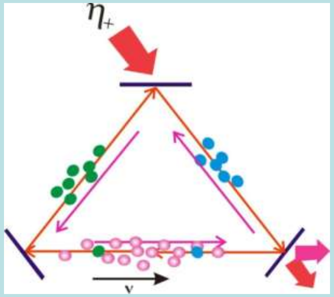
Innsbruck Physics Research Center

SFB FoQuS Foundations and Applications of Quantum Science

Selfordering and sympathetic cooling in optical resonators



Helmut Ritsch
Theoretische Physik
Universität Innsbruck

New physics with ultracold molecules
KITP, March 12, 2013

Austrian Science Foundation

Innsbruck Physics Research Center

SFB FoQuS Foundations and Applications of Quantum Science

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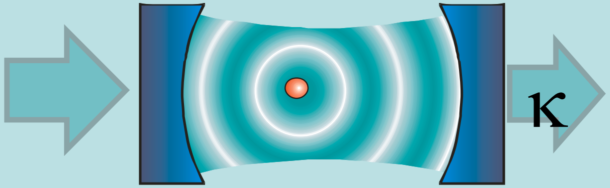
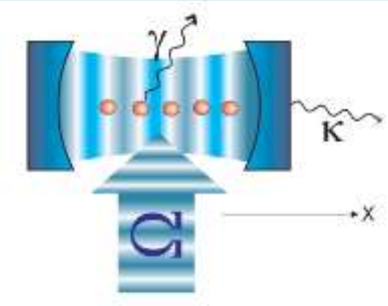
Igor Mekhov (Oxford), Maciej Lewenstein (IFCO)

contents

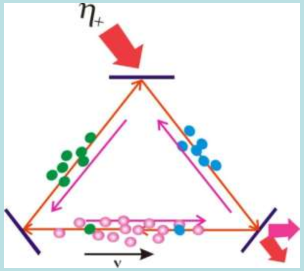
- *Cavity cooling basics and applications*



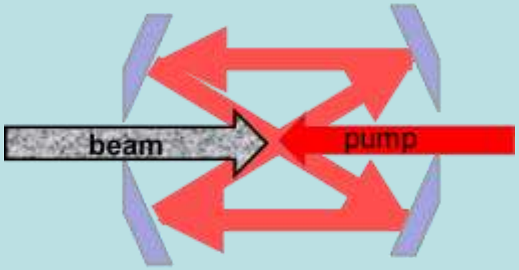
- *Selforganization and superradiant cooling in a cavity generated optical lattice*



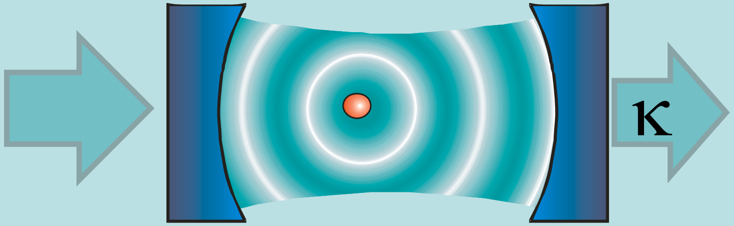
- *Multispecies cavity cooling and sympathetic self organisation*



- *Beam deceleration by cavity enhanced collective backscattering (COMORL)*



Lightforces on polarizable particles in optical resonators



dispersive regime at
large laser to particle detuning
⇒ dipole force dominates

***Light forces** of resonatorfield determine atomic motion*

interaction

trapping

friction + diffusion

correlation and entanglement

***Cavity QED** : atoms change resonator field dynamics*

***U(x)** = **optical potential per photon** =*
cavity frequency shift per atom

$$\gg$$

γ(x)** = **photon loss per particle

$$U \sim \kappa \gg \gamma$$

Classical dynamics in optical resonators

field amplitude: $\dot{E} = [-\kappa - \boldsymbol{\gamma(x)} + i\Delta_c - i\boldsymbol{U(x)}]\,E - \alpha,$

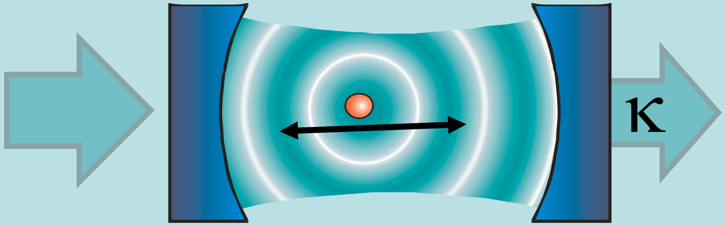
momentum: $\dot{p} = -|E|^2 \frac{d}{dx}\boldsymbol{U(x)},$

position: $\dot{x} = p/m.$

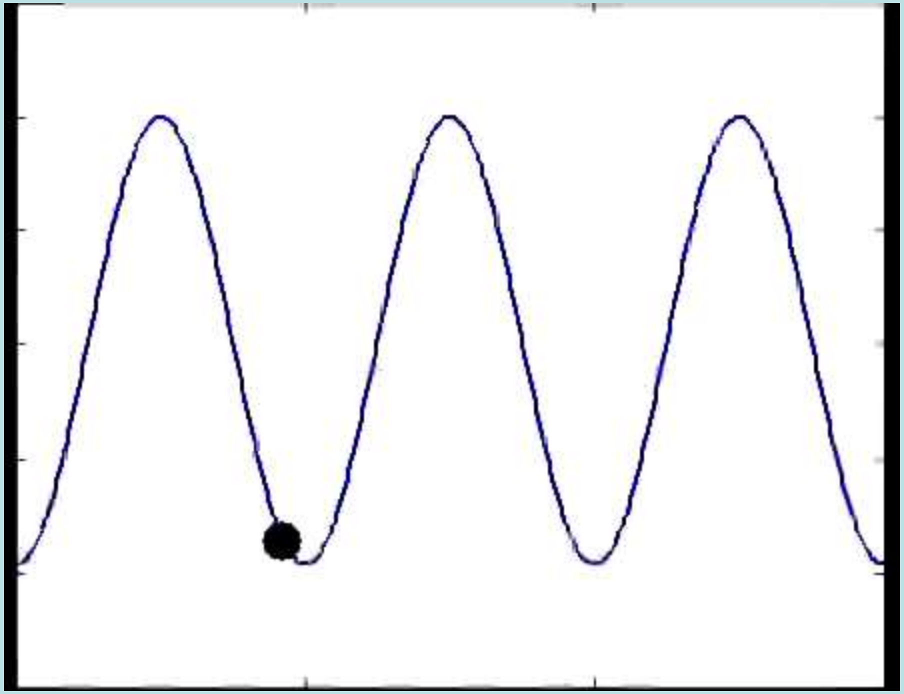
detuning + loss of mode
depend on atom position

- red detuning: atoms drawn to field maxima
- field gets maximal for atom at antinode

particle moving along axis



Lewenstein , PRL 95: ions
Horak, PRL 97: atoms
Vuletic, Chu, PRL 00: atoms
Vitali, PRL 02: mirrors



Cavity cooling

analytic solution for friction and diffusion for slow point partilces

friction

$$\overline{\overline{F}}_1 = -k^2 \frac{\eta^2 U_0^2}{4\kappa^4}$$

diffusion

$$\overline{D} = k^2 \kappa \frac{\eta^2 U_0^2}{8\kappa^4}$$

temperature

$$\boxed{k_B T = -\frac{\overline{D}}{\overline{\overline{F}}_1} = \frac{\kappa}{2}}$$

κ ... cavity linewidth

- ***sub-Doppler cooling for $\kappa < \gamma$ (good cavity)***
- ***no spontaneous emission needed***
- ***suitable for all polarizable particles (molecules, nanoparticles, beads)***

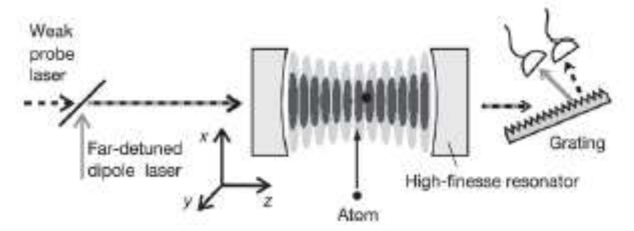
H. R., P. Domokos, F. Brenneke and T. Esslinger, RMP 2013,

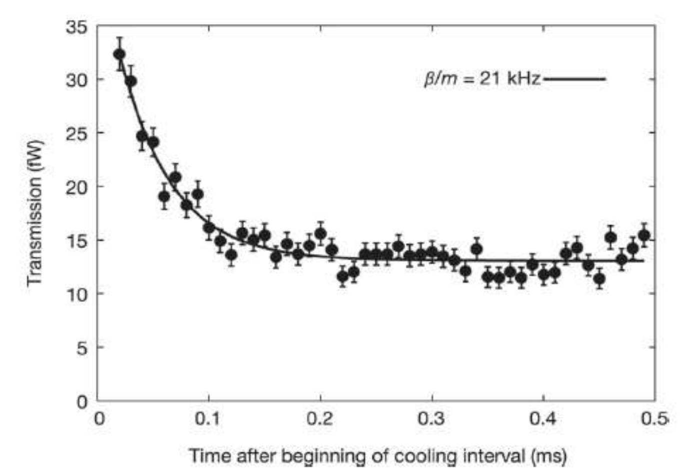
first dedicated experiment:
MPQ München, Nature 2004

Cavity cooling of a single atom

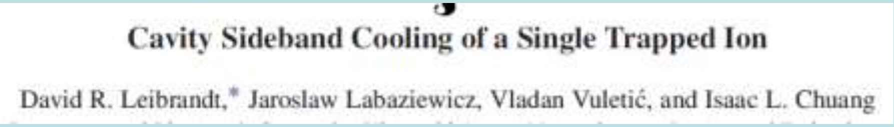
P. Maunz, T. Puppe, I. Schuster, N. Syassen, P. W. H. Pinkse & G. Rempe

Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Str. 1,
D-85748 Garching, Germany



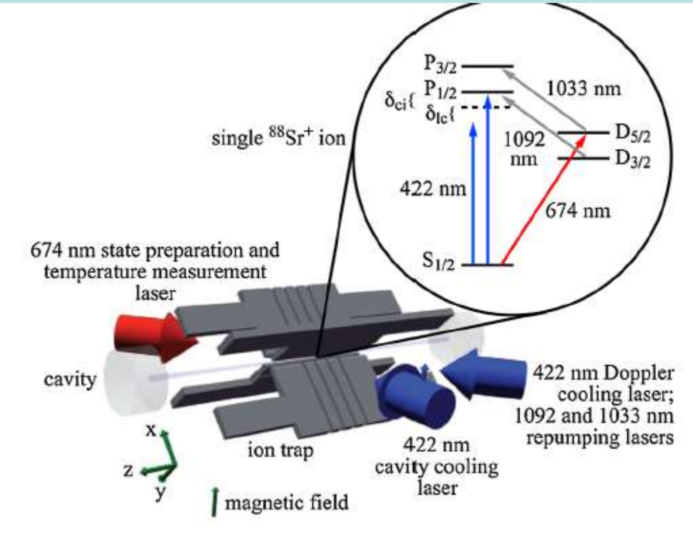


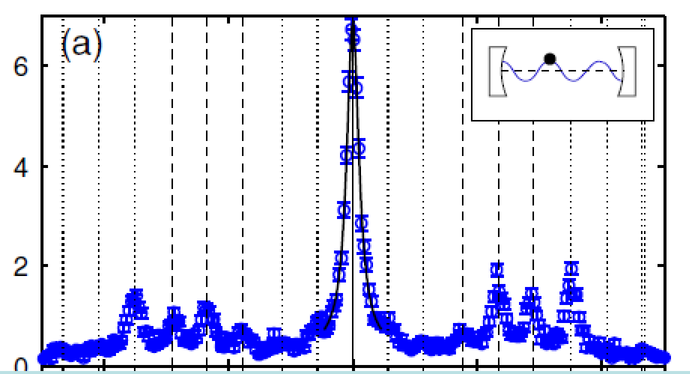
Ions: PRL 2009



Cavity Sideband Cooling of a Single Trapped Ion

David R. Leibrandt,* Jaroslaw Labaziewicz, Vladan Vuletić, and Isaac L. Chuang





- temperature und cooling rate agree well with theory
- Ions: multiple vibrational modes addressed (Vuletic 2011), Barrett (priv. commun.)
- **new results with atom ensembles (MIT), molecules + nanobeads (Vienna)**

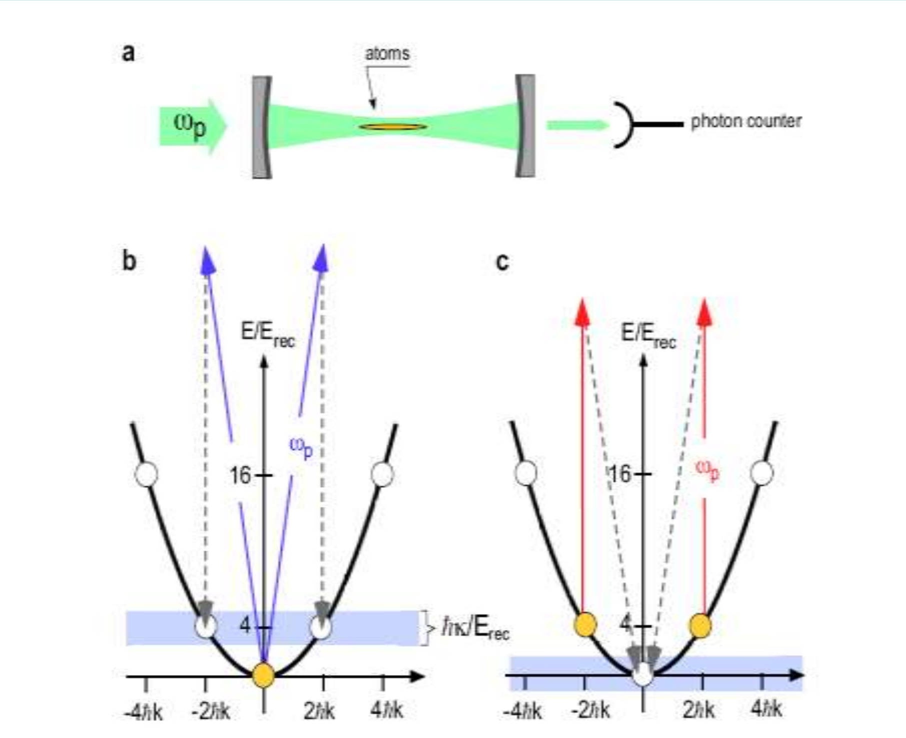
Experiment: cavity ground state cooling of free atoms

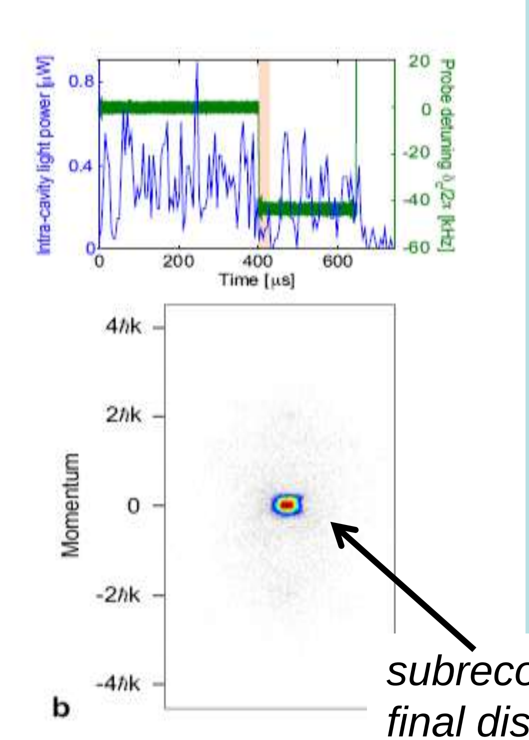
„sub-recoil“ regime :

$\kappa < \omega_r$

A. Hemmerich, Hamburg (Science 2012)

momentum distribution
smaller than
single photon recoil



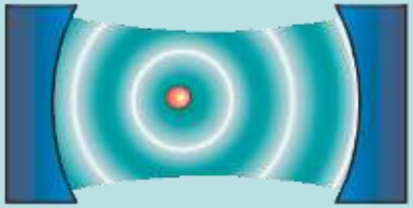


subrecoil final dist !

⇒ Cavity cooling with Bose stimulation to replace evaporation
⇒ BEC formation without particle loss

Wolke M., J. Klinner, H. Keler, and A. Hemmerich (2012), Science, **337** (6090)

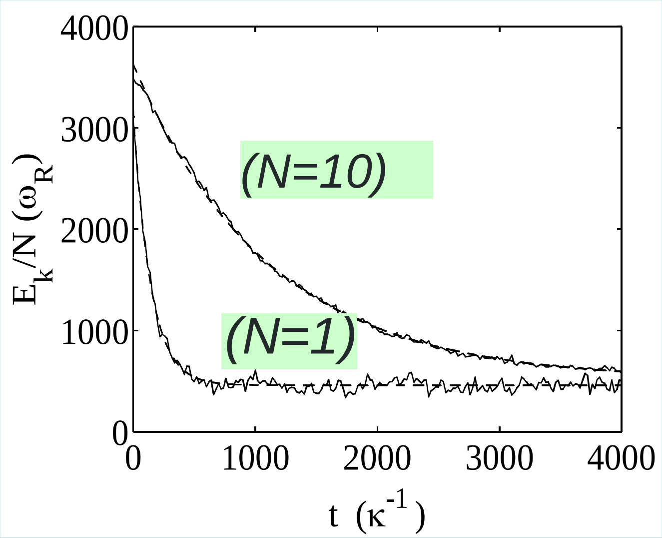
Scaling of resonator induced cooling

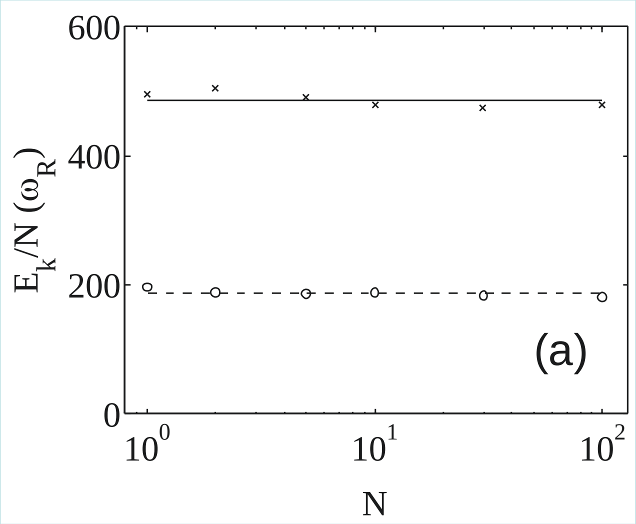


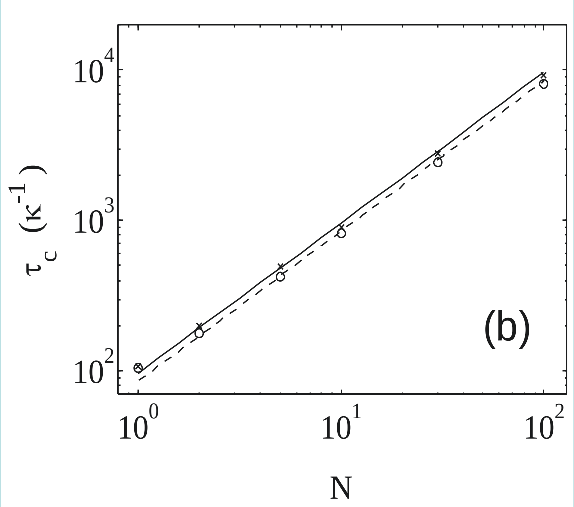
Is resonator cooling good for larger ensembles ?

temperature unchanged

cooling time grows





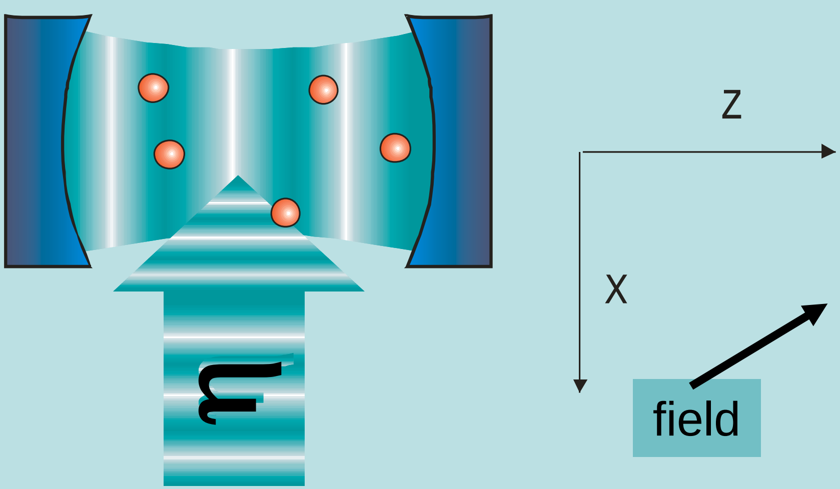


Slow cooling for large ensembles!

Selforganisation of large ensembles through super-radiant light scattering

***New-geometry:* transverse pump:**
direct excitation of atoms from side !

phase of excitation
light depends on position x



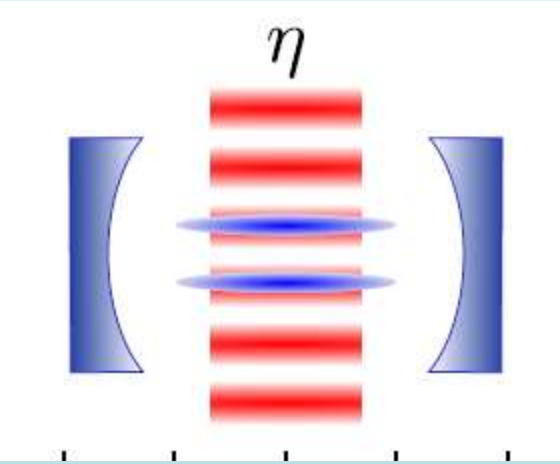
$$\dot{\sigma}_i = (i\Delta_A - \gamma)\sigma_i - g(z_i)a + \eta_x + \xi_A$$

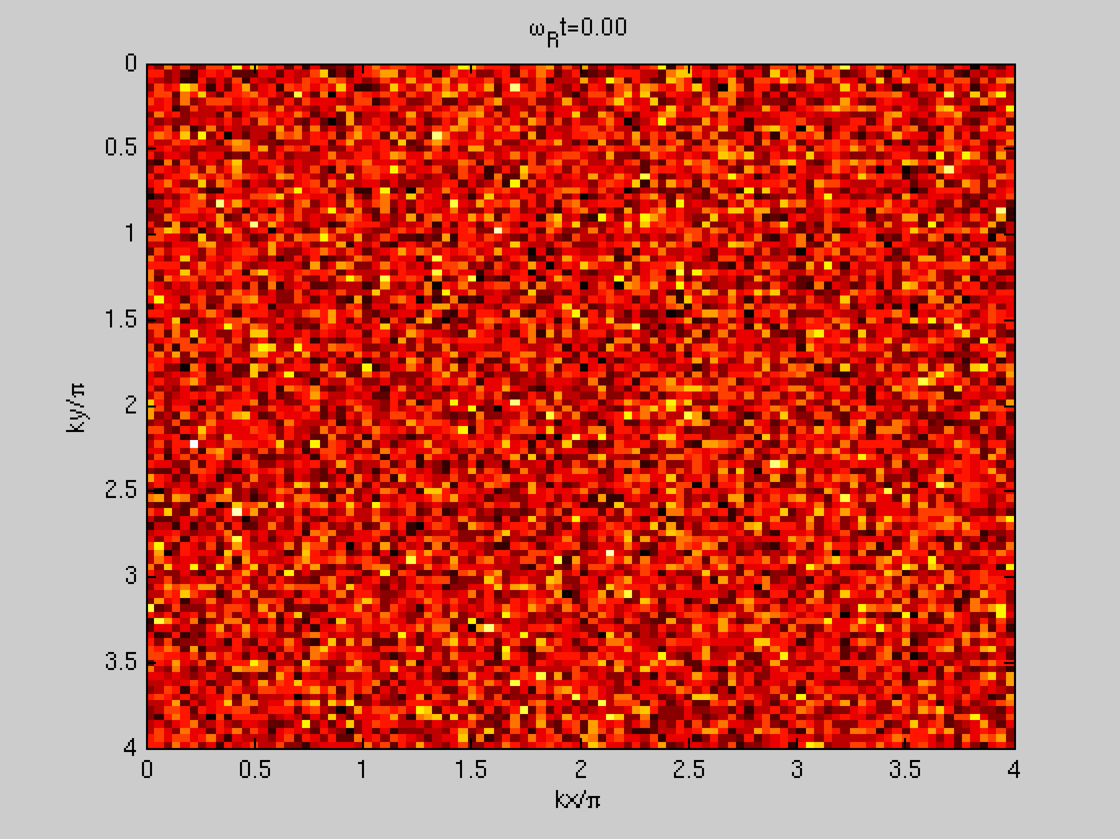
$$\dot{a} = (i\Delta_C - \kappa)a + \underbrace{\sum_{i=1}^{N} g^*(z_i)\sigma_i}+ \xi_i \,.$$

collective pumpstrength ***R***

Field in cavity generated only by atoms
R *= 0 for random atomic distribution*
R ~ Ng *for regular lattice distribution*

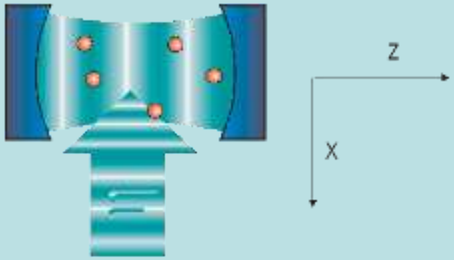
Numerical simulations of coupled dynamics including atomic motion (start with random distribution at Doppler temperature)

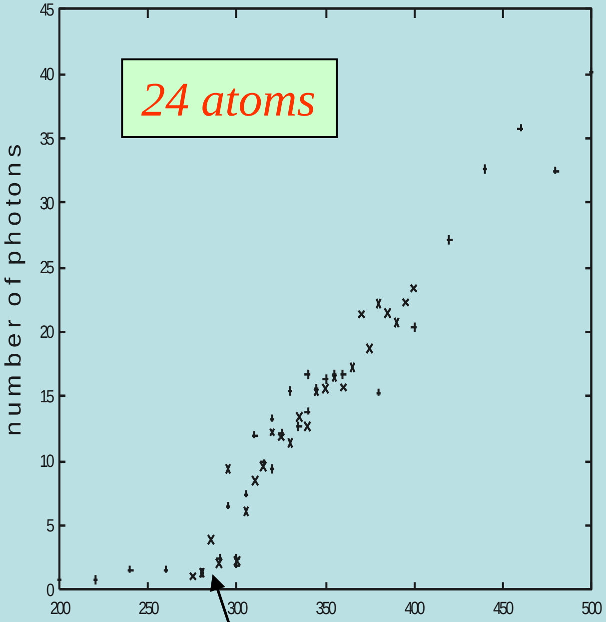




P. Domokos *et al.*, J. Phys. B 34, 187 (2001).

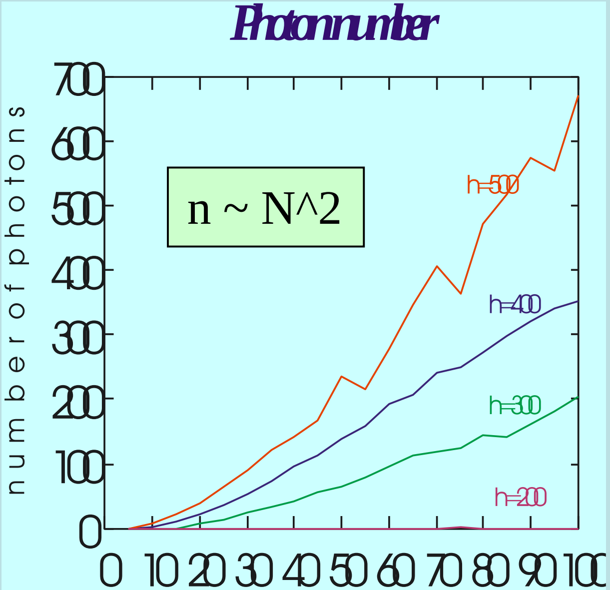
N-atoms:
Numerical simulations of coupled atom-field dynamics
(start with random distribution at Doppler temperature)





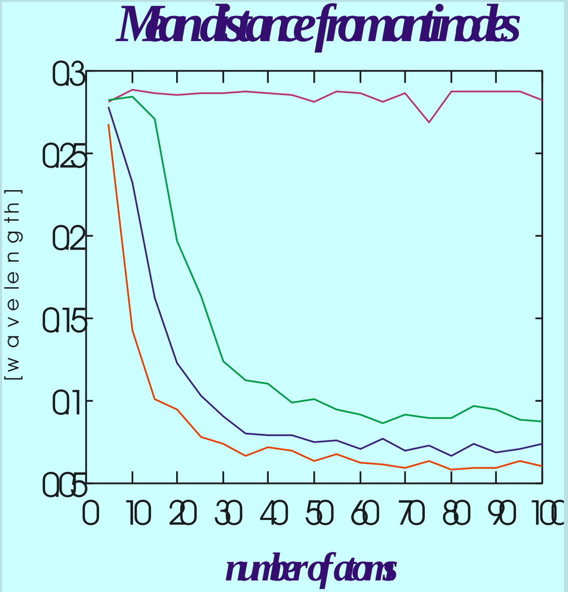
24 atoms

pump strength



n ~ N^2

atom number



clear threshold !

Superradiance !
quadratic dependence on
atom number !

Selforganization!

Atom-field dynamics for very large particle number : => Vlasov equation for particle distribution

Continuous density approximation for cold cloud: single particle distribution function

$$f_s(x,p,t) := \frac{1}{N_s}\left\langle \sum_{j_s=1}^{N_s} \delta(x - x_{j_s}(t))\delta(p - p_{j_s}(t)) \right\rangle$$

$$\Phi_s(x,\alpha) = \hbar U_{0,s}|\alpha|^2 \sin^2(kx) + \hbar\eta_s(\alpha + \alpha^*)\sin(kx)$$

Vlasov + field equation

$$\frac{\partial f_s}{\partial t} + \frac{p}{m_s}\frac{\partial f_s}{\partial x} - \frac{\partial \Phi_s(x,\langle\alpha\rangle)}{\partial x}\frac{\partial f_s}{\partial p} = 0$$

$$\dot{\alpha} = (i\Delta_c - \kappa)\,\alpha - i\sum_s \int \Big(\alpha\, U_{0,s}\sin^2(kx) + \eta_s \sin(kx)\Big)\, f_s\, dx\, dp$$

stability threshold of homogeneous distribution:

$$\frac{N\eta^2}{k_B T}\,\mathrm{vp}\int_{-\infty}^{\infty}\frac{g'(\xi)}{-2\xi}\mathrm{d}\xi < \frac{\delta^2+\kappa^2}{\hbar|\delta|}$$

Niedenzu W., T. Grießer, H. Ritsch (2011), EPL, 43001

threshold at thermal equilibrium:

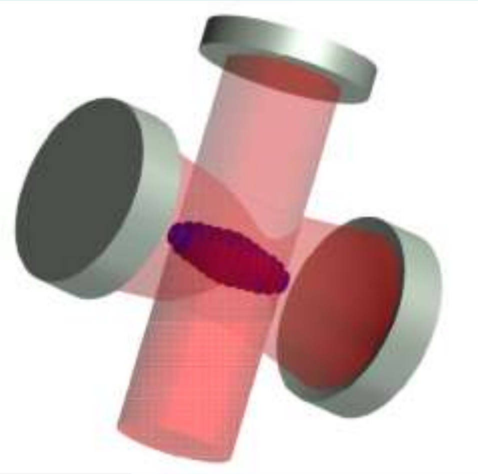
$$U_0 N V_{opt} > \kappa^2$$

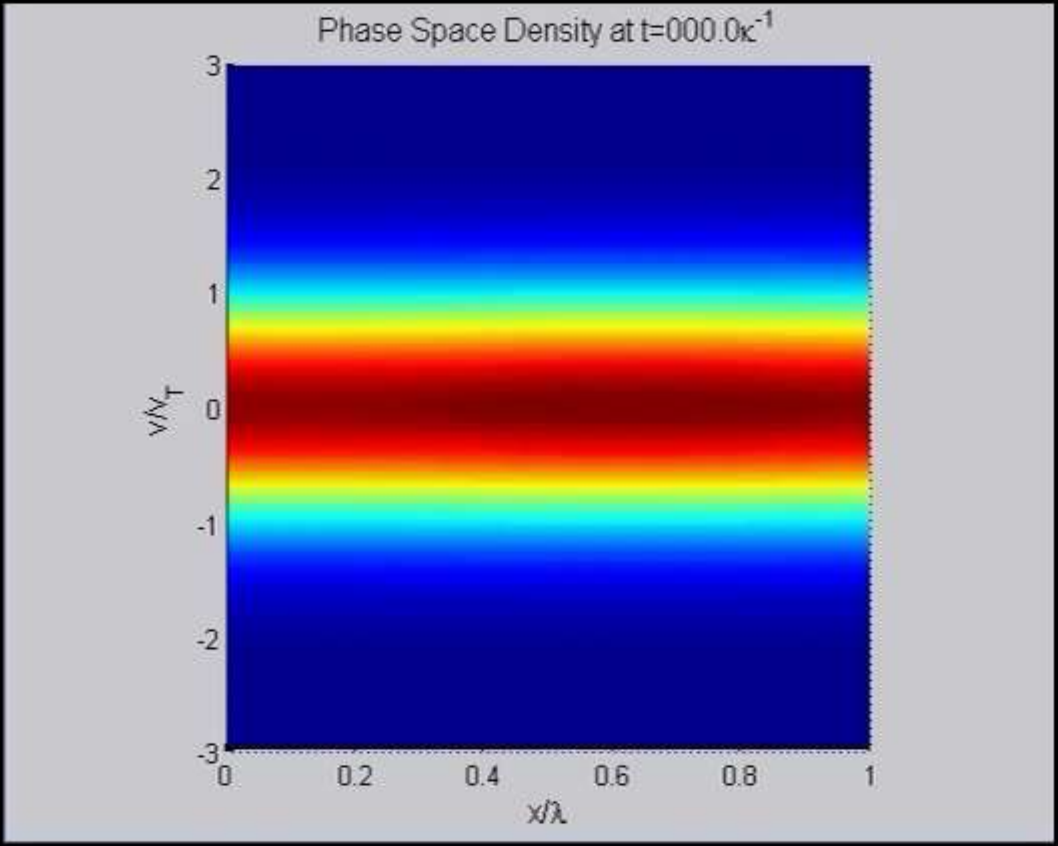
frequency shift of cavity

pump laser opt. potential

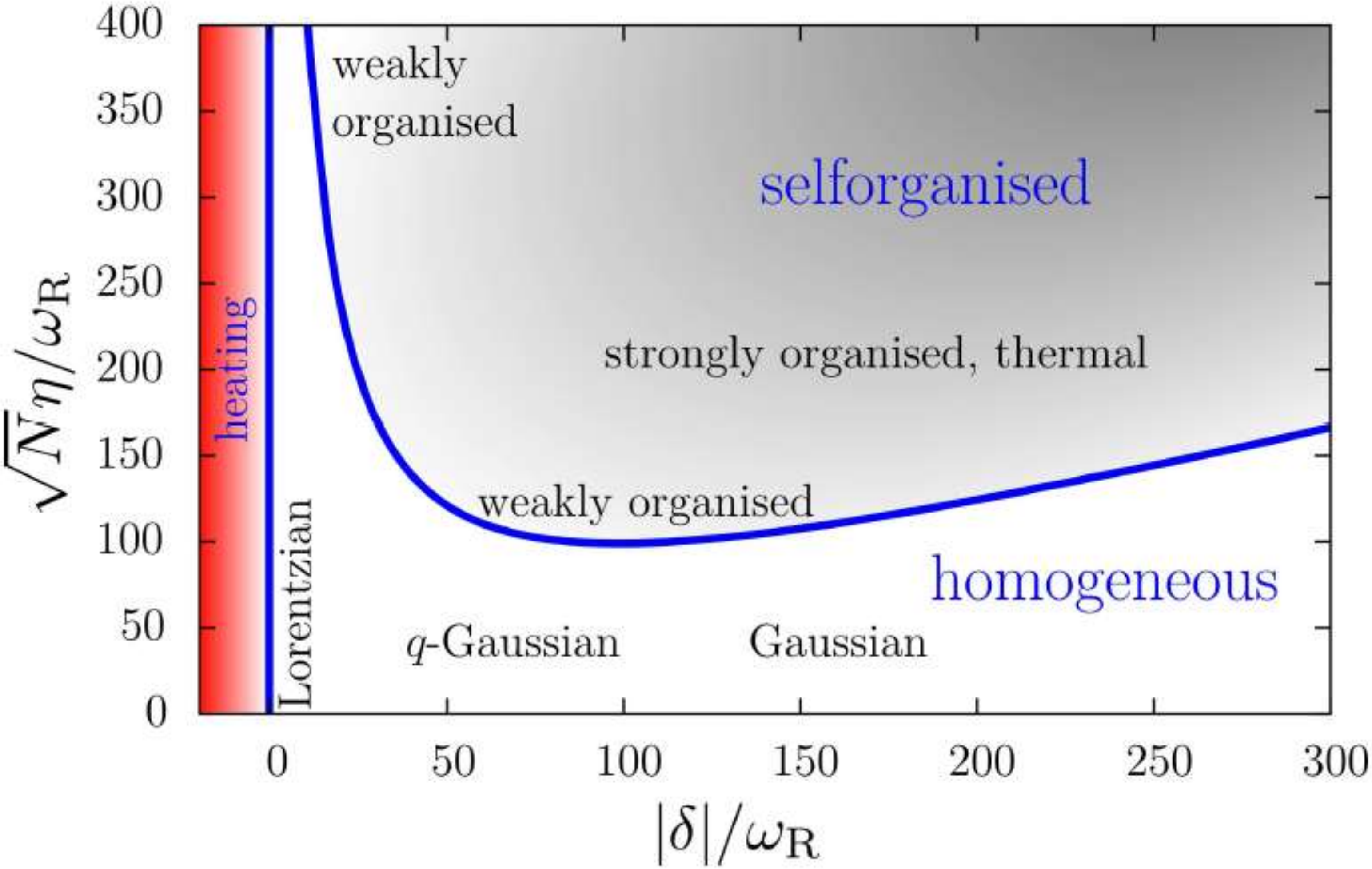
cavity damping

Numerical simulation of Vlasov equation (single optical period):

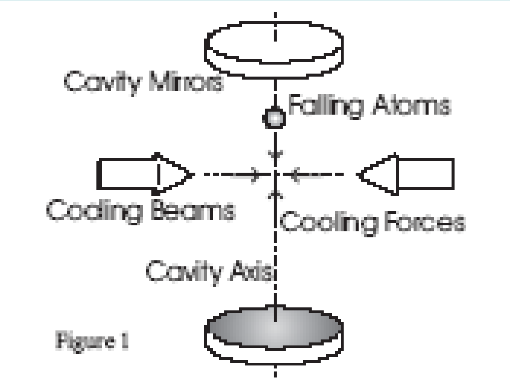




„phase diagram“

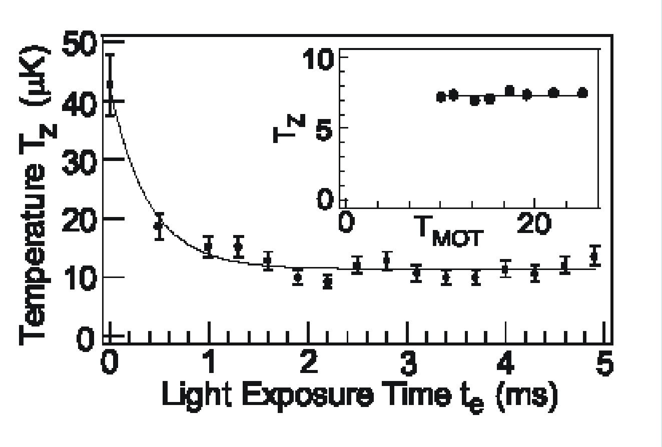


Experiment with atoms:



Vladan Vuletic,
Stanford University (=>MIT)

10^6 Caesium atoms in resonator with transverse coherent pump field

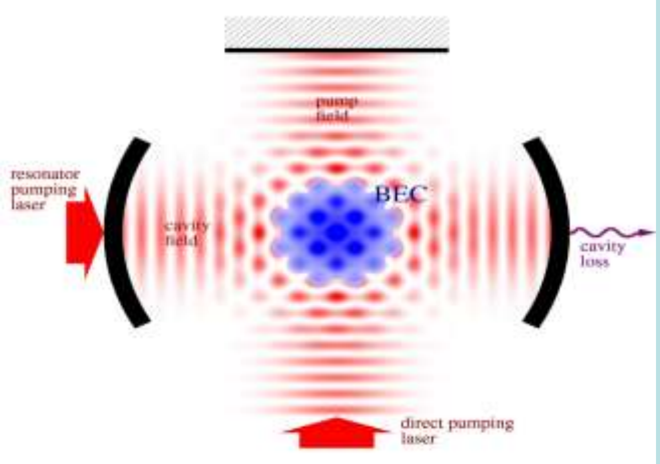


Phase stability of coherent emission with Pi-jumps (bistable pattern)

** >10^6 Atoms trapped and cooled to ~mK with simultaneous coherent light emission*

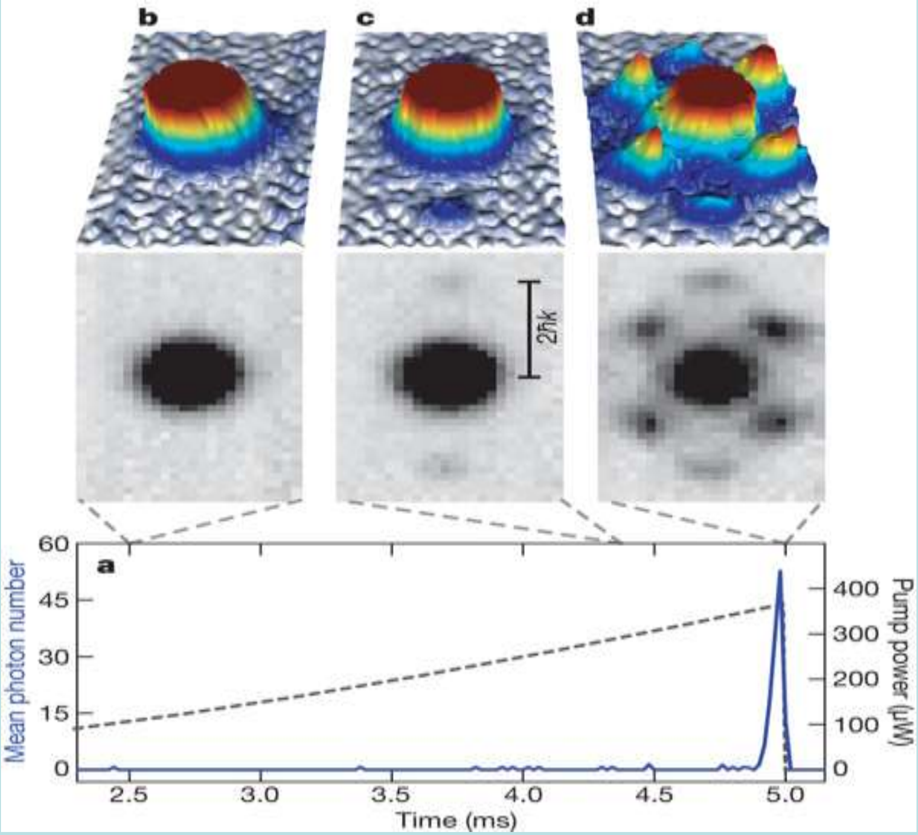
- ***Experiment works better than predictions and even close to cavity resonance***
- ***2-nd experiment with accelerations of >10^6 g at very low saturation***
- ***recent experiments: Renzoni (London), M. Baden + K. Arnold (Singapore)***
- ***more theory: multimode selfordering : P. Goldbart + B. Lev, Sadchdev, …***

BEC: Observation of the phase transition to new phase with coherence + ordering present



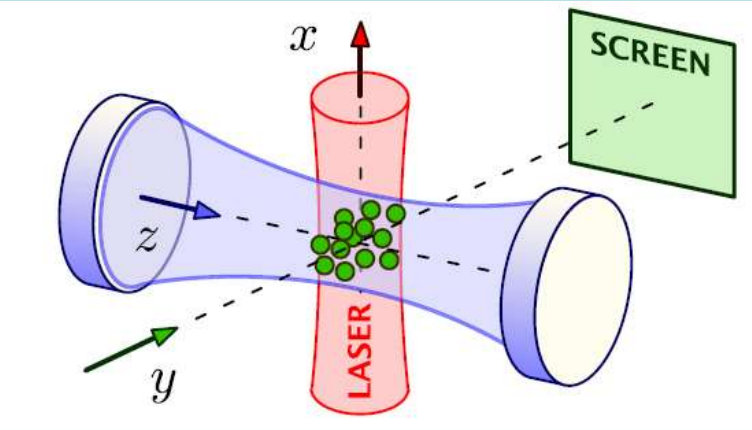
$$\Psi(x) = \frac{1}{\sqrt{L}} c_0 + \sqrt{\frac{2}{L}} c_1 \cos kx$$

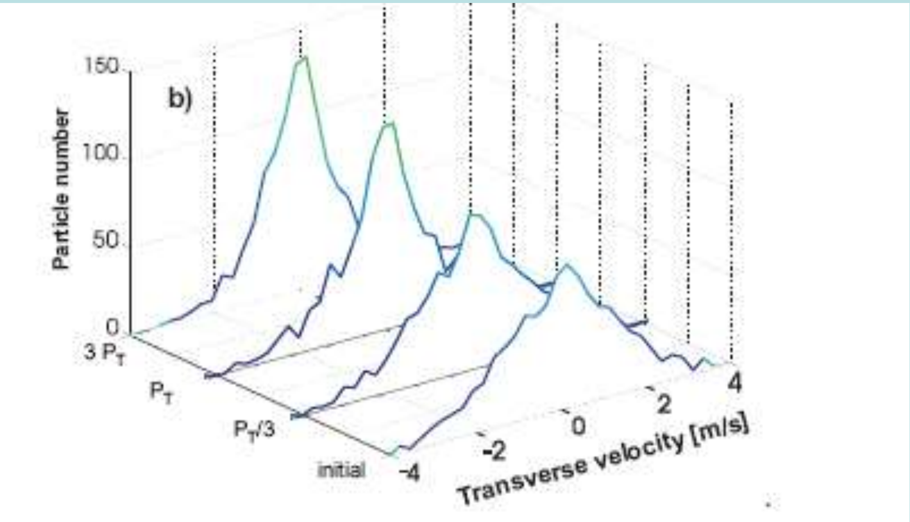
$$H = -\delta_C\, a^\dagger a + \omega_R \hat{S}_z + iy(a^\dagger - a)\hat{S}_x/\sqrt{N} + u a^\dagger a \left(\tfrac{1}{2} + \hat{S}_z/N\right)$$

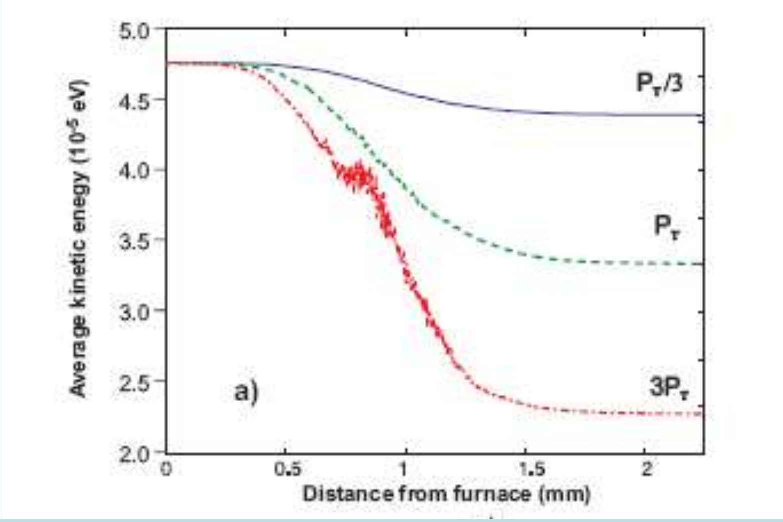


K Baumann *et al. Nature* 464, 1301-1306 (2010) doi:10.1038/nature09009

2D – transverse selforganization for collimation of a fast beam





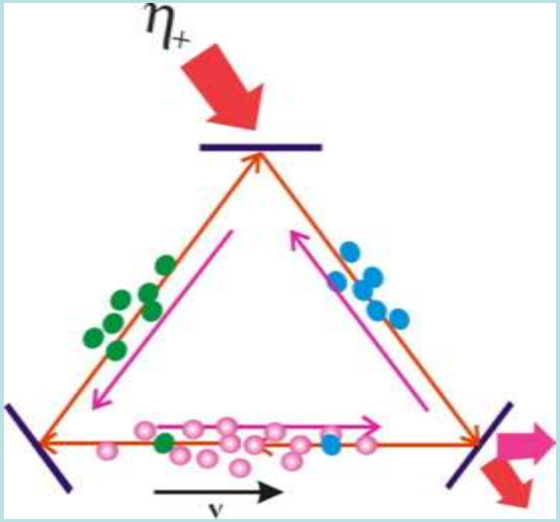


parameters for perfluoronated C60,
M. Arndt, Vienna

T. Salzburger, NJP 11, 55025 (2009)

Part III

Sympathetic selforganization and multispecies cooling



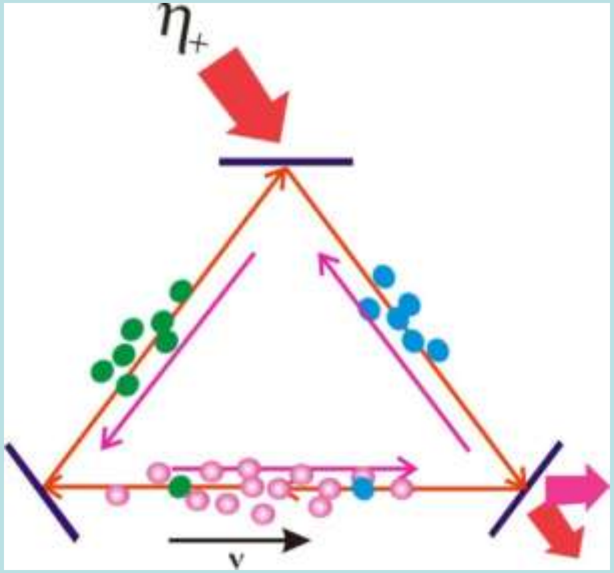
No (?) experiments with molecules yet !?

Why ?

B. Lev, et. al.
Phys. Rev. A **77** 023402

- Need suitable initial conditions to reach threshold !
- sufficient high starting phase space density: **U * N ~ κ**
  or
- sufficient intracavity power : V_opt ~ κ

Possible alternative solution:



Sympathetic selforganization and cooling

i.e: t**ake an atom experiment**
and
add some molecules !

both components selforganize
in the same pattern

Sympathetic multispecies dynamics

Field commonly scattered by all species

$$\dot{\alpha} = (-\kappa + i\Delta_c)\alpha - \\ -i\sum_{l=1}^{S} N_l \int \left(U_{0,l}\alpha\sin^2(kx) + \eta_l \sin(kx)\right) f_{K,l}(x,p)\,dx\,dp$$

Joint threshold condition

$$\sum_{l=1}^{S} \frac{N_l\eta_l^2}{k_B T_l}\left(\mathrm{P}\int_{-\infty}^{\infty}\frac{g_l'(u)}{-2u}dx\right) > \frac{\kappa^2+\delta^2}{\hbar|\delta|}$$

$$g(v/v_\mathrm{T}) := L v_\mathrm{T} f(v)$$

⇒ (‚thermal‘)

$$\sum_{l=1}^{S} \frac{N_l\eta_l^2}{k_B T_l} > \frac{\kappa^2+\delta^2}{\hbar|\delta|}.$$

common threshold strictly lower !

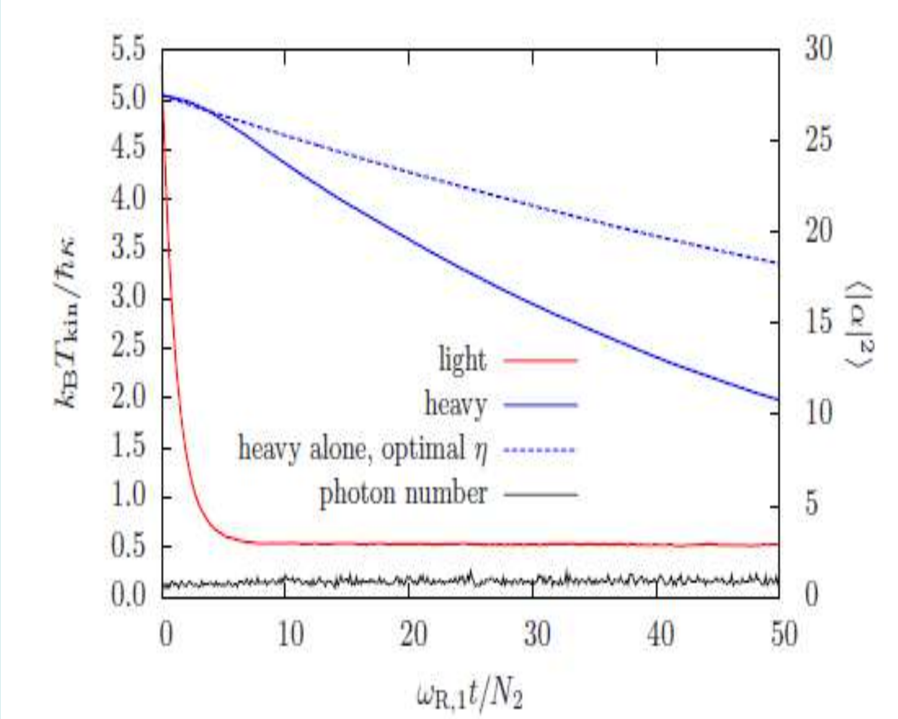
coupled kinetic equations individual enesmbles:

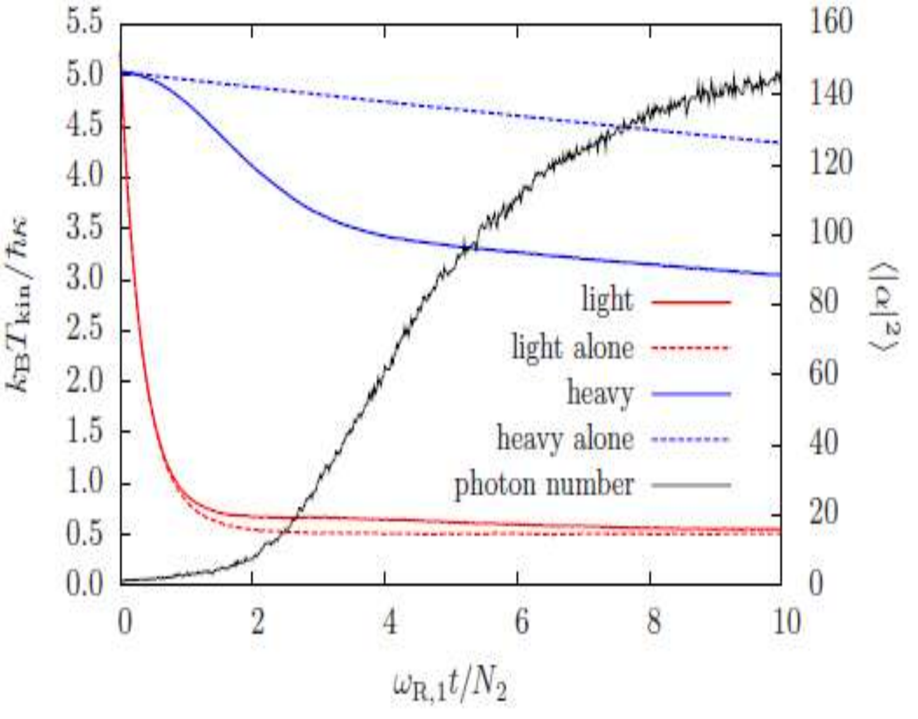
$$\dot{Q}_{2\to1} = -\frac{N_1 m_1}{N_2 m_2}\dot{Q}_{1\to2} \simeq N_1\eta_2^2\eta_1^2\frac{4\sqrt{\pi}\hbar\delta^2}{(\kappa^2+\delta^2)^2}\times \\ \times\sqrt{\frac{\hbar\omega_{\mathrm{R},1}}{k_\mathrm{B}T_1}}\left(1-\frac{T_2}{T_1}\right)\left(1+\frac{m_1T_2}{m_2T_1}\right)^{-3/2}$$

interspecies energy flux !!

Sympathetic two-species cooling at same initial temperature

$$m_2 = 200 m_1, \ N_1 = 200, \ N_2 = 200.$$





Below threshold:
enhanced cavity cooling

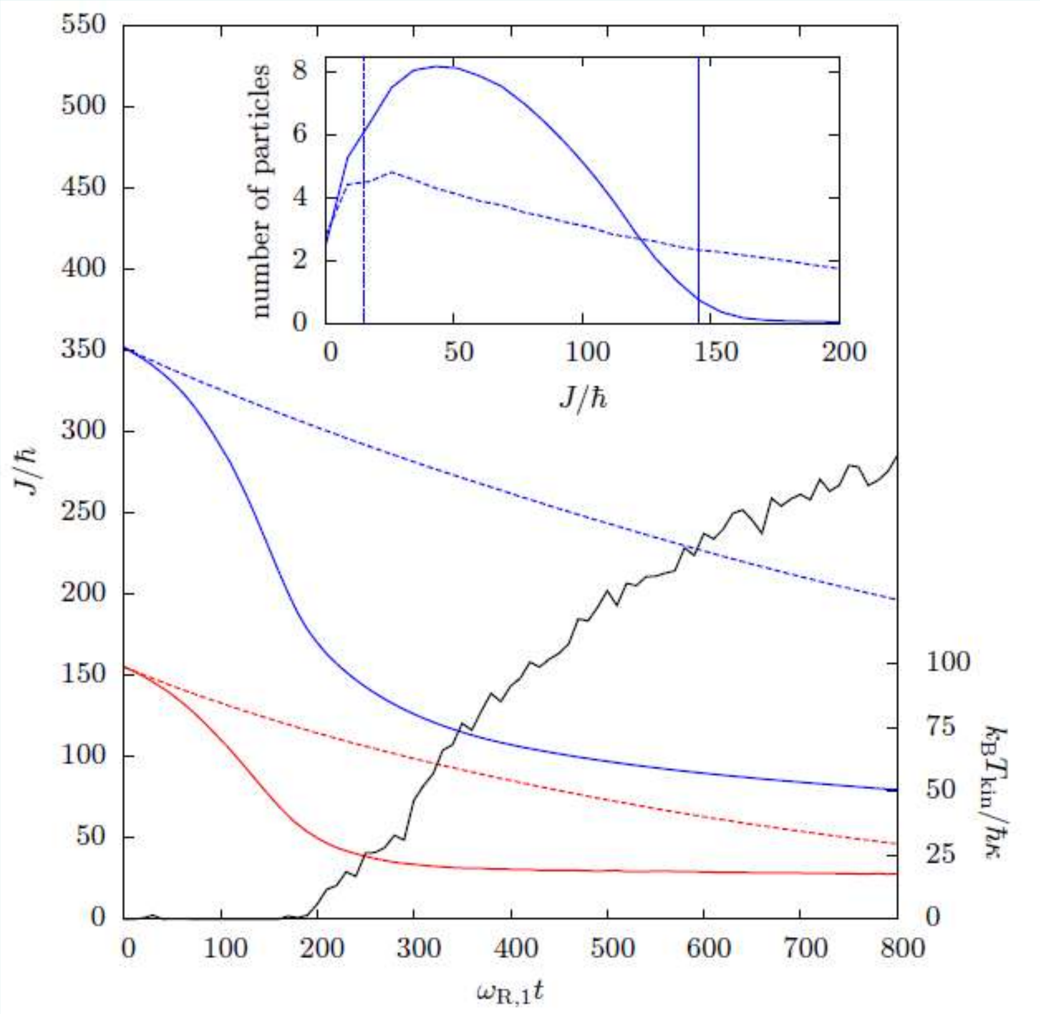
above threshold:
common self ordering

- *Cooling enhanced below and above theshold*
- *Coolind slows in fully organized phase*

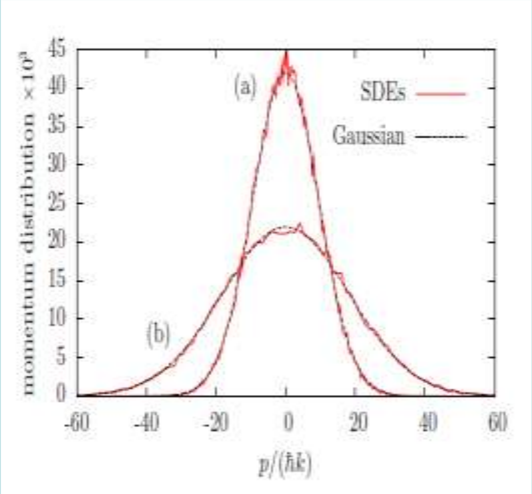
Tobias Grießer *et al* 2012 *New J. Phys.* **14** 053031

phase space „density“ evolution for two-species

$N_1 = 1500$, $N_2 = 100$, $m_2 = 80 m_1$

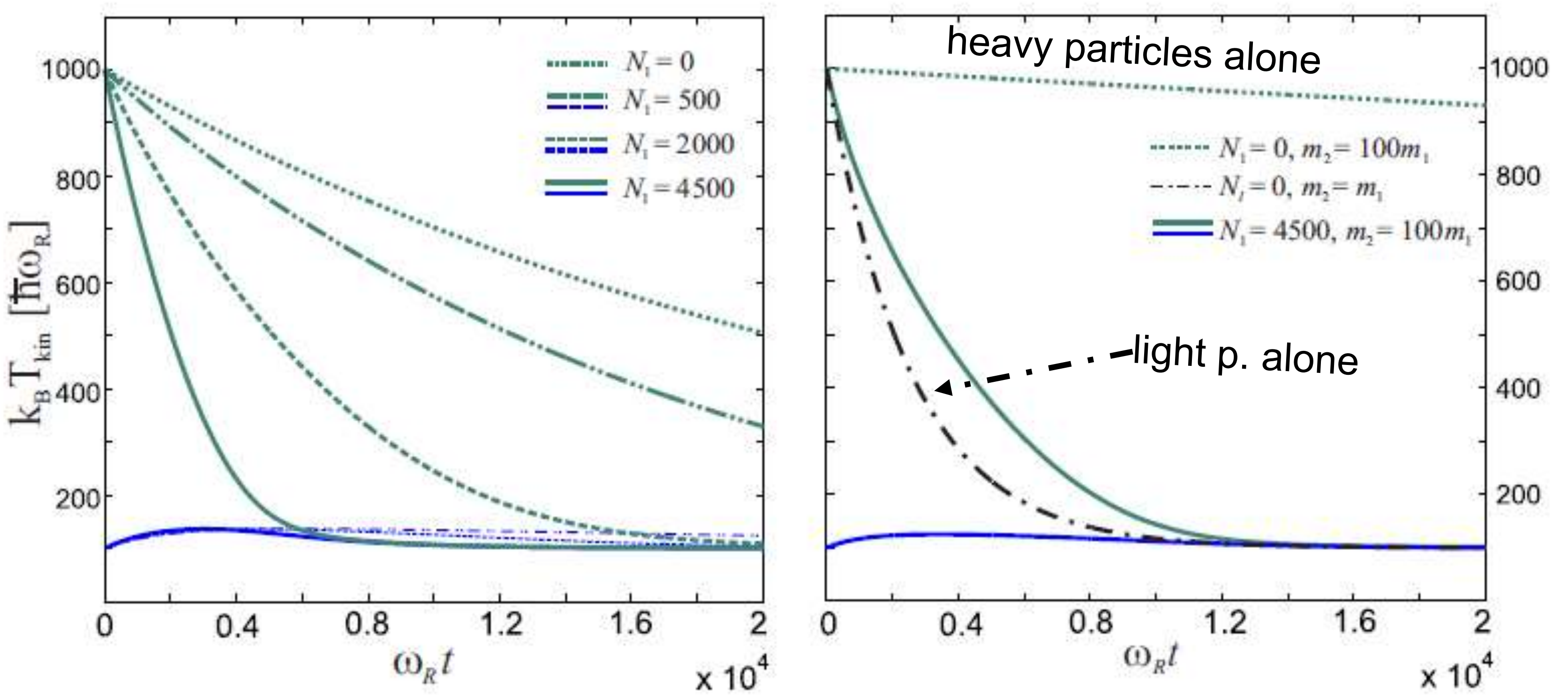


momentum distributions



selfordering increases phase space density !

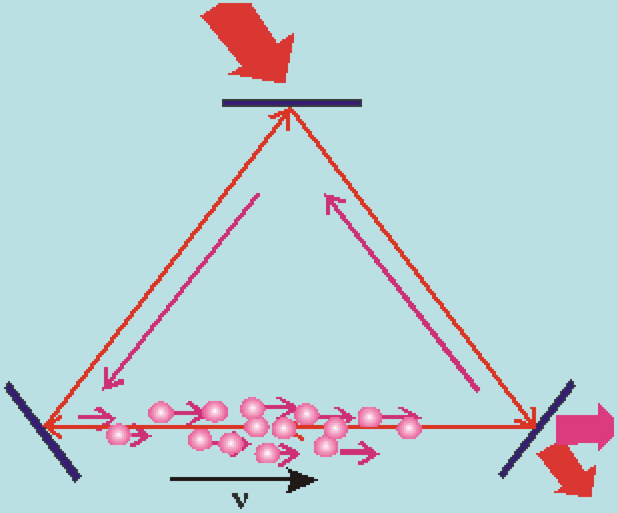
Energy flow for different initial temperatures (cold atoms + hot molecules)



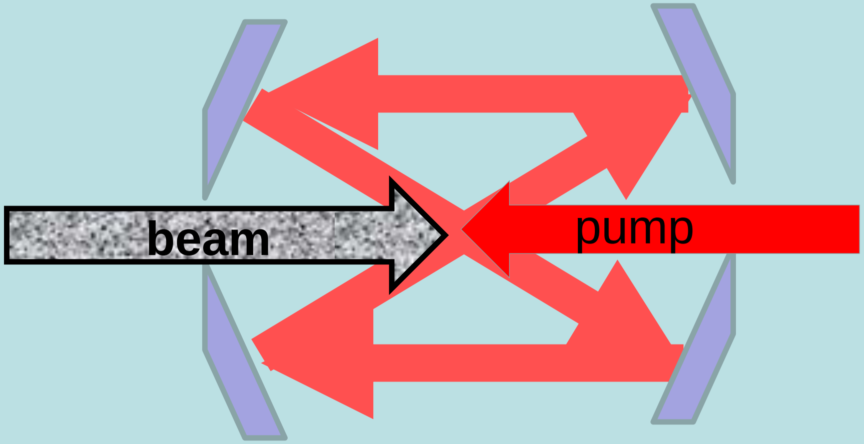
Fast thermalization and common cooling !

Part IV

Fast beam deceleration in ring cavity

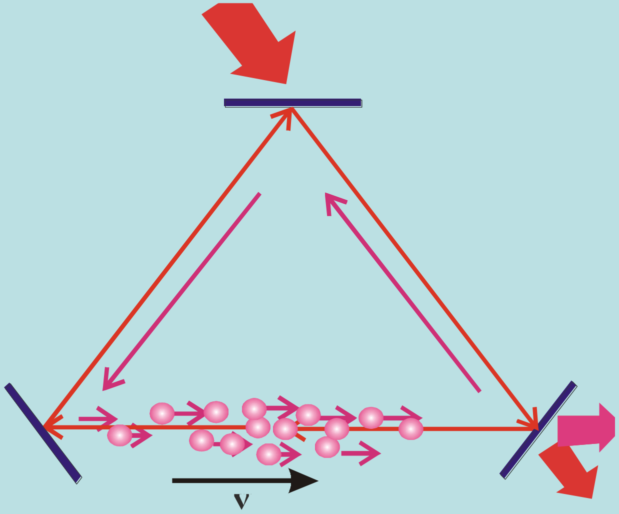


theoretical idea



theoretist‘s idea of
realistic experiment

collective dynamics of a polarisable cold gas in a ring resonator with ***single-side*** *pumping (COMORL - related work on FEL / CARL)*



$$R_- = \left\langle e^{2ikx} \right\rangle$$

particles rest frame

$$\frac{d}{dt} a_\pm(t) = [i\Delta_\pm - iNU_0 - \kappa] a_\pm(t) - iNU_0 \left\langle e^{\mp 2ikx} \right\rangle a_\mp(t) + \eta_\pm$$

collective backscattering acts like gain

$$a_+ a_-^* = |\eta|^2 \frac{(\Delta_- - NU_0 + i\kappa) NU_0 \, |R_-| \, e^{-ikx_0}}{\left| (\Delta_+ - NU_0 + i\kappa)(\Delta_- - NU_0 + i\kappa) - N^2 U_0^2 \, |R_-|^2 \right|^2} .$$

interference of pump and backscattered field creates periodic potential

selfordering threshold to l/2 periodic grating = moving Bragg lattice

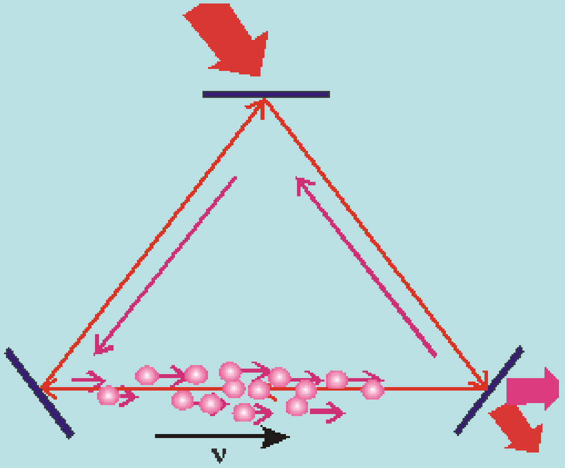
$$\eta_{thresh} > \sqrt{\left| \frac{k_B T \sqrt{(\Delta_- - NU_0)^2 + \kappa^2} \, ((\Delta_+ - NU_0)^2 + \kappa^2)}{NU_0^2} \right|} .$$

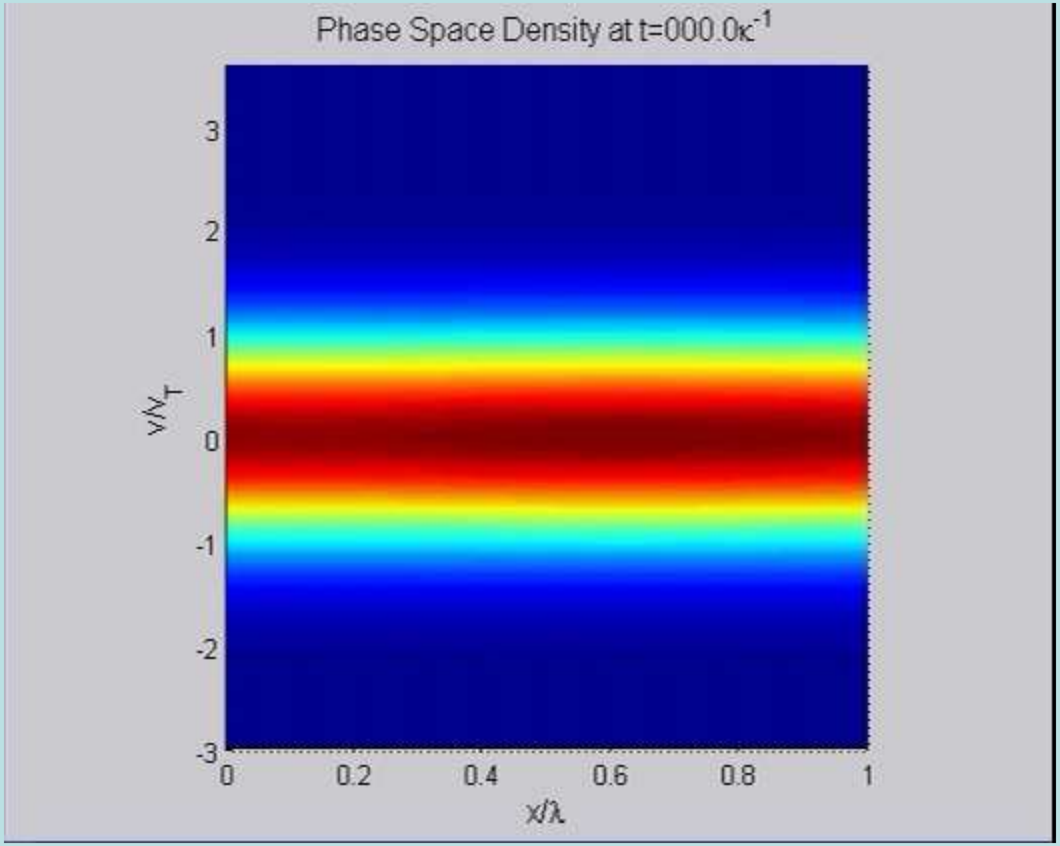
at resonance:

$$N_{cav} = \left(\frac{\eta_{thresh}}{\kappa} \right)^2 > \frac{k_B T \; \kappa}{NU_0^2}$$

Collective particle accelerator

very large particle number continuous distribution

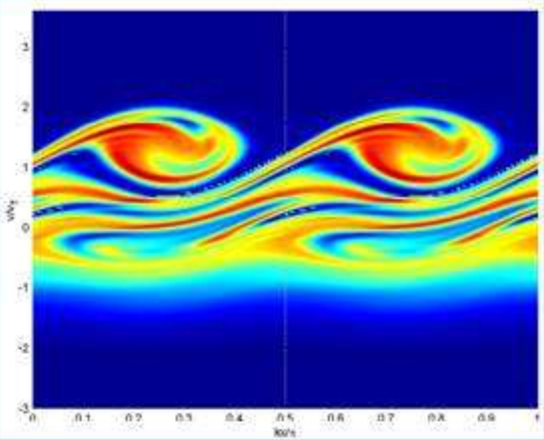




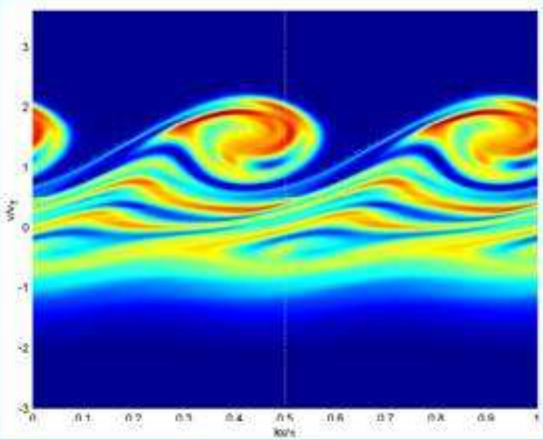
- ***backscattered light and gets amplified***

=> selfconsistent accelerated/decelerated lattice (FEL / CARL)

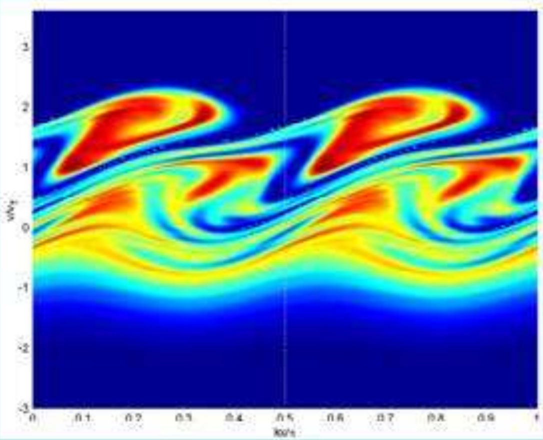
Example 1: Instability in unidirectional cavity



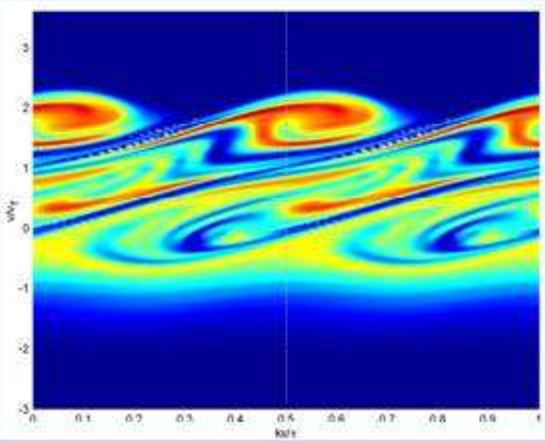
$t = 19\kappa$



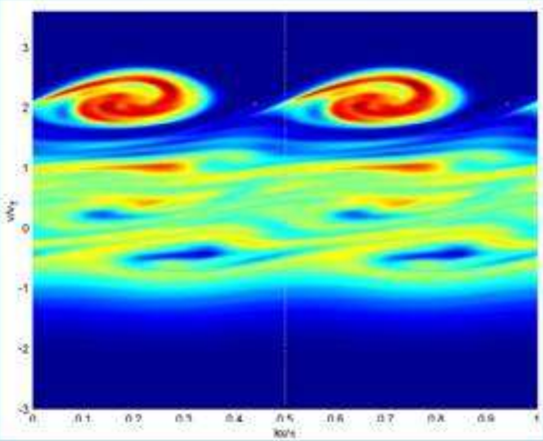
$t = 21\kappa$



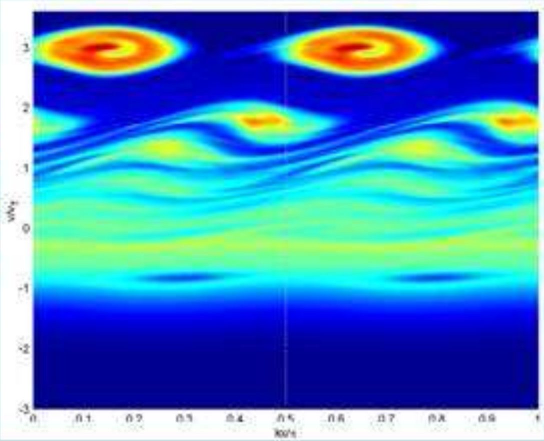
$t = 27\kappa$



$t = 30\kappa$



$t = 45\kappa$

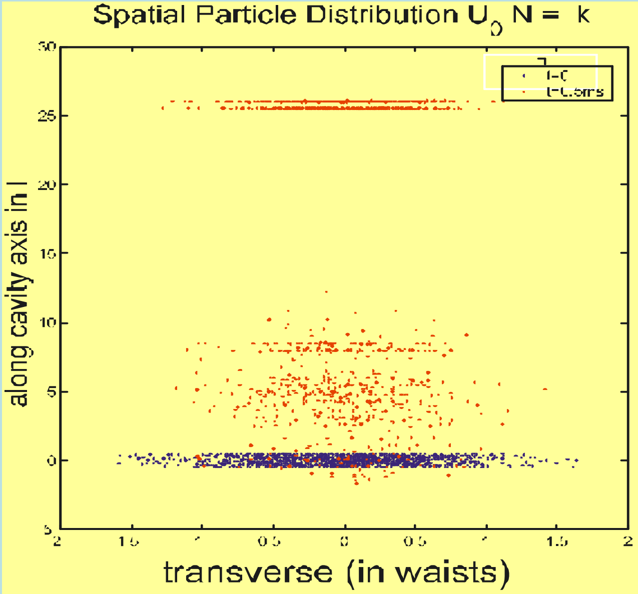


Space-time order forms !

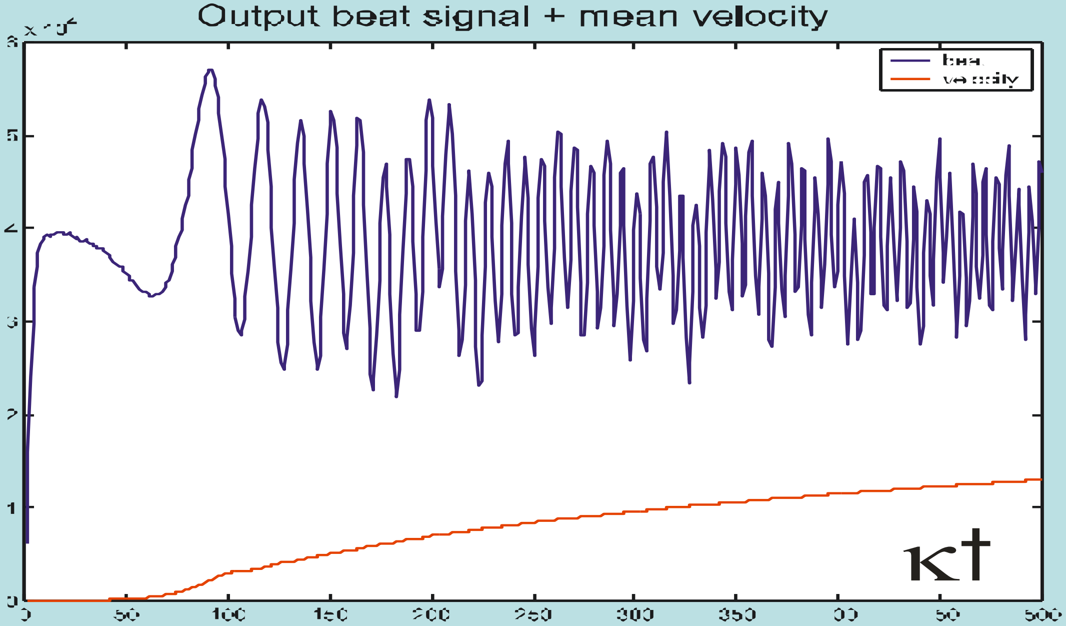
***3D**-particle simulation of ring cavity selfordering: inverse CARL*

collective atomic recoil laser (analogous to free electron laser)

particles:
initial - final



field evolution

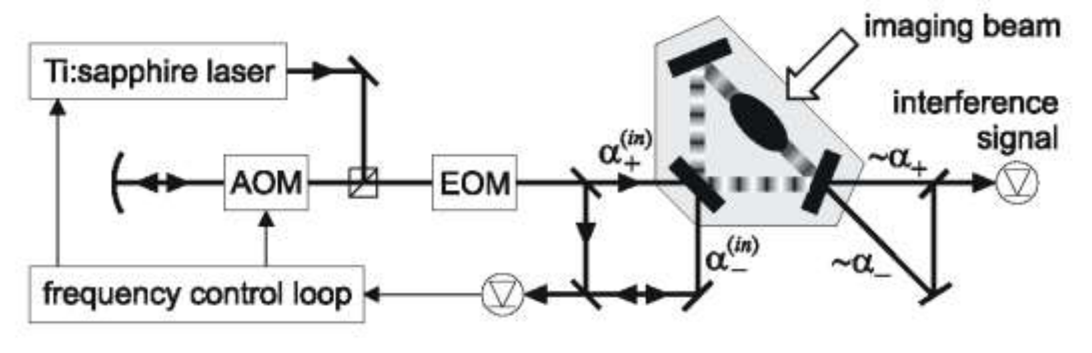


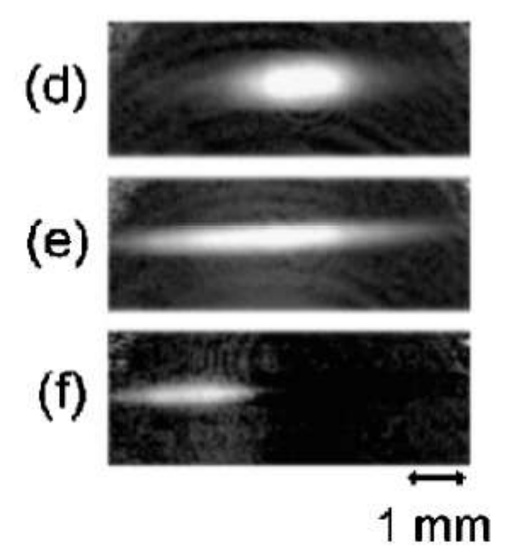
Experiments with ring resonators:

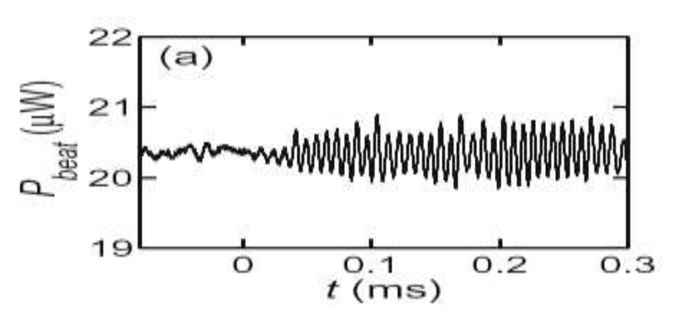
C. Zimmermann
Universität Tübingen

cold atoms at MOT temperature
large detuning: 5 nm

Setup with BEC in Tübingen



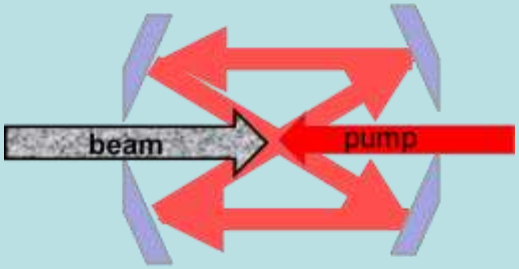




C. Zimmermann: >10^6 atoms collectively accelerated
A. Hemmerich: collective transverse oscillations of 10^6 atoms

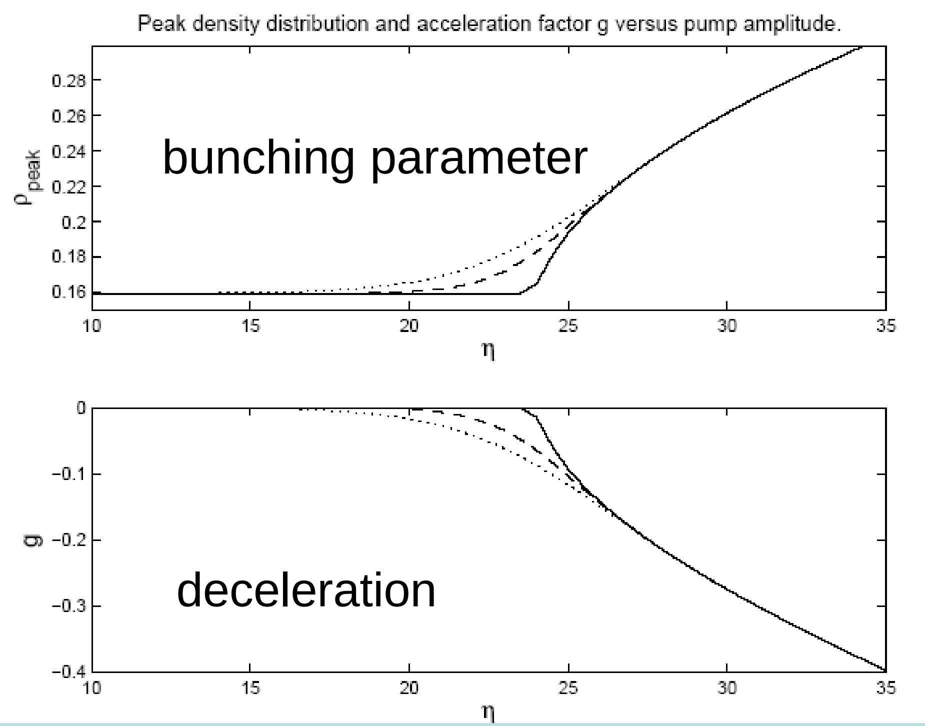
e.g: Cube C. et. al., PRL **93**, 083601.

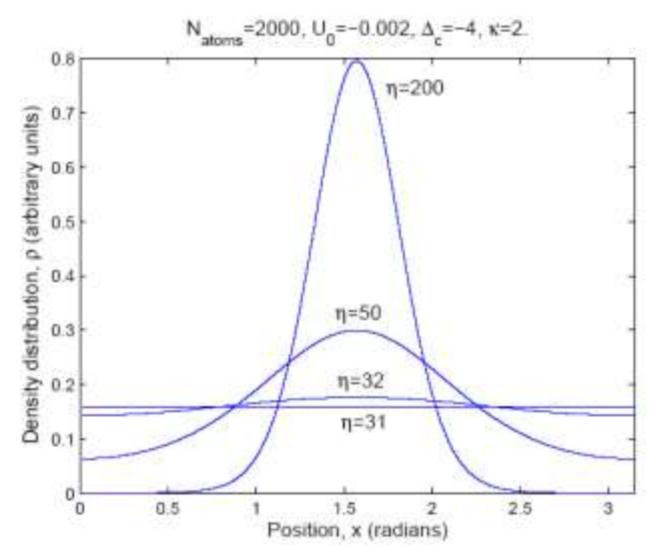
Inverse setup:
effective centre of mass deceleration
~ number of backscattered photons / particle



$$mg = -4\kappa \left| a_-^* a_- \right| \frac{k}{N}$$

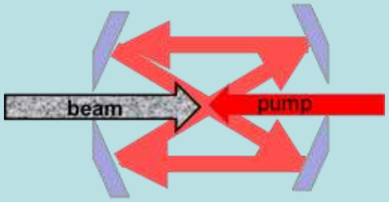
$$g = -\left|\eta^2\right| \frac{2k}{m} \frac{N\left|U_0\right|^2 \left|R_-\right| \kappa}{\left|(\Delta_+ - NU_0 + i\kappa)(\Delta_- - NU_0 + i\kappa) - N^2U_0^2 \left|R_-\right|^2\right|^2}.$$

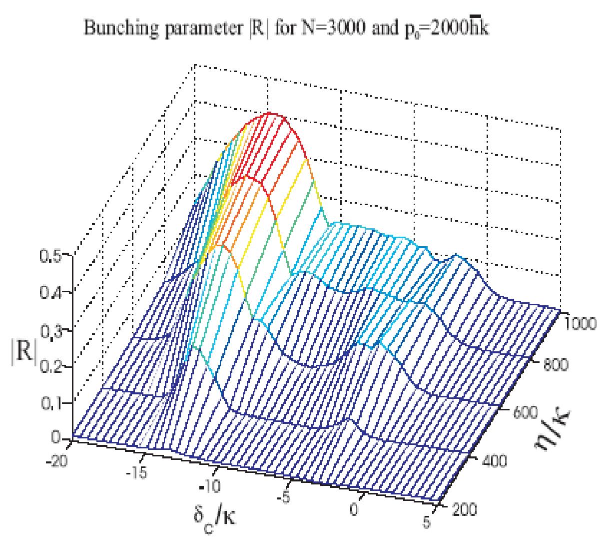


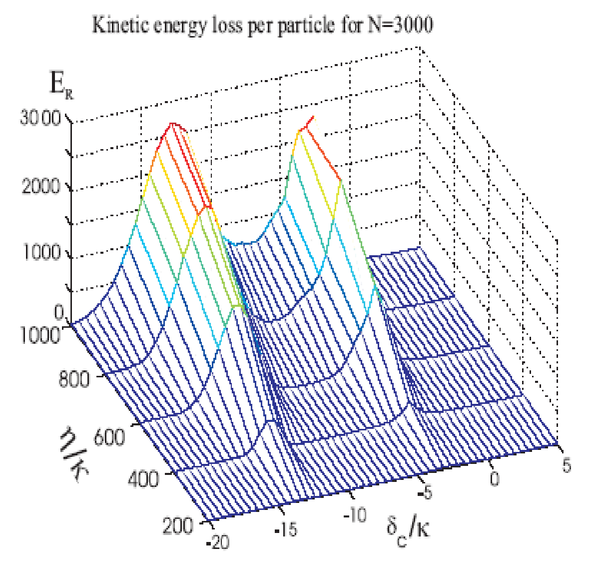


Force only limited by power – build in shutoff at low velocities

Stopping of a fast beam (particle simulation)




Bunching parameter |R| for N=3000 and $p_0=2000\hbar k$


Kinetic energy loss per particle for N=3000

for a fast beam two resonance frequencies appear:

** pump beam resonance and backscattering beam resonance*
** backscattering resonance exhibits lower threshold and more efficient stopping*

C. Maes, Optics Express, Vol. 15, Issue 10, 6019 (2007)

Summary

- *Light forces are strongly modified in optical resonators:*
  e.g: dipole force turns into a dissipative force through cavity decay

- *self trapping and cooling with suppressed spontaneous emission in driven mode for any sufficiently polarizable particle*

- *selforganisation and collective superradiance into prescribed mode (cold gas nearly at rest) allows for fast trapping/cooling of large ensembles*

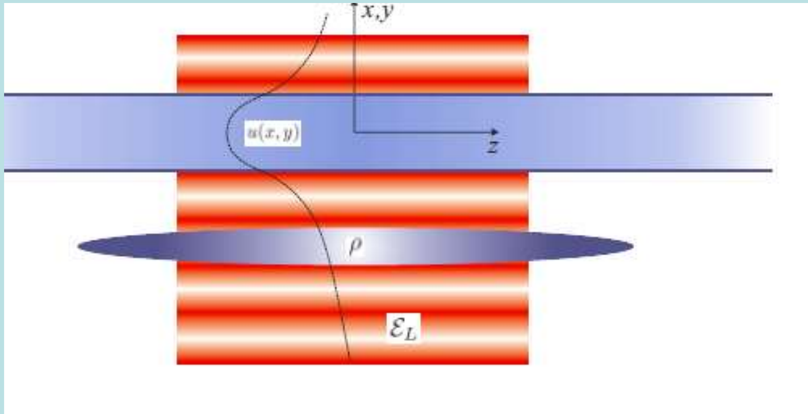
- *CARL type deceleration with suppression of fluorescence*

- *Sympathetic cooling (deceleration) of many species at same time*

Thanks for your attention !

Innsbruck University – visitors welcome !

Crystallization in 1D Systems

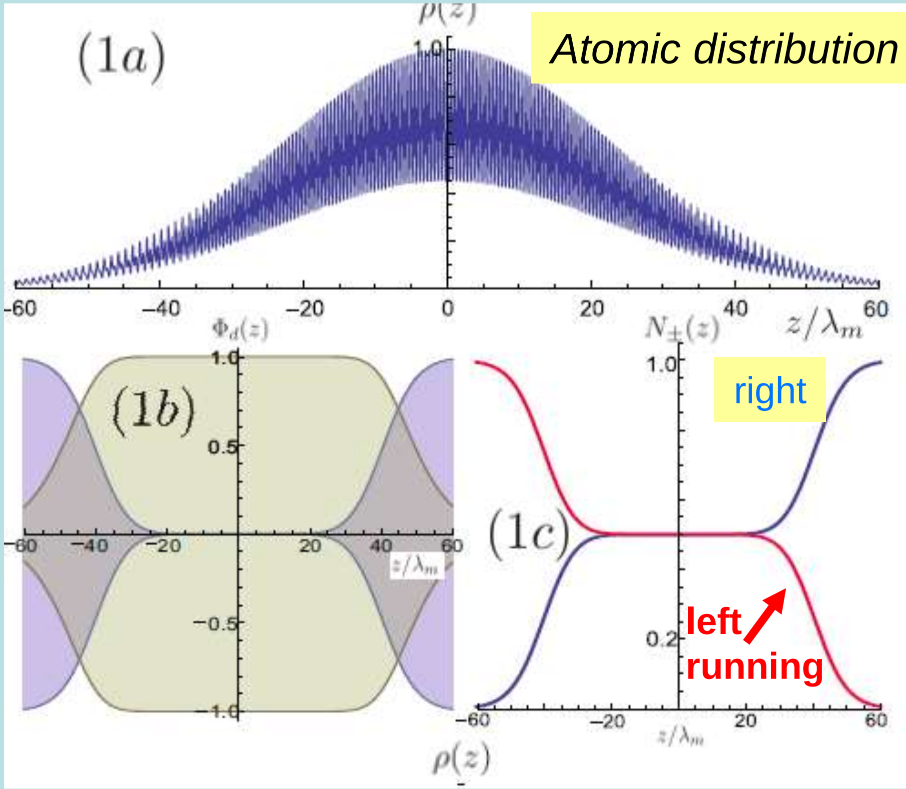


: Cigar-shaped atomic gas alongside optical nanofiber.

$$\frac{\partial^2 E}{\partial z^2} + \left(\beta_m^2 + k_L^2 \tilde{\chi}\right) E = -k_L^2 \tilde{\chi} E_L,$$

$$\frac{\partial f}{\partial t} + \frac{p_z}{m}\frac{\partial f}{\partial z} - \frac{\partial}{\partial z}\left(U - \alpha\left[|E|^2 + 2E_L E_r\right]\right)\frac{\partial f}{\partial p_z} = 0$$

Coupled Maxwell + mean field equation



Atomic distribution

right

left running

Field distribution

(J. Kimble + coworkers , PRL 2013)