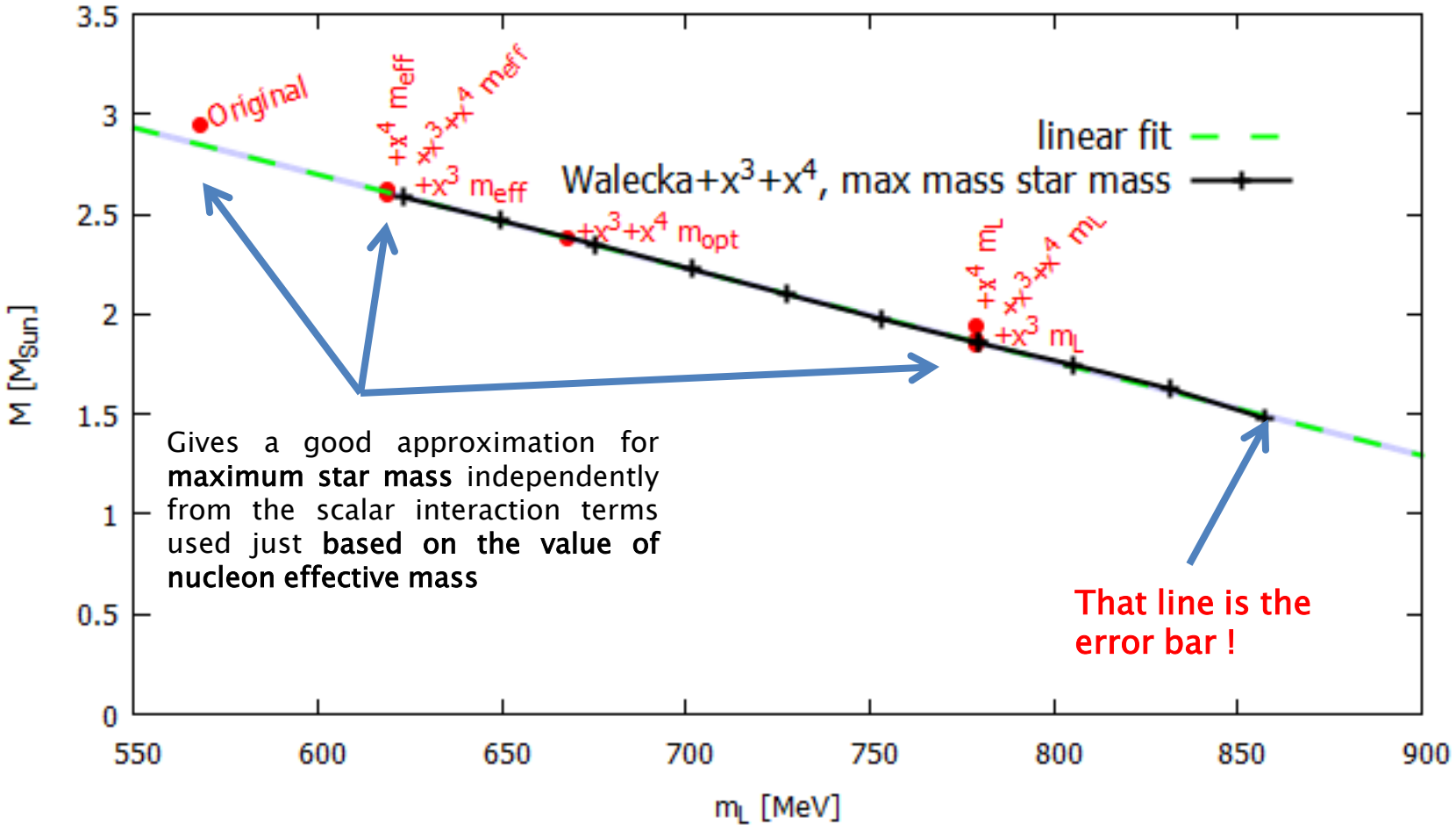
Maximum star mass linearly depends on Landau mass

Plot maximum star mass as function of Landau-mass



Maximum star mass linearly depends on Landau mass

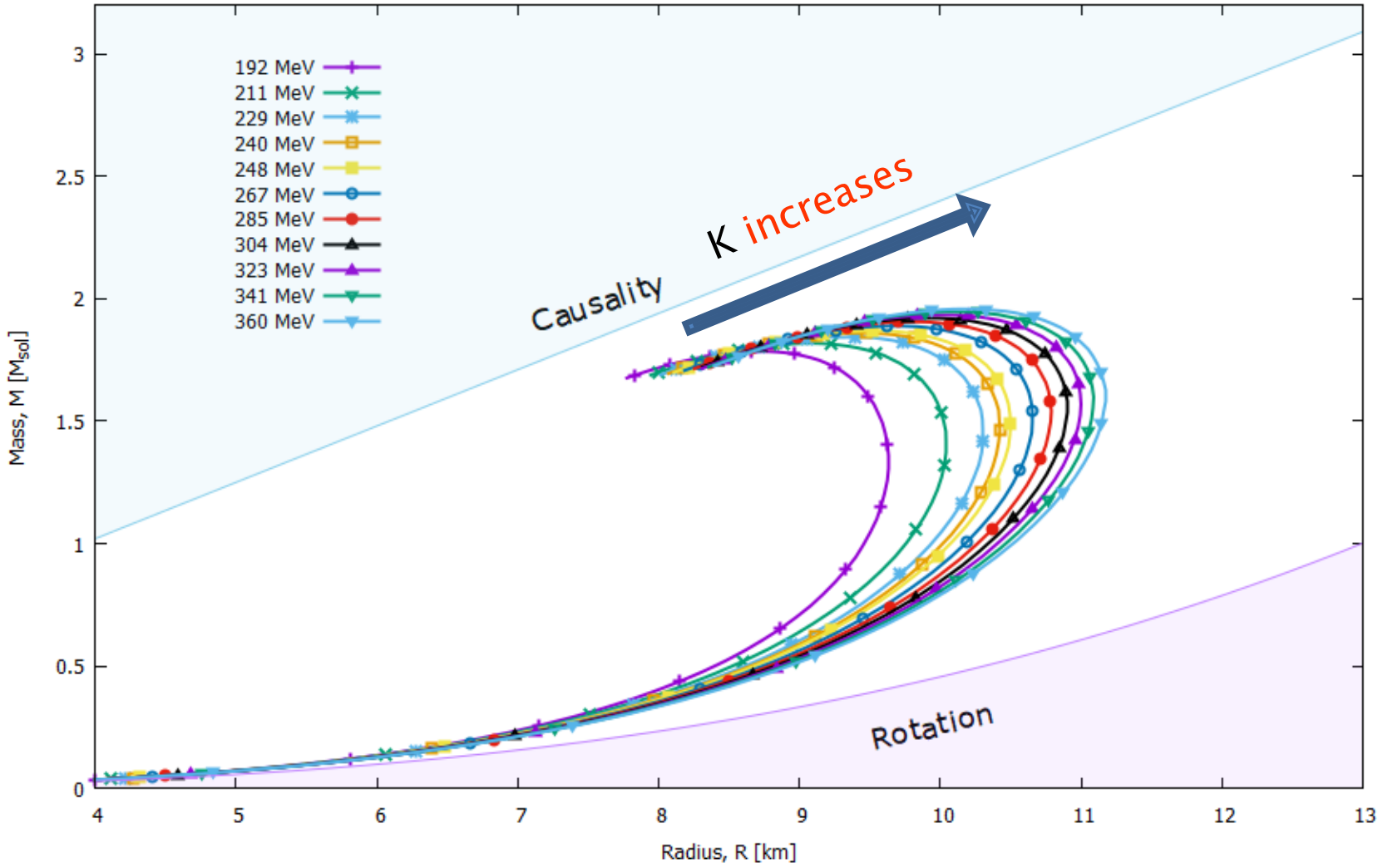
Plot maximum star mass as function of Landau-mass



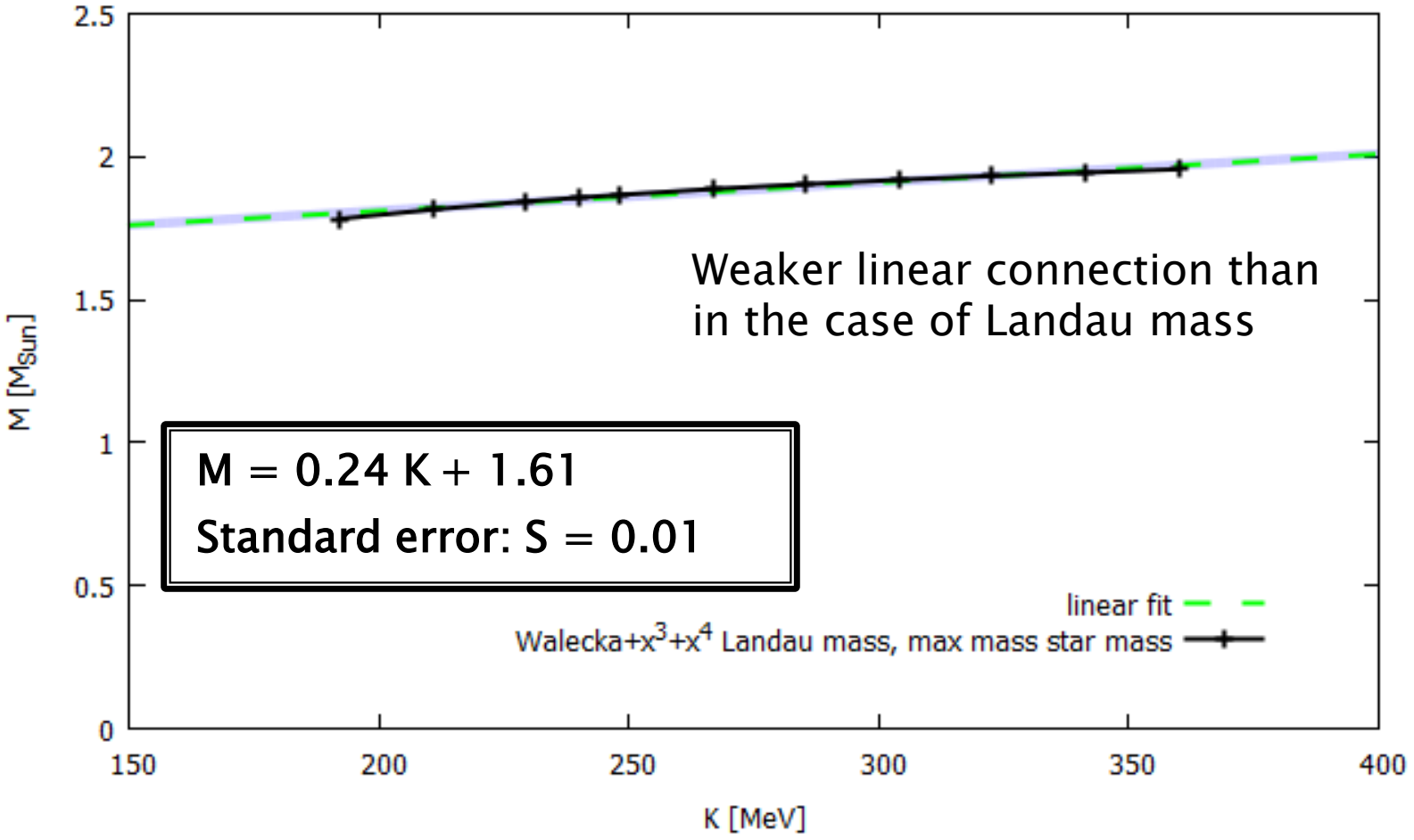
Gives a good approximation for **maximum star mass** independently from the scalar interaction terms used just **based on the value of nucleon effective mass**

That line is the error bar !

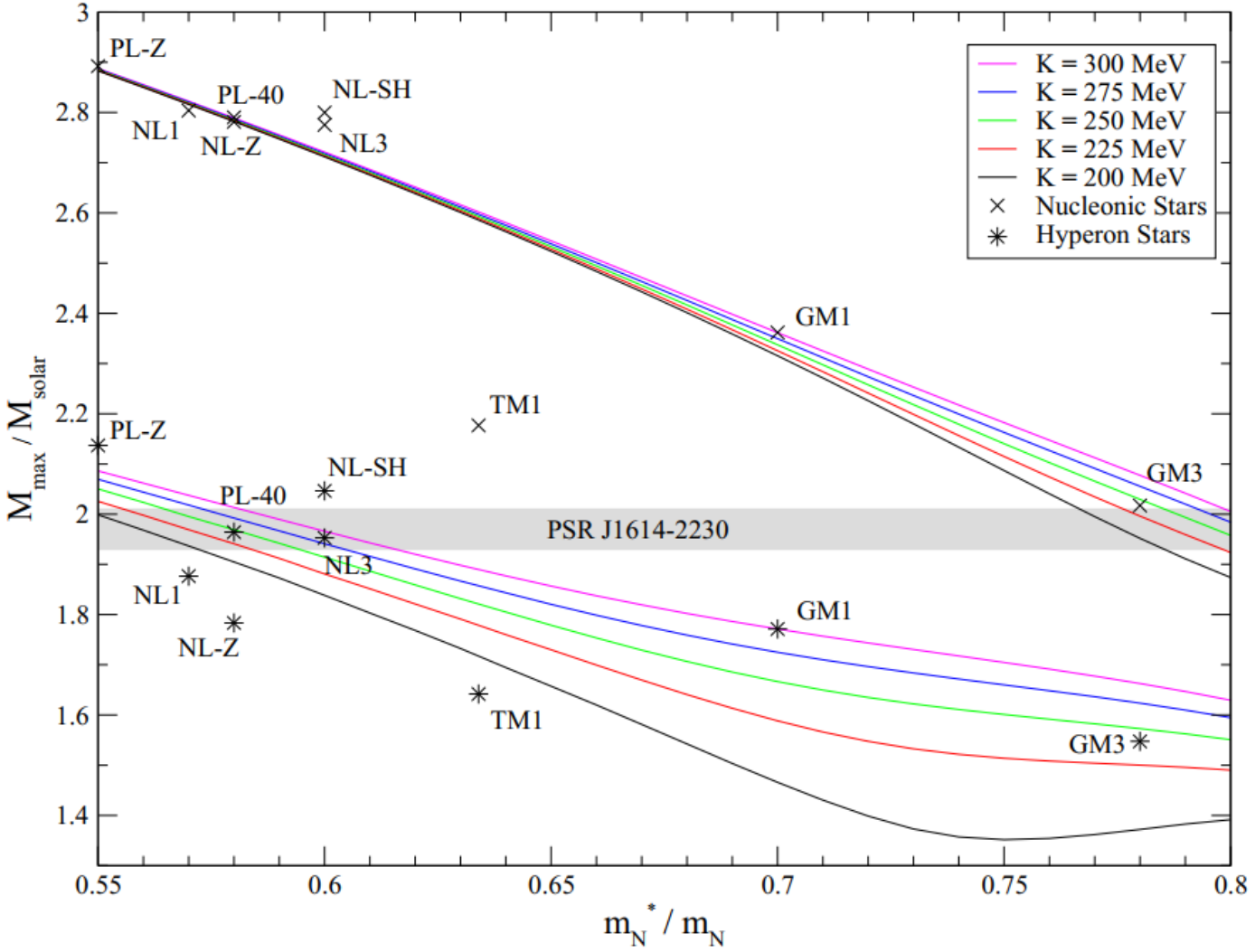
K dependence of the M-R diagram



Maximum star mass depends linearly on Compression modulus

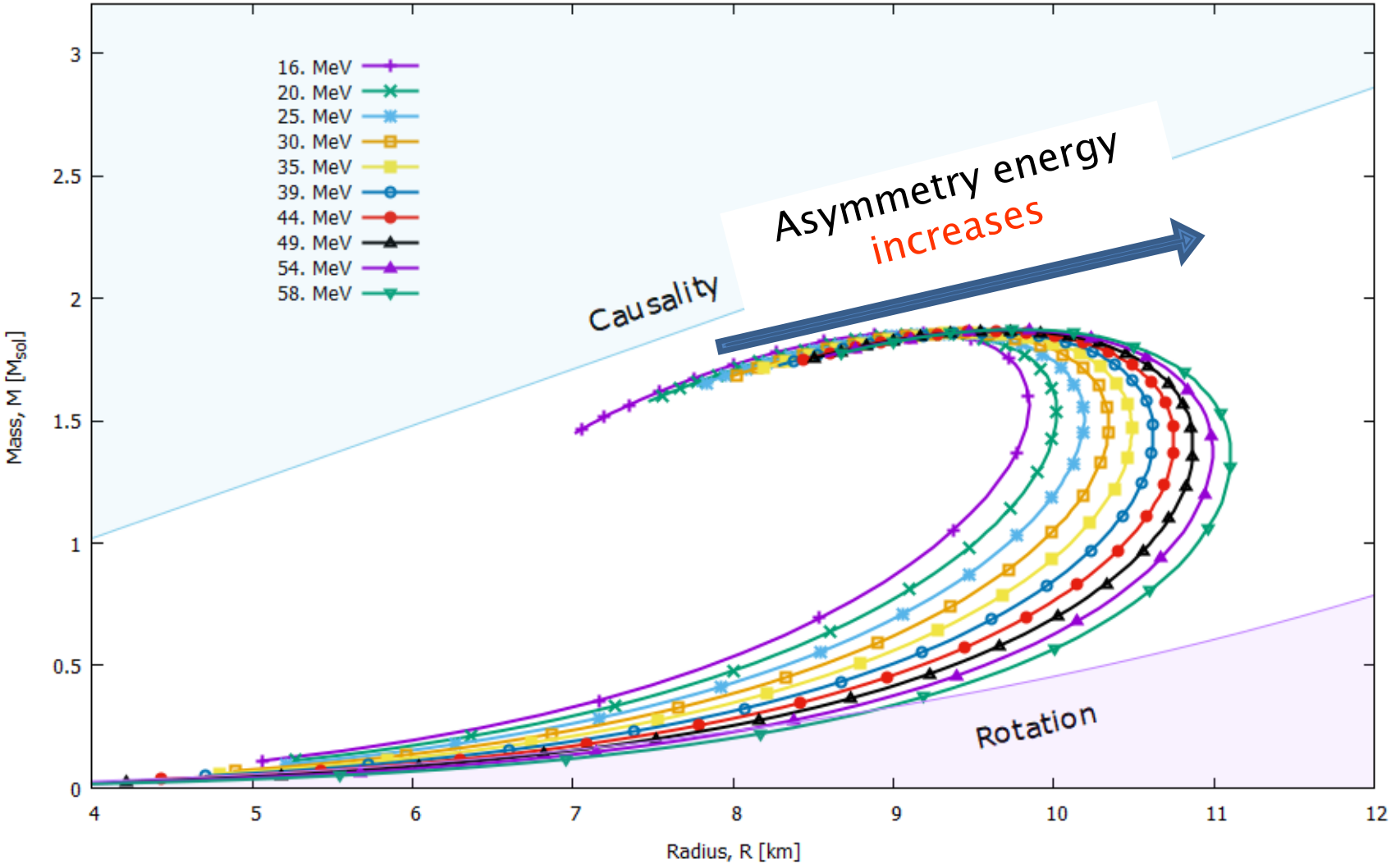


The feature is present in more realistic models too



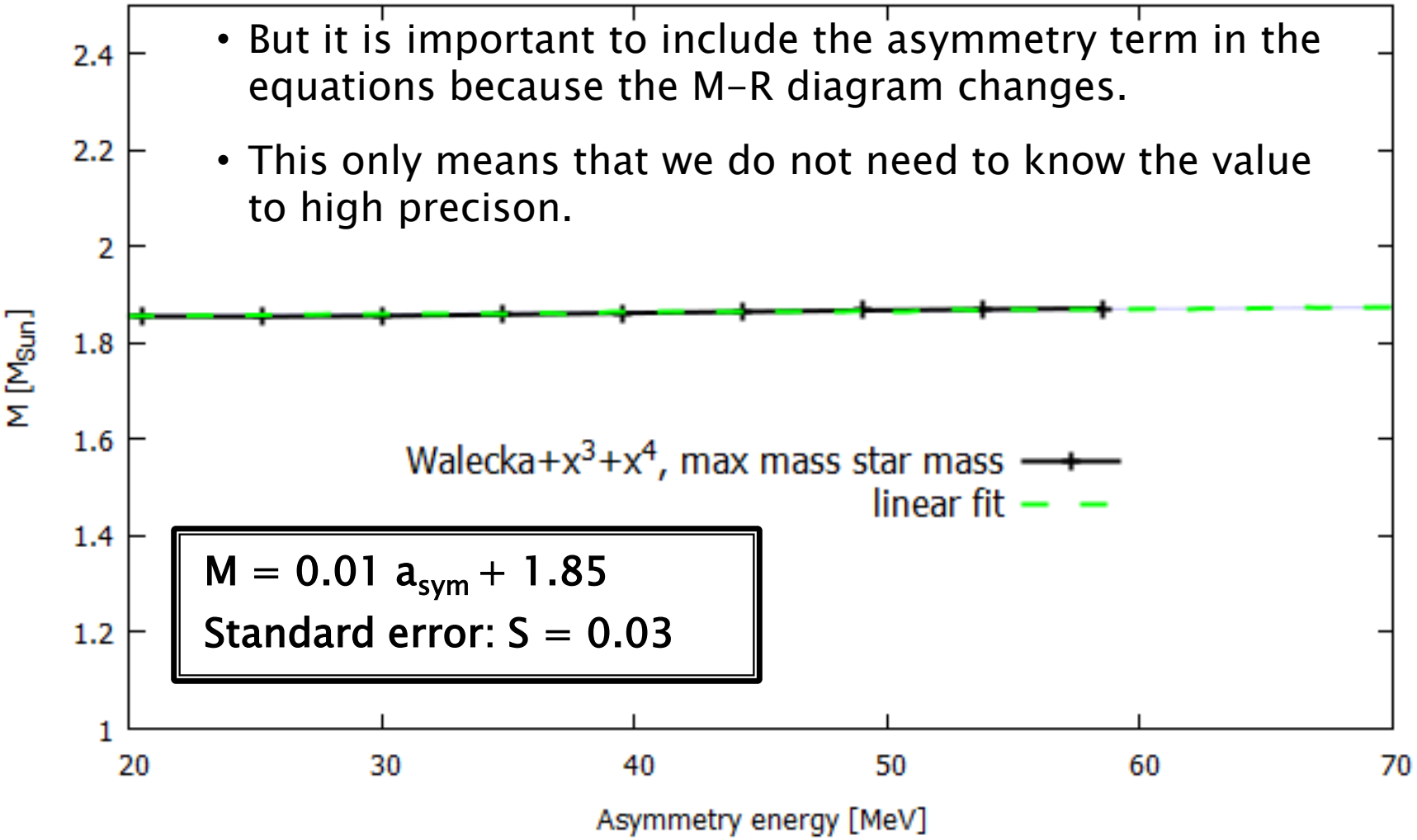
Weissenborn et al 2012 (Nuclear Physics A 881 (2012) 62)

K dependence of the M-R diagram



Maximum star mass is almost indepdent of the value of asymmetry energy

- But it is important to include the asymmetry term in the equations because the M-R diagram changes.
- This only means that we do not need to know the value to high precison.



Which microscopic parameter influences more the maximum star mass ?

Effective mass, Landau mass **× 10** **>** Compression modulus **× 10** **>** Asymmetry energy

Changing the **Landau mass by 10 %** changes

the maxium neutron star mass by 0.36 $M_\odot$

Which microscopic parameter influences more the maximum star mass ?

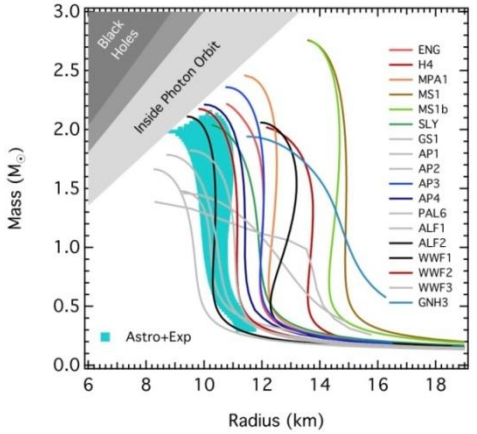
Effective mass, Landau mass **× 10** > Compression modulus **× 10** > Asymmetry energy

- The **maximum star mass** in the model can be **linearly tuned** using only the nuclear Landau mass
- The **maximum measured neutron star mass** can be used to determine the correct nuclear Landau mass
- Similar linear relations can be established for the **radius of the maximum mass star**, and for the mass and radius of the **maximum radius star**

Application

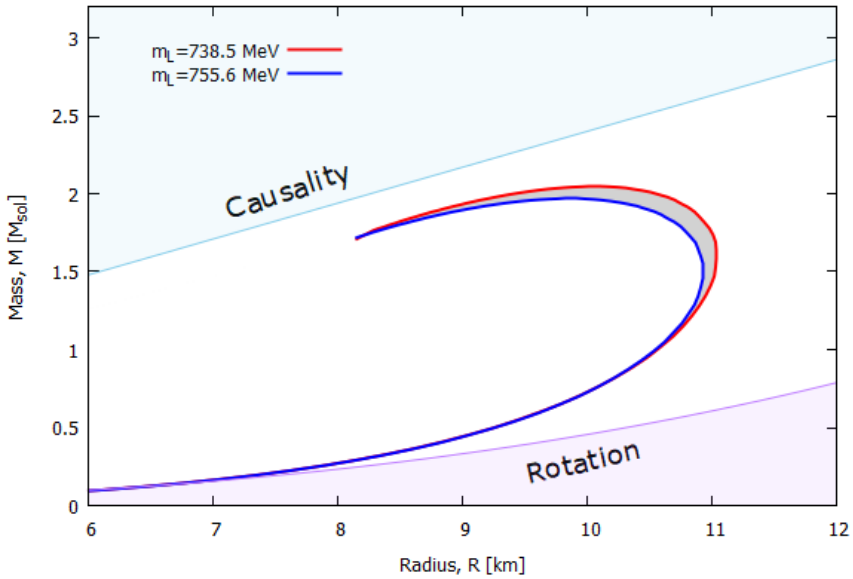
NUCLEAR MODEL
Microscopic paramaters

Effective / Landau mass



Max measured neutron star mass (J0348+0432): **M=2.01 $M_\odot$**

Landau mass value: 0.796 M_N
(96 % of the measured value)



WARNING!

Compression modulus changes by 25 %

Changes in neutron star observables

Max neutron star mass changes by 3 %

Max max mass neutron star radius changes by 5 %

Max Radius of Neutron star changes by 5 %

WARNING!

Compression modulus changes by 25 %

Max neutron star mass changes by 3 %

Max max mass neutron star radius changes by 5 %

Max Radius of Neutron star changes by 5 %

Problem 1

Observables can not (yet) be measured to this high accuracy

WARNING!

Compression modulus changes by 25 %

Max neutron star mass changes by 3 %

Max max mass neutron star radius changes by 5 %

Max Radius of Neutron star changes by 5 %

Problem 2

Calculating quantum correction to the EoS cause changes in the same order of magnitude

Pósfay, P., Barnaföldi, G., & Jakovác, A. PASA (2018), *35*, E019.

To correctly fit (assuming we already have precise measurements) we need full quantum calculations

WARNING!

Compression modulus changes by 25 %

Max neutron star mass changes by 3 %

Max max mass neutron star radius changes by 5 %

Max Radius of Neutron star changes by 5 %

Problem 3

The situation is 10 times worse for asymmetry energy
(change in observables is 10 times smaller)

Summary

- Modified σ–ω model in Meanfield
- **Maximal neutron star mass depends linearly** on
  - **m_L – nucleon Landau mass**
  - **K – Compression modulus**
  - **a_{sym} – symmetry energy**
- Maximum neutron star mass depends mainly on nucleon effective mass
- This can be used to fit the model using only one parameter
- To correctly fit the other nuclear parameters we need quantum calculations

Thank you for the attention!

http://pospet.web.elte.hu/

Köszönetnyilvánítás:
A munka az OTKA, NK106119, K104260, K104292, K120660, *TET 12 CN-1-2012-0016 ,* NewCompStar COST action 1304, és NKM-81/2016 MTA-UA bilaterális mobilitási program támogatásával készült.