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Thermal instability, evaporation, thermodynamics of 1D liquids in weakly interacting Bose-Bose mixtures. Perspectives for impurities.

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Quantum 2021: Dynamics and local control of impurities in complex quantum environments — 8 Sep 2021

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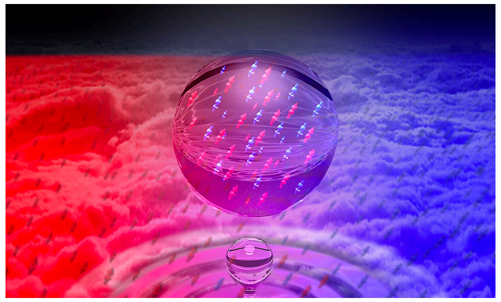
De Rosi, Astrakharchik and Massignan, Phys. Rev. A 103, 043316 (2021)

Bosonic Binary Atomic Mixtures

Beyond-mean-field Physics in bosonic mixtures

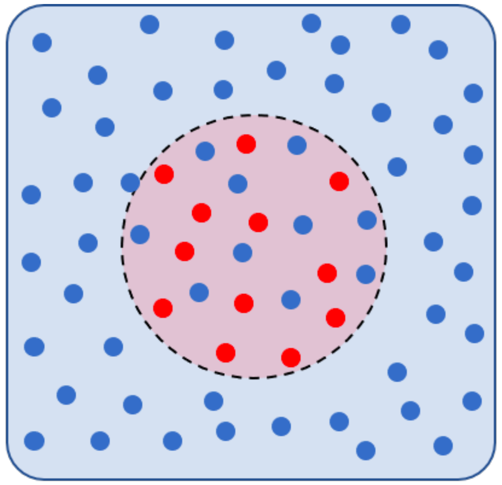
Densities of 2 atomic species of the same order

1) Liquid droplets with attractive inter-species interaction



Petrov (2015)
Cabrera et Al. (2018)
Semeghini et Al. (2018)

2) Mixed bubbles with repulsive inter-species interaction

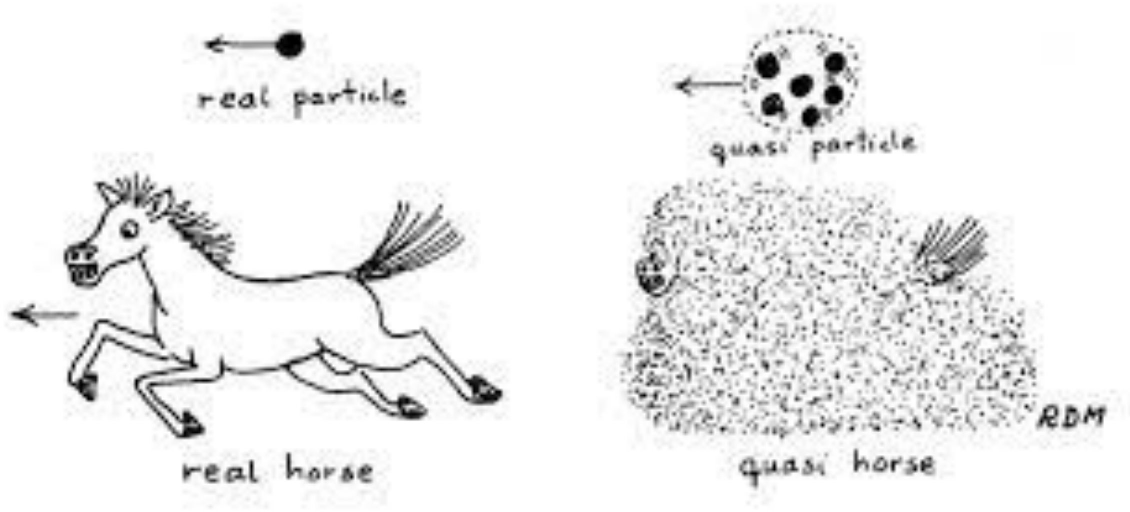


Naidon et Al. (2021)

The dressed impurity (polaron) problem

Density of one species (impurity) << density of the other (bath)

Impurity moves in the cloud of the bath excitations becoming dressed (polaron = quasiparticle)

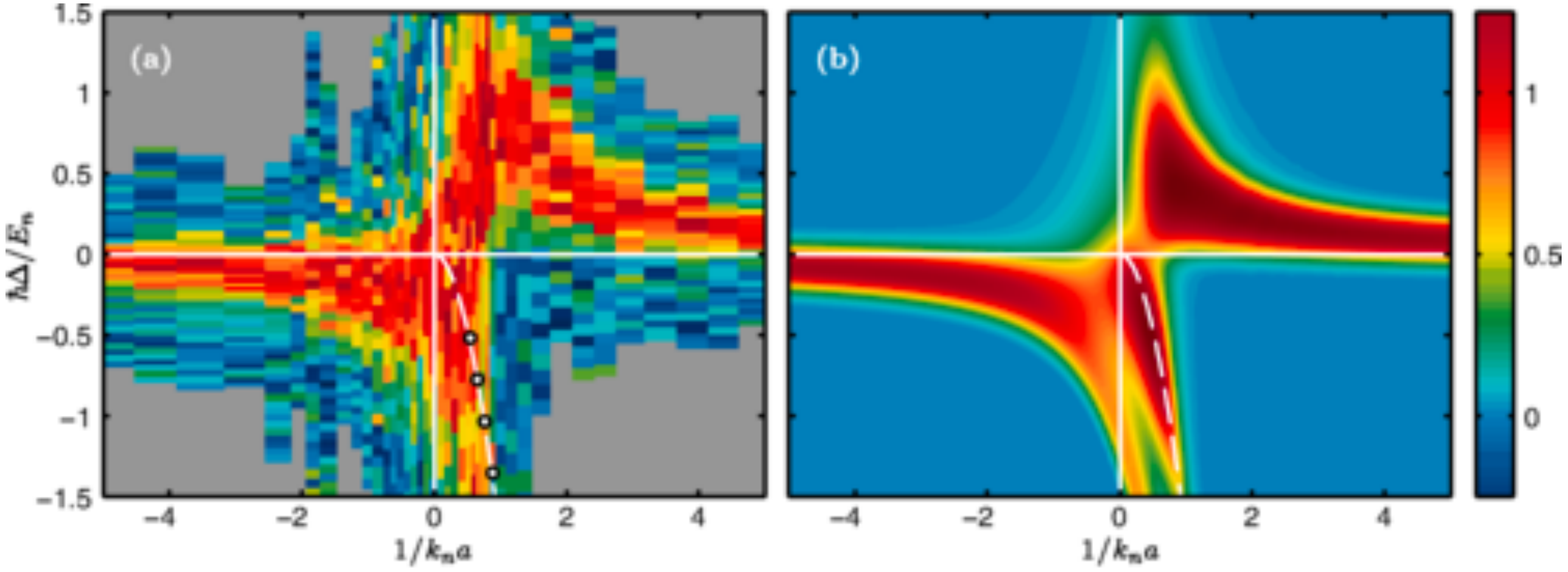


Mattuck's book (1967)

The cloud makes the polaron properties different from those of the bare impurity (effective mass, interaction…)

Observation of Bose Polaron

The polaron energy has been measured
for both attractive and repulsive impurity-bath interaction



Hu et Al. (2016)
Jørgensen et Al. (2016)

Ultracold Atomic Liquids in a nutshell

Classical liquids and gases

T increases: thermal kinetic energy VS attraction

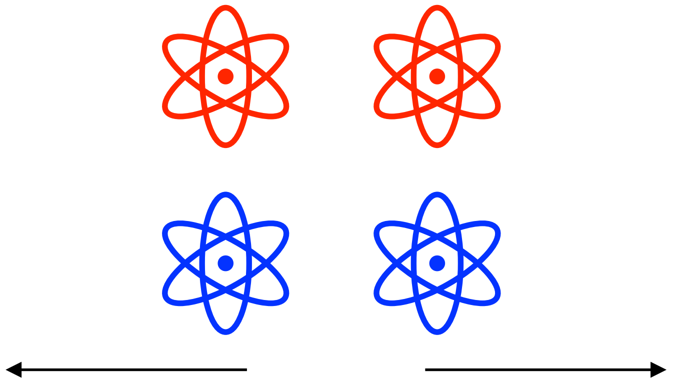
- Dense
- Self-bound
- Pressure positive and negative

- Dilute
- No self-bound
- Positive pressure

Equilibrium density in liquids:
zero pressure or min of free energy per particle
Attraction = repulsion

New quantum liquids in ultracold atomic gases

3D mixtures of 2 Bose gases at $T = 0$



Intra-species repulsion

Inter-species attraction

- Ultradilute (100 millions more than water)
- Ultracold (1 billion more than water)

Petrov (2015)

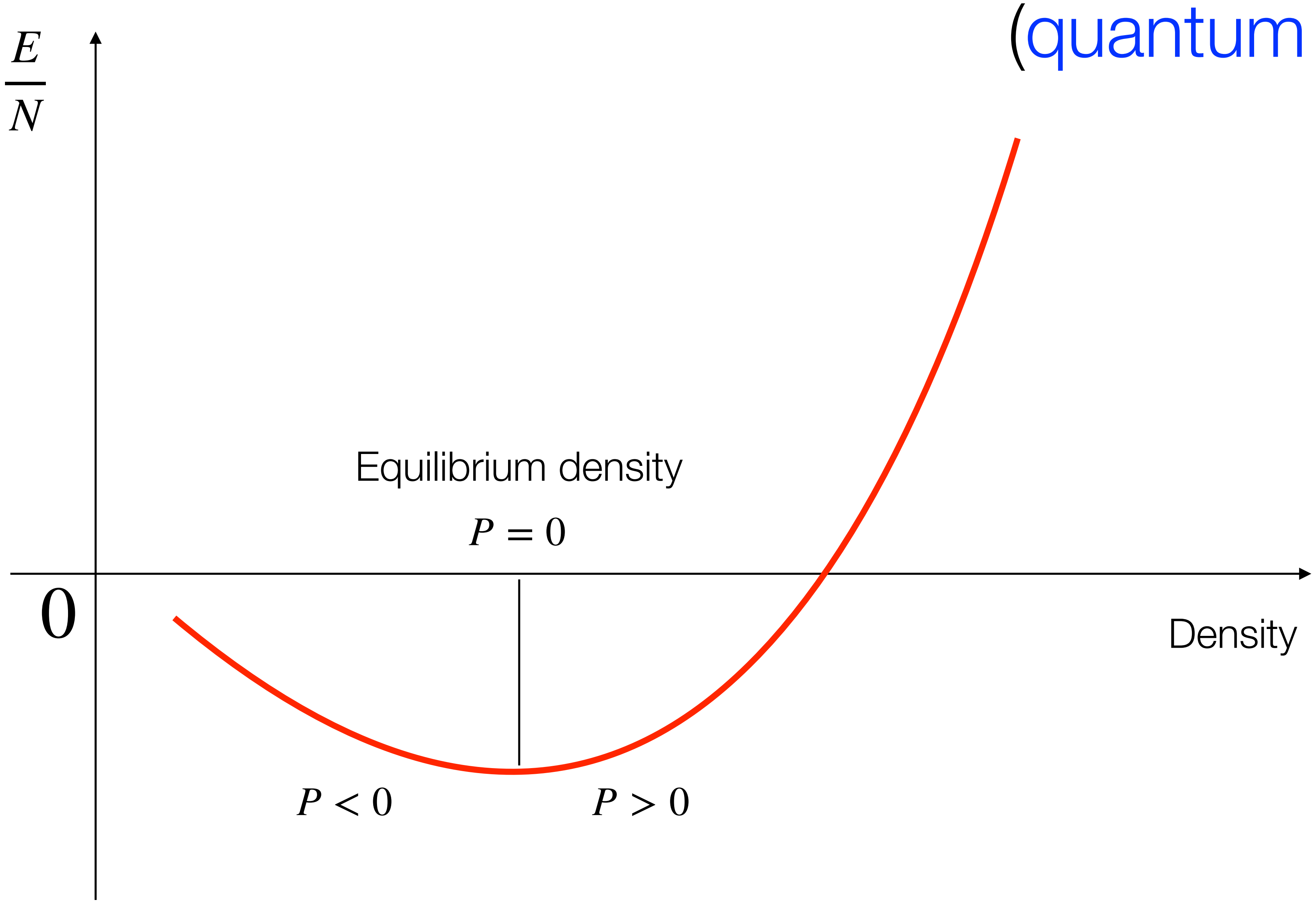
Stability of liquids at T = 0 for beyond-mean-field effects

$E = E_{\mathrm{MF}} + E_{\mathrm{BMF}} \longrightarrow$ Usually subleading in gases $\quad E_{\mathrm{MF}} \times E_{\mathrm{BMF}} < 1$

$\downarrow$

Mean-field made small
by tuning interactions

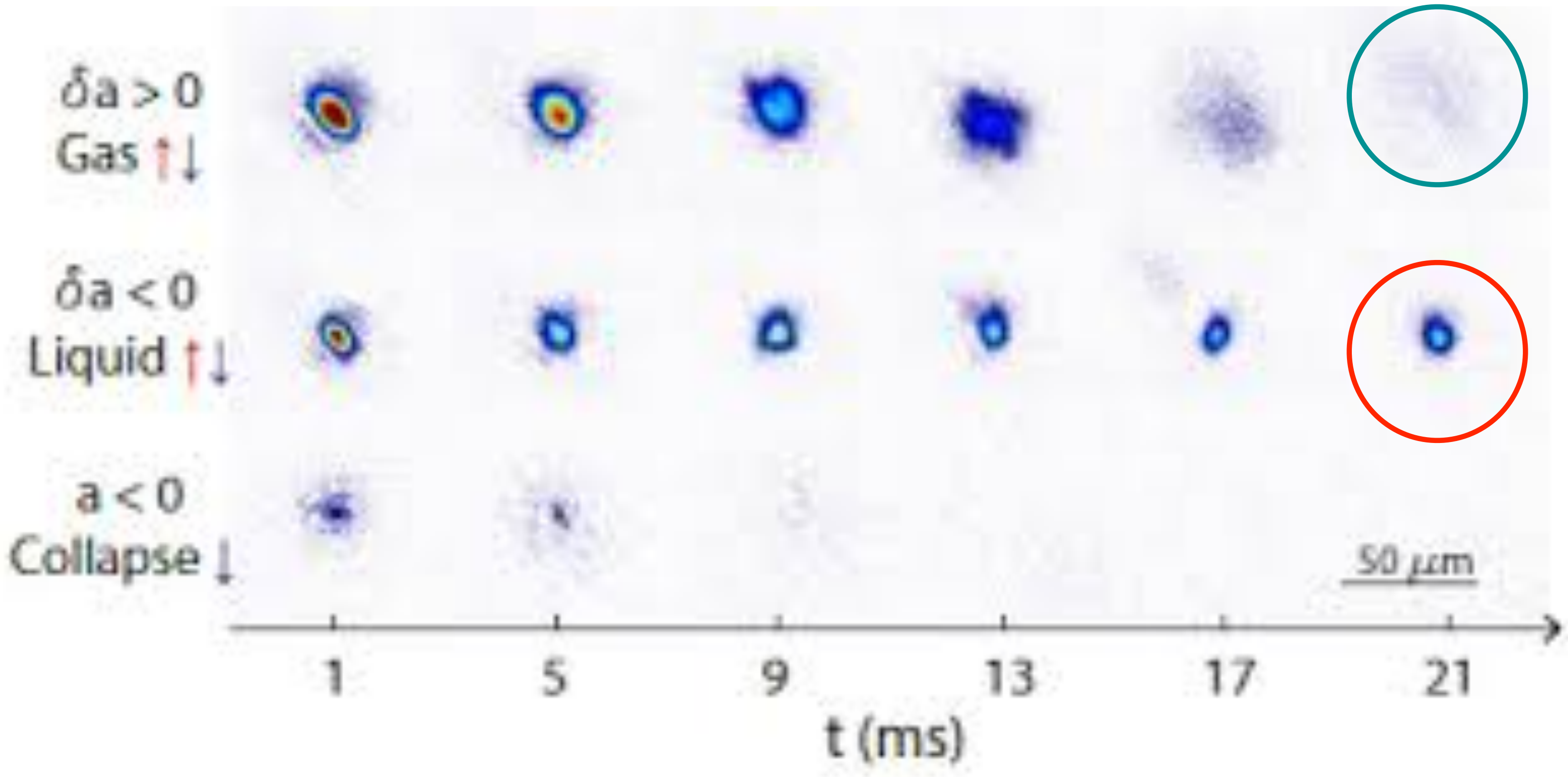
New importance of BMF
(quantum many-body effects)



Petrov (2015)

First observation of ultracold droplets in 3D

Droplet = “a small part of liquids”



Expansion of gas mixture

Self-bound liquid droplet

↓

Time after the turning off of the laser trap

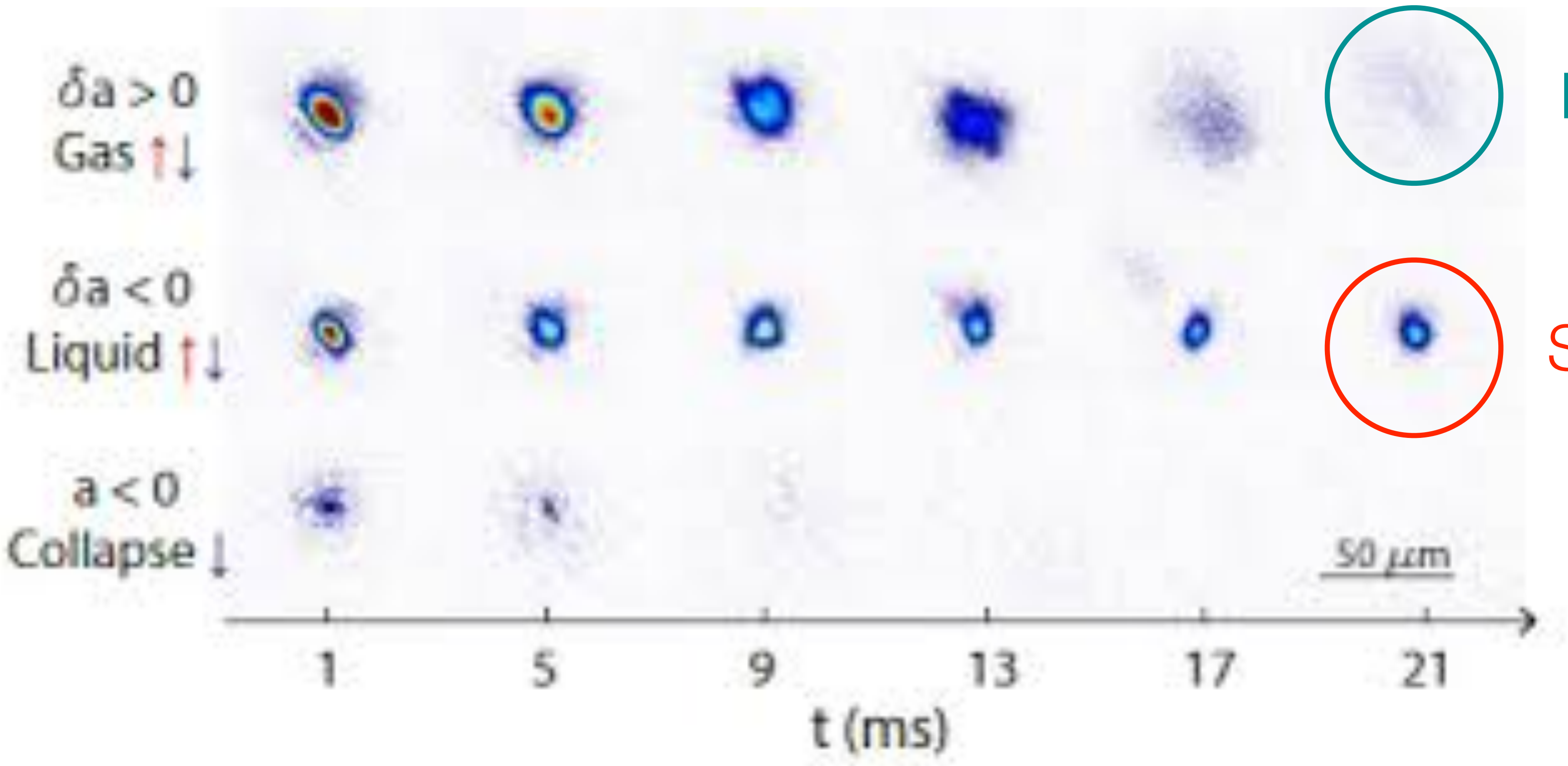
Cabrera et Al. (2018)
Semeghini et Al. (2018)

Experimental problems of ultracold droplets

1) short lifetime (e.g. observation of dynamics not possible)

2) T of liquids cannot be measured

Time-of-flight expansion method only for gases - final atomic velocity



Expansion of gas mixture

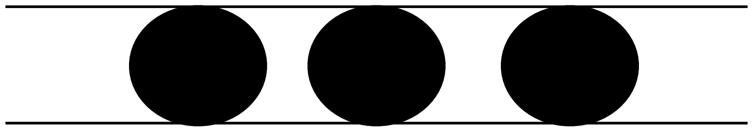
Self-bound liquid droplet

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

Why ultracold liquids in 1D?

Liquids in 1D are much more stable:

1) no 3-atom losses in 1D



2) Beyond-mean-field effects enhanced in 1D

Petrov et Al. (2016)

Weakly-interacting liquids in 1D Bose-Bose mixtures at low T

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

1D Bose-Bose mixture with contact interactions

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

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

Weakly-interacting 1D liquid at T = 0

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

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

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)
Parisi et Al. (2019)

Bogoliubov (BG) theory at low temperature

- weak interactions
- at low T: $T \ll T_d \quad k_B T_d = \dfrac{\hbar^2 n^2}{2m}$ Quantum degeneracy energy

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

Thermal free energy density:

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

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

Bogoliubov (BG) theory at finite temperature

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

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

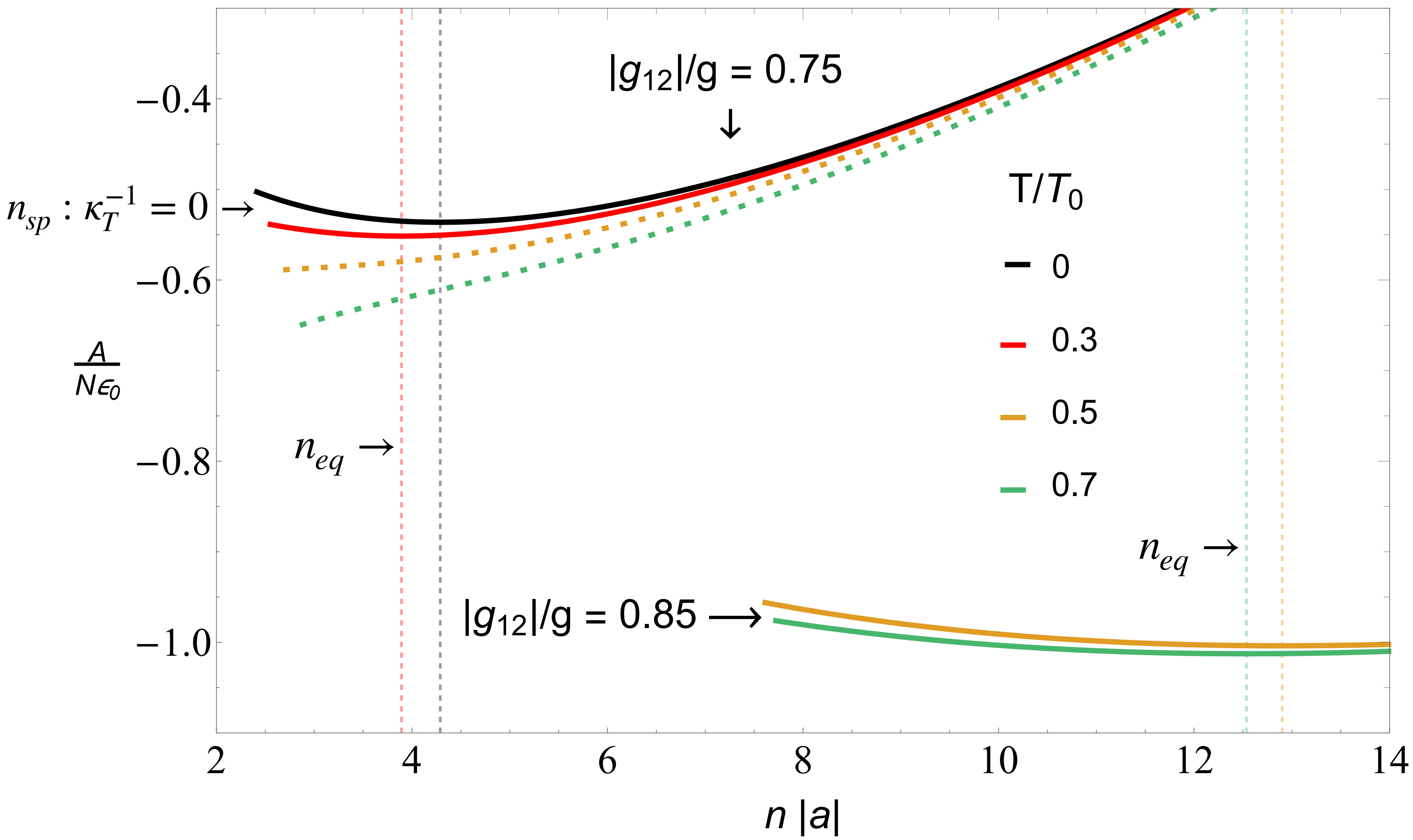
From $\kappa_T^{-1} = 0$ one finds the spinodal density n_{sp}

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

Liquid-gas transition at finite temperature

Free energy per particle as a function of density:

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



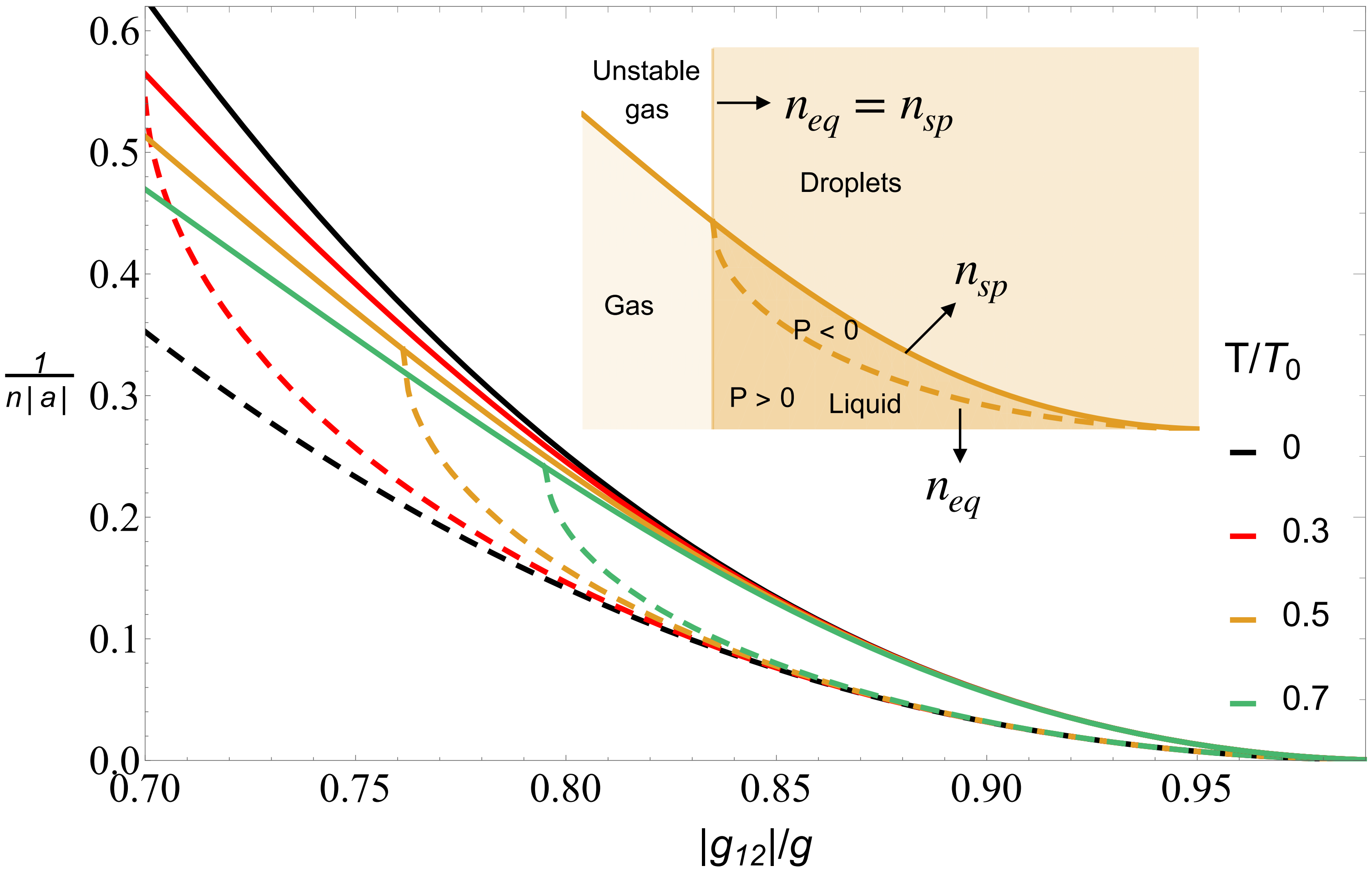
T increases: $n_{eq} \rightarrow n_{sp}$

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

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

De Rosi, Astrakharchik and Massignan (2021)

Phase transition driven by the dynamical instability



Liquid-gas transition at T_c given by $n_{eq} = n_{sp}$ (Dynamical Instability)

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

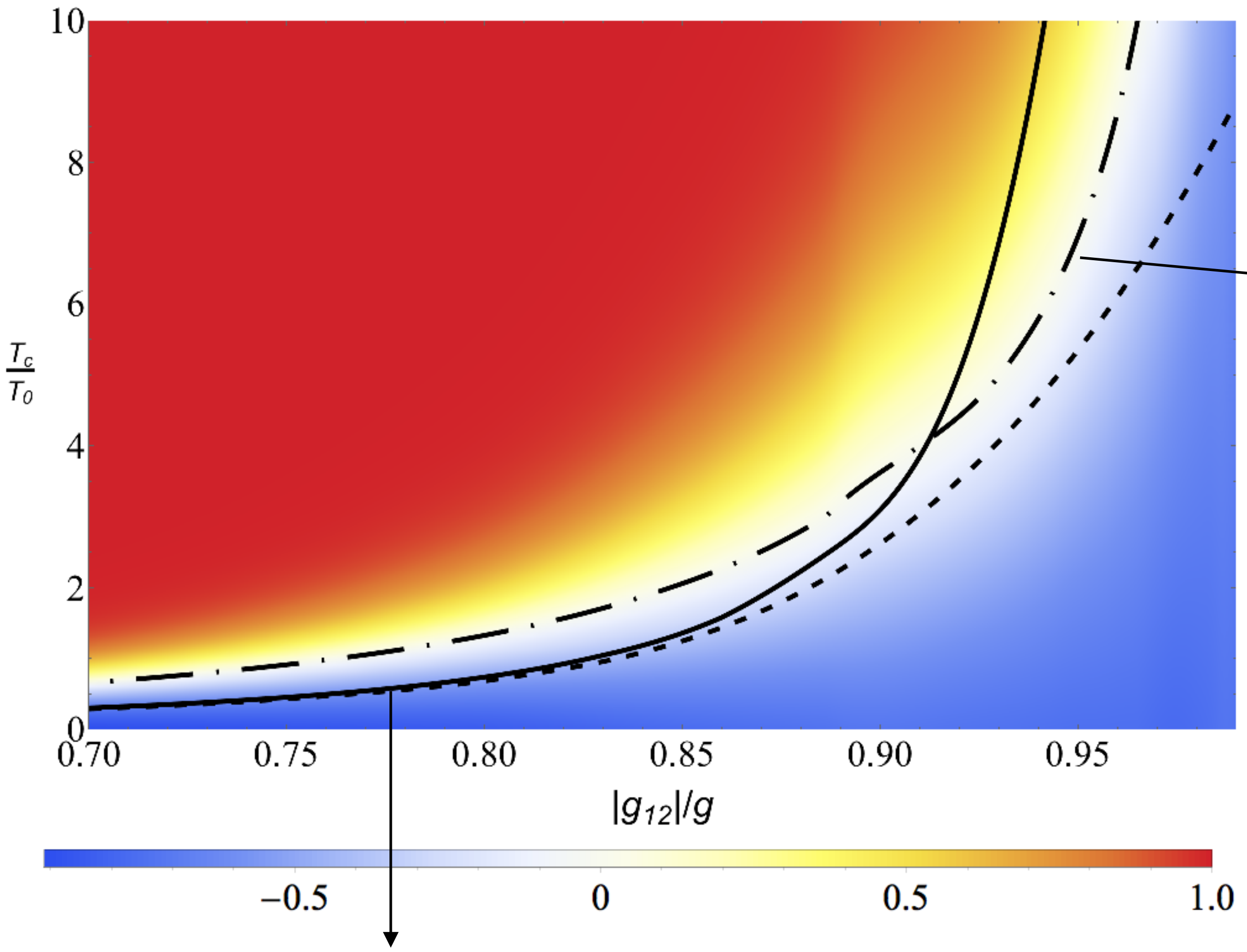
Dashed: **equilibrium densities** of liquid n_{eq} (Pressure P = 0 or min of free energy per particle)
Solid: **spinodal densities** n_{sp} (zero inverse isothermal compressibility)
Vertical: **equilibrium = spinodal** densities $n_{eq} = n_{sp}$ (**Dynamical Instability at critical temperature**)

De Rosi, Astrakharchik and Massignan (2021)

Dynamical instability and 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

Ota et Al. (2020)

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

De Rosi, Astrakharchik and Massignan (2021)

Summary and Future Perspectives

Weakly-interacting liquids in 1D Bose-Bose mixture at low T

- We also calculate the thermodynamic quantities of liquids

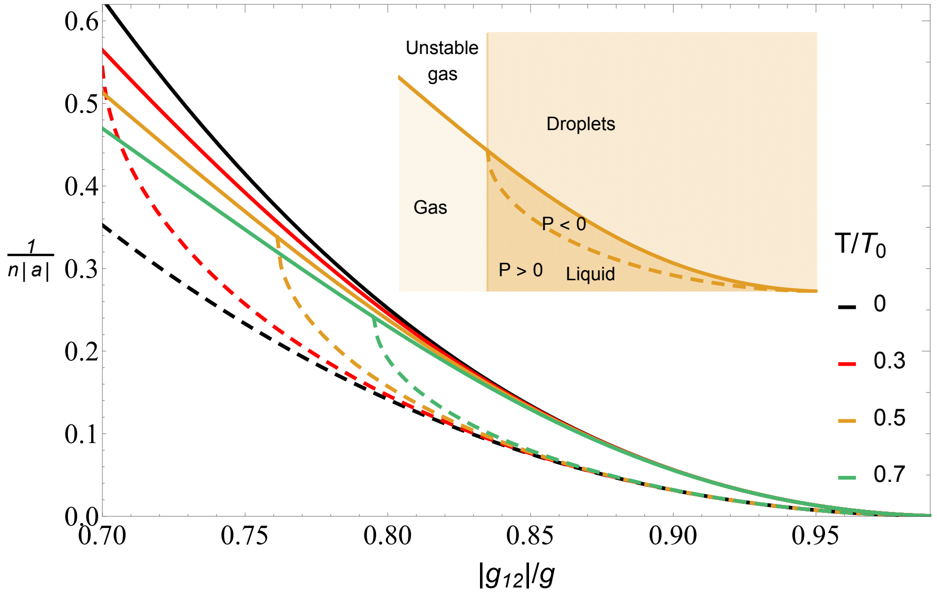
Perspective

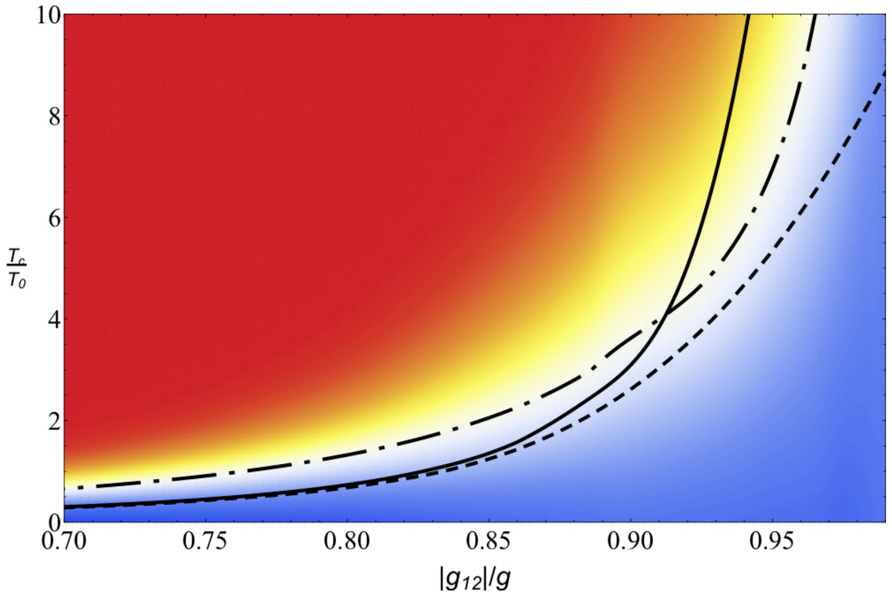
1) Observation of liquid-gas transition

2) Realization of a liquid by cooling a gas

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

4) new methods for measuring T in liquids:
- Critical T tuned with interactions
- Measurements of in-situ thermodynamics





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

Perspectives for Bose Polaron at finite temperature

1) Impurity + liquid

- probe for liquid properties

Wenzel et Al. (2018)
Bisset et Al. (2021)

- Bose Polaron at finite temperature in liquids

2) Liquid-to-gas transition by reducing the density of 1 species

Hu et Al. (2016)
Jørgensen et Al. (2016)
Levinsen et Al. (2017)
Guenther et Al. (2018)
Reichert et Al. (2019)
Pascual et Al. (2021)

- Bose Polaron at finite temperature
- Unified liquid-polaron description at finite temperature

thank you!

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