Dissipative cooling of Bogoliubov excitations

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merci à :

A. Johnson (ATI Vienna)
E. Reiß, T. Sauer (U Potsdam)

talks on web

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Motivation – Cooling a Bose gas

Evaporative cooling

– loss of energetic particles + thermalisation

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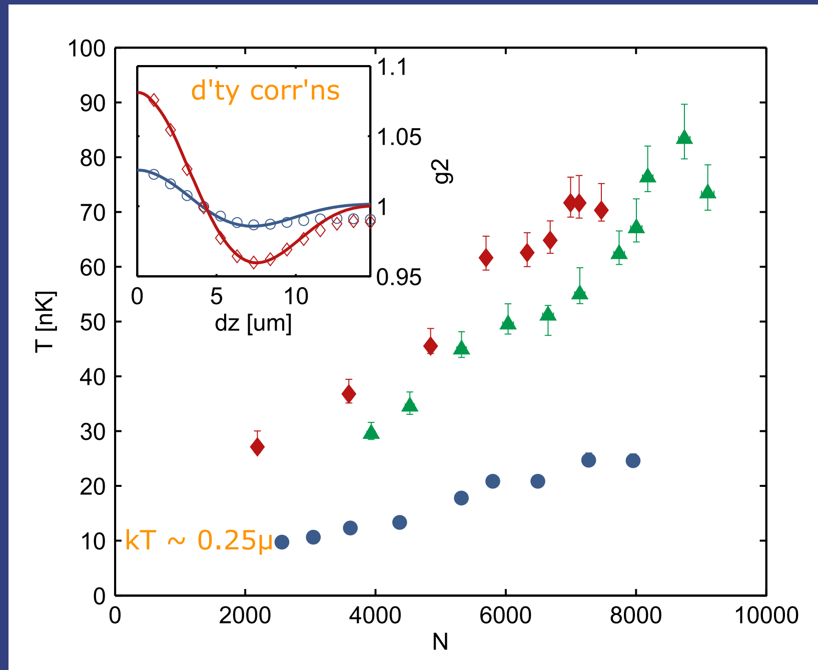
Dissipative cooling

– Vienna experiment: quasi-1D Bose gas

Rauer & Schmiedmayer group [*Phys Rev Lett* 2016]



– uniform particle loss

– nearly integrable system: no thermalisation

Motivation – Cooling and Dissipation

Evaporative cooling

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Dissipative cooling

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Rauer & Schmiedmayer group [*Phys Rev Lett* 2016]

Thermometers

– density fluctuations $g_2(z, z')$

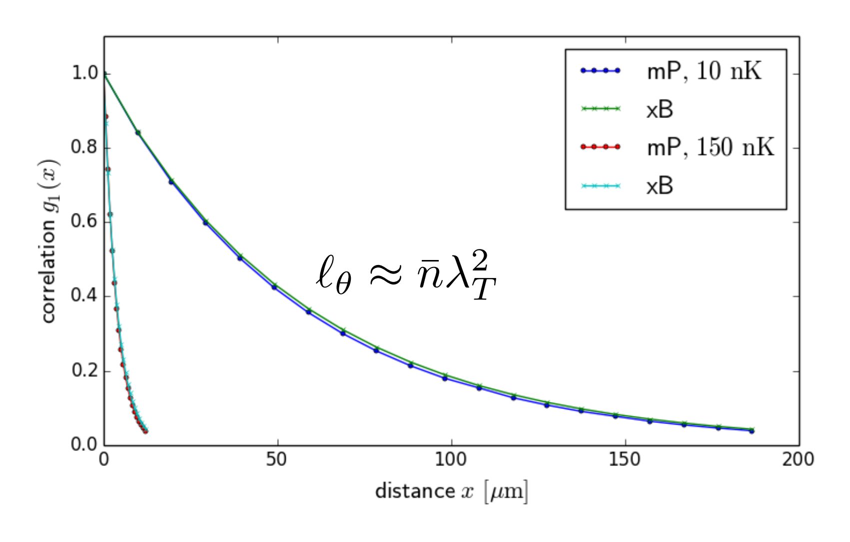
Jacqmin & IB group [*Phys Rev Lett* 2011]

dto after expansion

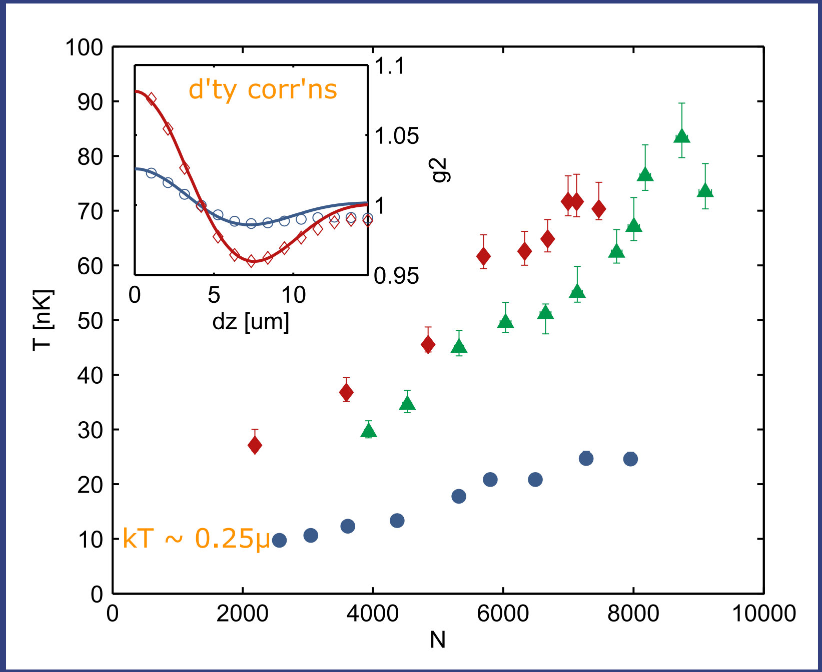
Manz & Schumm group [*Phys Rev A* 2010]

– density profile (wings)

– phase coherence length



CH, Sauer, Proukakis [*J Phys B* 2017]



– uniform particle loss

– nearly integrable system: no thermalisation

Model – stochastic Gross-Pitaevskii with Loss

Homogeneous quasi-1D Bose gas

$$\mathrm{i}\mathrm{d}\Psi = \left(-\frac{\hbar}{2m}\partial_z^2\Psi + \frac{g}{\hbar}|\Psi|^2\Psi\right)\mathrm{d}t - \frac{\mathrm{i}\Gamma}{2}\Psi\,\mathrm{d}t + \mathrm{d}\xi(z,t)$$

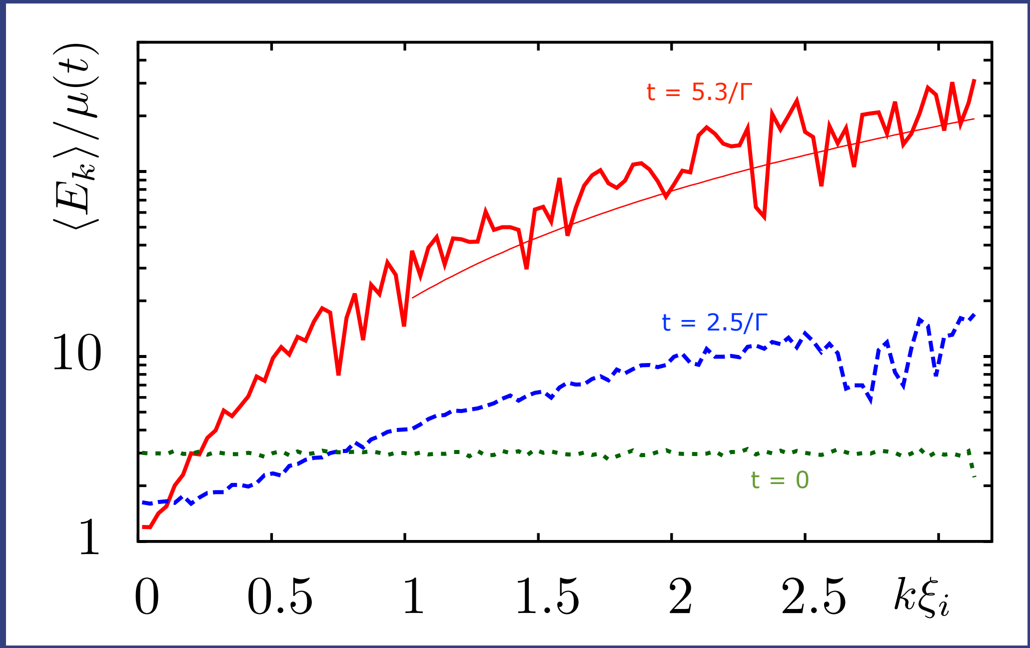
evaporation vs noise

Bogoliubov expansion $\Psi(z,t) \approx \sqrt{n(z,t)} + \sum_k \left\{ b_k(t)u_k(z;t) + b_k^\dagger(t)v_k(z;t) \right\}$

classical limit:

$\langle E_k \rangle = \hbar\omega_k \langle |b_k|^2 \rangle \approx k_\mathrm{B}T \to k_\mathrm{B}T_k$

Average mode energies



Johnson & IB group [*Phys Rev A* 2017]

– long-lived non-equilibrium state

weak/no mode coupling (• sGPe simulation)

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evaporation vs noise

Bogoliubov expansion $\Psi \approx \sqrt{n} + \sum_k \left\{ b_k u_k + b_k^\dagger v_k \right\}$

dropping density $n(t) \sim \mathrm{e}^{-\Gamma t} \mapsto \omega_k(t)$

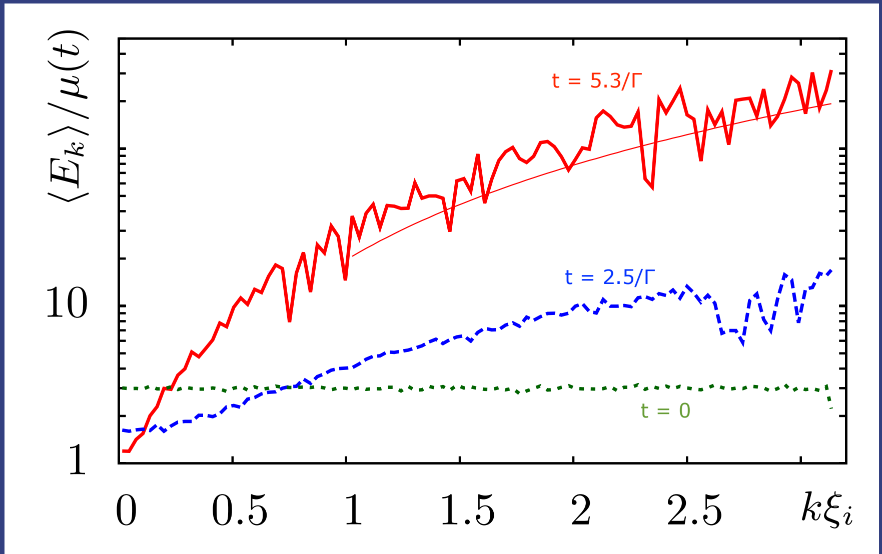
$$\mathrm{d}b_k = \left(-\mathrm{i}\omega_k - \frac{\Gamma}{2}\right) b_k\,\mathrm{d}t + \mathrm{d}\chi_k$$

mode-projected noise: squeezed

density $\langle(\mathrm{Re}\,\mathrm{d}\chi_k)^2\rangle = \frac{\Gamma \mathrm{d}t}{2}\int \mathrm{d}z\,(u_k + v_k)^2$

phase $\langle(\mathrm{Im}\,\mathrm{d}\chi_k)^2\rangle = \frac{\Gamma \mathrm{d}t}{2}\int \mathrm{d}z\,(u_k - v_k)^2$

Average mode energies



Johnson & IB group [*Phys Rev A* 2017]

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$$\text{density} \quad \langle(\mathrm{Re}\,\mathrm{d}\chi_k)^2\rangle = \frac{\Gamma\mathrm{d}t}{4}\int \mathrm{d}z\,(u_k + v_k)^2$$

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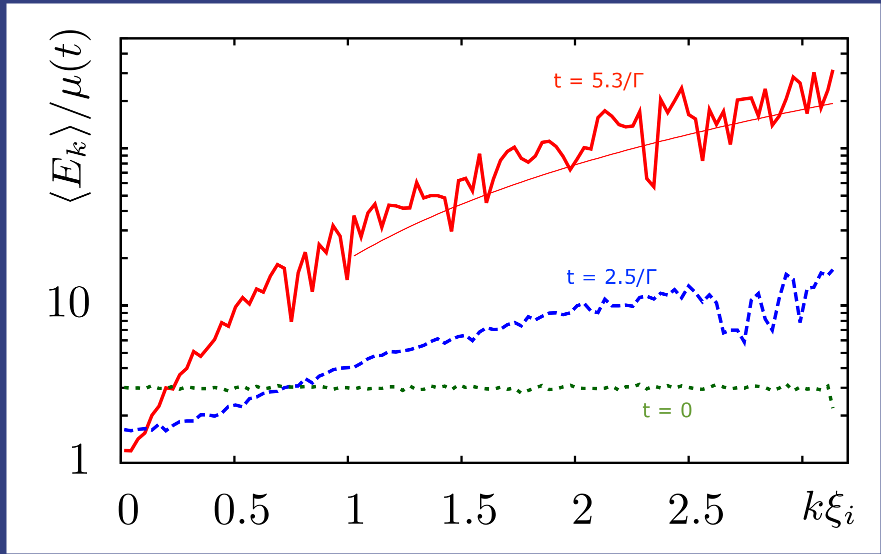
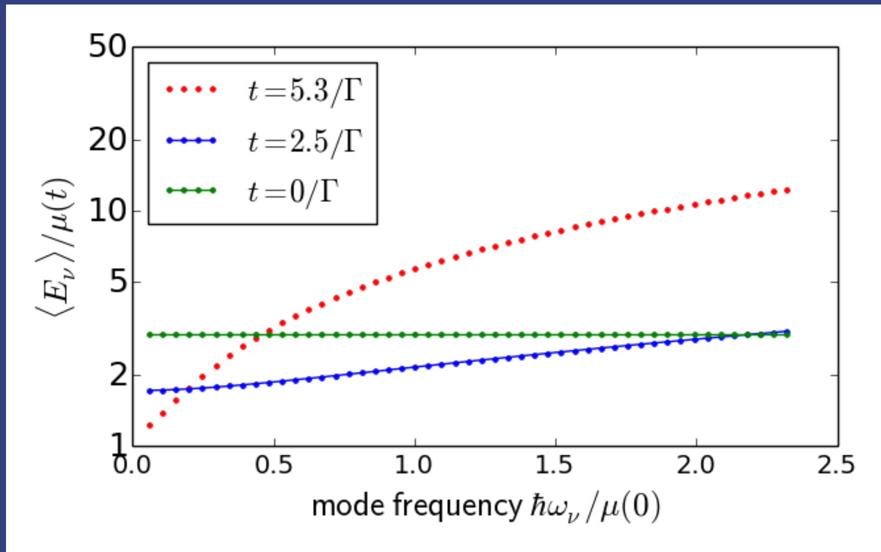
- this talk: trapped system

Average mode energies



Trapped system



Bogoliubov modes in harmonic trap

Thomas-Fermi approximation, radius R

$$gn(z,t) \approx \mu(t)\left(1 - z^2/R(t)^2\right)$$

Legendre polynomials, $\omega_\nu = \omega\sqrt{\nu(\nu+1)/2}$

$$u_\nu + v_\nu = \left(\frac{\hbar\omega_\nu}{2\mu}\right)^{1/2}\sqrt{\frac{2\nu+1}{2R}}\,\frac{P_\nu(z/R)}{\sqrt{1-z^2/R^2}}$$

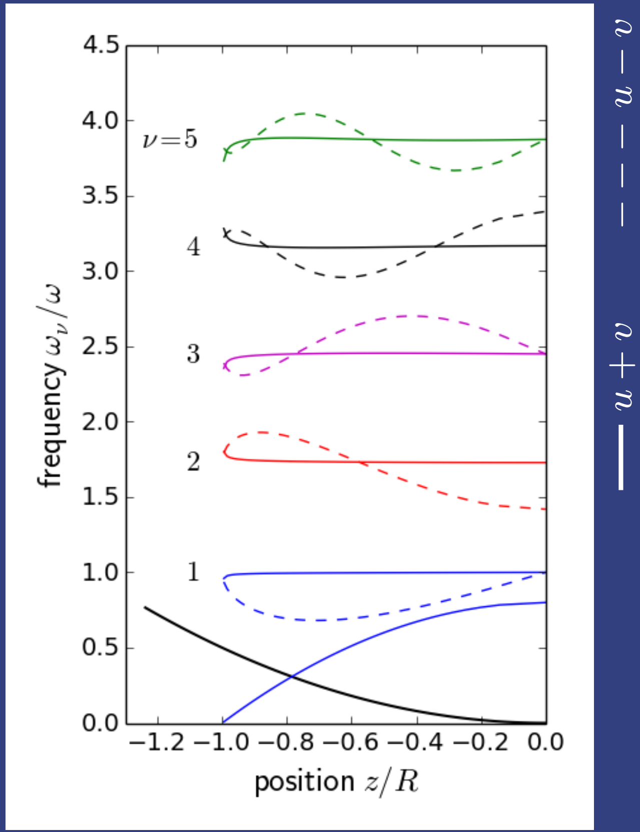
$$u_\nu - v_\nu = \frac{2\mu}{\hbar\omega_\nu}\left(1-\frac{z^2}{R^2}\right)(u_\nu + v_\nu)$$

Ho & Ma [*J Low Temp Phys* 1999]

adiabatically following $R(t)$

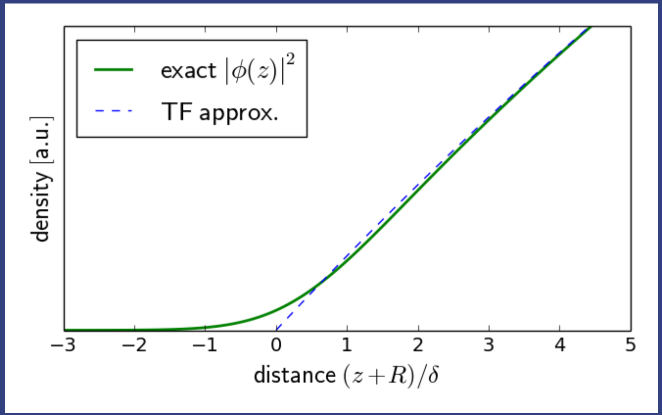
- not integrable at borders $z \to \pm R$

density noise $\langle(\mathrm{Re}\,\mathrm{d}\chi_\nu)^2\rangle \sim \int \mathrm{d}z\,(u_\nu + v_\nu)^2 \to \infty$



Bogoliubov modes at the borderline

divergence = artefact of TF approximation



check with numerical solution ↑ →

Boundary layer technique

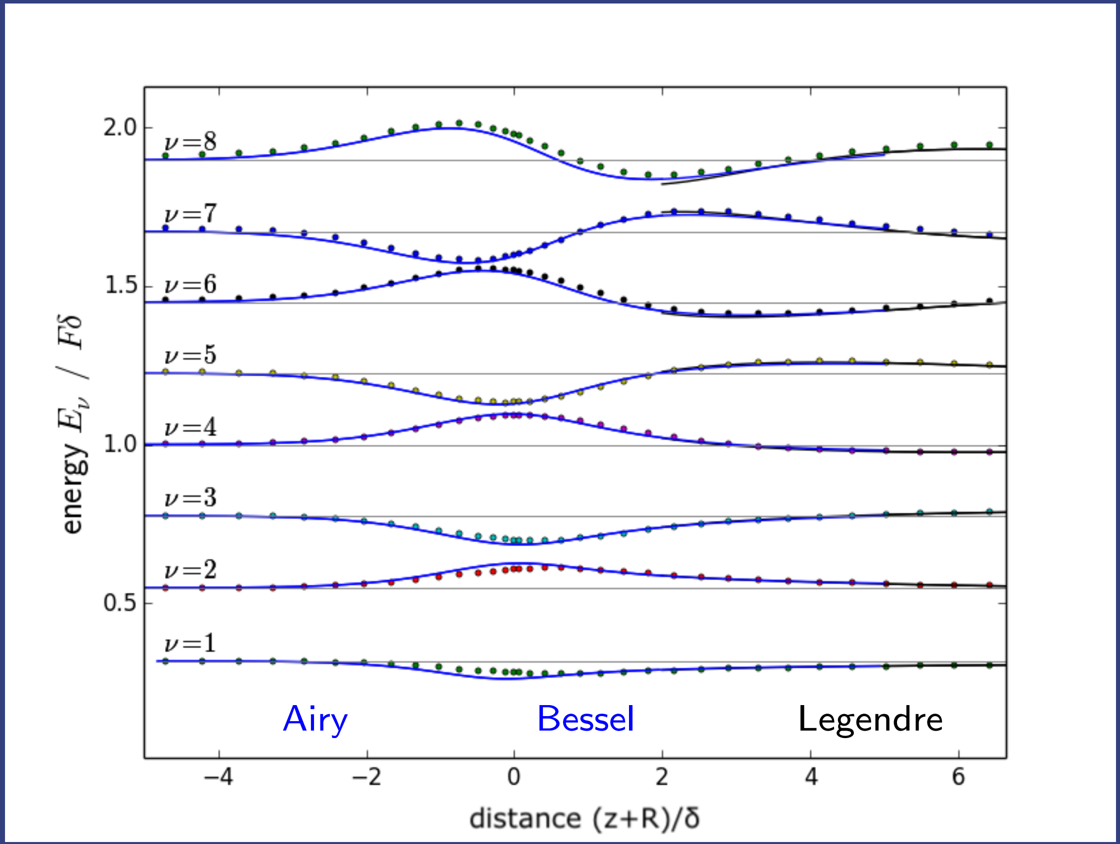
Fetter & Feder [*Phys Rev A* 1998]

Diallo & CH [*J Phys B* 2015]

linearised potential $V(z) \approx \mu - F(z+R)$

length scale $\delta = (\hbar^2/2mF)^{1/3} \ll R$

Smooth density modes $u_\nu(z) + v_\nu(z)$



• • • numerics — boundary layer — inner/Legendre

Energy loss of trapped modes

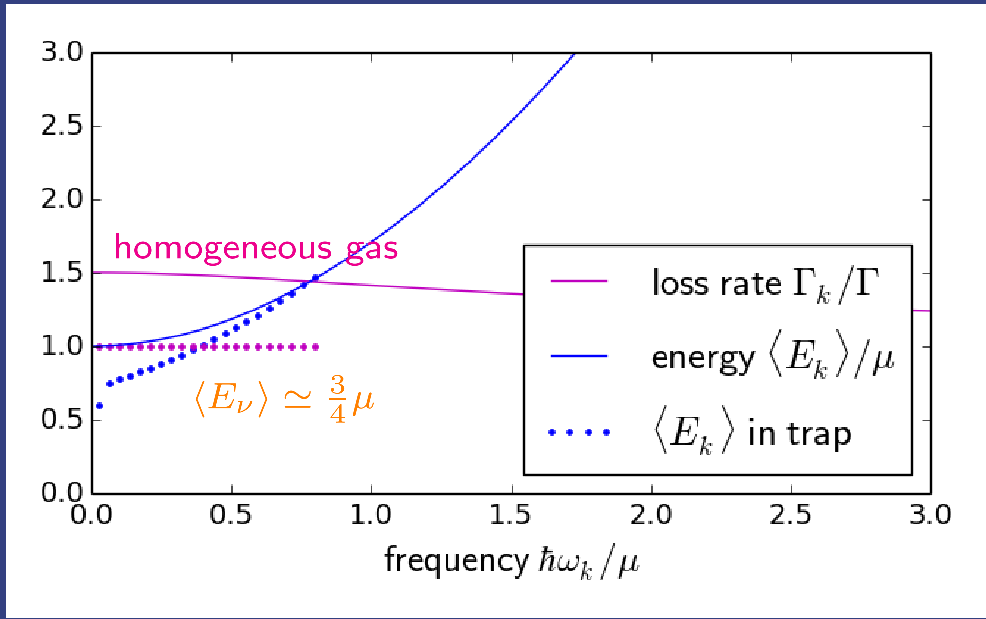
General theory

$$\mathrm{d}b_k = \left(-\mathrm{i}\omega_k - \frac{\Gamma}{2}\right) b_k\,\mathrm{d}t + \mathrm{d}\chi_k$$

$$\langle E_k \rangle = \hbar\omega_k \langle |b_k|^2 \rangle$$

$$\Rightarrow \quad \frac{\mathrm{d}}{\mathrm{d}t}\langle E_k \rangle \approx -\left(\Gamma + \frac{\dot{\omega}_k}{\omega_k}\right) E_k + \frac{\Gamma}{2}\hbar\omega_k \int \mathrm{d}z\,(u_k^2 + v_k^2)$$

– evaluate numerically →



- non-equilibrium mode temperatures T_ν generalised Gibbs ensemble
- lowest temperature ∼ Vienna experiment (?) in Palaiseau: $k_B T \gtrsim 0.3\,\mu$

Jacqmin & al [*Phys Rev Lett* 2011]

Conclusion

Dissipative vs evaporative cooling:

– non-uniform temperature

– weak coupling between excitations (. . . why?)

Model:

– Gross-Pitaevskii + shot noise = “beyond mean field”

– project on Bogoliubov modes: $\rightarrow T_k$ per mode

– compare to exp’tal temperatures: “nearly there”

expts: $k_{\rm B}T \quad \sim \quad 0.25 \ldots 0.3\,\mu$

theo: $\quad \gtrsim \quad 0.75\,\mu$