Bose-Einstein condensation (of strontium)

Cooling a gas from $10^3\,\mathrm{K}$ to $10^{-7}\,\mathrm{K}$ to study the Bose-Hubbard model

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Groupe Gaz Quantiques
LCF, IOGS

 05/2024

1. Degenerate atomic gases (as analogues?)

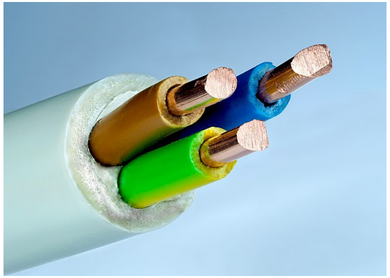
2. Laser cooling

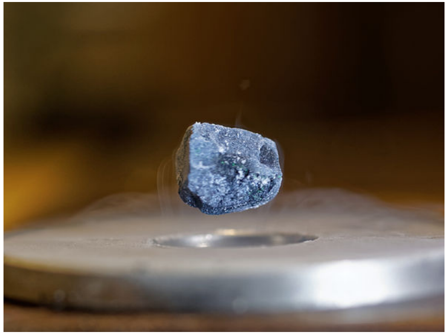
3. Evaporative cooling

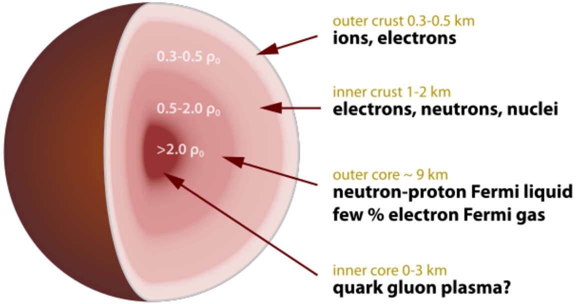
4. Bose-Hubbard physics

Fermions :

- Electronic matter : electrons in every material (cond-mat)
  - → Metals and insulators
  - → White dwarfs
  - → Superconductivity
  - → Magnetism... (spin systems, not really fermion gases)
- Nuclear matter : neutron stars
- ∼ Few-body : electron in molecules, nuclei...







Quantum-degenerate matter around us

Fermions :

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  - $\longrightarrow$ White dwarfs
  - $\longrightarrow$ Superconductivity
  - $\longrightarrow$ Magnetism . . .
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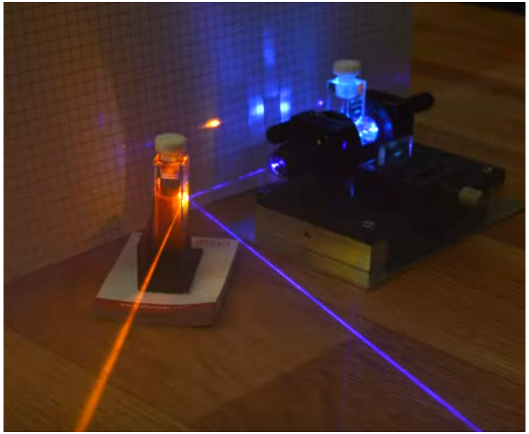
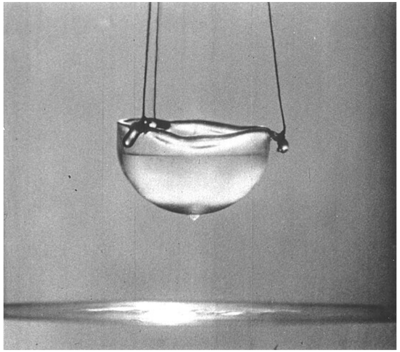
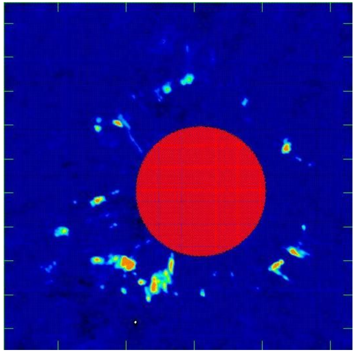
- Superfluid liquid $^3\mathrm{He}$



Bosons :

- Superfluid liquid $^4\mathrm{He}$
- Superluminescence/ASE & Lasers (in some sense . . .)

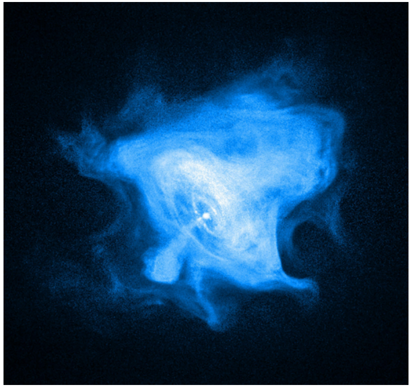


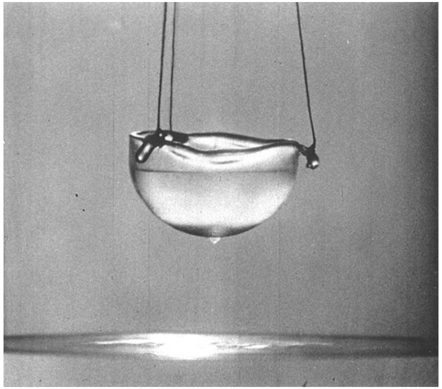


Early universe . . .

What is in common ?

Either very **dense** or very “**cold**”.





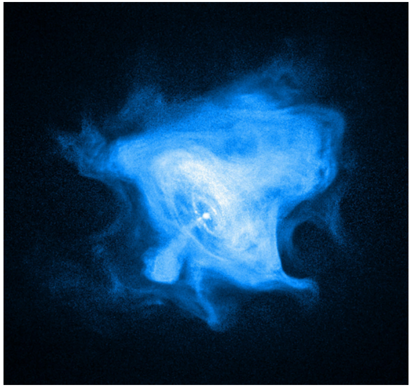
Either very **dense** or very “**cold**”.

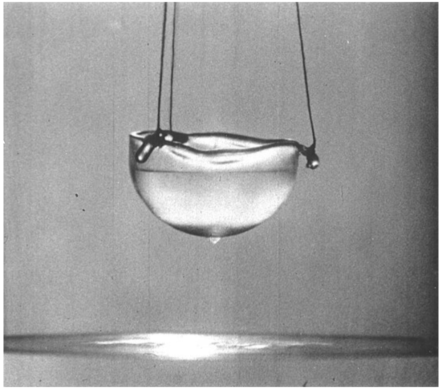
↓

slow-moving

↕

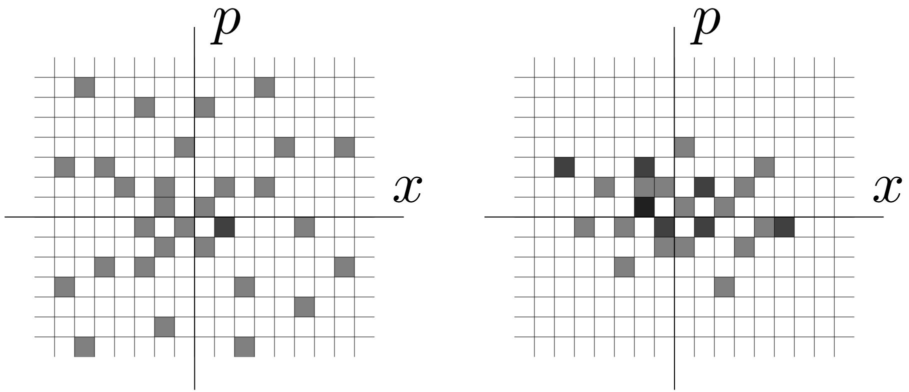
dense in
momentum space





Take N identical particules. And consider external d.o.f. only.

$$\textbf{phase-space density} = \frac{N}{\text{spatial volume} \times \text{momentum-space volume}} \quad (n\,\lambda_T^3 \text{ for a 3D gas, } \lambda_T \propto \frac{\hbar}{\sqrt{m k_B T}})$$



At high phase-space density $(\mathrm{PSD} \gtrsim 1)$, occupancy of some states $\not\ll 1$

$\rightarrow$ quantum statistics (sym./antisym.) become important

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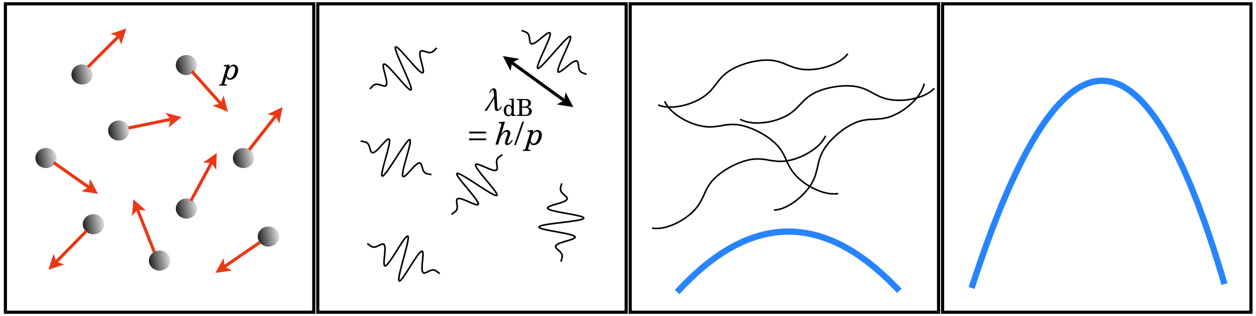

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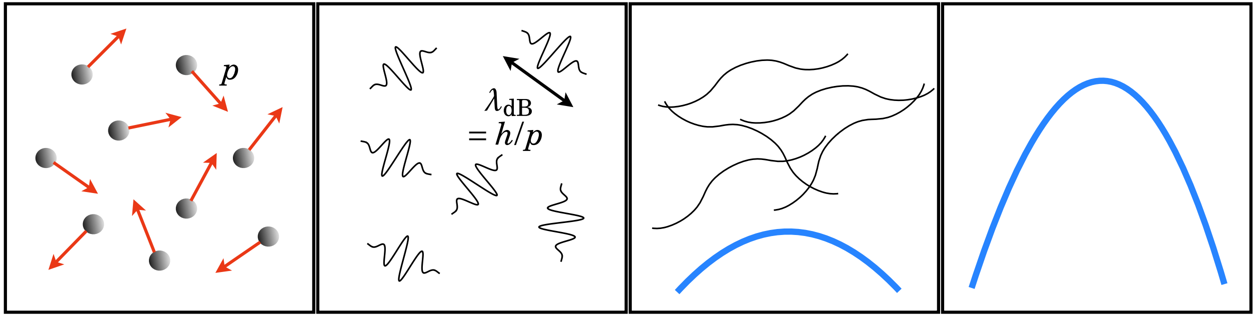
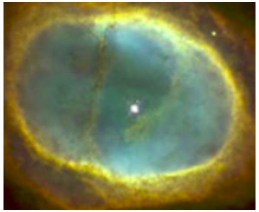


For fermions : $n\,\lambda_T^3 \gg 1 \iff k_\mathrm{B}T \ll E_\mathrm{F}$



- White dwarfs :

$$n \approx 3 \cdot 10^{\mathbf{29}}\,\mathrm{el/cm^3} \qquad T \approx 10^7\,\mathrm{K} \qquad \lambda_T \approx 20\,\mathrm{pm} \qquad n\,\lambda_T^3 \approx 4 \cdot 10^3$$

Some numbers

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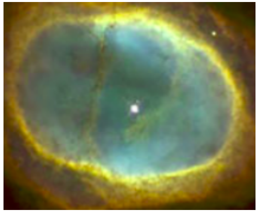
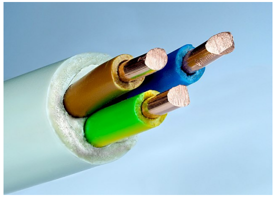


- Room-temp. solid state materials :

$$n \approx 10^{\mathbf{23}}\,\mathrm{el/cm^3} \qquad T = 300\,\mathrm{K} \qquad \lambda_T \approx 4\,\mathrm{nm} \qquad n\,\lambda_T^3 \approx 10^4$$



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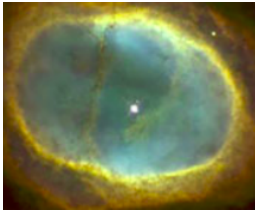

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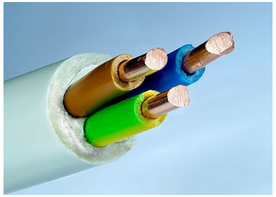
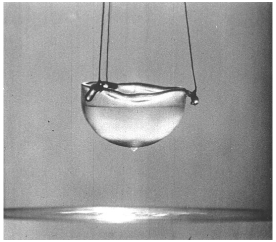


- Superfluid helium :

  $n \approx 2 \cdot 10^{\mathbf{22}}\,\mathrm{at/cm^3}$ $\quad T = 1\,\mathrm{K}$ $\quad \lambda_T \approx 1\,\mathrm{nm}$ $\quad n\,\lambda_T^3 \gtrsim 10$



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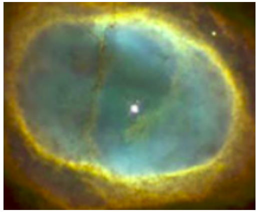

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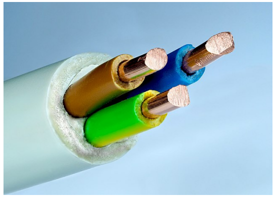

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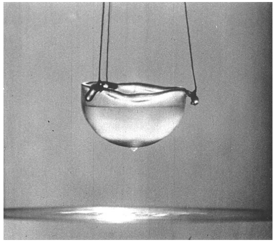
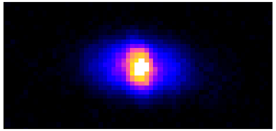
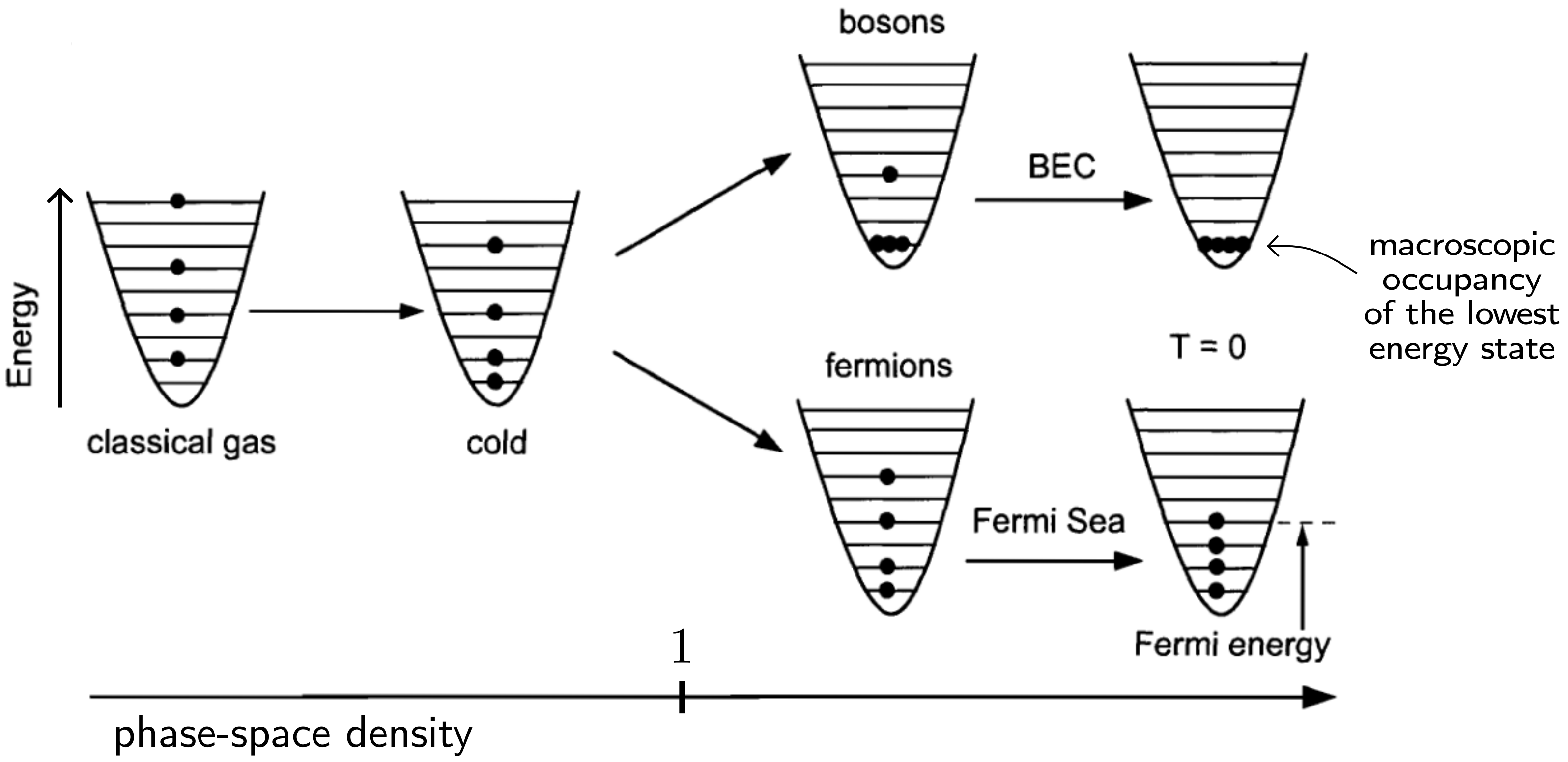


- Dilute atomic BECs :

  $n \approx 10^{\mathbf{12\sim14}}\,\mathrm{at/cm^3}$ $\quad T \lesssim 10^{-7}\,\mathrm{K}$ $\quad \lambda_T \approx 1\,\mathrm{\mu m}$ $\quad n\,\lambda_T^3 \gtrsim 10$



Condensed ideal Bose/Fermi gas



spontaneously emitted light

lasing threshold

⟶

laser light

long range coherence, diffraction
...

Bose-Einstein condensation

spontaneously emitted light

lasing threshold

$\longrightarrow$

laser light

long range coherence, diffraction ...

$\approx$

thermal phase $\longrightarrow$ **BEC phase**

phase transition

low PSD

$n\,\lambda_T^3 = 2.612$

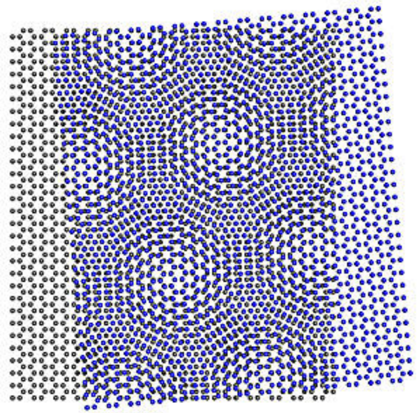
(ideal 3D homogeneous)

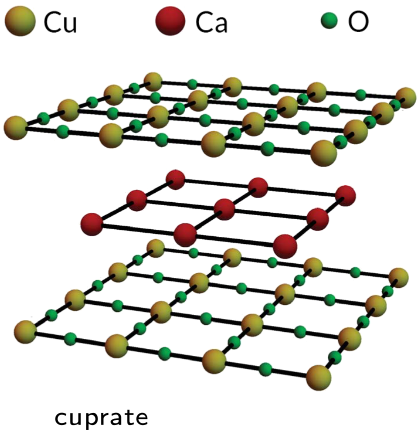
high PSD

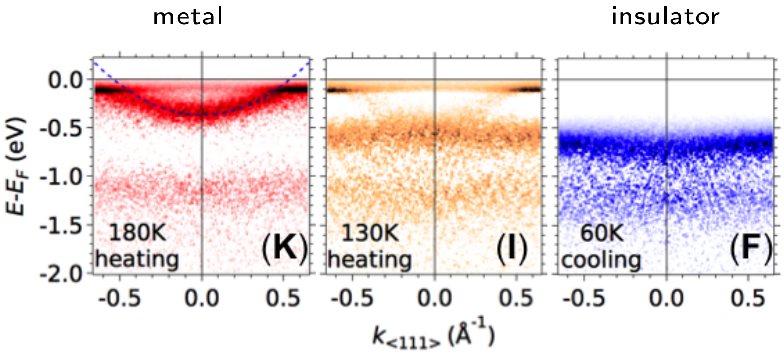
long range coherence, matter wave, superfluidity ...

Fermions :

- Electronic matter : all modern condensed matter → new / increasingly exotic materials
  - → Exotic geom. : monolayers, nanotubes, moirés…
  - → High-T_c superconductors
  - → Highly correlated
  - → Topological; quantum Hall…
- Exotic nuclear matter







More "man-made" degenerate systems

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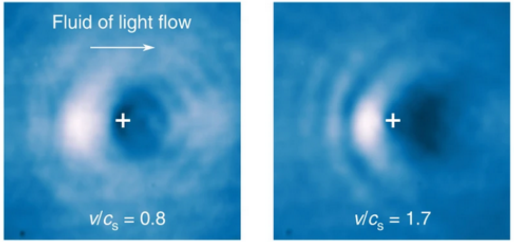
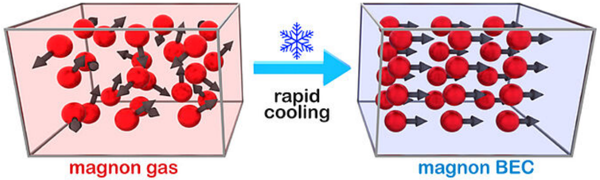
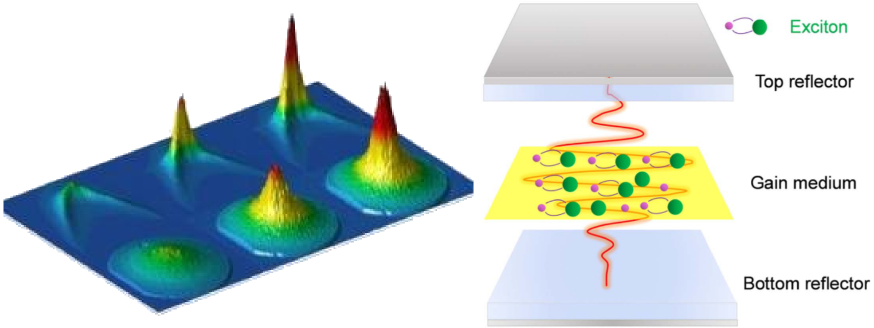


Bosons :

- Fluids of light (interacting laser light)
- Polariton condensates; Exciton systems
- Magnon condensates





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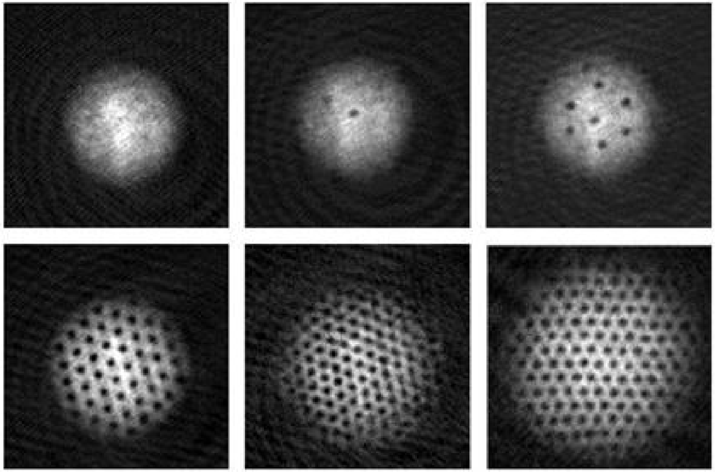


Bosons :

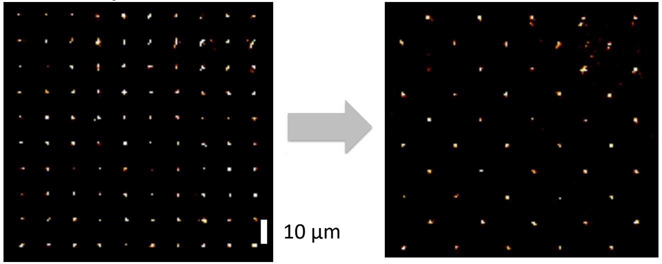
- Fluids of light (interacting laser light)
- Polariton condensates; Exciton systems
- Magnon condensates

Either or both :

- Dilute ultracold atomic gases

- AMO : ions; atoms or molecules in tweezer arrays or optical lattices

Browaeys



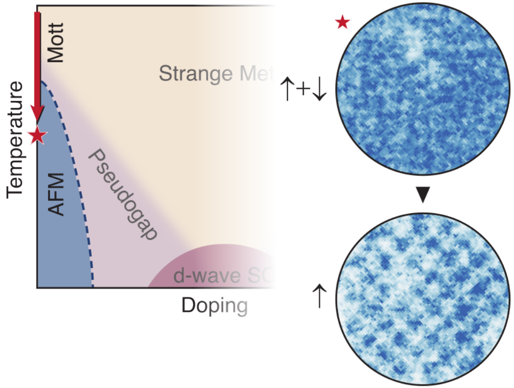
spin systems

Bose or Fermi(+spin) gases

→ Tunable interactions

→ With or without internal DoF

→ Particule-resolved



Greiner 2017

$\boldsymbol{H} = J \sum_{\langle i,j \rangle} \boldsymbol{\sigma}_i \boldsymbol{\sigma}_j$ Ising

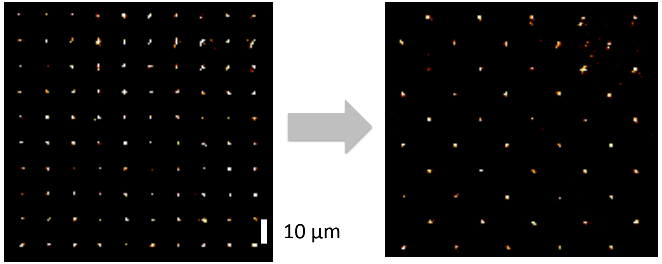
XY model

...

Harder : Heisenberg...

- AMO : ions; atoms or molecules in tweezer arrays or optical lattices

Browaeys



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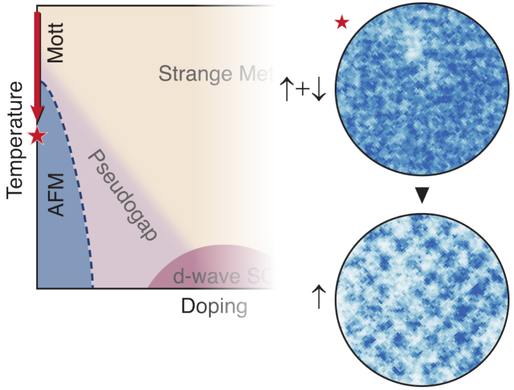
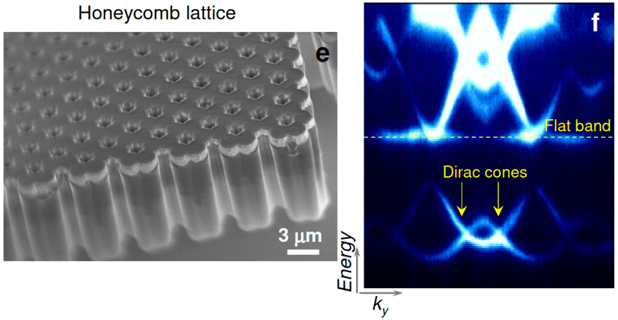


Greiner 2017

- Fluids of light. Polariton/electron-photon systems



↓

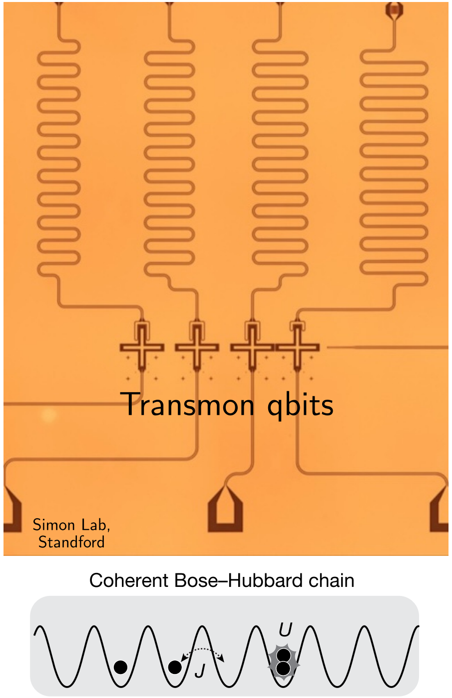
review: arXiv:2306.07313

Fake graphene more controllable than true graphene ?

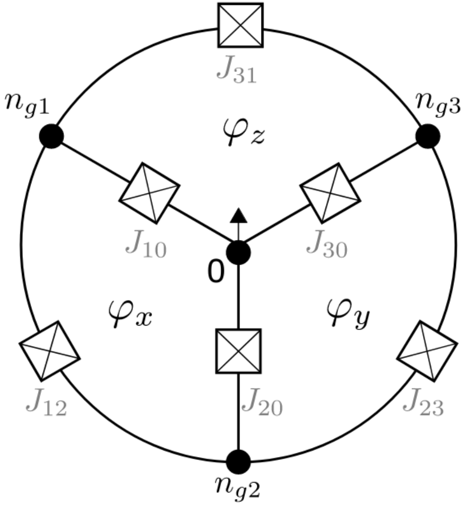
Polariton lattices for quantum simulation
A. Amo

Controllable systems : *synthetic*/bottom-up degenerate matter

- Superconducting quantum circuits (eg. transmon qubits arrays)



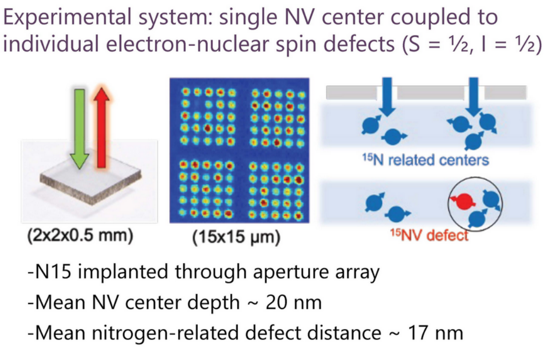
arXiv:1807.11342, Simon/Schuster



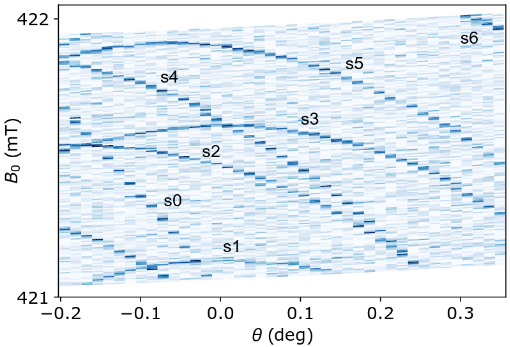
arXiv:2008.13758, LPMC, Polytechnique

Controllable systems : *synthetic*/bottom-up degenerate matter

- Superconducting quantum circuits (eg. transmon qubits arrays)
- Spins in solids (NV centers, RE-doped crystals, spin chains; NMR/ESR-controlled)

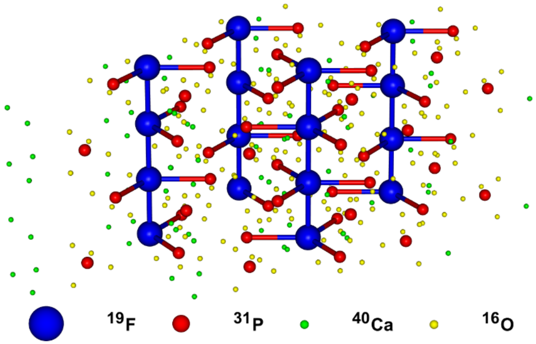


P. Cappellaro group



arXiv:2301.02653

E. Flurin, Quantronics group @ CEA



arXiv:2303.10238

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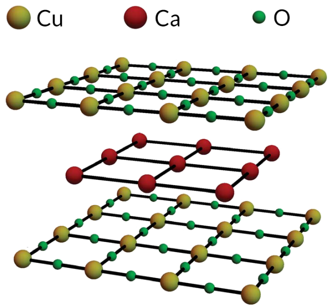
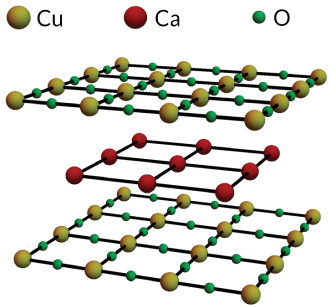
Controllable systems : *synthetic*/bottom-up degenerate matter

- Superconducting quantum circuits (eg. transmon qubits arrays)
- Spins in solids (NV centers, RE-doped crystals, spin chains; NMR/ESR-controlled)
- Photonic circuits
- ...

Hard-to-study quantum system





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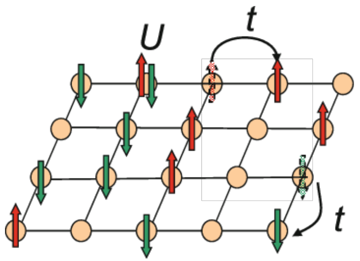
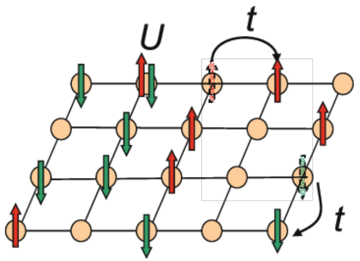
$$\updownarrow$$



Some model :

$$\boldsymbol{H} = -t \sum_{\langle i,j \rangle, \sigma} \boldsymbol{c}_{i\sigma}^{\dagger} \boldsymbol{c}_{j\sigma} + \mathrm{h.c.} + U \sum_{i} \boldsymbol{n}_{i\uparrow} \boldsymbol{n}_{i\downarrow}$$



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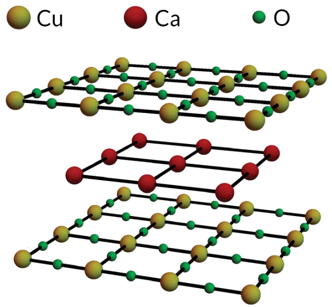

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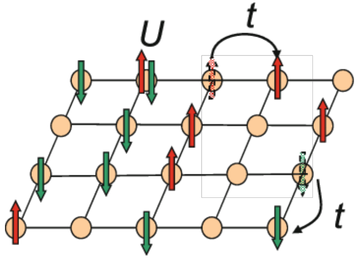

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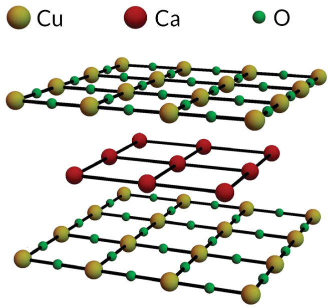

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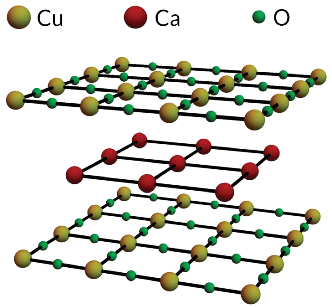
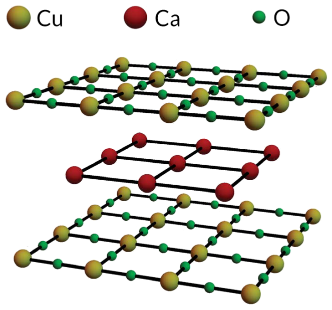
$\uparrow$ **hard or approximative**

Hard-to-study quantum system





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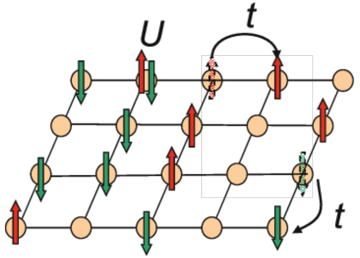
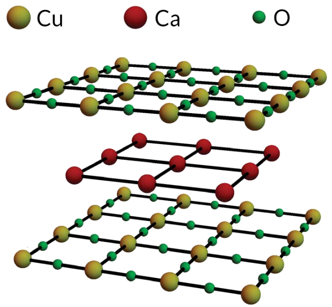
Some model :

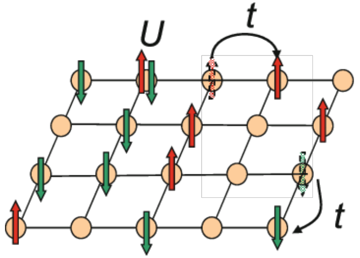


$$\boldsymbol{H} = -t \sum_{\langle i,j \rangle, \sigma} \boldsymbol{c}_{i\sigma}^{\dagger} \boldsymbol{c}_{j\sigma} + \text{h.c.} + U \sum_{i} \boldsymbol{n}_{i\uparrow} \boldsymbol{n}_{i\downarrow}$$

Hard-to-study quantum system



$\updownarrow$



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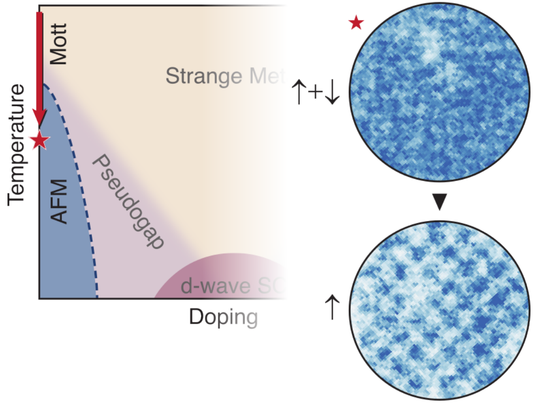
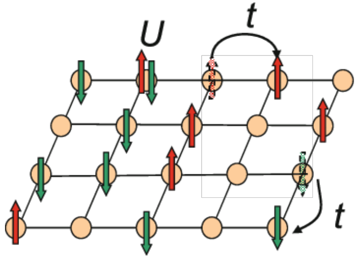


Implementation
with a controllable
and easy-to-study quantum system



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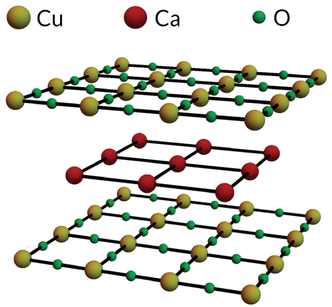
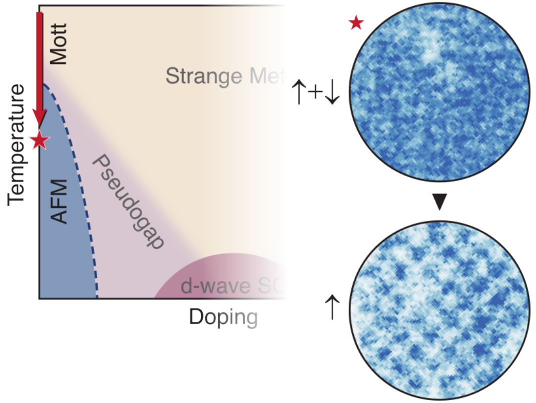
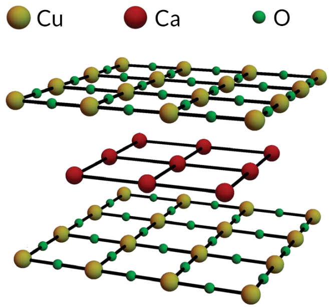
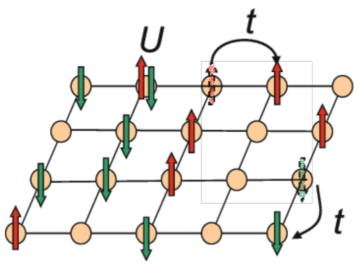






Hard-to-study quantum system

? ↕ approximate mapping

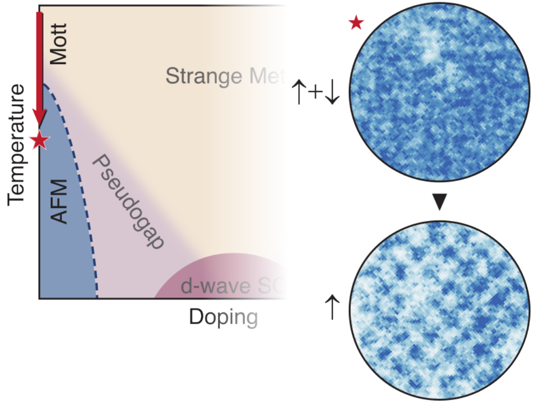


Some **simplified** model :

$$H = -t \sum_{\langle i,j \rangle,\sigma} c^\dagger_{i\sigma} c_{j\sigma} + \text{h.c.} + U \sum_i n_{i\uparrow} n_{i\downarrow}$$

~ ↕

Inexact implementation
with a ~ controllable
and easy-to-study quantum system



Facts :

- Despite the difficulties, numerical simulation advances *fast* $\longleftarrow$ more computing power, better models & approximations

Is quantum simulation useful ?

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- Fundamentally, quantum simulation scales better than classical computing.
- Condensed matter physics can advance without quantum simulators.

Is quantum simulation useful ?

- May become more relevant in the future ?

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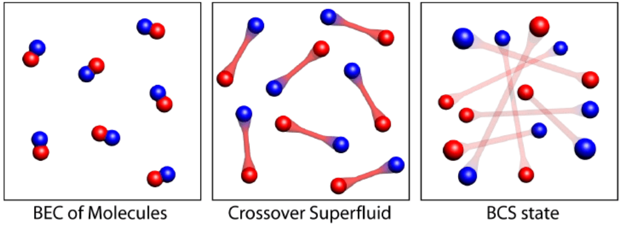
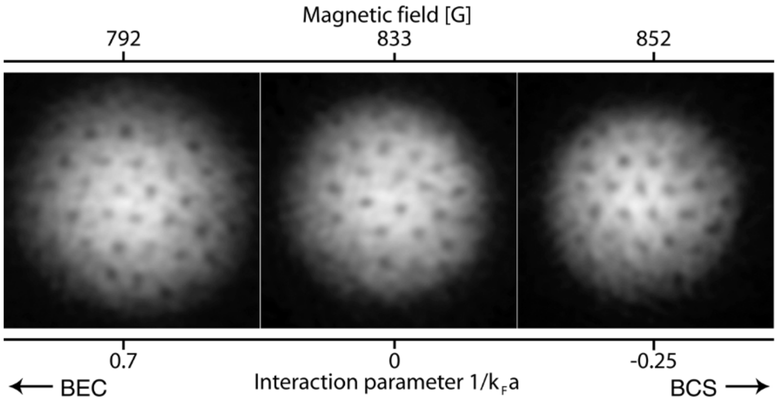
- Useful mostly for qualitative conclusions / proofs :

  → Superfuidity of degen. Fermi gases, even with very strong interactions





Vortices and Superfluidity in a Strongly Interacting Fermi Gas, Zwierlein et al.

- May become more relevant in the future ?

- Useful mostly for qualitative conclusions / proofs :
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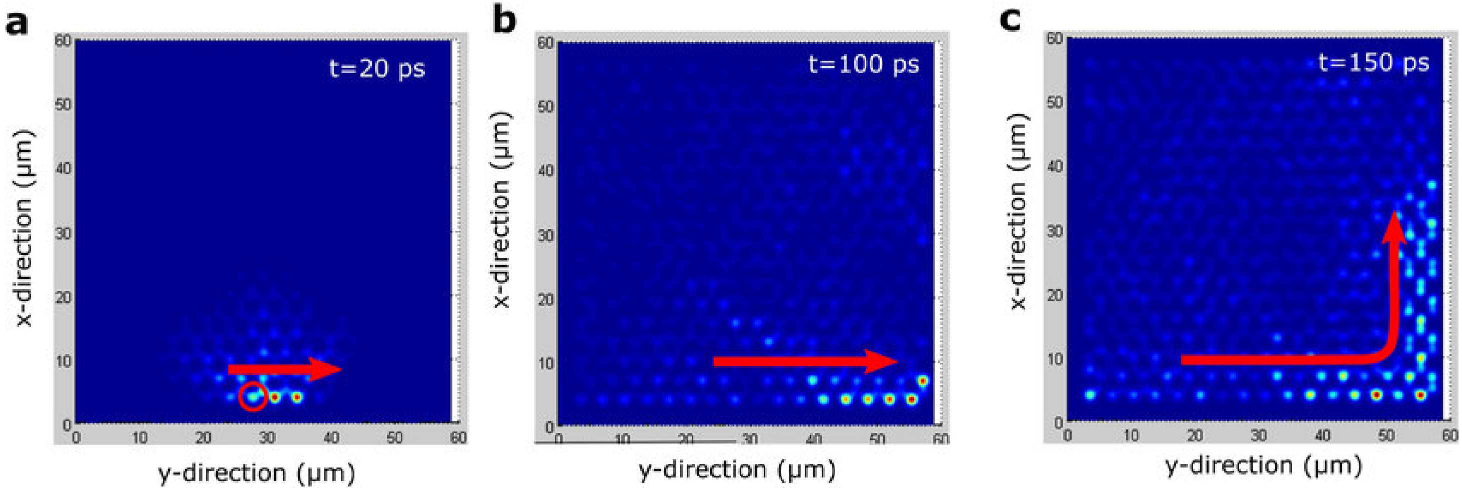
  - → Preparation of topological states & detection of edge states/modes



Exciton-polariton topological insulator
S. Klembt et al.

Is quantum simulation useful ?

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- Stimulates the theory

- Anyways, should we need such motivation ?

"Natural next step" :

- Control all d.o.f. of individual particules
- Isolate particules
- Control interactions $\longrightarrow$ arbitrary and non-local

(Abstraction & generalization → quantum computing)

"Natural next step" :

- Control all d.o.f. of individual particules
- Isolate particules
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→ Implement arbitrary quantum circuits / programs

"Natural next step" :

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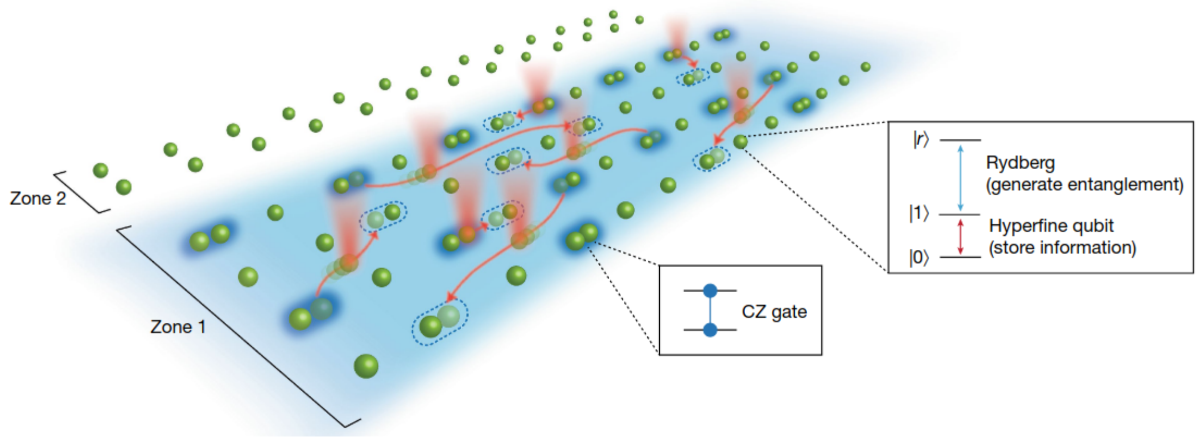
Attempts on many platforms :



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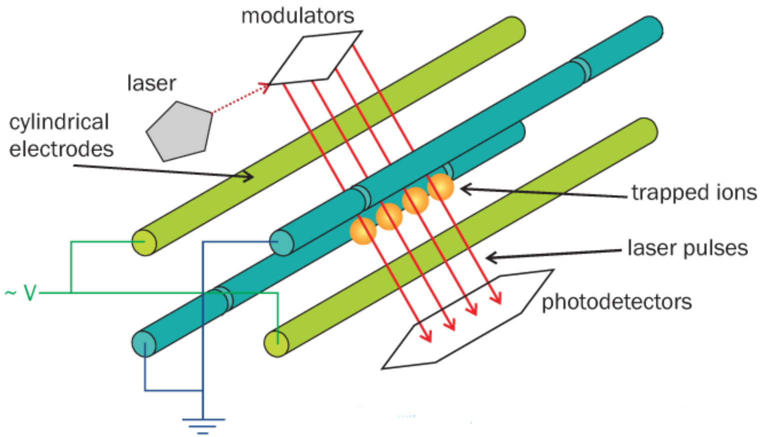

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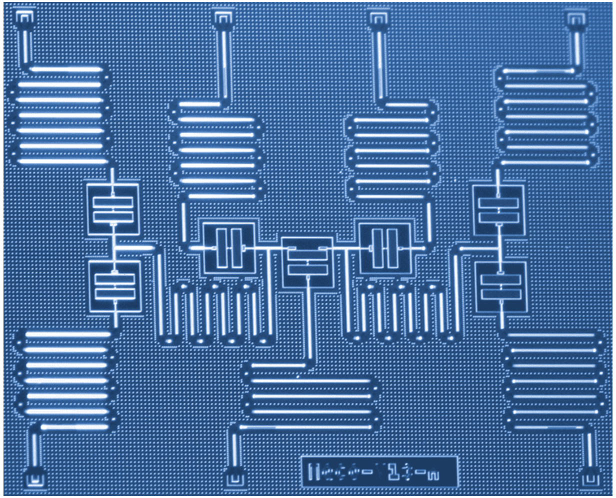

"Natural next step" :

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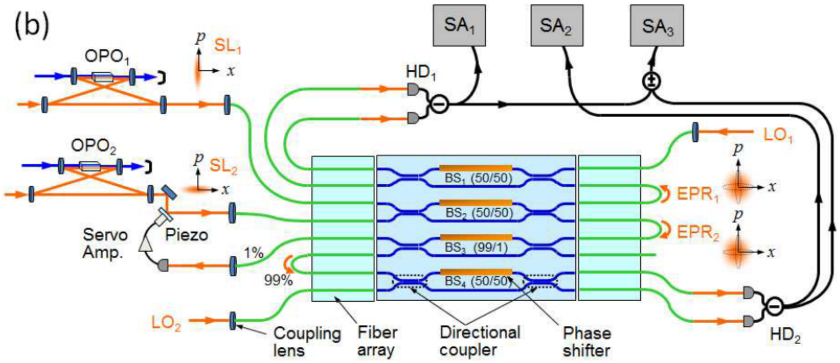
Attempts on many platforms :

Discrete-variable or continuous-variable quantum optics



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Hard

"Natural next step" :

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Hard $\propto e^N$

"Le problème à N corps qui se cache derrière l'ordinateur quantique",
Xavier Waintal, Reflets de la Physique n° 70

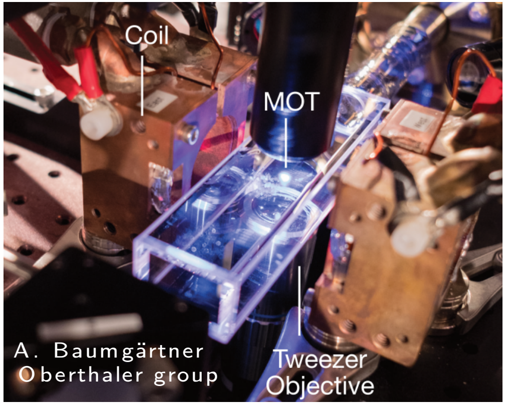
L'ordinateur quantique est une belle aventure mais, on le comprend, il est difficile de prédire à quoi va aboutir cet effort inédit pour créer et utiliser des états quantiques macroscopiques. L'auteur peine à envisager que l'on puisse parvenir à l'ordinateur quantique de type **#4** sans des ruptures conceptuelles majeures avec les approches suivies actuellement. L'ordinateur quantique souffre par ailleurs d'une différence

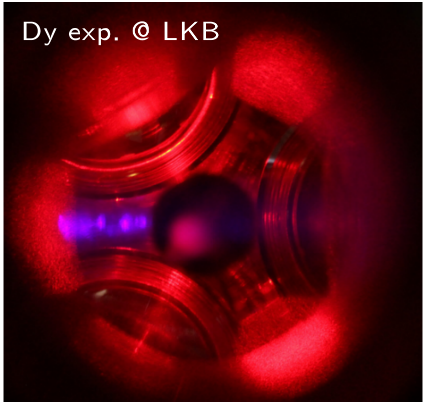
Difficulté	Type d'ordinateur quantique	Exemples d'applications
#1	Ordinateur analogique sans portes	Simulations quantiques
#2	Ordinateur analogique à portes, basse fidélité	Validation du système. « Suprématie quantique »
#3	Ordinateur analogique à portes, haute fidélité	Calculs variationnels de chimie quantique
#4	Ordinateur digitalisé sans mémoire quantique (calculs quasi déterministes)	Factorisation de nombres premiers Calculs exacts de chimie quantique
#5	Ordinateur digitalisé avec mémoire quantique	Intelligence artificielle, algèbre linéaire

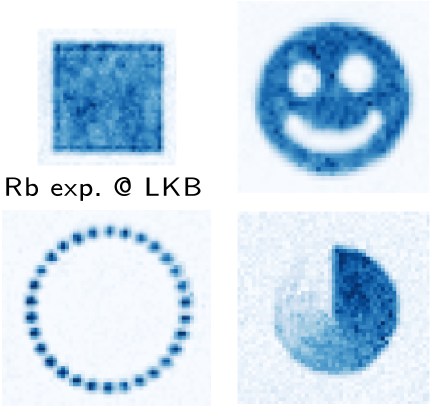
Tableau 1. Différents types d'ordinateurs quantiques et les applications qui peuvent être envisagées.

Quantum gases

Particules = neutral atoms in a dilute gas.





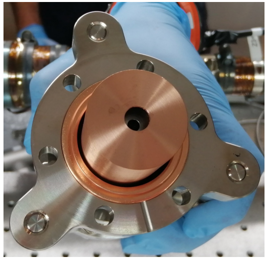


Nature's gift for controllable quantum matter :

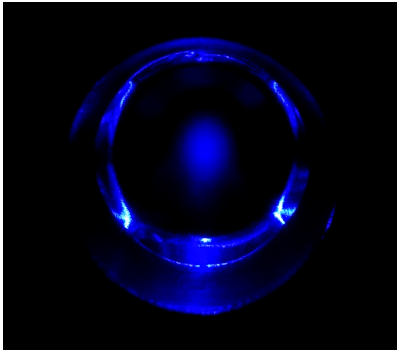
- identical particules
- stable (if dilute enough) & at equilibrium
- controllable by light, internal structure simple enough but useful enough
- can be trapped in ± arbitrary potentials (optical dipole traps / optical tweezers)
- can be cooled to degeneracy

The general idea

Solid



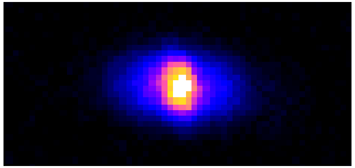
$\longrightarrow$ *Oven*



Vapor, $800\,\mathrm{K}$

very low phase-space density

Cooling $\downarrow$ *Compression*

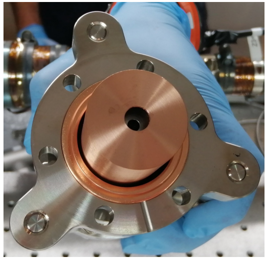


BEC, $10^{-7}\,\mathrm{K}$

degenerate atomic gas

The general idea

Solid



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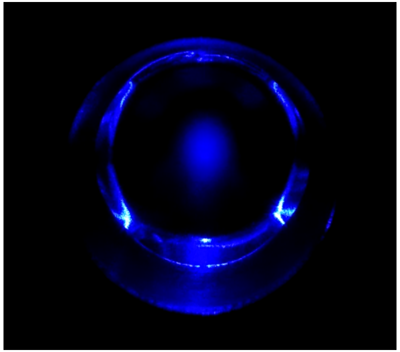

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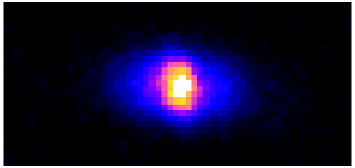


BEC, $10^{-7}\,\mathrm{K}$

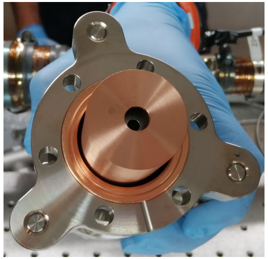
degenerate atomic gas

Timescales

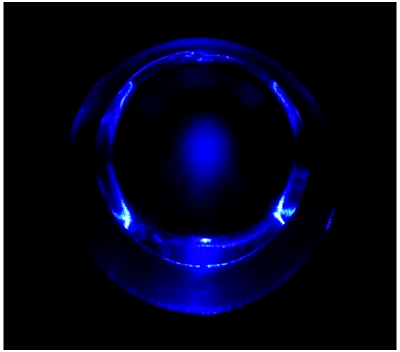
light-atom interaction	$\mathrm{ns} \sim \mathrm{\mu s}$
motion & atom-atom interact.	$\mathrm{\mu s} \sim \mathrm{ms} \sim \mathrm{s}$

The general idea

Solid



→ *Oven*



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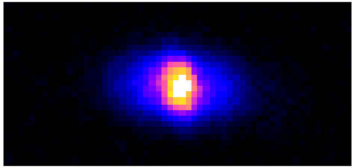

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degenerate atomic gas

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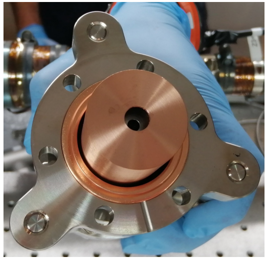
degen. gas production	few s
gas lifetime	$1\,\mathrm{s} \sim \mathrm{min.}$

The general idea

Solid



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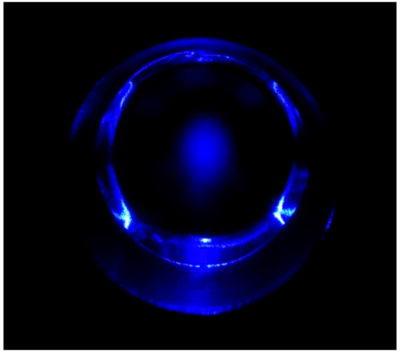


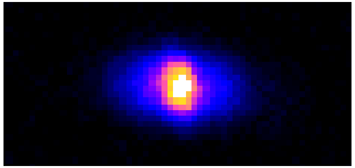
Vapor, $800\,\mathrm{K}$

very low phase-space density

3 b. recomb.

~~2 body inel.~~

Cooling ↓ *Compression*



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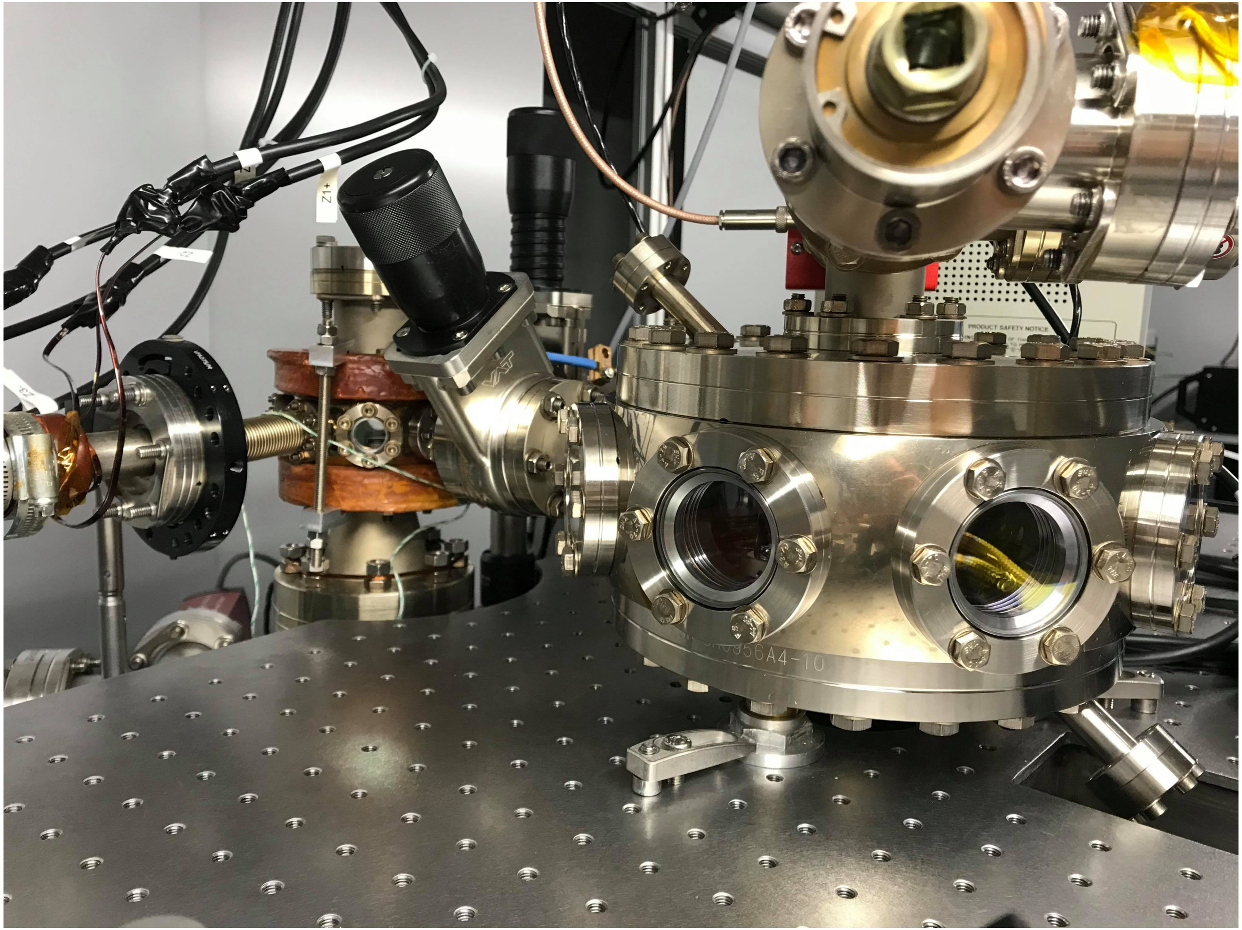
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VAT
PRODUCT SAFETY NOTICE

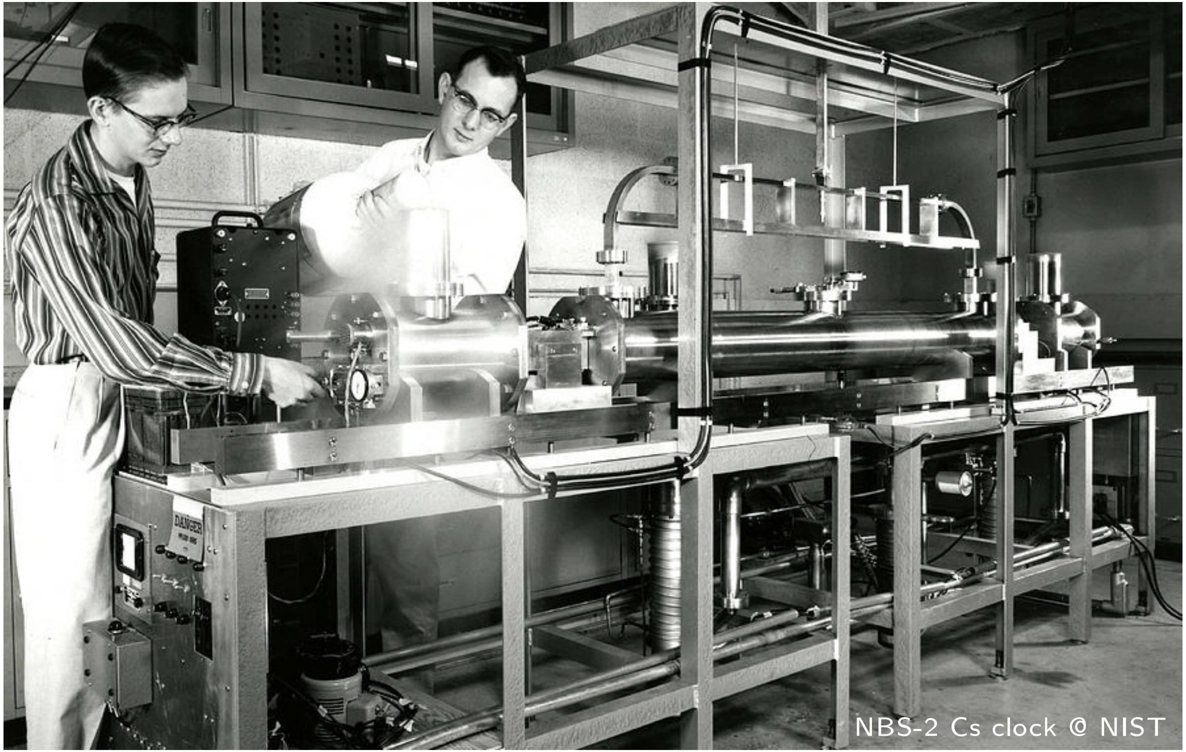
1. Degenerate atomic gases (as analogues?)

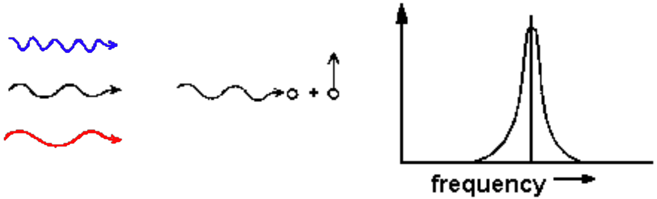
2. **Laser cooling**

3. Evaporative cooling

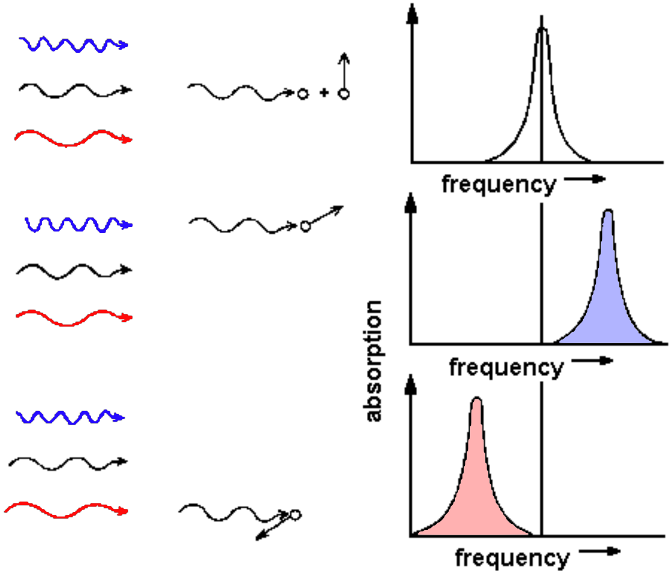
4. Bose-Hubbard physics

Why cooling atoms ? For spectroscopy. . .



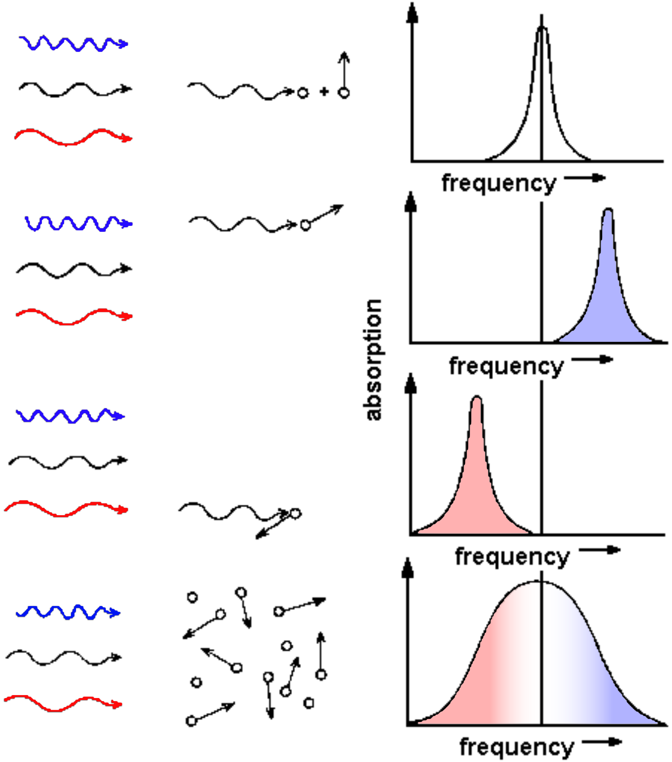

frequency

Why cooling atoms ? For spectroscopy...



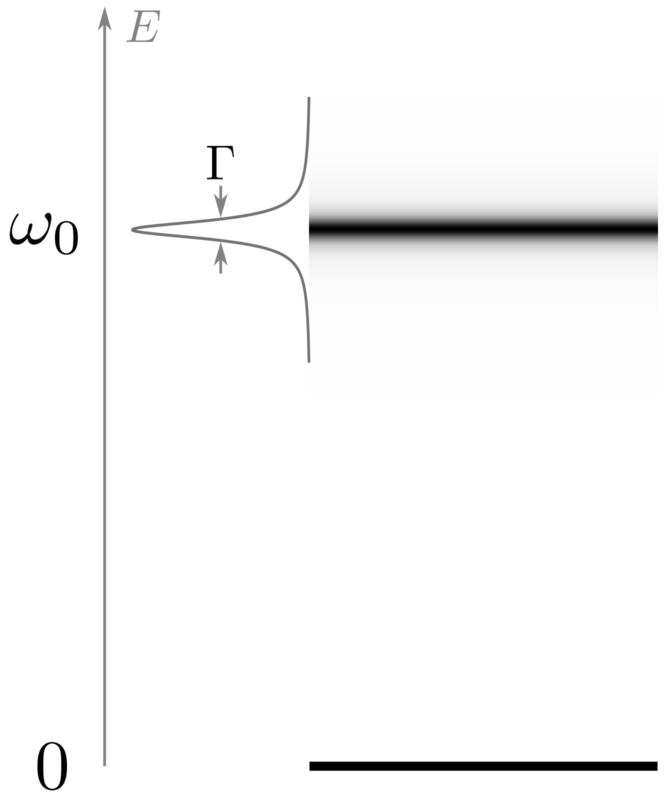
$$\delta = -\vec{k} \cdot \vec{v}$$

Why cooling atoms ? For spectroscopy...



$\delta = -\vec{k} \cdot \vec{v}$

$\longrightarrow$ Doppler broadening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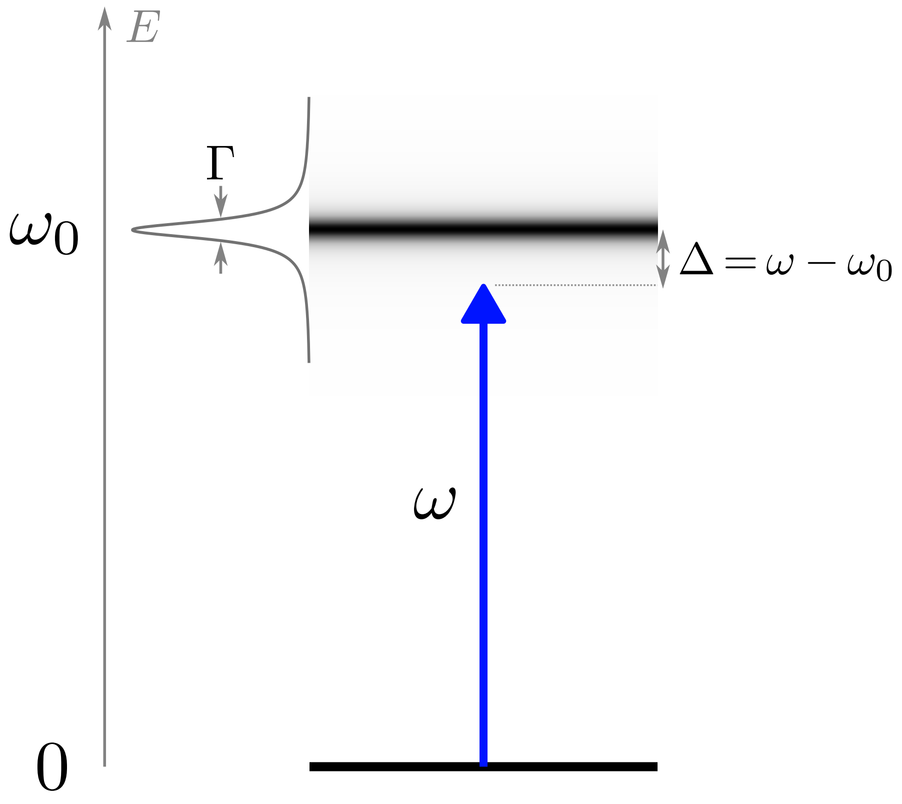
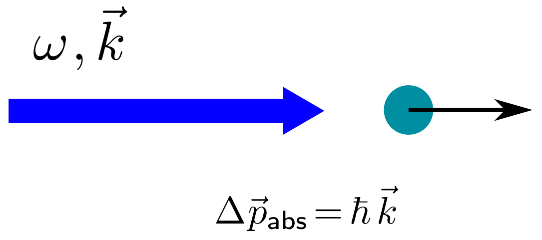
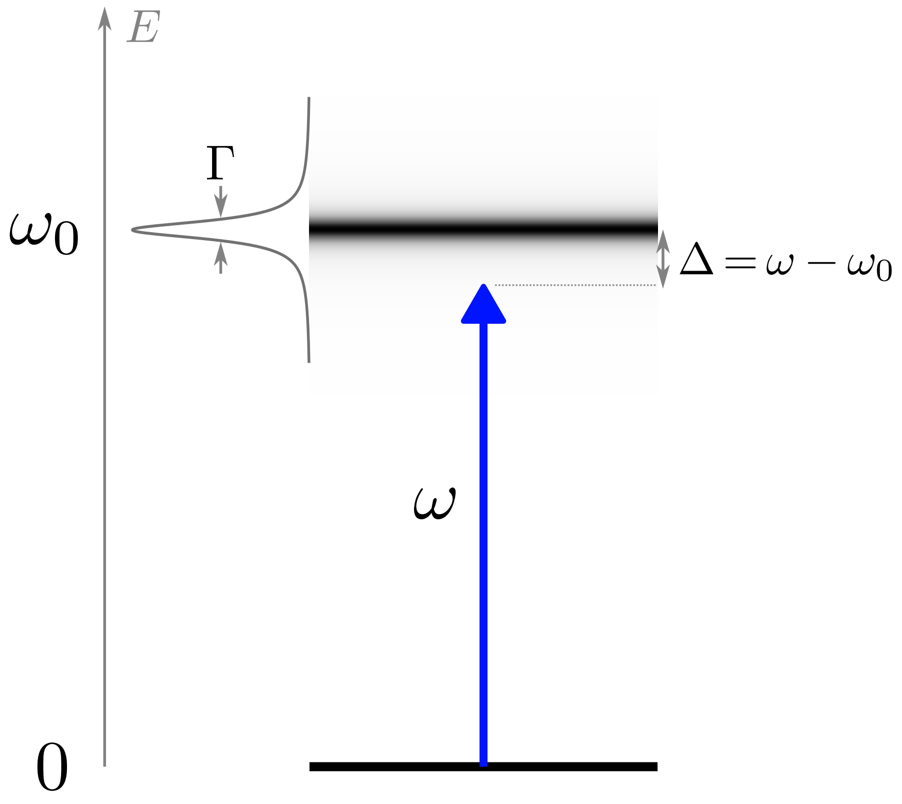


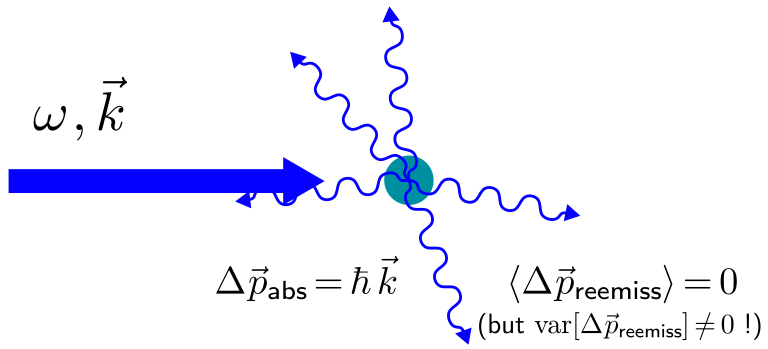
Radiation pressure



Light forces : resonant case



Spontaneous emission



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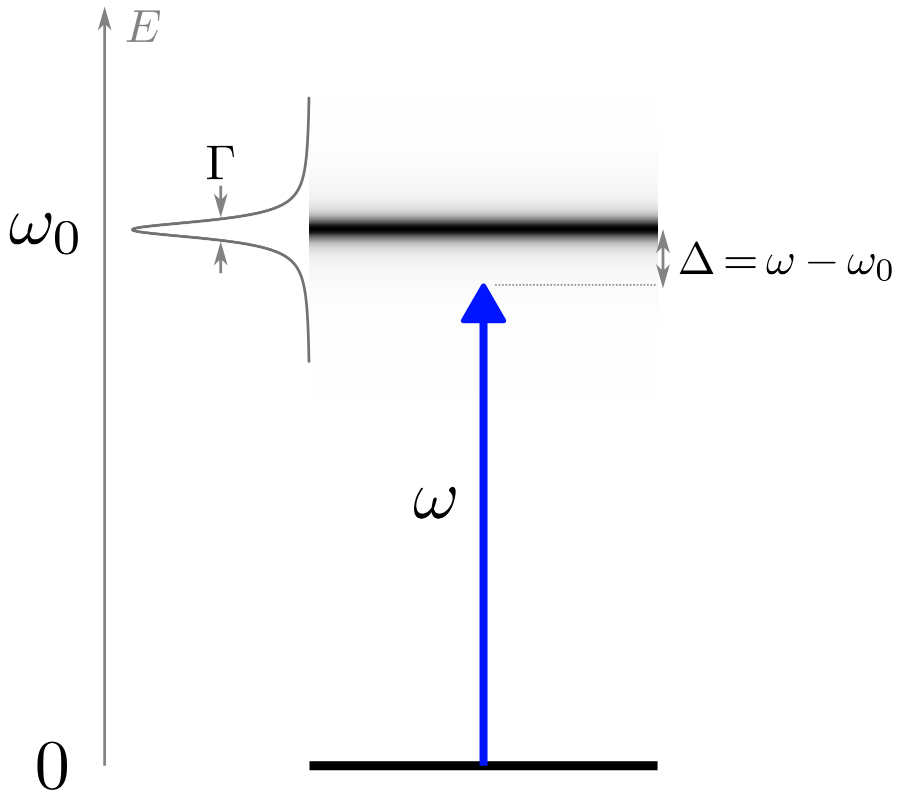
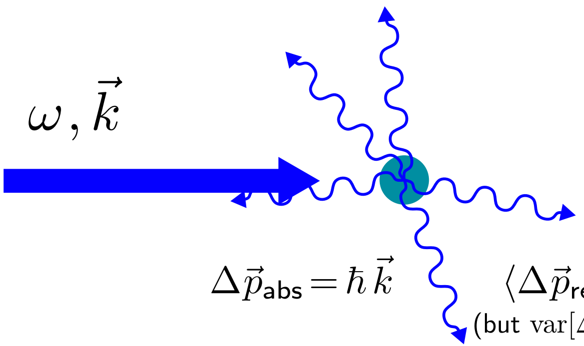




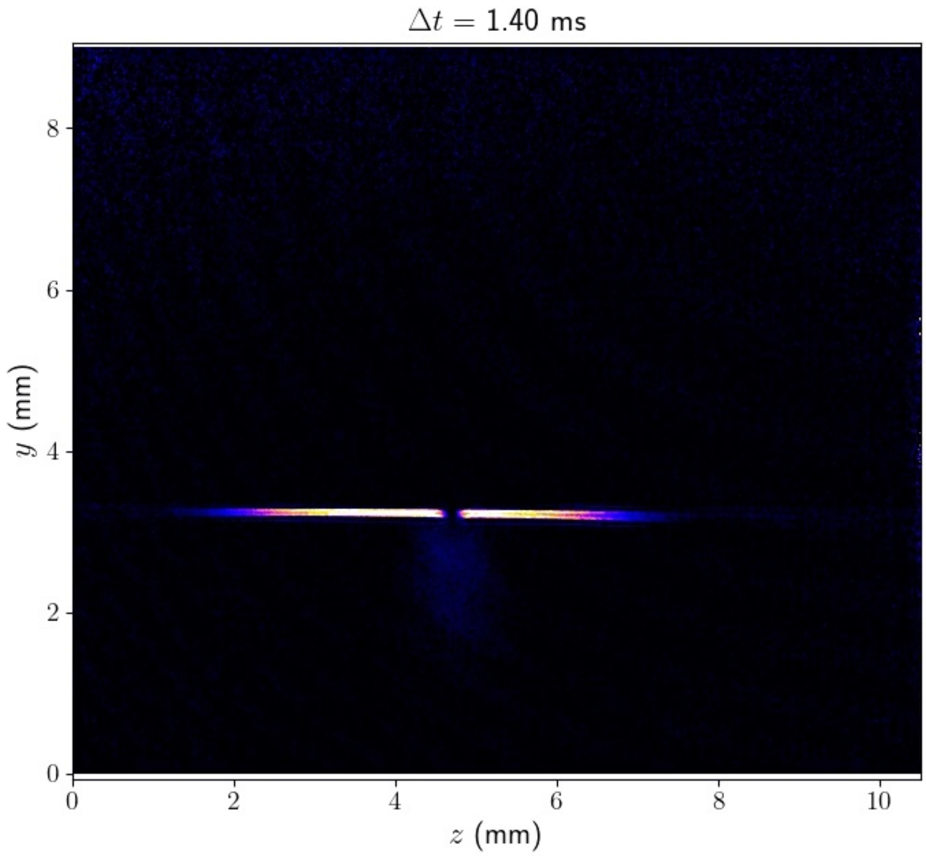
$\Delta\vec{p}_{\mathsf{abs}} = \hbar\,\vec{k}$

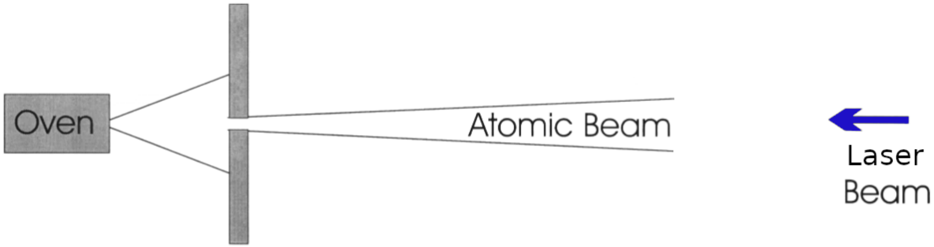
$\langle\Delta\vec{p}_{\mathsf{reemiss}}\rangle = 0$

(but $\mathrm{var}[\Delta\vec{p}_{\mathsf{reemiss}}] \neq 0$!)

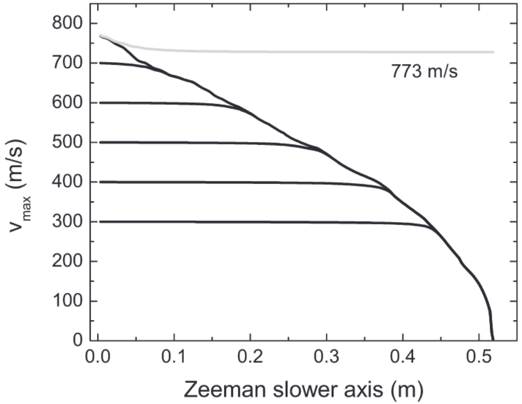
$\Rightarrow \quad \langle\Delta\vec{p}_{\mathsf{1cycle}}\rangle = \hbar\,\vec{k}$ and some heating…

Radiation pressure : blowing off atoms

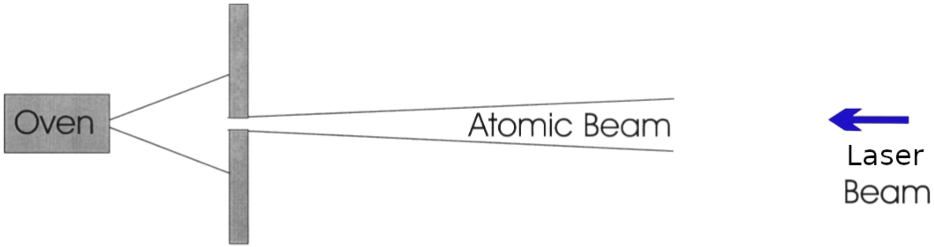



Oven
Atomic Beam
Laser
Beam

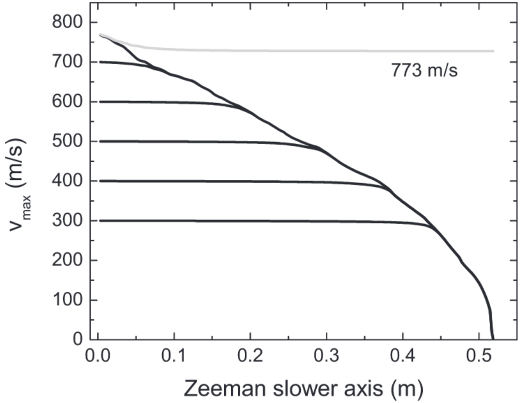
$\sim 10^5\, g$!

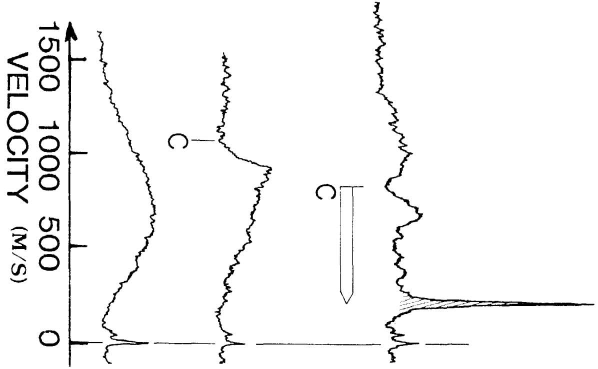

773 m/s
v_{max} (m/s)
Zeeman slower axis (m)
800
700
600
500
400
300
200
100
0
0.0
0.1
0.2
0.3
0.4
0.5

Atom slowers



$\sim 10^5\, g$!

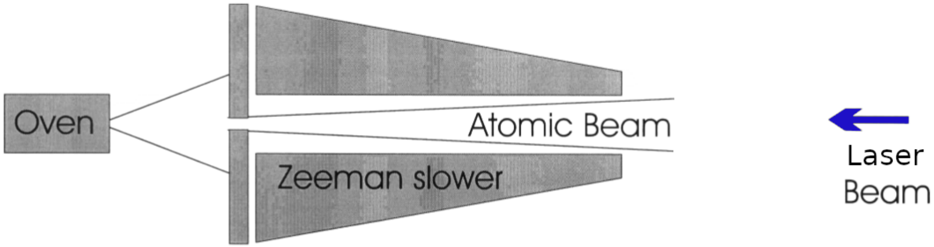


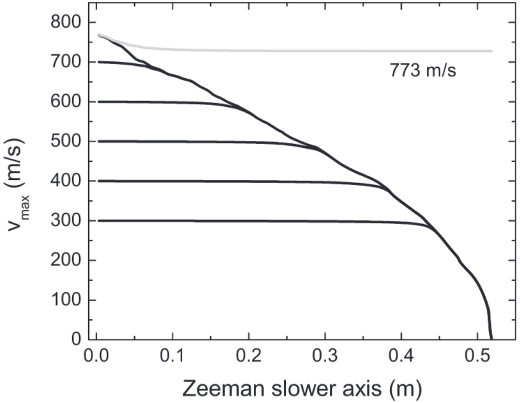


1978-84, Institute of Spectroscopy, Moscow

1984, Boulder

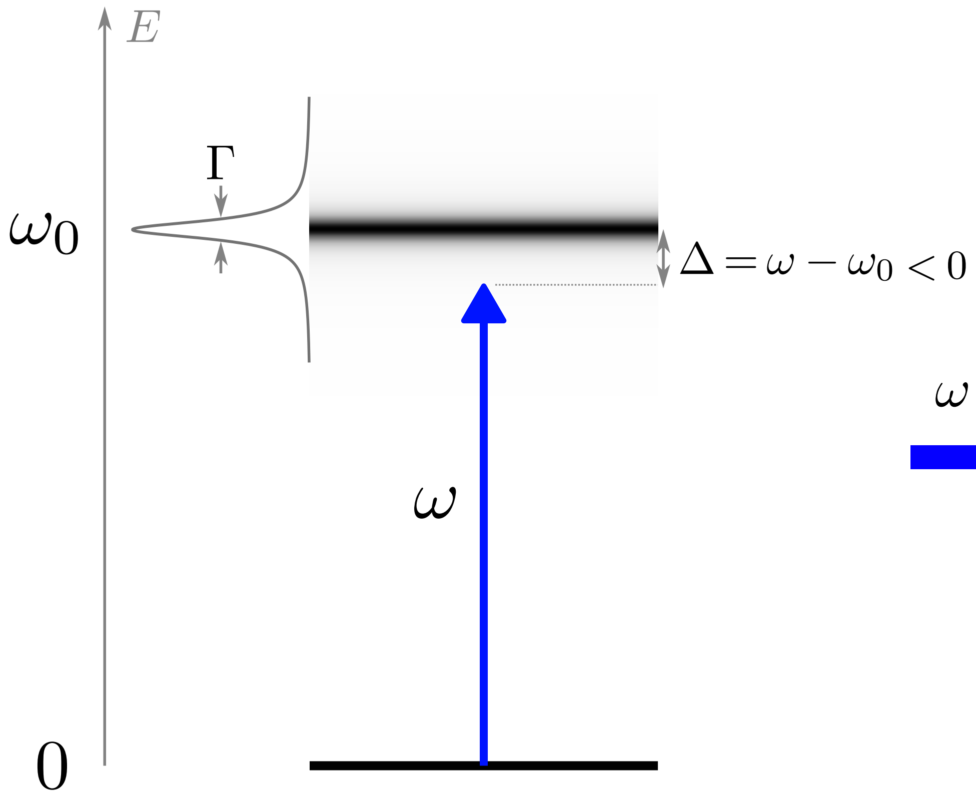
Zeeman slowers

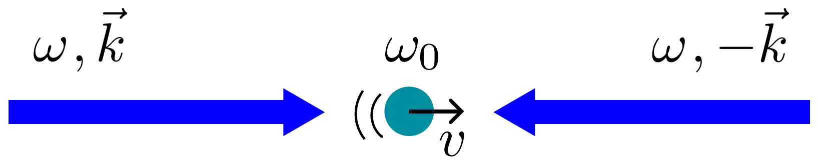


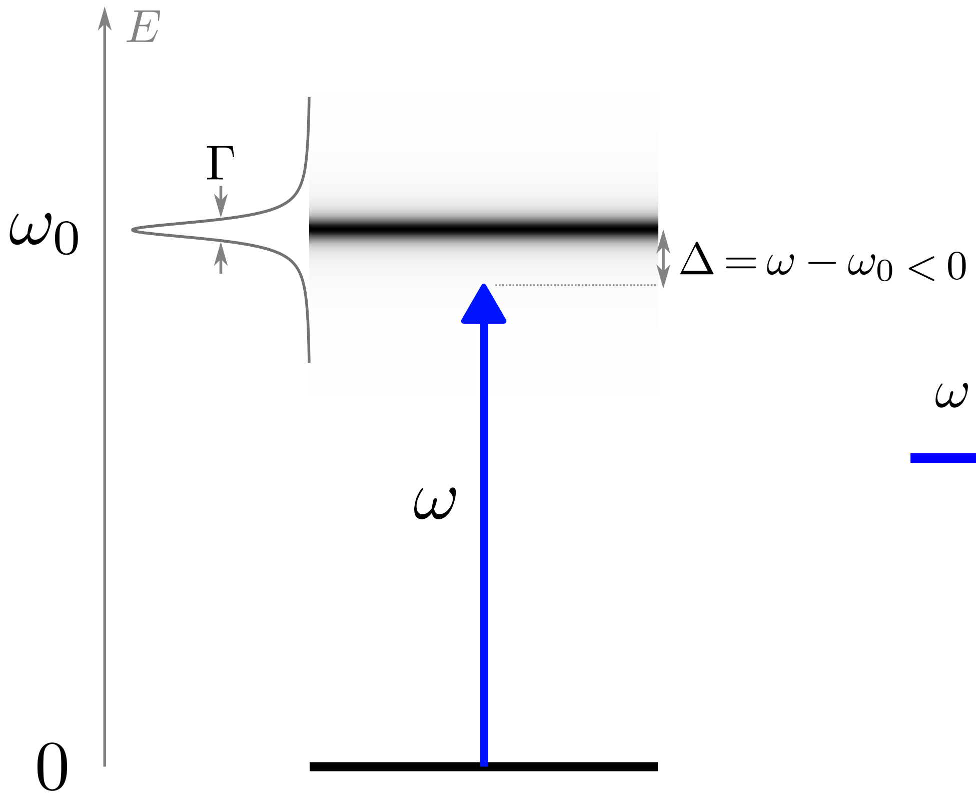


1982, NIST (Gaithersburg, USA)

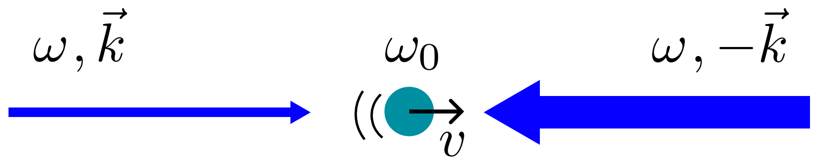
Light forces : optical molasses







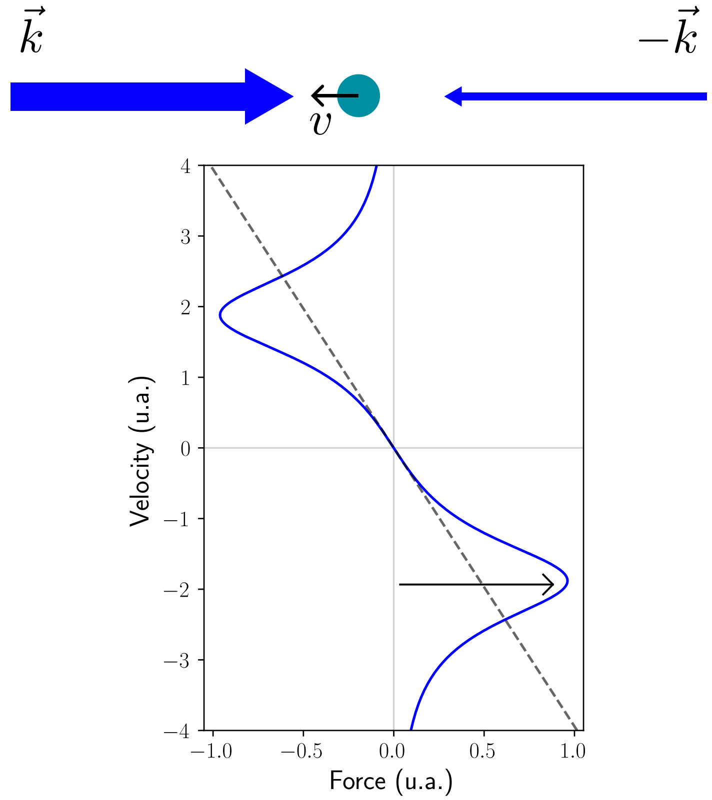
Absorption imbalance

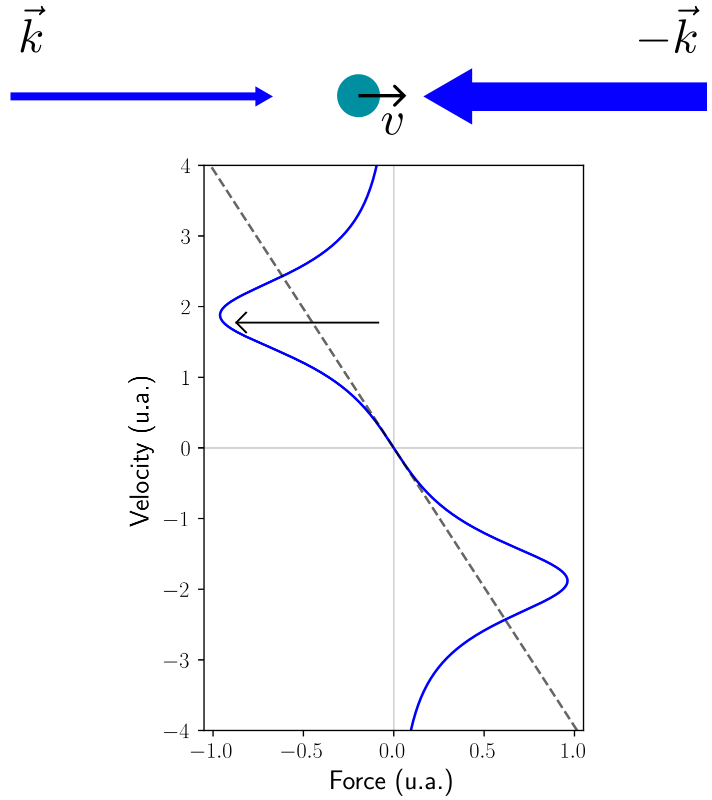


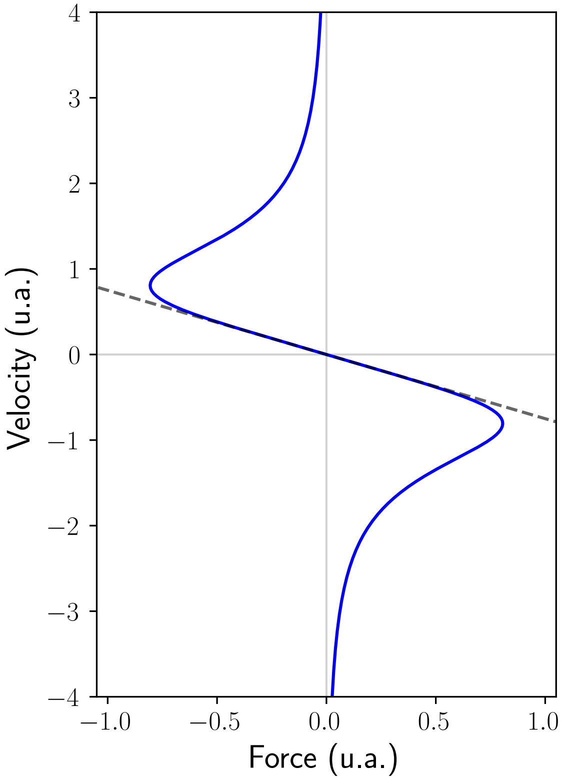
Doppler shift :

$$\Delta_{\text{seen by the atom}} = \Delta_{\text{laser}} - \vec{k} \cdot \vec{v}$$

Light forces : optical molasses



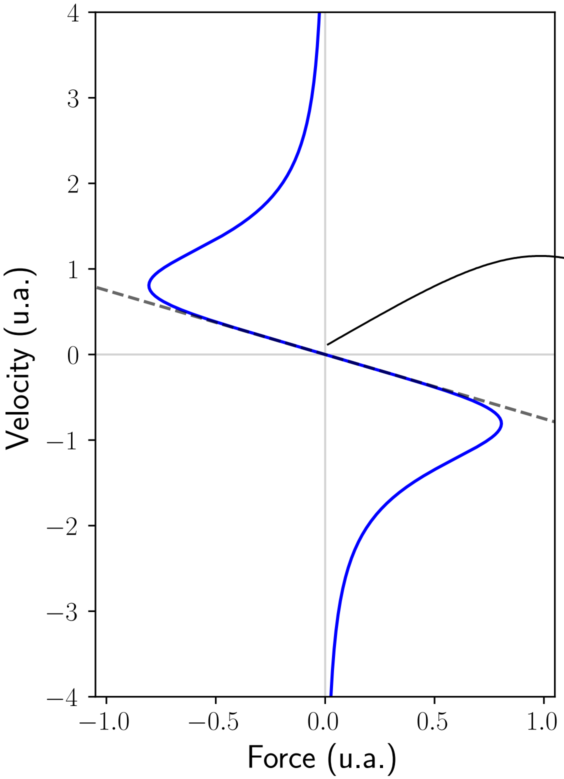

$\vec{k}$
$-\vec{k}$
$\vec{v}$
4
3
2
1
0
−1
−2
−3
−4
−1.0
−0.5
0.0
0.5
1.0
Velocity (u.a.)
Force (u.a.)



$$\Rightarrow \quad \langle \vec{F}_{\text{molasses}} \rangle \propto -\vec{v}$$

friction/damping force

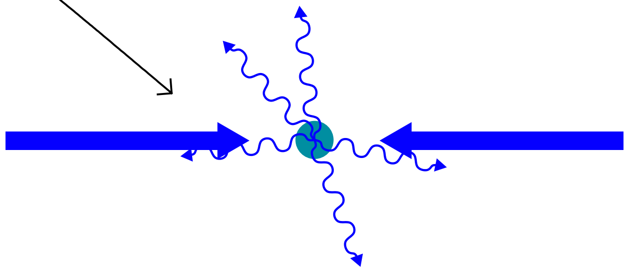
Optical molasses



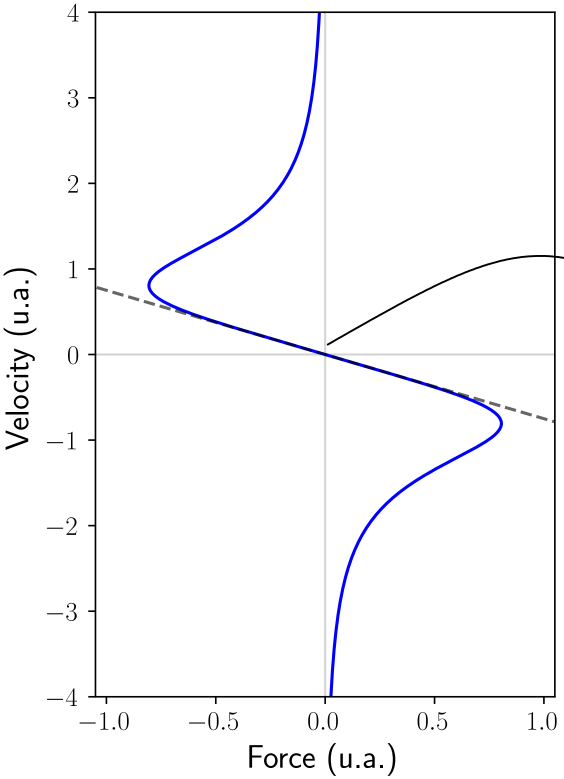
Cooling, $\langle \vec{F}_{\text{molasses}} \rangle \propto -\vec{v}$

$+$

Heating, even at $v = 0$



Optical molasses



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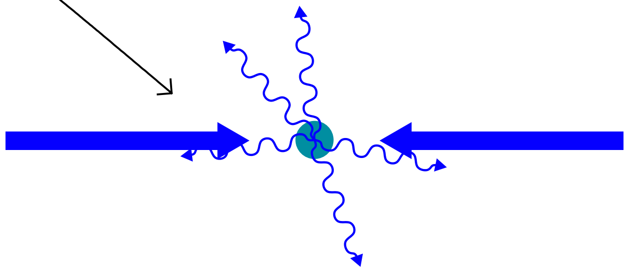
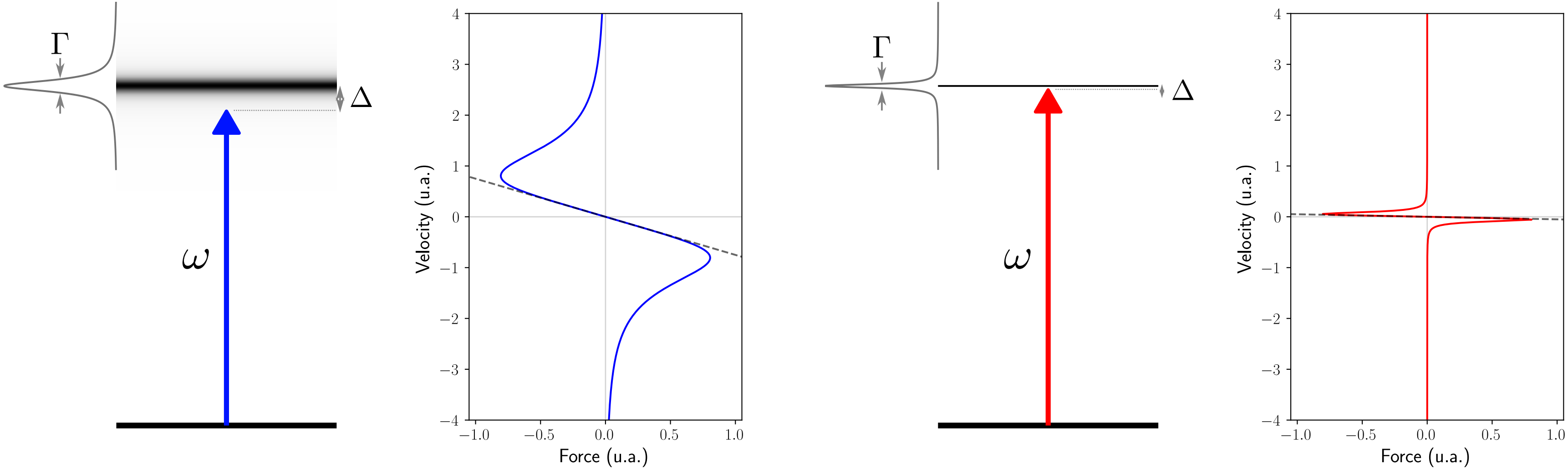
Heating, even at $v = 0$



$\Rightarrow$ non-zero equilibrium avg. velocity

Optical molasses



small linewidth Γ $\Longleftrightarrow$ selective in frequency $\underset{\text{Doppler effect}}{\Longleftrightarrow}$ selective in velocity $\Longrightarrow$ better $\dfrac{\text{damping}}{\text{heating}}$ $\Longrightarrow$ $\searrow v$'s

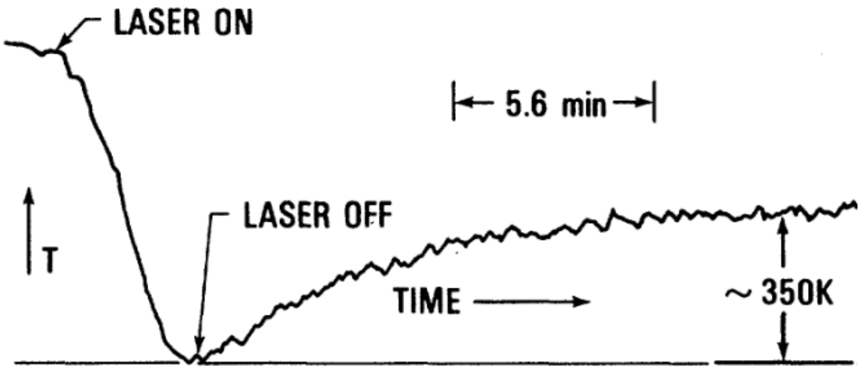
$$k_{\mathrm{B}}\, T_{\mathrm{min}} = \frac{\hbar\,\Gamma}{2}$$

A bit of history [ions]

Idea : **1974**, Hänsch & Schawlow

First Doppler/sideband cooling on trapped ions : **1978**,

Wineland @ Boulder



Dehmelt @ Heidelberg

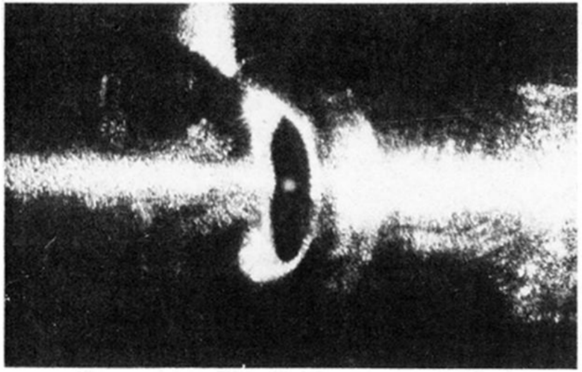


FIG. 2. Photograph of trap looking in $-x'$ direction. The Ba^+ cloud is visible in the center.

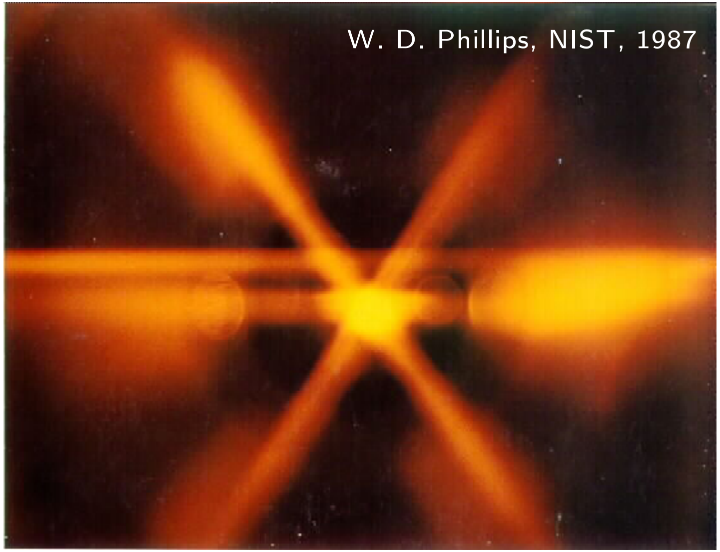
2D molasses (atomic beam) : **1984**, Letokhov & Minogin, Institute of Spectroscopy, Moscow

$\longrightarrow \quad 3.5\,\mathrm{mK}$

3D molasses : **1985**, S. Chu @ Bell Labs

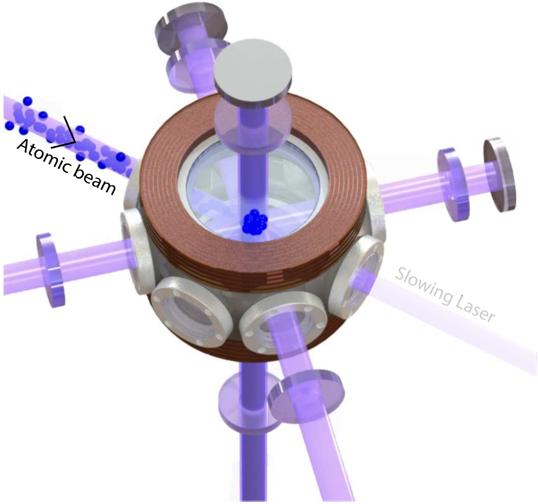
$\longrightarrow \quad 240\,\mu\mathrm{K}$

Then ENS, NIST, JILA...



3D molasses + restoring force $\Rightarrow$ Cooling *and trapping*

$$\langle \vec{F}_{\text{molasses}} \rangle \propto -\vec{v} \qquad \langle \vec{F}_{\text{restoring}} \rangle \propto -\vec{r}$$



The magneto-optical trap

3D molasses + restoring force $\Rightarrow$ Cooling *and trapping*

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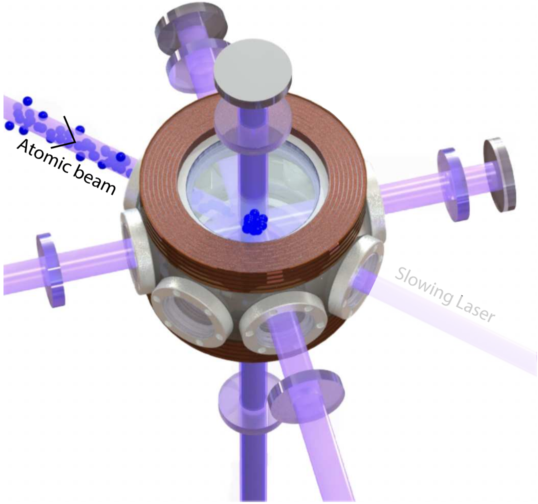

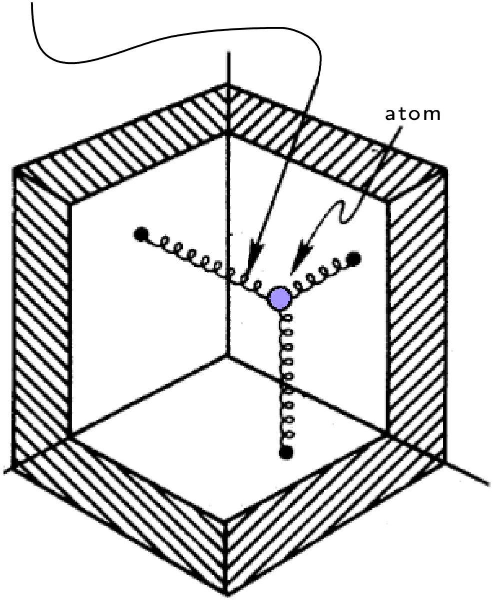

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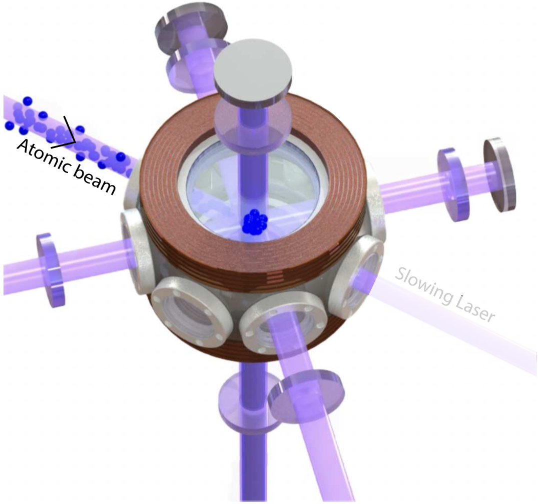
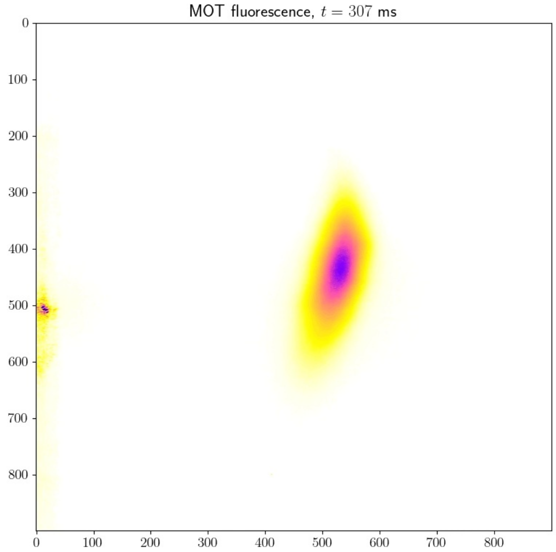
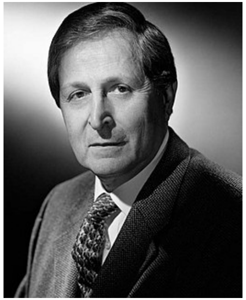




First magneto-optical trap : **1985**, Raab, S. Chu, Prichard @ Bell Labs
+ ideas of J. Dalibard

Typ. maximum MOT PSD : 10^{-4} (alkali elements)
Confirmation of sub-Doppler cooling : 1988

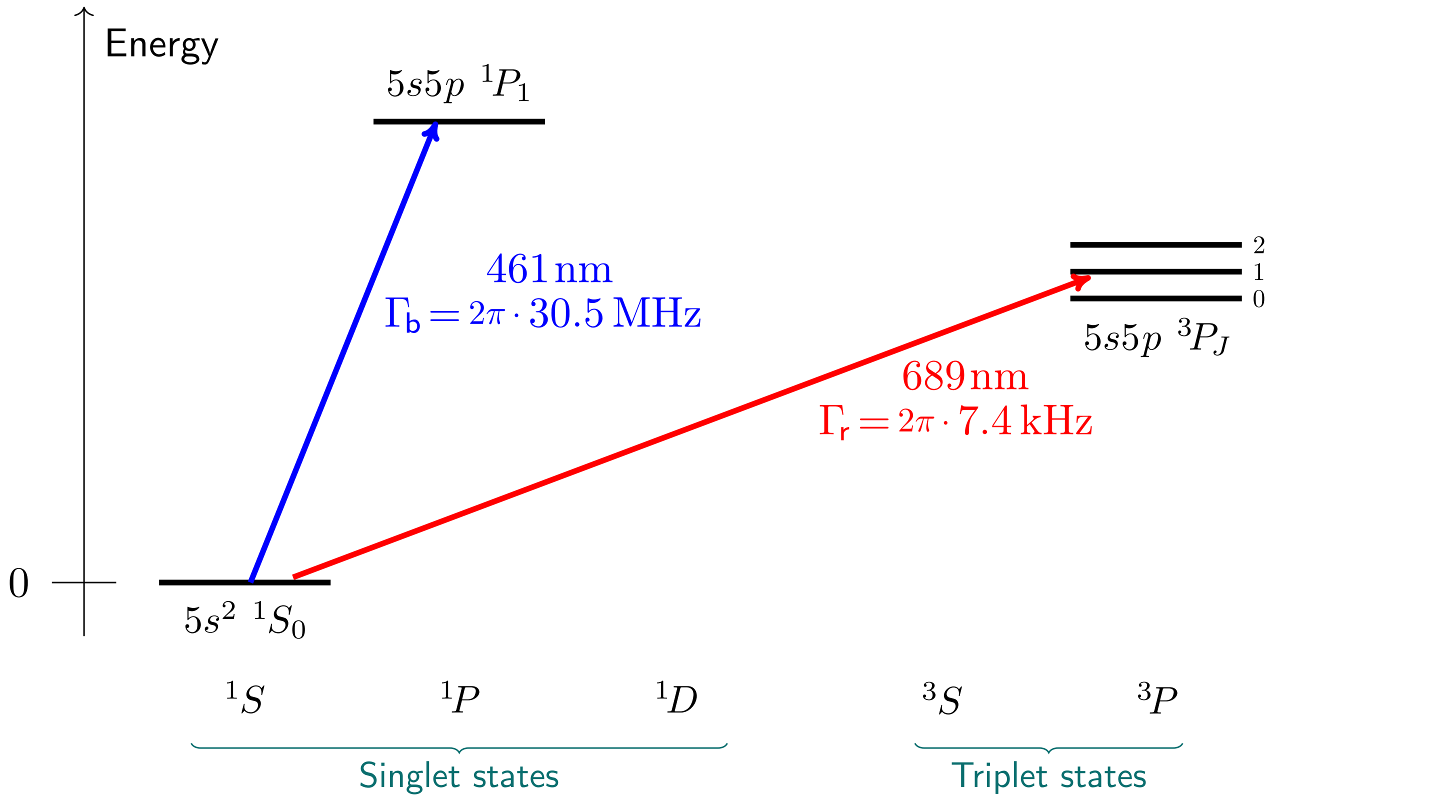
Nobel prize for C. Cohen-Tannoudji, S. Chu, W. D. Phillips



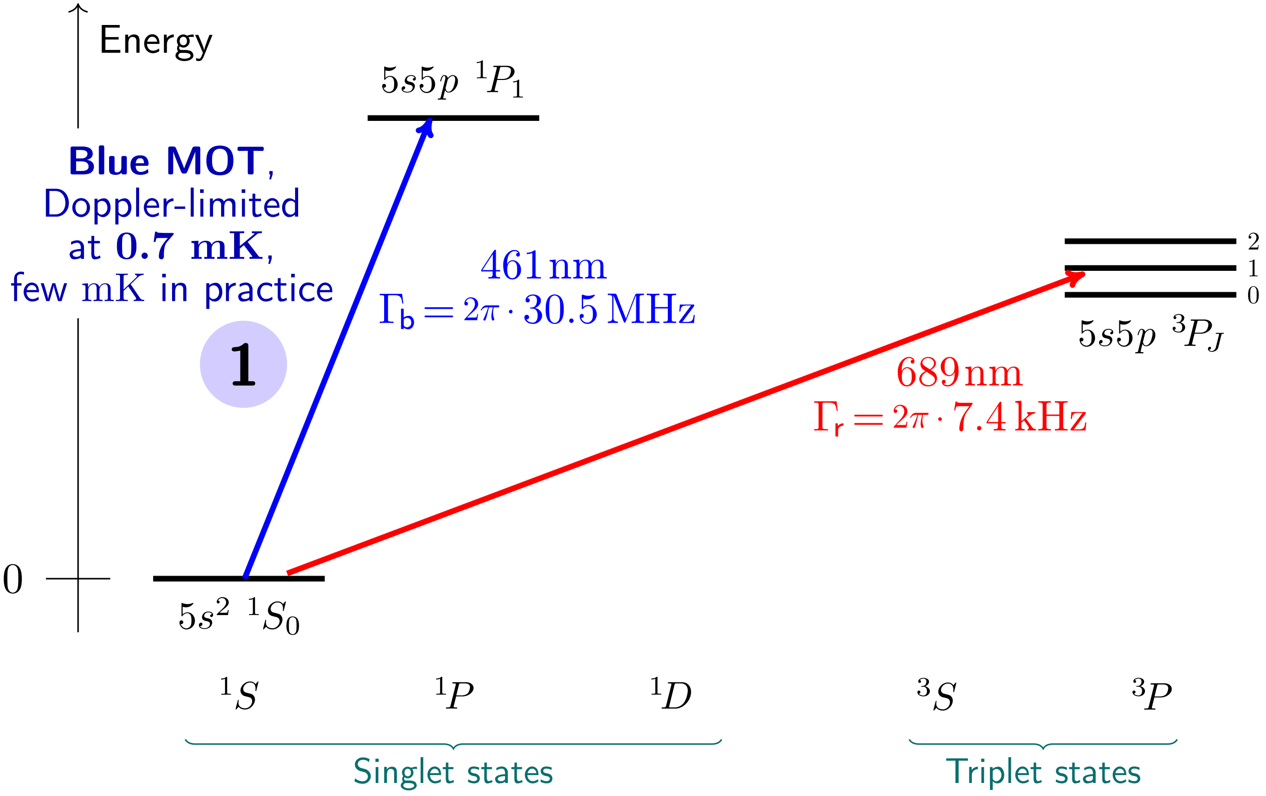
Strontium : a two-valence-electons atom

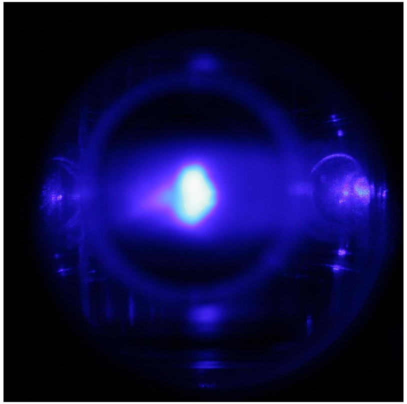
Group → / ↓ Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba		72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra		104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Ms	116 Lv	117 Ts	118 Og
Lanthanides			57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	
Actinides			89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr	

Laser cooling of strontium

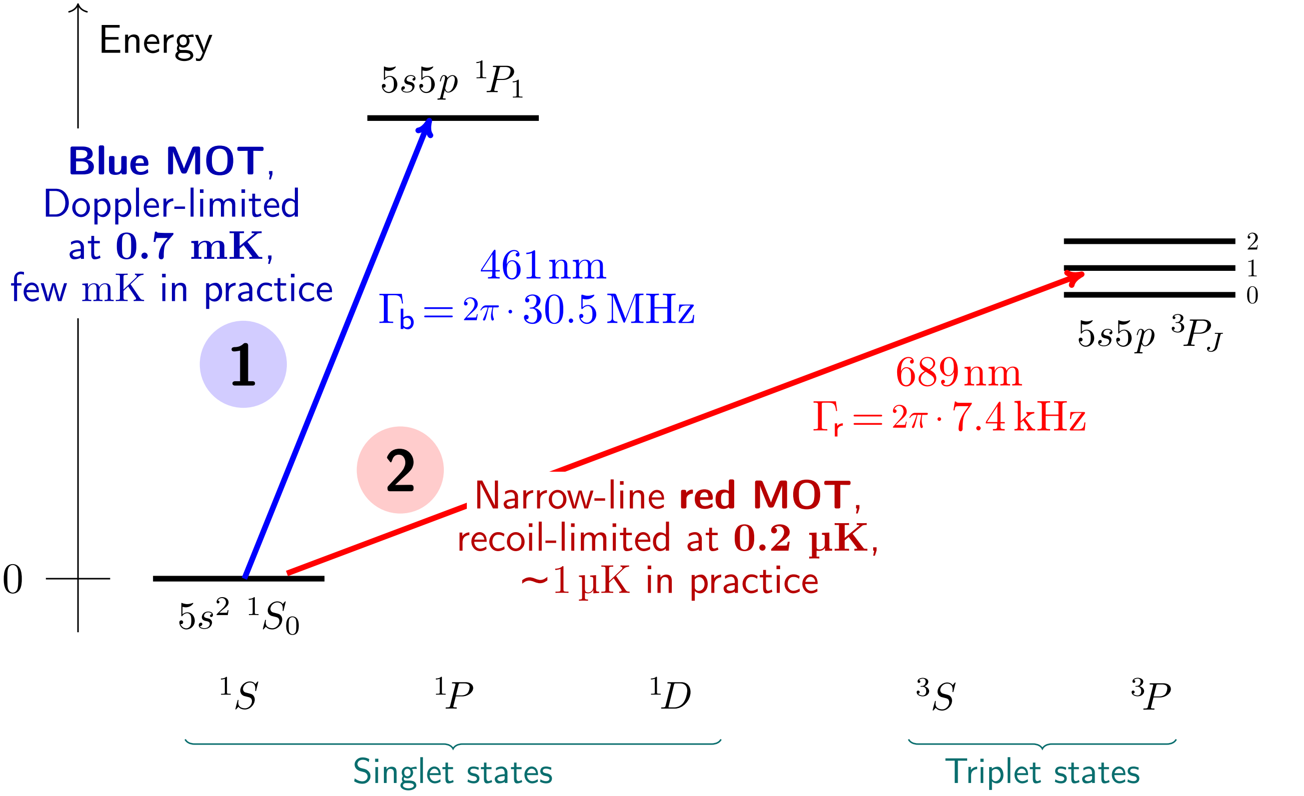


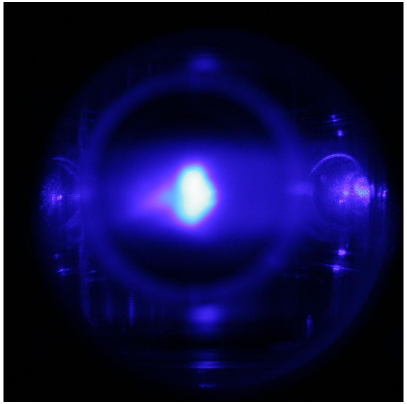
Laser cooling of strontium : blue $^1P_1$ transition

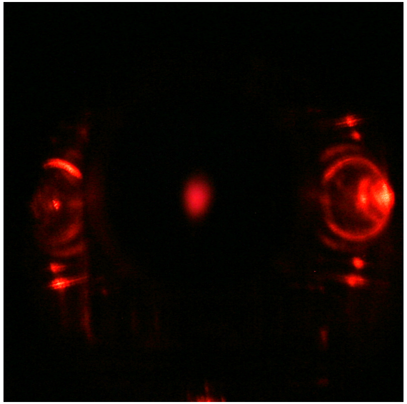




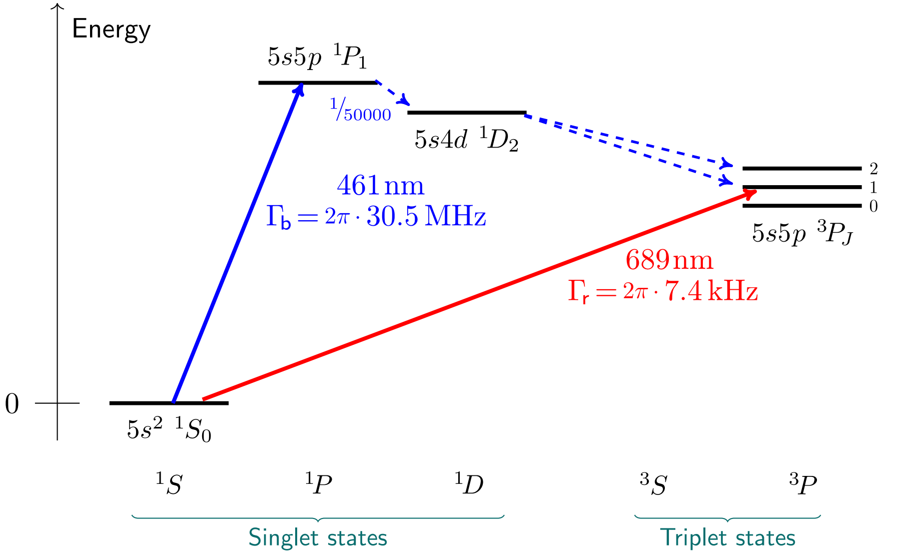
Laser cooling of strontium : red $^3P_1$ transition







E1-forbidden : $\langle S{=}0,\ldots|\,\vec{\boldsymbol{D}}\,|S{=}1,\ldots\rangle = 0$

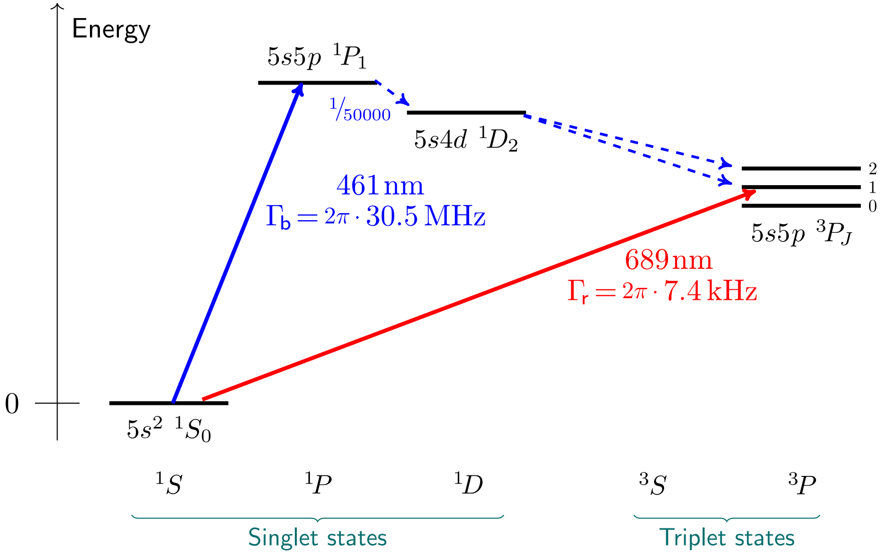


(The red $^1S_0 \leftrightarrow {}^3P_1$ transition)

E1-forbidden : $\langle S{=}0,\ldots\,|\,\vec{\boldsymbol{D}}\,|S{=}1,\ldots\rangle = 0$

Spin-orbit (not just $\vec{\boldsymbol{L}}\cdot\vec{\boldsymbol{S}}$ term !)
weak but non-negligible in Sr ($Z=38$).

$\rightarrow$ L, S not strictly good quantum numbers (J is)



E1-forbidden : $\langle S{=}0, \ldots | \vec{\boldsymbol{D}} | S{=}1, \ldots \rangle = 0$

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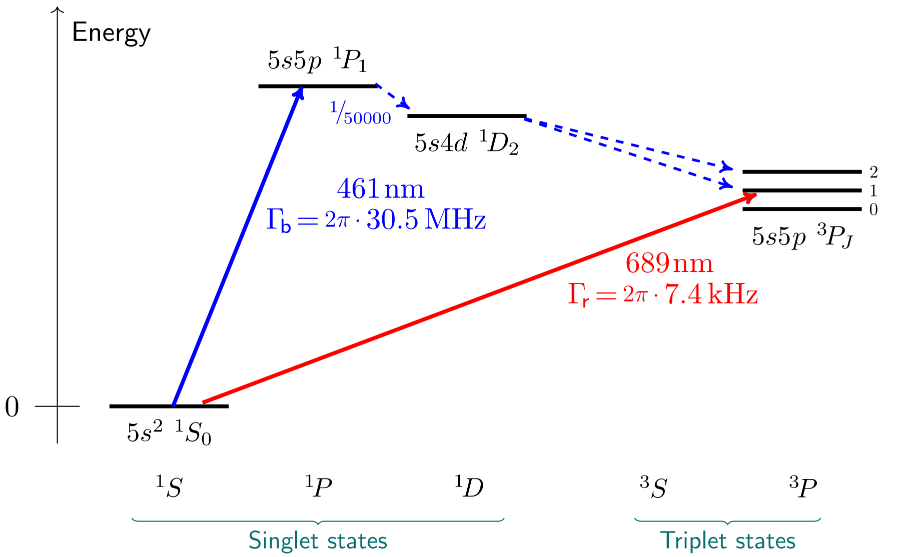

$\rightarrow$ Spin-orbit mixes LS terms with same J,
and in particular

$$|5s5p\,{}^3P_1\rangle = (1-\varepsilon)\,|5s5p, S{=}1, L{=}1, J{=}1\rangle + \varepsilon\,|5s5p, S{=}0, L{=}1, J{=}1\rangle + \cdots$$

E1-forbidden : $\langle S{=}0, \ldots | \vec{\boldsymbol{D}} | S{=}1, \ldots \rangle = 0$

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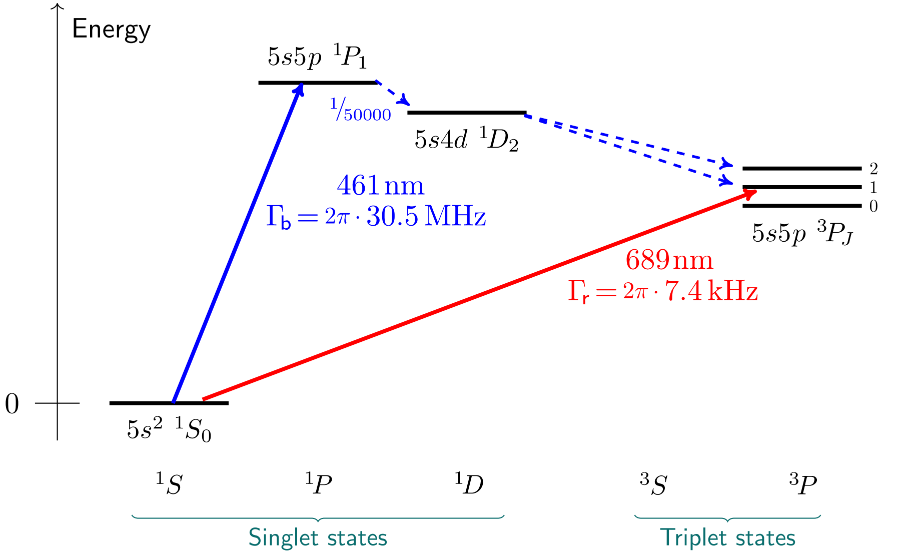

$\rightarrow$ Spin-orbit mixes LS terms with same J,
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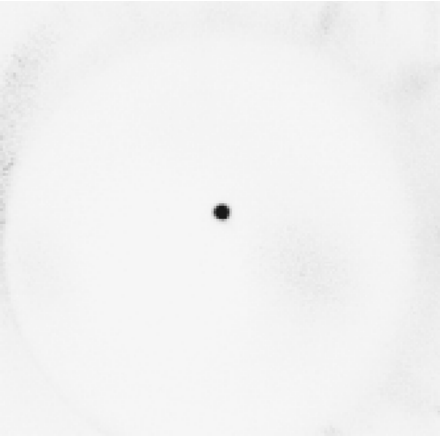
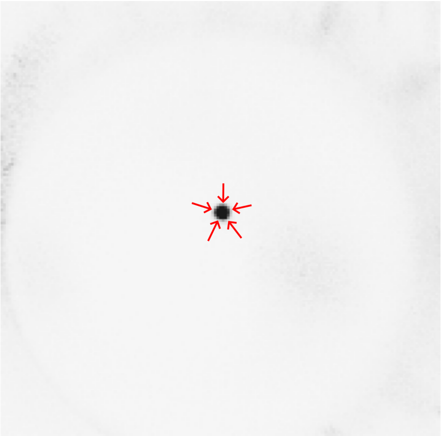
$$\Rightarrow \quad \langle ^1S_0 | \vec{\boldsymbol{D}} | ^3P_1 \rangle \neq 0 \quad (\propto \varepsilon) \qquad \Rightarrow \quad \text{finite (long) lifetime, E1 decay}$$

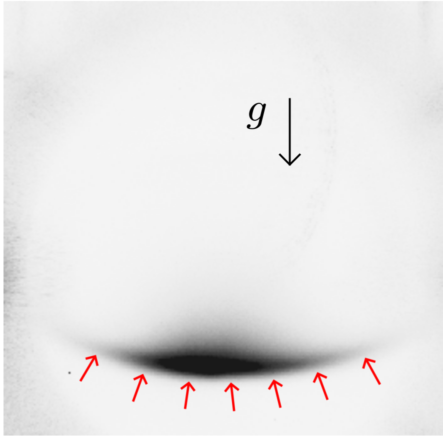
The narrow-line red MOT



The narrow-line red MOT

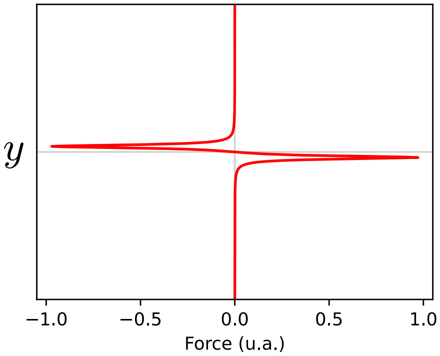


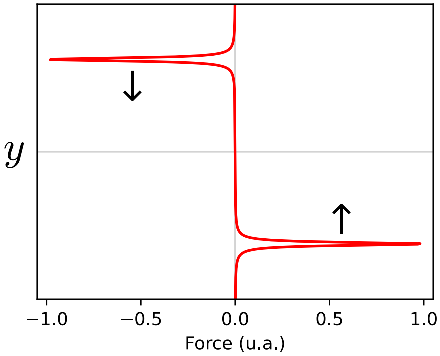
$\Delta = -\text{few}\ \Gamma$



$\Delta = -300\,\Gamma$

$\Delta = -10\,\Gamma$





$T_{\text{min}} = 0.2\,\mu\text{K}$

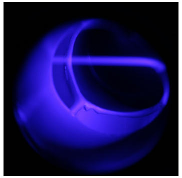
$1 \sim 2\,\mu\text{K}$ in practice

$\sim 50 \cdot 10^6$ at in $\sim (100\,\mu\text{m})^3$

$\text{PSD} \approx 10^{-2}$!

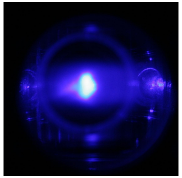
Summary

$800\,\mathrm{K}$
$\sim 400\,\mathrm{m/s}$
$\mathrm{PSD} \approx 10^{-14}$



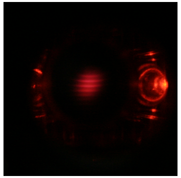
$\longrightarrow$ Transverse molasses
Zeeman slower

$\sim 0.5\,\mathrm{K}$
$\sim 10\,\mathrm{m/s}$
$\mathrm{PSD} \approx 10^{-14}$
10^{-12} acheivable



$\longrightarrow$ blue MOT

$5\,\mathrm{mK}$
$\sim 1\,\mathrm{m/s}$
$\mathrm{PSD} \approx 10^{-10}$
10^{-8} acheivable



$\longrightarrow$ red MOT

$2\,\mu\mathrm{K}$
$\sim 0.02\,\mathrm{m/s}$
$\mathrm{PSD} \approx 10^{-3}$
10^{-2} acheivable

1. Oven $\longrightarrow$ atomic beam
2. Transverse cooling
3. Zeeman slower
4. Blue MOT ($\sim 1\,\mathrm{s}$ for loading 10^8 atoms)
5. Broadened red MOT ($\sim 0.1\,\mathrm{s}$)
6. Narrow-line red MOT ($\sim 0.1\,\mathrm{s}$)
7. ...we're not there yet !

1. Degenerate atomic gases (as analogues?)

2. Laser cooling

3. Evaporative cooling

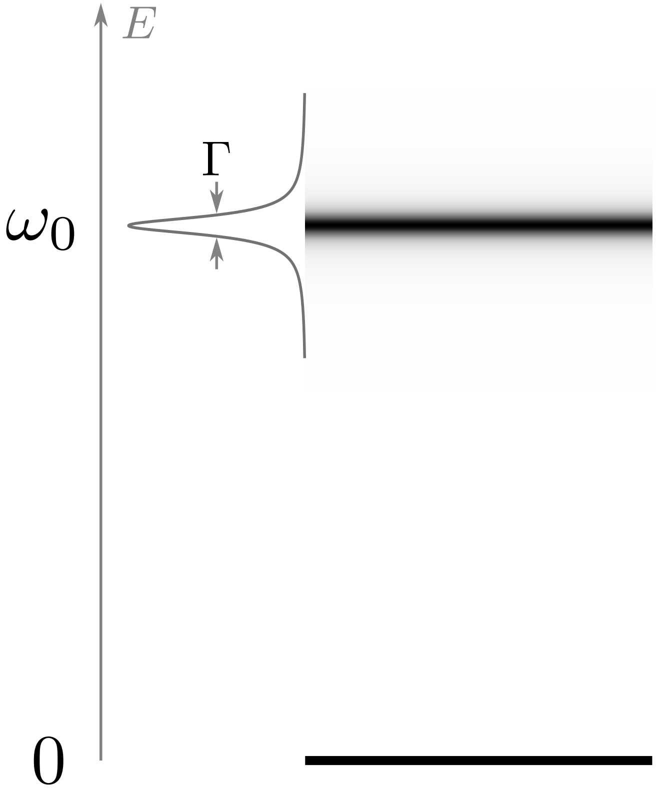
4. Bose-Hubbard physics

How to cool down even more ?

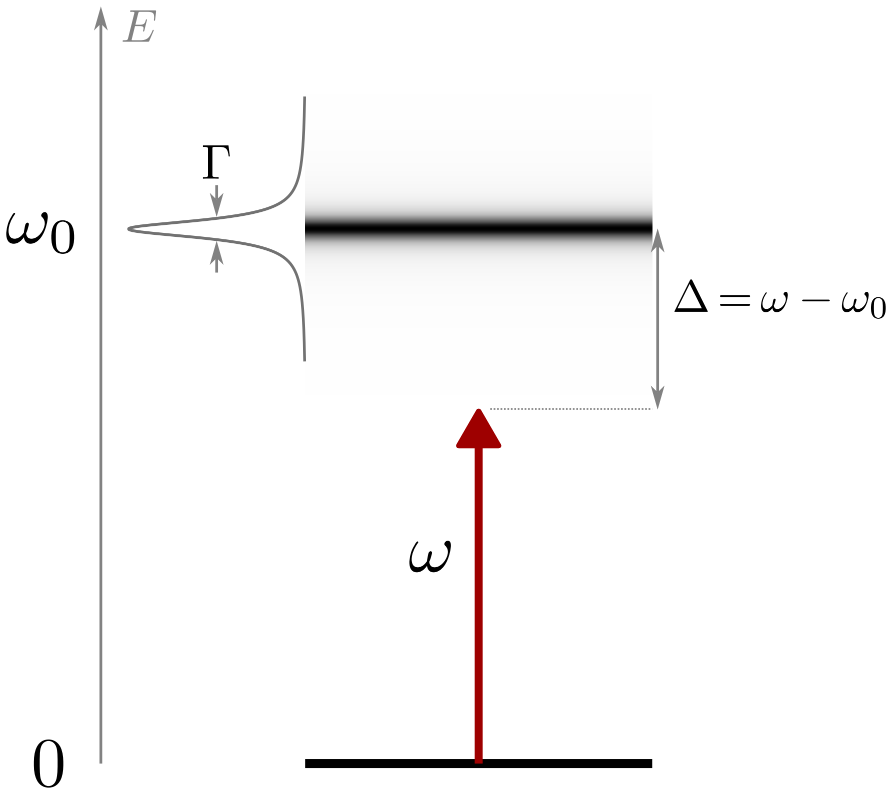
Cannot really use resonant light / dissipative cooling : residual random motion + losses

$\Rightarrow$ Conservative potentials

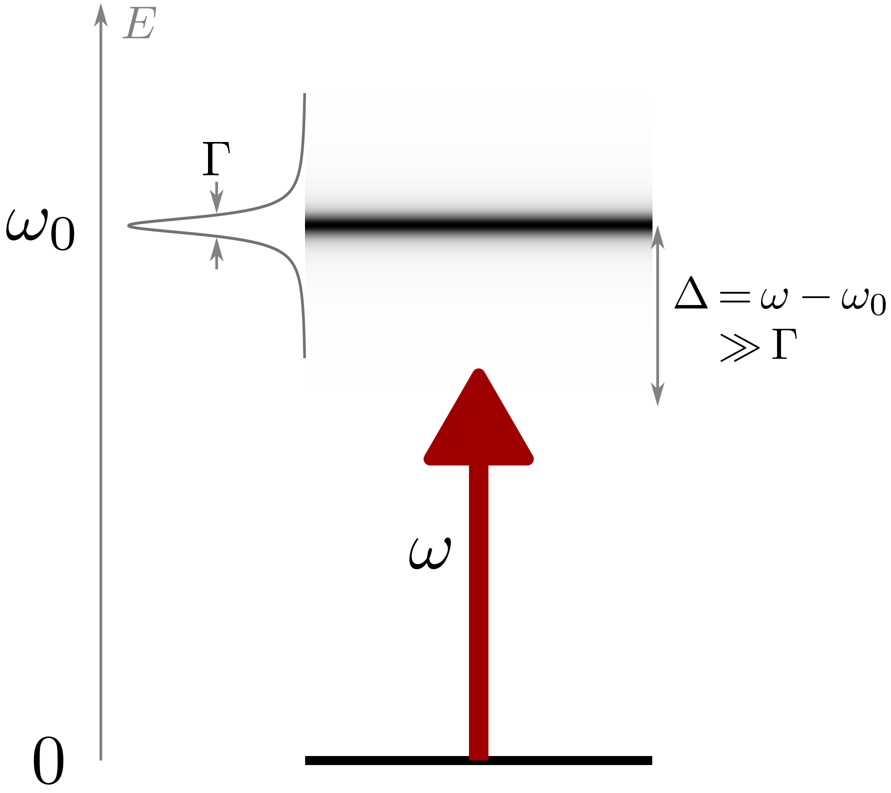
- $\longrightarrow$ Magnetic traps
- $\longrightarrow$ Optical traps


E
Γ
ω_0
0

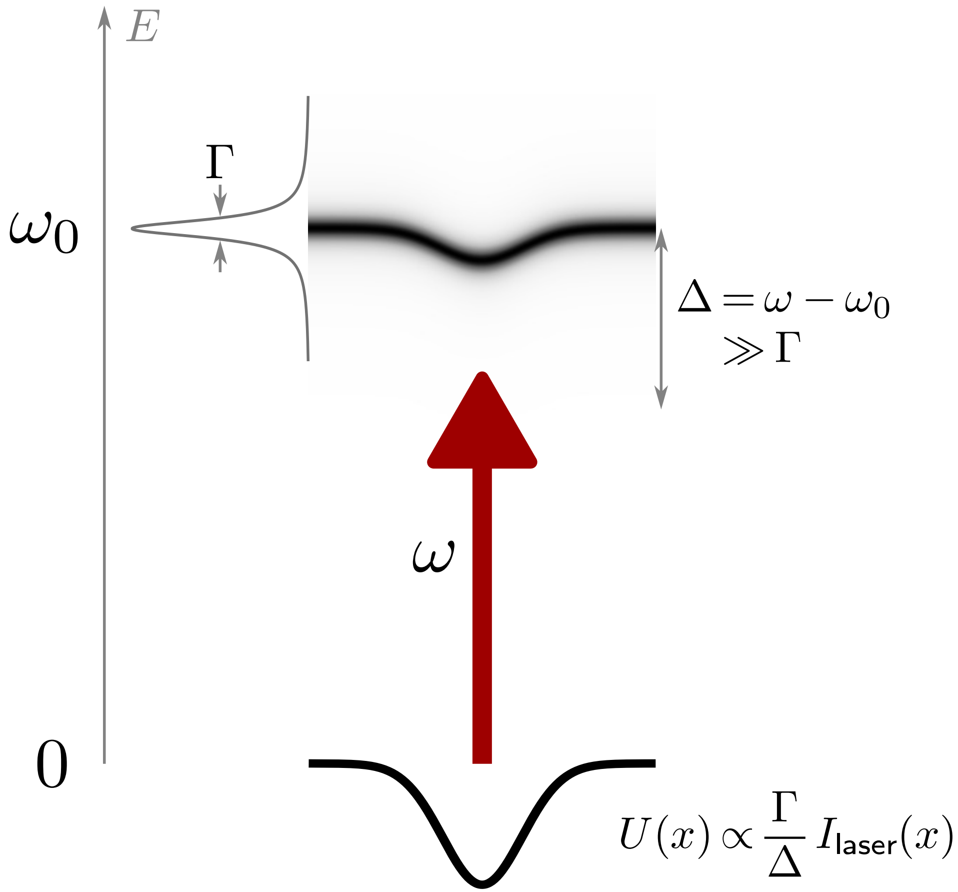
Light forces : far-off-resonant case

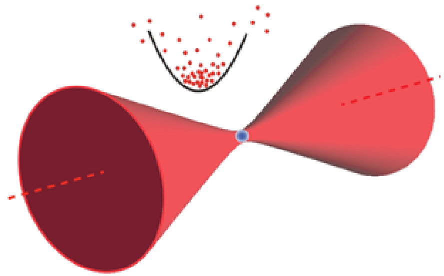


Light forces : far-off-resonant case



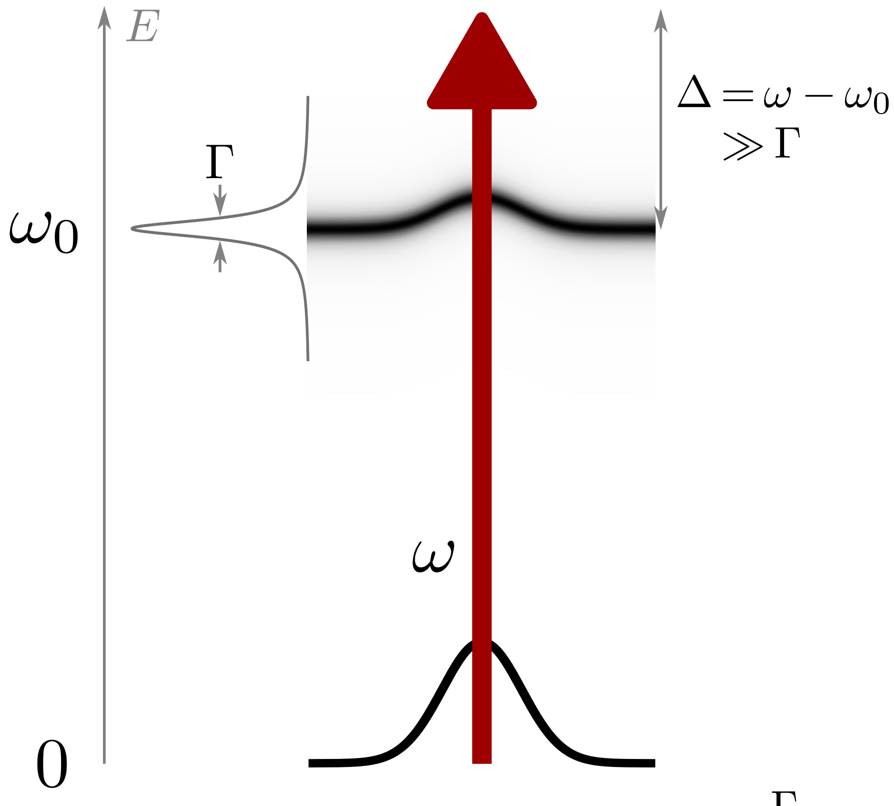
Light forces : far-off-resonant case



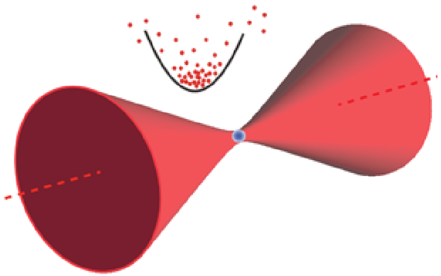


eg. gaussian beam

Light forces : far-off-resonant case

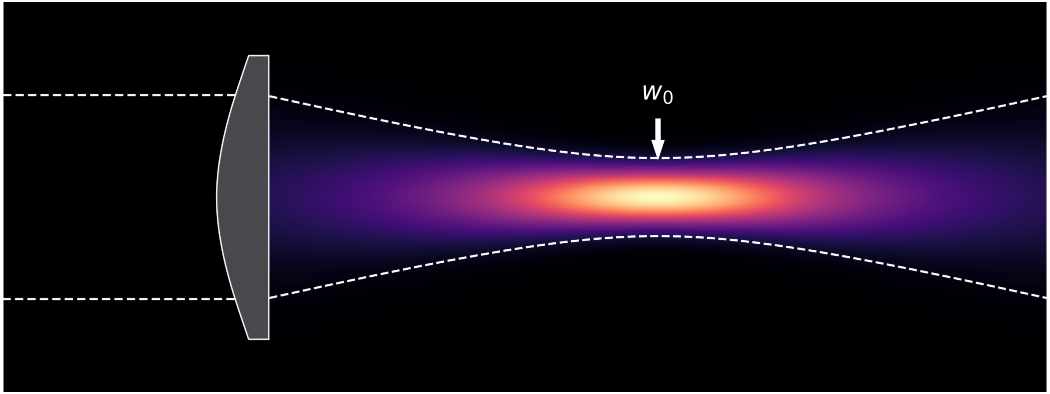


$$U(x) \propto \frac{\Gamma}{\Delta} I_{\text{laser}}(x)$$



eg. gaussian beam

Optical traps



$$\text{potential}(\vec{x}) \propto -\text{intensity}(\vec{x})$$

We want to study a 2D gas

We want to study a 2D gas

$\longrightarrow$ we need to **freeze vertical motion** (while keeping a large system horizontally)

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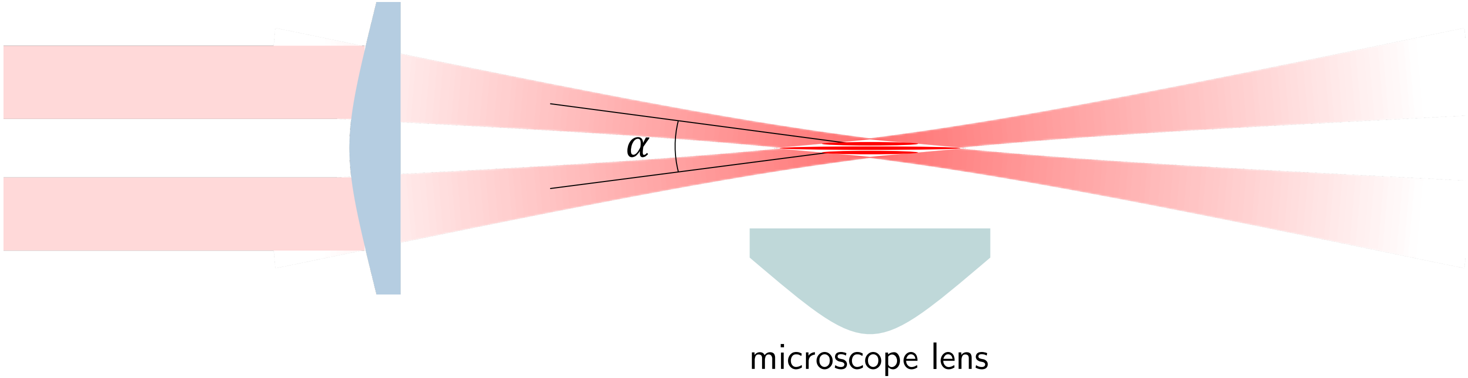
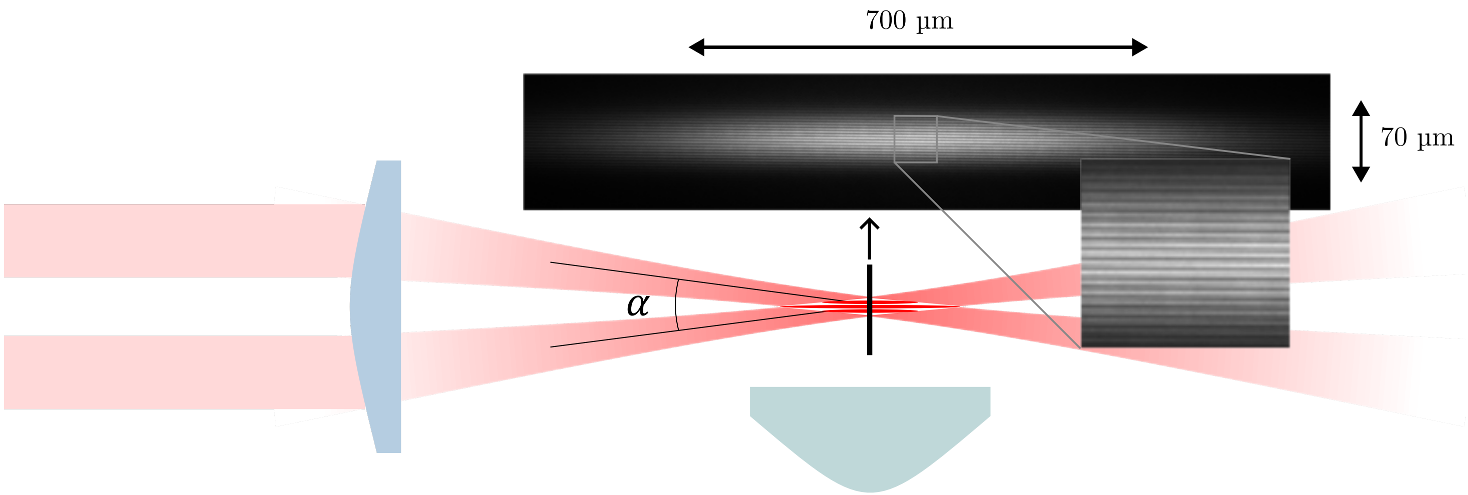
$\longrightarrow$ we need to **freeze vertical motion** (while keeping a large system horizontally)



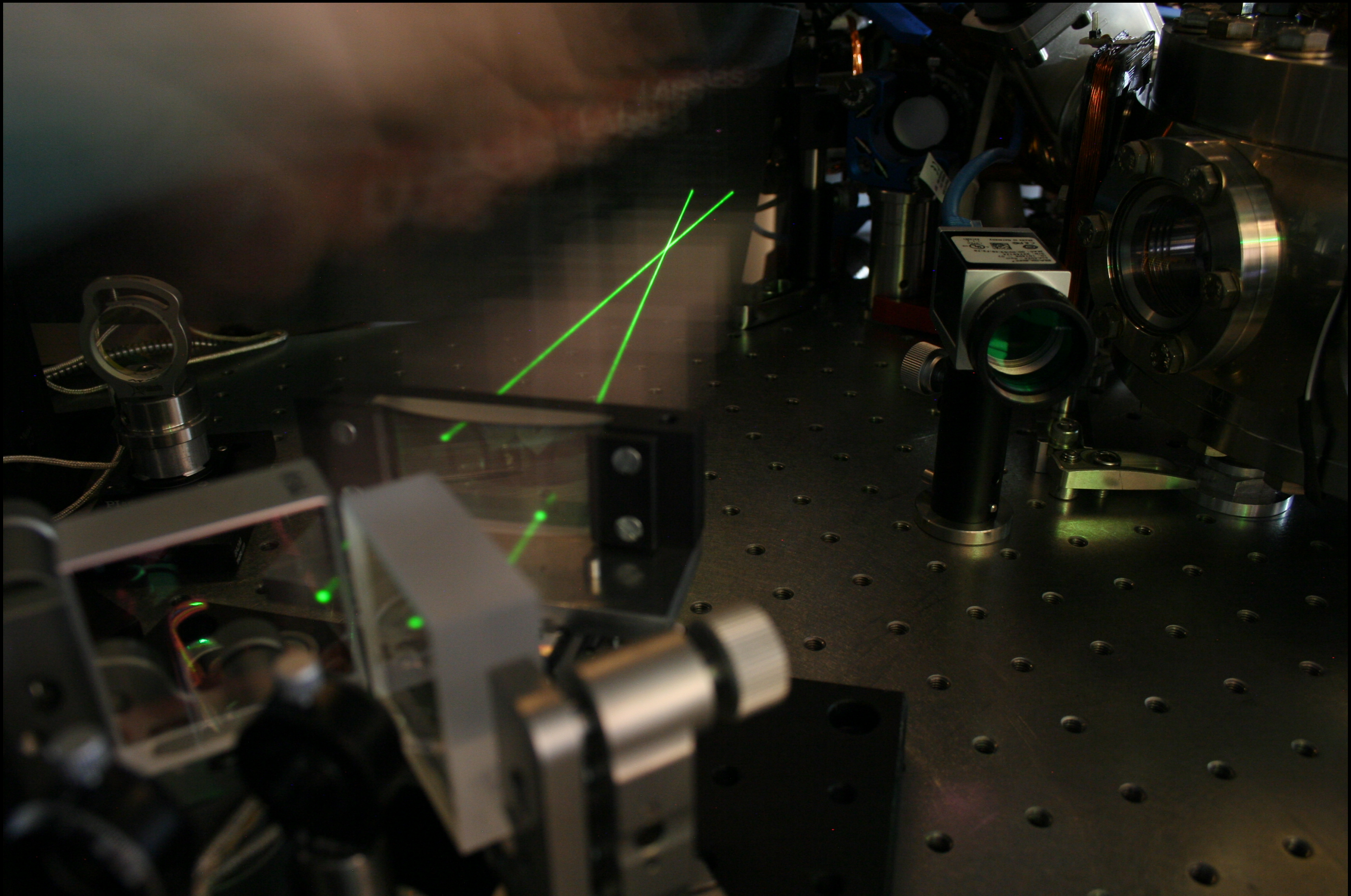
$\alpha = 12^\circ \rightarrow 5\,\mu\mathrm{m}$ fringe-to-fringe

We want to study a 2D gas

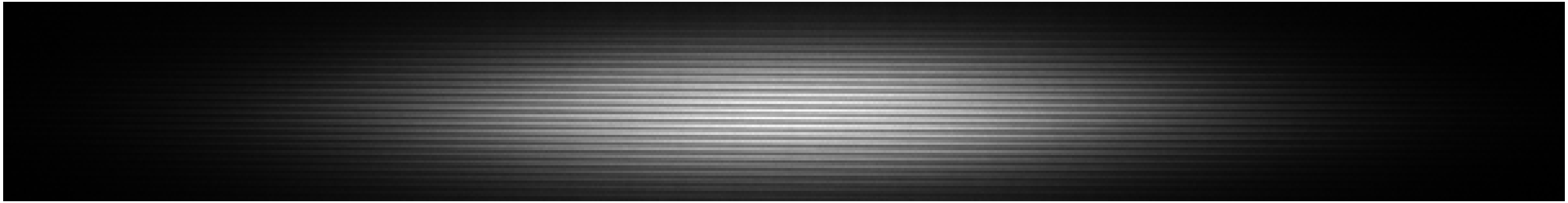
→ we need to **freeze vertical motion** (while keeping a large system horizontally)

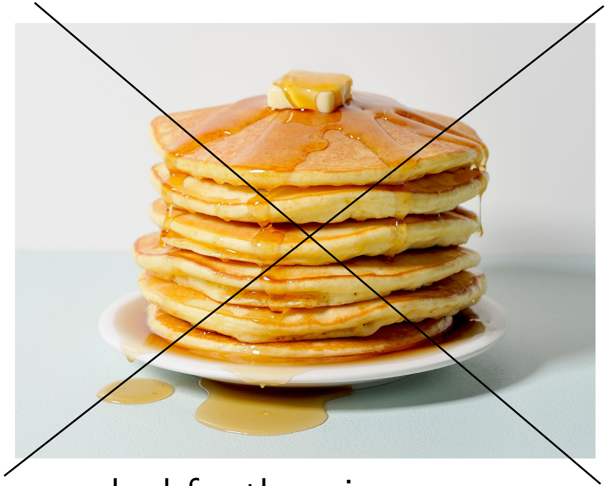


$\alpha = 12° \rightarrow 5\,\mu m$ fringe-to-fringe



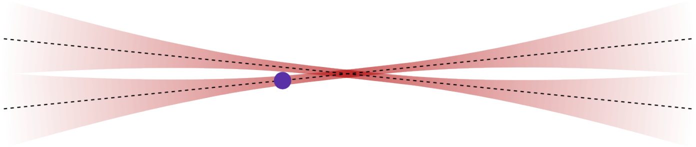
Challenge :

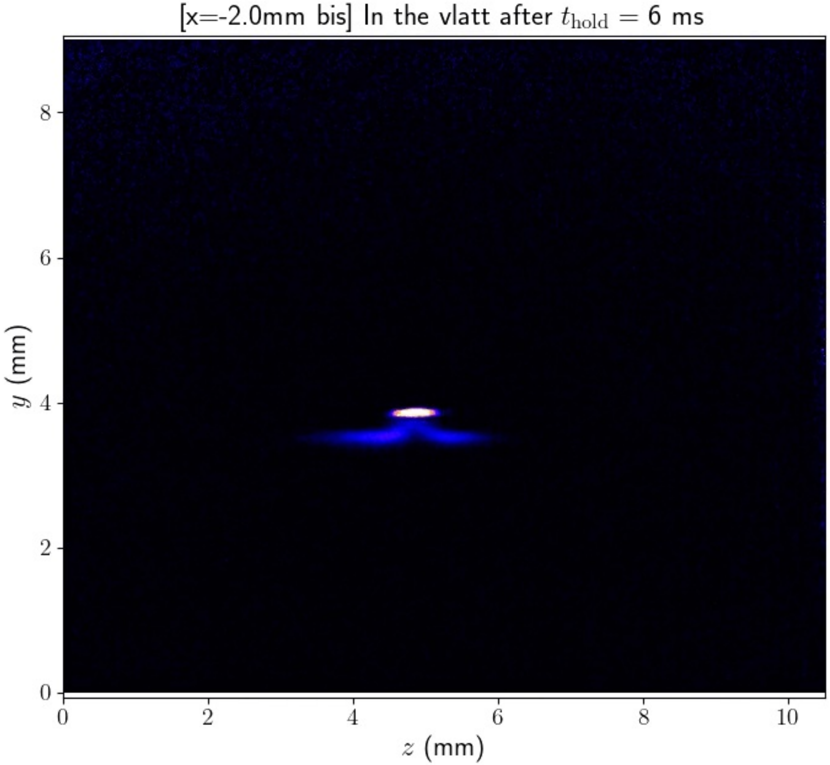




bad for the microscope

(Transfer in the vertical lattice)





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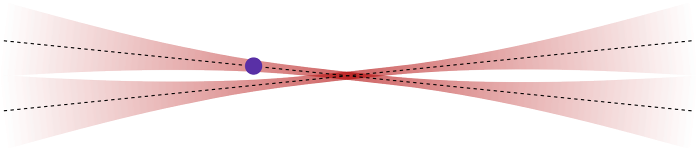

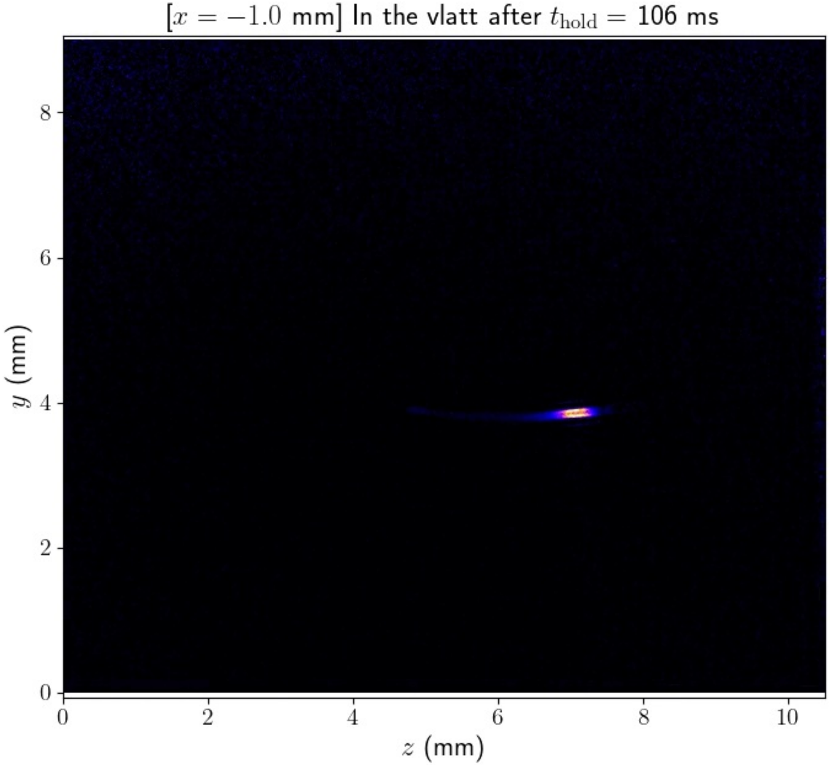

How to reach degeneracy now ?

Cloud tightly trapped : denser ($n \nearrow$), but also hotter ($\lambda_T \searrow$) $\;\longrightarrow\;$ same $\mathrm{PSD} = n\,\lambda_T^3$

More laser cooling ?

How to reach degeneracy now ?

Cloud tightly trapped : denser ($n \nearrow$), but also hotter ($\lambda_T \searrow$) $\rightarrow$ same $\mathrm{PSD} = n\,\lambda_T^3$

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No : lossy, and not quite enough ($1 \sim 2\,\mu\mathrm{K}$ min.)

How to reach degeneracy now ?

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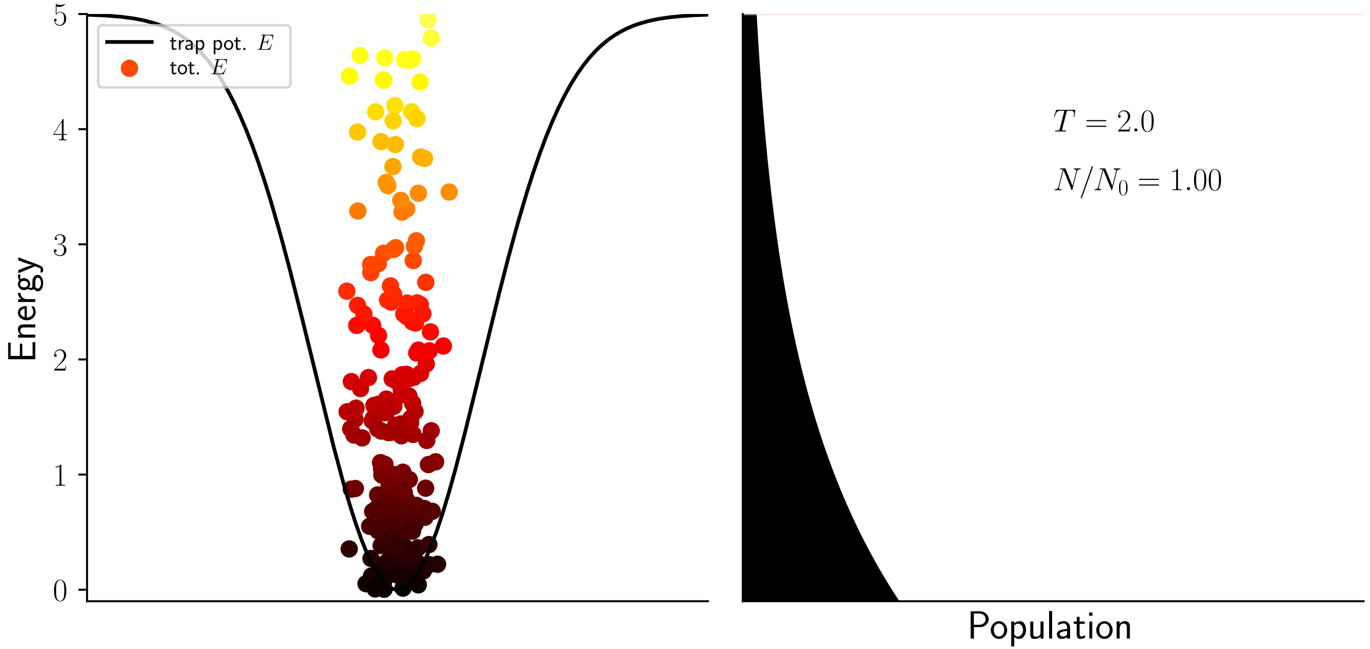
More laser cooling ?

No : lossy, and not quite enough ($1 \sim 2\,\mu\mathrm{K}$ min.)

Remove hot atoms → **evaporative cooling**.

Evaporative cooling [**with thermalisation**]



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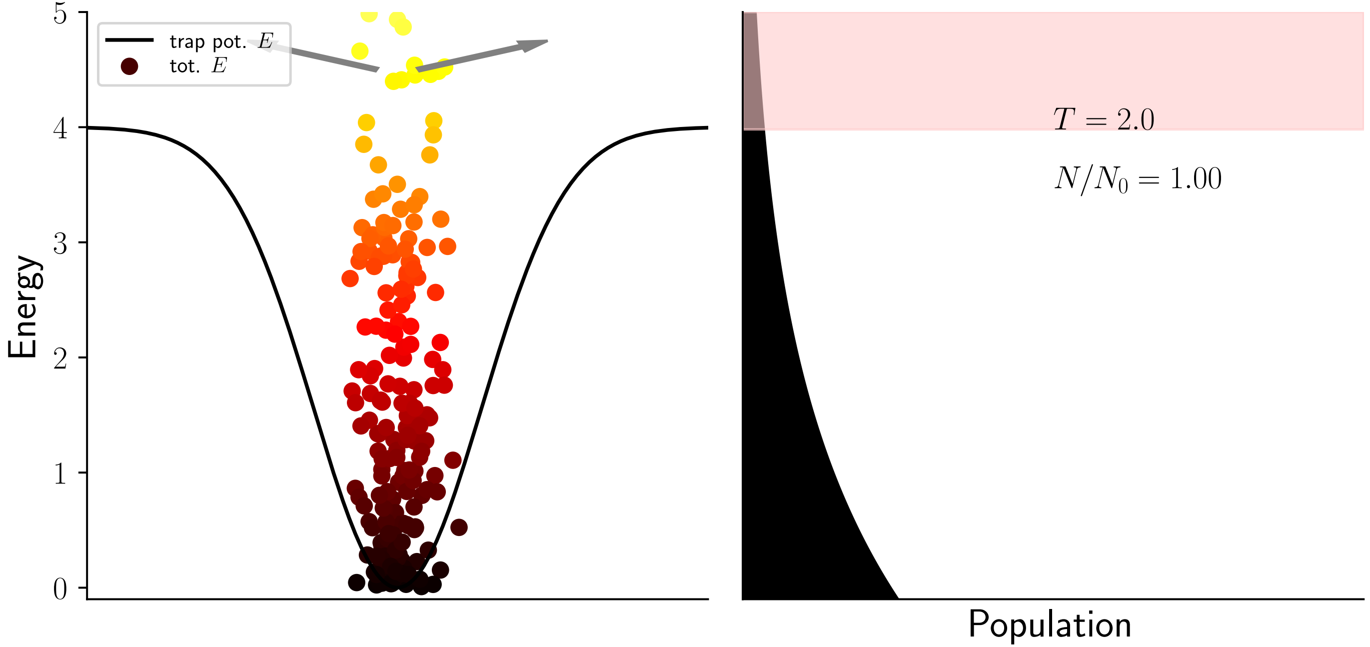

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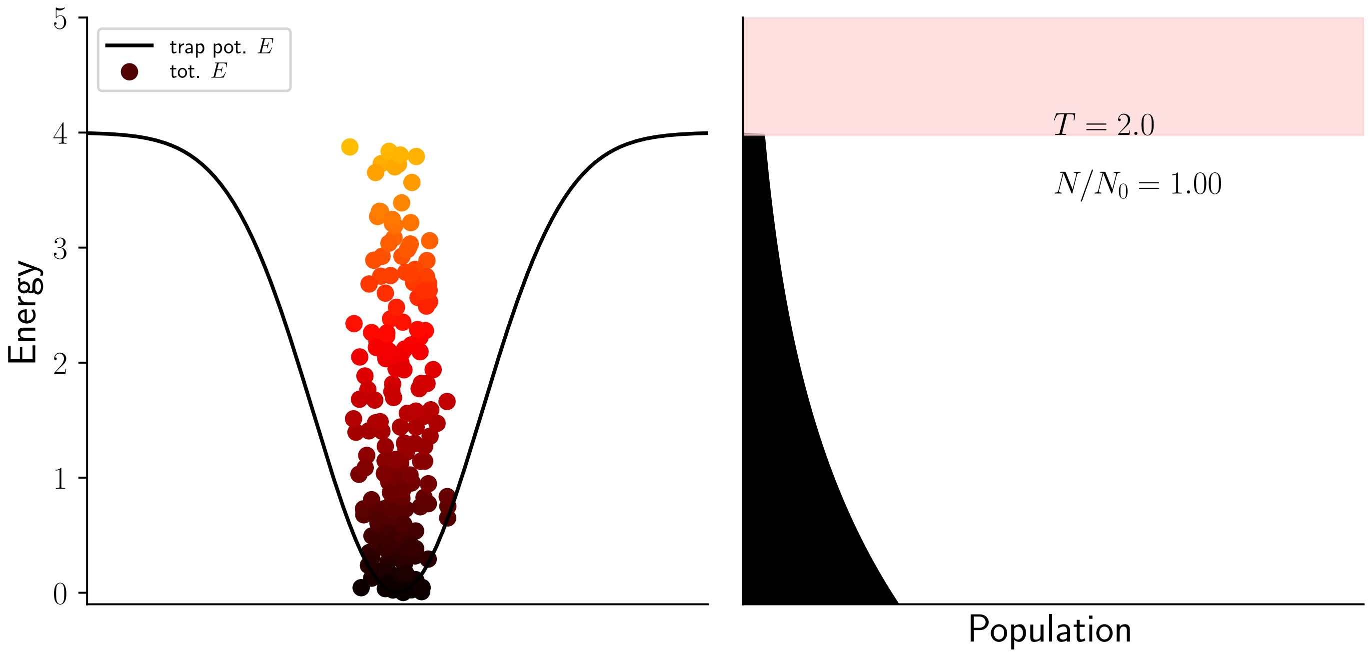

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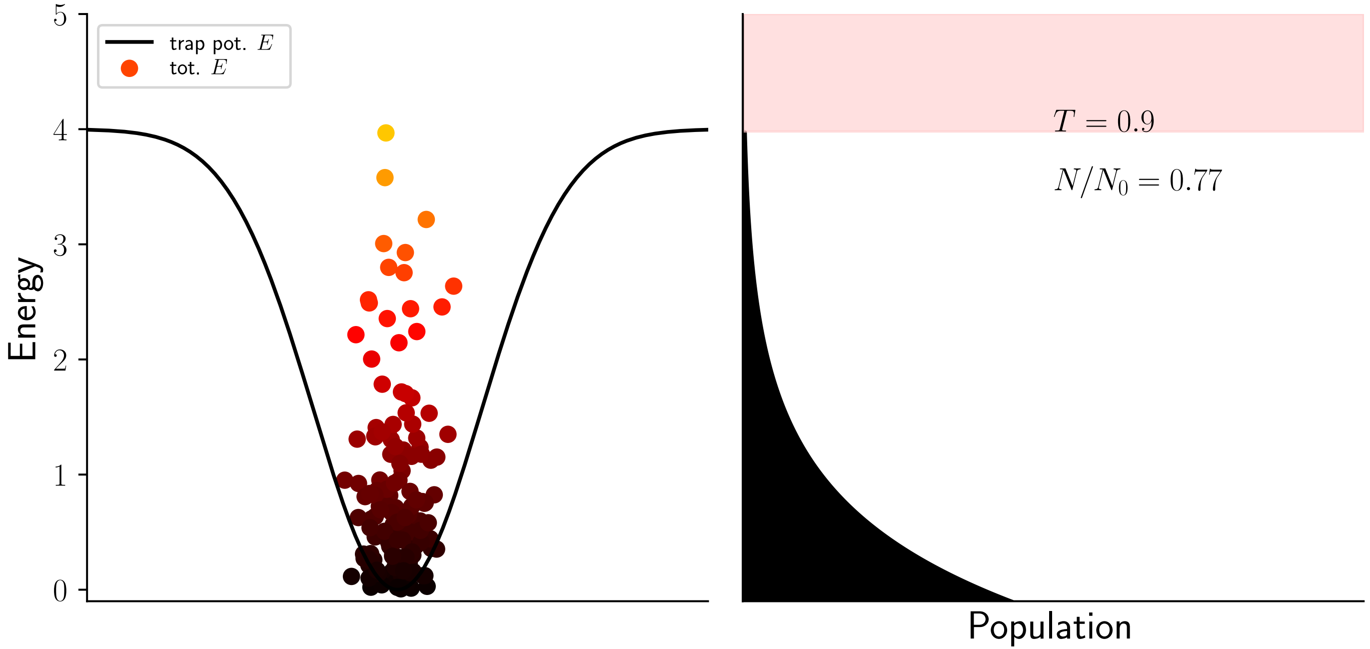

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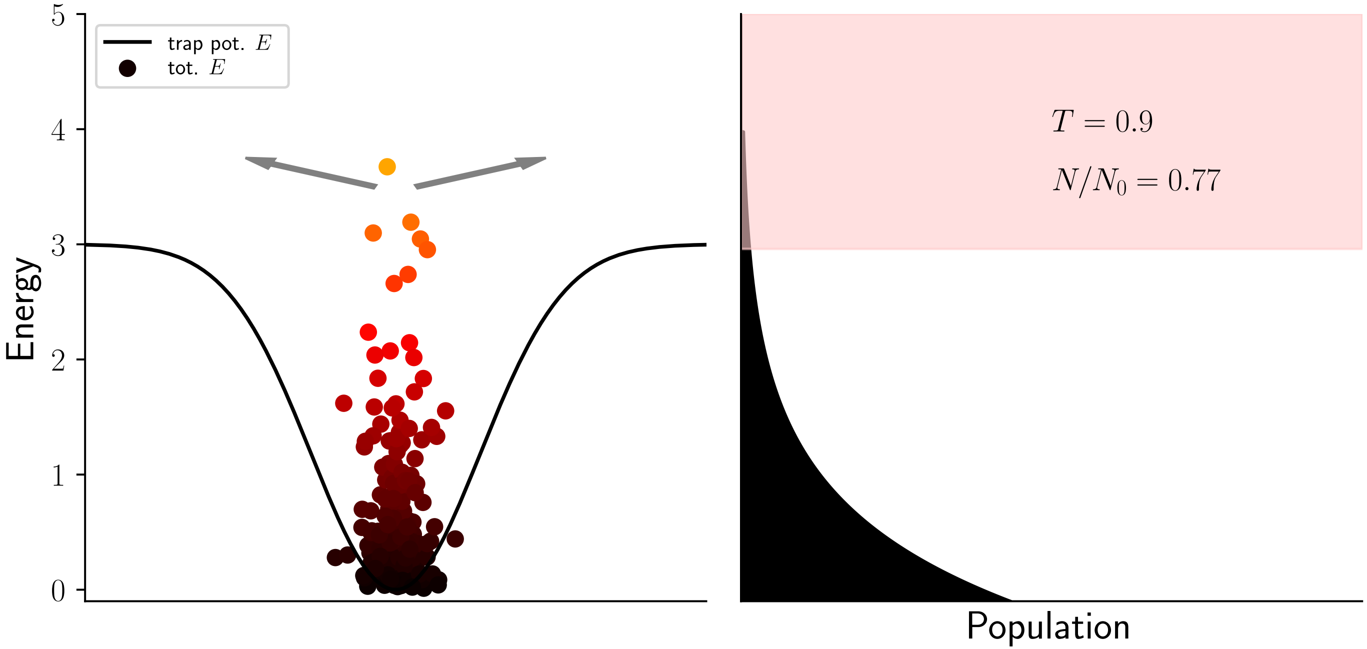

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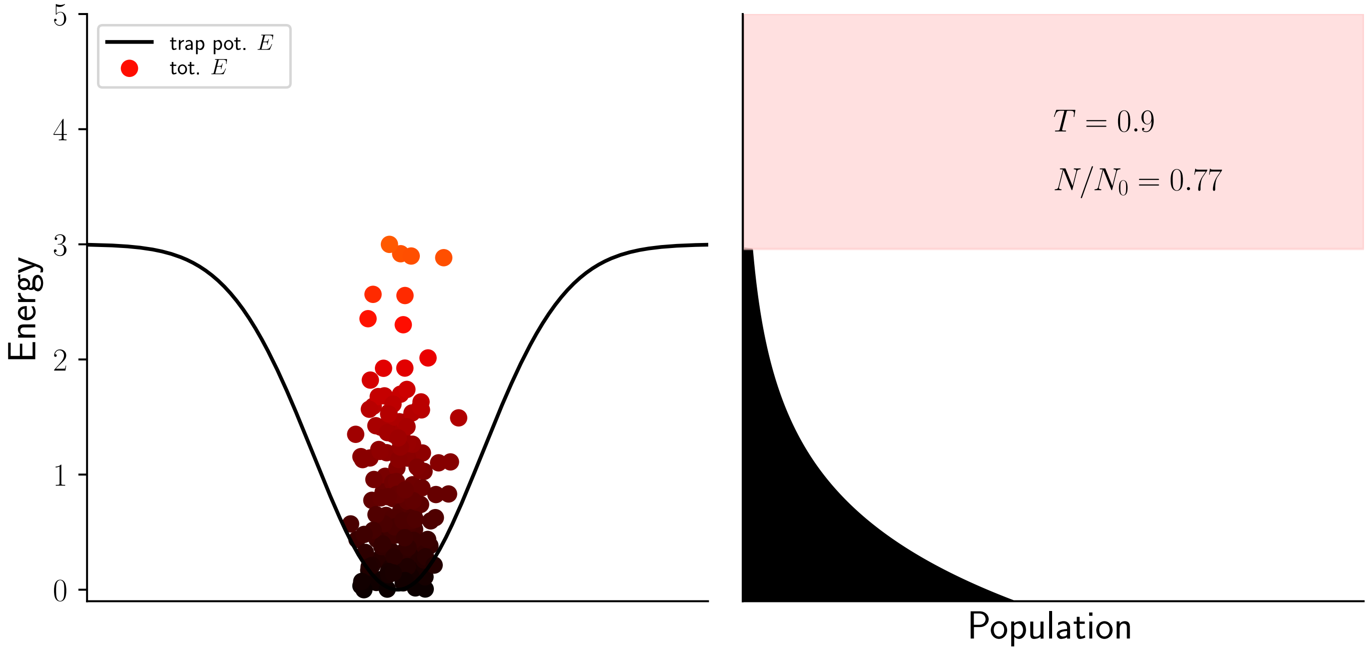

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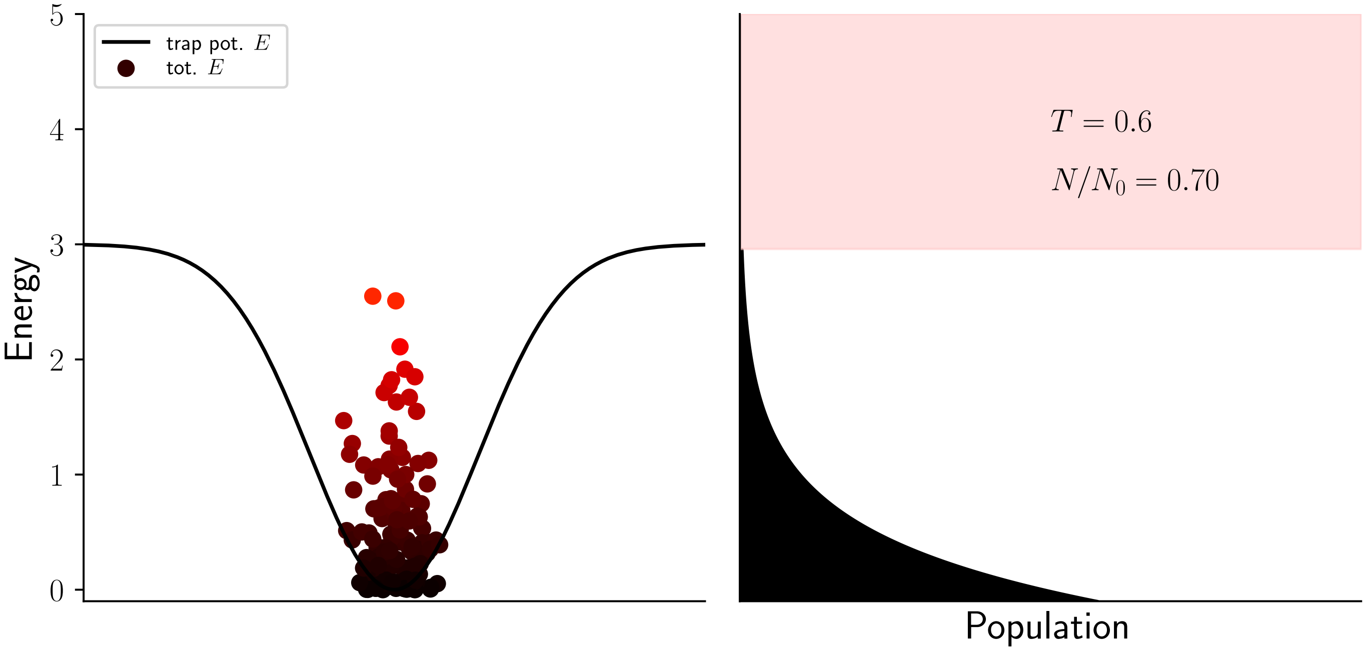

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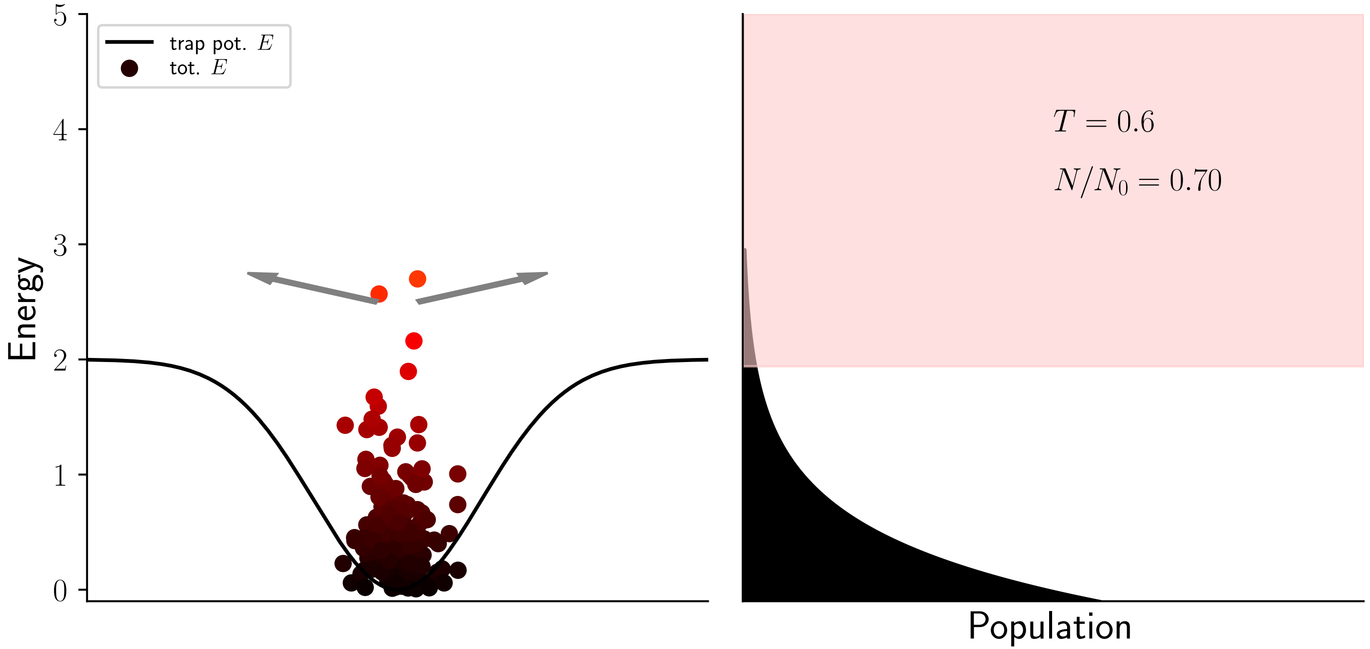

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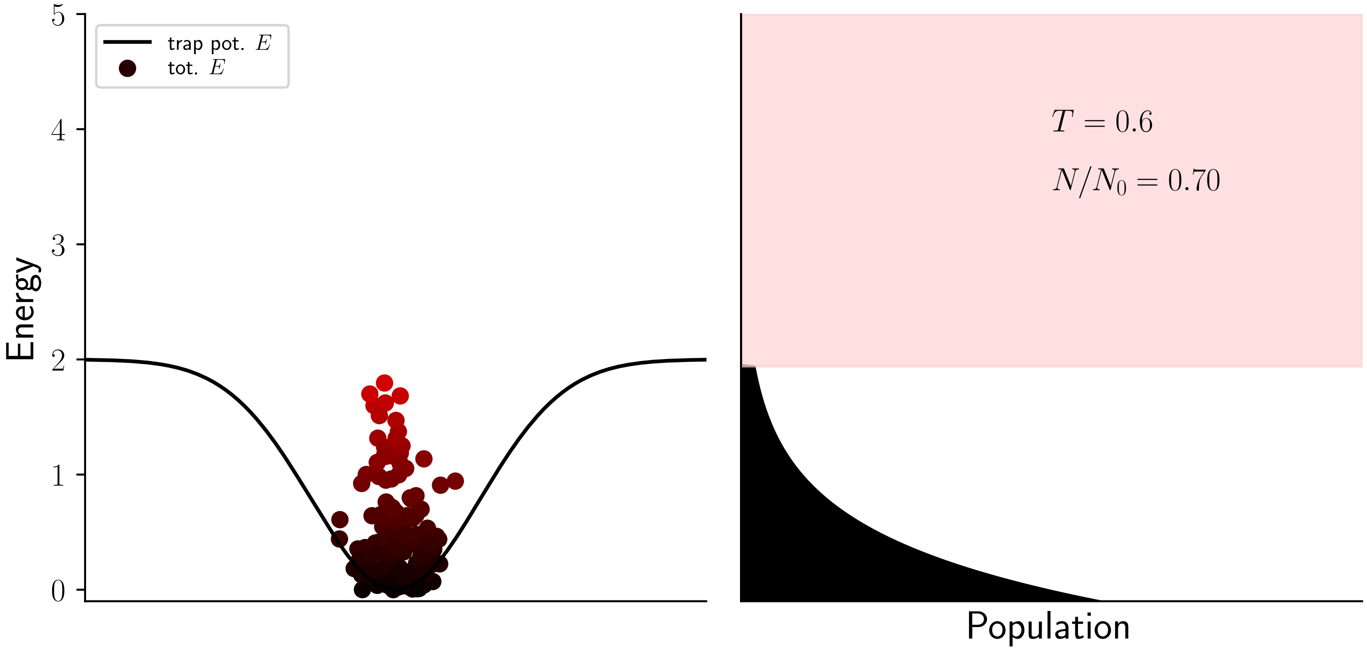

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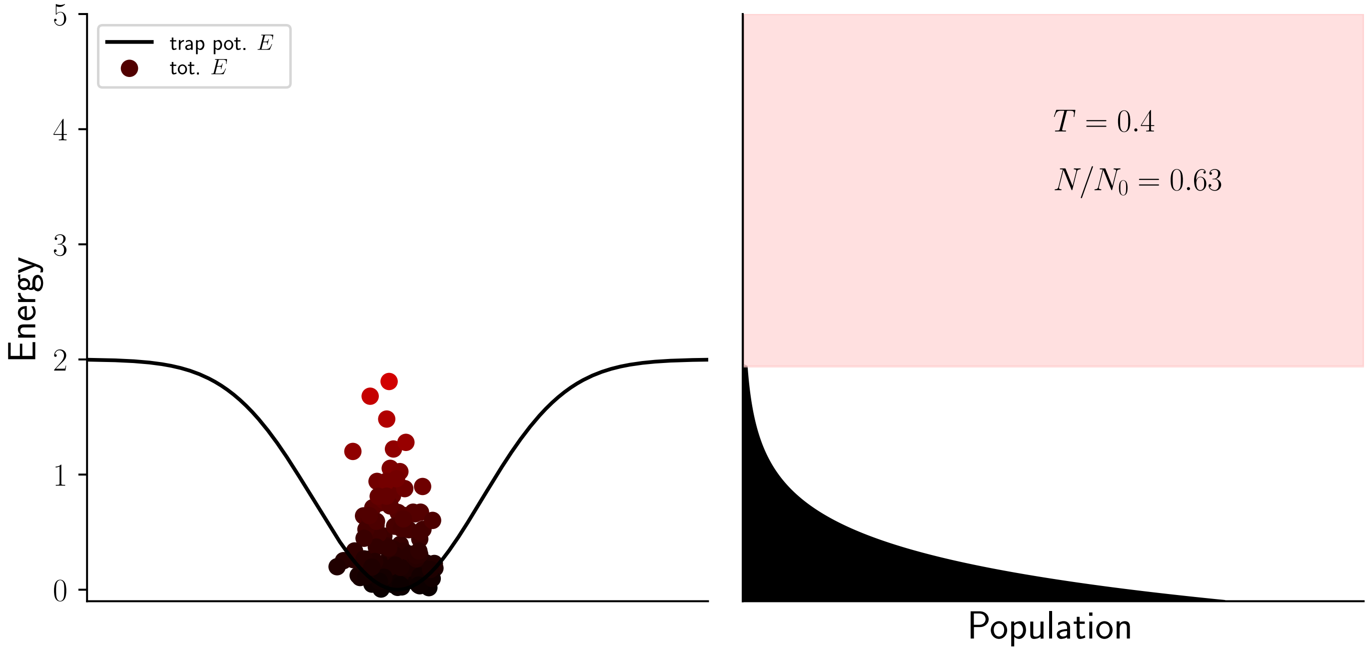

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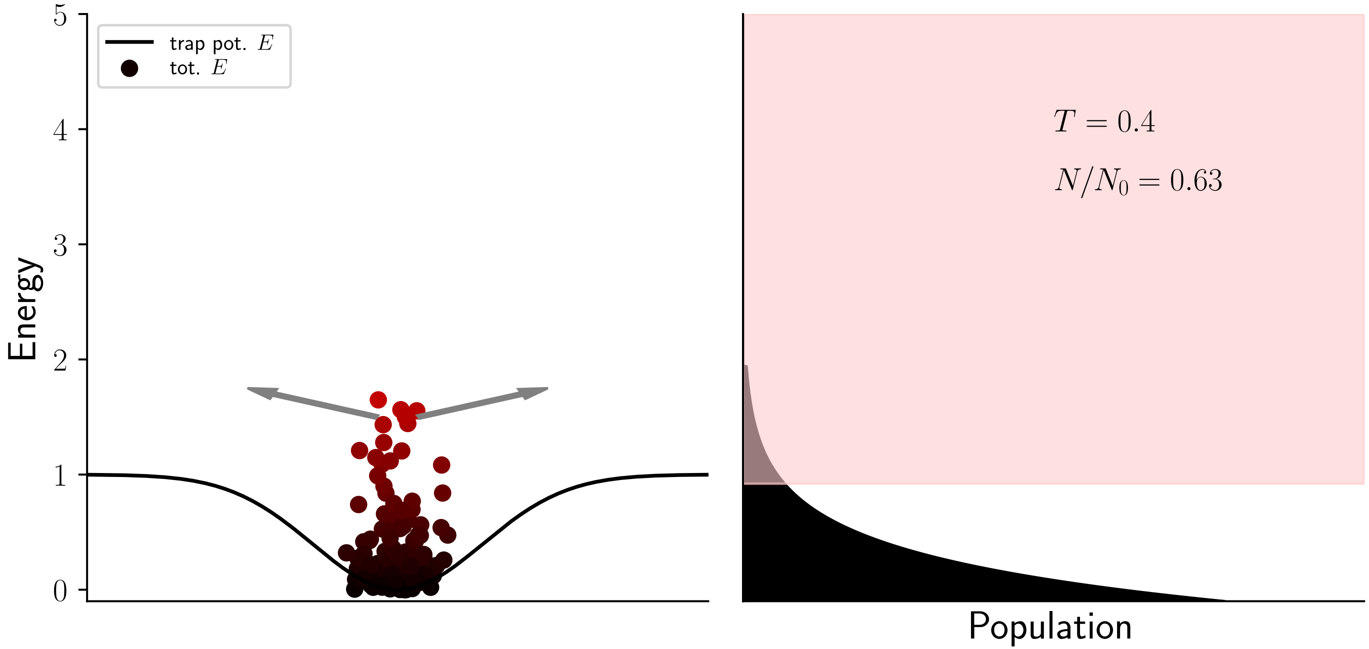

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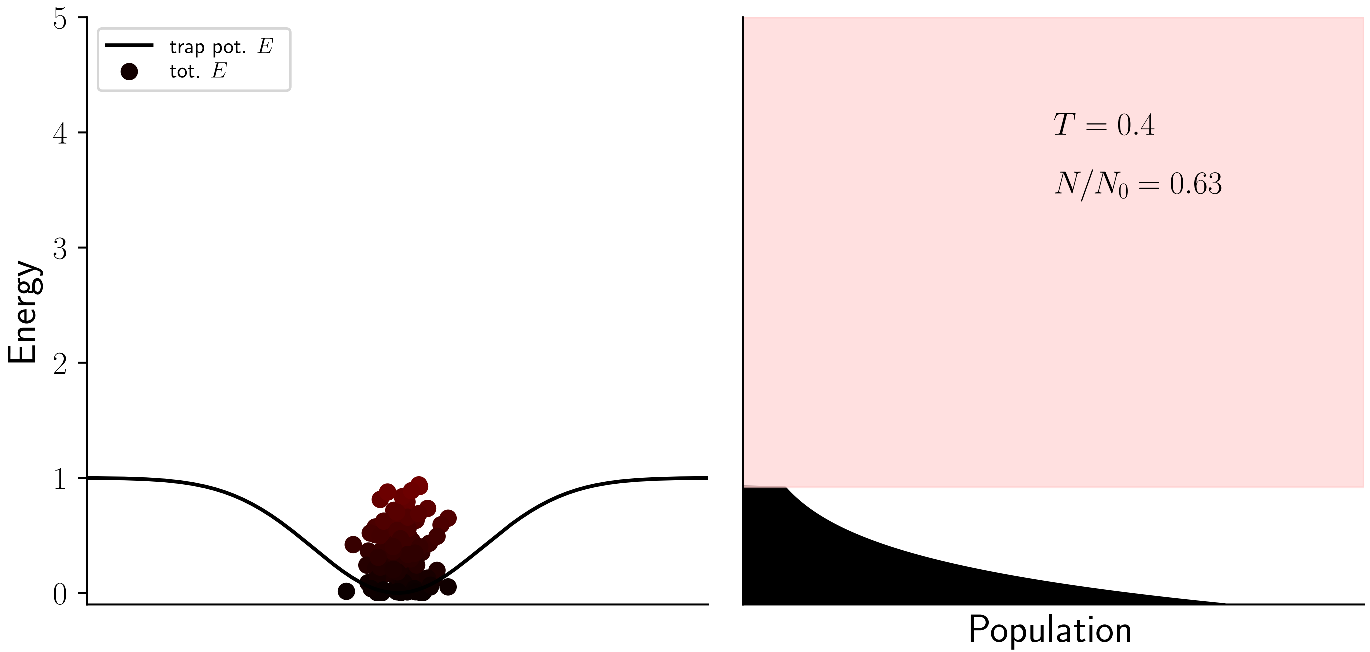

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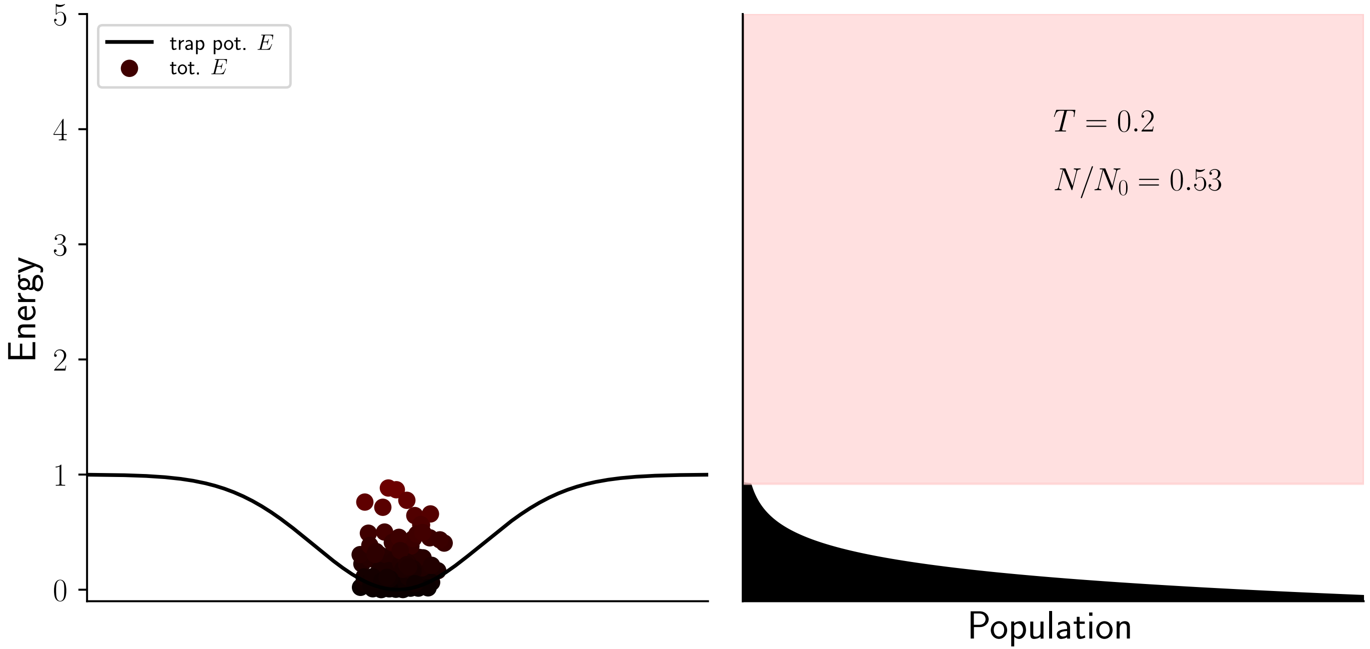

$\Rightarrow$ factor 10 on the temperature, factor 2 on N only !

$\Rightarrow$ increase in phase space density

Collisions, collisions, collisions !

Ellastic collisions must be frequent

Collisions, collisions, collisions !

Ellastic collisions must be frequent $\longleftarrow$ density must be high

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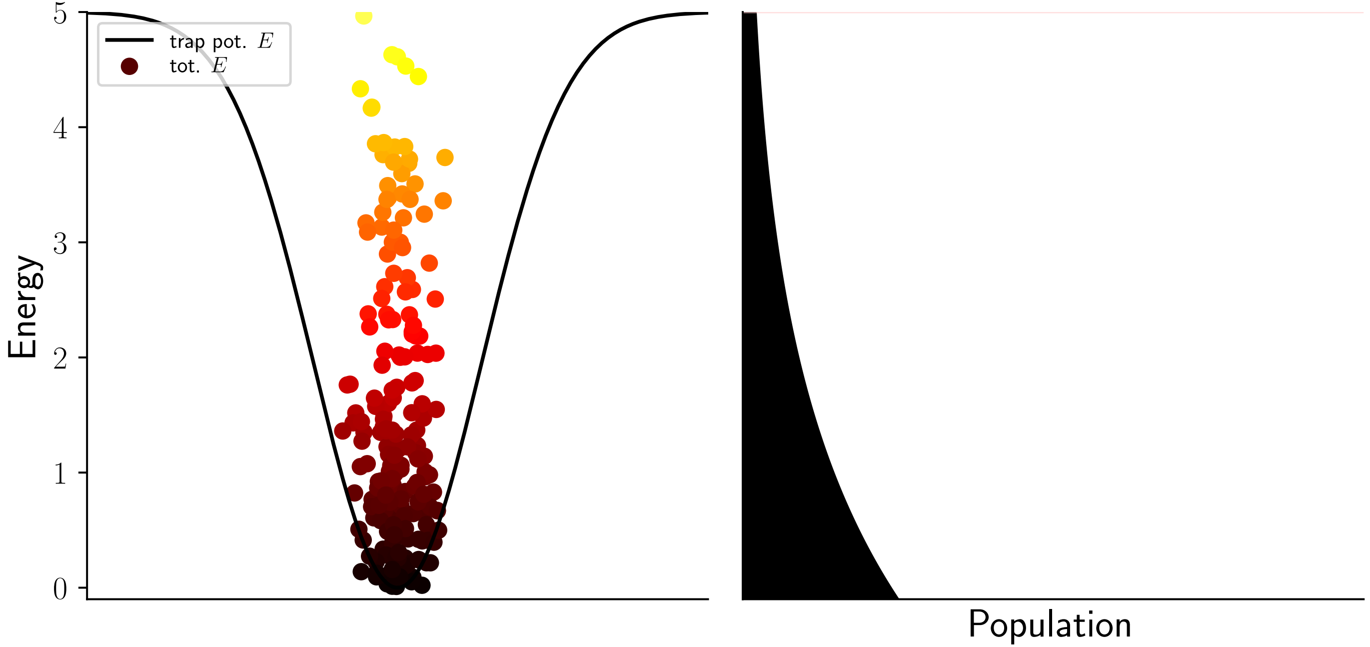
Evaporative cooling [**no thermalisation**]



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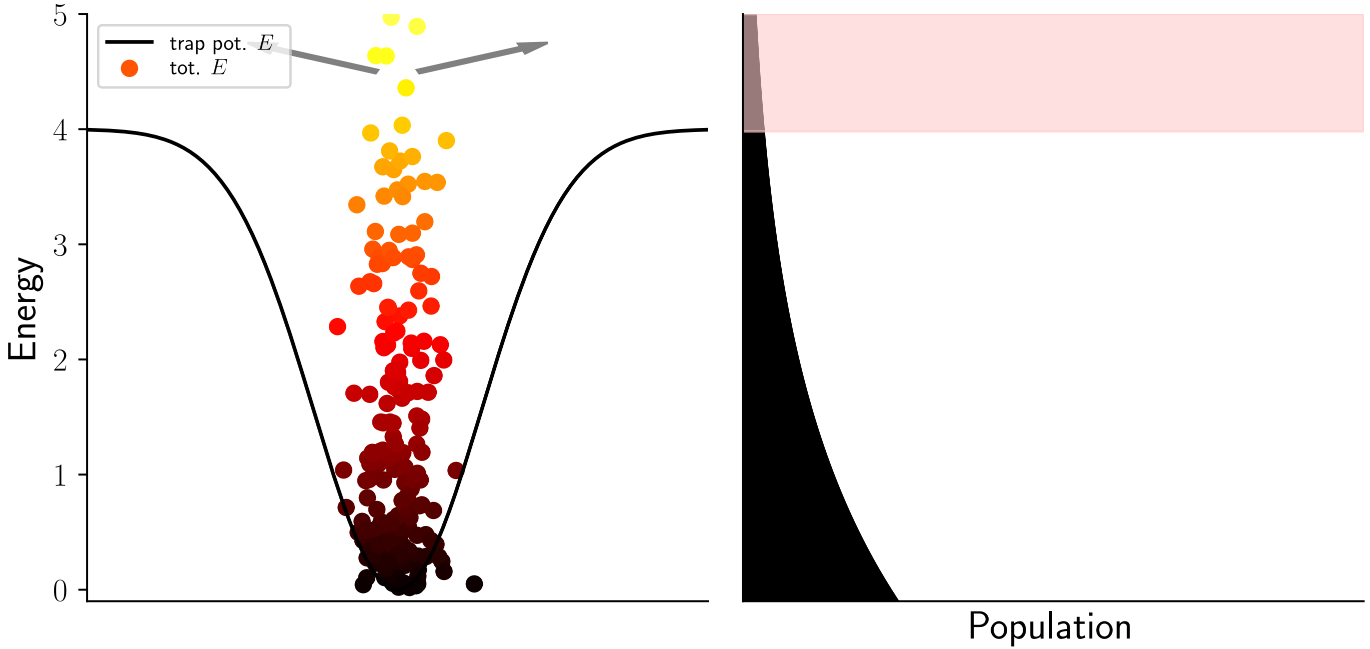

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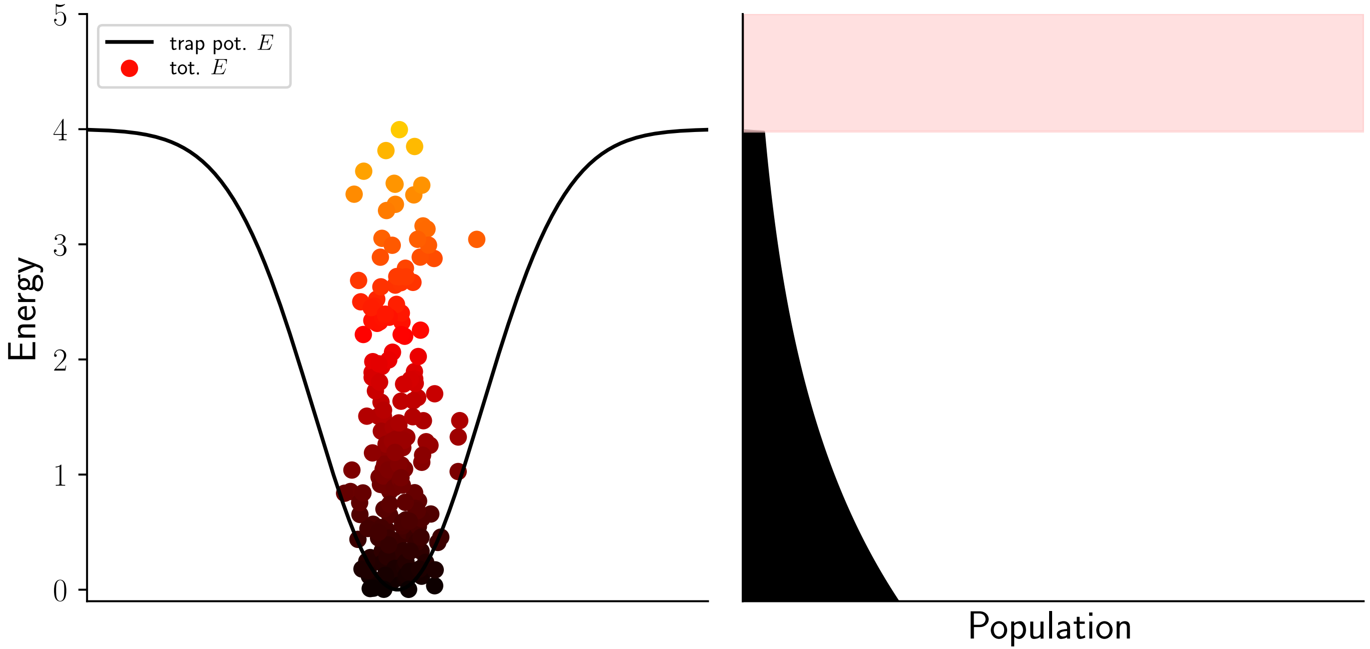

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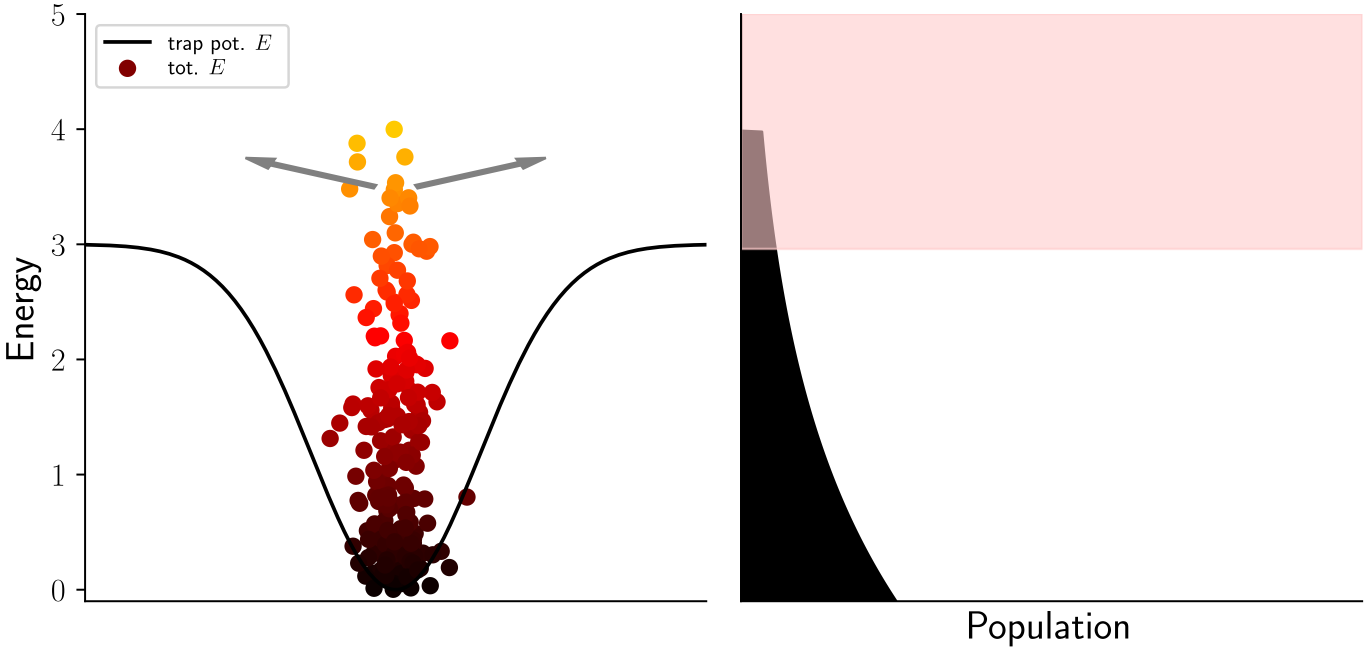

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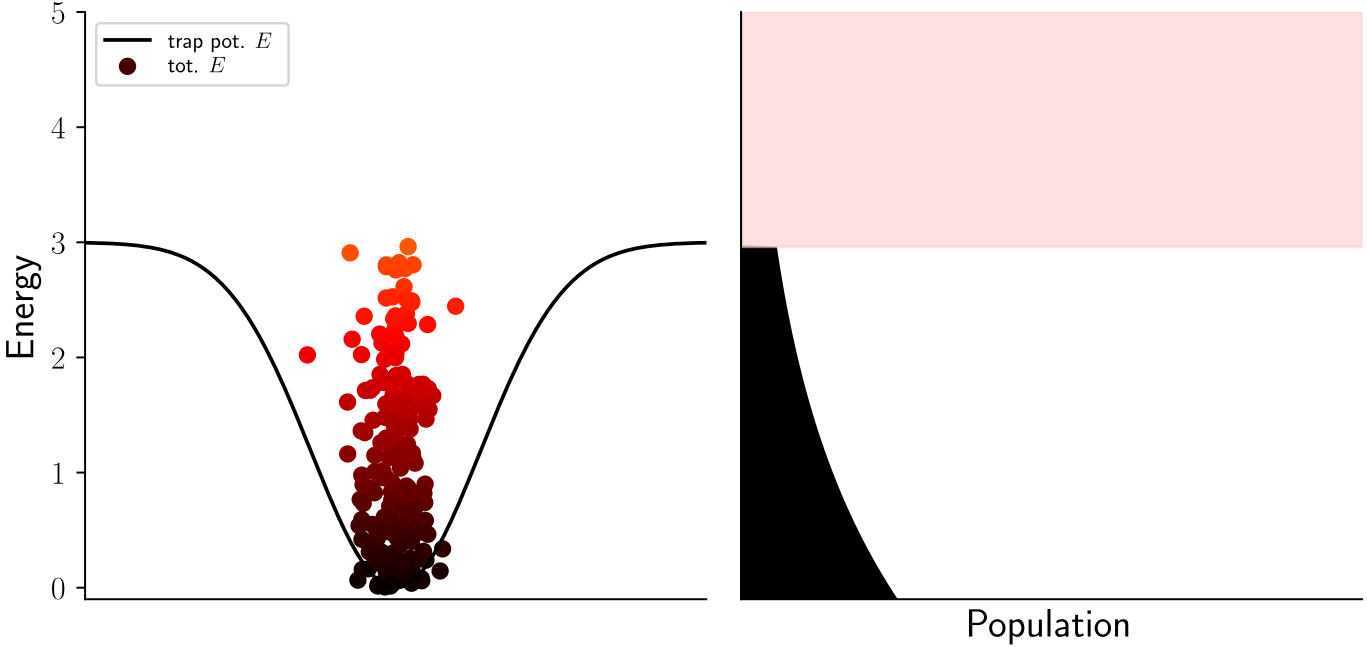

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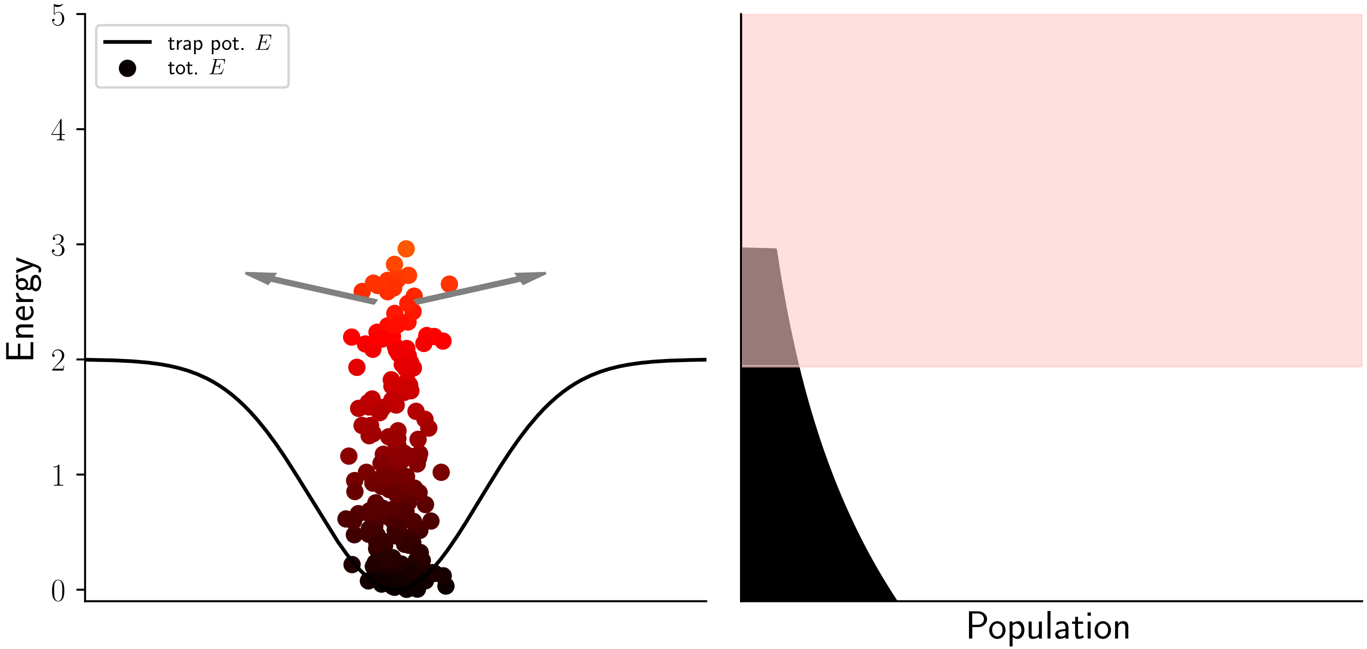

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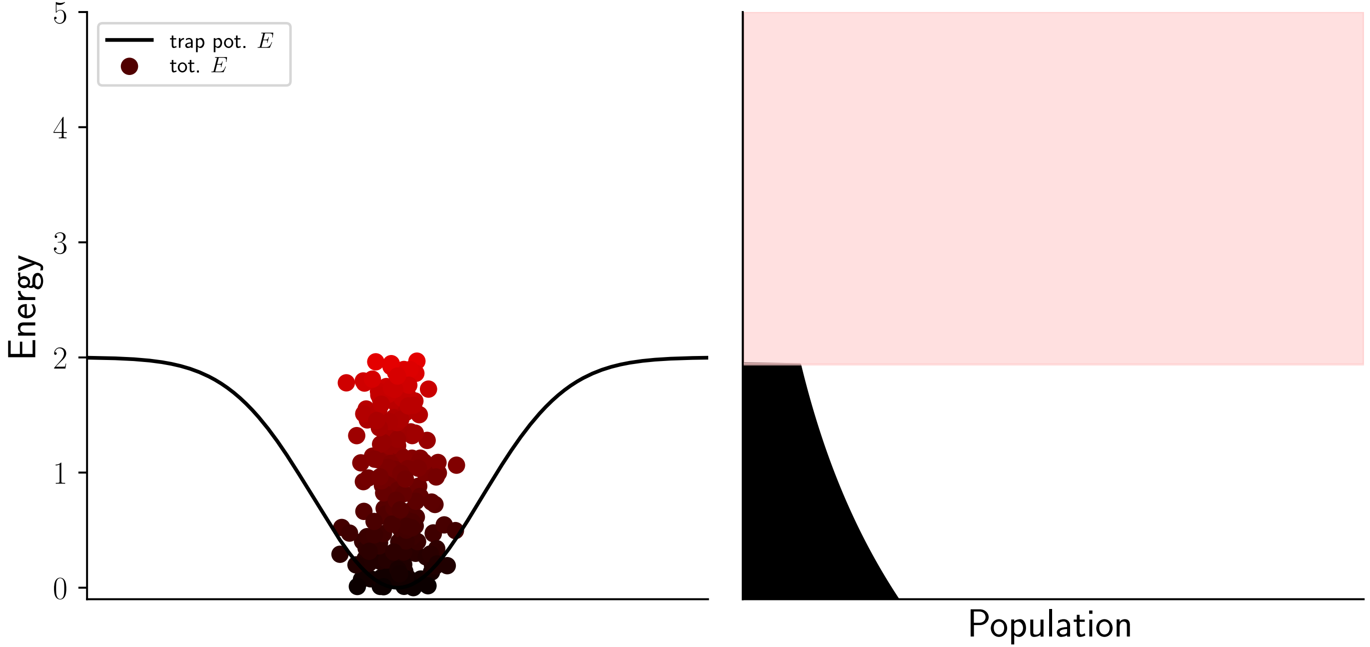

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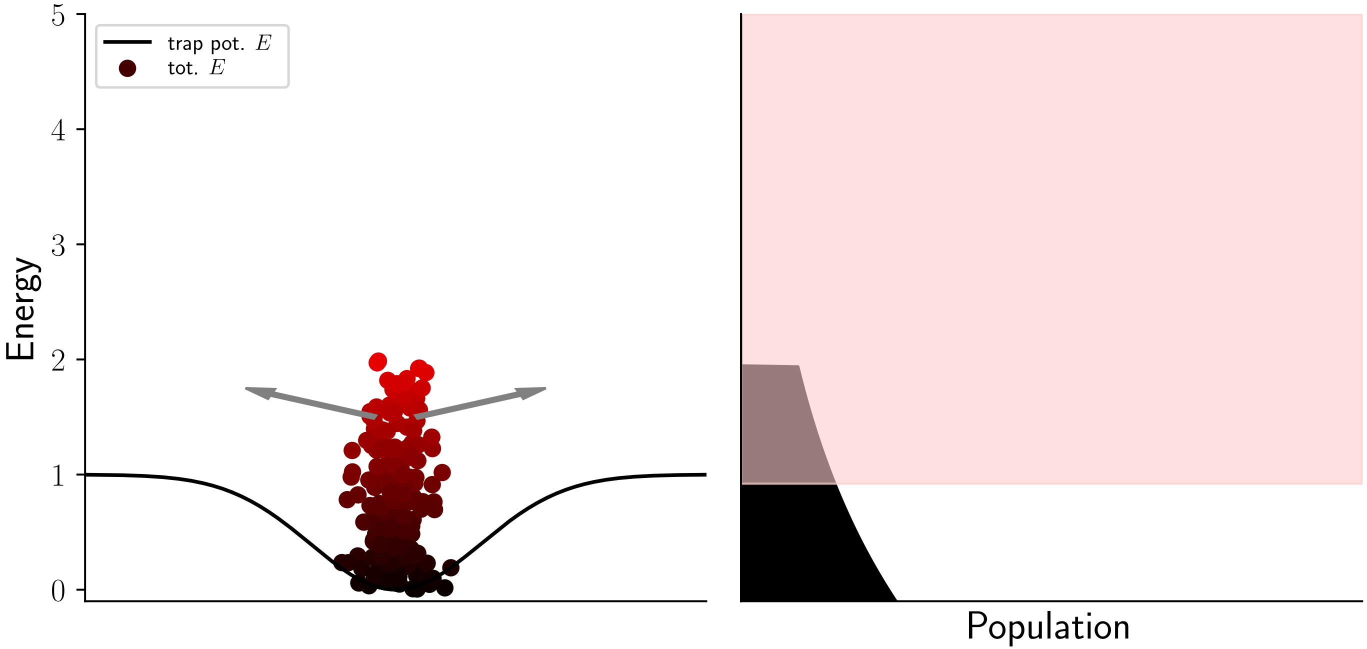
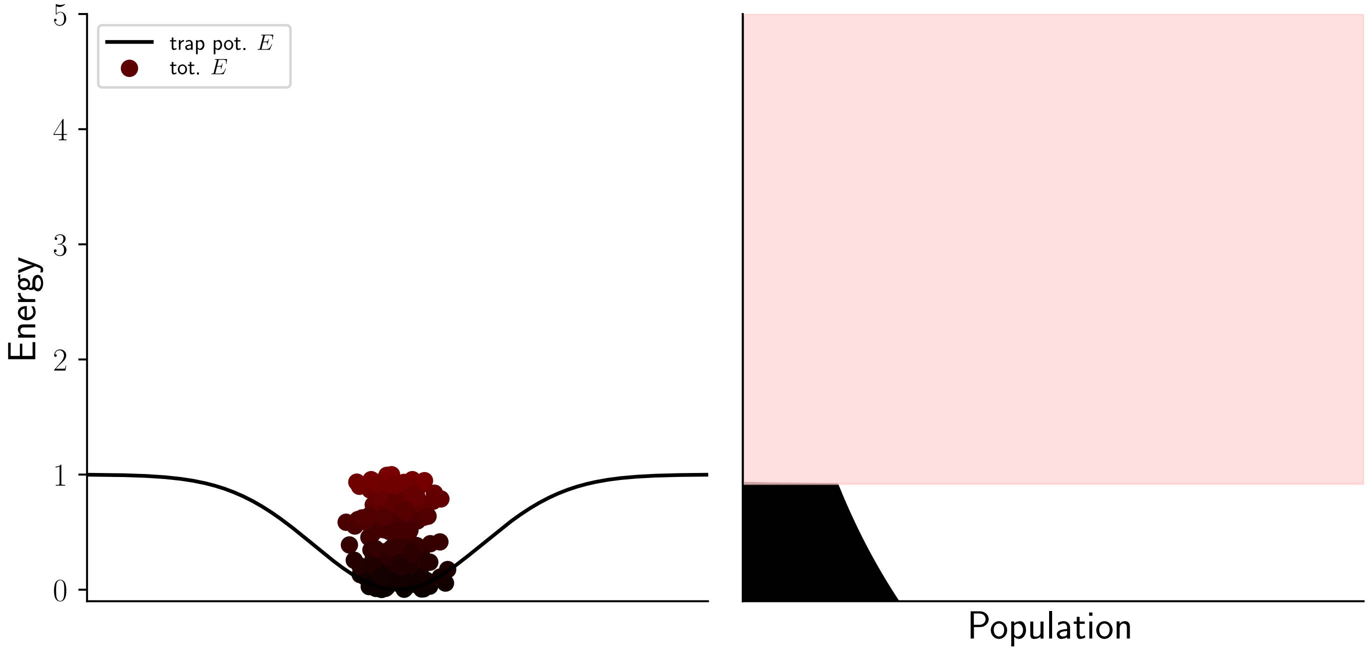


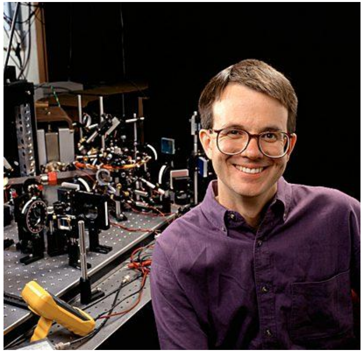


$\bar{E} \searrow$ but $n \searrow$ $\Rightarrow$ **no** increase in phase space density

A bit of history

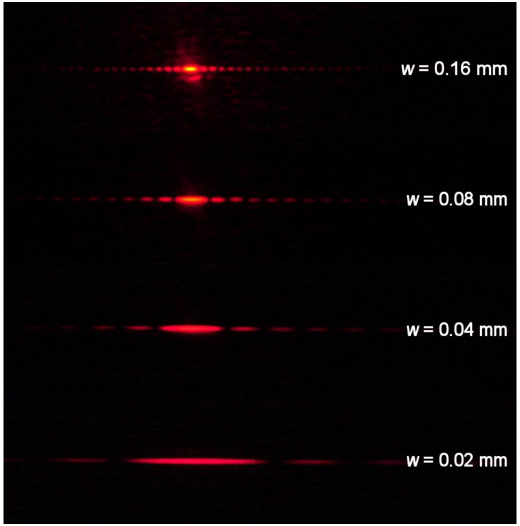
Initial works in *magnetic* traps rather than *optical* traps.
Work on evaporative cooling in the 90's, borrowed from the hydrogen community.

Mid. **1995** : *Bose-Einstein condensate* @ JILA, MIT and Rice within a few month (Na, Rb, Li)
Nobel prize for E. Cornell, W. Ketterle, C. Wieman



1999 : Degenerate Fermi gas ($^{40}\mathrm{K}$), D. S. Jin @ JILA

Optics : slit in far field :



*The **narrower** the slit, the **larger** the **far-field** diffraction pattern.*

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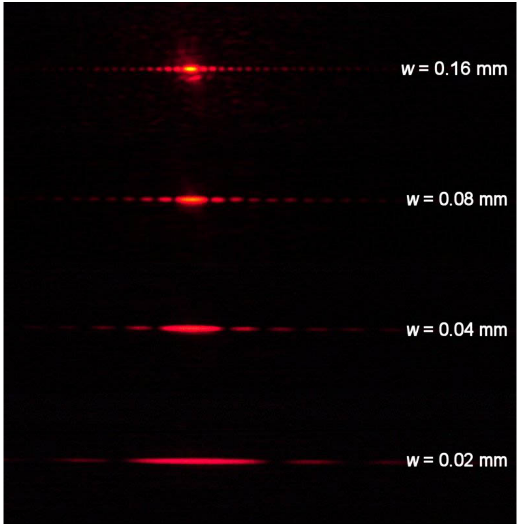


*The **narrower** the slit, the **larger** the **far-field** diffraction pattern.*

Atoms : far field = momentum-space distribution $n(\vec{p})$ = imaging after **time-of-flight** (long enough).

$\longrightarrow$ BEC will do the same… but not thermal gases

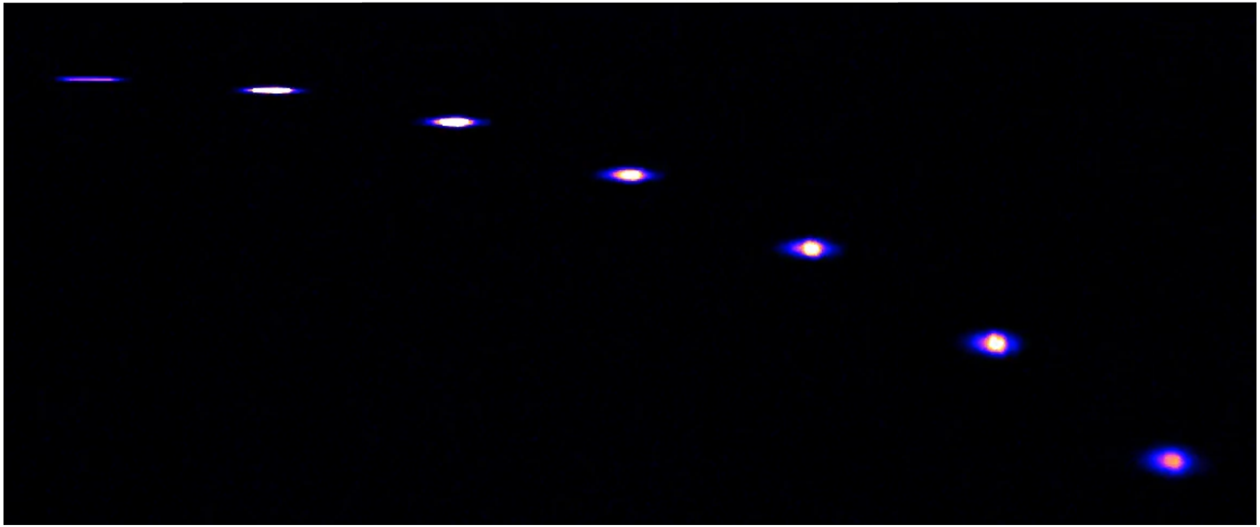
How do we know we have BEC ?

Imaging after a time-of-flight :

$$n_{\text{after ToF}}(\vec{r}\,') = n_{\text{cloud}}\left(\vec{p} = m\,\frac{\vec{r}\,'}{t_{\text{ToF}}}\right)$$

($r' \gg$ cloud size)

TOF : 0.1 ms TOF : 4.1 ms TOF : 8.1 ms TOF : 12.1 ms TOF : 16.1 ms TOF : 20.1 ms TOF : 24.1 ms



How do we know we have BEC ?

- **BEC** (not interacting $\longrightarrow$ harmonic oscillator ground state) :

$$\psi_0^{\rm 1D}(x) \propto \exp\left(-\frac{m\,\omega\,x^2}{2\,\hbar}\right) \quad ; \quad \text{must obey } \boxed{\Delta x\,\Delta p \geqslant \hbar/2}$$

$\omega_x \neq \omega_y \neq \omega_z \quad \Rightarrow \quad$ **anisotropic $\boldsymbol{n(\vec{p})}$**

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$\omega_x \neq \omega_y \neq \omega_z \quad \Rightarrow \quad$ **anisotropic $\boldsymbol{n(\vec{p})}$**

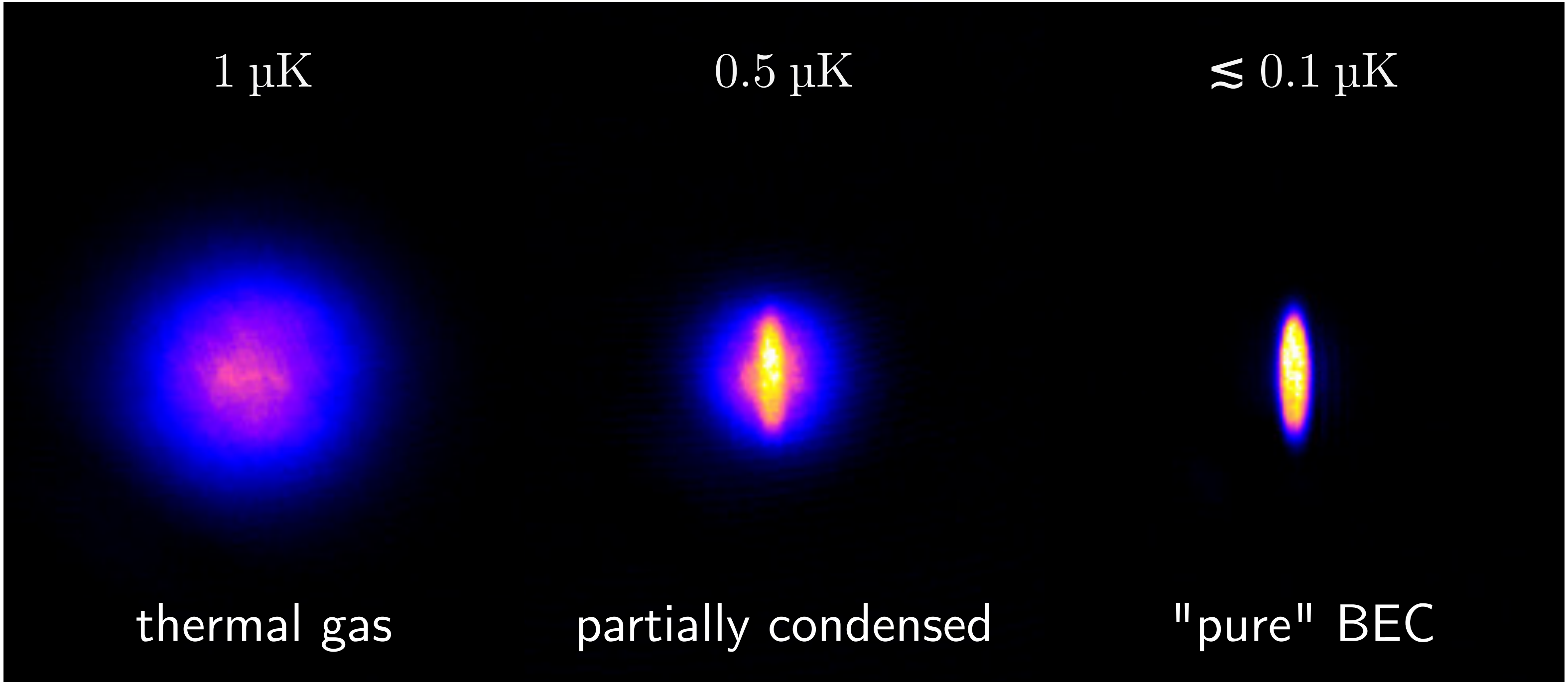
- **Thermal cloud** in harmonic potential (Boltzmann distrib. approx.) :

$$H = \frac{1}{2m}\,p^2 + \frac{m\,\omega^2}{2}\,x^2 \quad \Rightarrow \quad n(\vec{x},\vec{p}) \propto \mathrm{e}^{-H(x,p)/k_\mathrm{B}T} \quad \Rightarrow \quad \boxed{n(\vec{p}) \propto \exp\left(-\frac{p^2}{2\,m\,k_\mathrm{B}T}\right)}$$

… does not depend on the confinement ω, **same along $\boldsymbol{x}$, $\boldsymbol{y}$, $\boldsymbol{z}$**.

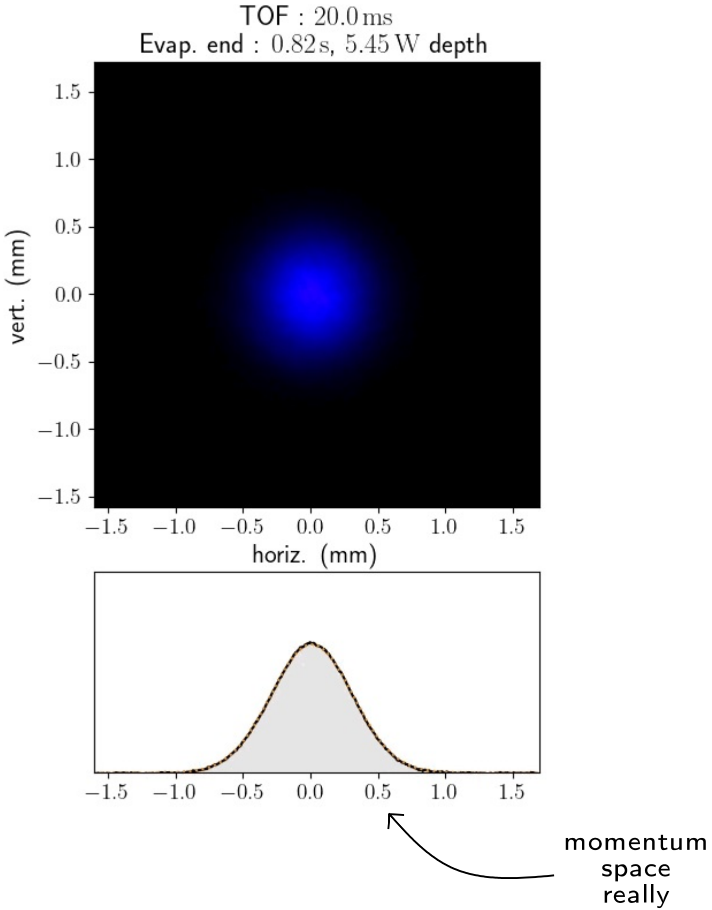
Thermal gas	**BEC**
$\Delta p_i \propto T$	$\Delta p_i \propto \frac{1}{\Delta x_i} \propto$ confinement along i

How do we know it's a BEC ?

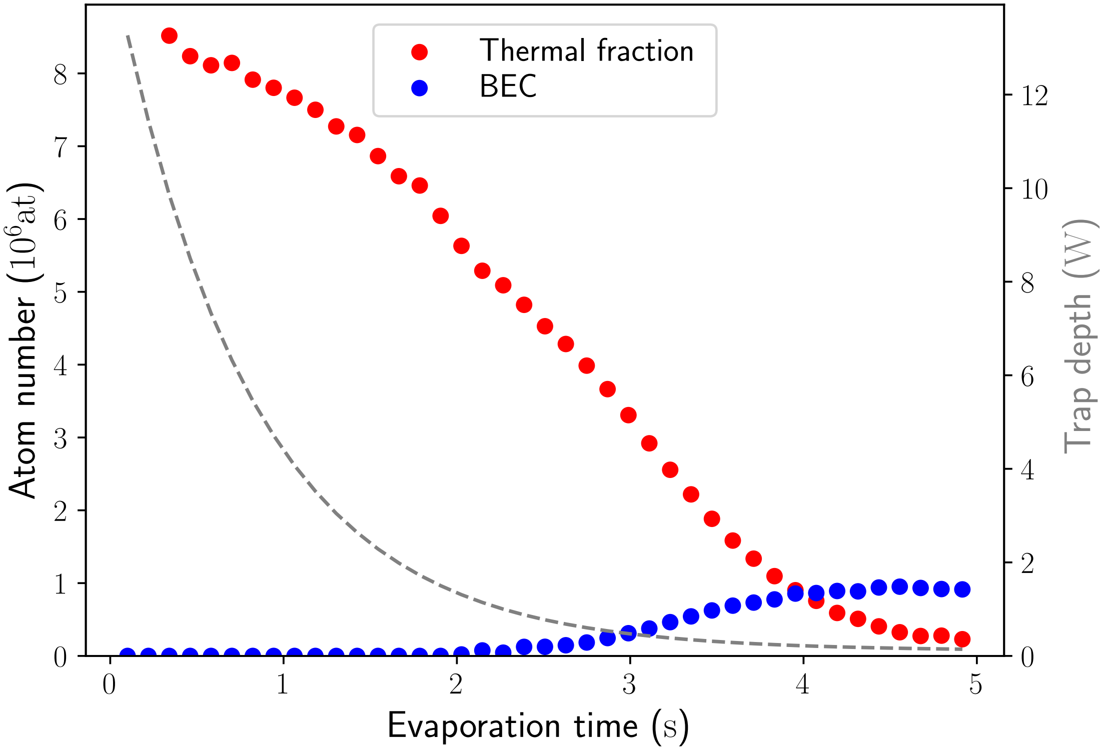


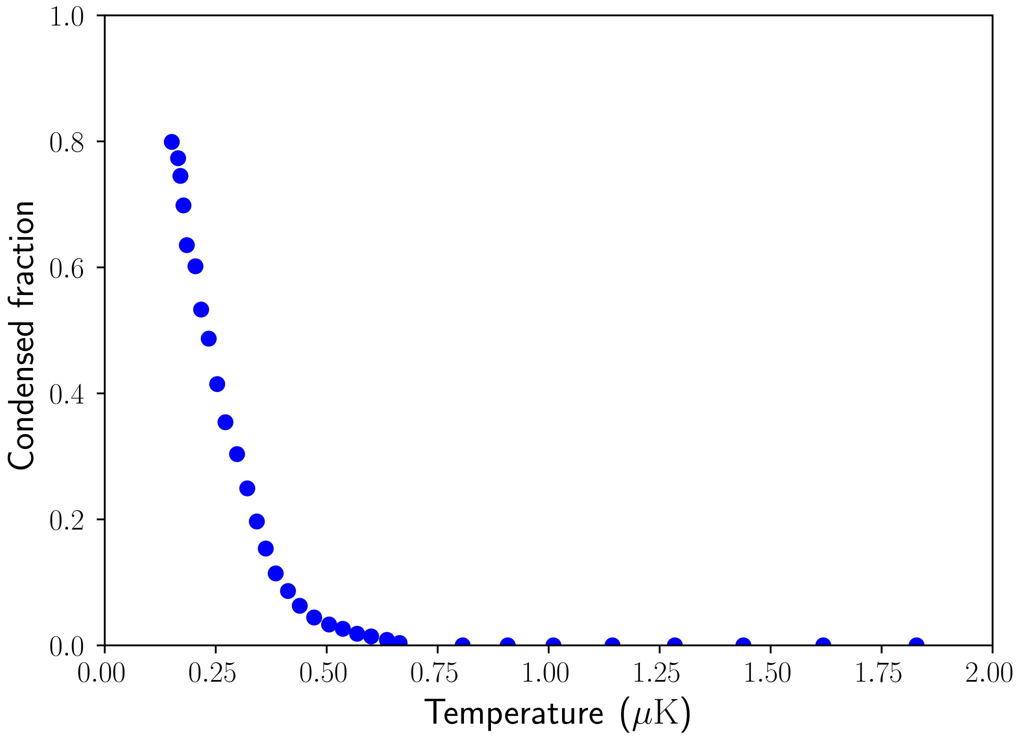
Evaporation of ^{84}Sr

After TOF : $n(p)$ $\longrightarrow$



Evaporation of ^{84}Sr

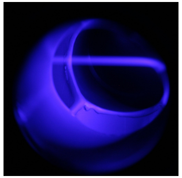




1.0
0.8
0.6
0.4
0.2
0.0
Condensed fraction
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
Temperature (μK)

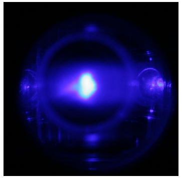
Summary

800 K
∼400 m/s
PSD ≈ 10^{-14}



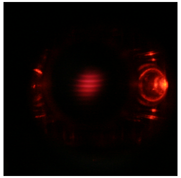
Transverse molasses
Zeeman slower

∼0.5 K
∼10 m/s
PSD ≈ 10^{-14}
10^{-12} acheivable



Blue MOT

5 mK
∼1 m/s
PSD ≈ 10^{-10}
10^{-8} acheivable

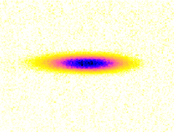


Red MOT

2 μK
∼0.02 m/s
PSD ≈ 10^{-3}
10^{-2} acheivable

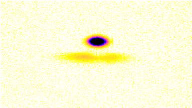
transport

10 μK
∼0.05 m/s
PSD ≈ 10^{-4}



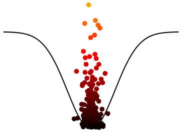
Red molasses

2 μK
∼0.02 m/s
PSD ≈ 10^{-2}



Vertical lattice
loading

∼3 μK
∼0.03 m/s
PSD ≈ 10^{-1}



Evaporation

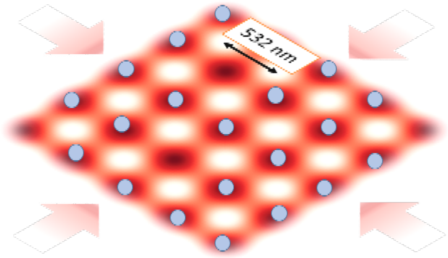
$<$ 100 nK
few mm/s
PSD $\gtrsim$ 12

1. Degenerate atomic gases (as analogues?)

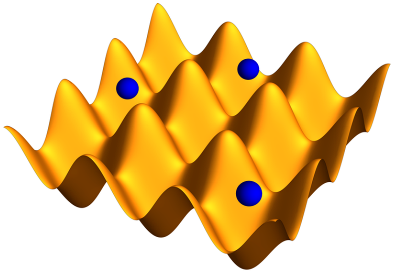
2. Laser cooling

3. Evaporative cooling

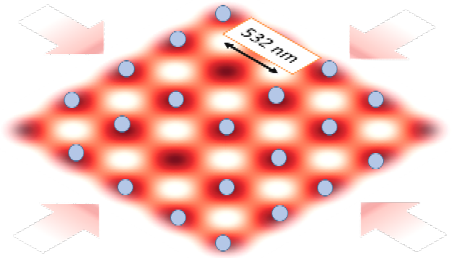
4. **Bose-Hubbard physics**

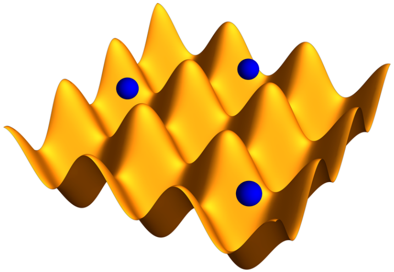


Put the 2D condensate in a periodic potential (**square optical lattice**)



2D Bose-Hubbard

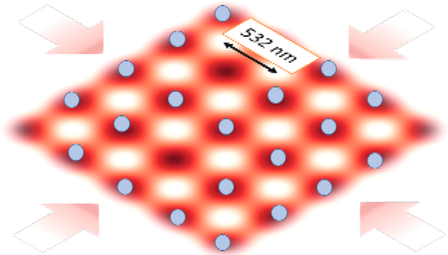


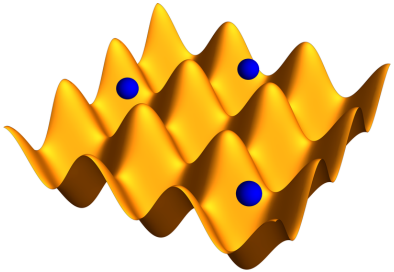


Put the 2D condensate in a periodic potential (**square optical lattice**)

→ **Bose-Hubbard model**

$$\boldsymbol{H} = \underbrace{-J \sum_{\langle i,j \rangle} \boldsymbol{b}_i^\dagger \boldsymbol{b}_j + \mathrm{h.c.}}_{\text{tunneling / jump}} + \underbrace{\tfrac{1}{2} U \sum_i \boldsymbol{n}_i (\boldsymbol{n}_i - 1)}_{\text{on-site repulsion}} - \mu \sum_i \boldsymbol{n}_i$$





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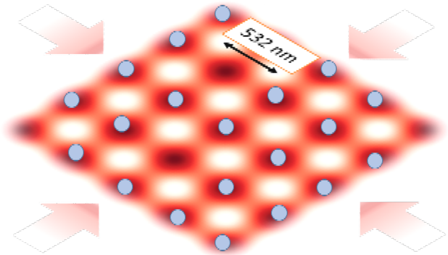
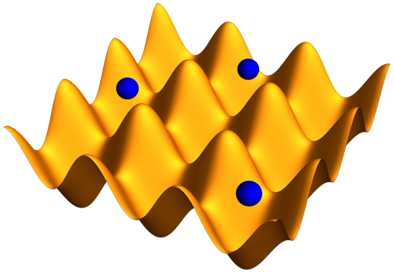
2D Bose-Hubbard





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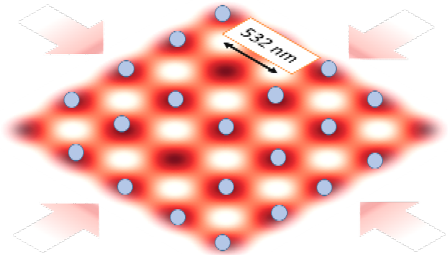
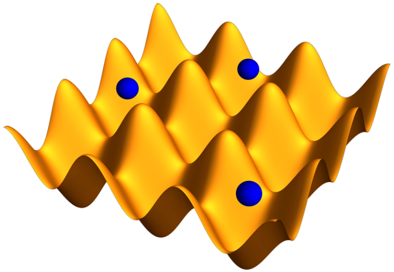
$\downarrow$ delocalization for kin. energy lowering

$\downarrow$ prevents delocalization

2D Bose-Hubbard





Put the 2D condensate in a periodic potential (**square optical lattice**)

$\longrightarrow$ **Bose-Hubbard model**

$$\boldsymbol{H} = \underbrace{-J \sum_{\langle i,j \rangle} \boldsymbol{b}_i^\dagger \boldsymbol{b}_j + \text{h.c.}}_{\text{tunneling / jump}} + \underbrace{\tfrac{1}{2} U \sum_i \boldsymbol{n}_i (\boldsymbol{n}_i - 1)}_{\text{on-site repulsion}} - \mu \sum_i \boldsymbol{n}_i$$

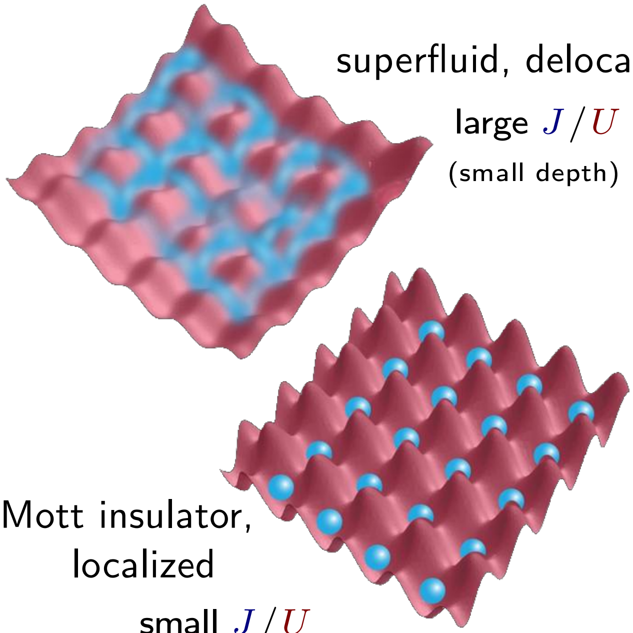
tunneling / jump $\downarrow$ delocalization for kin. energy lowering

on-site repulsion $\downarrow$ prevents delocalization

$\Rightarrow$ delocalization / localization **competition**, controled by $U / J = f$(lattice depth)

$\Rightarrow$ phases & quantum phase transition

2D Bose-Hubbard phases



superfluid, delocalized

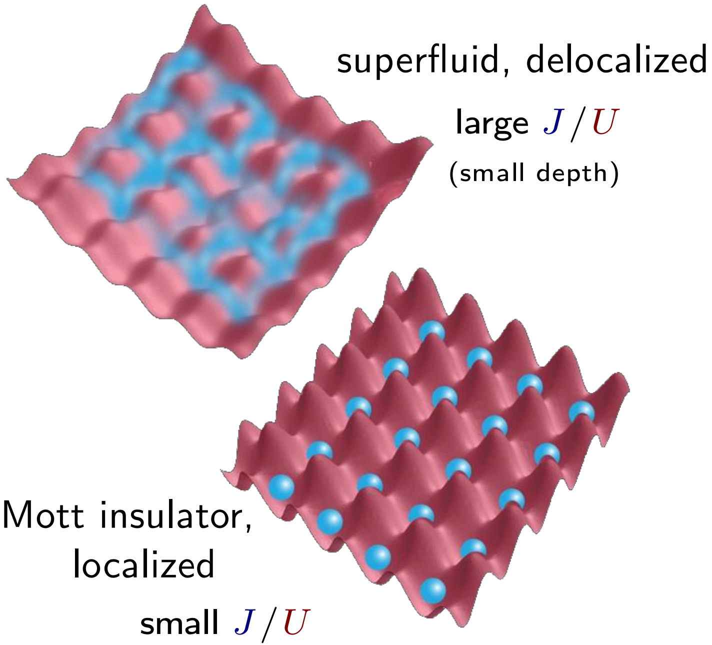
large J/U

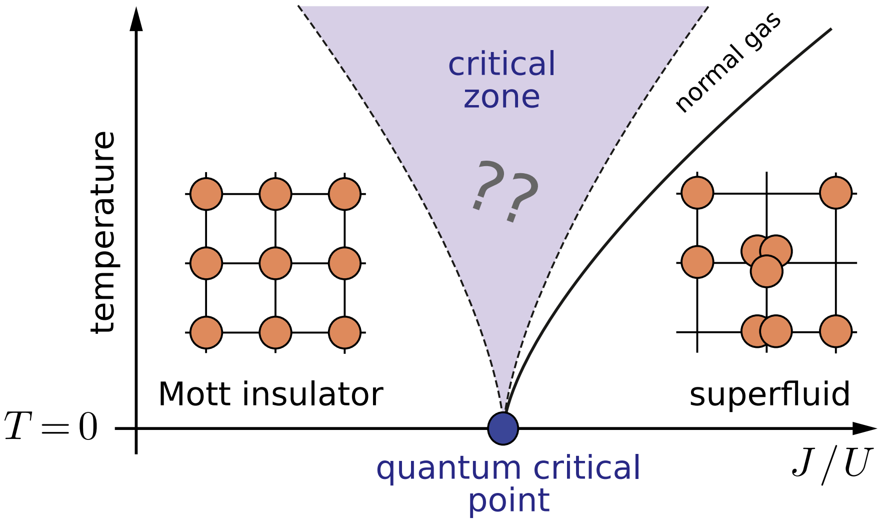
(small depth)

Mott insulator,
localized

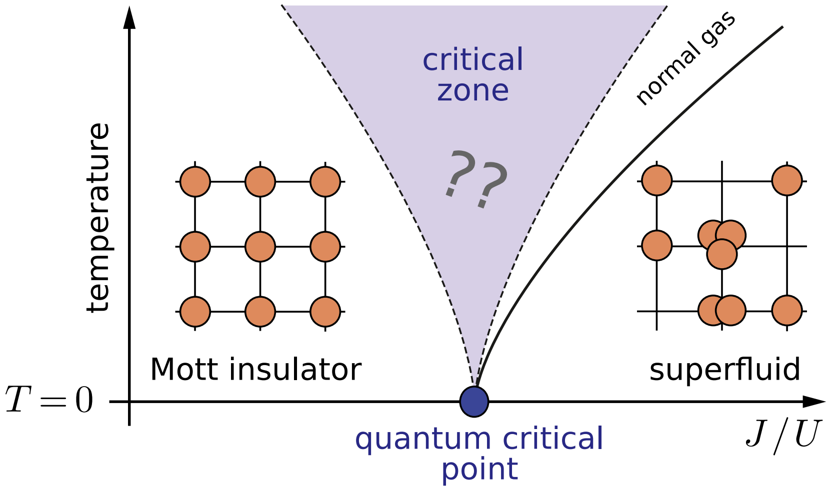
small J/U

2D Bose-Hubbard phases



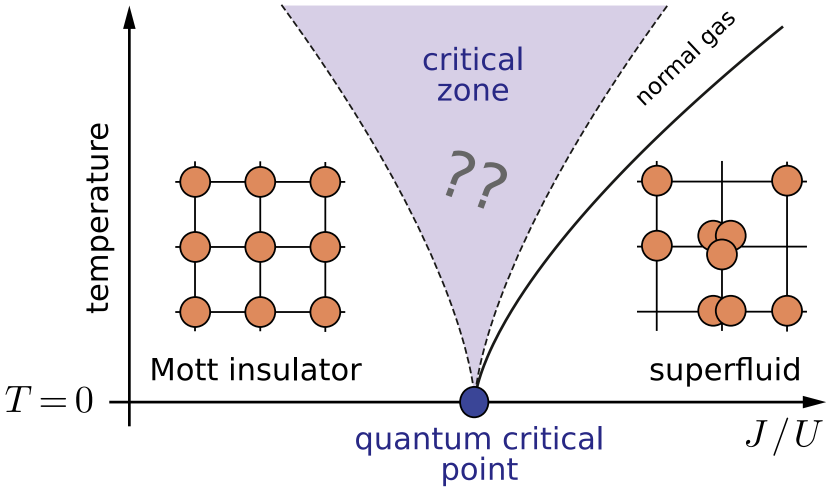


Excitations ?



$\rightarrow$ Outside of critical zone, **excitations = quasi-particles** (doublons-holons / phonons)

Excitations ?

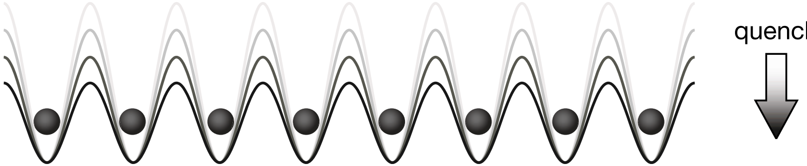


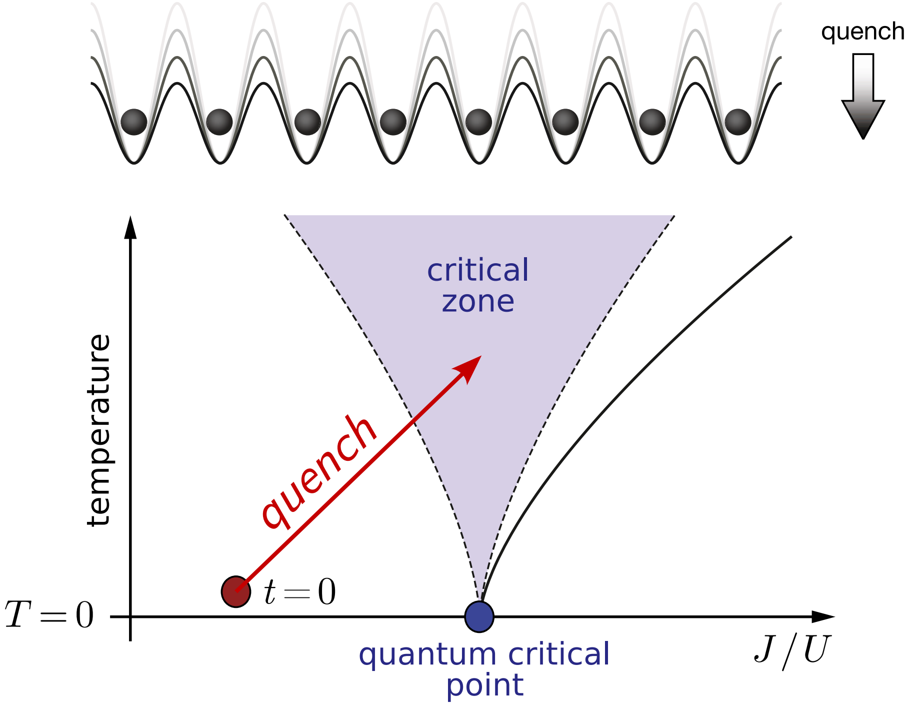
→ Outside of critical zone, **excitations = quasi-particles** (doublons-holons / phonons)

→ But *no long-lived quasi-particles* in the critical zone !
(2D-specific)

→ What are the excitations then ?

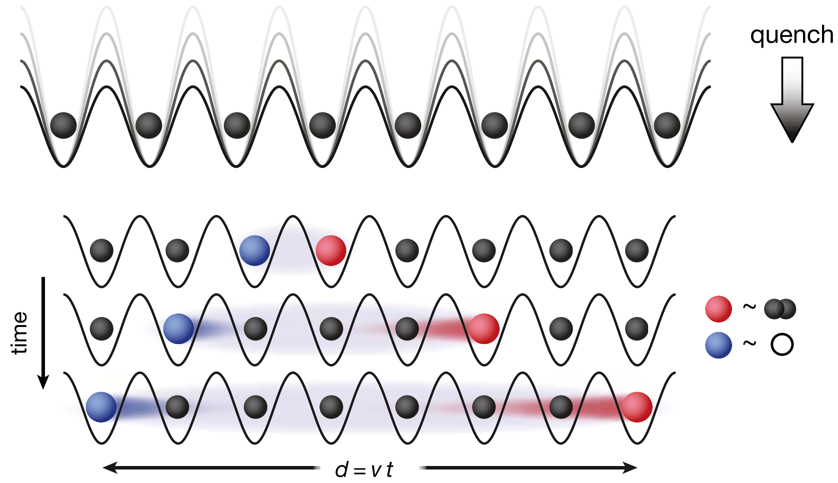
Out-of-equilibrium : shake it up !





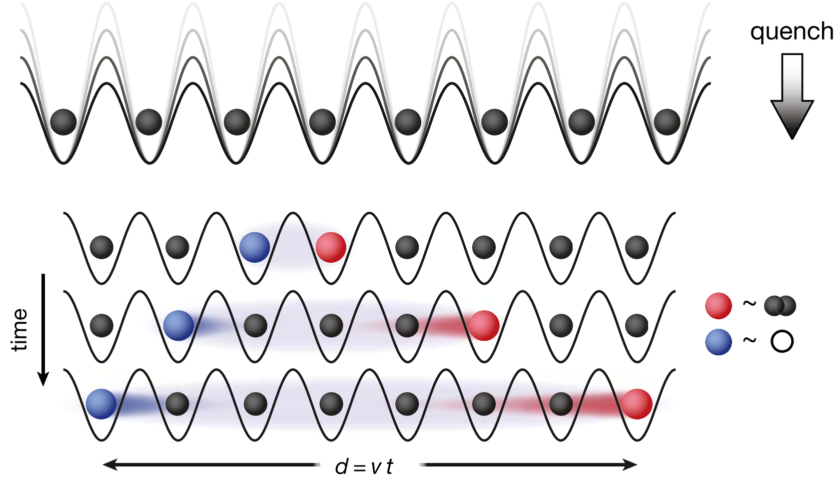
Relaxation :

Thermalization ?   Final state ?   How fast ?

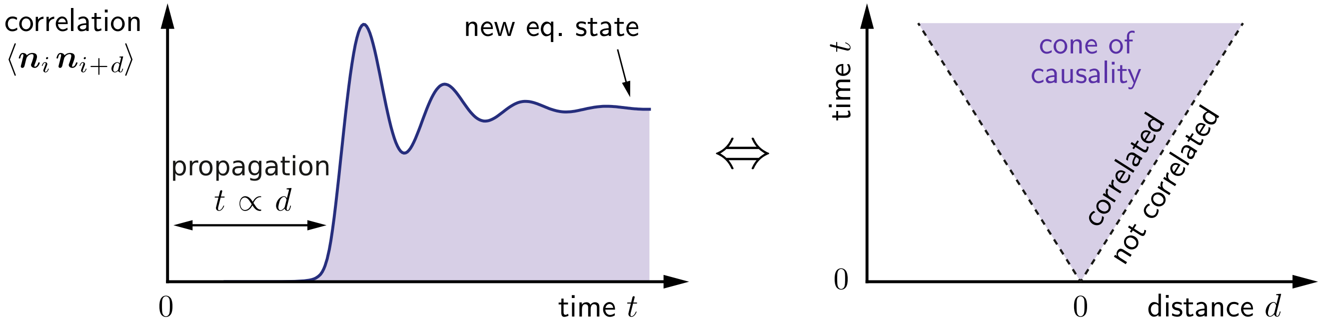


← 1D

Correlation $\langle \boldsymbol{n}_i \, \boldsymbol{n}_{i+d} \rangle$ after a delay t ?


quench
time
~
~
d = v t

← 1D


correlation
$\langle \boldsymbol{n}_i \, \boldsymbol{n}_{i+d} \rangle$
new eq. state
propagation
$t \propto d$
0
time t
$\Leftrightarrow$
time t
cone of
causality
correlated
not correlated
0
0
distance d

Excitations ?

When $\exists$ long-lived quasi-particules (eg. deep in insulator or superfluid) :

- correlation spreading = q-p propagation
- speed = q-p group velocity

Excitations ?

When $\exists$ long-lived quasi-particules (eg. deep in insulator or superfluid) :

- correlation spreading = q-p propagation
- speed = q-p group velocity

When $\nexists$ long-lived quasi-particules (eg. critical zone) :

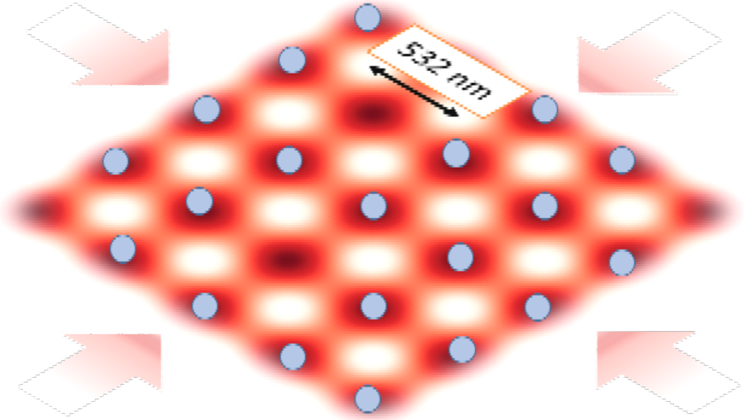
???

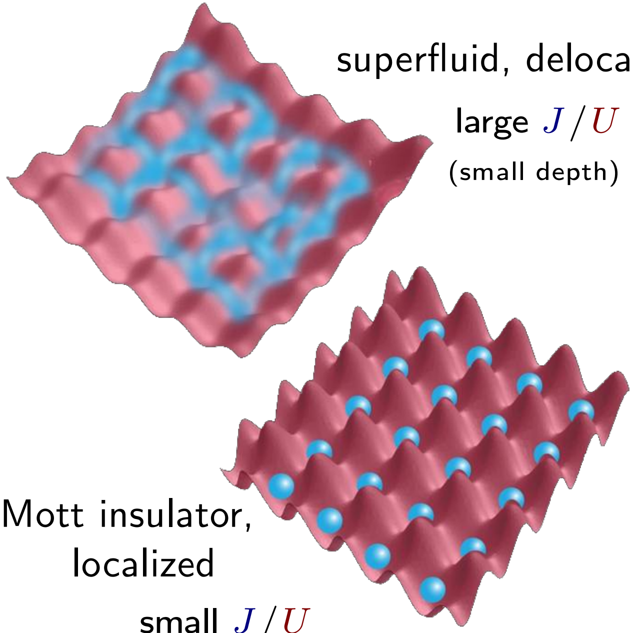
ballistic ? diffusive ? ...

$\longrightarrow$ let's look experimentally !

BEC : only the starting point.

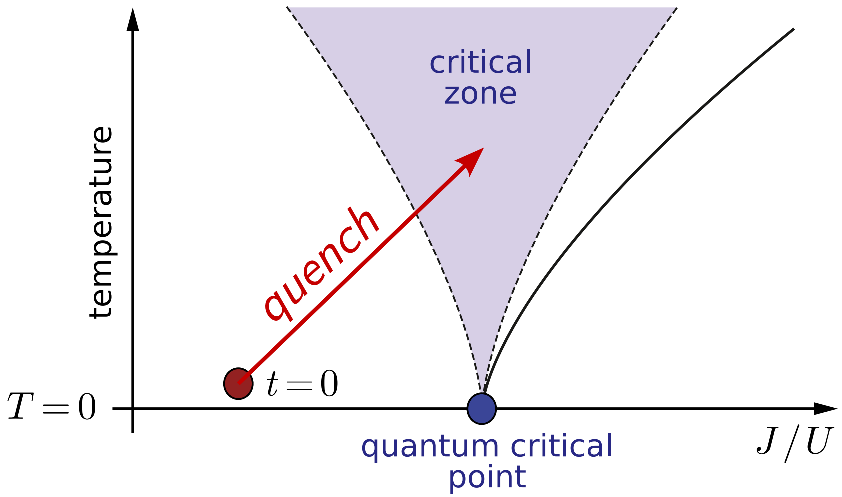
1. Make it strongly interacting $\rightarrow$ optical lattice; many-body quantum system





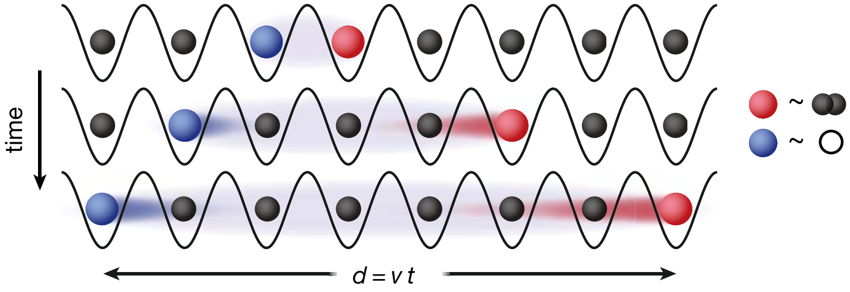
BEC : only the starting point.

1. Make it strongly interacting $\longrightarrow$ optical lattice
2. Put it out-of-equilibrium $\longrightarrow$ sudden change of parameter



BEC : only the starting point.

1. Make it strongly interacting → optical lattice
2. Put it out-of-equilibrium → sudden change of parameter
3. Observe how n-body correlations propagate spatially in the system



With density/momentum profiles, we can only access **1-body** correlation functions $(\langle \boldsymbol{n}(\vec{p})\rangle\langle \boldsymbol{n}(\vec{p}\,')\rangle \ldots)$

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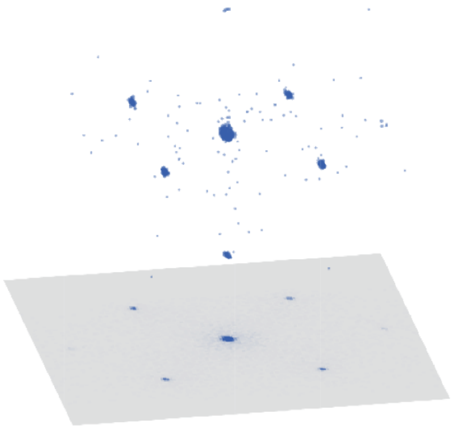
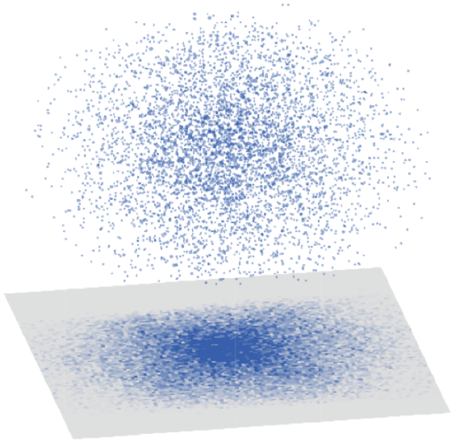
We want **2-body** (or more) correlation functions ! Only possible with **single-particule detection**

- Time-of-flight $\longrightarrow$ MCP $\longrightarrow$ $\langle \boldsymbol{n}(\vec{p})\,\boldsymbol{n}(\vec{p}')\rangle$ $(\mathrm{He}^*$ experiments @ LCF)



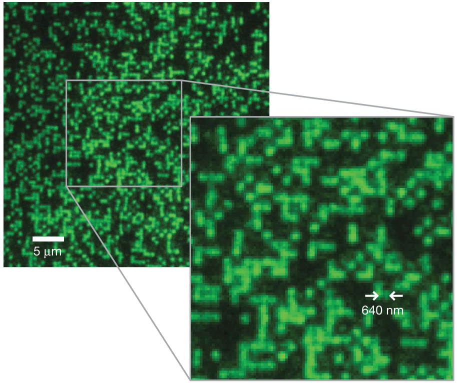


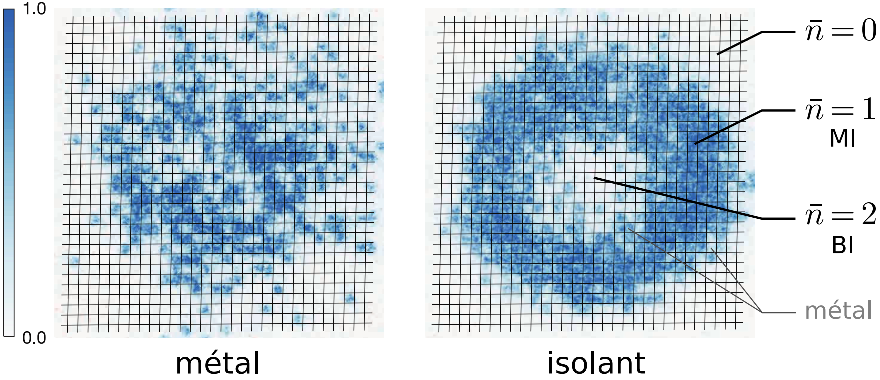
Single-particule detection

With density/momentum profiles, we can only access **1-body** correlation functions $(\langle \boldsymbol{n}(\vec{p})\rangle\langle \boldsymbol{n}(\vec{p}\,')\rangle \ldots)$

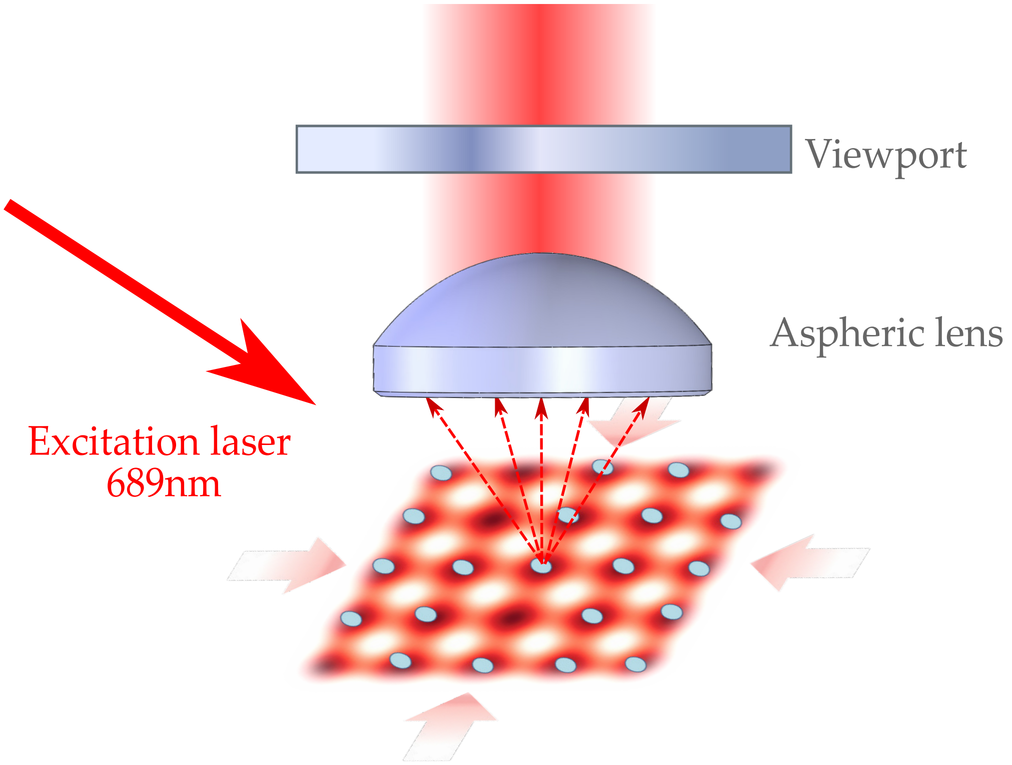
We want **2-body** (or more) correlation functions ! Only possible with **single-particule detection**

- In-situ fluorescence imaging : *quantum gas microscopes* $\longrightarrow \langle \boldsymbol{n}(\vec{r})\, \boldsymbol{n}(\vec{r}\,')\rangle$

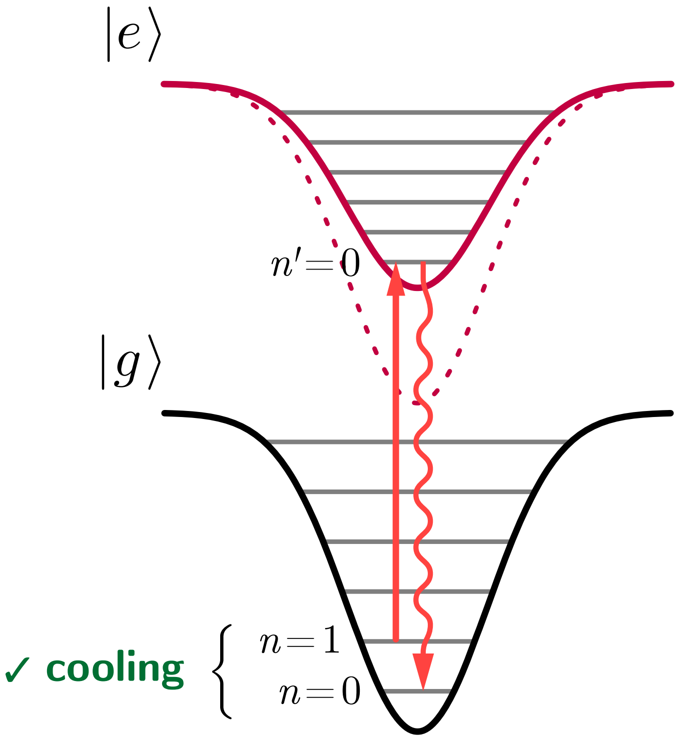




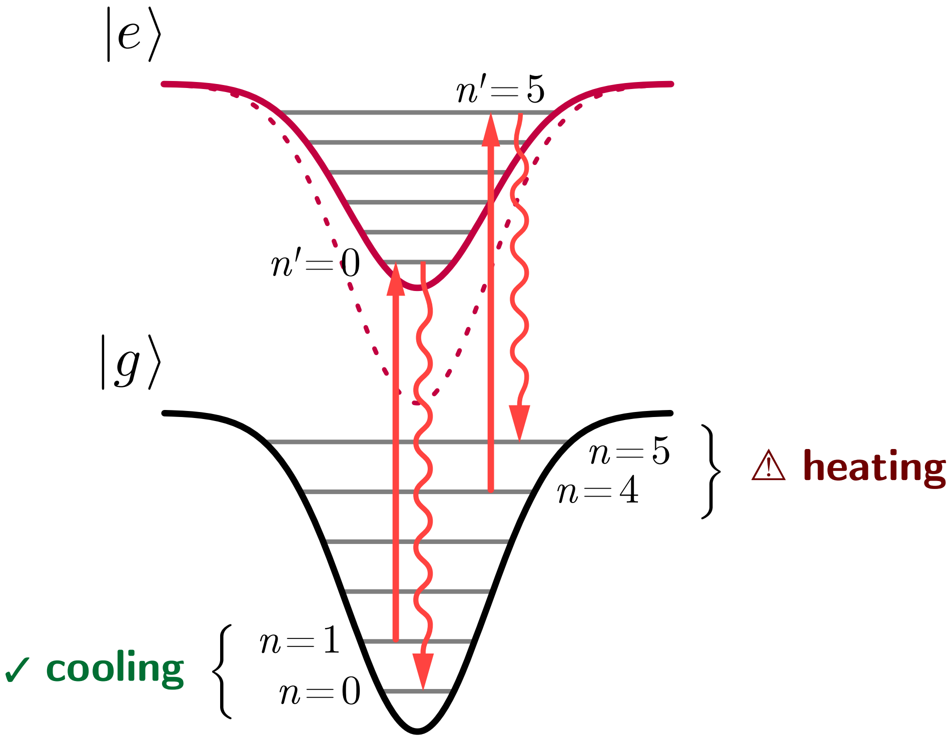
Our microscope



Cooling in the lattice (overly simplified picture)

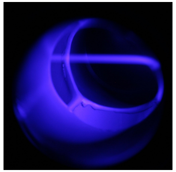


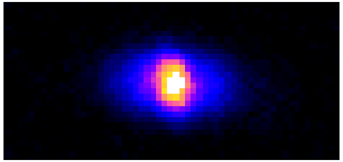
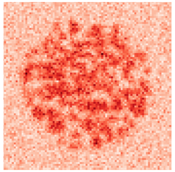
Cooling in the lattice (overly simplified picture)

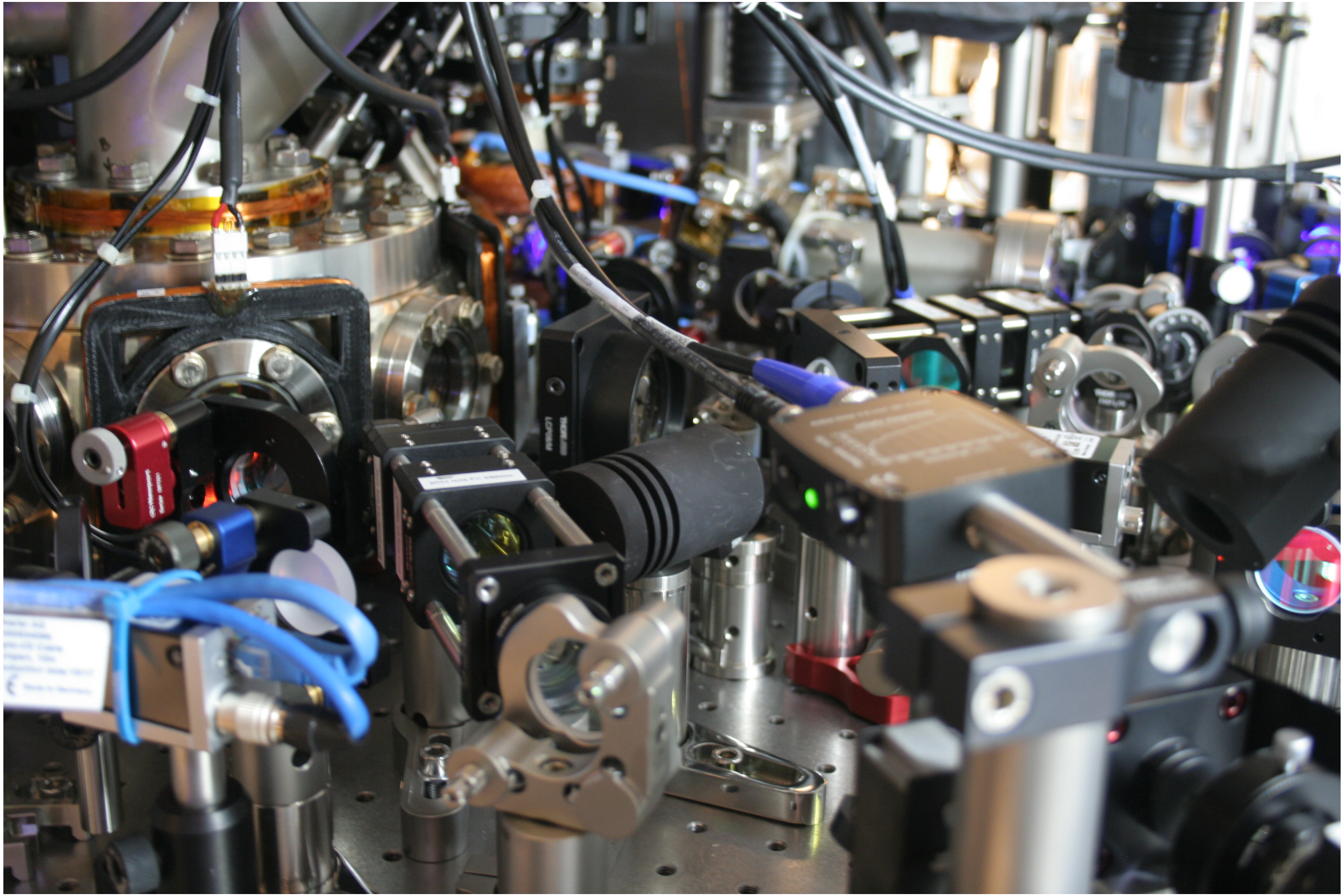


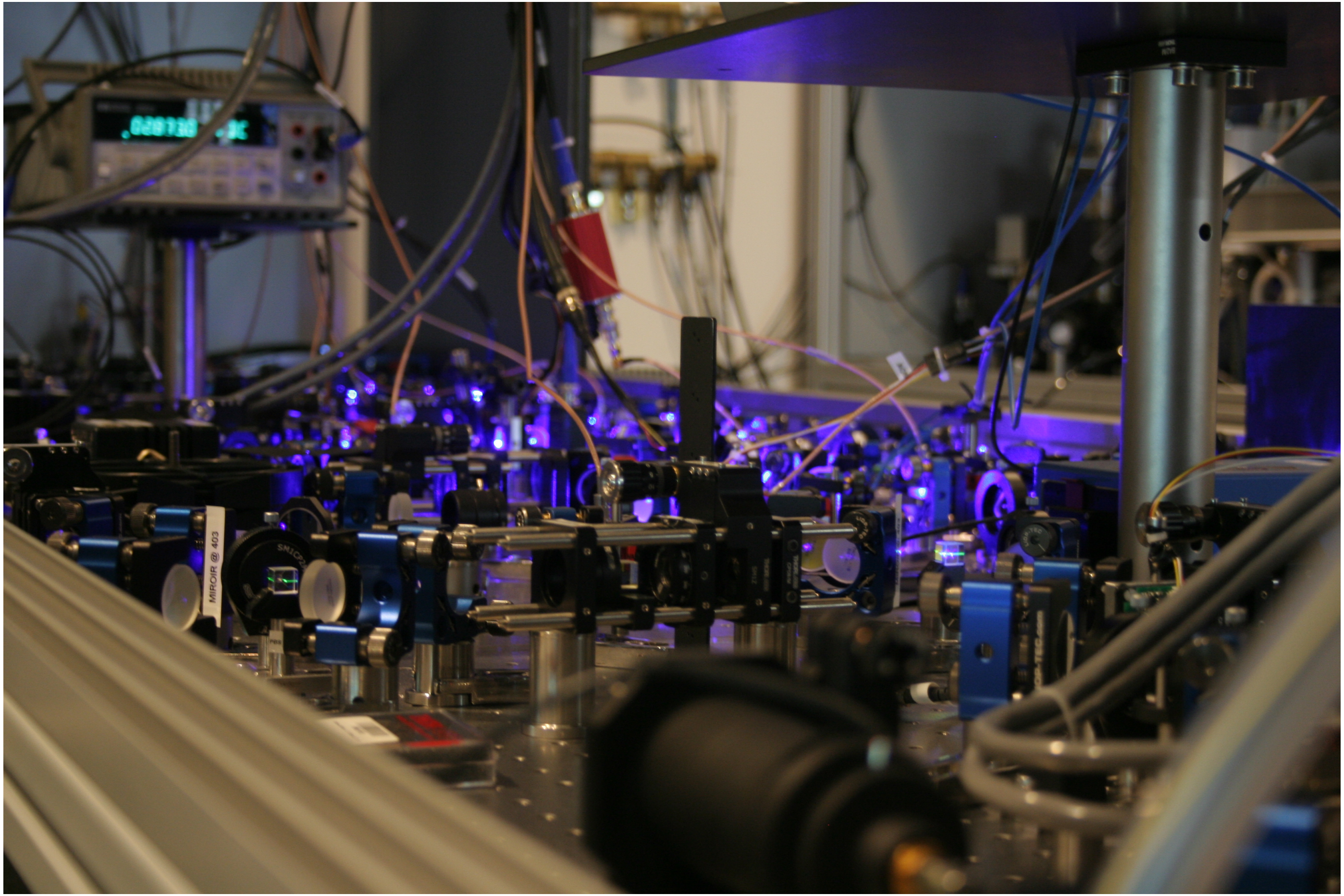
Full future sequence

1. Oven $\longrightarrow$ atomic beam
2. Transverse cooling
3. Zeeman slower
4. Blue MOT ($\sim 1\,\mathrm{s}$ for loading 10^8 atoms)
5. Broadened red MOT ($\sim 0.1\,\mathrm{s}$)
6. Narrow-line red MOT ($\sim 0.1\,\mathrm{s}$)
7. Loading of the transport trap
8. Transport ($2\,\mathrm{s}$)
9. Red molasses for post-transport cooling ($\sim 0.5\,\mathrm{s}$)
10. Transfer transport trap $\longrightarrow$ evaporation trap
11. Evaporative cooling ($1 \sim 4\,\mathrm{s}$?) $\longrightarrow$ 3D BEC
12. Loading a single plane of the vertical lattice $\longrightarrow$ 2D "BEC"
13. Ramping-up of the horizontal lattices $\longrightarrow$ 2D Bose-Hubbard
14. **Physics !** (quench ...)
15. Pinning; Microscopy imaging ($1 \sim 2\,\mathrm{s}$?)



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