"Thermal instability, evaporation, and thermodynamics of 1D liquids in weakly interacting Bose-Bose mixtures"

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Classical liquids and gases

Water → evaporation: thermal kinetic energy VS attraction → Vapor

Water
- Dense
- Self-bound
- Pressure > 0 or < 0

Vapor
- dilute
- no self-bound
- pressure > 0

- Equilibrium density n_{eq} (attraction = repulsion): pressure = 0 or min of free energy per particle

New quantum liquids in ultracold gases

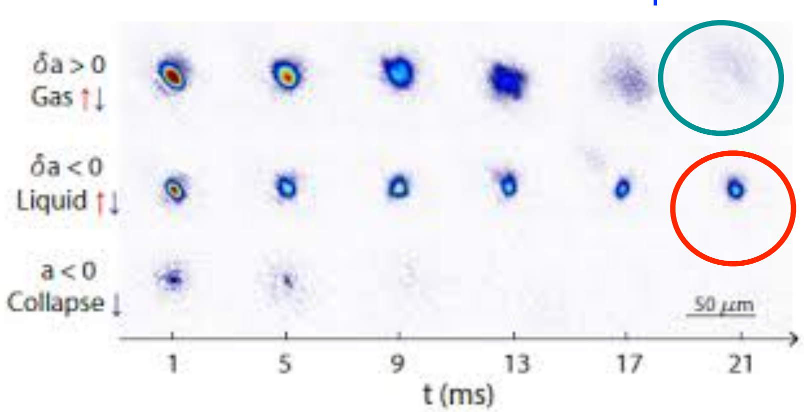
3D mixtures of 2 Bose atomic gases at T = 0
- intra-species repulsion
- inter-species attraction

- Ultradilute (100 millions > water)
- Ultracold (1 billion > water)

Stability for beyond-mean-field quantum many-body effects
- Mean-field (MF) energy made small by tuning interaction
- Beyond-mean-field (BMF) energy usually subleading in gases
- MF and BMF energies with opposite signs → equilibrium density

Petrov (2015)

Observation of ultracold droplets in 3D - Droplet = "a part of liquid"



Expansion of gas mixture

Self-bound liquid droplet

→ Time after the turning off of the laser trap

- short lifetime
- T no with time-of-flight

Cabrera et Al. (2018)
Semeghini et Al. (2018)

1D Bose-Bose contact-interacting mixture

$$H = \sum_{\sigma=1}^{2}\left[-\frac{\hbar^2}{2m}\sum_{i=1}^{N_\sigma}\frac{\partial^2}{\partial x_i^2} + g\sum_{i>j}^{N_\sigma}\delta(x_i - x_j)\right] + g_{12}\sum_{i>j}^{N_1,N_2}\delta(x_i - x_j)$$

- $N_\sigma, \sigma = 1{,}2$ components of number of atoms (balanced: $N_1 = N_2 = N/2$)
- Intra-species repulsive interaction $g = -\frac{2\hbar^2}{ma} > 0 \quad a < 0$
- Inter-species attractive interaction $g_{12} = -\frac{2\hbar^2}{ma_{12}} < 0 \quad a_{12} > 0$

Liquids in 1D are much more stable
- no 3-atom losses
- beyond-mean-field effects enhanced

Weakly-interacting 1D liquid at T = 0

Energy density from Bogoliubov (BG) theory $\quad n|a| \gg 1 \quad na_{12} \gg 1$

$$\mathcal{E}_0 = \frac{1}{2}nmc_-^2 - \frac{2}{3}\frac{m^2}{\pi\hbar}\sum_{\pm} c_\pm^3,$$

Total density
$$n = n_1 + n_2 = N/L$$

Phononic sound velocities
$$c_\pm^2 = \frac{n}{m}\frac{g \pm |g_{12}|}{2}$$

BG spectra
$$E_\pm(p) = \sqrt{c_\pm^2 p^2 + \left(\frac{p^2}{2m}\right)^2}$$

$$E_- < E_+$$

Petrov et Al. (2016)

Bogoliubov theory at low temperature

weak interactions $T \ll T_d$ $k_B T_d = \frac{\hbar^2 n^2}{2m}$ quantum degeneracy energy

gas of non-interacting bosonic quasi-particles (with $\mu_0 = 0$)

Thermal free energy density: $$\Delta\mathscr{A} = \mathscr{A} - \mathscr{E}_0 = k_B T \sum_{\pm} \int_{-\infty}^{+\infty} \frac{dp}{2\pi\hbar} \ln\left[1 - e^{-\beta E_{\pm}(p)}\right]$$

$$E_{\pm}(p) = \sqrt{c_{\pm}^2 p^2 + \left(\frac{p^2}{2m}\right)^2} \qquad c_{\pm}^2 = \frac{n}{m}\frac{g \pm |g_{12}|}{2}$$

Chemical Potential $\mu = \left(\frac{\partial\mathscr{A}}{\partial n}\right)_{T,a,a_{12},L}$ Pressure $P = n\mu - \mathscr{A}$

Inverse Isothermal compressibility $$\kappa_T^{-1} = \left(\frac{\partial^2\mathscr{A}}{\partial n^2}\right)_{T,a,a_{12},N}$$

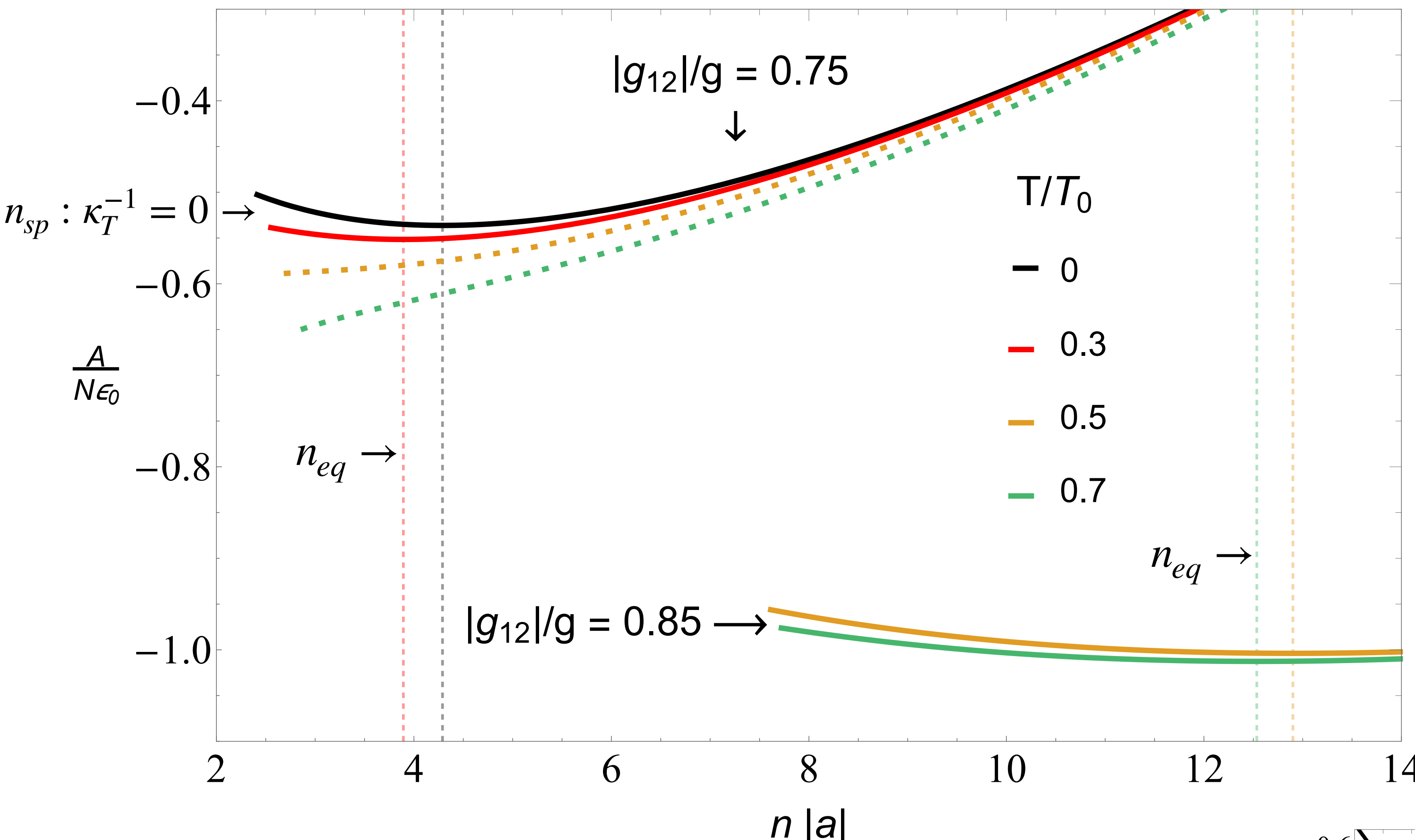
From $\kappa_T^{-1} = 0$ one finds the spinodal density n_{sp}

- $n > n_{sp} \rightarrow \kappa_T^{-1} > 0$ stable liquid
- $n < n_{sp} \rightarrow \kappa_T^{-1} < 0$ unstable liquid breaking down into droplets

De Rosi, Astrakharchik and Massignan, Phys. Rev. A 103, 043316 (2021)

$$\epsilon_0 = k_B T_0 = \frac{\hbar^2}{m|a|^2}$$

Dynamical instability



Free energy per particle VS density

Vertical: equilibrium densities of liquid (min of A/N or P = 0)
Solid: Liquid
Dotted: Gas

T increases: $n_{eq} \rightarrow n_{sp}$

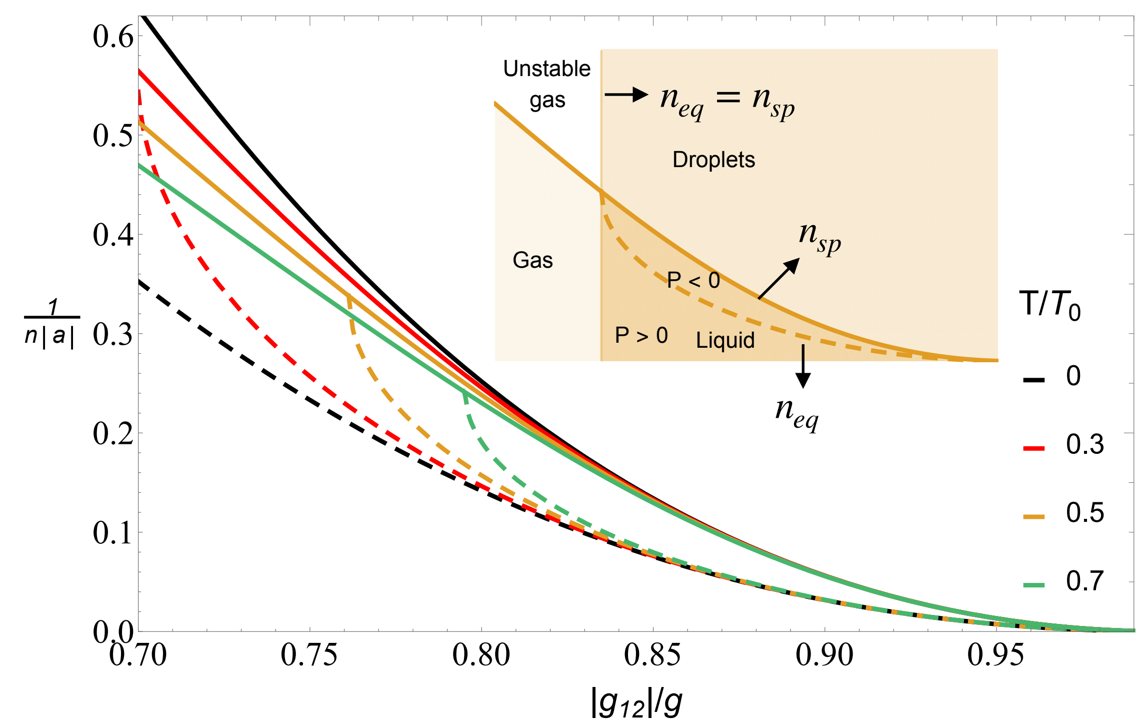
Liquid-gas transition at T_c given by $n_{eq} = n_{sp}$

Dashed: **equilibrium densities** of liquid n_{eq}

Solid: **spinodal densities** n_{sp} (zero inverse isothermal compressibility)

Vertical: $n_{eq} = n_{sp}$ (**Dynamical Instability at critical temperature**)

T-effects dominant at small $|g_{12}|/g$ → smaller attraction

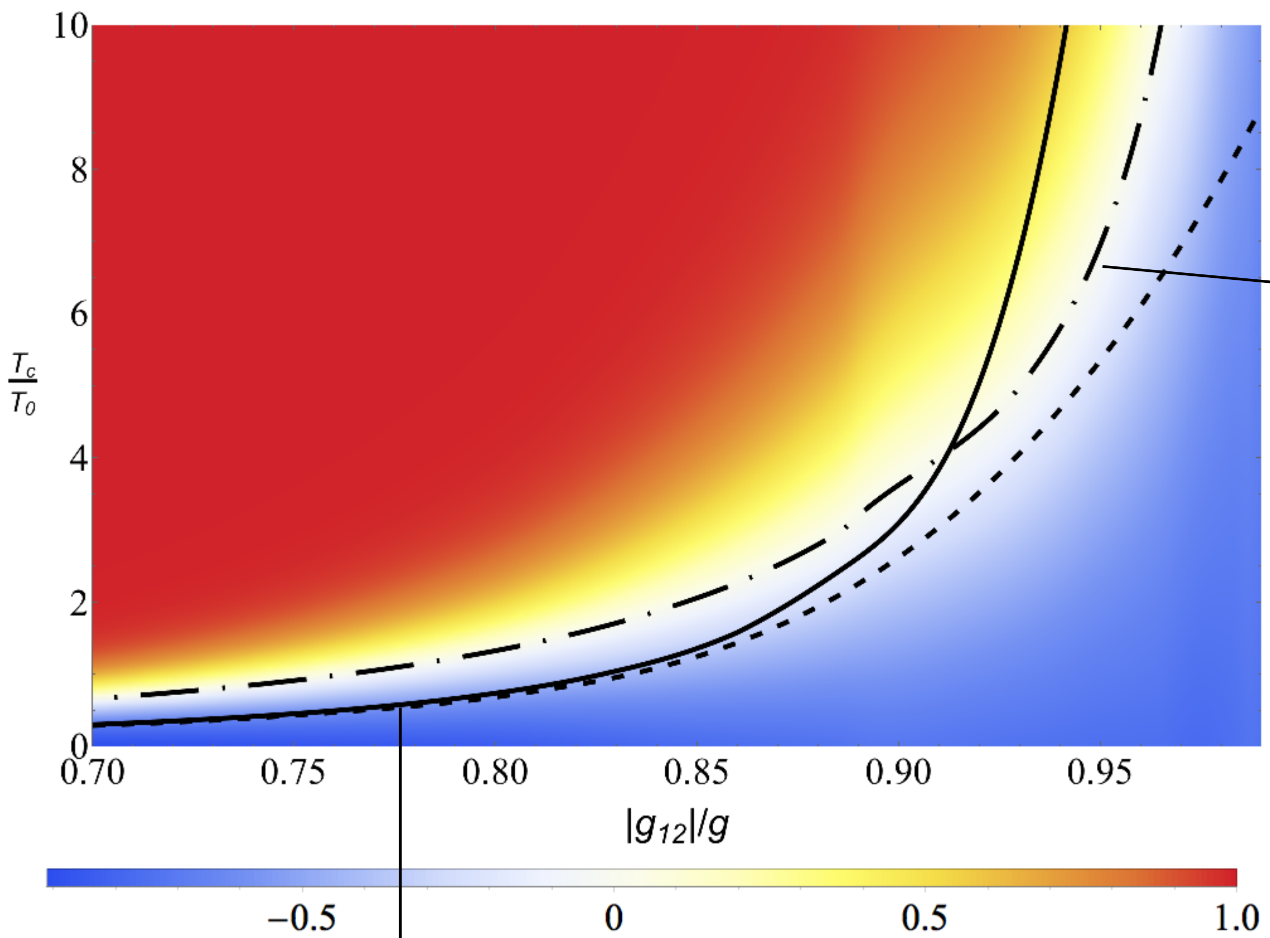


De Rosi, Astrakharchik and Massignan, Phys. Rev. A 103, 043316 (2021)

Dynamical instability & evaporation

$$k_B T_0 = \frac{\hbar^2}{m|a|^2}$$

2 thermal mechanisms driving the liquid-gas transition at the critical temperature



Chemical Potential at T = 0

Evaporation for $k_B T/2 = -\mu_0[n_{eq}(T)]$ dominant for larger $|g_{12}|/g$ (Smaller T_c)

Dot-dashed

Dynamical Instability for $n_{eq} = n_{sp}$ dominant for smaller $|g_{12}|/g$ (Smaller T_c)

Solid: BG spectra (our theory)

Dashed: phononic spectra

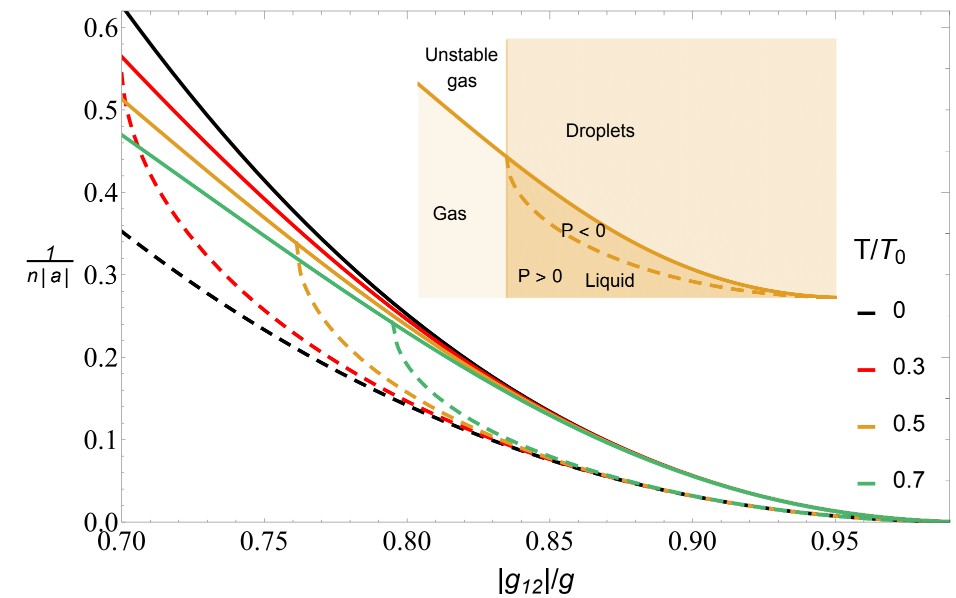
$$E_{\pm}(p) = \sqrt{c_{\pm}^2 p^2 + \left(\frac{p^2}{2m}\right)^2}$$

Ota et Al. (2020)

De Rosi, Astrakharchik and Massignan, Phys. Rev. A 103, 043316 (2021)

Summary & Perspectives

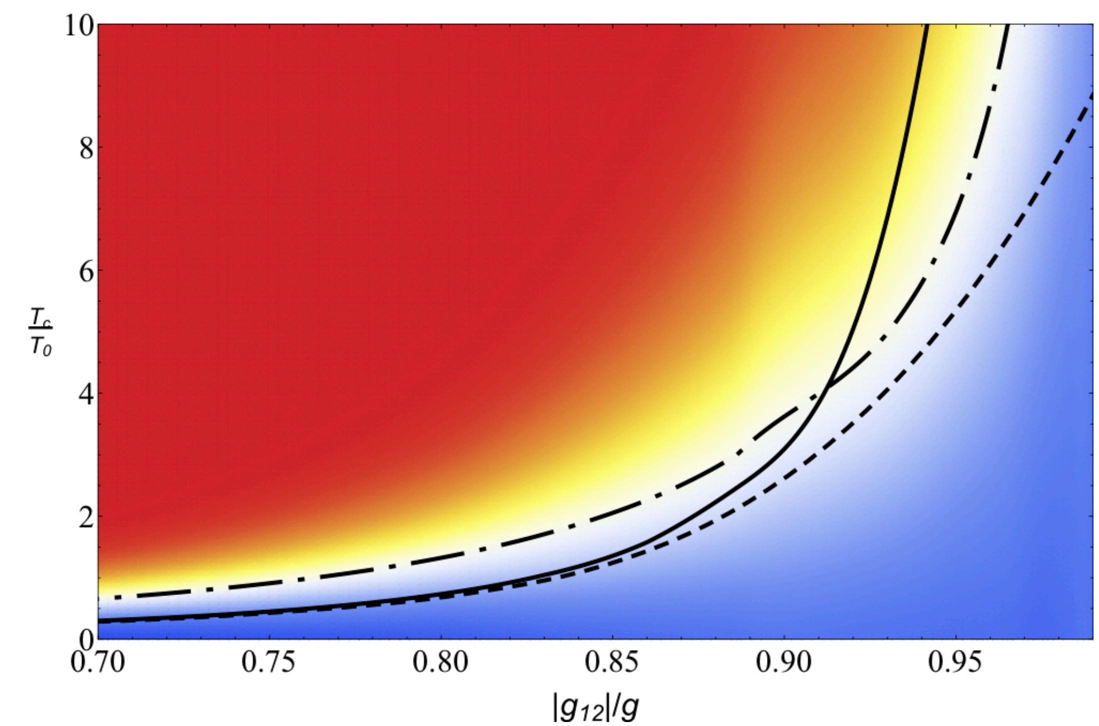
- Calculation of thermodynamic quantities of liquids
- Observation of liquid-gas transition
- Realization of a liquid by cooling a gas



- + stability in 1D: no 3-atom losses and experimental identification of evaporation

- new methods for measuring T in liquids:

Critical T tuned with interactions and in-situ thermodynamics



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thank you!

De Rosi, Astrakharchik and Massignan, Phys. Rev. A 103, 043316 (2021)