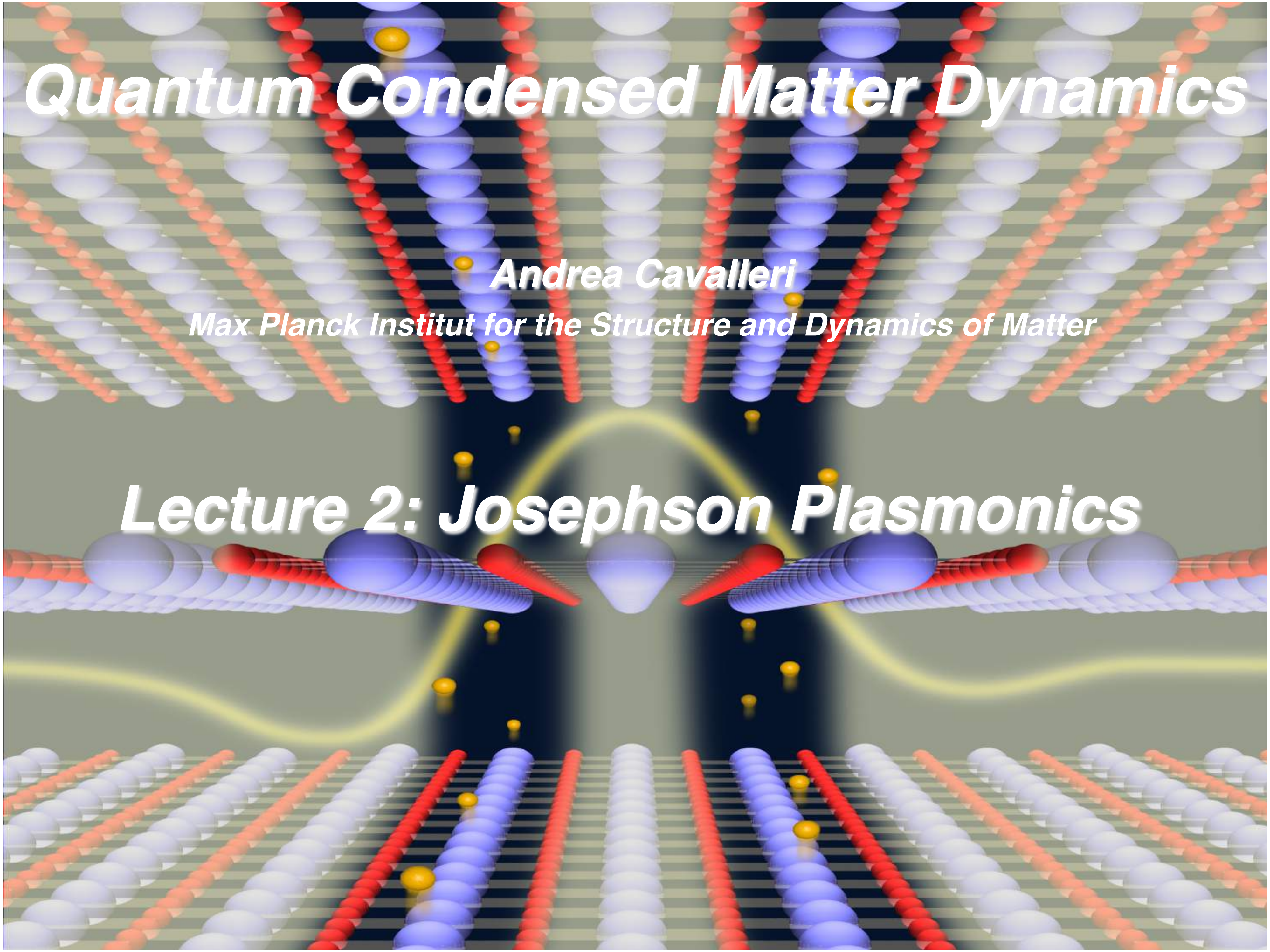
Quantum Condensed Matter Dynamics

Andrea Cavalleri
Max Planck Institut for the Structure and Dynamics of Matter

Lecture 2: Josephson Plasmonics



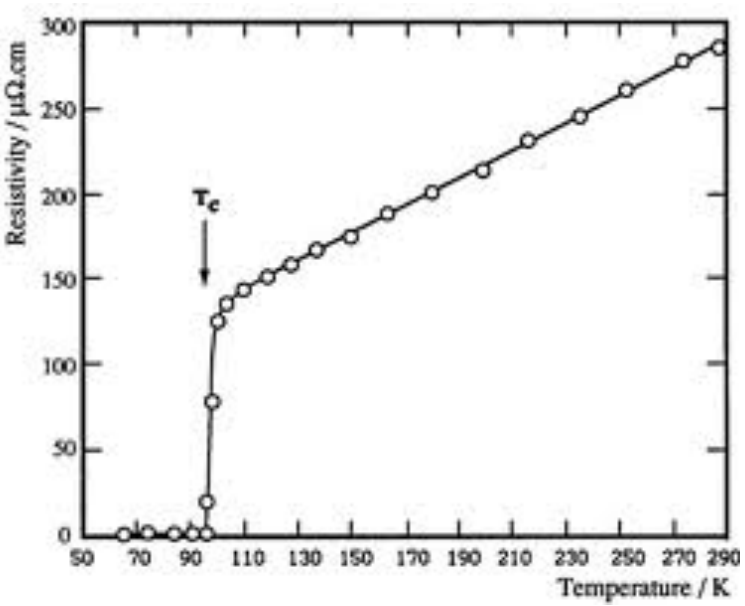
Quantum Materials

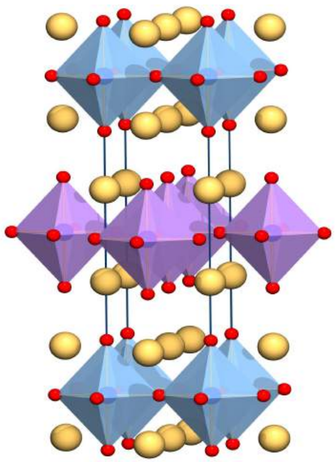
Quantum Materials are those solids which exhibit macroscopic behavior that cannot be understood, even qualitatively, without quantum mechanics.

A prominent example of a Quantum Material is a High T_c Superconductor

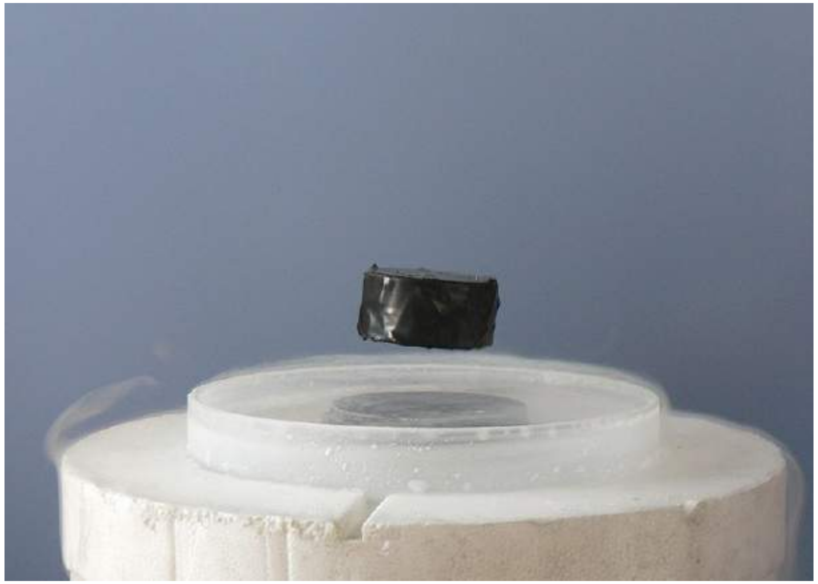
High T_c Superconductivity

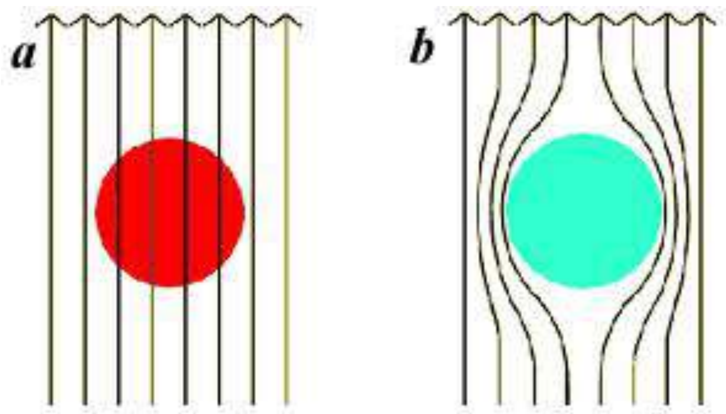
Zero DC resistance





Meissner effect





Optical Control

mpsd

We study the nonlinear excitation of collective modes of quantum materials – generally using light

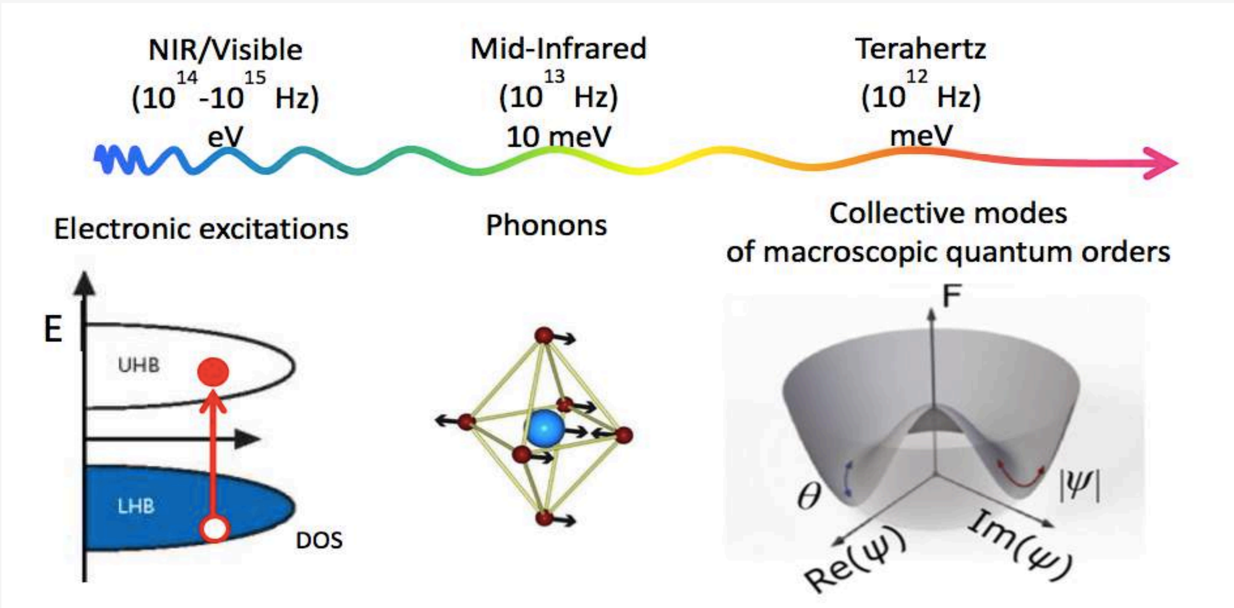
Goal 1: reveal and create functionalities that are hidden or not present at equilibrium.

Goal 2: Control high speed phenomena - explore new strategies for device applications.

Excitation of quantum solids: frequency scales

Driving frequency

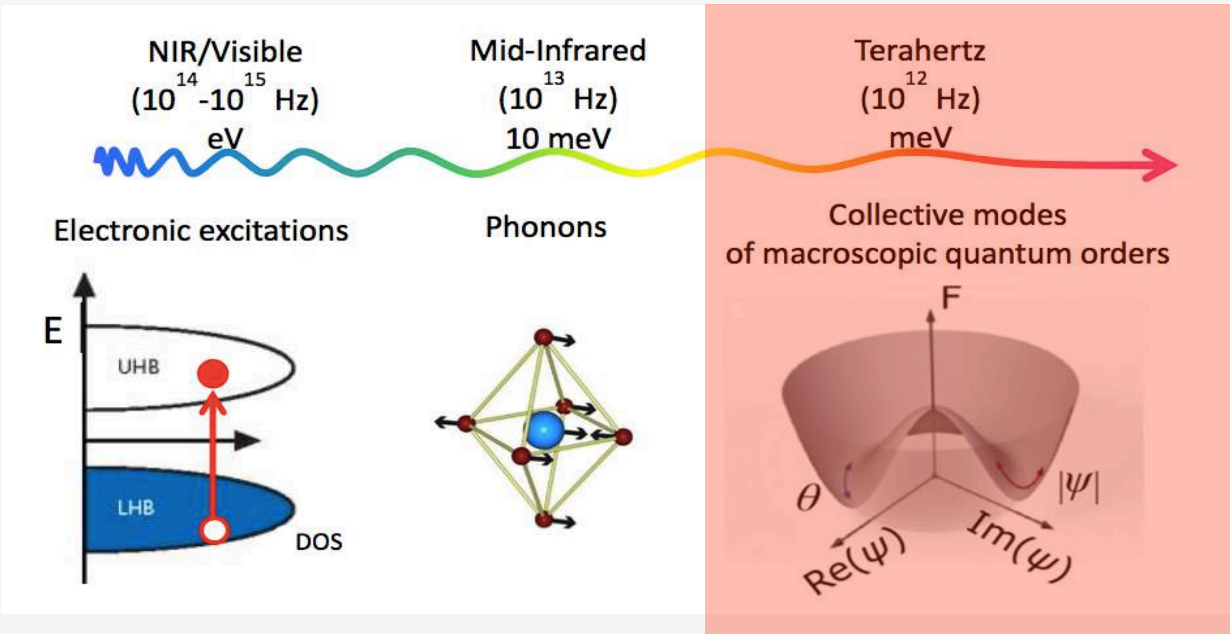
We want to excite collective modes of quantum materials beyond their linear response



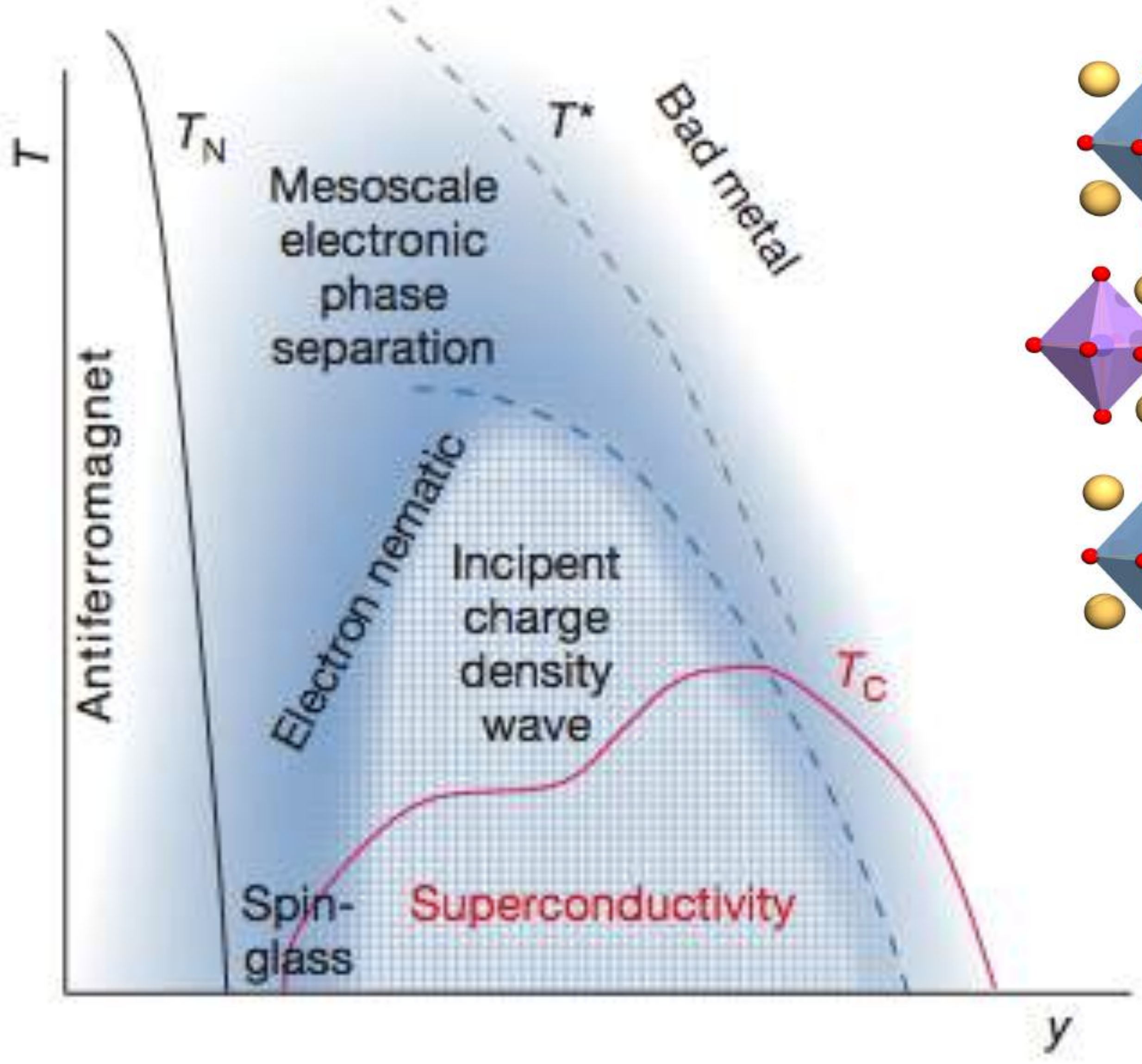
Today: driving collective order

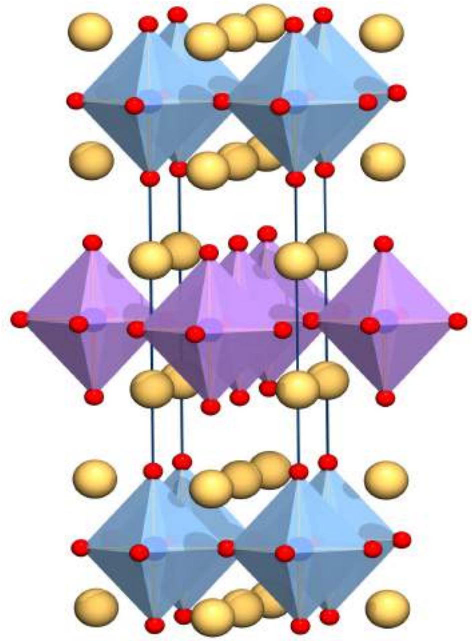
Driving frequency

We want to excite collective modes of quantum materials beyond their linear response



Cuprate superconductors: complexity at work

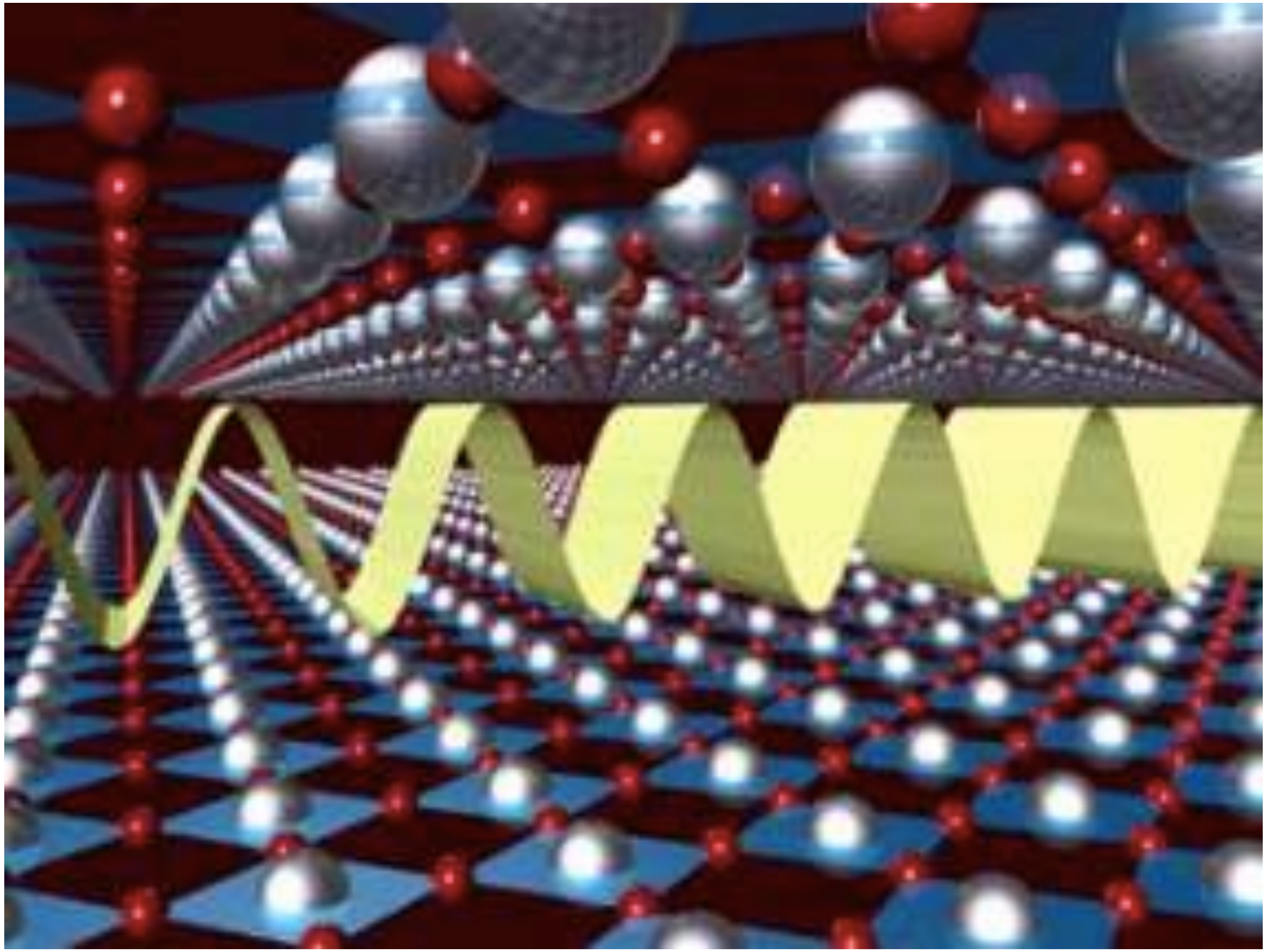




doping

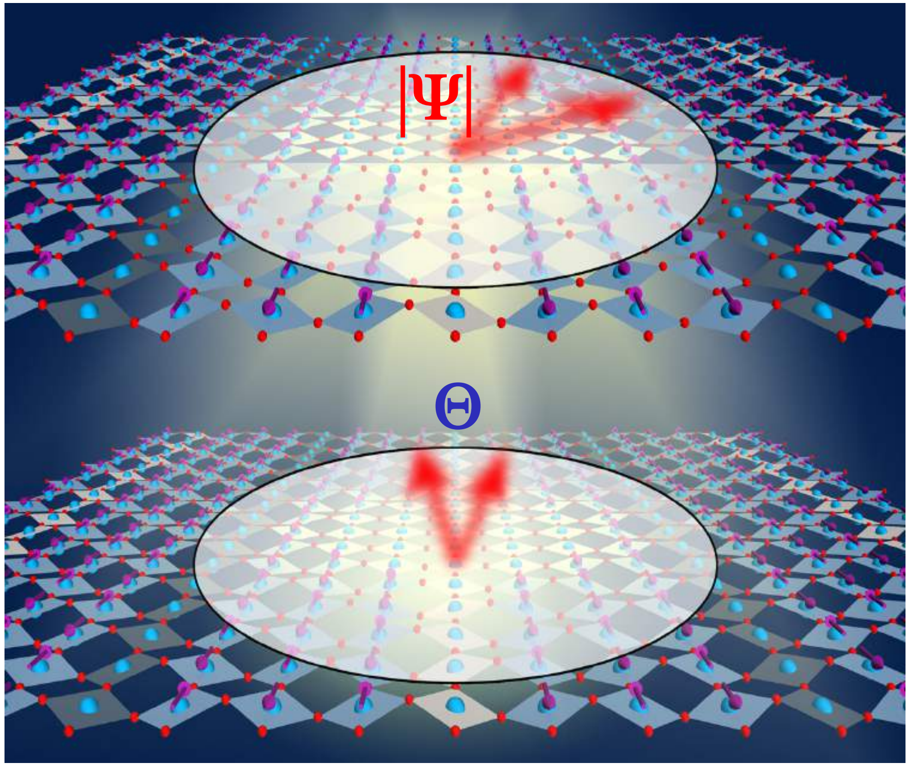
Fradkin and Kivelson, Nature Physcs (2012)

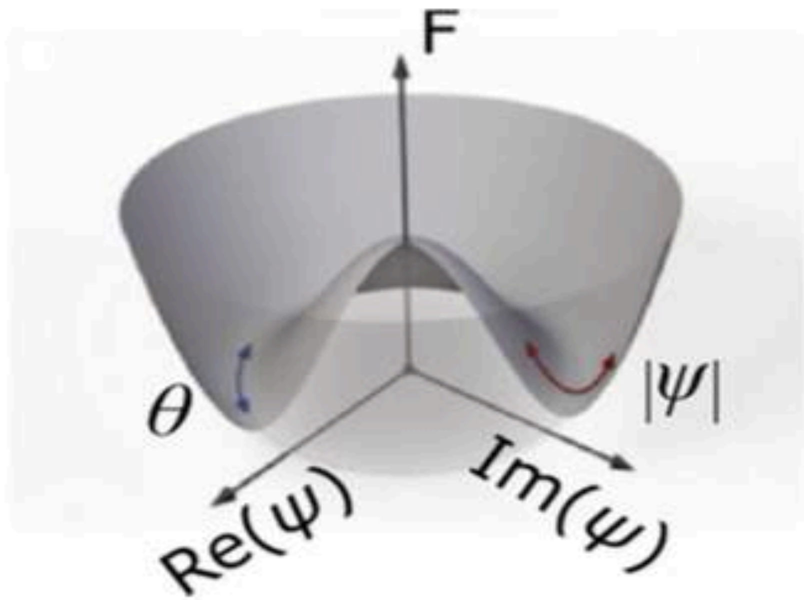
Superconducting Plasma Waves



Y. Laplace & A. Cavalleri *Advances In Physics X* 1, 387 (2016)

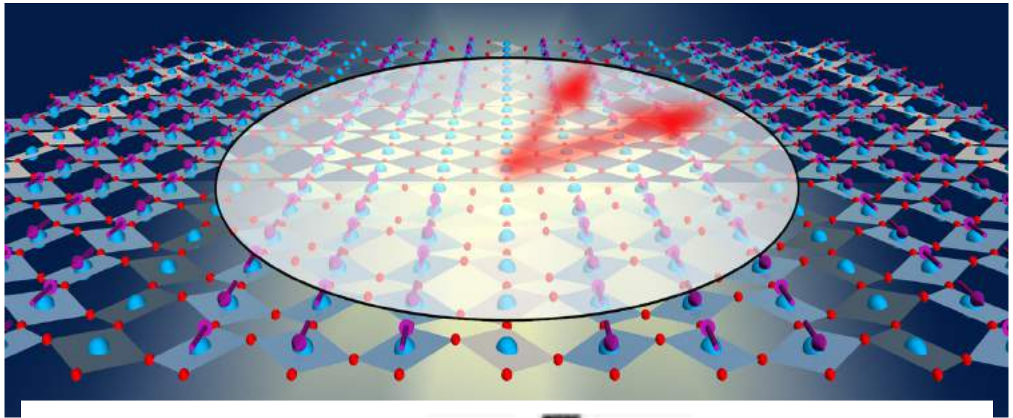
Superconducting order in cuprates

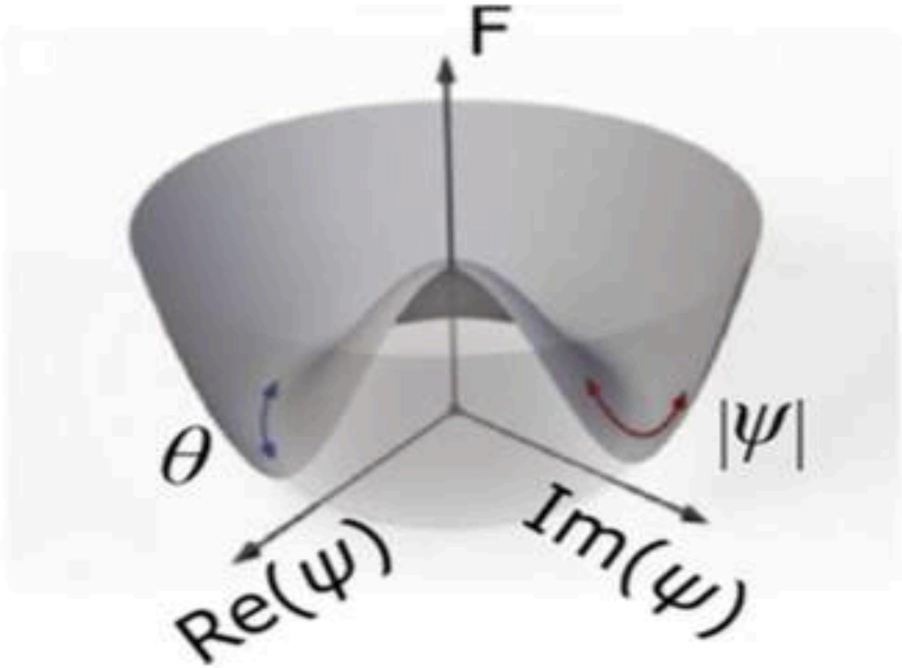




What do I see if E(ω) is polarized the plane

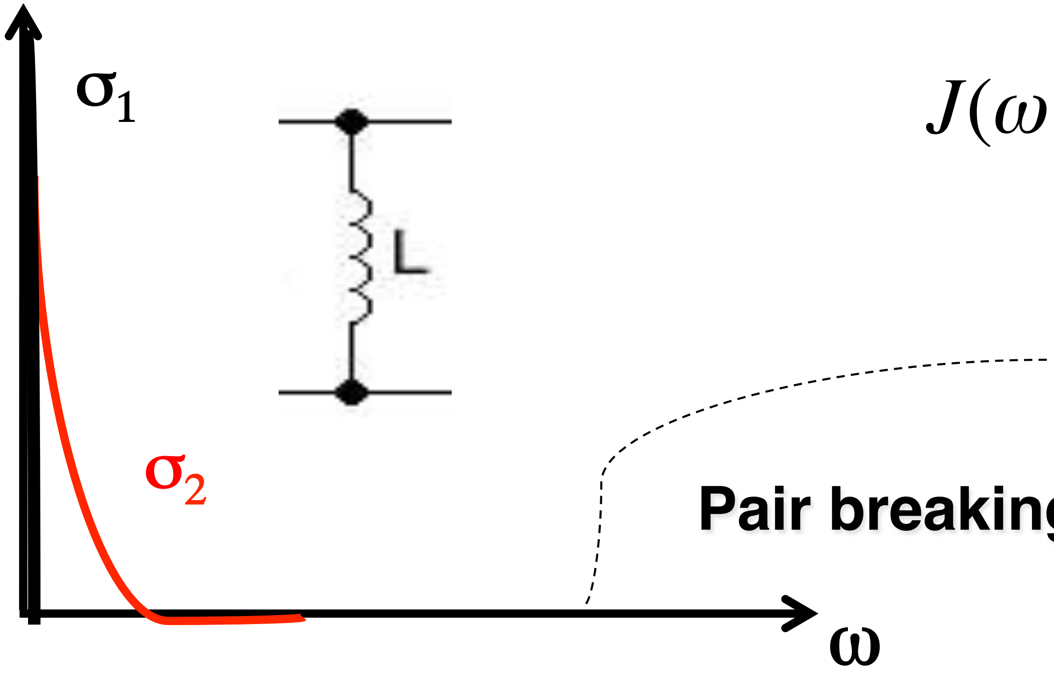
E(ω) →





- In plane

Reminder: Optics in a Superfluid



$$J(\omega) = \left[\sigma_1(\omega) + i\sigma_2(\omega)\right]E(\omega)$$

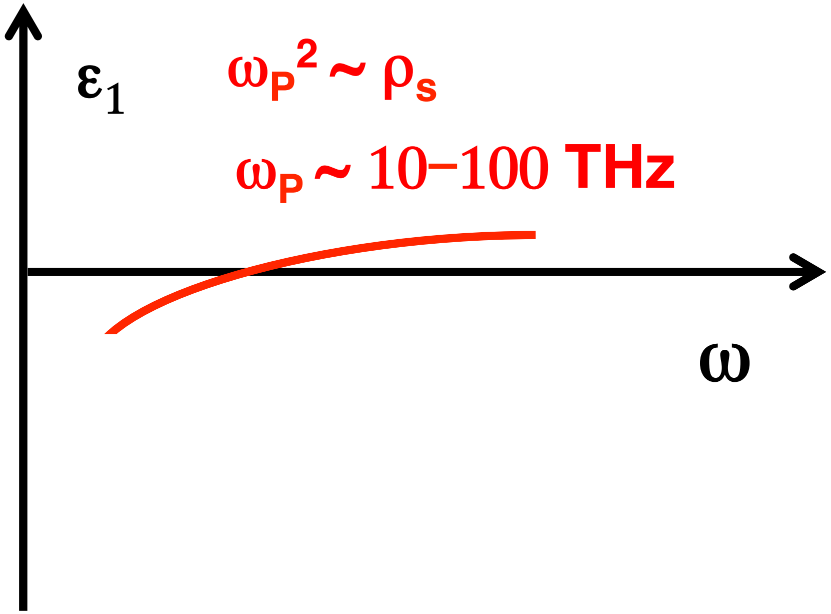
Pair breaking excitations (2Δ)

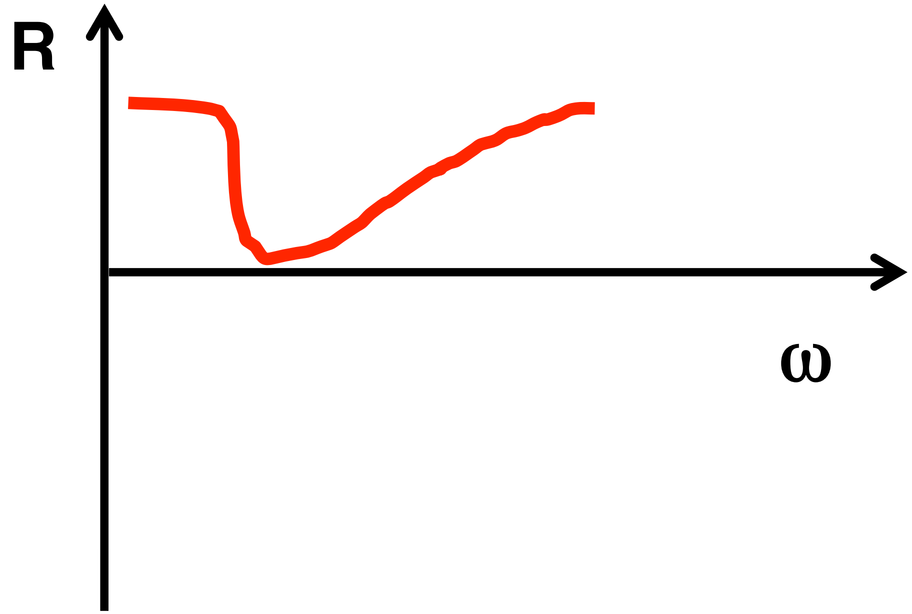
London superconductor

$$\sigma_1(\omega) = \pi/2(n_s e^2/m^*)\delta(0)$$

$$\sigma_2(\omega) = n_s e^2/m^*\omega$$

Optics in a Superfluid





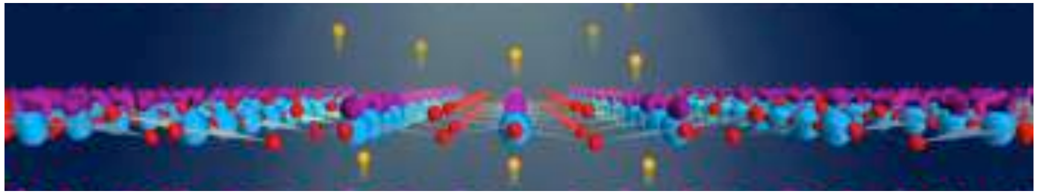
London superconductor

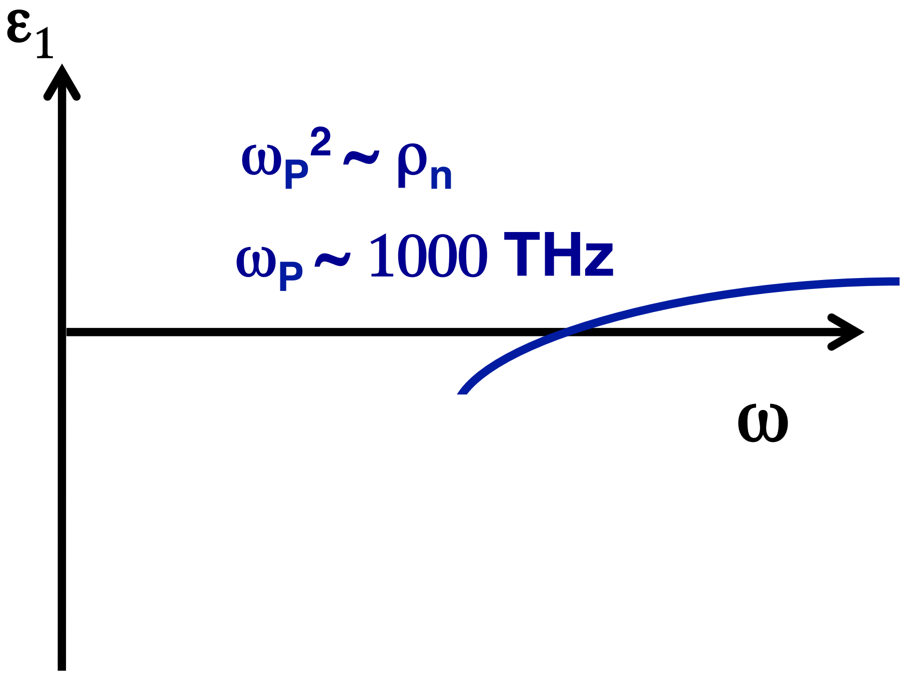
$$\varepsilon_1(\omega) = \varepsilon_0 - \frac{n_s e^2}{m^* \omega^2}$$

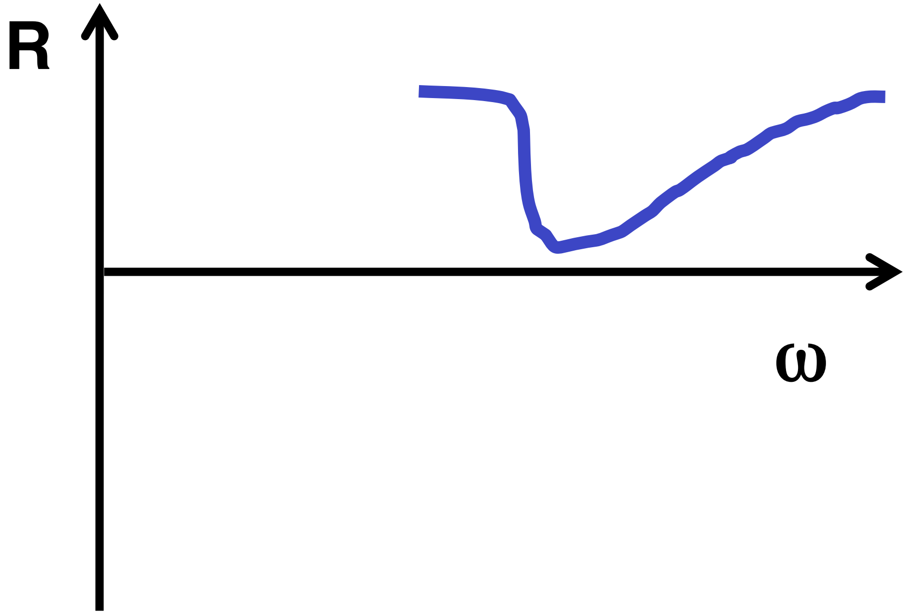
$$\varepsilon_2(\omega) = \frac{n_s e^2}{m^* \omega}\delta(0)$$

Also, response of quasi-particles

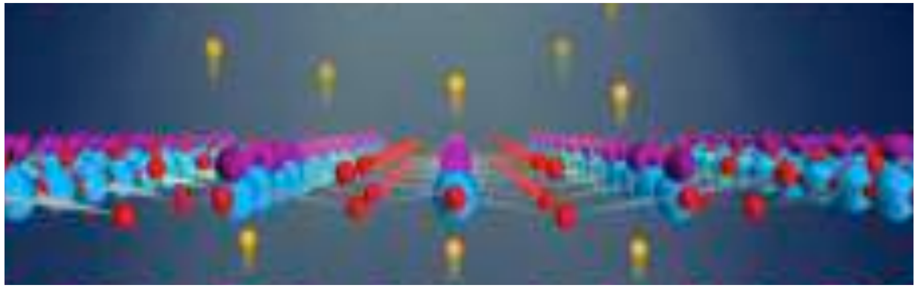
$E(\omega)$

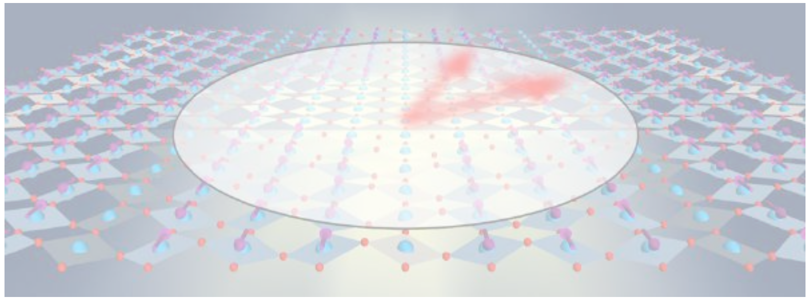


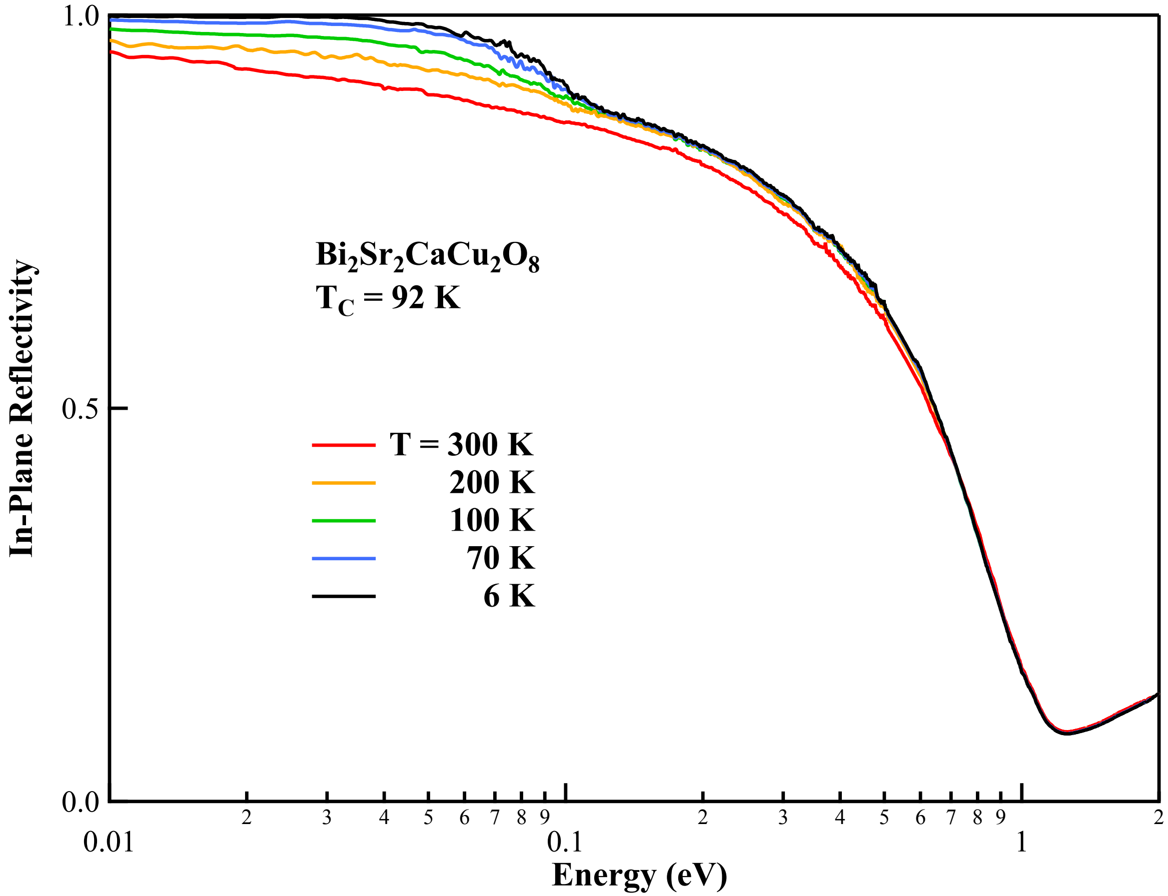




Quasi-particles dominate the in-plane response







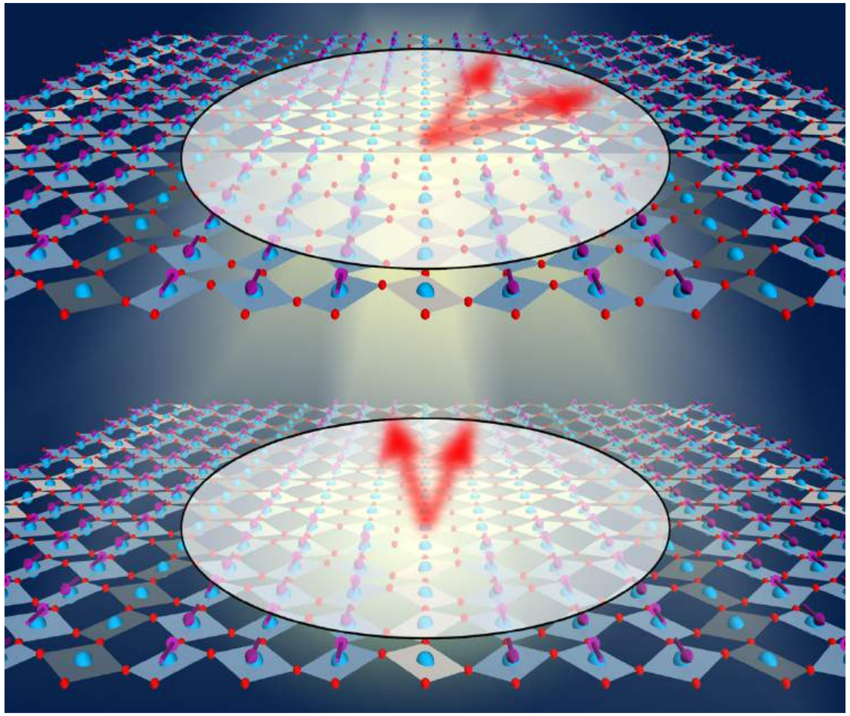
Out of Plane

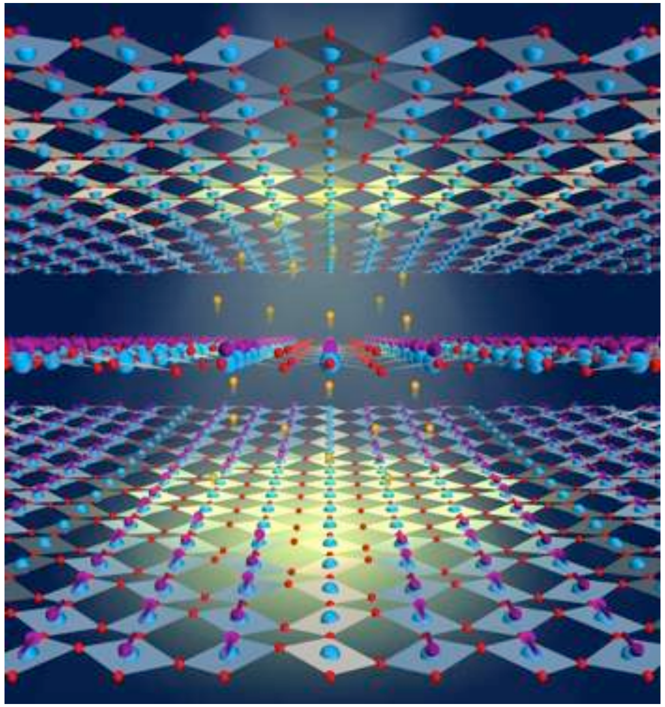
$\omega_P^2 \sim \rho_s$

$\omega_P \sim 0.1 - 10$ **THz**

$\omega_P^2 \sim \rho_{nz}$

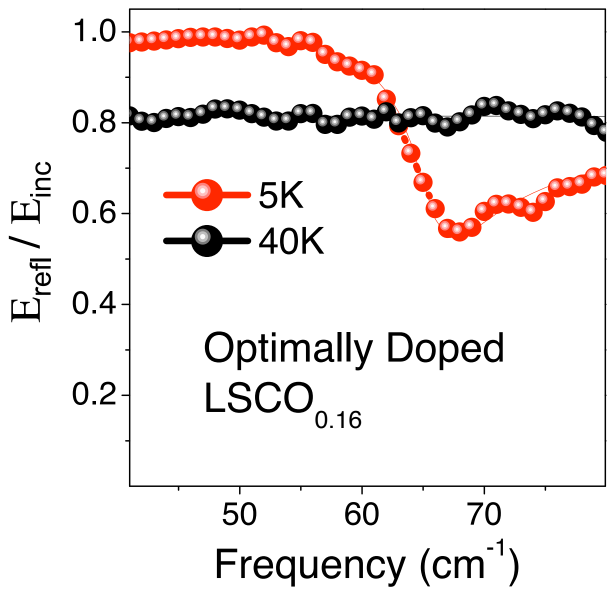
$\omega_P \sim 0$

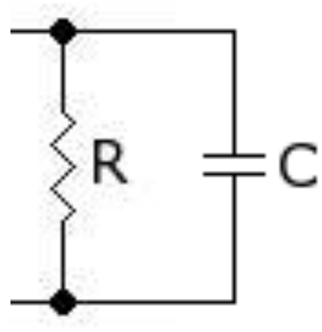




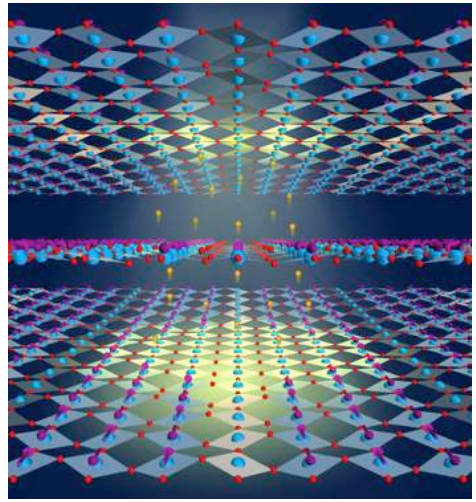
E(ω)

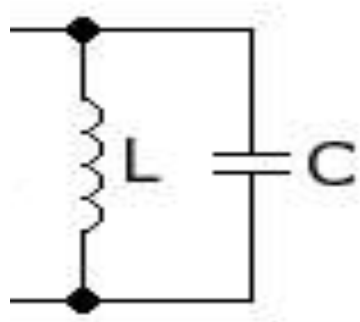
Josephson plasmons in cuprates



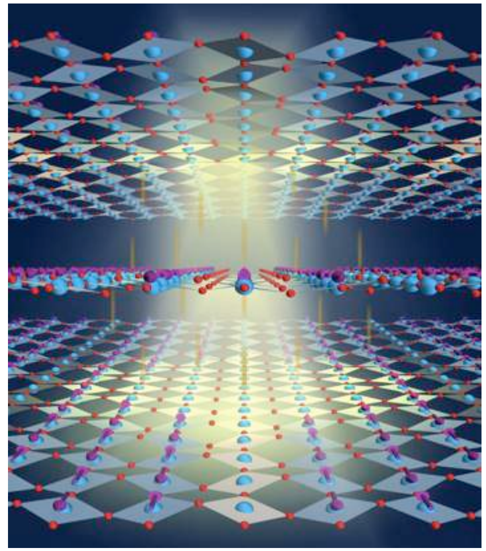


$T > T_c$





$T < T_c$



Kresin and Morawitz Phys. Rev. B (1988)

van der Marel and A. A. Tsvetkov Czech. J. Phys. (1996)

D.N. Basov et al. Science 283, 49 (1999)

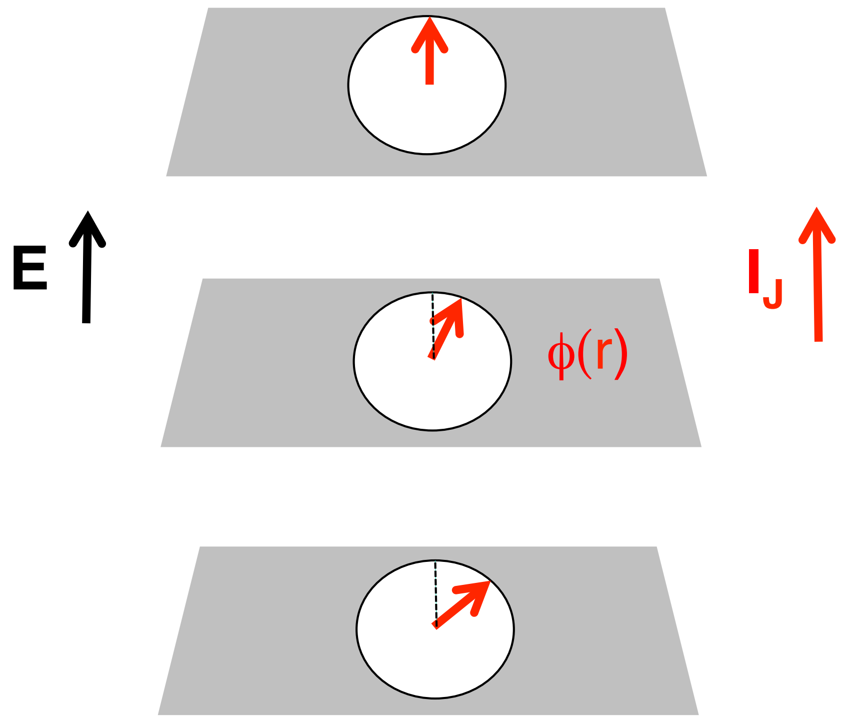
Microscopic physics

First Josephson Equation

$$I_J = I_c \sin\phi$$

Second Josephson Equation

$$\frac{\partial}{\partial t}\phi = \frac{2eV}{\hbar}$$



A nonlinear inductor

First Josephson Equation

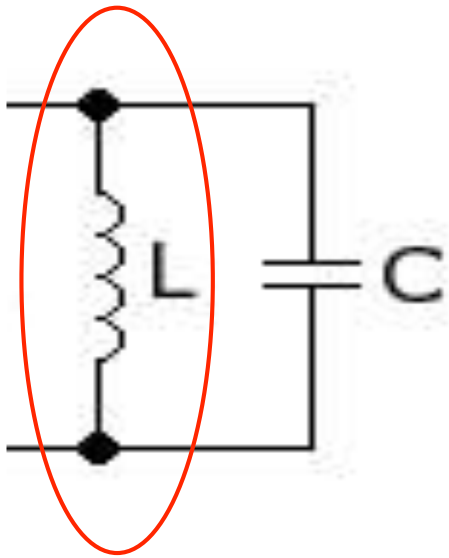
$$dI_J = I_c(\cos\phi)d\phi$$

$$dV = \frac{\hbar}{2e}\frac{1}{I_c\cos\phi}\frac{\partial}{\partial t}dI$$

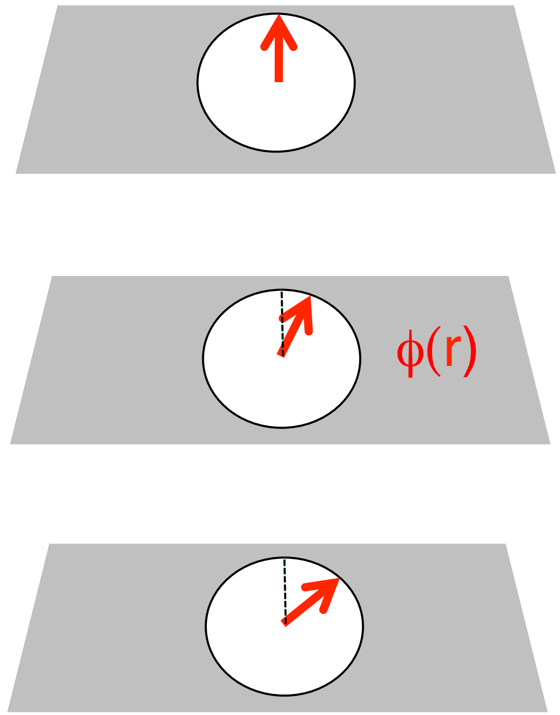
Second Josephson Equation

$$\frac{\partial}{\partial t}\phi = \frac{2eV}{\hbar}$$

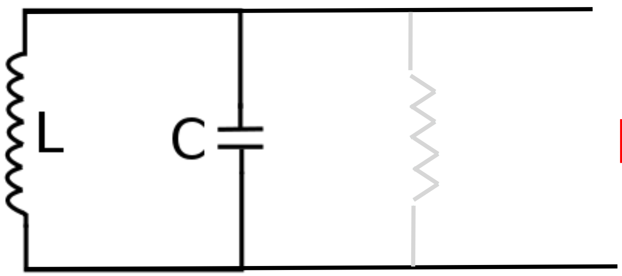
$$L = \frac{\hbar}{2e}\frac{1}{I_c\cos\phi}$$



Linear response: small phase gradients

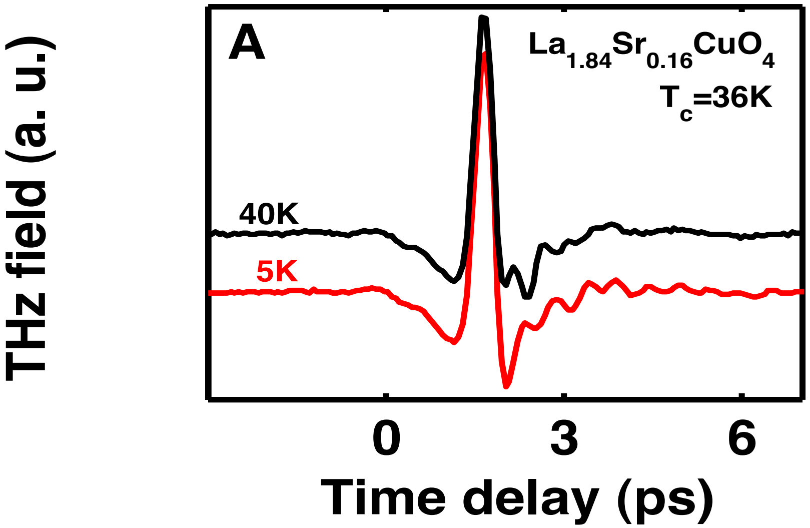


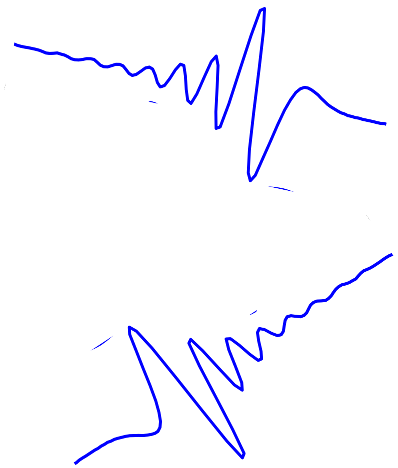
$$L = \frac{\hbar}{2e}\frac{1}{I_c \cos\phi} \approx \frac{\hbar}{2eI_c}$$

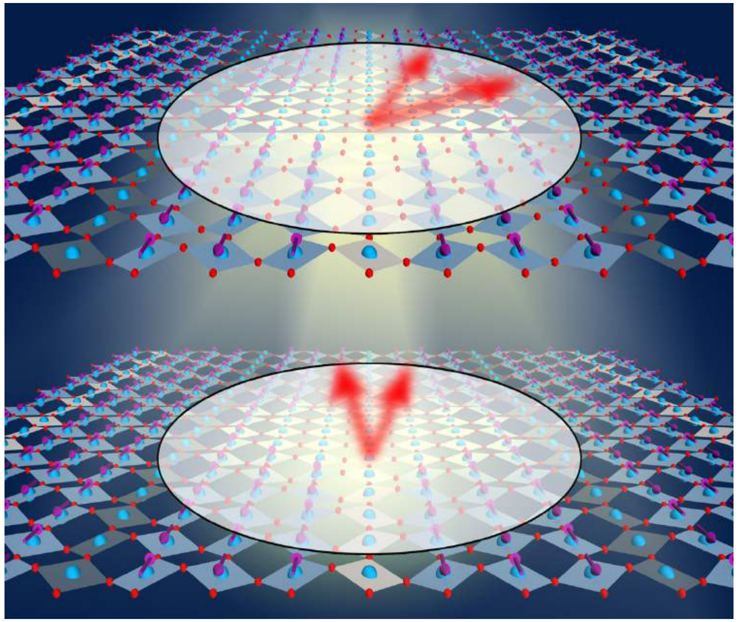


R >> ω L

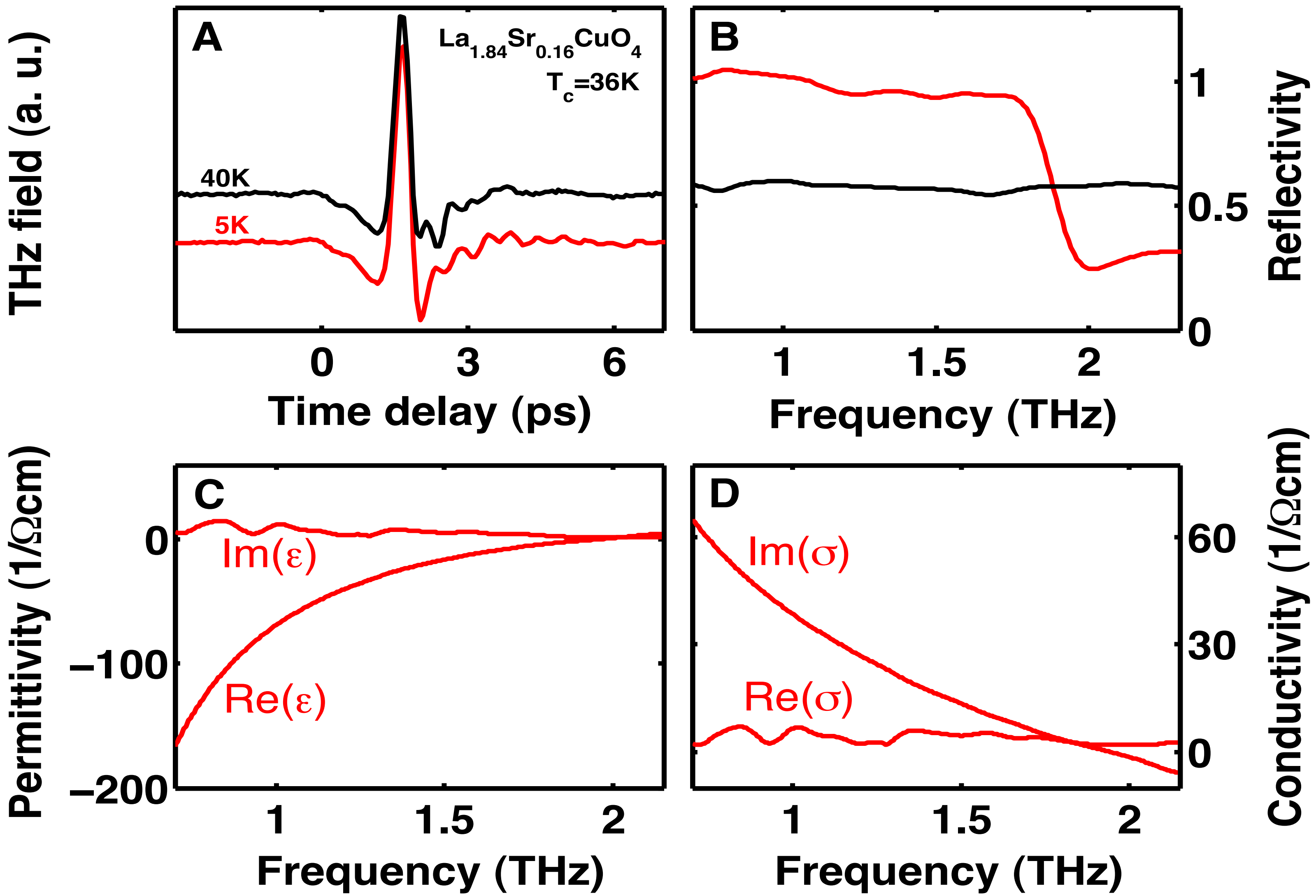
$La_{1.84}Sr_{0.16}CuO_4$ (at 5K): THz reflection







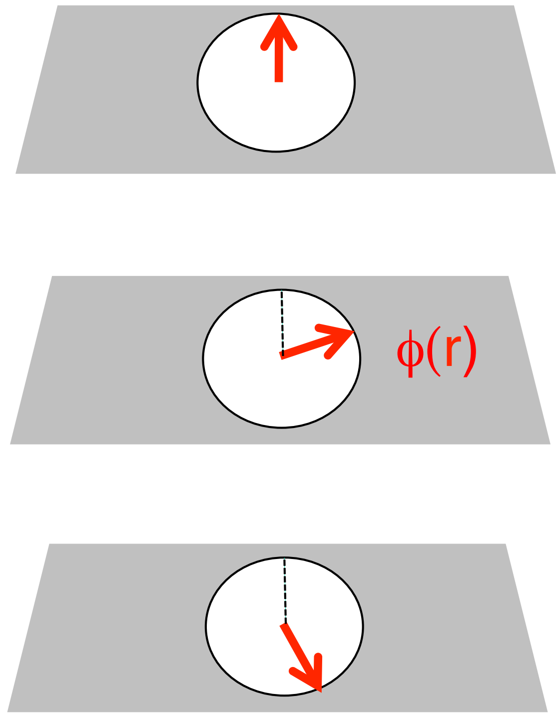
$La_{1.84}Sr_{0.16}CuO_4$ (at 5K)

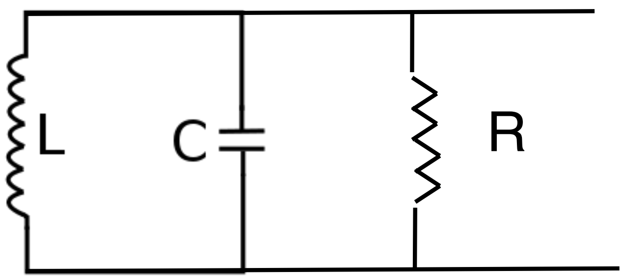


Expected Response: Large Phase Differences

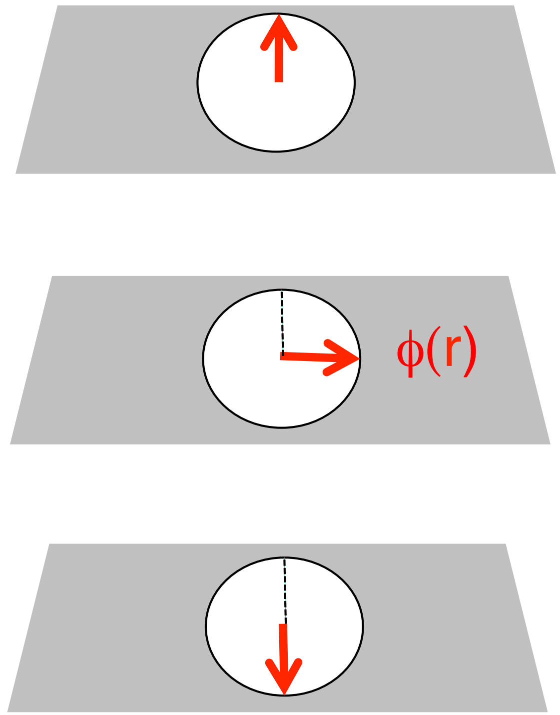
Resistive coupling is no longer shorted

$$L = \frac{h}{2e}\frac{1}{I_c \cos\phi} >> \frac{h}{2eI_c} \approx R$$





Phase Differences: π/2



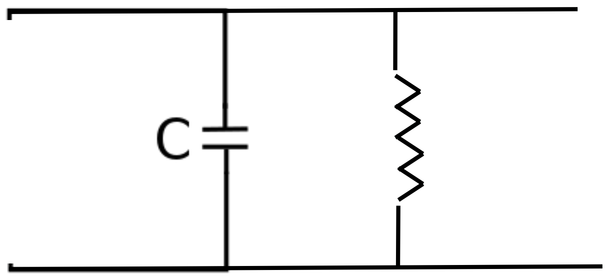
Second Josephson Equation

$$\frac{\partial}{\partial t}\phi = \frac{2eV}{h}$$

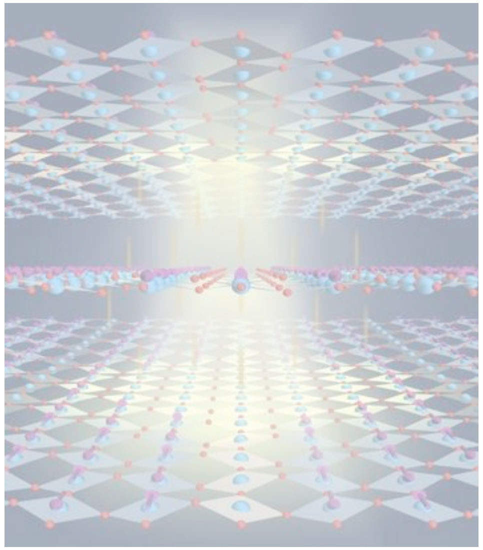
$$\phi(t) = \int_{-\infty}^{t} \frac{2eV(\tau)d\tau}{\hbar} = \frac{\pi}{2}$$

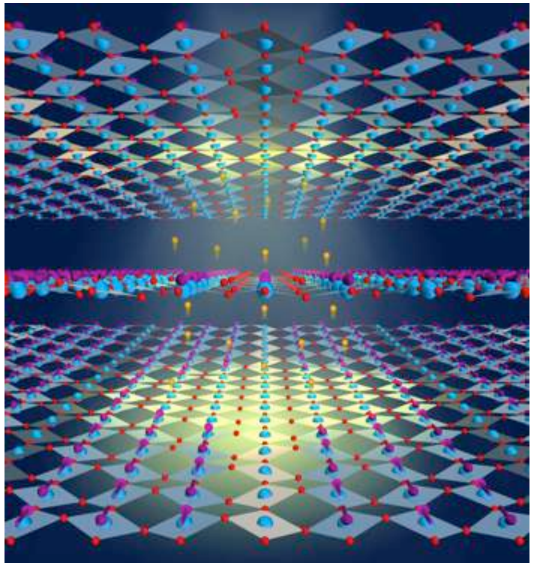
Inductive coupling is zero

$$L = \frac{\hbar}{2e}\frac{1}{I_c \cos\phi} = \infty$$



Phase Differences: π/2





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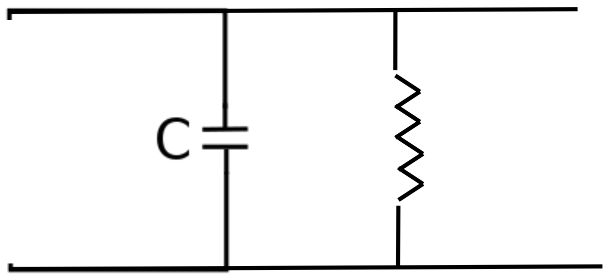

Phase Difference: π

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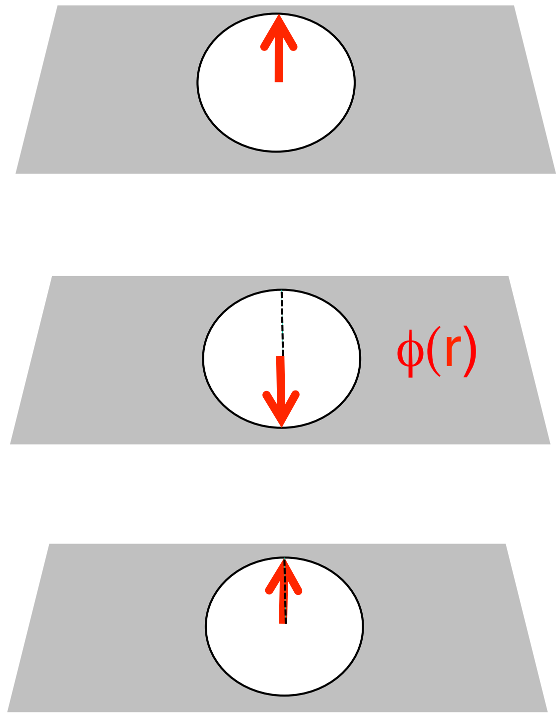
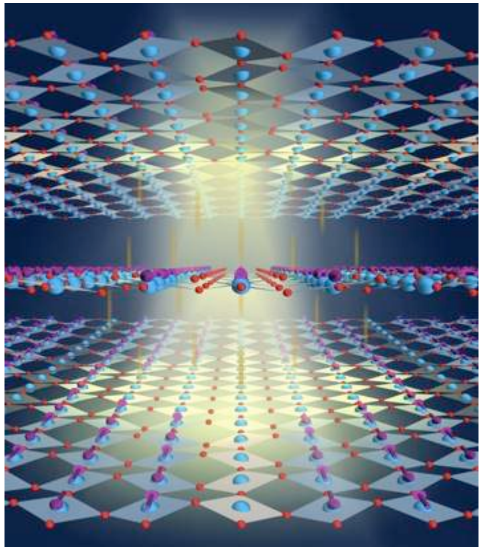
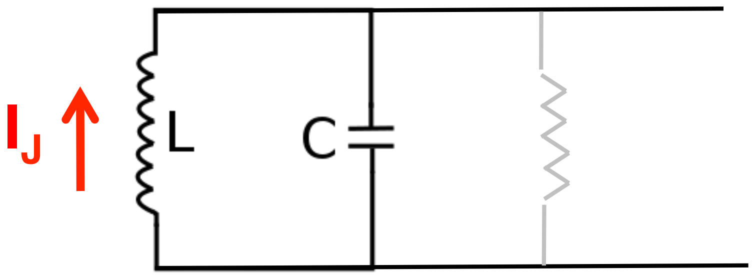


Phase Difference: π

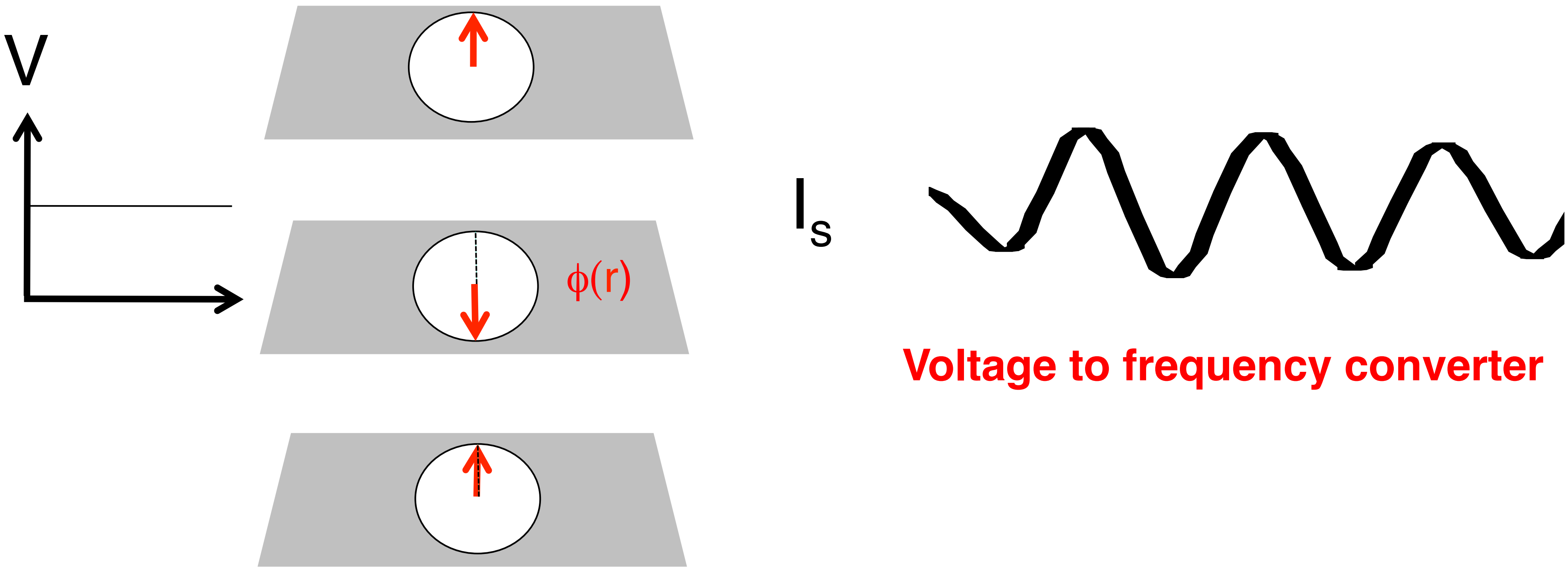


Inductive coupling is negative

$$L = \frac{\hbar}{2e}\frac{1}{I_c \cos\phi} \approx -\frac{\hbar}{2eI_c}$$

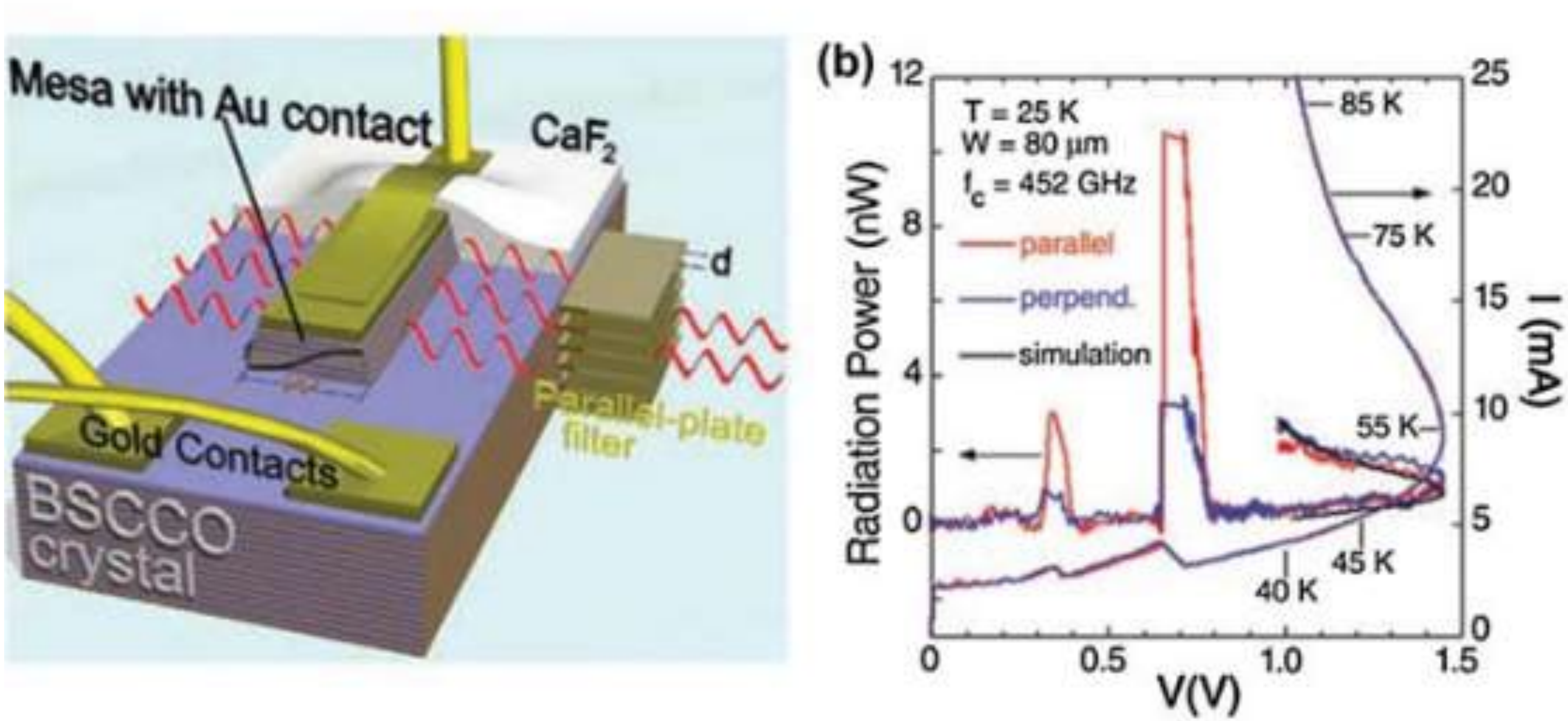


The AC Josephson effect



Voltage to frequency converter

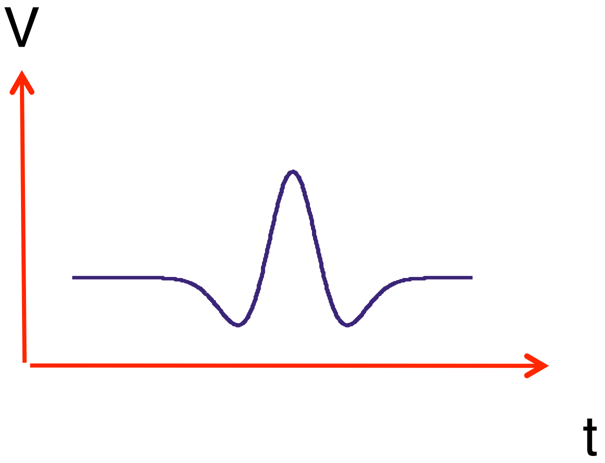
In Cuprates: Coherent THz radiation with DC Bias

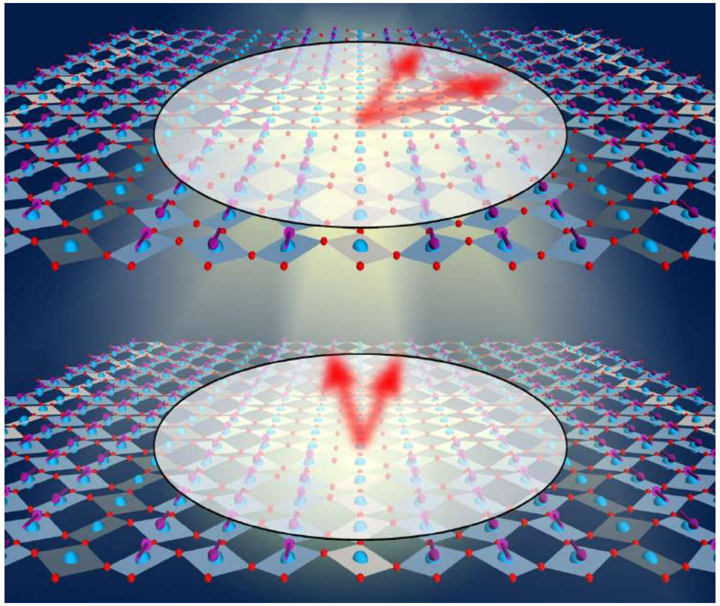


L. Ozyuzer et al. *Science* 1291, 318 (2007)

Can we flip phase at ultrafast rates ?

$$\phi(t) = \int_{-\infty}^{t} \frac{2eV(\tau)d\tau}{\hbar} = \frac{\pi}{2}$$

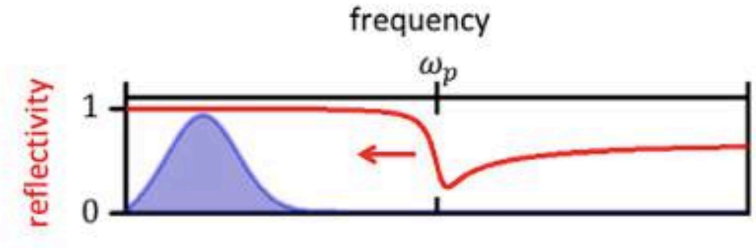




$$V = \frac{\pi}{4e}\frac{\hbar}{100\,fs} \approx mV$$

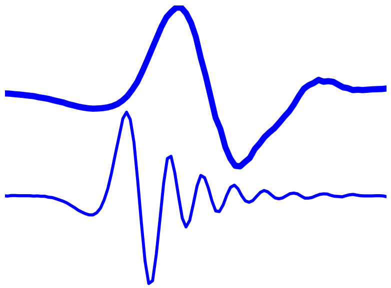
$$E \approx mV/(1nm) \approx \underline{100kV/cm}$$

Pump probe experiments

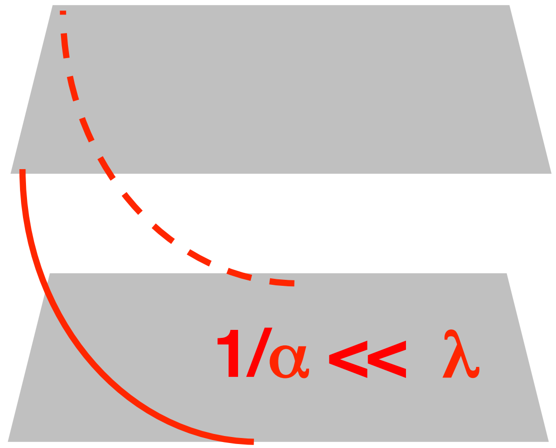


Pump

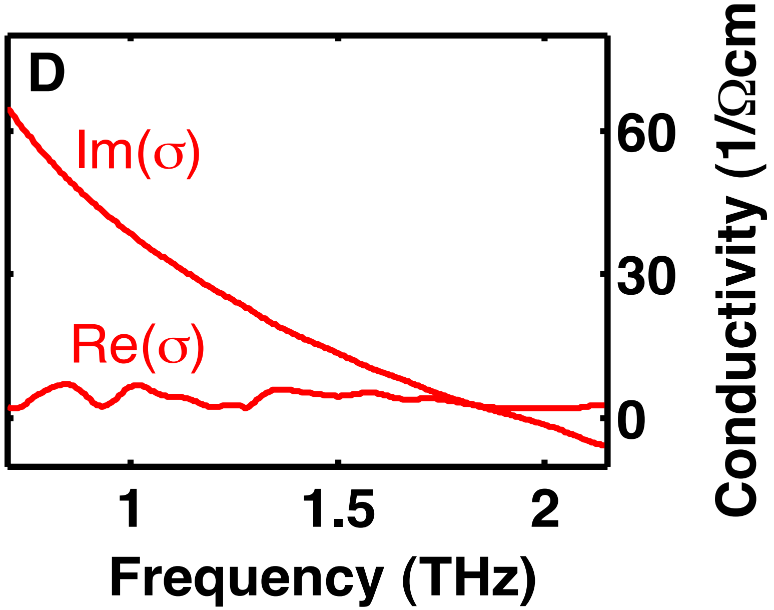
Pump

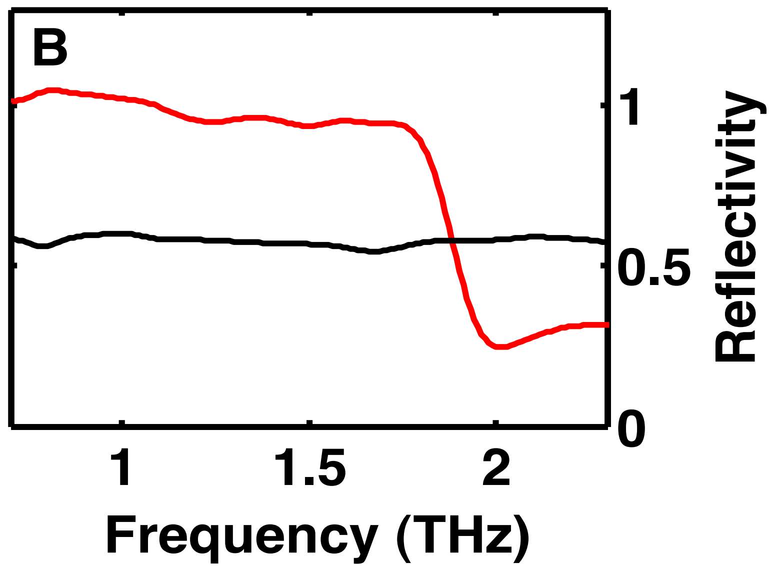


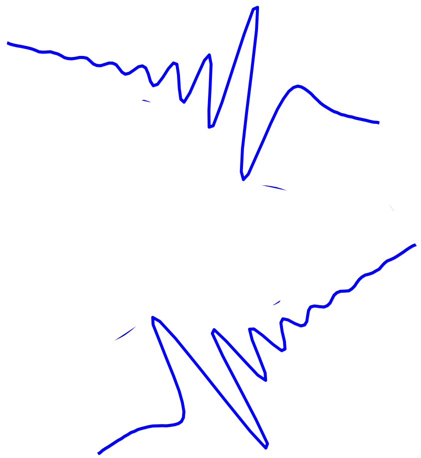
Probe

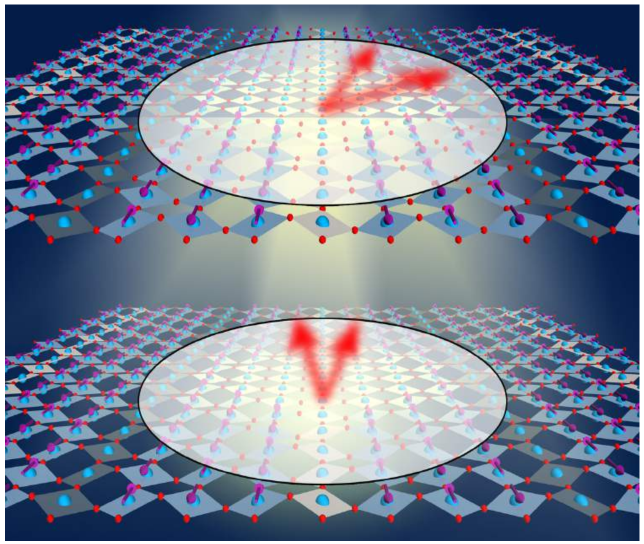


Probe alone: $La_{1.84}Sr_{0.16}CuO_4$ (at 5K)

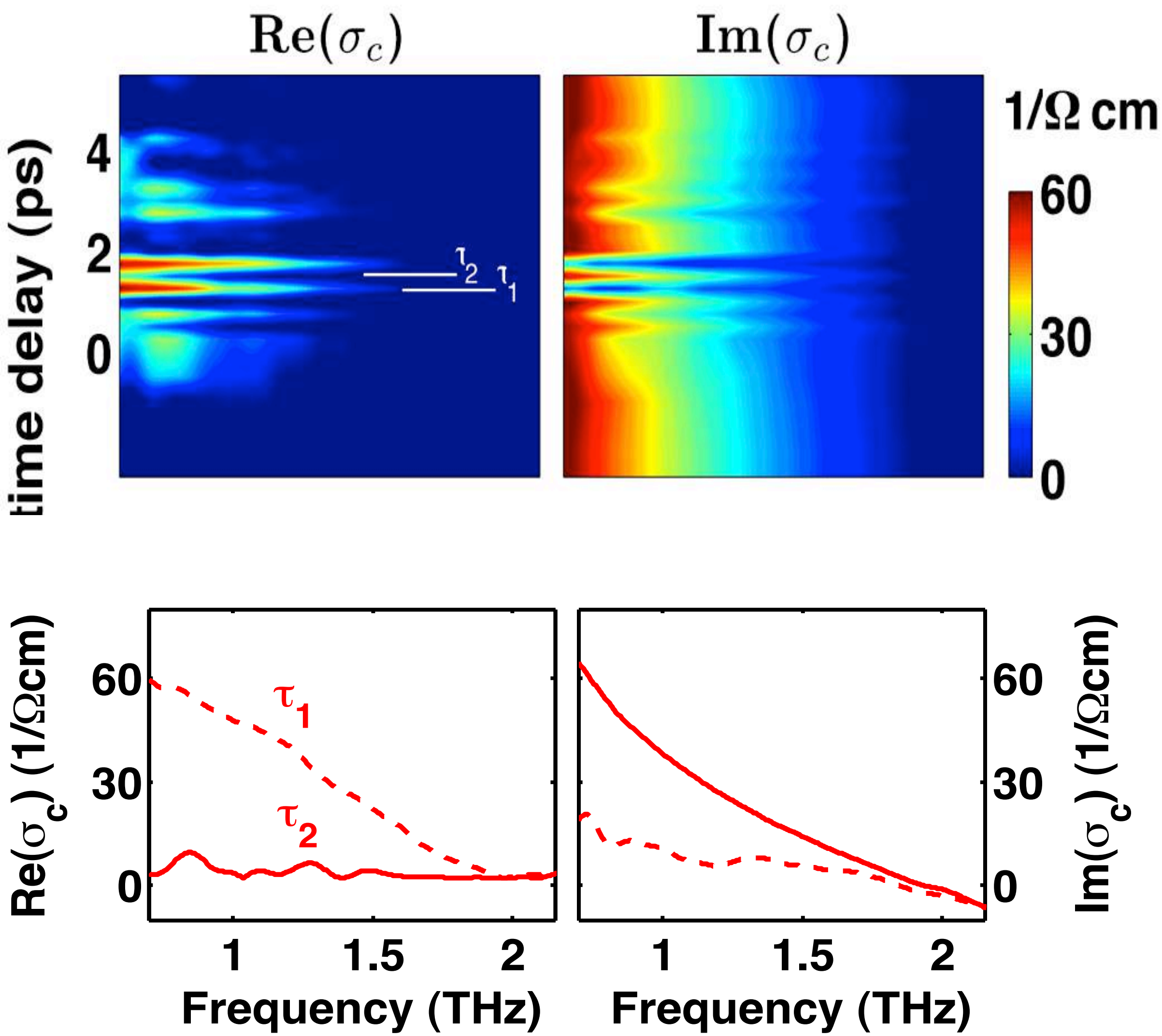








Large Conductivity Oscillations

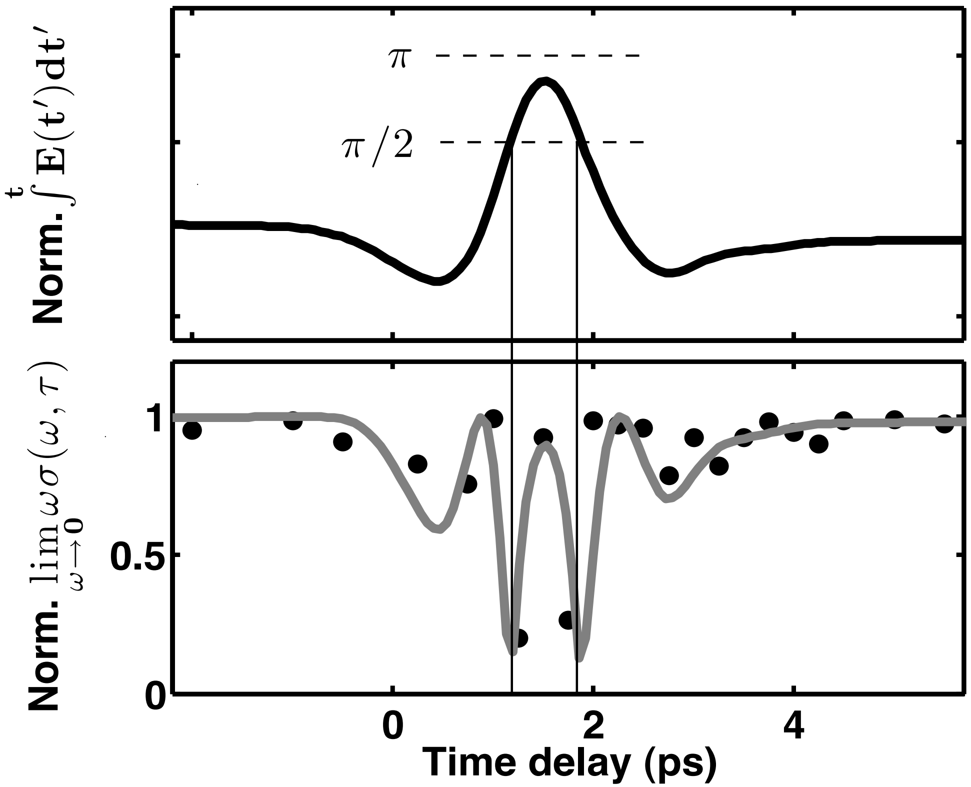


Oscillations in the interlayer coupling

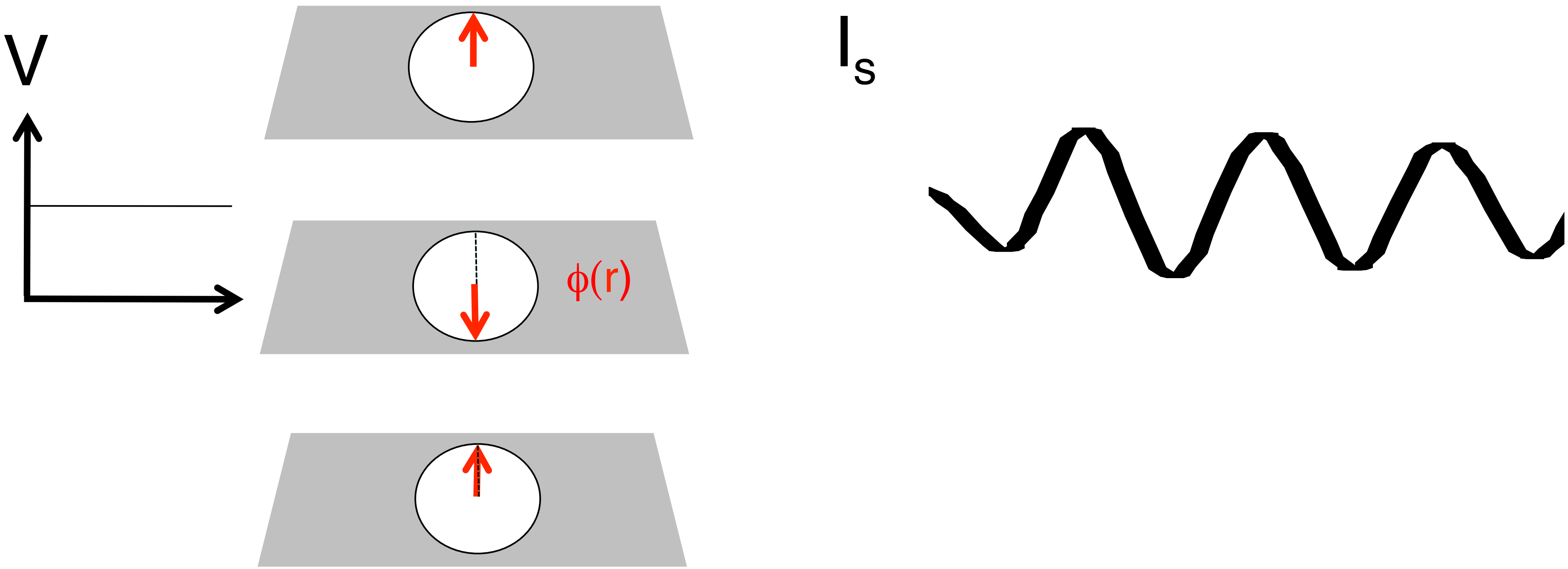
$$\sigma_1(\omega) = \pi/2(n_s e^2/m^*)\delta(0)$$

$$\sigma_2(\omega) = n_s e^2/m^* \omega$$

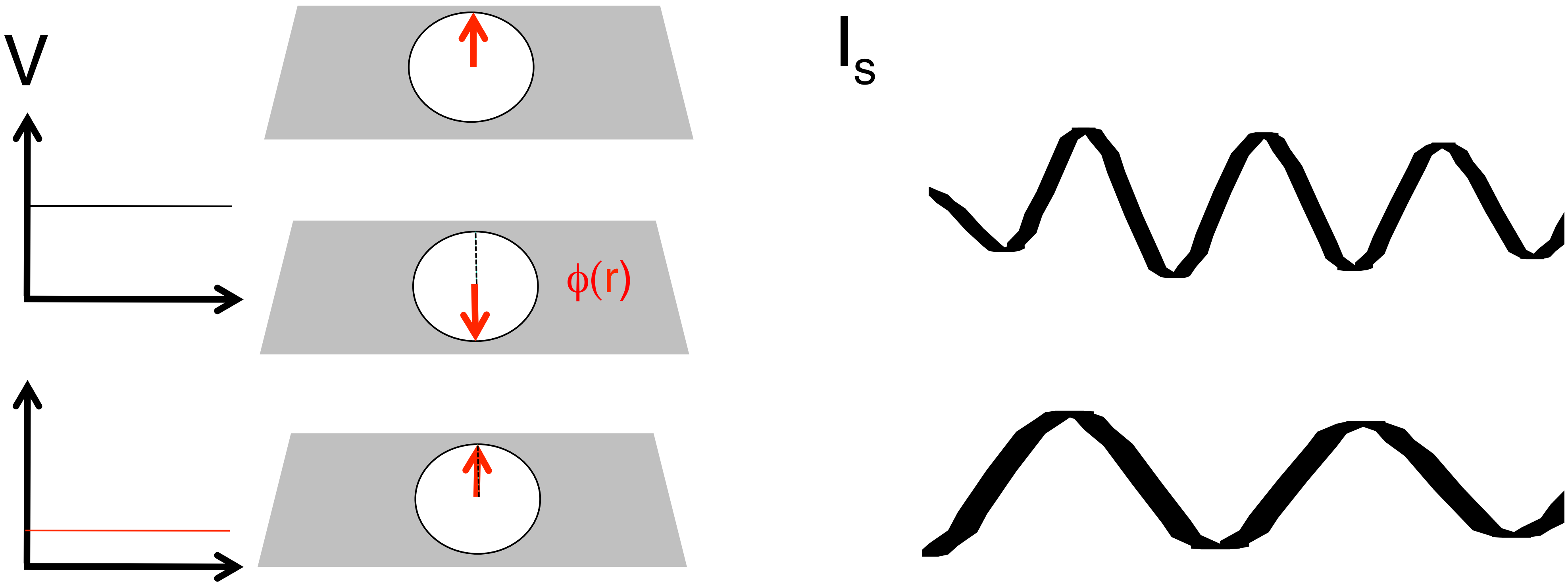
$$n_s \propto \lim_{\omega \to 0} \omega \sigma_2(\omega)$$



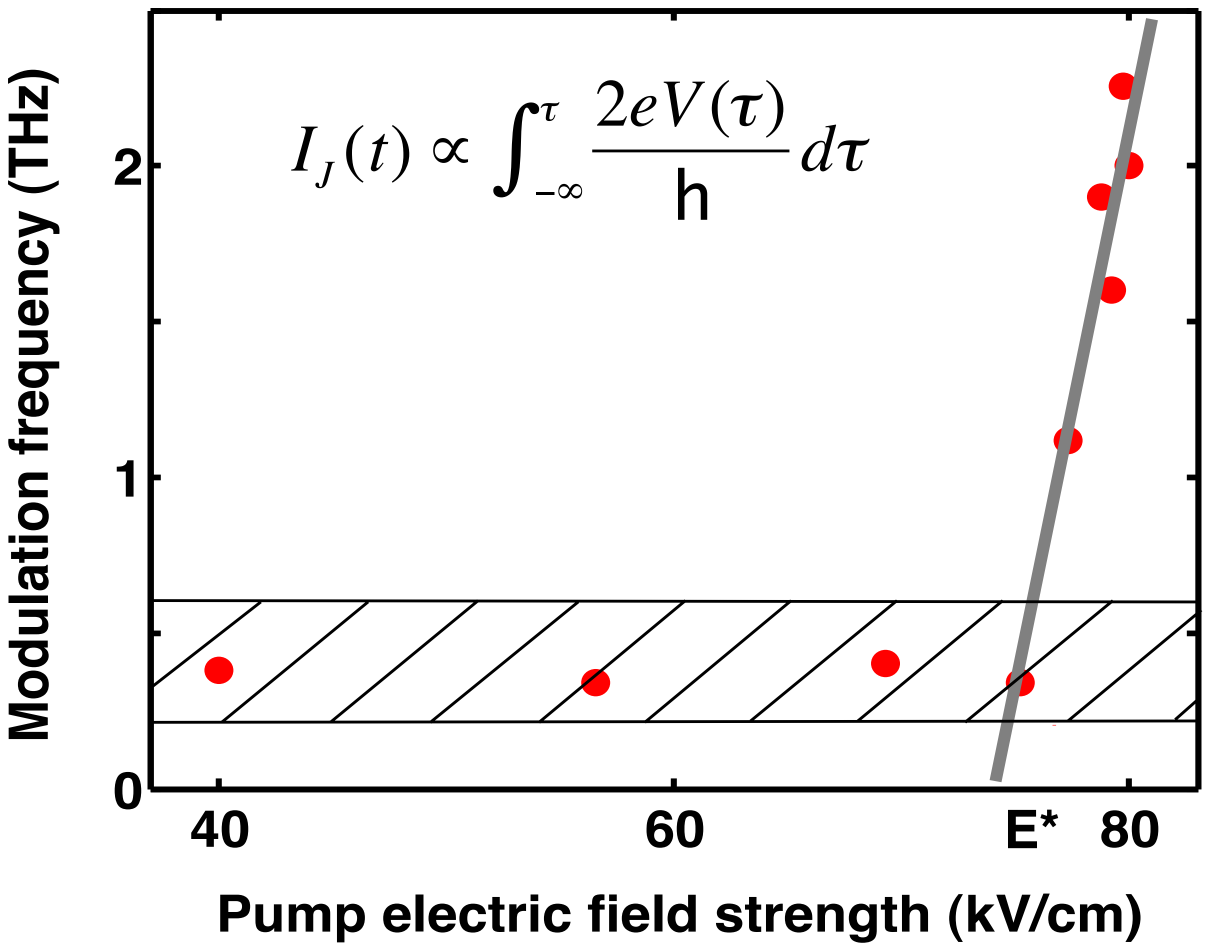
Quasi-DC field: Conductivity Oscillations



Expected: Voltage dependent frequency

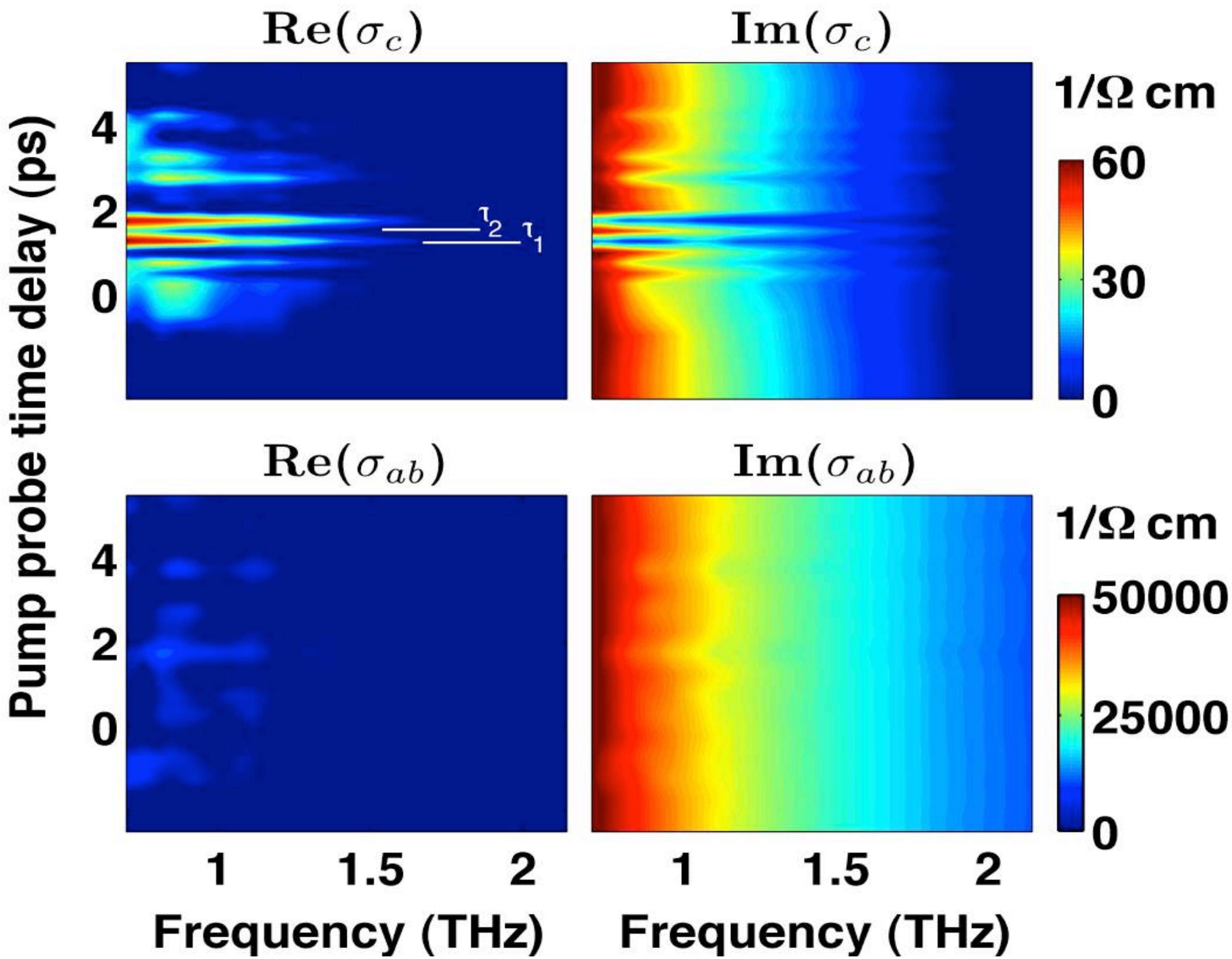


The oscillation frequency depends on field



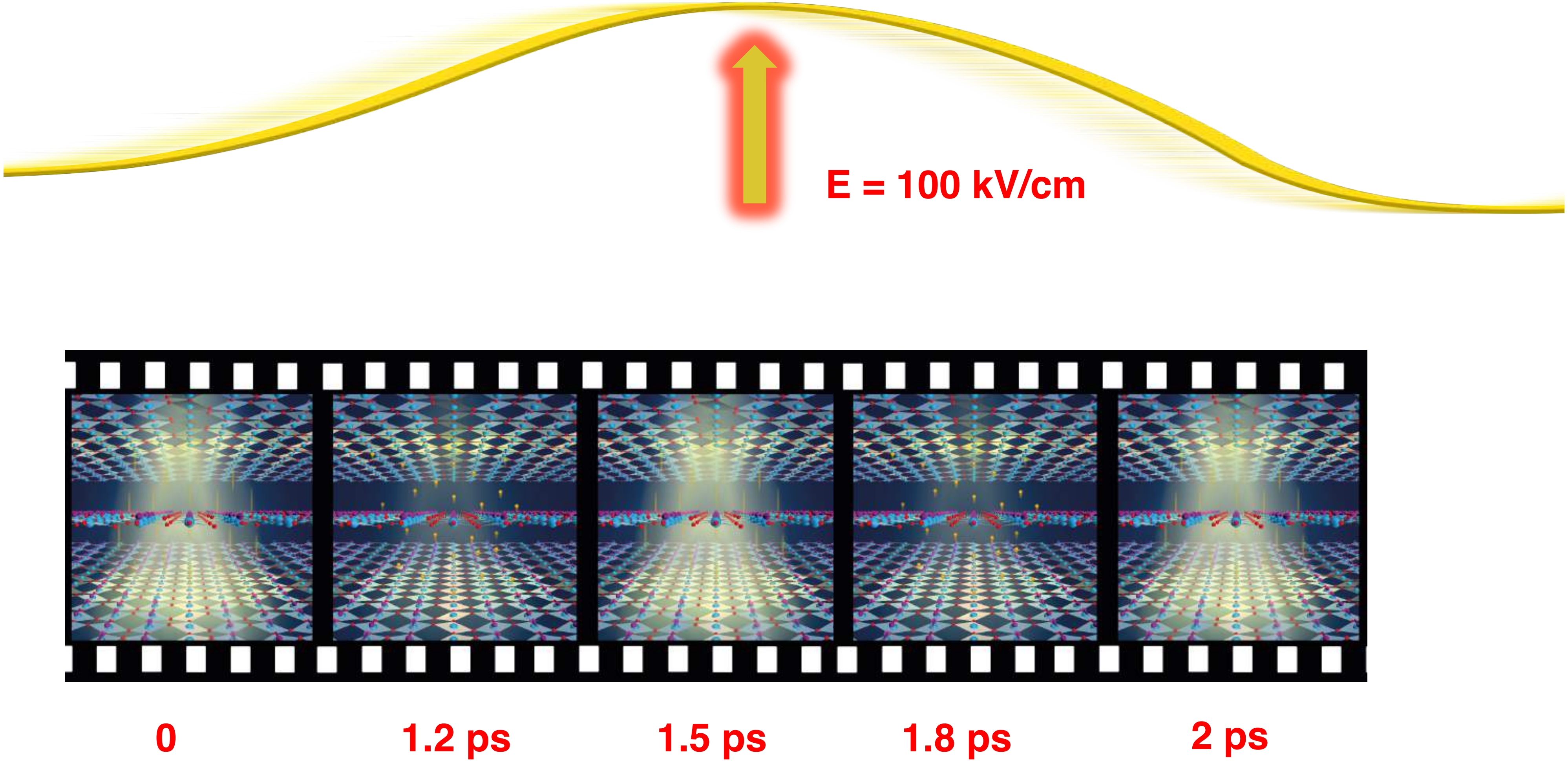
A. Dienst et al., *Nature Photonics* 5, 485 (2011)

Response in the Plane does not change



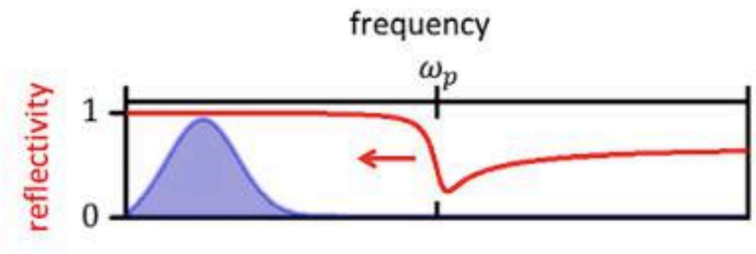
A. Dienst et al., *Nature Photonics* 5, 485 (2011)

THz dimensionality oscillations

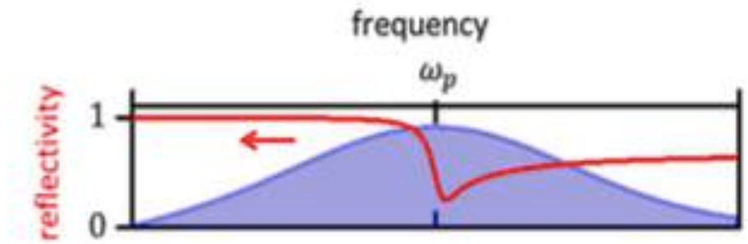


A. Dienst et al., Nature Photonics 5, 485 (2011)

Tuning the pump wavelength to resonance

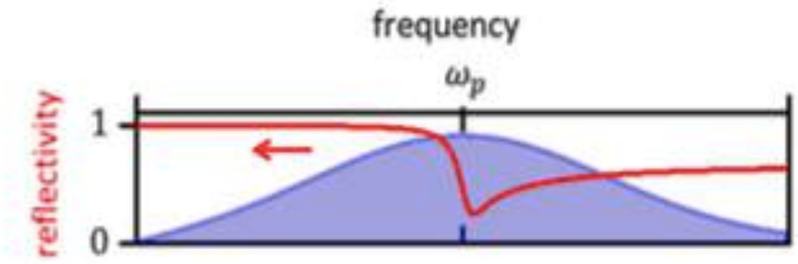


$\omega_{THz} << \omega_p$



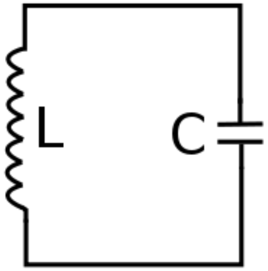
$\omega_{THz} \sim \omega_p$

Driven Plasma

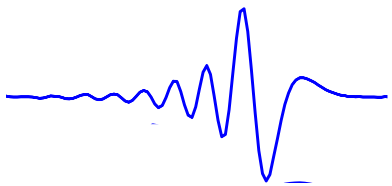


$\omega_{THz} \sim \omega_p$

$$L = \frac{\hbar}{2e}\frac{1}{I_c \cos\phi}$$

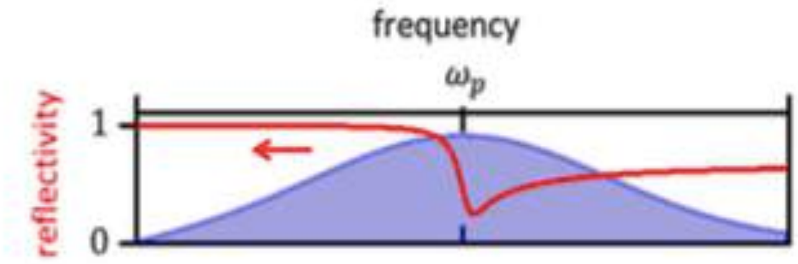


$$E(t) = E_0 \sin(\omega_{JP0} t)$$



$$\theta_{i,i+1}(t) = \theta_0 \cos(\omega_{JP0} t)$$

Driven Plasma



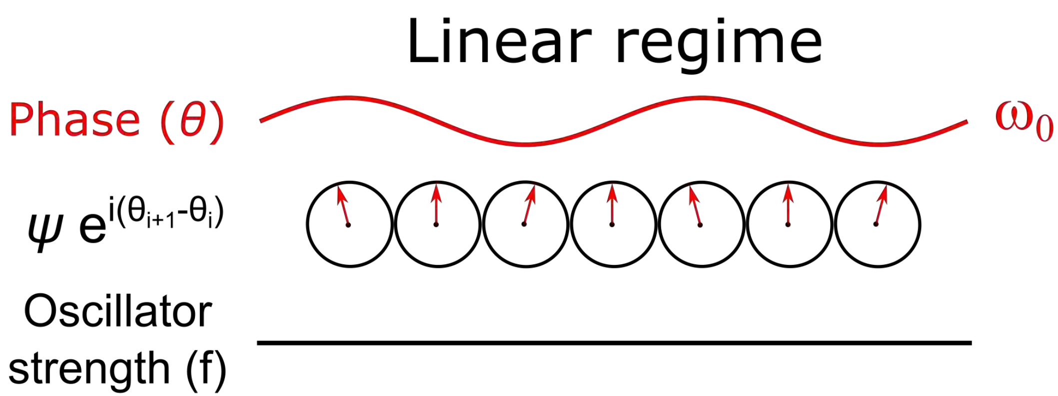
$\omega_{THz} \sim \omega_p$

$$\omega_{P'}^2 = \omega_P^2 \cos[\theta_0 \cos(\omega_{JP0} t)]$$

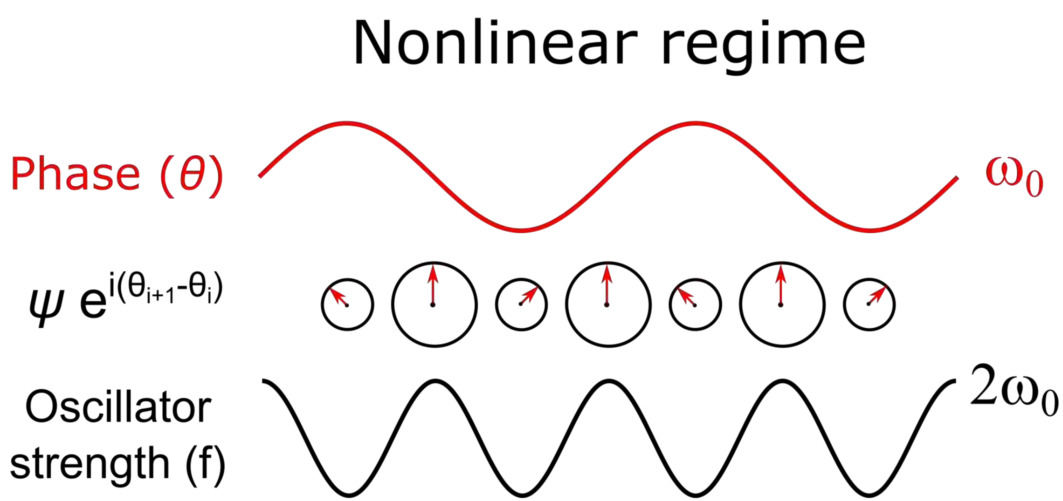
$$\omega_{P'}^2 = \omega_P^2 \left(1 - \frac{\theta_0^2 + \theta_0^2 \cos(2\omega_{JP0} t)}{4}\right)$$

Strongly Driven Plasma

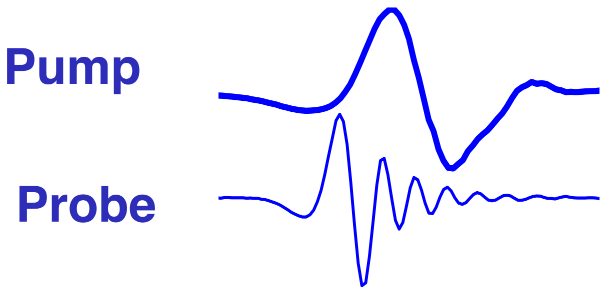
$$\theta_0 << \frac{\pi}{4}$$

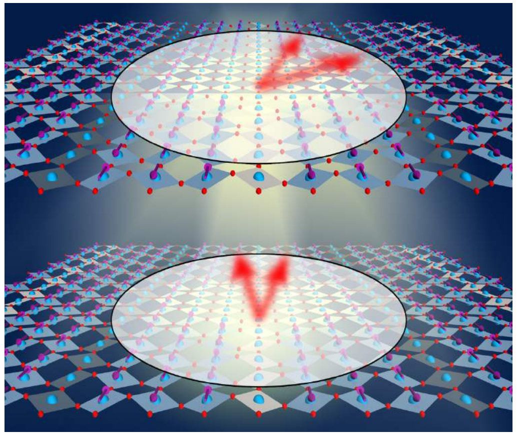


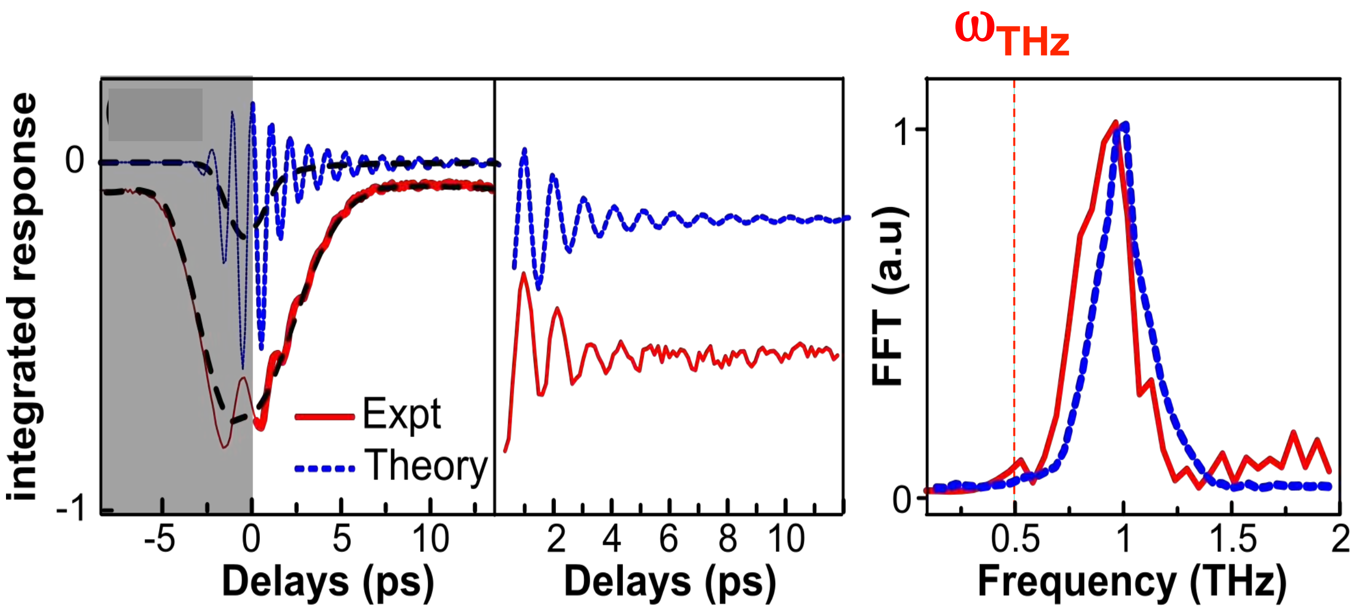
$$\omega_{P'}^2 = \omega_P^2\left(1 - \frac{\theta_0^2 + \theta_0^2\cos(2\omega_{JP0}t)}{4}\right)$$



Superfluid stiffness driven at 2 ω_{THz}



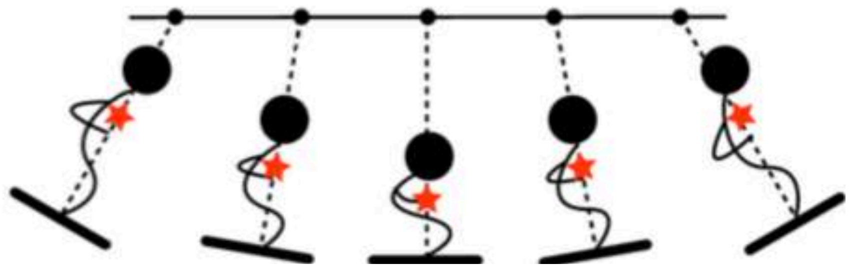




Superfluid stiffness driven at 2 ω_{THz}

Is this interesting ?

A parametrically driven pendulum

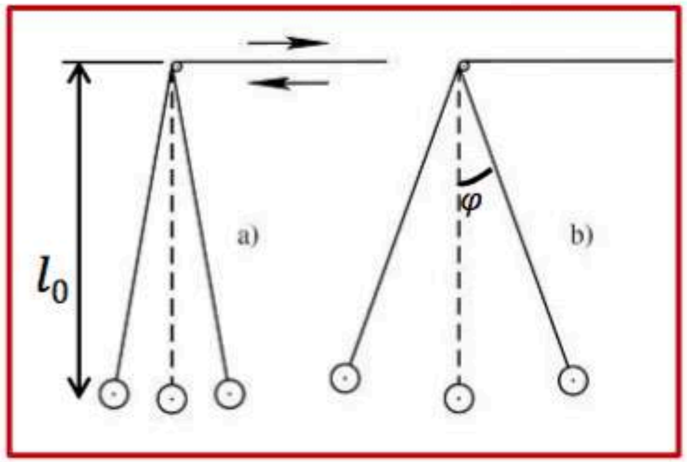


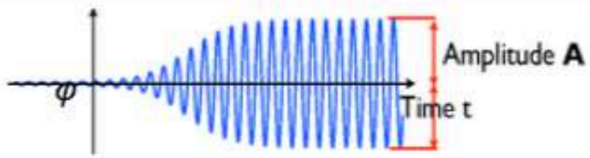
Oscillator strength is driven at 2ω

Mathieu's equation for parametric amplification is

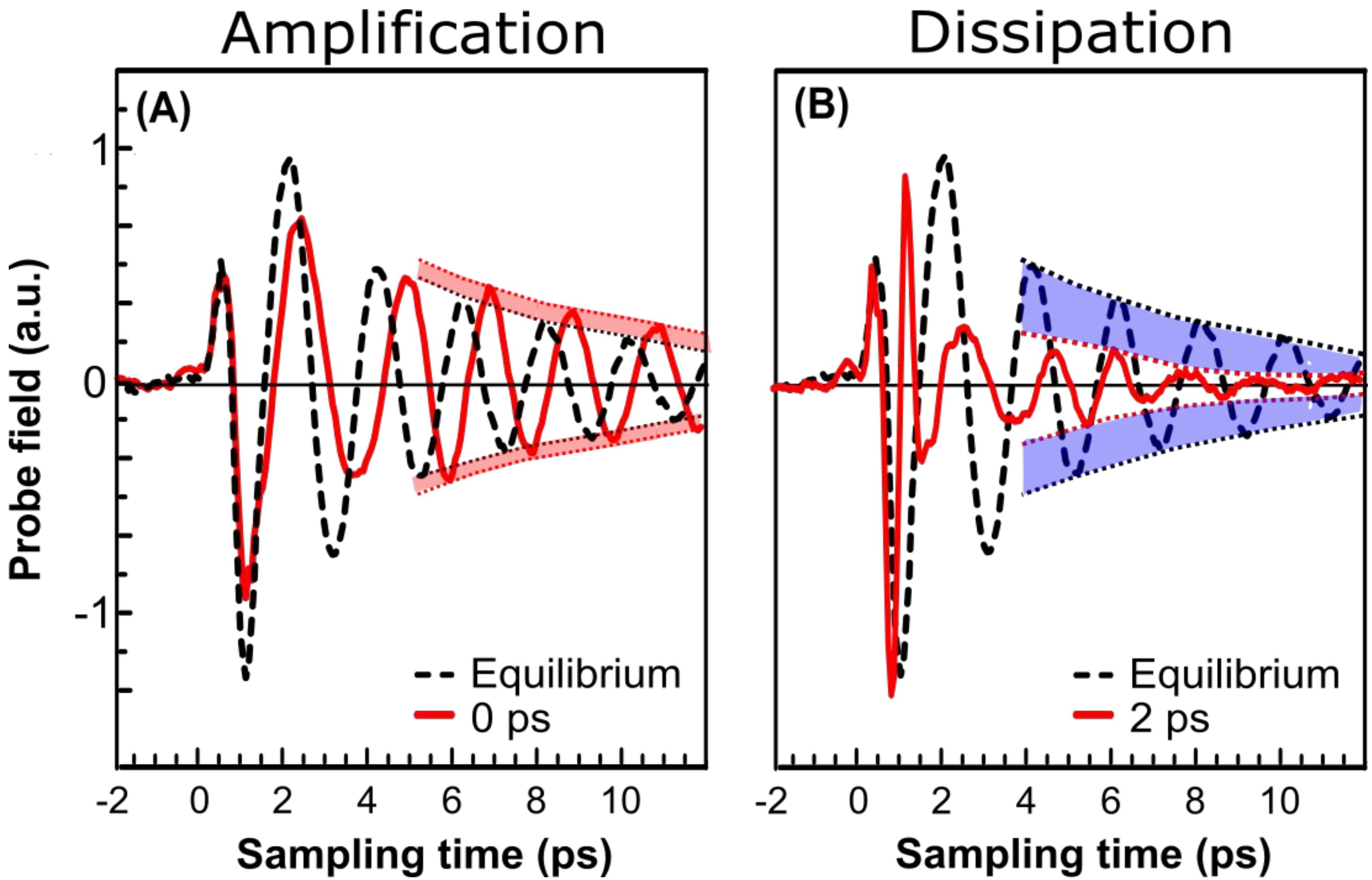
$$\frac{\partial^2\varphi}{\partial t^2} + \omega_p{}^2\{1 + l_0(\cos(2\omega_p{*}t))\}\,\varphi = 0$$

$$F_{driver} = l_0(\cos(2\omega_p{*}t))$$





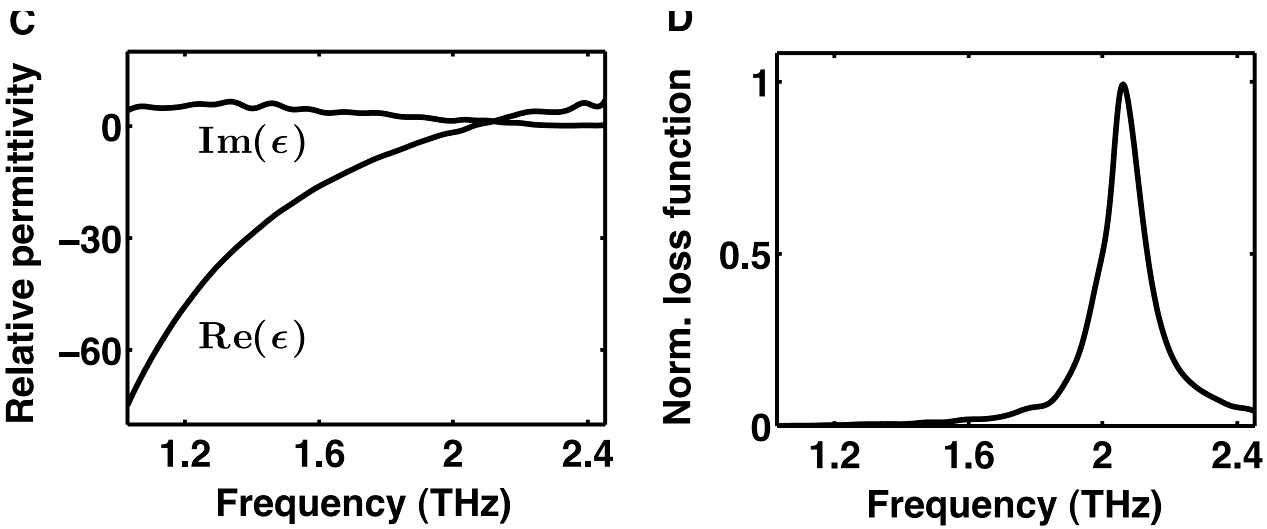
SC fluctuations are amplified or de-amplified



Rajasekaran et al., *Nature Physics 12, 1012* (2016)

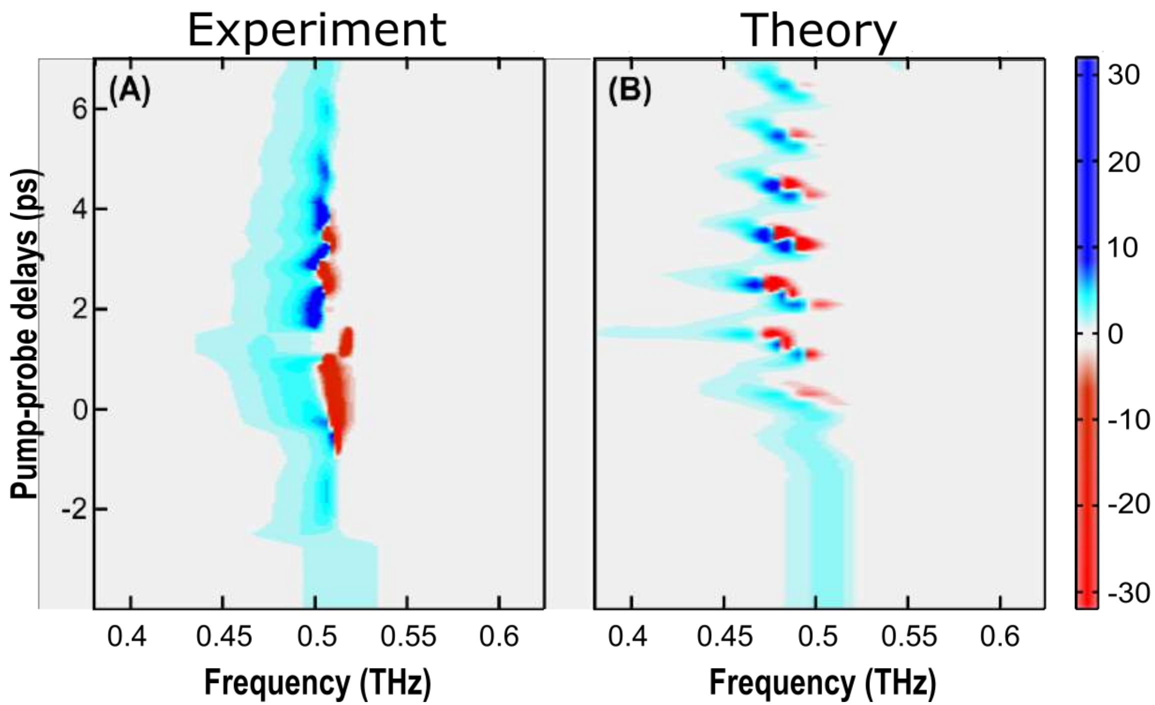
Loss function

$$-\mathrm{Im}\left(\frac{1}{\varepsilon(\omega)}\right)$$



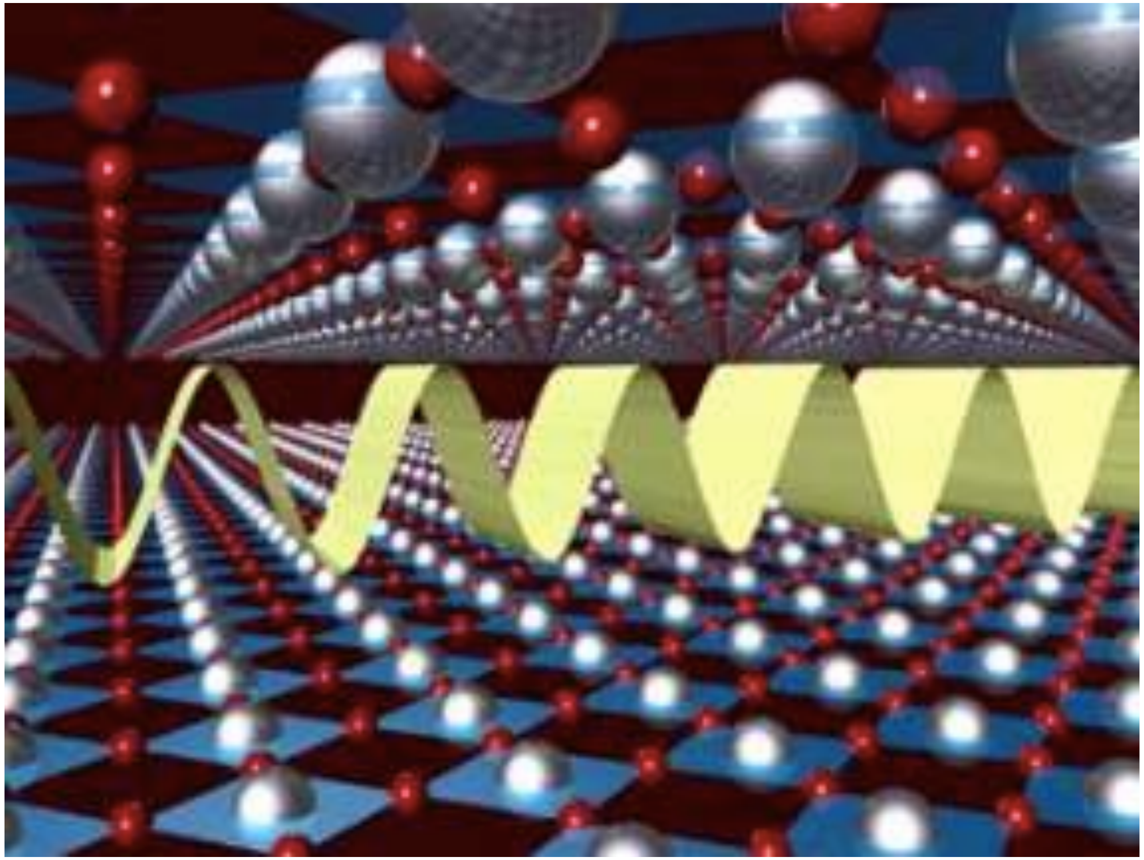
SC fluctuations are amplified or de-amplified

L(ω) oscillates between positive and negative values



Rajasekaran et al., *Nature Physics 12, 1012* (2016)

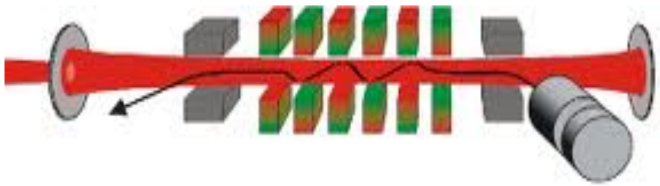
Amplification and de-amplification of SC fluctuations



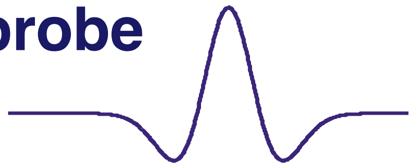
Rajasekaran et al., *Nature Physics 12, 1012* (2016)

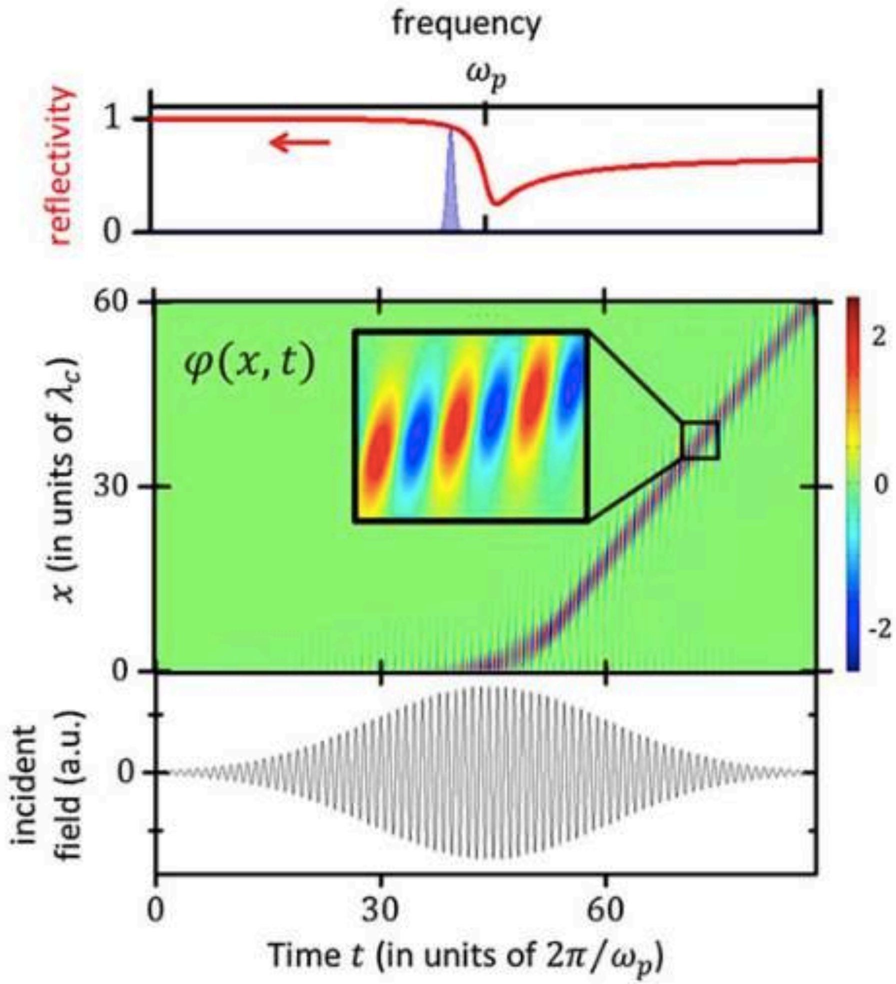
Other work: Travelling Vortex-antivortex pairs

Free Electron Laser - pump



probe

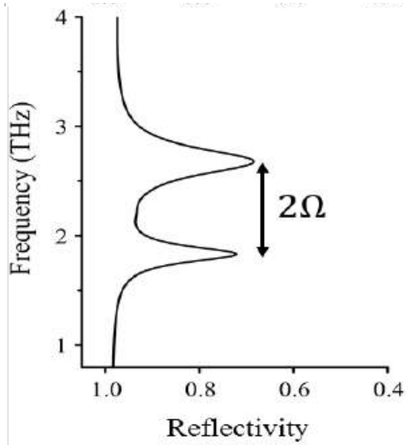


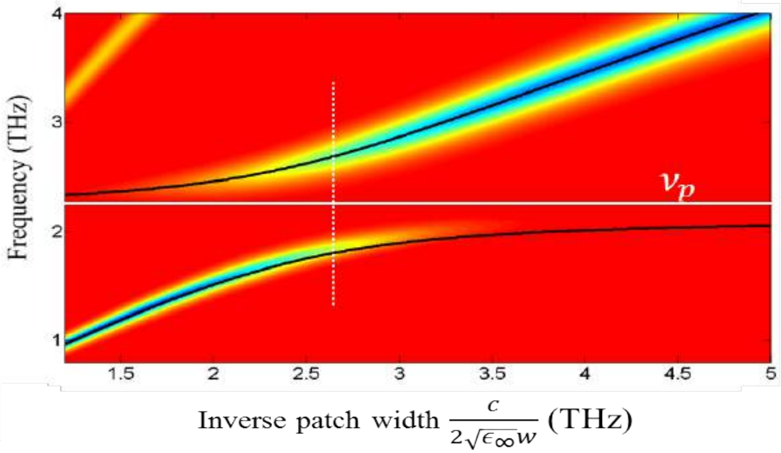


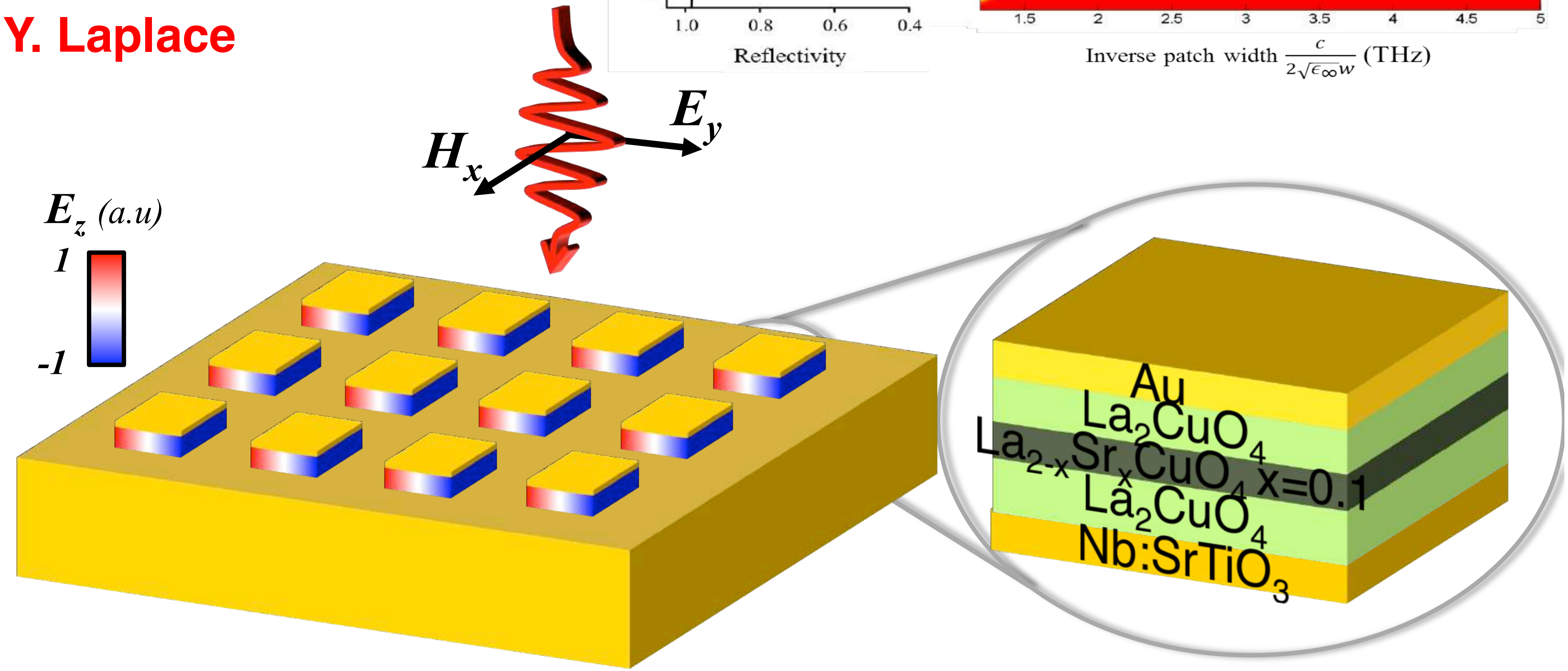
A. Dienst et al. *Nature Materials* 12, 535 (2013)

Ultrastrong coupling between light and superfluid

Y. Laplace



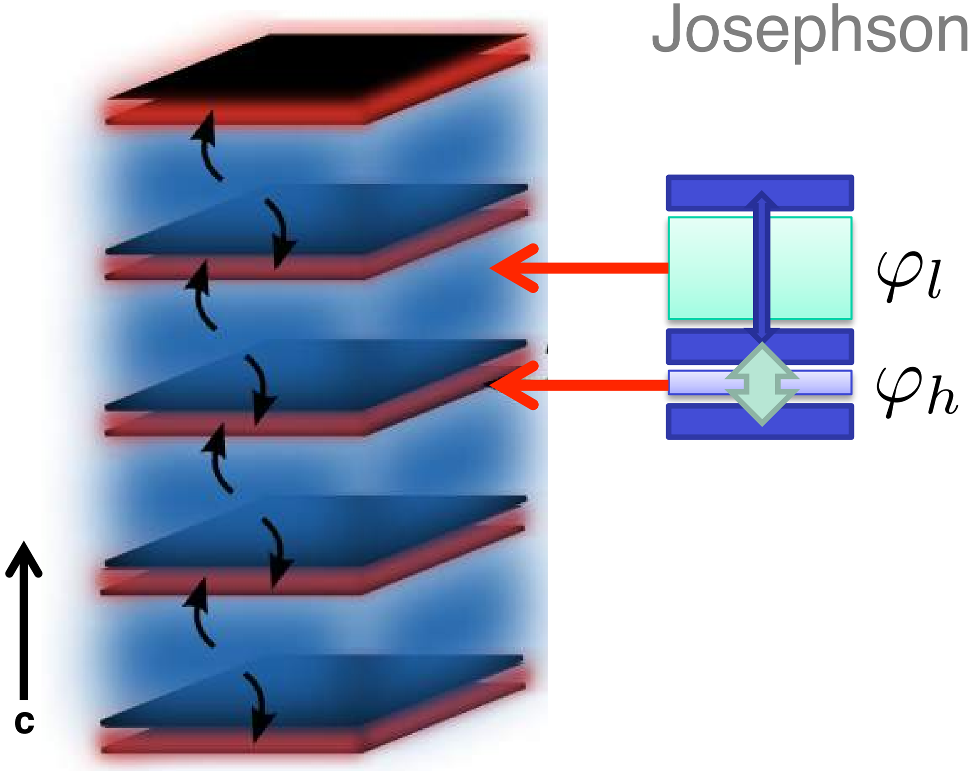


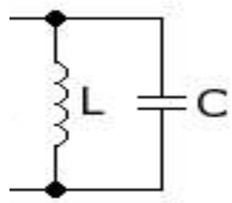


Y. Laplace et al., Phys Rev. B (2016)

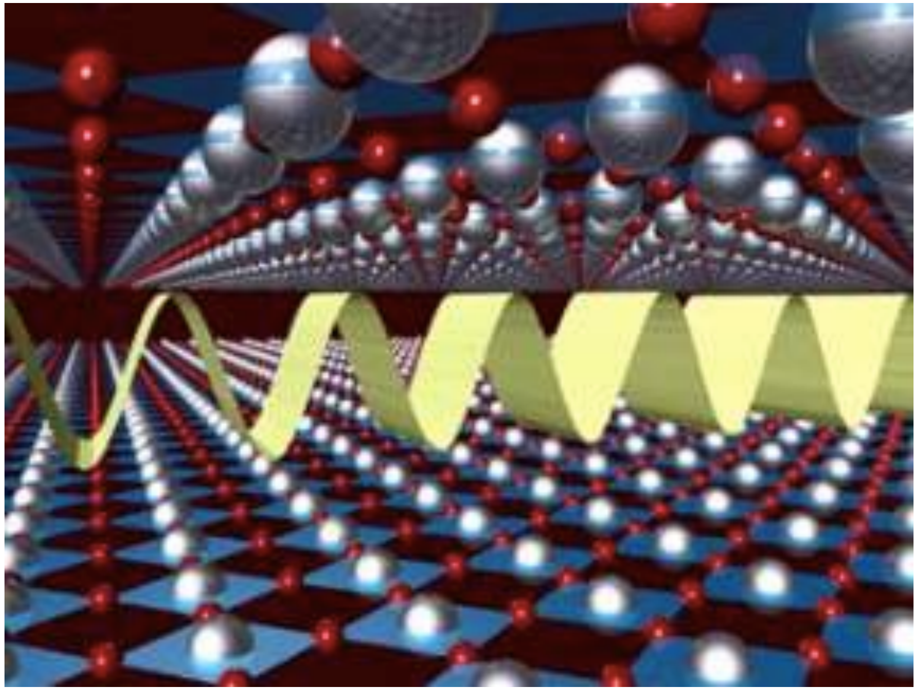
Parametric cooling

YBCO as a stack of Josephson junctions:





Manipulating Superconducting order in cuprates



A. Dienst et al., *Nature Photonics* 5, 485 (2011)

A. Dienst et al. *Nature Materials* 12, 535 (2013)

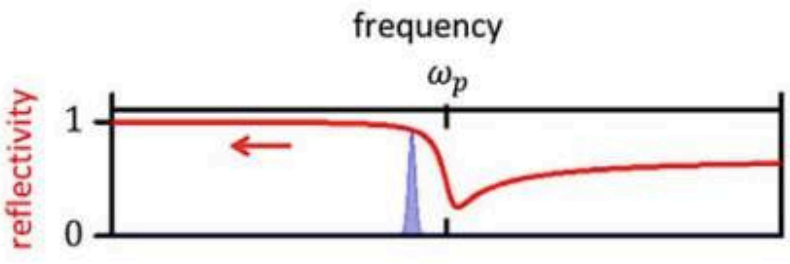
S. Denny, et al. *Phys. Rev. Lett.* 114, 137001 (2015)

J. Okamoto, et al. *Phys. Rev. Lett.* 117, 227001 (2016)

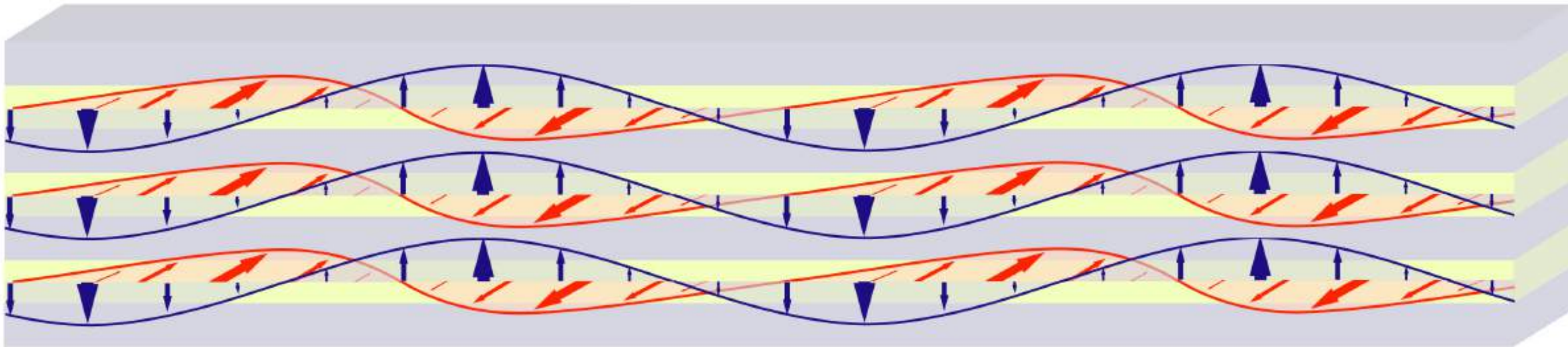
Rajasekaran et al., *Nature Physics 12, 1012* (2016)

Y. Laplace & A. Cavalleri *Advances In Physics X* – 1, 387 (2016)

Theme 3: Understand Nonlinear Propagation



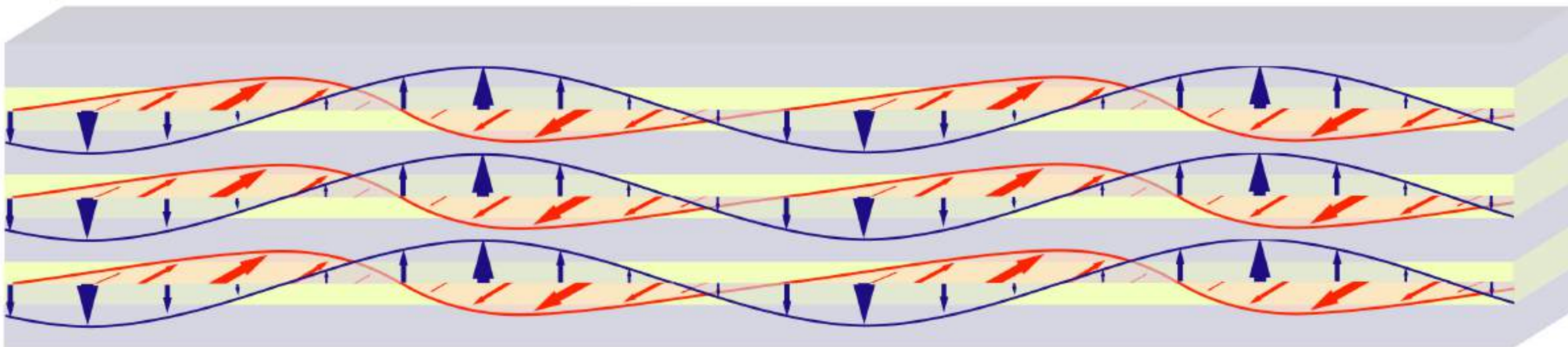
Spectrally pure nonlinear modes



General Case: Nonlinear propagation

Sine Gordon Equation

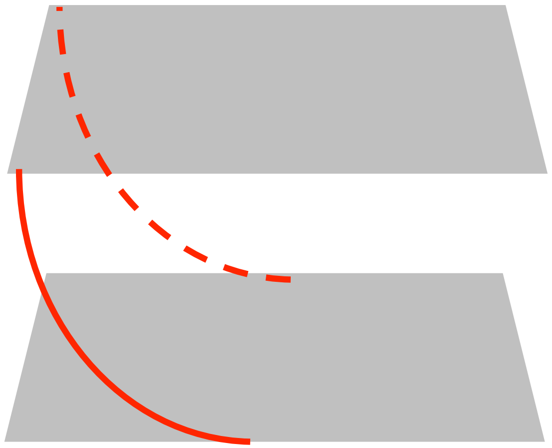
$$\frac{\partial^2 \phi_z(x,t)}{\partial x^2} - \frac{\varepsilon_r}{c^2}\frac{\partial^2 \phi_z(x,t)}{\partial t^2} = \frac{1}{\lambda_J^2}\sin\phi_z(x,t)$$



S. Savel'ev *et al.*, *Nature Physics* 2, 521-525 (2006).

Small magnetic field - no time dependence

$$\frac{\partial^2 \phi_z(x,t)}{\partial x^2} = \frac{1}{\lambda_J^2}\phi_z(x,t)$$



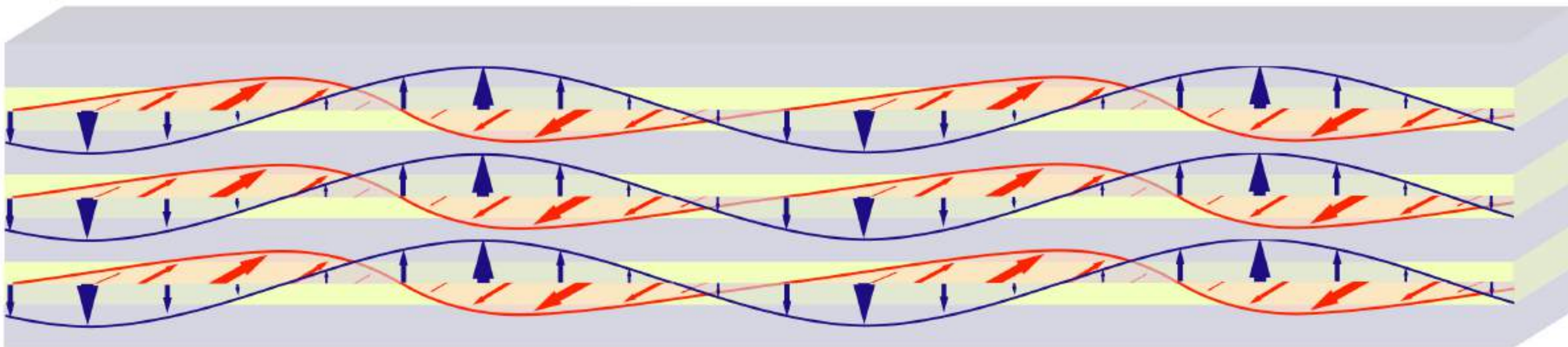
Meissner effect

S. Savel'ev *et al.*, *Nature Physics* 2, 521-525 (2006).

Small Electromagnetic Fields

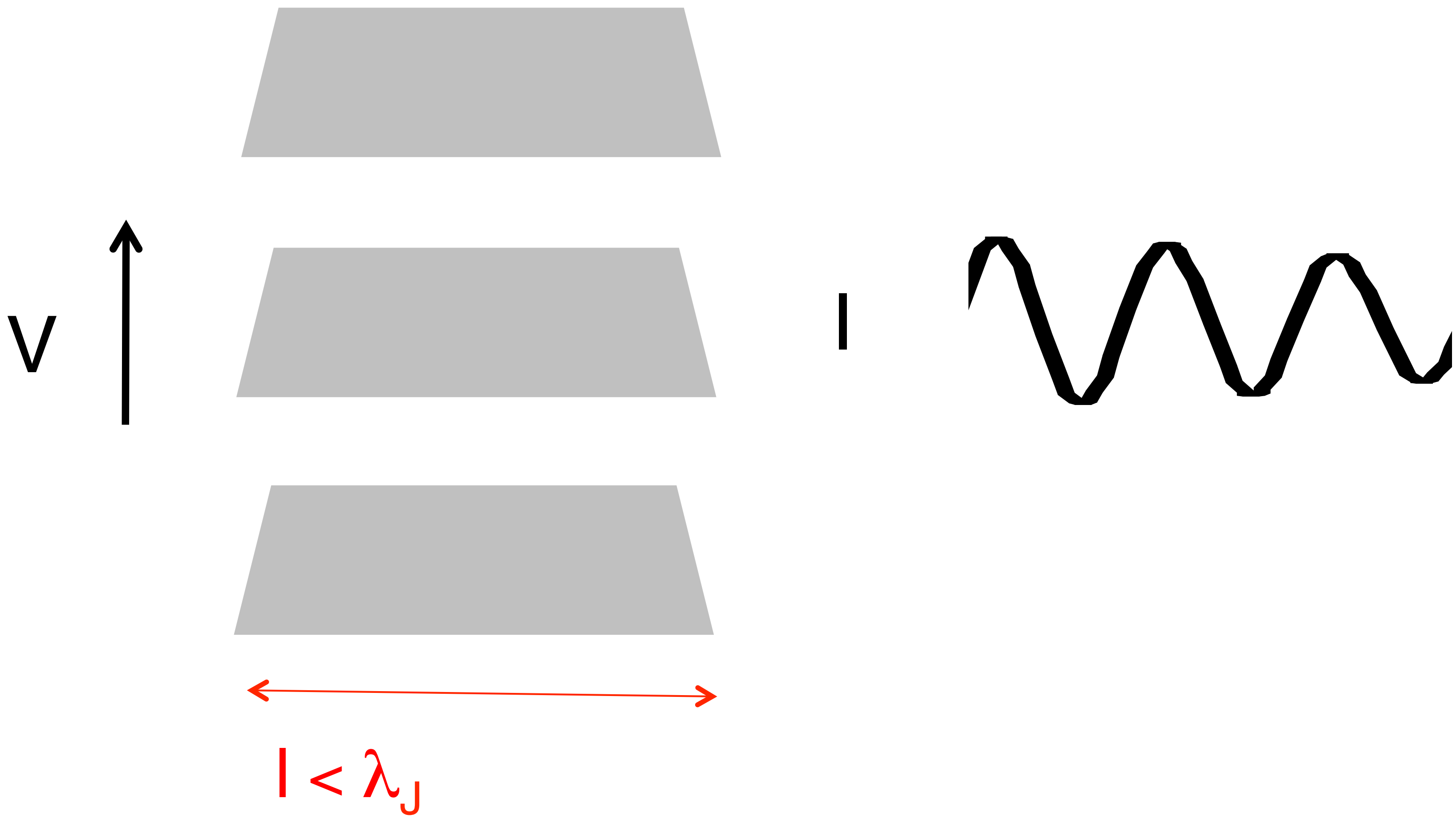
Linear Wave equation

$$\frac{\partial^2 \phi_z(x,t)}{\partial x^2} - \frac{\varepsilon_r}{c^2}\frac{\partial^2 \phi_z(x,t)}{\partial t^2} = \frac{1}{\lambda_J^2}\phi_z(x,t)$$



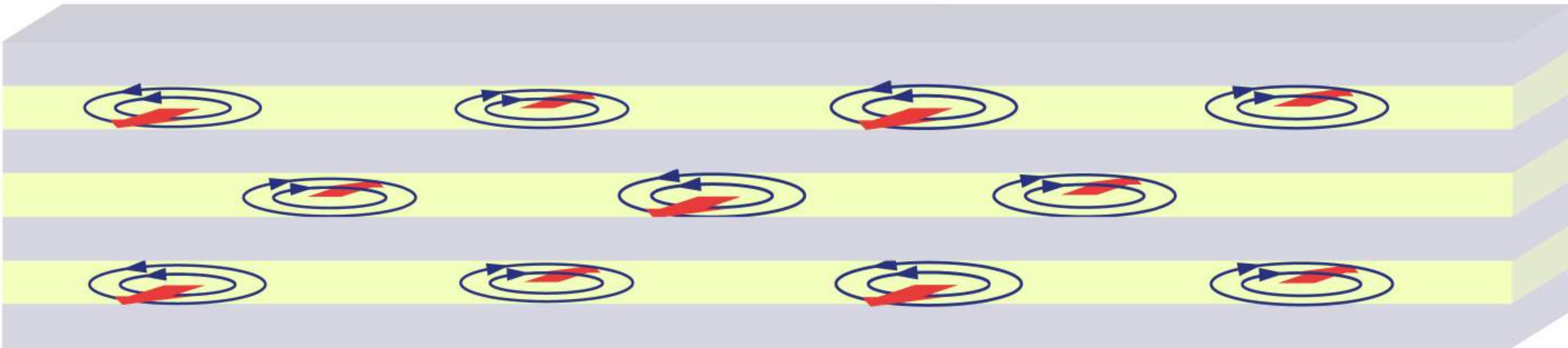
No space dependence – DC Voltage

$$\frac{\varepsilon_r}{c^2}\frac{\partial^2\phi_z(t)}{\partial t^2} = \frac{1}{\lambda_J^2}\sin\phi_z(t)$$



High Magnetic fields - vortex lattice

$$\frac{\partial^2 \phi_z(x,t)}{\partial x^2} = \frac{1}{\lambda_J^2} \sin \phi_z(x,t)$$



General Case: Nonlinear propagation

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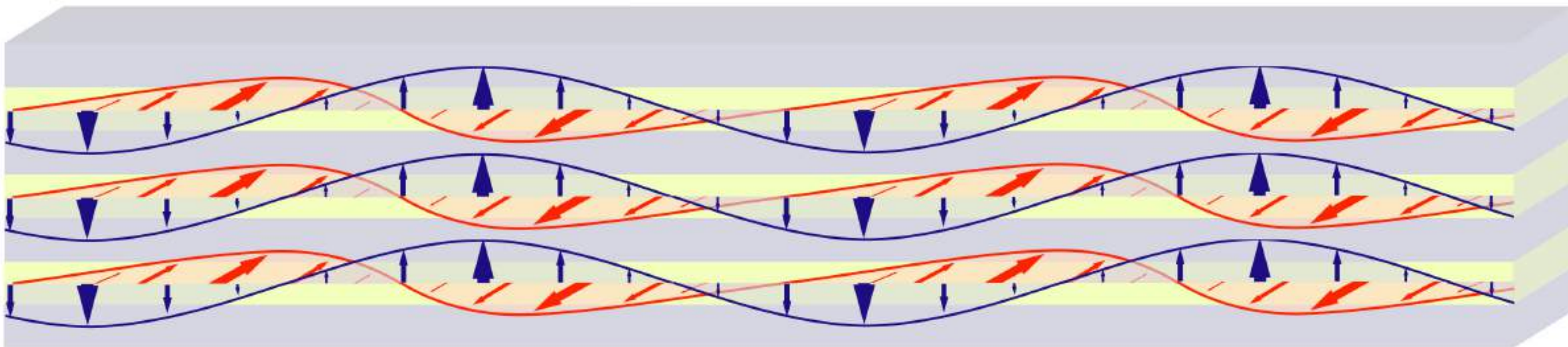
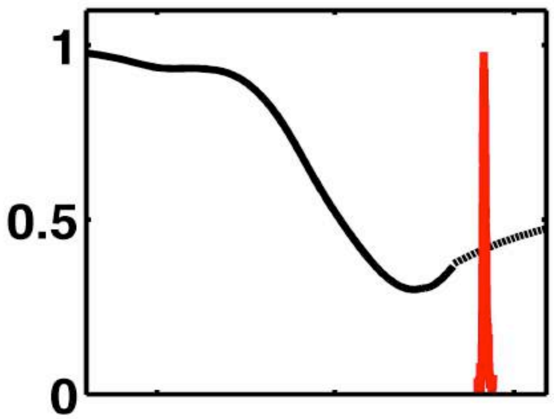
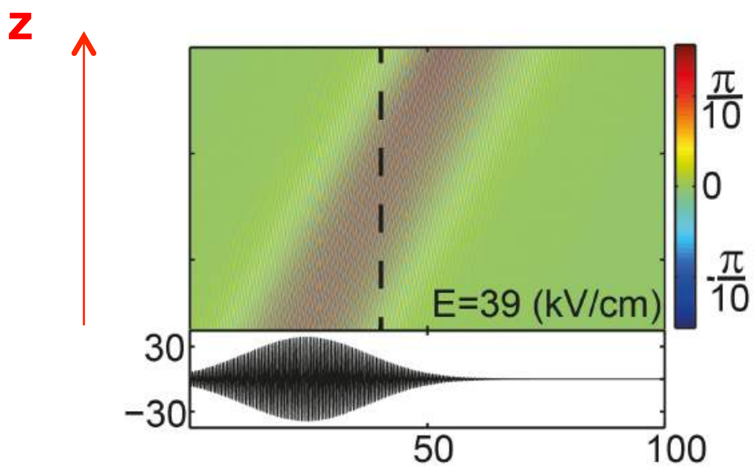
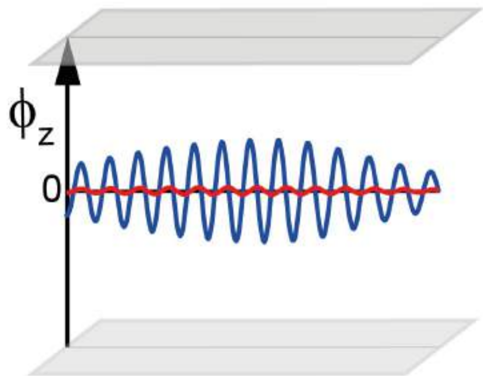


S. Savel'ev *et al.*, *Nature Physics* 2, 521-525 (2006).

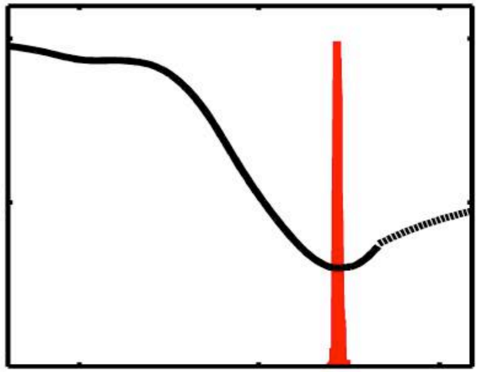
Simulations: 1.1 ω_{JPR}

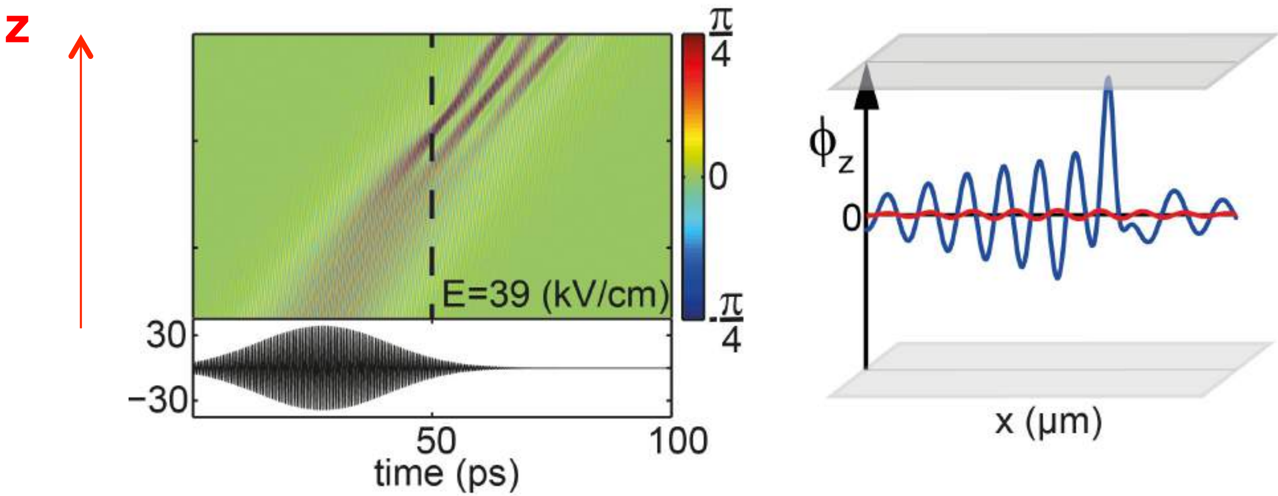




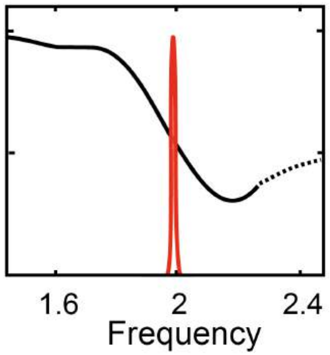


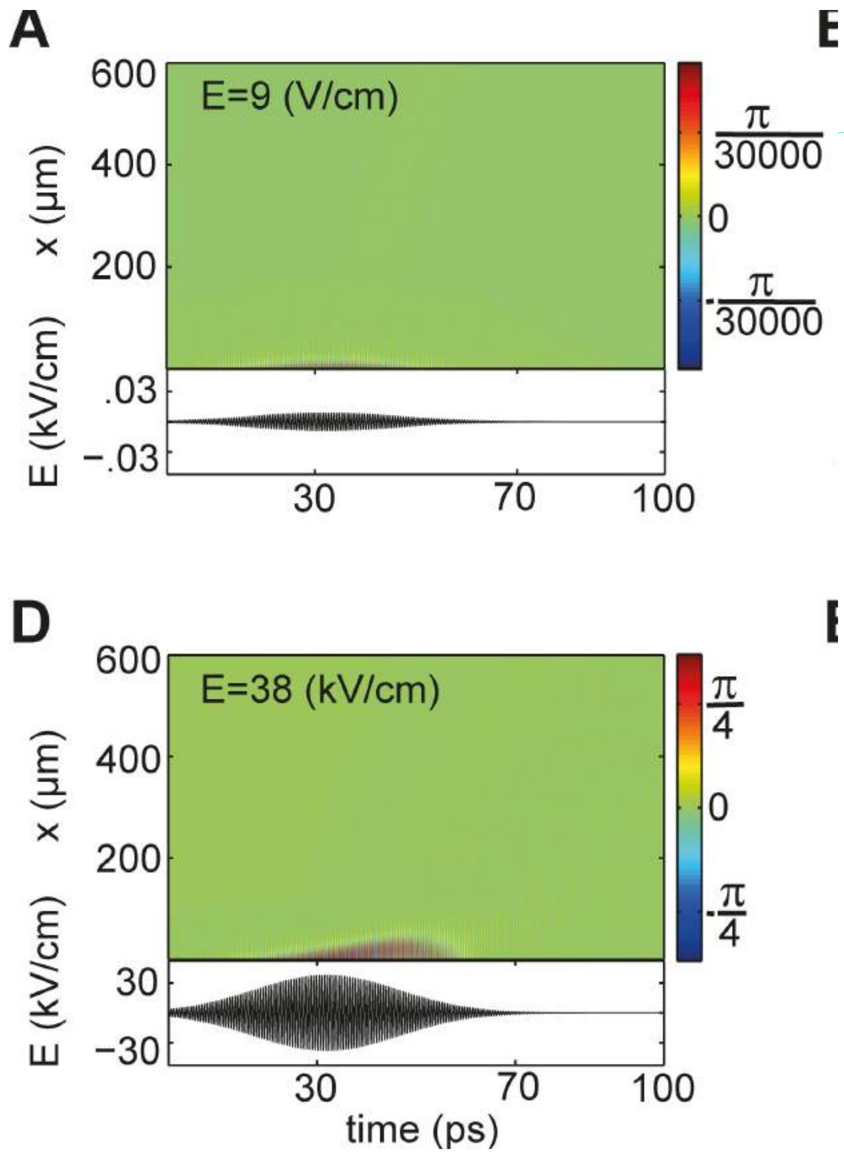
Simulations: 1.05 ω_{JPR}



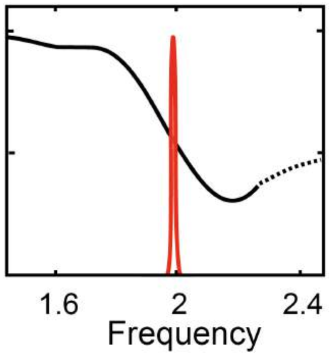


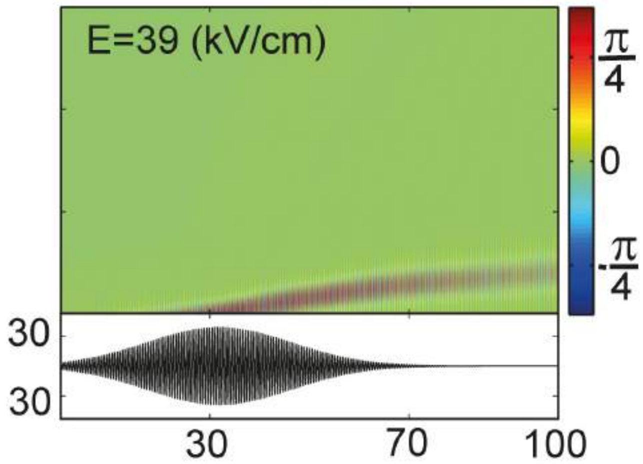
Simulations – below the edge: 0.97 ω_{JPR}

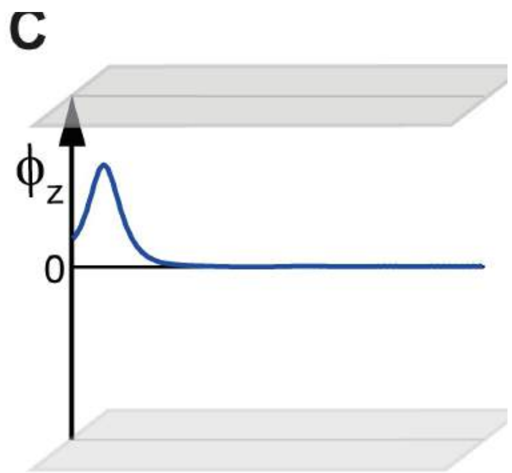


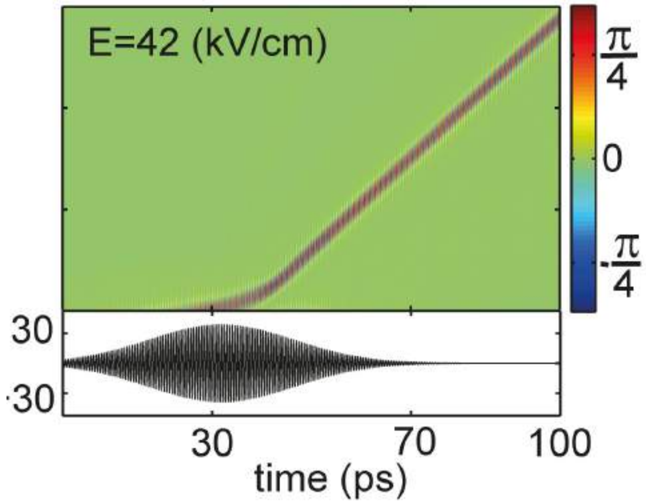


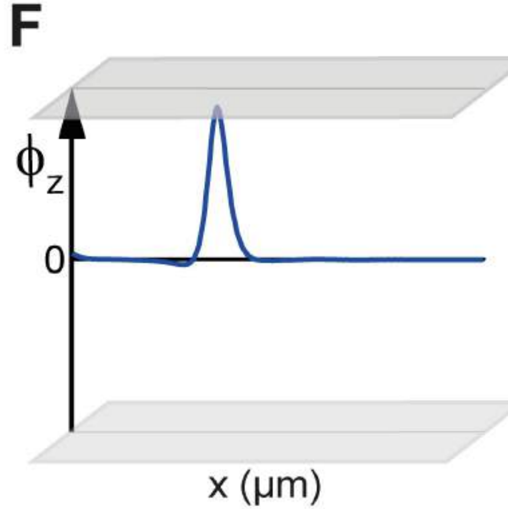
Simulations – high fields : 0.97 ω_{JPR}



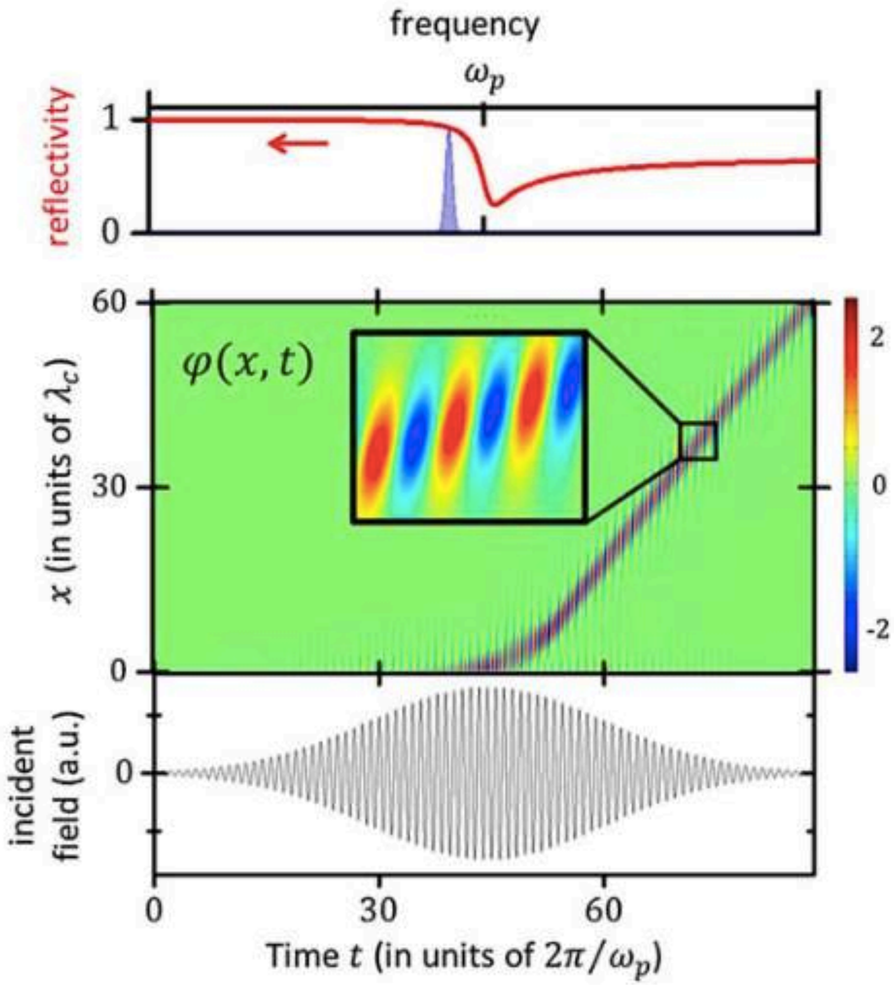




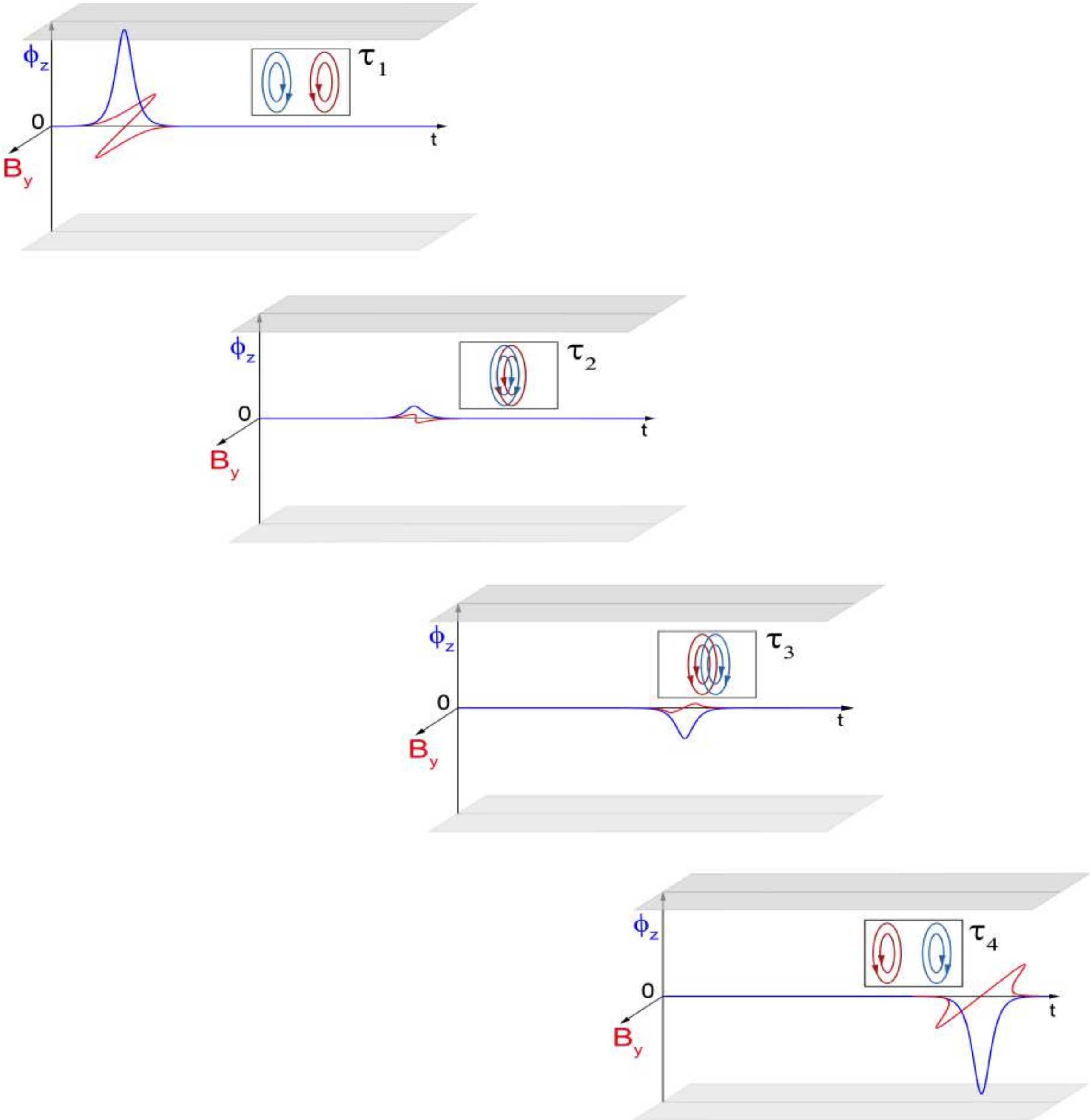




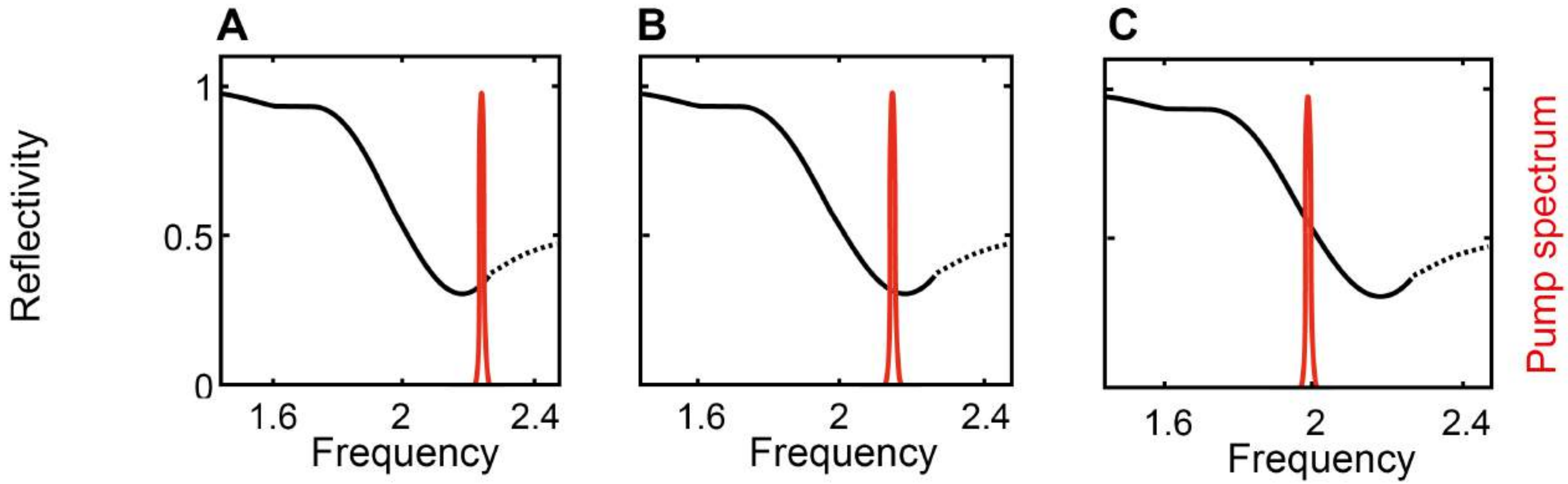
Nonlinear Propagation below the edge



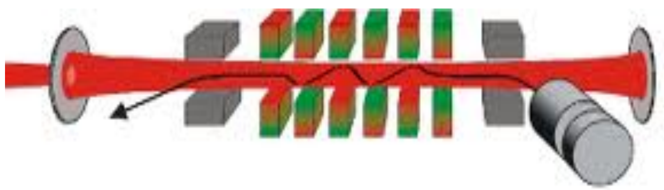
A travelling vortex-antivortex pair



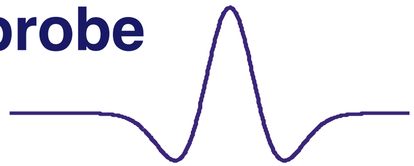
Experimental realization: narrowband pump



Free Electron Laser - pump

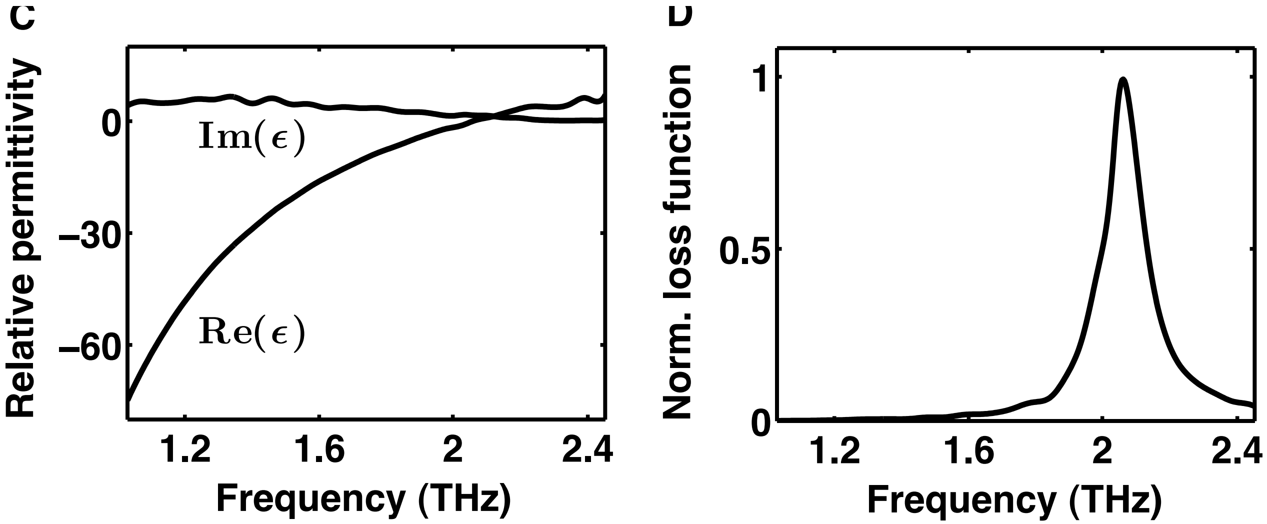


probe

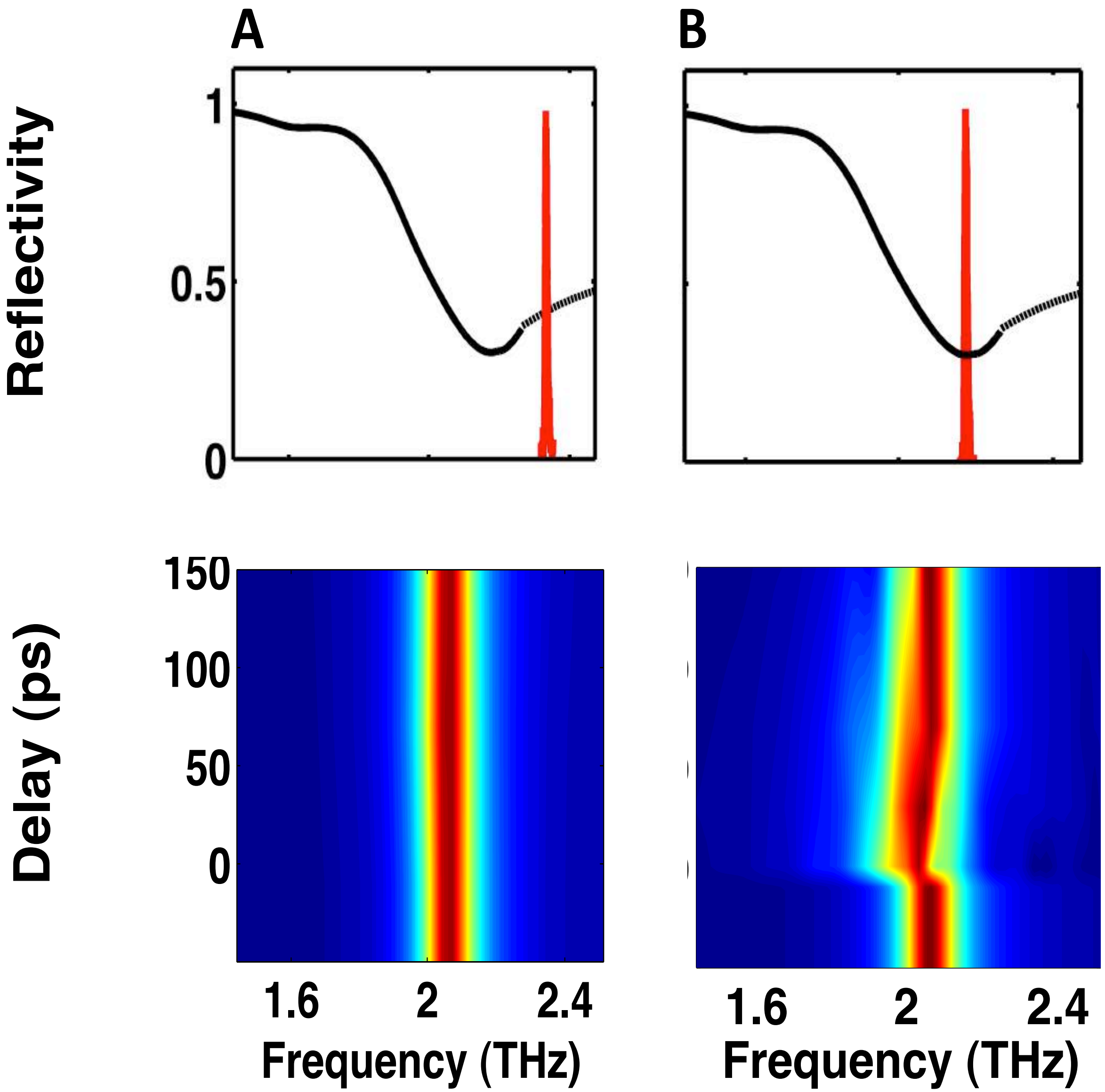


Loss function

$$-\mathrm{Im}\left(\frac{1}{\varepsilon(\omega)}\right)$$

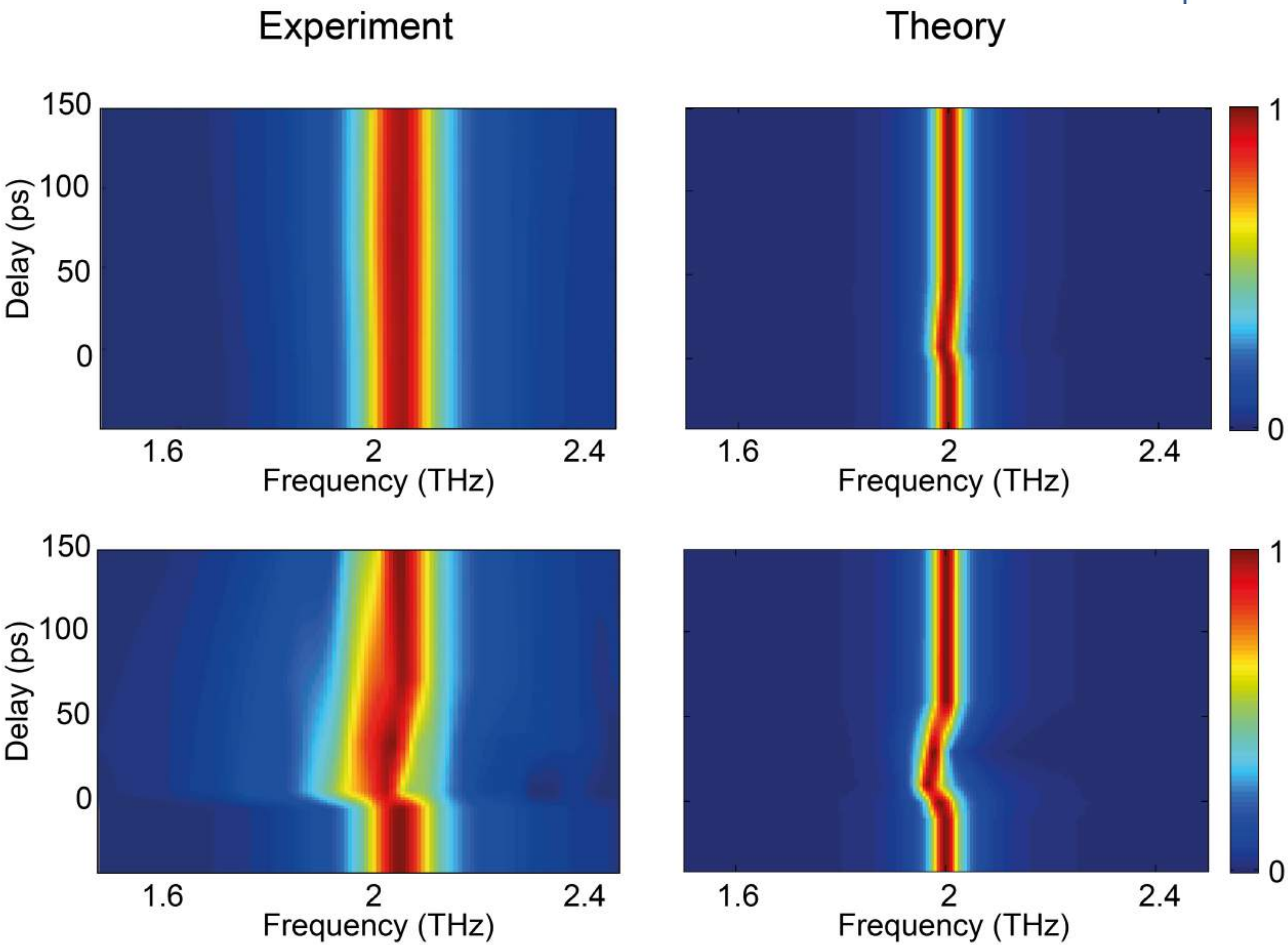


Experiments: 1.1 ω_{JPR} and 1.05 ω_{JPR}

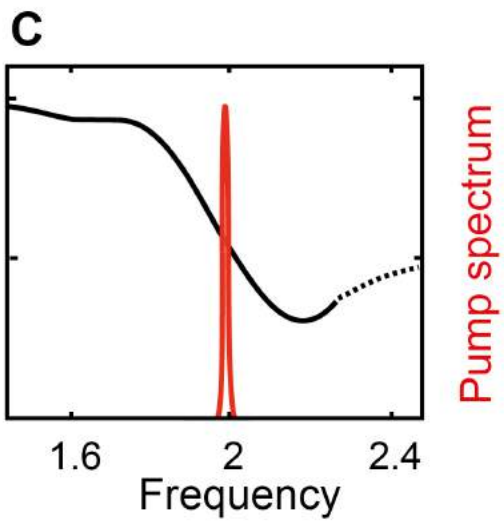


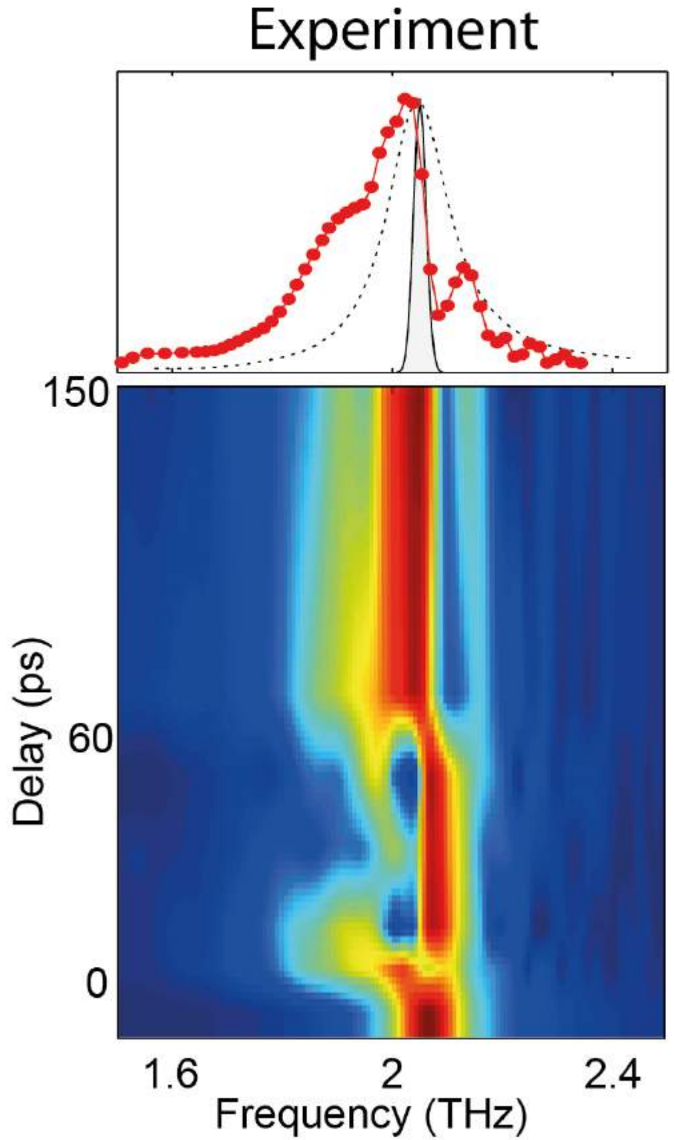
A. Dienst et al. *Nature Materials* 12, 535 (2013)

Nonlinear THz response: light induced transparency

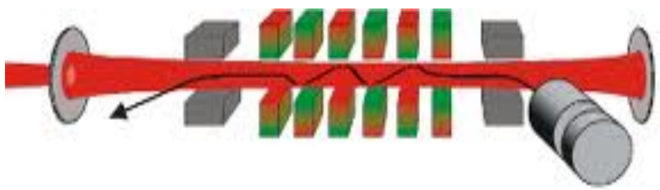


Experimental realization: narrowband pump

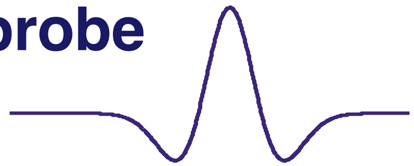




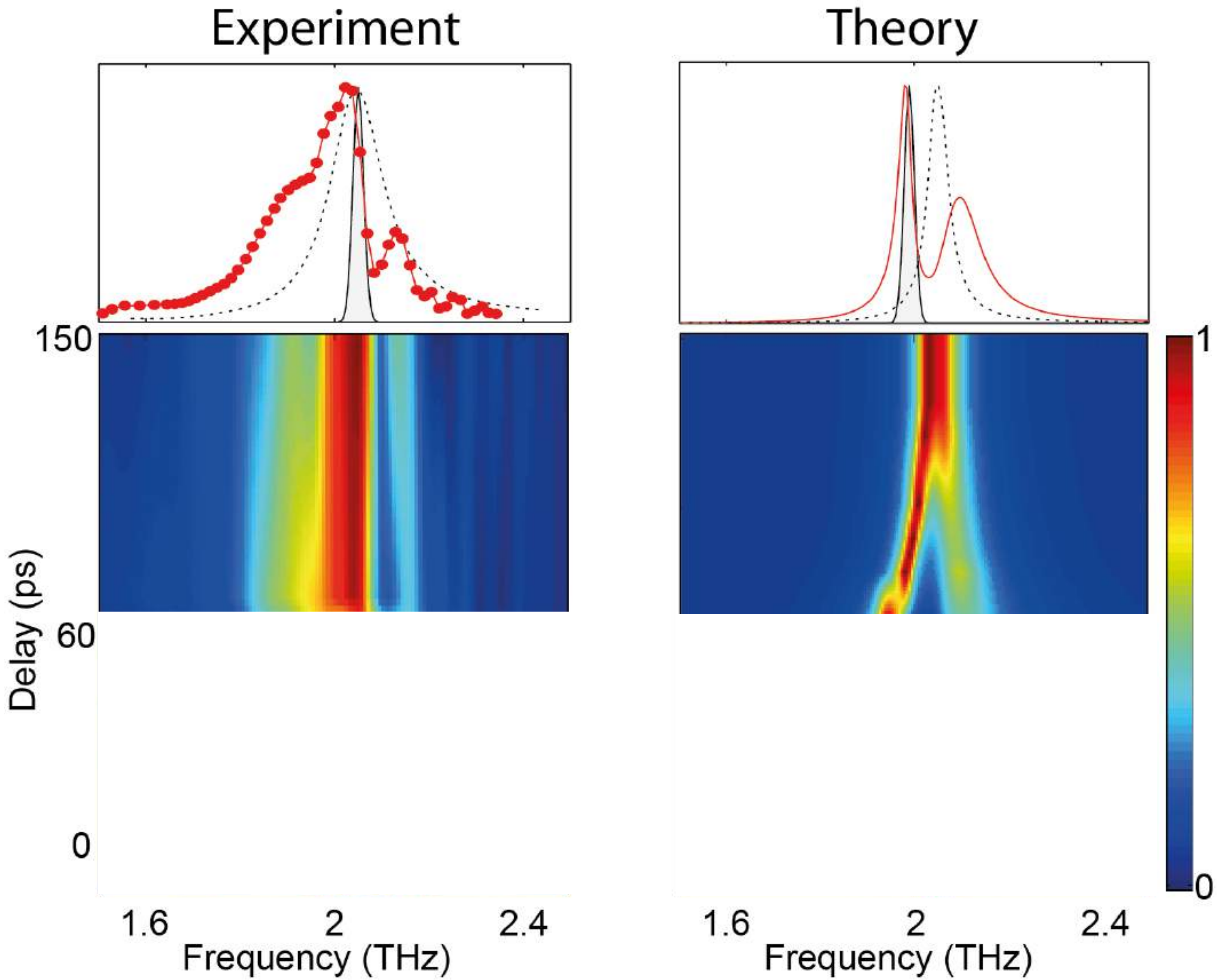
Free Electron Laser - pump



probe

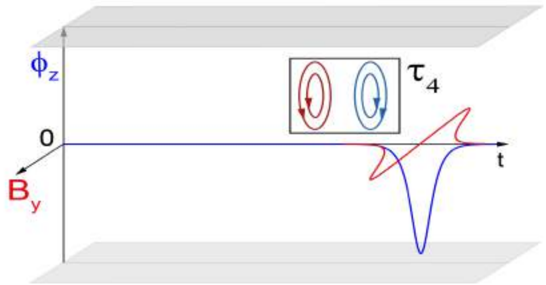


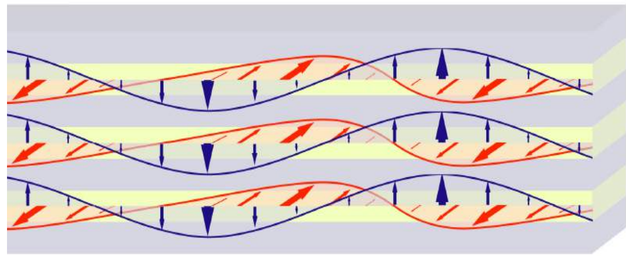
At resonance: Transparency window

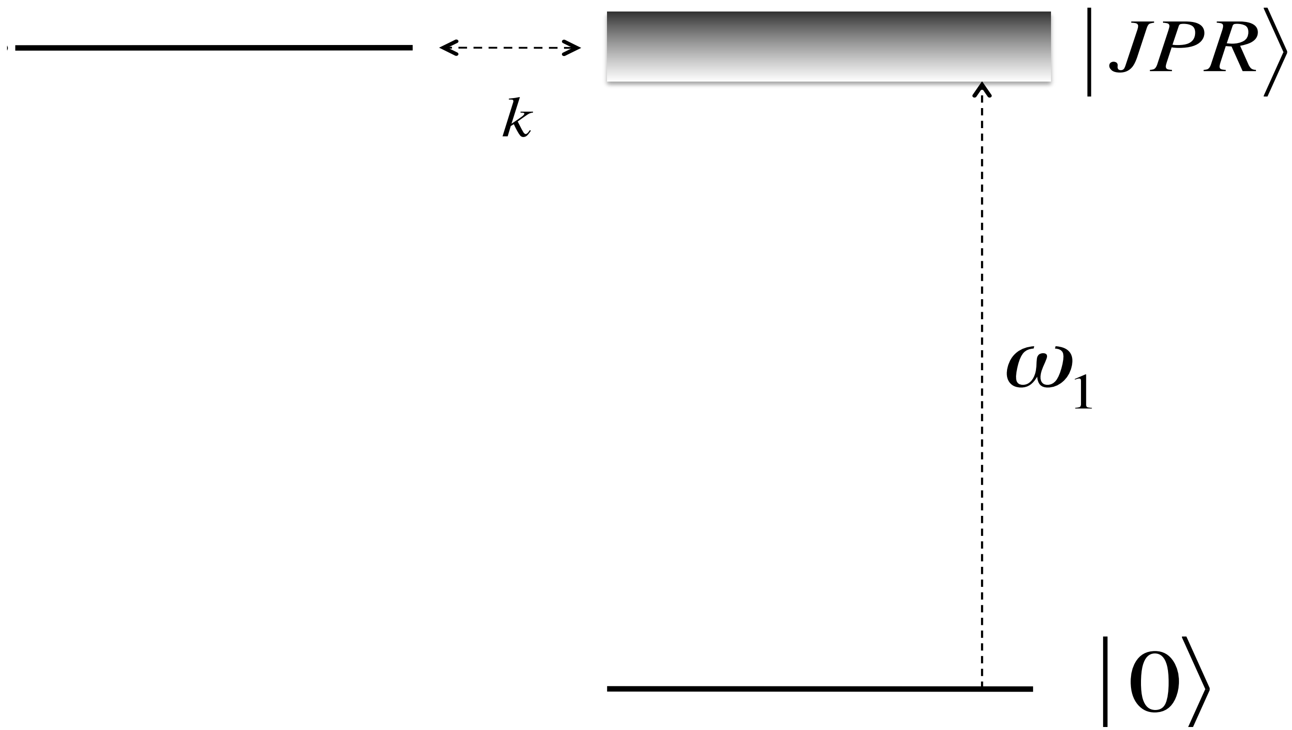


A. Dienst et al. *Nature Materials* 12, 535 (2013)

Linear Waves interfere with Josephson Solitons







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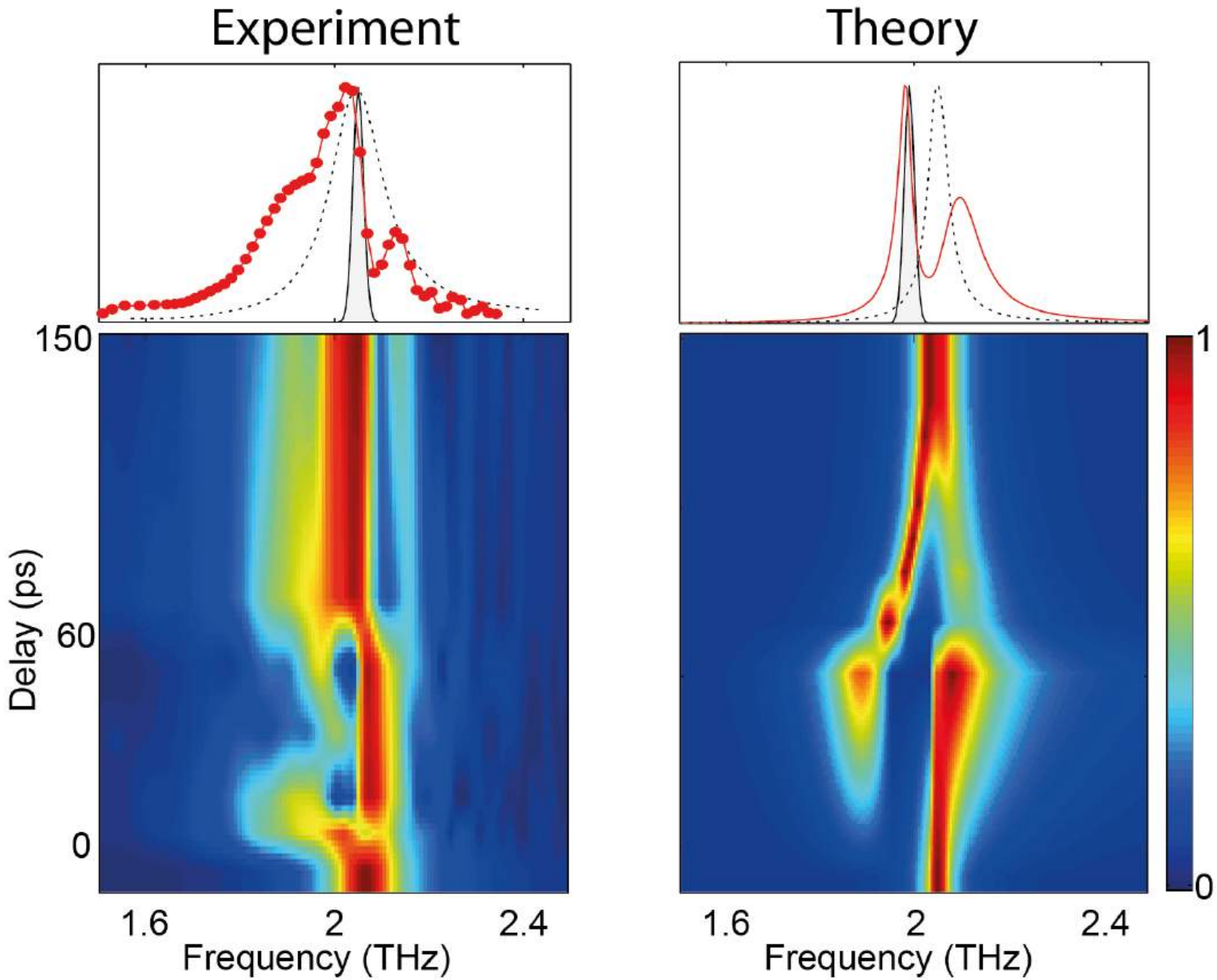
At resonance: Transparency window



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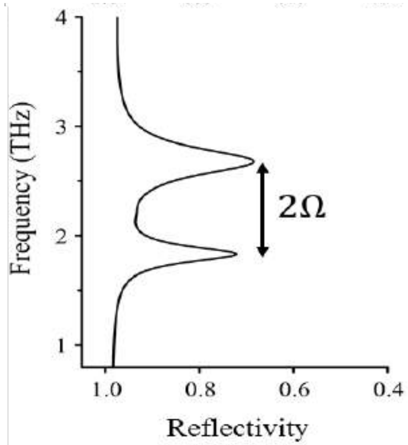
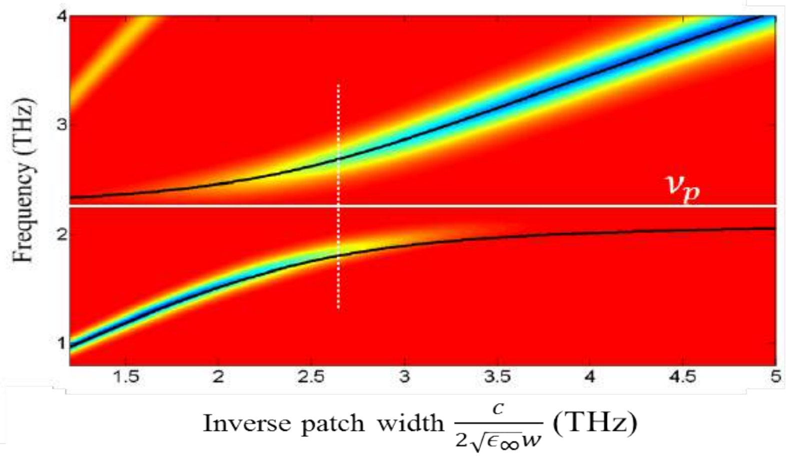
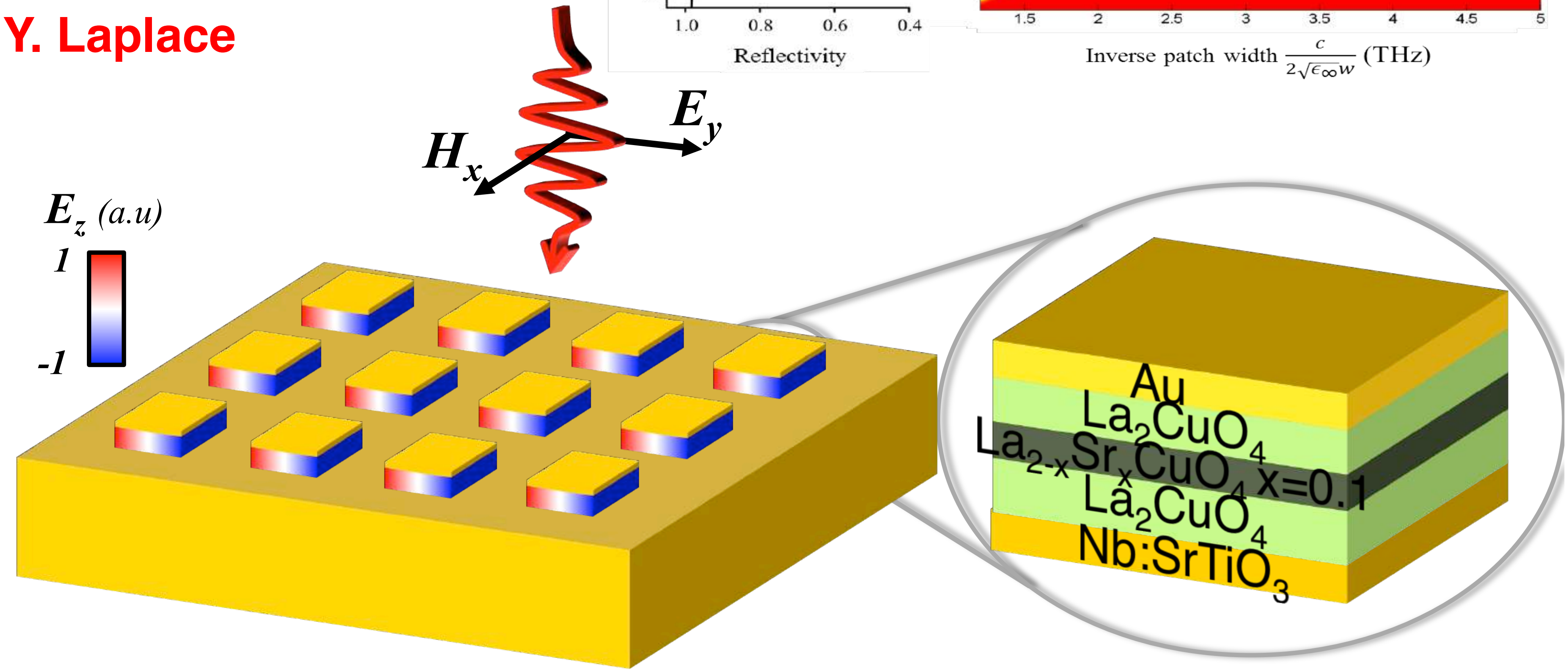
Ultrastrong coupling between light and superfluid

Y. Laplace



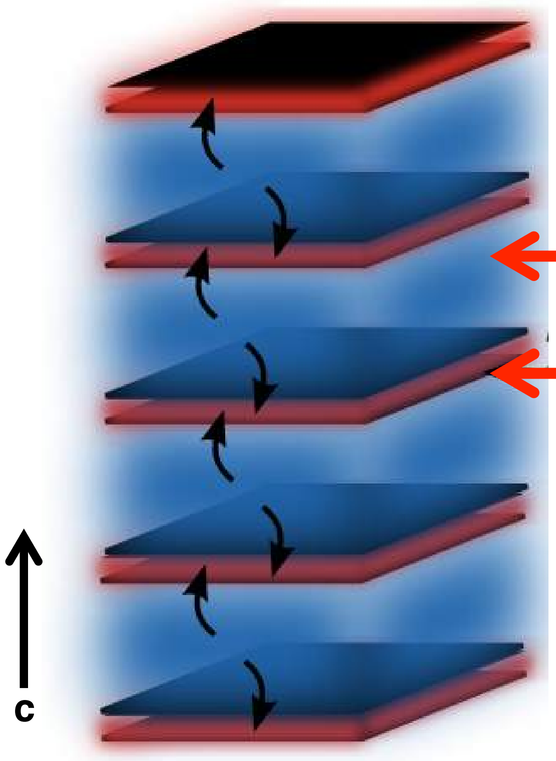


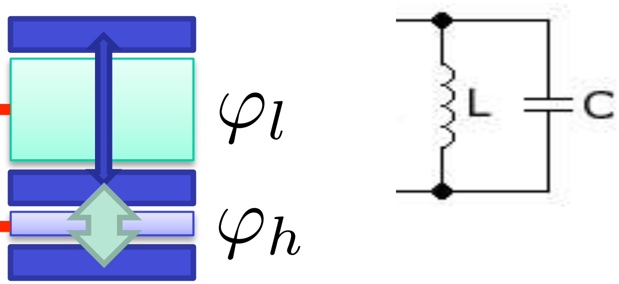


Y. Laplace et al., Phys Rev. B (2016)

Parametric cooling

YBCO as a stack of
Josephson junctions:

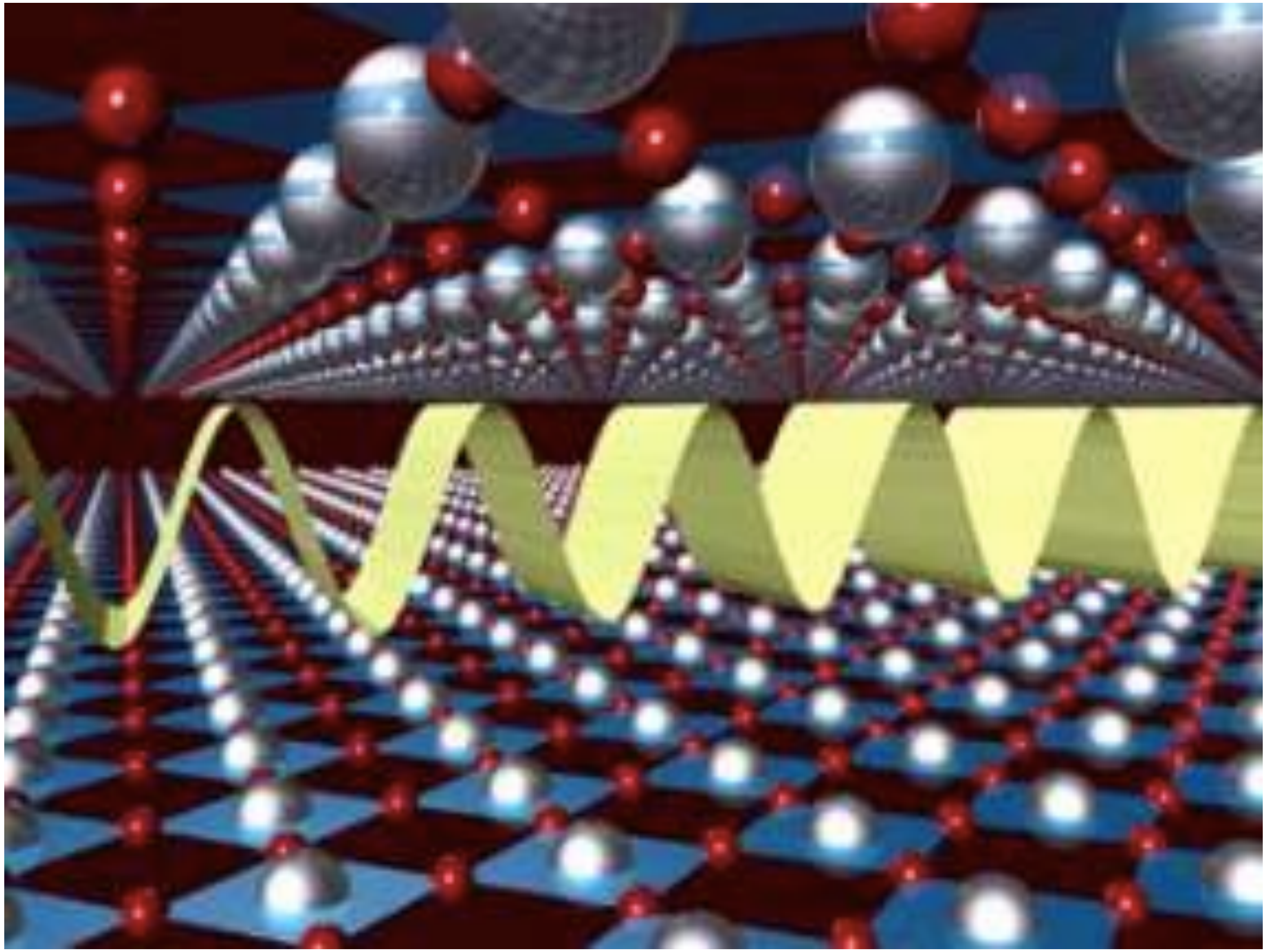




S. Denny, S. Clark. A. Cavalleri, D. Jaksch *Phys. Rev. Lett.* 114, 137001 (2015)

J. Okamoto, A. Cavalleri, L. Mathey *Phys. Rev. Lett.* 117, 227001 (2016)

Manipulating Superconducting order in cuprates



Y. Laplace & A. Cavalleri *Advances In Physics X* 1, 387 (2016)