

Non-linear optics with collective excitations and photoinduced superconductivity

Marios Michael Harvard University

Collaborators Eugene Demler (Harvard), Alex von Hoegen (MPSD), Michael Fechner (MPSD), Michael Forst (MPSD), Andrea Cavalleri (MPSD)

Work in progress Leonid Glazman (Yale University), Pavel Dolgirev (Harvard)

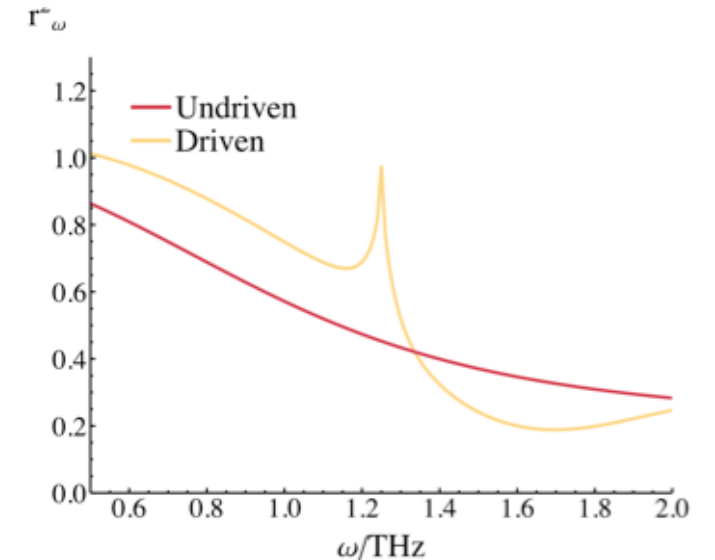
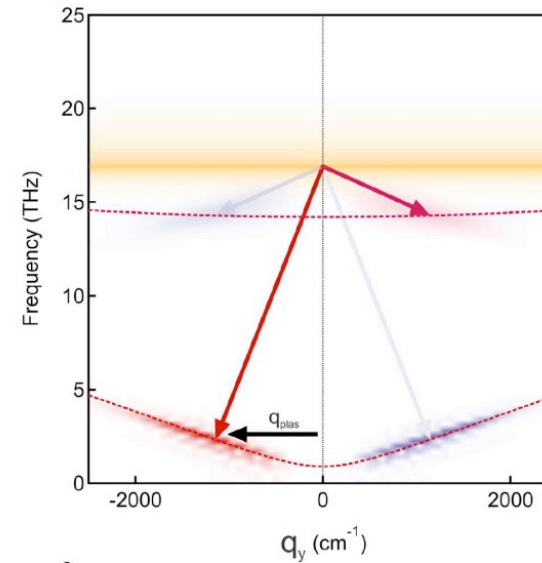
Harvard-MIT



\$\$ NSF, AFOSR MURI,
DARPA DRINQS

Outline

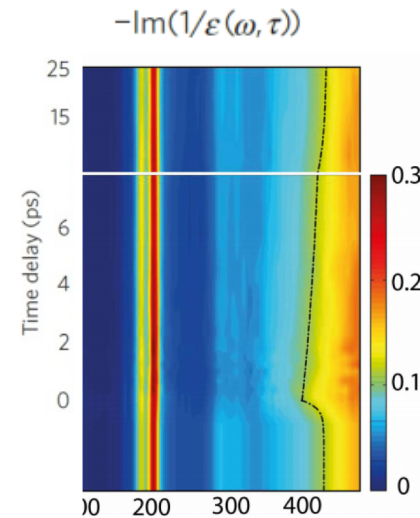
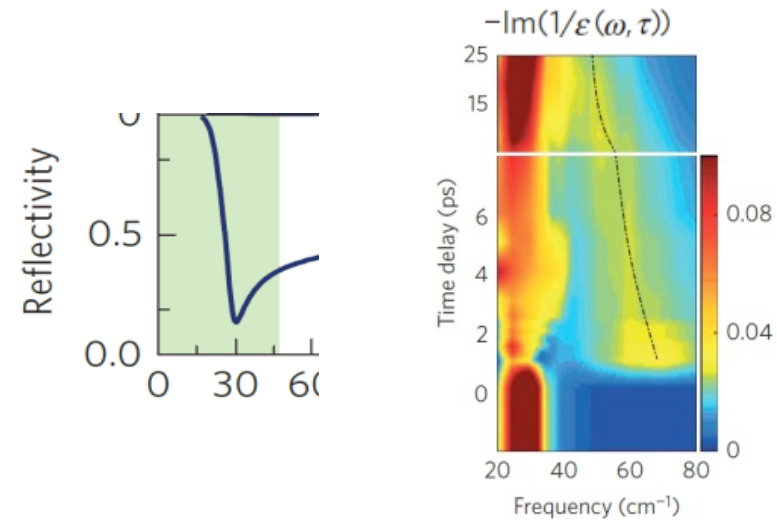
1. Motivation
2. Josephson Plasmons in YBCO
3. Phonon-plasmon interaction and parametric instability
4. Mechanism of previous signatures of photoinduced superconductivity:
 - Below T_c :
Photoinduced reflection peak near lower plasmon edge and blue shift.
Red shift of upper plasmon edge.
 - Above T_c : photoinduced blue shifted plasmon edge.



Experimental facts in pump and probe YBCO

1. Below T_c :

- Higher energy peak appears near lower Josephson edge
- Blue shift of the lower JP edge.
- Red shift of the upper JP edge.



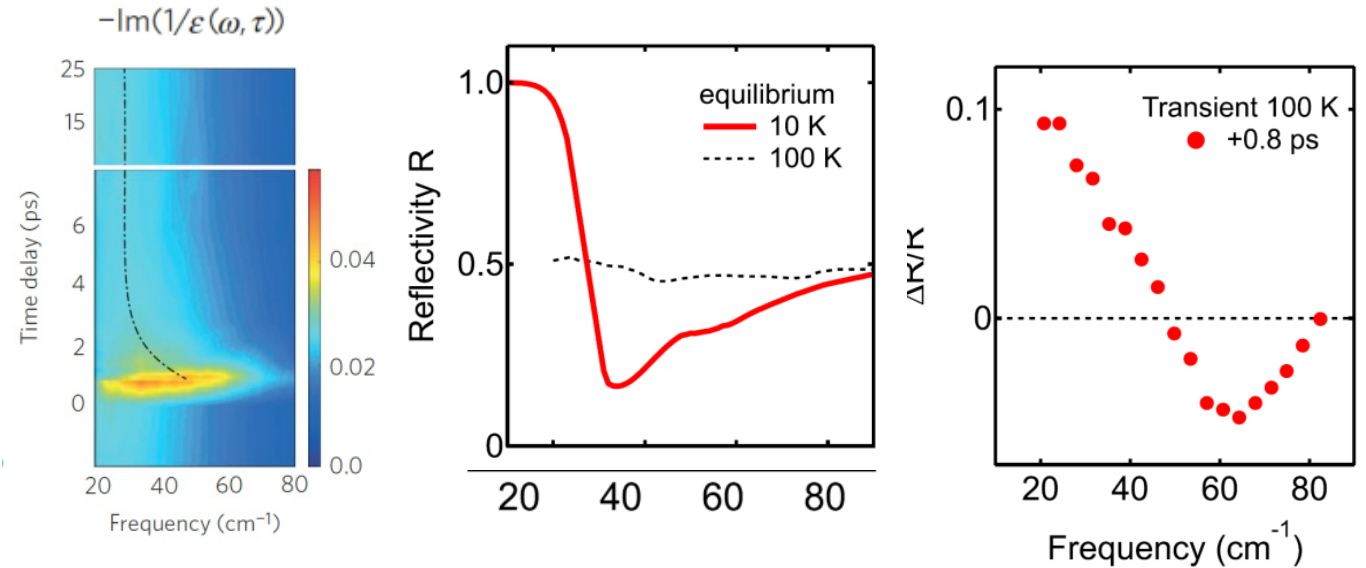
Hu et al., Nature Materials 13:705 (2013)

Experimental facts in pump and probe YBCO

2. Above T_c :

Photoinduced Josephson plasmon edge

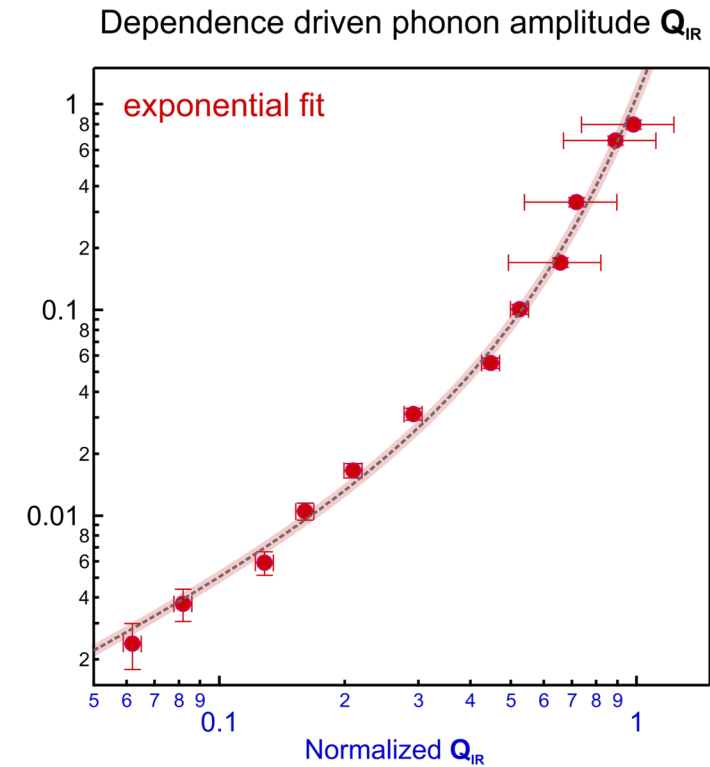
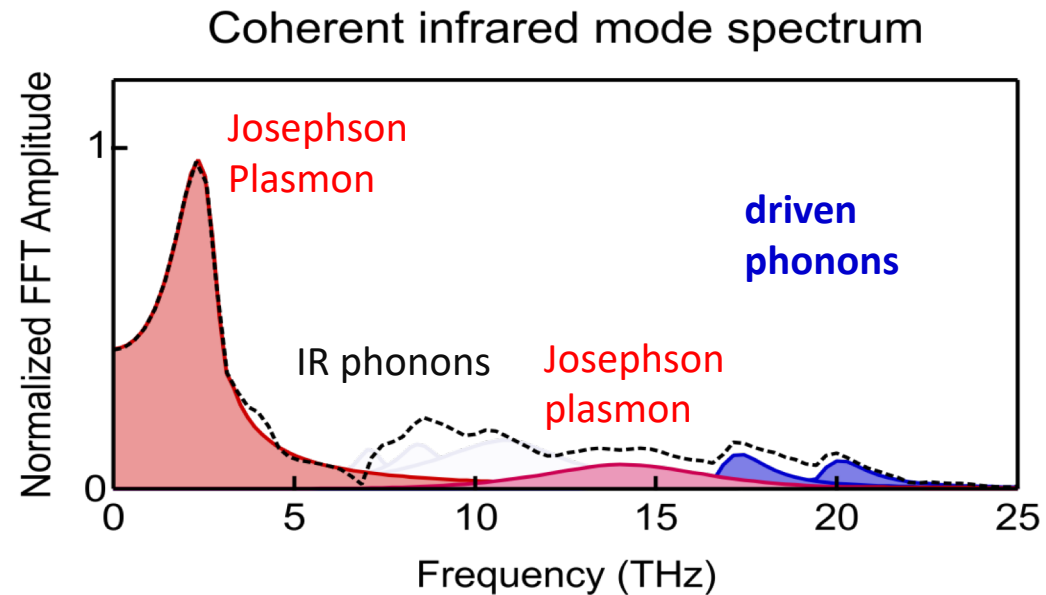
Renormalization of the plasmon frequency.



Mankowski et al., Structural Dynamics 4:044007 (2017)

Experimental facts in pump and probe YBCO

3. Parametric generation of pair of Josephson plasmons:



A. Von Högen et al. forthcoming

Theory of Josephson plasmons

Superconducting bilayer



$$\phi = \phi_1 - \phi_2$$

$$\rho = \rho_1 - \rho_2$$

$$V = \mu_1 - \mu_2$$

$$\frac{\partial \phi}{\partial t} = V = \Gamma \rho$$

Josephson relation

$$\frac{\partial \rho}{\partial t} + J_{\perp} + \vec{\nabla}_{\parallel} \vec{j}_{\parallel} = 0$$

Continuity equation

$$J_{\perp} = J_c \sin \phi$$

Interlayer Josephson current

$$\vec{j}_{\parallel} = \rho_s \vec{\nabla}_{\parallel} \phi$$

In-plane superfluid current

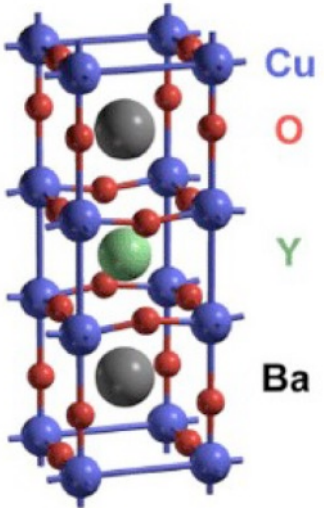
Neglecting in-plane variations

$$\frac{d^2 \phi}{dt^2} = \Gamma \frac{d\rho}{dt} = -\Gamma J_{\perp} = -\Gamma J_c \sin \phi$$

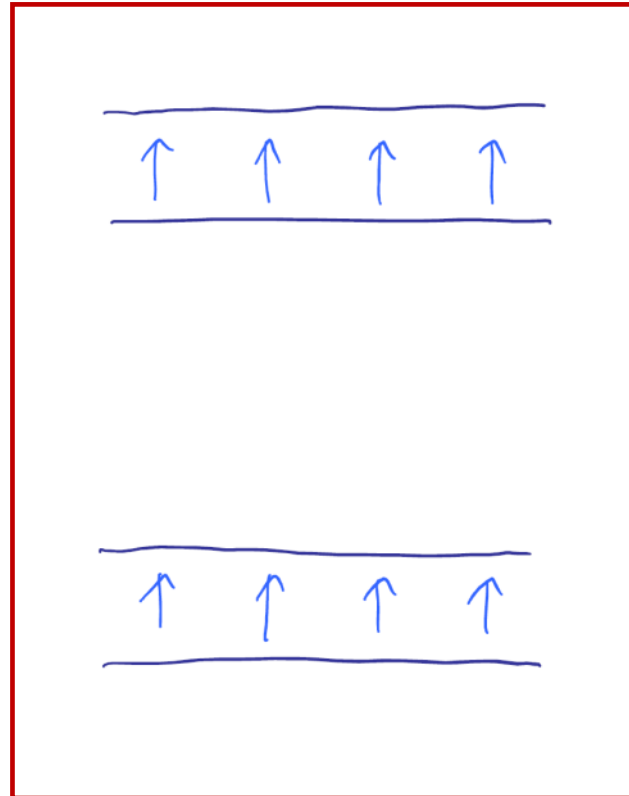
$$\omega_J^2 = \Gamma J_c$$

Josephson plasmons in bilayer YBCO

$\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$
(YBCO)

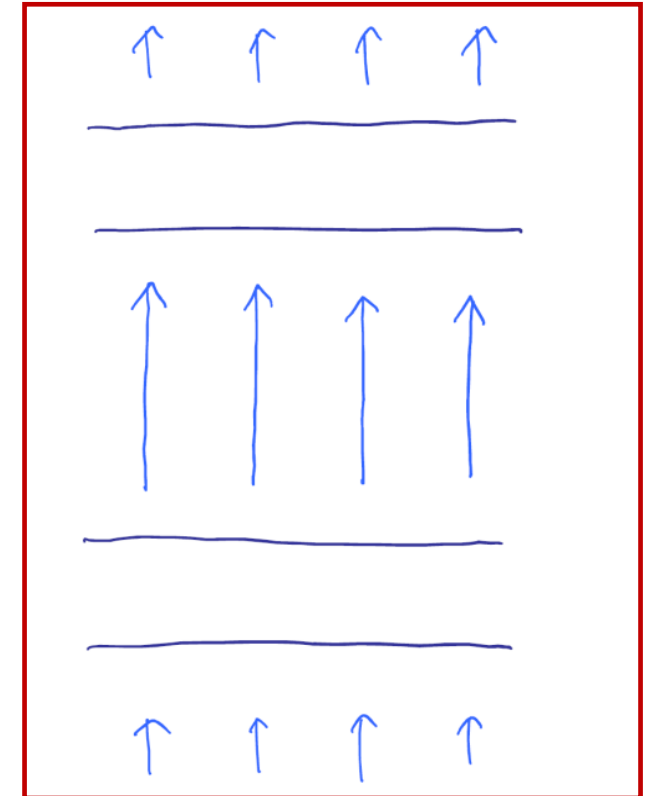


Higher energy
Josephson plasmon



14 THz

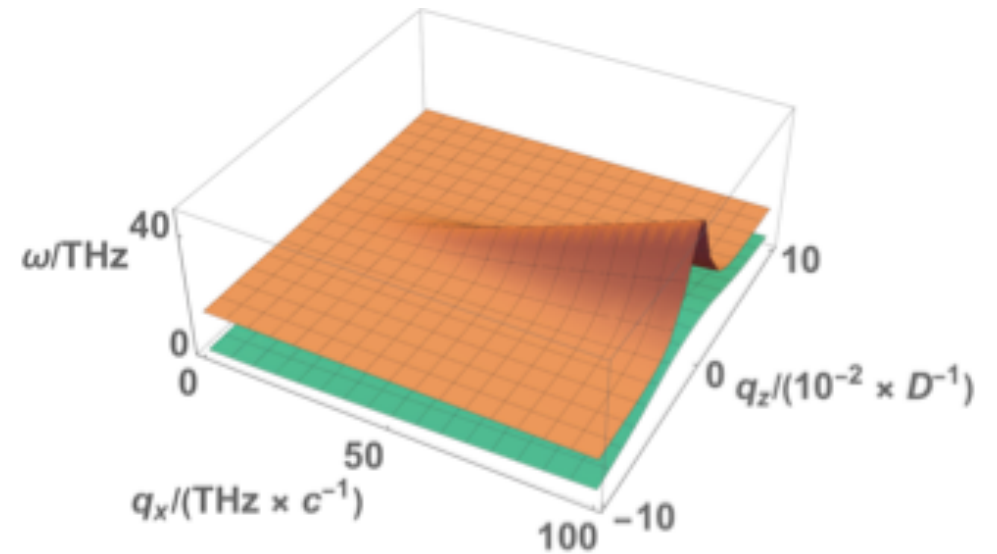
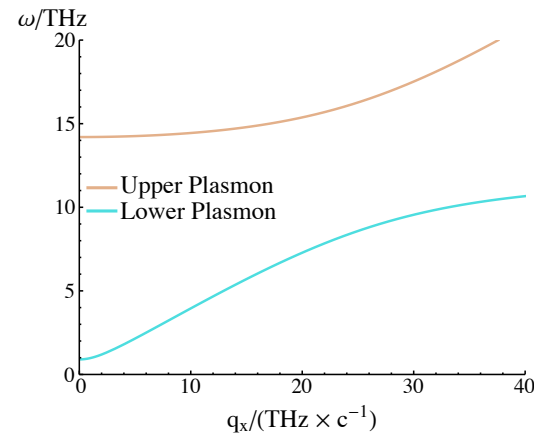
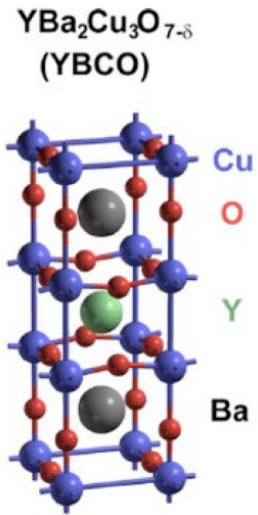
Lower energy
Josephson plasmon



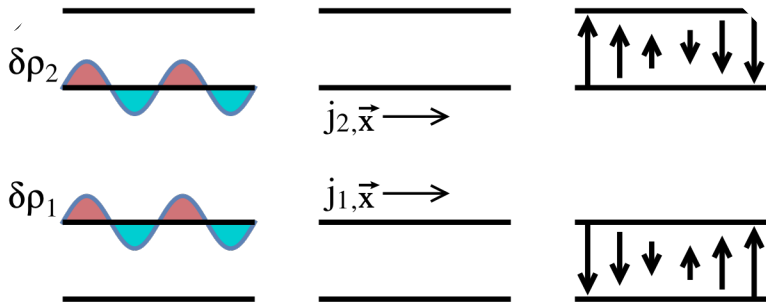
0.9 THz

Josephson plasmons in YBCO

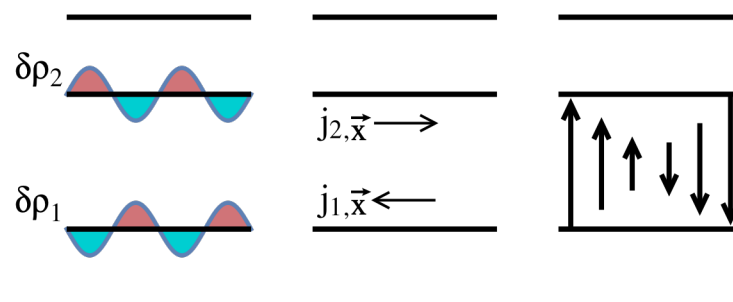
First theoretical work on Josephson plasmons in YBCO: van der Marel, Tsvetkov, PRB (2001)



High frequency plasmon
at finite $q_{||}$



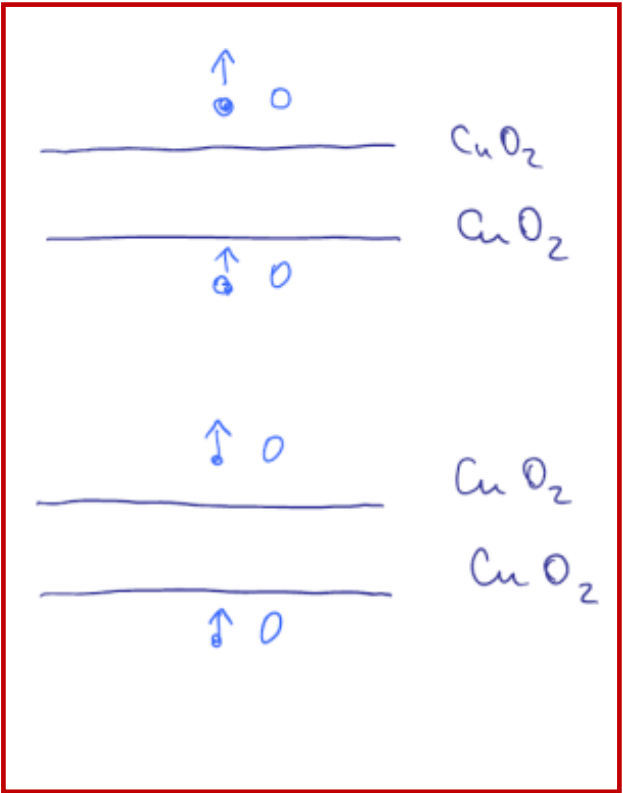
Low frequency plasmon
at finite $q_{||}$



M. Michael et al.,

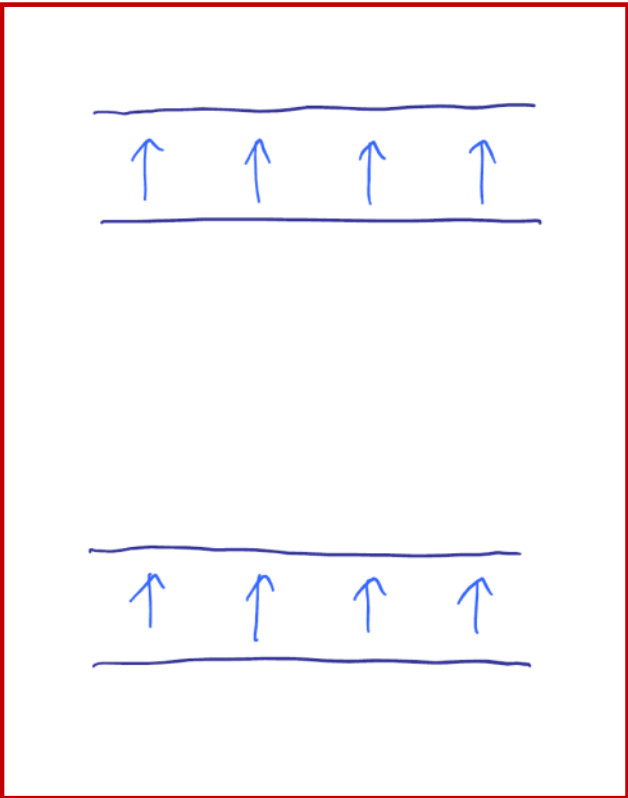
Apical oxygen phonon and Josephson plasmons in bilayer YBCO

Oxygen phonon



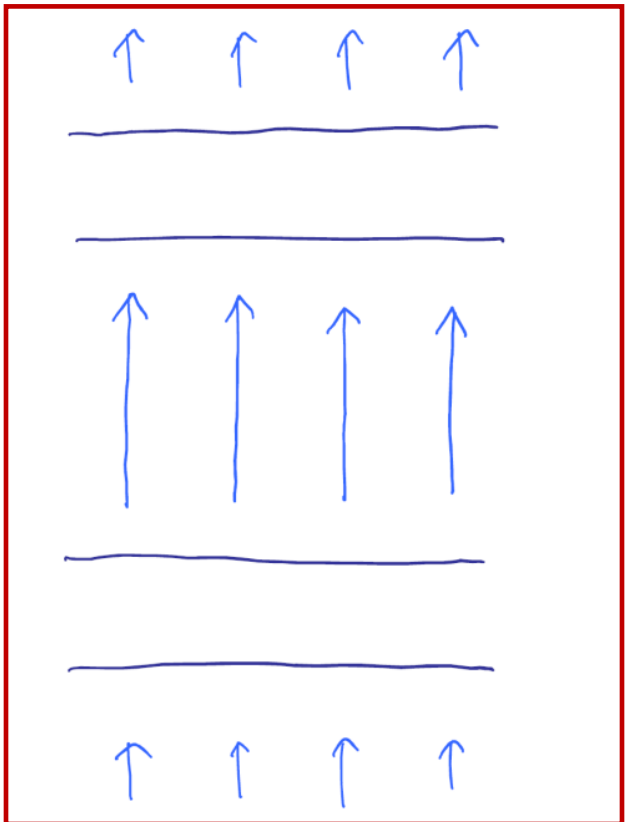
17 and 19.5 THz

Higher energy
Josephson plasmon



14 THz

Lower energy
Josephson plasmon



0.9 THz

Coupling between apical oxygen phonon and Josephson plasmons

Theory: M. Michael et al.

Phonon changes in-plane superfluid density

$$\rho_{s,1} = \rho_{s,0} - Q(t) + \rho_1$$

$$\rho_{s,2} = \rho_{s,0} + Q(t) + \rho_2$$

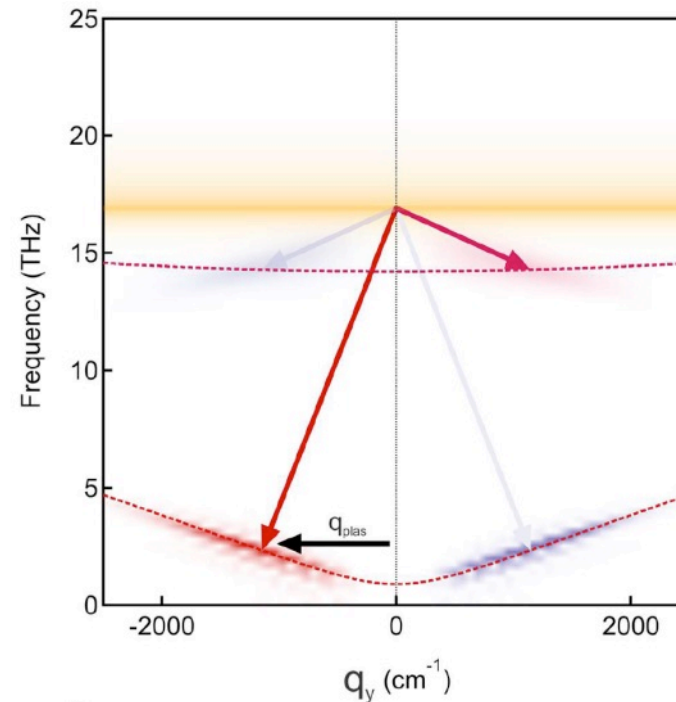
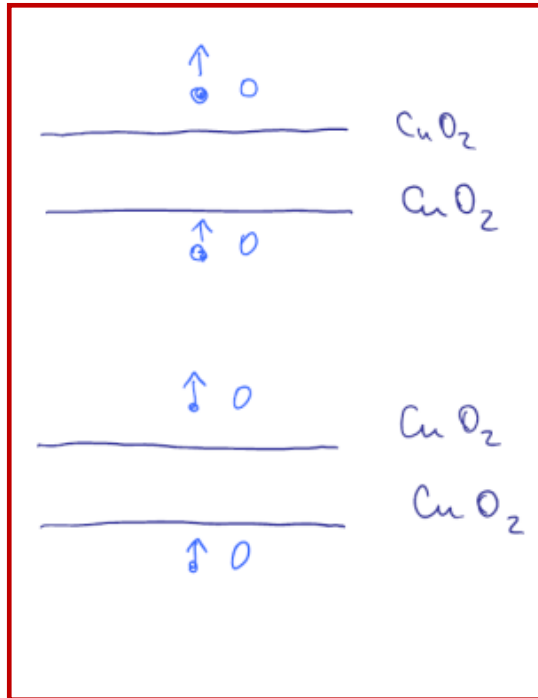
$$\mathcal{H}_{||} = \rho_{s1}(\nabla\phi_1)^2 + \rho_{s2}(\nabla\phi_2)^2$$

Phonon plasmon interaction

$$\mathcal{H}_{\text{int}} = Q((\nabla\phi_1)^2 - (\nabla\phi_2)^2) = Q(\nabla\phi_1 - \nabla\phi_2)(\nabla\phi_1 + \nabla\phi_2)$$

$$\mathcal{H}_{\text{int}} \sim q_{||}^2 Q J_{\text{upper}} J_{\text{lower}}$$

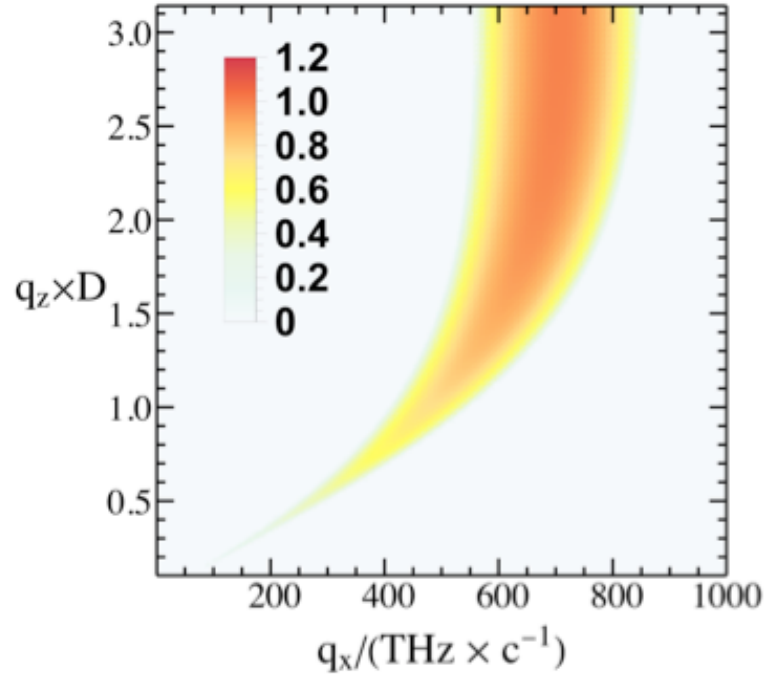
Coupling at finite $q_{||}$



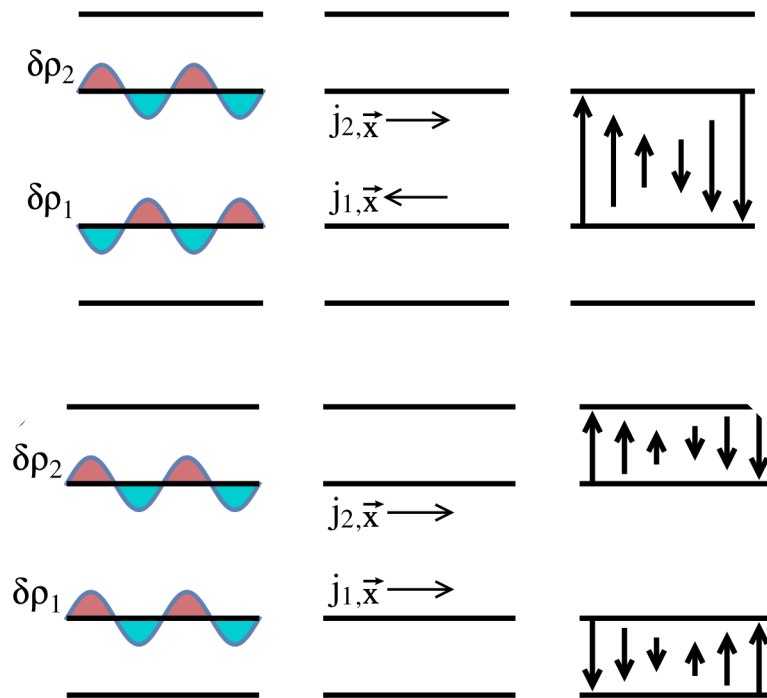
This argument correctly predicts frequencies of unstable modes: 14.5THz and 2.5THz

Searching for most unstable modes

Instability Growth rate of Josephson plasmon pairs



Most unstable pair



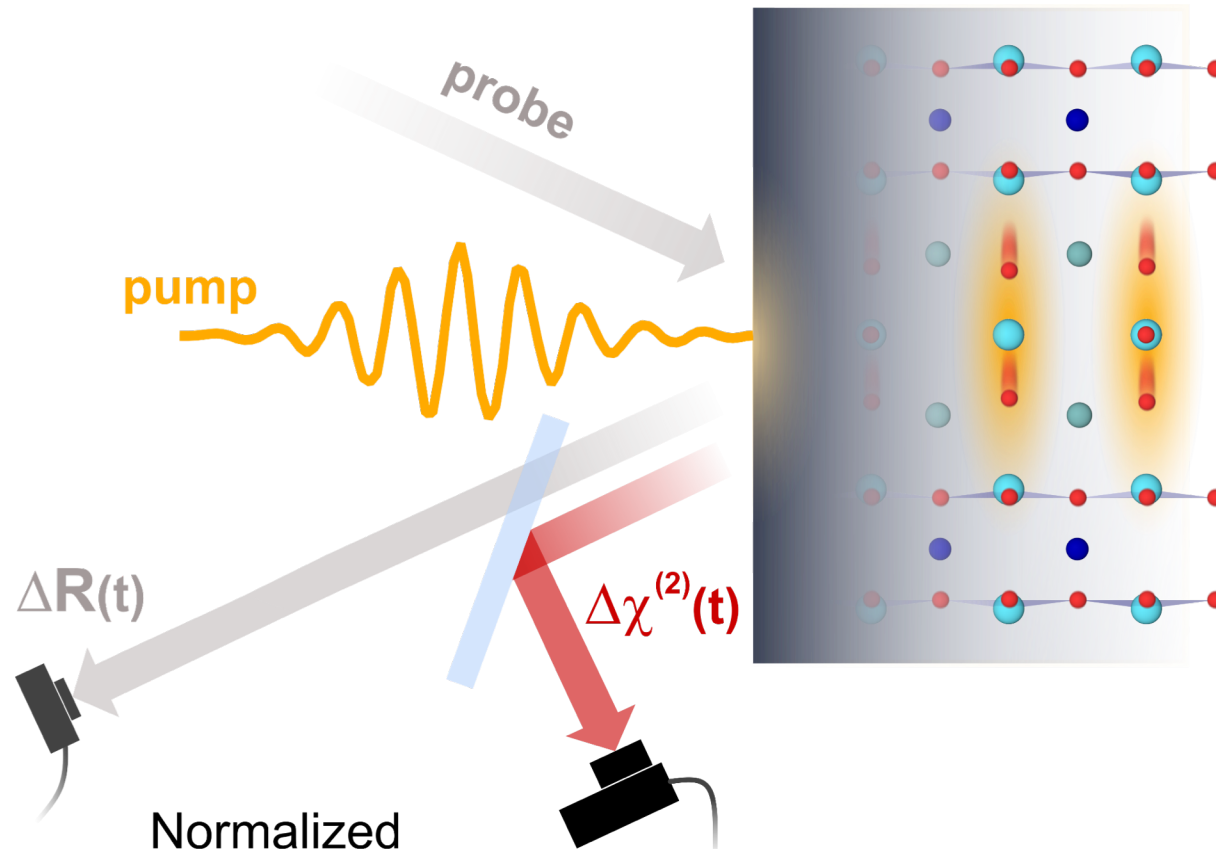
Lower plasmon with
 $k_z = \frac{\pi}{D}$ *at 2.5 THz*

Upper plasmon with
 $k_z = \frac{\pi}{D}$ *at 14.5 THz*

Supercurrents break inversion – induce $\chi^{(2)}$

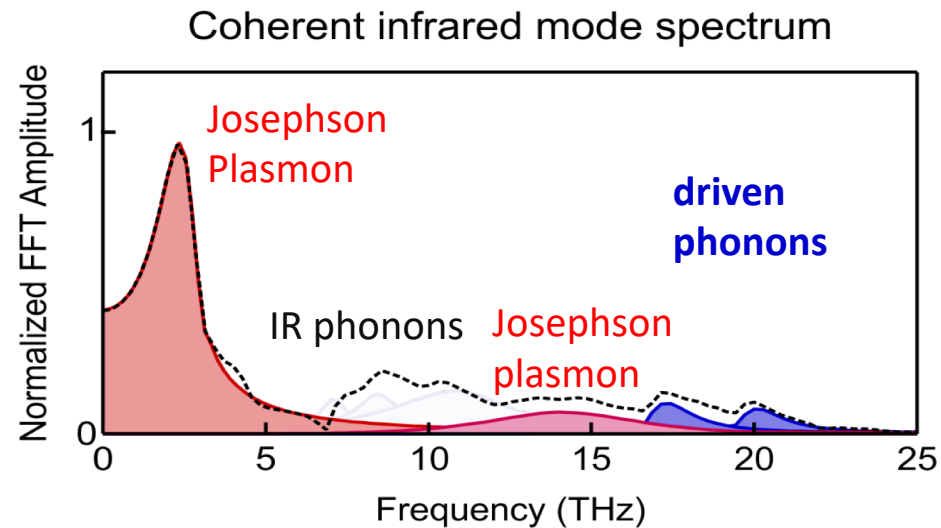
Oscillatory phonons and super currents induce voltage/currents

Use second harmonic generation to perform “instantaneous” measurement of inversion symmetry breaking

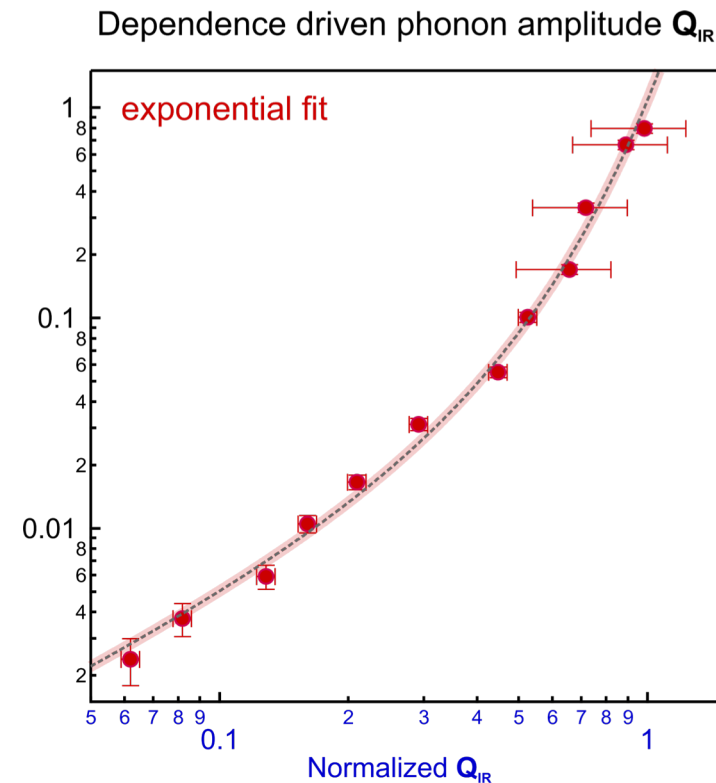


Experimental observation of three wave mixing process

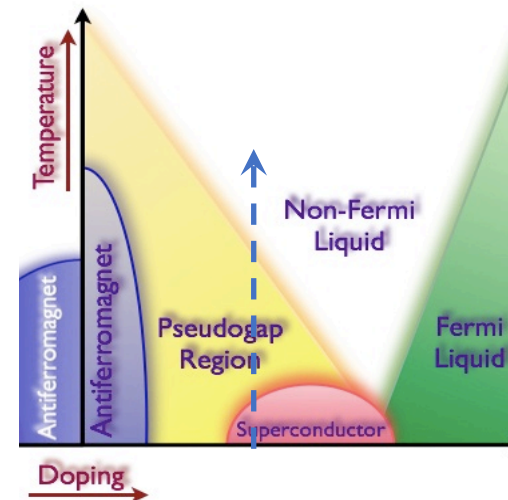
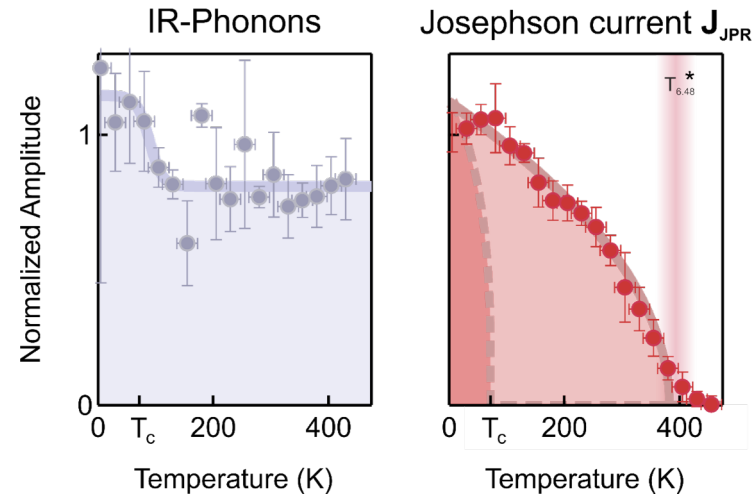
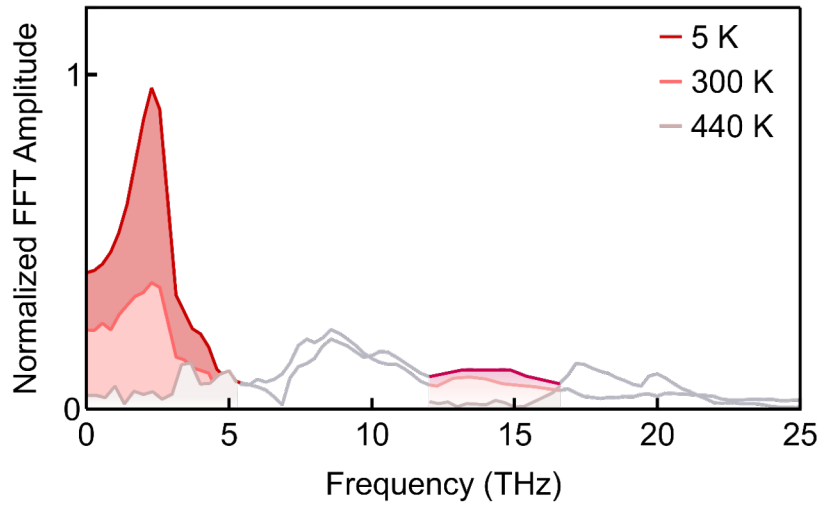
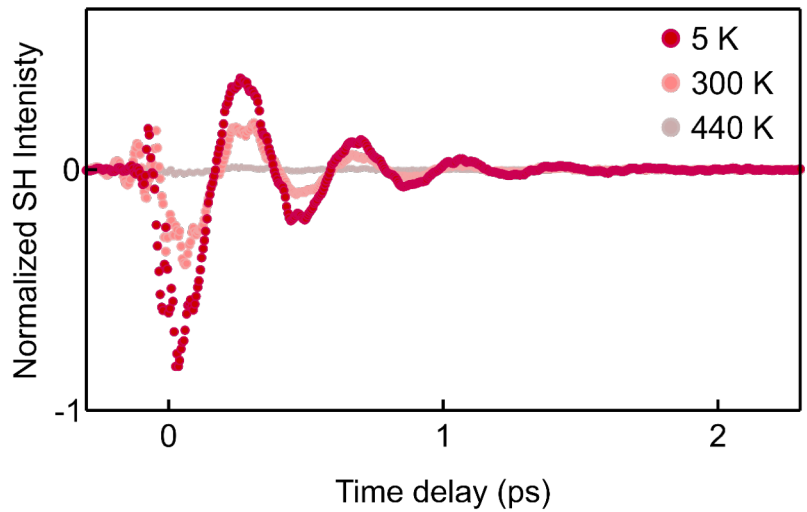
Modes excited after the pump



Scaling consistent with parametric resonance



Josephson oscillations up to high temperatures



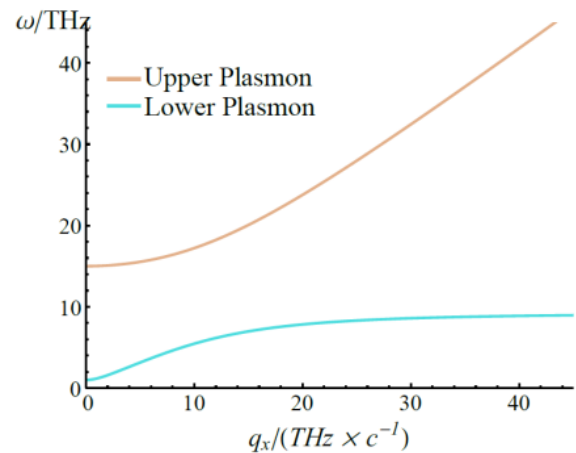
A. Von Högen et al.

Photoinduced superconductivity above T_c
Parametric driving making supercurrent fluctuations more coherent

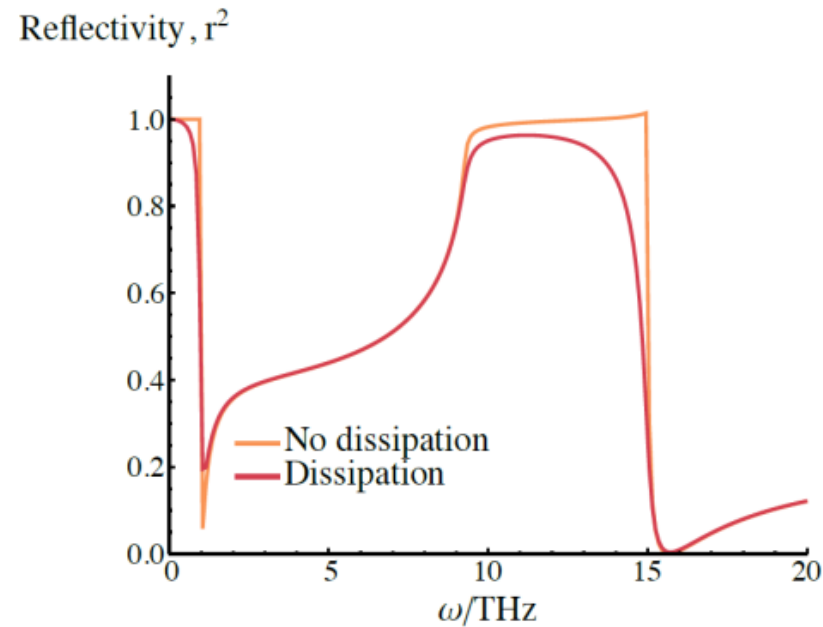
Prediction of reflectivity spectra in pump
and probe experiments in YBCO
using this framework

Josephson plasmons and reflectivity of YBCO

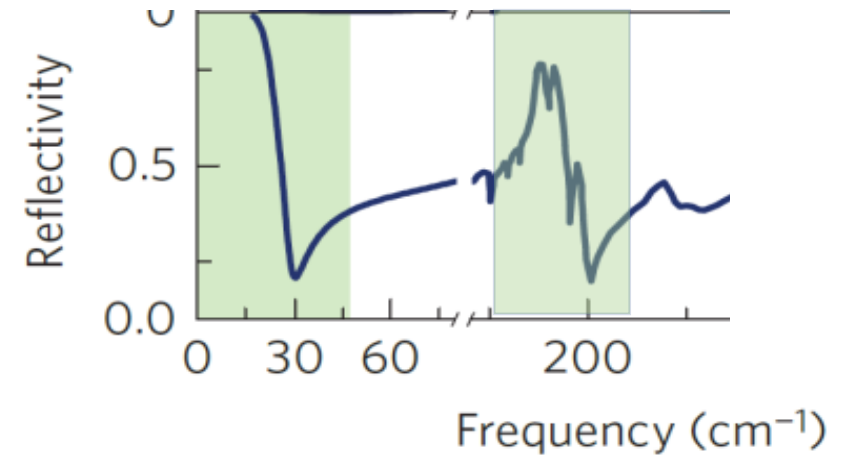
Plasmon dispersion



Reflectivity

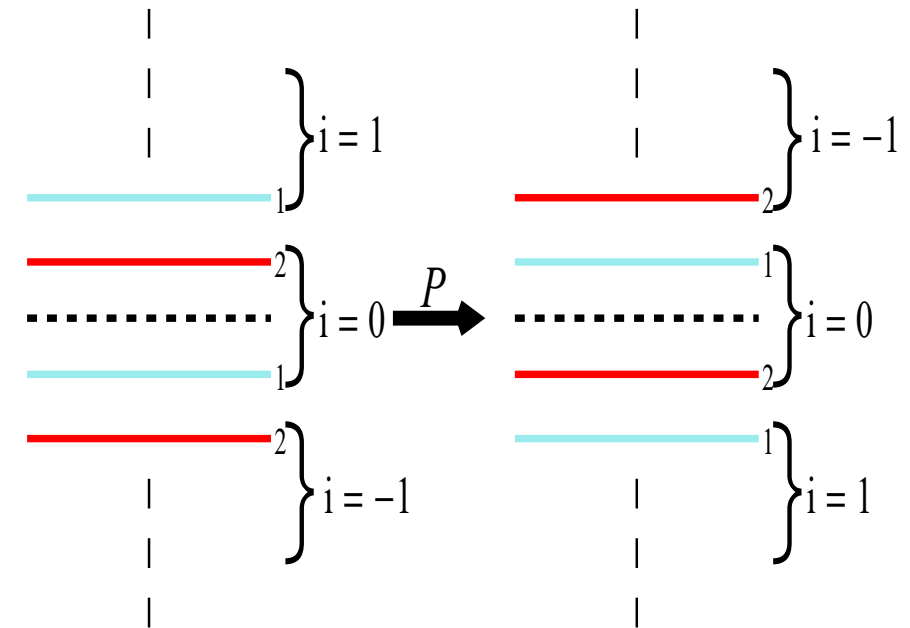


YBCO Josephson plasmon edge in equilibrium
Hu et al., Nature Materials 13:705 (2013)



Symmetries of collective modes and selection rules

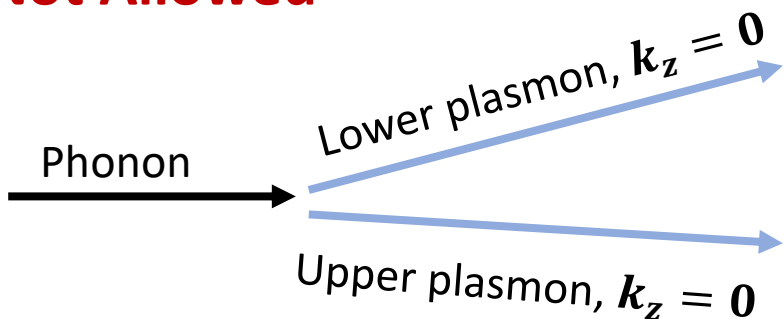
Mode	Reflection symmetry
AO Phonon @ 17 THz	Odd
Neighboring phonon @ 19.5 THz	Odd
Lower plasmon, $k_z = \frac{\pi}{D}$	Odd
Upper plasmon, $k_z = \frac{\pi}{D}$	Even
Lower plasmon, $k_z = 0$	Odd
Upper plasmon, $k_z = 0$	Odd



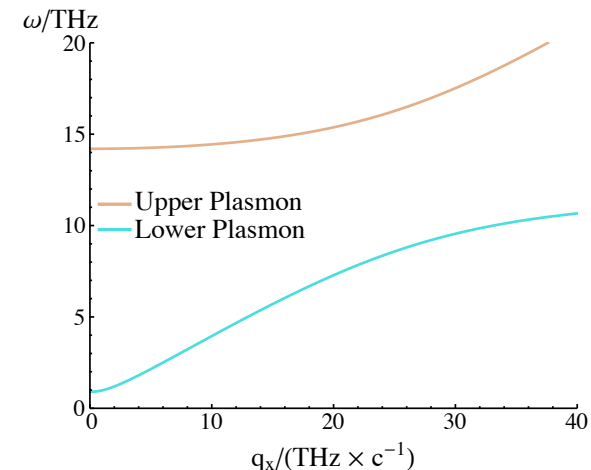
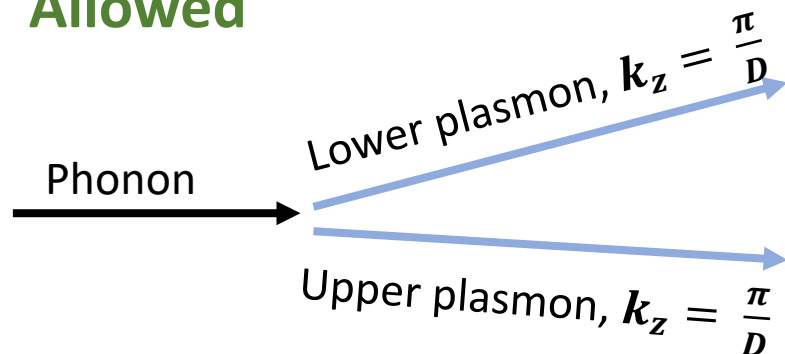
Symmetries of collective modes and selection rules

Three wave processes:

Not Allowed

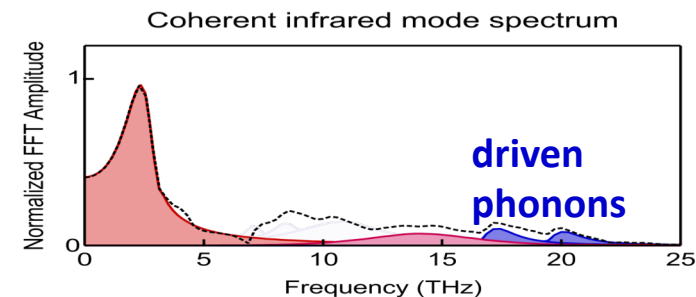
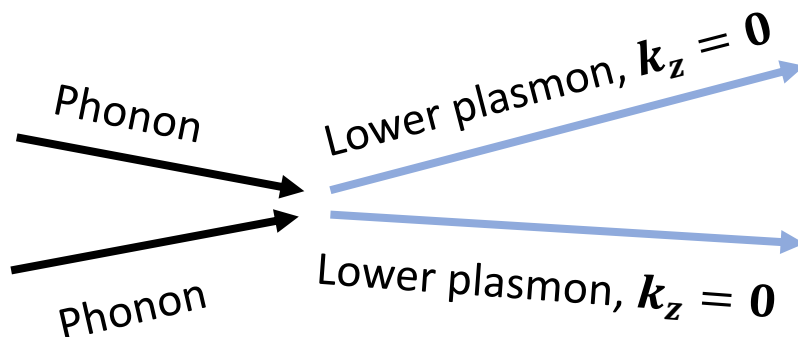


Allowed



Four wave processes:

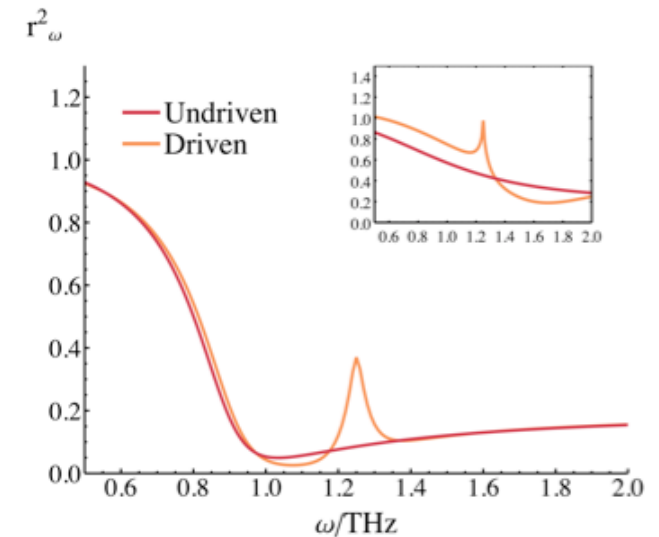
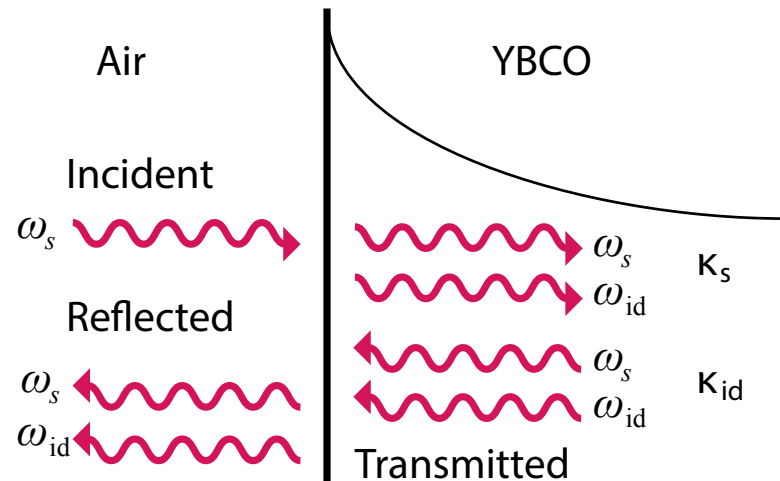
Allowed



A. Von Högen et al.
forthcoming

Light reflection from Floquet medium and parametric amplification

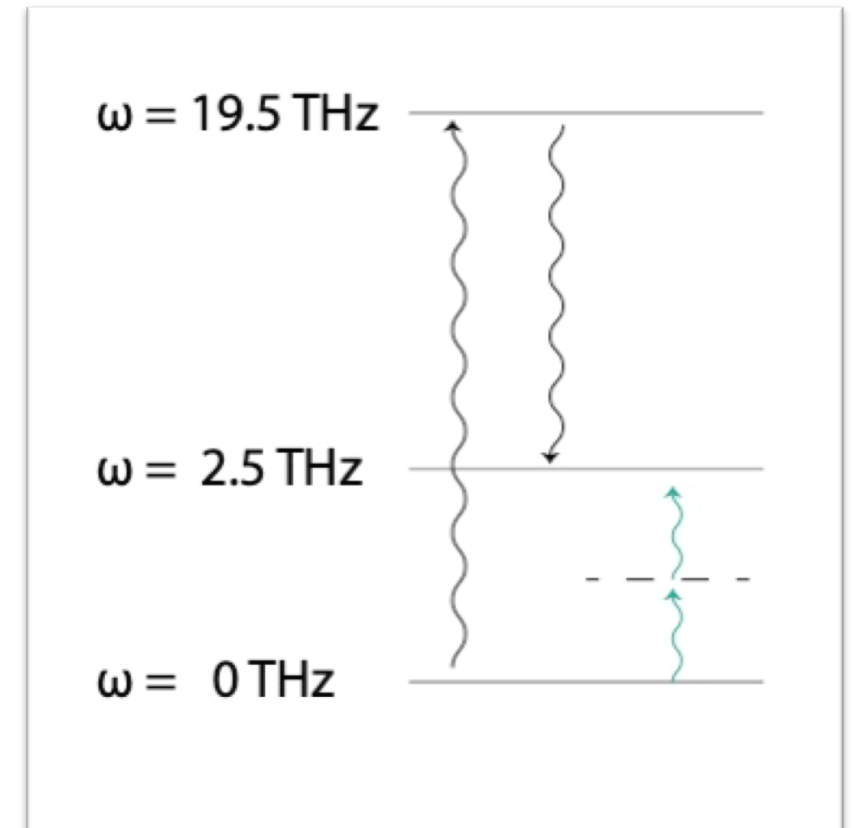
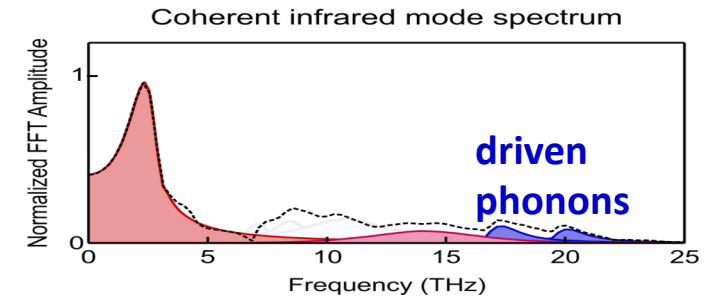
- Oscillating currents and apical oxygens induce frequency mixing in the equations of motion.
- Incident beam couples to $\mathbf{k}_z = \mathbf{0}$ Josephson plasmons. Find process that can couple to $\mathbf{k}_z = \mathbf{0}$ and is closest to parametric resonance.
- Upon solving Fresnel-Floquet equations of motion, retain mixing only between ω_s and ω_{id} . Use boundary conditions to find k_s and k_{id} for fixed ω_s and ω_{id} .
- To determine orientation of k_s and k_{id} introduce infinitesimal damping and insist that the imaginary part is such that it decays away from the surface. Close to resonance the idler contribution propagates towards the surface corresponding to emission of energy from the oscillating material.



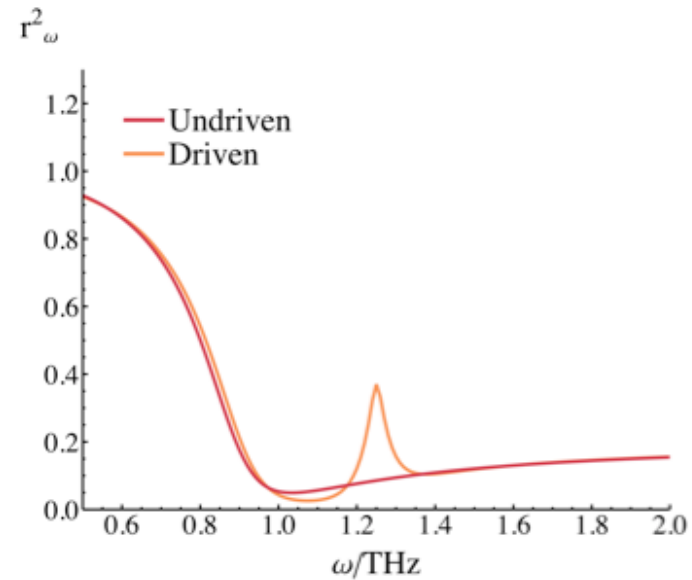
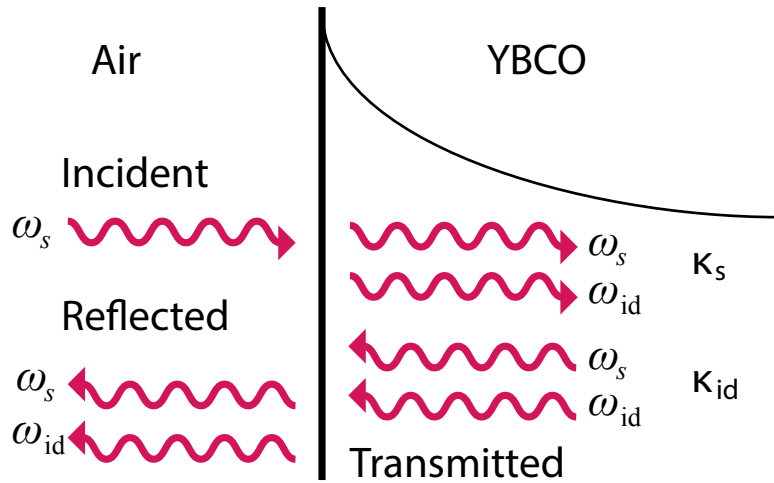
Example of Floquet modulation - Four wave mixing with two phonons

- Two neighboring phonons can act together as a single drive at their frequency difference.
- Assuming here that this frequency difference is 2.5 THz, this drive can parametrically drive a pair of lower Josephson plasmons at $k_z = 0$ relevant for reflectivity experiments.
- Effective Hamiltonian has the form:

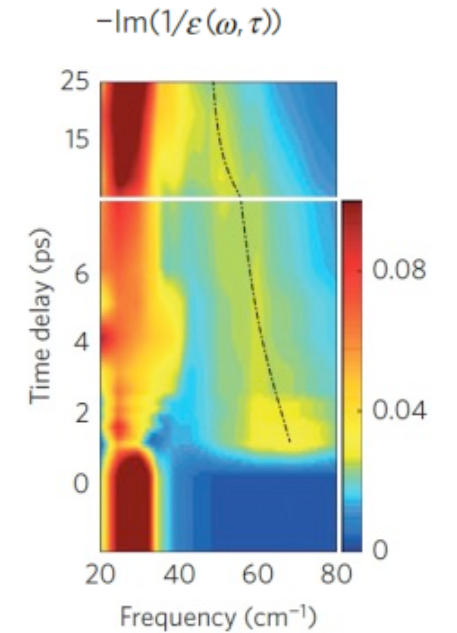
$$H = \sum_k \lambda_k \langle Q^2 \rangle (t) b_{1,k} b_{1,-k} + h.c.$$



Parametrically amplified reflection on resonance



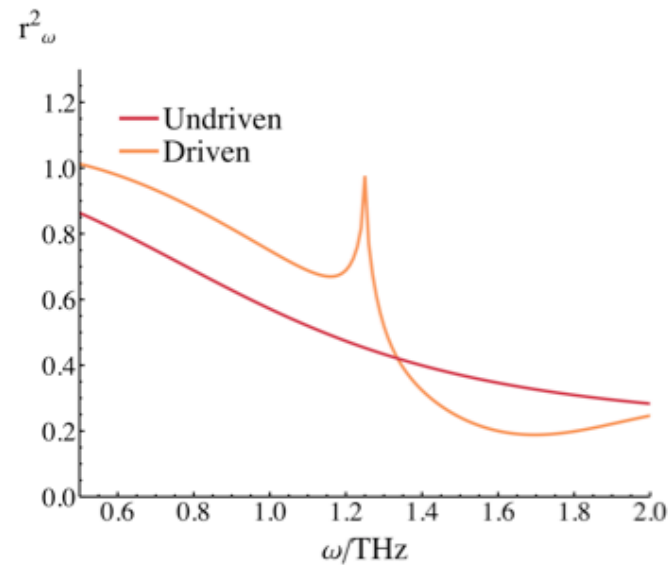
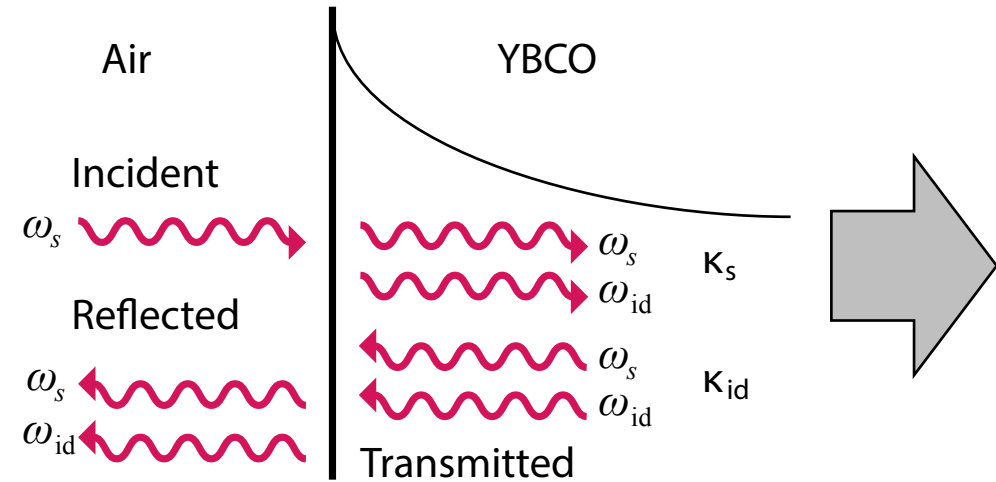
M. Michael et al.



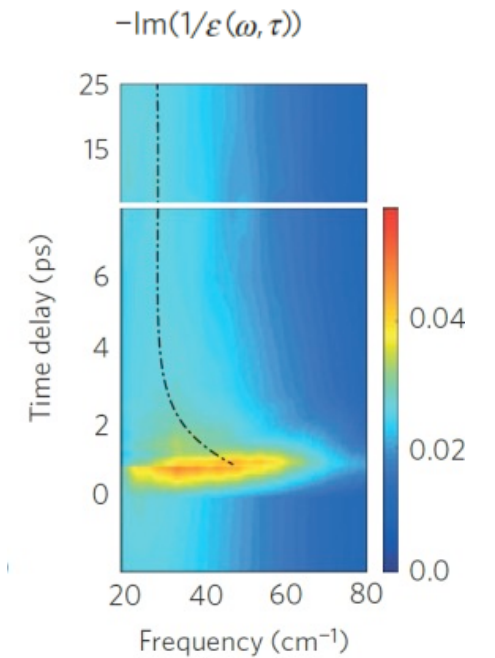
Hu et al.,
Nature Materials
13:705 (2013)

See also N. L. Wang

Photoinduced plasmon edge above T_c



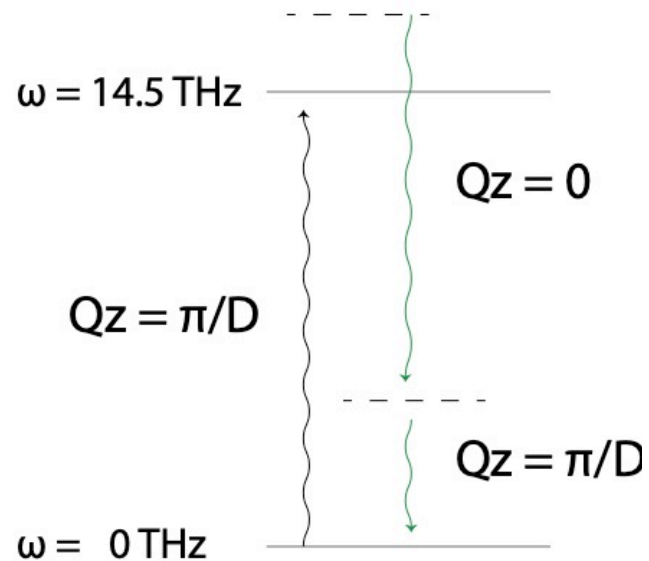
M. Michael et al.



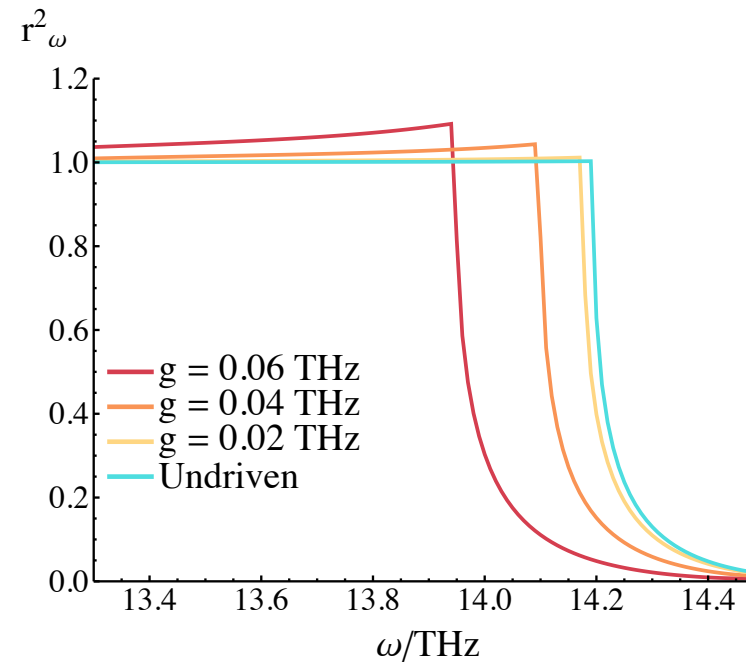
Hu et al.,
Nature Materials
13:705 (2013)

Renormalization of upper plasmon edge

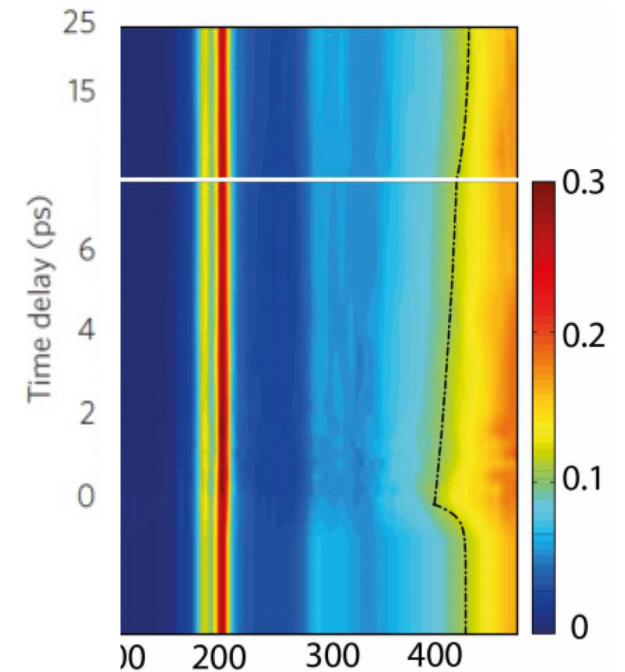
Dominant driving mechanism



Floquet renormalization of upper plasmon edge



M. Michael et al.



Hu et al.,
Nature Materials
13:705 (2013)

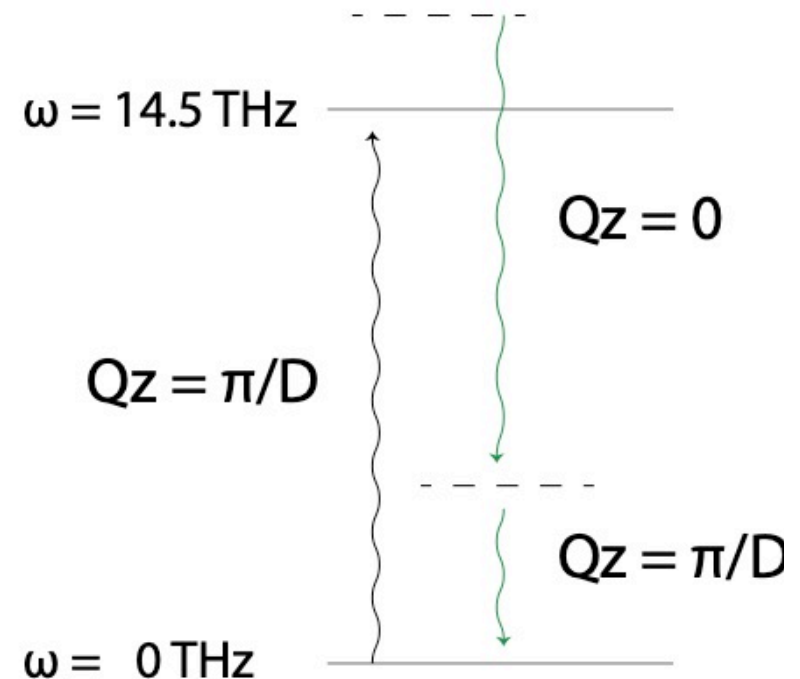
Renormalization of upper plasmon edge

- **Level attraction:**

In every parametric process where a drive with frequency, ω_d , parametrically driving states at energies ω_1 and ω_2 then these states are:

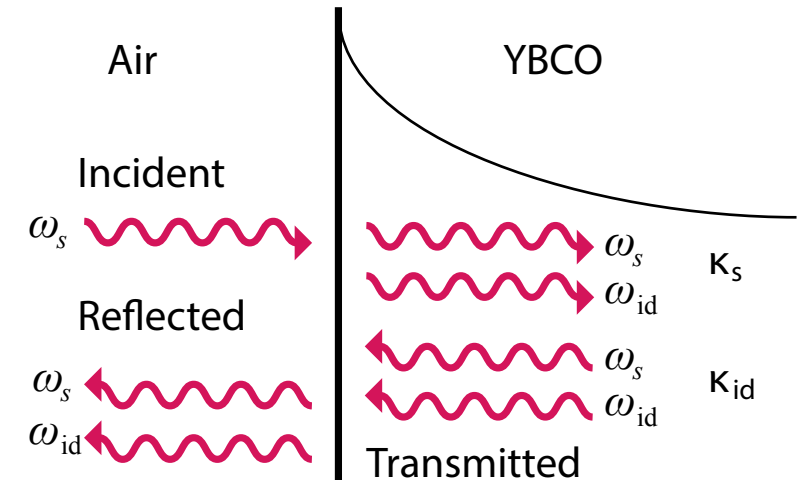
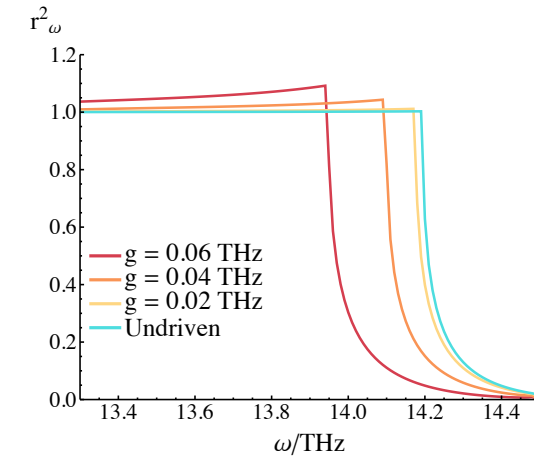
- **Blue shifted:** $\omega_1 + \omega_2 < \omega_d$

- **Red shifted:** $\omega_1 + \omega_2 > \omega_d$



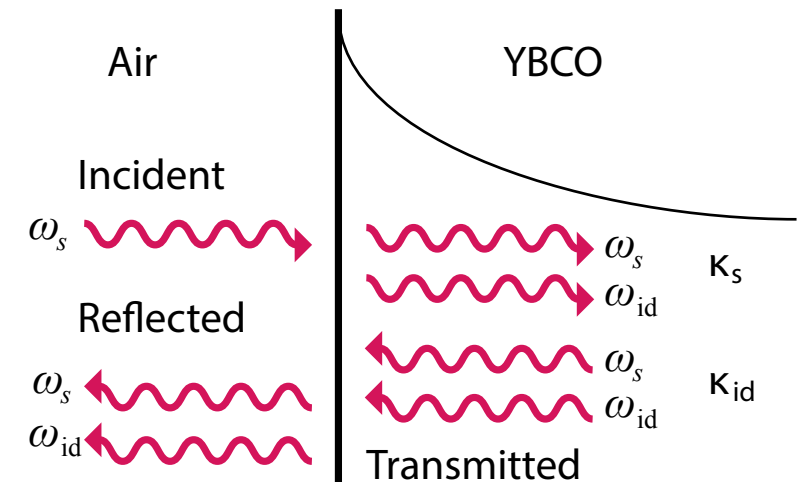
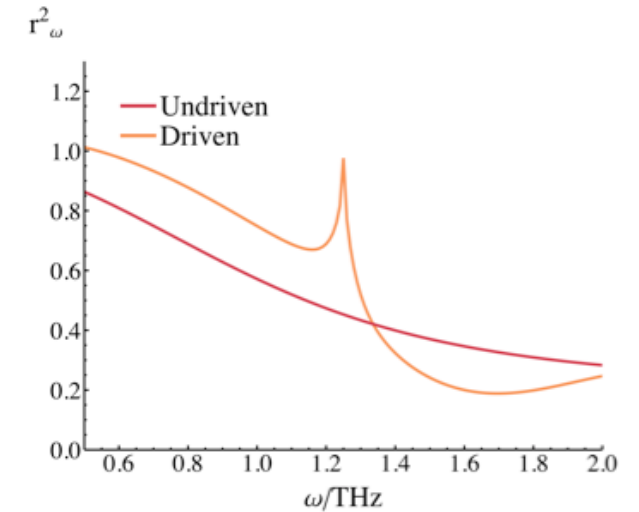
Summary – Effects of parametric resonance

- Floquet dressing of equilibrium modes.
- Parametric instability competes with dissipation and can make resonant modes more coherent.
- Parametric amplification in the reflectivity spectrum.



Summary

- Introduced a theory of JPs in YBCO coupled to phonons through superfluid renormalization.
- Can capture the phenomenology of various experiments both below and above T_c using a single framework.
- Highly suggestive of the pseudogap phase in YBCO.



Questions ?

