The effect of Quantum Fluctuations in Compact Star Observables

An Application of Functional Renormalization Group Method for Superdense Nuclear Matter

Gergely Gábor Barnaföldi, Péter Pósfay, Antal Jakovác

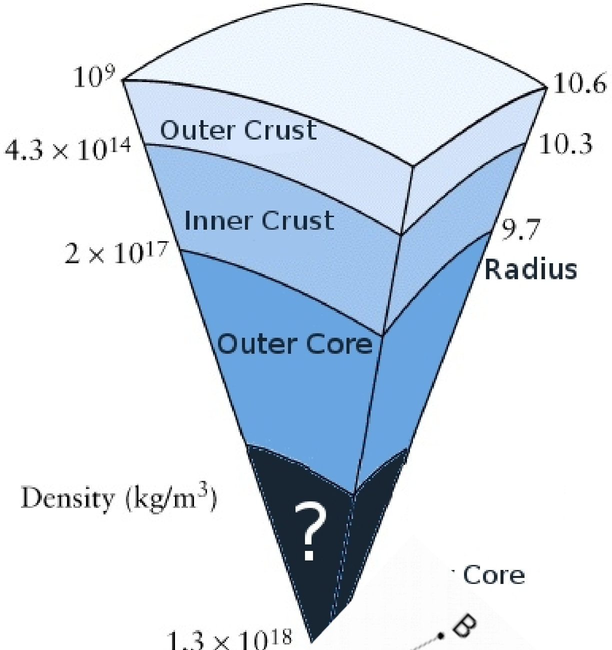
References:
arXiv:1604.01717 [hep-th], *Eur. Phys.* J. C (2015) **75**: 2, PoS(EPS-HEP2015)369

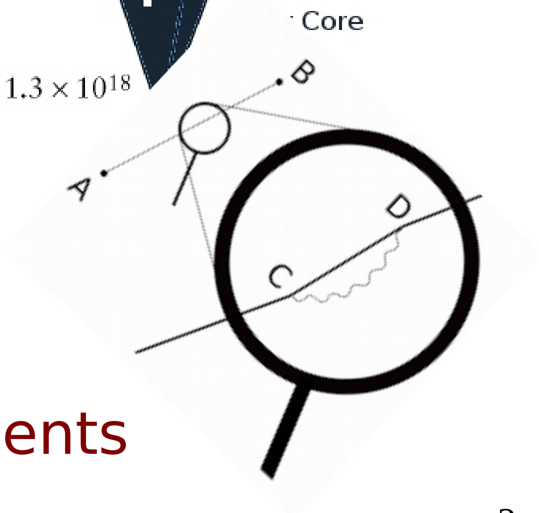
Support: *Hungarian OTKA grants, NK123815, K104260, K104292, K120660, the NewCompStar MP1304 and THOR CA15213 COST actions.*

CSQCD 2017, Dubna, Russia, 26th-29th September 2017

Outline

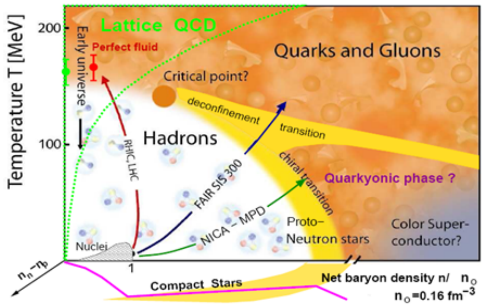
- Motivation
  - Predict the uncertainty of quantum fluctuation using FRG
- Introduction to the FRG method & our model
  - Ansatz Fermi gas model at finite temperature with a Yukawa couplin
  - Wetterich equation at finite chemical potential, LPA, T=0,
- Results and comparison of the FRG results to other model
  - Microscopic observables: phase structure & EoS at different approximations
  - Macroscopic astrophysical compact star observables
- Aim: Comparison in the resolution of the recent measurements

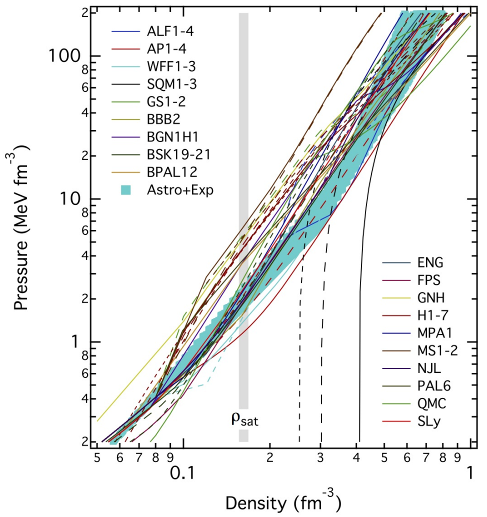




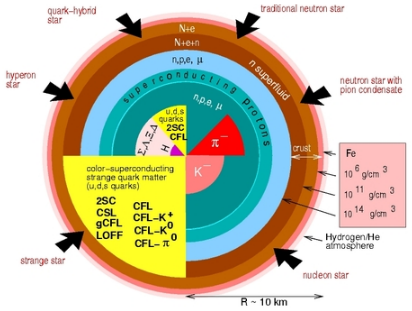
NewCompStar Motivation

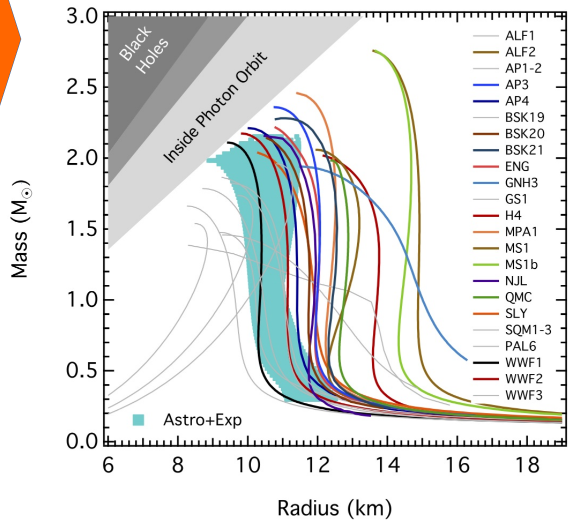
EoS from exp & theory



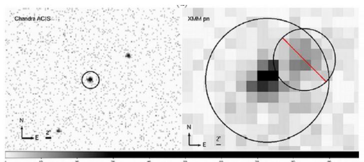


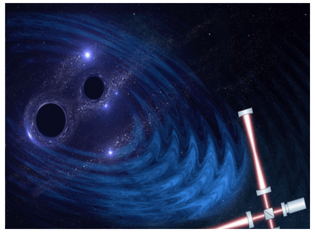
Application in compact stars

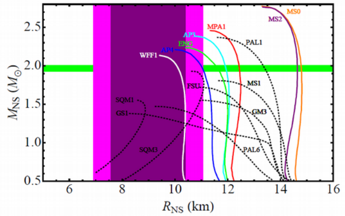


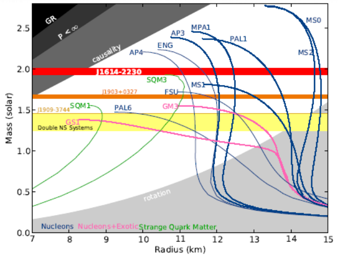


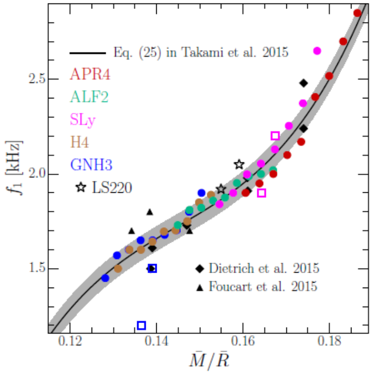
Constraints by astropysical observations











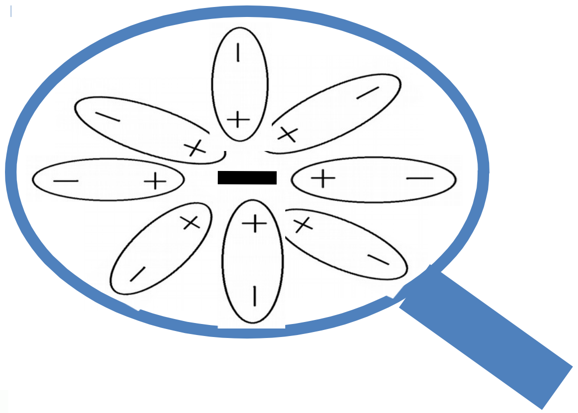
Motivation for FRG

- **Observation:** Considering a point charge, which polarizes the medium seems like point charge with a modified charge.
- **Basic idea:** Due to the interaction, the measurable (effective) properties differs from the bare quantities.
- **Quantum corrections:**
  - Heisenberg uncertainty

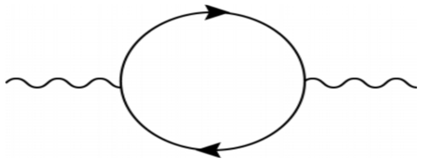
    high-energy reaction for a short time is allowed
  - Pair production & annihilation

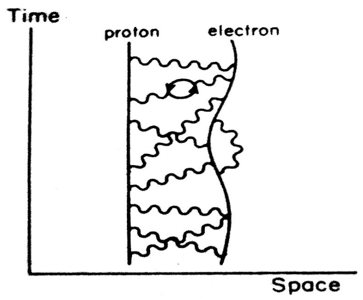
    bosonic propagator is modified due to the pair production
  - Self-interaction

    Interaction is a sum of many tiny- and self interaction



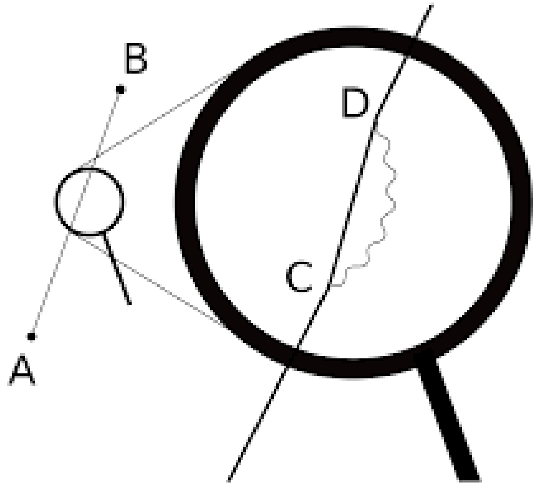
$$\Delta E\ \Delta t\ \geq \frac{\hbar}{2}$$

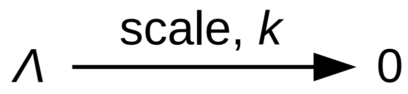


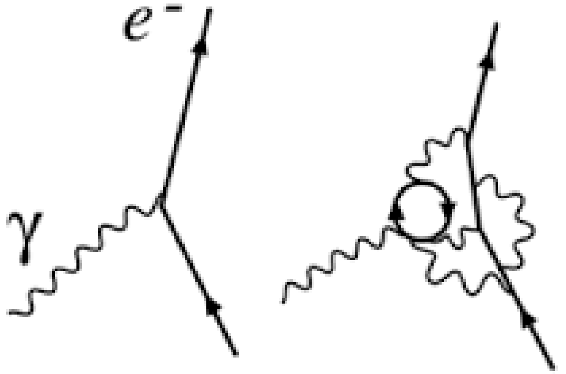


Motivation for FRG

- It is hard to get effective action for an interacting field theory: e.g.: EoS for superdense cold matter ($T \to 0$ and finite μ)
- Taking into account quantum fluctuations using a scale, k
  - Classical action, $S = \Gamma_{k \to \Lambda}$ in the UV limit, $k \to \Lambda$
  - Quantum action, $\Gamma = \Gamma_{k \to 0}$ in the IR limit, $k \to 0$
- FRG Method
  - Smooth transition from macroscopic to microscopic
  - RG method for QFT
  - Non-perturbative description
  - Not depends on coupling
  - BUT: Technically it is NOT simple







Functional Renormalization Group (FRG)

- FRG is a general non-perturbative method to determine the effective action of a system.
- **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

k=0
Quantum fluctuations included

Integration

Functional Renormalization Group (FRG)

- FRG is a general non-perturbative method to determine the effective action of a system.
- **Scale dependent effective action (k scale parameter)**

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

Wetterich equation

- **Ansatz** for the integration,
  - not need to be perturbative
  - scale-dependent coupling

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

Functional Renormalization Group (FRG)

- FRG is a general non-perturbative method to determine the effective action of a system.
- **Scale dependent effective action (k scale parameter)**

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

Wetterich equation

- **Regulator**
  - Determines the modes present on scale, k
  - Physics is regulator independent

Ansatz: Interacting Fermi-gas model

Ansatz for the effective action:

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

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

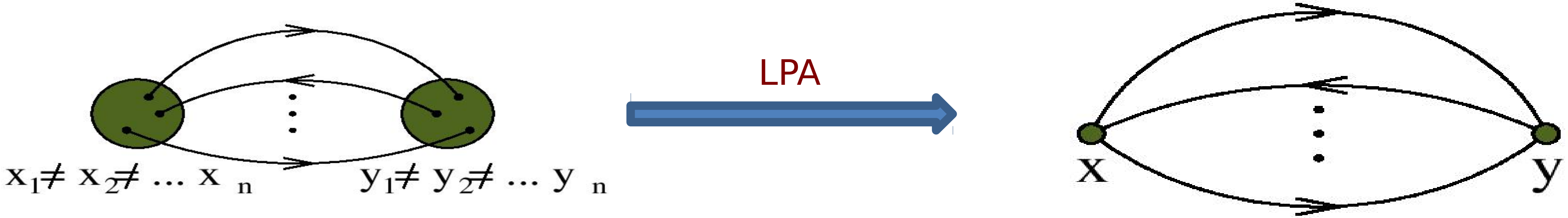
Bosons: the **potential** contains self interaction terms

We study the scale dependence of the potential only!!

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:

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

Interacting Fermi-gas at finite temperature

Ansatz for the effective action:

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

Wetterich -equation

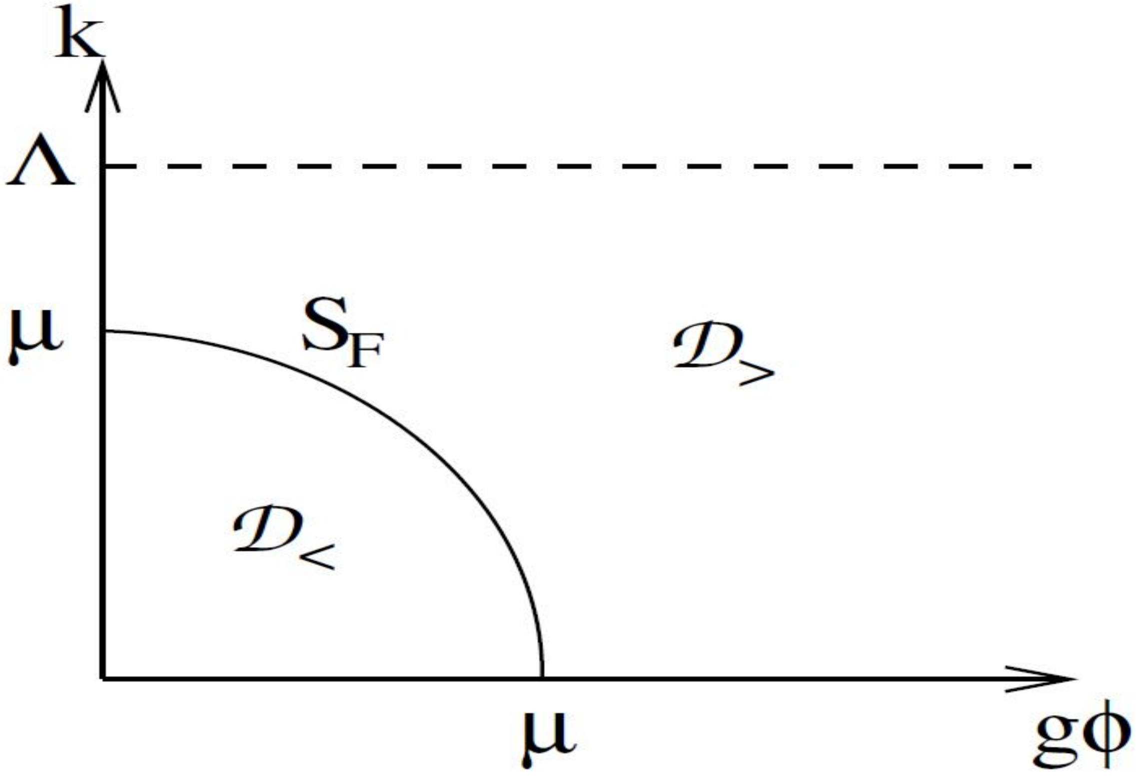
$$\partial_k U_k = \frac{k^4}{12\pi^2}\left[\underbrace{\frac{1+2n_B(\omega_B)}{\omega_B}}_{\text{Bosonic part}} + 4\underbrace{\frac{-1+n_F(\omega_F-\mu)+n_F(\omega_F+\mu)}{\omega_F}}_{\text{Fermionic part}}\right]$$

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

Interacting Fermi-gas at zero temperature

$T=0$, $\mu \neq 0$ $\Longrightarrow$ $n_F(\omega) \rightarrow \Theta(-\omega)$

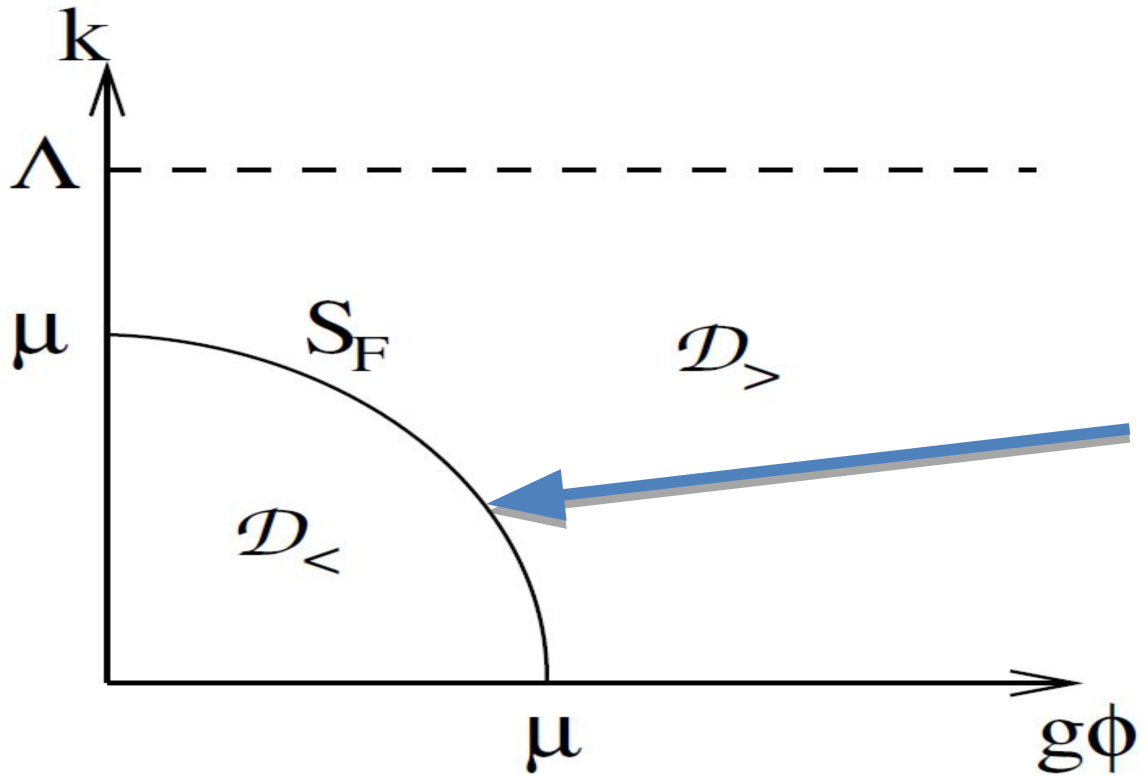
We have two equations for the two values of the step function each valid on different domain



Interacting Fermi-gas at zero temperature

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

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



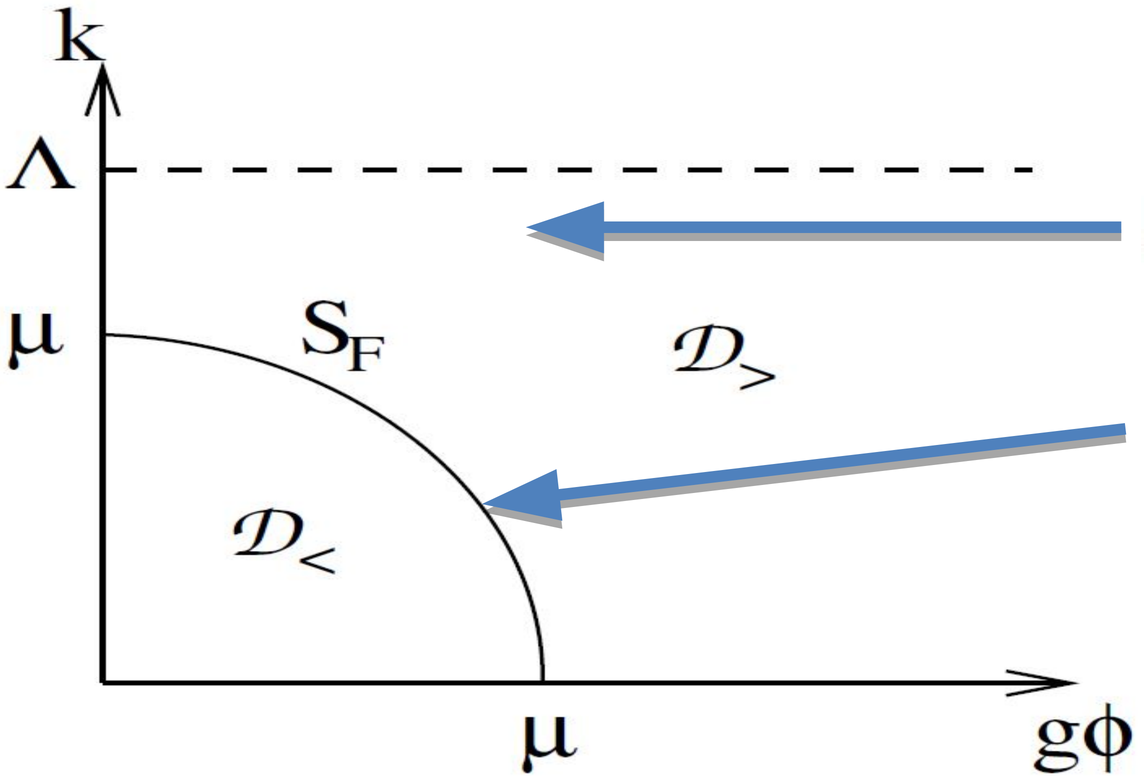
$k_F = \sqrt{\mu^2 - g^2\varphi^2};$

Fermi-surface

Interacting Fermi-gas at zero temperature

T=0 , μ≠0 $\Longrightarrow$ $n_F(\omega) \to \Theta(-\omega)$

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



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

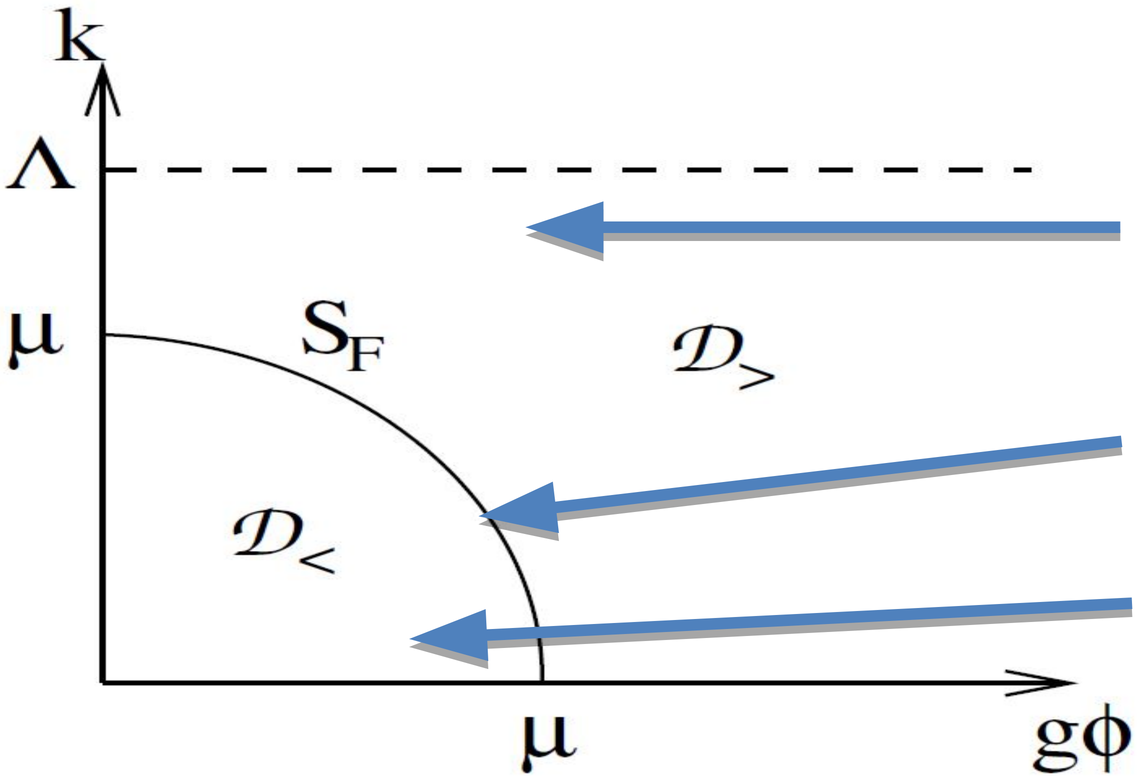
$$k_F = \sqrt{\mu^2 - g^2\varphi^2};$$

Fermi-surface

Interacting Fermi-gas at zero temperature

$T=0$, $\mu\neq0$ $\Rightarrow$ $n_F(\omega) \rightarrow \Theta(-\omega)$

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



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

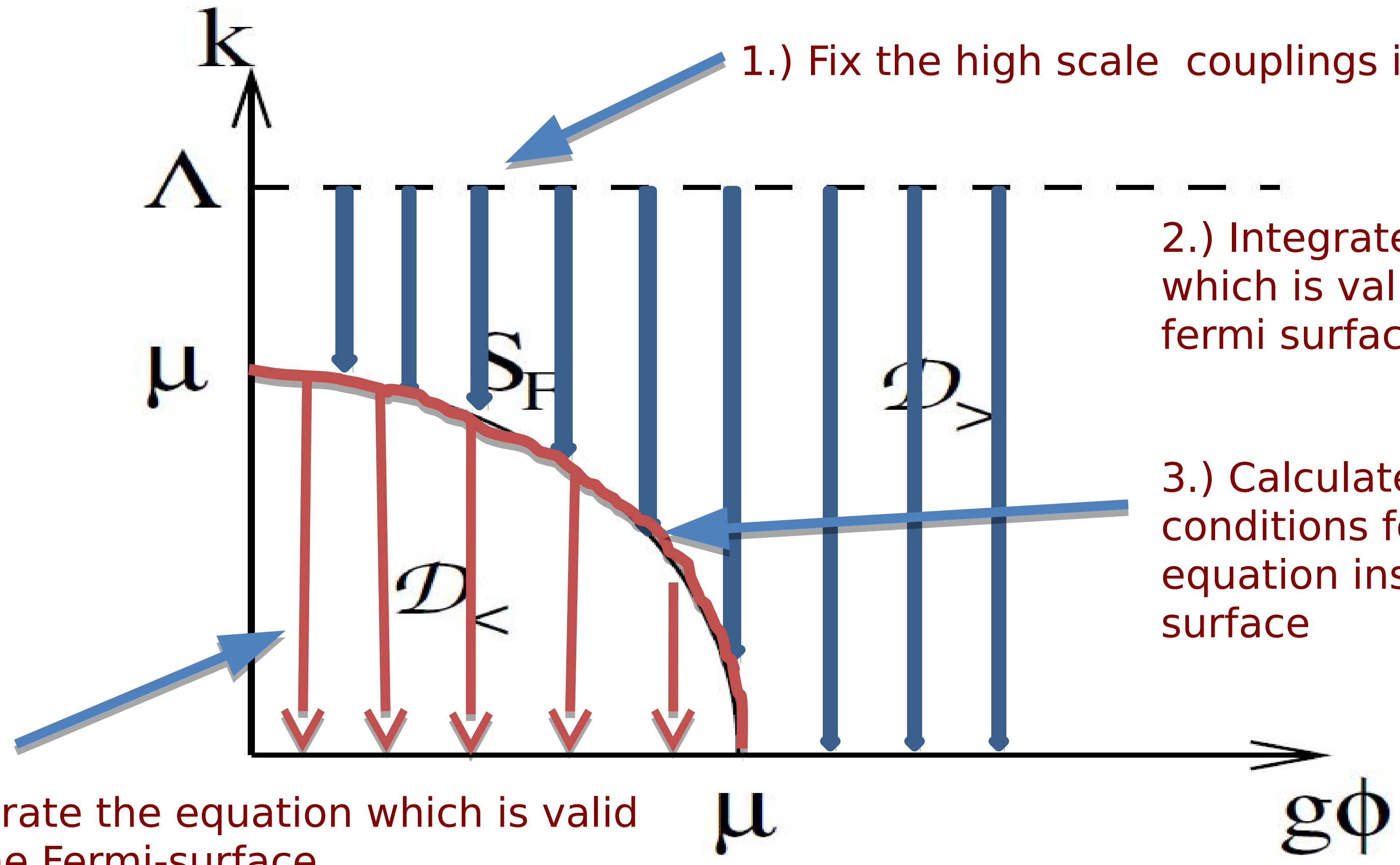
$$k_F = \sqrt{\mu^2 - g^2\varphi^2},$$

Fermi-surface

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

Fermionic vacuum fluctuations and thermodynamic fluctuations cancel

Integration of the Wetterich-equaiton



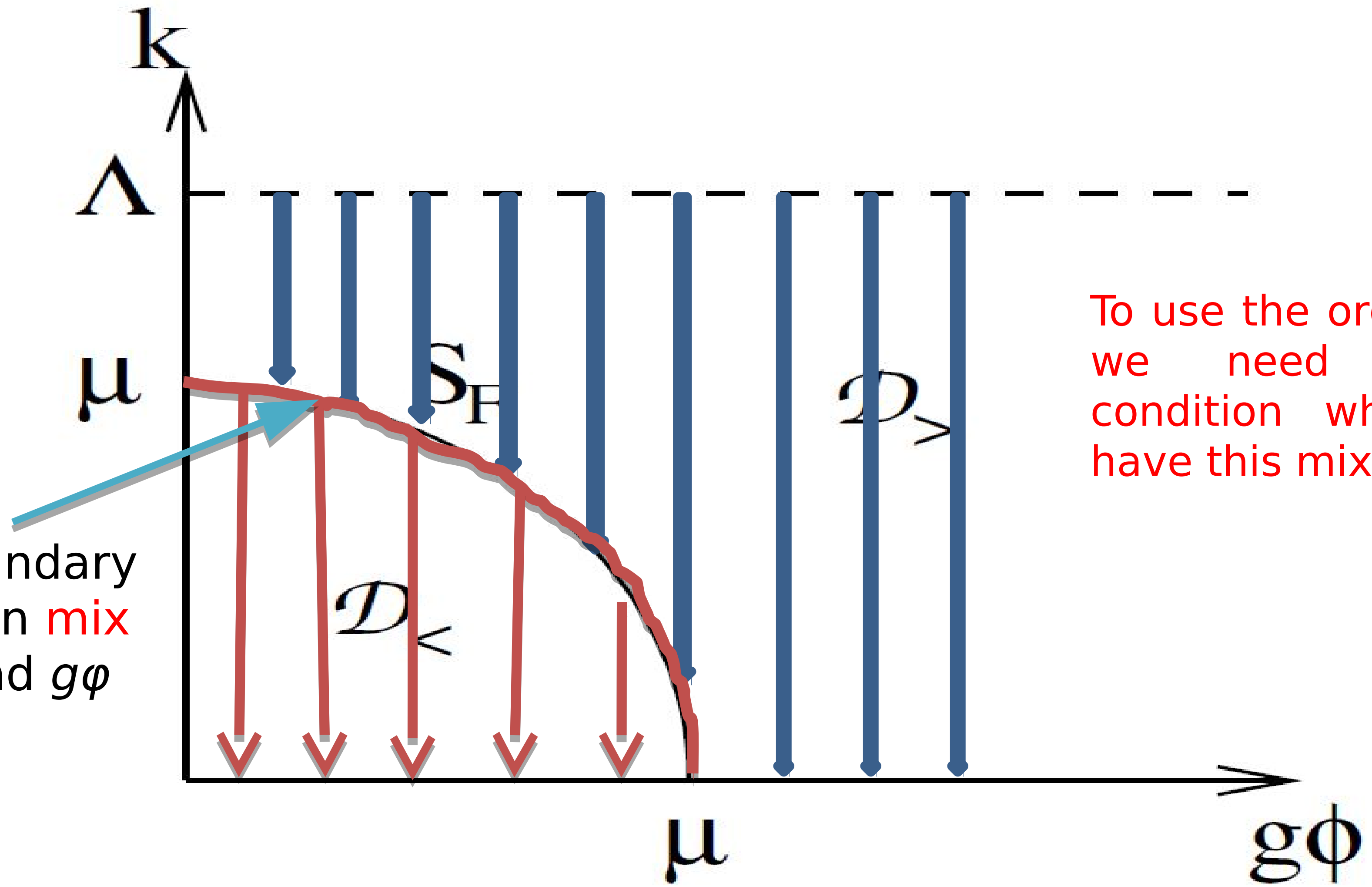
1.) Fix the high scale couplings in the theory

2.) Integrate the equation which is valid outside of the fermi surface

3.) Calculate the initial conditions for the other equation inside the fermi surface

4.) Integrate the equation which is valid below the Fermi-surface

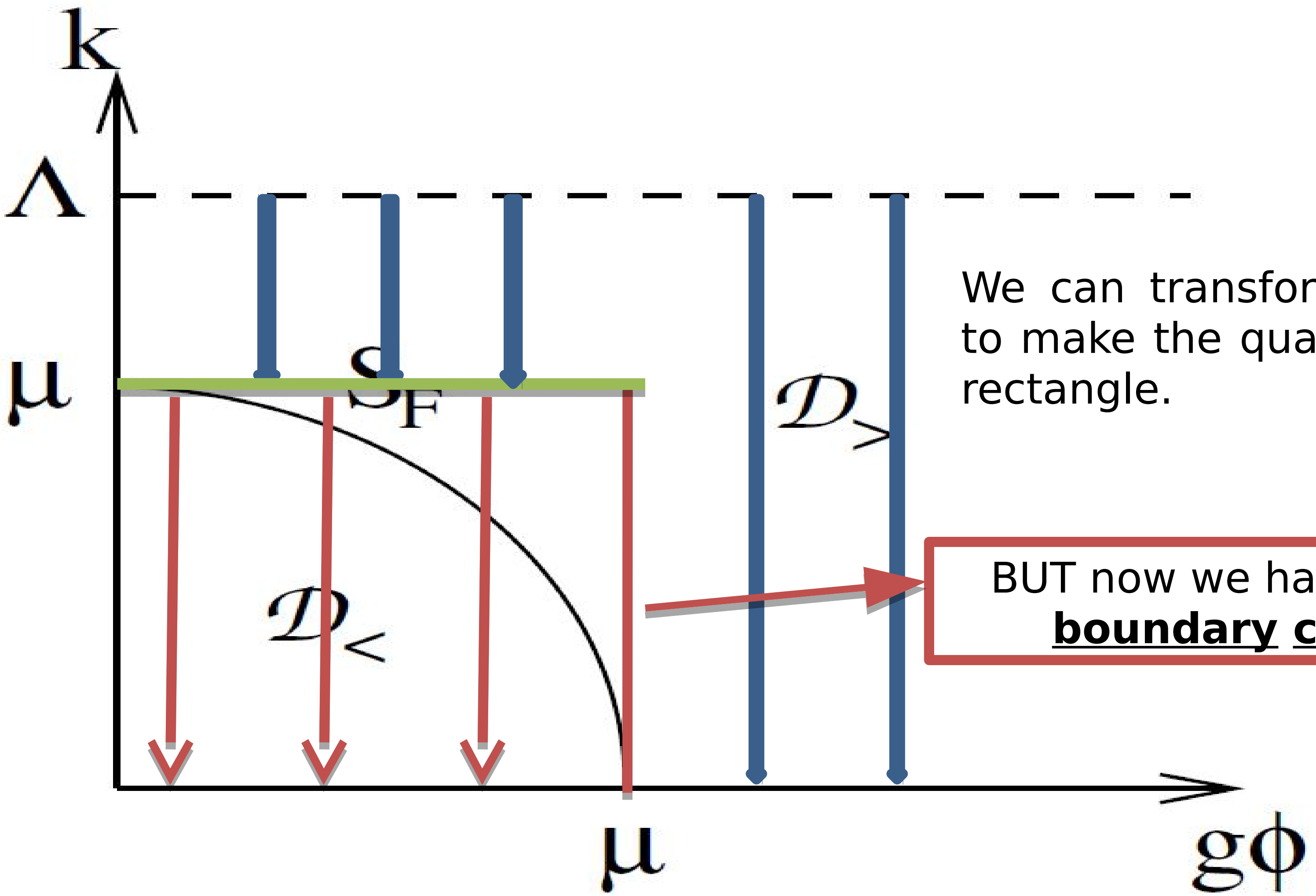
BUT…



The boundary condition mix the *k* and *gφ*

To use the orginal method we need an initial condition which do not have this mixing

Solution: Need to transform the variables

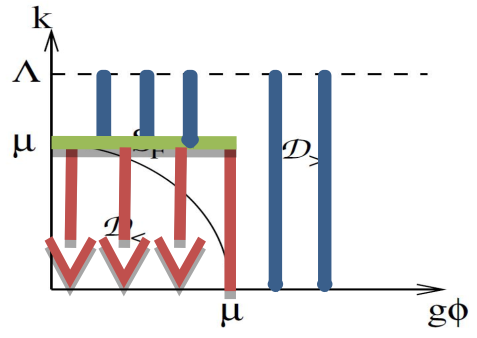


We can transform the variables to make the quarter circle into a rectangle.

BUT now we have a well defined **boundary condition** too!

Solution: Circle → Rectangle transformation

- Coordinate transformation is required with: $(k, \varphi) \mapsto (x, y)$
  - mapping the Fermi-surface to rectangle
  - Keep the symmetries of the diff. eq.
  - Circle-rectangle transformation: $x = \varphi_F(k), \quad y = \dfrac{\varphi}{x}$



- Transformation of the potential: $\tilde{U}(x, y) = V_0(x) + \tilde{u}(x, y)$

with boundary condition at the Fermi-surface, V_0

- Transformed Wetterich-eq: $$x\partial_x \tilde{u} = -xV_0' + y\partial_y \tilde{u} - \frac{g^2(kx)^3}{12\pi^2} \frac{1}{\sqrt{(kx)^2 + \partial_y^2 \tilde{u}}}.$$

- and the new boundary conditions: $\tilde{u}(x = 0, y) = \tilde{u}(x, y = \pm 1) = 0.$

Solution of transformed Wetterich by an orthogonal system

- Solution is expanded in an orthogonal basis to accommodate the strict boundary condition in the transformed area

$$\tilde{u}(x,y) = \sum_{n=0}^{\infty} c_n(x) h_n(y) \quad h_n(1) = 0 \quad \int_0^1 dy\, h_n(y) h_m(y) = \delta_{nm}$$

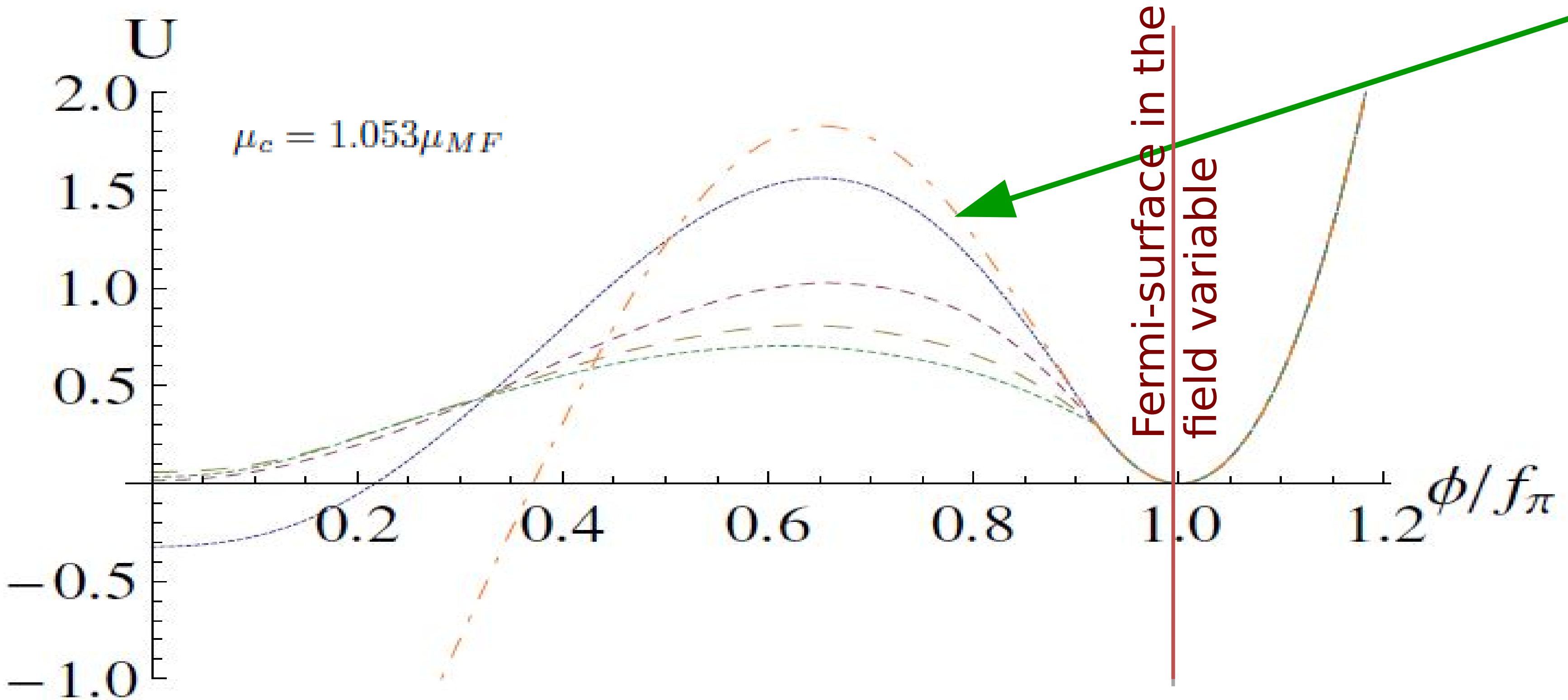
- The square root in the Wetterich-equation is also expanded:

$$x c_n'(x) = \int_0^1 dy\, h_n(y) \left[-x V_0' + y \partial_y \tilde{u} - \frac{g^2 (kx)^3}{12\pi^2} \underbrace{\sum_{p=0}^{\infty} \binom{-1/2}{p} \frac{(\partial_y^2 \tilde{u} - M^2)^p}{\omega^{2p+1}}}_{\text{Expanded square root}} \right]$$

Where: $\omega^2 = (kx)^2 + M^2$

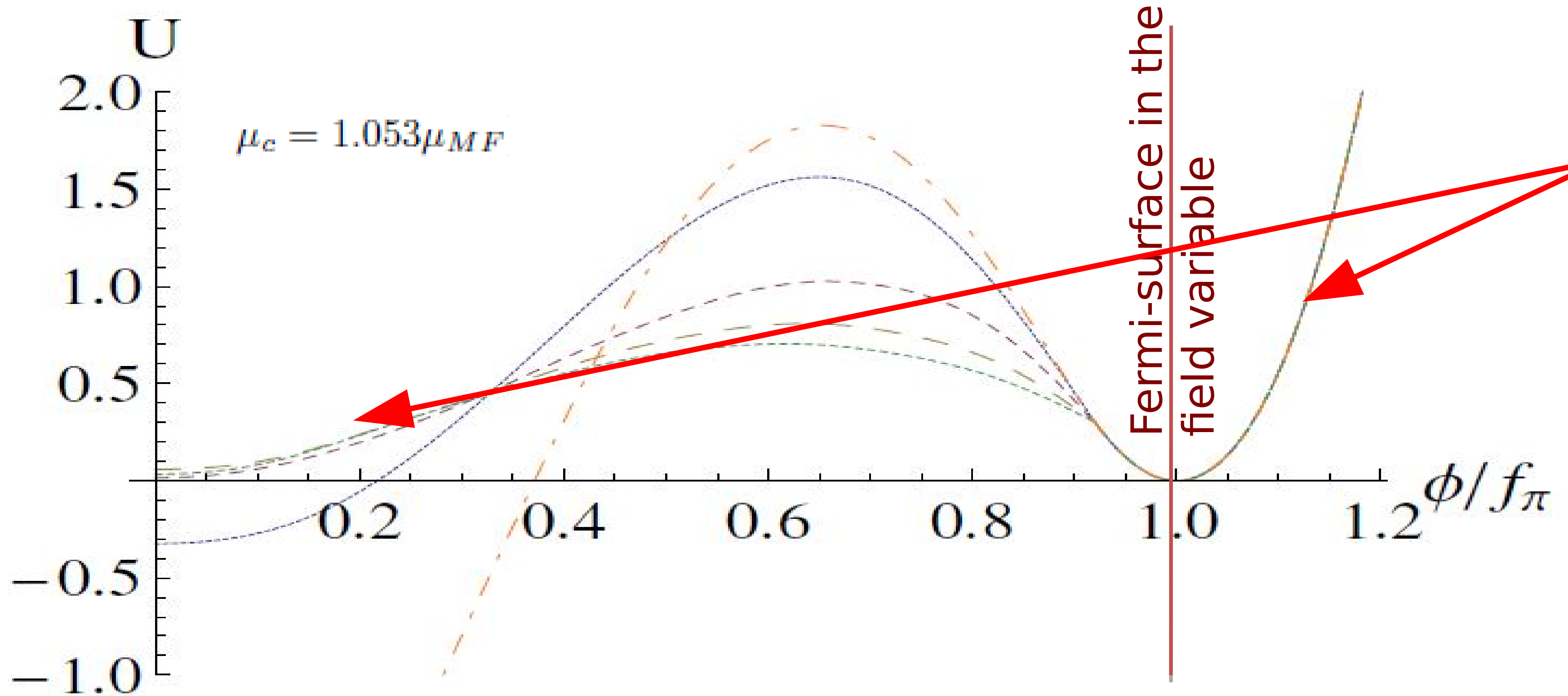
We use harmonic base: $h_n(y) = \sqrt{2} \cos q_n y, \quad q_n = (2n+1)\frac{\pi}{2}$

Result: The Effective Potential & Comparison



Potential in one-loop approximation

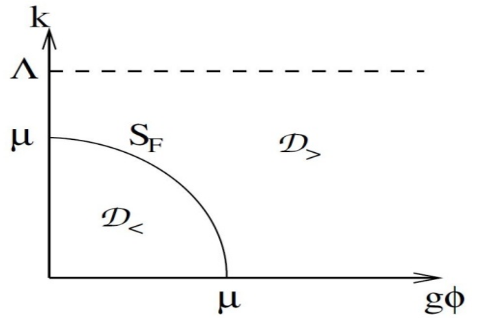
Result: The Effective Potential & Comparison



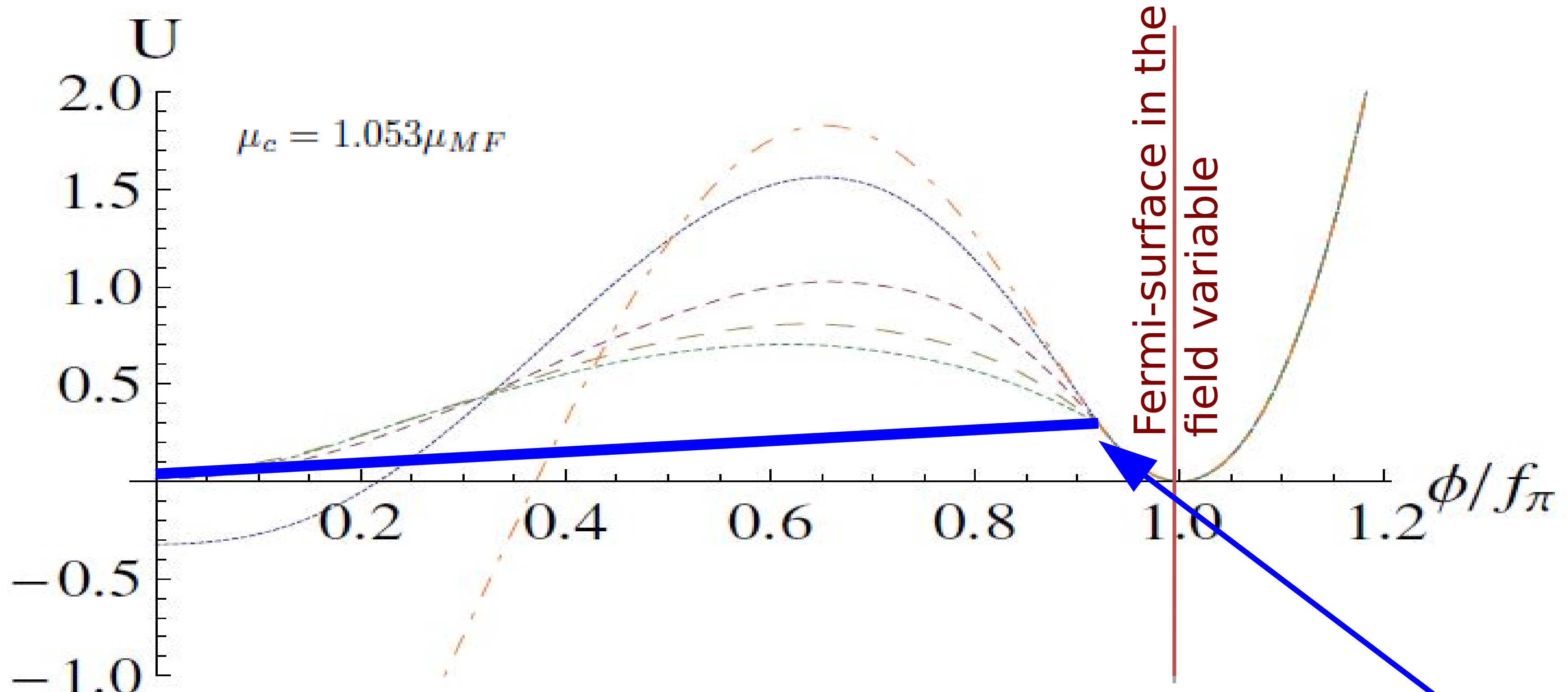
Potential in one-loop approximation

Higher orders of the Taylor-expansion for the square root converge fast where the potential is **convex**
→ **coarse grained action**

Solution changes only below Fermi-surface, since switch to another equation



Result: The Effective Potential & Comparison

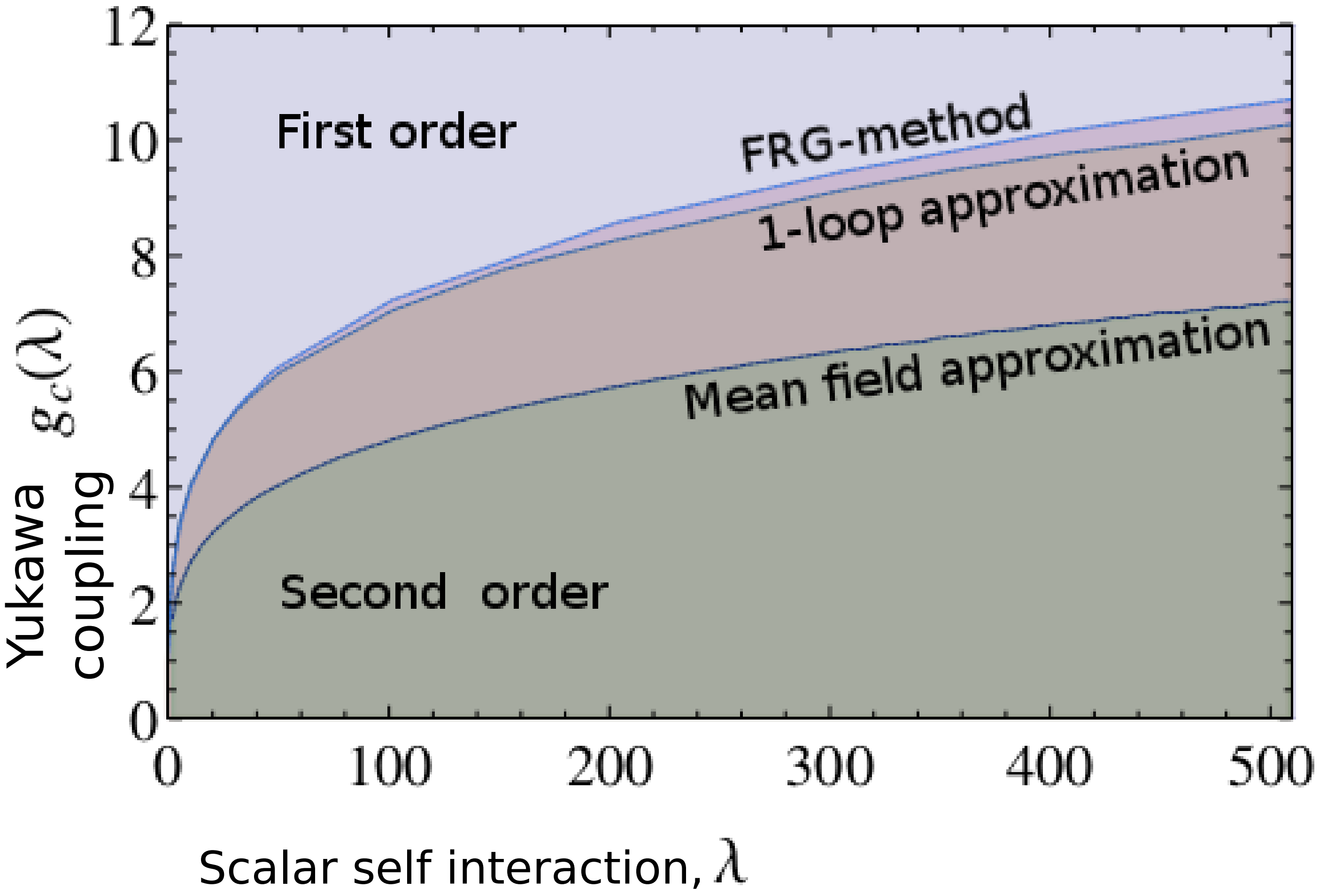


Potential in one-loop approximation

Higher orders of the Taylor-expansion for the square root converge fast where the potential is **convex**
→ **coarse grained action**

In the **concave** part of the potential solution is slowly converges to a straight line, because the free energy (effective potential) must be convex from thermodynamical reasons
→ **Maxwell construction**

Result: Phase structure of interacting Fermi gas model



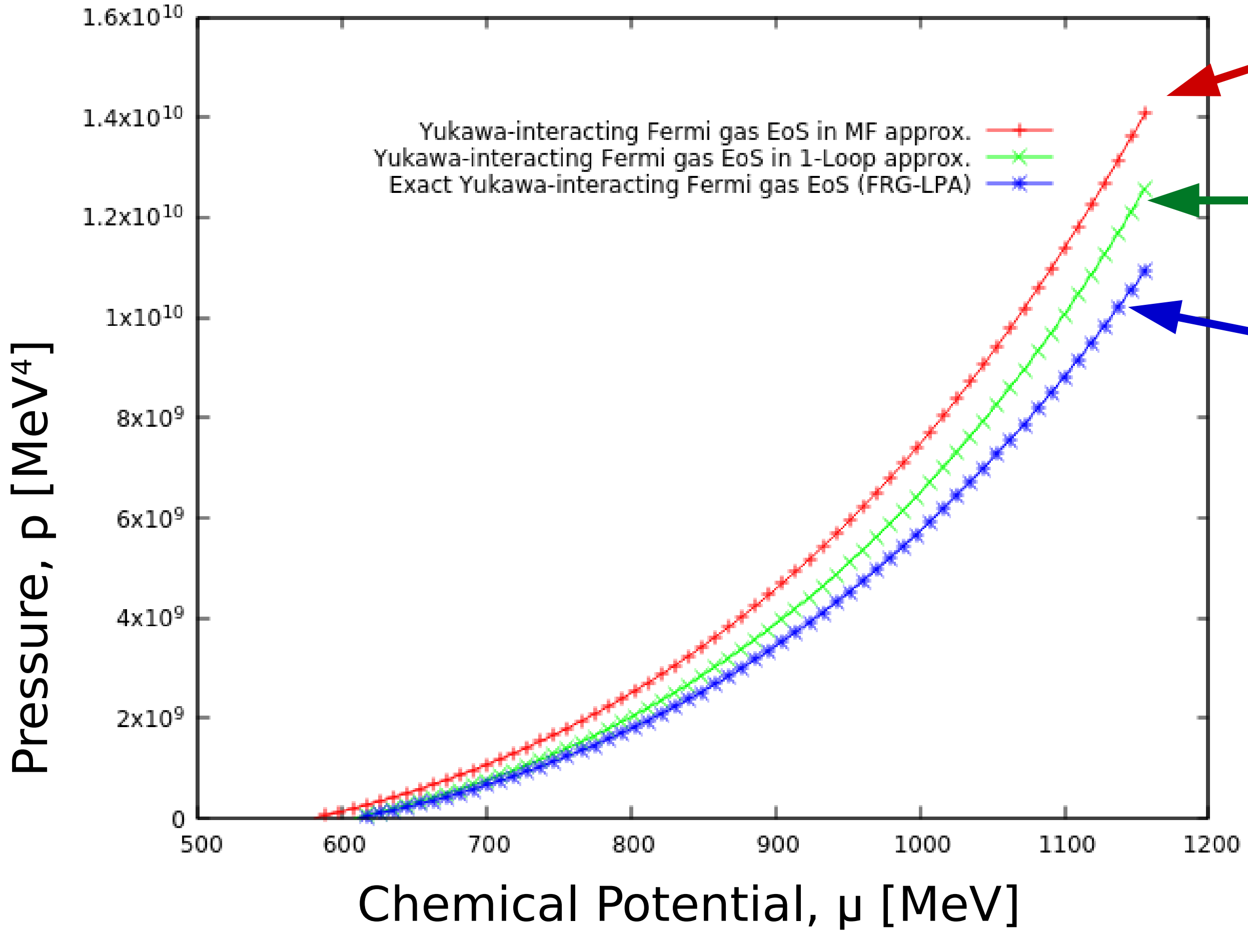
Exact FRG solution counts all quantum fluctuations

1-Loop approximation has only tree diagrams

Mean Filed solution contains averaged effect of interactions

In the phase structure, FRG and 1L are very similar if the LO has the strongest contribution.

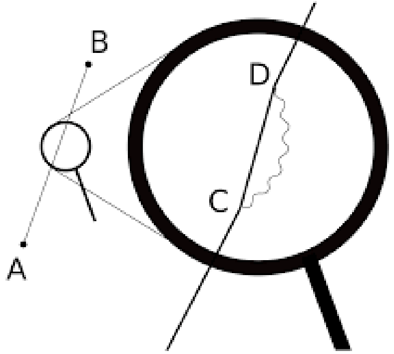
Result: Comparison of MF, 1L, & FRG-based EoS



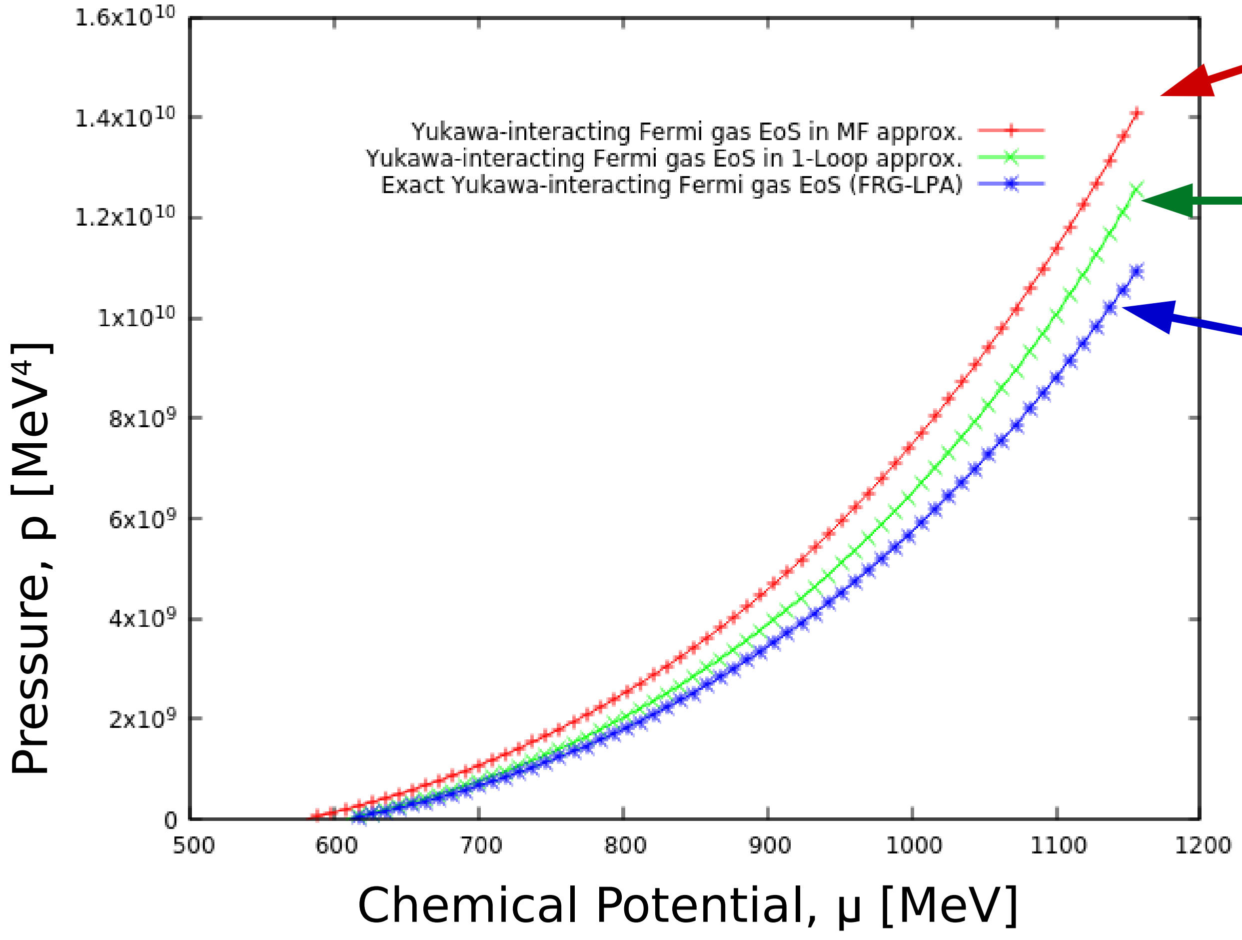
Mean Filed is the stiffest

1-Loop approximation

Exact FRG solution softest



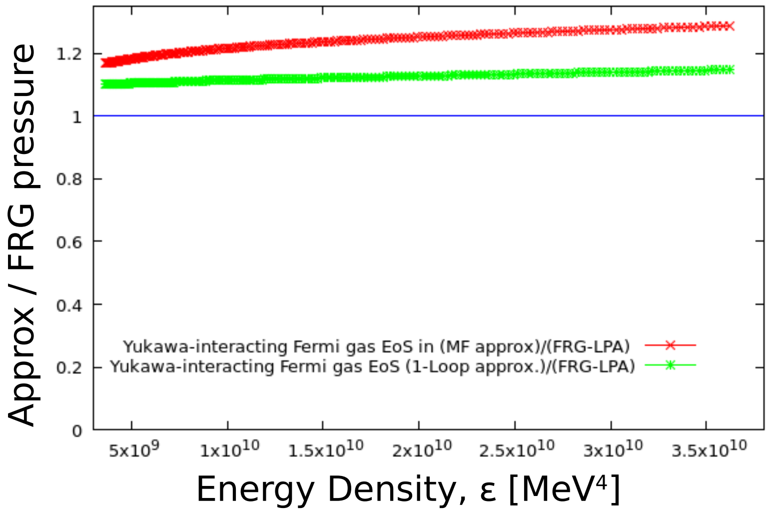
Result: Comparison of MF, 1L, & FRG-based EoS



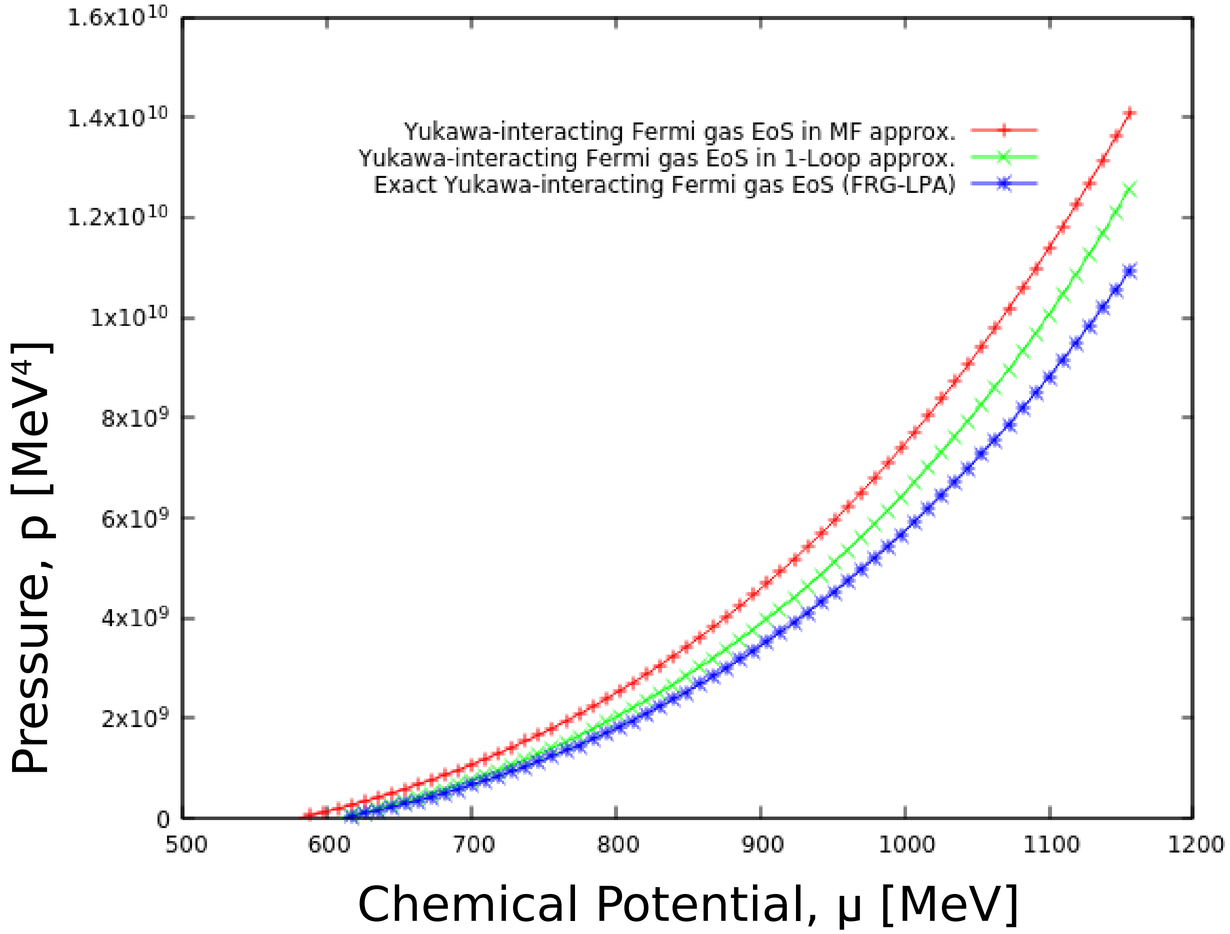
MF is 25% stiffer than the FRG

1L is 10% stiffer than the FRG

Exact FRG solution softest

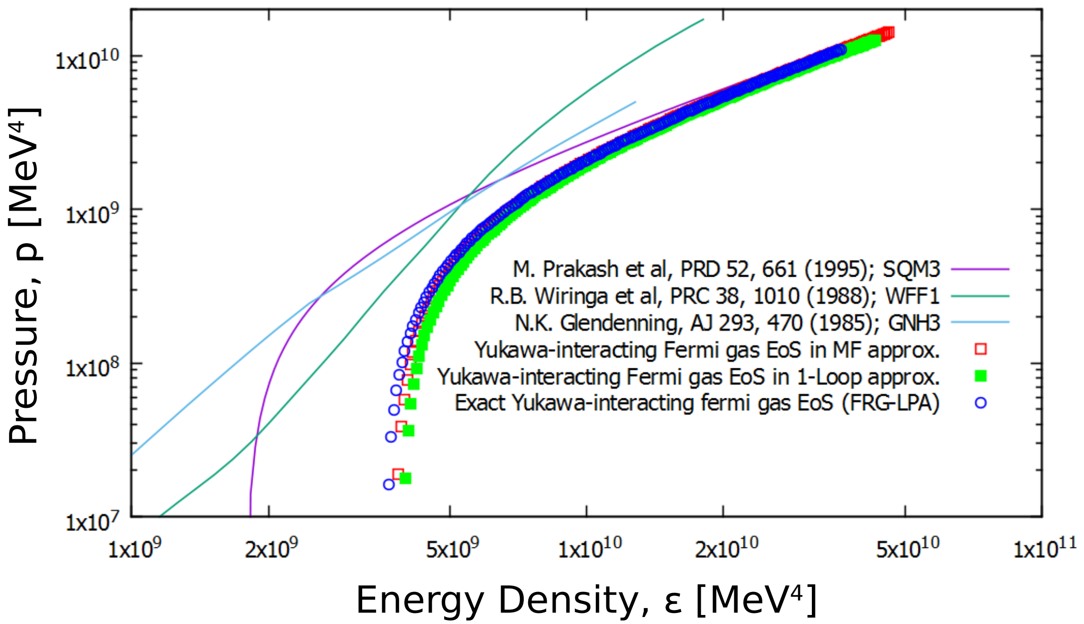


Result: Comparison to other EoS models

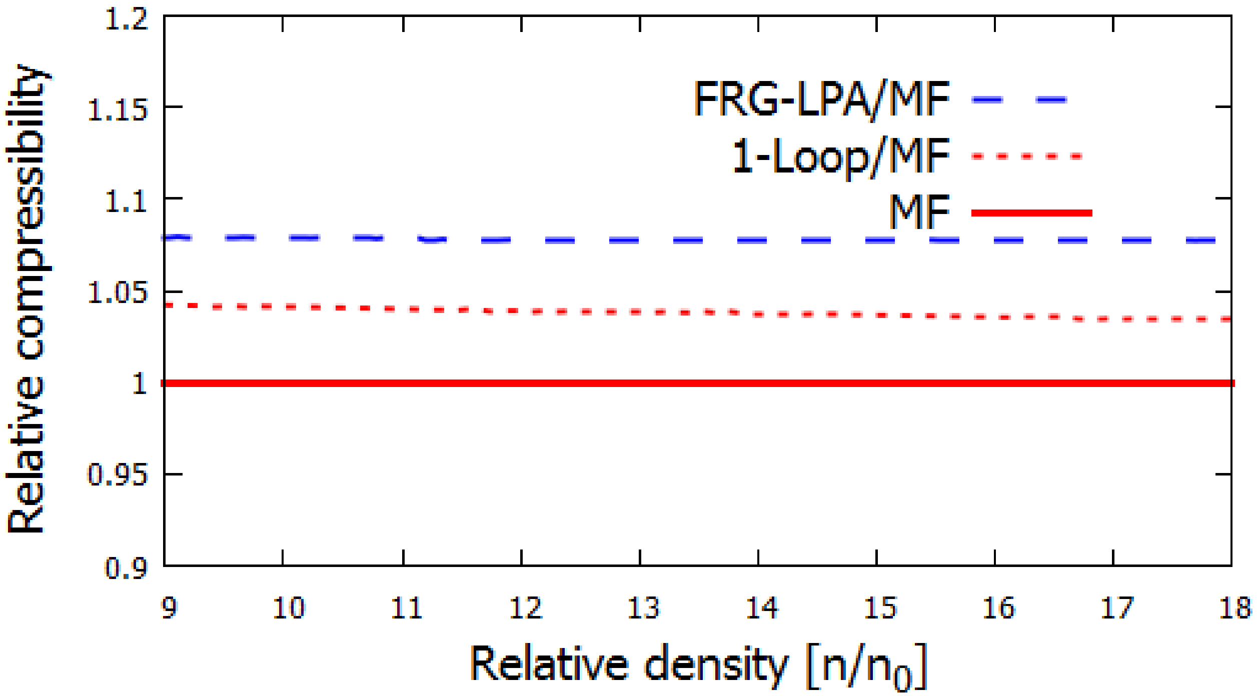


Compare FRG to SQM3, GNH3, WFF1

- Overlap with SQM3 at high ε
- Cutoff, ε_{Cut} is also higher
- Approximations differ slightly



Result: Comparison of compressibility in the models



Compare FRG to 1L and MF

- Compressibility:

$$\frac{1}{\chi} = n\frac{\partial P}{\partial n} = 2n^2\frac{\partial}{\partial n}(E/A) + n^3\frac{\partial^2}{\partial n^2}(E/A)$$

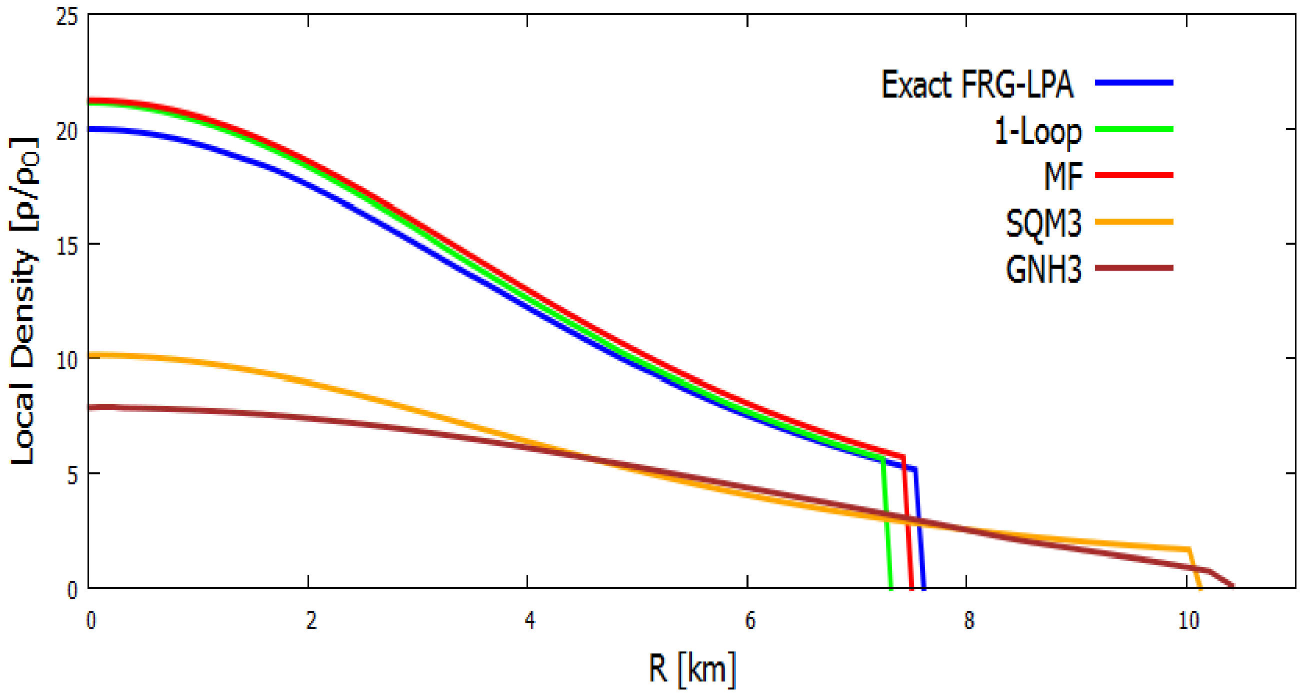
- Compression modulus

$$K = k_F^2\frac{\partial^2}{\partial k_F^2}(E/A) = \frac{9}{n_0\,\chi}$$

- The difference between the models is about ~10%

Result: Test in a Compact Star

- Compare FRG EoS to SQM3, GNH3 → TOV result: density function



Compare FRG to 1L and MF

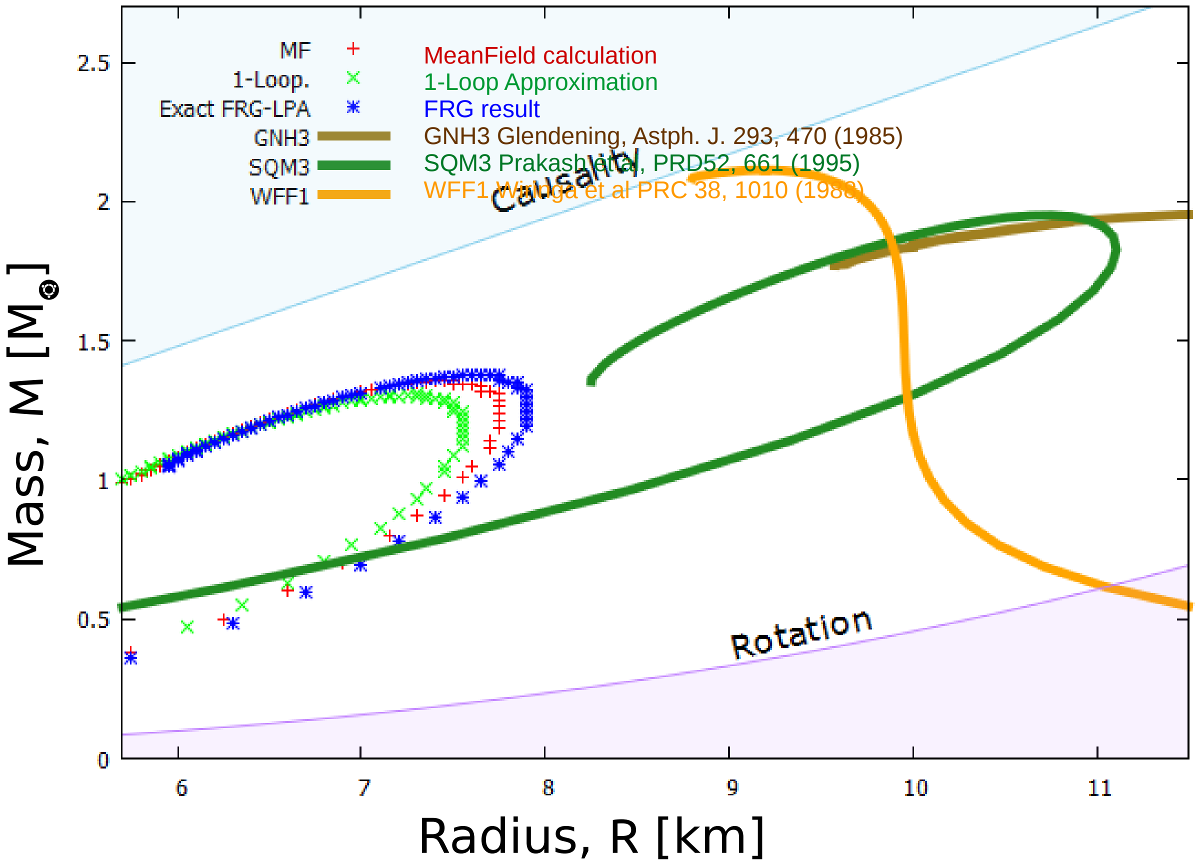
- Soft FRG make biggest star
- High-ε part is similar for all
- Difference: ~5% (.1 $M_\odot$ and .5 km)

FRG to SQM3, GNH3

- FRG: small stars 1.4$M_\odot$ and 8 km
- Other models: larger radii and less central density

Result: Test in a Compact Star

- Compare FRG EoS to SQM3, GNH3, WFF1 → TOV result on M(R) diagram



Compare FRG to 1L and MF

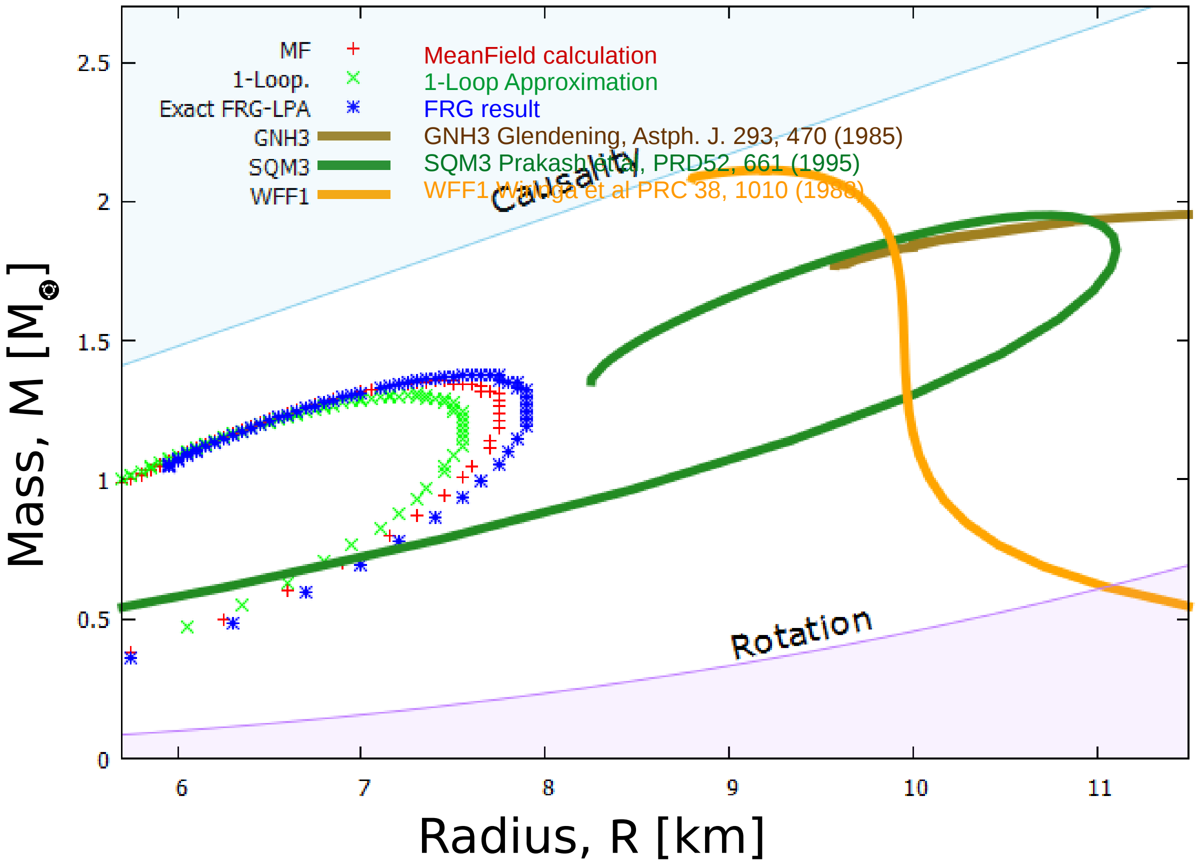
- Soft FRG make biggest star
- High-ε part is similar for all
- Difference: ~5% (.1 $M_\odot$ and .5 km)

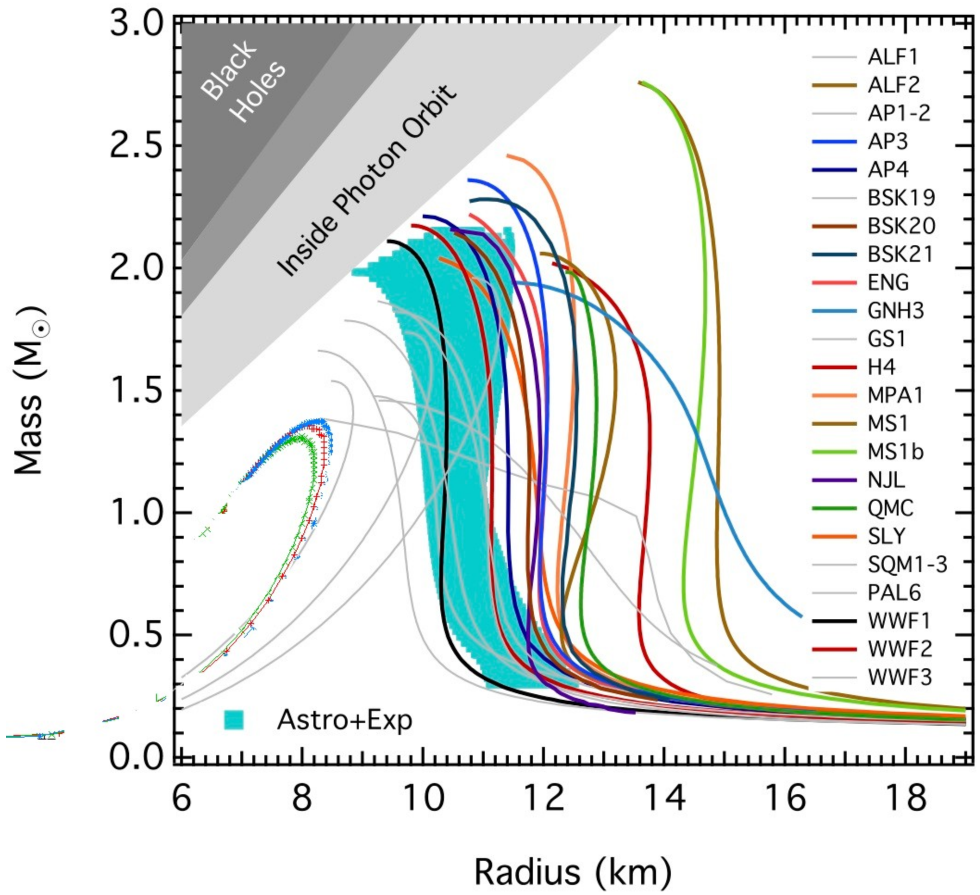
FRG to SQM3, GNH3, WFF1

- Small stars 1.4 $M_\odot$ and 8 km
- Overlap with SQM3 at high ε
- Interaction (ω) will increase

Result: Test in a Compact Star

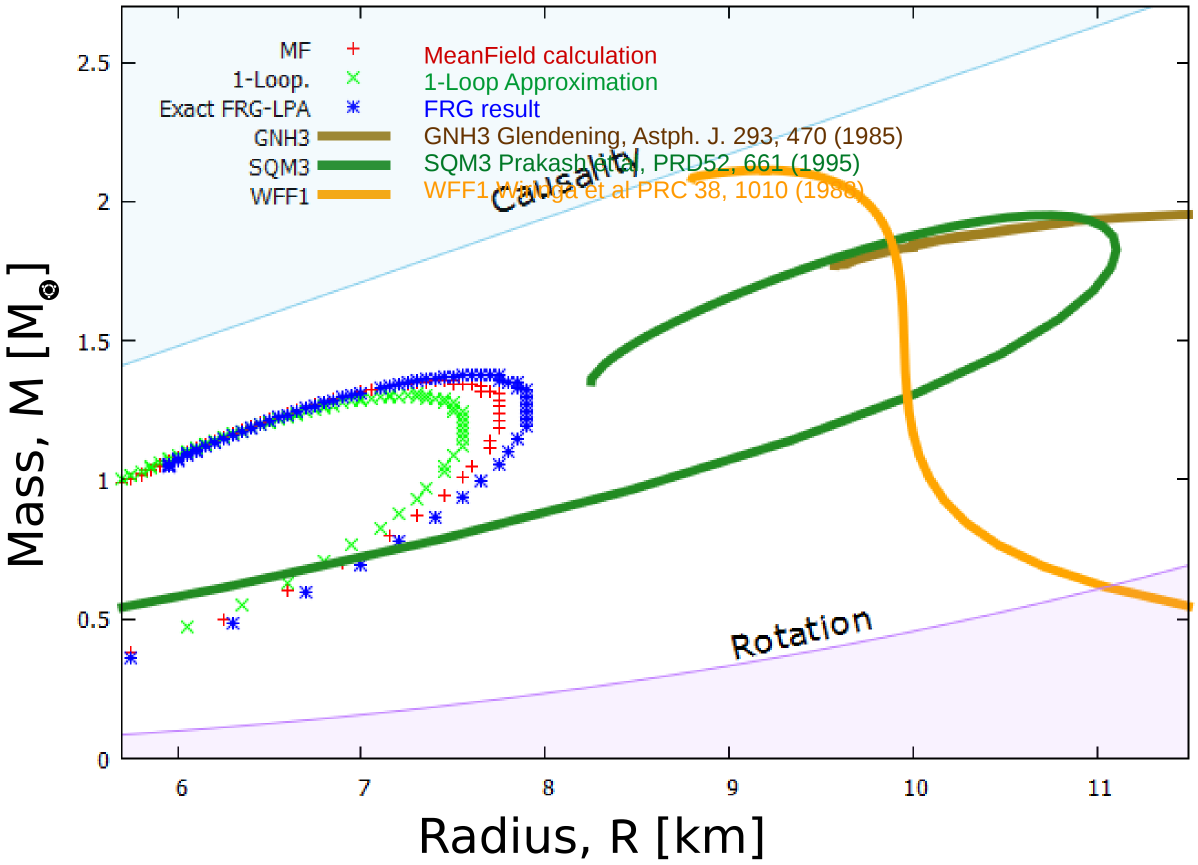
- Compare FRG EoS to SQM3, GNH3, WFF1 → TOV result on M(R) diagram

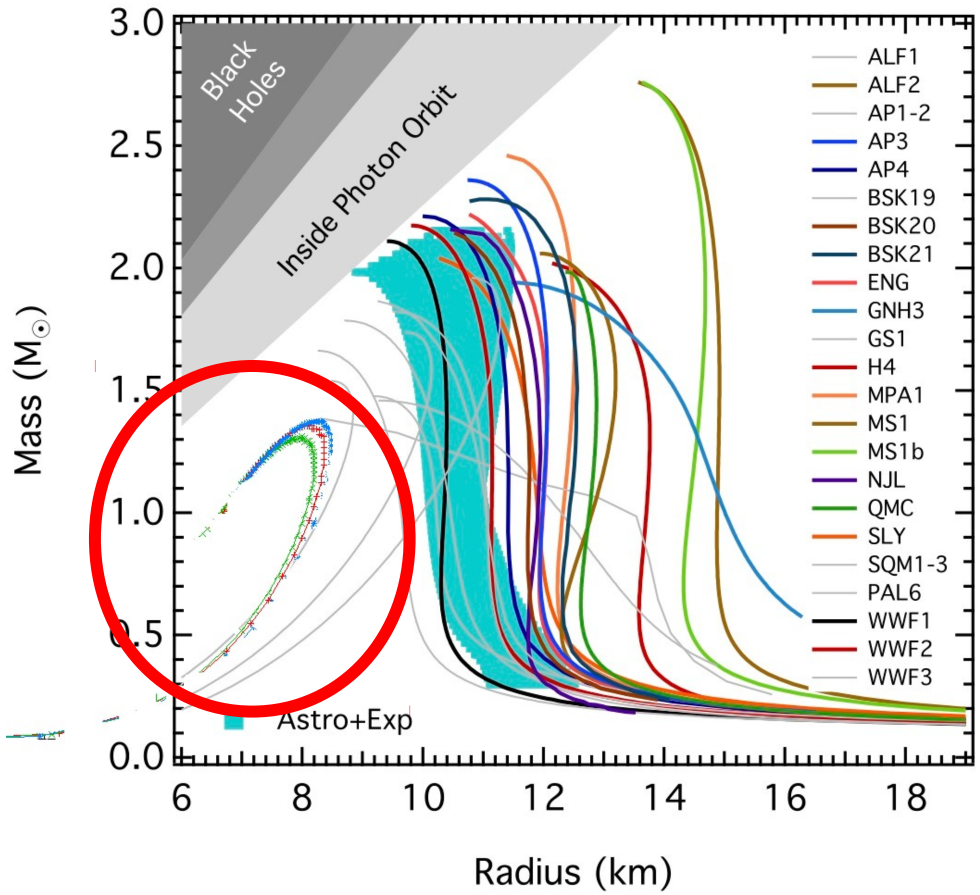




Result: Test in a Compact Star

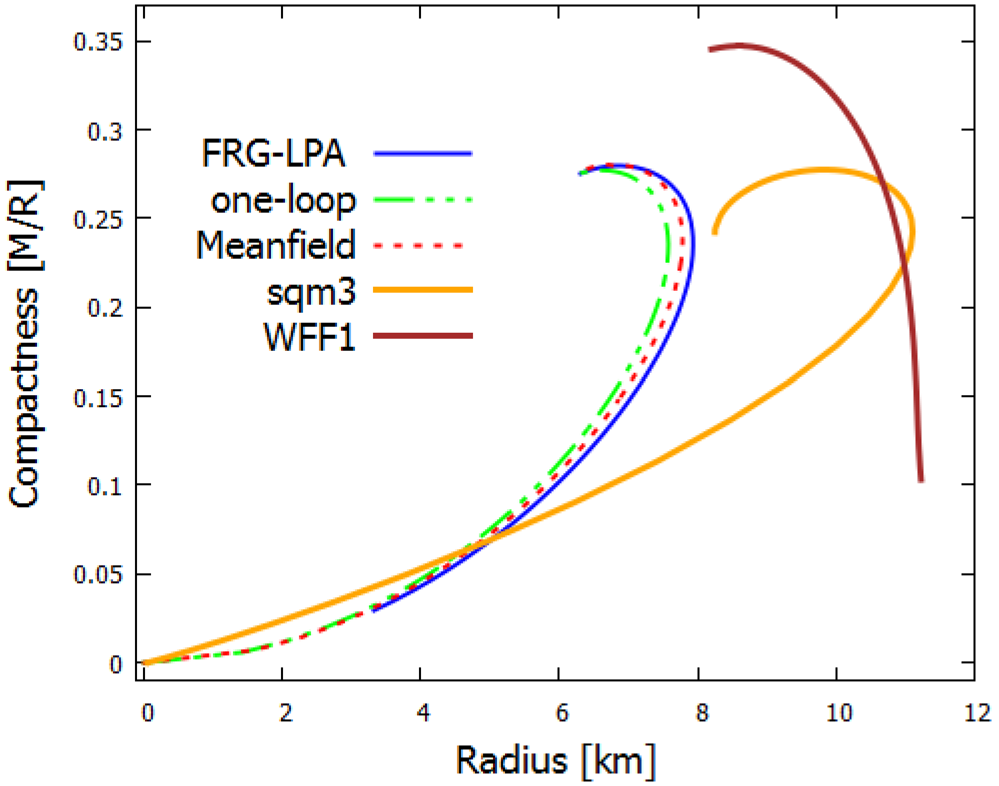
- Compare FRG EoS to SQM3, GNH3, WFF1 → TOV result on M(R) diagram





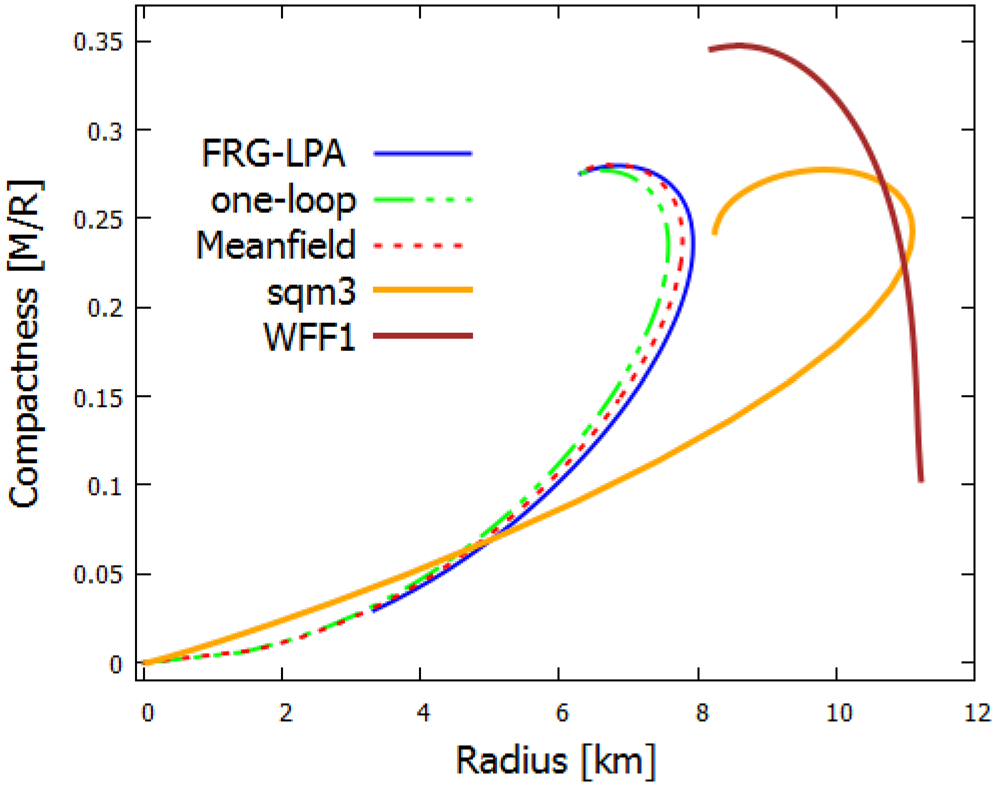
Test: Can we test this by observations?

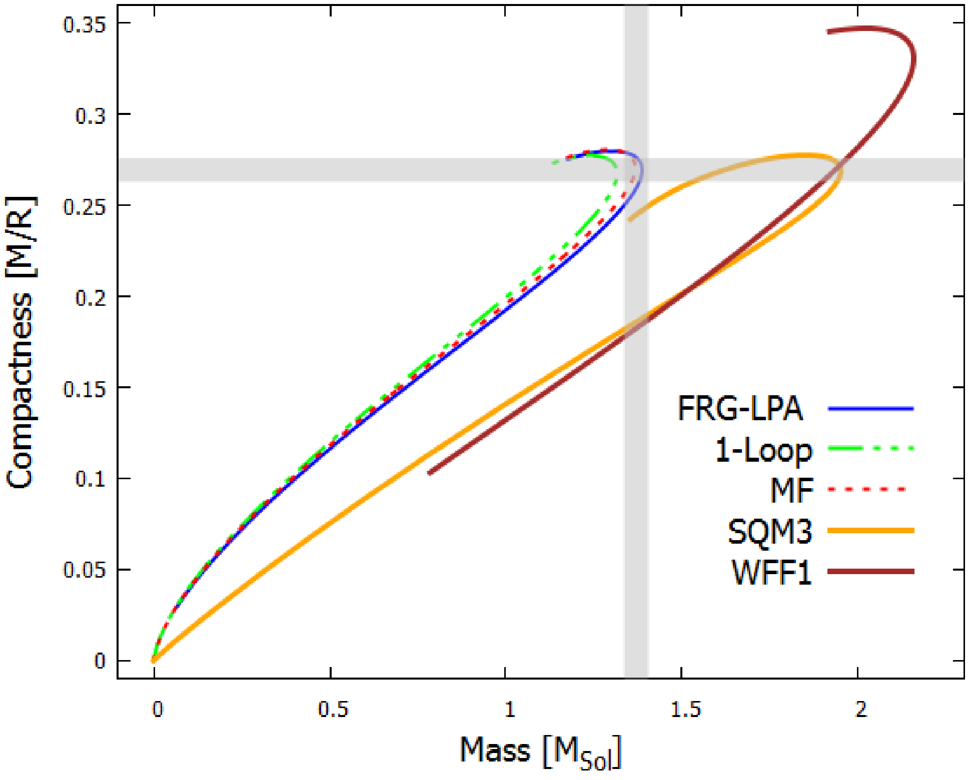
- Compare Compactness by FRG, MF, 1L, SQM3, and WFF1 EoS



Test: Can we test this by observations?

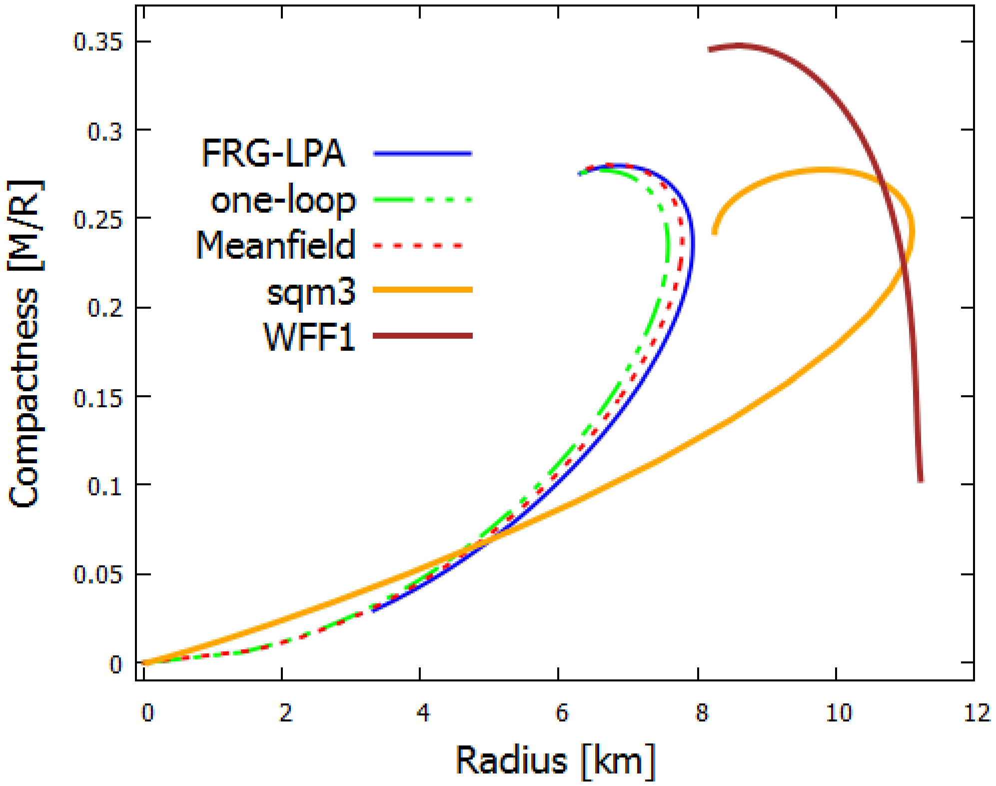
- Compare Compactness by FRG, MF, 1L, SQM3, and WFF1 EoS

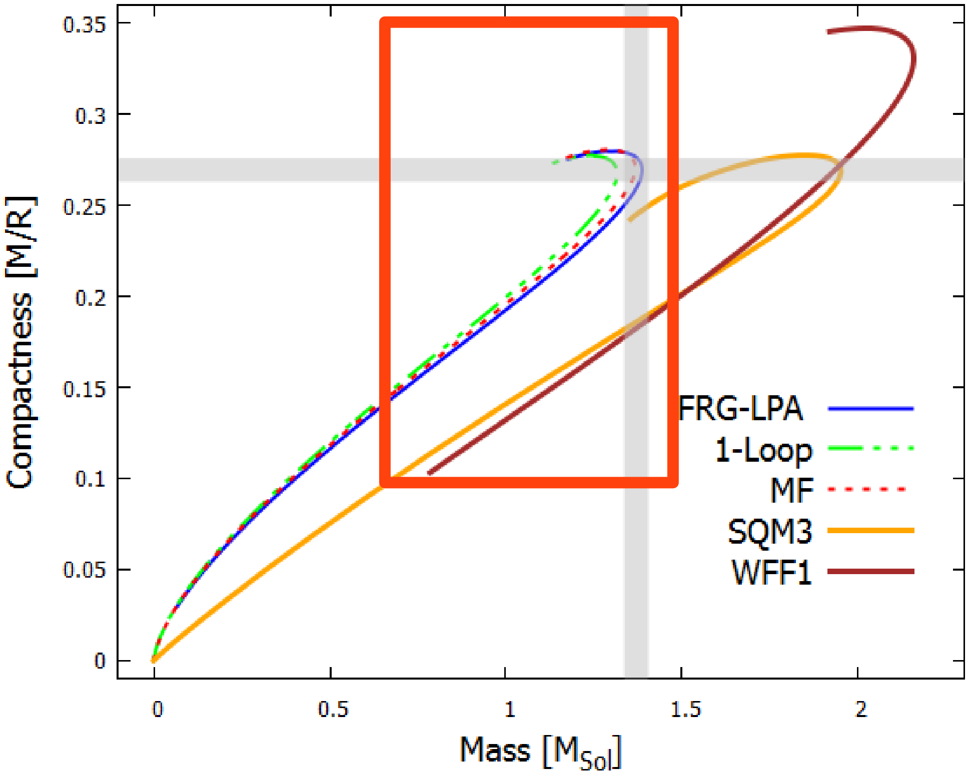




Test: Can we test this by observations?

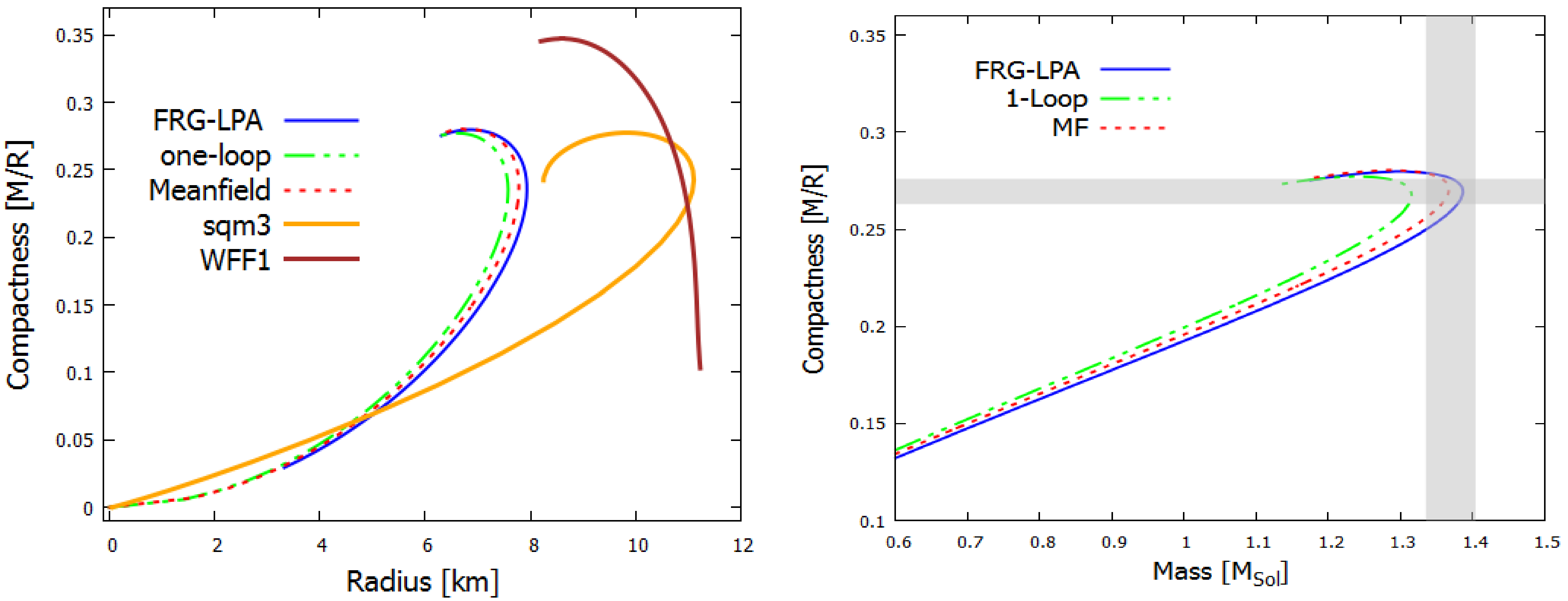
- Compare Compactness by FRG, MF, 1L, SQM3, and WFF1 EoS





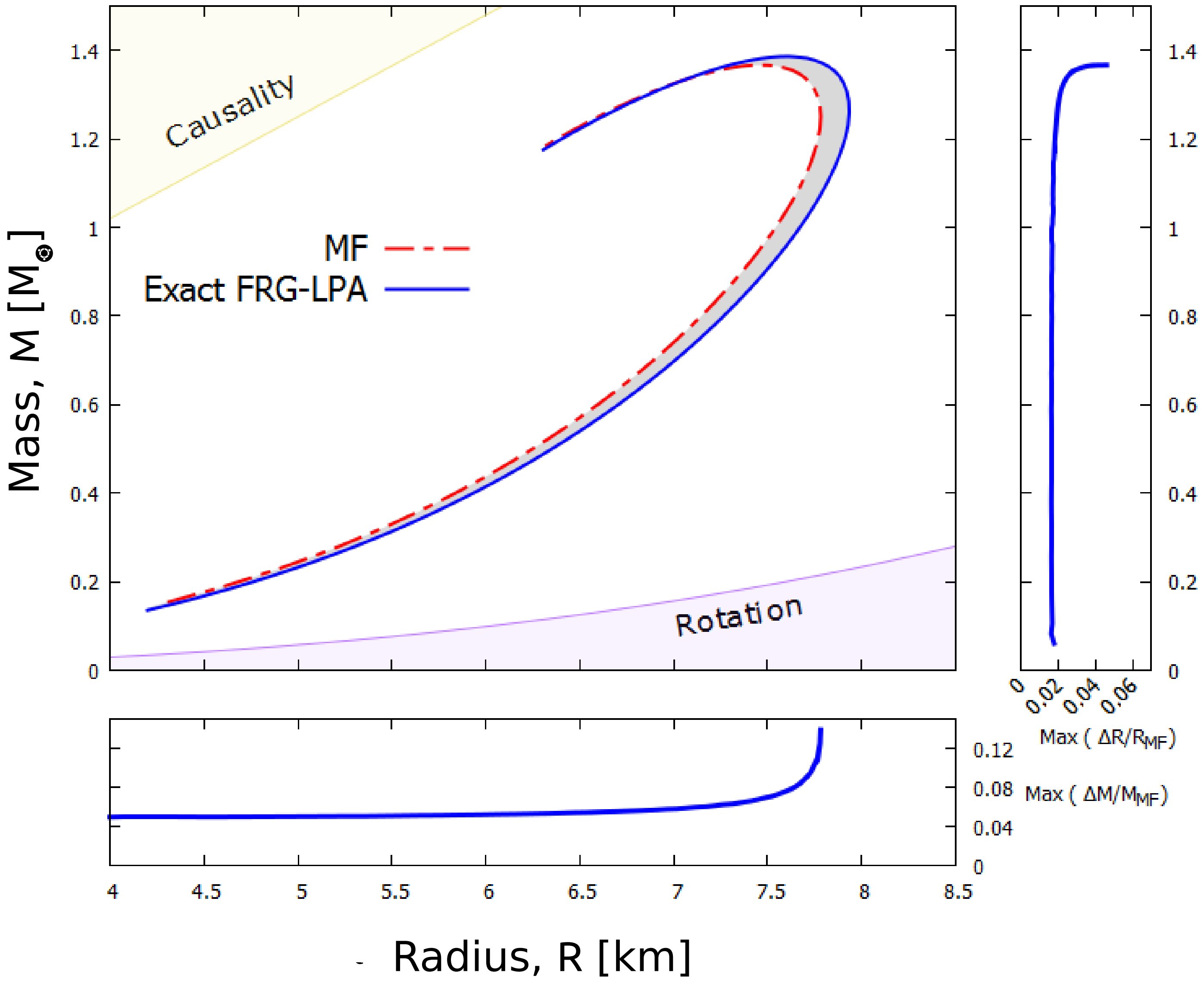
Test: Can we test this by observations?

- Compare Compactness by FRG, MF, 1L, SQM3, and WFF1 EoS



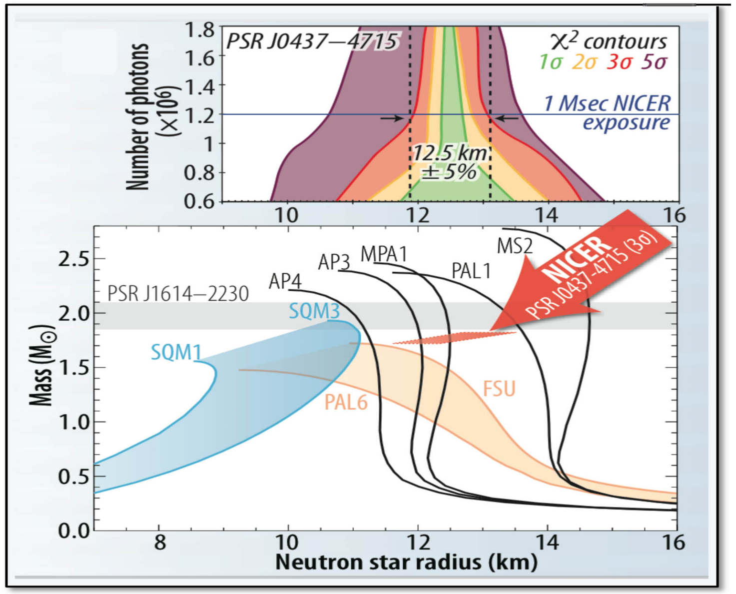
Test: Can we test this by observations?

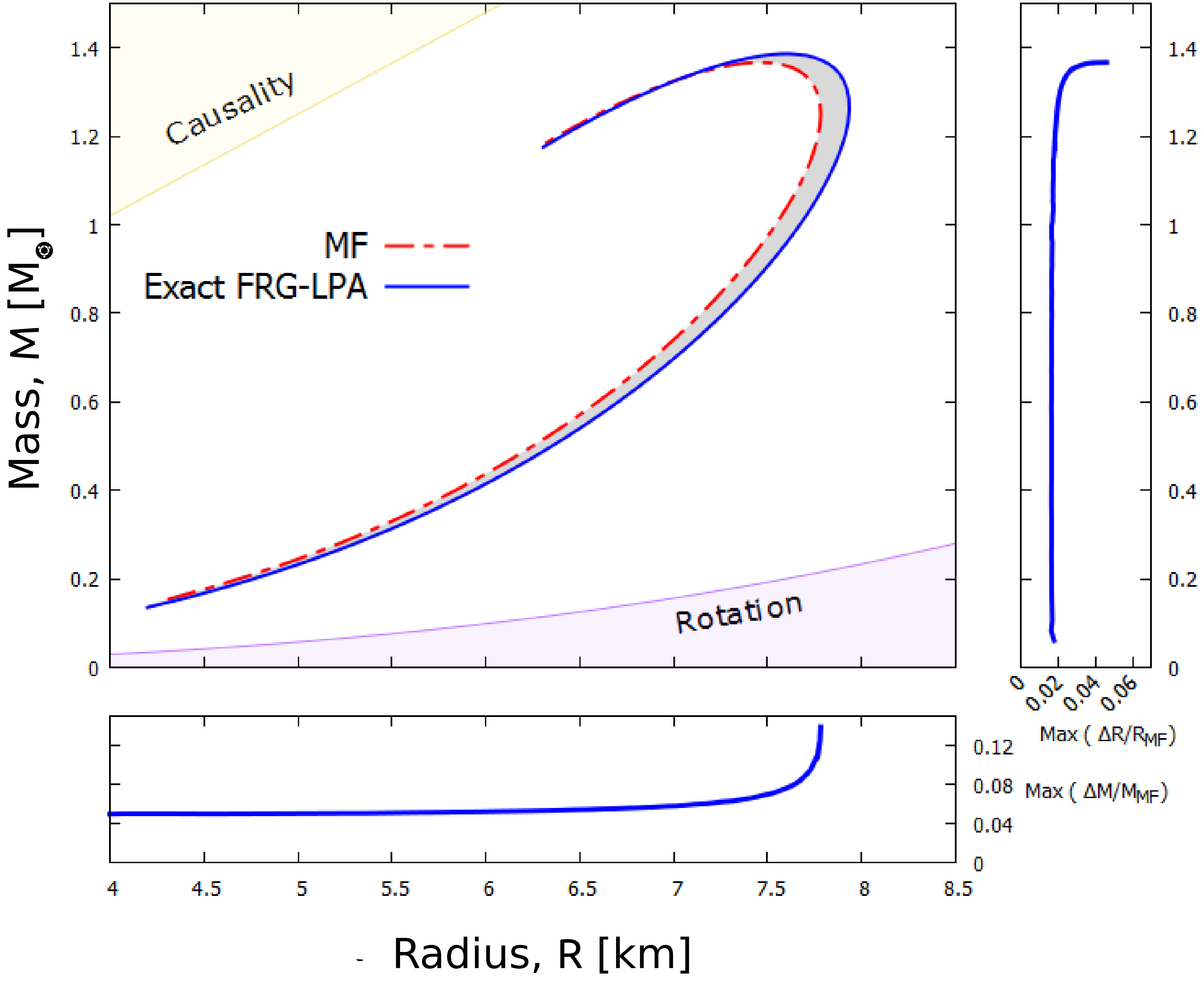
- Compare different EoS results on M(R) diagram: MF & FRG
- Maximal relative differences are also plotted



Test: Can we test this by observations?

- Compare different EoS results on M(R) diagram: MF & FRG
- Maximal relative differences are also plotted





The summary of uncertainties

- The magnitude of the uncertainties of (astro)physical observables
  - Microscopical observables are maximum: 10-25%
  - Macroscopical astrophysical ones are maximum: 5-10%
  - Measurement resolution limit is about: 10%

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

To take away…

- **Uncertainties were tested in the FRG-framework**
  - Effect of the quantum fluctuations in comparison to MF & 1L
  - One-component Fermi gas with a simple Yukawa-like coupling

- **Uncertainties were determined in**
  - Microscopical level (EoS, phases, compressibility): 10-25%
  - Macroscopical astrophysical level (M,R,compactness): 5-10%

- **Resolution of observations (based on NICER)**
  - We are almost there: ~10% uncertainties

Some related events

- New perspectives on Neutron Star Interiors
  - Date: 9-13 October, 2017
  - ECT*, Trento, Italy
  - Web: http://www.ectstar.eu/node/2230

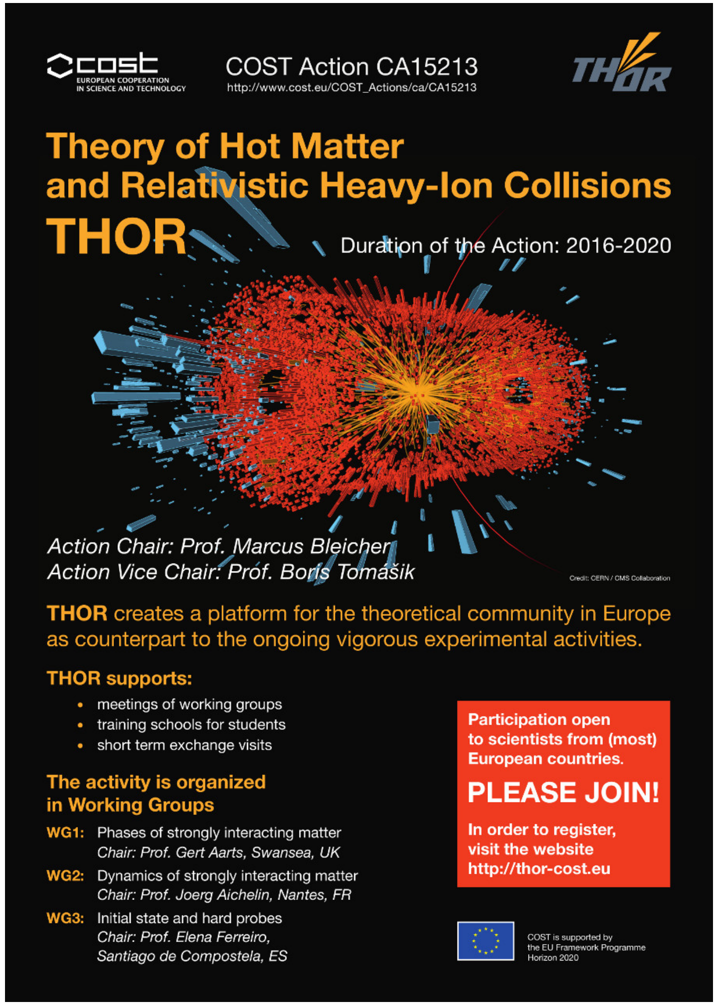
- 17th Zimányi Winter School 2017
  - Date: 4-8 December 2017
  - Wigner Research Centre for Physics & THOR Budapest, Hungary
  - Web: http://zimanyischool.kfki.hu/17/

Summary

- FRG method were used to obtain the effective potential for
  - One-component Fermi gas with a simple Yukawa-like coupling
  - Concave part of the potential converges slowly to a line → Maxwell construction
  - Convex part of the potential → Coarse Grained action
  - Chiral phase transition is reproduced → Order depends on the applied approximation
- EoS can be compared to other ones, close to the SQM3 (Prakash, 1995)
  - Softness depends on the approximation (FRG → 1L → MF)
  - MF differs 25%, 1L differs 10% from the exact FRG solution, slight evolution at high ε
  - Simple model → Relative small compact stars M< 1.4 M, and R< 8 km
  - Size (both mass and radius) sensitive to quantum fluctuations (5% effect)
- Based on FRG method, now we can have a technique to make:
  - An effective model for the hardly accessible part of the phase diagram (T=0, finite μ, high ρ)

Advertisement:

- **THOR EU COST Action CA15213**
  - Theory of Hot Matter and Relativistic Heavy Ion Collisions
    http://thor-cost.eu
- **NewCompStar EU COST Action MP1304**
  - Theory of Compact Stars (ending 2017)
    http://compstar.uni-frankfurt.de
- **PHAROS EU COST Action CA16214**
  - The multi-messenger physics and astrophysics of neutron stars



Result: Comparison to other EoS models

- Compare FRG EoS to SQM3, GNH3, WFF1