Coherence in semiconductor nanostructures
Part III: Spontaneous collective coherence & superradiance in ensembles of excitons & polaritons

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UNIWERSYTET WARSZAWSKI
ZINTEGROWANY PROGRAM ROZWOJU

Equipe mixte CEA-CNRS "Nanophysique et semicondcuteurs"
Institut Néel - CNRS
Grenoble France

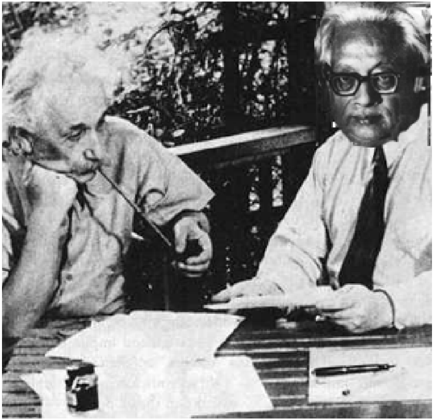
Warsaw University, October-December 2020

Outline

Condensation Phenomenon

Idea, 1924: The theory is pretty, but is there also some truth to it?

- Boson Statistics at High Density in Thermal Equilibrium
- Massive Occupation of the Ground State
- Saturation of the Excited States



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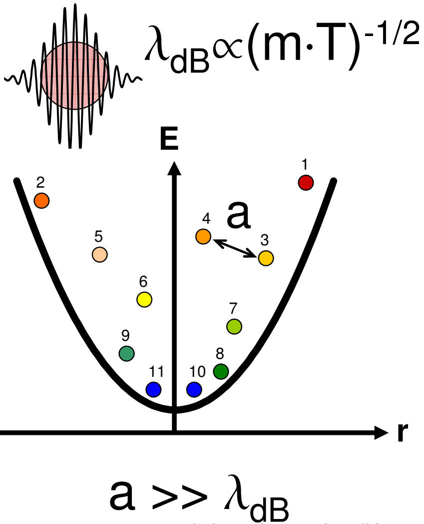

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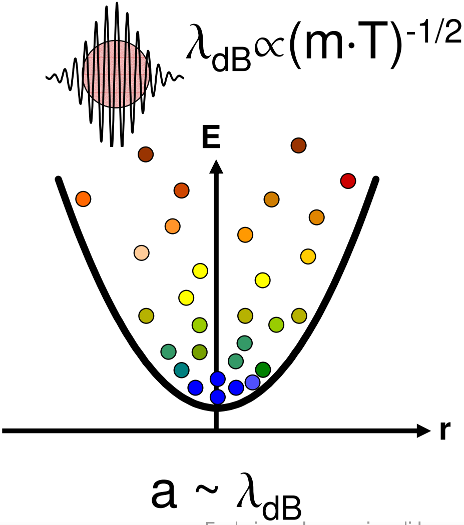

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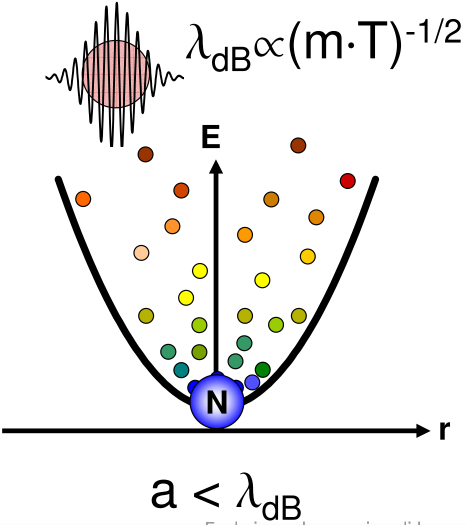

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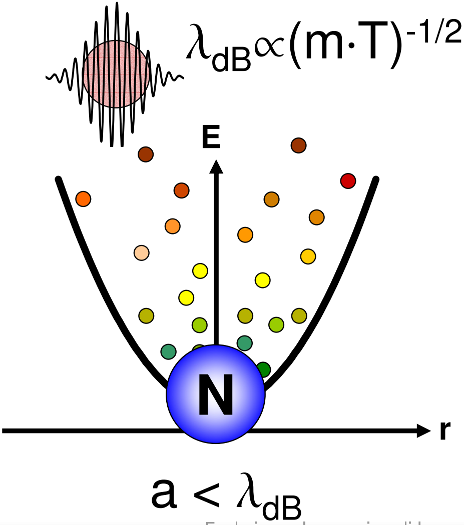

Bose-Einstein Condensation

First Achievement: Boulder, MIT - 1995

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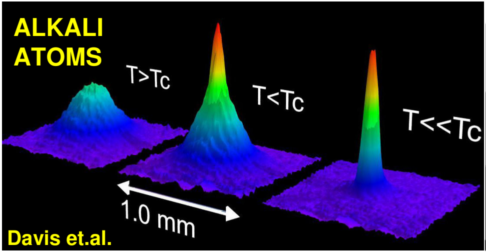
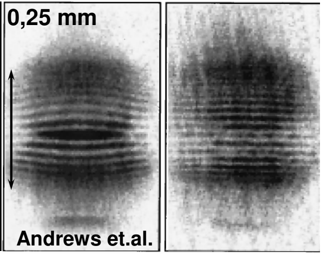


- Long Range Coherence Interference



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- Polaritons: $\sim (20K, 5x10^{8}cm^{-2})$
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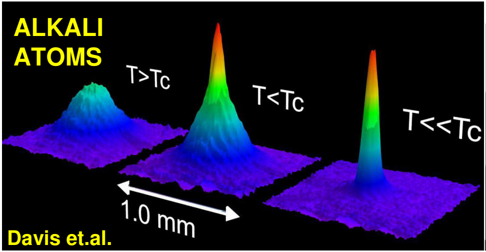

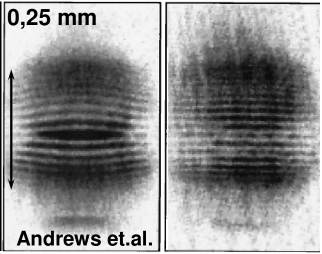

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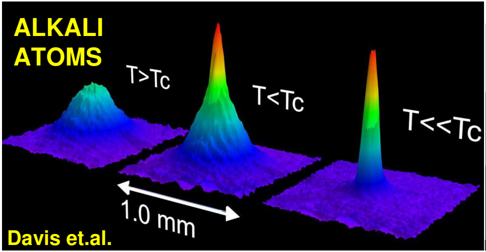

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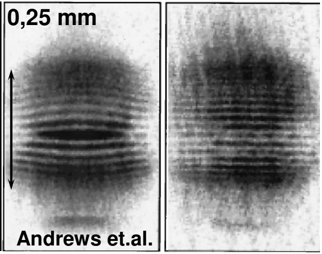

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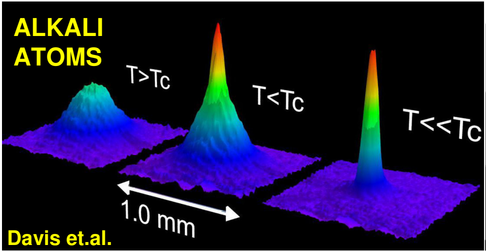

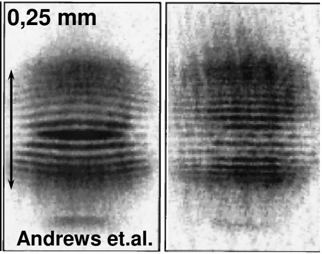

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Outline

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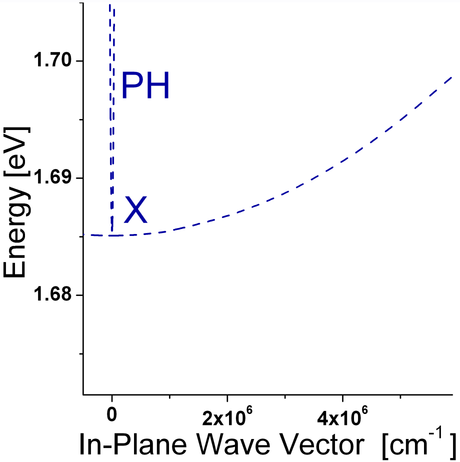

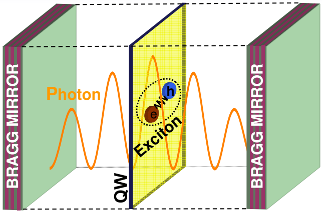

Strong Coupling

$$\Omega > \Gamma_X, \Gamma_{PH}$$

Momentum Conservation

$$k_{||} = \frac{E}{\hbar c} \sin \theta_{ext}$$

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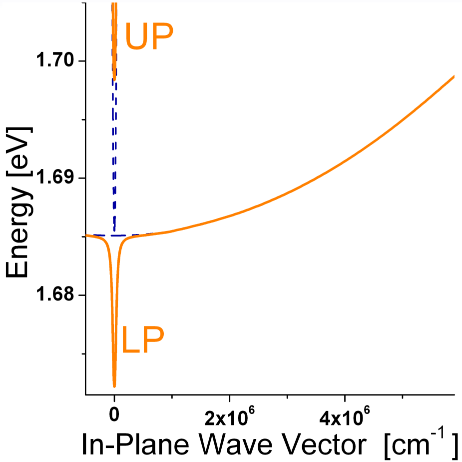

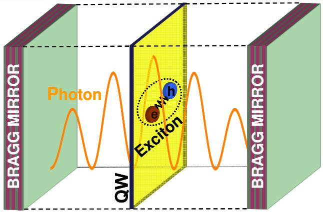

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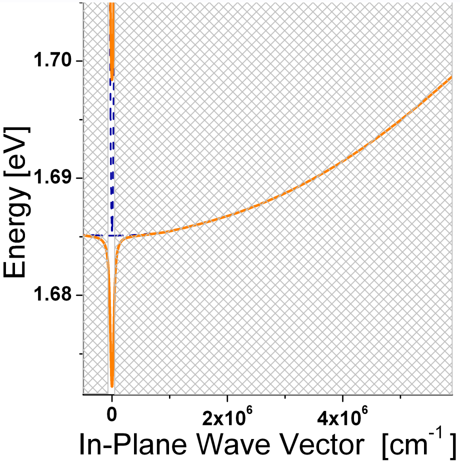

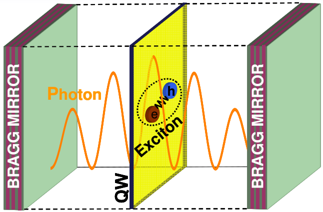

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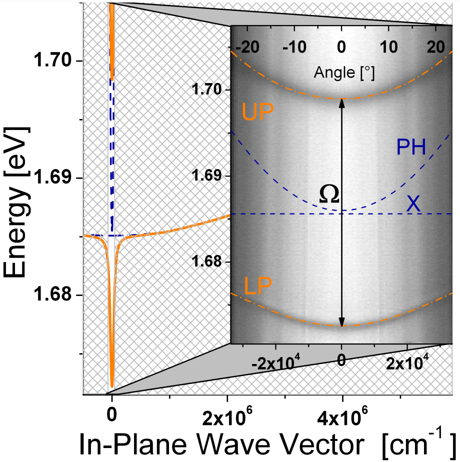

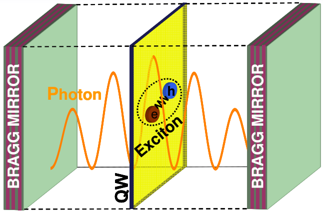

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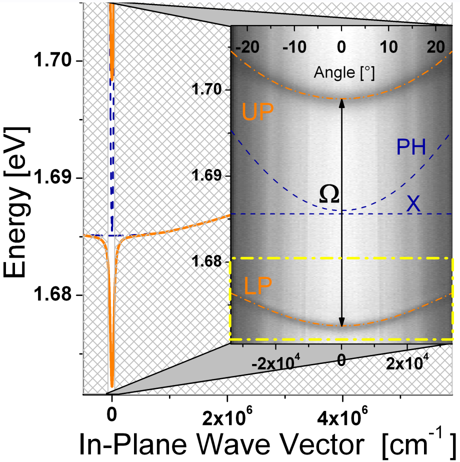

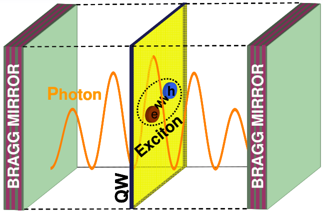

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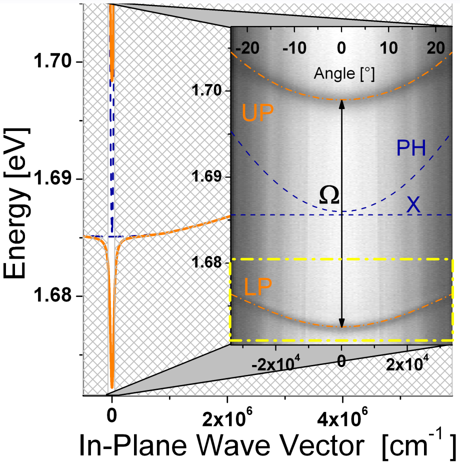

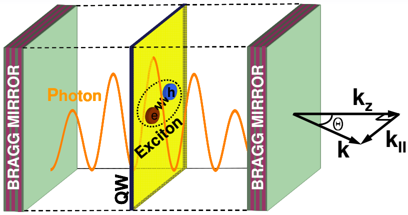

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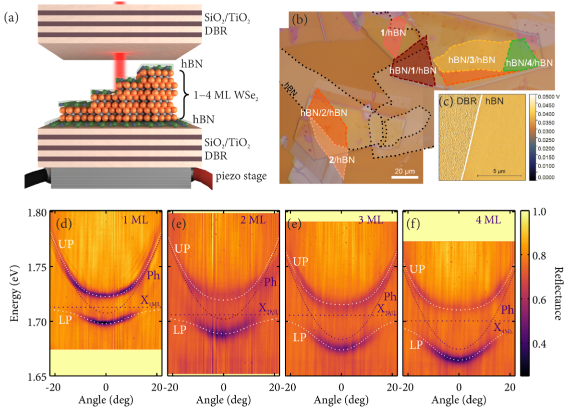
Digression: Polaritons in a tunable cavity with TMDs

M. Król et al.2D Materials 7, 015006 (2020)



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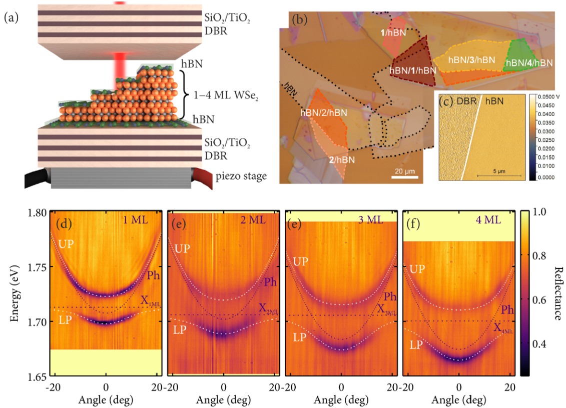

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Polariton versus Atom

Polariton≈Boson

$$N \ll N_{sat} \sim 10^{11} cm^{-2}$$

Parameter	Atom	Polariton
m $[m_e]$	10^4	10^{-4}
T [K]	10^{-6}	20
$\lambda_{dB} \sim a$ $[\mu m]$	0.7	3
N $[cm^{-2}]$	10^8	$5 \cdot 10^8$ (10^{10})
Life Time	"long" s	"very short" $10^{-12} s$
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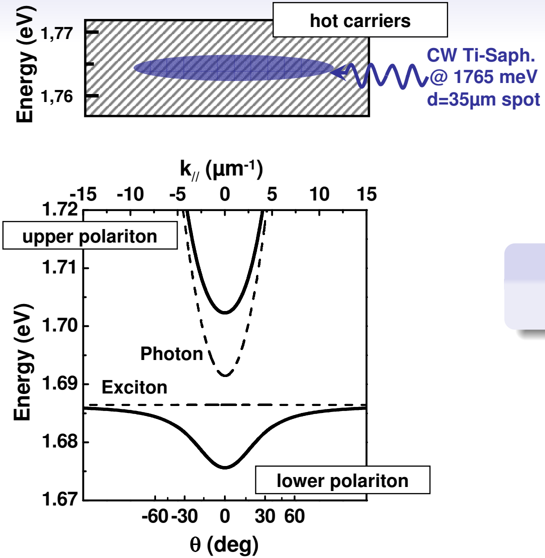
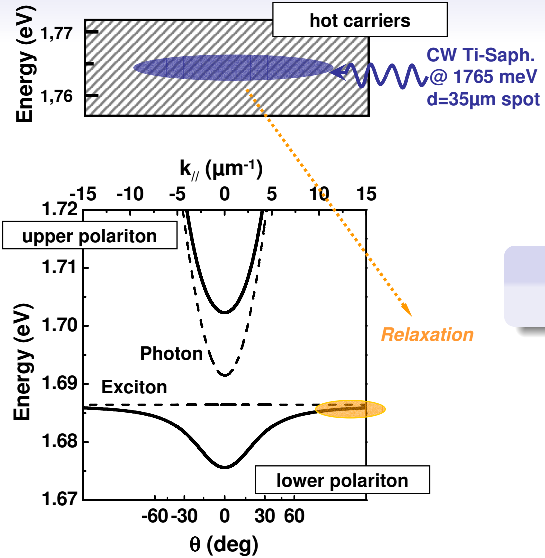


Excitation

Strictly Non-resonant

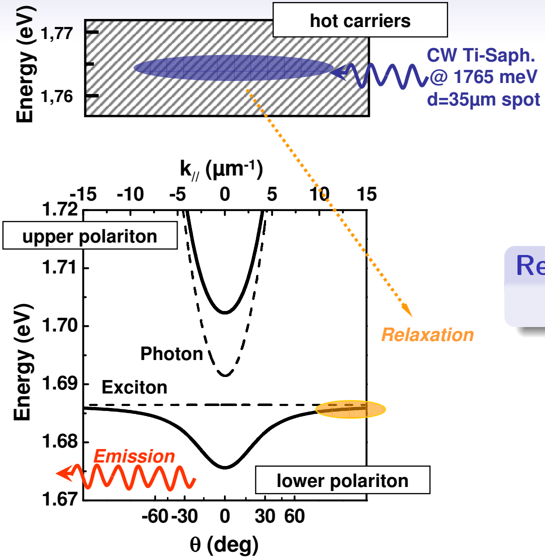
How to demonstrate polariton condensation ??



Initial State

Incoherent Excitons

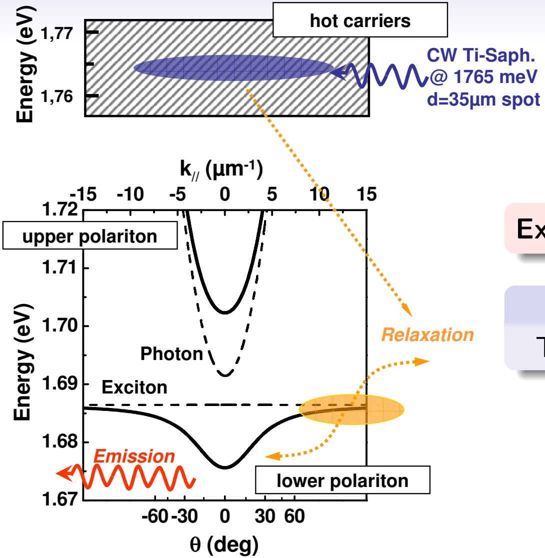
How to demonstrate polariton condensation ??



Relaxation < Emission

Bottleneck

How to demonstrate polariton condensation ??

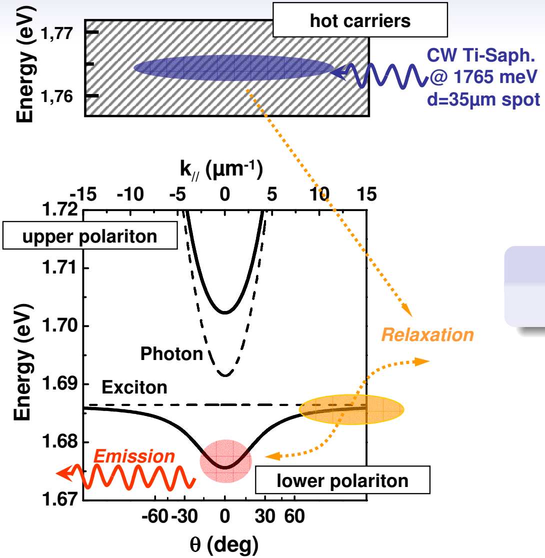


Exciton-Polariton Scattering

Relaxation ∼ Emission

Thermalization, Stimulation

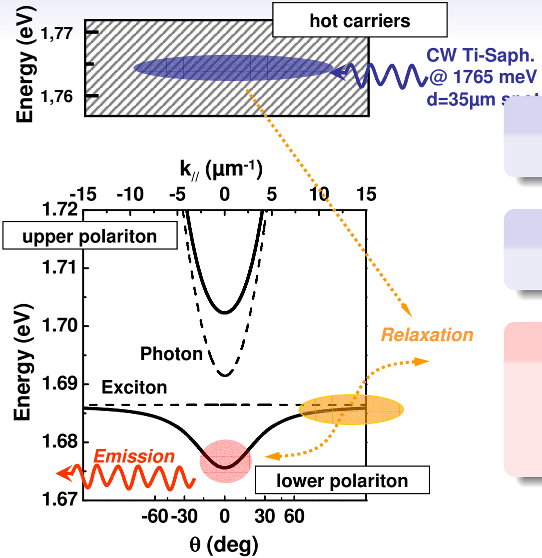
How to demonstrate polariton condensation ??



Final State

Coherent Condensate

How to demonstrate polariton condensation ??



Initial State

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Final State

Coherent Condensate

Spontaneous Transition

T=const, N ↗

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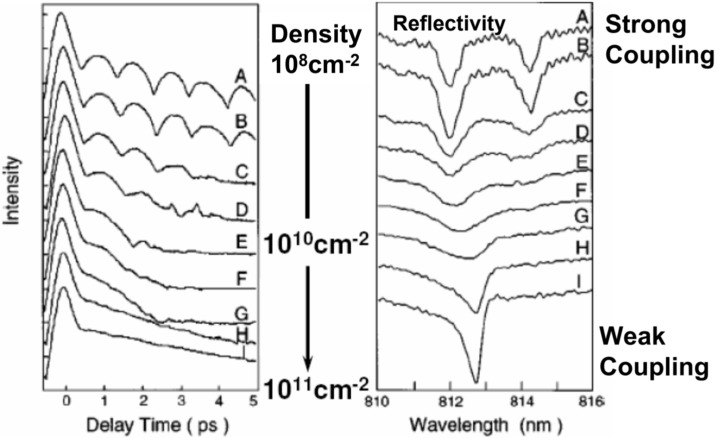
GaAs Microcavity with a single QW

S. Jiang et al. APL 73, 3031, 1998



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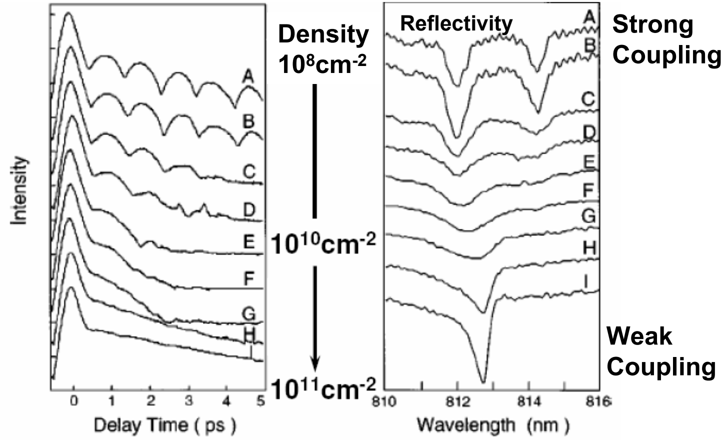

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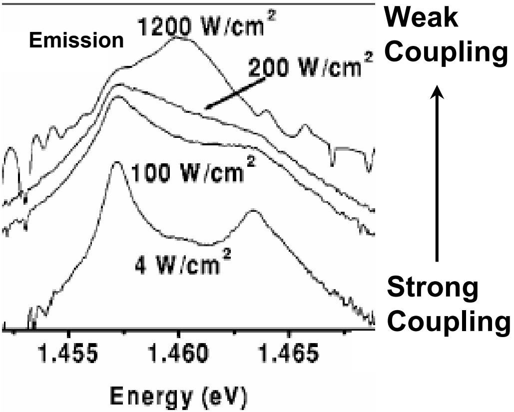

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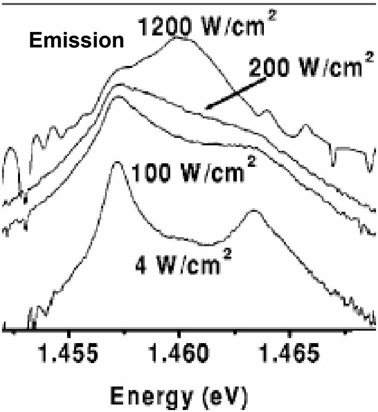

Weak Coupling

Strong Coupling

Exciton dissociation before condensation

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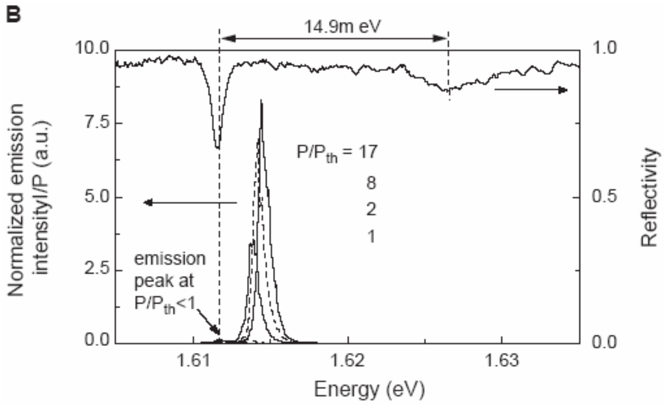
H. Deng et al. Science, 298, 199, 2002



Stimulated scattering in strong coupling

Coherence ?? Non-resonant ??

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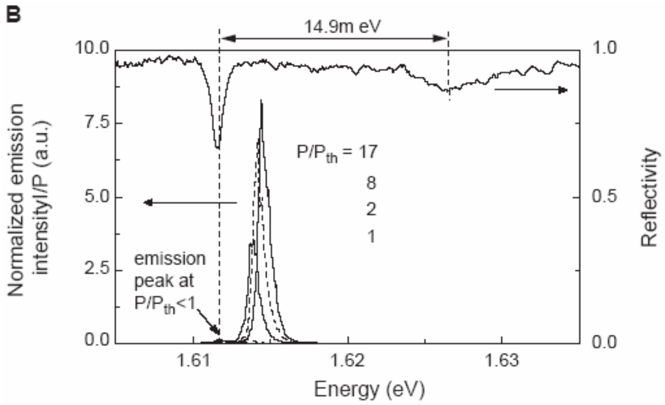

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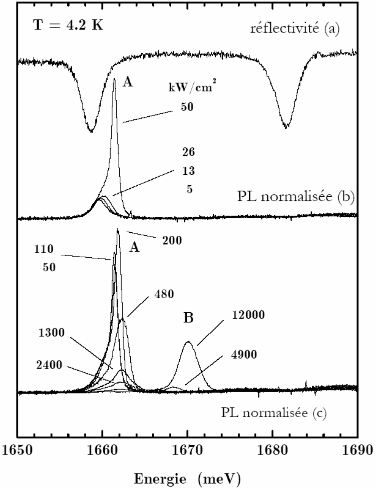

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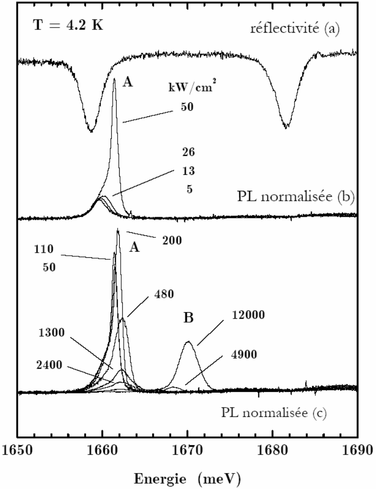
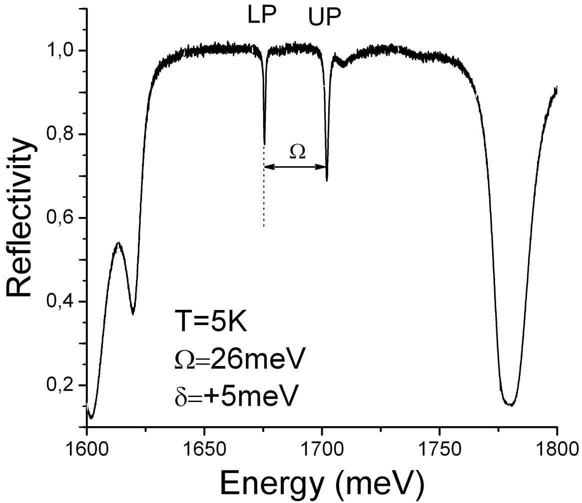


Optical Response of the CdTe Microcavity

$16PQs \Rightarrow \Omega = 26meV$



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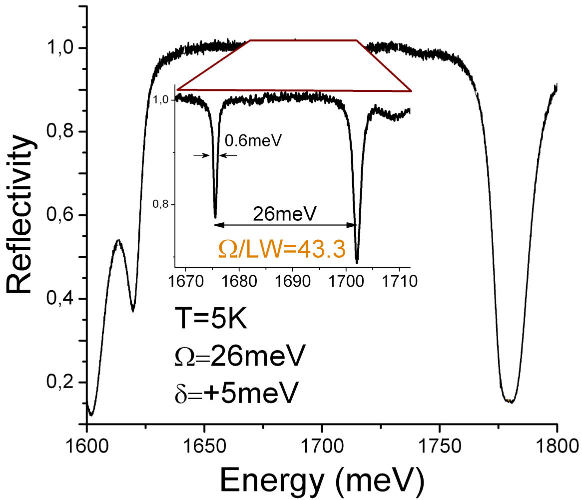
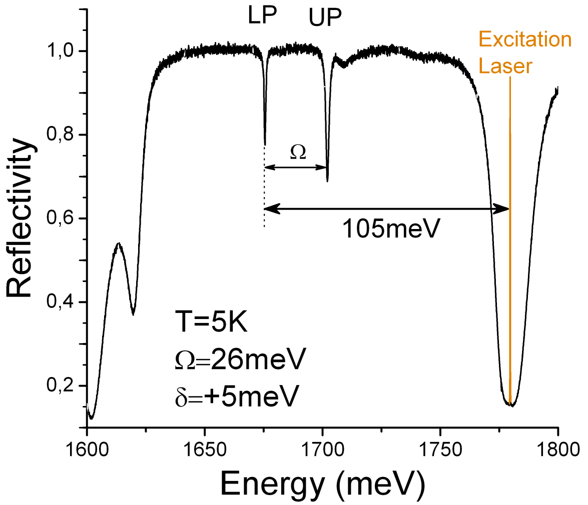


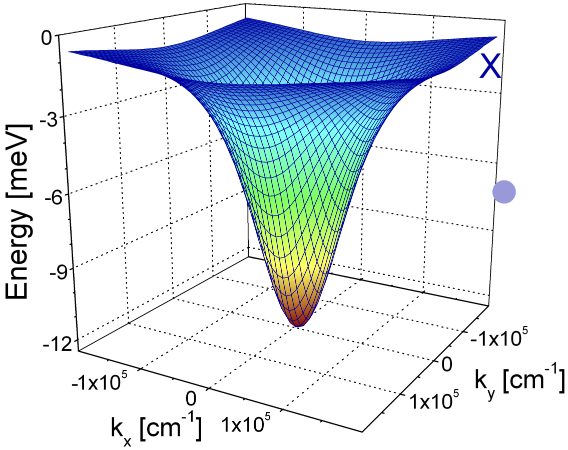
Optical Response of the CdTe Microcavity

Non-resonant Excitation



Polariton Condensation in Momentum space

Far Field Imaging



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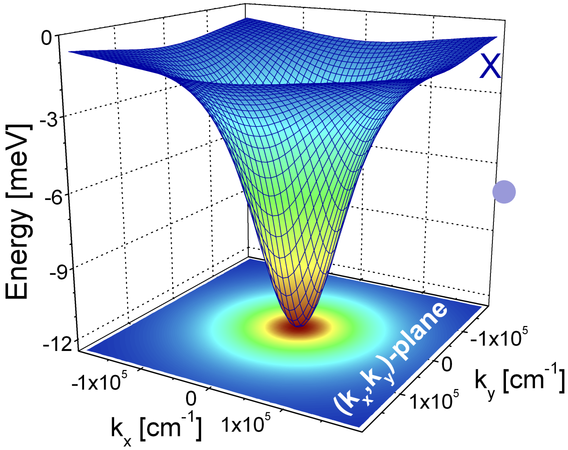
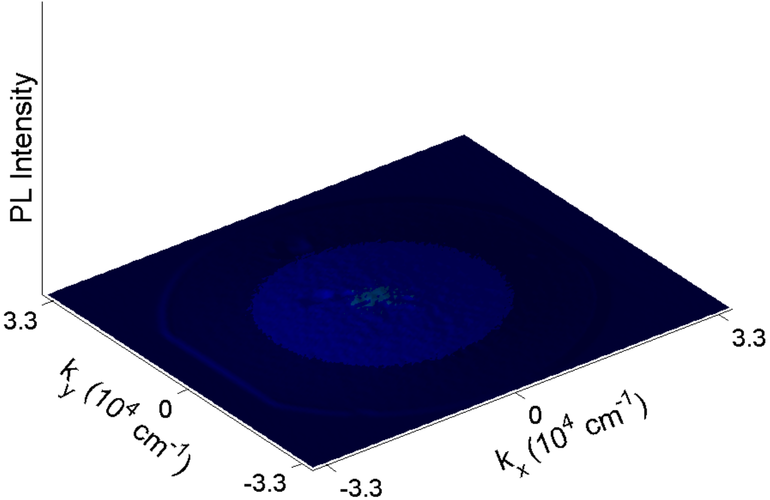


Outline

Plan

Polariton Condensation in Momentum Plane

Non-resonant, CW Excitation



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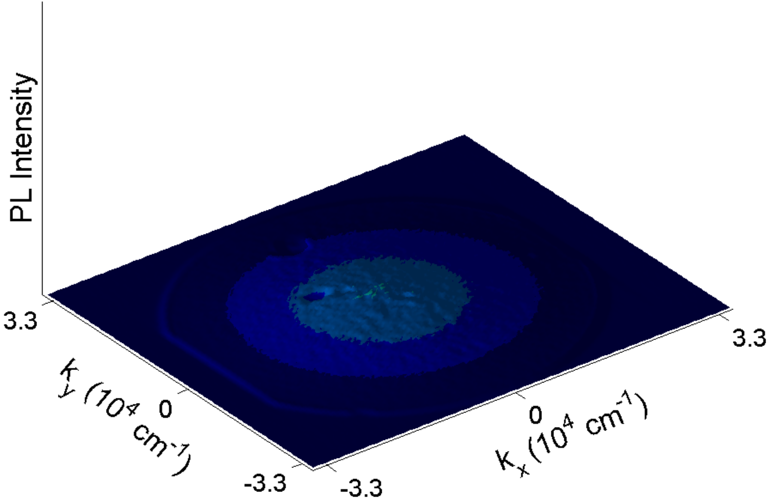

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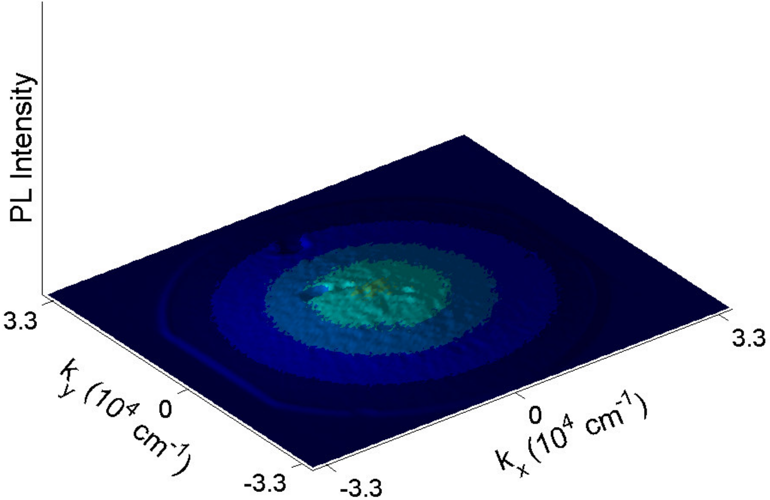

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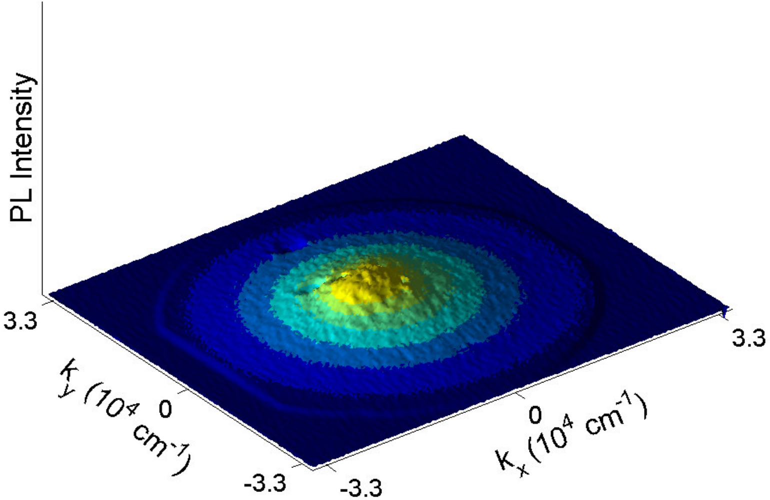

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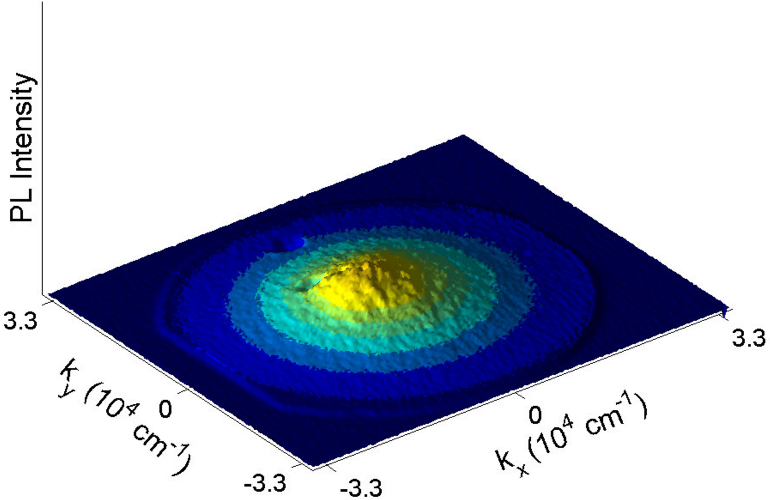

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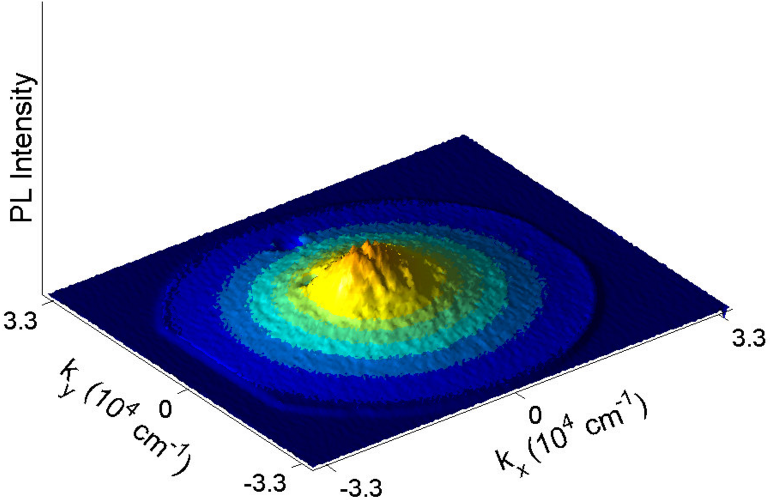

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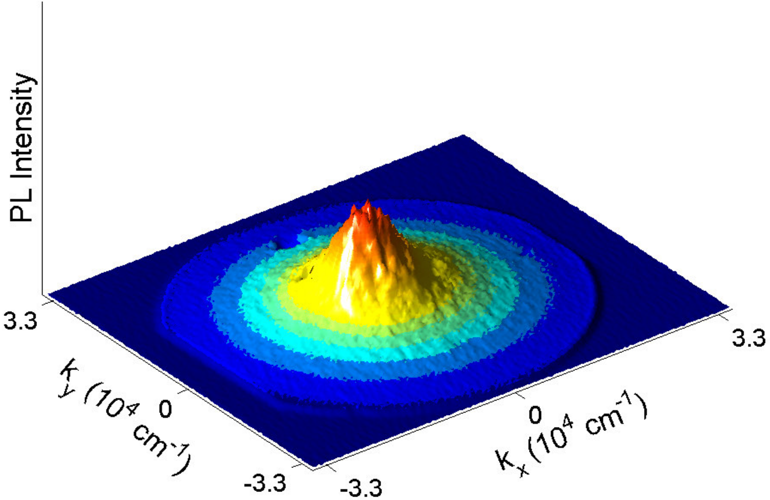

Polariton Condensation in Momentum Plane

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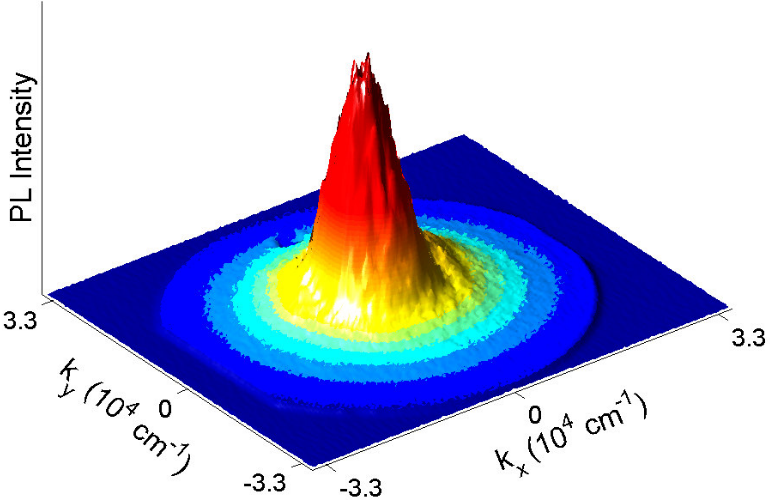

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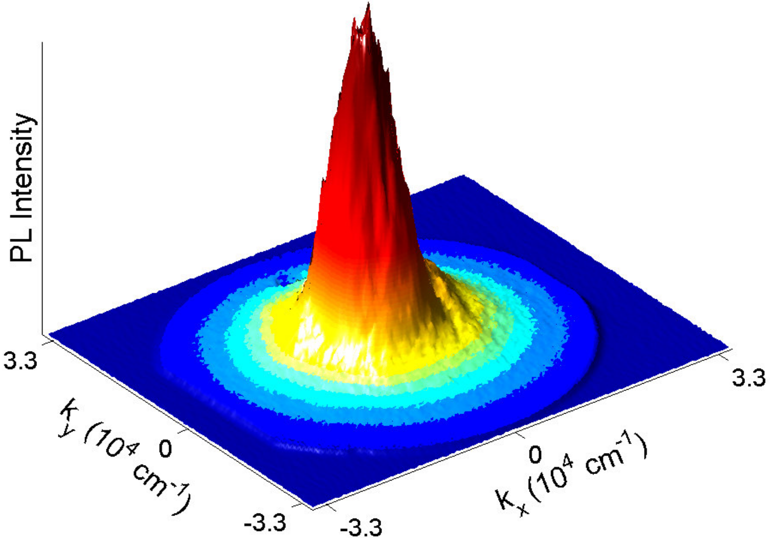
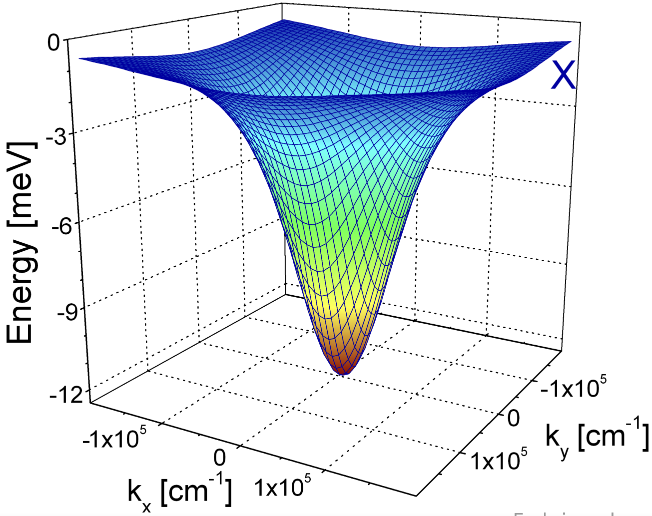


Polariton Condensation in Dispersion Plane

Spectrally Resolved Far Field Imaging



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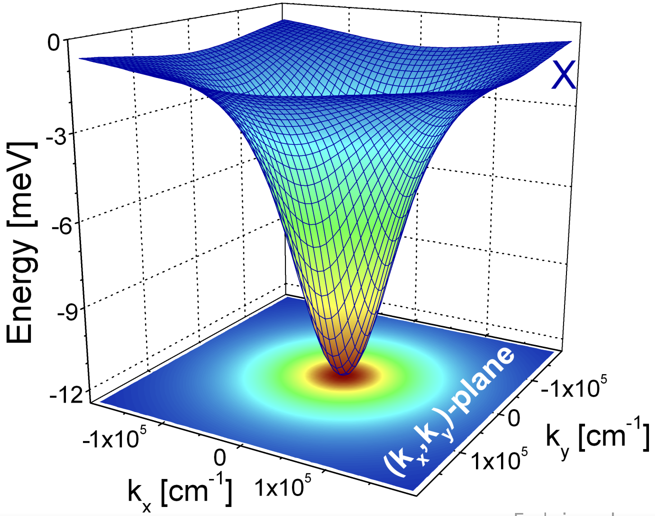

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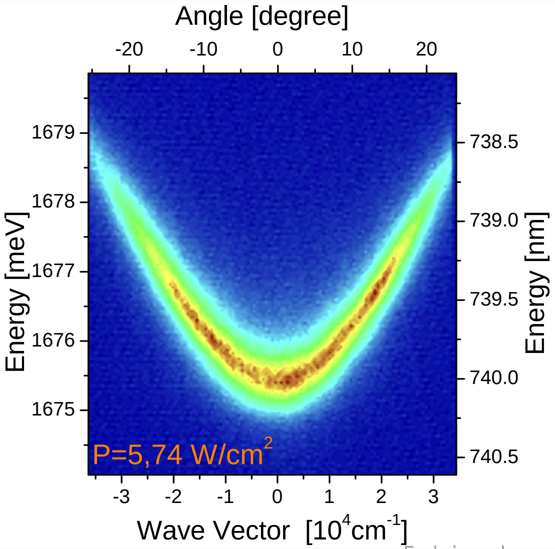

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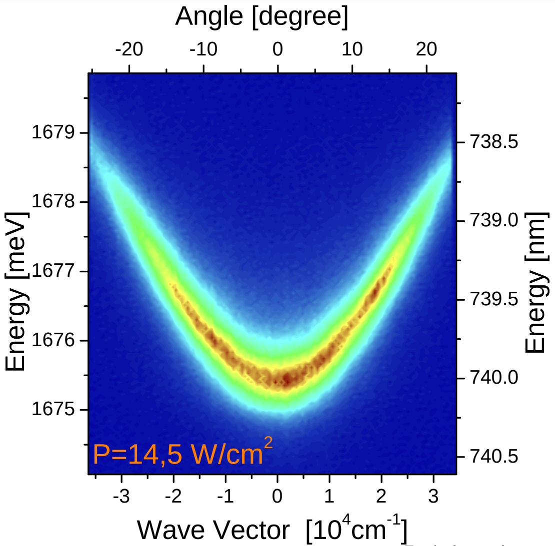

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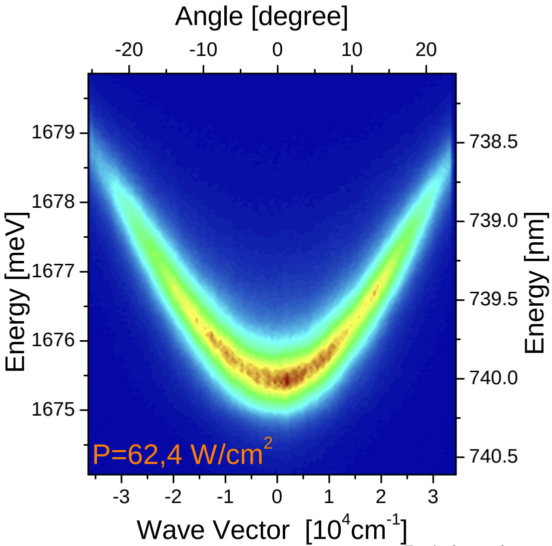

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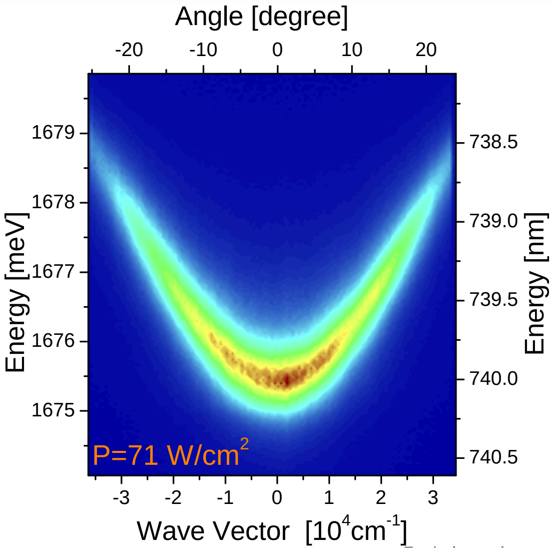

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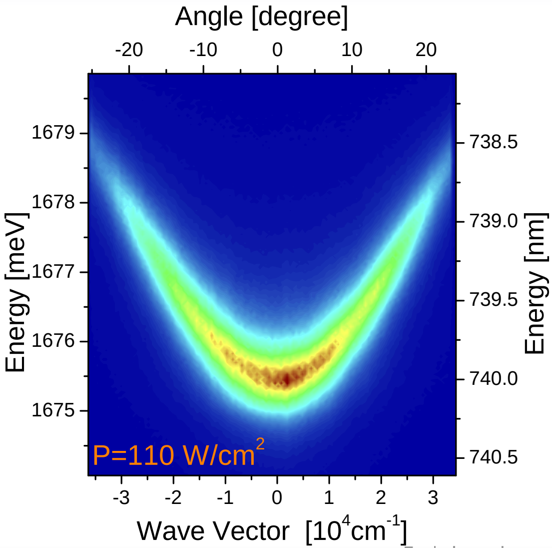

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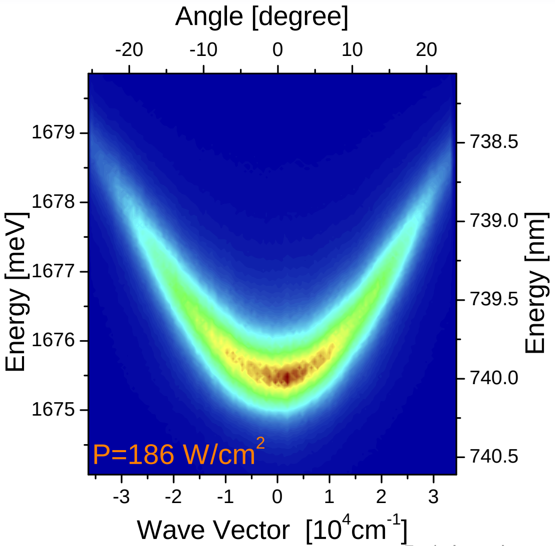

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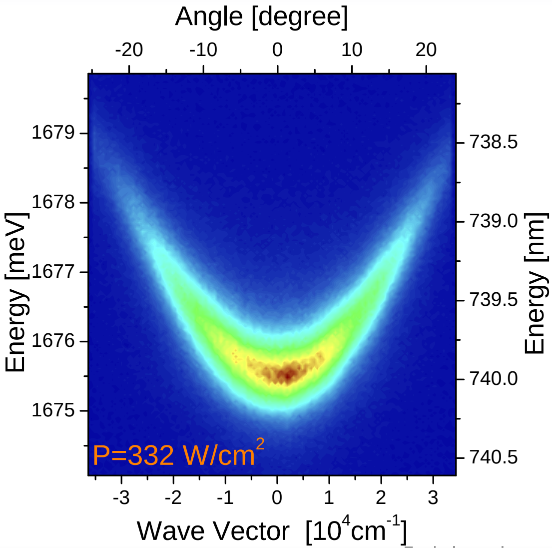

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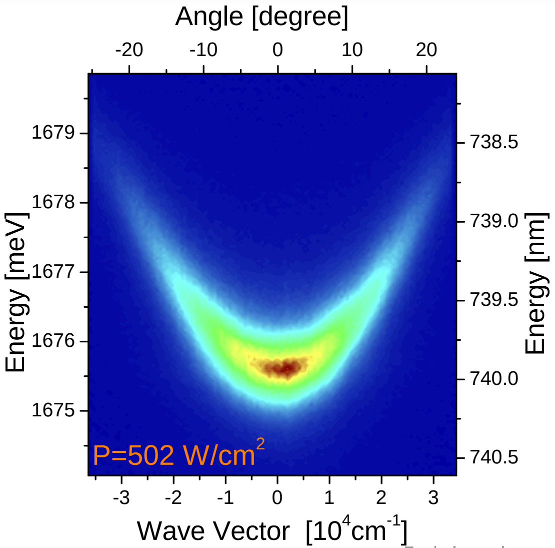

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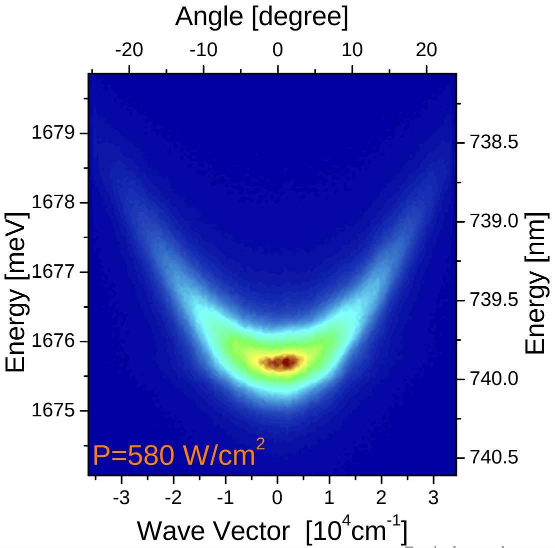

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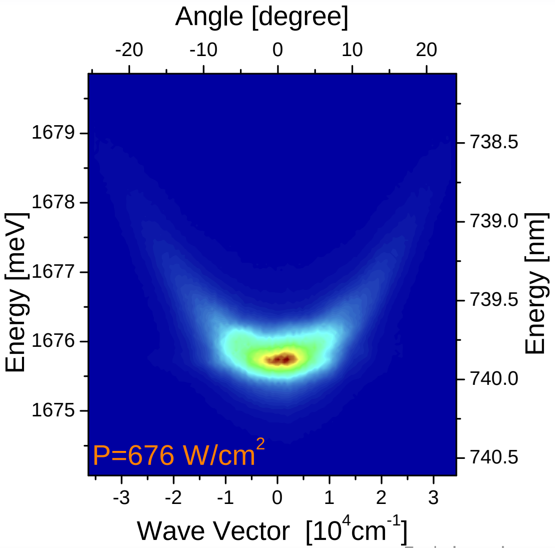

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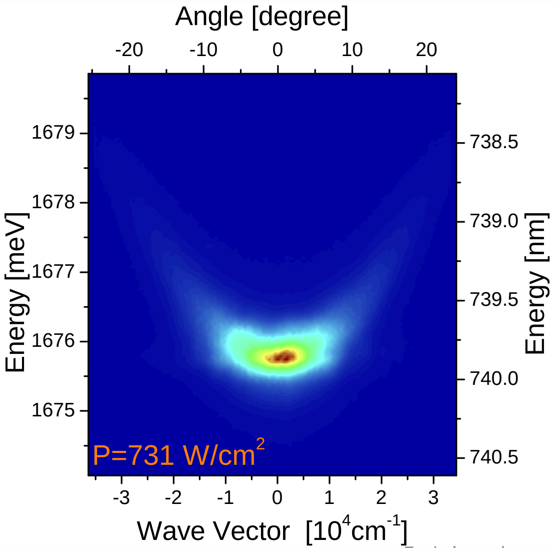

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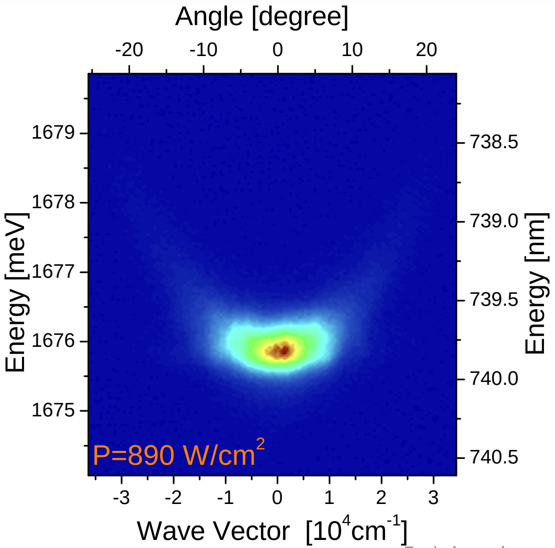

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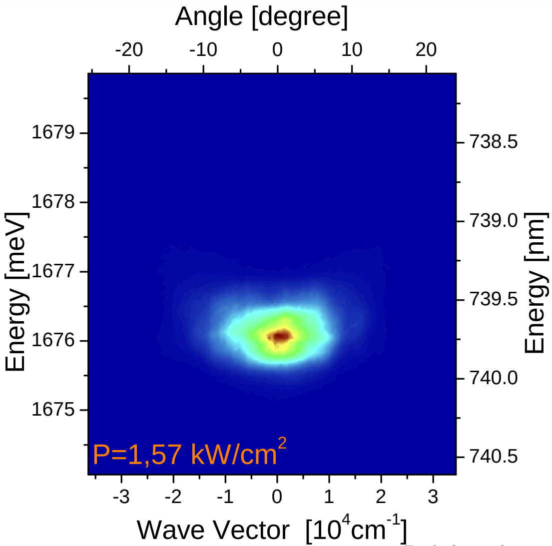
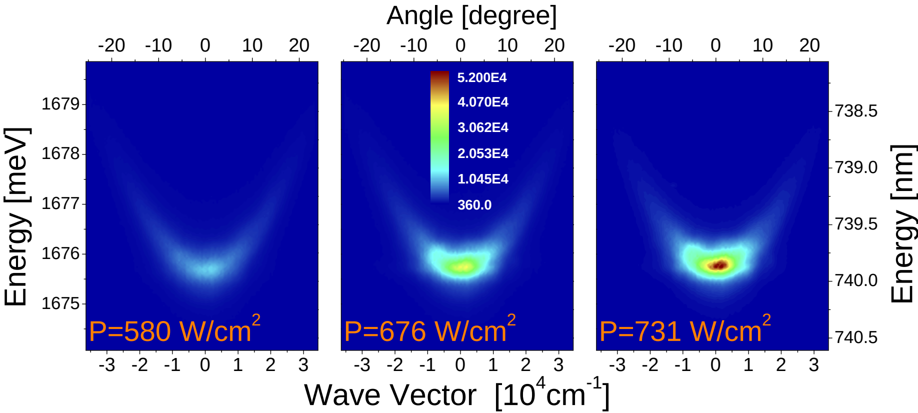
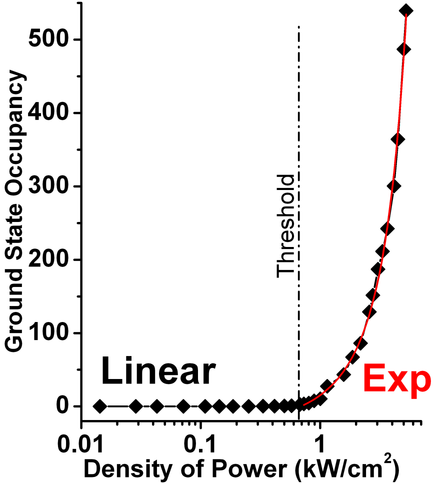


Saturation of the Excited States



Log Scale

Massive Occupation of the Ground State



Stimulated Scattering

- Exponential Threshold
- Critical Density for Occupancy∼1

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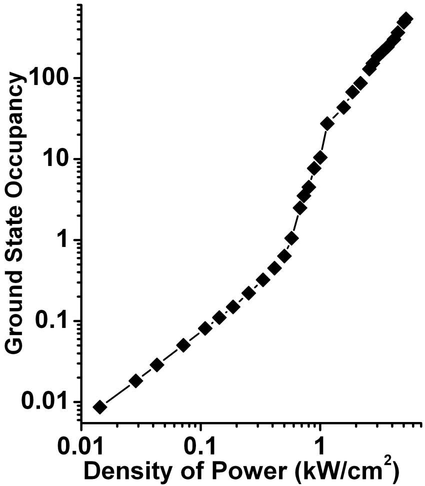

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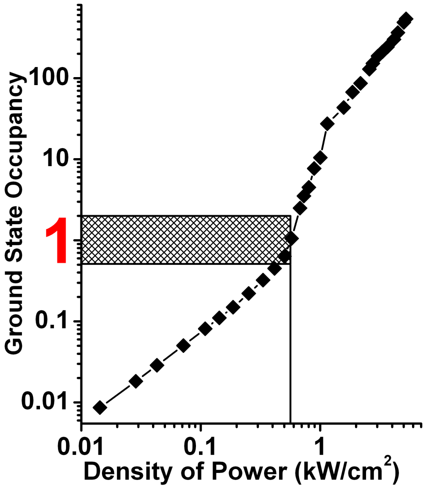

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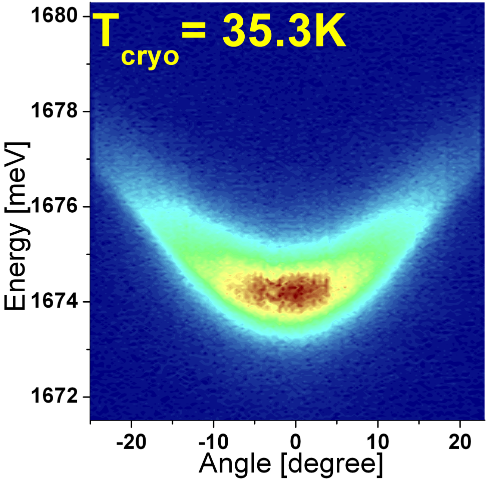
Polariton Condensation in Dispersion Plane

Temperature as a Control Parameter

P=const, T_C Exists !



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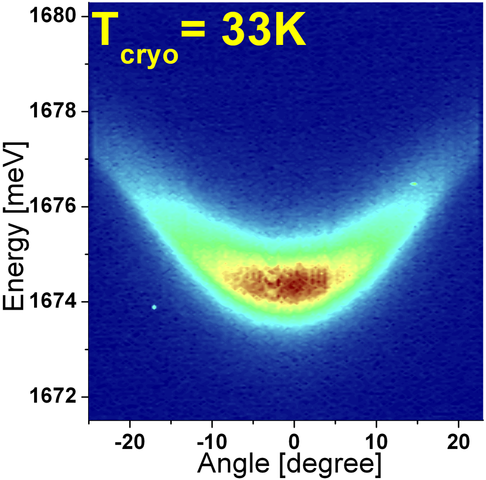

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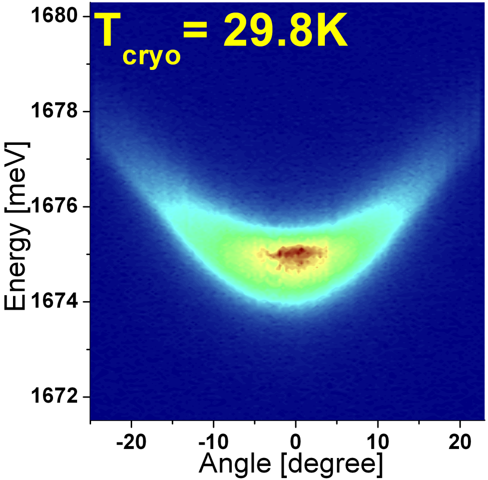

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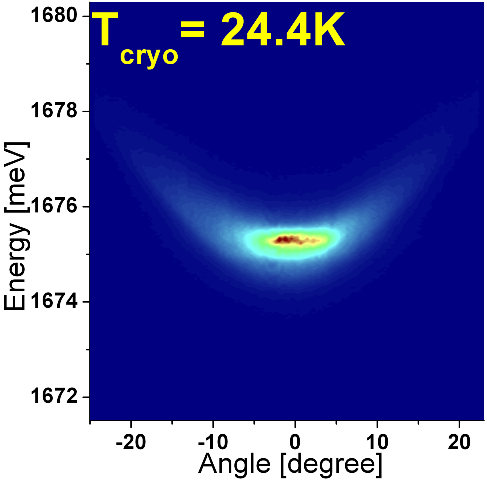

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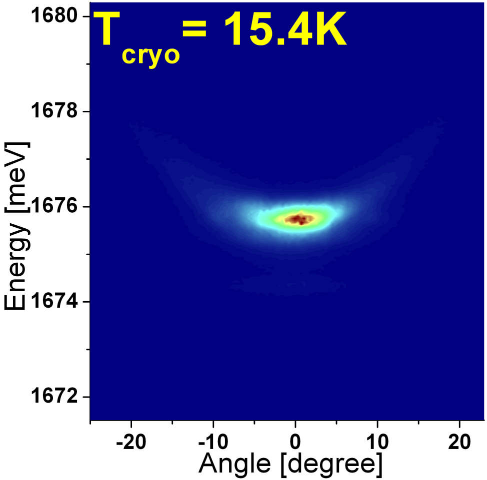

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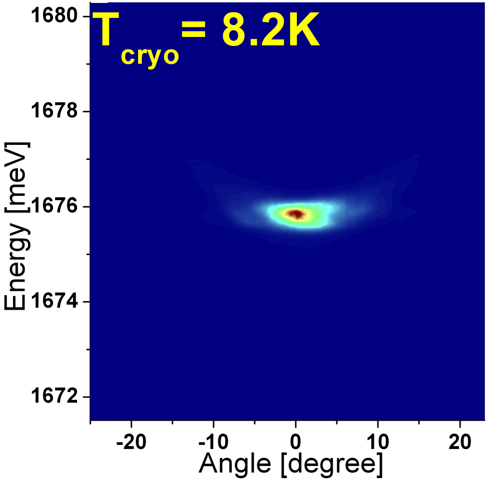

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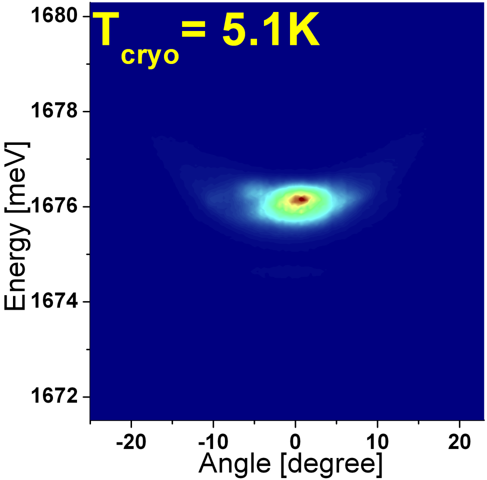
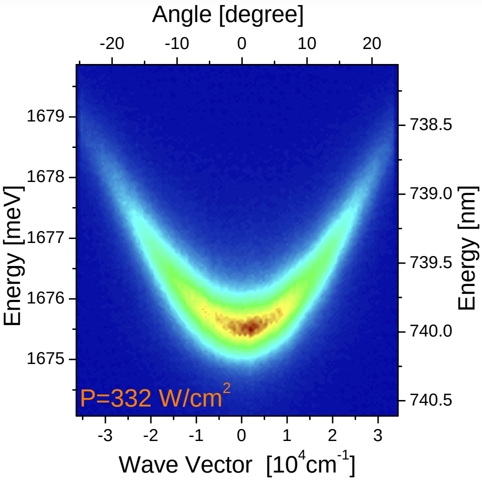


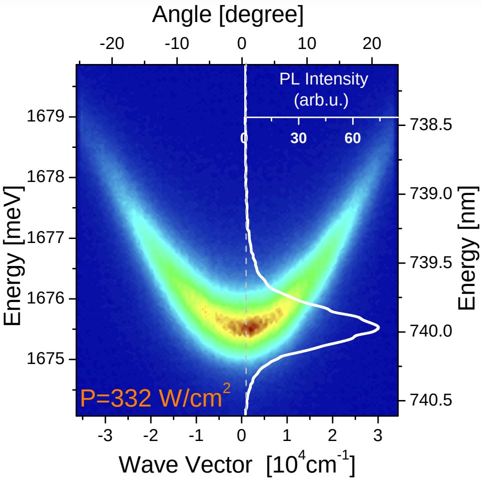
Plan

Thermalized Polariton Gas ??



- Energy, **E**
- Number of Photons
  ⇒Occupation, **n**
- Statistics **n(E)**

Thermalized Polariton Gas ??



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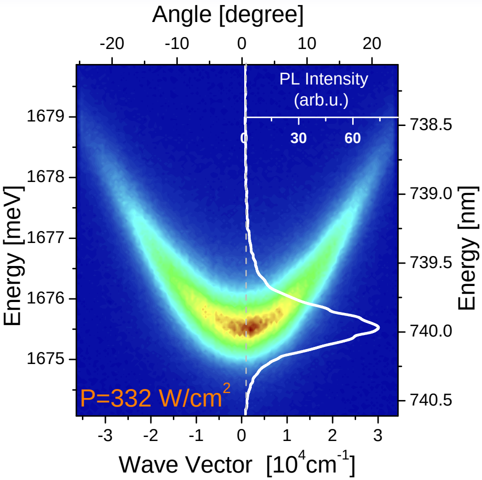

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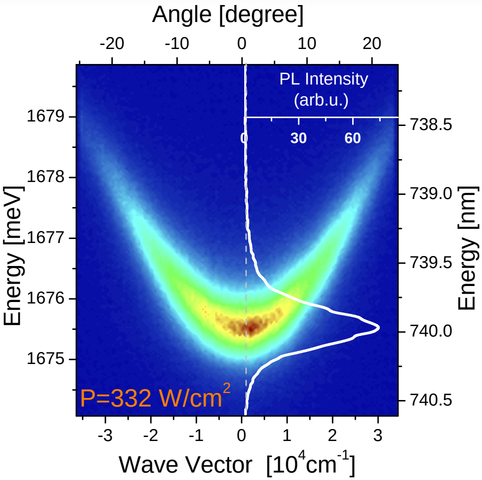
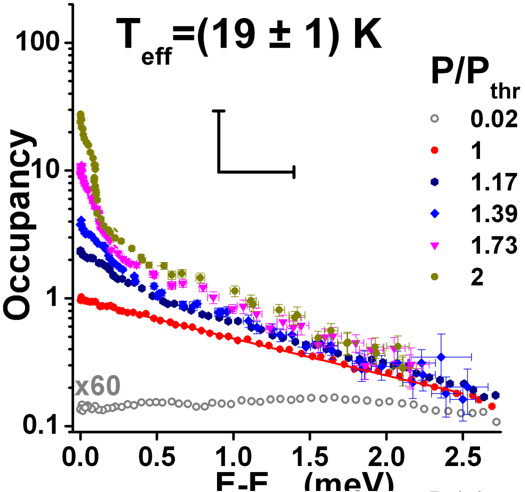


- Energy, **E**
- Number of Photons
  $\Rightarrow$Occupation, **n**
- Statistics **n(E)**

Internal Temperature of the Polariton Gas

… In from the cold: $T_{C\ Polariton} \simeq 100\,000\,000 x T_{C\ Atom}$

Critical Density: $N_{C\ Polariton} \simeq 5 \times 10^8 cm^{-2}$

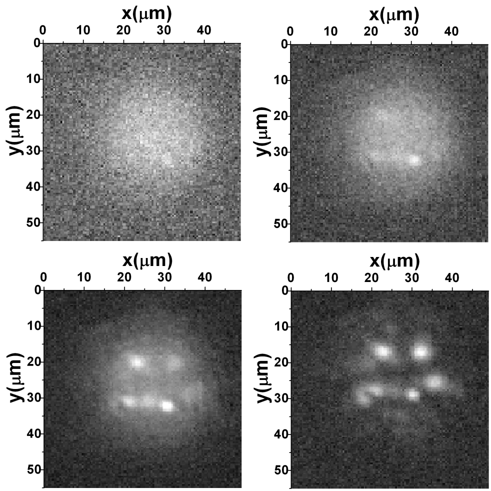


Plan

1. Condensation Phenomenon
2. Why Polariton Condensation ?
3. **Demonstration of the Polariton Condensation**
   - Massive Occupation (N,T)
   - Thermalization
   - **Long Range Spatial Coherence**
4. Discussion
   - Single State
   - Quantum State

Condensation in Real Space

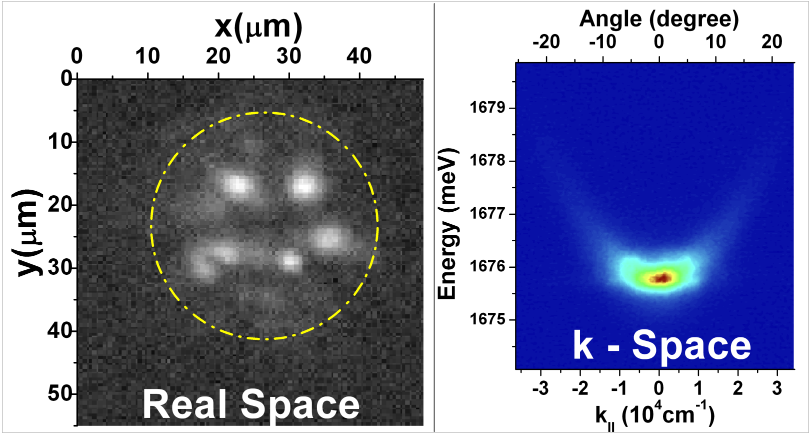
Condensation in Real Space



Spatial Localization by the Photonic Disorder

Long Range Spatial Coherence

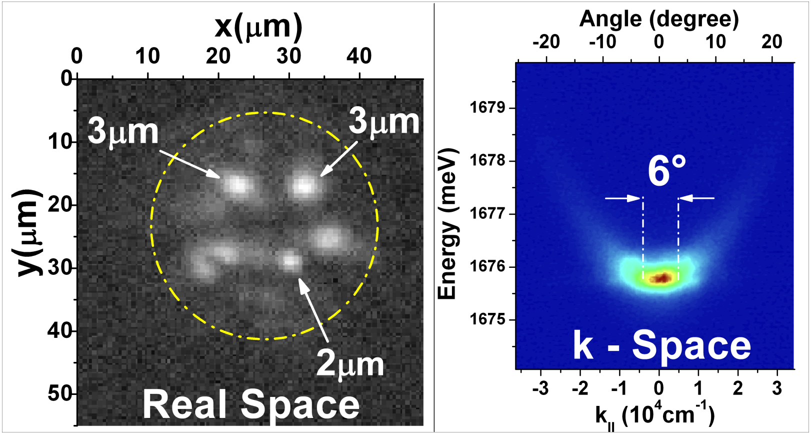
M. Richard et al. PRB 72, 201301(R), 2005



Mutual Coherence Between Localized Spots

Long Range Spatial Coherence

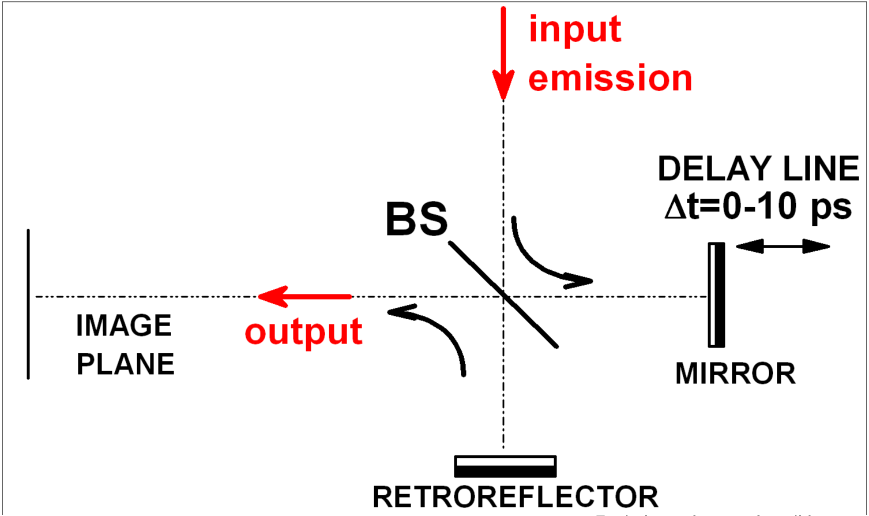
M. Richard et al. PRB 72, 201301(R), 2005



Mutual Coherence Between Localized Spots

Long Range Spatial Coherence

Michelson Interferometer



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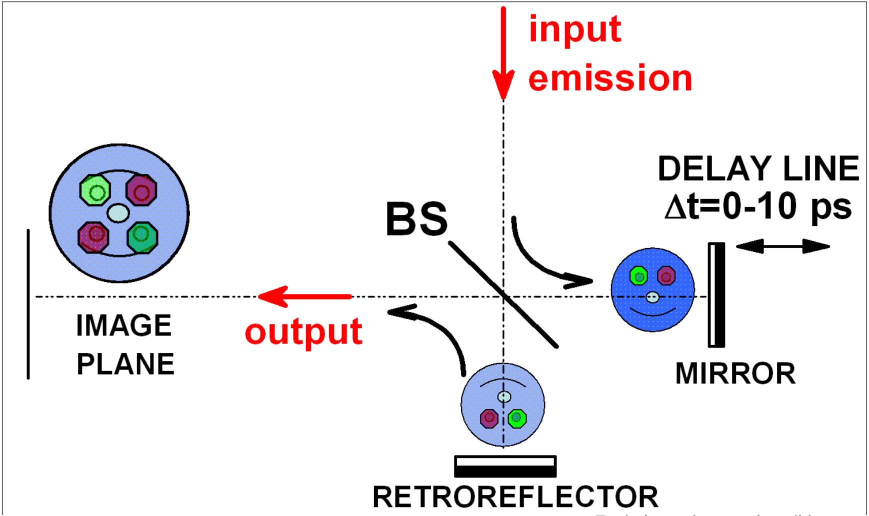
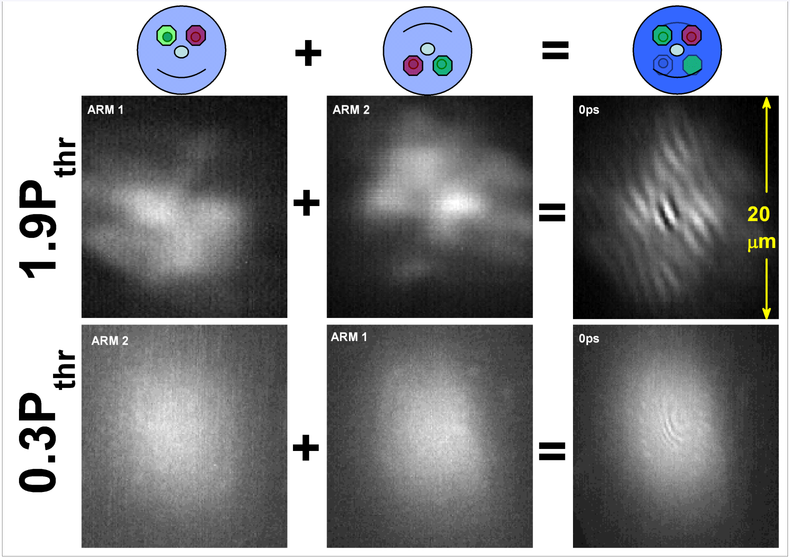


Long Range Spatial Coherence

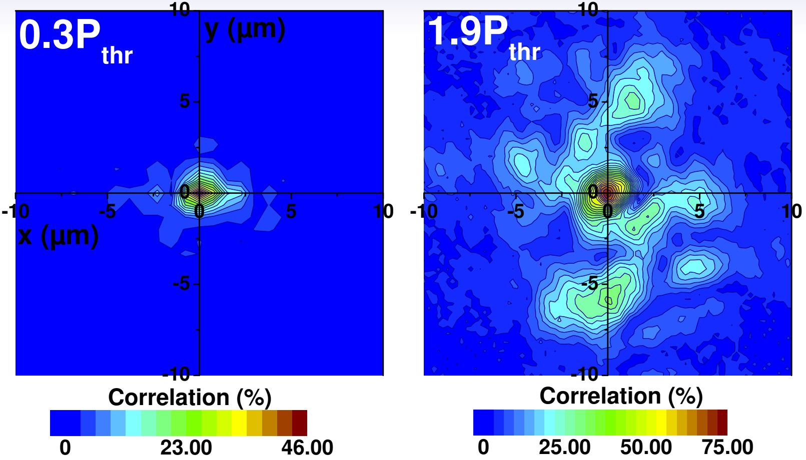
Interference over the Entire Excitation Spot



Long Range Spatial Coherence

Probing of the Phase...

Mapping of the First Order Correlation



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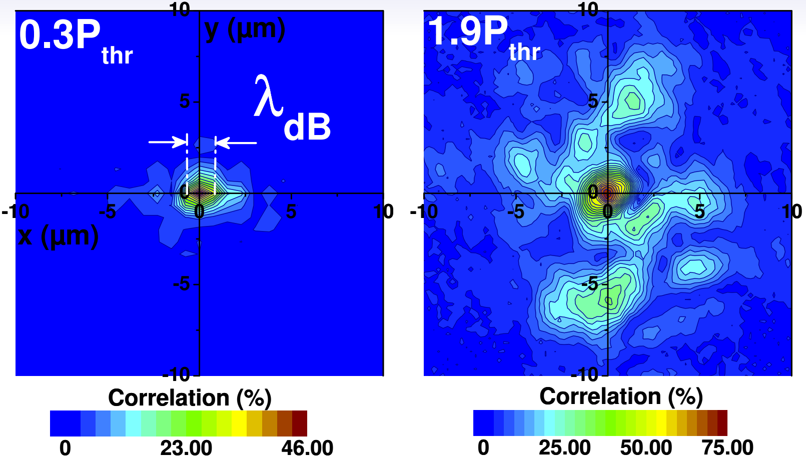

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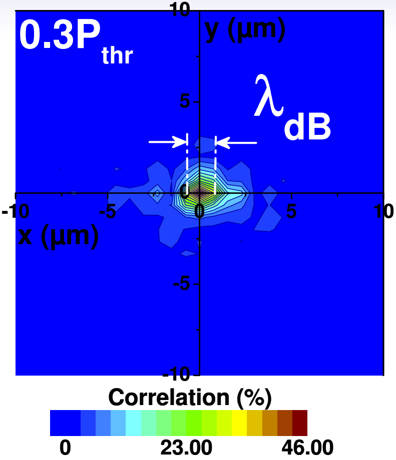

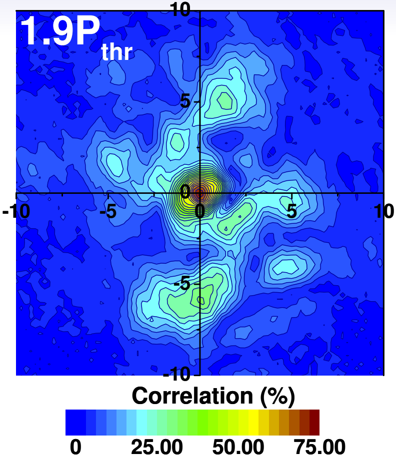

Long Range Spatial Coherence

Outline

1. Condensation Phenomenon
2. Why Polariton Condensation ?
3. Demonstration of the Polariton Condensation
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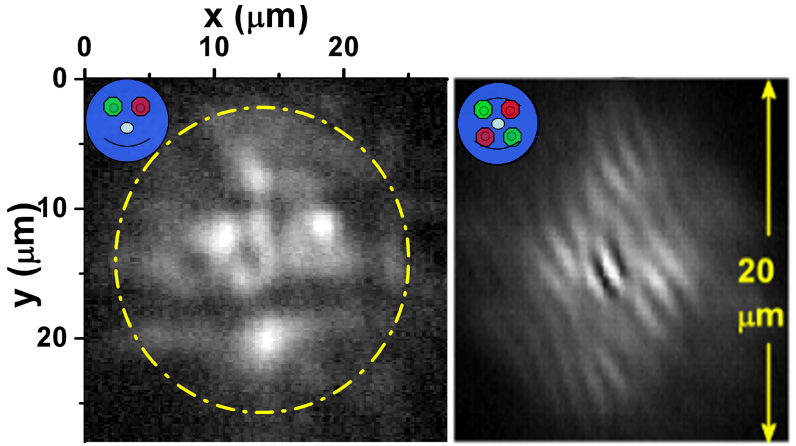
Plan

Condensation into the Single State ??



Stationary Interference Pattern !!

Condensation into the Single State ??

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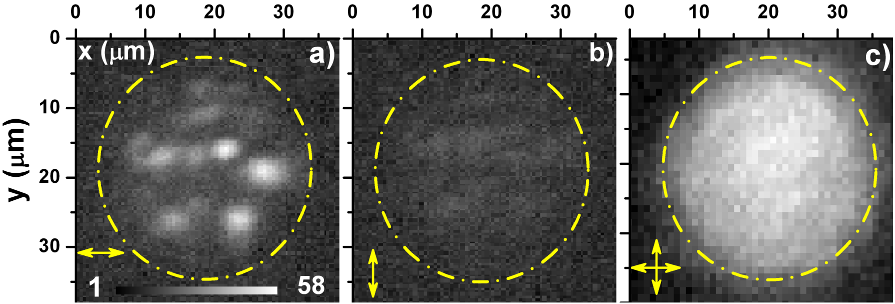
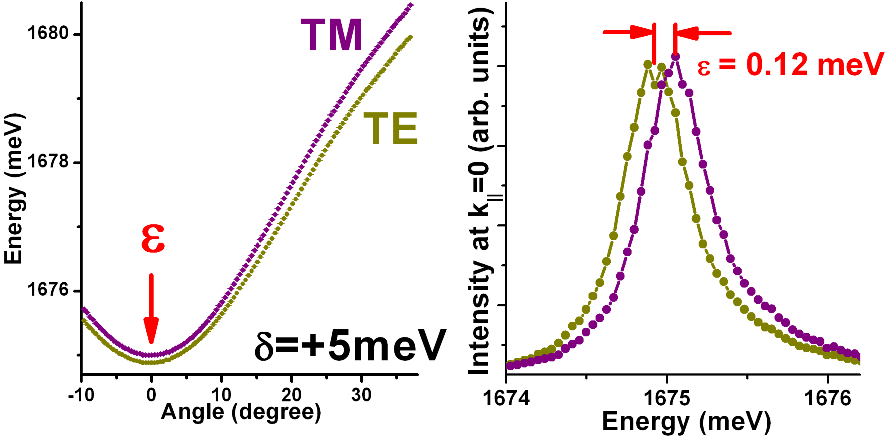
Condensation into the Single State ??



Homogenous Linear Polarization

Condensation into the Single State ??



Ground State Splitting

$$\varepsilon \simeq 0.12meV \ll kT \simeq 1.6meV$$

Plan

Condensation into the Quantum State ??

Photon Statistics ⇒ Intensity Correlation

Second Order Coherence

$$g_2(\tau) \propto \langle I(t) \cdot I(t+\tau) \rangle_t$$

Source	Statistics	$g_2(\tau = 0)$	$g_2(\tau = \infty)$
Coherent	Poisson	1	1
Thermal	B-E	2	1

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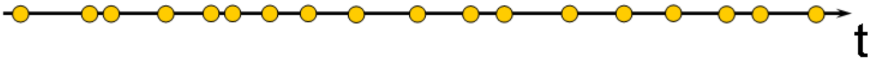

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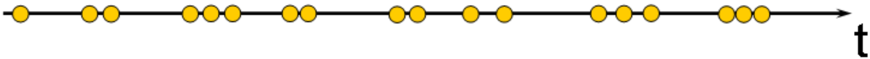

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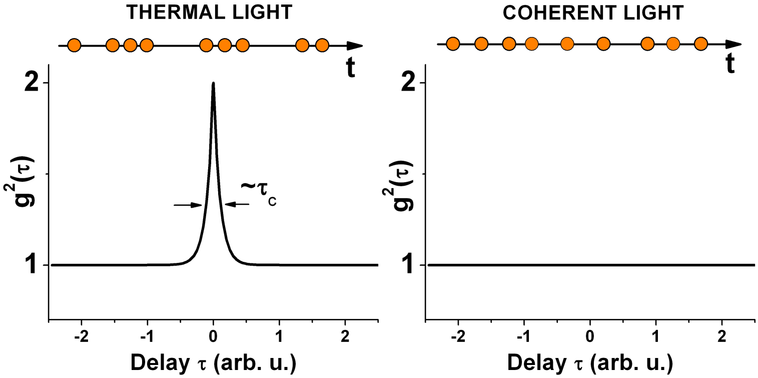
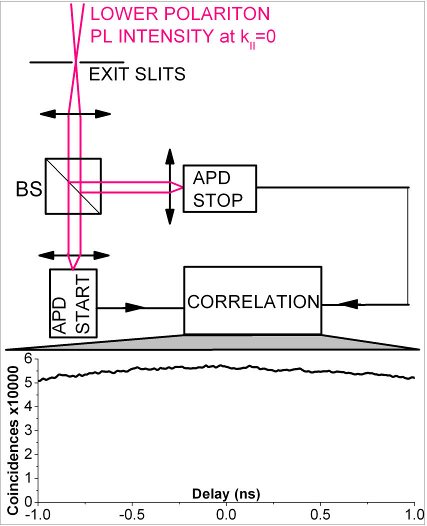
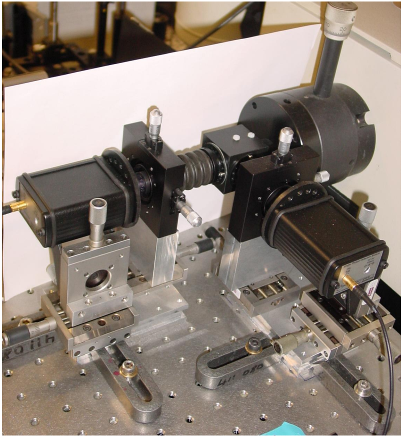


Intensity Correlation

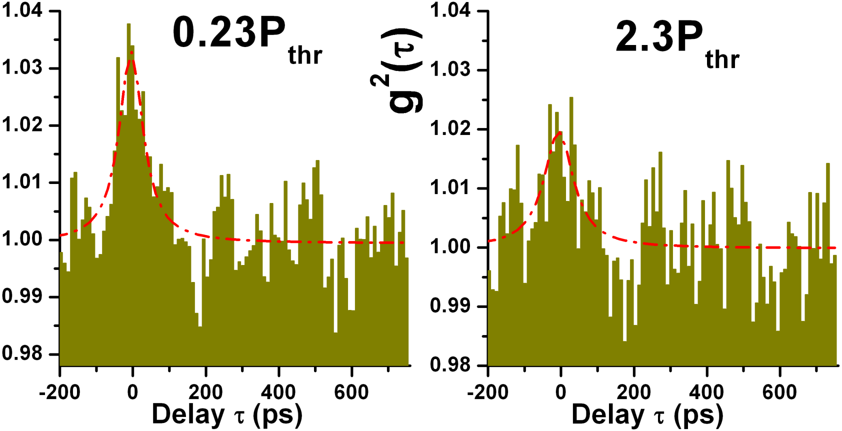
Experimental Setup





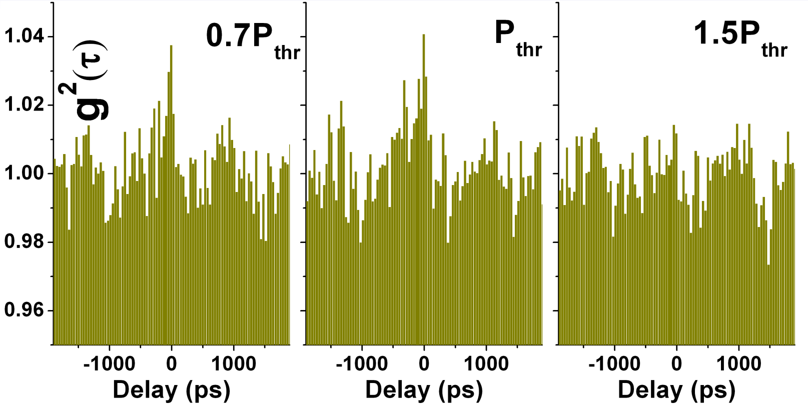
Intensity Correlation

Reduction of the Bunching



Build up of the Second Order Coherence

Intensity Correlation



Transition from Thermal towards Coherent State

Conclusions

Realization of the Polariton Condensation

- Thermalization $T_{eff} = (16 - 20)K$
- Massive Occupation of the Ground State
- Saturation of the Excited States
- Long Range Spatial Coherence
- Homogenous, Linear Polarization of the Condensate
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Alternatives for spontaneous coherence in solids

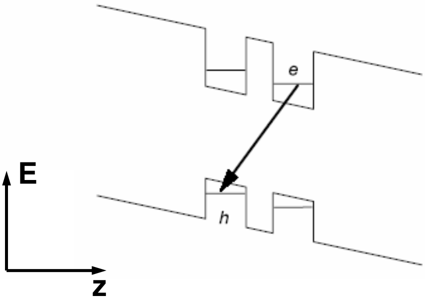
Indirect excitons in coupled quantum wells

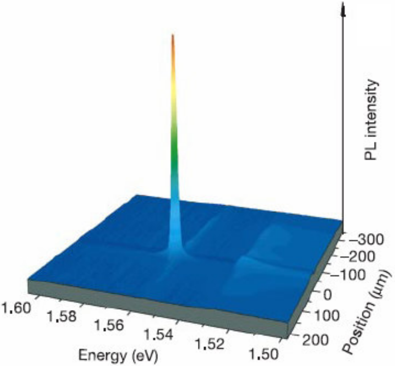
Spatial Separation

Long Lifetime: $10^{-7}s$

Coherence, Statistics

?????





Butov et. al., Nature, 214, 47 (2002)

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Long Lifetime: $10^{-7}s$

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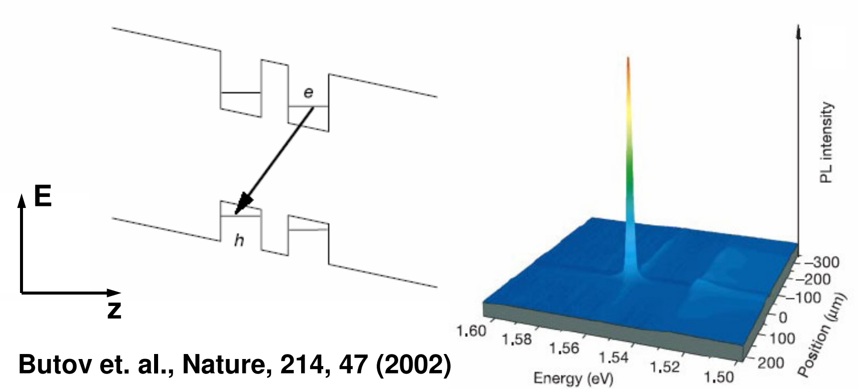
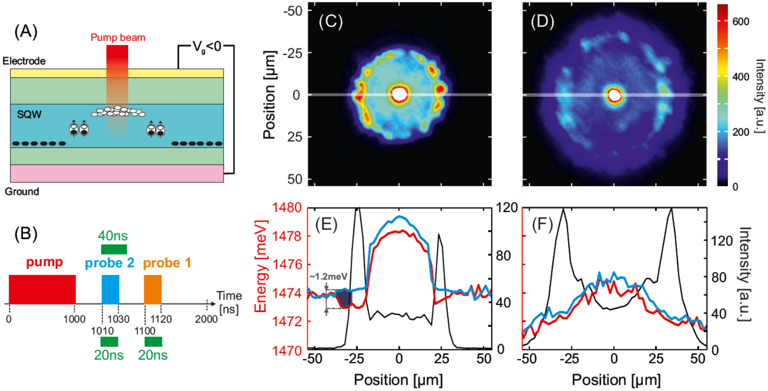


Butov et. al., Nature, 214, 47 (2002)

Alternatives for spontaneous coherence in solids

Excitons in a 25 nm GaAs QW in a field-effect device:
electrons and holes are spatially separated



Evidence for a BEC of excitons at 500 mK, EPL (2014)

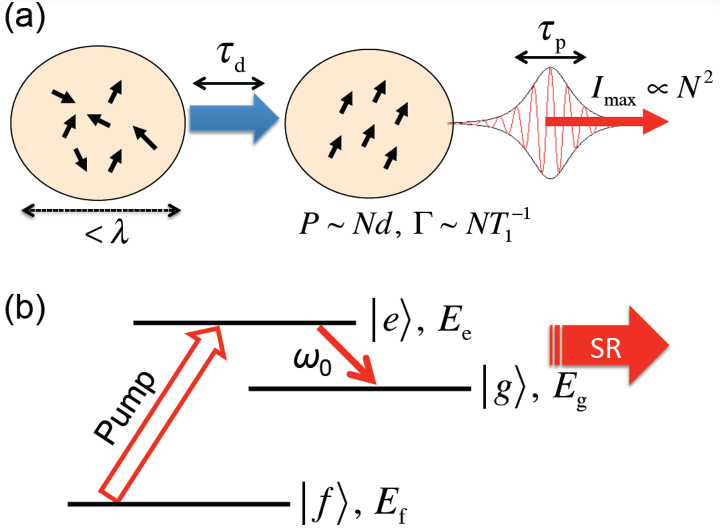
Exciton gas in spatial traps, linear polarization, spatial coherence

Alternatives for spontaneous coherence in solids

Superradiance ⇒ **spontaneous and self-organized build up of coherent radiation within an ensemble of quasi-degenerate emitters** [M. Gross and S. Haroche, Physics Reports 93, 301 (1982)]. It was first noted by R. Dicke back in 1954 [Phys. Rev. 93, 99 (1954)] that, with increasing their density, the collection of N emitters starts to radiate much faster and stronger comparing to spontaneous emission of individuals or their diluted ensemble. More precisely, when packing up N identical emitters into a volume of size much smaller than the radiation wavelength, instead of observing isotropic and exponentially decaying emission, one produces a fierce, directional radiation blast, having a lagged peak intensity scaling like N^2 and N-times reduced duration with respect to the spontaneous emission.

Alternatives for spontaneous coherence in solids

Superradiance in Solids, J. Kono JOSAB (2016)



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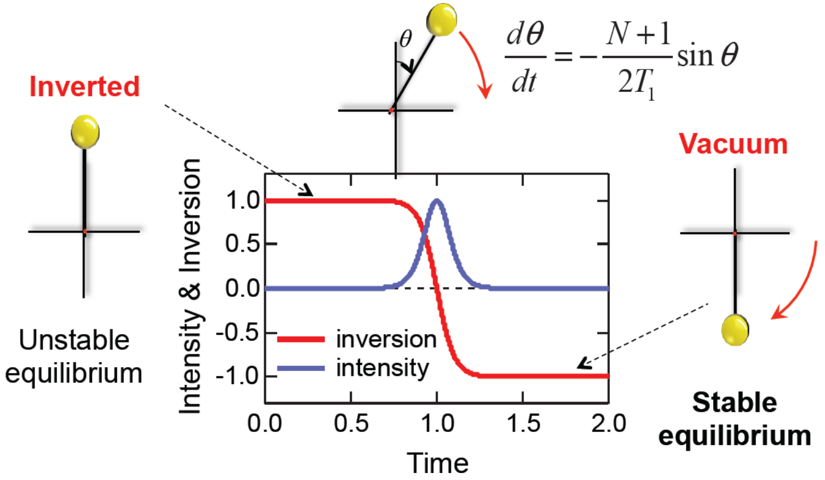
Superradiance in Solids, J. Kono JOSAB (2016)



Alternatives for spontaneous coherence in solids

Superradiance in Solids: most convincing examples

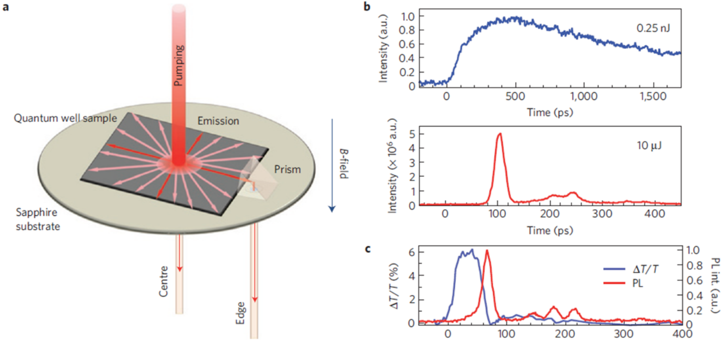
nature physics

ARTICLES

PUBLISHED ONLINE: 29 JANUARY 2012 | DOI: 10.1038/NPHYS2207

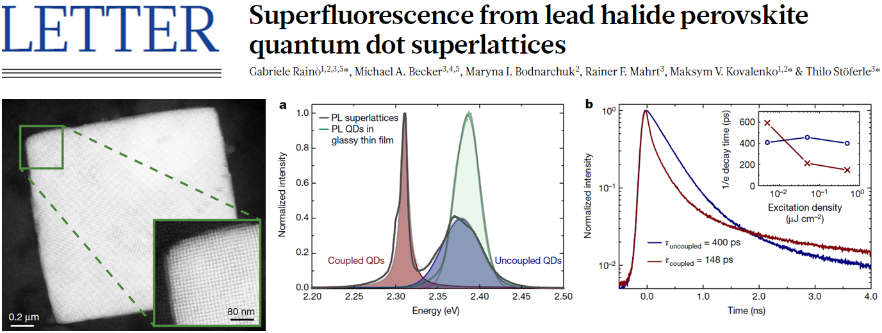
Giant superfluorescent bursts from a semiconductor magneto-plasma

G. Timothy Noe II[1], Ji-Hee Kim[1], Jinho Lee[2], Yongrui Wang[3], Aleksander K. Wójcik[3], Stephen A. McGill[4], David H. Reitze[2], Alexey A. Belyanin[3] and Junichiro Kono[1]*



Alternatives for spontaneous coherence in solids

Superradiance in Solids: most convincing examples


LETTER

Superfluorescence from lead halide perovskite quantum dot superlattices

Gabriele Rainò[1,2,3,5*], Michael A. Becker[3,4,5], Maryna I. Bodnarchuk[2], Rainer F. Mahrt[3], Maksym V. Kovalenko[1,2*] & Thilo Stöferle[3*]

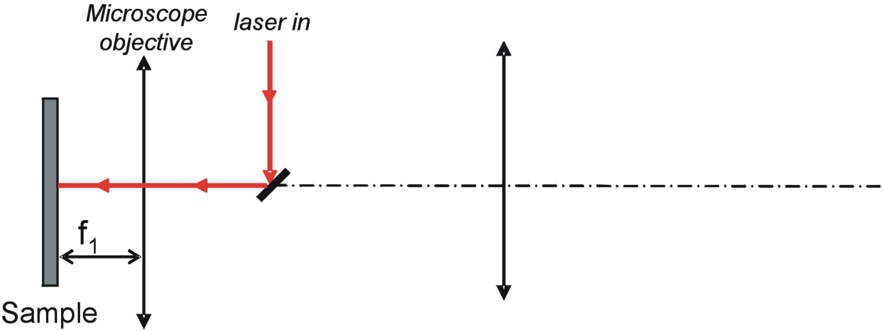
Outline

5 Appendix

Plan

Imaging

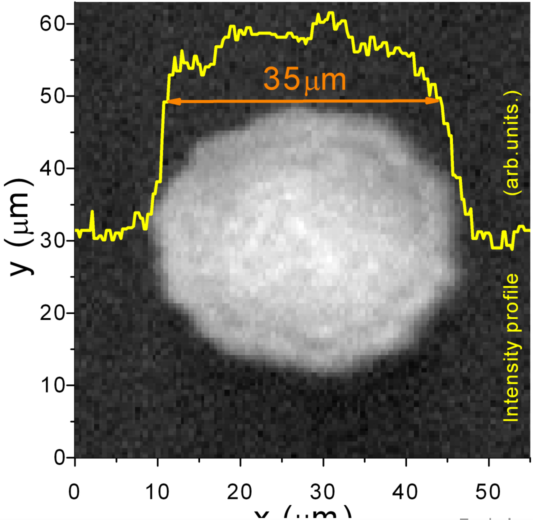
Excitation - Ti:Sapphire, CW



Far Field

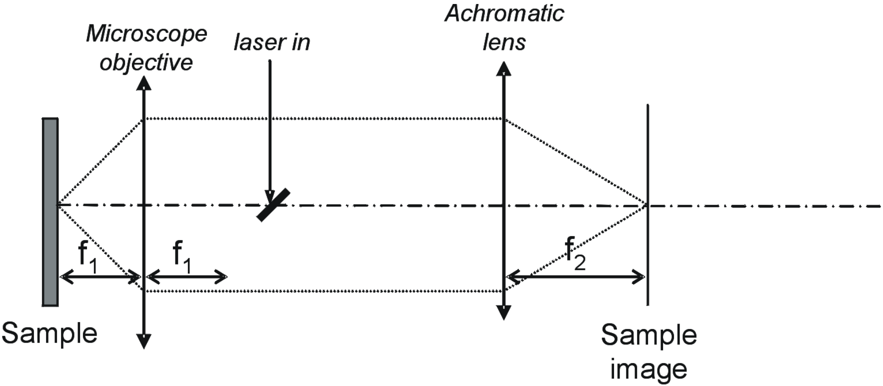
Excitation

"Top Hat" Spot $\sim 30\mu m$



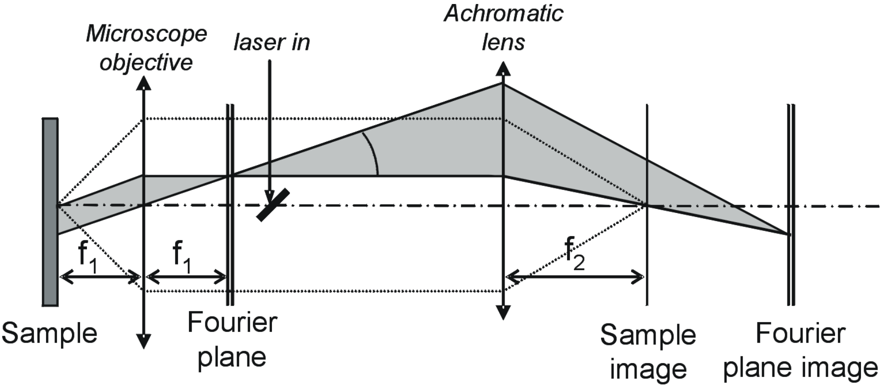
Imaging

Near Field: Sample Image - $f_1 = 9mm$, $N.A. = 0.4$



Far Field

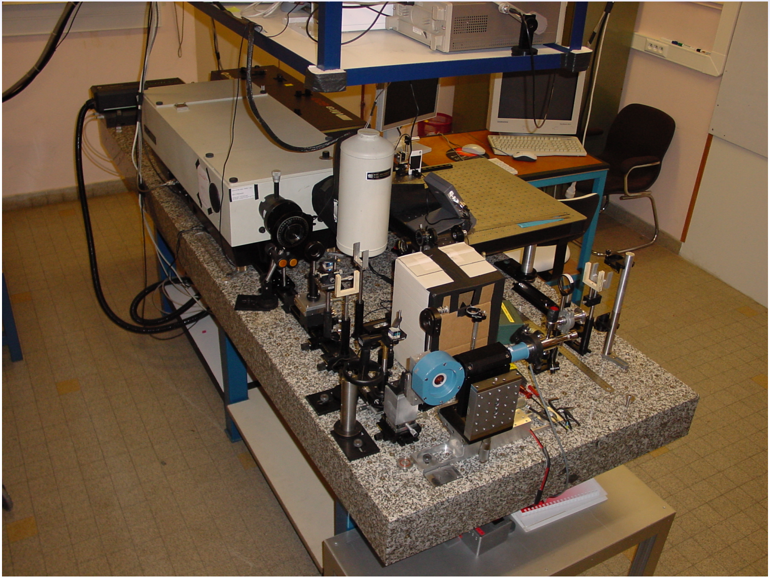
Imaging
Far Field: Fourier Plane Image



Far Field

Experimental Setup - Photos

Experimental Setup - Photos



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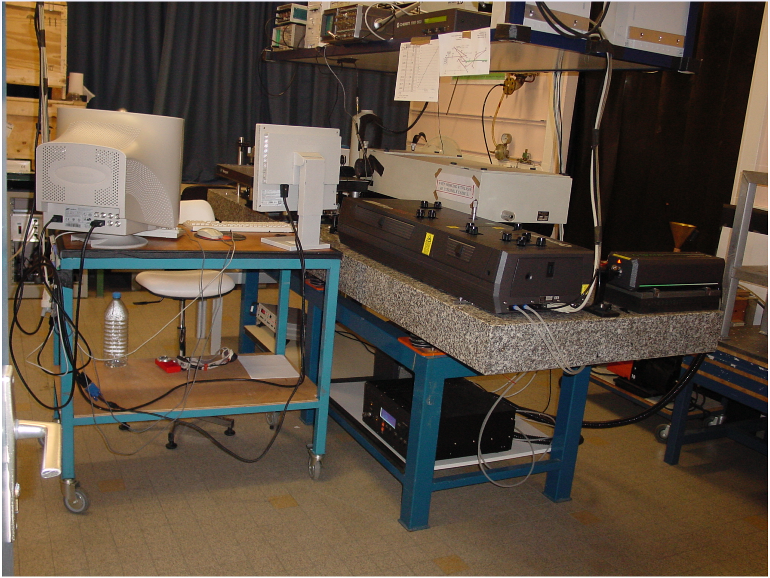
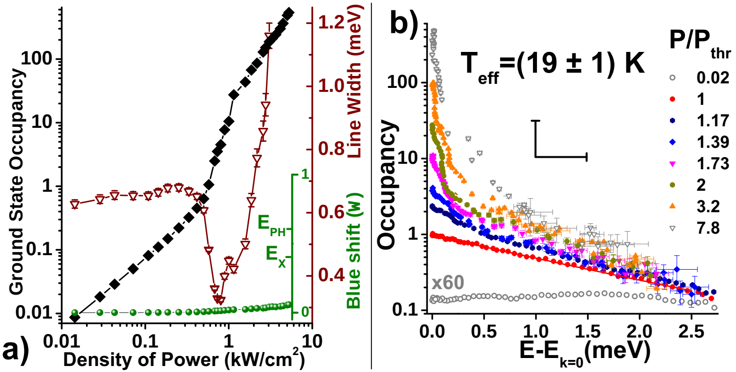


Plan

5 Appendix

Polariton Condensation in Momentum Space

Threshold, Linewidth, Blueshift, Statistics



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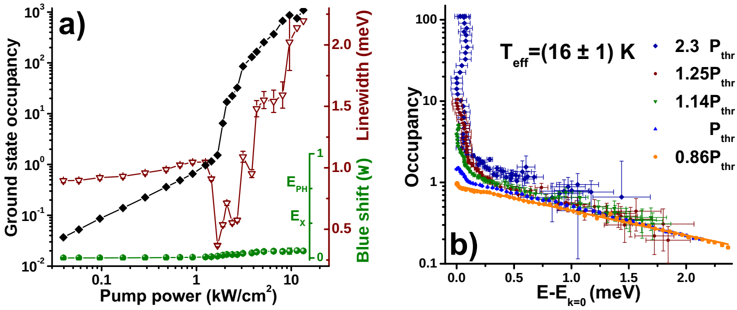
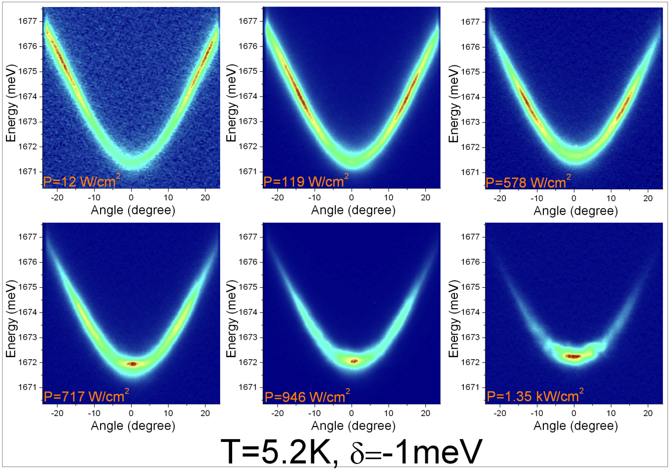


Plan

How to get Thermalization ??

Role of Detuning



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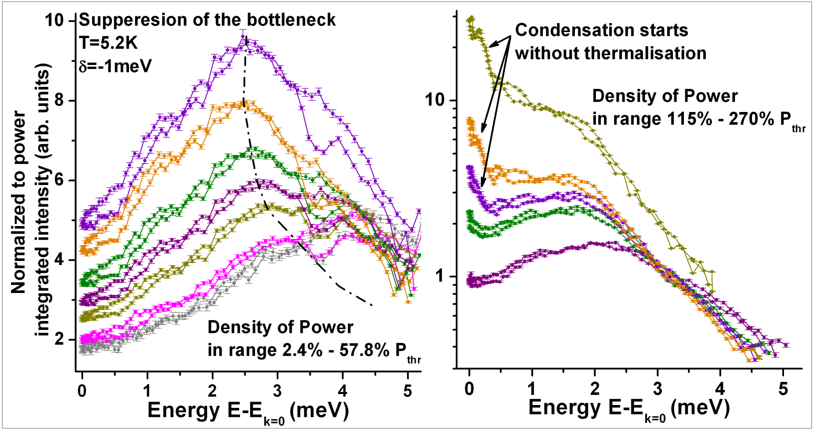
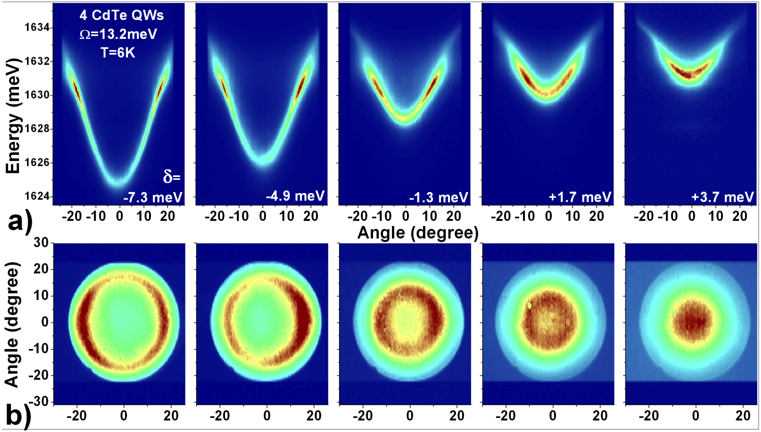


Positive Detuning

Shallower Trap, High X Fraction $\Rightarrow$ Enhanced Relaxation



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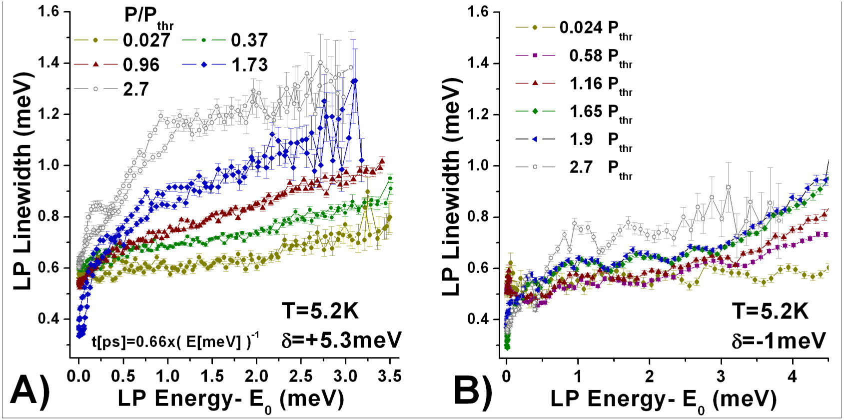
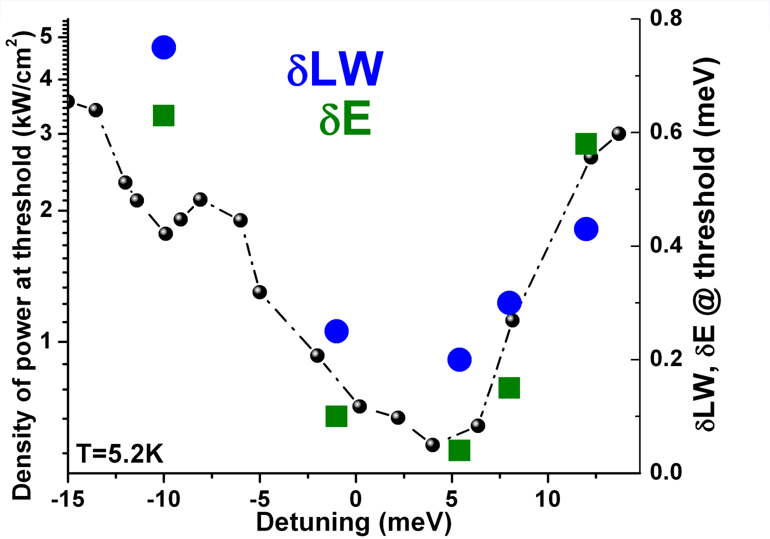


Plan

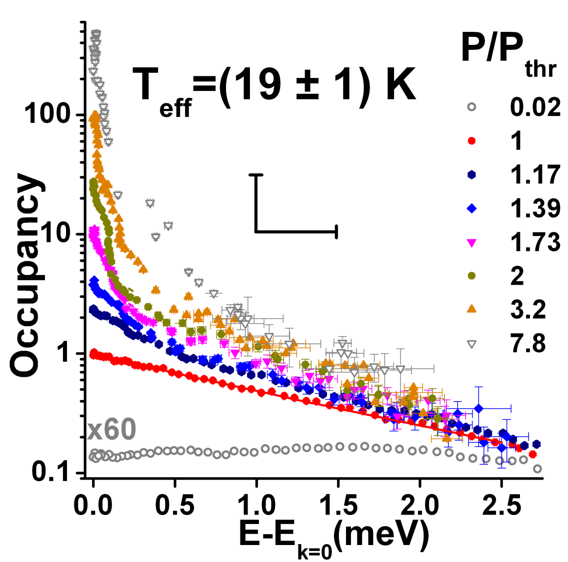
Influence of the reservoir on the ground state



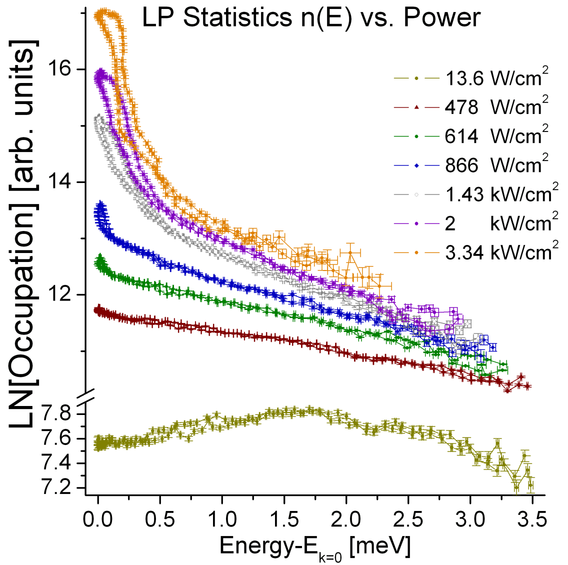
Plan

5 Appendix

Depletion of the Condensate ??



Depletion of the Condensate ??



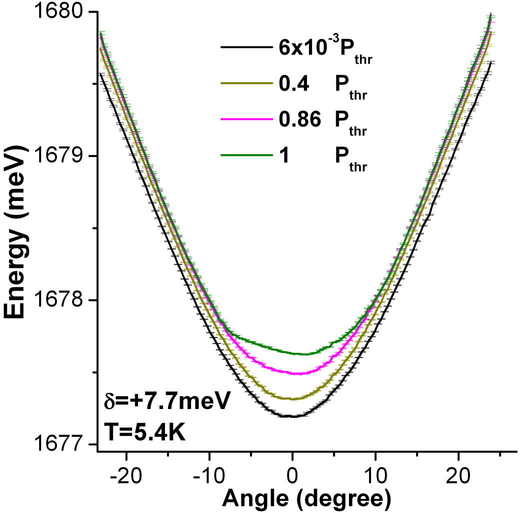
Plan

5 Appendix

Dispersion Flattening at k=0

Localization, Non-equilibrium effects ??

Not a rigid shift !



Dispersion Flattening at k=0

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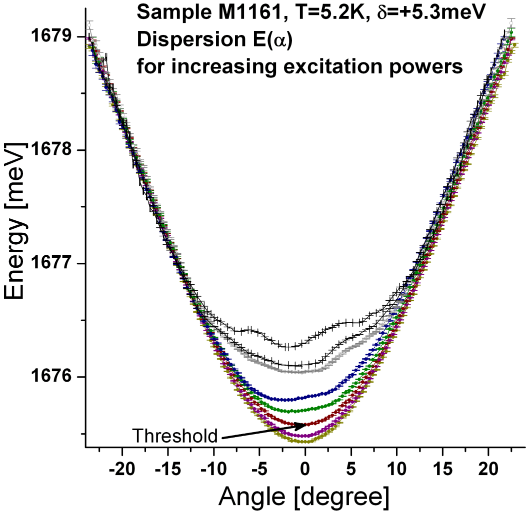
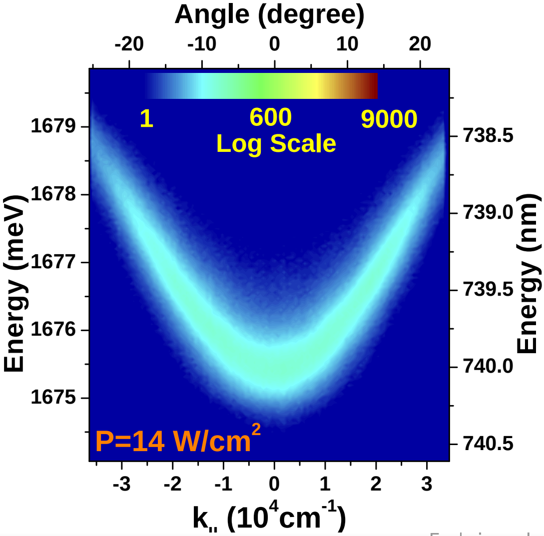


Plan

Polariton Condensation in Momentum Space

Saturation of Excited States

Saturation



Polariton Condensation in Momentum Space

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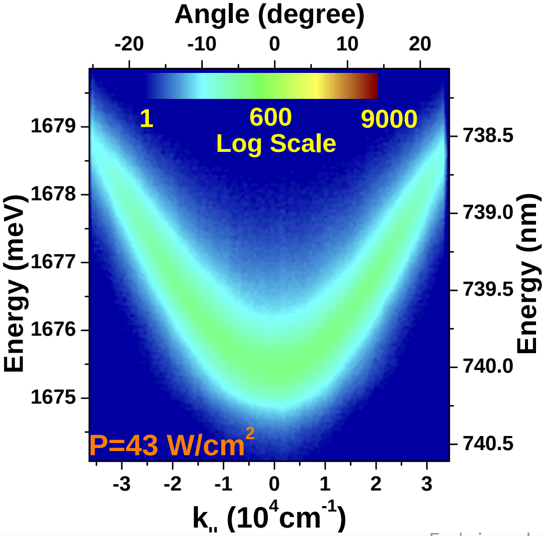
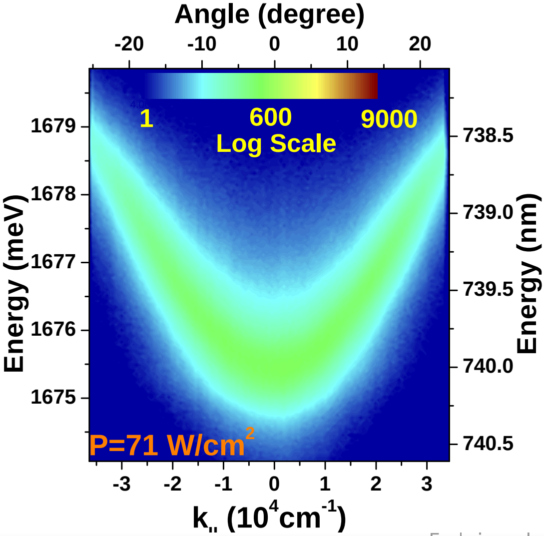
Saturation



Polariton Condensation in Momentum Space

Saturation of Excited States

Saturation



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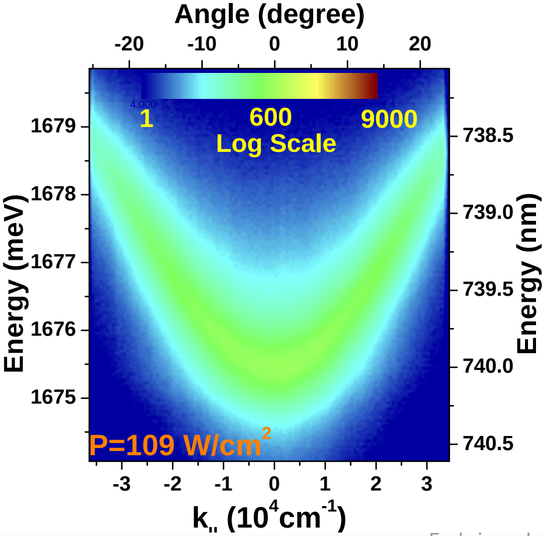
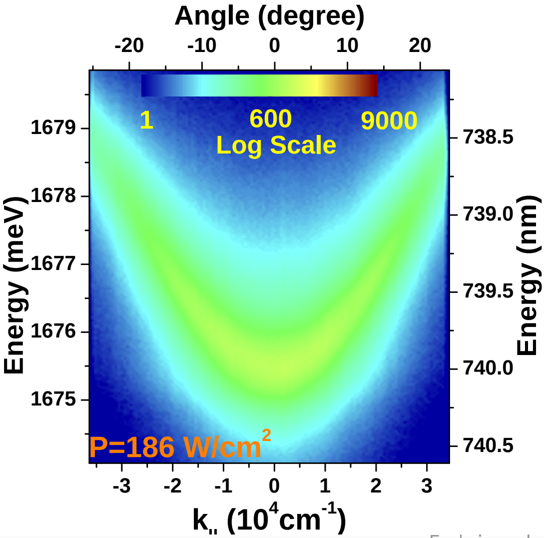


Polariton Condensation in Momentum Space

Saturation of Excited States

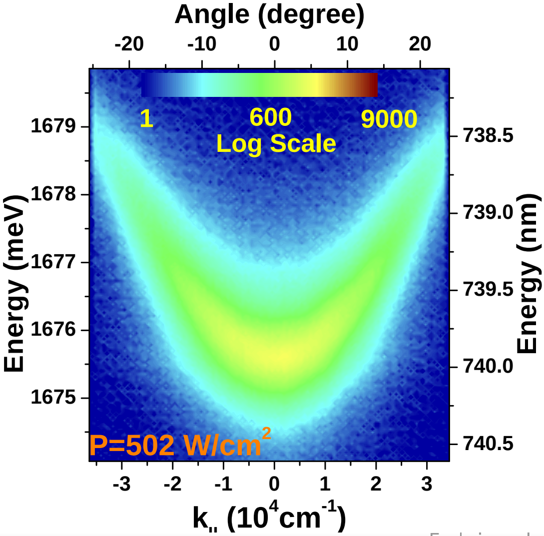
◂ Saturation



Polariton Condensation in Momentum Space

Saturation of Excited States

Saturation



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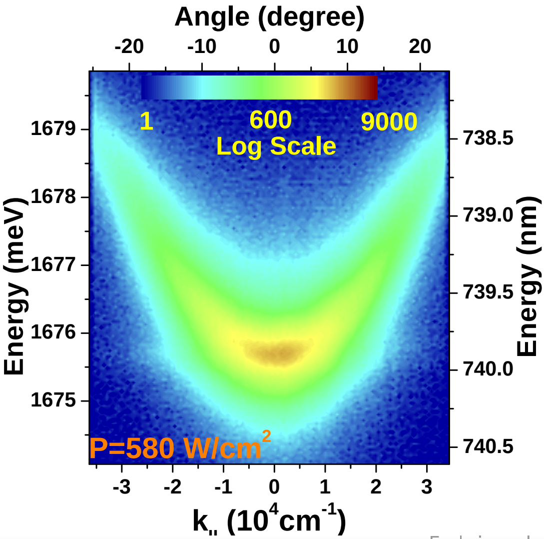

Polariton Condensation in Momentum Space

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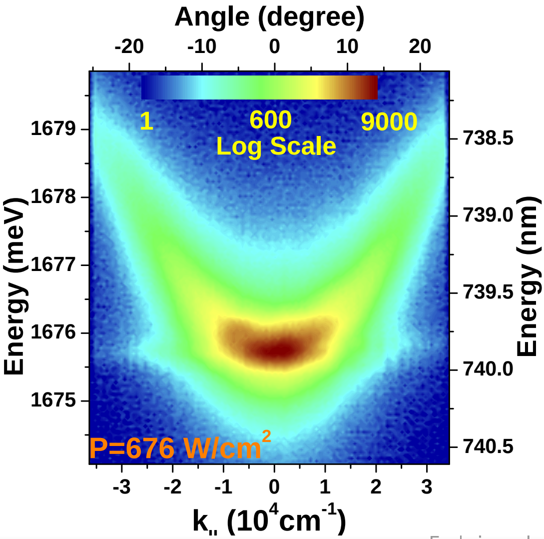
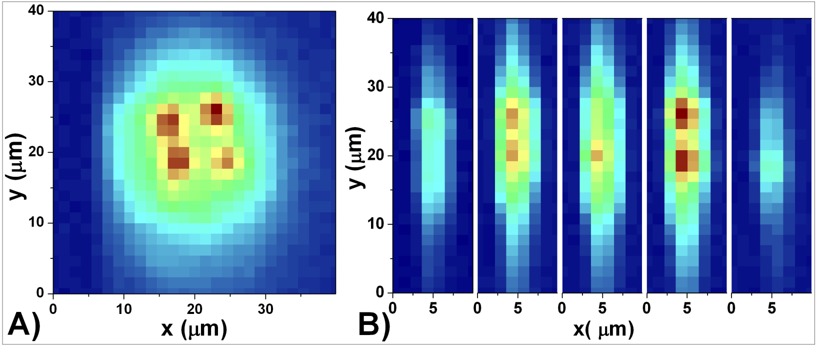
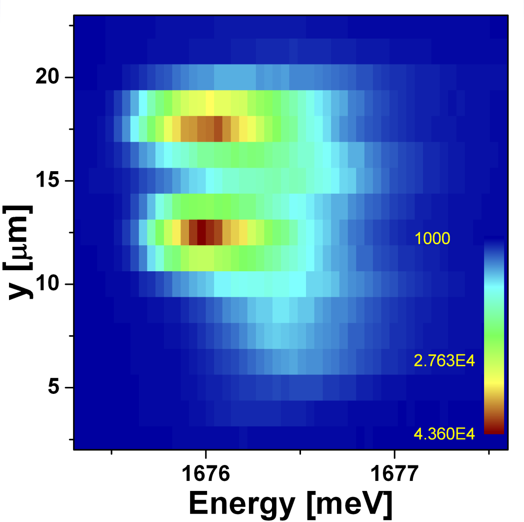


Plan

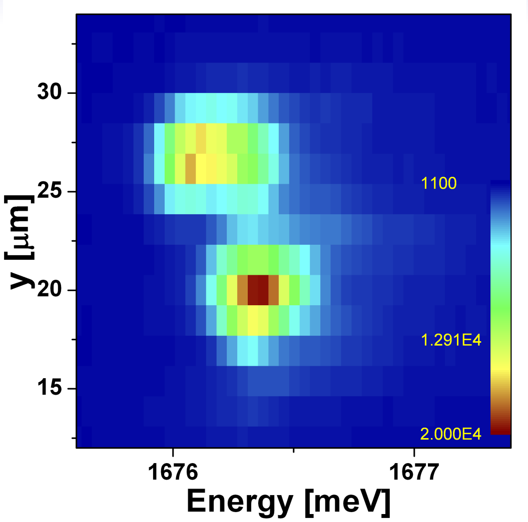
(x, λ)-measurements



(x, λ)-measurements

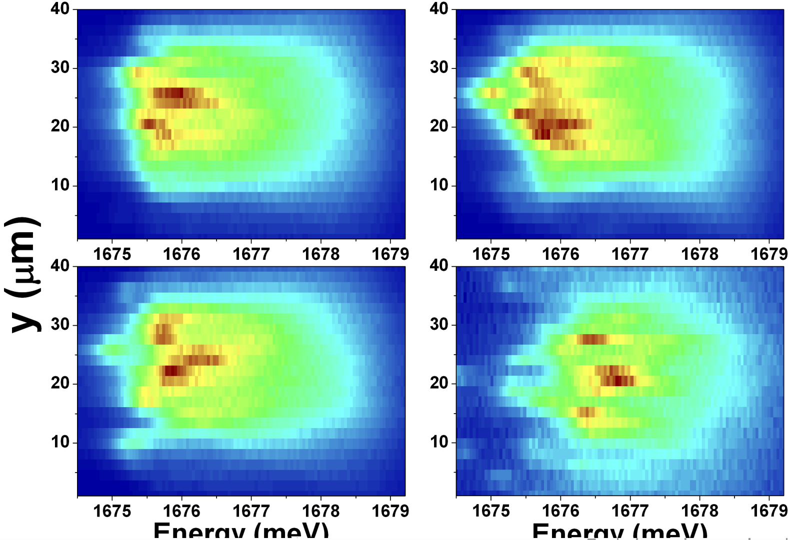


(x, λ)-measurements

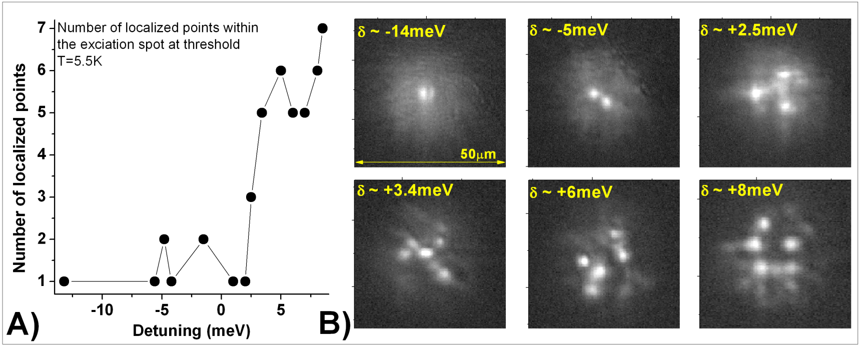


(x, λ)-measurements

Desorder visible below threshold



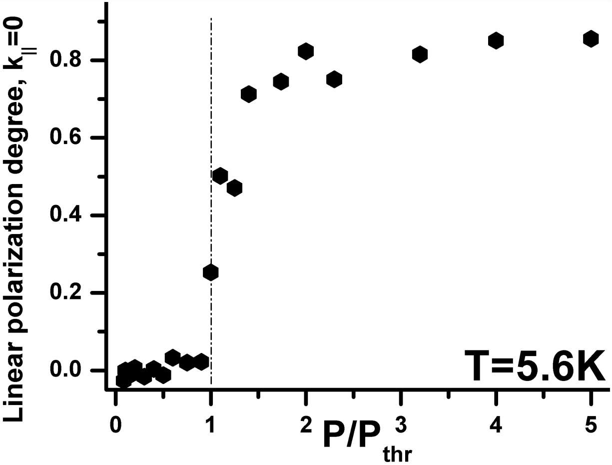
Detuning dependence



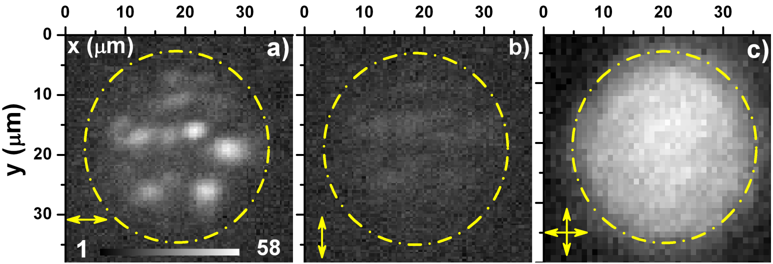
Plan

5 Appendix

Linear Polarization Build-up

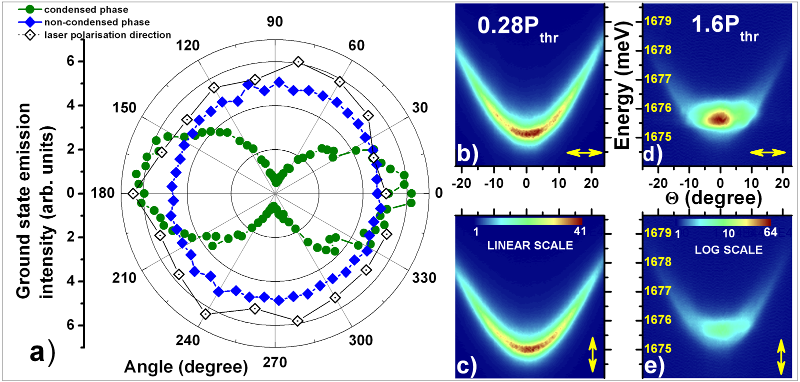


Emission Structure vs. Power vs. Polarization



Linear Polarization Probing

Spontaneous Build-up of Linear Polarization



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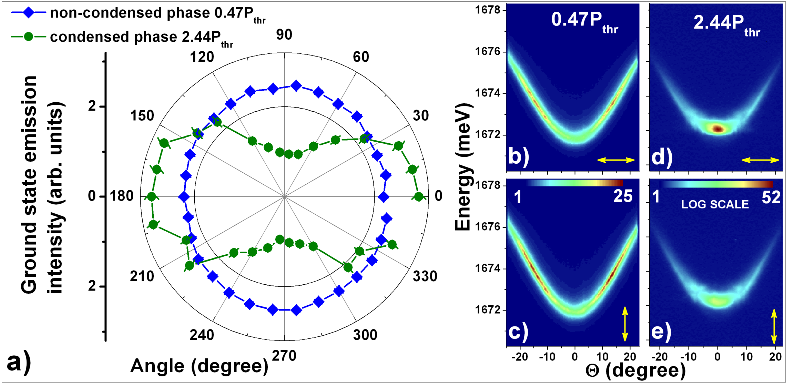
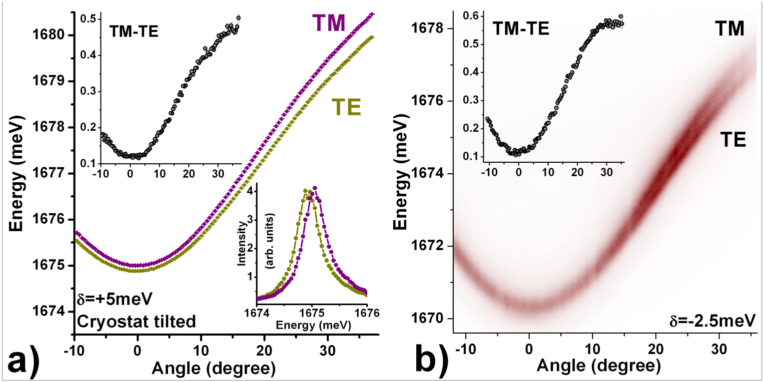


Origin of the Linear Polarization

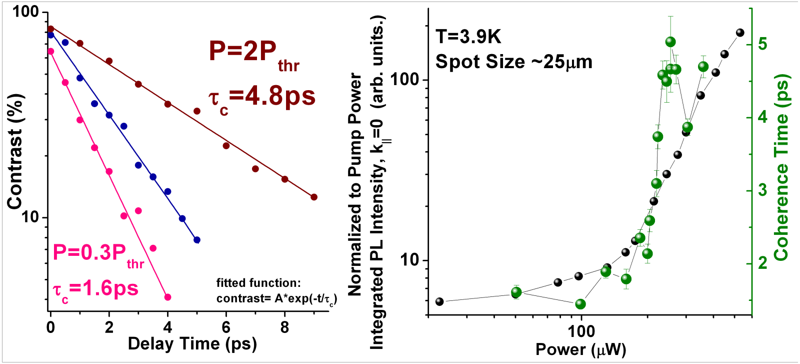
Ground State Splitting



Plan

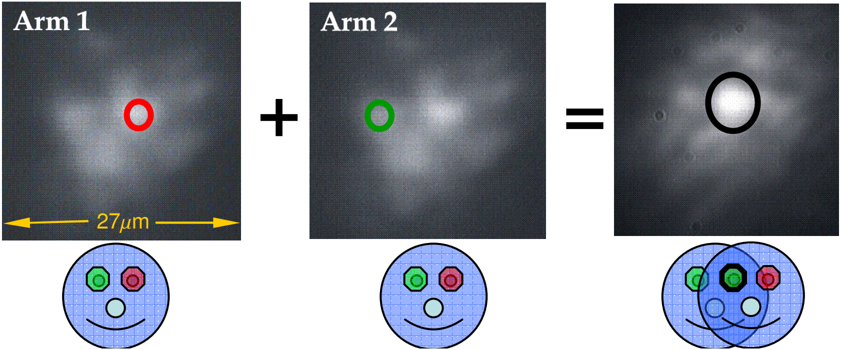
5 Appendix

Temporal Coherence



Spatial Coherence

Interference Between Different Spots



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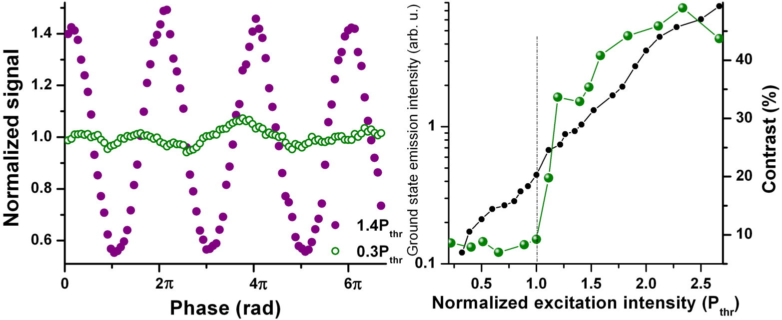
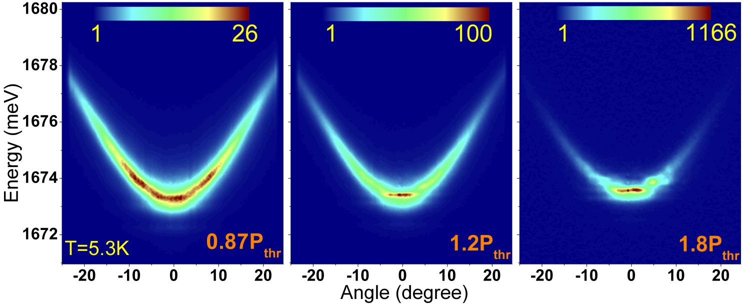


Plan

5 Appendix

Nonequilibrium Polariton Condensation

Non-resonant, Pulsed Excitation



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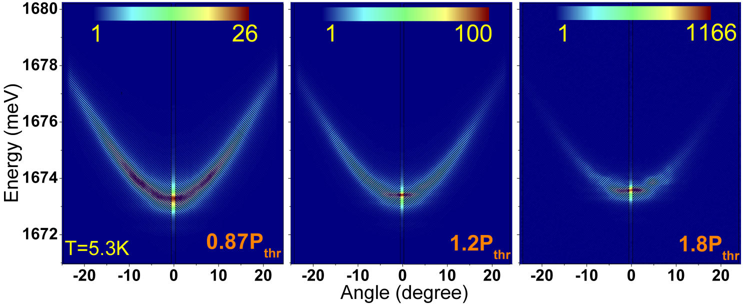
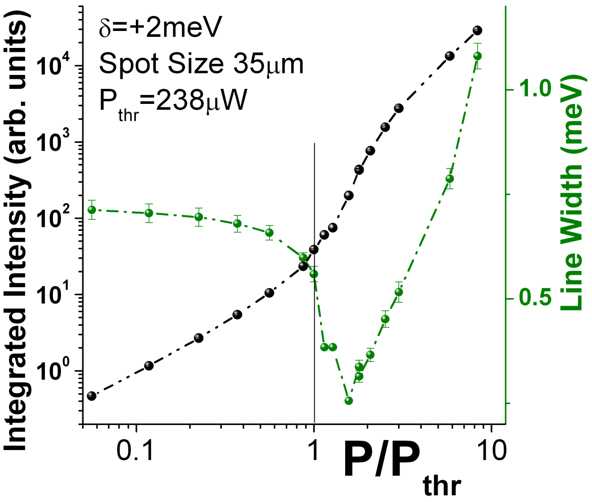


Transition Characteristics

Threshold, Line Width



What Can We Learn From the Photon Statistics

2nd Order Coherence Function

$$g_2(\tau) \propto \langle I(t) \cdot I(t+\tau) \rangle_t$$

Source	Statistics	$g_2(\tau = 0)$	$g_2(\tau = \infty)$
Coherent	Poisson	1	1
Thermal	B-E	2	1

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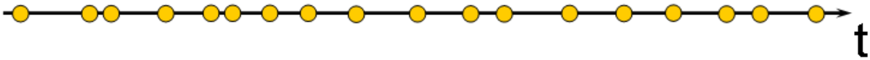
Source
- Coherent
- Thermal

Statistics
- Poisson
- B-E

$g_2(\tau = 0)$
- 1
- 2

$g_2(\tau = \infty)$
- 1
- 1



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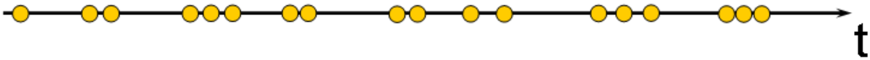
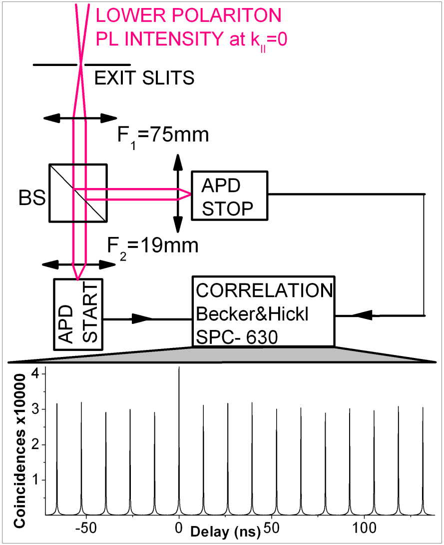
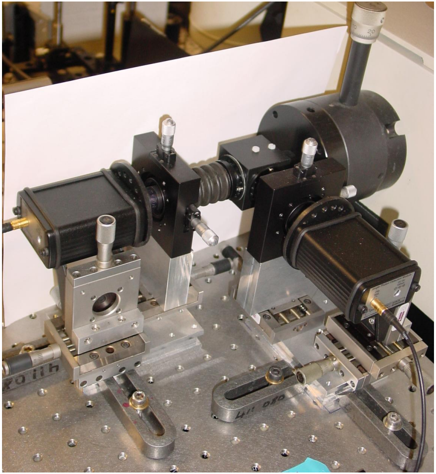
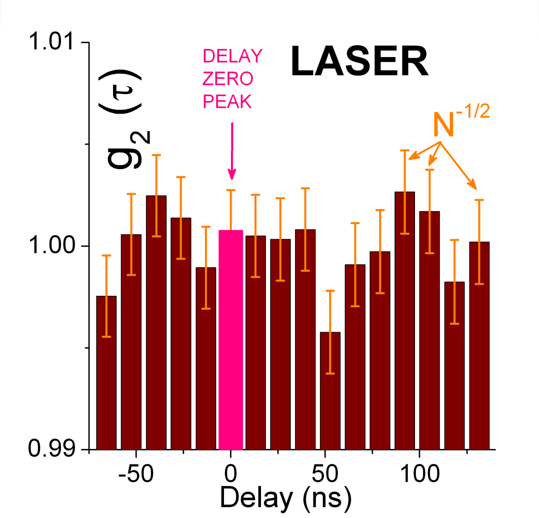


Intensity Correlation Experiment





Laser Check


1.01
1.00
0.99
$g_2(\tau)$
DELAY
ZERO
PEAK
LASER
$N^{-1/2}$
-50
0
50
100
Delay (ns)

What Do We Expect ?

Characteristic Timescales

P/P_{thr}	Decay Time [ps]	Coherence Time [ps]	Expected Bunching
< 1	100-200	1-2	1%
$(1, 2)$	7	5-7	No Bunching
> 2	3-7	1	$10 - 30\%$

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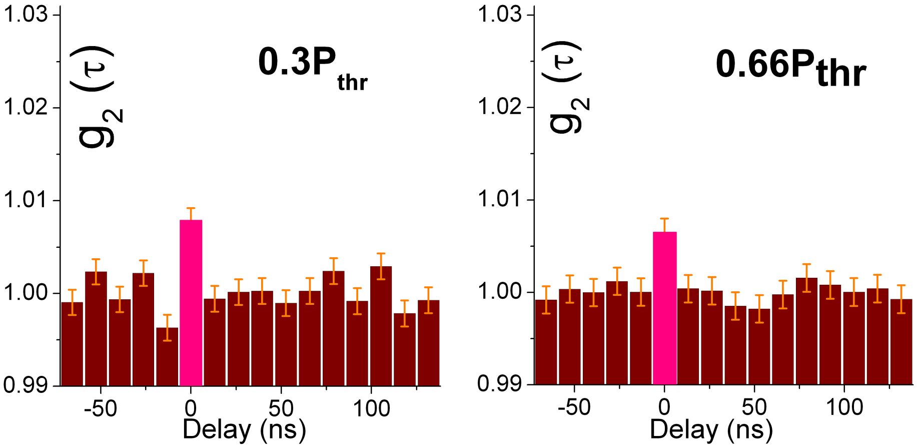
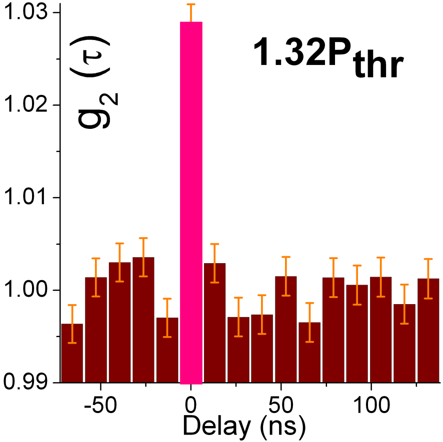
Result - $g_2(\tau = 0)$ Values

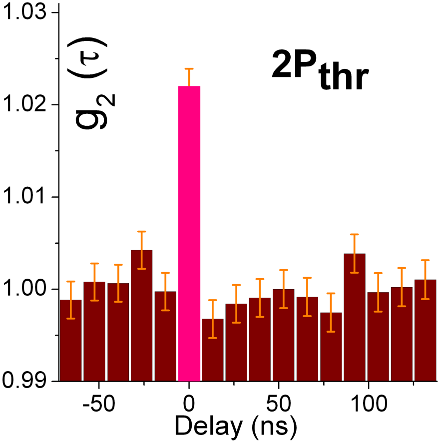
Below Threshold



Result - $g_2(\tau = 0)$ Values

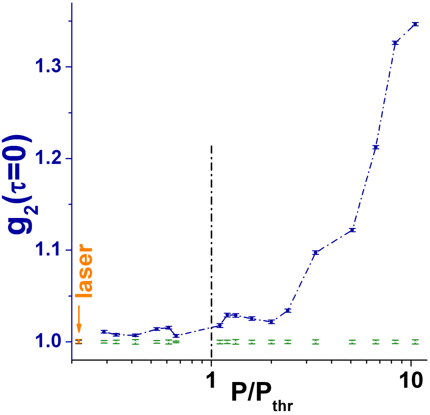
At Threshold





Summary

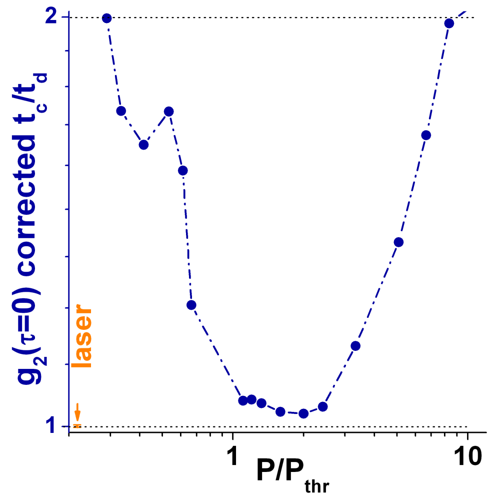
$\delta \approx +2meV$, T=5.4K, Counting Rate $\sim 3 \cdot 10^5 \frac{c}{s}$, Pulsed, Non-Resonant



Relaxation

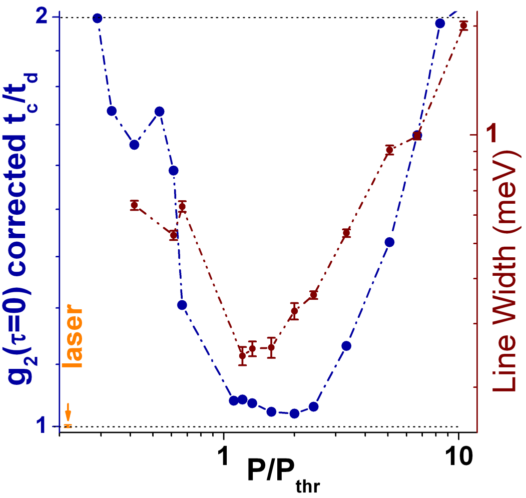
Summary

$g_2(\tau = 0)$ Corrected



Summary

$g_2(\tau = 0)$ Corrected



Interpretation

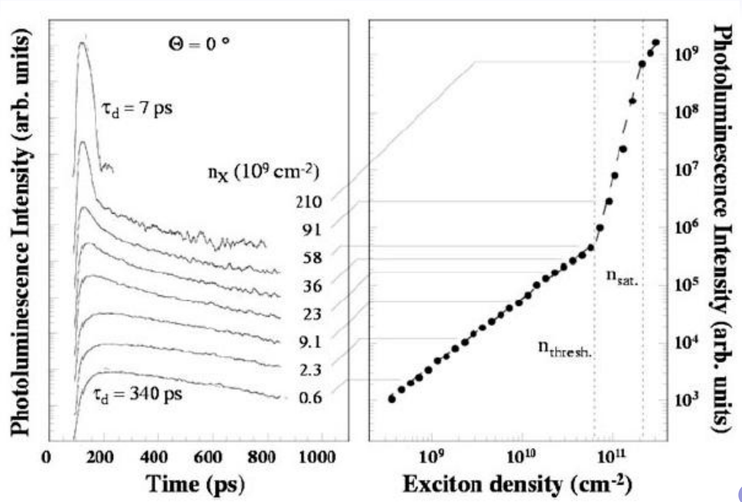
$P/P_{thr} < 1$ - Thermal Source

$1 < P/P_{thr} < 2$ - Coherent Source

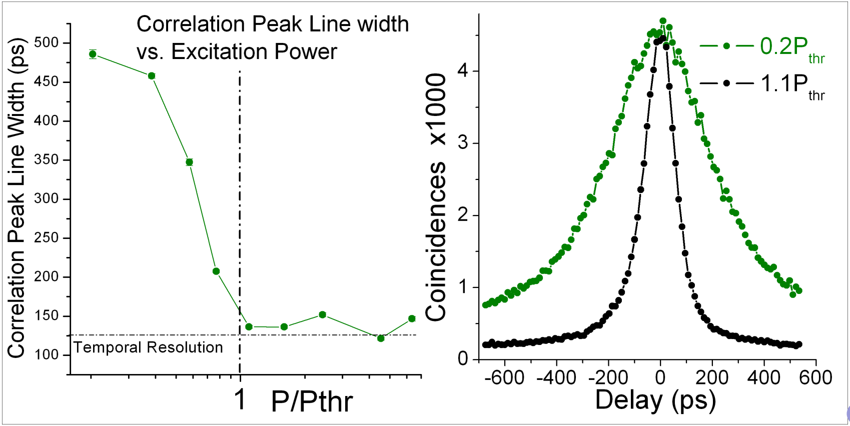
$P/P_{thr} > 2$ - Decoherence - Interaction Within the Condensate

Speed Up of the Relaxation

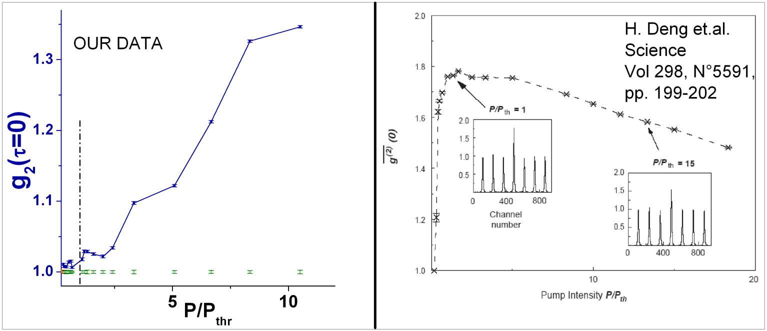
M. Müller Thesis - Grenoble 2000



Speed Up of the Relaxation

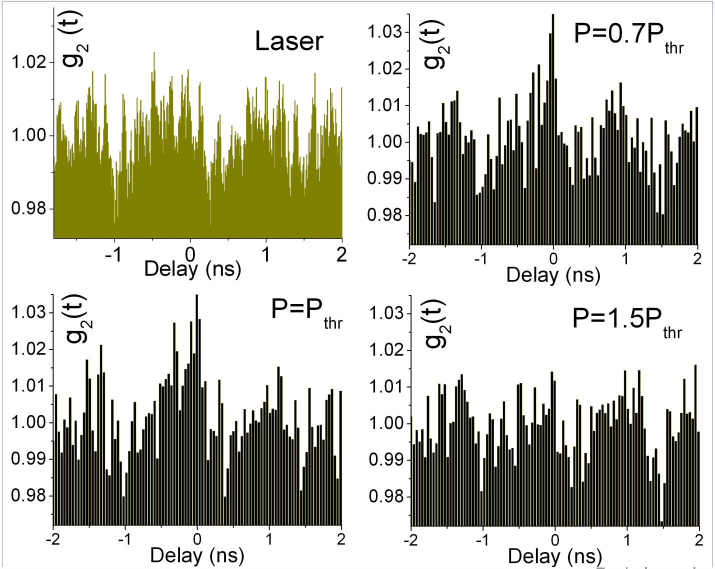


How About the Other Results ?



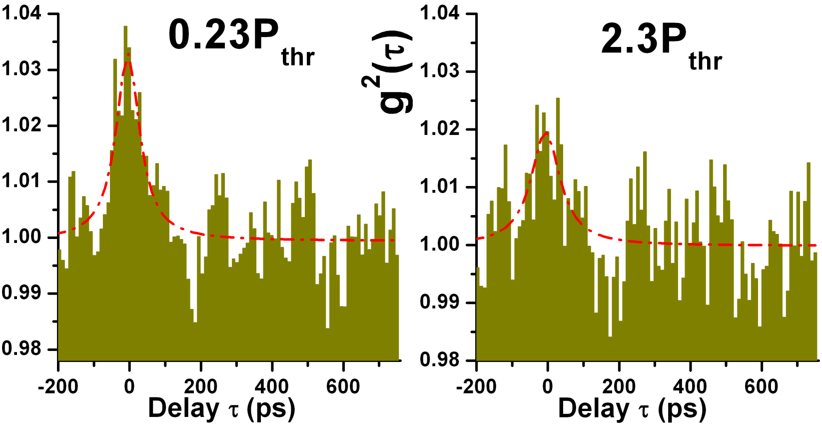
CW Measurements

...Much More Difficult !!!



CW Measurements

Reduction of bunching ⇔ Build up of the 2^{nd} Order Coherence

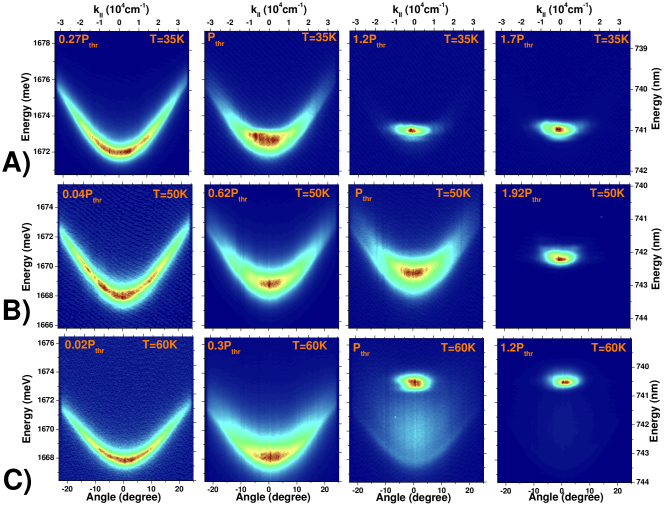


Plan

5 Appendix

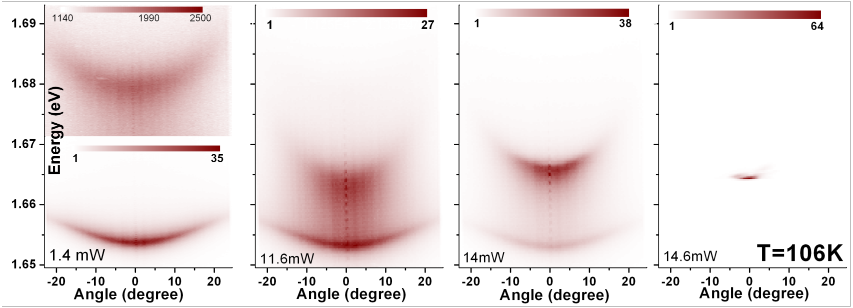
Polariton Condensation in CdTe Microcavities

High Temperature Limit - $T_{cryo} = 50K$



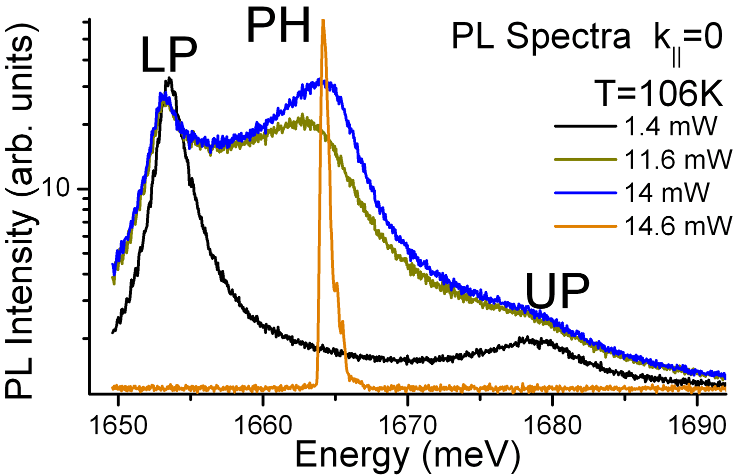
Transition Towards Weak Coupling Regime

$$T_{cryo} = 106K$$



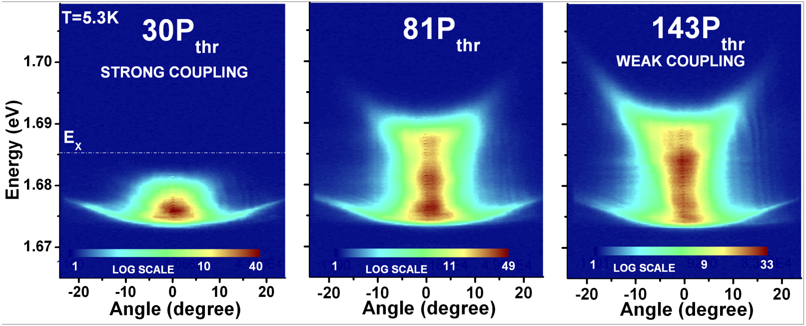
Transition Towards Weak Coupling Regime

$T_{cryo} = 106K$



Transition Towards Weak Coupling Regime

$$T_{cryo} = 5K$$



Polariton Lasing versus Photon Lasing

$\boxed{\text{High finesse microcavity} + \text{QW Exciton} \Rightarrow \text{Strong Coupling}}$

High excitation

Large E_{BX}

Small E_{BX}

Polariton Lasing versus Photon Lasing

High finesse microcavity + QW Exciton $\Rightarrow$ Strong Coupling

High excitation

Large E_{BX}	Small E_{BX}
↓	↓
X - Strong Coupling	(e,h) - Weak Coupling
BEC, Polariton Lasing	VCSEL

Polariton Lasing versus Photon Lasing

High finesse microcavity + QW Exciton $\Rightarrow$ Strong Coupling

High excitation

Large E_{BX}

Small E_{BX}

X - Strong Coupling

BEC, Polariton Lasing

(e,h) - Weak Coupling

VCSEL

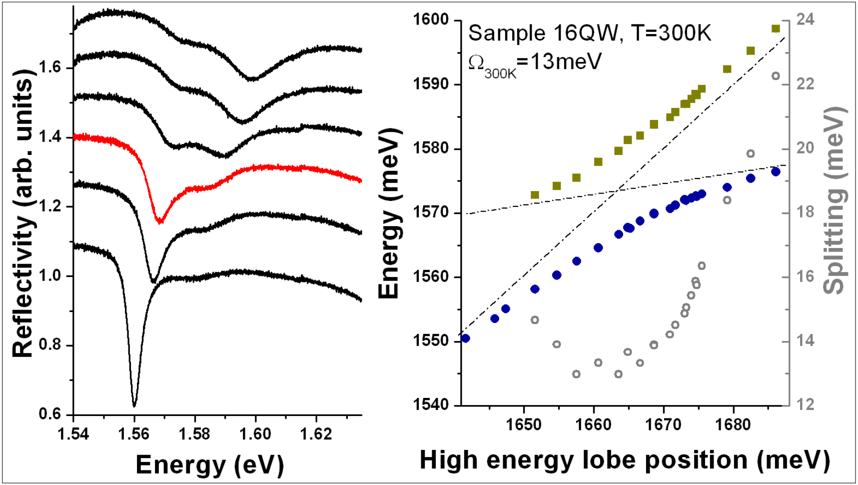
Higher Excitation and/or high T

Exciton Saturation

Plan

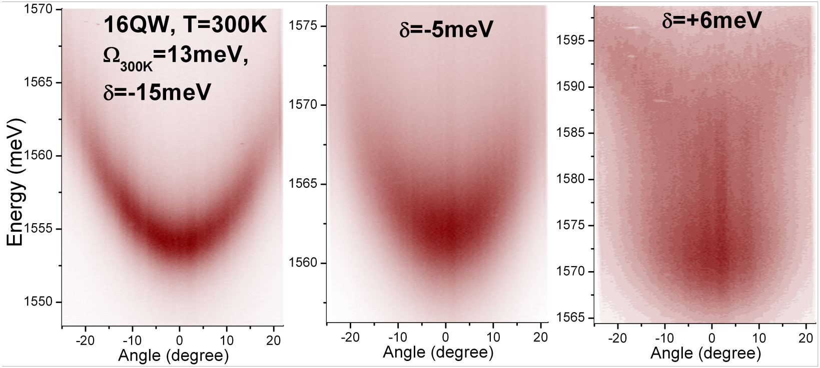
Strong coupling at room temperature

Nonlinearities not observed



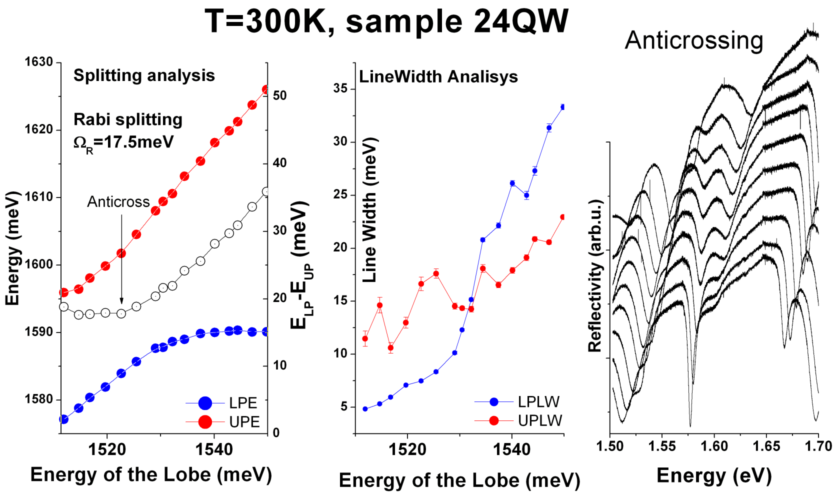
Strong coupling at room temperature

Nonlinearities not observed



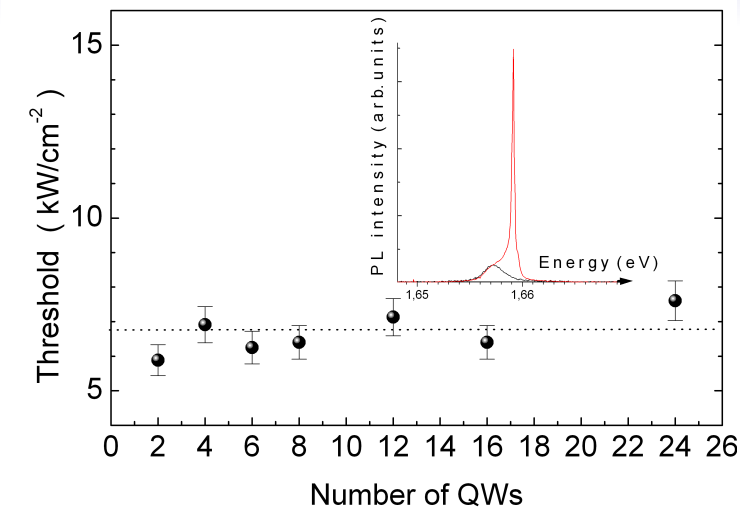
Strong coupling at room temperature

Nonlinearities not observed



Plan

Threshold vs. Number of QWs

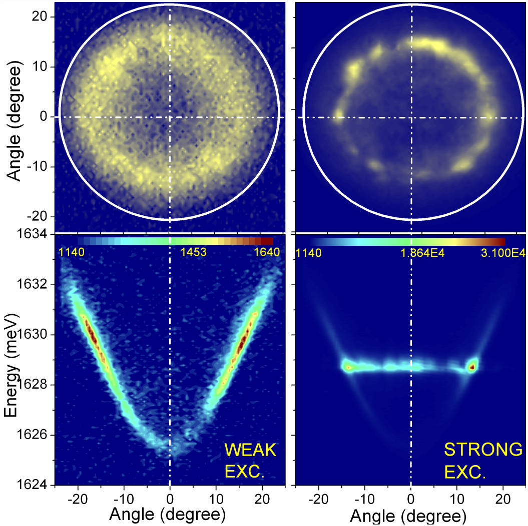


Plan

5 Appendix

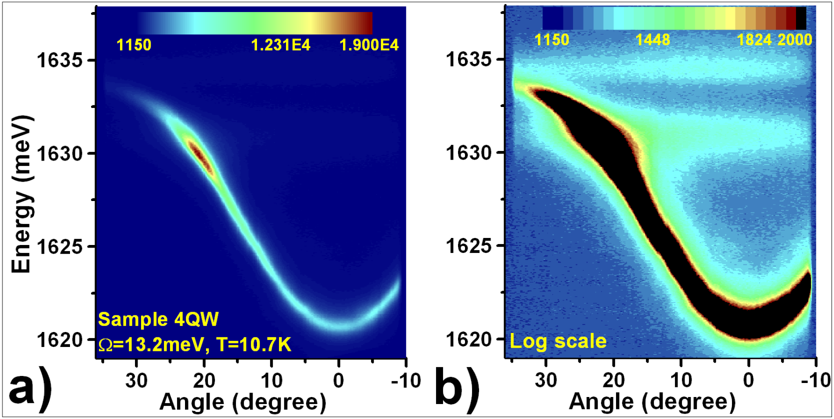
Stimulation on the Ring of Excited States

Spot Size $\sim 3\mu m$ - Strong Localization



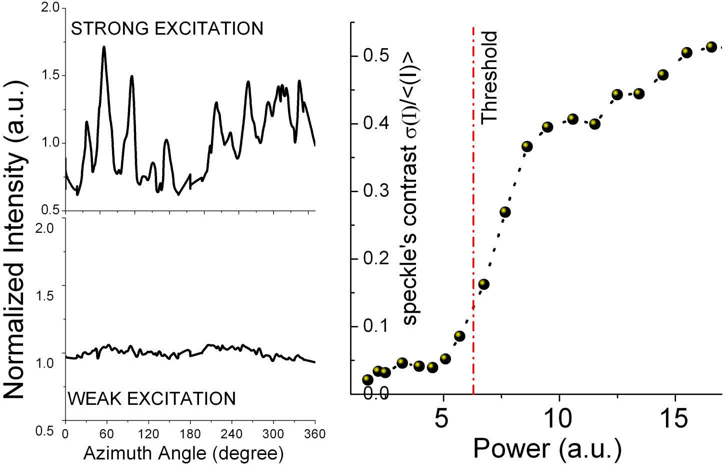
Stimulation on the Ring of Excited States

Non-dispersive Bar-Geometrical Artefact



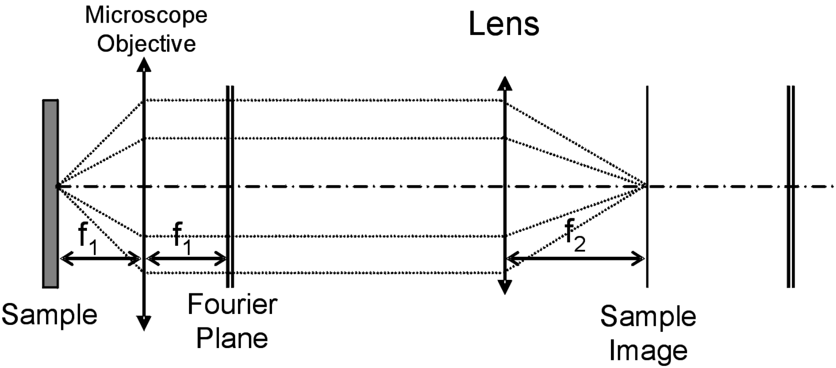
Stimulation on the Ring of Excited States

Speckled Emission Above Threshold



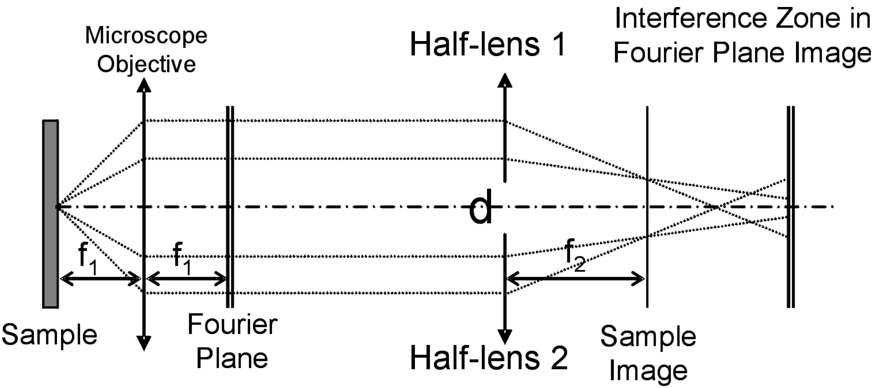
Stimulation on the Ring of Excited States

Transverse Field Interferometer - Principle



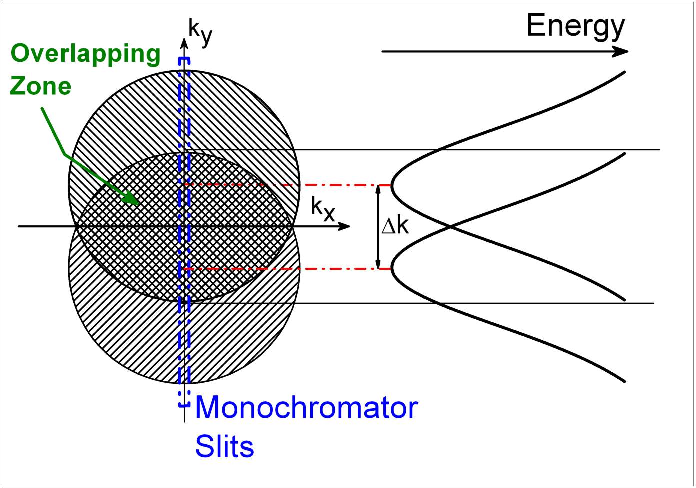
Stimulation on the Ring of Excited States

Transverse Field Interferometer - Principle



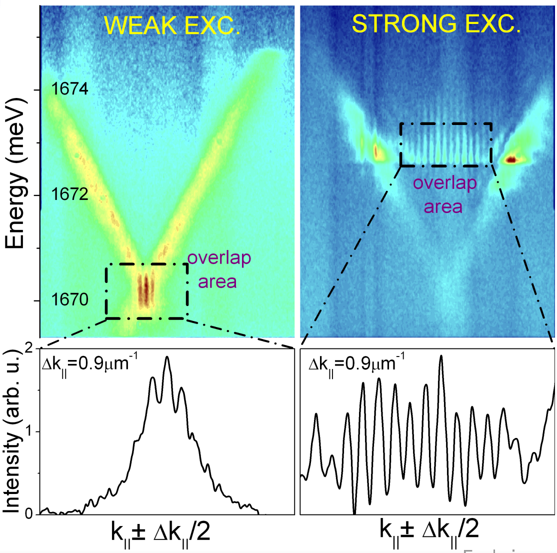
Stimulation on the Ring of Excited States

Billet Interferometer - Zone of the Overlap



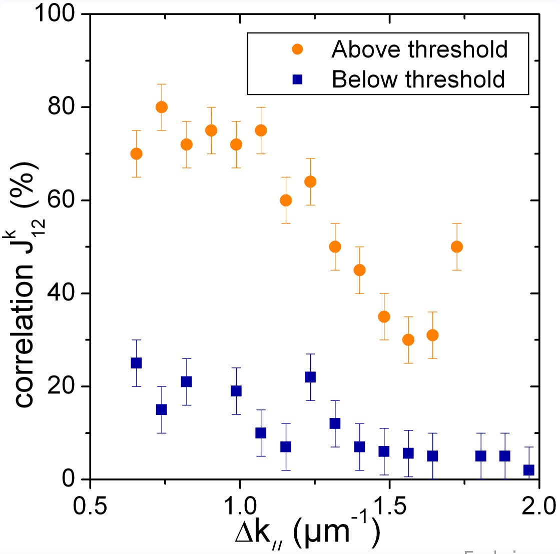
Build-up of Coherence - Further Proofs

Interference Pattern



Build-up of Coherence - Further Proofs

Enhancement of Contrast $\times 4$



Stimulation on the Ring of Excited States

Spotsize Dependence, explained in Phys. Rev. B **77**, 115340 (2008)