Polaritons for optronic applications

A. Bramati

Quantum Optics Group

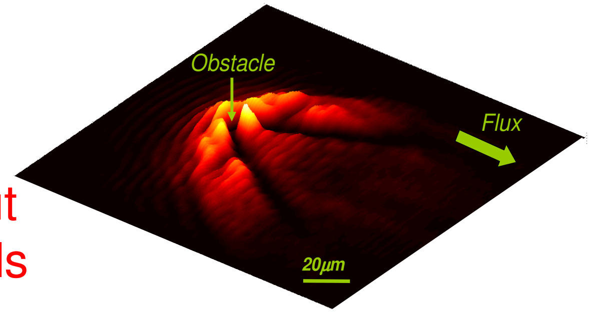
Laboratoire Kastler Brossel
Physique quantique et applications

Quantum Optics Team: topics

Laboratoire Kastler Brossel
Physique quantique et applications

Quantum fluid phenomena in polariton gases

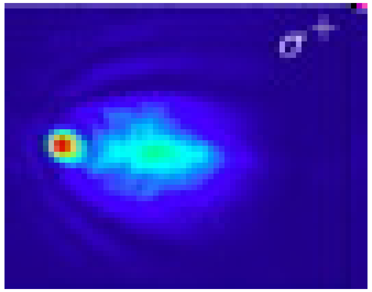
⇒ An ideal system to study out of equilibrium quantum fluids



Superfluidity, hydrodynamic dark solitons and vortices
(*Nature Physics 2009, Science 2011, Nature Photonics 2011, Journal du CNRS, 2011*)

Spin dependent non linearities in microcavities

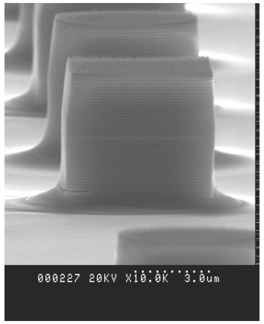
⇒ Towards integrated optoelectronic devices



Logic gates, All Optical Spin Switches *(Nature Physics 2007, PRL 2007, Nature Photonics 2010, PRL 2011)*

Quantum Effects in semiconductor nano and microcavities in strong coupling regime

⇒ Towards a compact, integrable nano- source of entangled beams



Microcavities, quantum wires, micropillars *(PRL 2007, APL 2010,PRB 2011)*

Quantum Optics Team: people

Permanent Staff: **Elisabeth Giacobino, Alberto Bramati**

PhDs

G. Leménager
V.G. Sala
M. Manceau
} Time resolved experiments, pulsed excitation; micropillars and microcavities

T. Boulier
R. Hivet
} CW excitation; micropillars and microcavities

S. Vezzoli Experiments on nanocrystals

Post-Docs

Emiliano Cancellieri Theoretical modeling

Post-doc Quandyde Experimentalist

A. Avoine Experiments on nanocrystals

Collaborations

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Lab. LPA, Paris

J.Tignon

NNL Lab., Lecce

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EPFL, Lausanne

R. Houdré

Lab. MPQ, Paris

C. Ciuti

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I. Carusotto

Lab. LASMEA, Clermont Ferrand

G. Malpuech

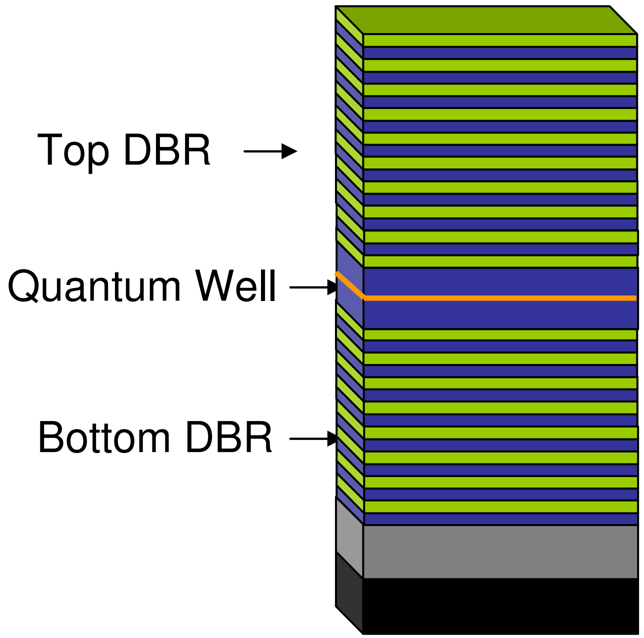
University of Southampton

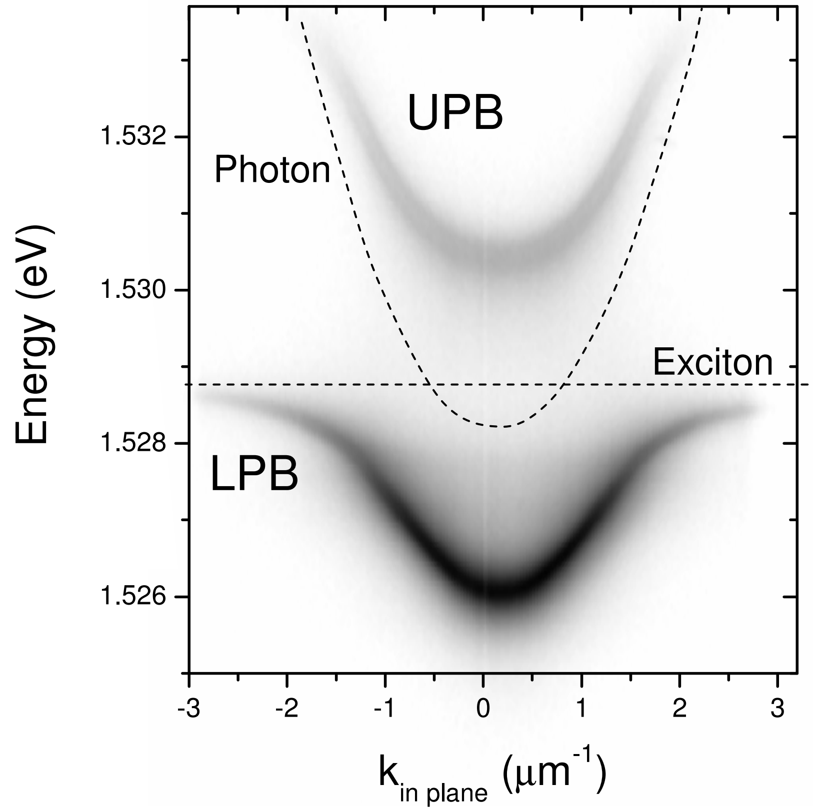
A. Kavokin

Outline

- Introduction
- Linear regime: Optical Spin Hall effect
- Non Linear regime: Polariton Spin switches
- Summary and perspectives

Microcavity Polaritons





Linear combination of excitons and photons

$$\begin{cases} P_+ = -C\,a + X\,b \\ P_- = X\,a + C\,b \end{cases}$$

Polaritons for optronic applications

Semiconductor Microcavities in the strong coupling regime

POLARITONS

Photons

- **Propagate fast** (~ 1% speed of light)
- **Short lifetime** (a few ps)
  → high repetition rate

Excitons

- **High non-linearities**
  ↓
  extremely low thresholds

\+

SPIN

- $s_z = +1$ → σ+
- $s_z = -1$ → σ-

Polaritons for optronic applications

Semiconductor Microcavities in the strong coupling regime

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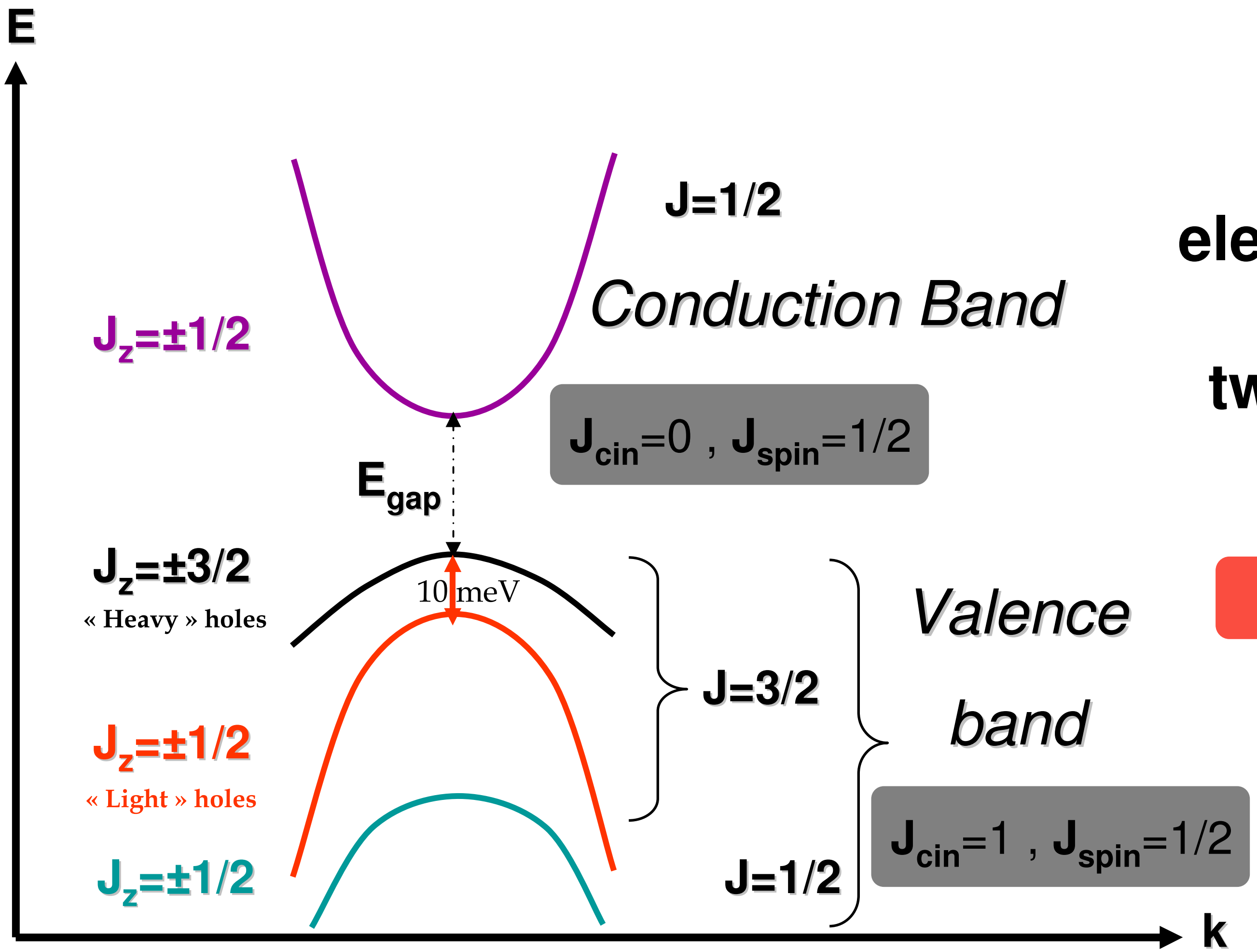
SPIN

- $s_z = +1$ → σ+
- $s_z = -1$ → σ-

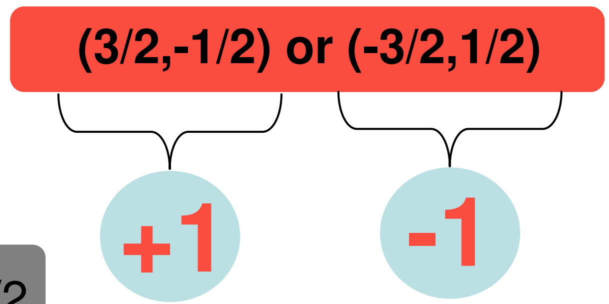
- **All optical, ultrafast, low power, spin sensitive devices**
- **Semiconductor platform** → **INTEGRABILITY**

Exciton Spin Dynamics

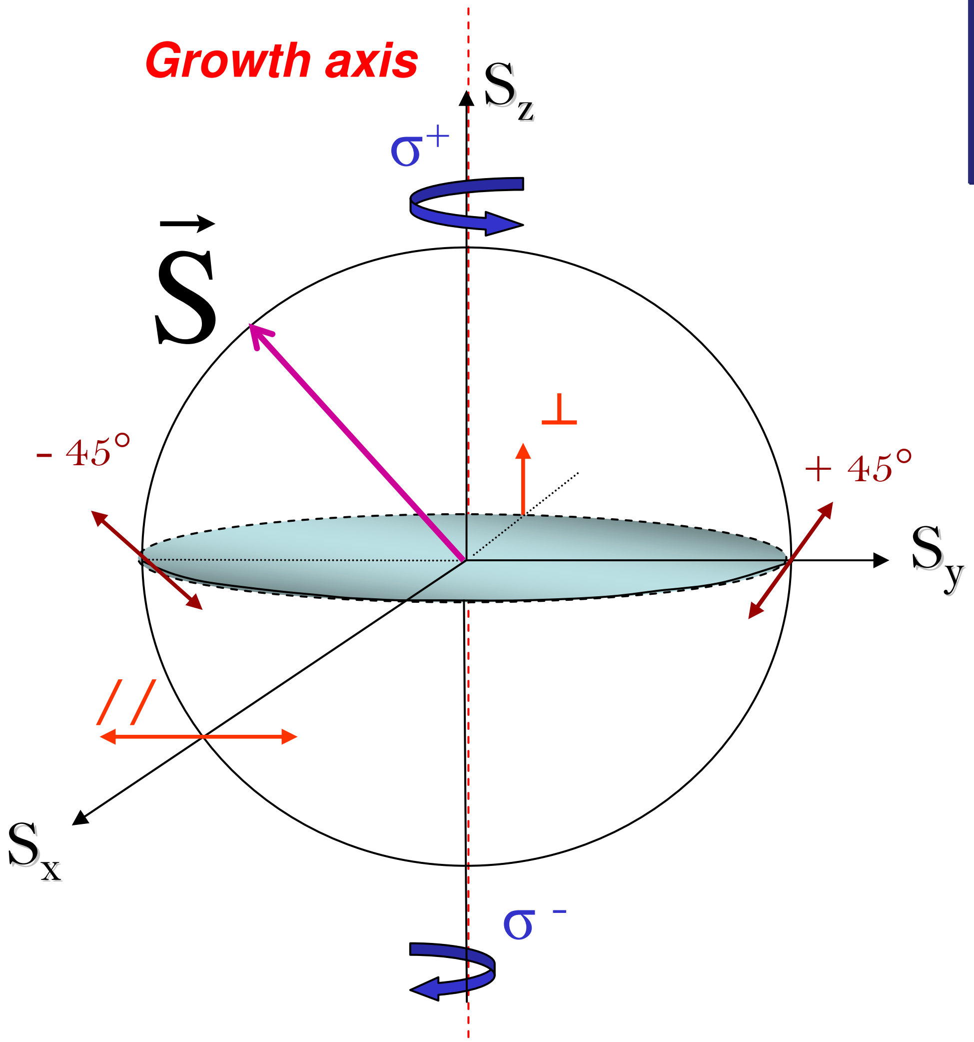
Band Structure



Coupling electrons (J=1/2) and holes (J=3/2) : two states coupled to light



Polariton Pseudospin



Poincaré sphere

Two levels polariton system : +1 et -1

Polariton spin state

⇕

Analysis of the photon spin state

$$\rho_c = \frac{I_{\sigma^+} - I_{\sigma^-}}{I_{\sigma^+} + I_{\sigma^-}}$$

Optical Spin Hall Effect

Pseudospin Precession

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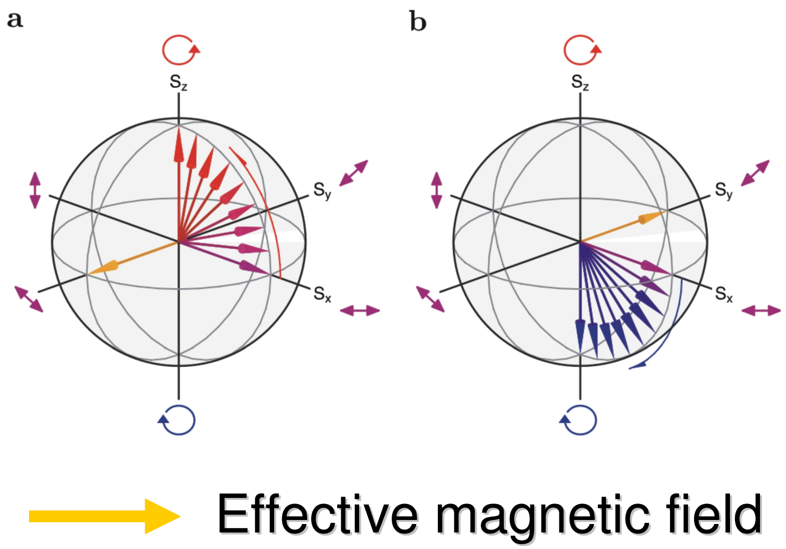
Coupling between +1 et -1 states (via the long-range exchange interaction) and TE-TM optical splitting

Longitudinal-Transverse Splitting Δ_{LT}

Similar to an *effective magnetic field* in the *xy plane*

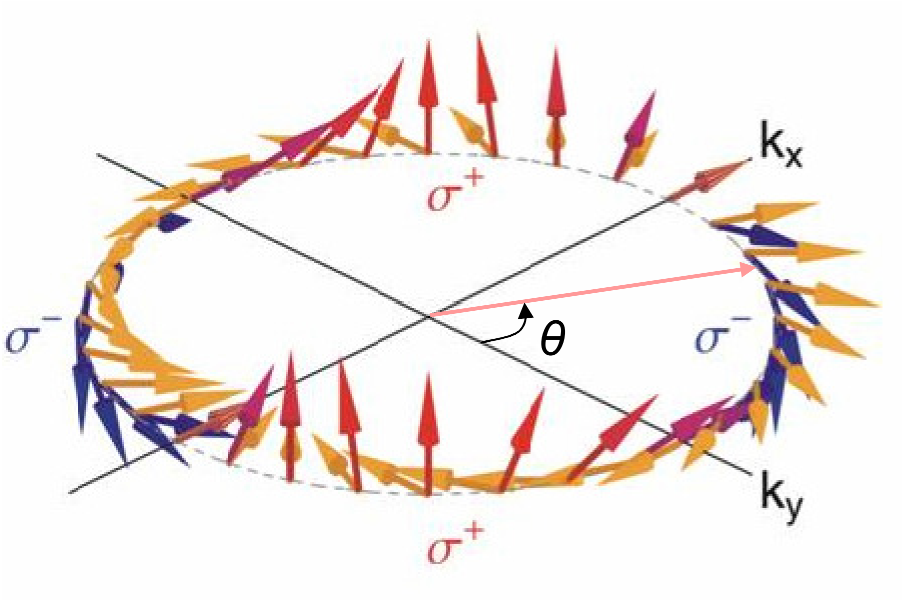


Pseudospin Precession around the *effective magnetic field*

$$\frac{\partial \vec{S}}{\partial t} = \vec{S} \wedge \vec{\Omega}$$

Optical Spin Hall Effect

A. Kavokin et al, **PRL**, *95:136601, 2005*



Effective magnetic field

$$\vec{\Omega}(\theta) = \begin{pmatrix} \frac{\Delta_{LT}}{\hbar} \cos 2\theta \\ \frac{\Delta_{LT}}{\hbar} \sin 2\theta \end{pmatrix}$$

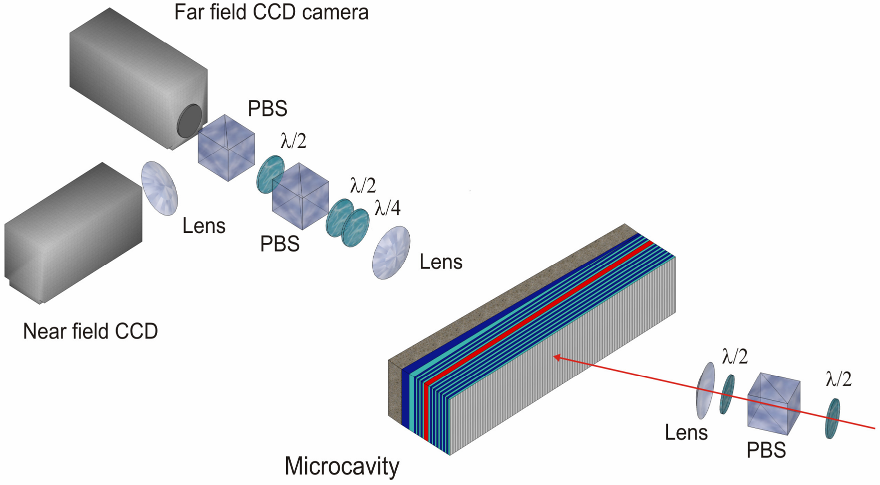
$$\frac{\partial \vec{S}}{\partial t} = \vec{S} \wedge \vec{\Omega}(\theta) + \frac{\vec{S}_0}{\tau_1} - \frac{\vec{S}}{\tau}$$

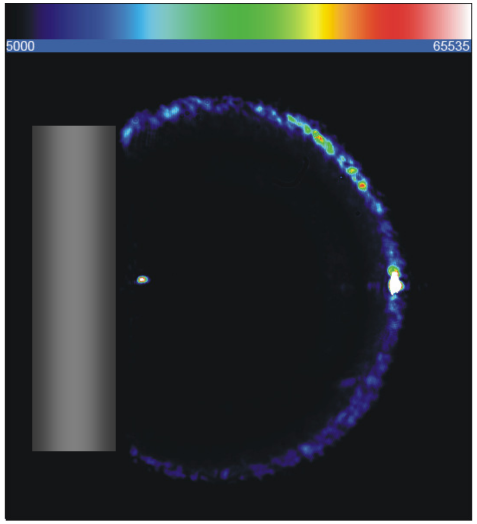
Rayleigh Diffusion of the initial state

Precession around the effective magnetic field

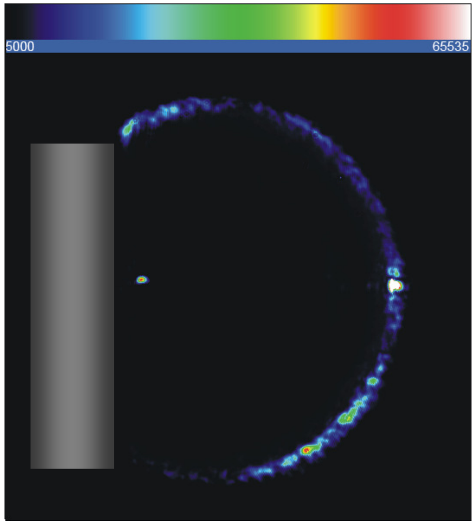
Radiative Decay

Experimental Setup





σ^+



σ^-

Measure of the Longitudinal-Transverse Splitting

$\Delta_{LT} = 50\ \mu eV$

Far Field results

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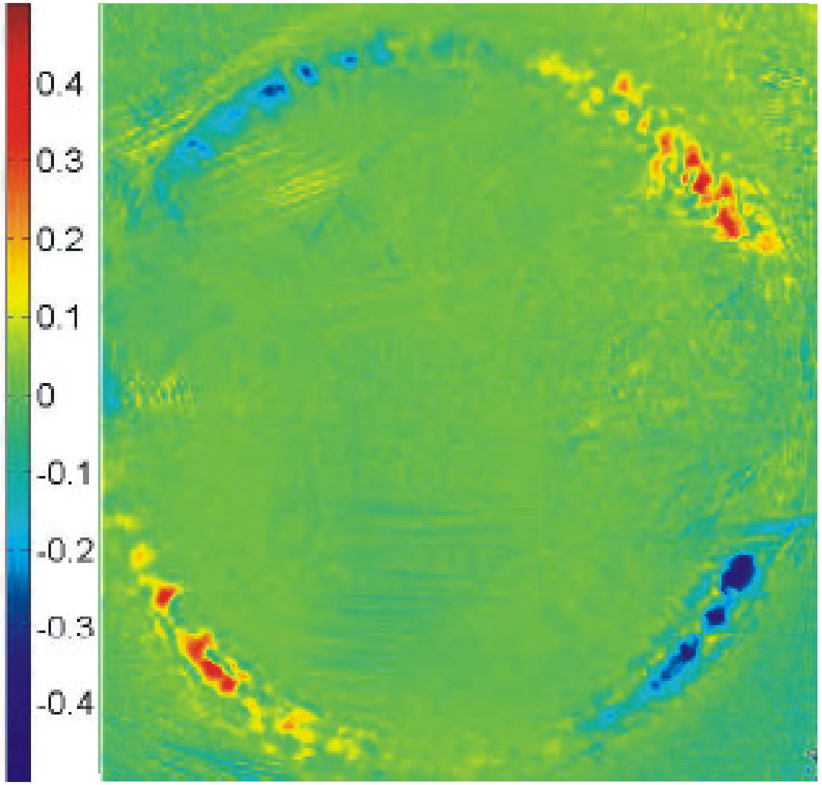
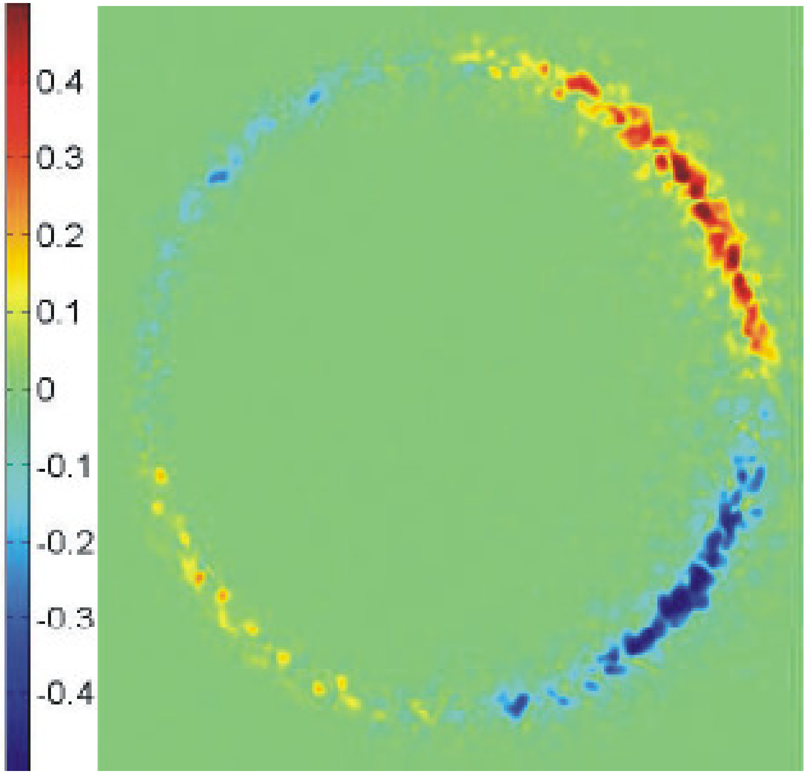
Excitation TE

Experiment



Theory



Circular polarization degree in far field

Near-Field Results: Spin Currents

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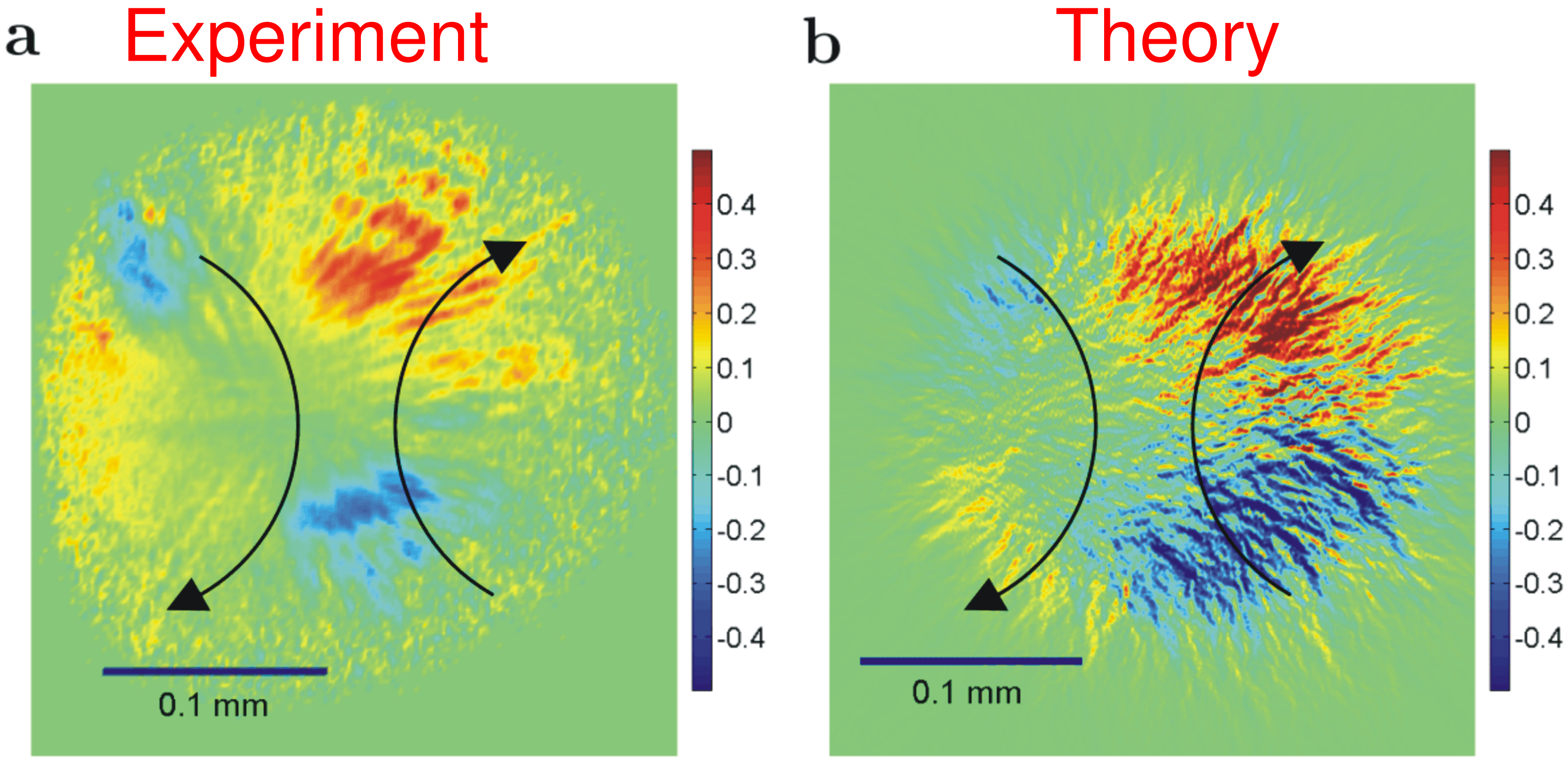


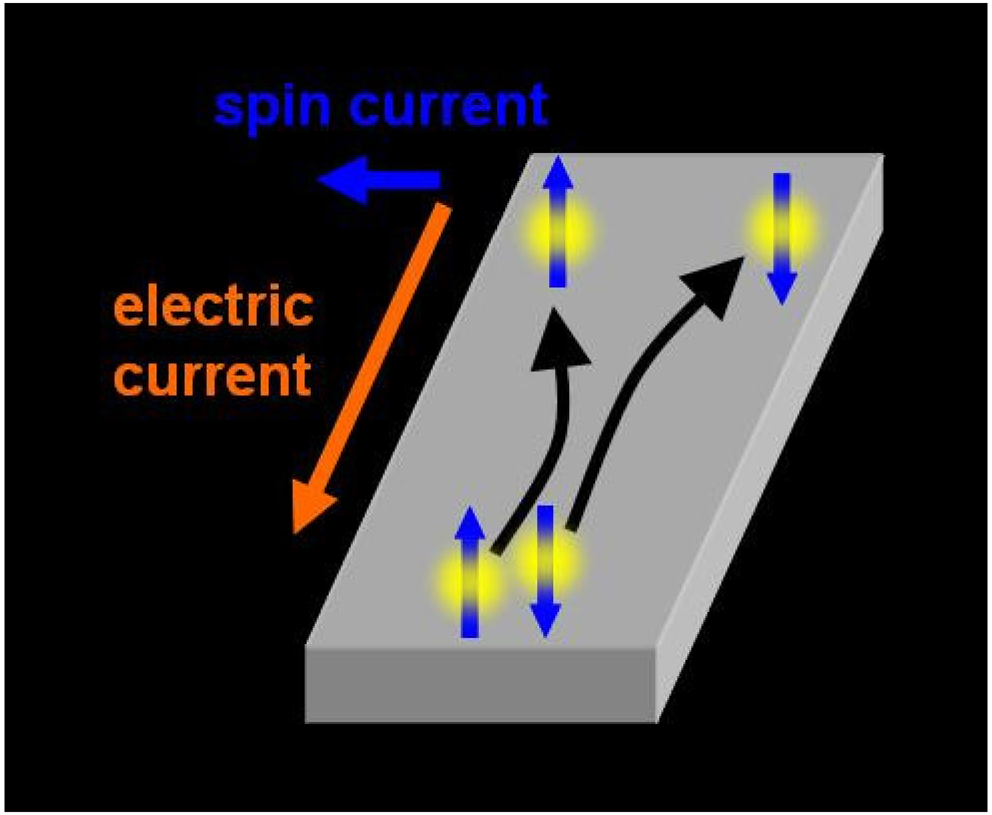
- Separation in the real space of «spin up» & «spin down» excitons

- **Spin Currents Propagation > 100 µm**

Spintronic applications?

Leyder et al, Nature Physics, 3, 628 (2007), Liew et al,PRB (2009), Amo et al, PRB (2009)

Spintronic: Spin Hall effect



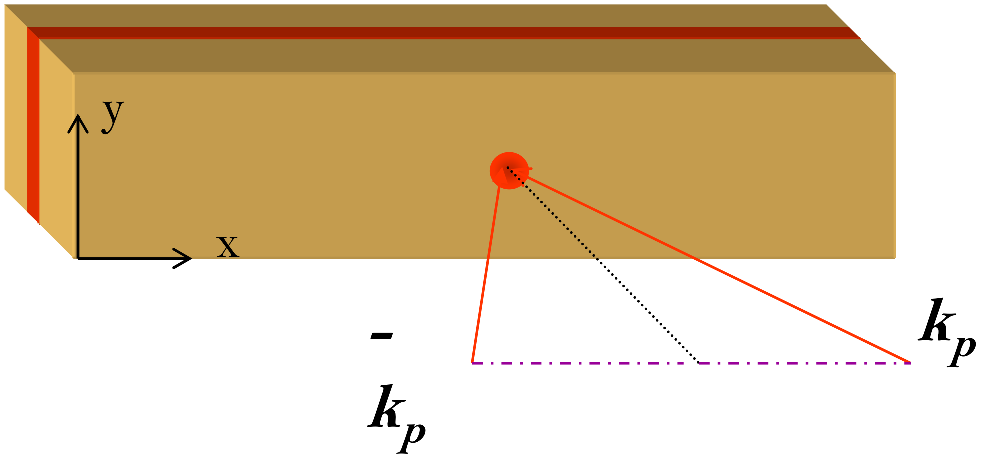
The spin Hall effect generates spin currents

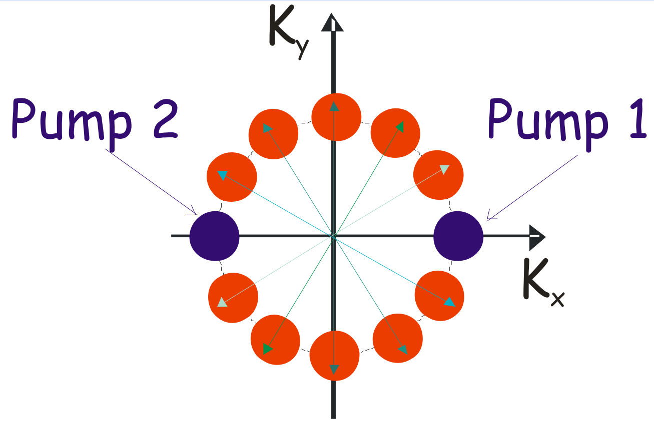
propagation on very short distances (<10µm)

OSHE : 300 µm

All Optical Logic Gate

Two-pumps excitation scheme: Polariton-Four-Wave Mixing





Momentum Conservation

$\{-k_p, k_p\} \longrightarrow \{-k', k'\}$

Energy conservation

$|k_p| = |k'|$

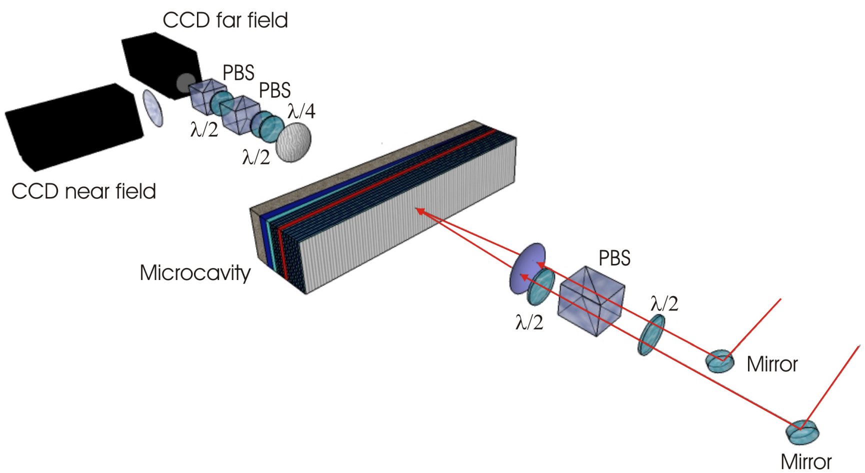
Generation of correlated polariton modes

Romanelli, Leyder et al, PRL, 98, 106401 (2007)

Dispositif Expérimental

Nonlinearities depend on spin

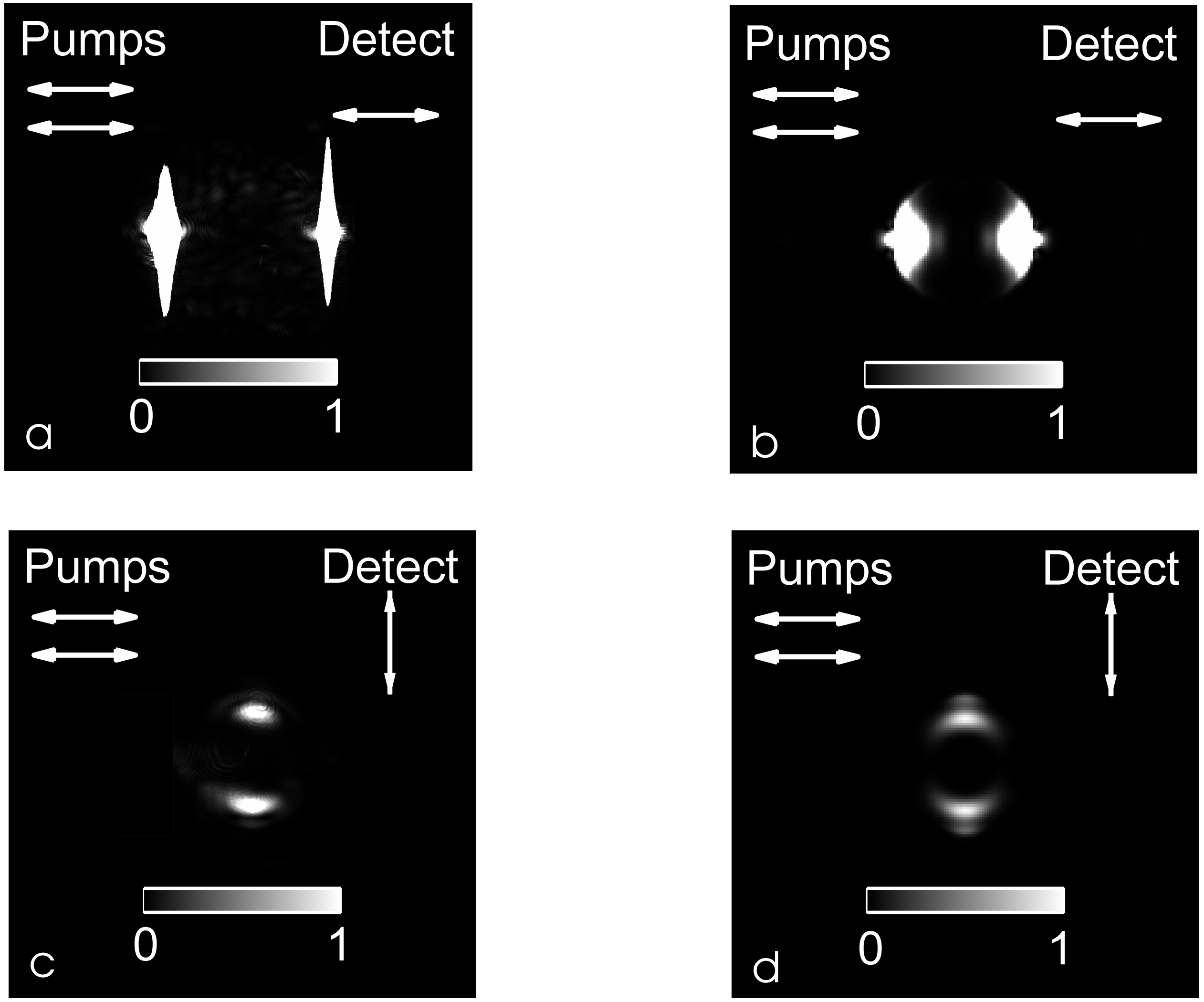
Study of the role played by polarization in four-wave mixing process



Copolarized pumps: Observation in far field

Experiment

Theory



Cross polarized pumps: Observation in far field

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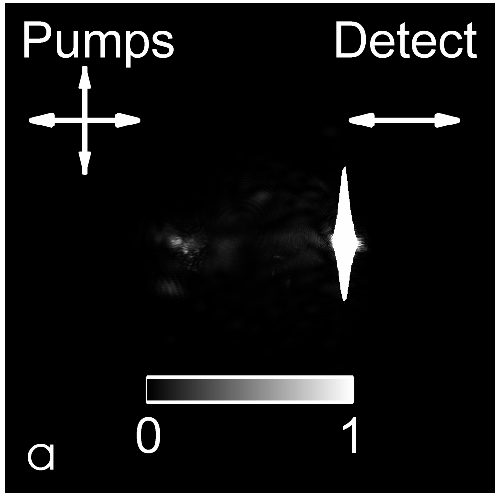
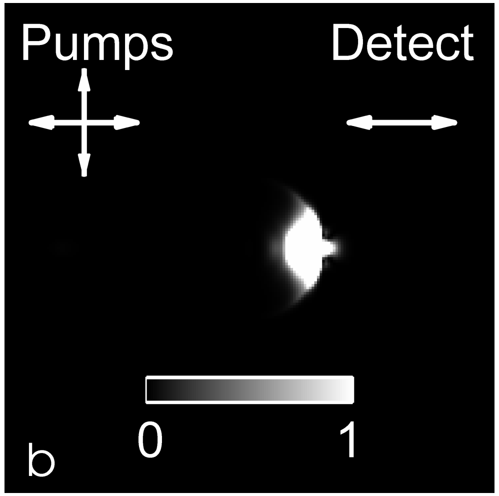
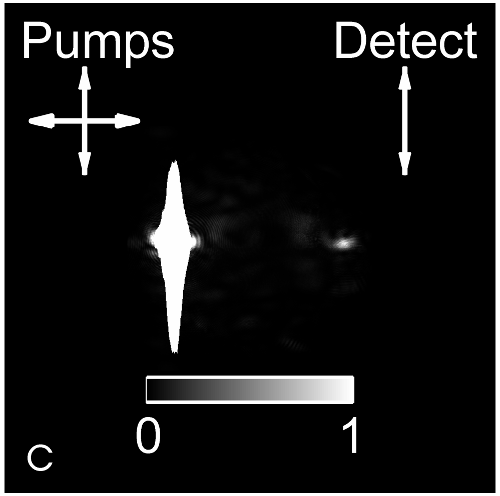
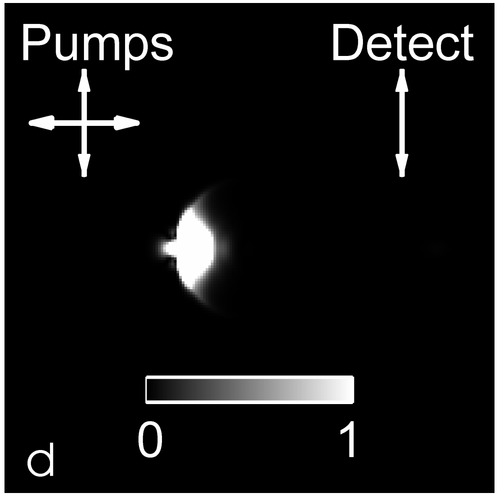
Experiment

Theory









All-Optical Logic Gate

INPUT
- Polarization ↔ → 1
- Polarization ↕ → 0

OUTPUT
- FWM ON → 1
- FWM OFF → 0

Truth Table

A / B	0	1
0	1	0
1	0	1

→ XNOR

All-optical Logic Gate

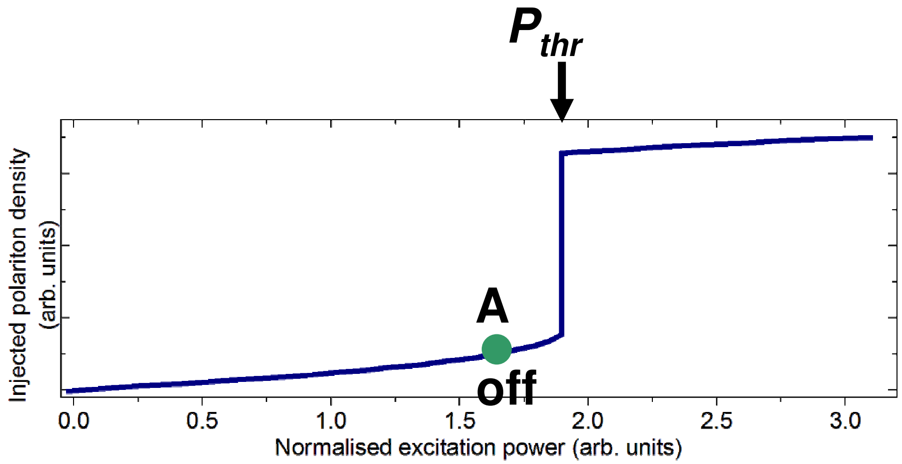
Rate > Gbits/s

C. Leyder et al, Phys. Rev. Lett., 99, 196402 (2007)

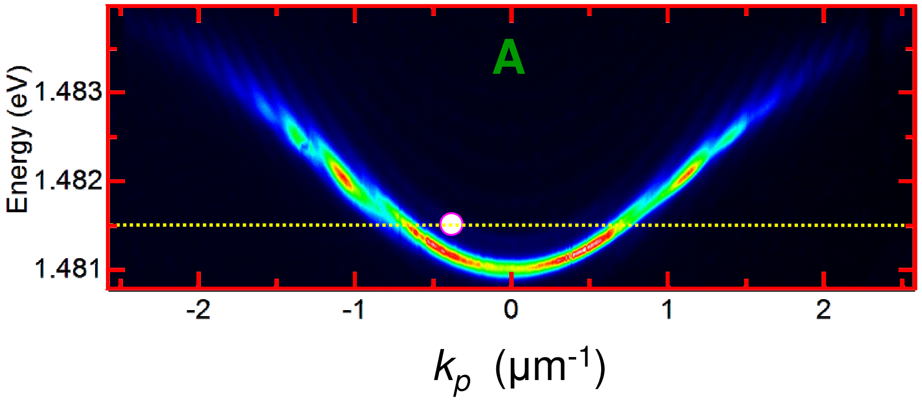
All Optical switch

All-optical switch

Non-linear transmission (*k≠0*)



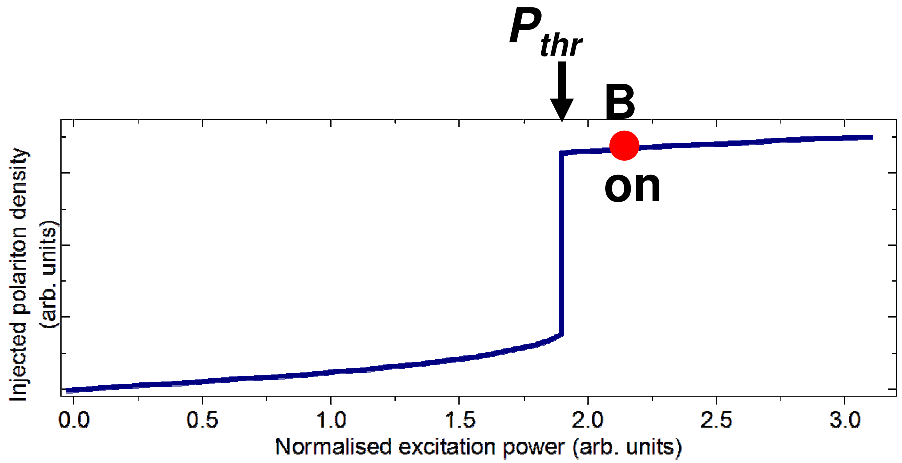
$P_A < P_{thr}$



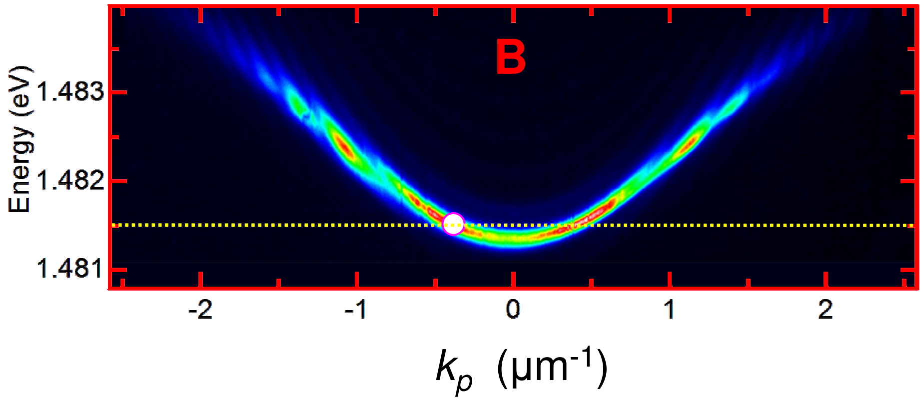
LPB

All-optical switch

Non-linear transmission (*k≠0*)



$P_B > P_{thr}$

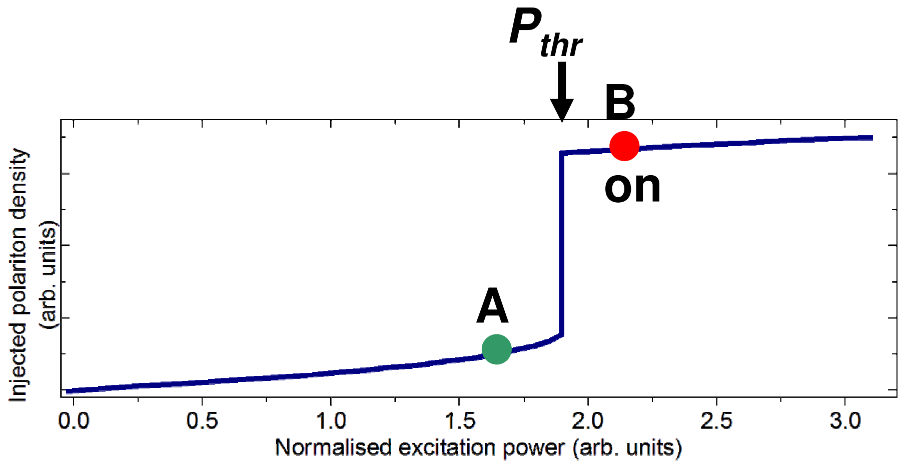


LPB

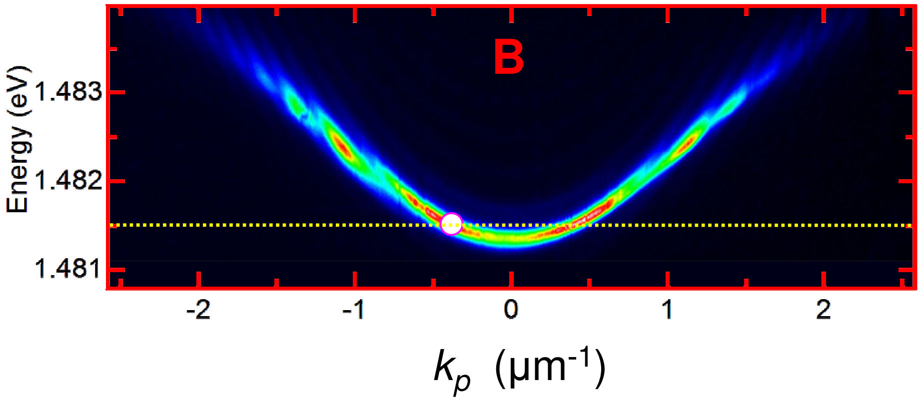
Renormalization of the dispersion curve

All-optical switch

Non-linear transmission (*k≠0*)



$P_B < P_{thr}$



LPB

Renormalization of the dispersion curve

Polariton switch configuration: **a weak probe** provides the additional power to switch to the **on state**.

Experimental set-up

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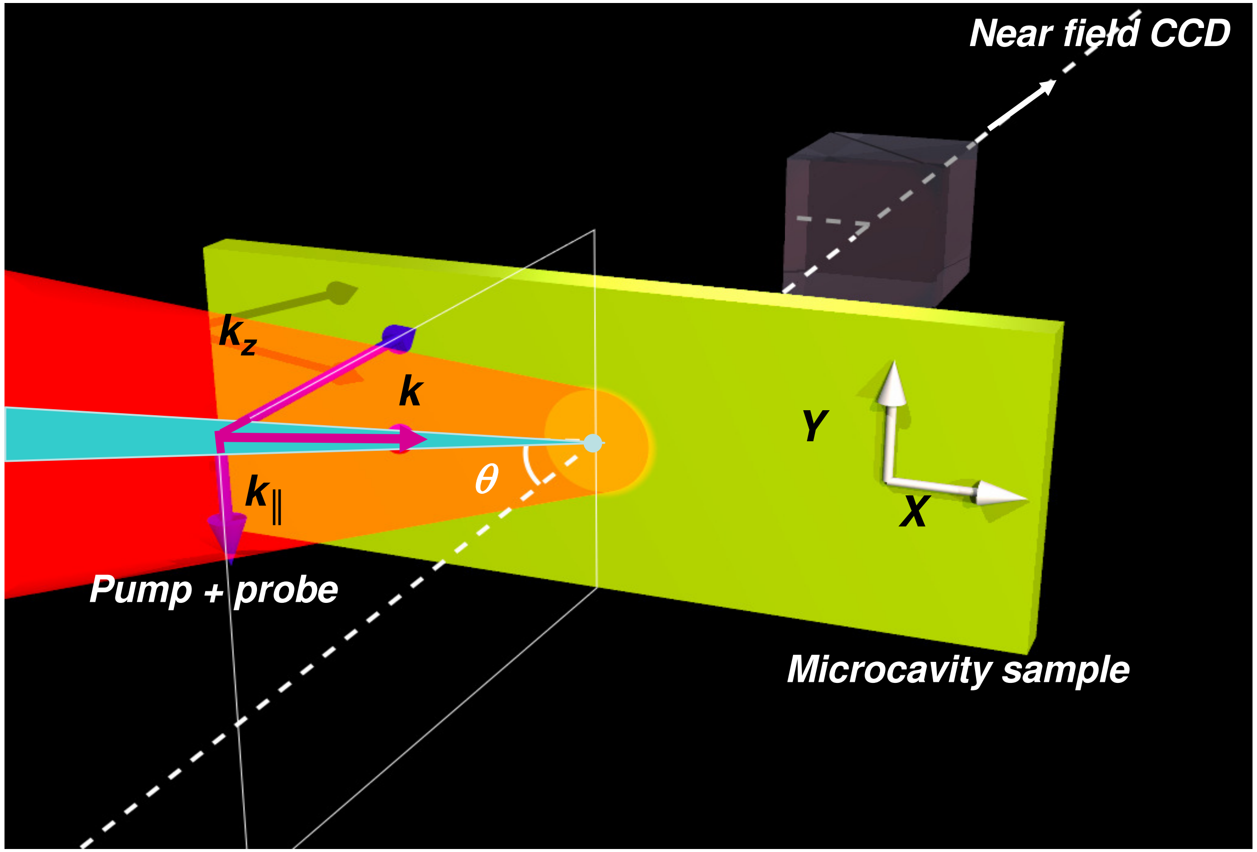
Pump: big spot 60 µm

Probe: small spot 6 µm

} incident in plane angle = 3.8°



All-optical switch:propagation effects

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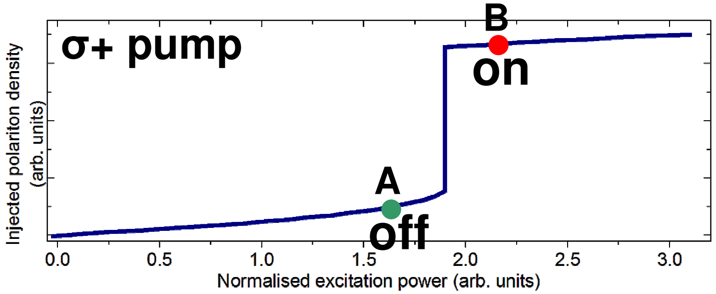
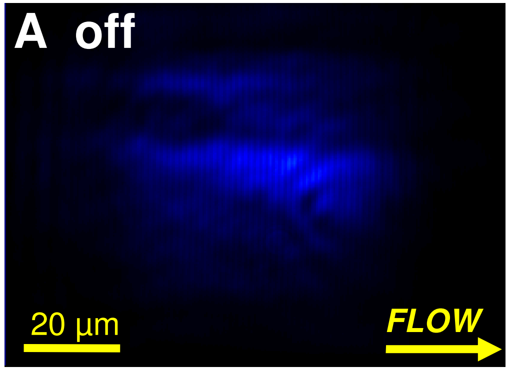
- **Sub-threshold Pump**
- **Weak probe**
- **Angle of incidence: 3.8°**



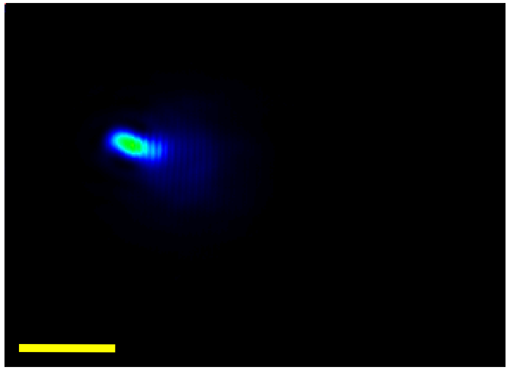
Pump (**σ+**)



Transmitted power
9 mW

+

Probe (**σ+**)



Transmitted power
3 mW

All-optical switch:propagation effects

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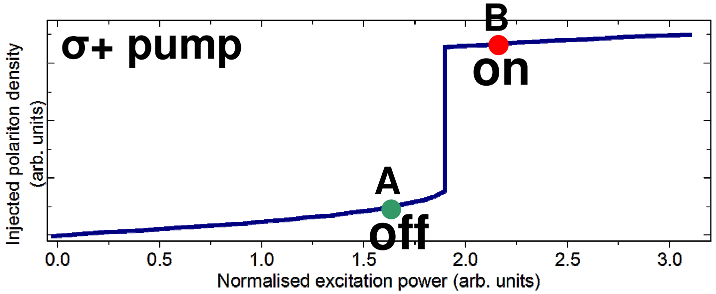
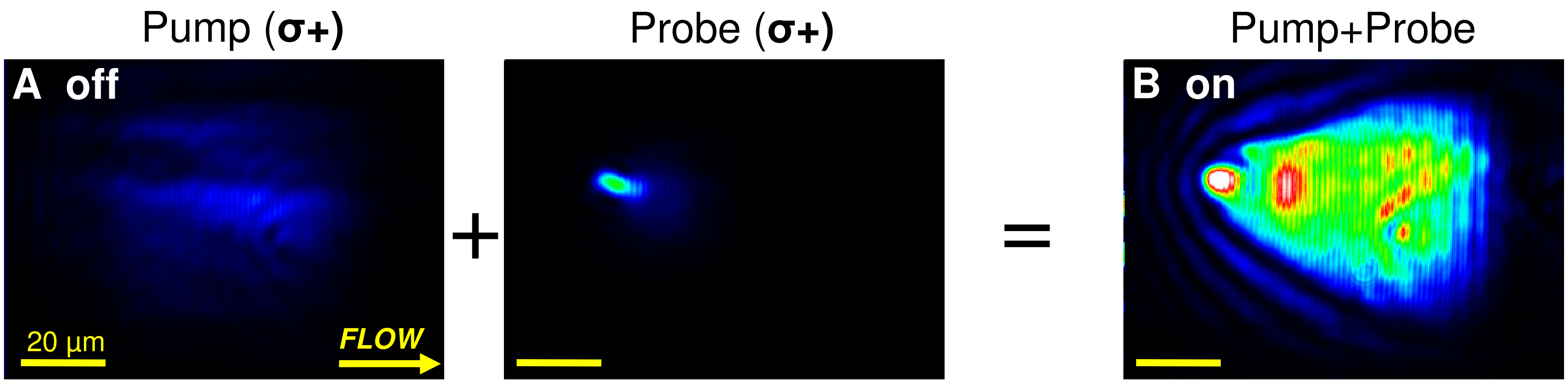
- **Sub-threshold Pump**
- **Weak probe**
- **Angle of incidence: 3.8°**





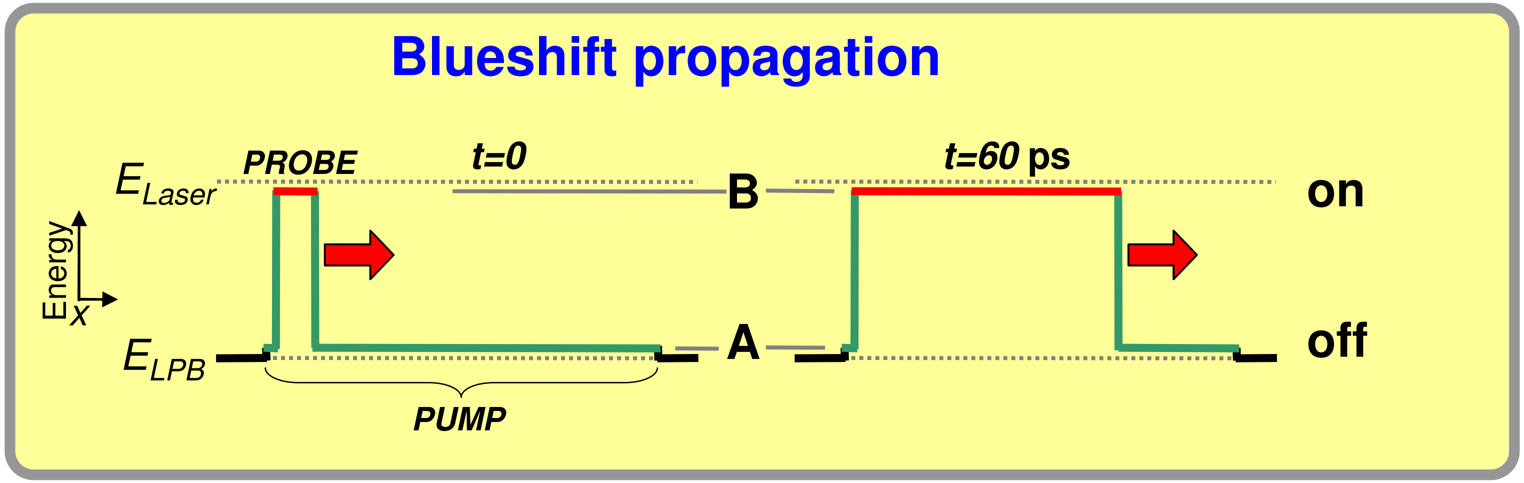
Transmitted power **9 mW**

Transmitted power **3 mW**

Transmitted power **54 mW**

The whole pump spot switches ON

All-optical switch:propagation effects



- Pump and probe polariton propagation all over the pump spot
- $v_{polariton} = hk_{//}/m_{polariton}$= ***0.94 µm/ps***

All-optical switch:propagation effects

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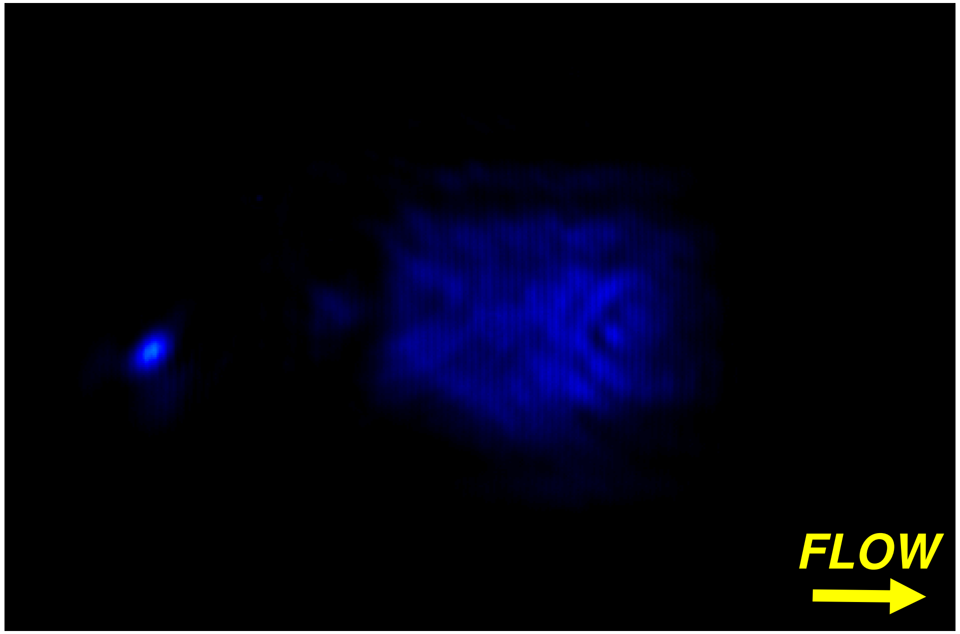
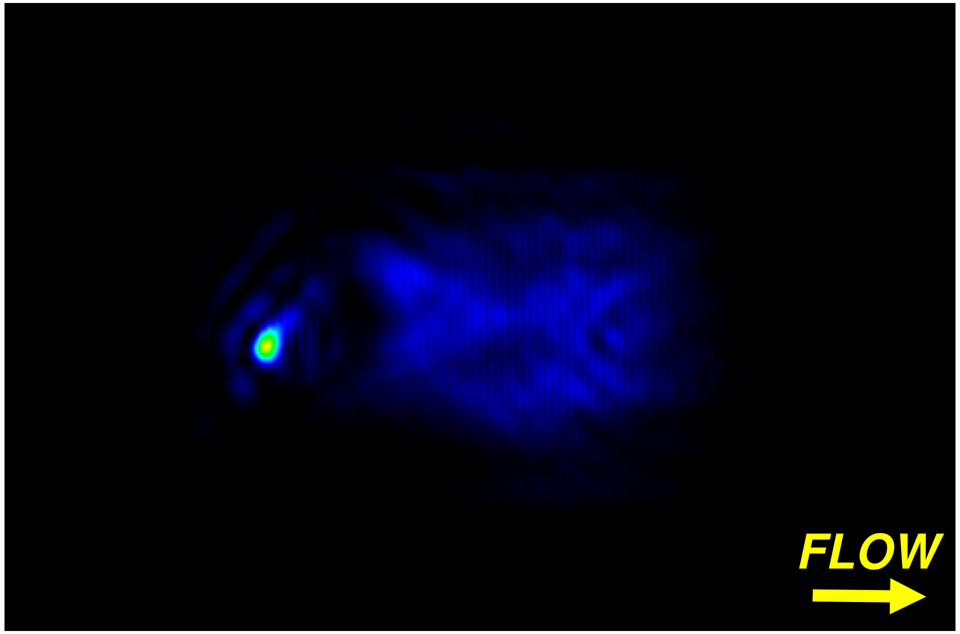


All-optical switch:propagation effects



All-optical switch:propagation effects

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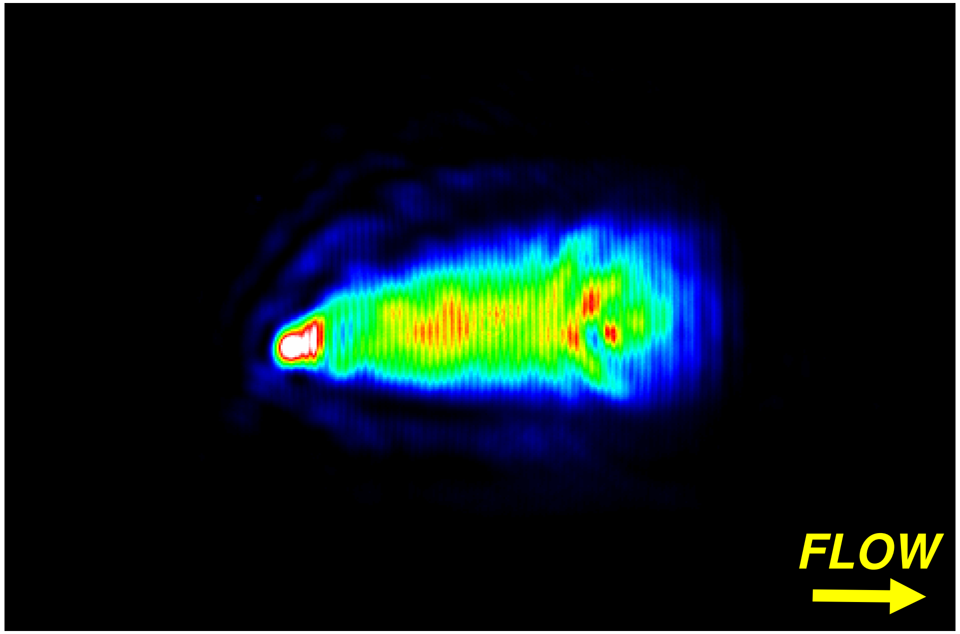

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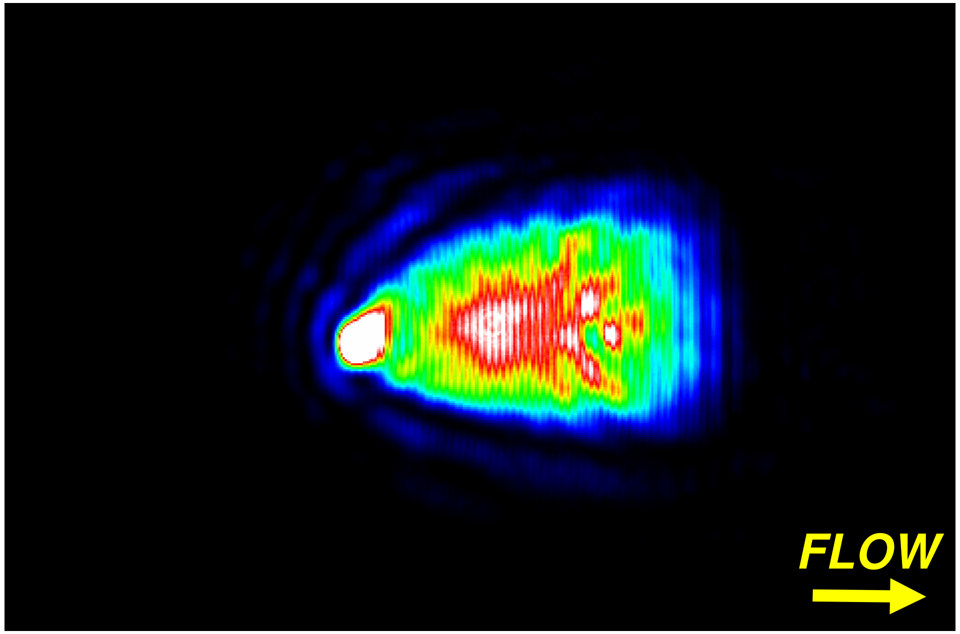

All-optical switch:propagation effects

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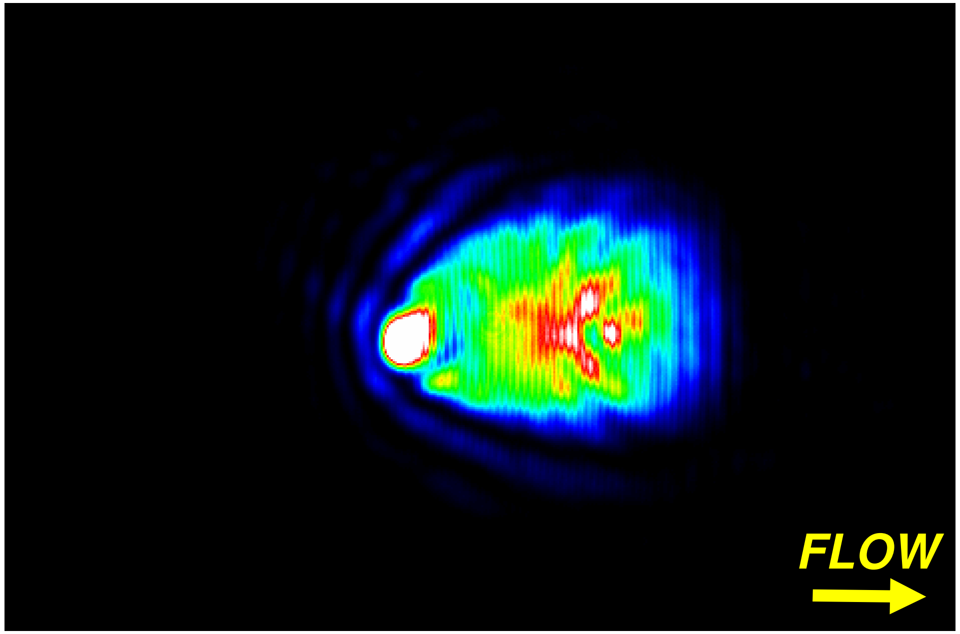
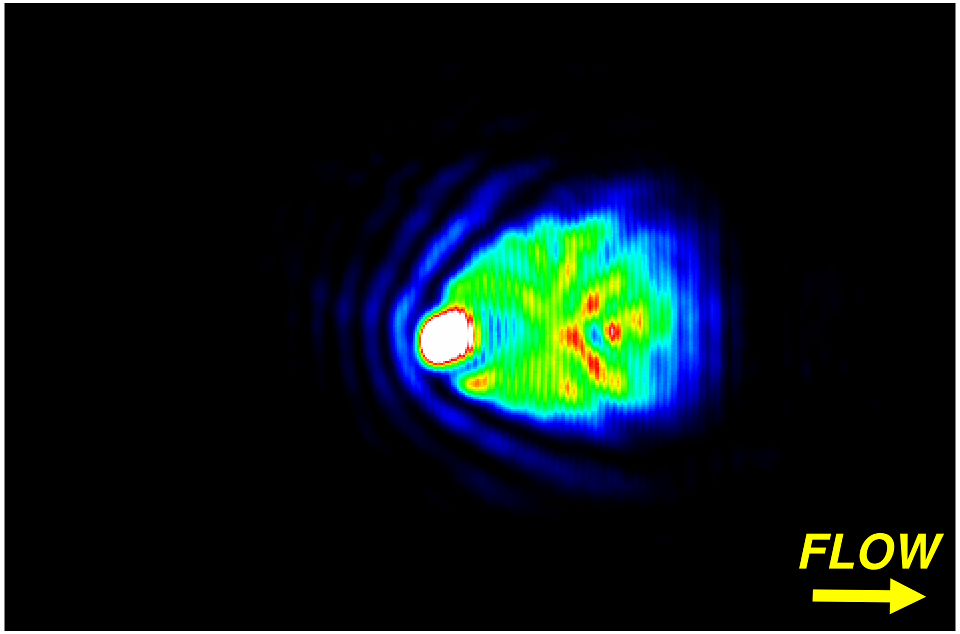


All-optical switch:propagation effects



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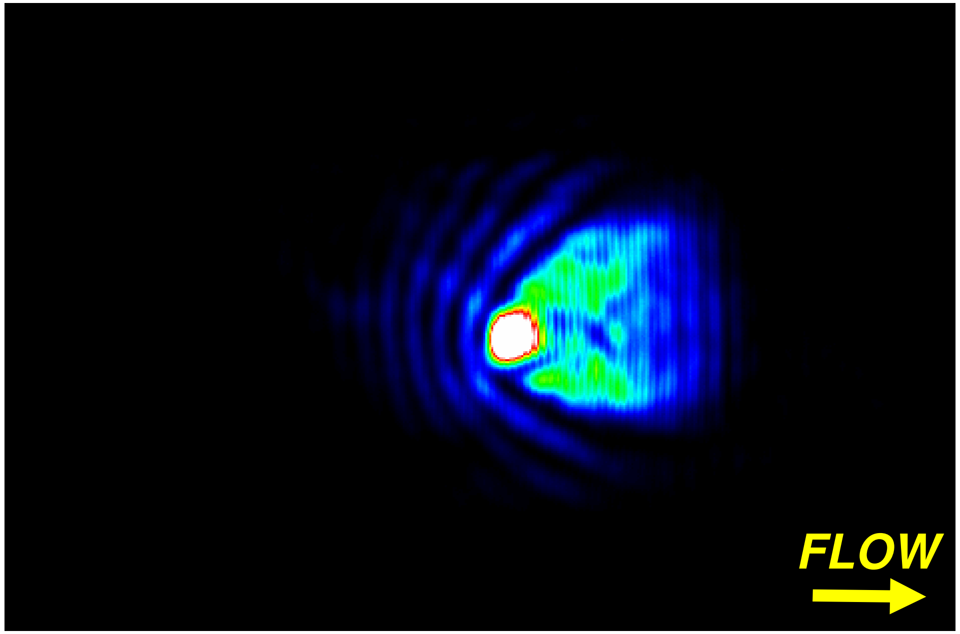
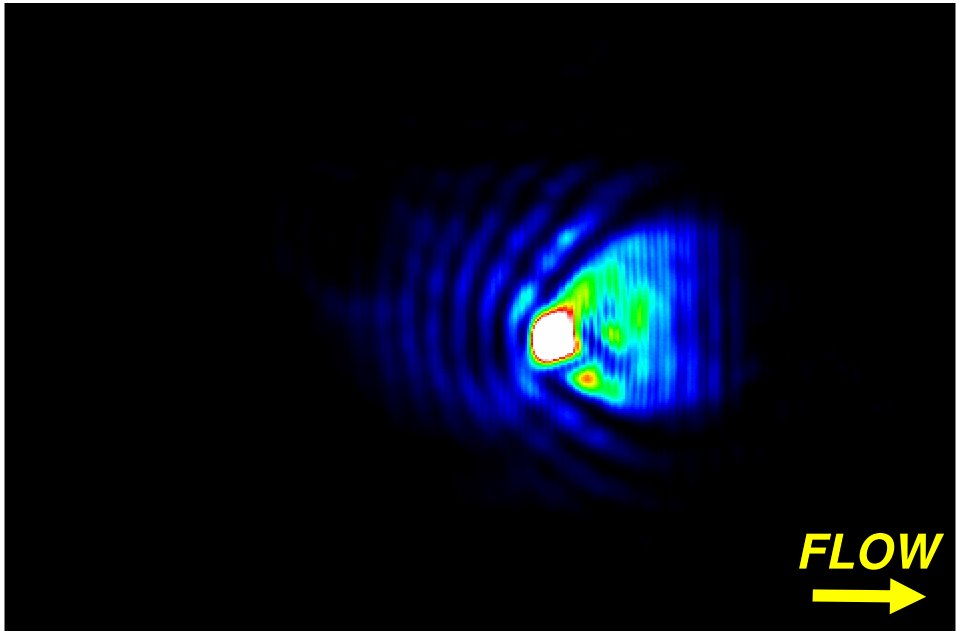


All-optical switch:propagation effects



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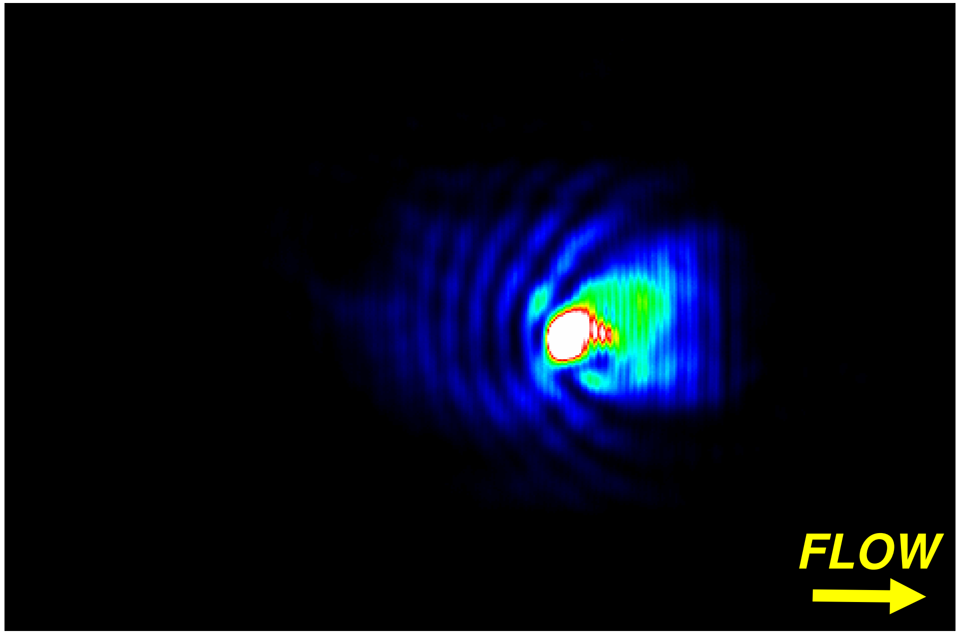

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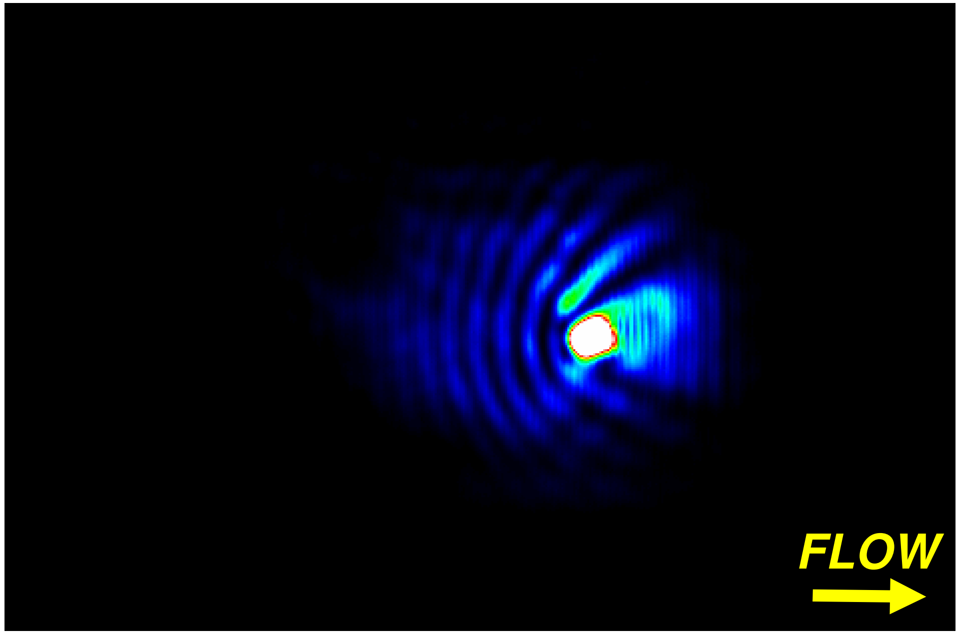

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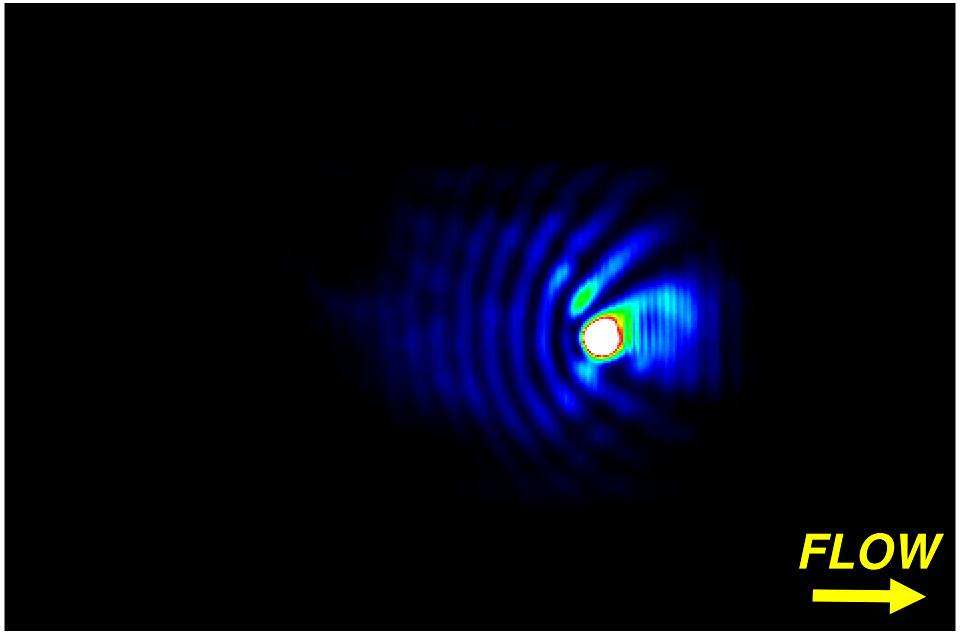

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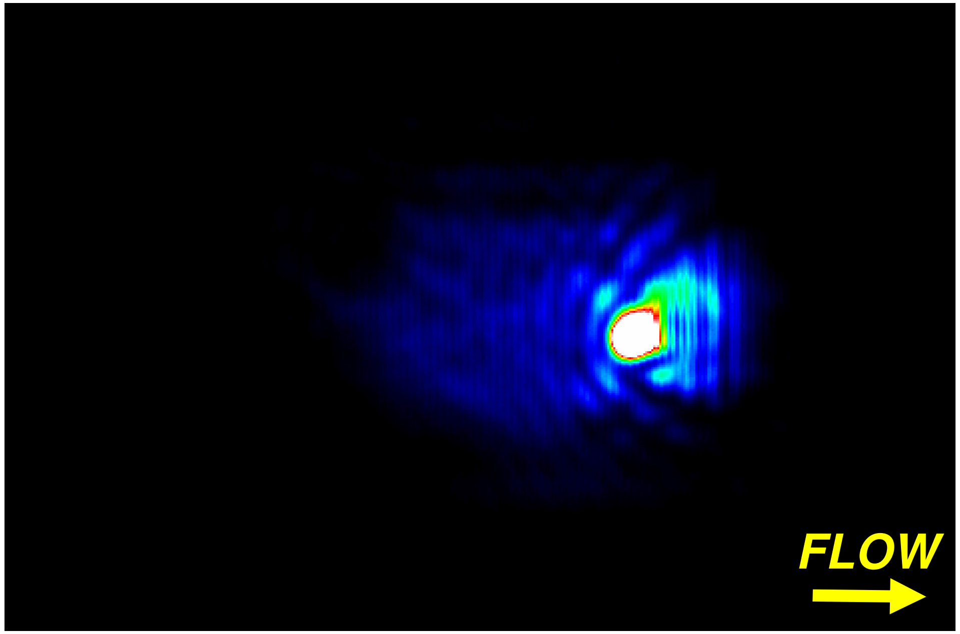

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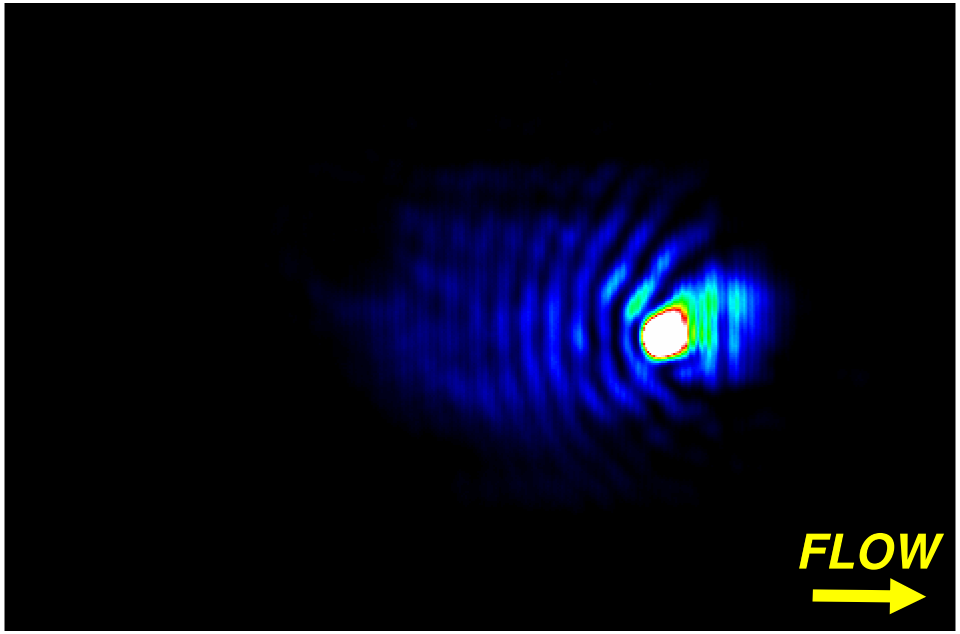

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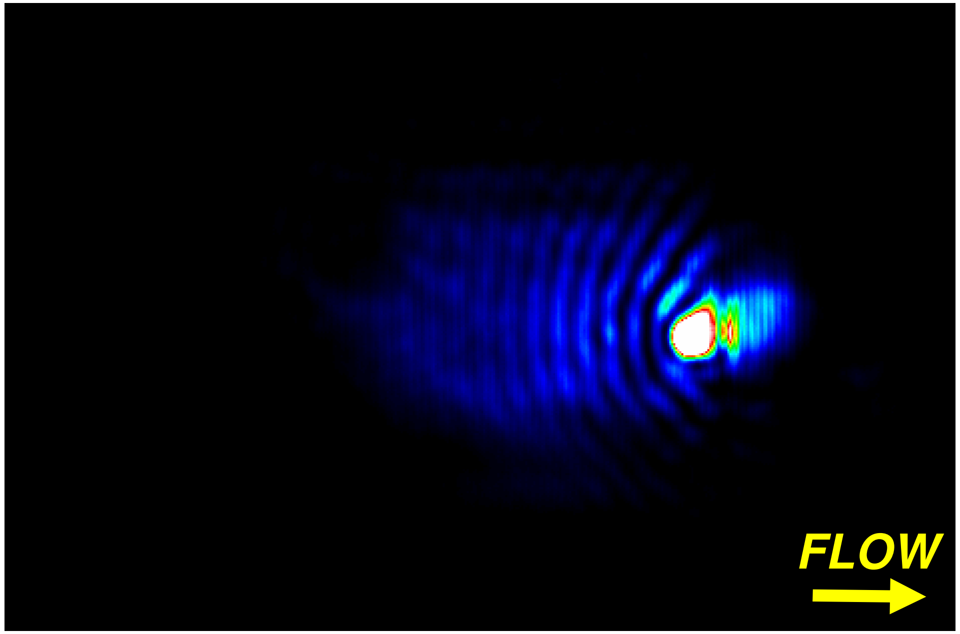

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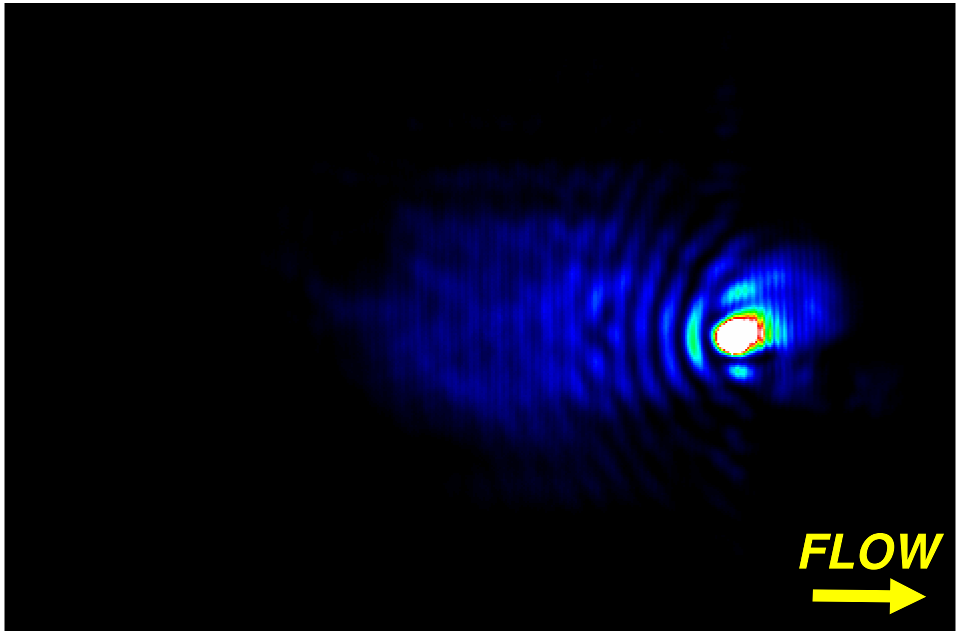

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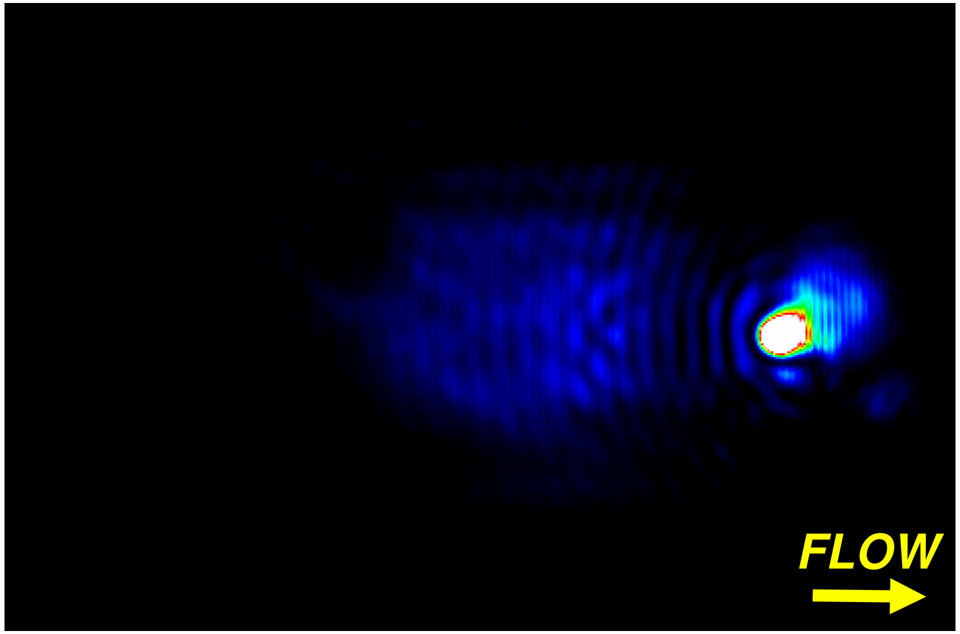
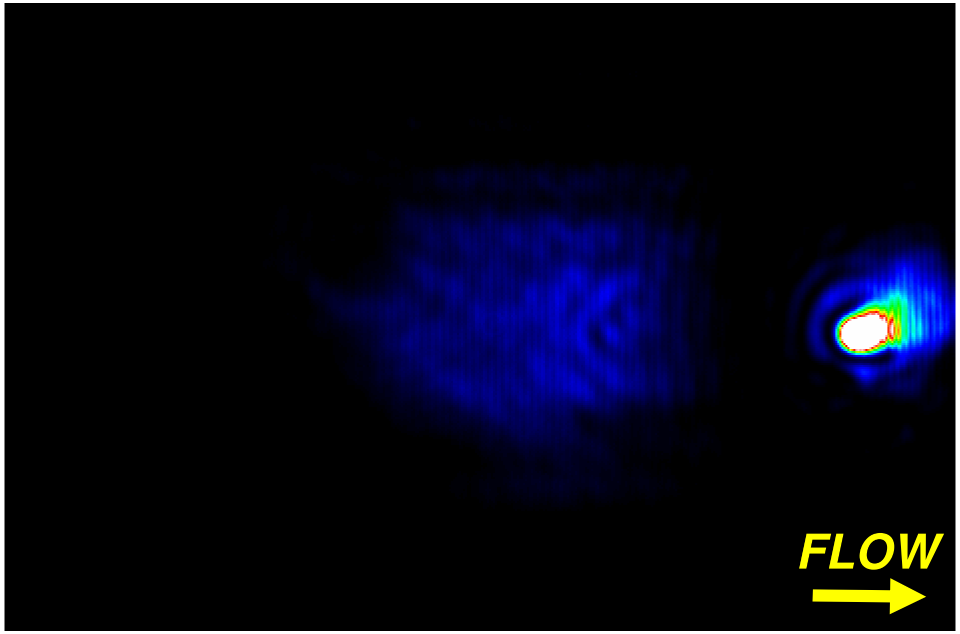
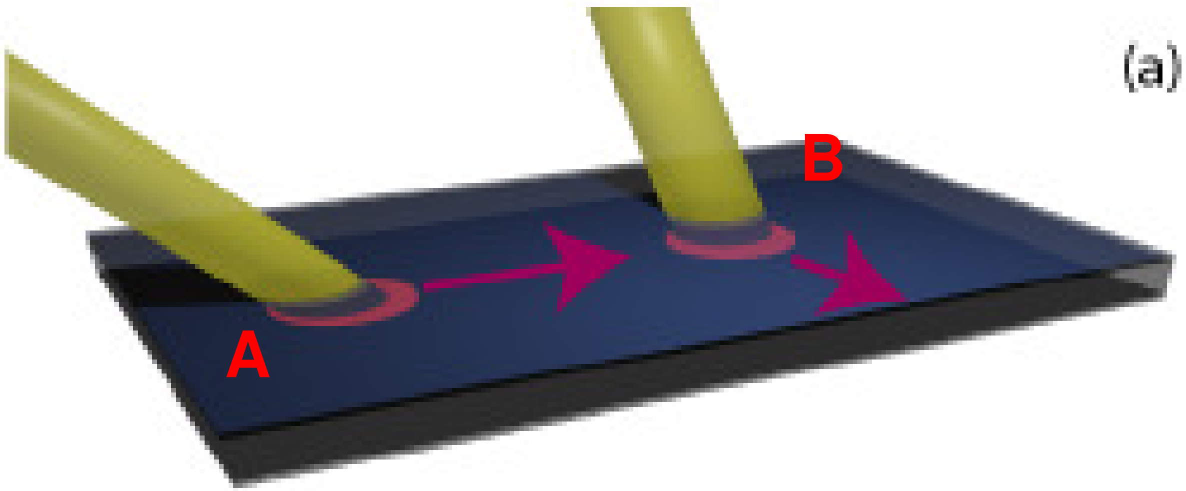


All-optical switch: propagation effects

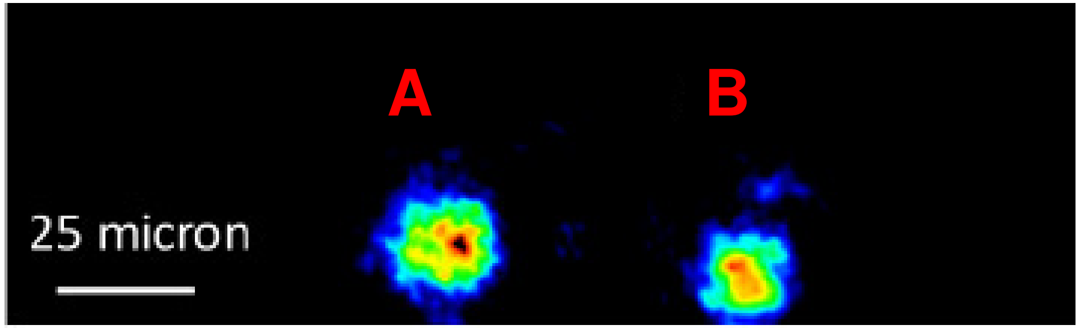


Propagation effects: polariton circuits?

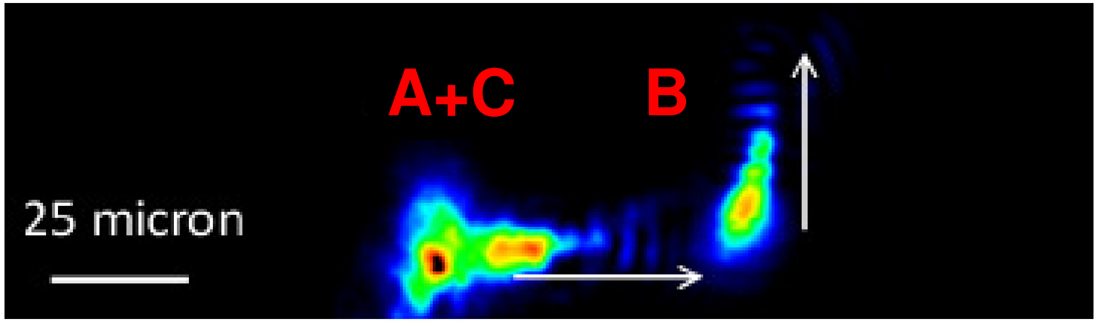


Idea : to exploit polariton flow in 2D coming from the address A to control the ON, OFF states of the address B, spatially separated.

Propagation effects: polariton circuits?



Below threshold ; Intensity x 20

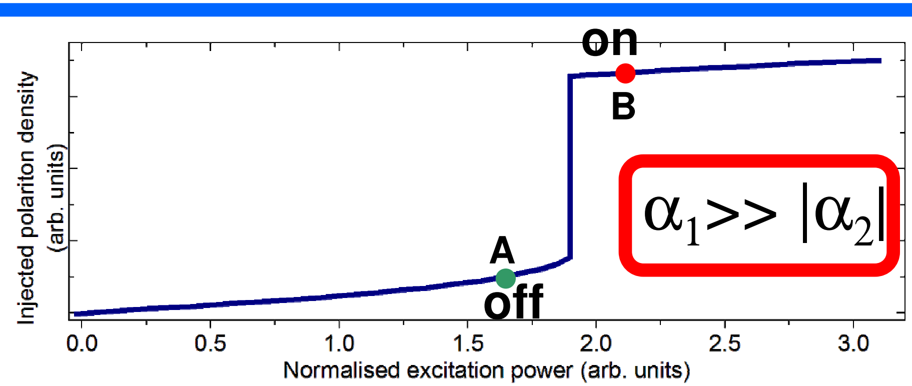


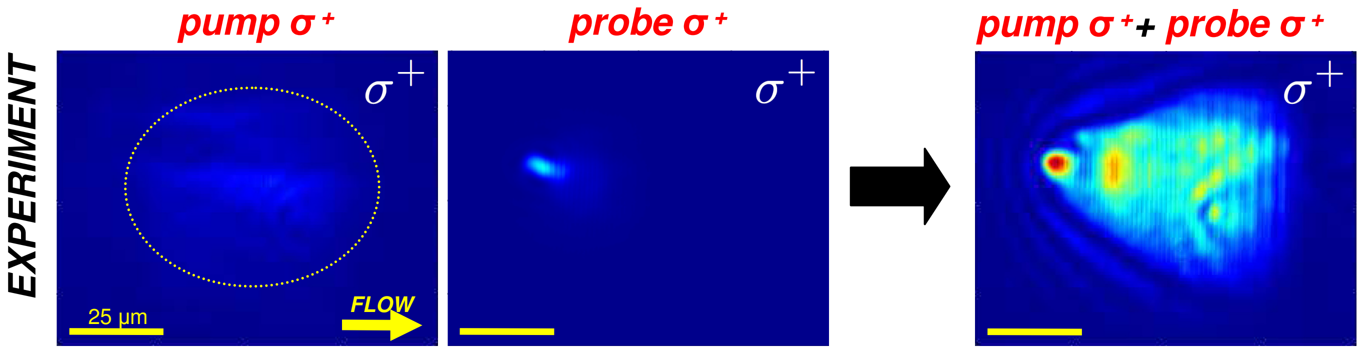
Above threshold

First step towards implementation of polariton circuits

Spin-selective switch

CIRCULAR polarisation pump (σ+)

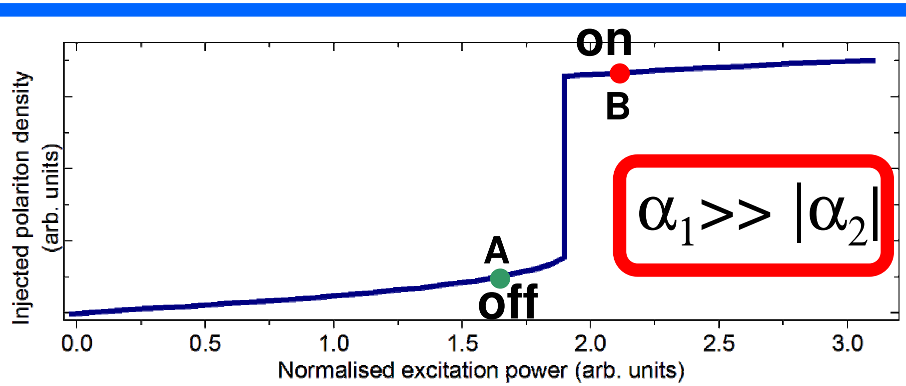


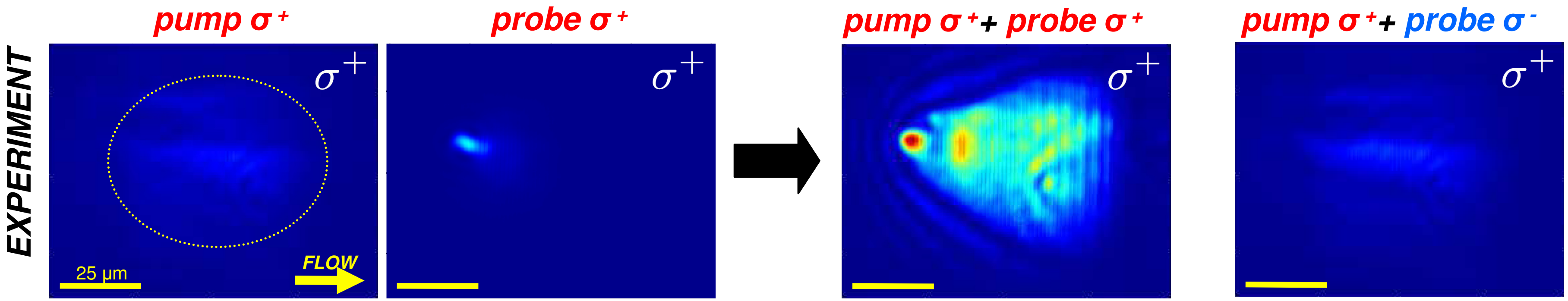


Only a co-polarised probe switches the system on

Spin-selective switch

CIRCULAR polarisation pump (σ+)

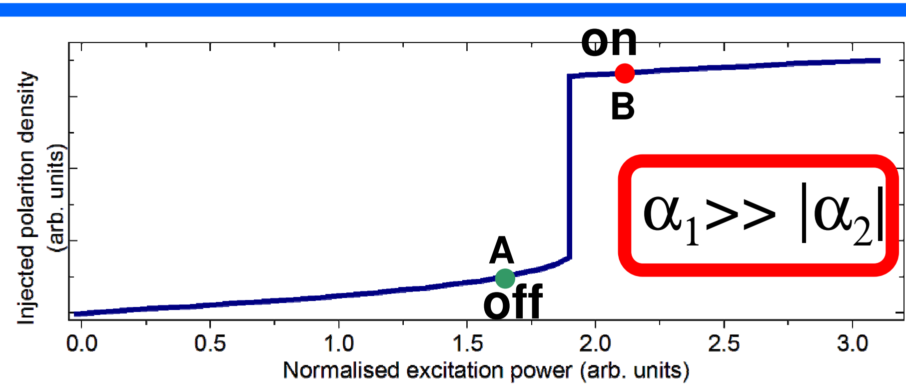


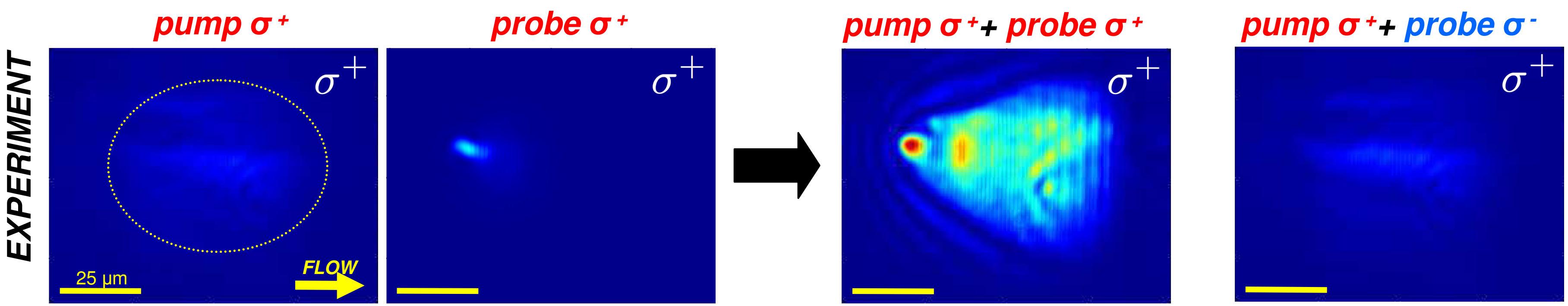


Only a co-polarised probe switches the system on

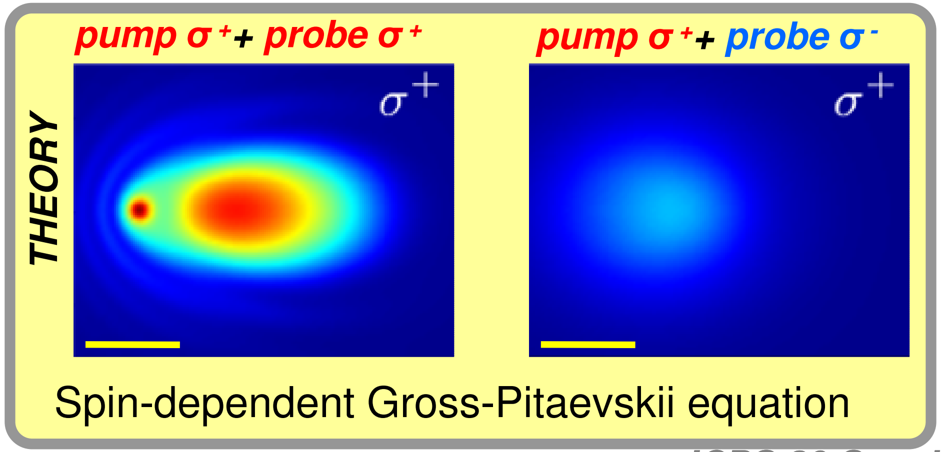
Spin-selective switch

CIRCULAR polarisation pump (σ+)



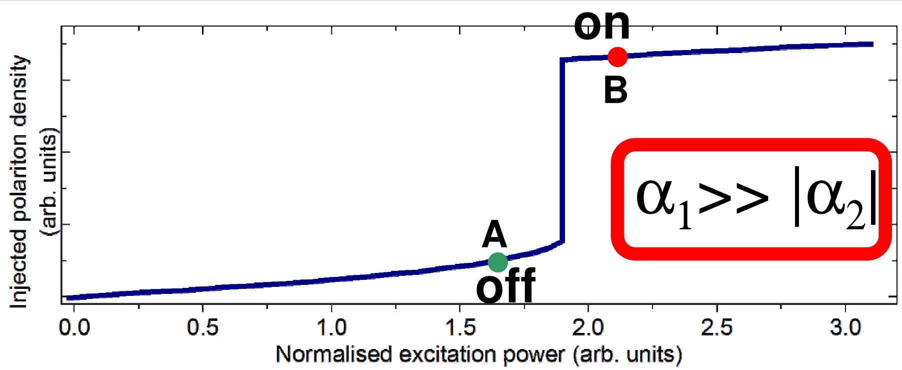


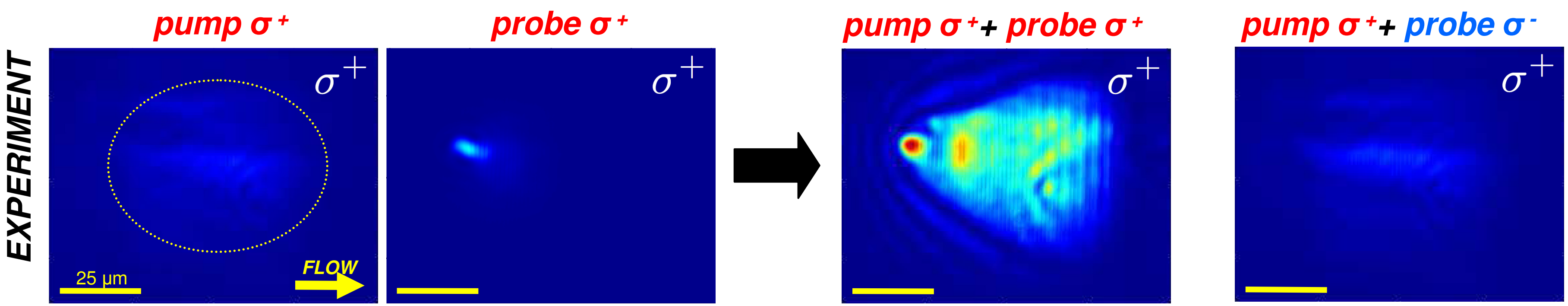
Only a co-polarised probe switches the system on



Spin-selective switch

CIRCULAR polarisation pump (σ+)





Only a co-polarised probe switches the system on

pump	probe	emission
σ+	σ+	Yes (σ+)
σ+	σ-	No
σ-	σ+	No
σ-	σ-	Yes (σ-)

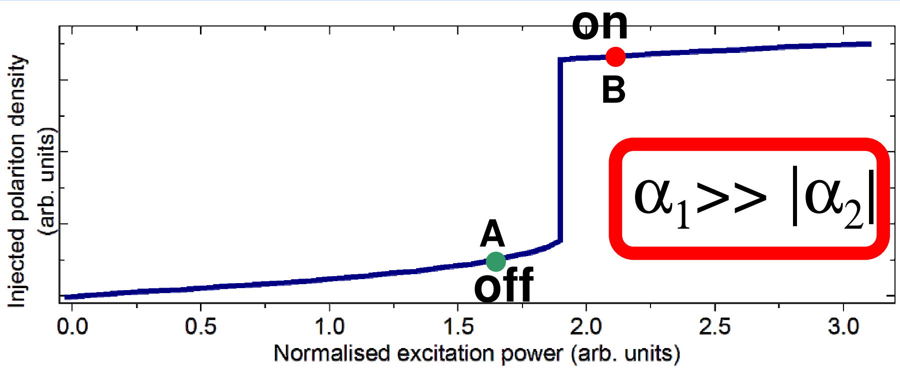
X-NOR gate

Polarisation control

LINEAR polarisation pump

⬇

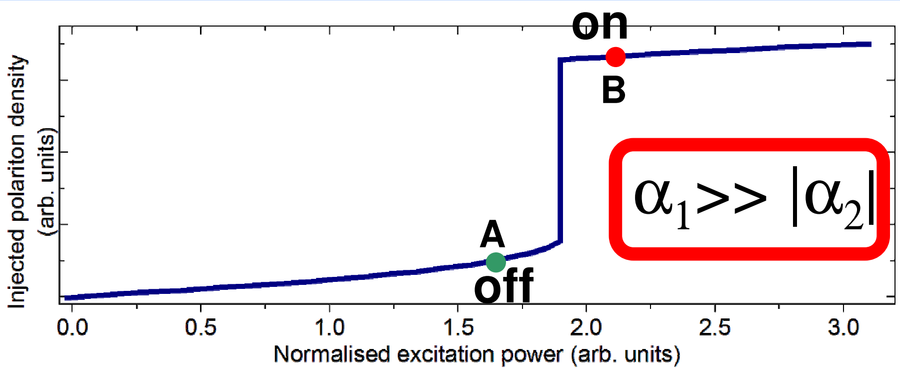
Final polarization: **<u>that of the probe</u>**



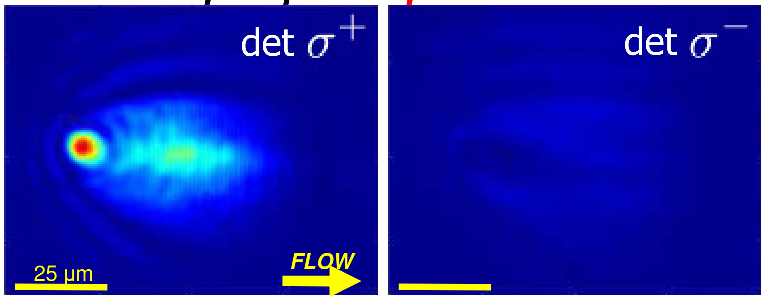
Polarisation control

LINEAR polarisation pump

Final polarization: **<u>that of the probe</u>**



pump TE + probe σ⁺

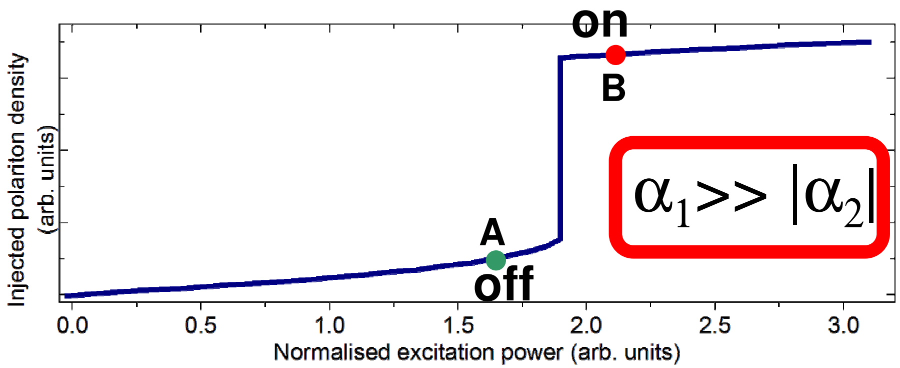


Polarisation control

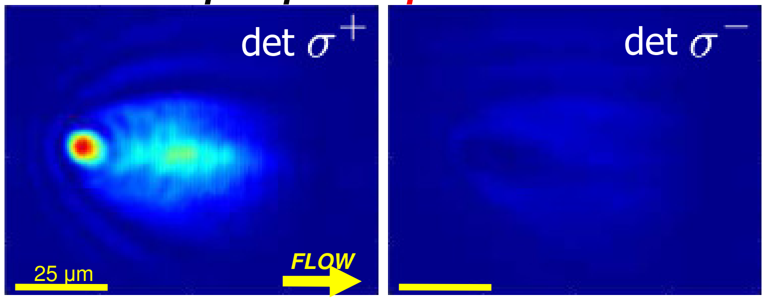
LINEAR polarisation pump

⬇

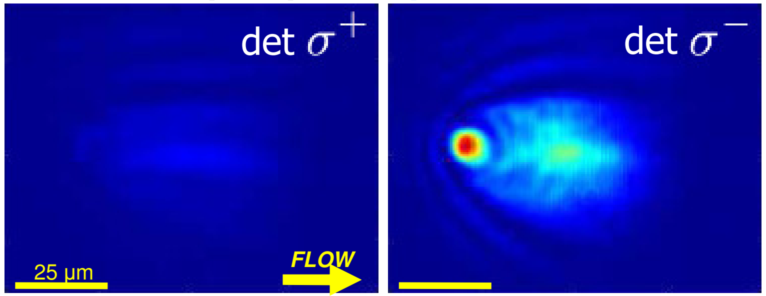
Final polarization: **<u>that of the probe</u>**



pump TE + probe σ⁺



pump TE + probe σ⁻



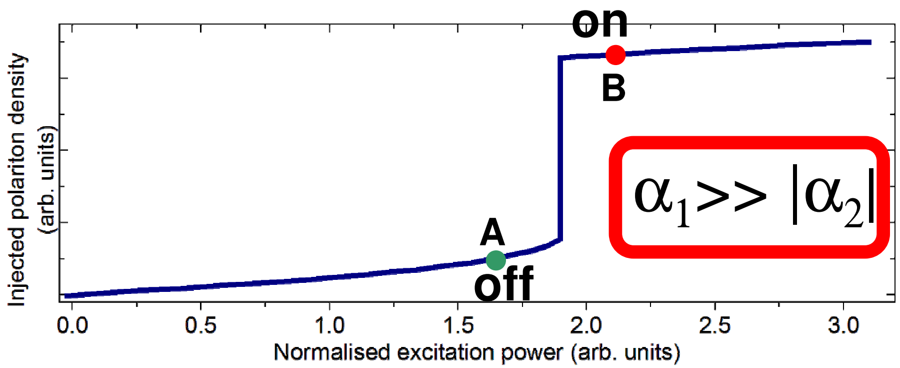
Polarisation control

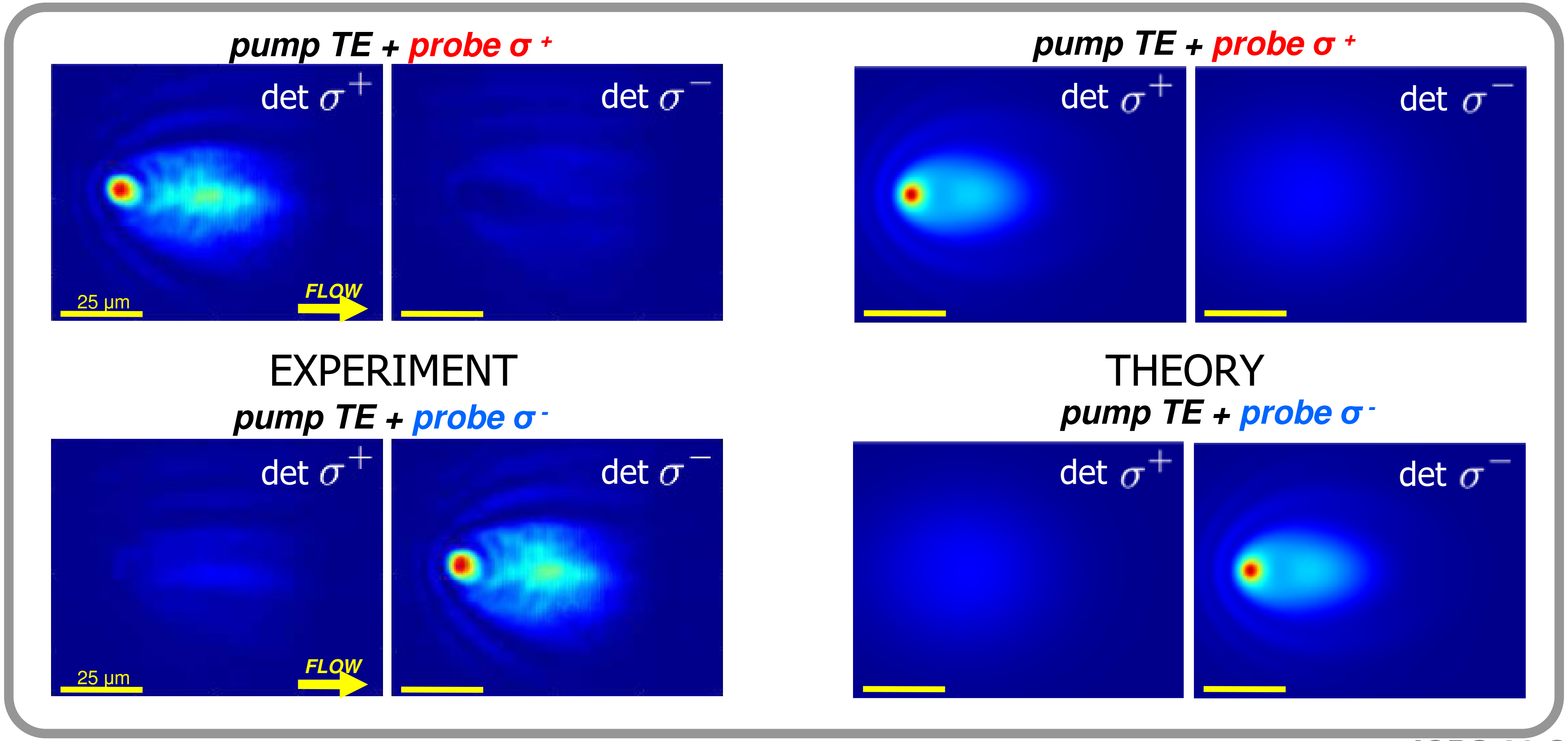
Laboratoire Kastler Brossel
Physique quantique et applications

LINEAR polarisation pump

⬇

Final polarization: **<u>that of the probe</u>**

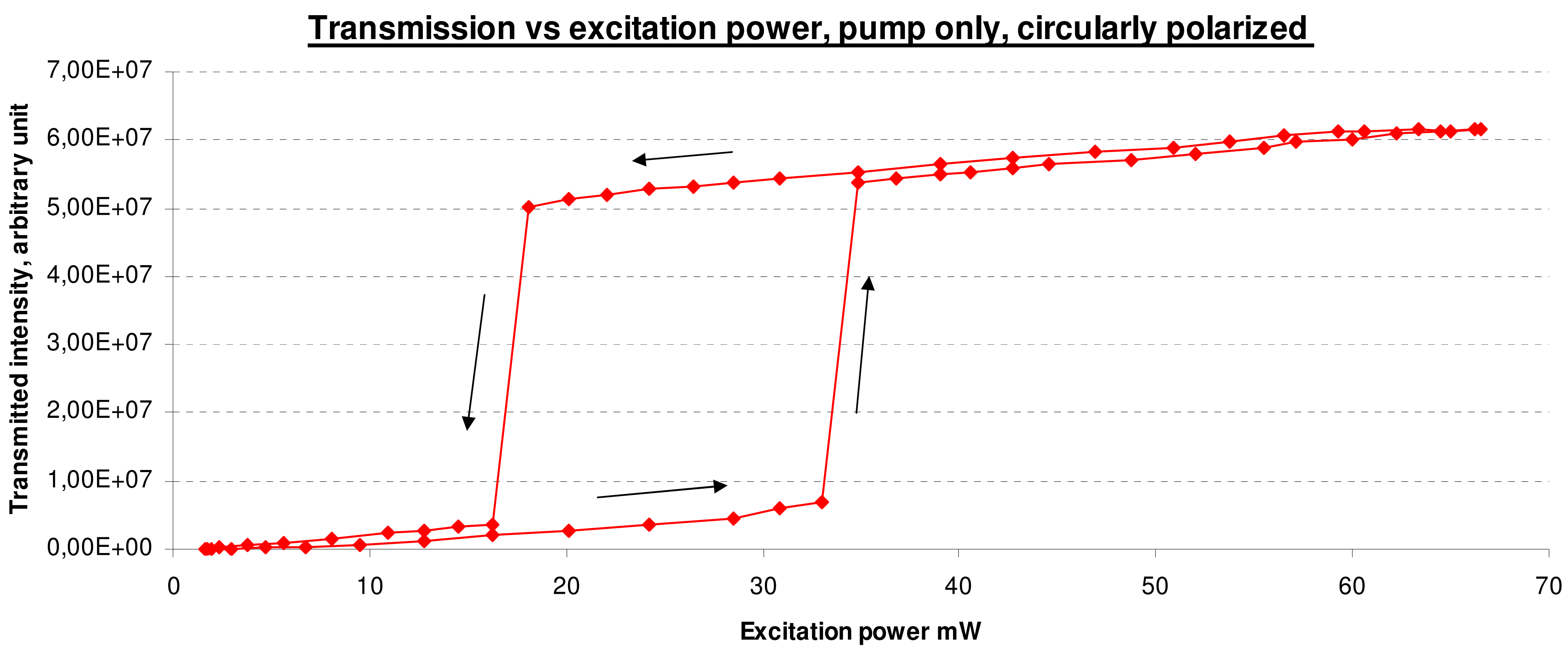




Spin-bistability

At **normal incidence**, we can observe a **hysteresis cycle**

(ref : A.Baas, PRB 70, 161307(R), 2004)



Spin-bistable switch

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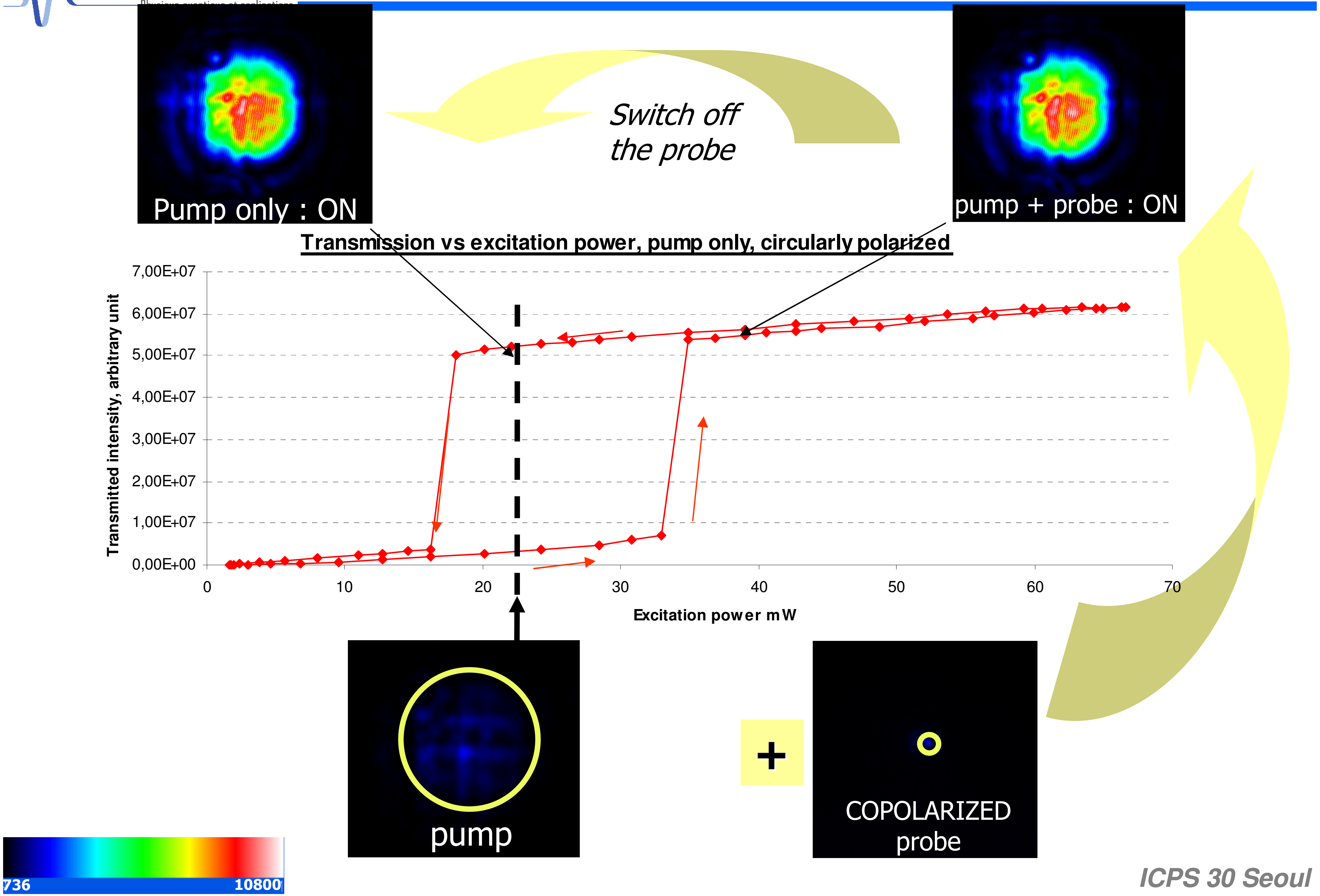
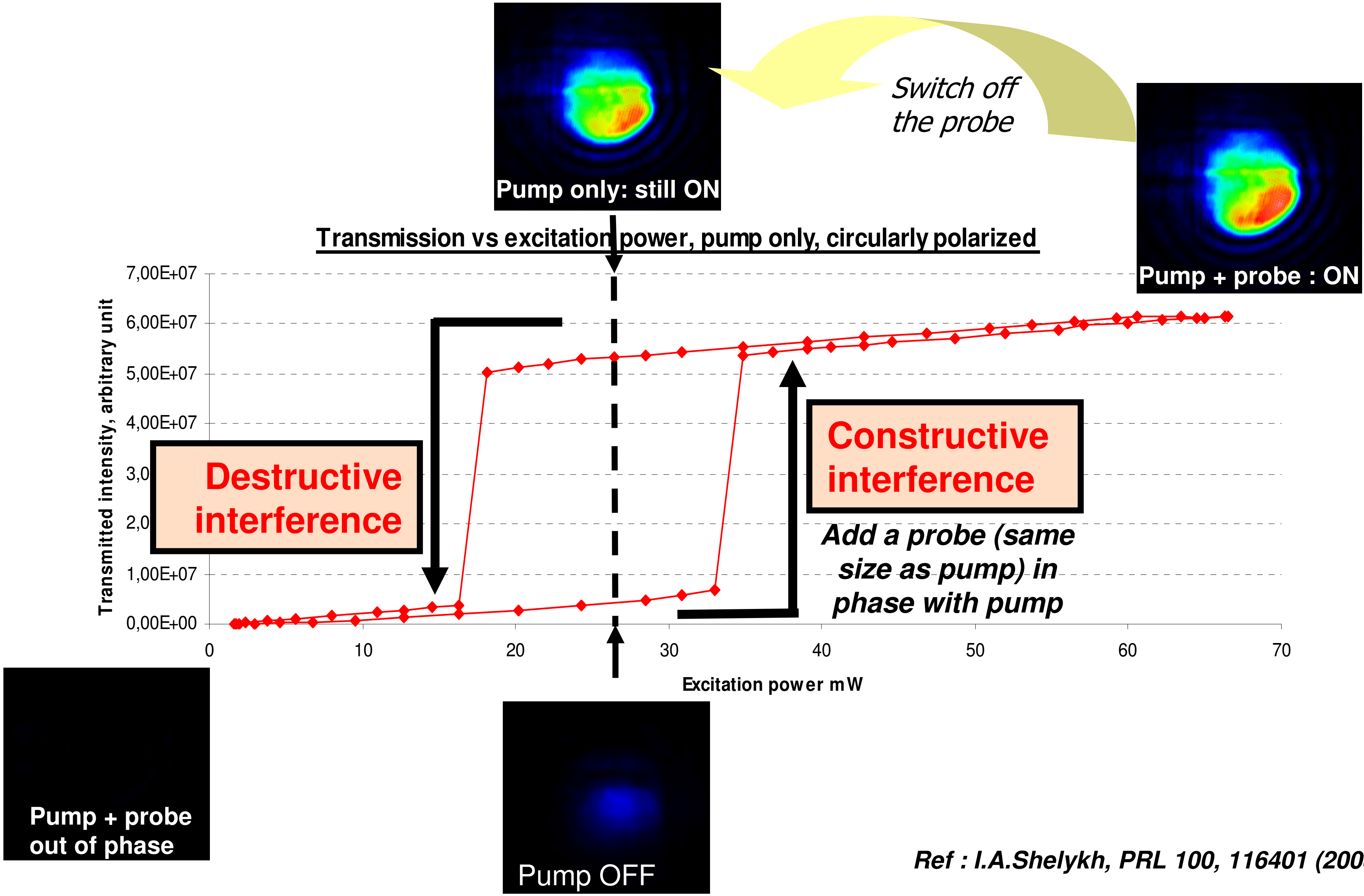


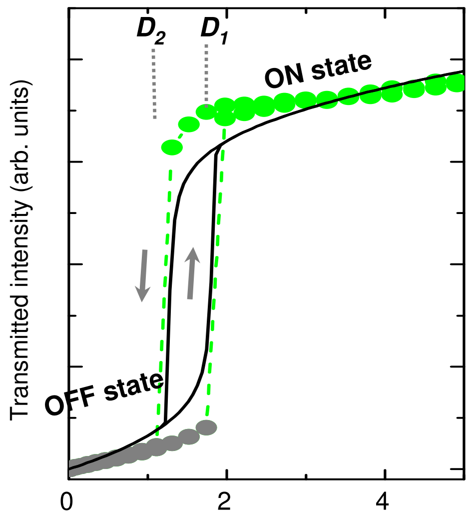
Spin-bistable switch

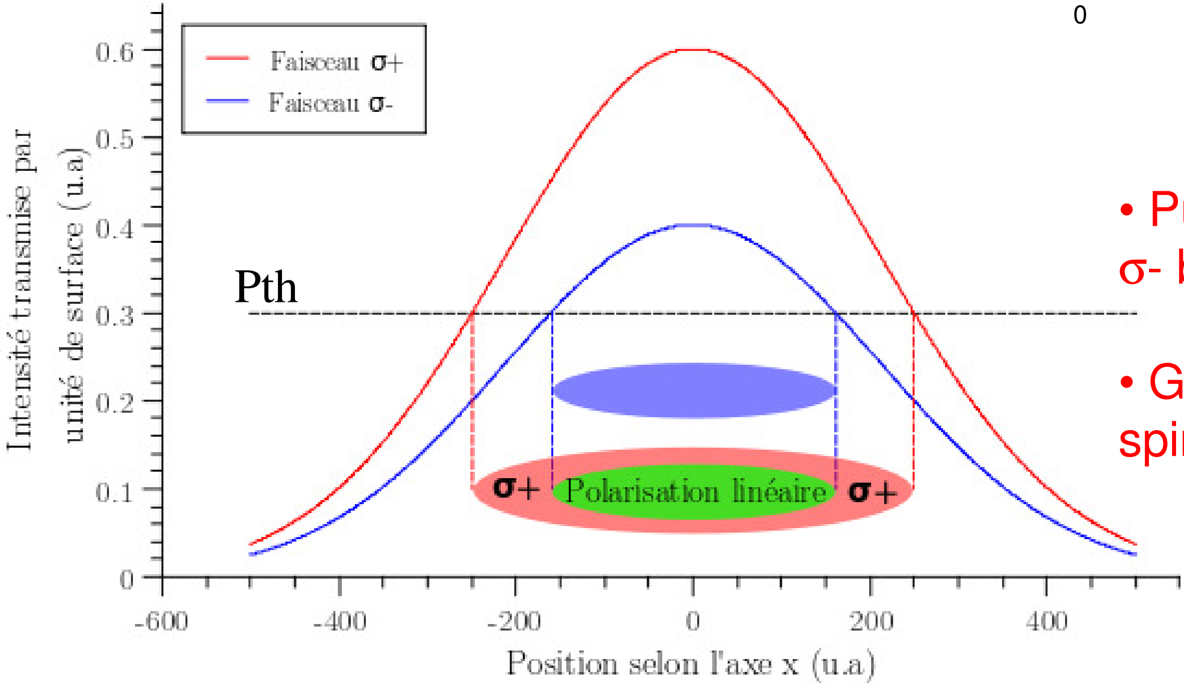


Ref : I.A.Shelykh, PRL 100, 116401 (2008)

Spin rings

- Non-linear (bistable) system

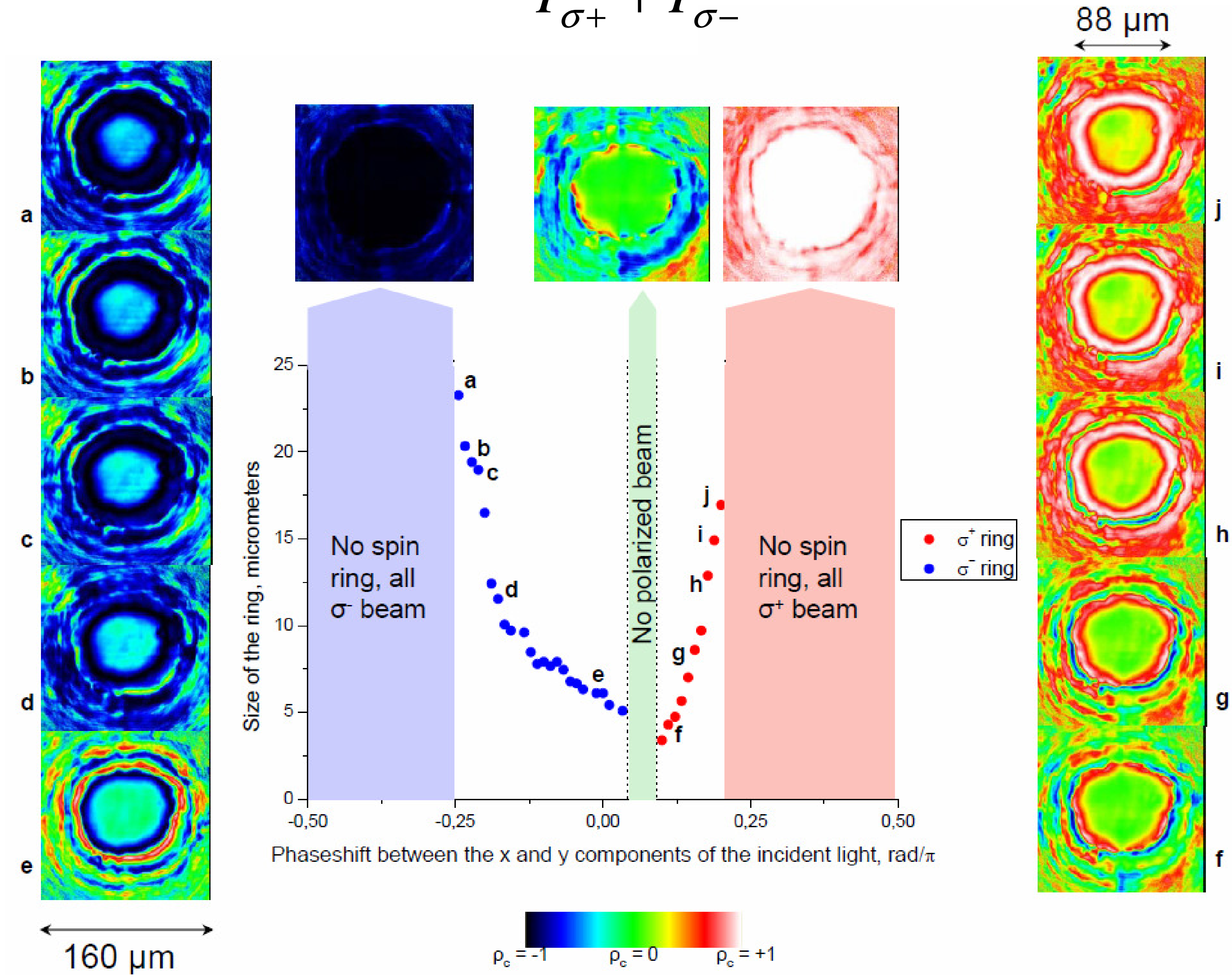




- Pump elliptically polarized: σ+, σ- beams with different intensities
- Gaussian profile of the pump: spin rings

Spin spatial control : Spin rings

$$\rho_c = \frac{I_{\sigma+} - I_{\sigma-}}{I_{\sigma+} + I_{\sigma-}}$$



Summary and perspectives

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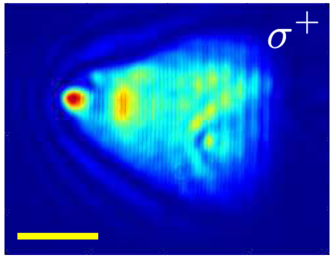
Physique quantique et applications

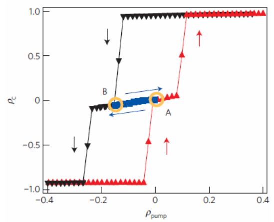
- **Polarisation switching and propagation (non-local)**



- Non-local X-NOR gate
- Polarisation propagation
- Very low switching power (~1fJ/µm)

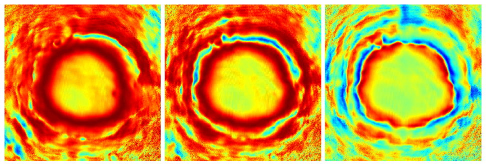
Amo et al., Nature Photonics **4**, 361 (2010)

- **Polarisation multistability**



Paraïso et al., Nature Materials **9**, 655 (2010)

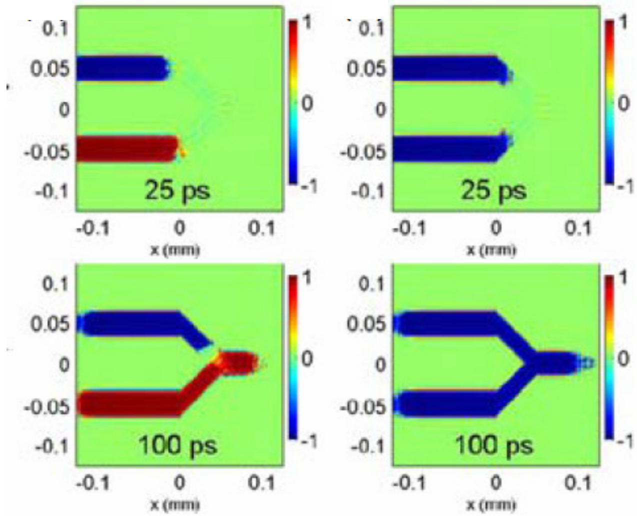
- **Spin rings**



Adrados et al., PRL, 2010

Sarkar et al., PRL, 2010

Towards realistic spin-optronic applications



Liew et al., PRL **101**, 016402 (2008)