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

PHAROS
THE MULTI-MESSENGER PHYSICS AND ASTROPHYSICS OF NEUTRON STARS

[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.

[4] Péter Pósfay, Gergely Gábor Barnaföldi, Antal Jakovác Universe 5 (2019) no.6, 153

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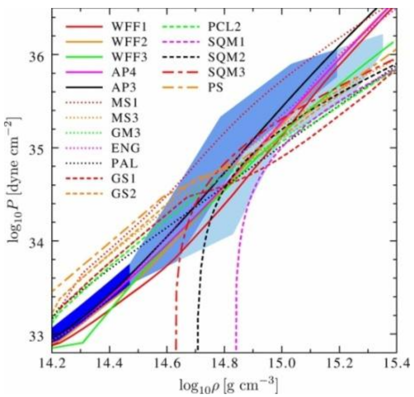
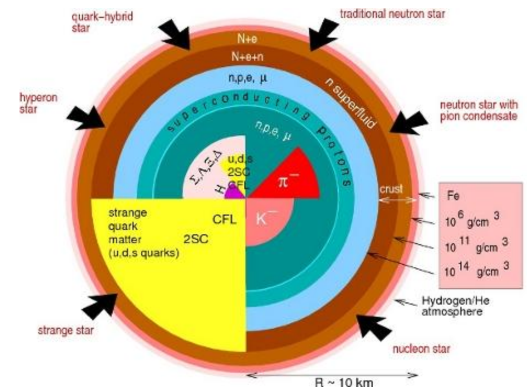
From nuclear matter to neutron stars

EoS



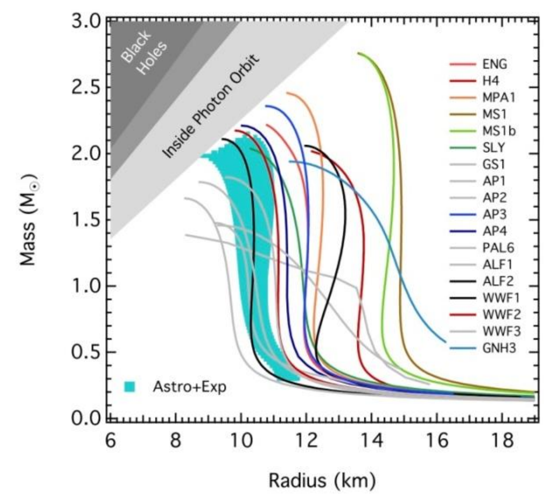
TOV equations

Star Structure



Termodynamics

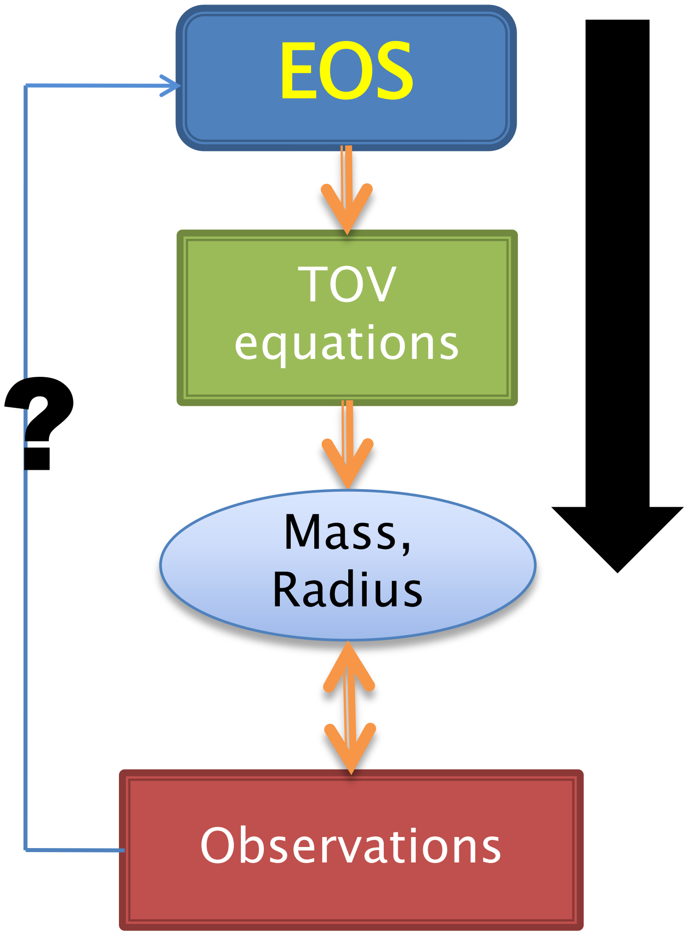
M-R diagram



NUCLEAR MODEL

Microscopic paramaters

Masquarade problem



Different nuclear models produce very similar neutron star parameters

? What is the reason behind this?

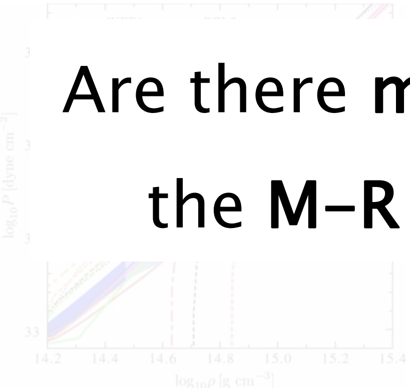
? How can it be circumvented?

? What can be learned from neutron star measurements?

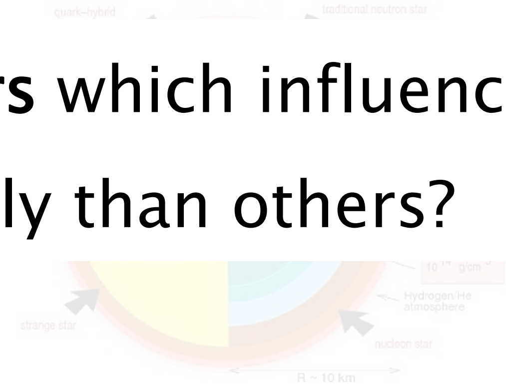
? What is the connection between the microscopic parameters of the nuclear matter and neutron star observables?

Motivation

EoS



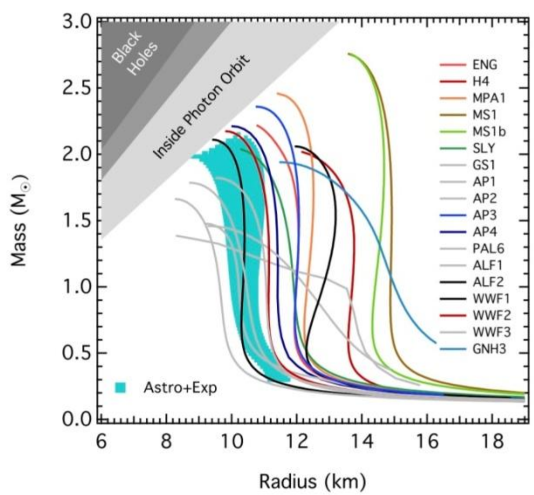
Star Structure



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

Termodynamics

M-R diagram



NUCLEAR MODEL

Microscopic paramaters

Large effect

Parameters influence 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 the easiest

Termodynamics

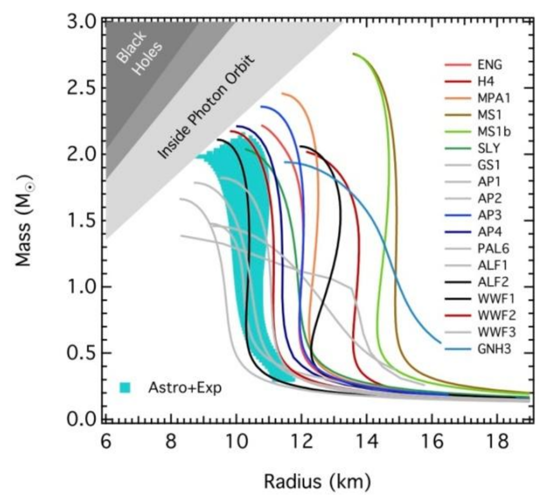
NUCLEAR MODEL

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

Modified σ–ω model in Meanfield

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

Proton and neutron

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

Scalar meson self interaction terms

Extra terms

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

Vector meson

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

Tensor meson

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

Electron in β–equilibrium

$$\boxed{\mu_n = \mu_p + \mu_e}$$

Modified σ−ω model in Meanfield

Nucleon effective mass

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

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Scalar meson self interaction terms

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

Extra terms

p – n Nuclear force

Vector meson

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Tensor meson

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Isospin asymmetry

Tensor meson

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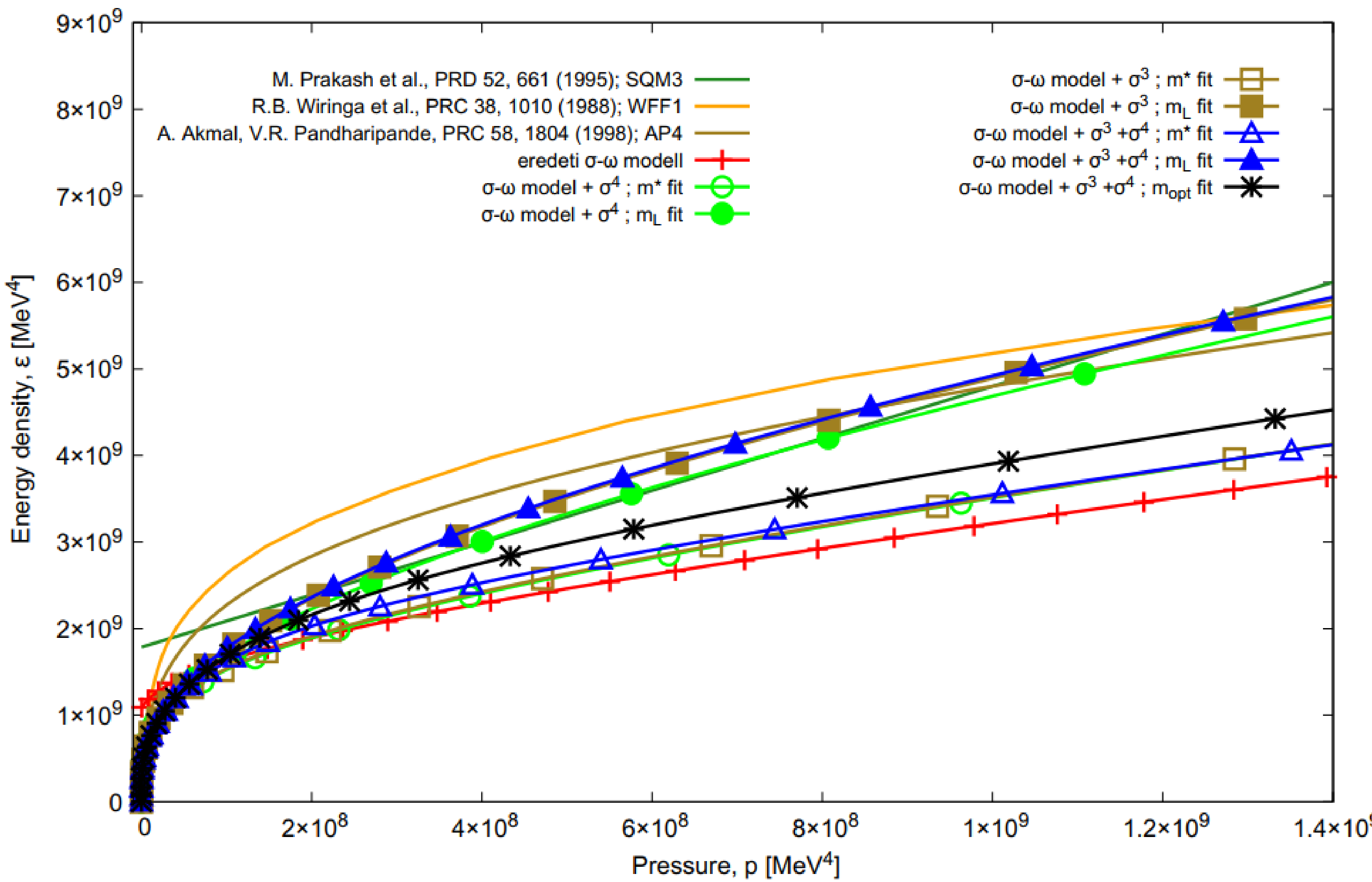
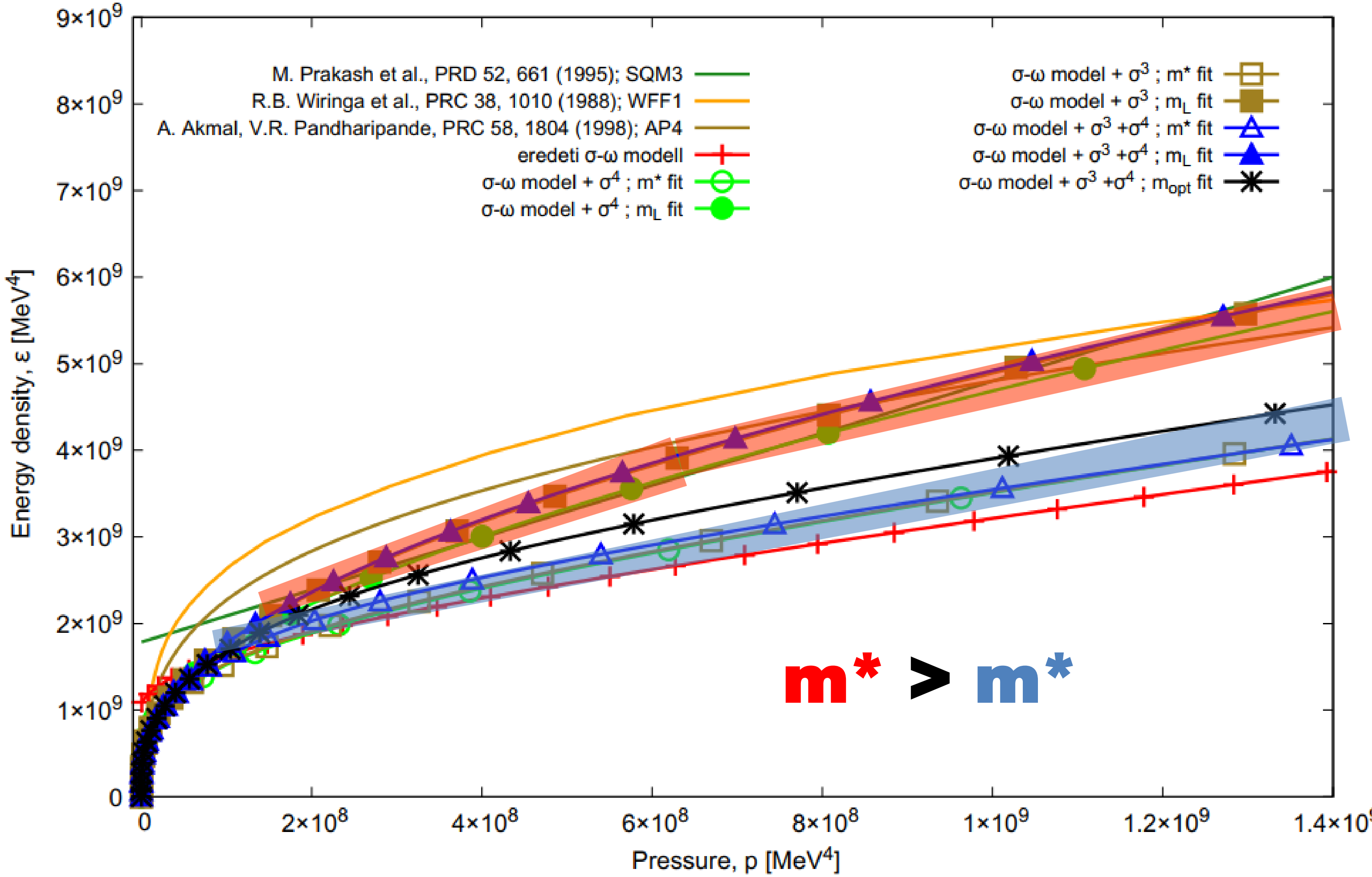
Electron in β–equilibrium

$$\boxed{\mu_n = \mu_p + \mu_e}$$

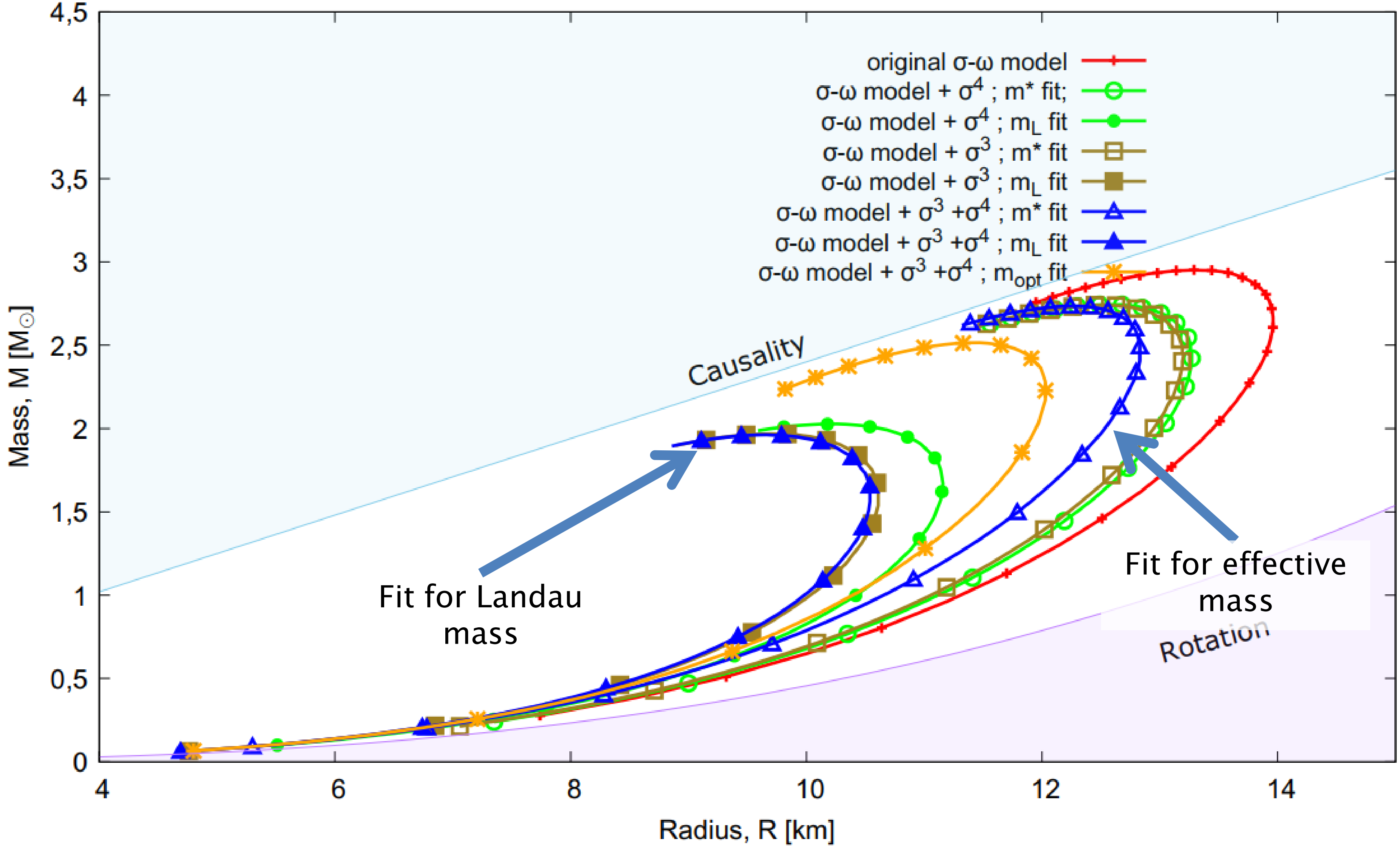
EoS of different models



EoS of different models



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



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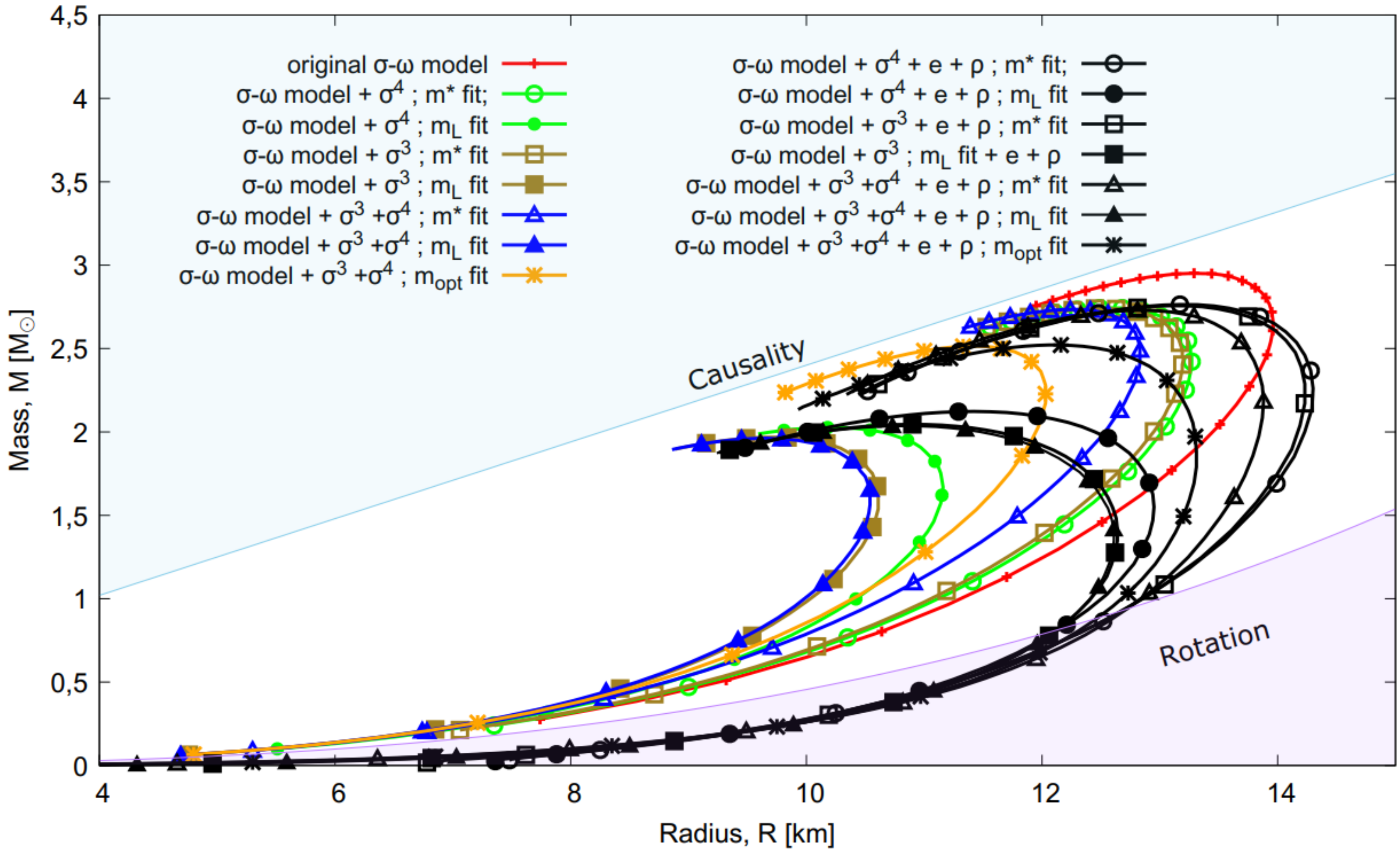
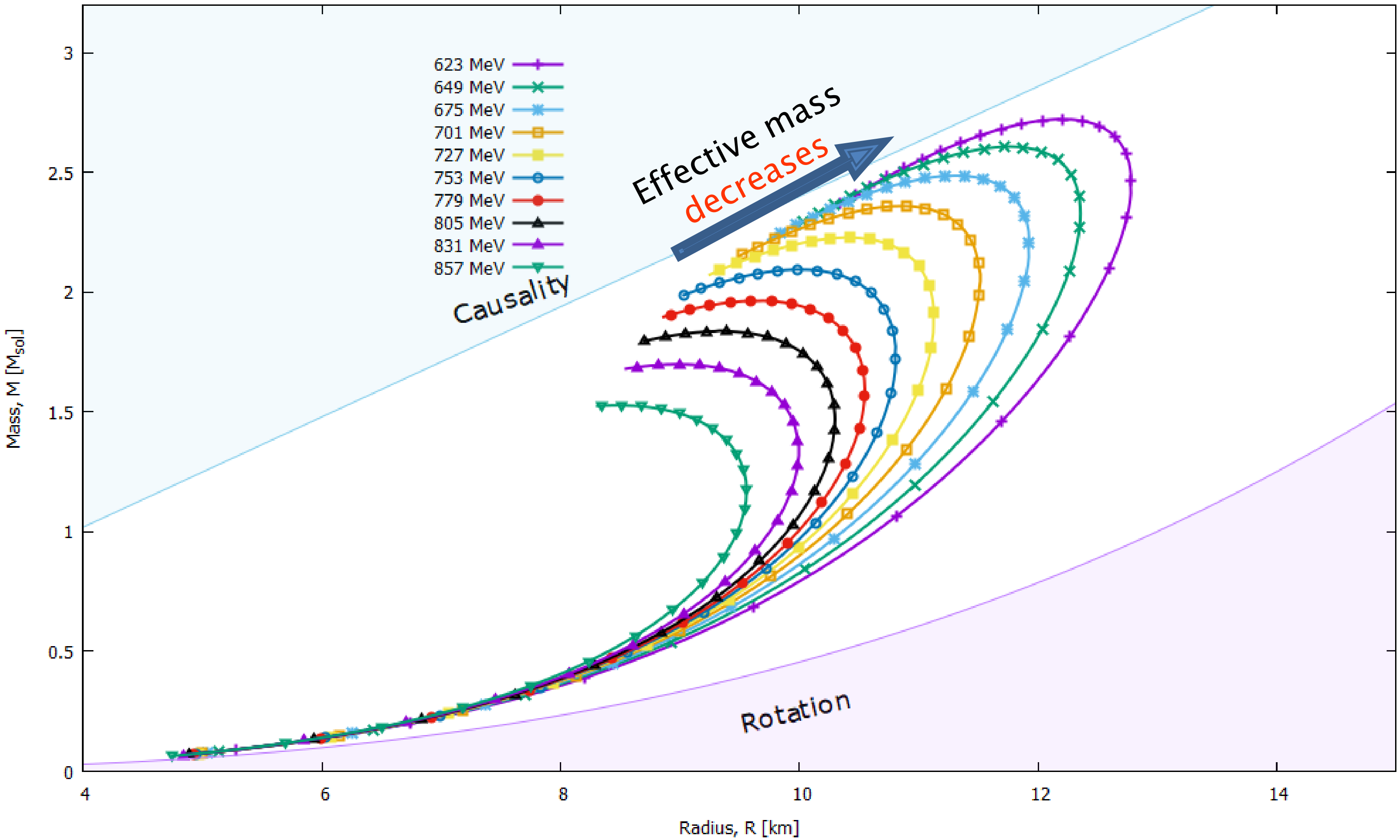


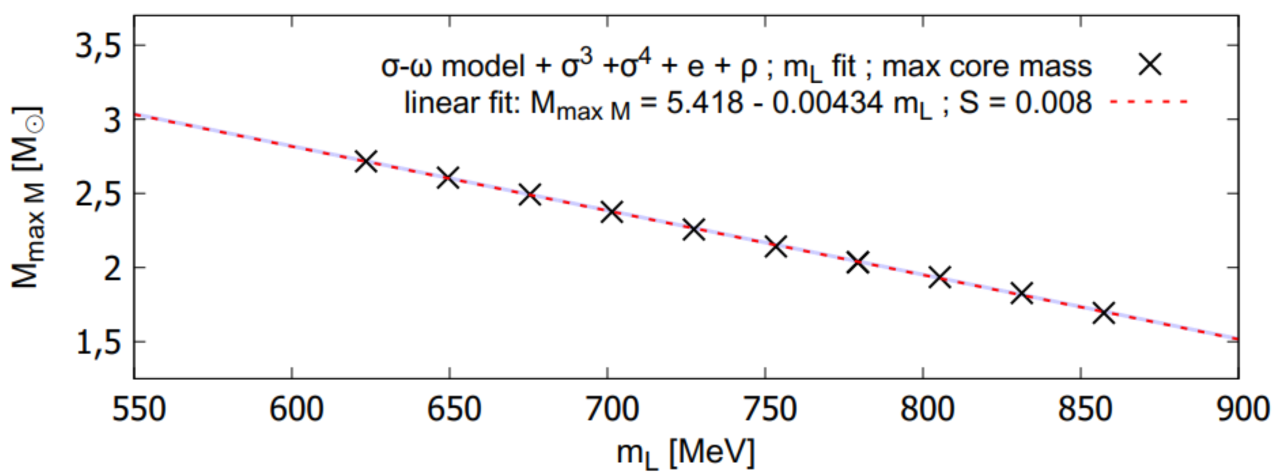
Parameter dependence of the M-R diagram

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



The M–R diagram and the microscopic parameters of nuclear matter

- **The β–equilibrium**
  - Maximal mass increases little
  - Maximal radius is greatly increased
  - The effect is very similar for different scalar interaction terms
- The maximal neutron star mass and radius is linearly dependent on
  - Nucleon effective mass
  - Symmetry energy
  - Compression modulus



Which microscopic parameter influences more the maximum star mass ?

× 10 × 10

Effective mass, Landau mass > Compression modulus > Asymmetry energy

- This is the reason of the masquarade problem in this model
- The nuclear effective mass dominates the behaviour of the M-R diagram
- Very precise observations are required to see the effect of the other paramteres

Which microscopic parameter influences more the maximum star mass ?

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

Thank you for the attention!

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