Performances of a Polaritonic Refrigerant

Maxime Richard[1]

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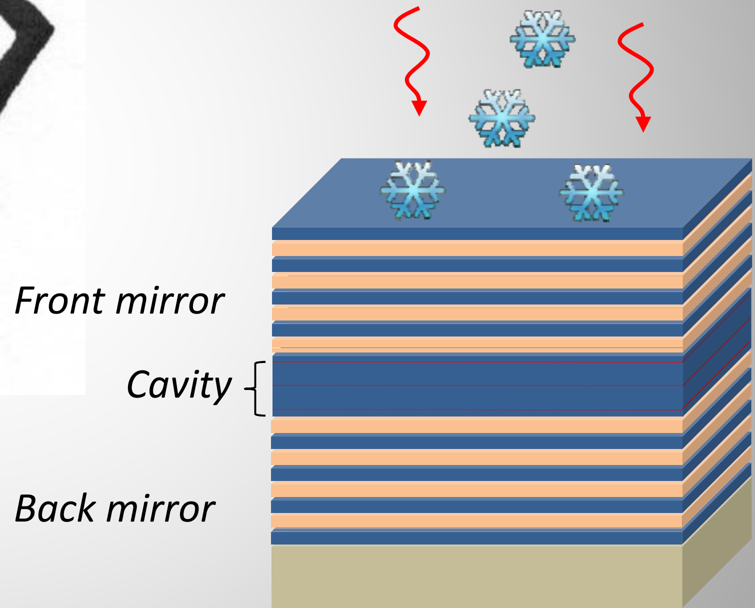
[3] *Institut für Festkörperphysik, Universität Bremen, Otto-Hahn-Allee, 28359 Bremen, Germany*
[4] *Laboratoire FOTON, CNRS, INSA de Rennes, 35708 Rennes, France*

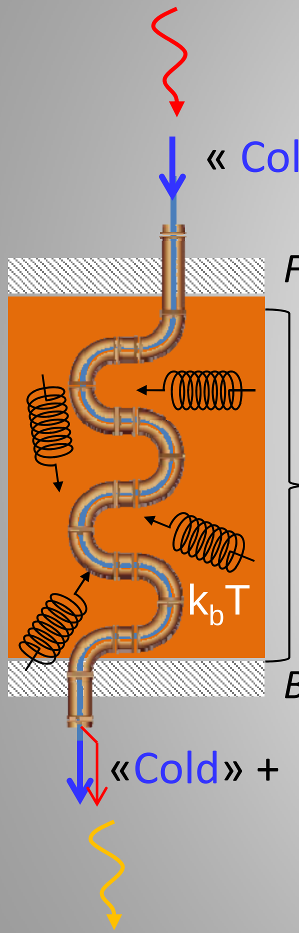
Outline

1- **Can we use polariton fluids to cool down solids ?**



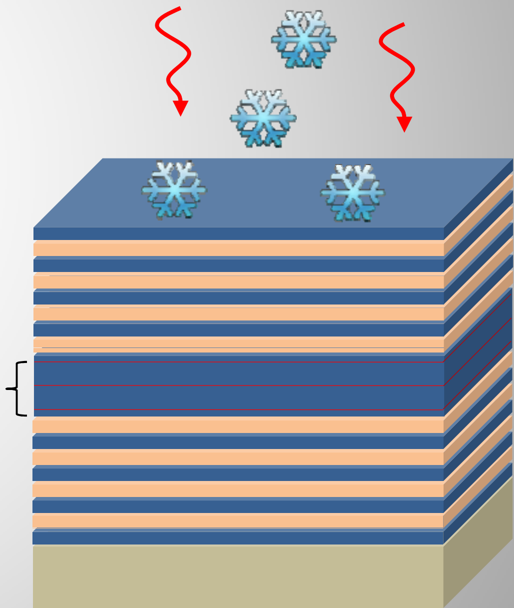
Microcavity in the strong coupling regime

Outline



2- What kind of heat exchange fluid is that ?

1- Can we use polariton fluids to cool down solids ?



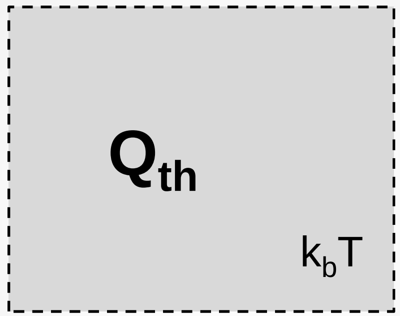
Microcavity in the strong coupling regime

Outline

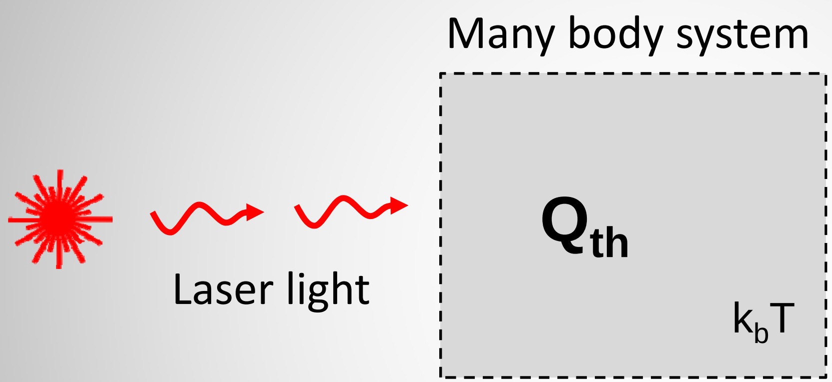
0 – Back to the principle of cooling many body systems with light

Principle of optical cooling

Many body system



Principle of optical cooling



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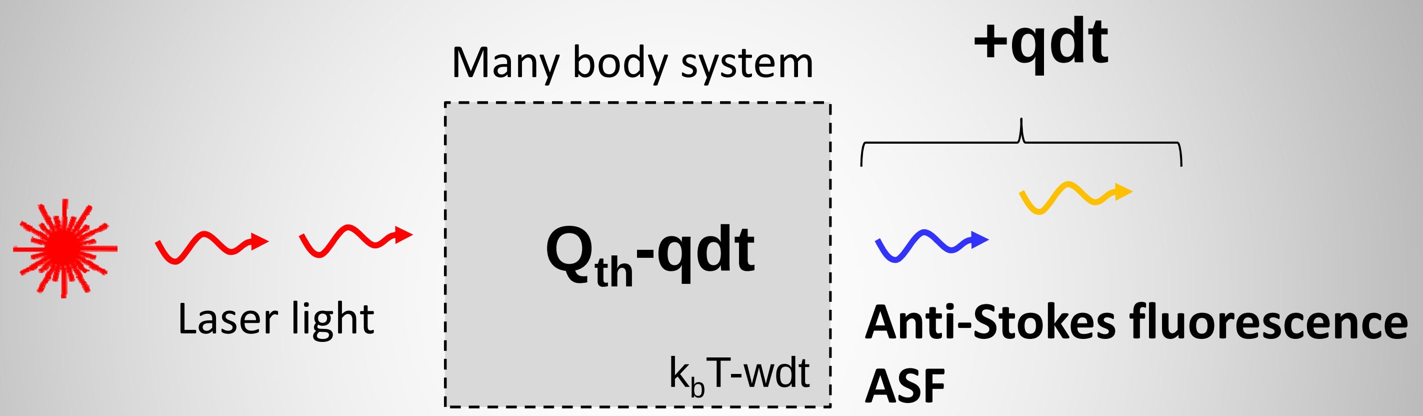

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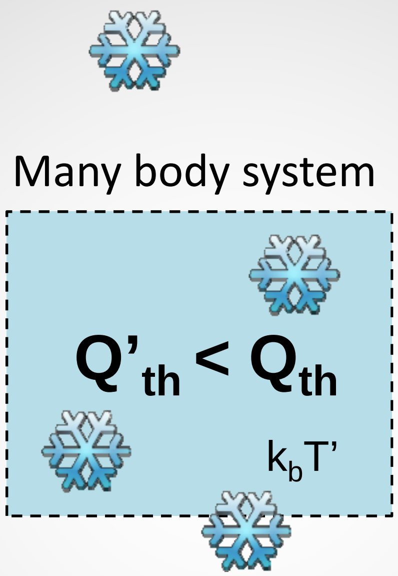
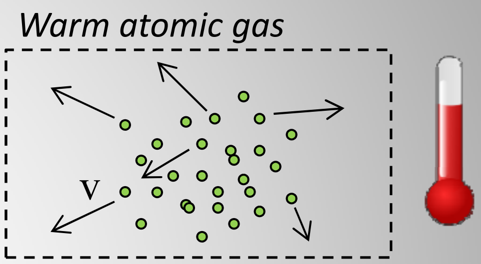


Principle of optical cooling

Doppler cooling

Cooling the translational degrees of freedom



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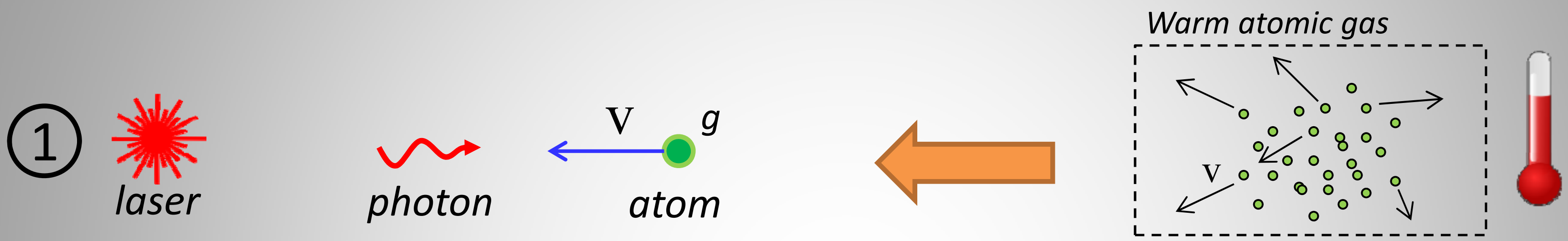

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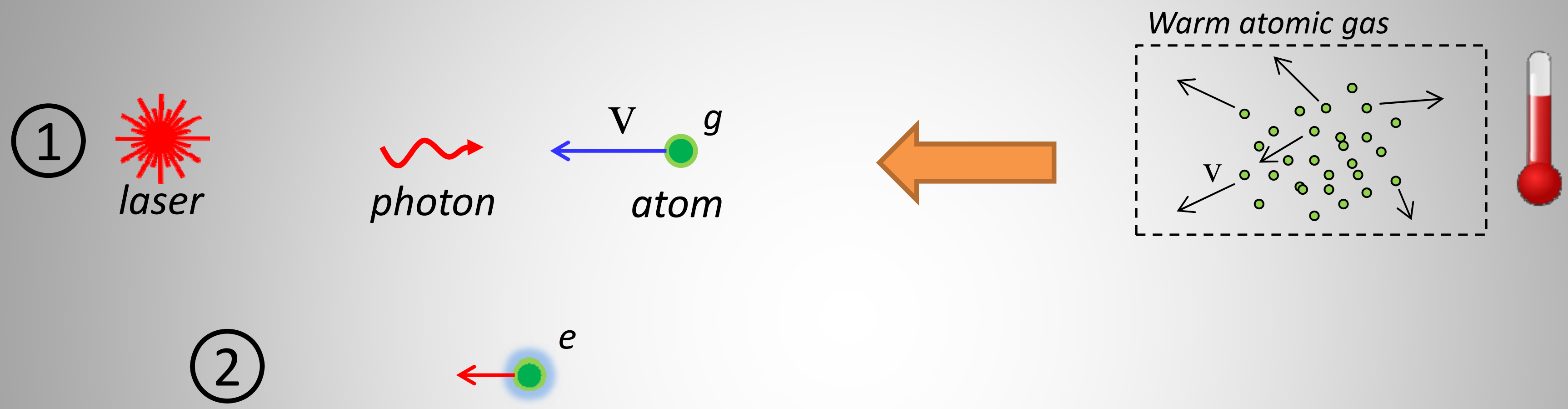
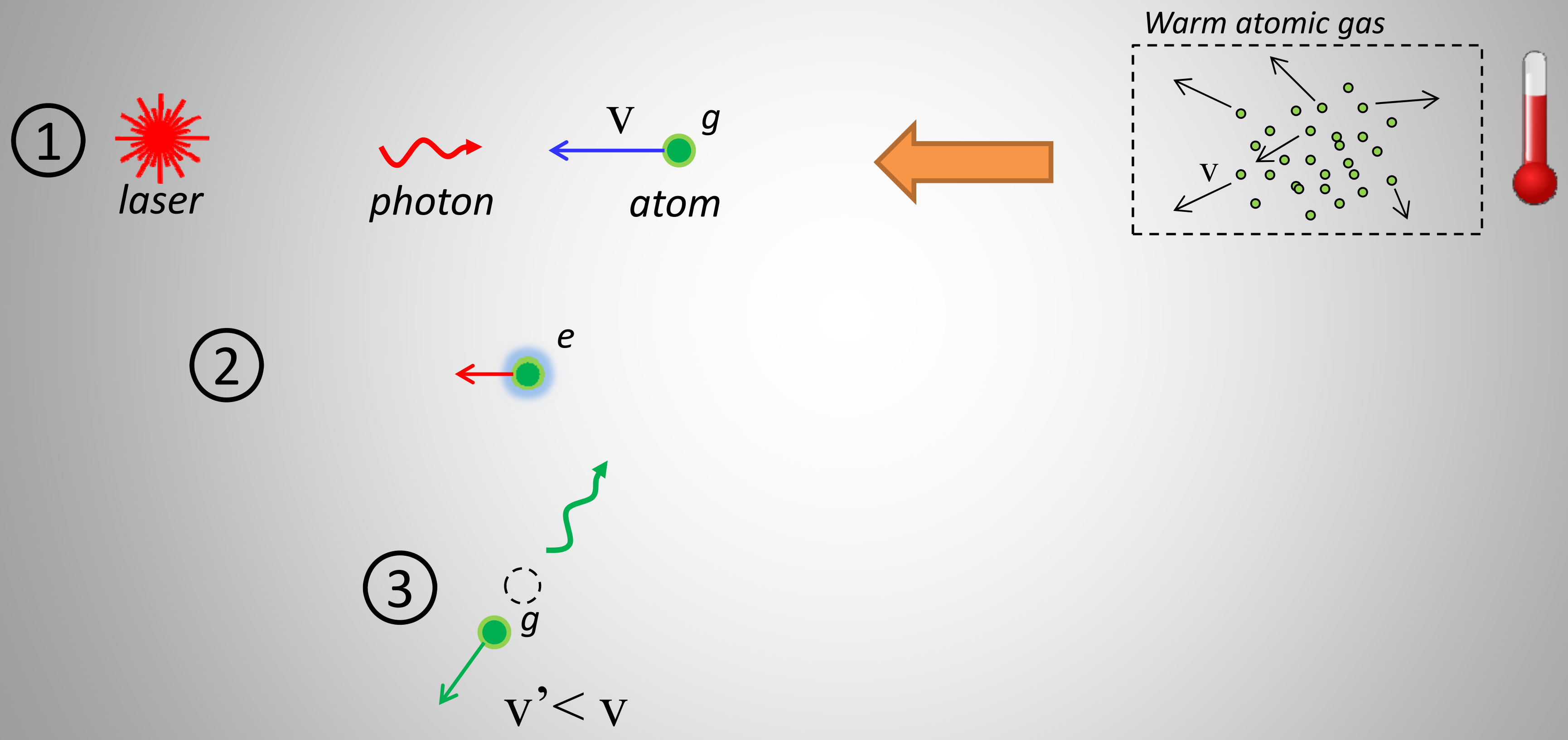


Principle of optical cooling

Doppler cooling

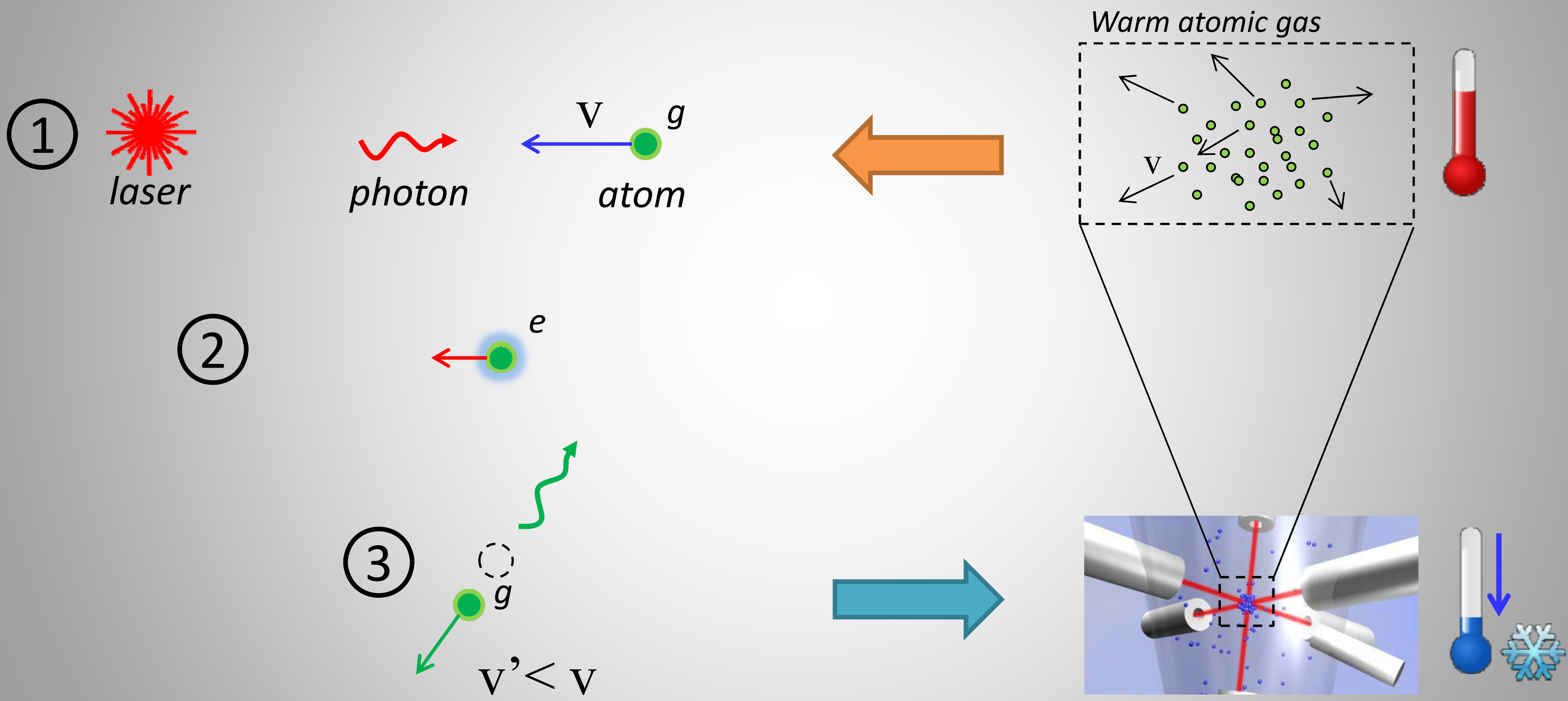
Cooling the <u>translational</u> degrees of freedom



Principle of optical cooling

Doppler cooling

Cooling the <u>translational</u> degrees of freedom

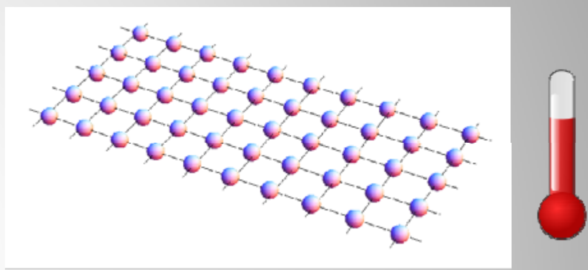


Schematic arrangement of a doppler cooling setup

Principle of optical cooling

Cooling by anti-Stokes fluorescence (ASF)

Cooling the vibrational degrees of freedom

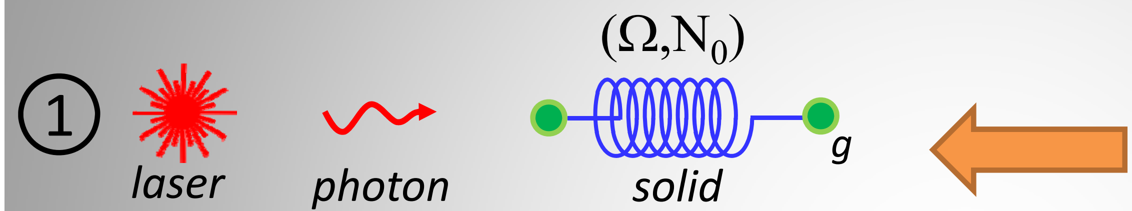


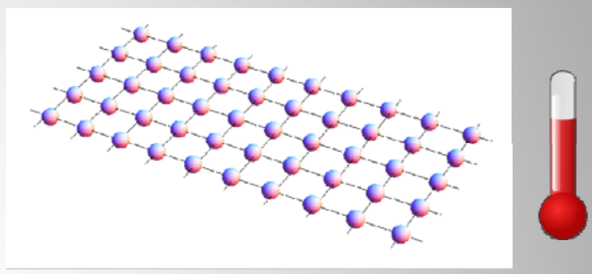
Thermal vibrations (phonons) in a solid

Principle of optical cooling

Cooling by anti-Stokes fluorescence (ASF)

Cooling the vibrational degrees of freedom





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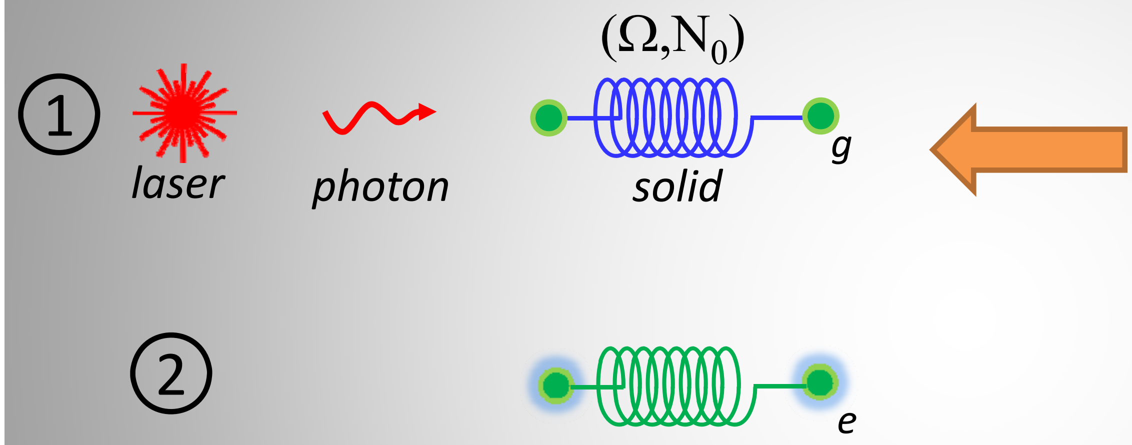
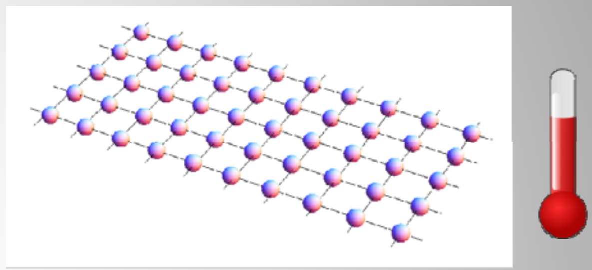


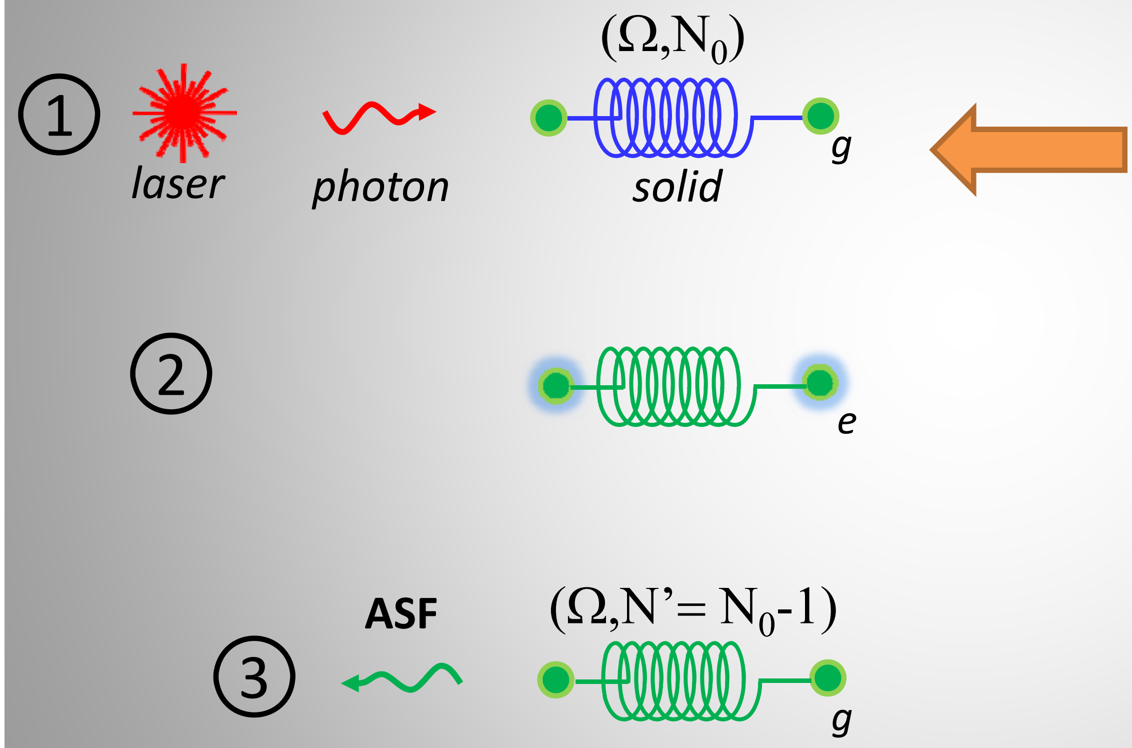


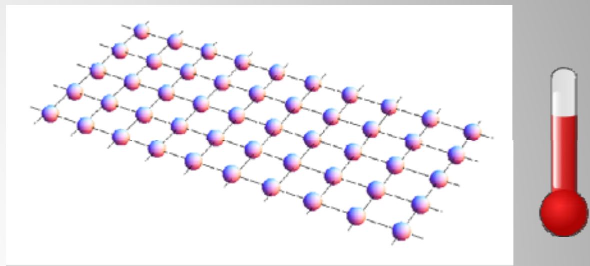
Thermal vibrations (phonons) in a solid

Principle of optical cooling

Cooling by anti-Stokes fluorescence (ASF)

Cooling the <u>vibrational</u> degrees of freedom





Thermal vibrations (phonons) in a solid

Principle of optical cooling

Cooling by anti-Stokes fluorescence (ASF)

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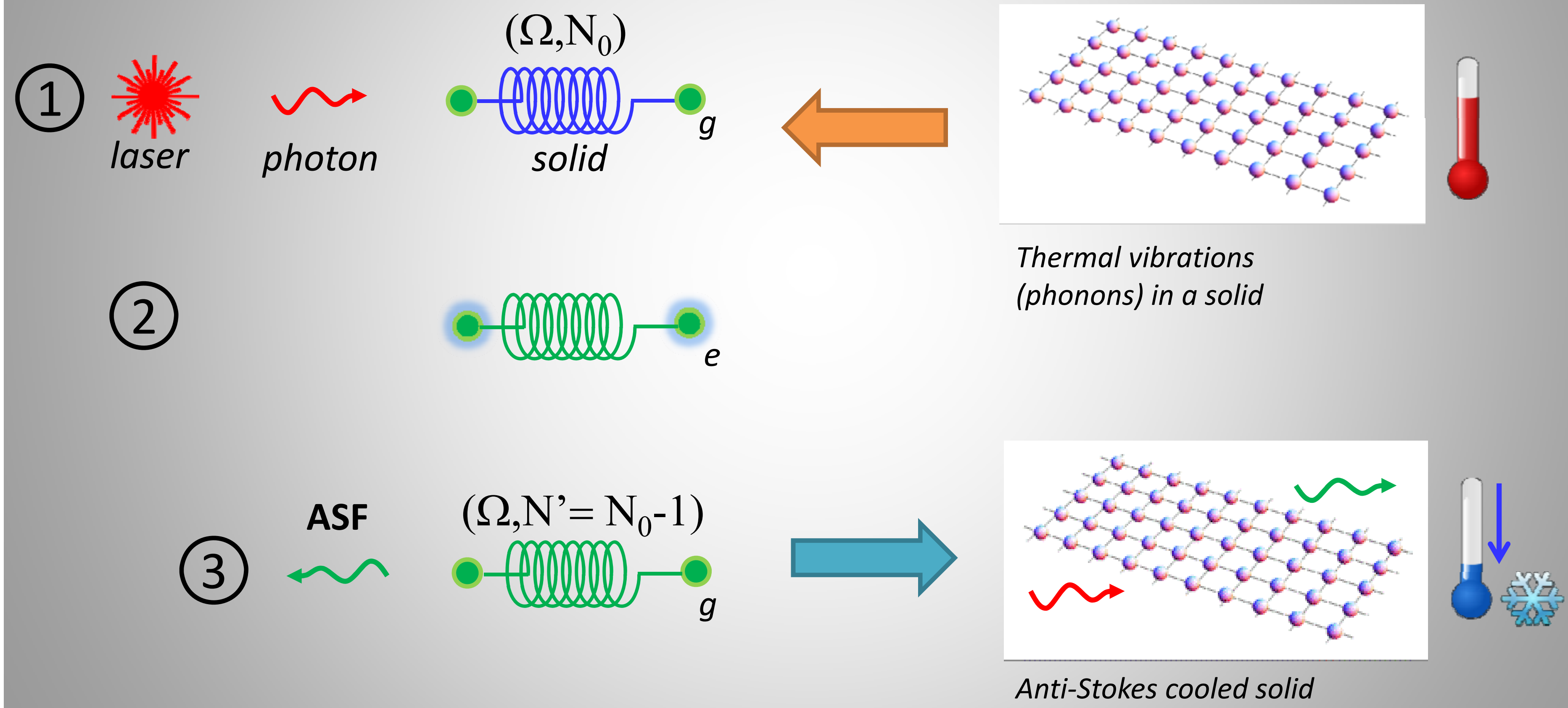
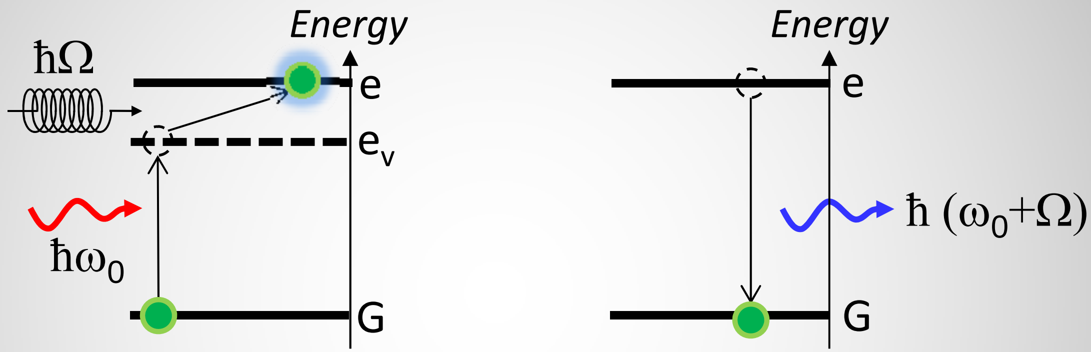
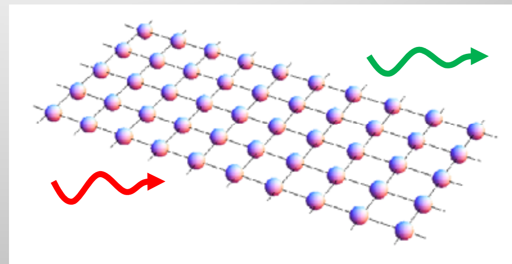


Principle of optical cooling

1- Anti-Stokes fluorescence mechanism

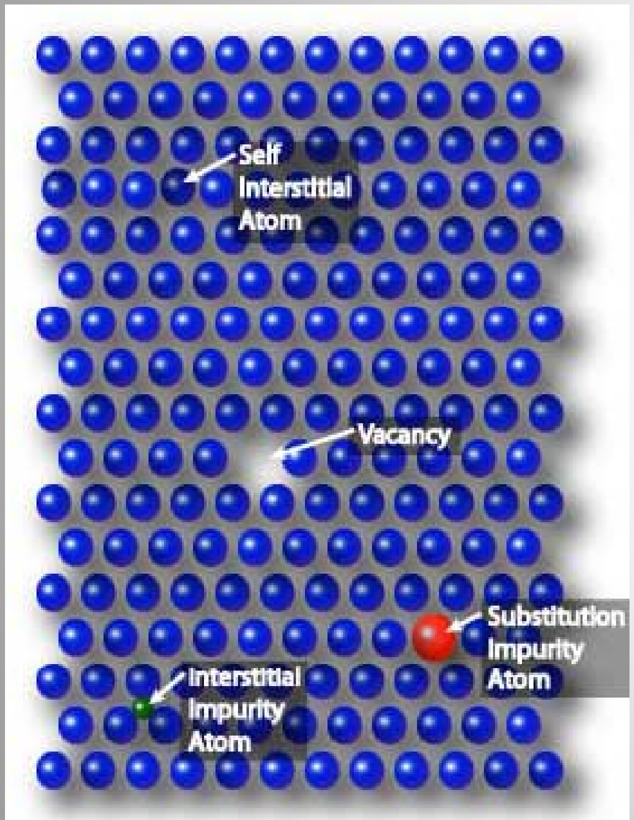


Removes **ħΩ** per scattering event from the thermal phonons bath



Principle of optical cooling

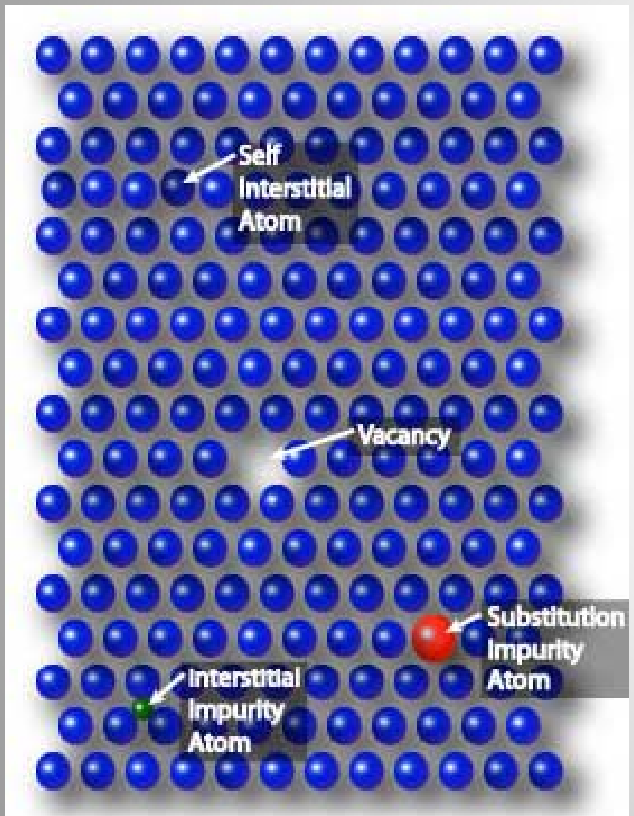
Realistic solids have defects



Credit: NDT Education Resource Center

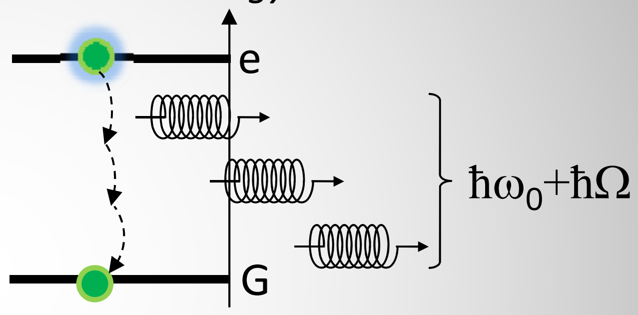
Principle of optical cooling

Realistic solids have defects

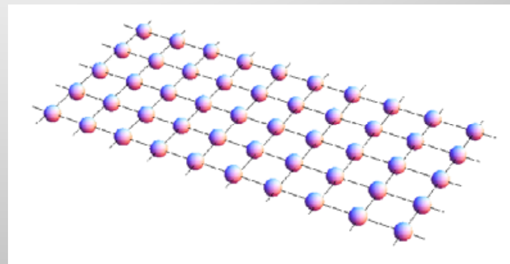


Credit: NDT Education Resource Center

2- Non-radiative recombination



Adds $\hbar\omega_0$ per scattering event to the thermal phonons bath



Vibrations (phonons) in a lattice

Requirements to achieve net cooling power in solids

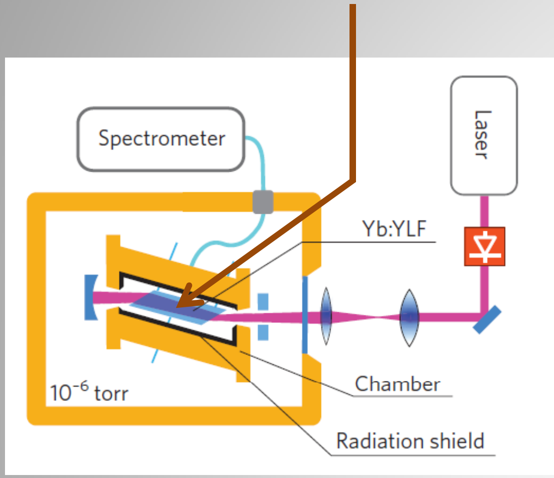
To achieve  power in solids you need :

→ **Largest possible quantum efficiency η**

→ **Largest possible oscillator strength f**
i.e. short radiative lifetime τ of e

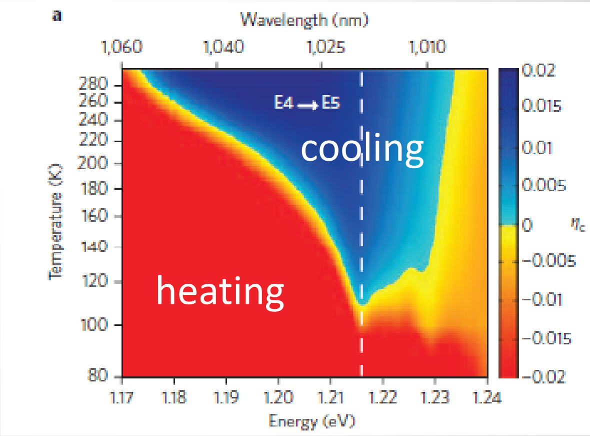
atoms embedded in solid matrix

Ytterbium dopped glass



Setup for optical cooling of a $LiYF_4$:Yb rod [1]

- **Excellent** η
- Poor f
- Coupling with phonons is of 2nd order



Cooling efficiency in $LiYF_4$:Yb under optical cooling [1]

From room temperature down to T~110K [2]

[1] D. V. Seletskiy *et al.* Nature Photonics **4** 161 (2010)
[2] D. V. Seletskiy *et al.* Optics Express **19**, 18229 (2011)

Semiconductor hetero/nanostructures

CdS nanobelts

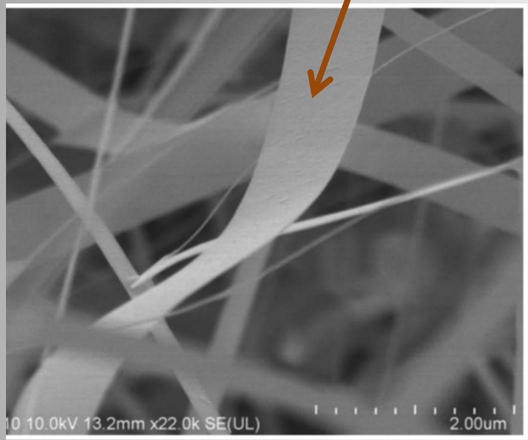
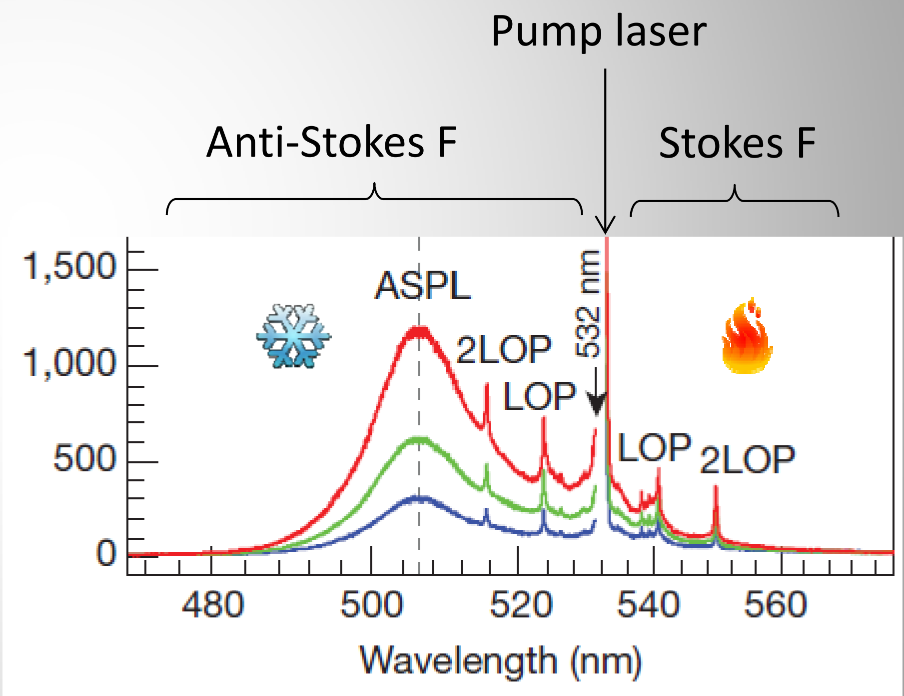


image credit: L. Li *et al.* Sensors **14**, 7332 (2014)

- Lower η
- **larger *f*** (excitonic enhancement [4])
- Coupling with phonons is of 2[nd] order

From room temperature down to T~260K [3]



Raman spectra of a single CdS nanobelt: from ref [3]

[3] J. Zhang et al. , Nature **493**, 504-508 (2013)
[4] G. Rupper et al. Phys. Rev. Lett. **97** 117401 (2006)

Outline

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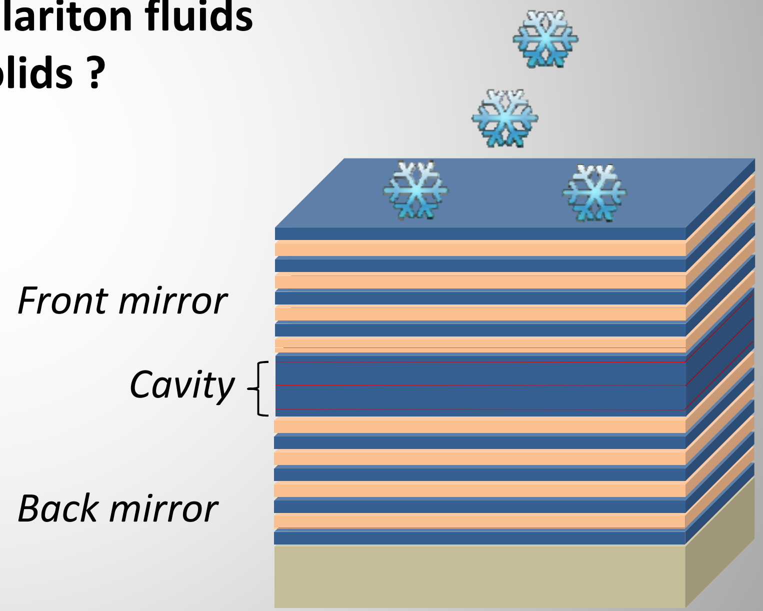
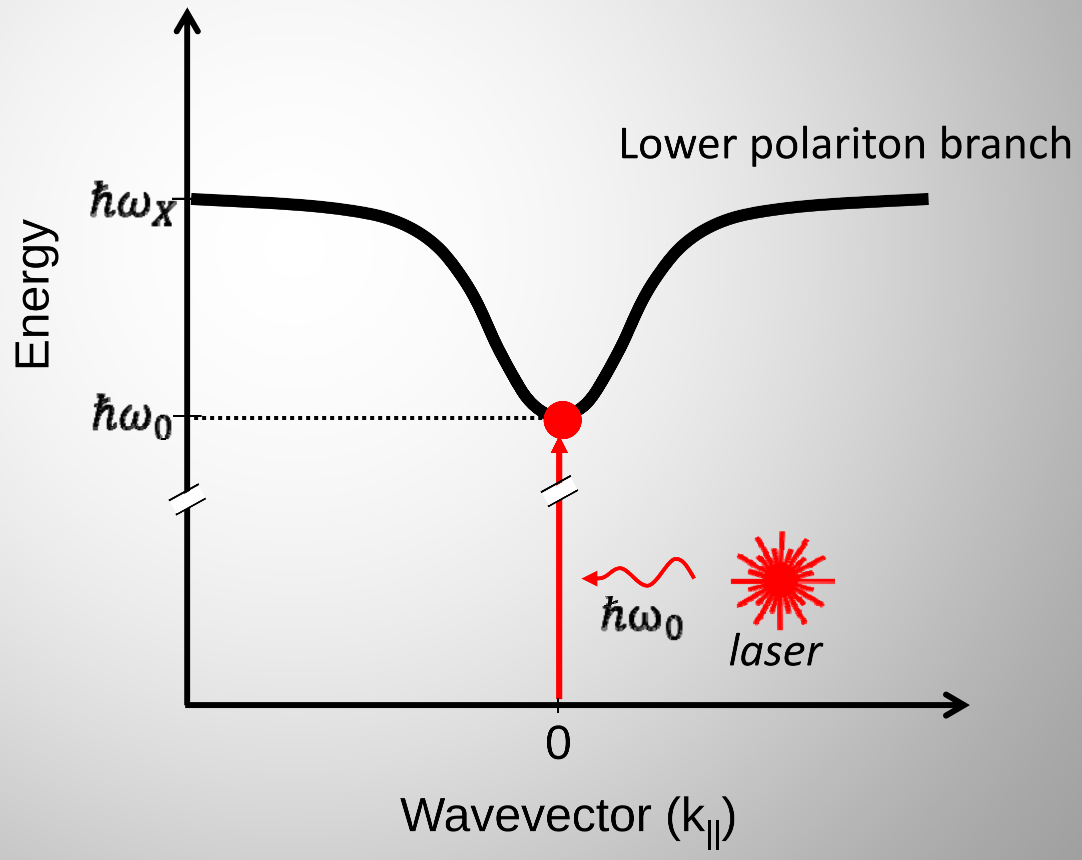


Microcavity in the strong coupling regime

Cooling a solid-state μ-cavity with polaritons

Polariton anti-Stokes fluorescence

Principle :



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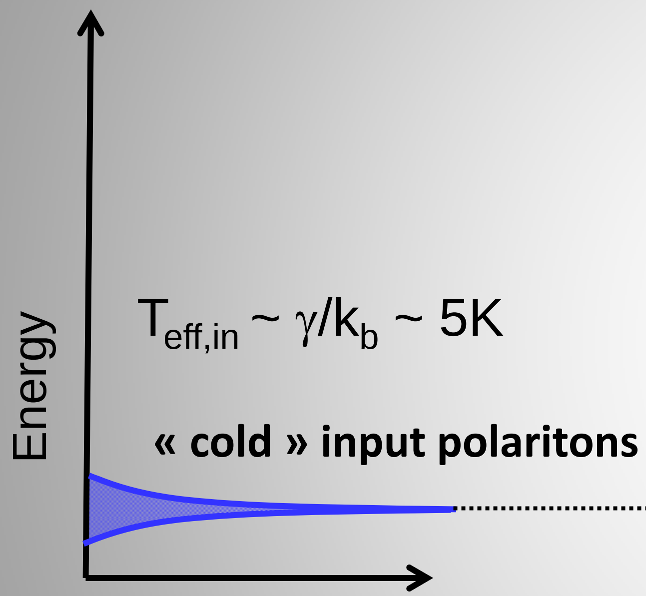
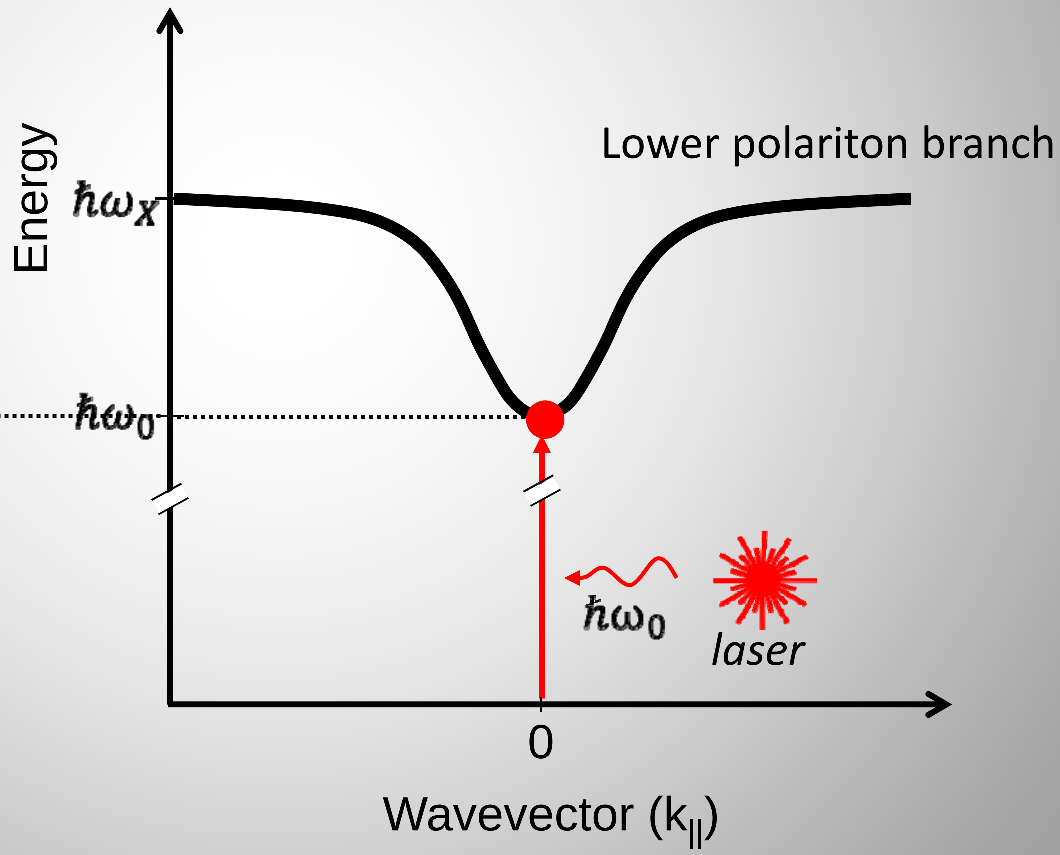


Input polariton distribution

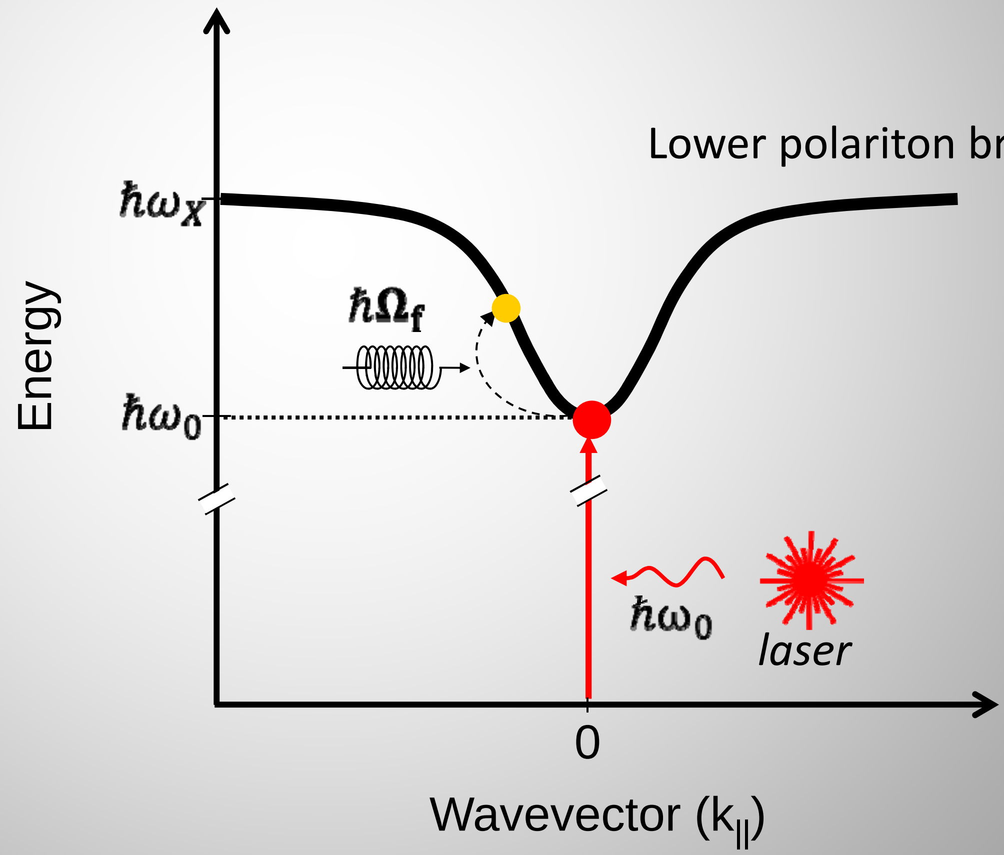
Polariton anti-Stokes fluorescence
Principle :



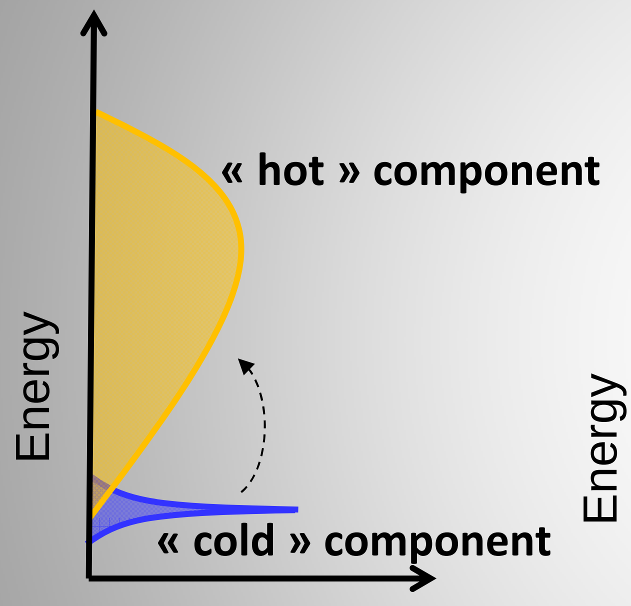
Cooling a solid-state µ-cavity with polaritons

Polariton anti-Stokes fluorescence

Principle :



Cooling a solid-state μ-cavity with polaritons

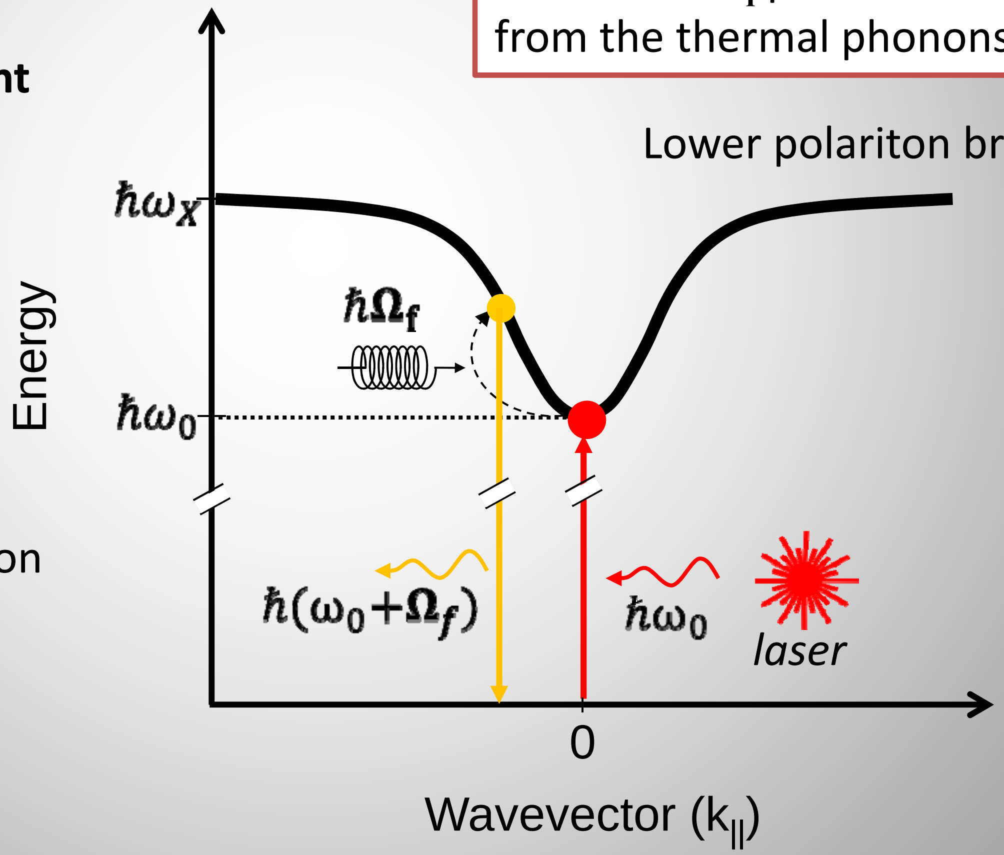


Output polariton distribution

Polariton anti-Stokes fluorescence

Principle :

Removes $\hbar\Omega_f$ per scattering event from the thermal phonons bath

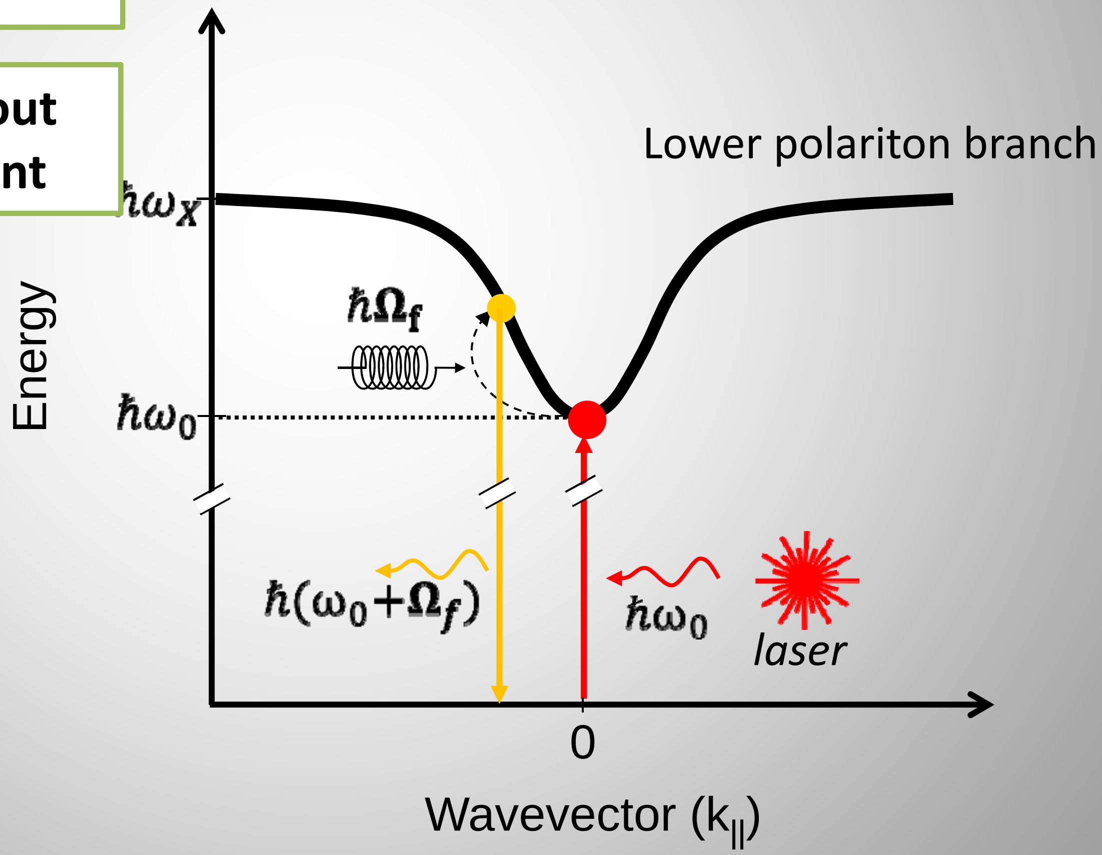


Cooling a solid-state μ-cavity with polaritons

- **Excitonic fraction**

→Large, **1st order coupling** with phonons [5]

→**Expt. Realization of an out of equilibrium refrigerant**

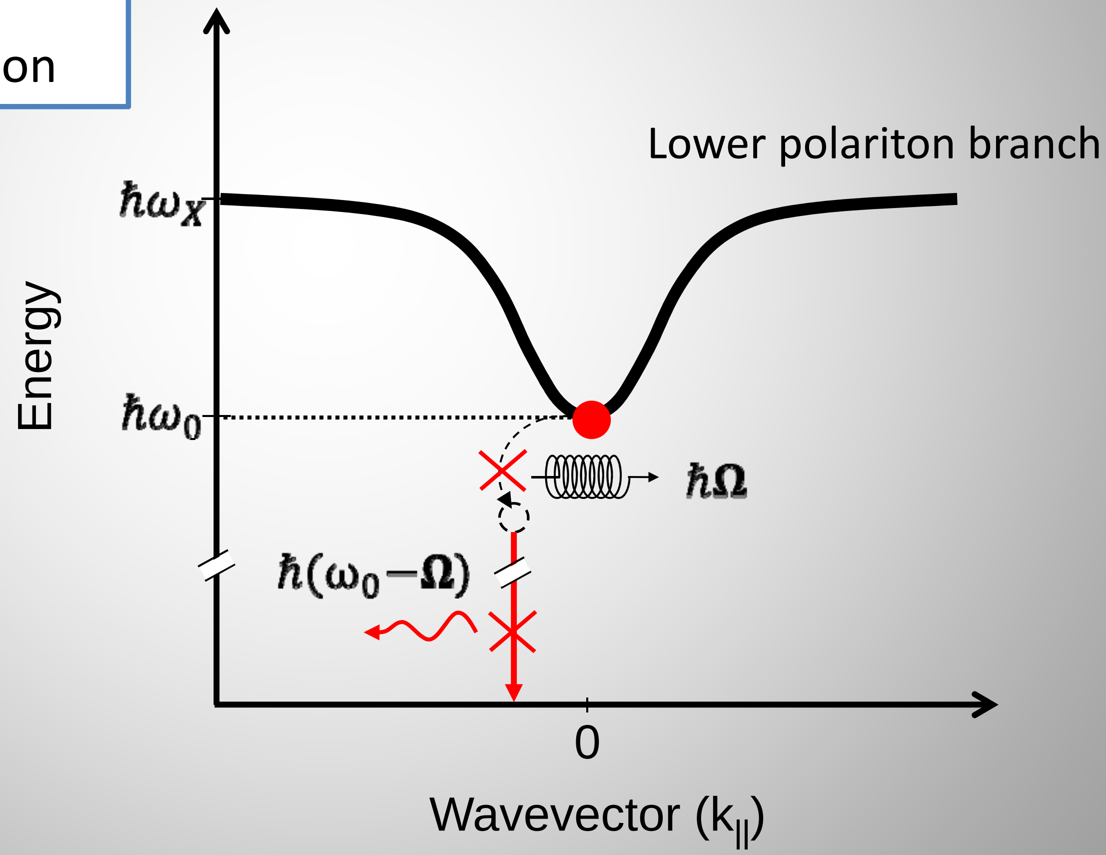


[5] G. Rozas *et al.* arXiv:1405.0886 (2014)

Cooling a solid-state μ-cavity with polaritons

- **Polaritonic dispersion**

→quenched Stokes emission



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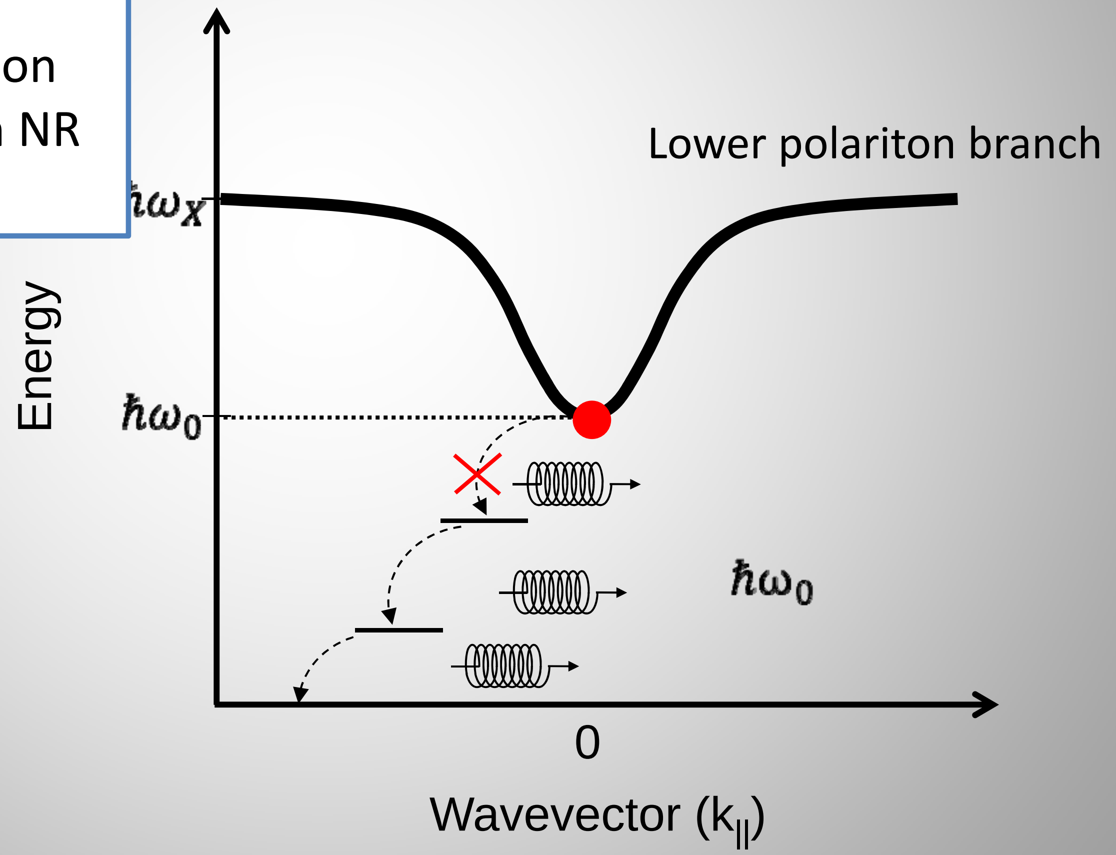
Cooling a solid-state μ-cavity with polaritons

- **Polaritonic dispersion**

→quenched Stokes emission
→quenched coupling with NR point defects

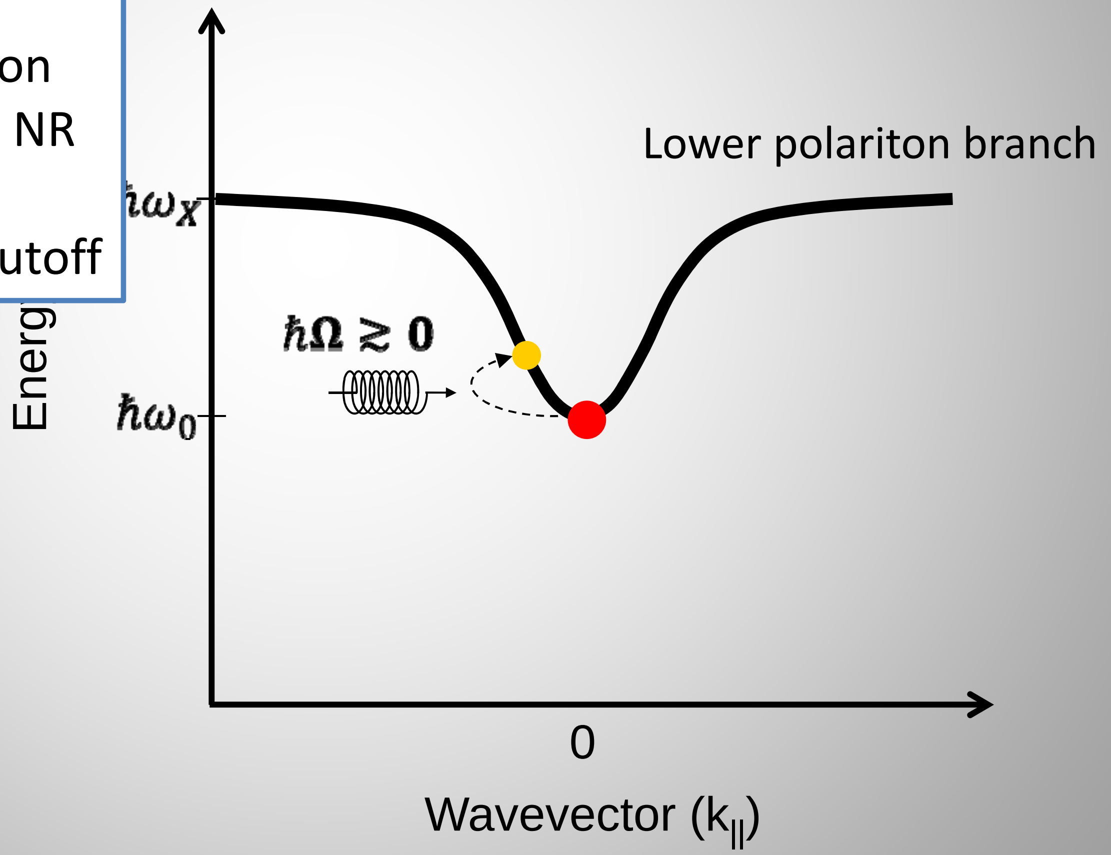


[5] G. Rozas *et al.* arXiv:1405.0886 (2014)

Cooling a solid-state μ-cavity with polaritons

- **Polaritonic dispersion**

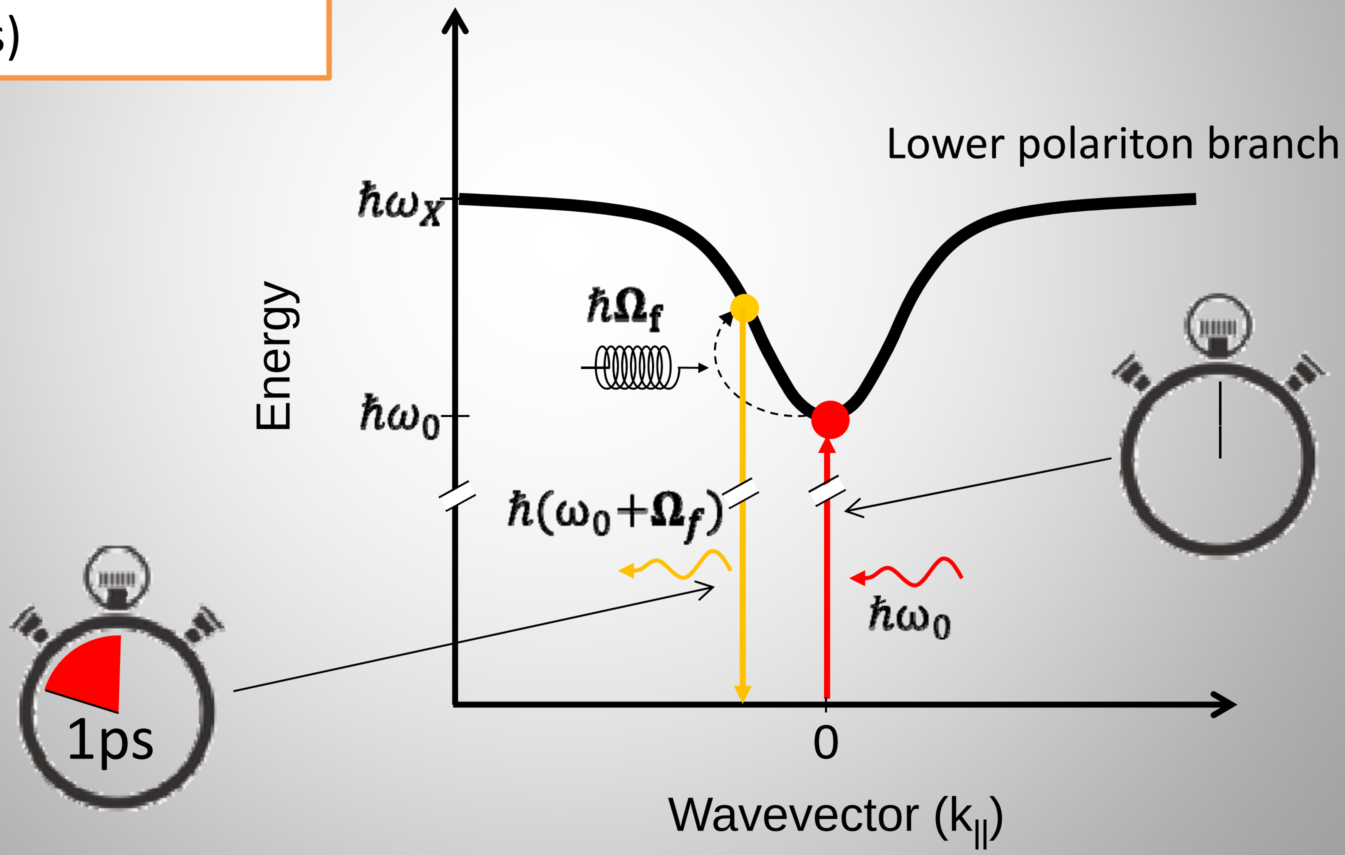
→quenched Stokes emission
→quenched coupling with NR point defects
→~ No low temperature cutoff



Cooling a solid-state μ-cavity with polaritons

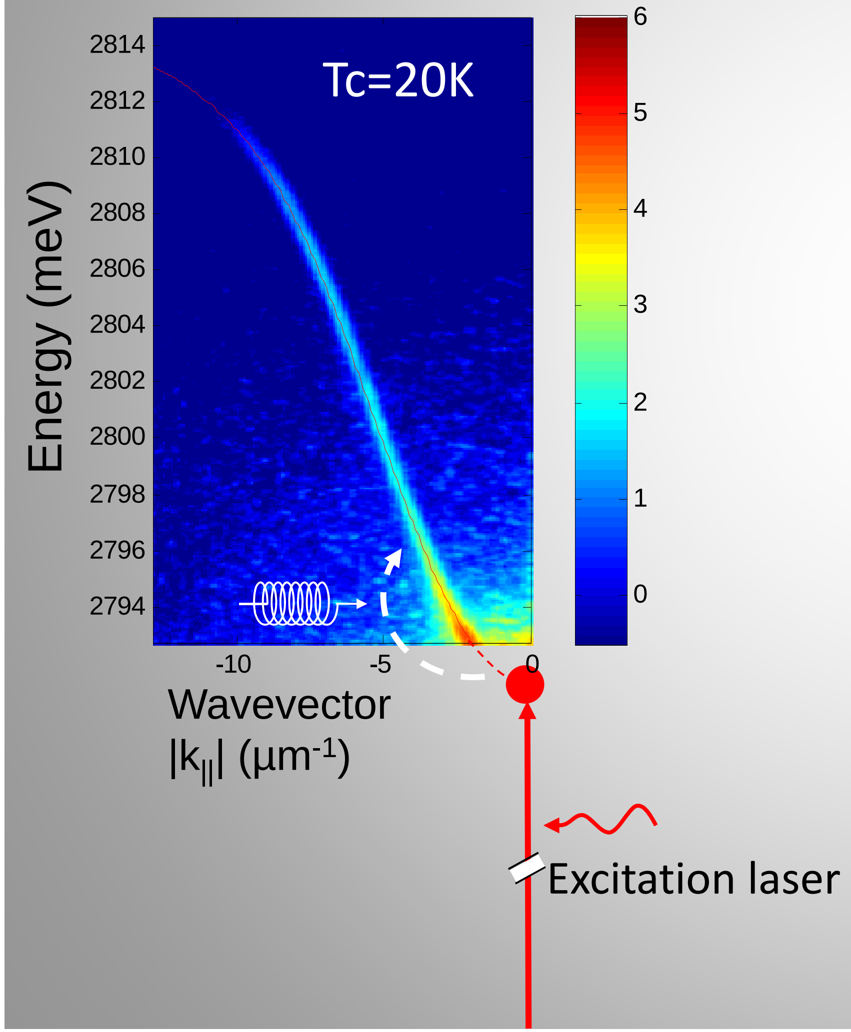
- **Photonic fraction**

→ **Extra short** radiative lifetime, i.e. ultrafast cooling dynamics (~1ps)



anti-Stokes fluorescence of polaritons

Measured ASF intensity cts/s (log scale)



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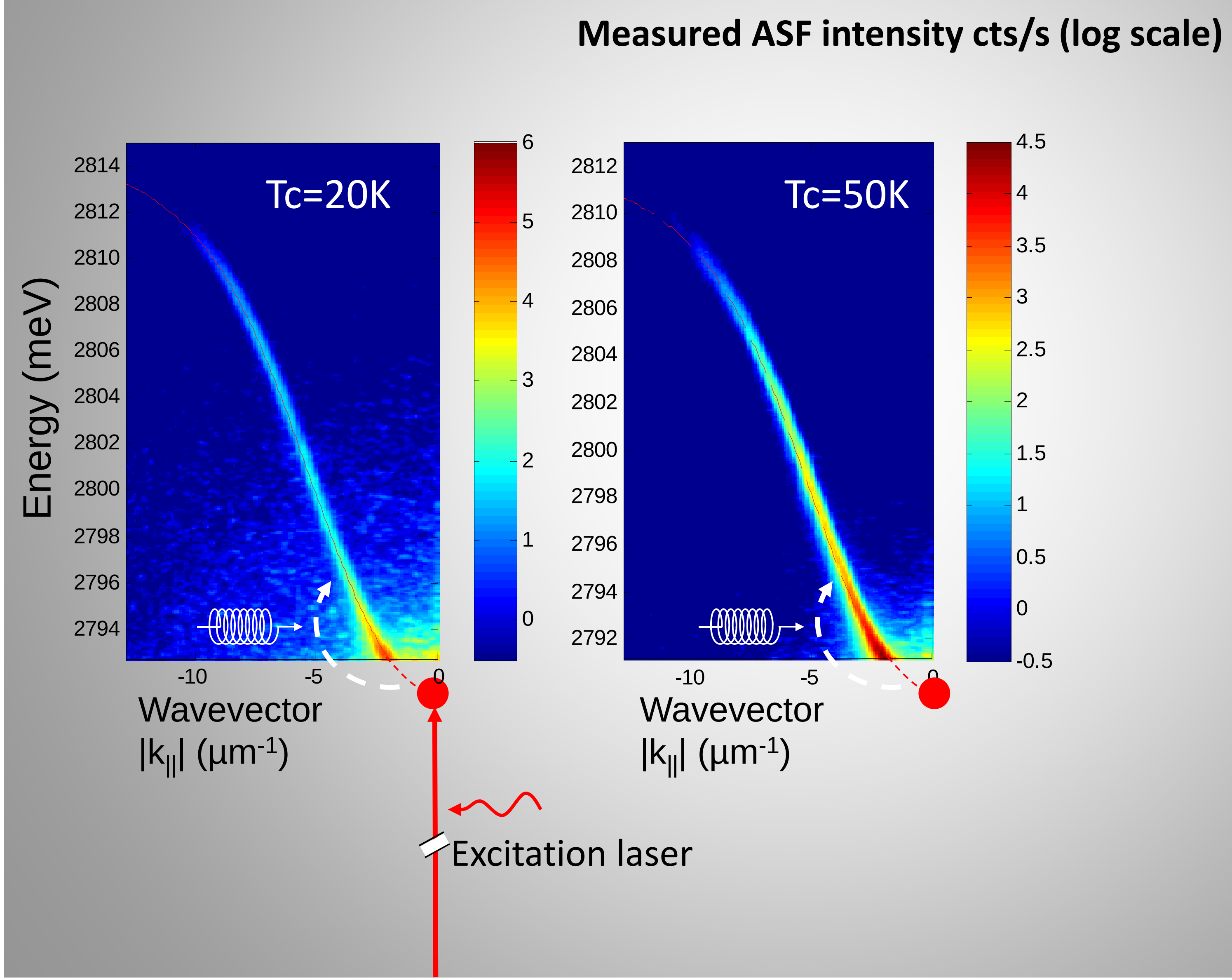

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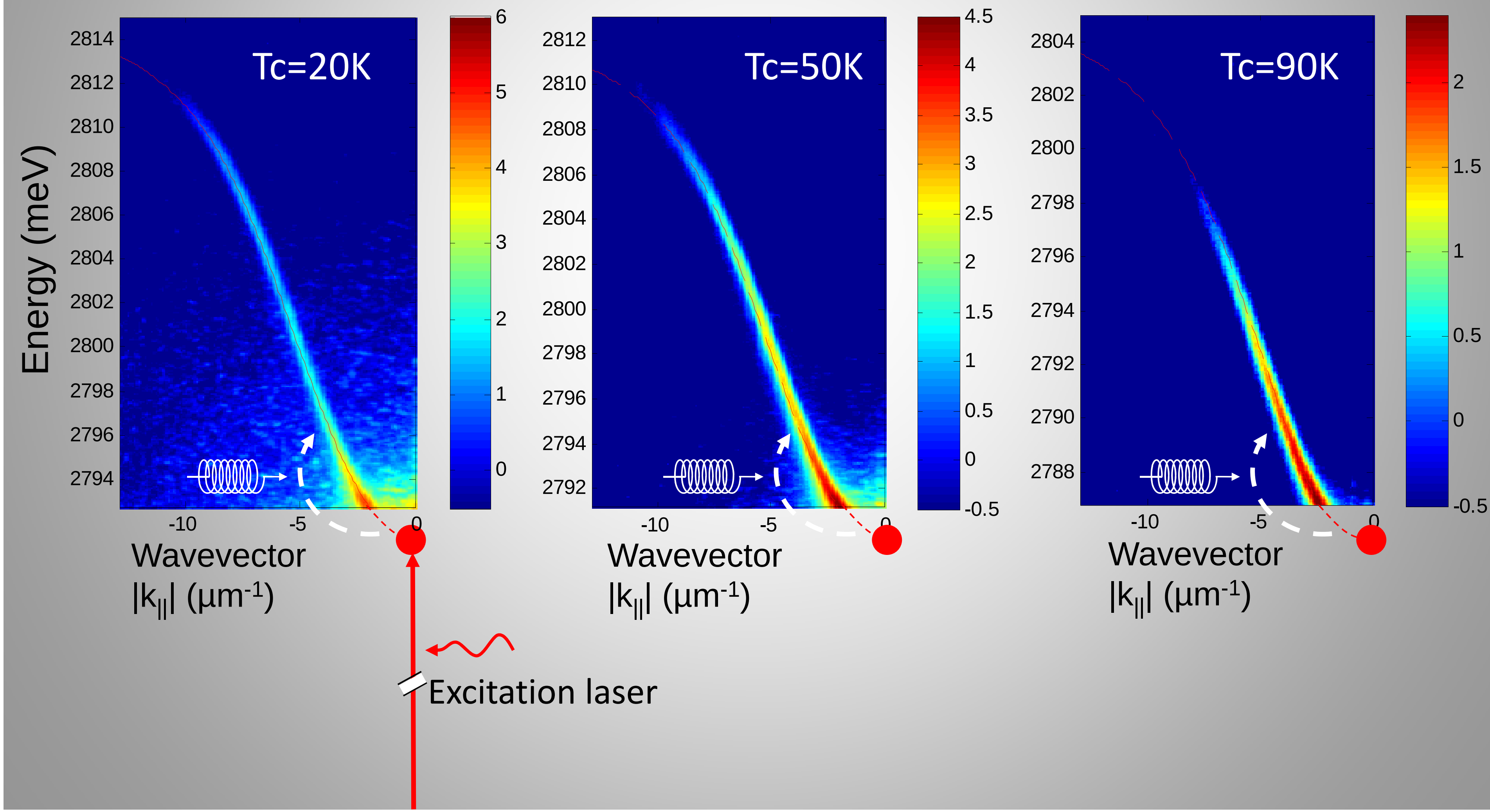

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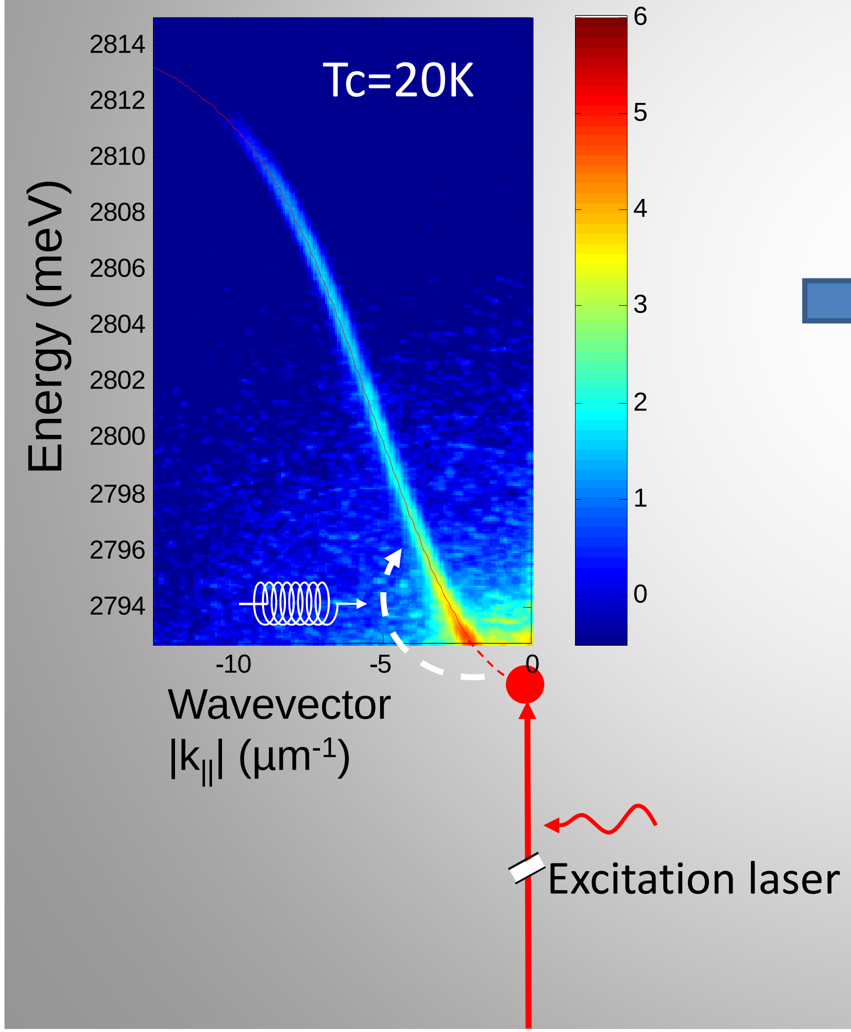
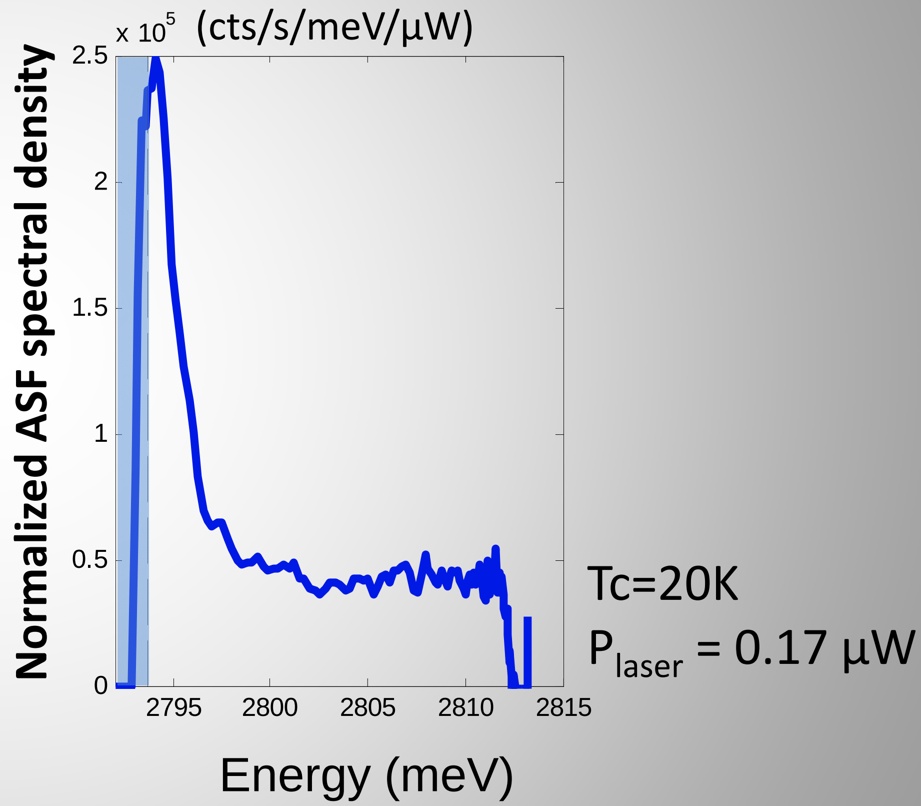
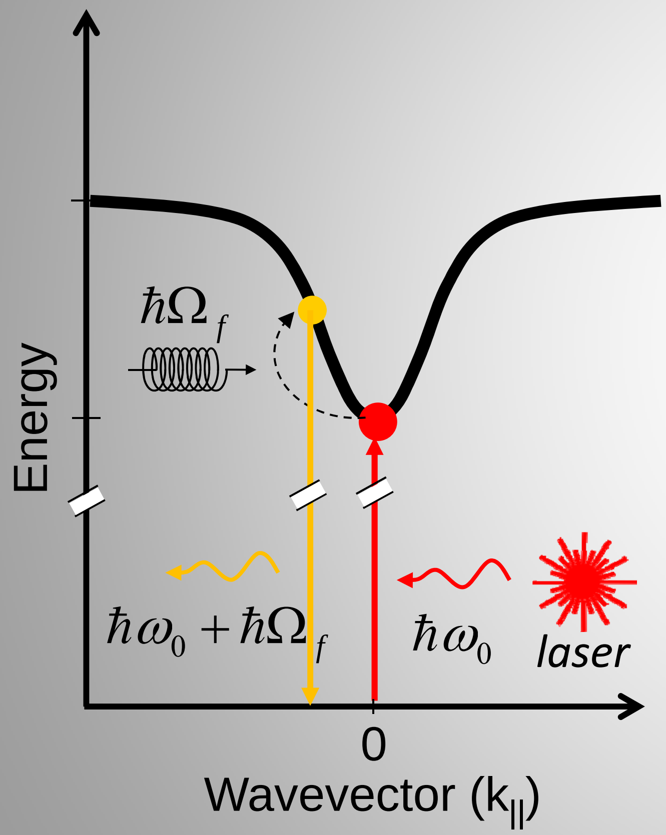
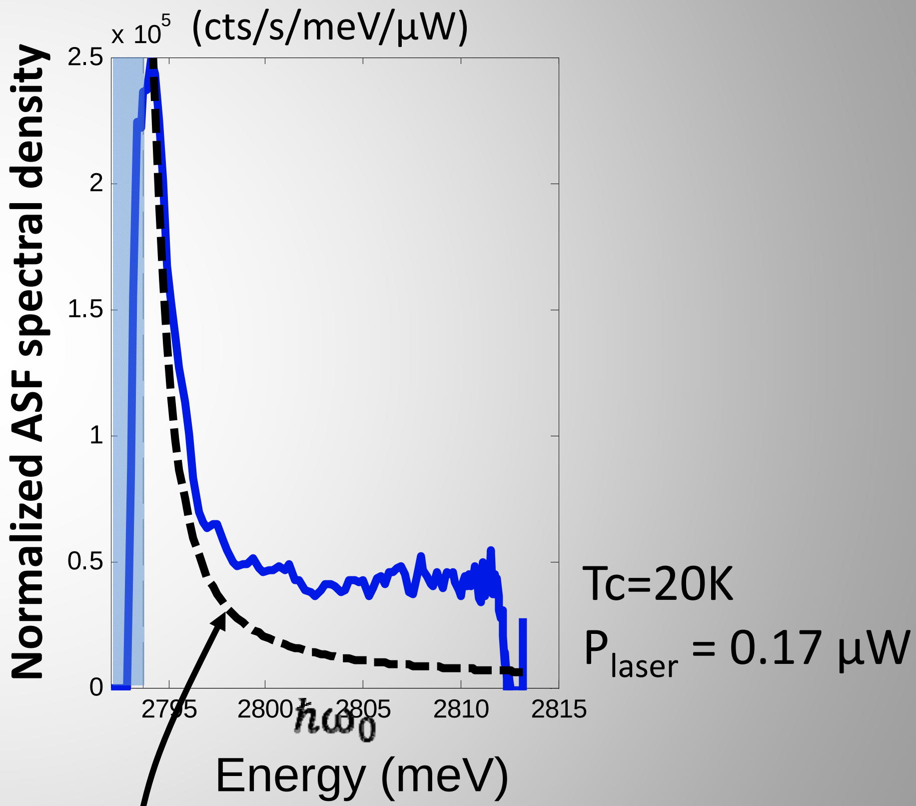




anti-Stokes fluorescence of polaritons

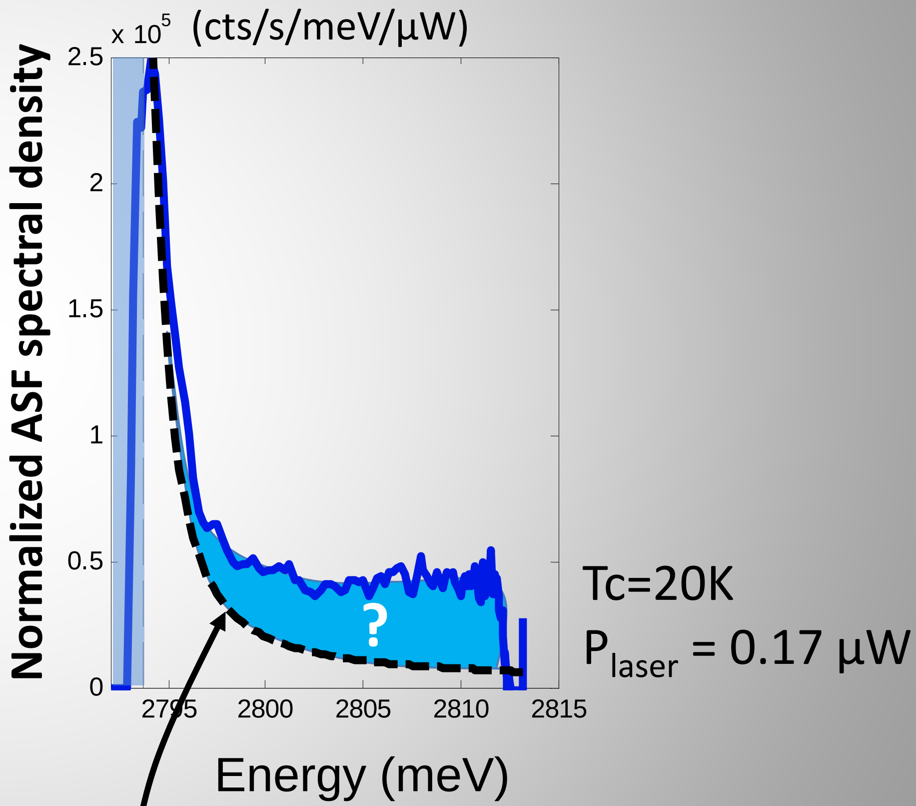
Fast cooling mechanism





Theoretical calculation of the **fast** ASF spectrum (FG rule)

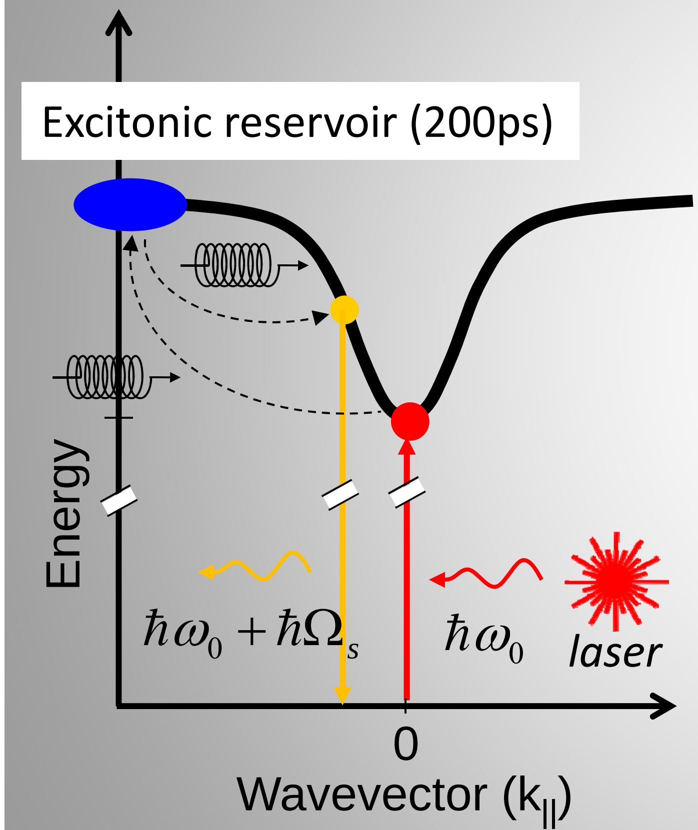
anti-Stokes fluorescence of polaritons

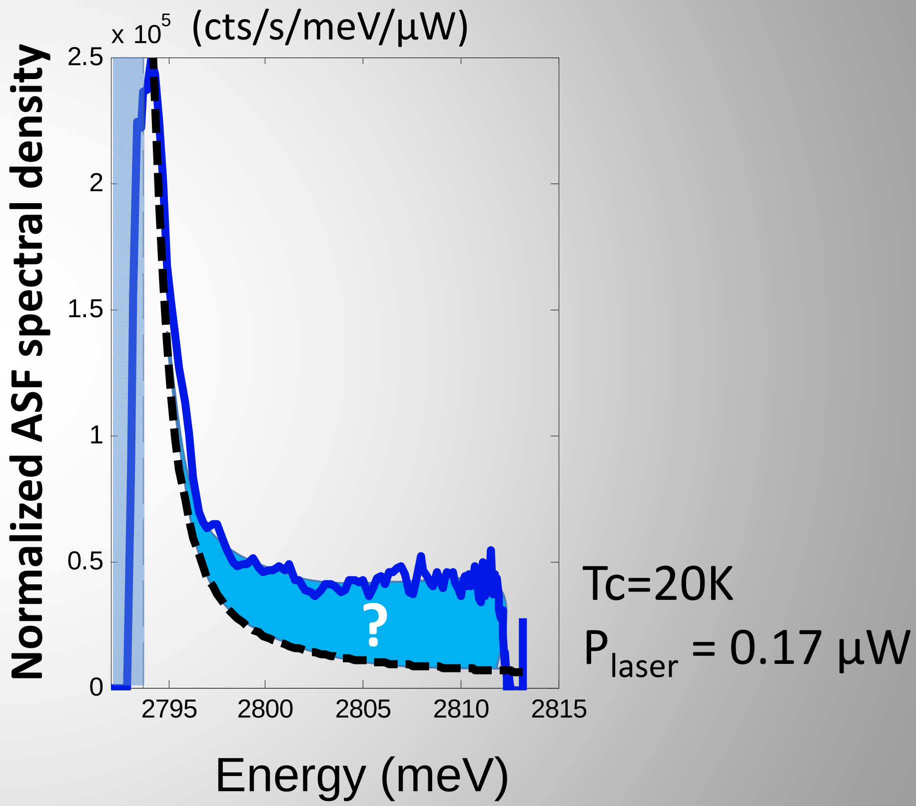


Theoretical calculation of the « fast » ASF spectrum (FG rule)

anti-Stokes fluorescence of polaritons

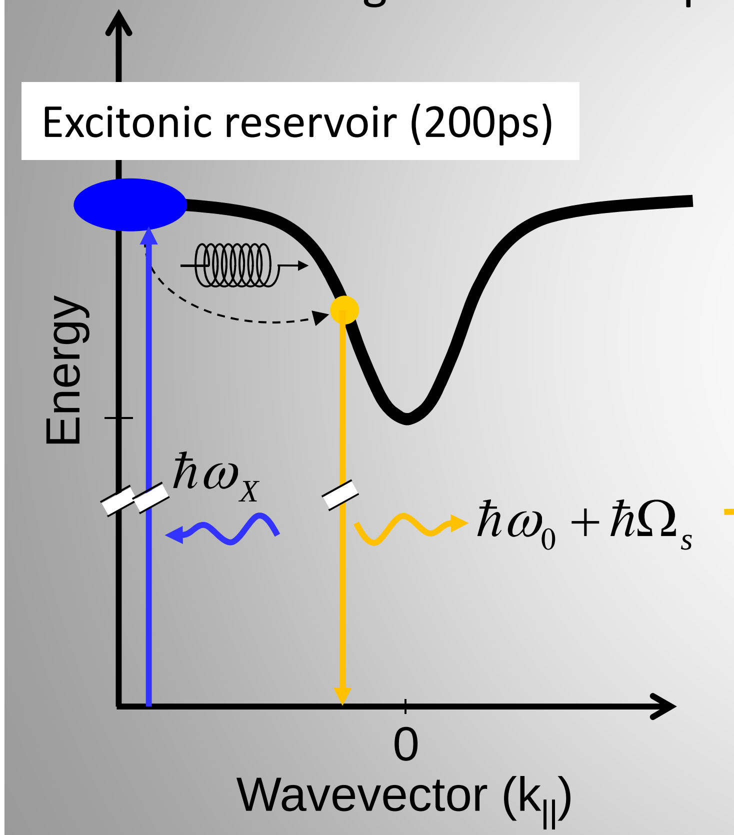
Slow cooling mechanism

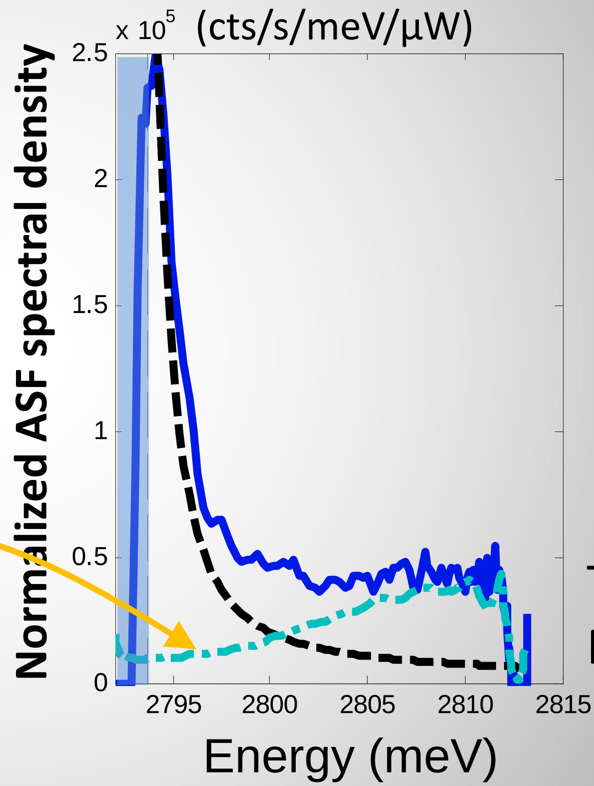




anti-Stokes fluorescence of polaritons

Measurement of the **Slow** cooling mechanism spectrum



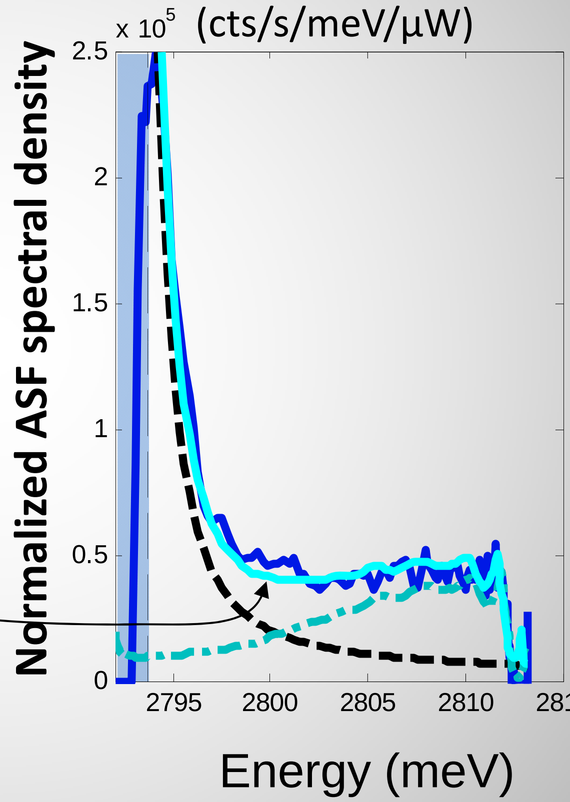


Tc=20K

P_{laser} = 0.17 µW

anti-Stokes fluorescence of polaritons

Fast + **Slow** cooling mechanisms



Tc=20K

P_{laser} = 0.17 µW

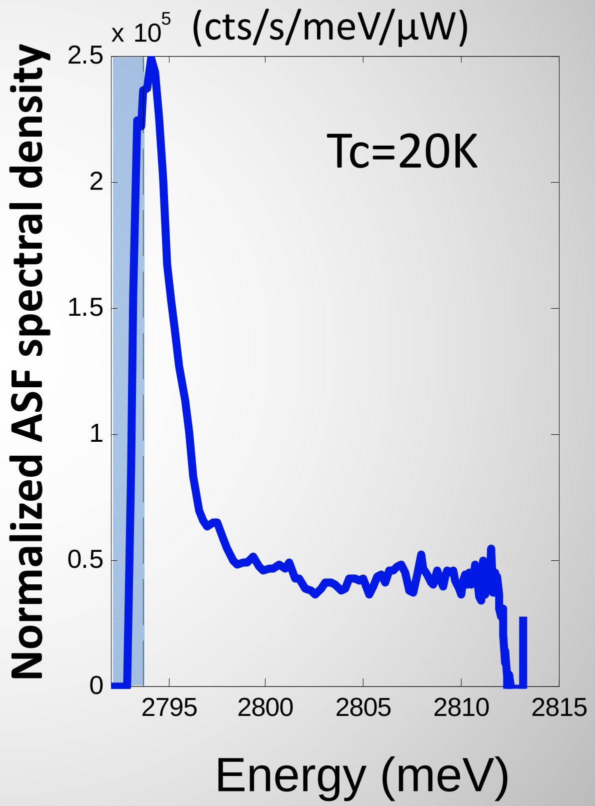
anti-Stokes fluorescence of polaritons

Laser power dependence

$\propto P_{las}$

P_{laser} = 0.17 µW

I_{las} / P_{las}



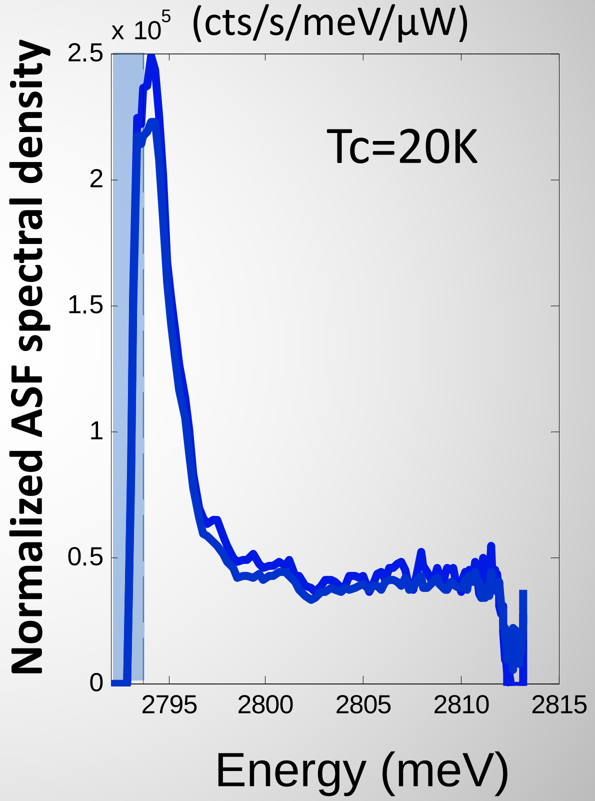
anti-Stokes fluorescence of polaritons

$$I_{las} / P_{las}$$

Laser power dependence

$$\propto P_{las}$$

P_{laser} = 0.31 μW
P_{laser} = 0.17 μW



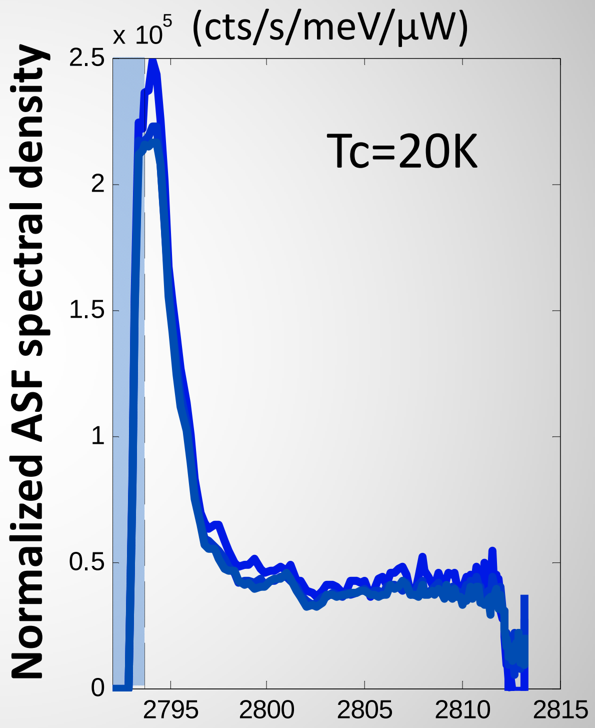
anti-Stokes fluorescence of polaritons

$$I_{las}/P_{las}$$

Laser power dependence

$$\propto P_{las}$$

P_{laser} = 0.48 µW
P_{laser} = 0.31 µW
P_{laser} = 0.17 µW



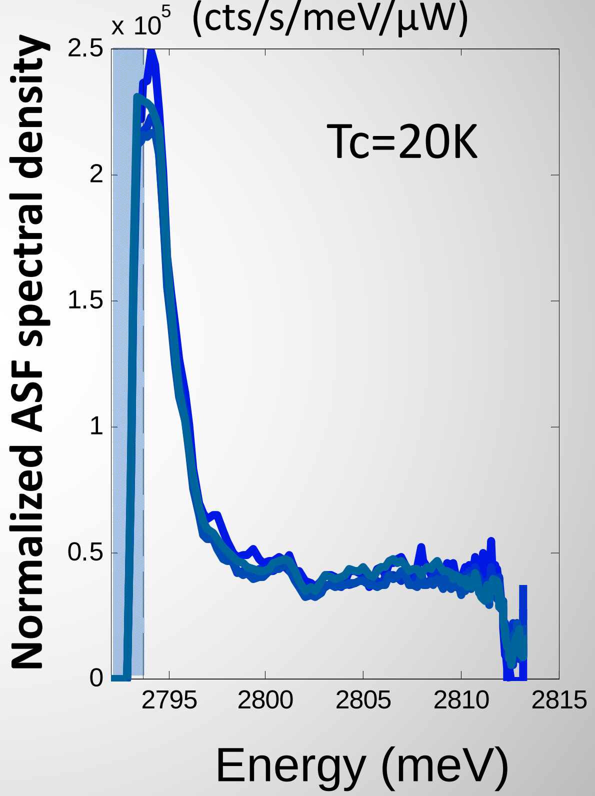
anti-Stokes fluorescence of polaritons

Laser power dependence

$\propto P_{las}$

P_{laser} = 1.26 µW
P_{laser} = 0.48 µW
P_{laser} = 0.31 µW
P_{laser} = 0.17 µW

I_{las} / P_{las}



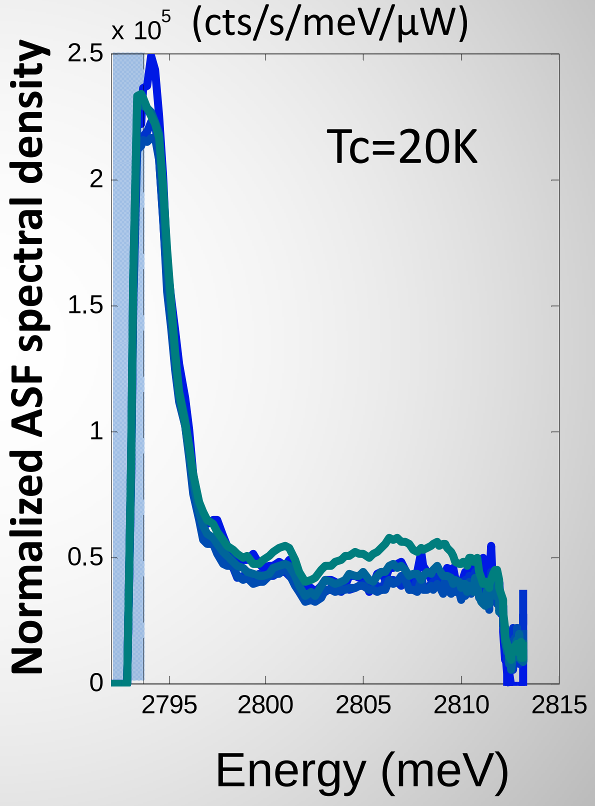
anti-Stokes fluorescence of polaritons

Laser power dependence

$\propto P_{las}^2$

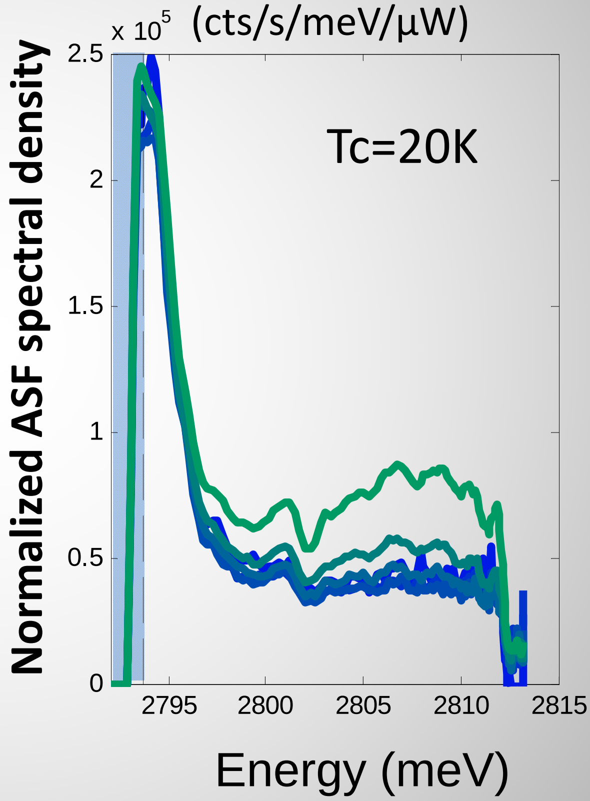
P_{laser} = 3.30 µW

I_{las} / P_{las}



anti-Stokes fluorescence of polaritons

$$I_{las} / P_{las}$$



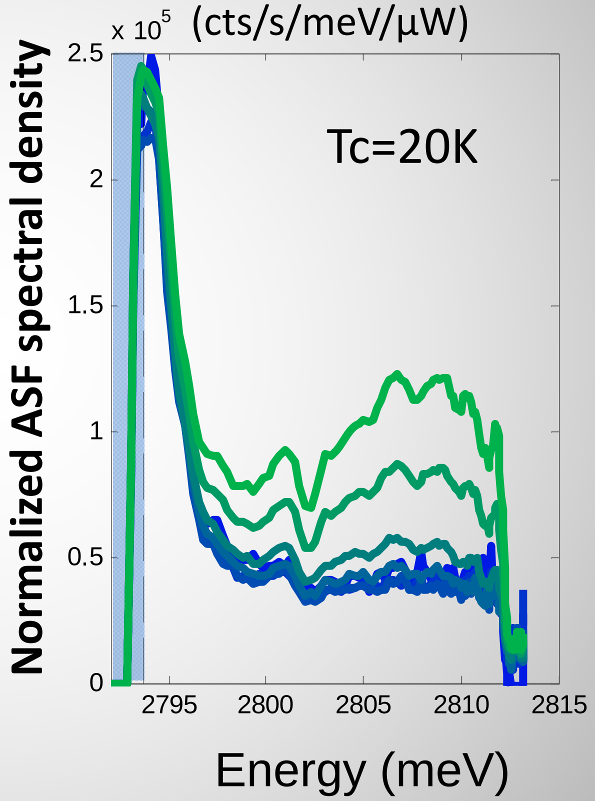
Laser power dependence

$$\propto P_{las}^2$$

P_{laser} = 3.30 µW
P_{laser} = 11.16 µW

anti-Stokes fluorescence of polaritons

$$I_{las} / P_{las}$$



Laser power dependence

$$\propto P_{las}^2$$

P_{laser} = 3.30 µW
P_{laser} = 11.16 µW
P_{laser} = 26.20 µW

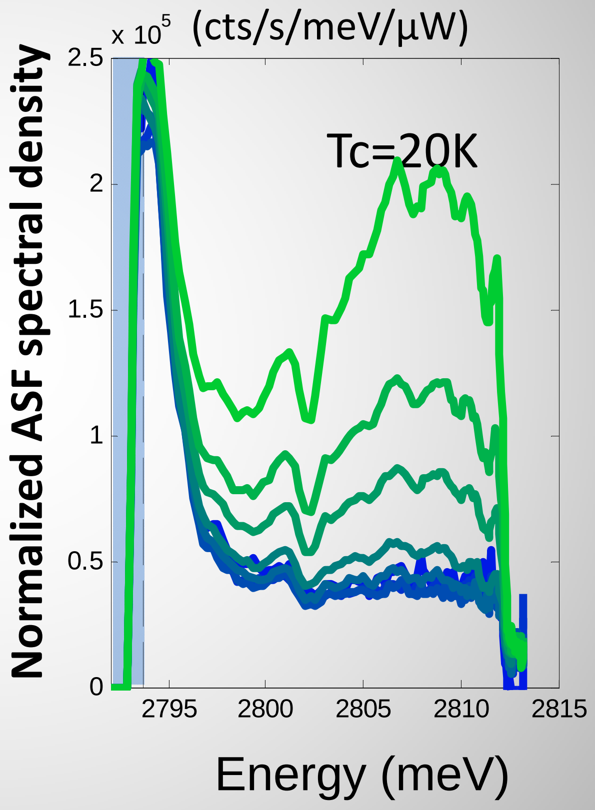
anti-Stokes fluorescence of polaritons

Laser power dependence

$$\propto P_{las}^2$$

P_{laser} = 3.30 μW
P_{laser} = 11.16 μW
P_{laser} = 26.20 μW
P_{laser} = 83.71 μW

$$I_{las} / P_{las}$$

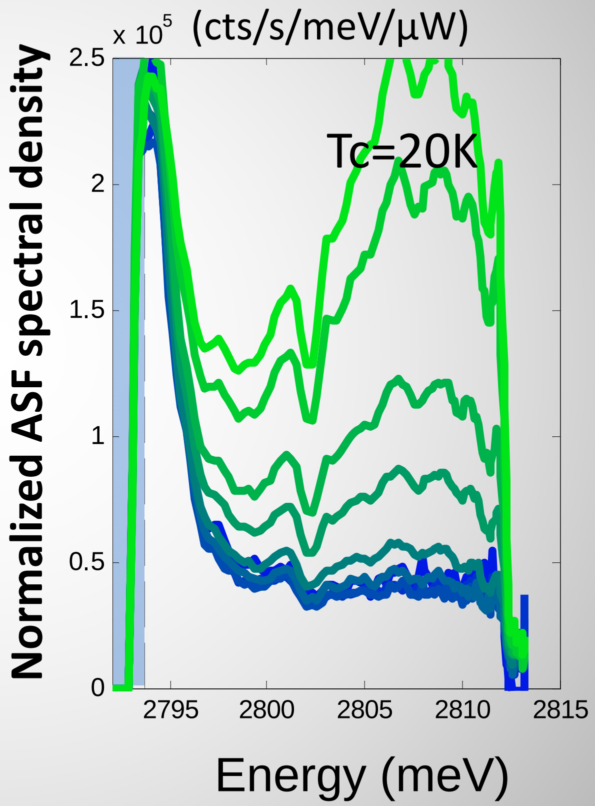


anti-Stokes fluorescence of polaritons

$$I_{las}/P_{las}$$

Laser power dependence

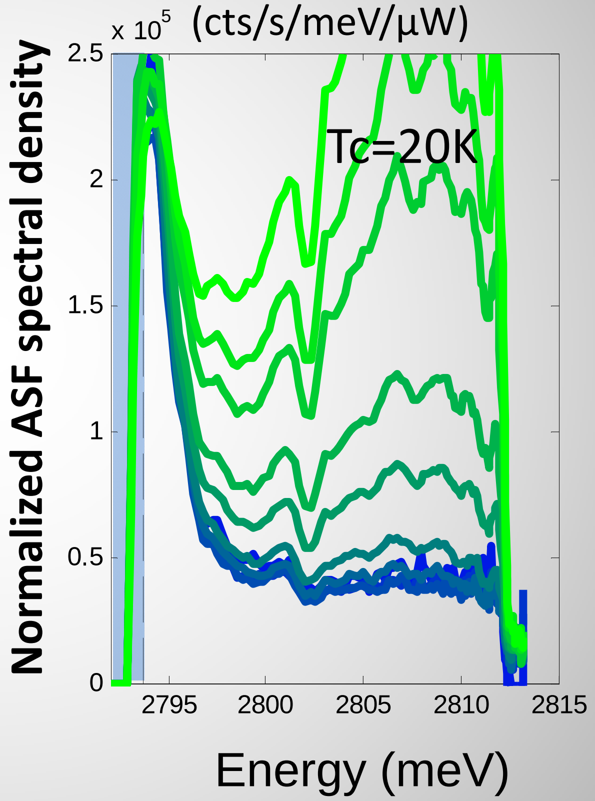
$$\propto P_{las}^2$$



P_{laser} = 3.30 µW
P_{laser} = 11.16 µW
P_{laser} = 26.20 µW
P_{laser} = 83.71 µW
P_{laser} = 196.53 µW

anti-Stokes fluorescence of polaritons

$$I_{las}/P_{las}$$

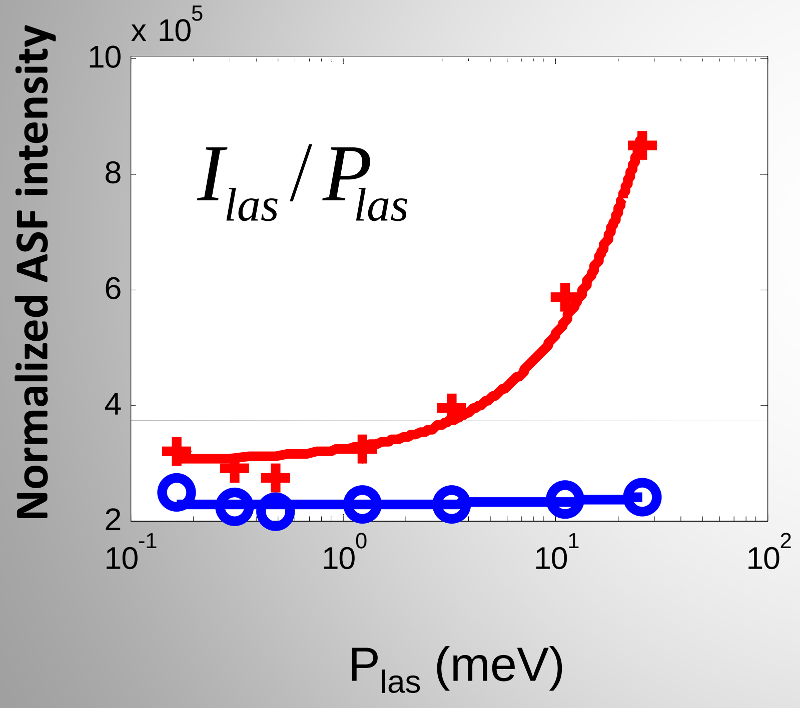


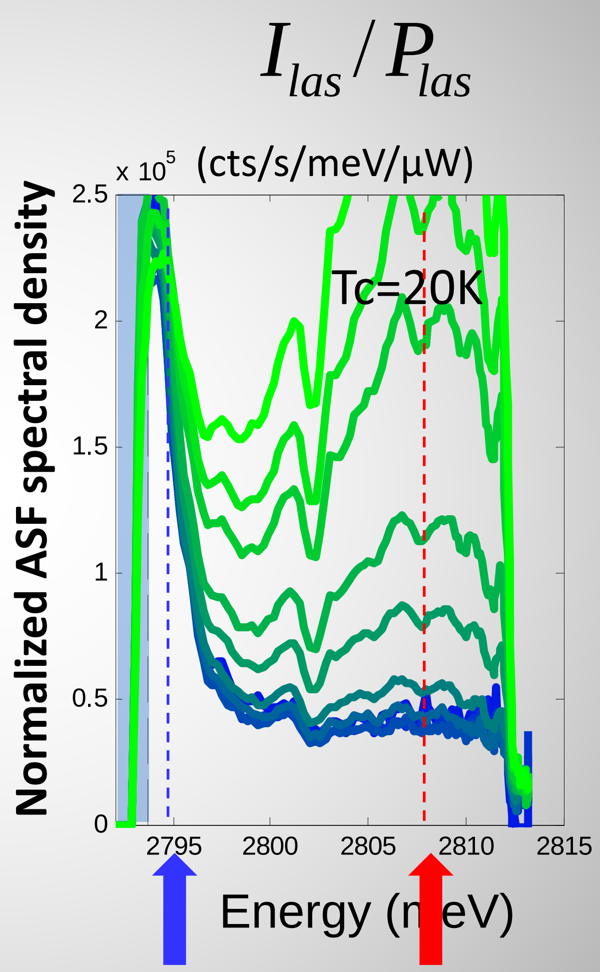
Laser power dependence

$$\propto P_{las}^2$$

P_{laser} = 3.30 µW
P_{laser} = 11.16 µW
P_{laser} = 26.20 µW
P_{laser} = 83.71 µW
P_{laser} = 196.53 µW
P_{laser} = 500.00 µW

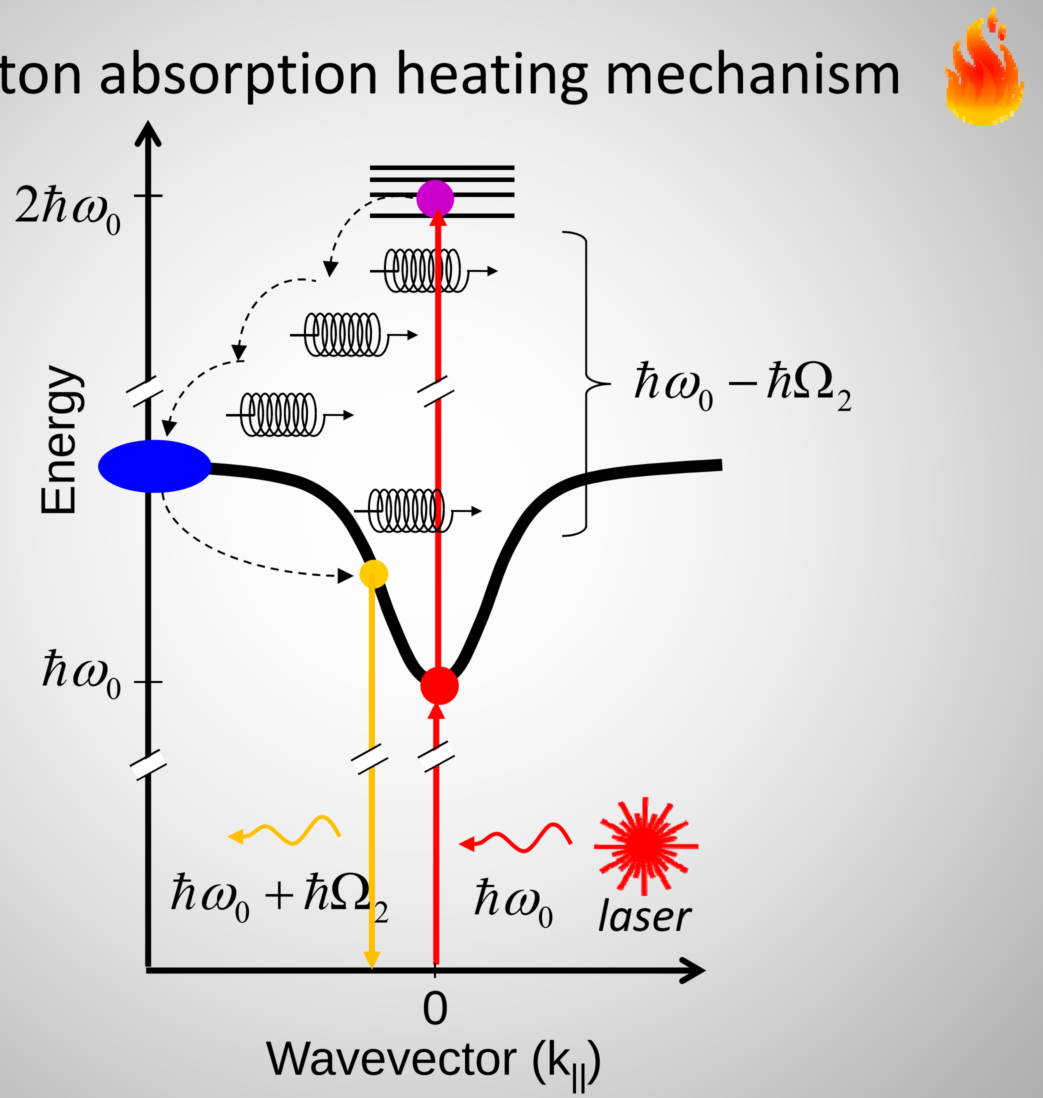
anti-Stokes fluorescence of polaritons





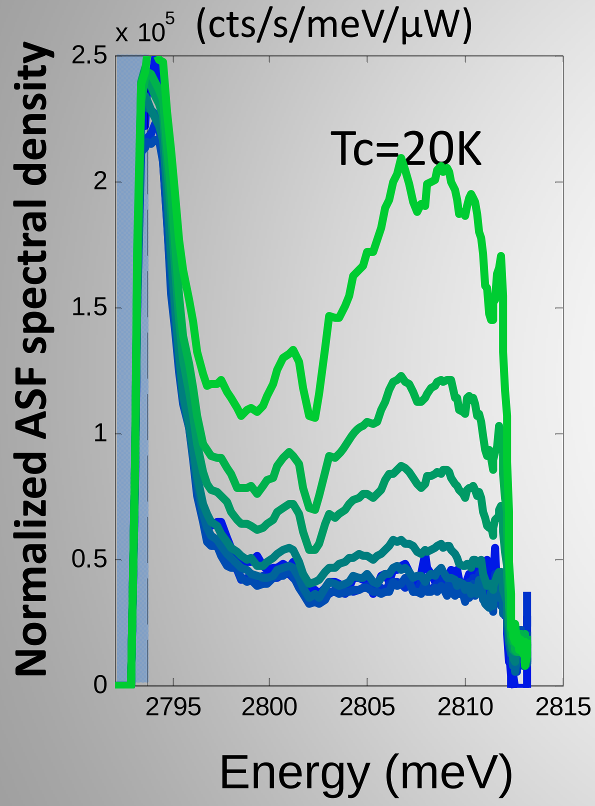
anti-Stokes fluorescence of polaritons

2-photon absorption heating mechanism



Intermediate summary

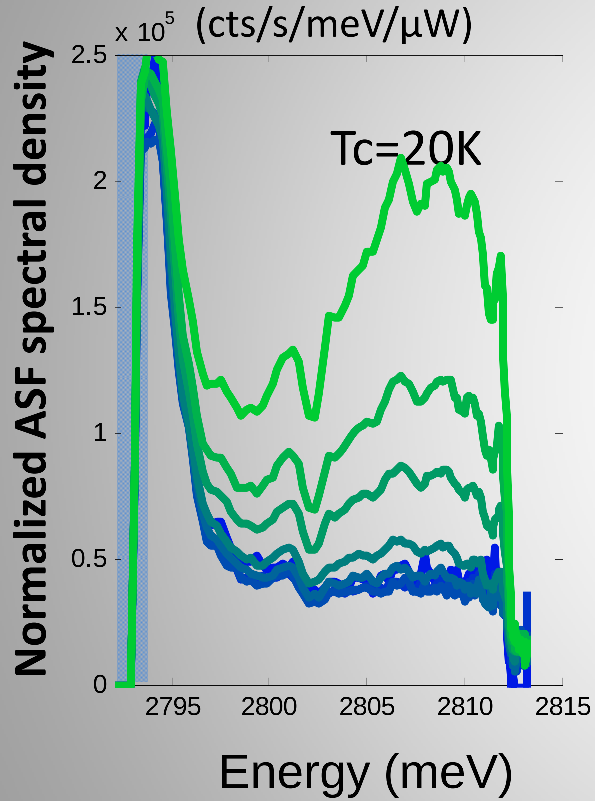
$$I_{las} / P_{las}$$



+ Setup detection efficency calibration η=1.1%

Intermediate summary

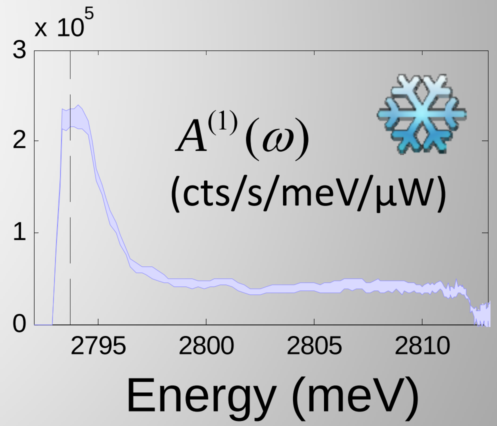
I_{las} / P_{las}



$\propto P_{las}$

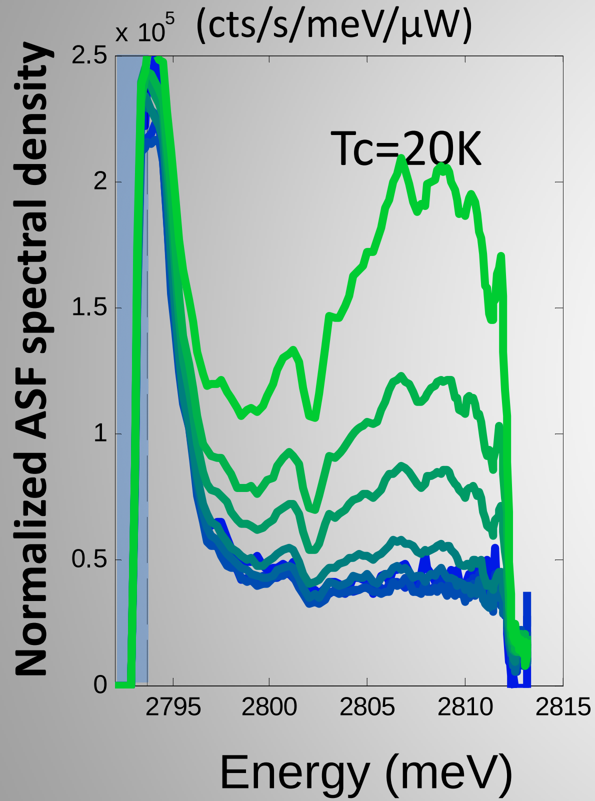
Slow cooling mechanism

Fast cooling mechanism



Intermediate summary

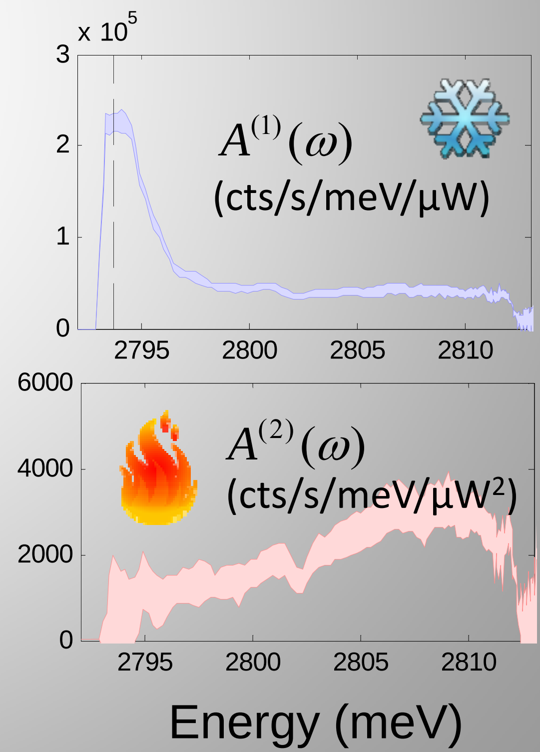
I_{las}/P_{las}



$\propto P_{las}$

Slow cooling mechanism

Fast cooling mechanism



$\propto P_{las}^2$ 2-photon abs. heating

Quantitative thermal Balance

Cooling power (Watts)

Absorbed phonon energy

Fast and **slow** cooling event rate

$$P_{\mathrm{fr}} = \int \mathrm{d}\omega \left\{ P_{\mathrm{las}} \hbar(\omega - \omega_0) A^{(1)}(\omega) \right.$$
$$\left. - P_{\mathrm{las}}^2 \hbar(2\omega_0 - \omega) A^{(2)}(\omega) \right\}$$

Quantitative thermal Balance

Cooling power (Watts)

Absorbed phonon energy

Fast and **slow** cooling event rate

$$P_{\mathrm{fr}} = \int \mathrm{d}\omega \left\{ P_{\mathrm{las}} \hbar(\omega - \omega_0) A^{(1)}(\omega) - P_{\mathrm{las}}^2 \hbar(2\omega_0 - \omega) A^{(2)}(\omega) \right\}$$

2-photon absorption rate

phonon cascade emission energy

Quantitative thermal Balance

Cooling power (Watts)

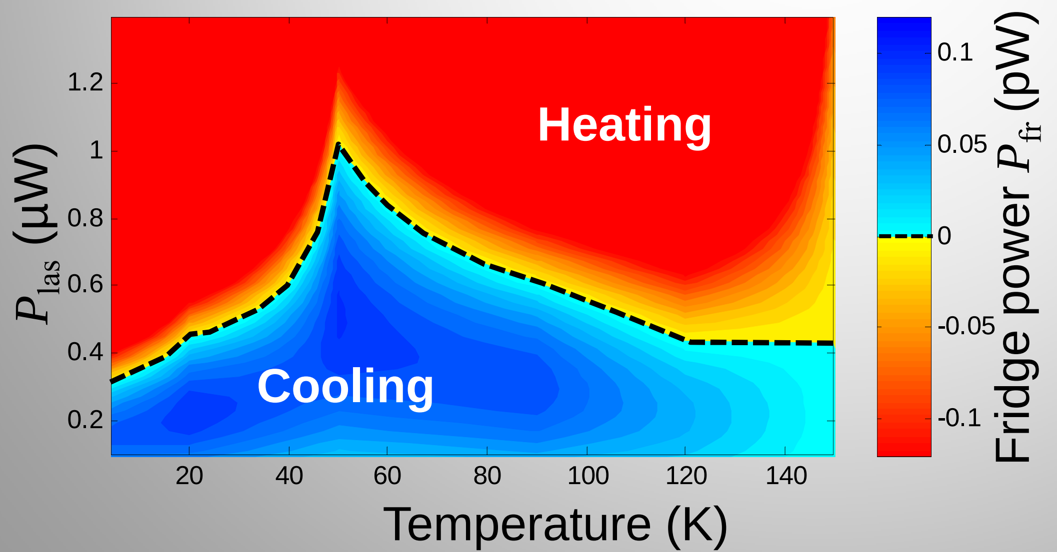
Absorbed phonon energy

Fast and **slow** cooling event rate

$$P_{\mathrm{fr}} = \int \mathrm{d}\omega \left\{ P_{\mathrm{las}} \hbar(\omega - \omega_0) A^{(1)}(\omega) - P_{\mathrm{las}}^2 \hbar(2\omega_0 - \omega) A^{(2)}(\omega) \right\}$$

2-photon absorption rate

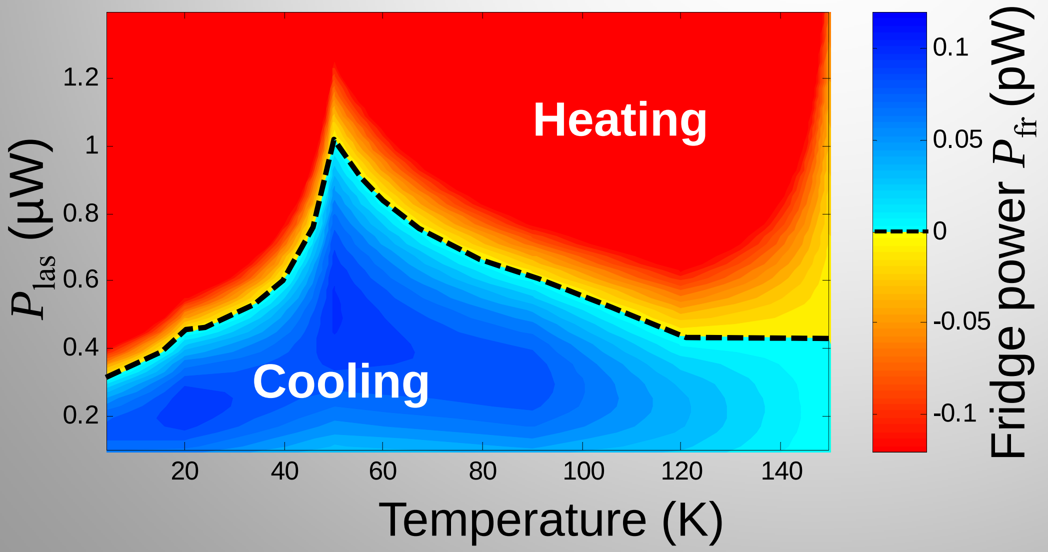
phonon cascade emission energy



- $P_{fr,\ max}$ = 0.1±0.02 pW
- **$p_{fr,\ max}$ = 80±16μW/cm³**

Quantitative thermal Balance

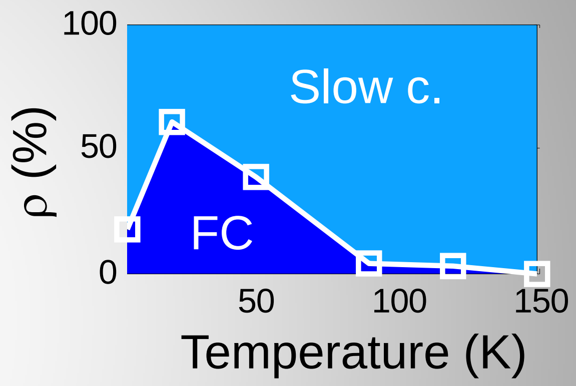
- No temperature cutoff

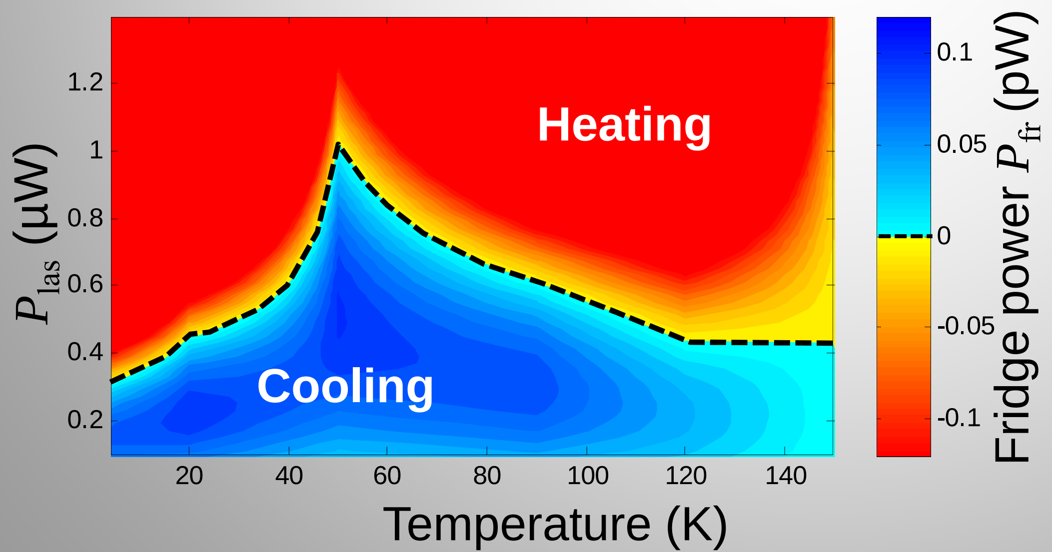


- $P_{fr,\,max}$ = 0.1±0.02 pW
- $p_{fr,\,max}$ = 80±16µW/cm^3

Quantitative thermal Balance

- No temperature cutoff
- High participation ratio ρ of **fast** cooling mechanism





- $P_{fr,\,max}$ = 0.1±0.02 pW
- $p_{fr,\,max}$ = 80±16µW/cm³

What does the heated polariton gas looks like?

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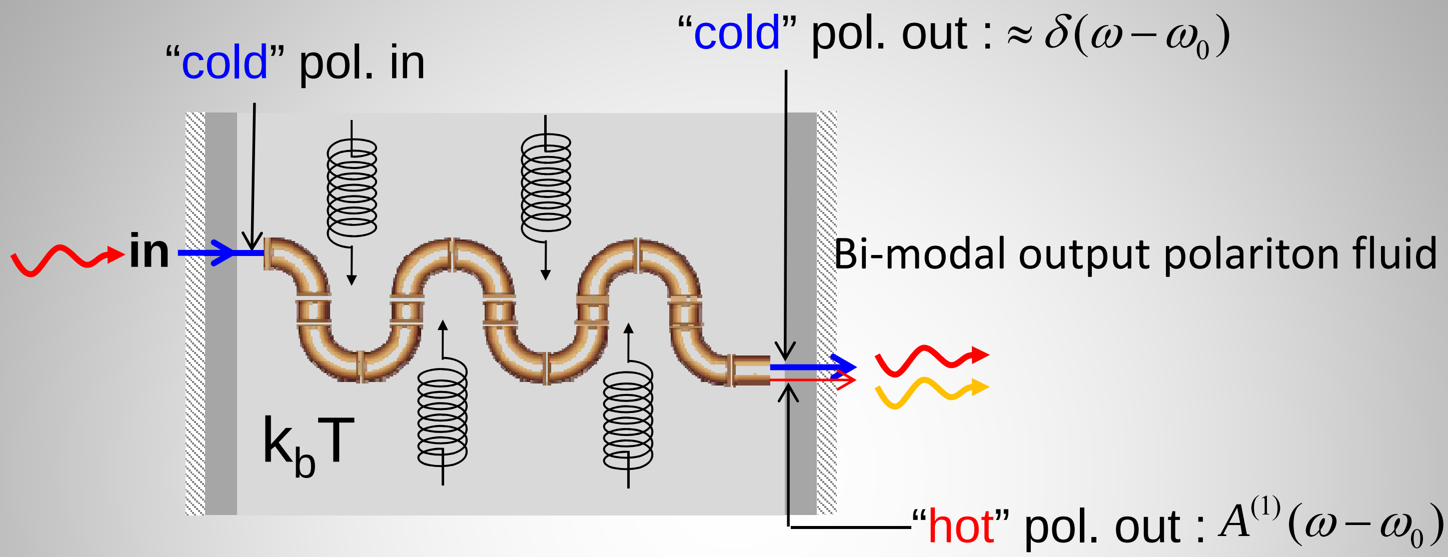
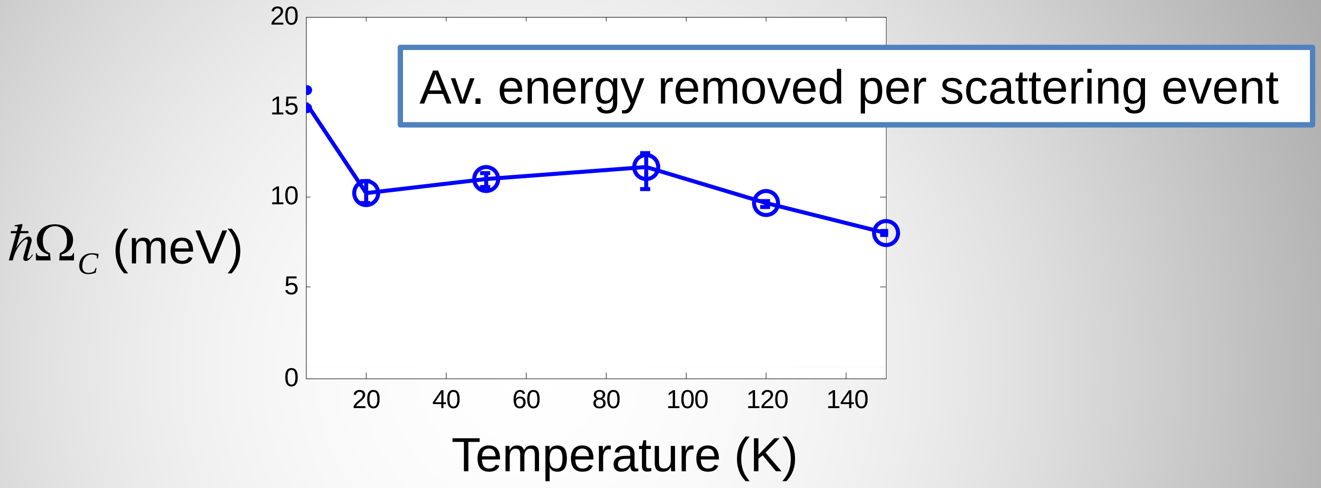


- No internal equilibration (vanishing pp interaction regime)

→Bi-modale polariton distribution : a « cold » and a « hot » fluid coexist

What does the heated polariton gas looks like?

« hot » polariton fluid properties = polaritonsthat
did interact with thermal phonons



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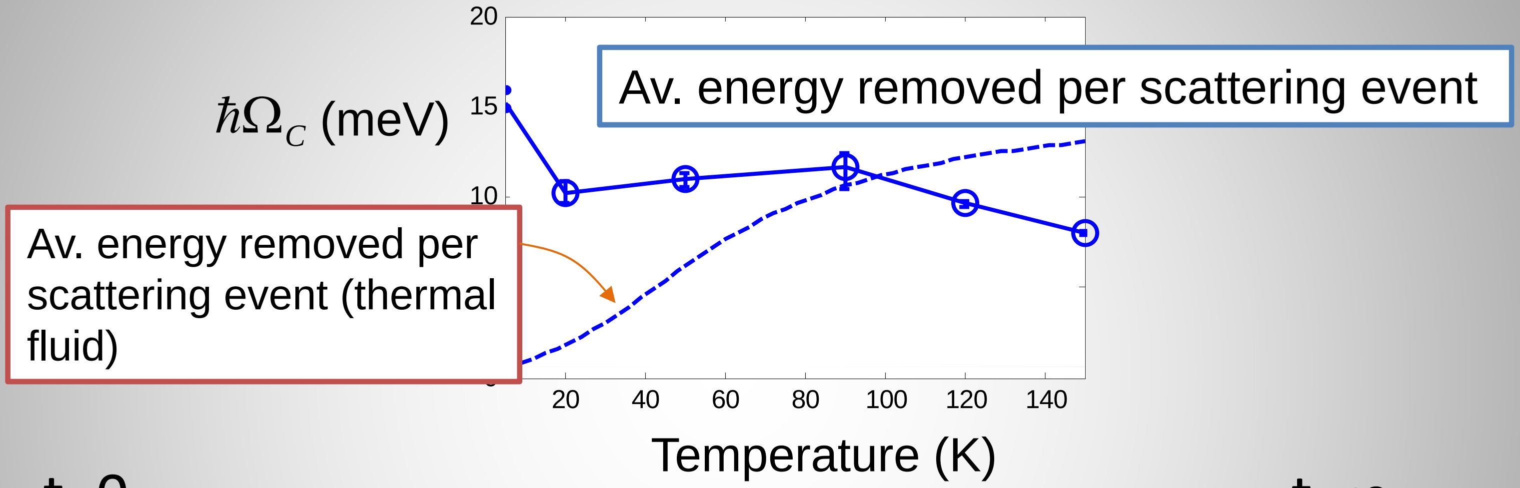

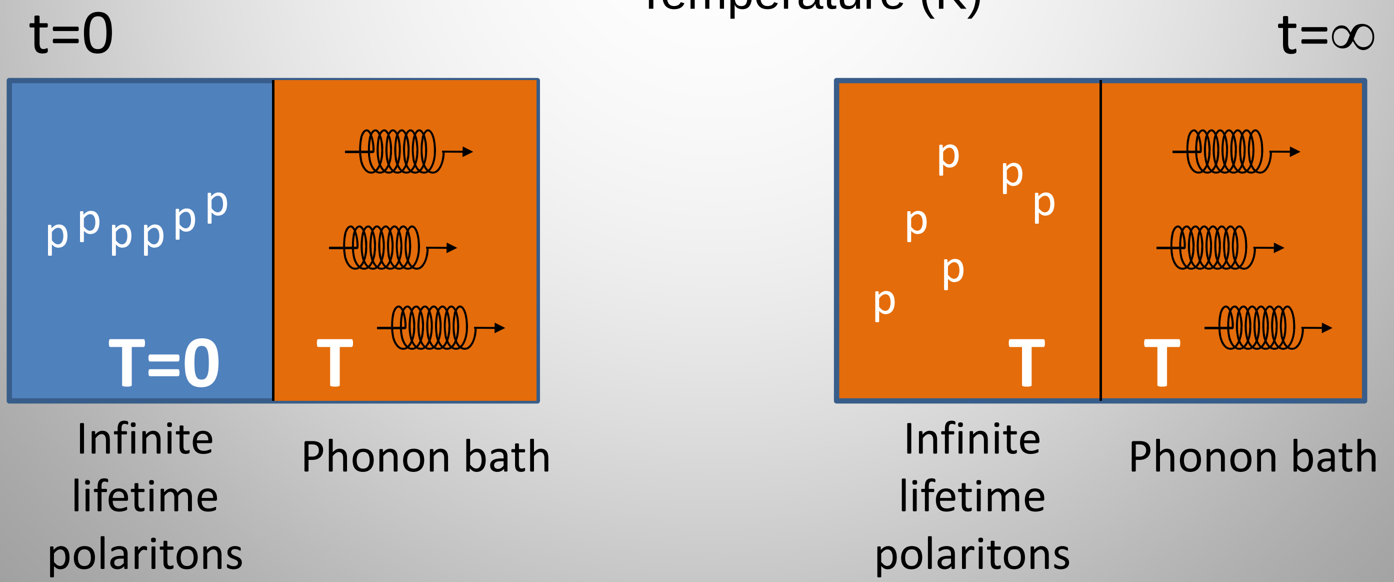

What does the heated polariton gas looks like?

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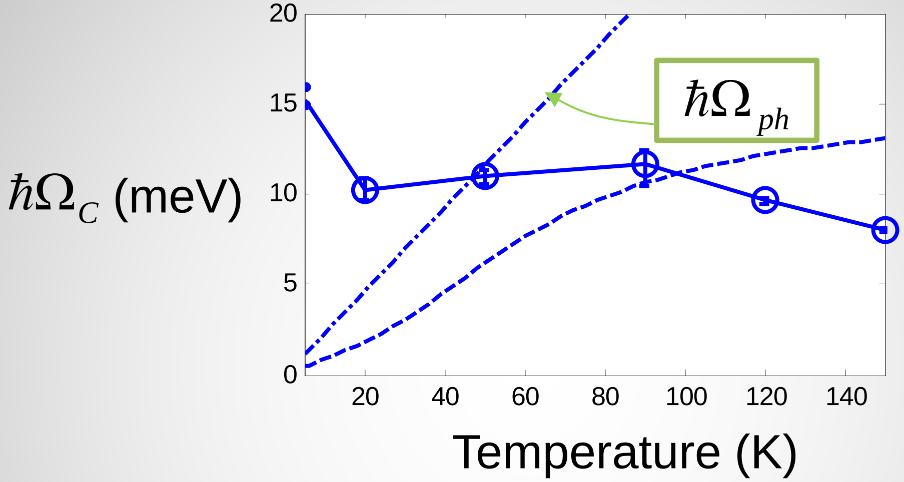
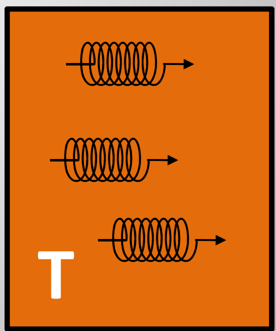


Heated polaritons are "hotter" than the phonon thermsleves !



Phonon bath

Conclusion

Properties of a polaritonic refrigerent

- Net Positive cooling power at low laser power
- Involves an ultrafast cooling dynamics mechanism (1ps)
- No temperature cutoff
- Full optical access to thermidynamical properties

- Main limitation so far : 2-photon absorption

« Cold » injected polaritons behave like an out-of-equilibrium refrigerant fluid

→ Bi-modal « cold » and « hot » fluid
→ at low T, polaritons removes thermal phonons of higher energy than normally allowed by thermal equilibrium
→non-eq. can be a resource !

Outlook

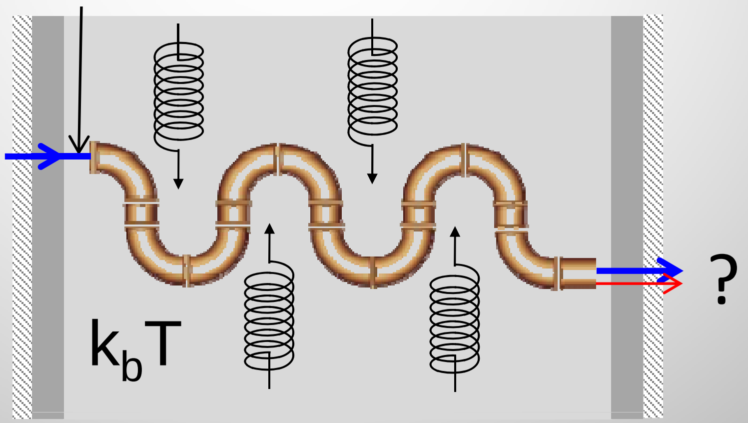
Non thermal character is fully tunable ! :

- pp interactions ⇔ internal equlibrations
- A tunable thermal reservoir can be added : externally pumped excitons

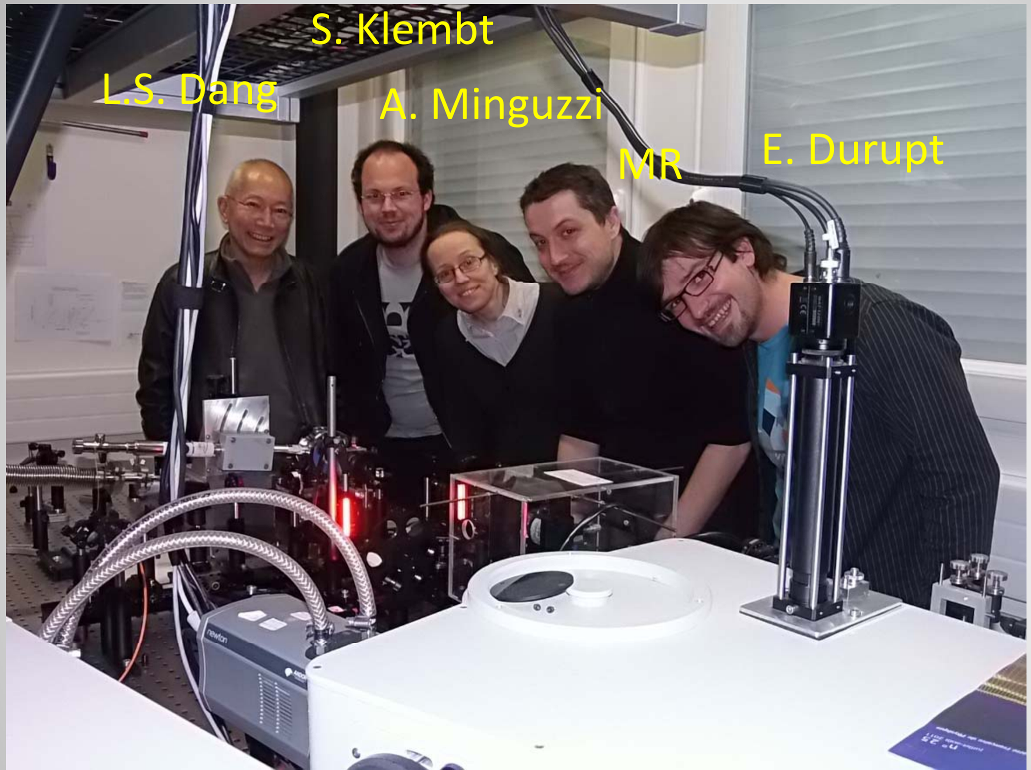
- **Thermodynamical properties of polariton superfluids**

= thermodynamics of a (out-of-eq.) weakly interacting Bose gas exchanging heat with a thermal reservoir

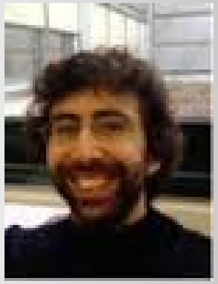
Polariton superfluid in



Acknowledgements



S. Datta



Y. Léger

A. Baas

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