Laser Refrigeration using Exciplex Resonances in Gas filled Hollow-Core Fibres

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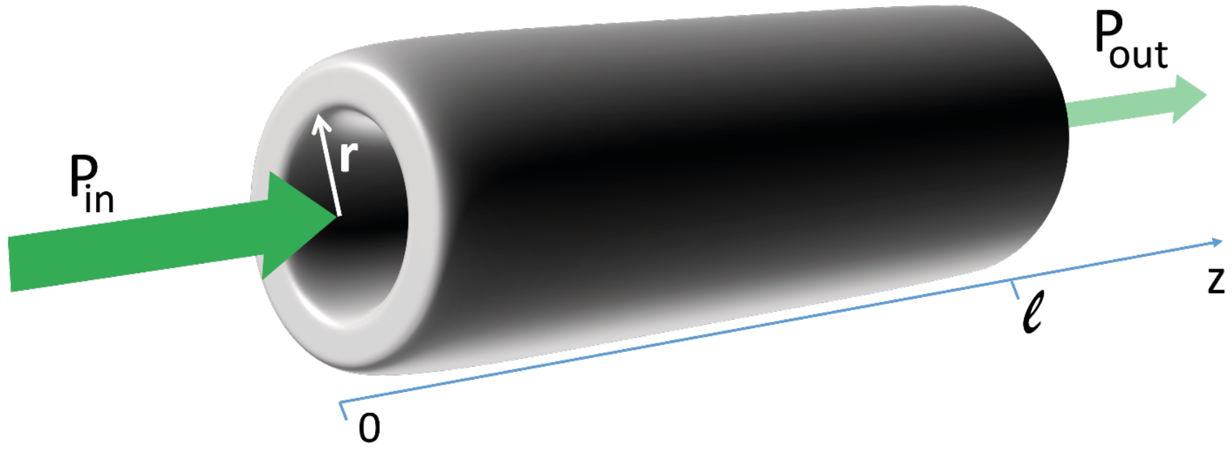
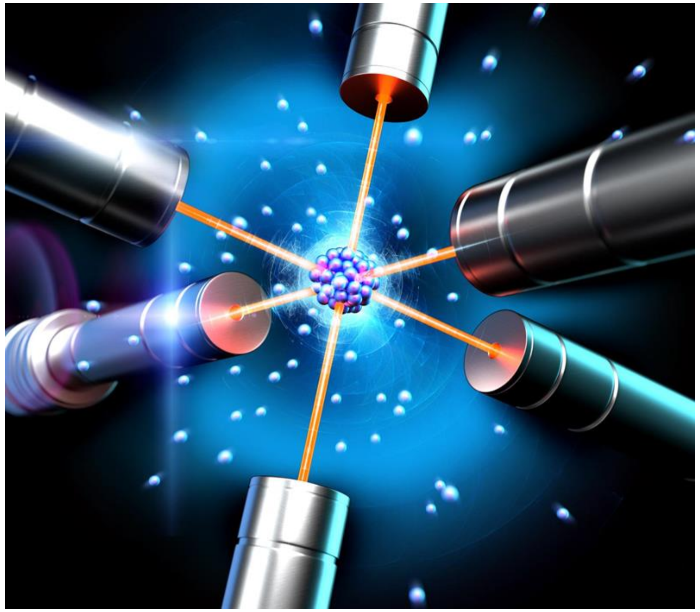
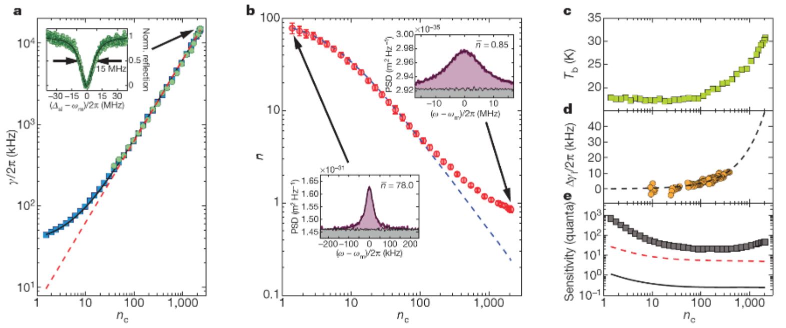


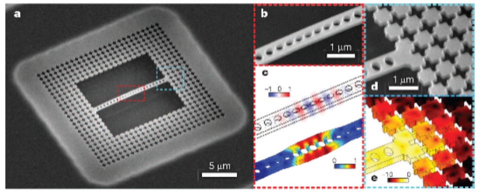
Macroscopic Laser Refrigeration



Macroscopic Laser Refrigeration

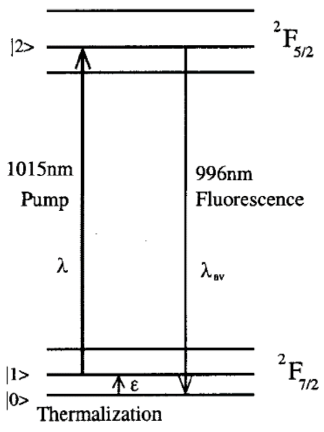
- Optomechanics: Cooling resonator and membrane modes to the ground state



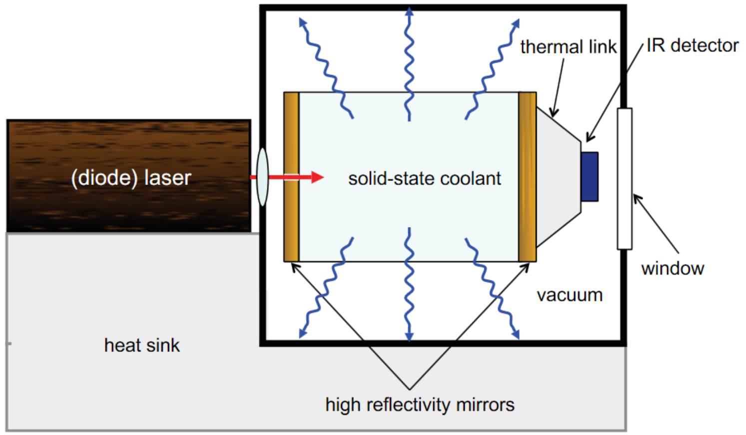


Nature 478, 89-92 (2011)

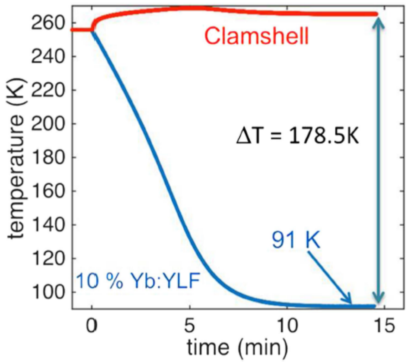
- Laser cooling: Anti-Stokes fluorescence cooling for macroscopic solid state cooling



JOSA B 20, 1037-1053 (2003)



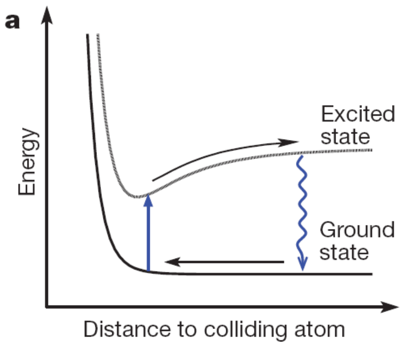
Journal of Physics B 49, 174001 (2016)

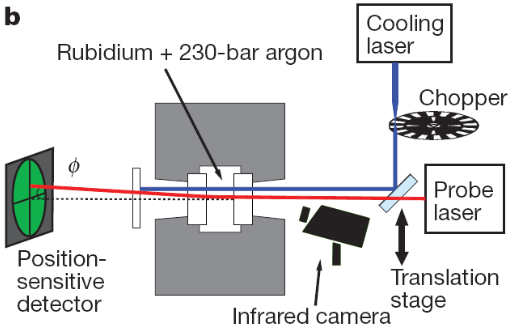


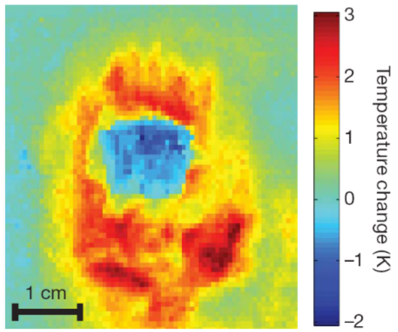
Scientific reports 6, srep20380 (2016)

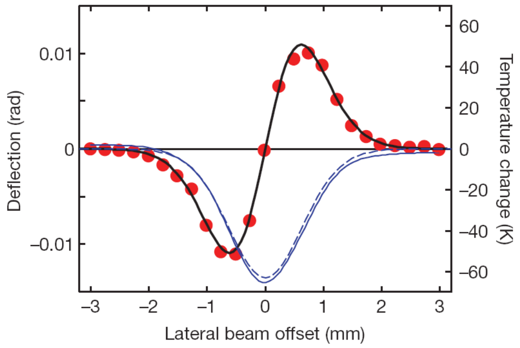
Macroscopic Laser Refrigeration

Laser cooling by collisional redistribution (Weitz group @ Bonn, Germany)





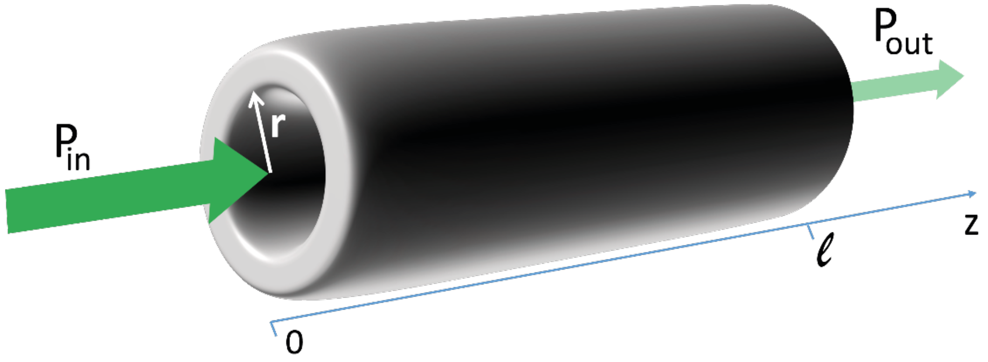




Nature 461, 70 (2009)

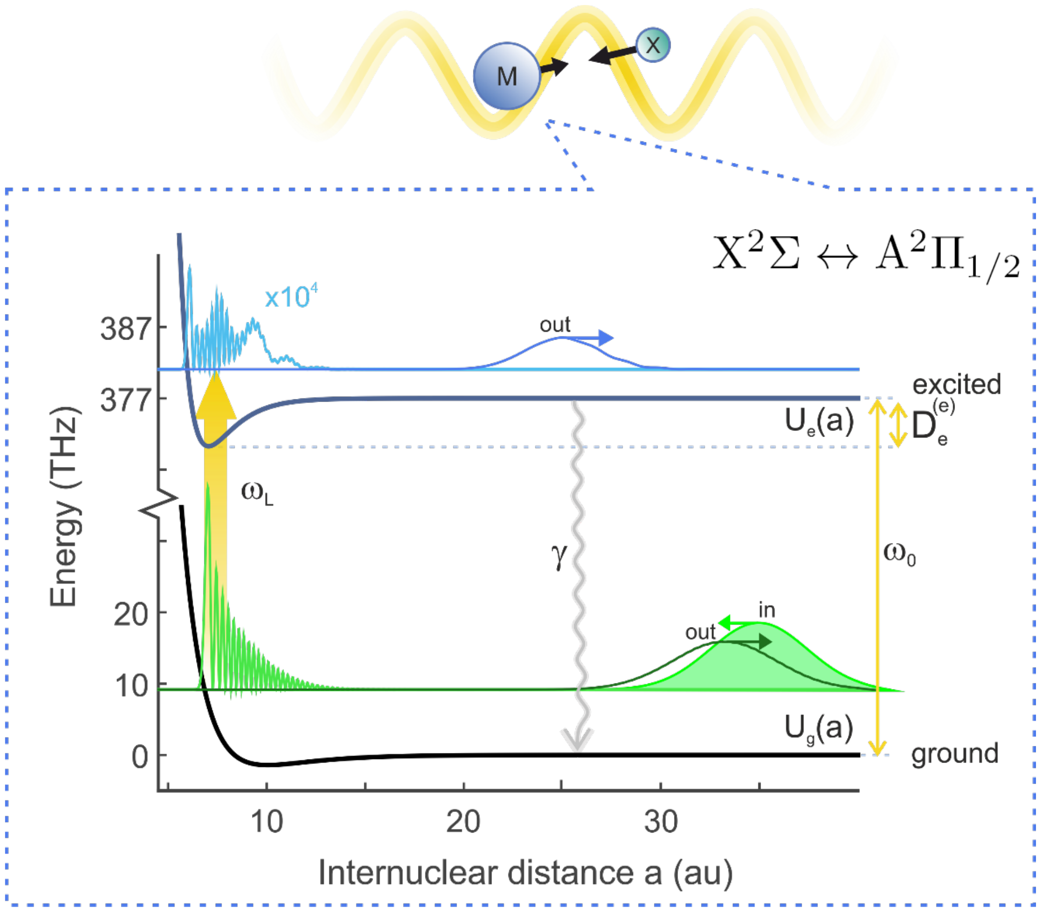
Hollow-core-fibre

(strong light confinement)



Cooling Process for Rubidium-Argon Collisions

Potential curves for the collision modified Rubidium D1 line:



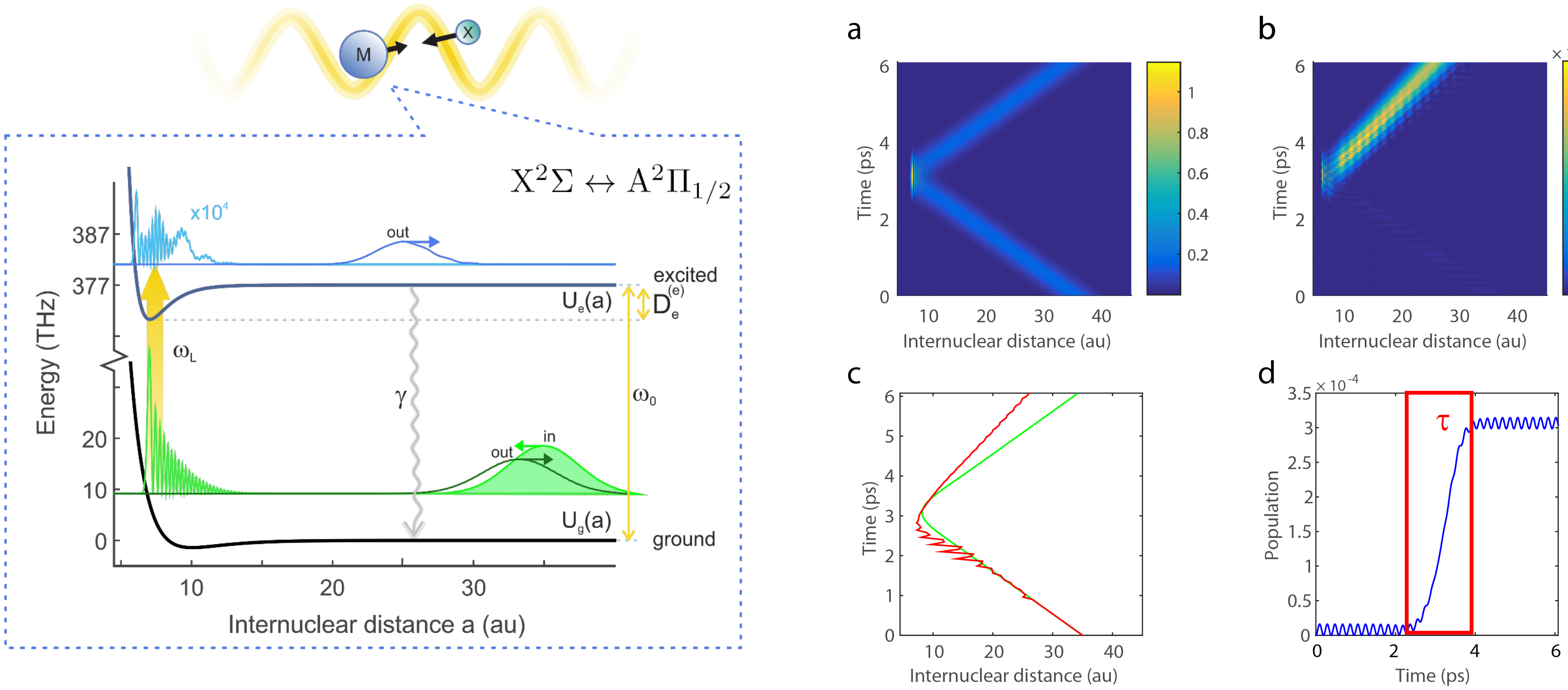
A red detuned laser beam ω_L pumps population from the ground state to the excited state at the collision event

After the collision event the Rubidium atom decays back to the ground state with ω_0 blue shifted from the laser frequency

$$\boxed{\Omega = \omega_0 - \omega_L}$$

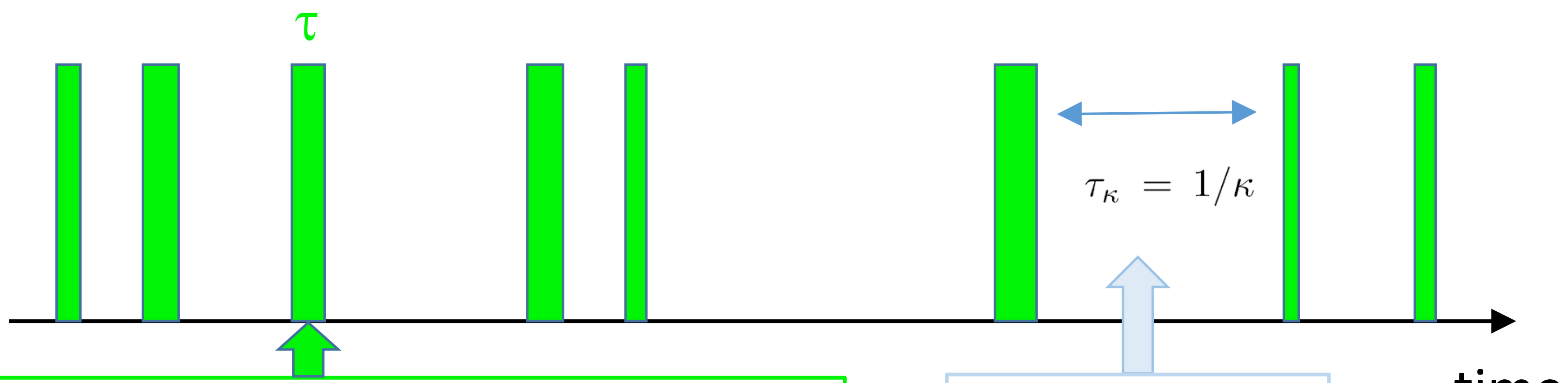
Cooling Process for Rubidium-Argon Collisions

Potential curves for the collision modified Rubidium D1 line:



Excited State Population

Theoretical model (Every collision event resembles an excitation pulse):



$$\boxed{H_R = \hbar\tilde{\chi}_R(z)|g\rangle\langle e| + \hbar\tilde{\chi}_R^*(z)|e\rangle\langle g|}$$

Hamiltonian during collision

$$\boxed{H_0 = \hbar\Omega|e\rangle\langle e|}$$

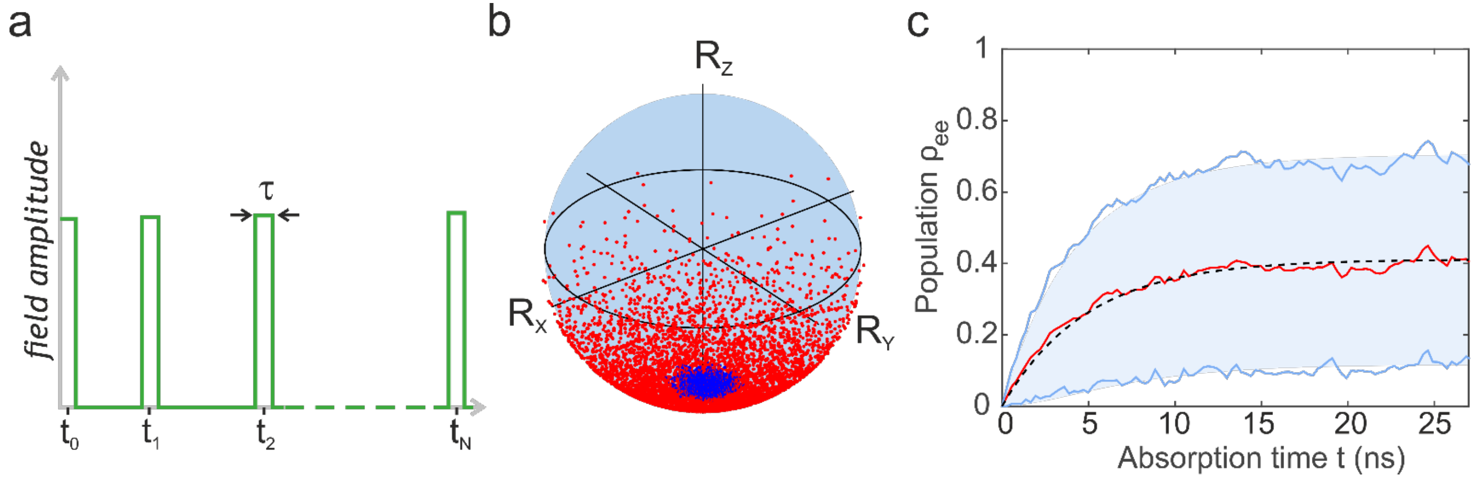
Hamiltonian inbetween collisions (random phase accumulation)

Rabi frequency

$$\tilde{\chi}_R(z) = -\tilde{d}_{eg}\mathcal{E}(z)/\hbar$$

$\boxed{\text{Rotating frame with } \omega_{\mathrm{L}}}$

Excited State Population



We derive Diffusion equation on the Blochsphere

$$\partial_t u = \frac{\mathcal{D}(z)}{\sin(\theta)} \left\{ \partial_\theta \left[\sin(\theta) \partial_\theta \right] u + \frac{1}{\sin(\theta)} \partial_{\varphi\varphi} u \right\} - \gamma u + \frac{\gamma}{\pi} \delta(\cos(\theta) - 1),$$

Diffusion constant

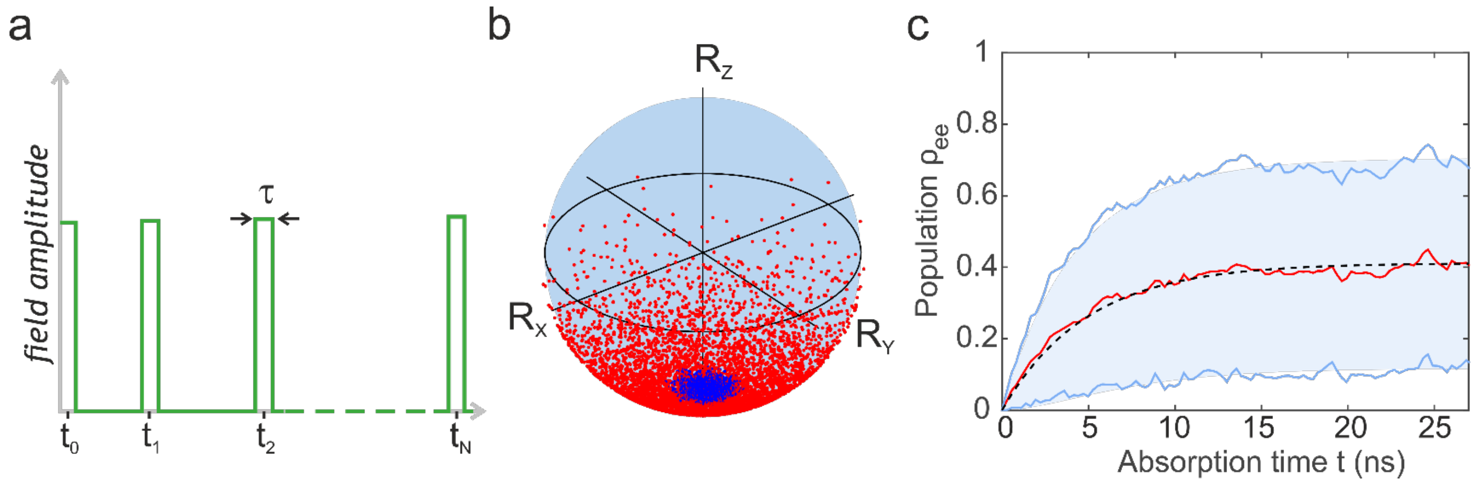
$$\mathcal{D}(z) = \tilde{\chi}_R^2(z) \kappa \tau^2 / \pi \propto \mathcal{P}(z)$$

Solution starting from the groundstate

$$\boxed{u = \sum_{n=0}^{\infty} \frac{2n+1}{4\pi} \left[\frac{(\xi_n(z) - \gamma) e^{-\xi_n(z) t} + \gamma}{\xi_n(z)} \right] P_n(\cos\theta)}$$

$$\xi_n(z) = \mathcal{D}(z) n(n+1) + \gamma$$

Excited State Population



Excited state population

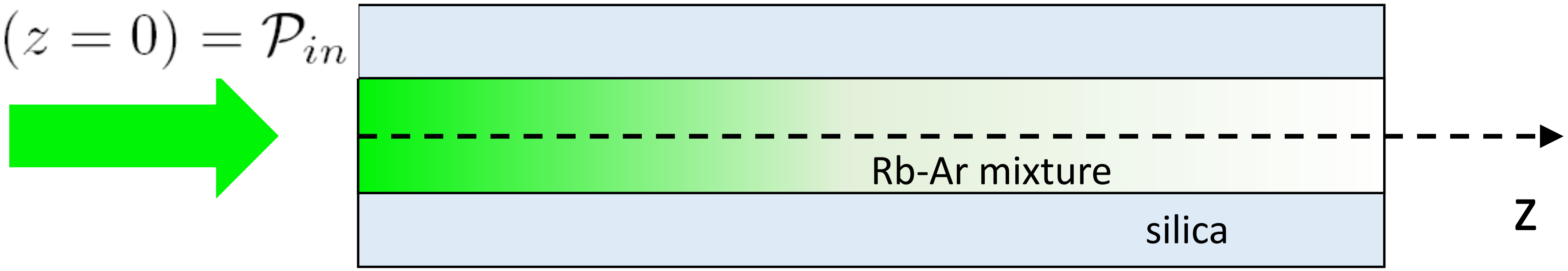
$$\rho_{ee}(z,t) = \left(1 - \int_{-1}^{1} d(\cos\theta) u(\theta, z, t) \cos\theta\right) / 2$$

$$\boxed{\rho_{ee}(t,z) = \frac{\mathcal{D}(z)}{2\mathcal{D}(z)+\gamma}\left(1 - e^{-(2\mathcal{D}(z)+\gamma)t}\right)}$$

Power Absorption

Absorption HC-PCF hollow-core photonic crystal fiber

$$\mathcal{P}(z=0)=\mathcal{P}_{in}$$



Power change due to absorption over the fiber extension:

$$d\mathcal{P}(z)=-\gamma\hbar\omega_{\mathrm{L}}\pi r^2 n_{\mathrm{M}}\rho_{ee}(z)dz$$

$$\boxed{\rho_{ee}(t,z)=\frac{\mathcal{D}(z)}{2\mathcal{D}(z)+\gamma}}$$

$$\boxed{\mathcal{D}(z)=\tilde{\chi}_R^2(z)\kappa\tau^2/\pi\propto\mathcal{P}(z)}$$

Power Absorption

The absorbed power is the inverse function of:

$$z(\mathcal{P}) = \frac{(\mathcal{P}_{in} - \mathcal{P})}{\mathcal{A}} - \frac{1}{\mathcal{B}\mathcal{A}} \ln\left(\frac{\mathcal{P}}{\mathcal{P}_{in}}\right)$$

$$\mathcal{P} \in \{0, \mathcal{P}_{in}\}$$

$$\mathcal{B}\mathcal{P}_{in} \gg 1 \ \text{(linear regime)}$$

$$\boxed{\mathcal{P}(z) = \mathcal{P}_{in} - \mathcal{A}z}$$

Strong light confinement in a fibre

$$\mathcal{B}\mathcal{P}_{in} \ll 1 \ \text{(exponential regime)}$$

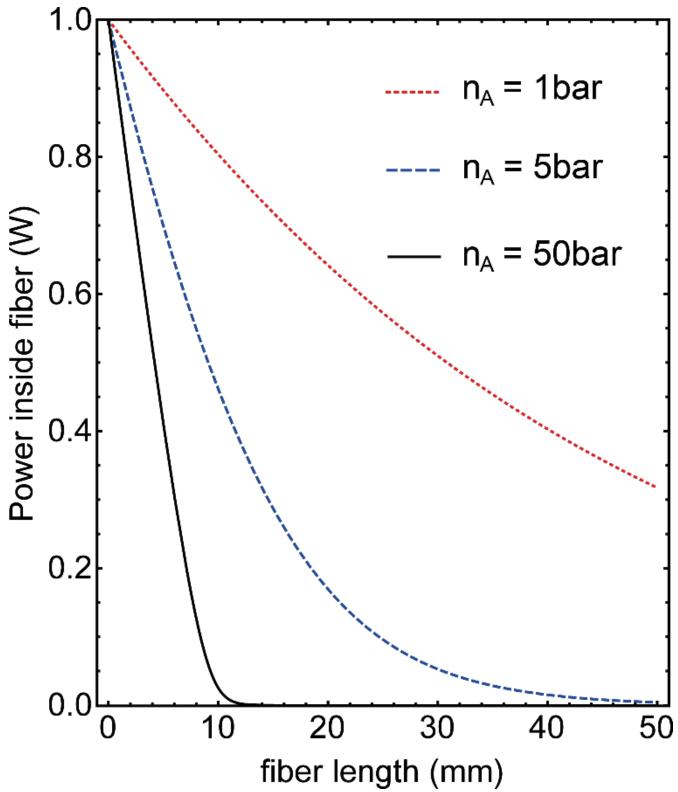
$$\boxed{\mathcal{P}(z) = \mathcal{P}_{in} e^{-\mathcal{A}\mathcal{B}z}}$$

Beer-Lambert law

(Weitz experiment)

$$\mathcal{A} = \frac{1}{2}\hbar\omega_{\mathrm{L}}\gamma\pi r^2 n_{\mathrm{M}},$$

$$\mathcal{B} = \frac{2\tilde{d}_{eg}^2\sigma_{\mathrm{cool}}\sqrt{3k_{\mathrm{B}}}}{\hbar^2\pi^2\epsilon_0\sqrt{\mu}\gamma c}\frac{\sqrt{T}n_{\mathrm{X}}\tau^2}{r^2}$$



Cooling Power

Total cooling power up to the fibre length l

$$\mathcal{P}_{cool} = \frac{\Omega}{\omega_{\rm L}} \int_{\mathcal{P}_{in}}^{\mathcal{P}(\ell)} d\mathcal{P}(z) = \frac{\Omega}{\omega_{\rm L}} (\mathcal{P}_{out} - \mathcal{P}_{in})$$

Heating power over the fibre length l

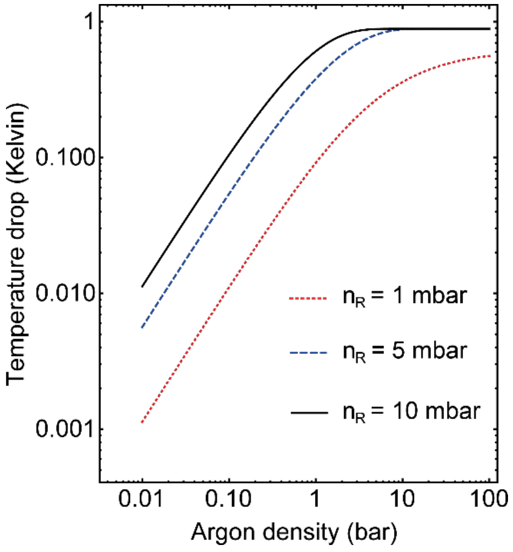
$$\mathcal{P}_{heat} = 2\pi k_g \frac{T_e - T}{\ln r_e / r} \ell$$

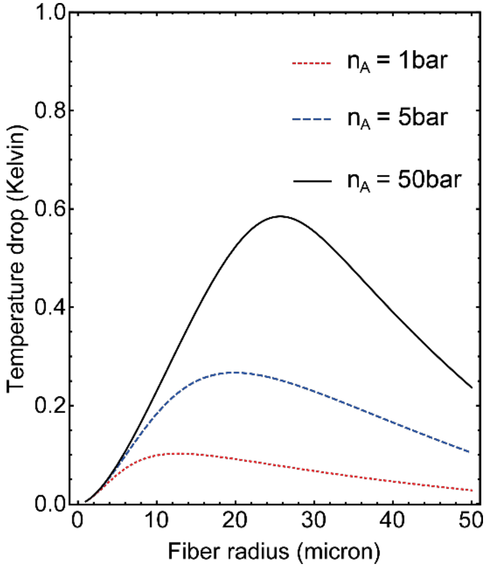
Gas-Glass interface temperature

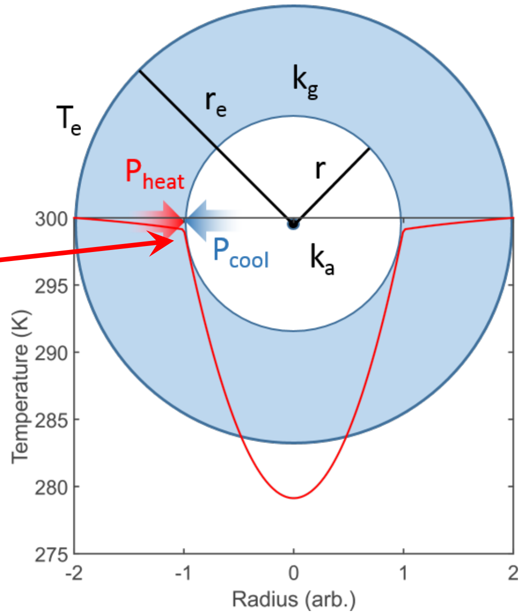
$$\mathcal{P}_{cool} + \mathcal{P}_{heat} = 0$$

$$\boxed{(\delta T)_{max} = \gamma n_{\rm M} \frac{\hbar \Omega}{4 k_g} r^2 \ln\left(\frac{r_e}{r}\right)}$$

Linear regime







Cooling Rate

Cooling rate:

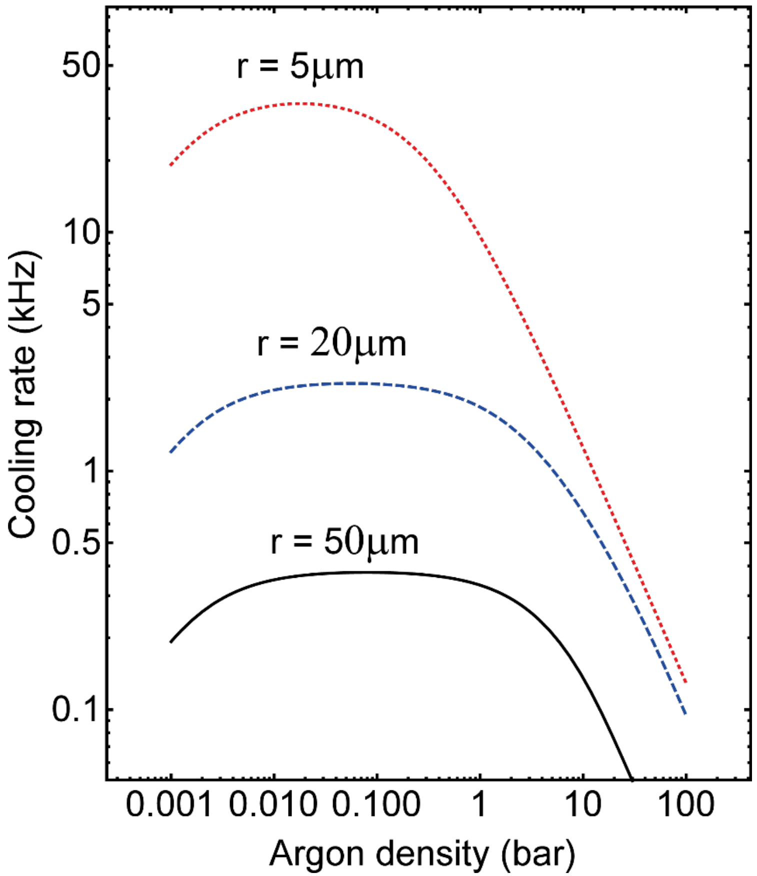
$$\beta_{cool}(T) = -\mathcal{P}_{cool}/E_{kin}(T)$$

(linear regime)

$$\beta^{lin}_{cool}(T) \approx \frac{\hbar\Omega}{k_{\mathrm{B}}T}\frac{n_{\mathrm{M}}}{n_{\mathrm{M}}+n_{\mathrm{X}}}\gamma$$

(exponential regime (Weitz experiment))

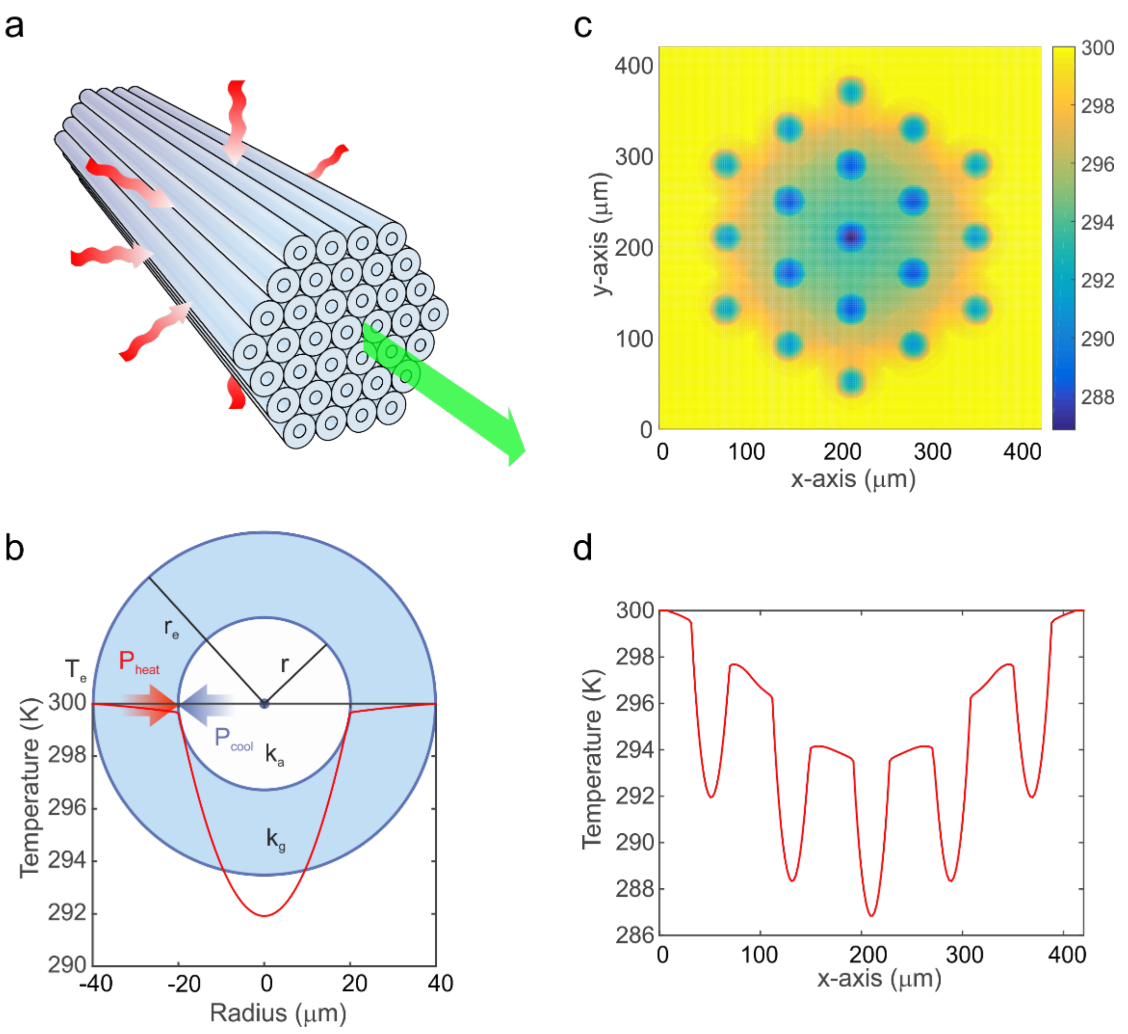
$$\beta^{exp}_{cool}(T) \approx \mathcal{BP}_{in}\beta^{lin}_{cool}(T) \qquad \mathcal{BP}_{in} \ll 1$$



Fibre Stack

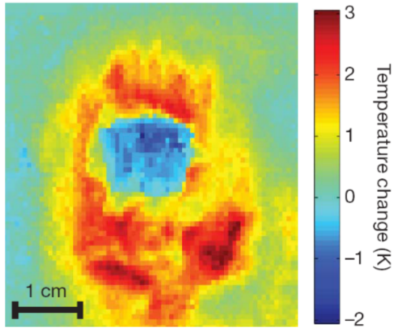
Fibrestacks where the **outside** insulates the **inner fibre** allowing
to reach **lower temperatures** in the center

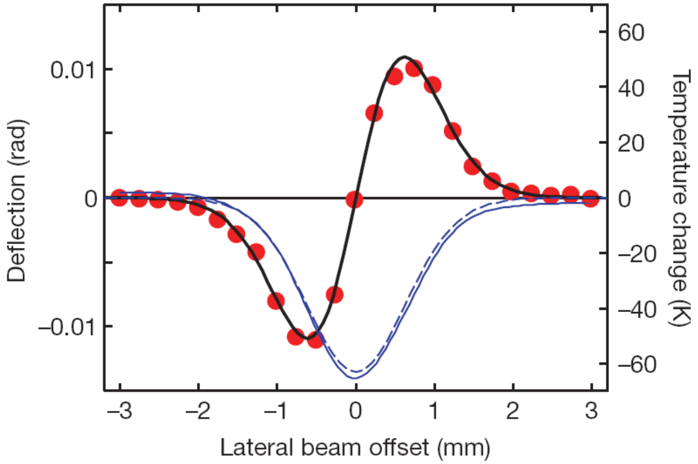
(simulation results: heat equation)



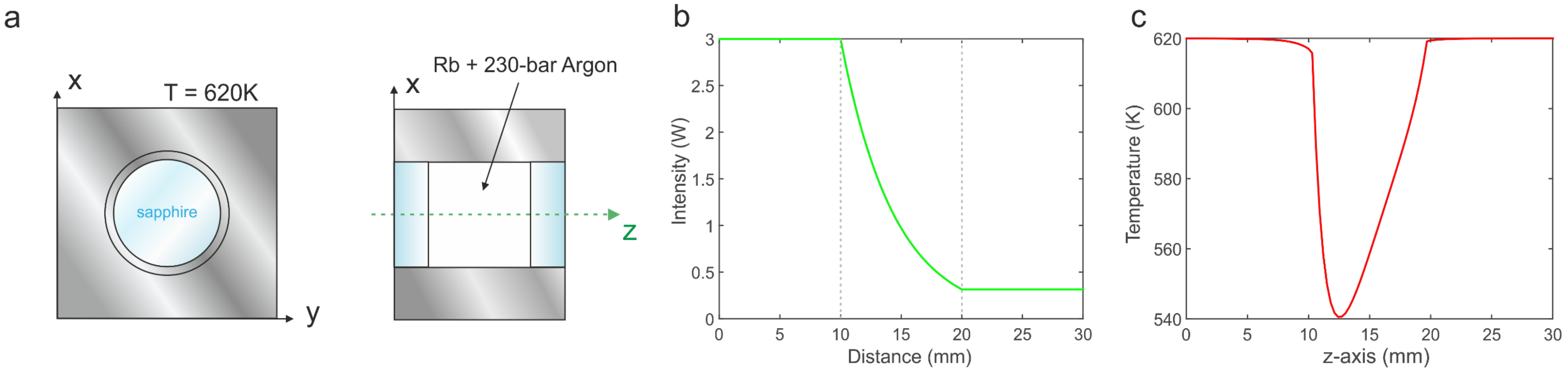
Comparison with experimental results

Nature 461, 70 (2009)





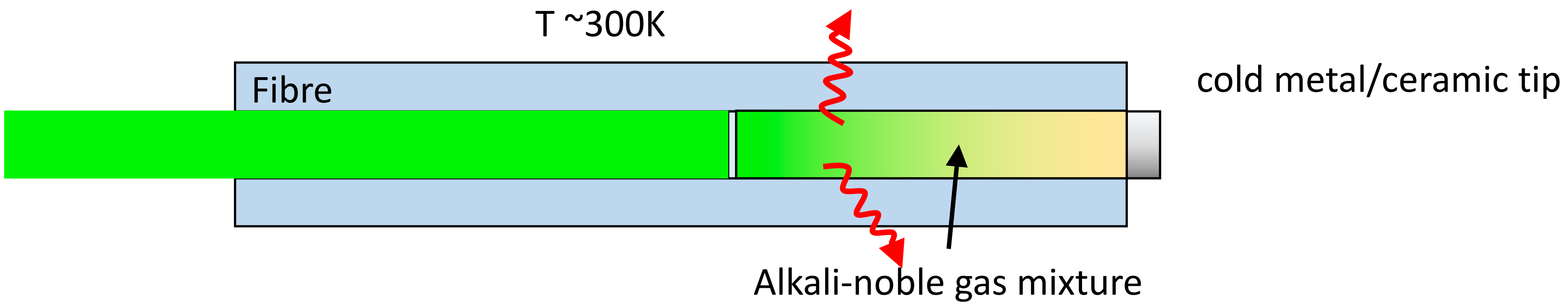
Simulations using parameters from Nature 461, 70 (2009)



Conclusion

Strong fibre cooling in room temperature environment (no vacuum and temperature shielding required)

Up to 10 - 100 K can be extracted from the gas mixture and possibly from the close environment.



Thanks for your Attention!

$$\dot{\boldsymbol{R}} = \boldsymbol{\chi}_R \times \boldsymbol{R} \qquad (\theta, \varphi) \in [0, \pi) \times [0, 2\pi)$$

$$d\theta = -\tilde{\chi}_R \sin(\varphi) dt$$

$$\begin{aligned}
\Phi_{n+1}(m) &= p_+ \Phi_n(m+1) + p_0 \Phi_n(m) + p_- \Phi_n(m-1) \\
&= \left(\frac{1}{\pi} + \frac{\Delta\theta}{2\pi} \cot(m\Delta\theta) \right) \Phi_n(m+1) \\
&\quad + \left(1 - \frac{2}{\pi} \right) \Phi_n(m) \\
&\quad + \left(\frac{1}{\pi} - \frac{\Delta\theta}{2\pi} \cot(m\Delta\theta) \right) \Phi_n(m-1)
\end{aligned}$$

$$\Delta\theta = \tilde{\chi}_R \tau$$

$$\Phi_{n+1}(m) - \Phi_n(m) = \frac{1}{\pi}\Big(\Phi_n(m+1) + \Phi_n(m-1)$$
$$-2\Phi_n(m) + \frac{\Delta\theta}{2}\cot(m\Delta\theta)$$
$$\times\left(\Phi_n(m+1) - \Phi_n(m-1)\right)\Big)$$

$$\tau_\kappa \partial_t \Phi \cong \frac{\Delta\theta^2}{\pi}\left(\partial_{\theta\theta}\Phi + \cot(\theta)\partial_\theta\Phi\right)$$

$p_0 = 1 - 2/\pi - p_\gamma$ $\qquad$ $p_\gamma = \gamma\tau_\kappa$ $\qquad$ $\gamma\tau_\kappa\delta_{0m}$

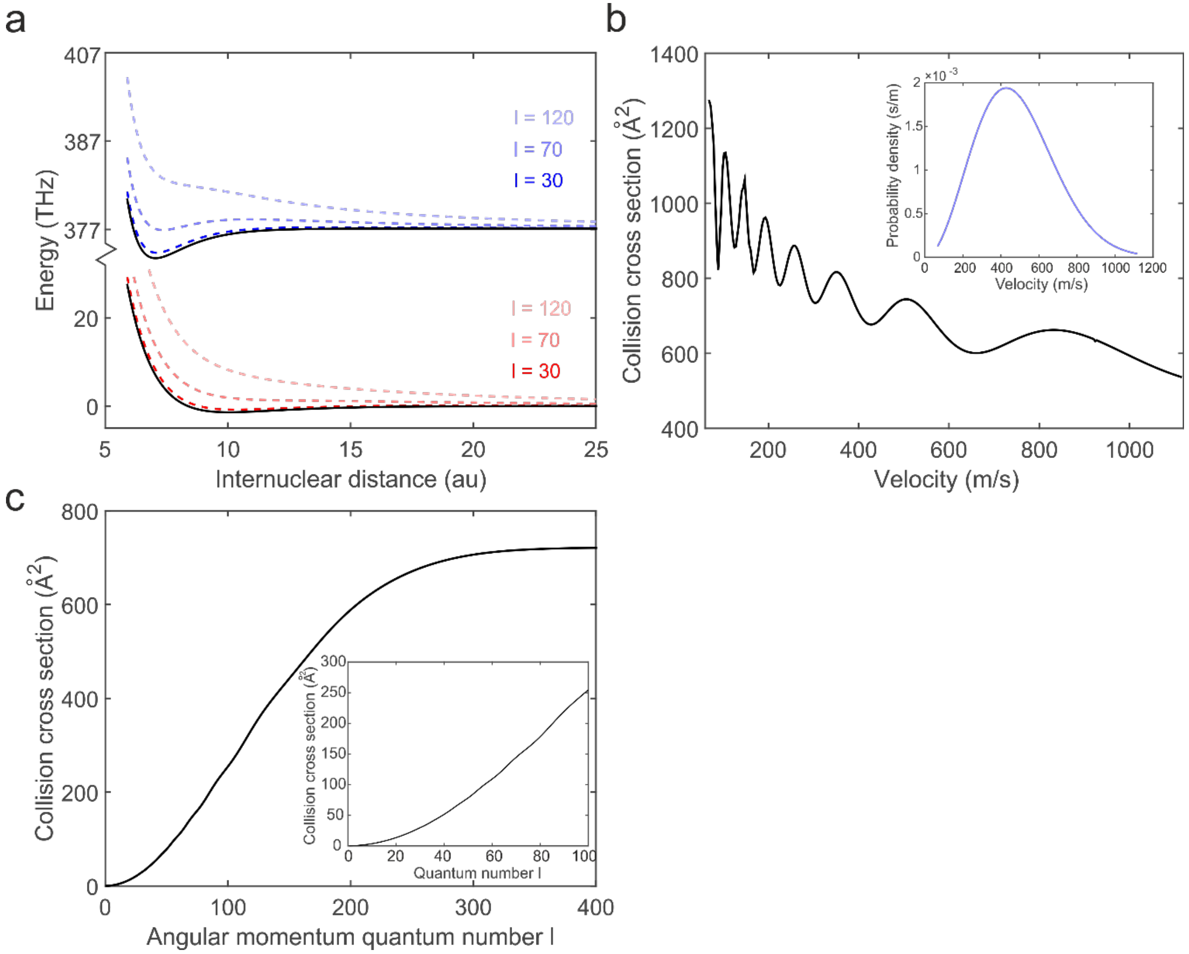
$$\partial_t u = \mathcal{D}\left\{\frac{1}{\sin(\theta)}\partial_\theta(\sin(\theta)\partial_\theta u) + \frac{1}{\sin^2(\theta)}\partial_{\varphi\varphi}u\right\}$$
$$-\gamma u + \frac{1}{\pi}\delta(\cos(\theta) - 1)$$

$$\partial_t u = \frac{\mathcal{D}(z)}{\sin(\theta)} \left\{ \partial_\theta \left[\sin(\theta) \partial_\theta \right] u + \frac{1}{\sin(\theta)} \partial_{\varphi\varphi} u \right\}$$
$$-\gamma u + \frac{\gamma}{\pi} \delta(\cos(\theta) - 1),$$

$$u = \sum_{n=0}^{\infty} \frac{2n+1}{4\pi} \left[\frac{(\xi_n(z) - \gamma) e^{-\xi_n(z) t} + \gamma}{\xi_n(z)} \right] P_n(\cos\theta)$$

$$\xi_n(z) = \mathcal{D}(z) n(n+1) + \gamma$$

$$\rho_{ee}(t, z) = \frac{\mathcal{D}(z)}{2\mathcal{D}(z) + \gamma} \left(1 - e^{-(2\mathcal{D}(z) + \gamma) t} \right)$$



a
407
387
377
20
0
Energy (THz)
l = 120
l = 70
l = 30
l = 120
l = 70
l = 30
5
10
15
20
25
Internuclear distance (au)
b
1400
1200
1000
800
600
400
Collision cross section (Å^2)
200
400
600
800
1000
Velocity (m/s)
Probability density (s/m)
×10^{-3}
2
1.5
1
0.5
0
0
200
400
600
800
1000
1200
Velocity (m/s)
c
800
600
400
200
0
Collision cross section (Å^2)
0
100
200
300
400
Angular momentum quantum number l
300
250
200
150
100
50
0
Collision cross section (Å^2)
0
20
40
60
80
100
Quantum number l