EFFECT OF QUANTUM CORRECTIONS ON A REALISTIC NUCLEAR MATTER EOS AND ON COMPACT STAR OBSERVABLES

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HOW TO USE NEUTRON STAR DATA TO TEST MODELS OF NUCLEAR MATTER?

EOS → TOV-equations → Mass, Radius ↔ Observations

Can the same model provide different EOS and neutron star parameters based on the method of solutions?

Masquarade problem: different models for EoS produce similar neutron stars

Same assumptions for the Lagrangian → Different methods for calculating QUANTUM FLUCTUATIONS → Different
- EOS
- Neutron Star

INTERACTING FERMI-GAS MODEL

$$\Gamma_k[\varphi,\psi] = \int d^4x \left[\bar{\psi}\left(i\partial\!\!\!/ - g\varphi\right)\psi + \frac{1}{2}\left(\partial_\mu\varphi\right)^2 - U_k(\varphi)\right]$$

Fermions : $m=0$, **Yukawa-coupling** generates mass for fermions

Bosons: the **potential** contains self interaction terms

We study the scale dependence of the potential only!!

FUNCTIONAL RENORMALIZATION GROUP METHOD

$$\partial_k\Gamma_k = \frac{1}{2}\int dp^D\, STr\left[\frac{\partial_k R_k}{\Gamma_k^{(1,1)} + R_k}\right]$$

- Wetterich equation determines the couplings
- Non-perturbative description
- Continous transition from microscopic to macroscopic scale

$\Gamma_{k=\Lambda}$ UV scale, classical
$\Gamma_{k=0}$ IR scale, included quantum fluctuations

THE WETTERICH-EQUATION FOR THE FERMI-GAS MODEL:

$$\partial_k U_k = \frac{k^4}{12\pi^2}\left[\frac{1+2n_B(\omega_B)}{\omega_B} + 4\frac{-1+n_F(\omega_F-\mu)+n_F(\omega_F+\mu)}{\omega_F}\right]$$

Bosonic part / Fermionic part

$$U_\Lambda(\varphi) = \frac{m_0^2}{2}\varphi^2 + \frac{\lambda_0}{24}\varphi^4 \qquad \omega_F^2 = k^2 + g^2\varphi^2 \qquad \omega_B^2 = k^2 + \partial_\varphi^2 U \qquad n_{B/F}(\omega) = \frac{1}{1 \mp e^{-\beta\omega}}$$

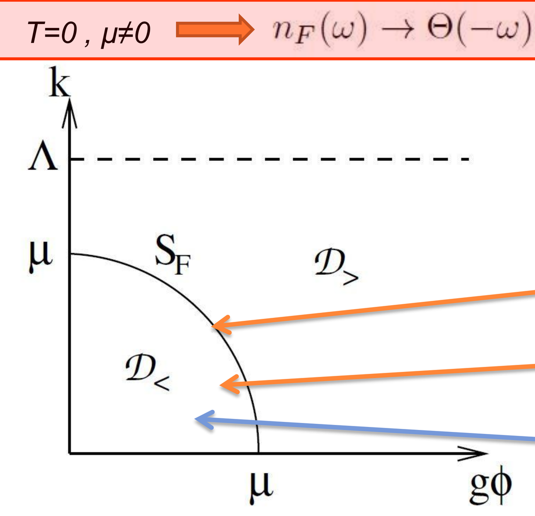
- The differential equation has to be solved at zero temperature and finite chemical potential to provide an equation of state of nuclear matter in neutron stars.
- The *Yukawa-coupling (g)* modifies the the chemical potential of the fermions
- At zero temperature the Fermi-distribution becomes a step funciton which makes this equation difficult to solve, because the lack of stability of the result

SOLUTION METHOD

At zero temperature, the Fermi-Dirac distribution becomes a step function and divides the *k-φ plane* into two different regions. There is a differential equation corresponding to each region which has to be solved separately, but they have to match at the boundary.

$T=0$, $\mu\neq 0$ → $n_F(\omega) \to \Theta(-\omega)$

We have two equations for the two values of the step function each valid on different domain



$$\partial_k U_k = \frac{k^4}{12\pi^2}\left[\frac{1}{\omega_B} - \frac{4}{\omega_F}\right]$$

$$k_F = \sqrt{\mu^2 - g^2\varphi^2}, \quad \text{Fermi-surface}$$

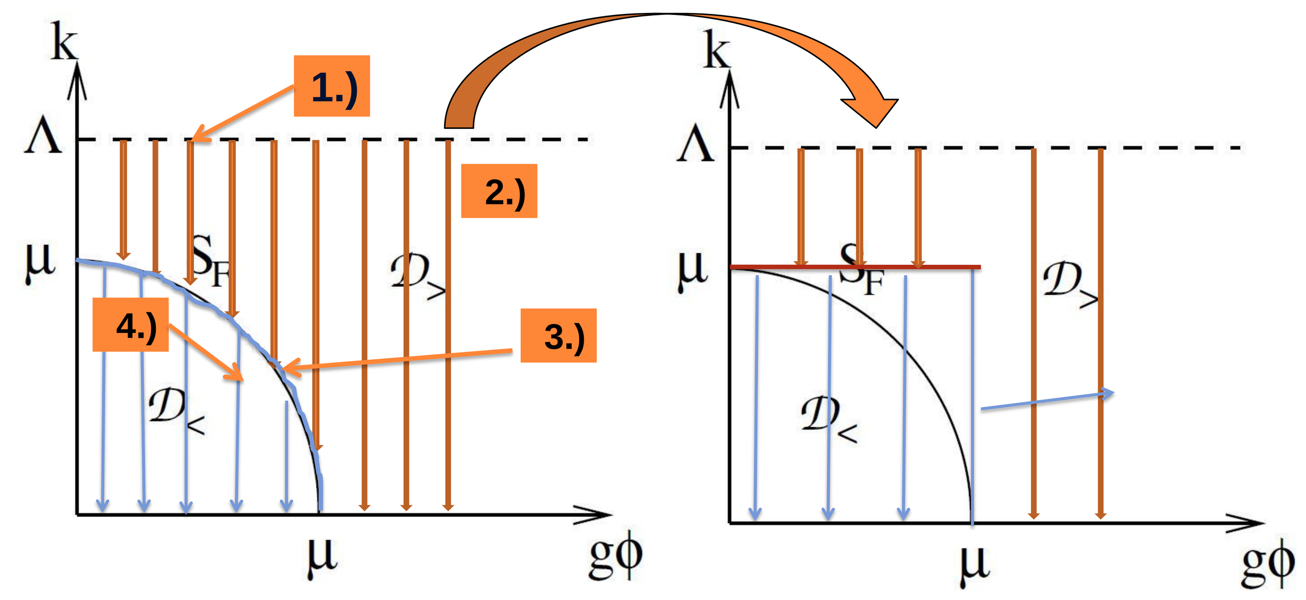
$$\partial_k U_k = \frac{k^4}{12\pi^2}\frac{1}{\omega_B}$$

Fermionic vacuum fluctuations and thermodynamic fluctuations cancel

SOLUTION IN STEPS

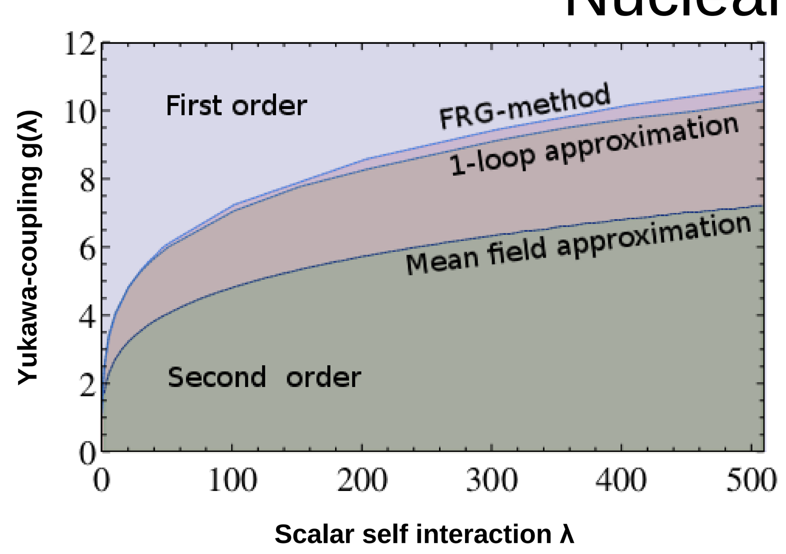
1) Fix the high scale couplings in the theory at scale Λ.
2) Integrate the equation which is valid outside of the Fermi surface.
3) Calculate the initial conditions for the equation inside the Fermi surface.
4) Integrate the equation which is valid below the Fermi surface.

Transform the circle into a rectangle to make the boundary conditions simpler

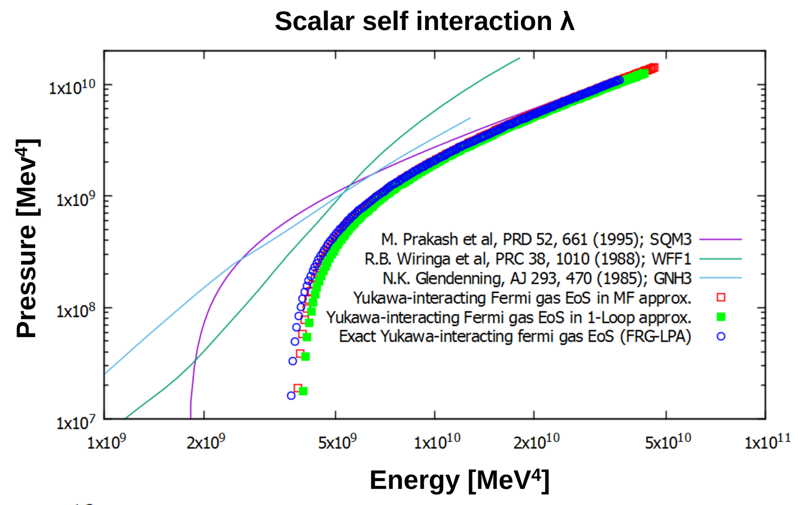


RESULTS

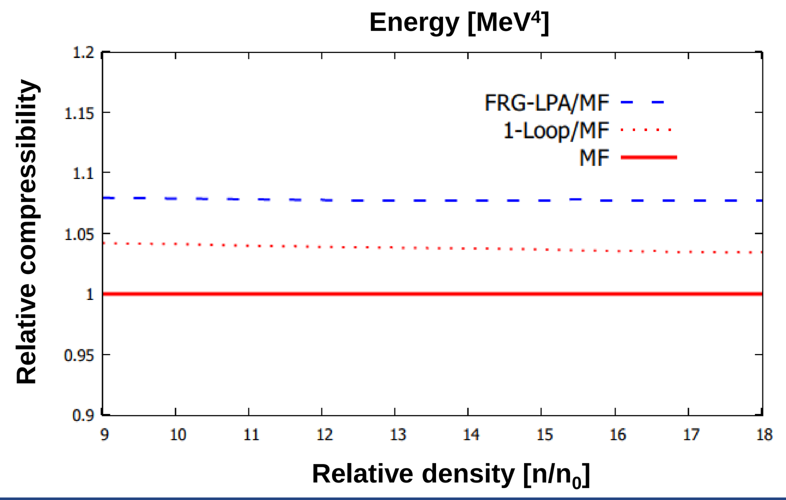
Nuclear matter properties



- The **phase diagram** of the interacting Fermi gas in different approximations shows the type of the **phase transition** in the system when the **couplings** are specified.
- The FRG and **one loop calculations are very** close and both of them are different from the main field result: **FRG is a relevant** improvement. (quantum effects)
- **FRG makes the phase transition smoother**: first order in mean field turns into second order in the FRG calculation.

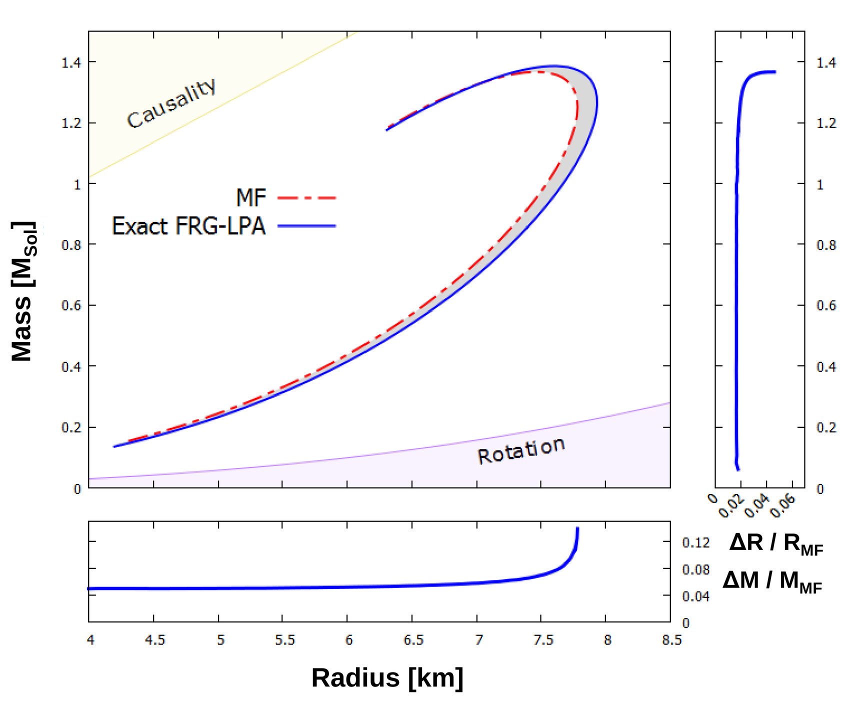


- Comparison of the interacting Fermi gas EOS in different approximations to other models. (SQM3, WFF1, GNH3)
- **Consistency**: at high energies they approach SQM3.
- The mean field, one loop and exact calculations gives very **similar equation of state**, despite their different results in the phase diagram.

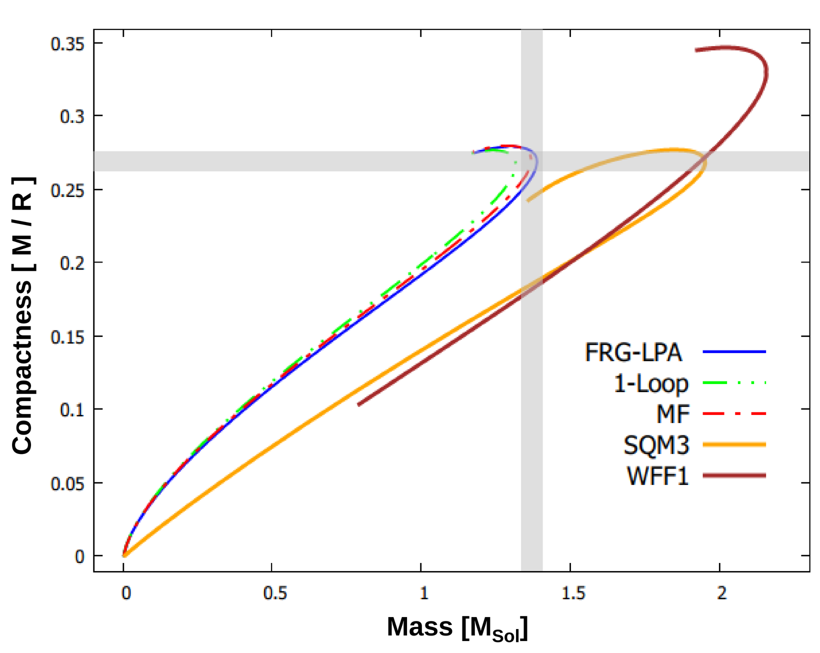


- The compressibility of the fermi gas model in different approximations
- The high order FRG calculation gives approximately 8% difference compared to the meanfield
- One loop is not as good approximation as it was in the case of the phase diagram.

Neutron star properties



- M-R diagram corresponding to the mean field and high order calculatiion.
- The difference in R and M compered to mean field is plotted on the sides
- The mass difference is the largest at the highest radius stars
- The radius difference is the largest at high mass stars
- The two curves intersect at two points at small density and high density.
- At low density fluctuations does not play a relevant role
- At high density the renormalization conditions gives a small difference



- The mass compactness diagram of the models compared to other EoS
- Timing measurements can predict the compacness of neutron stars
- Gray band: Predicted sensitivty of the NICER experiment in compactness measurement (5%)
- The experiments are close to the threshold where they can differentiate between different methods of quantum calculations

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TAKE-HOME MESSAGE

1. **Neutron star and nuclear matter parameters corresponding to a given model depend on the method of calculating quantum fluctuations**
2. **Mean field calculations work well for calculating the mass and radius of neutron stars considering the current sensitivity of experiments**
3. **High order calculations are needed in the case of nuclear matter parameters**
4. **We developed a method to calculate quantum fluctuations at zero temperature and finite chemical potential in FRG LPA (local potential approximation)**

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