Liquid-Gas Phase Transition in Nuclear Matter from a Correlated Approach

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A “hot” day in Barcelona’s history!

A day like today...

19 July 1936

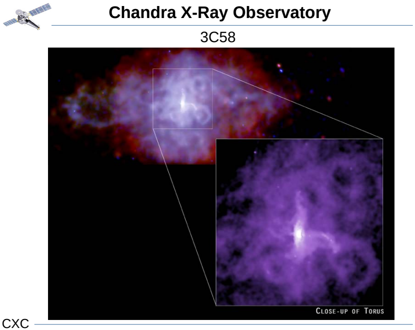
Outline

1. Nuclear Matter at Finite Temperature
2. Self-Consistent Green's Functions at Finite Temperature
3. Thermodynamical Properties of Nuclear Matter
4. Summary and conclusions

Motivation: "hot" nuclear systems

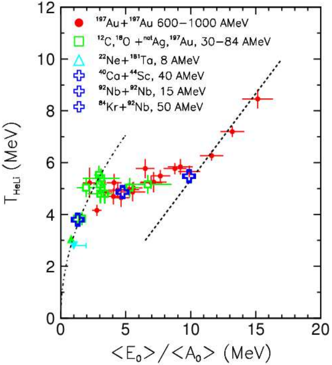
$$E \sim 1 \text{ MeV} \Rightarrow T \sim 10^{10} \text{ K}$$

Proto-neutron stars



SN 1181 remnant (SNR3C58) and
Pulsar PSRJ0205+6449

AA collisions



Nuclear caloric curve

Motivation: basic considerations

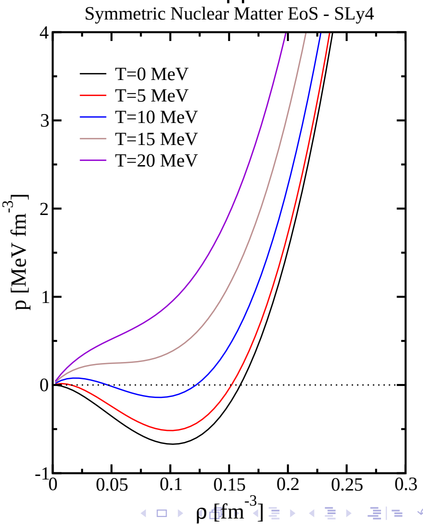
Nuclear Matter

- Infinite system of nucleons
- No surface effects
- Densities $\rho \sim 10^{14}$ g cm^{-3}
- Model interior of heavy nuclei and neutron stars

Liquid-Gas phase transition

- NN interaction $\Rightarrow$ SR repulsion, LR attraction
- Van der Waals-like EoS
- $T_c \sim E/A|_0 \sim 16$ MeV

Mean-field approach



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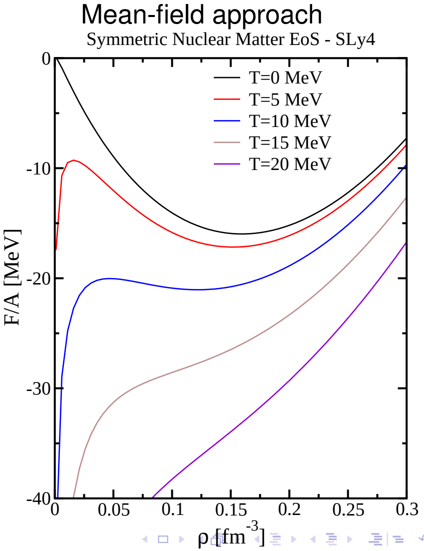

Motivation: one-body Green's function

- Definition

$$i\mathcal{G}(\vec{r}t,\vec{r}'t') = \left\langle \mathcal{T}\left[\hat{a}(\vec{r}t)\hat{a}^\dagger(\vec{r}'t')\right]\right\rangle$$

All the one-body properties of a many-body system can be derived from the one-body Green's function:

$$\langle\hat{X}\rangle = -i\int \mathrm{d}^3r \lim_{\substack{\vec{r}'\to\vec{r} \\ t'\to t^+}} x(\vec{r})\mathcal{G}(\vec{r}t,\vec{r}'t')$$

- Two-body properties can also be obtained $(E, S...)$

SCGF: Ingredients

- Main approximation: decoupling at the level of $\mathcal{G}_{III}$
- Includes short-range and tensor correlations
- Full off-shell energy dependence is considered
- Based on the perturbative expansion of the propagator at $T = 0$ and $T \neq 0$
- Thermodynamically consistent (conserving) theory
- Ladder includes hole-hole propagation (beyond BHF), which leads to a pairing instability for $T = 0$ ...
- Finite temperature actually solves theoretical problems!

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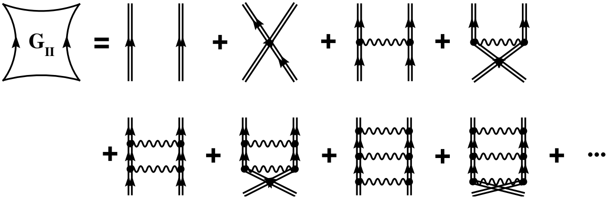
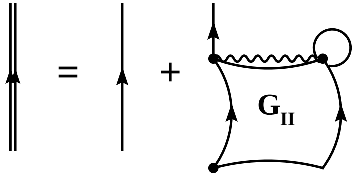
Ladder approximation



- Valid for strong interactions and low densities
- Self-consistency is imposed at each step
- Solved in terms of Dyson's equation
- Ladder self-energy
- In-medium interaction accounts for ladder scattering

Ladder approximation



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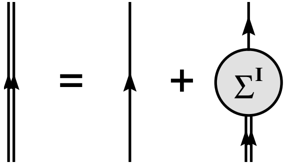

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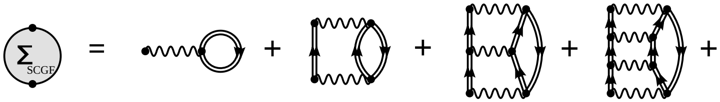

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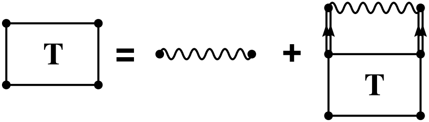

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Ladder approximation

$$\langle \mathbf{k}_1 \mathbf{k}_2 | T(Z_\nu) | \mathbf{k}_3 \mathbf{k}_4 \rangle = \langle \mathbf{k}_1 \mathbf{k}_2 | V | \mathbf{k}_3 \mathbf{k}_4 \rangle$$
$$+ \mathcal{V} \int \frac{d^3 k_5}{(2\pi)^3} \mathcal{V} \int \frac{d^3 k_6}{(2\pi)^3} \langle \mathbf{k}_1 \mathbf{k}_2 | V | \mathbf{k}_5 \mathbf{k}_6 \rangle \, \mathcal{G}^0_{II}(Z_\nu; k_5 k_6) \, \langle \mathbf{k}_5 \mathbf{k}_6 | T(Z_\nu) | \mathbf{k}_3 \mathbf{k}_4 \rangle$$

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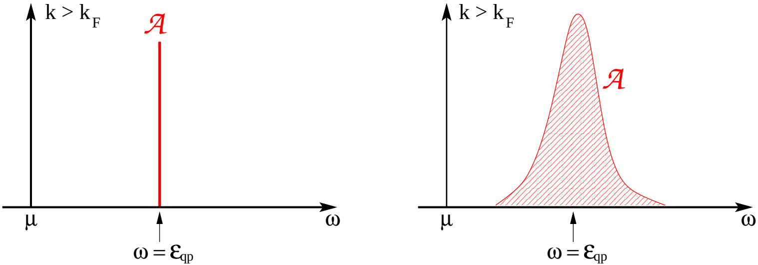
Spectral decomposition of the propagator

- Momentum-frequency space representation

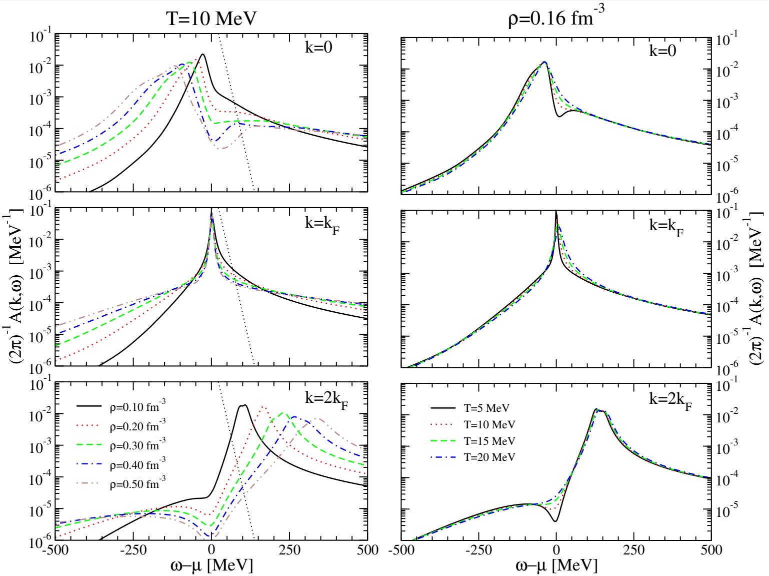
$$\mathcal{G}(k,\omega) = \int_{-\infty}^{\infty} \frac{d\omega'}{2\pi} \mathcal{A}(k,\omega') \left\{ \frac{f(\omega')}{\omega - \omega' - i\eta} + \frac{1 - f(\omega')}{\omega - \omega' + i\eta} \right\}$$

- Spectral function:

$$\mathcal{A}(k,\omega) = \frac{-2 \mathrm{Im}\, \Sigma(k,\omega)}{\left[\omega - \frac{k^2}{2m} - \mathrm{Re}\, \Sigma(k,\omega)\right]^2 + \left[\mathrm{Im}\, \Sigma(k,\omega)\right]^2}$$

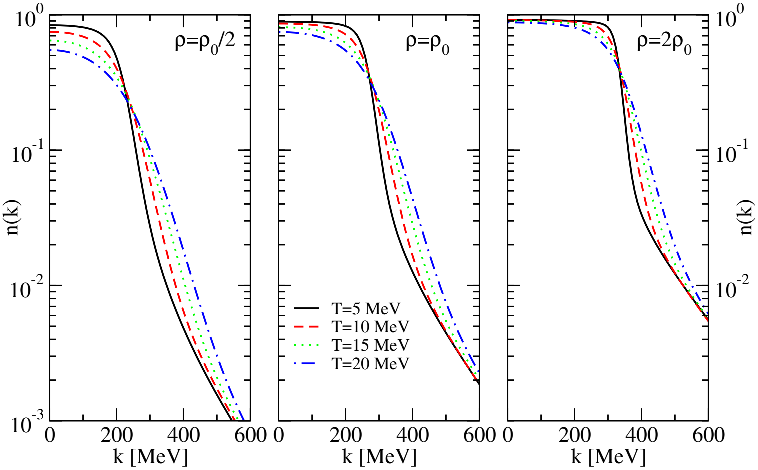


Spectral functions



Momentum distributions

$$n(k) = \langle \hat{a}_k^\dagger \hat{a}_k \rangle = \int_{-\infty}^{\infty} \frac{d\omega}{2\pi} \mathcal{A}(k,\omega) f(\omega)$$



Thermodynamics of correlated nucleons

Free energy: $F(\rho, T) = E - TS$

- Energy (GMK sum rule)

$$E^{GMK} = \sum_k \int_{-\infty}^{\infty} \frac{d\omega}{2\pi} \frac{1}{2} \left\{ \frac{k^2}{2m} + \omega \right\} \mathcal{A}(k,\omega) f(\omega)$$

- Entropy

$$S = ???$$

  - Can one compute S from the one-body propagator?
  - Does fragmentation affect the TD properties?

Luttinger-Ward formalism

Luttinger and Ward, PR **118**,1417 (1960)

- Non-perturbative LW functional for the partition function

$$\ln Z\{\mathcal{G}\} = \widetilde{\mathrm{Tr}}\,\ln\left[-\mathcal{G}^{-1}\right] + \widetilde{\mathrm{Tr}}\,\Sigma\mathcal{G} - \Phi\{\mathcal{G}\}$$

- Φ-functional such that:

$$\left.\frac{\delta \ln Z}{\delta \mathcal{G}}\right|_{\mathcal{G}_0} = 0 \quad \Rightarrow \quad \Sigma\{\mathcal{G}\} = \left.\frac{\delta \Phi}{\delta \mathcal{G}}\right|_{\mathcal{G}_0}$$

Baym, PR **127**,1391 (1962)

- Thermodynamically consistent

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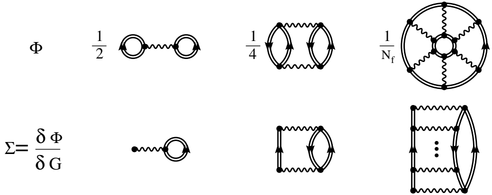

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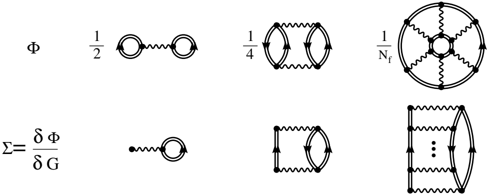

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Entropy within the LW formalism

$$S = \frac{\partial T \ln Z}{\partial T}\bigg|_{\mu} = S^{DQ} + S'$$

- Dynamical quasi-particle entropy

$$S^{DQ} = \sum_k \int_{-\infty}^{\infty} \frac{\mathrm{d}\omega}{2\pi}\, \sigma(\omega)\, \mathcal{B}(k,\omega)$$

with the statistical factor σ and the $\mathcal{B}$ spectral function:

$$\sigma(\omega) = -\left\{ f(\omega) \ln \left[f(\omega) \right] + \left[1 - f(\omega) \right] \ln \left[1 - f(\omega) \right] \right\}$$

$$\mathcal{B}(k,\omega) = \mathcal{A}(k,\omega) \left[1 - \frac{\partial \mathrm{Re}\, \Sigma(k,\omega)}{\partial \omega} \right] + \frac{\partial \mathrm{Re}\, \mathcal{G}(k,\omega)}{\partial \omega} \Gamma(k,\omega)$$

- Higher order entropy $\Rightarrow$ neglected at low T's
  Carneiro and Pethick, PR **11**,1106 (1975)

$$S' = -\frac{\partial}{\partial T} T \Phi\{\mathcal{G}\} + \sum_k \int_{-\infty}^{\infty} \frac{\mathrm{d}\omega}{2\pi} \frac{\partial f(\omega)}{\partial T} \mathcal{A}(k,\omega) \mathrm{Re}\, \Sigma(k,\omega)$$

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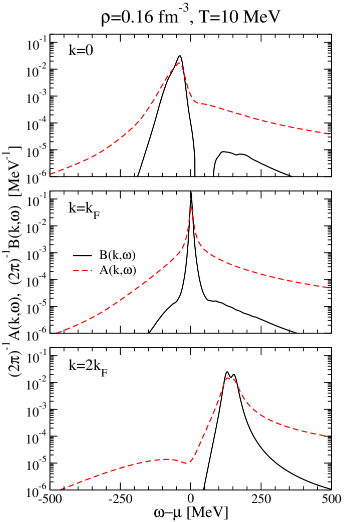
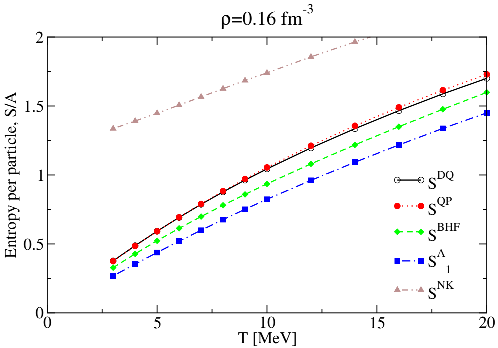
$\mathcal{B}$ spectral function



- $\mathcal{B}$ has a larger quasi-particle peak
- $\mathcal{B}$ has less strength at large energies
- Fragmentation of the qp peak plays a small role

Different approximations



$$S^{DQ} = \sum_k \int_{-\infty}^{\infty} \frac{d\omega}{2\pi}\, \sigma(\omega)\, \mathcal{B}(k,\omega)$$

$$S^{QP} = \sum_k \int_{-\infty}^{\infty} d\omega\, \sigma(\omega)\, \delta\left[\omega - \varepsilon_{SCGF}(k)\right]$$

$$S^{BHF} = \sum_k \int_{-\infty}^{\infty} d\omega\, \sigma(\omega)\, \delta\left[\omega - \varepsilon_{BHF}(k)\right]$$

- $S^{DQ} \sim S^{QP} \Rightarrow$ width effects unimportant
- S^{BHF} within a 15%, S^{A} within a 30%
- S^{NK} too large
- Different lineal slopes $\Rightarrow$ different $N(0)$'s

Thermodynamics of correlated nucleons

Free energy "recipe": $F = E^{GMK} - TS^{DQ}$

- Energy (GMK sum rule)

$$E^{GMK} = \sum_k \int_{-\infty}^{\infty} \frac{d\omega}{2\pi} \frac{1}{2} \left\{ \frac{k^2}{2m} + \omega \right\} \mathcal{A}(k,\omega) f(\omega)$$

- Entropy (LW formalism)

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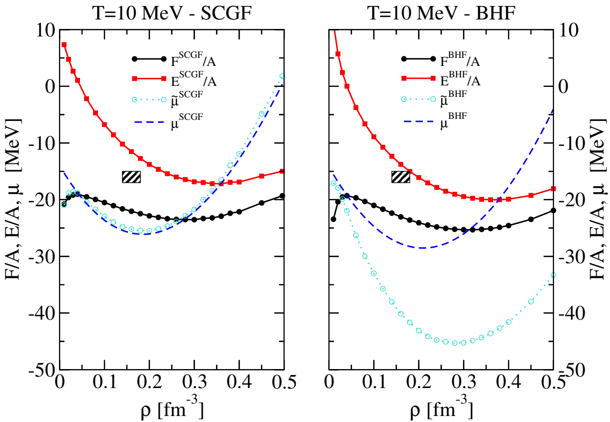
- TD consistency

$$\mu = \frac{\partial F/\mathcal{V}}{\partial \rho} \quad \text{vs.} \quad \rho = \nu \int \frac{d^3k}{(2\pi)^3} n(k, \tilde{\mu})$$

Thermodynamical consistency

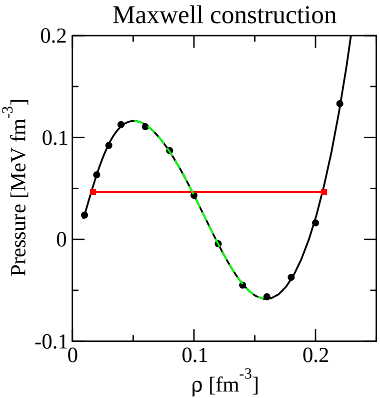


- SCGF + LW yields $\mu \sim \tilde{\mu}$
- BHF violates HvH theorem by 20 MeV
- Far from correct saturation

$$\mu = \frac{\partial F/\mathcal{V}}{\partial \rho} \Leftrightarrow \rho = \nu \int \frac{d^3k}{(2\pi)^3} n(k, \tilde{\mu})$$

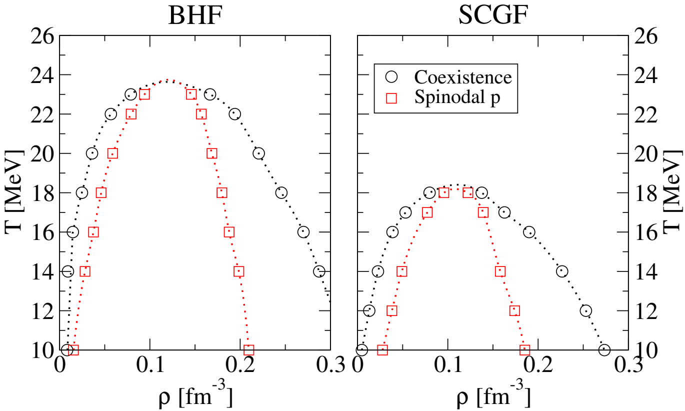
Liquid-gas phase transition

$$p = \rho(\tilde{\mu} - F/A)$$



- Spinodal zone related to mechanical instability
- Maxwell construction sets phase coexistence

Liquid-gas phase transition



- $T_c^{BHF} >> T_c^{SCGF}$
- Very different critical behaviour!
- Upper estimate of finite nuclei T_c

Summary

- The SCGF scheme is a consistent framework for nuclear many-body calculations at finite temperatures
- The LW formalism can be used to find the TD properties of a many-body system from the one-body propagator
- First time that the correlated entropy is computed for nuclear matter
- Different realistic approaches lead to different $T_c \Rightarrow$ room for improvement!

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Outlook

- Dependence on the 2-body NN potential
- Inclusion of 3-body effects
- Different methods to obtain the TD properties of the system
- ρ and T dependences of the microscopic properties
- Isospin asymmetry and its consequences
- Pairing phase transition beyond quasi-particle approach
- Extension to time-dependent systems (HIC)

Thank you!

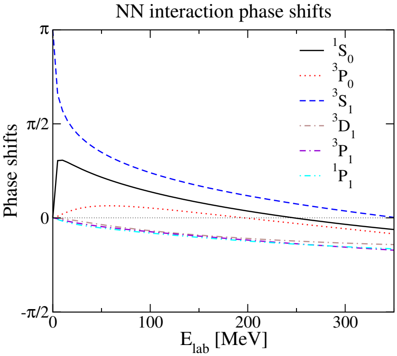
For further reading I

- T. Frick and H. Müther,
  Self-consistent solution to the nuclear many-body problem at finite temperature,
  Physical Review C **68**, 034310 (2003).
- T. Frick, H. Müther, A. Rios, A. Polls and A. Ramos,
  Correlations in hot asymmetric nuclear matter,
  Physical Review C **71**, 014313 (2005).
- A. Rios, A. Polls and H. Müther,
  Sum rules of single-particle spectral functions in hot asymmetric nuclear matter,
  Physical Review C **73**, 024305 (2006).

For further reading II

- V. Soma and P. Bozek,
  Diagrammatical calculation of thermodynamical quantities in nuclear matter,
  Physical Review C **74**, 045809 (2006).
- A. Rios, A. Polls, A. Ramos and H. Müther,
  Entropy of a correlated system of nucleons,
  Physical Review C **74**, 054317 (2006).

Realistic NN interactions



NN interaction properties

- NN scattering phase-shifts
- Deuteron phenomenology
  - Bound state
  - Tensor component
- Different phase-shift equivalent potentials **CDBONN**, Av18, etc.

back

Analytical continuation

- Spectral decomposition of Matsubara coefficients

$$\mathcal{G}(k,z_\nu) = \int_{-\infty}^{\infty} \frac{d\omega'}{2\pi} \frac{\mathcal{A}(k,\omega')}{z_\nu - \omega'}$$

- Analytical continuation

$$\mathcal{G}(k,z_\nu) \xrightarrow{??} \mathcal{G}(k,z)$$

  - Can be done under certain assumptions
    Baym and Mermin, Jour. Math. Phys. **2**, 232 (1961)

- Relation to the retarded propagator

$$\mathcal{G}(k,z) = \int_{-\infty}^{\infty} \frac{d\omega'}{2\pi} \frac{\mathcal{A}(k,\omega')}{z - \omega'} \xrightarrow{z \to \omega + i\eta} \mathcal{G}^R(k,\omega) = \int_{-\infty}^{\infty} \frac{d\omega'}{2\pi} \frac{\mathcal{A}(k,\omega')}{\omega - \omega' + i\eta}$$

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Analytical continuation

- Spectral decomposition of Matsubara coefficients

$$\mathcal{G}(k, z_\nu) = \int_{-\infty}^{\infty} \frac{d\omega'}{2\pi} \frac{\mathcal{A}(k, \omega')}{z_\nu - \omega'}$$

- Analytical continuation

$$\mathcal{G}(k, z_\nu) \xrightarrow{??} \mathcal{G}(k, z)$$

  - Can be done under certain assumptions
    Baym and Mermin, Jour. Math. Phys. **2**, 232 (1961)

- Relation to the retarded propagator

$$\mathcal{G}(k, z) = \int_{-\infty}^{\infty} \frac{d\omega'}{2\pi} \frac{\mathcal{A}(k, \omega')}{z - \omega'} \xrightarrow{z \to \omega + i\eta} \mathcal{G}^R(k, \omega) = \int_{-\infty}^{\infty} \frac{d\omega'}{2\pi} \frac{\mathcal{A}(k, \omega')}{\omega - \omega' + i\eta}$$

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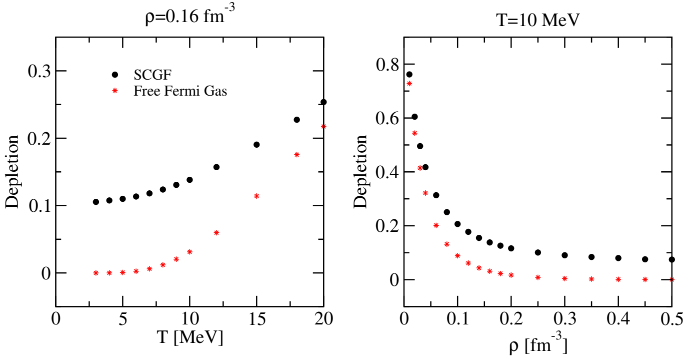
Depletion



- T dependence $\Rightarrow f(\omega)$
- ρ dependence $\Rightarrow$ correlations
- Measure of both thermal and dynamical correlations

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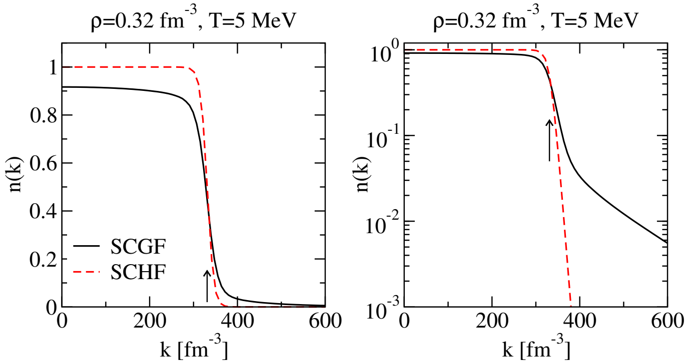
Correlated and non-correlated $n(k)$



- Less populated at low k
- More populated at high k
- Strong fall-off near k_F

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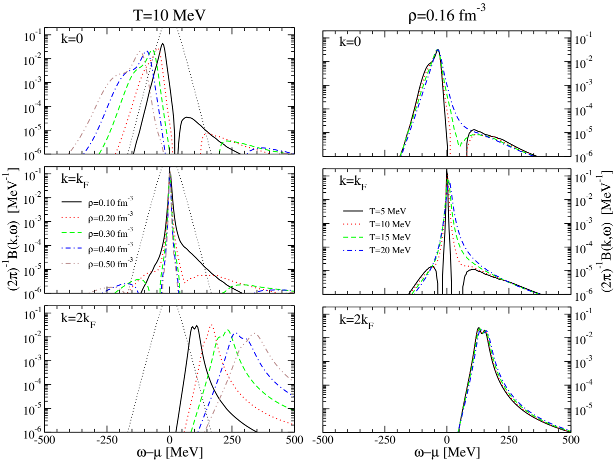
$\mathcal{B}$ spectral function



- Different ρ and T dependence
- High energy tails measure importance of correlations

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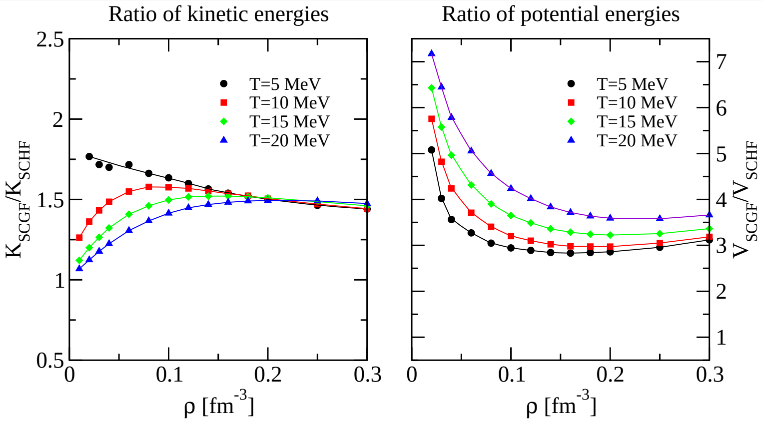
Mean-field to correlated energy ratios



- Kinetic energy $\Rightarrow$ ρ and T independent
- Potential energy $\Rightarrow$ large modification

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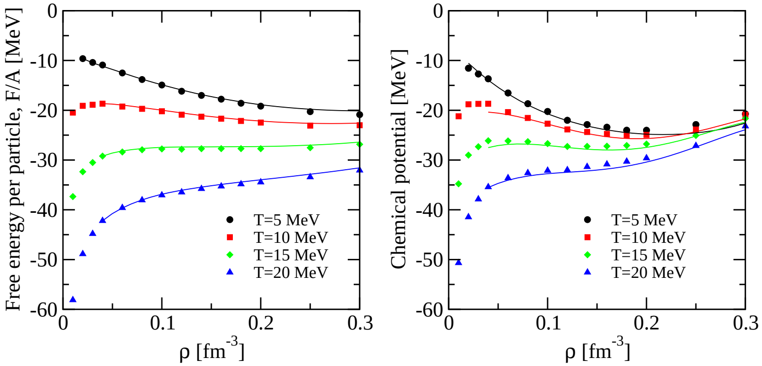
Free energy and $\tilde{\mu}$



- F/A minimum disappears with $T \Rightarrow T_{fl}$
- T_c where F/A looses inflexion point
- μ and $\tilde{\mu}$ coincide within 2 MeV

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