The role of quantum corrections in effective theories of cold nuclear matter

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(Submitted to Phys. Rev. C)

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Péter Pósfay

Supervisors : Antal Jakovác, Gergely G. Barnaföldi

Have you ever thought about calculating quantum corrections to a Neutron Star ?

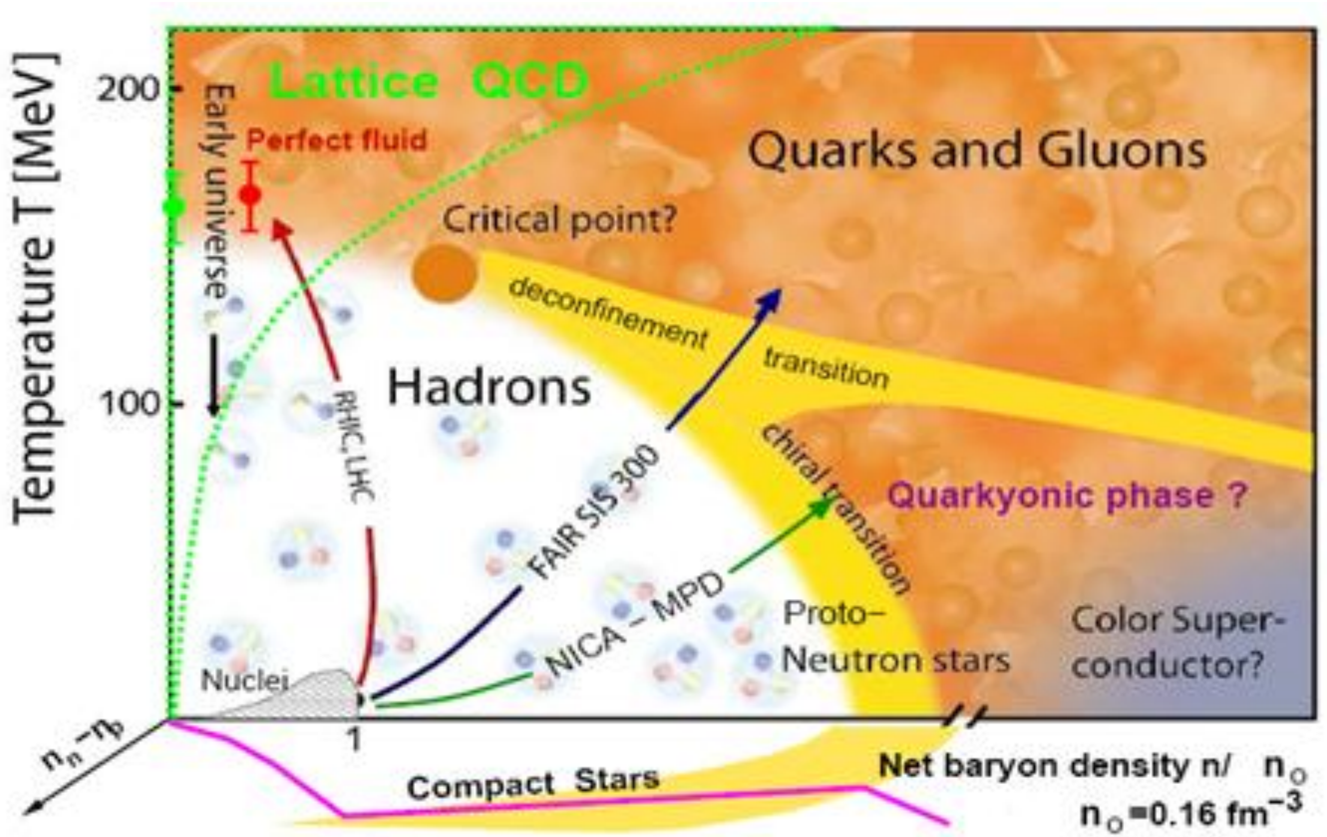
Have you ever thought about calculating

quantum corrections to

a Neutron Star ?

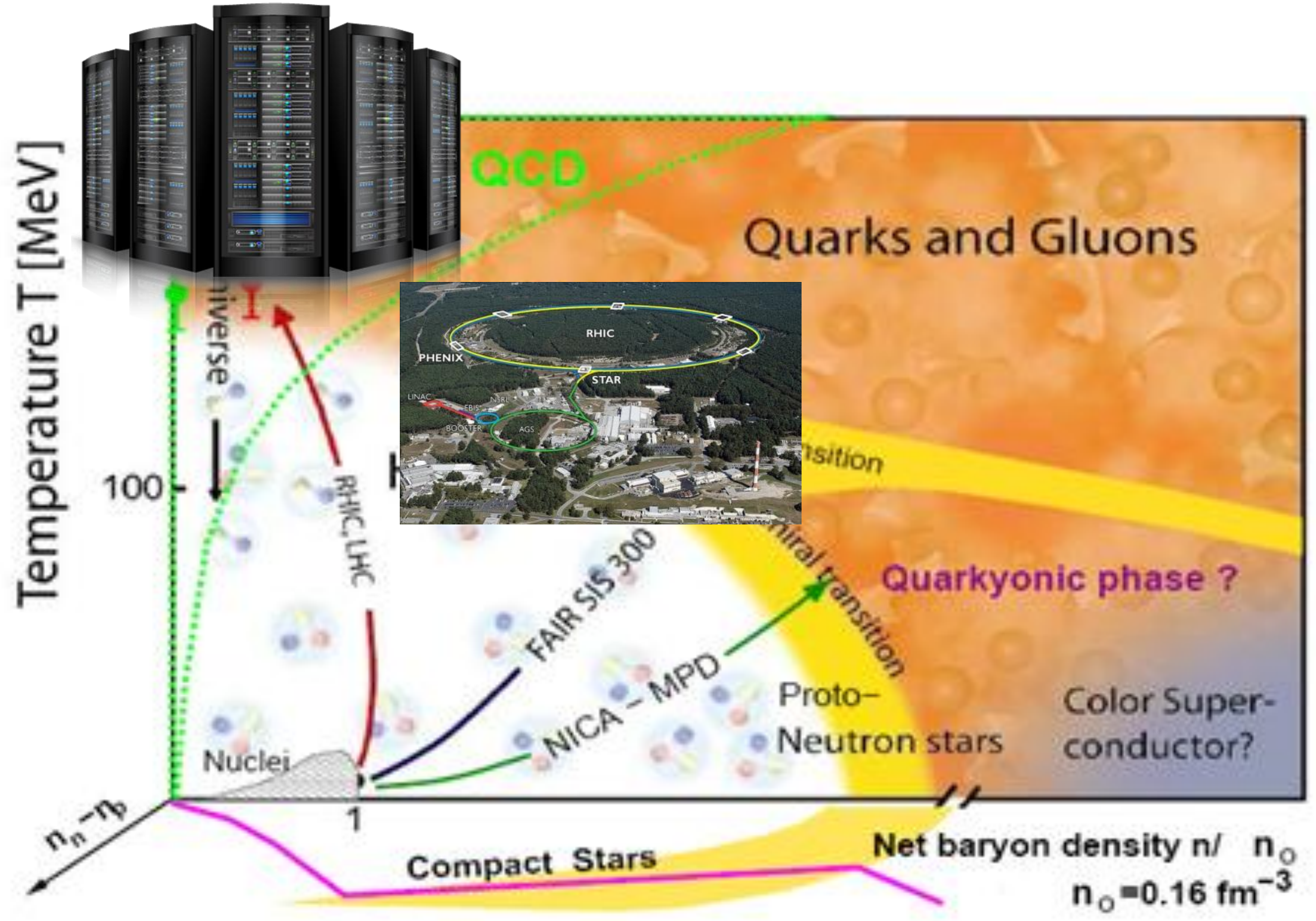
We did … But why?

Motivation



Temperature T [MeV]
200
100
Lattice QCD
Early universe
Perfect fluid
Quarks and Gluons
Critical point?
deconfinement
transition
Hadrons
RHIC,LHC
FAIR SIS 300
chiral transition
Quarkyonic phase ?
NICA – MPD
Proto-
Neutron stars
Color Super-
conductor?
Nuclei
1
n_n-n_p
Compact Stars
Net baryon density n/ n_o
n_o=0.16 fm^{-3}

Motivation


QCD
Quarks and Gluons
RHIC
PHENIX
STAR
Temperature T [MeV]
100
RHIC,LHC
FAIR SIS 300
NICA – MPD
Quarkyonic phase ?
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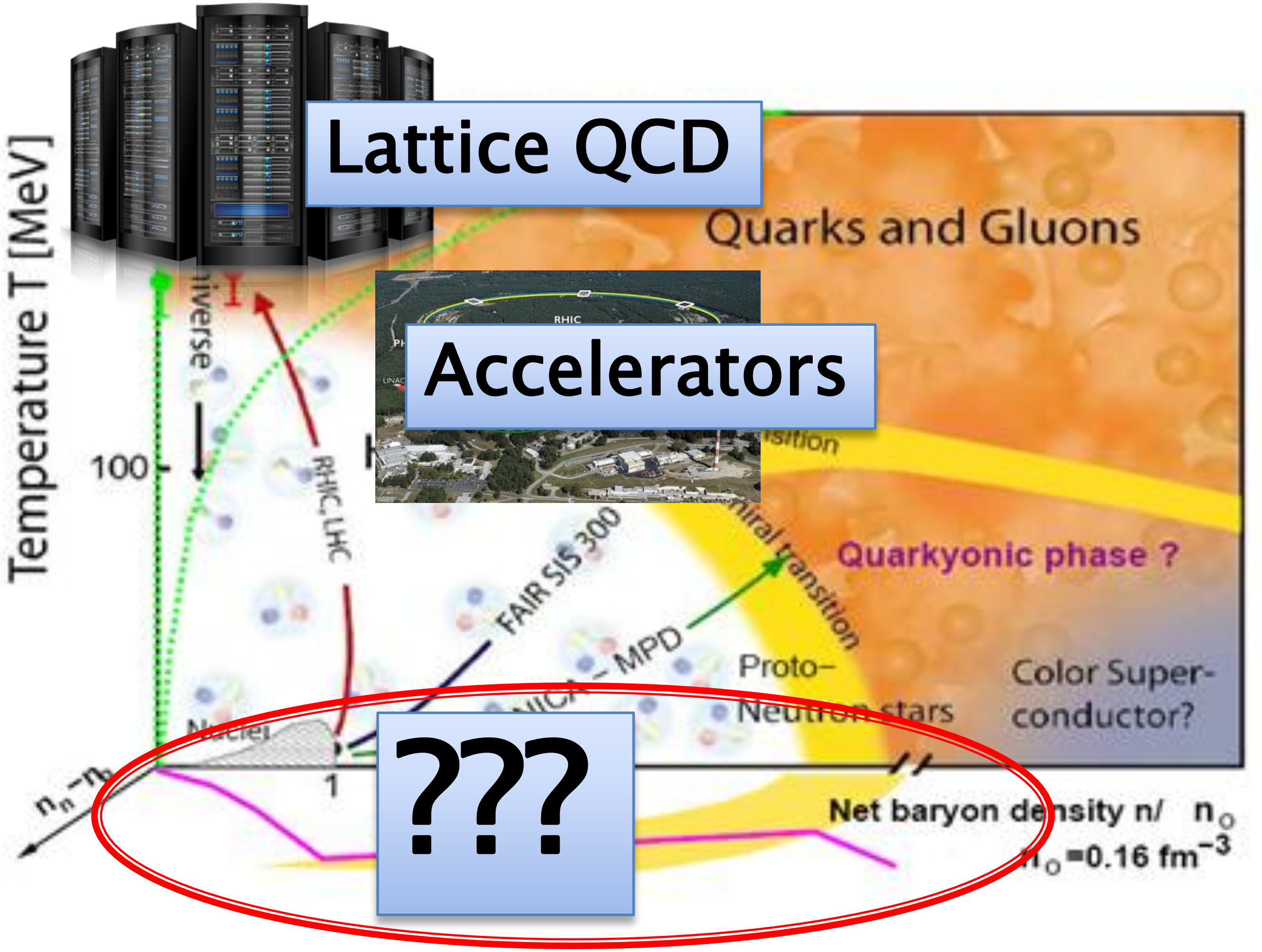
Lattice QCD
Accelerators
???
Quarks and Gluons
Temperature T [MeV]
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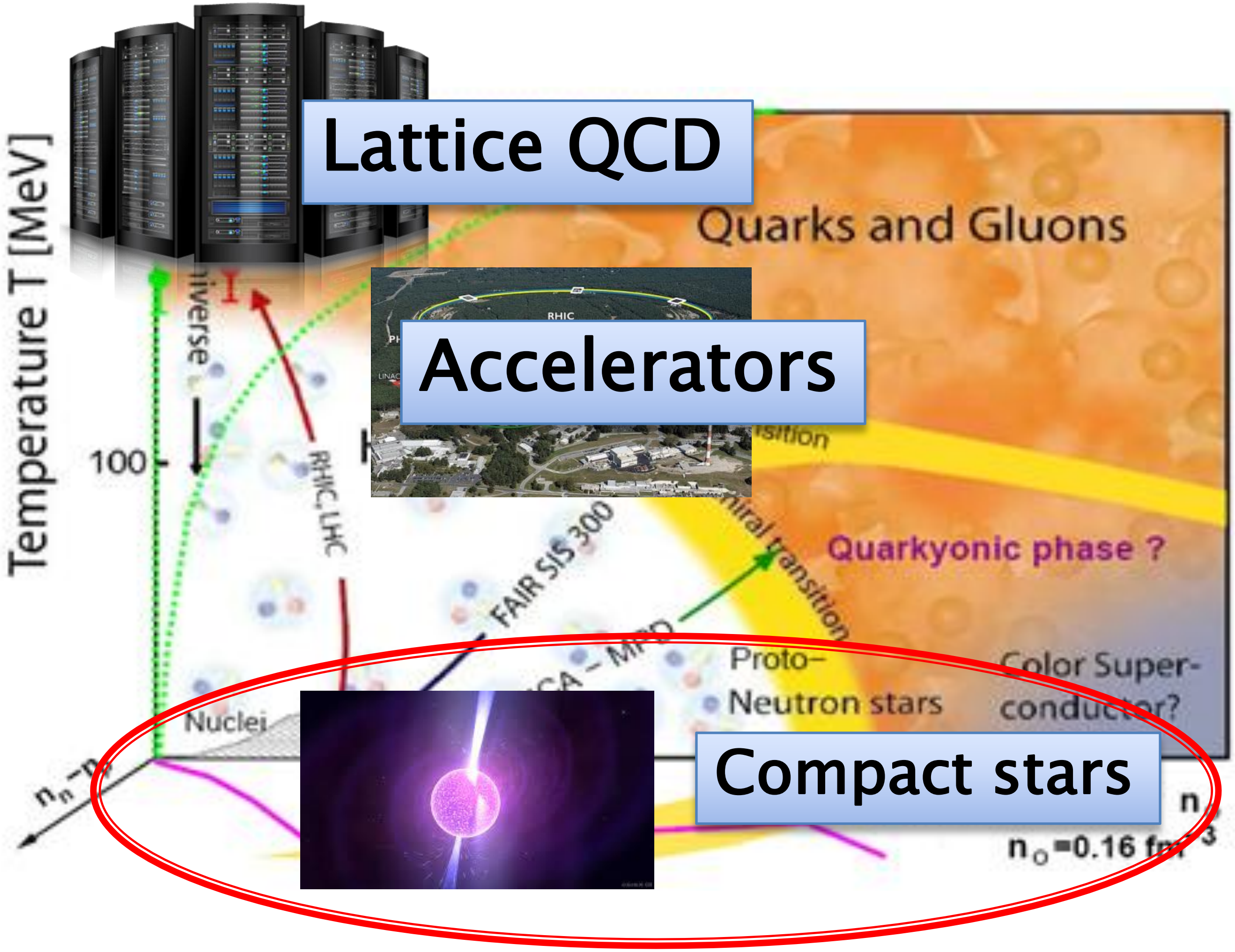
Motivation


Lattice QCD
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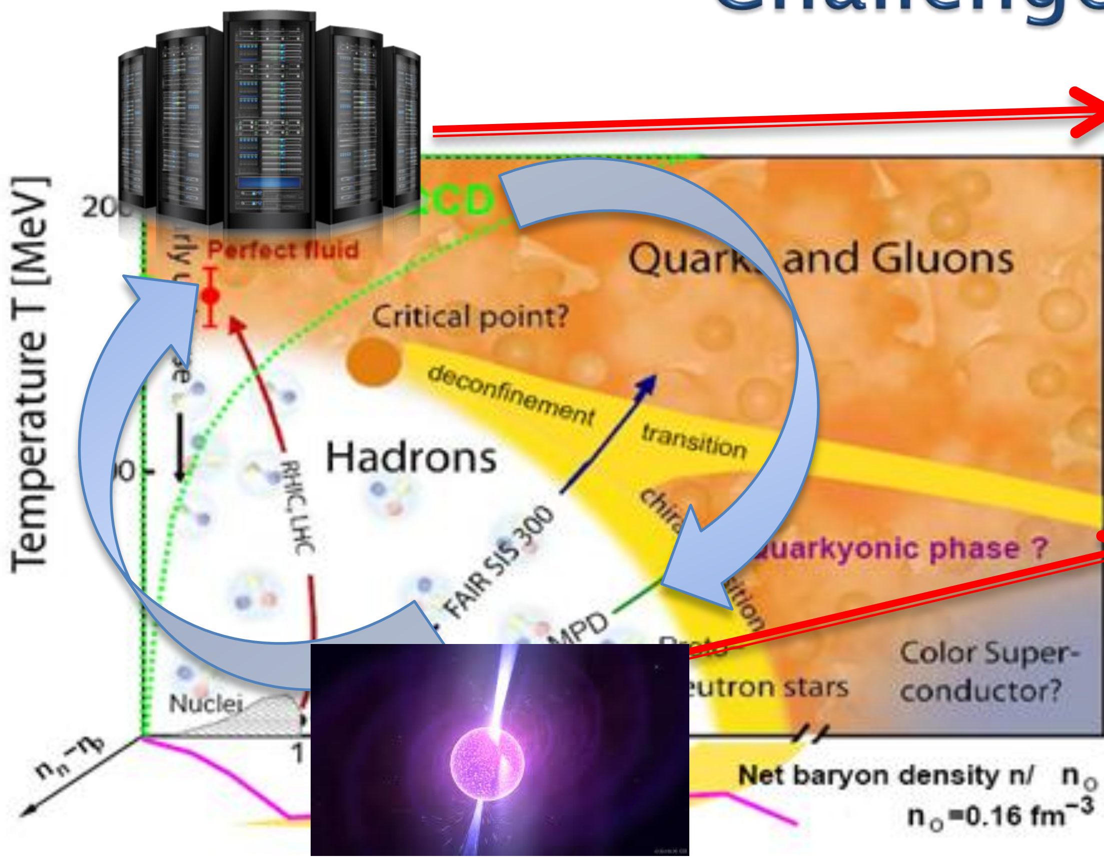
Challenges



This region known:
Interaction, particles, degrees of freedom

Using this knowledge, how can we understand the behavior of matter in a different state?

Analogy: to describe fluid flow, the knowledge of the quantum mechanics of fluid molecules is not needed. This separation makes hard to predict fluid flow based on laws describing the elementary particles of water.

The Method: FRG

The Wetterich equation

- Exact equation for the effective action, but it is very hard to solve directly
  - **Scale dependent effective action (k scale parameter)**

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

Wetterich equation

k=Λ

Classical action

Integration

k=0

Quantum fluctuations included

The Wetterich equation

- Exact equation for the effective action, but it is very hard to solve directly
  - **Scale dependent effective action (k scale parameter)**

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

We need an ansatz for the integration

Not necessarly perturbative ansatz!

$$\Gamma_k = \sum_{l=1}^{l=N} \frac{g_l(k)}{l!} \hat{O}_l$$

Scale dependent coupling

The Wetterich equation

- Exact equation for the effective action, but it is very hard to solve directly
  - **Scale dependent effective action (k scale parameter)**

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

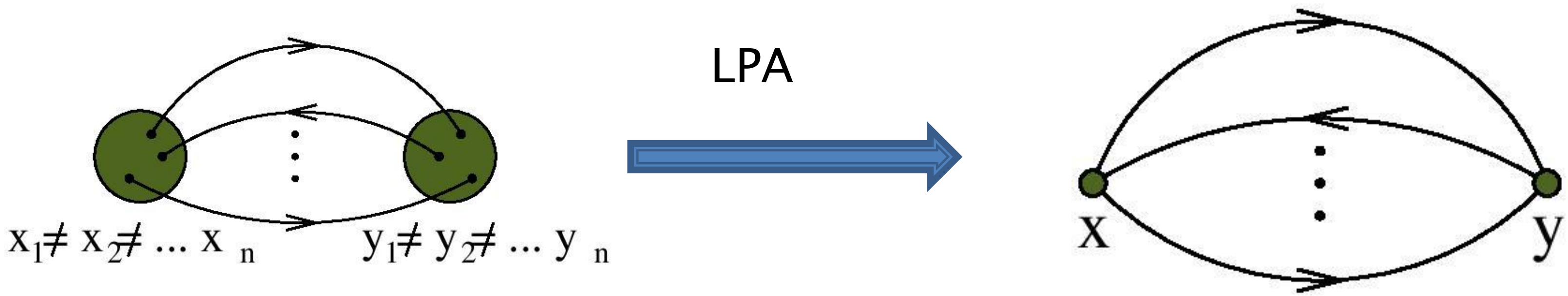
Regulator:
- determines the modes present on scale *k*
- physics is regulator independent

Local Potential Approximation (LPA)

What does the ansatz exactly mean ?

LPA is based on the assumption that the contribution of these two diagrams are close.

(momentum dependence of the vertices is suppressed)



This implies the following ansatz for the effective action:

$$\Gamma_k[\psi] = \int d^4x \left[\frac{1}{2} \psi_i K_{k,ij} \psi_j + U_k(\psi) \right]$$

A demonstrative model

Interacting Fermi-gas model

Ansatz for the effective action:

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

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

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

We study the scale dependence of the potential only!!

Interacting Fermi-gas at finite temperature

Ansatz for the effective action:

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

Wetterich -equation

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

Bosonic part

Fermionic part

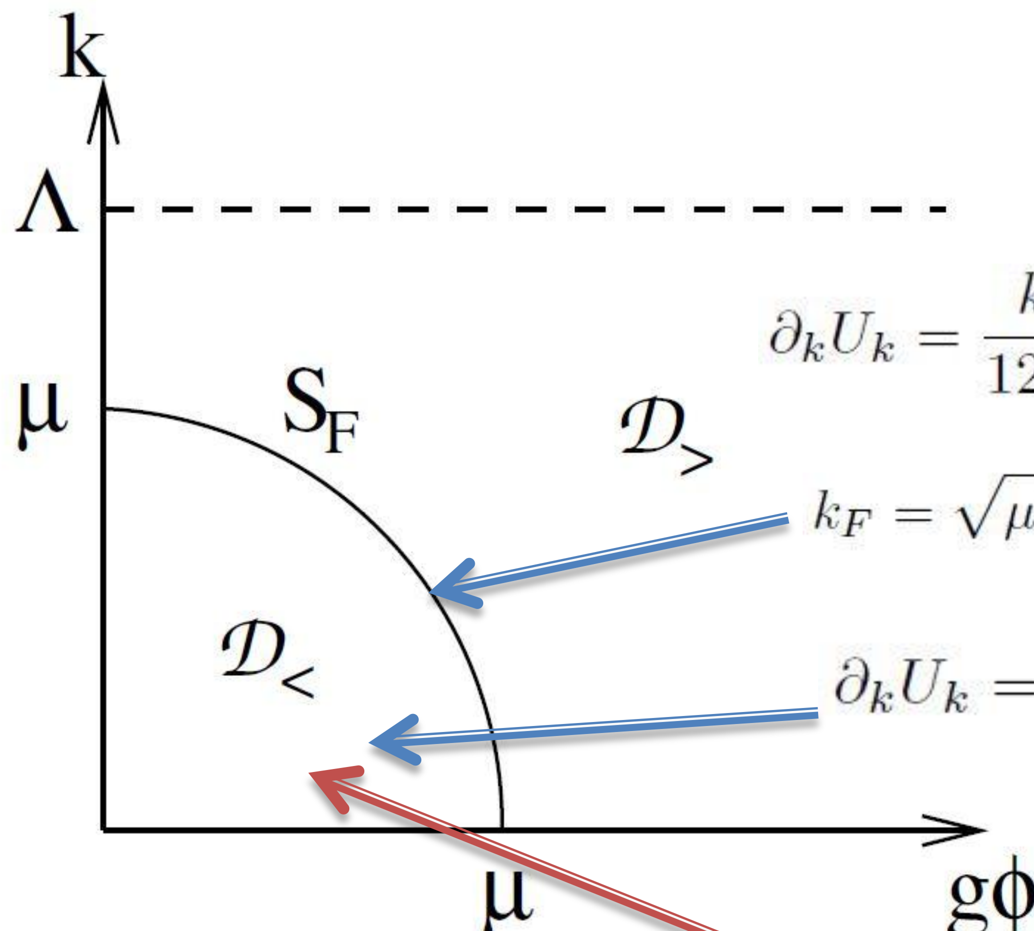
$$U_\Lambda(\varphi) = \frac{m_0^2}{2}\varphi^2 + \frac{\lambda_0}{24}\varphi^4 \qquad \omega_F^2 = k^2 + g^2\varphi^2 \qquad \omega_B^2 = k^2 + \partial_\varphi^2 U \qquad n_{B/F}(\omega) = \frac{1}{1 \mp e^{-\beta\omega}}$$

Solution at zero temperature $\mu \neq 0$

Demonstrative model at zero temperature

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

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



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

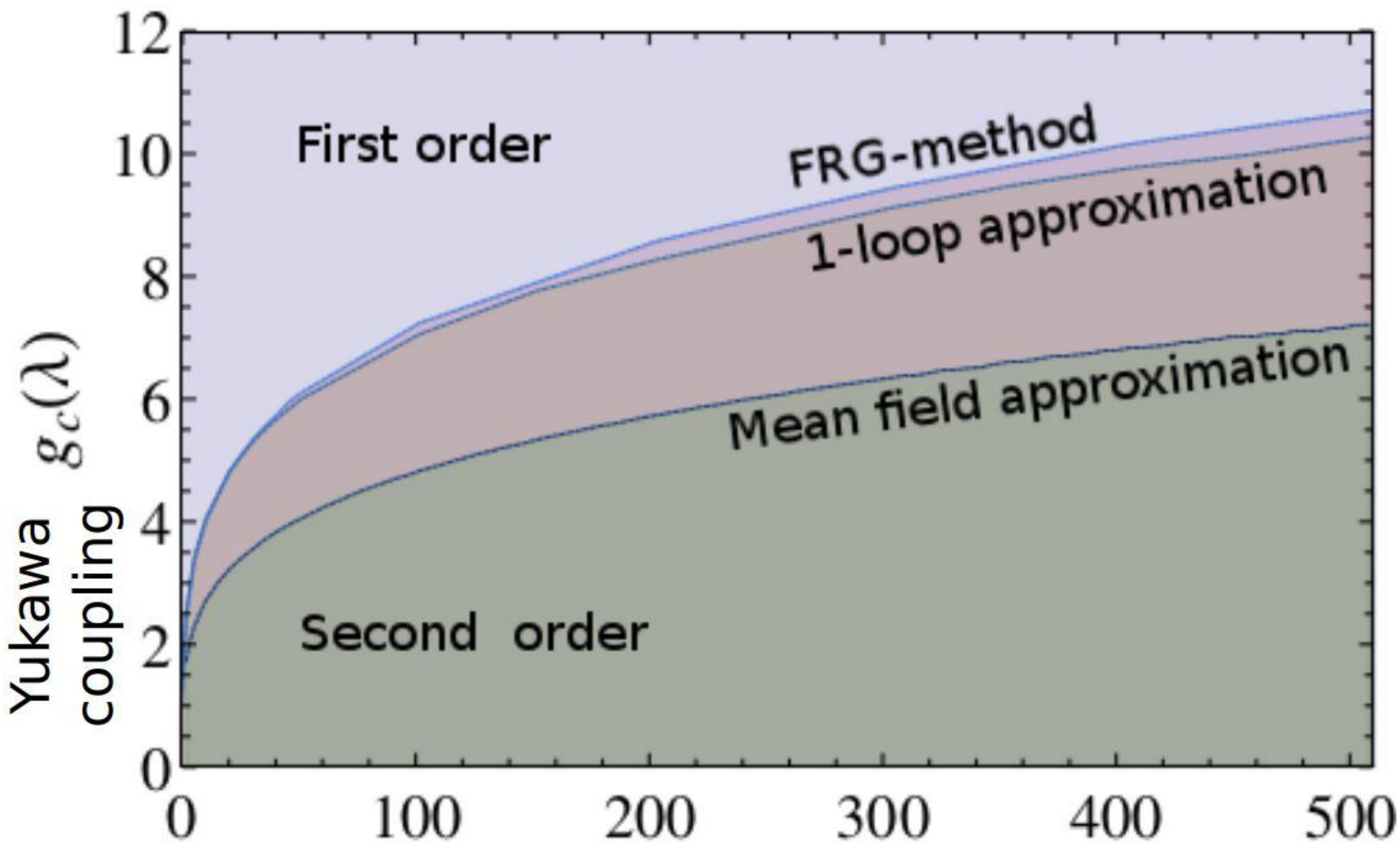
$$k_F = \sqrt{\mu^2 - g^2\varphi^2}$$ Fermi-surface

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

Fermionic vacuum fluctuations and thermodynamic fluctuations cancel

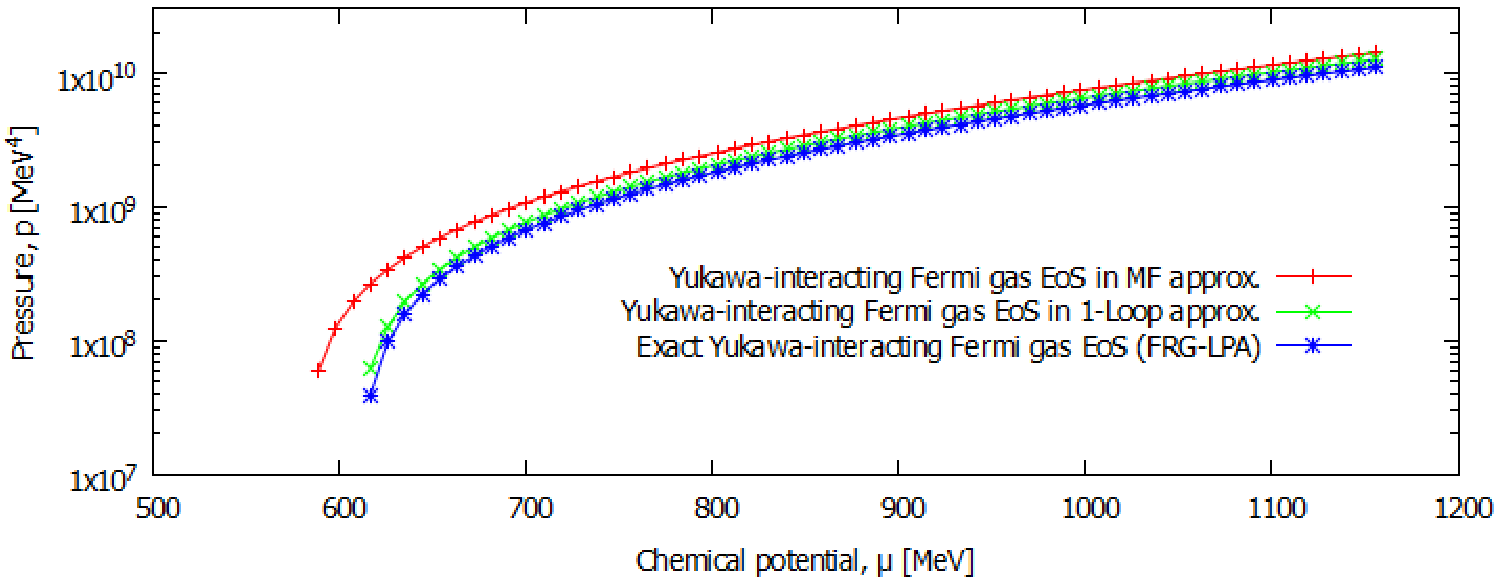
Thermodynamical properties

Phase structure



Scalar self interaction

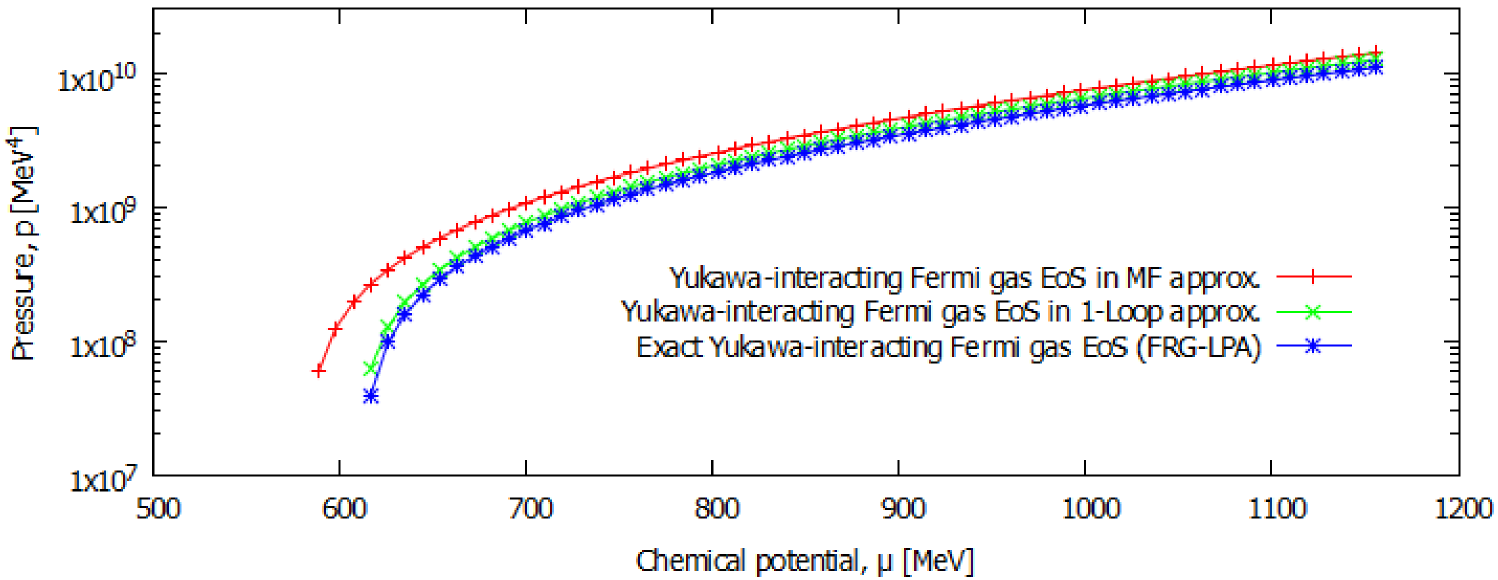
The equation of state

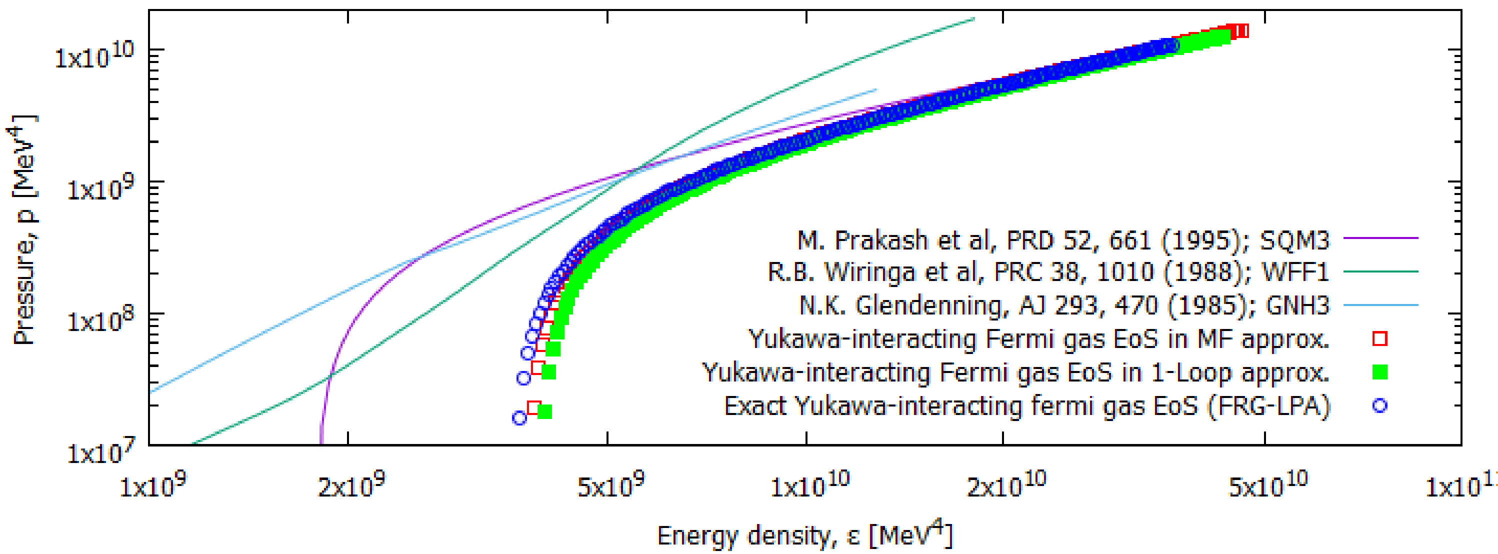


PRESSURE

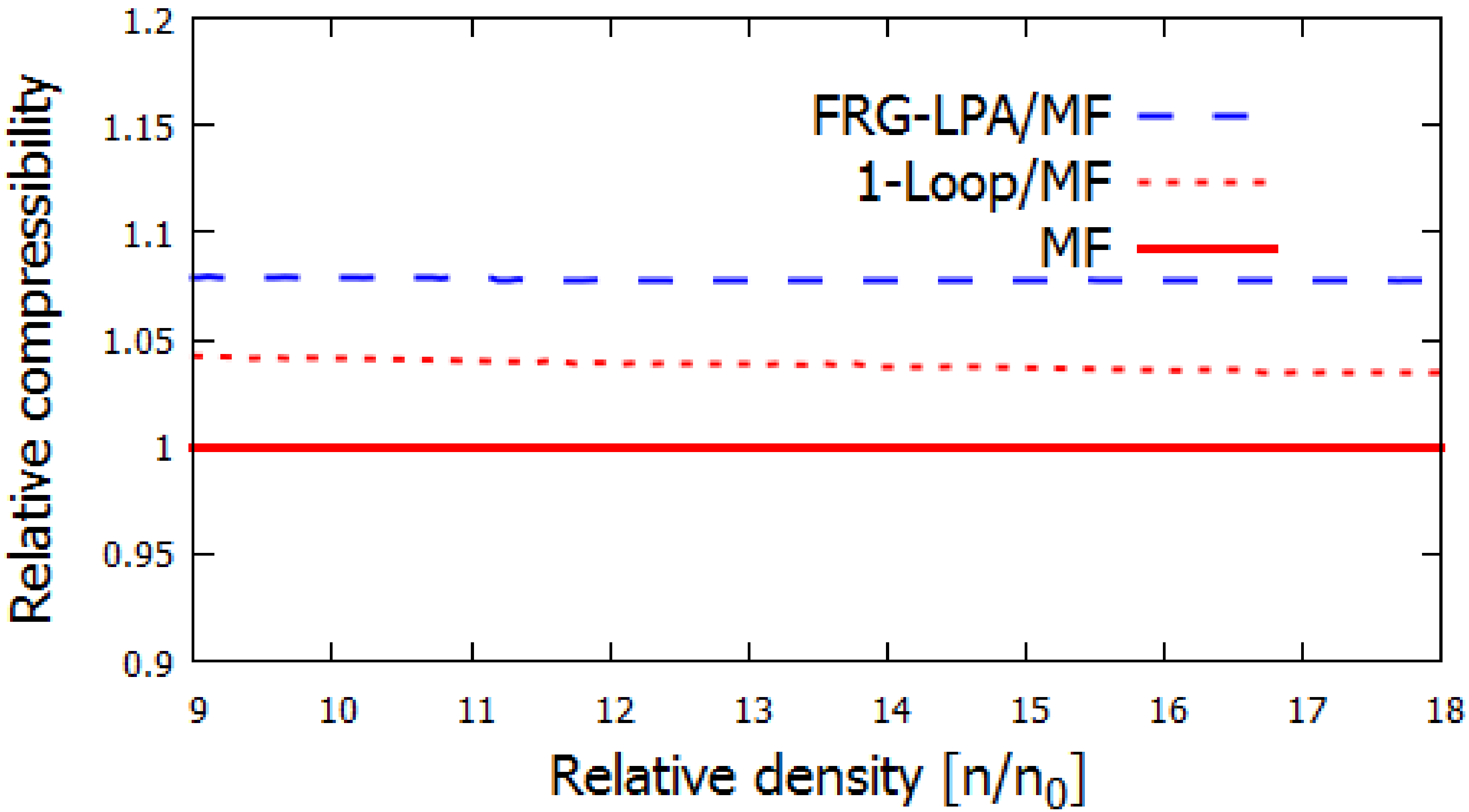
Mean Field > 1-LOOP > FRG

The equation of state



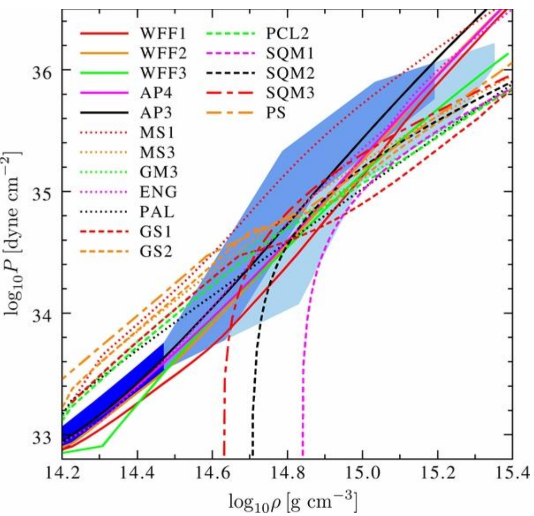


Compressibility

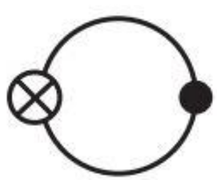


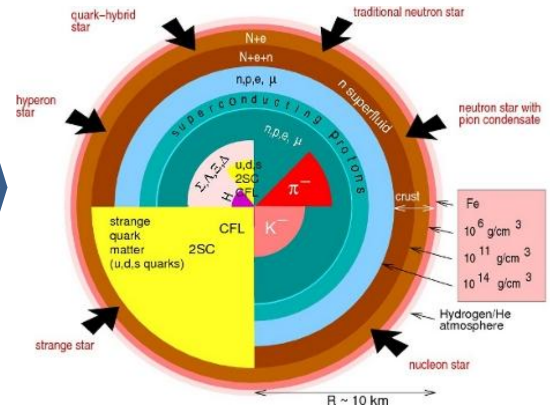
From EoS to Compact Stars

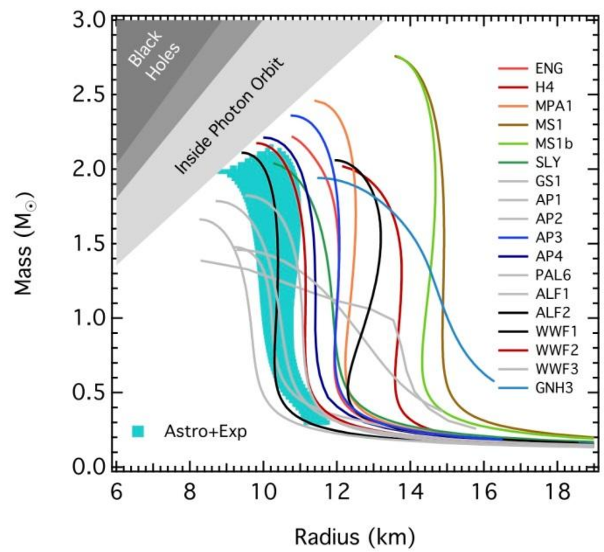
EOS

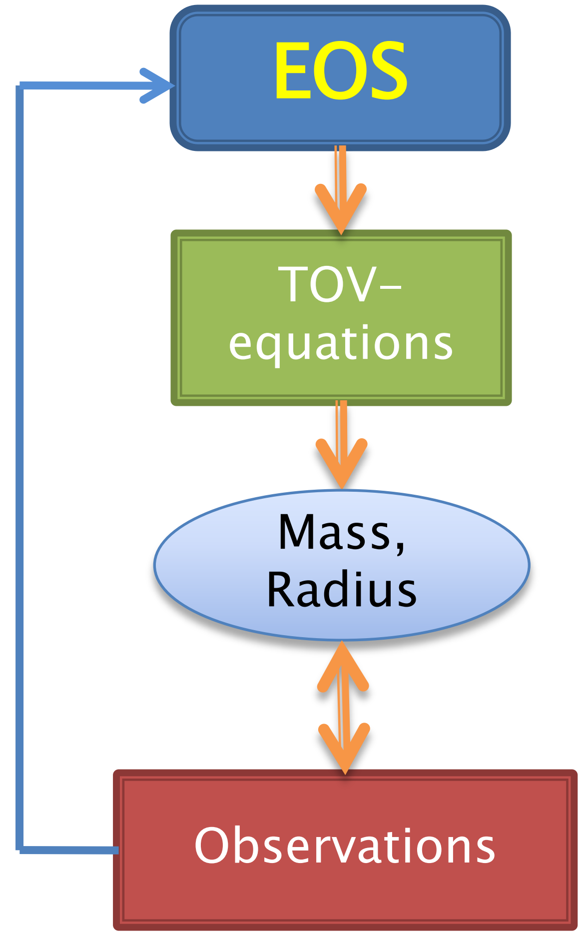


FRG









Application for compact stars

The Fermi-gas is not a realistic model of a neutron star, this is just demonstrates that an apparently small change in the EoS, due to quantum fluctuations means a noticeable change in the solution of the TOV equations.

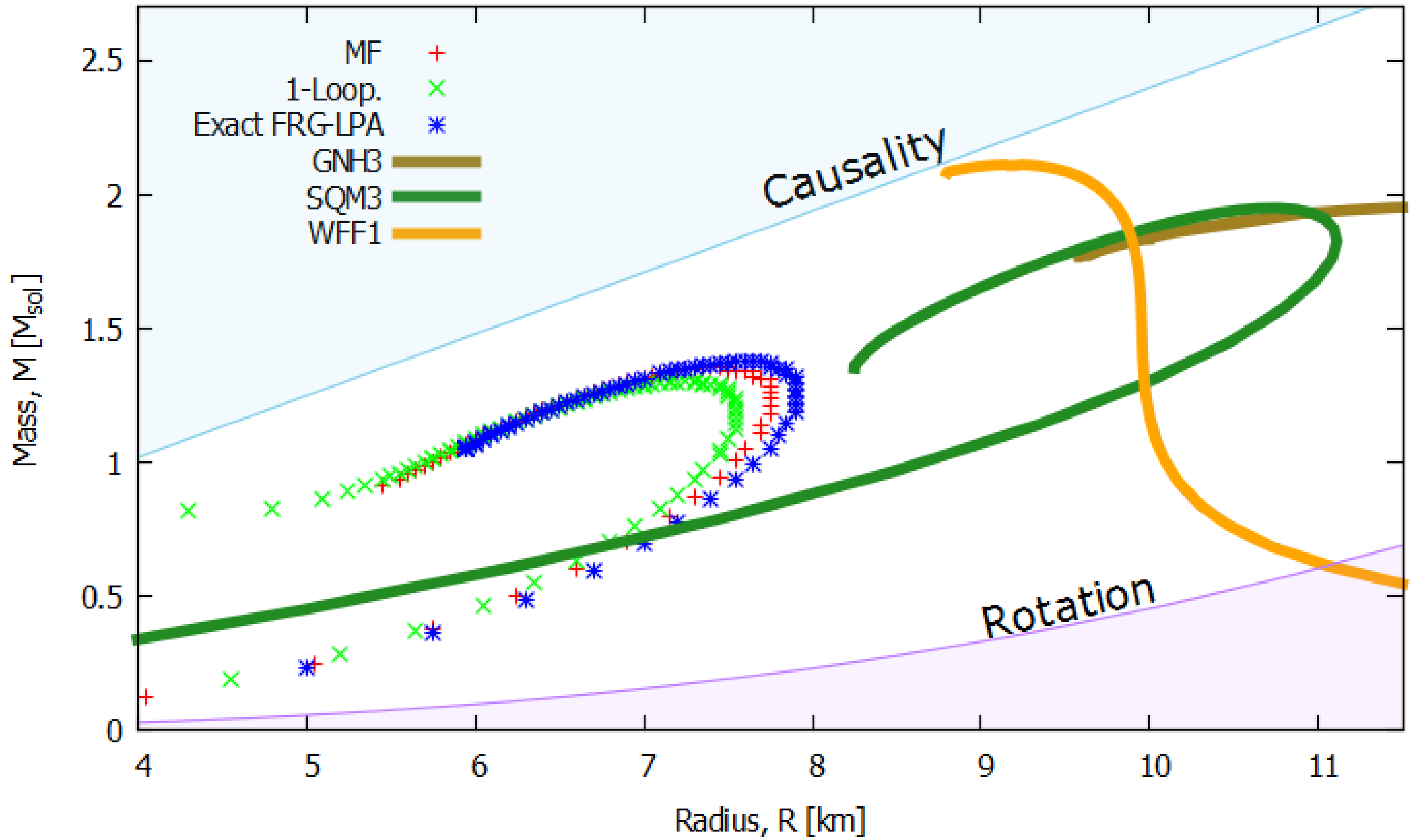
$M_{FRG}=1.377$

+1.5 %

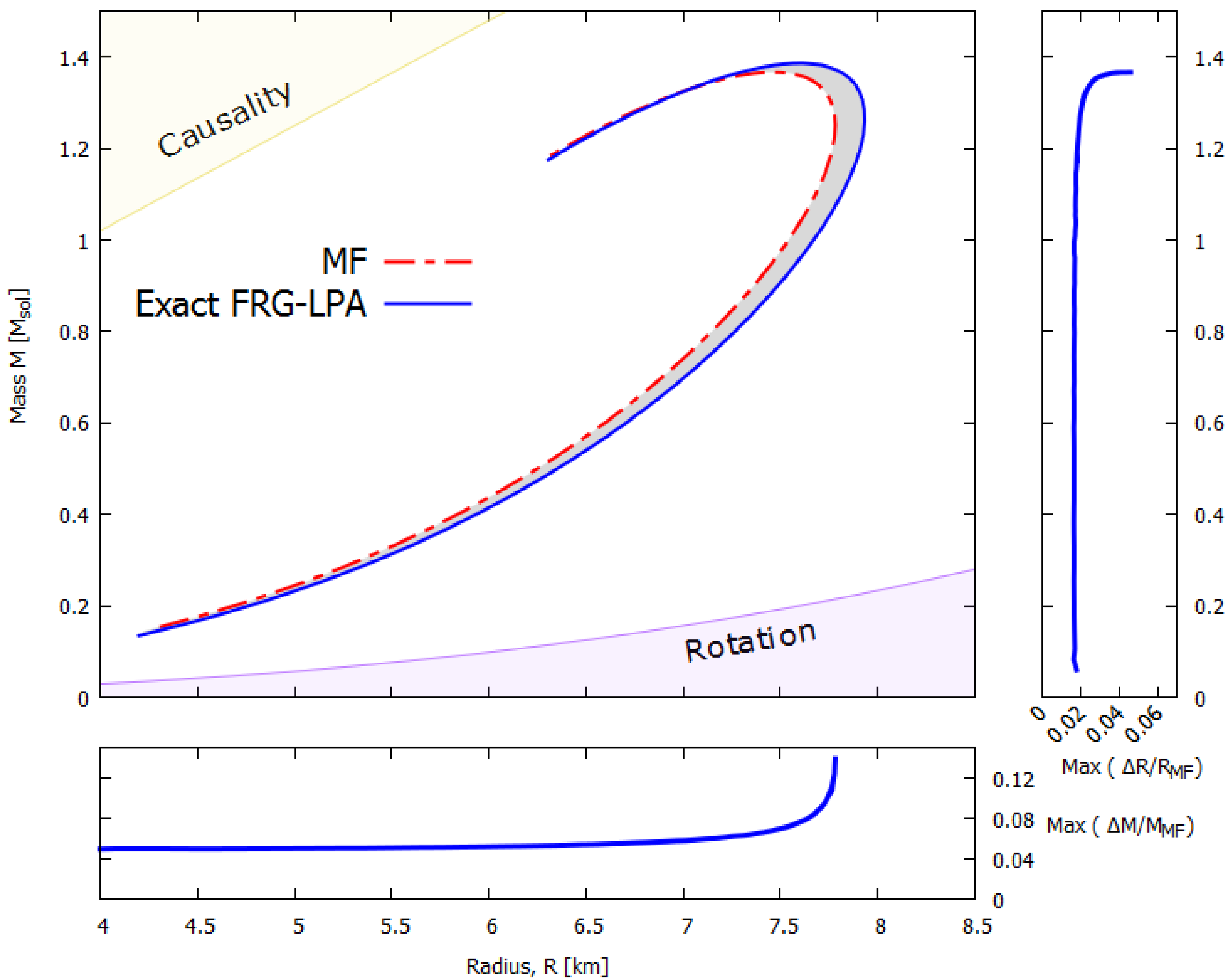
$M_{MF}=1.358$

-3.5 %

$M_{1L}=1.309$

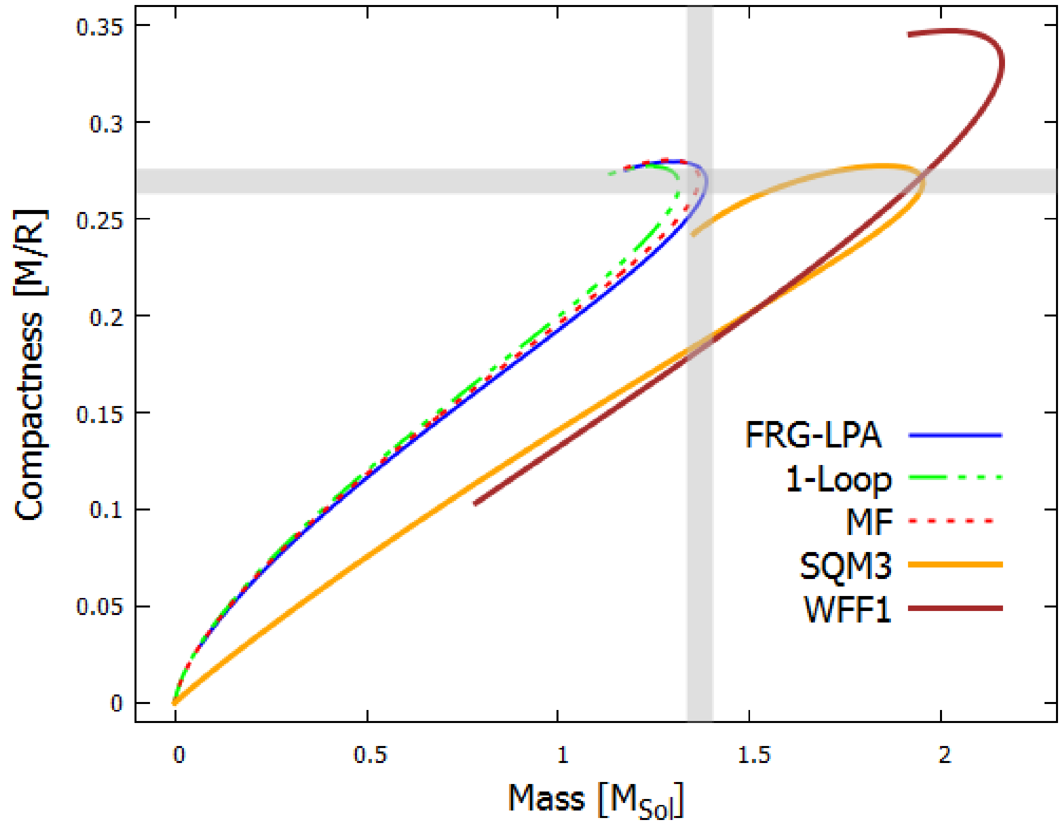


Application for compact stars



Gravity waves and compactness

- The **compactness** (M/R) of the neutron stars can be extracted from **gravity waves** and **pulsar timing** measurements.
  - Discovery of GW170817: the first detected gravity wave originating from a neutron star
- The **NICER experiment** will be able to determine compactness with error less than 10%
- This is a new method to distinguish between models.



Summary

- Microscopical observables are maximum: 10–25 %
- Macroscopical astrophysical ones are maximum: 5–10 %
- **Measurement resulotion limit is about: 10 %**

Observable	Max uncertainty (%)
Potential, U(ϕ)	<25 %
Phase diagram (g)	< 25 %
EoS p(μ),p(ε)	< 25 %
Compressibility	< 10 %
M(R) diagram	<10% (M) <5% (R)
Compactness	<10% (M) < 5% (R)

Thank you for the attention !

Acknowledgements:
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