



Probing the ground state of Landau polaritons with transport and ultrafast field measurements

Jérôme Faist
ETH Zurich



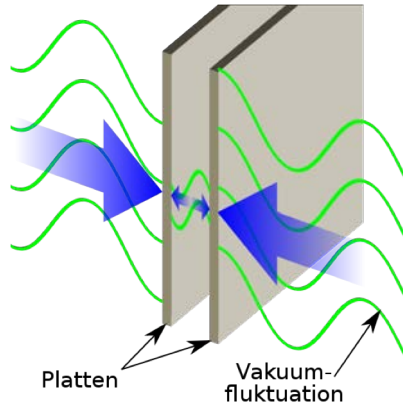
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Engineering the vacuum via cavities

Casimir effect

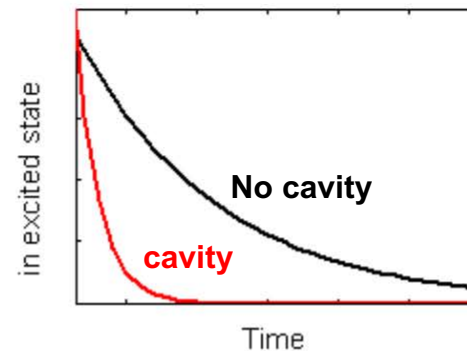


Mathematics. — *On the attraction between two perfectly conducting plates.* By H. B. G. CASIMIR.

(Communicated at the meeting of May 29, 1948.)

Casimir, H.B.G., Proc. K. Ned. Akad. Wet. B **51**, 793795 (1948).
 Raimond, J.M. et al. Rev. Mod. Phys, 73 (2001)

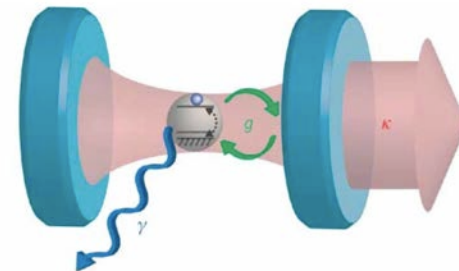
Light-matter coupling (weak)



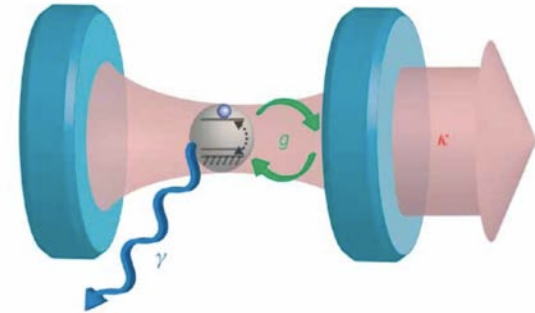
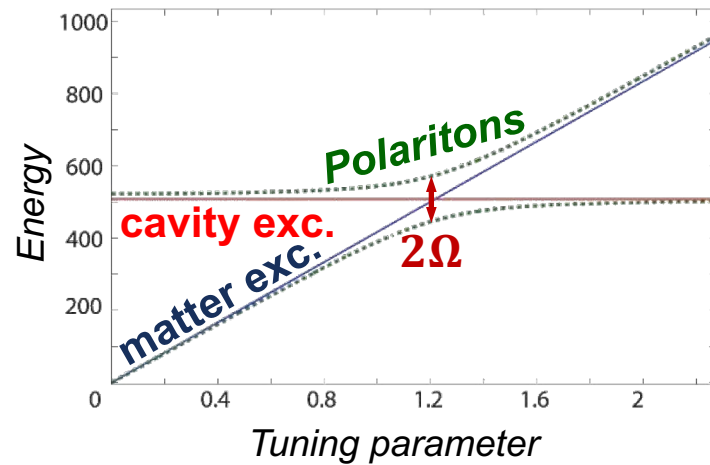
$$\Omega = d \times E_{vac} / \hbar$$



Edward M. Purcell
 (1912–1997)
 Nobel Prize 1952



Strong light-matter coupling

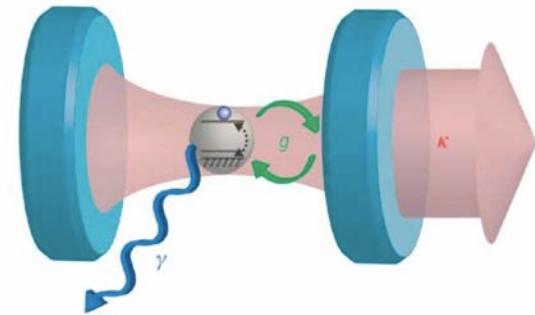
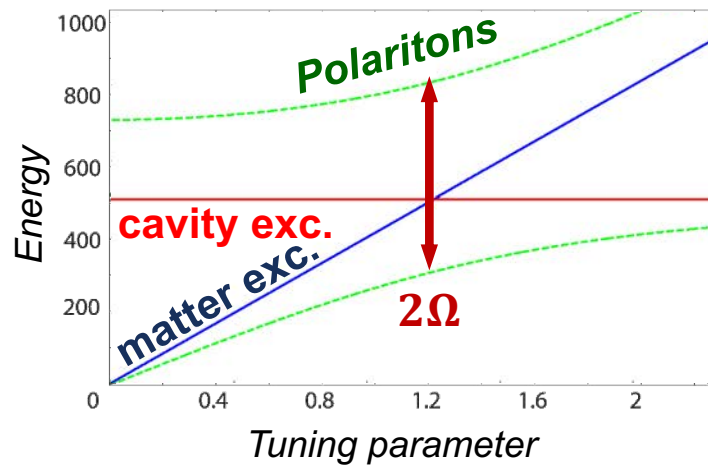


Vacuum Rabi frequency Ω

$$H = \hbar\omega_{cav}a^\dagger a + \hbar\omega_c b^\dagger b + i\hbar\Omega(a^\dagger b - ab^\dagger)$$

Ciuti et al., Phys. Rev. B 72, 115303 (2005)

Ultra-strong light-matter coupling (Hopfield model)



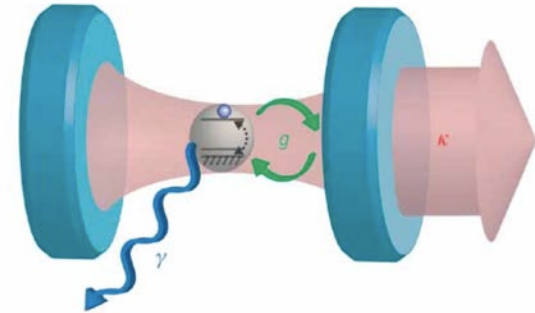
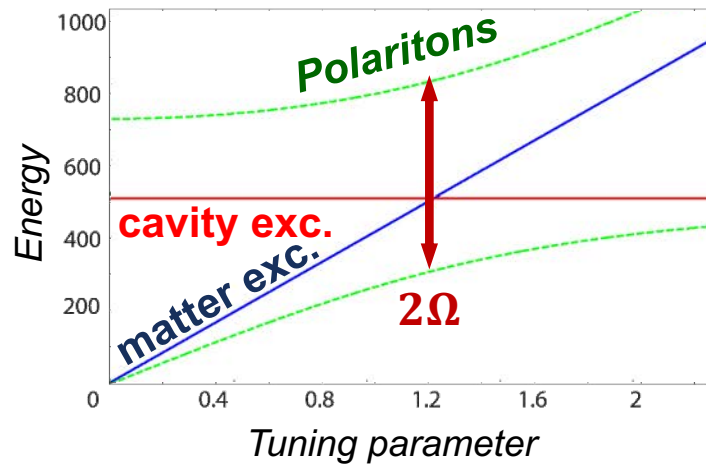
Vacuum Rabi frequency Ω

$$\begin{aligned}
 H = & \hbar\omega_{cav}a^\dagger a + \hbar\omega_c b^\dagger b \\
 & + i\hbar\Omega(a^\dagger b - ab^\dagger) + D(a^\dagger a + aa^\dagger) \\
 & + i\hbar\Omega(ab - a^\dagger b^\dagger) + D(aa + a^\dagger a^\dagger)
 \end{aligned}$$

anti-resonant and
diamagnetic terms

Ciuti et al., Phys. Rev. B 72, 115303 (2005)

Ultra-strong light-matter coupling (Hopfield model)



Vacuum Rabi frequency Ω

$$H = \hbar\omega_{cav}a^\dagger a + \hbar\omega_c b^\dagger b$$

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$$+ i\hbar\Omega(ab - a^\dagger b^\dagger) + D(aa + a^\dagger a^\dagger)$$

anti-resonant and
diamagnetic terms

**Ground state
contains photons!**

What are the implications for the material?

New phases of matter

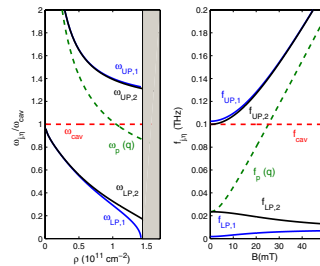
Superradiant phase transition in Graphene

PRL **109**, 267403 (2012) PHYSICAL REVIEW LETTERS week ending 28 DECEMBER 2012

Cavity QED of the Graphene Cyclotron Transition

David Hagenmüller and Cristiano Ciuti

Laboratoire Matériaux et Phénomènes Quantiques, Université Paris Diderot-Paris 7 and CNRS, Bâtiment Condorcet,
10 rue Alice Domon et Léonie Duquet, 75205 Paris Cedex 13, France
(Received 15 November 2011; published 27 December 2012)



Superradiant phase transition in excitonic insulators

PHYSICAL REVIEW LETTERS **122**, 017401 (2019)

Superradiant Quantum Materials

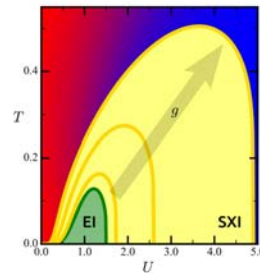
Giacomo Mazza^{1,2,*} and Antoine Georges^{2,3,1,4}

¹CPHT, Ecole Polytechnique, CNRS, Université Paris-Saclay, 91128 Palaiseau, France

²Collège de France, 11 place Marcelin Berthelot, 75005 Paris, France

³Center for Computational Quantum Physics, Flatiron Institute, 162 Fifth Avenue, New York, New York 10010, USA

⁴DQMP, Université de Genève, 24 quai Ernest Ansermet, CH-1211 Genève, Suisse



Cavity-induced superconductivity

PHYSICAL REVIEW LETTERS **122**, 133602 (2019)

Cavity-Mediated Electron-Photon Superconductivity

Frank Schlawin^{1,*}, Andrea Cavalleri^{1,2} and Dieter Jaksch¹

¹Clarendon Laboratory, University of Oxford, Parks Road, Oxford OX1 3PU, United Kingdom

²Max Planck Institute for the Structure and Dynamics of Matter, Luruper Chaussee 149, 22761 Hamburg, Germany

(Received 21 May 2018; revised manuscript received 6 February 2019; published 4 April 2019)

No-go theorems (recent)

PRL **109**, 267404 (2012) PHYSICAL REVIEW LETTERS week ending 28 DECEMBER 2012

Drude Weight, Cyclotron Resonance, and the Dicke Model of Graphene Cavity QED

Luca Chiriacoli,¹ Marco Polini,^{2,*} Vittorio Giovannetti,¹ and Allan H. MacDonald³

¹NEST, Scuola Normale Superiore and Istituto Nanoscienze-CNR, I-56126 Pisa, Italy

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³Department of Physics, University of Texas at Austin, Austin, Texas 78712, USA

(Received 30 July 2012; published 27 December 2012)

The unique optoelectronic properties of graphene make this two-dimensional material an ideal platform for fundamental studies of cavity quantum electrodynamics in the strong-coupling regime. The celebrated Dicke model of cavity quantum electrodynamics can be approximately realized in this material when the cyclotron transition of its 2D massless Dirac fermion carriers is nearly resonant with a cavity photon mode. We develop the theory of strong matter-photon coupling in this circumstance, emphasizing the essential role of a dynamically generated matter energy term that is quadratic in the photon field and absent in graphene's low-energy Dirac model.

Cavity QED of Strongly Correlated Electron Systems: A No-go Theorem for Photon Condensation

G.M. Andolina,^{1,2} F.M.D. Pellegrino,^{3,4} V. Giovannetti,⁵ A.H. MacDonald,⁶ and M. Polini²

¹NEST, Scuola Normale Superiore, I-56126 Pisa, Italy

²Istituto Italiano di Tecnologia, Graphene Labs, Via Morego 30, I-16163 Genova, Italy

³Dipartimento di Fisica e Astronomia "Ettore Majorana",

Università di Catania, Via S. Sofia 64, I-95123 Catania, Italy

⁴INFN, Sez. Catania, I-95123 Catania, Italy

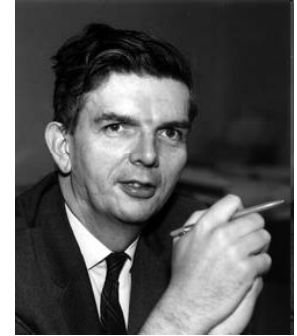
⁵NEST, Scuola Normale Superiore and Istituto Nanoscienze-CNR, I-56126 Pisa, Italy

⁶Department of Physics, The University of Texas at Austin, Austin, TX 78712, USA

How can we probe these phases?

Systems in the ultrastrong light-matter coupling

- Studying the Landau polariton system
- Engineering strong coupling via metamaterial
 - Enhancing the vacuum field
- Probe the ultrastrong coupling beyond optical response?
 - Electro-optic sampling
 - Transport



R. H. Dicke

Maximize Coupling strength

- The coupling energy is given by

$$\hbar\Omega_R = q\sqrt{N}d_{ij}\mathcal{E}_v$$

Increase the number
of oscillators

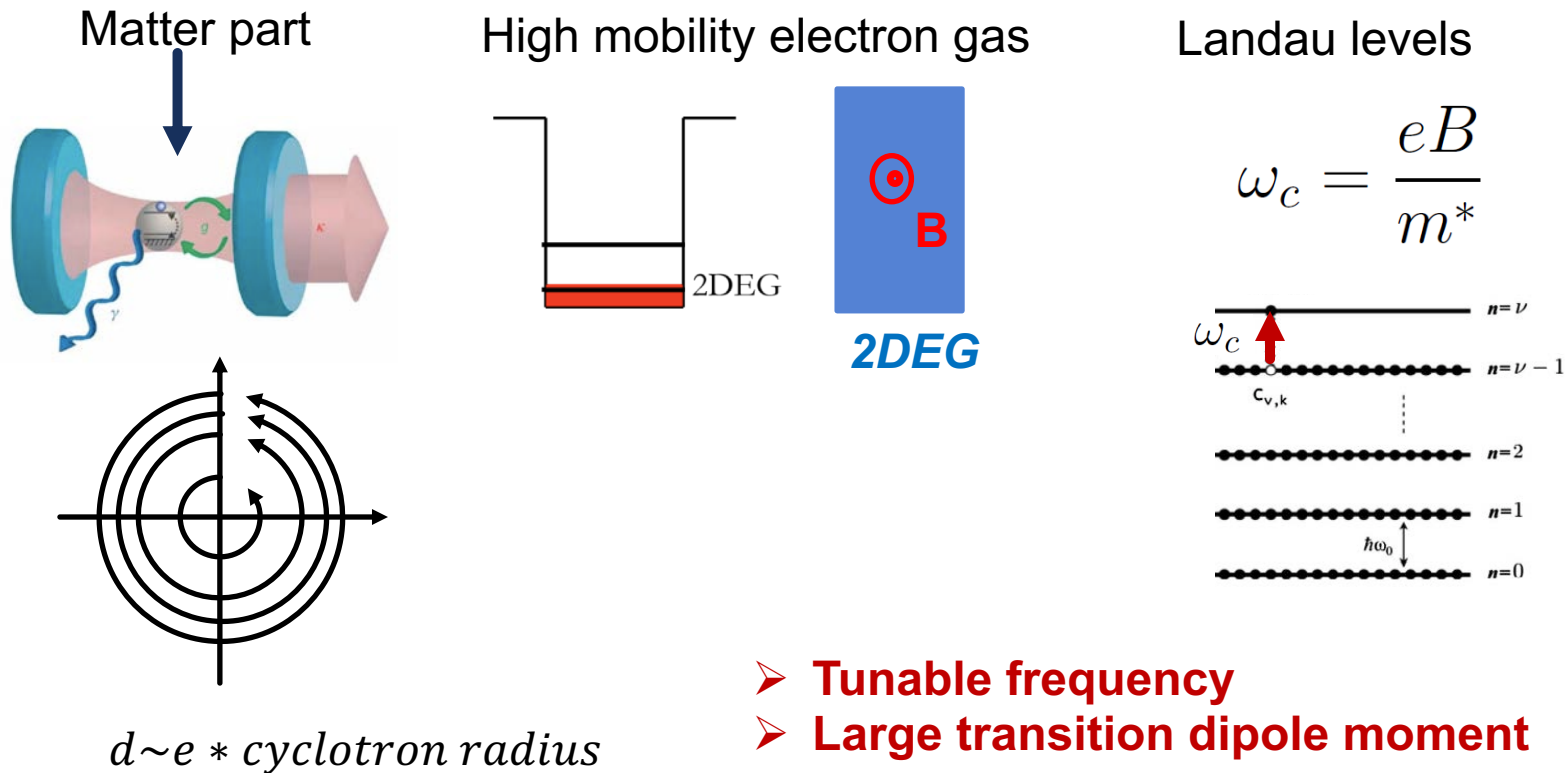
Large dipole
Matrix element

$$\mathcal{E}_v = \sqrt{\frac{\hbar\omega}{2\epsilon_r\epsilon_0 V}}$$

The vacuum electric field for a
single photon:

Minimize volume V:

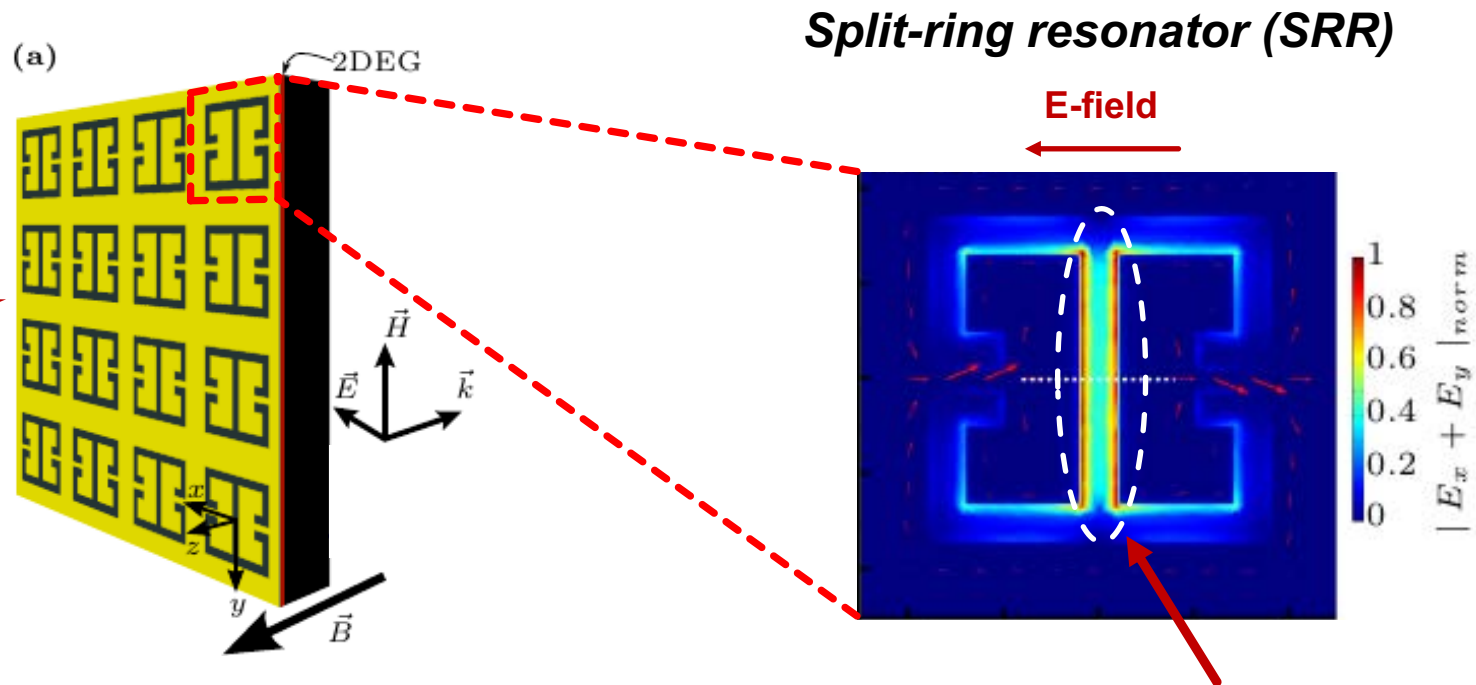
Landau levels of a 2D electron gas



Hagenmüller et al., PRB 81, 235303 (2010)

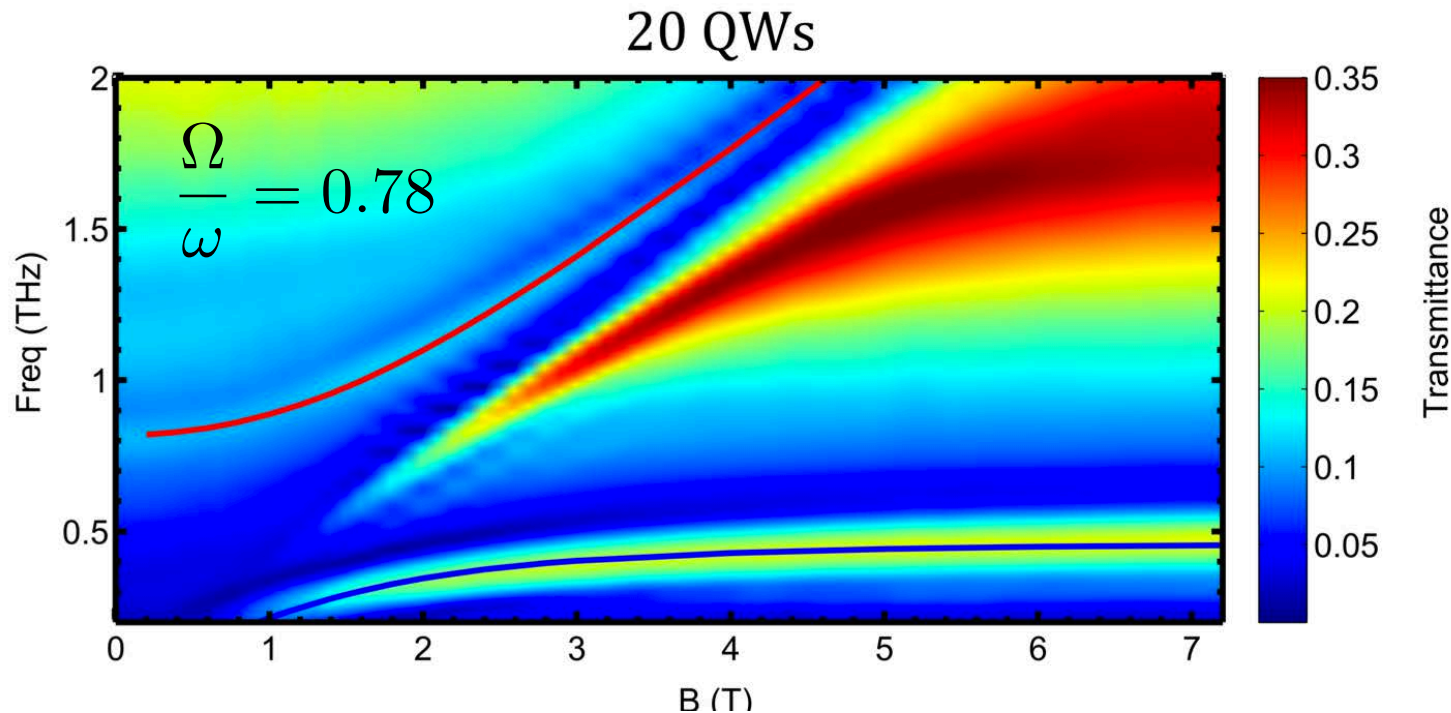
G. Scalari et al., Science, **335**, 1323 (2012)

Our system: SRR resonator as Cavity



- Subwavelength Cavity $V_{cav} \sim 10^{-4} \left(\frac{\lambda}{2n} \right)^3$
- Strong Vacuum field $E_{vac} \sim 50 \text{ V/m}$

Ratio of Rabi to transition Ω_R/ω of unity or above



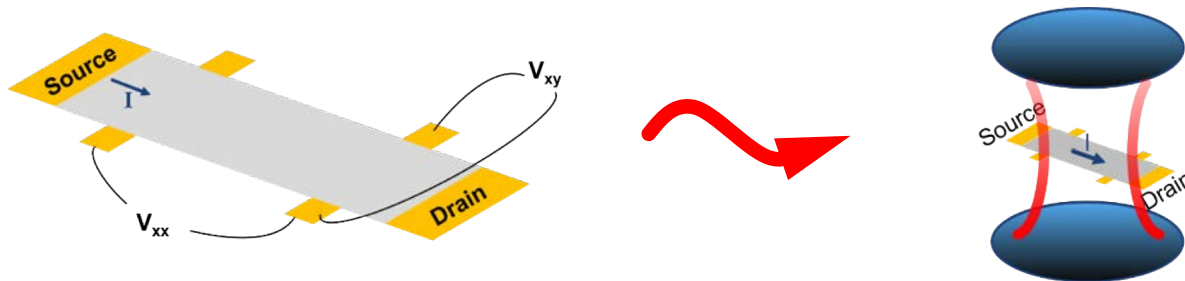
G. Scalari et al., *Science*, **335**, 1323 (2012)

C. Maissen, G. Scalari, *JF Phys. Rev. B*, 90, no. 20, p. 205309, (2014)

Recent results: $\Omega/\omega = 1.43$

A. Bayer, et al., *Nano Lett*, pp. acs.nanolett.7b03103–5, Sep. 2017.

Can vacuum change electronic transport?



Carrier transport enhanced by coupling to vacuum fields

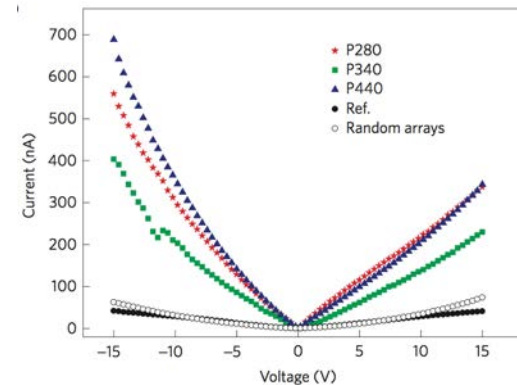
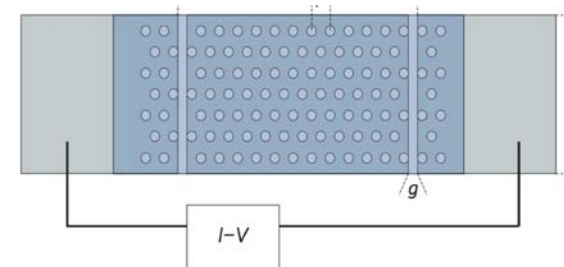
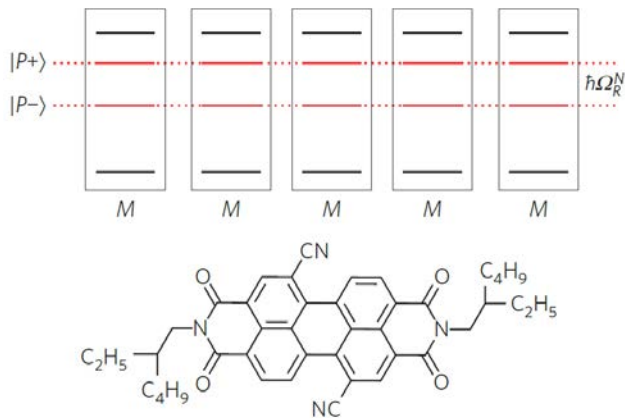
nature
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ARTICLES

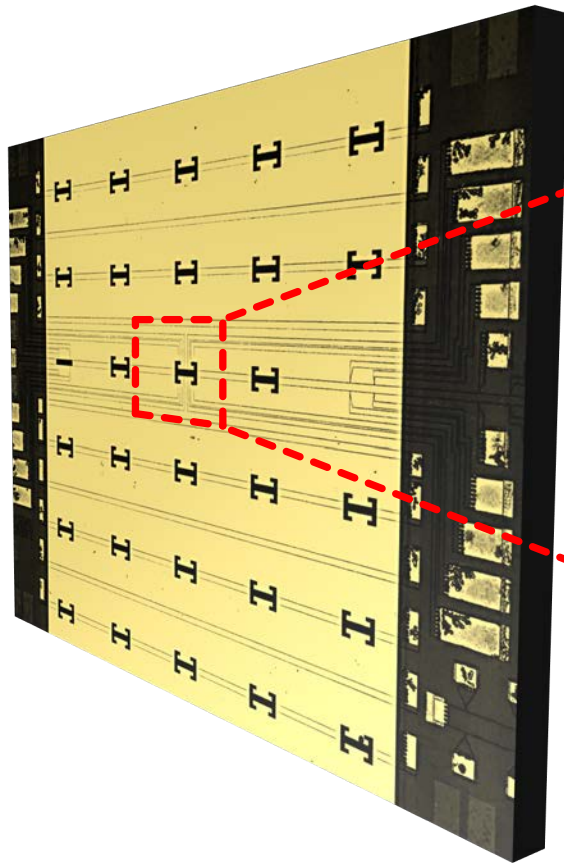
PUBLISHED ONLINE: 14 SEPTEMBER 2015 | DOI: 10.1038/NMAT4392

Conductivity in organic semiconductors hybridized with the vacuum field

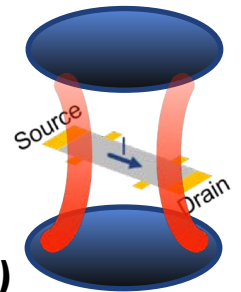
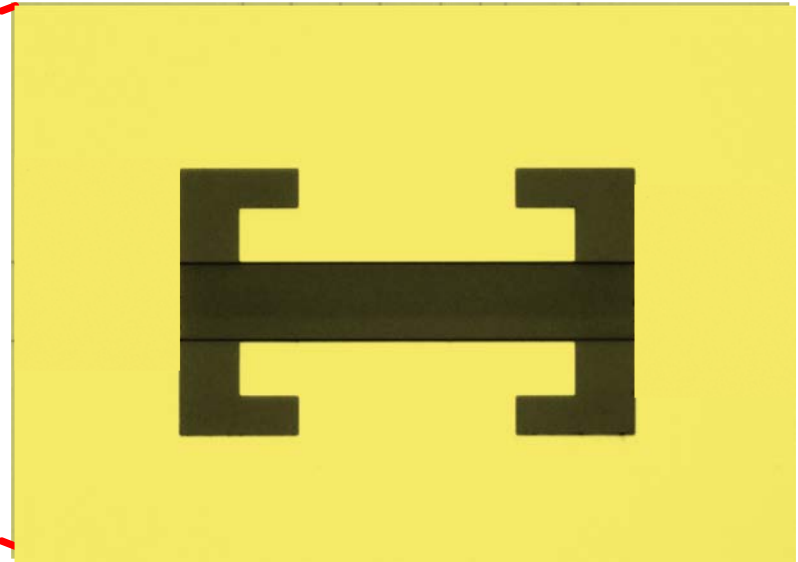
E. Orgiu^{1†}, J. George^{1†}, J. A. Hutchison^{1†}, E. Devaux¹, J. F. Dayen², B. Doudin², F. Stellacci³, C. Genet¹, J. Schachenmayer⁴, C. Genes⁵, G. Pupillo^{1,2}, P. Samori¹ and T. W. Ebbesen^{1*}



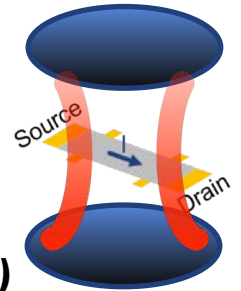
Transport in SRR cavity



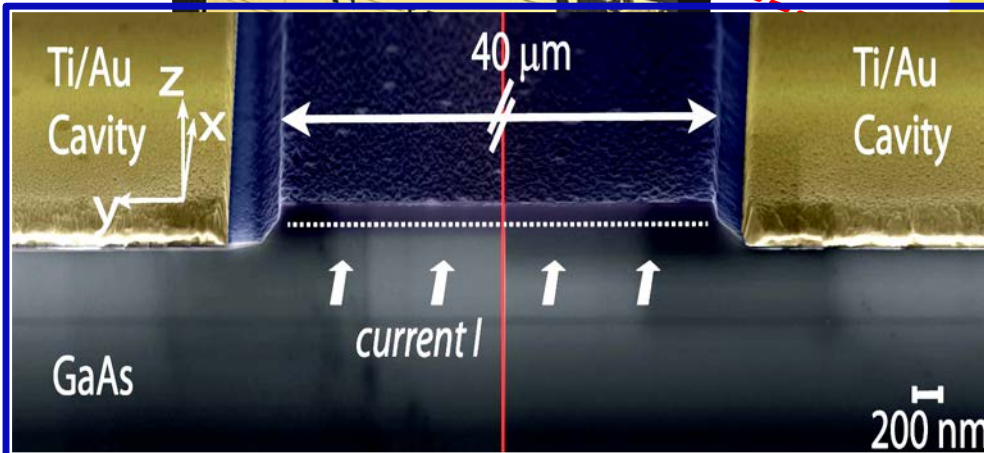
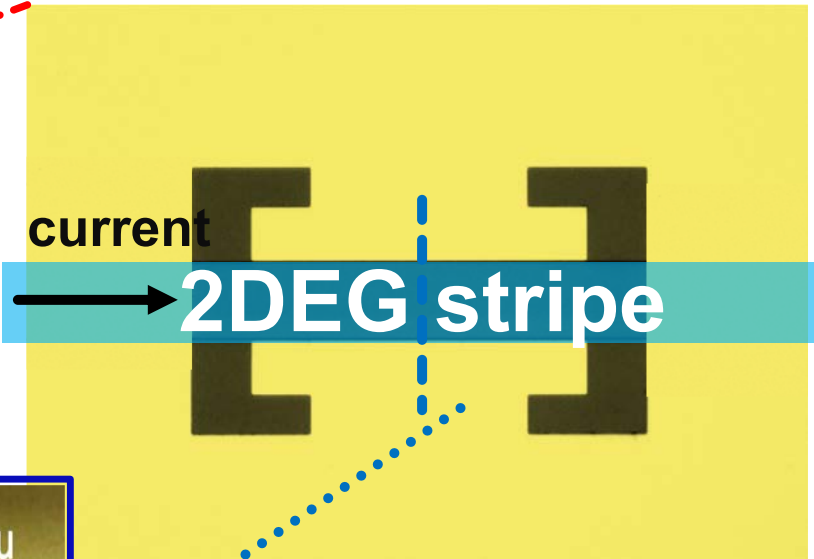
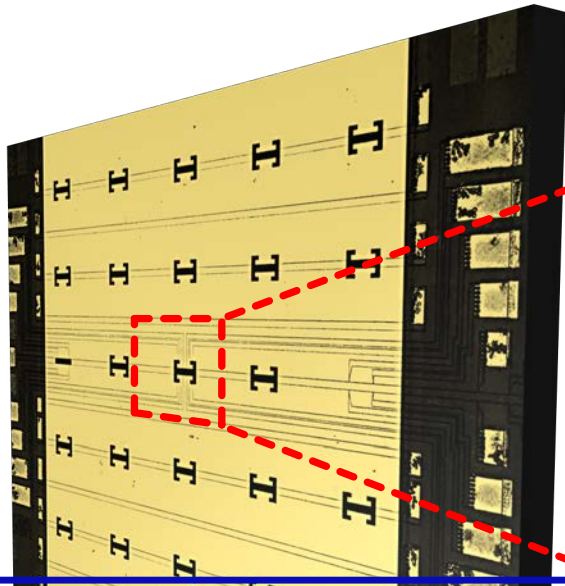
Split-ring resonator (SRR)



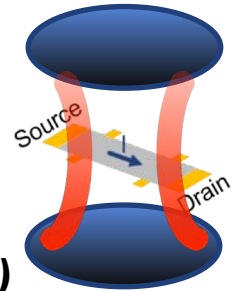
Transport in SRR cavity



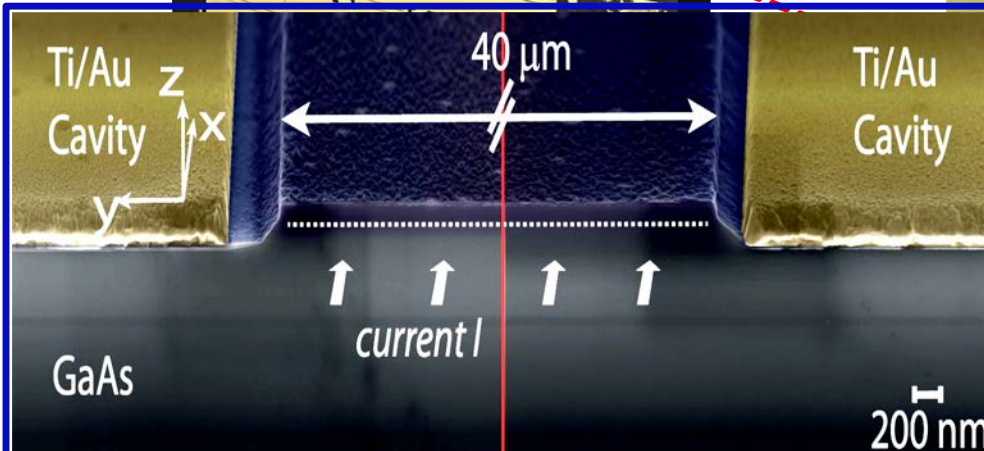
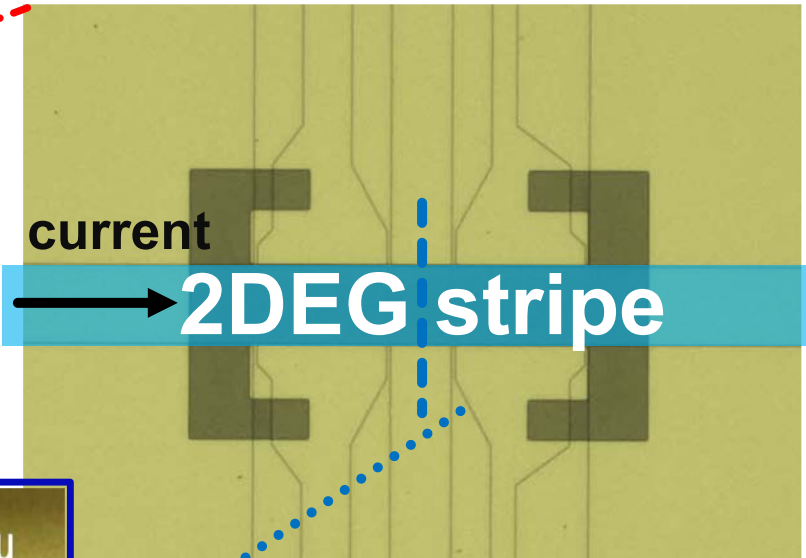
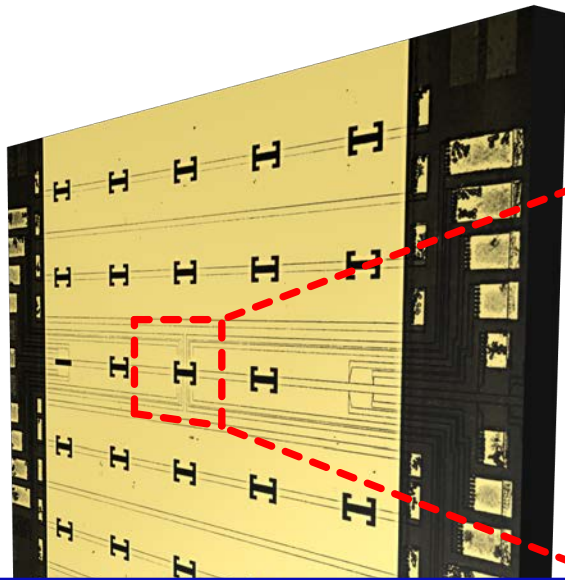
Split-ring resonator (SRR)



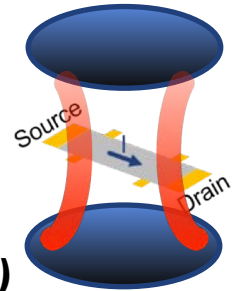
Transport in SRR cavity



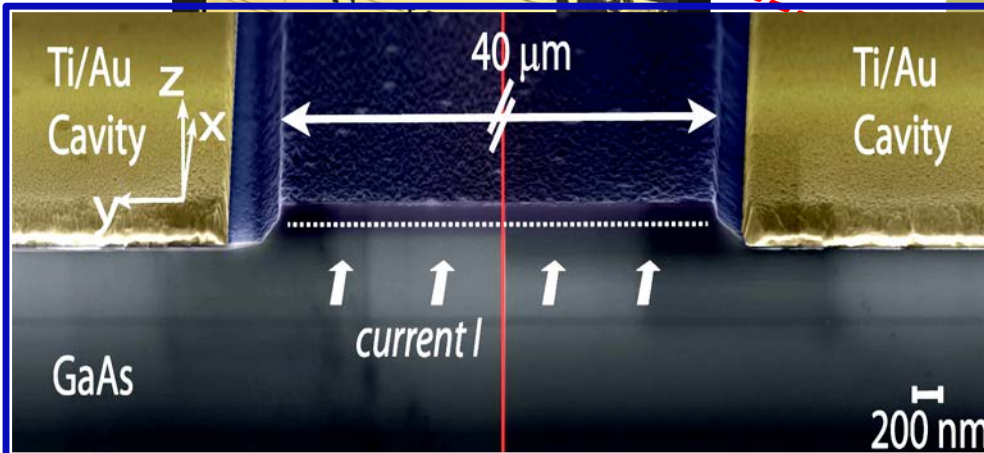
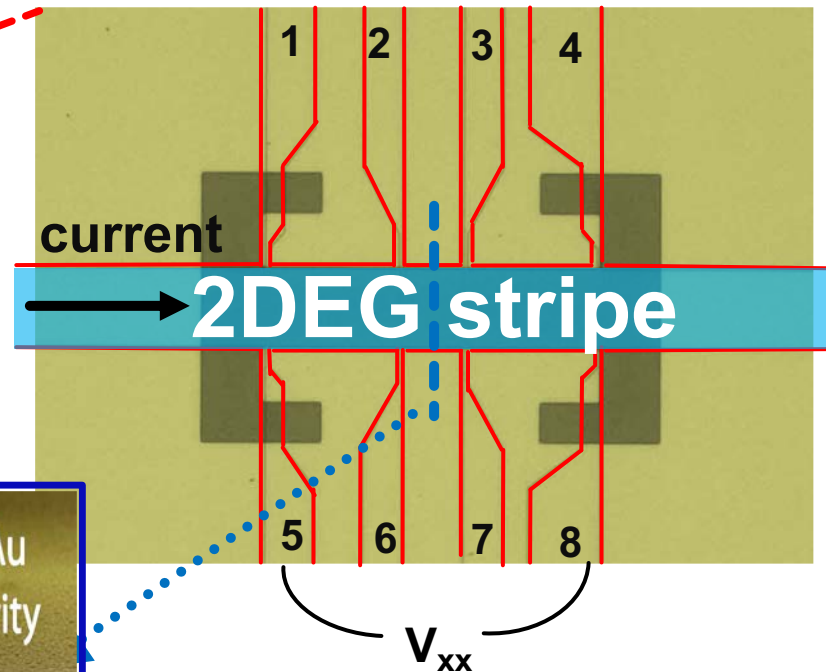
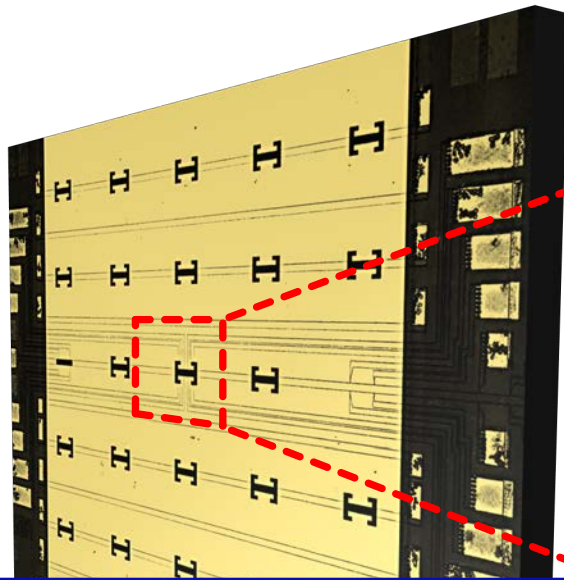
Split-ring resonator (SRR)



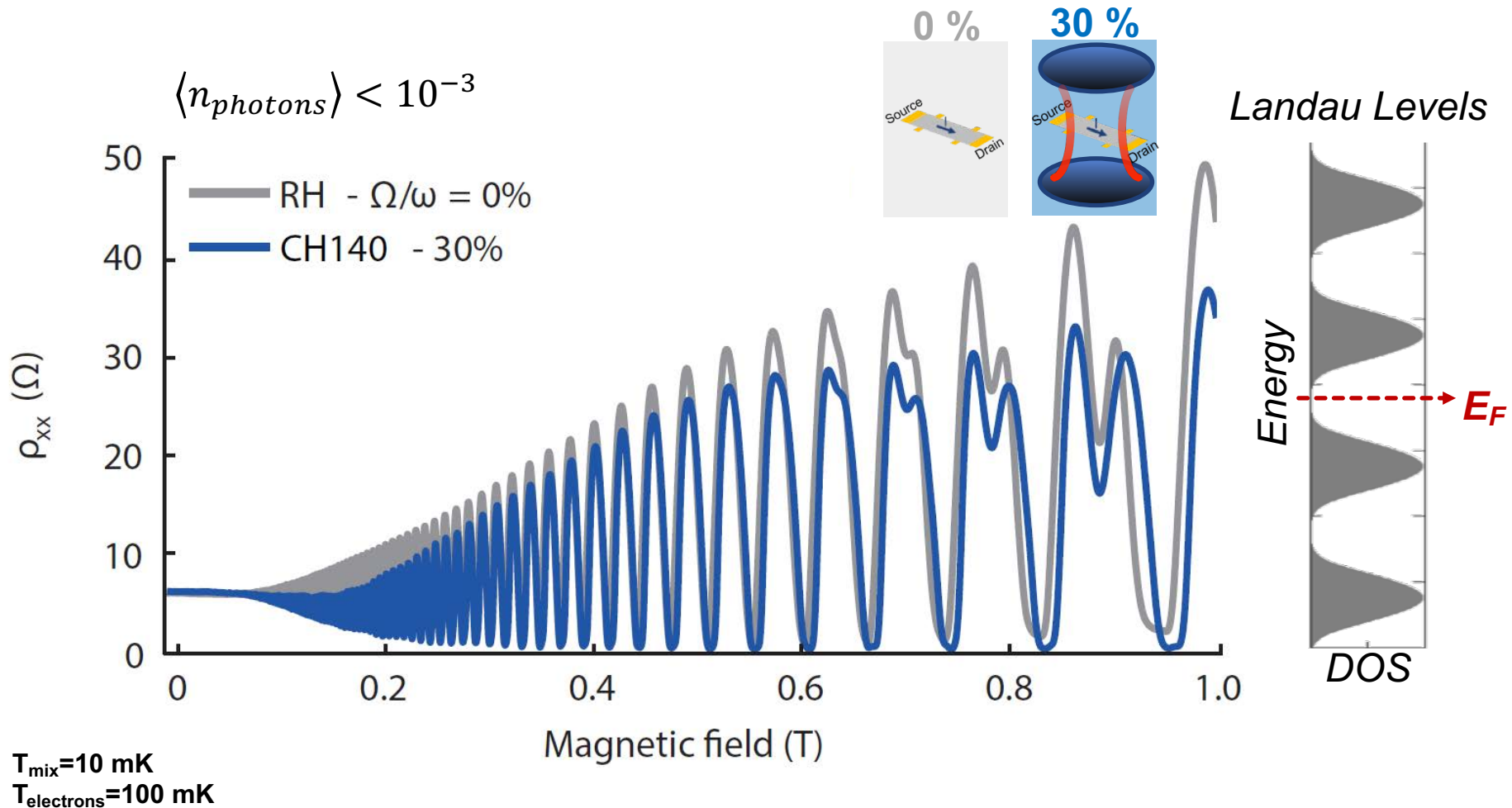
Transport in SRR cavity



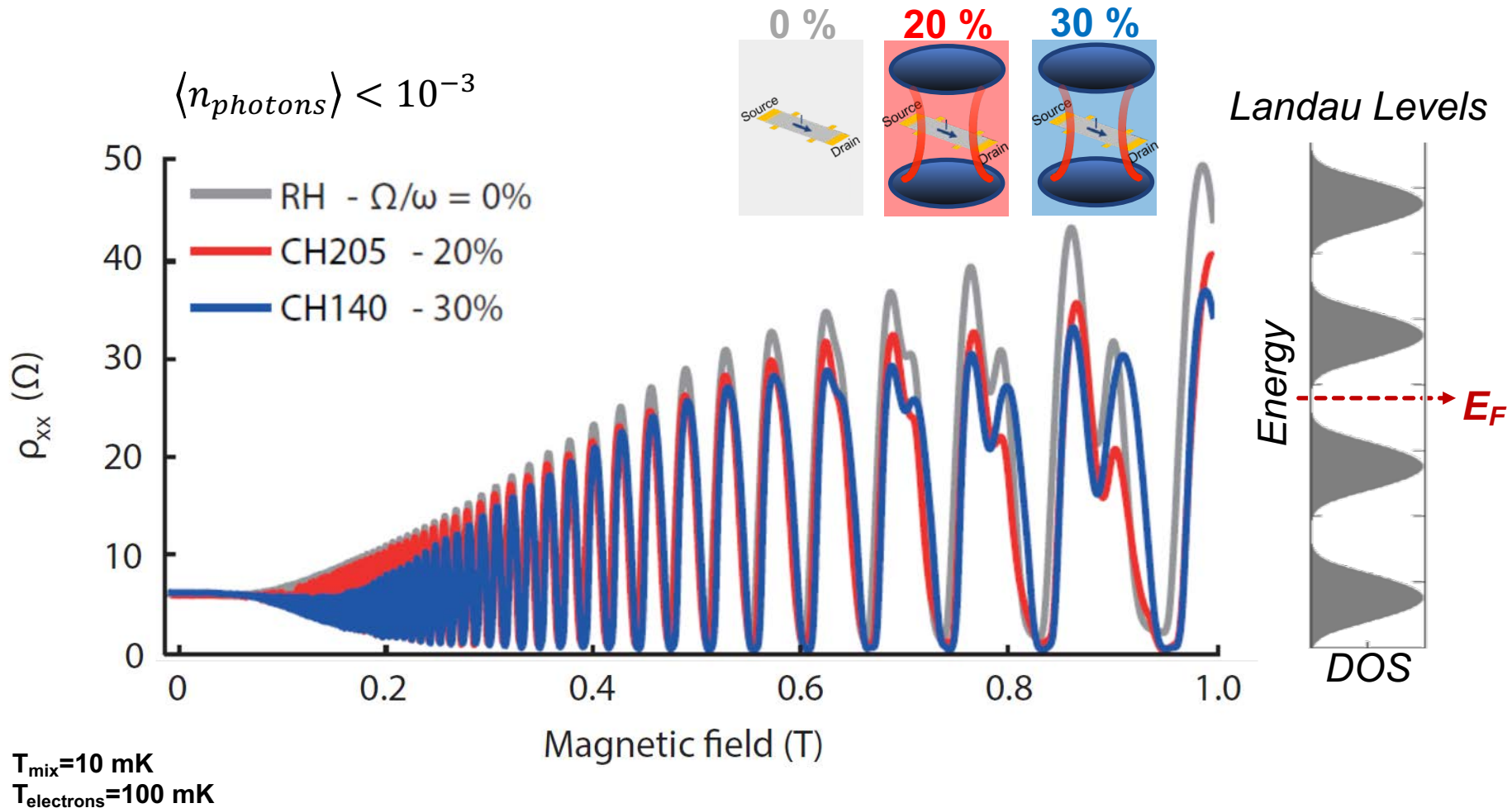
Split-ring resonator (SRR)



Vacuum fields change magneto-transport no real photons!



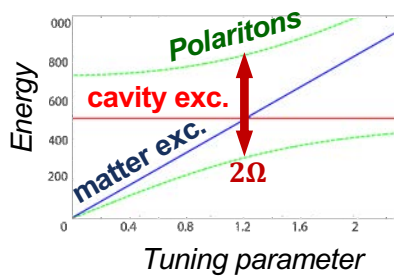
Vacuum fields change magneto-transport no real photons!



Theory: Kubo approach

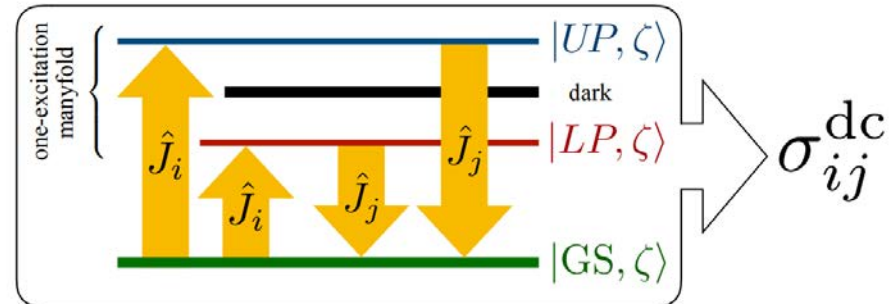
The main idea is to follow a Kubo approach to determine the dc magneto conductivity

$$\sigma_{ij}^{\text{dc}} = i \sum_{\xi \neq \xi'} \frac{e^{-\beta E_{\xi'}} - e^{-\beta E_{\xi}}}{\mathcal{A}Z(E_{\xi} - E_{\xi'})} \frac{\langle \xi | \hat{J}_j | \xi' \rangle \langle \xi' | \hat{J}_i | \xi \rangle}{(\omega_{\xi} - \omega_{\xi'}) + i/\tau_{\xi\xi'}}$$



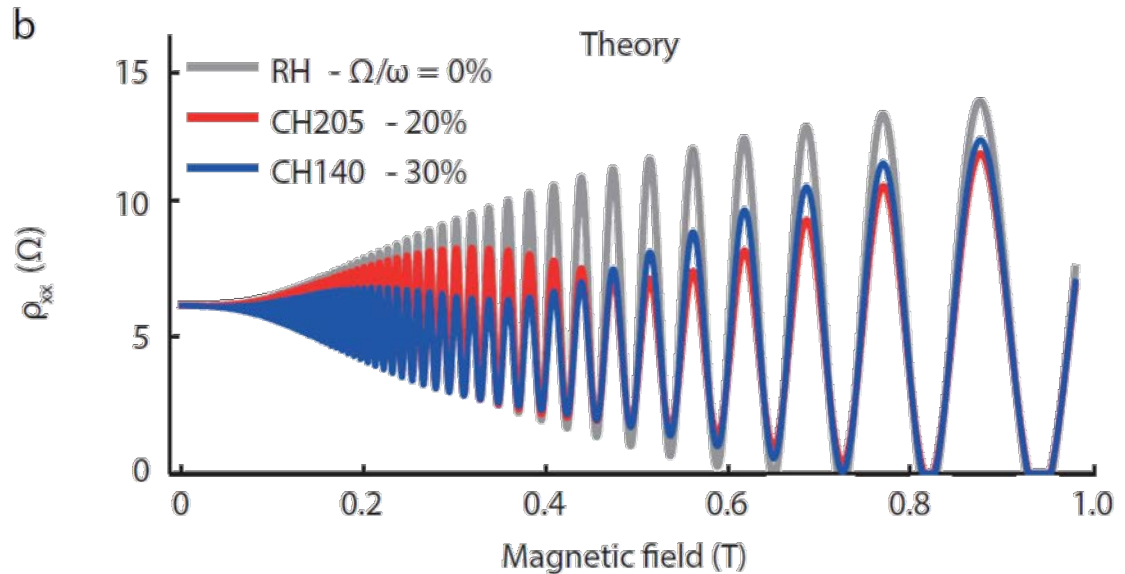
$$H = \hbar\omega_{\text{cav}}a^{\dagger}a + \hbar\omega_c b^{\dagger}b + i\hbar\Omega(a^{\dagger}b - ab^{\dagger}) + D(a^{\dagger}a + aa^{\dagger}) + i\hbar\Omega(ab - a^{\dagger}b^{\dagger}) + D(aa + a^{\dagger}a^{\dagger})^2$$

→ Bright excitations control also transport!



→ Low T: dc conductivity depends on transitions from ground to excited states

Comparison to experiment

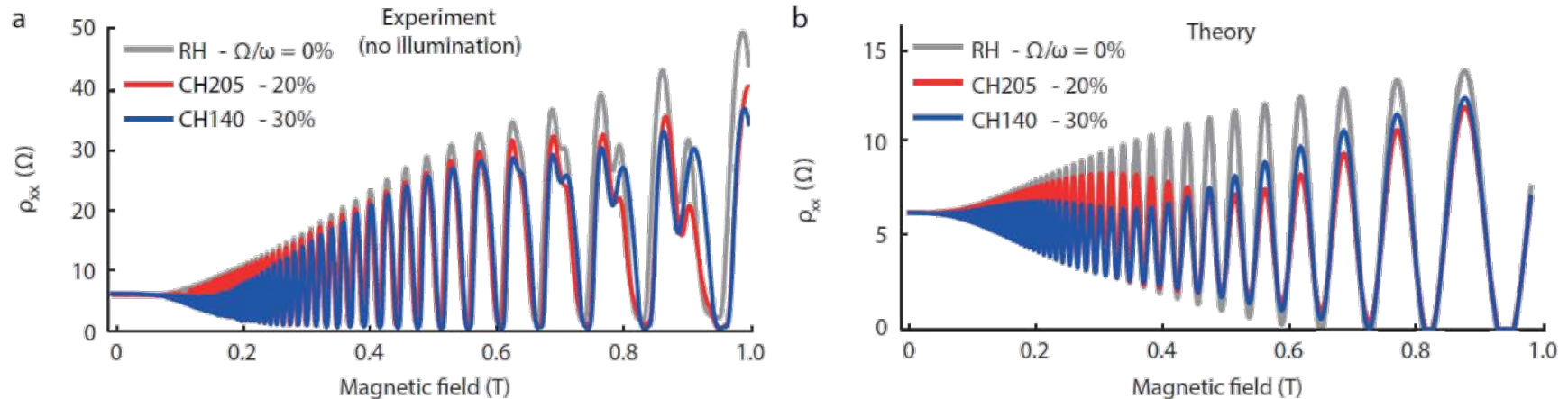


$$\sigma^{\text{dc}} = \frac{n_e e^2}{m_\star} \sum_r \frac{|x_r - z_r|^2 \tau_r}{1 + (\omega_r \tau_r)^2} \begin{pmatrix} \frac{\omega_r}{\omega_{\text{cyc}}} & -\omega_r \tau_r \\ \omega_r \tau_r & \frac{\omega_{\text{cyc}}}{\omega_r} \end{pmatrix}$$

$r \in \{LP, UP\}$

$$\frac{1}{\tau_r} = \frac{W_{e,r}}{\tau_e} + \frac{W_{p,r}}{\tau_p}$$

Comparison to experiment

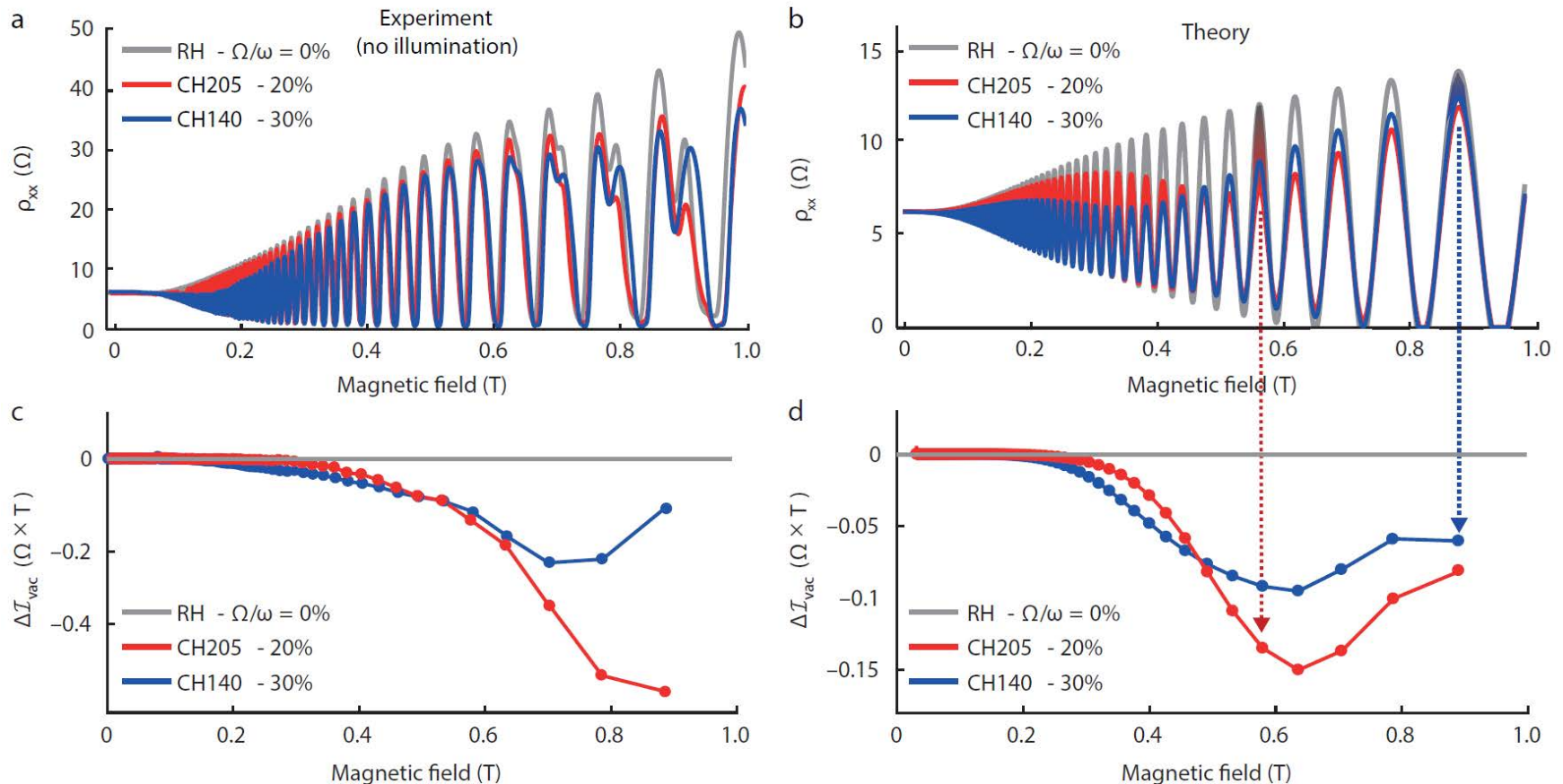


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$\uparrow$
 $r \in \{LP, UP\}$

$\frac{1}{\tau_r} = \frac{W_{e,r}}{\tau_e} + \frac{W_{p,r}}{\tau_p}$

Comparison to experiment

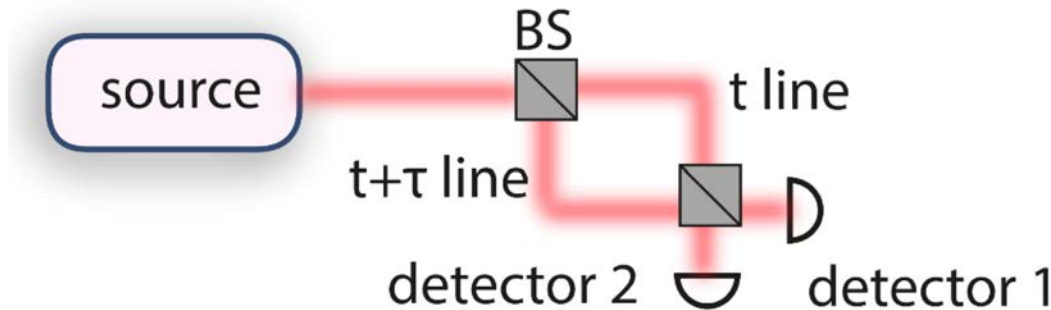


How to probe a ground state optically? (start with vacuum)

Revisit field correlation function: $G^{(1)}(\tau)$

Typical measurement: an interferometer

$$G^{(1)}(\tau, \delta\vec{r}) = \langle E^*(t, \vec{r}) E(t + \tau, \vec{r} + \delta\vec{r}) \rangle$$



$$\langle I_1(\tau) \rangle \sim (1 + \Re\{g^{(1)}(\tau)\})$$

The correlation of fields is inferred from an intensity measurement at the detector $\langle \hat{a}^\dagger \hat{a} \rangle$

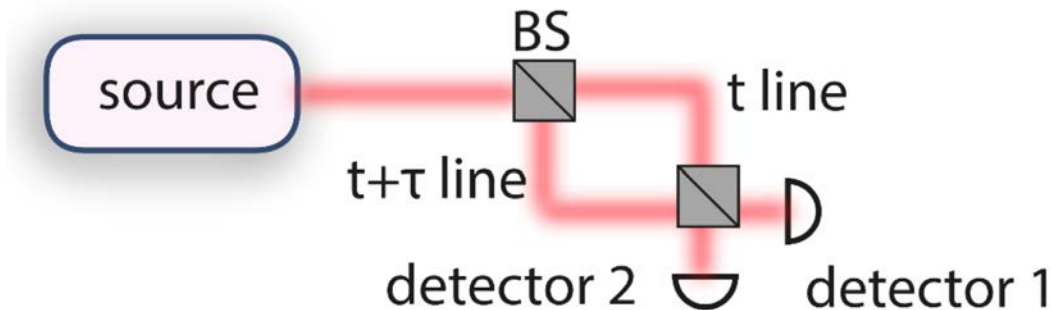
Will yield zero if applied to the ground state of the radiation

$$G^{(1)}(\tau, \delta\vec{r}) = \langle 0 | \hat{E}^-(t, \vec{r}) \hat{E}^+(t + \tau, \vec{r} + \delta\vec{r}) | 0 \rangle = 0$$

Revisit field correlation function: $G^{(1)}(\tau)$

Typical measurement: an interferometer

$$G^{(1)}(\tau, \delta\vec{r}) = \langle E^*(t, \vec{r}) E(t + \tau, \vec{r} + \delta\vec{r}) \rangle$$

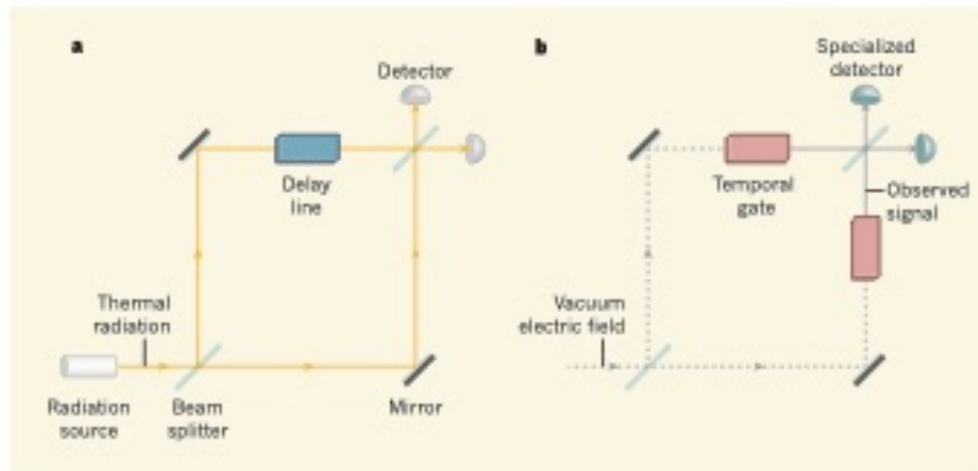


$$\langle I_1(\tau) \rangle \sim (1 + \Re\{g^{(1)}(\tau)\})$$

What about measuring the field directly?

Measuring the fields directly

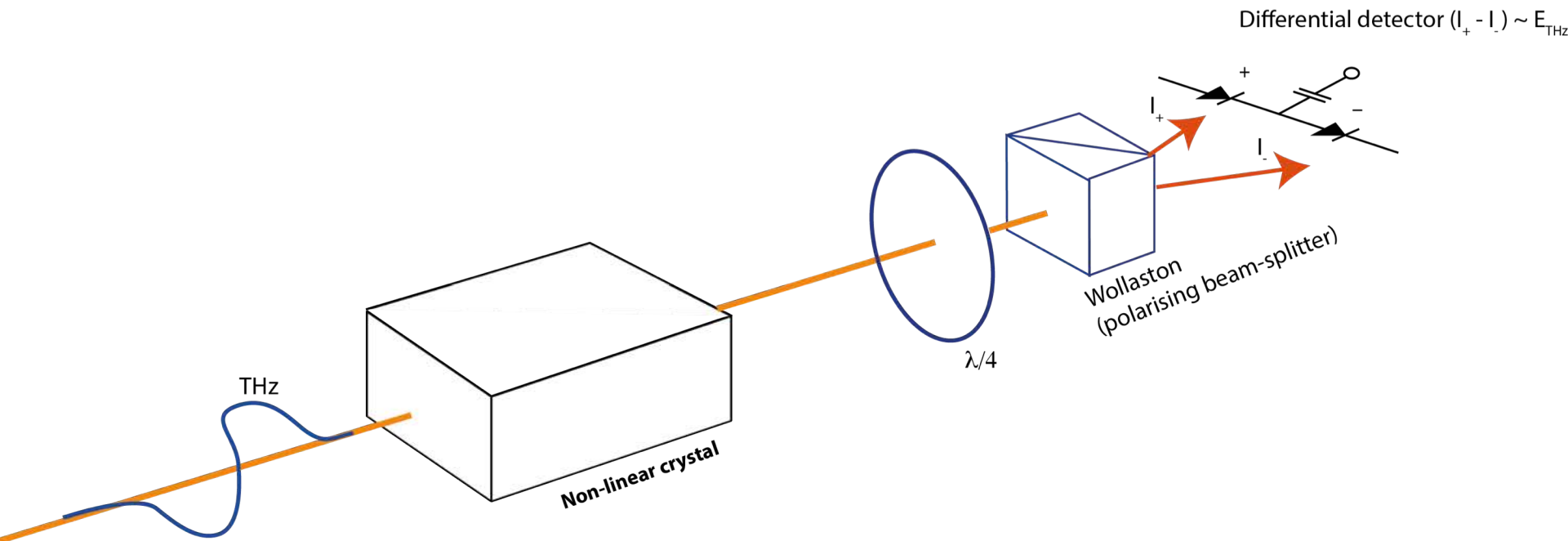
- Implementing a field measurement enables a direct construction of the correlator



$$G^{(1)}(\tau, \delta\vec{r}) = \langle \hat{E}(t, \vec{r}) \hat{E}(t + \tau, \vec{r} + \delta\vec{r}) \rangle$$

A. S. Moskalenko and T. C. Ralph, Nature **568**, p 178 (2019)

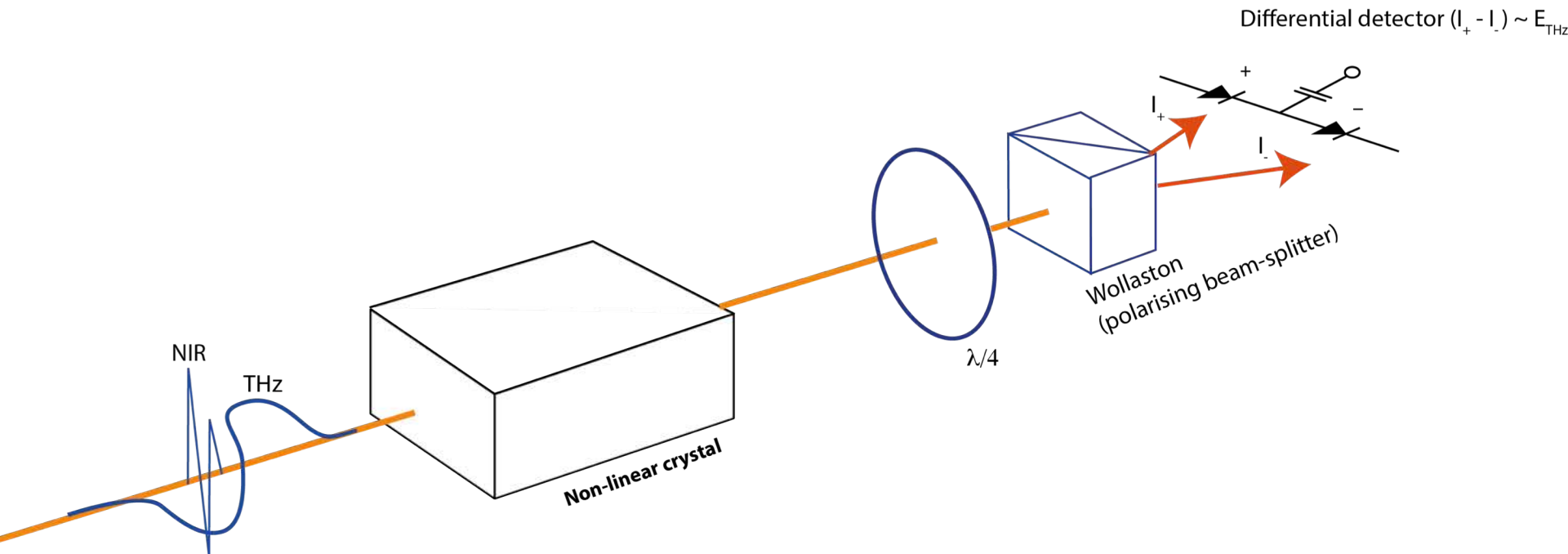
Field measurement: electro-optic sampling



Q. Wu and X.C. Zhang, Appl Phys Lett **67**, 3523 (1995).

G. Zhao, R.N. Schouten, N. van der Valk, W.T. Wenckebach, and P.C.M. Planken, Rev Sci Instrum **73**, 1715 (2002).

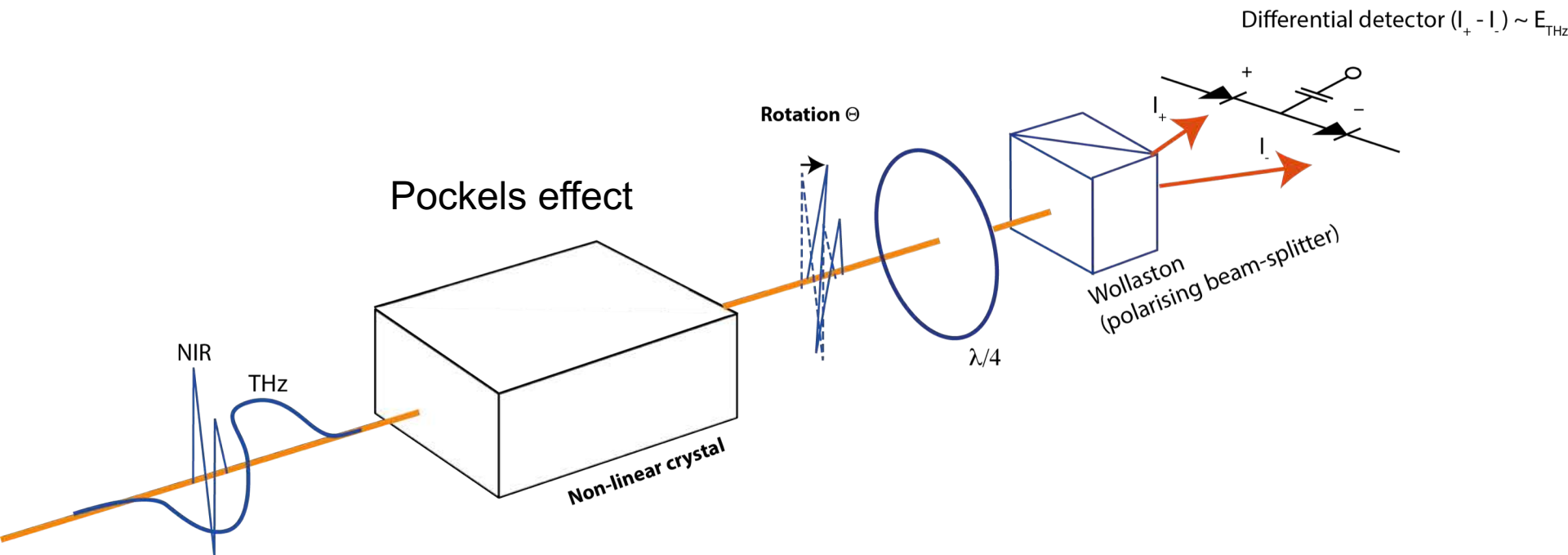
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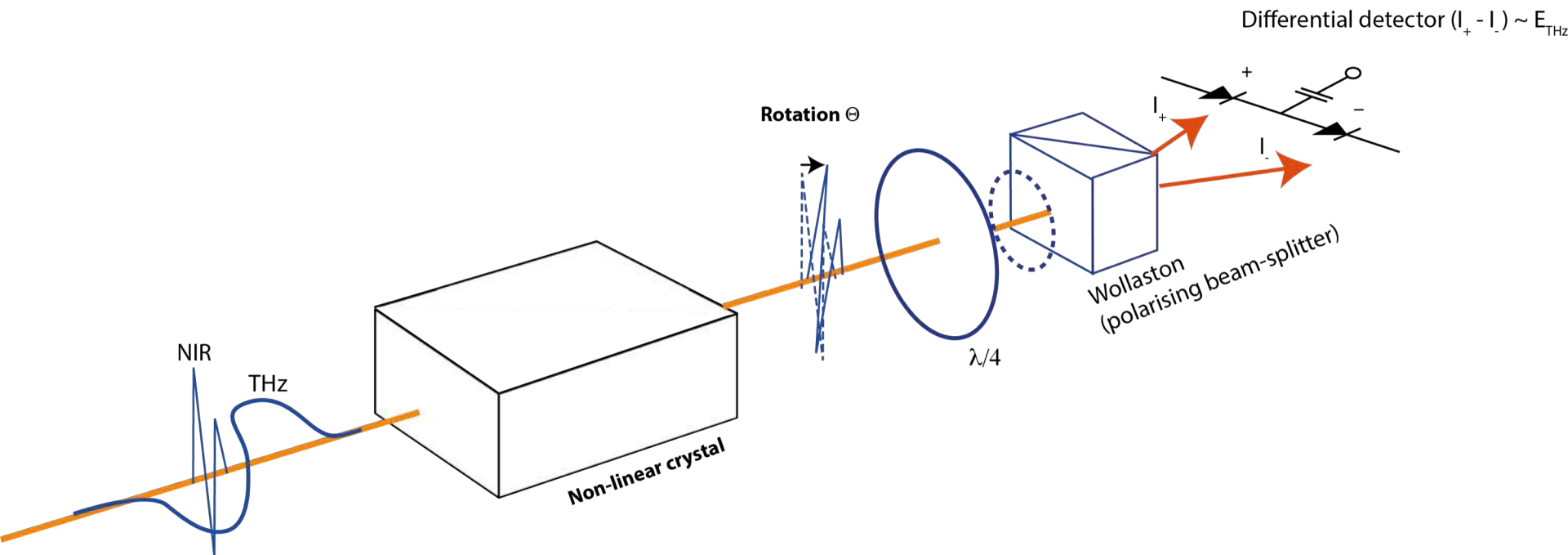
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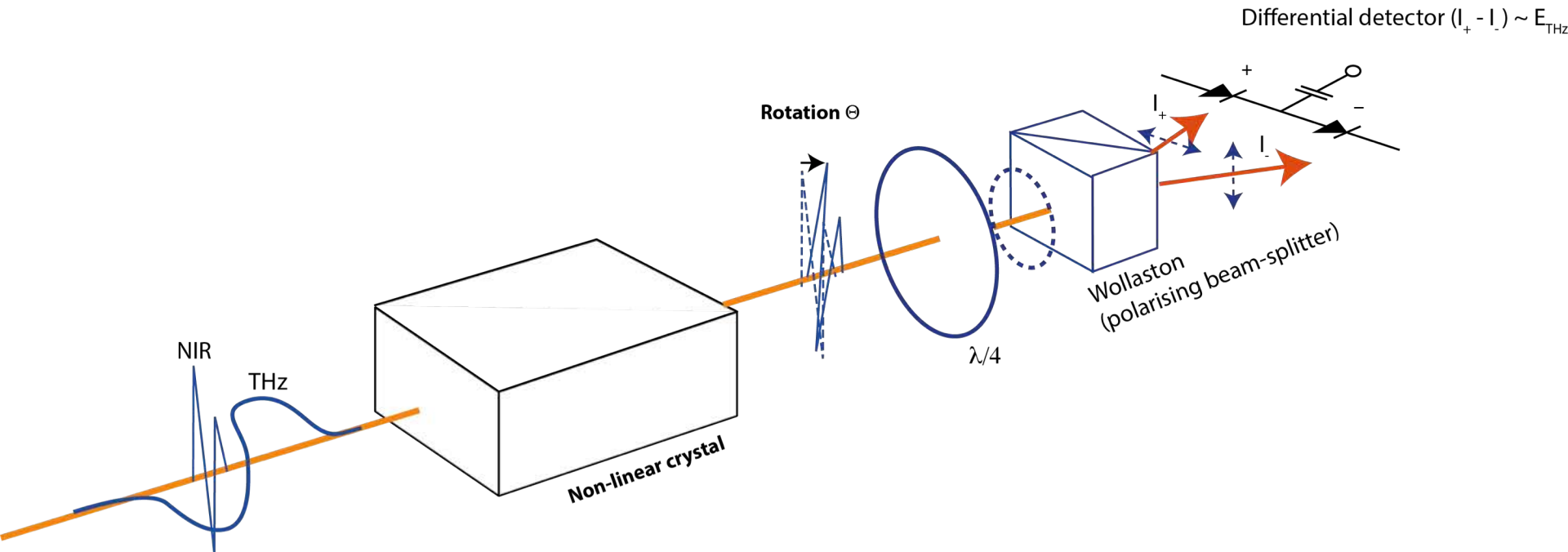
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Field measurement: electro-optic sampling



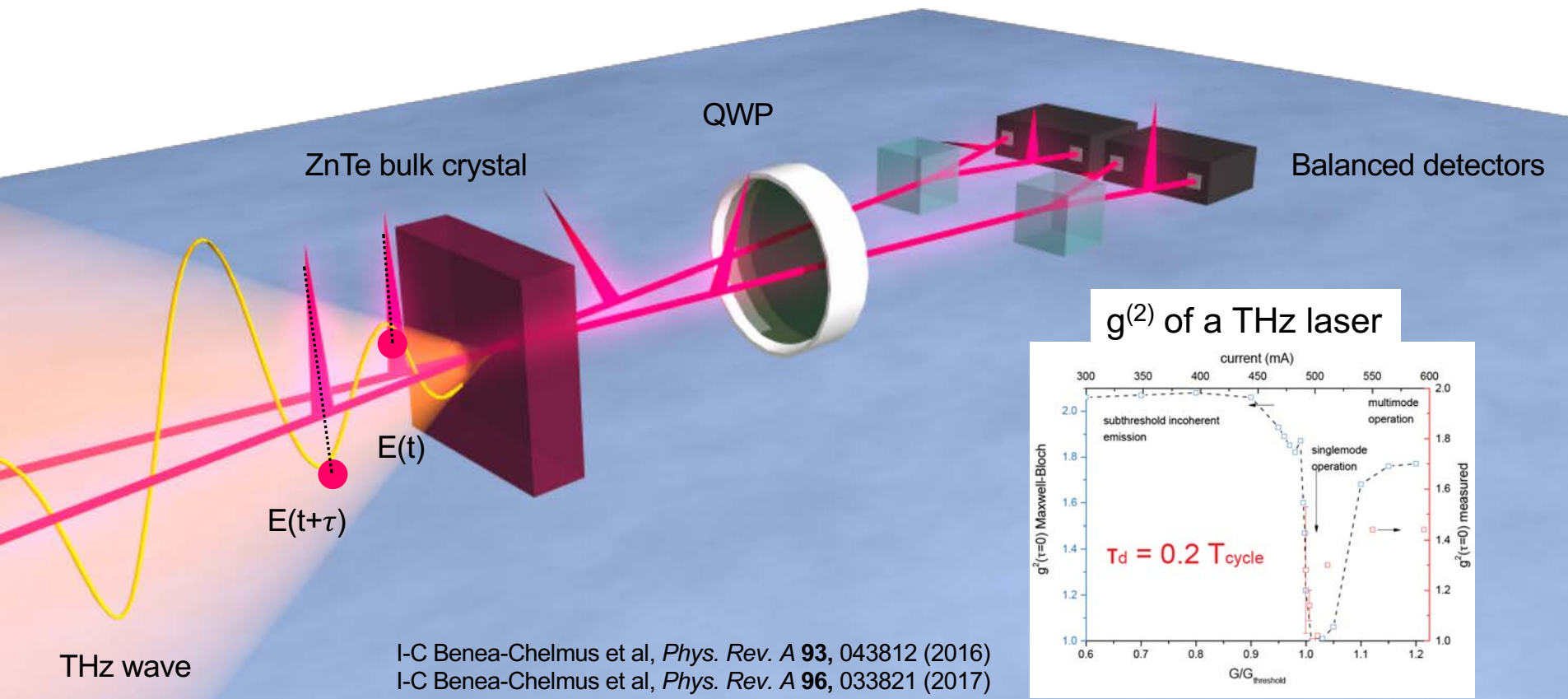
Q. Wu and X.C. Zhang, Appl Phys Lett **67**, 3523 (1995).

G. Zhao, R.N. Schouten, N. van der Valk, W.T. Wenckebach, and P.C.M. Planken, Rev Sci Instrum **73**, 1715 (2002).

Vacuum field sensing: C. Riek et al, *Science*, vol. 350, no. 6259, pp. 420–423, 2015.

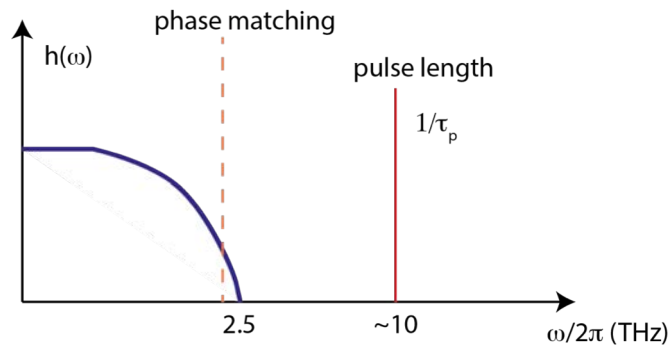
Department of Physics / Institute for Quantum Electronics / Quantum Optoelectronics Group

Field correlation using electro-optic sampling

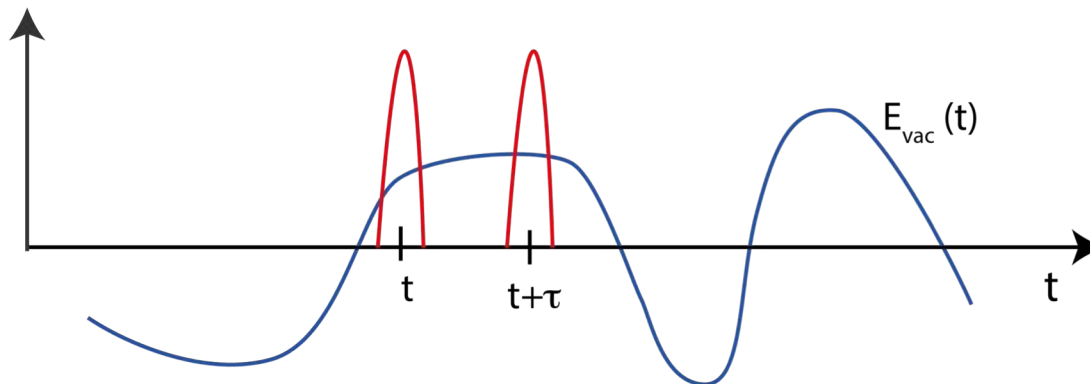


Interpretation:

- Pulse length shorter than 1/bandwidth experimental setup:



- Vacuum field fluctuations should show correlations at short time scales



Quantum mechanical interpretation

- Electro-optic measurement is basically a field measurement

$$\hat{S}_{eo}(t, \vec{r}) = \sqrt{C} \sum_{\Omega} \sqrt{\frac{\hbar \Omega}{2\epsilon_0 \epsilon_r}} (\hat{a}(\Omega) R(\Omega) e^{-i(\Omega t - \vec{k} \vec{r})} - h.c.)$$

Responsivity: phase matching, pulse length..

A. Moskalenko et al, PRL 2015

- Therefore the "electro-optic" $G^{(1)}$ is $\hat{G}_{eo}^{(1)} = -\frac{1}{2C} \left\{ \hat{S}_{eo}(t + \tau, \vec{r} + \delta \vec{r}), \hat{S}_{eo}(t, \vec{r}) \right\}$
- Yields on a thermal photon state

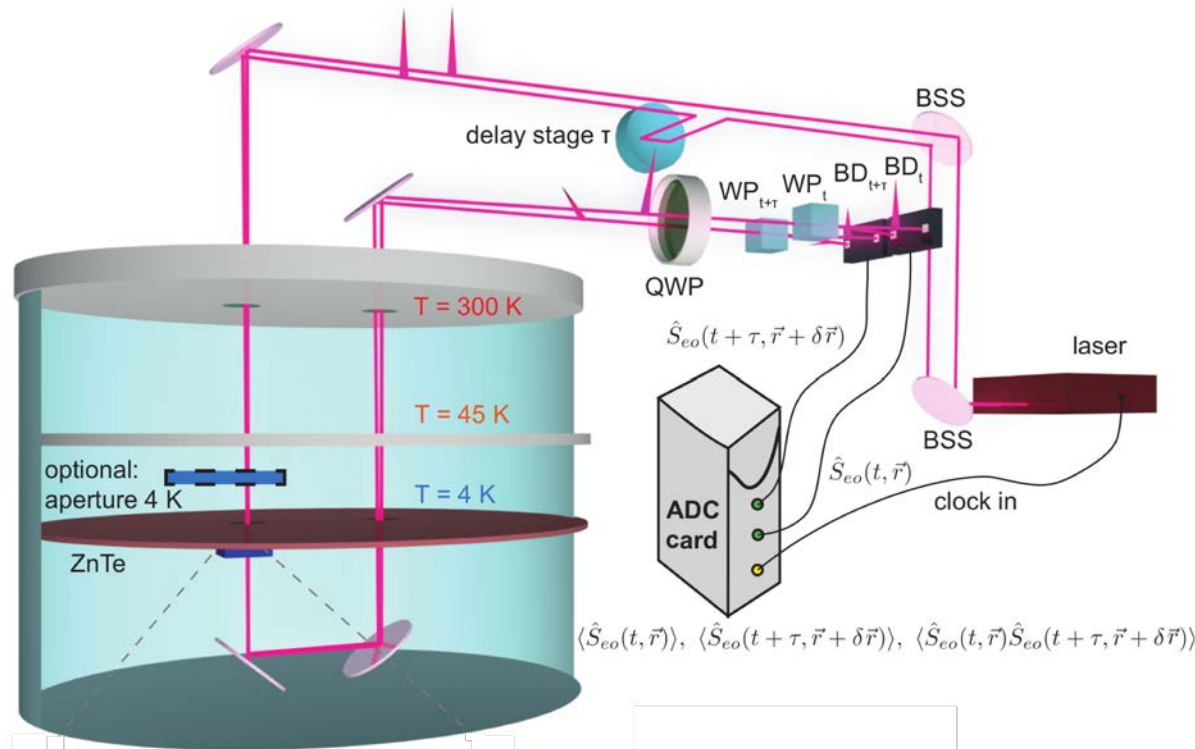
$$G_{eo}^{(1)}(\tau, 0) = \sum_{\Omega} \frac{\hbar \Omega}{2\epsilon_0 \epsilon_r V} (1 + 2\langle \hat{n}(\Omega) \rangle) |R(\Omega)|^2 \cos(\Omega \tau)$$

Non-zero even on the vacuum state!

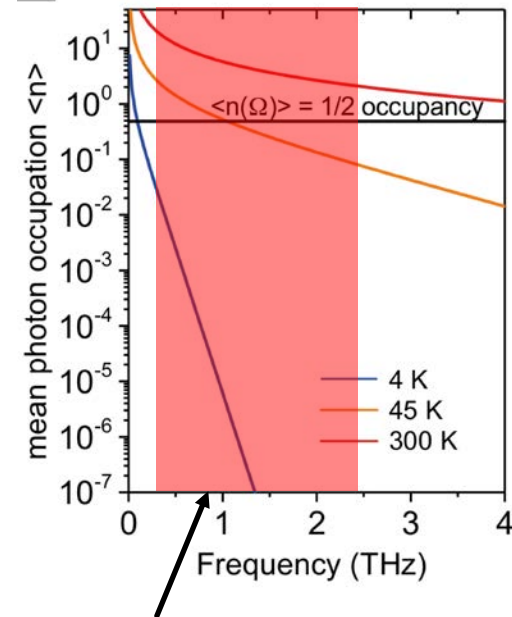
$$\langle 0 | \hat{a} \hat{a}^\dagger | 0 \rangle = 1$$

Experimental setup

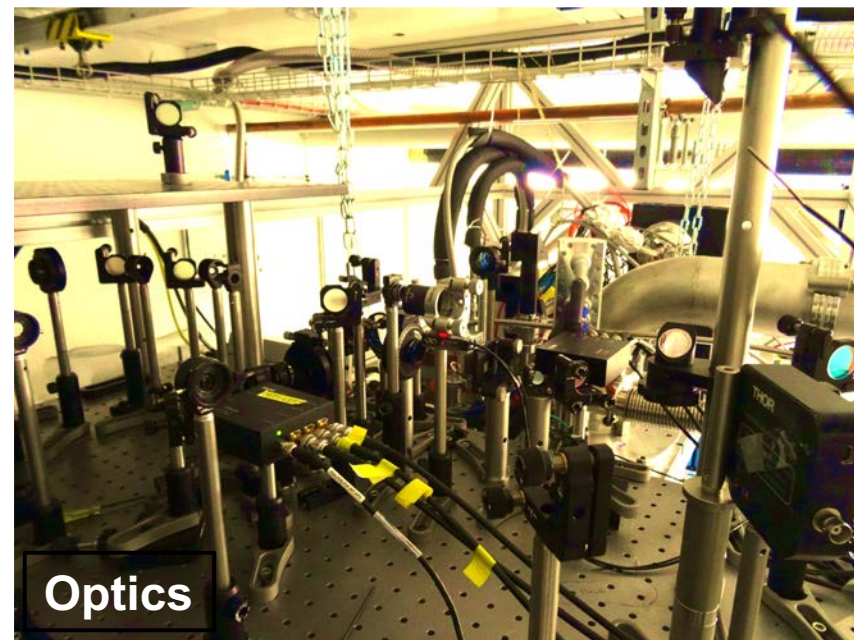
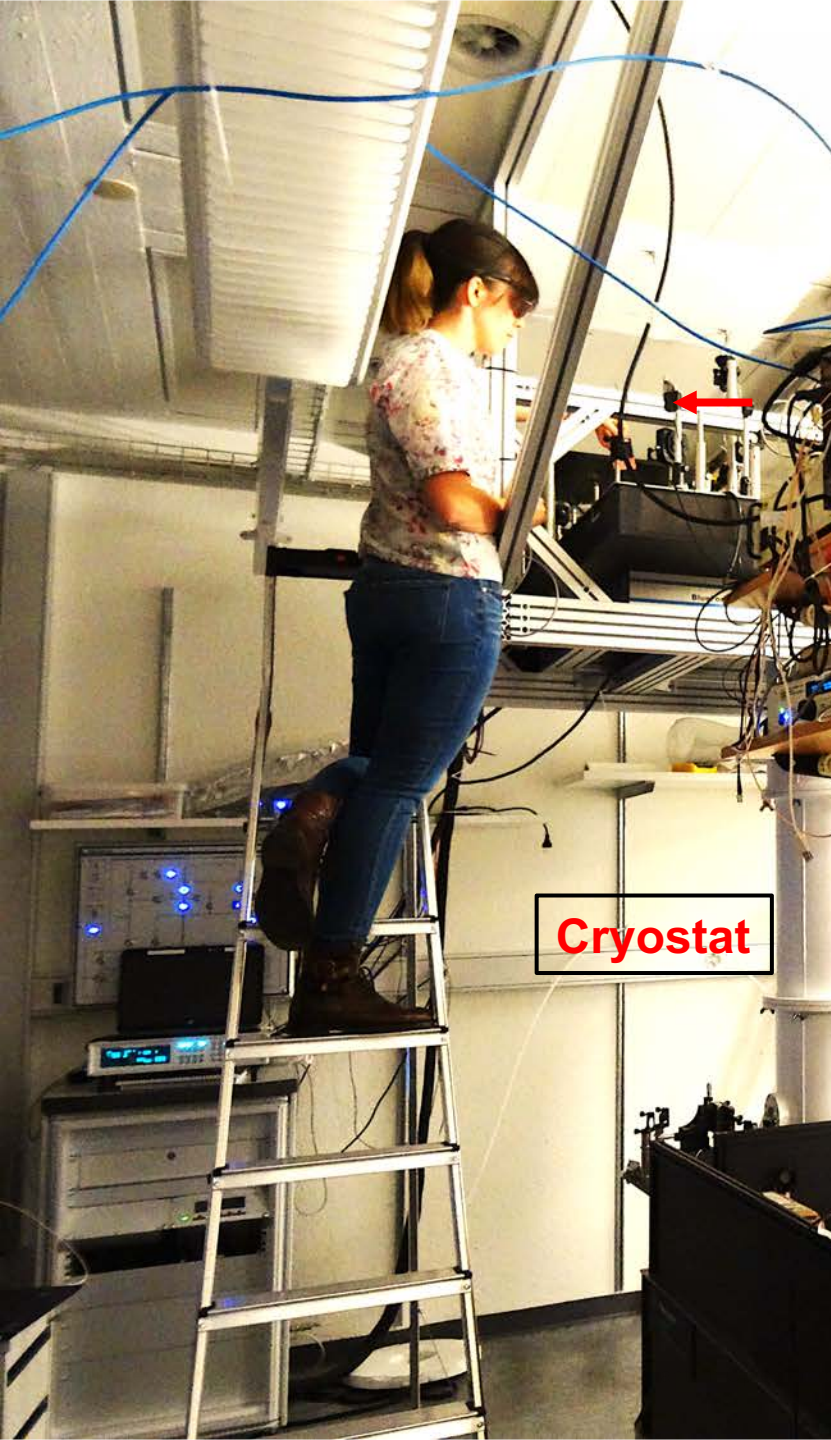
To control the thermal population, the measurement must be performed in a cryostat



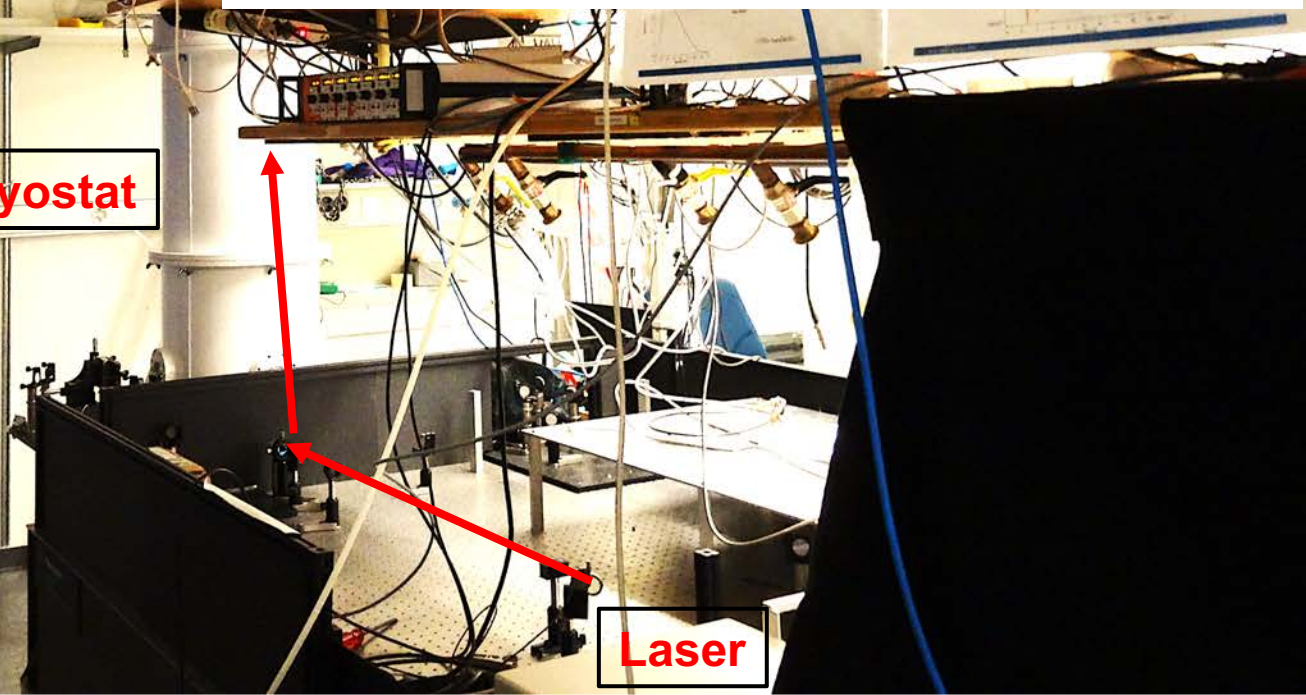
Photon population



Experiment bandwidth



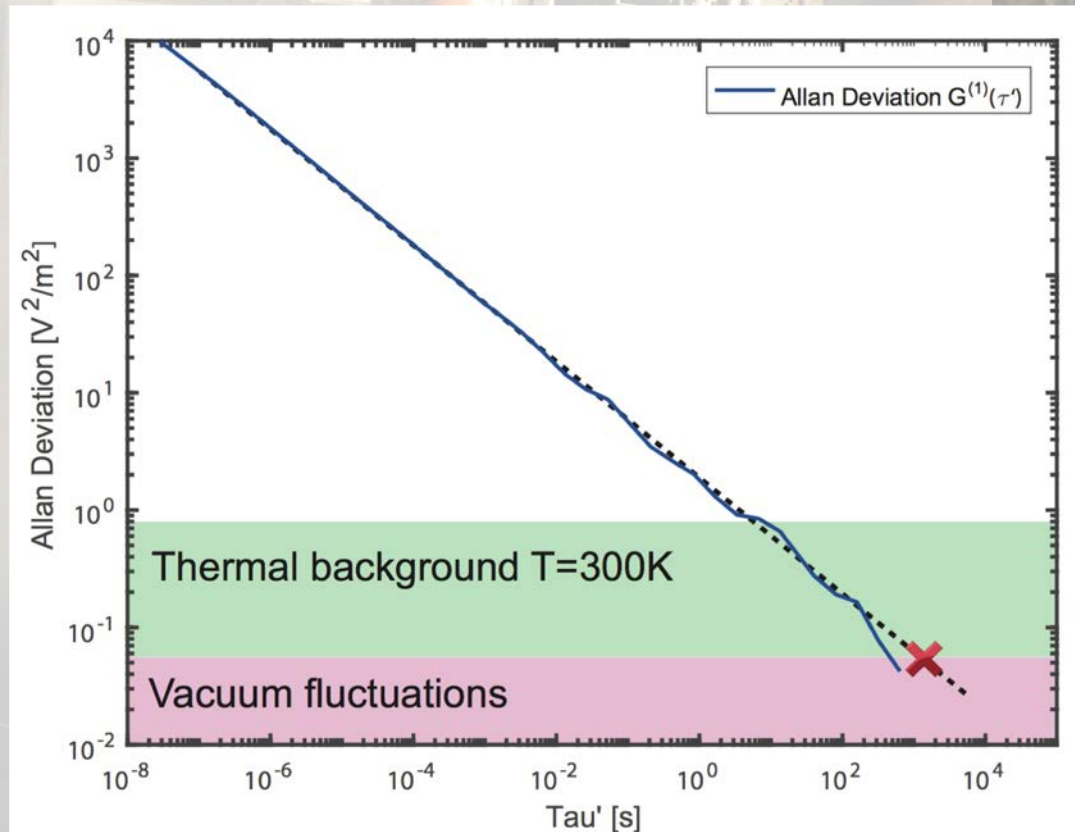
Cryostat



Signal-to-noise properties

$$\Delta \hat{E}_{vac} = \sqrt{\int_0^\infty d\Omega \frac{\hbar \Omega}{2\epsilon_0 \epsilon V} |R(\Omega)|^2} \sim \frac{1}{\lambda^2}$$

	SNR single pulse
Field measurement	0.001
$G^{(1)}(\tau)$ measurement	$3 \cdot 10^{-6}$

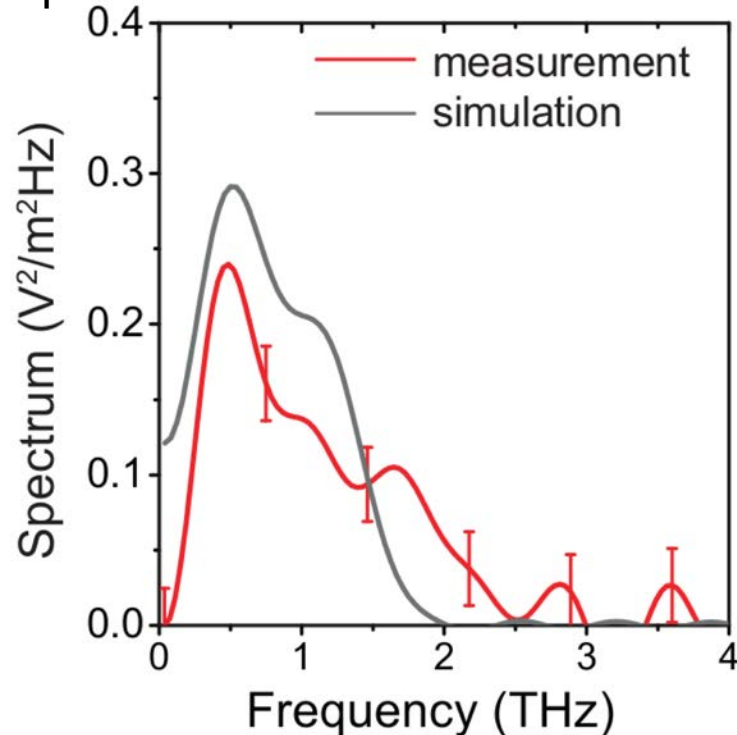
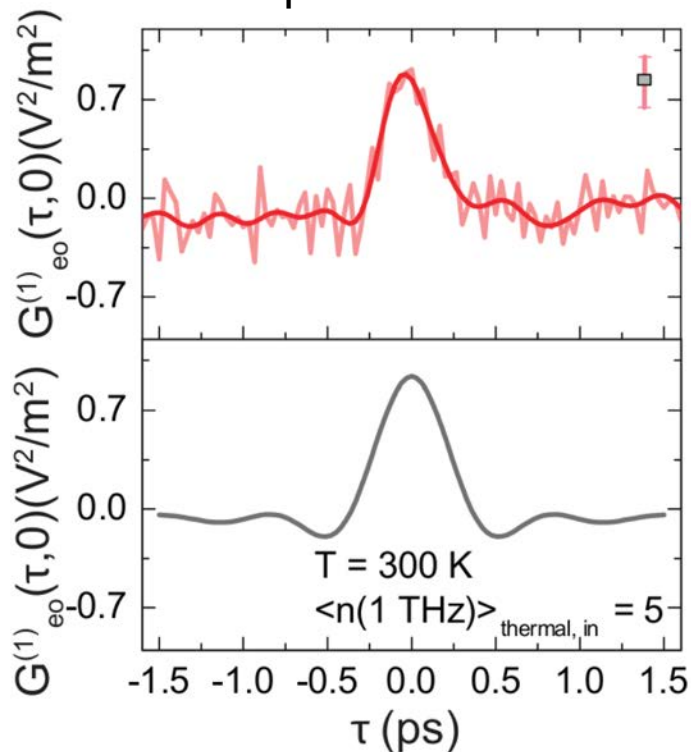


Integration over at least **10^{11} pulses!**

Room temperature measurement

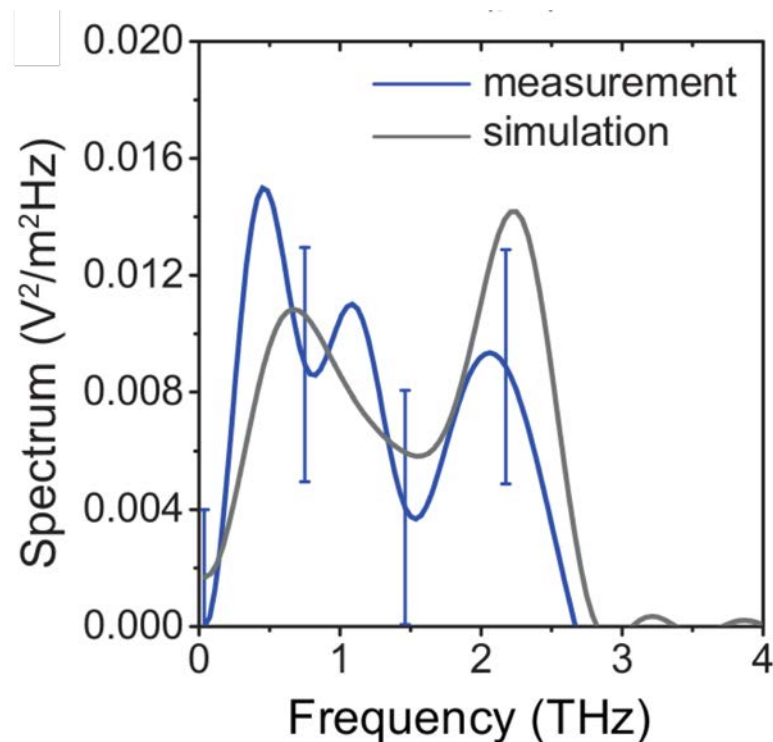
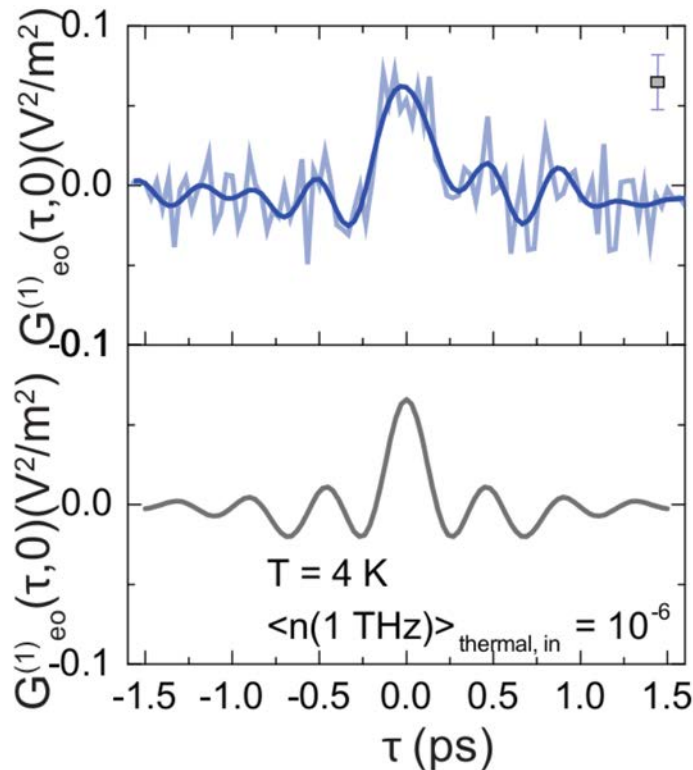
$$G_{eo}^{(1)}(\tau, 0) = \sum_{\Omega} \frac{\hbar \Omega}{2\epsilon_0 \epsilon_r V} (1 + 2\langle \hat{n}(\Omega) \rangle) |R(\Omega)|^2 \cos(\Omega \tau)$$

Response dominated by thermal photons



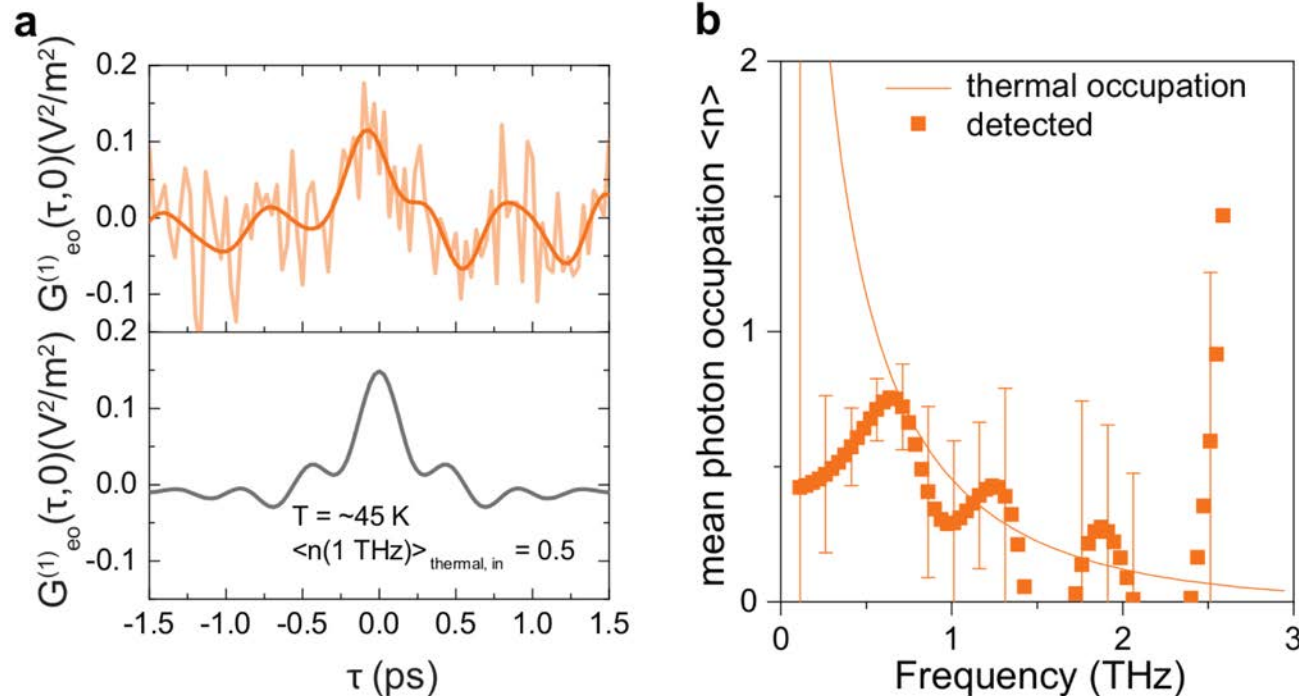
Going to 4K ($\langle n \rangle = 0$)

$$G_{eo}^{(1)}(\tau, 0) = \sum_{\Omega} \frac{\hbar \Omega}{2\epsilon_0 \epsilon_r V} (1 + 2\langle \hat{n}(\Omega) \rangle) |R(\Omega)|^2 \cos(\Omega \tau)$$



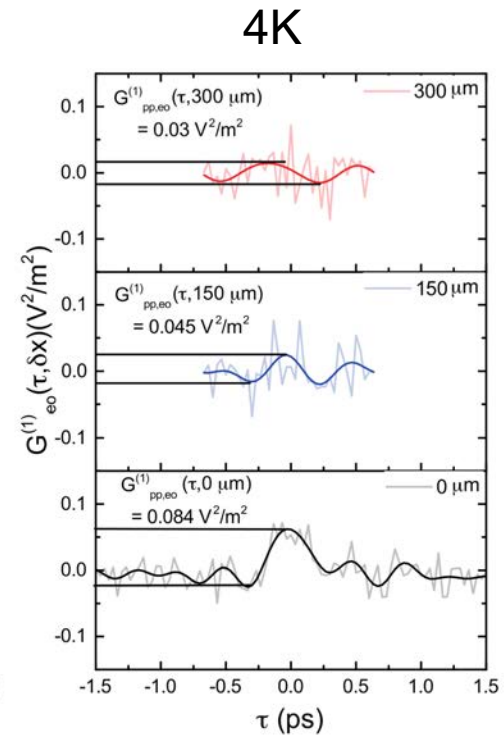
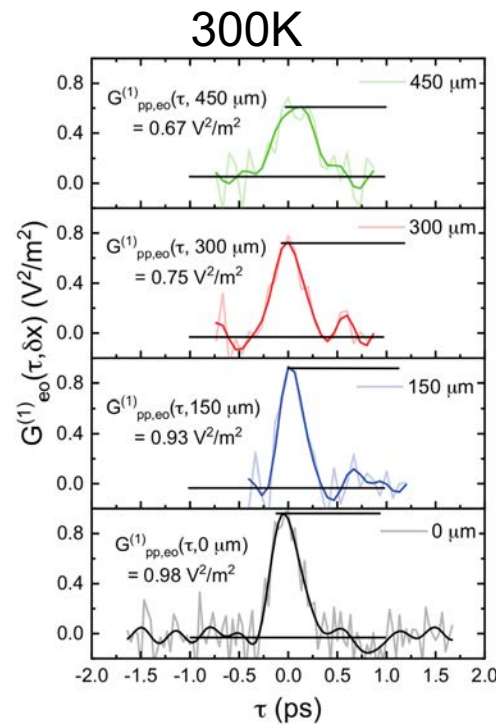
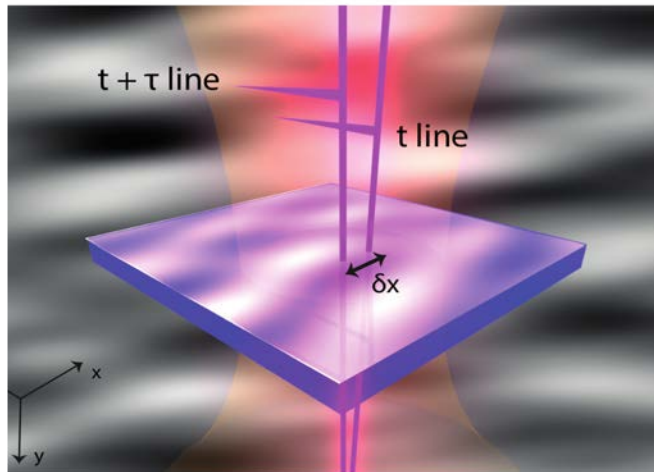
Check: $T = 45\text{K}$

Enables the comparison because refractive index (phase matching) are approximately the same

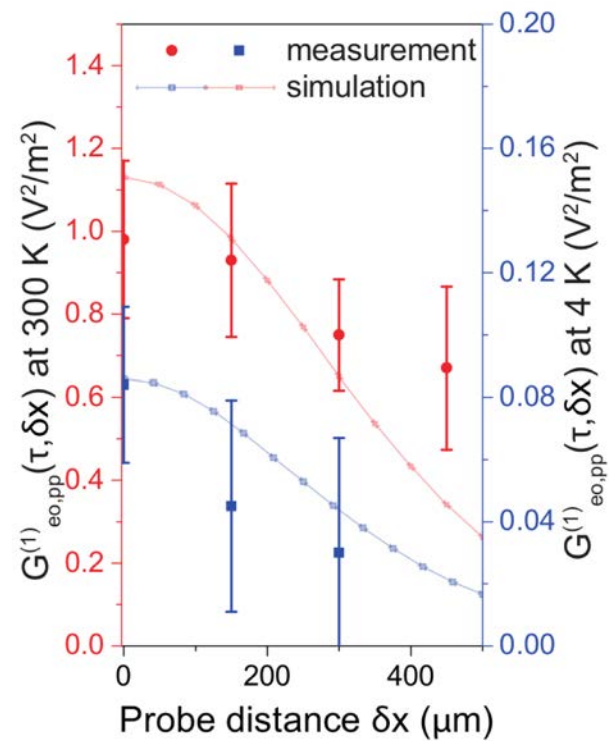
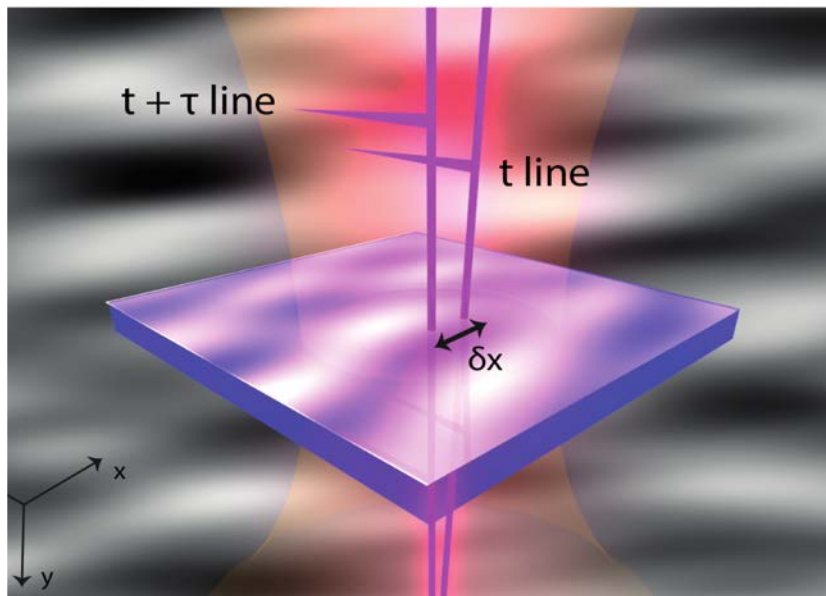


Spatial coherence

Measuring the field at two different spatial locations



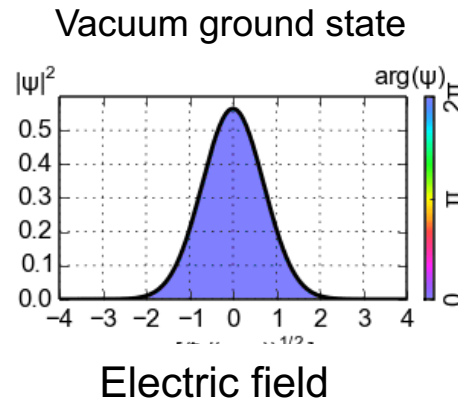
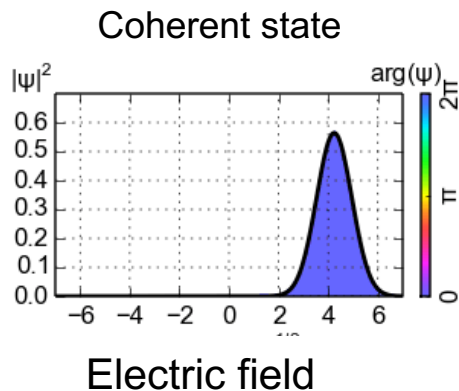
Spatial coherence



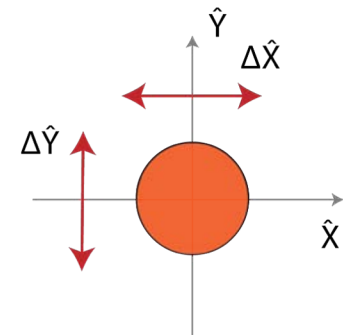
I.-C. Benea-Chelms, F. F. Settembrini, G. Scalari, and J. Faist, *Nature*, pp. 1–6, Apr. 2019.

Interpretation of the measurement

- In contrast to the coherent state, the vacuum state has no well-defined time dependence of the electric field

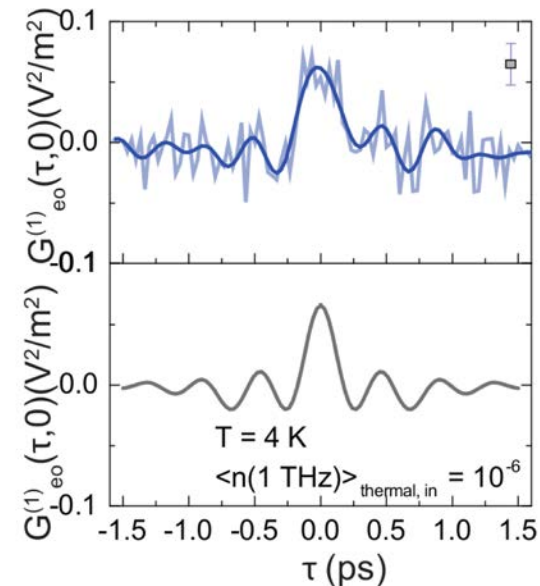
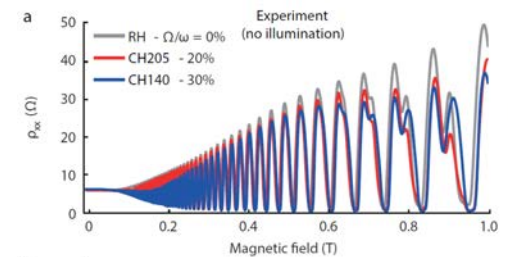


- Classical value of the two-time correlation should be 0!
- Correlation arises from the effect of the first measurement



Conclusion

- In the ultra-strong light-matter coupling, the ground state is modified
- Measured the effect on electronic transport
 - Transport is driven by the polaritons!
 - See a strong change in the Shubnikov-de Haas oscillations as predicted.
- Developed a THz field correlation measurement
 - Performed the measurement on both thermal and vacuum state
 - Found correlation function as function of delay and displacement, a maximum value of $0.25 \text{ V}^2/\text{m}^2$ is measured
 - Result requires the back-action of one measurement on the second one, and can be interpreted in the framework of a spontaneous parametric down conversion.
 - Could be a technique to generate entangled photon pairs



Thanks

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- Metamaterial Study:
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 - Fabiana Settembrini
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 - W. Wegscheider,