

Excitonic Insulators Cavities and Polarized phases of matter

Giacomo Mazza

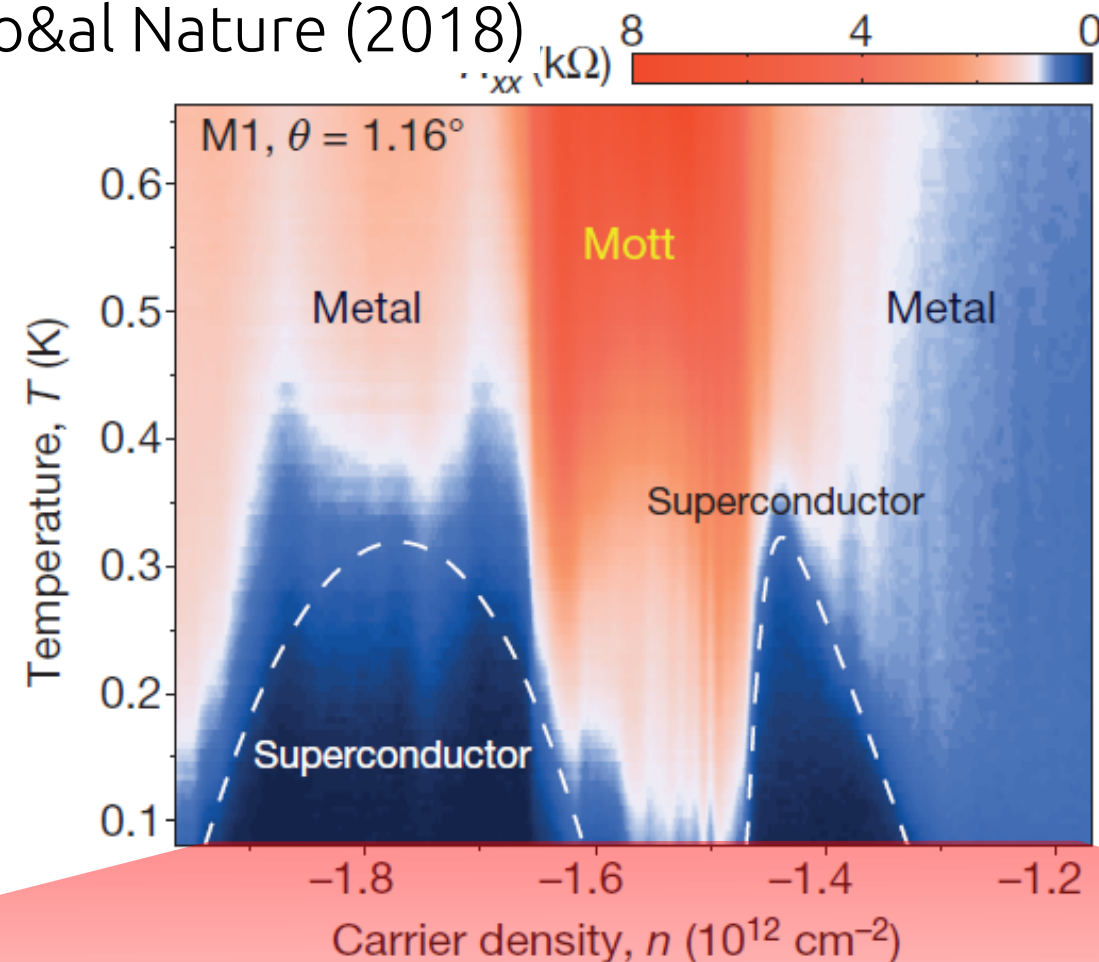
Ecole Polytechnique & College de France - Paris -

NYC, 11 July 2019

Light Control of Quantum Materials

Emergent phenomena for quantum technology

TBLG Cao & al Nature (2018)



Strong
Correlations

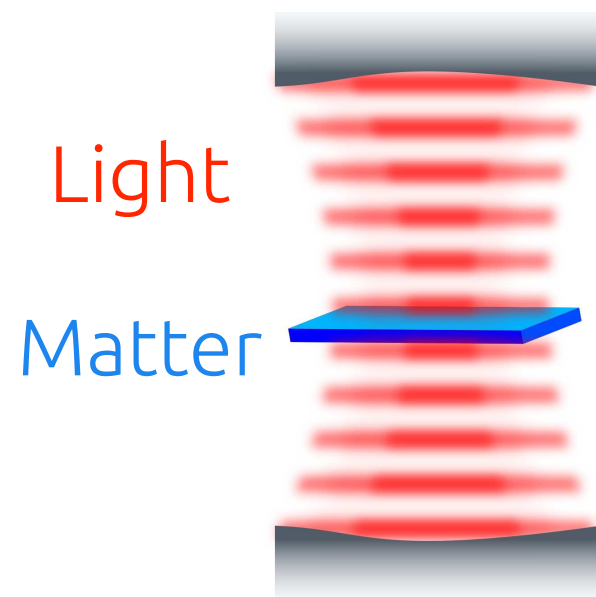
Tunability

Light

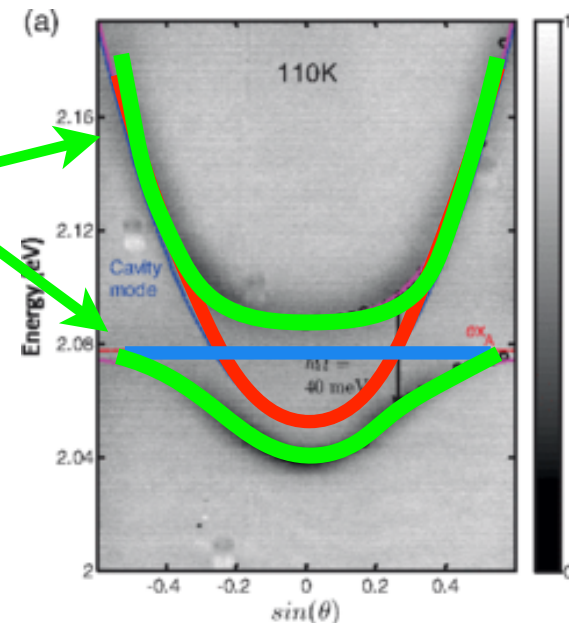
e.g. Superconductivity. Mitrano & al *Nat*(2016)/Fausti & al *Sci*(2010)

Ferroelectrics. Mankowski & al *PRL*(2017)

Why cavities?



Polaritons



Liu & al,
PRL(2017)

Tune the energy of matter excitation

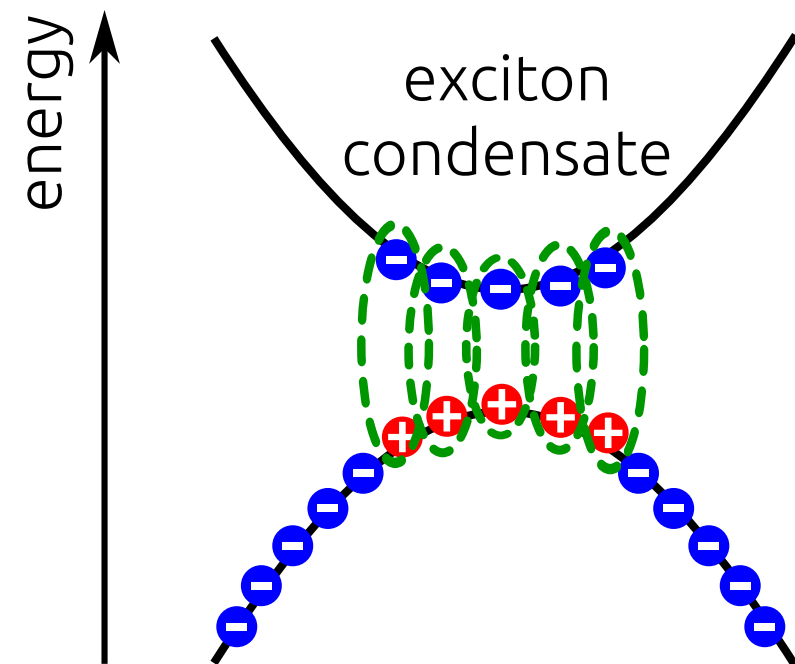
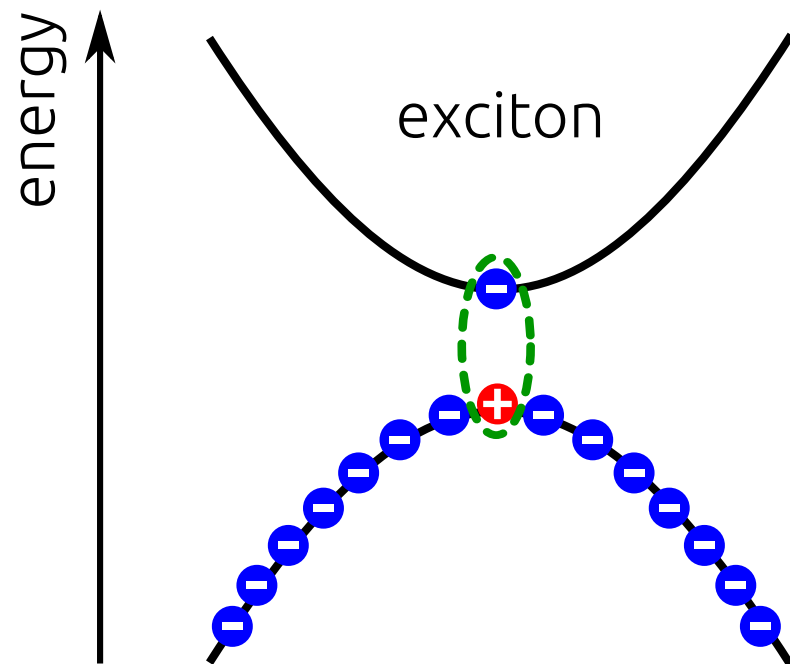
Mediated effective interactions in the material

e.g. superconductivity Curtis & al *PRL*'19/Schlawin & al *PRL*'19/Sentef & al *SciAdv*'19

Excitonic Insulators **GM** & Georges '19

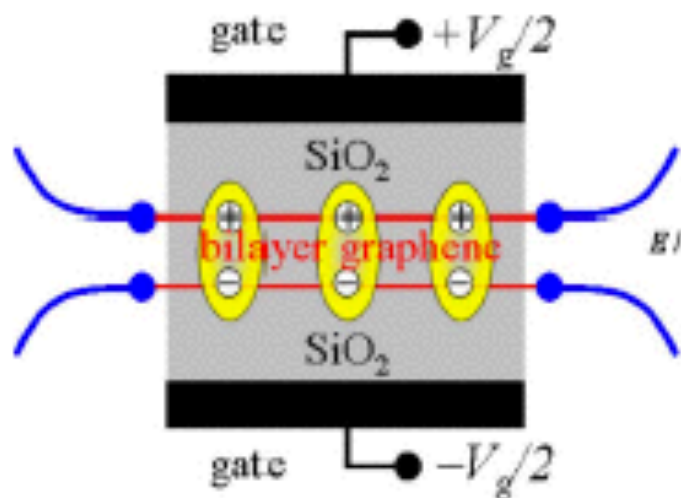
Excitonic Insulators

instability towards the formation of excitons



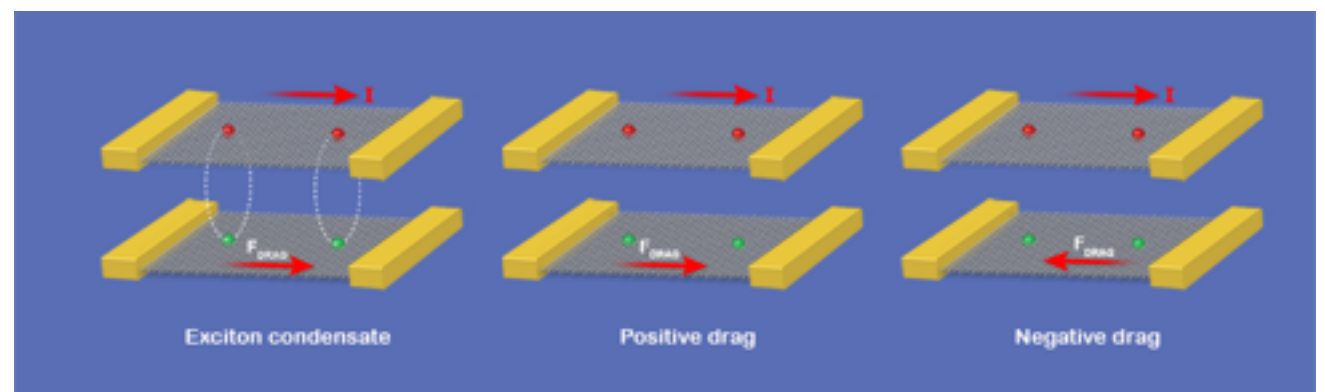
Excitonic Insulators and Exciton condensation

Indirect excitons in bilayers



H.Min & al *PRB* '08
JJ Sung & MacDonald *NatPhys* '08
Tutuc & al *PRL* '04
Nandi & al *Nat* '12
Li & al *NatPhys* '17
Liu & al *NatPhys* '17

Physics: Viewpoint '16
Chasing the exciton condensate

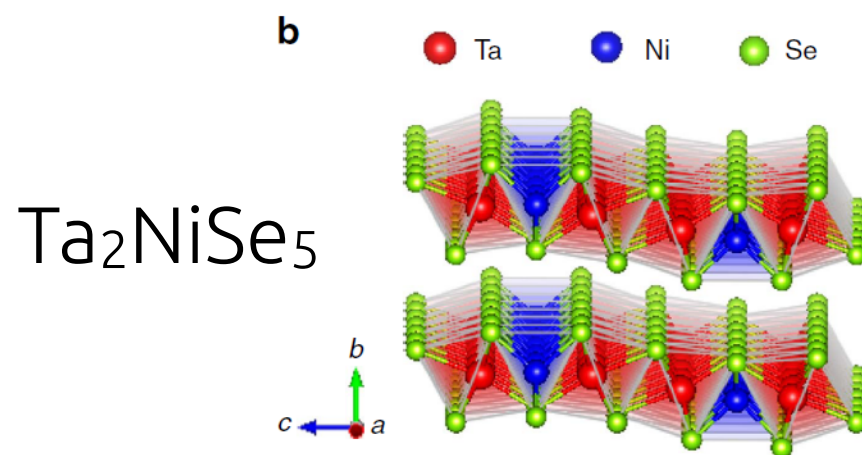
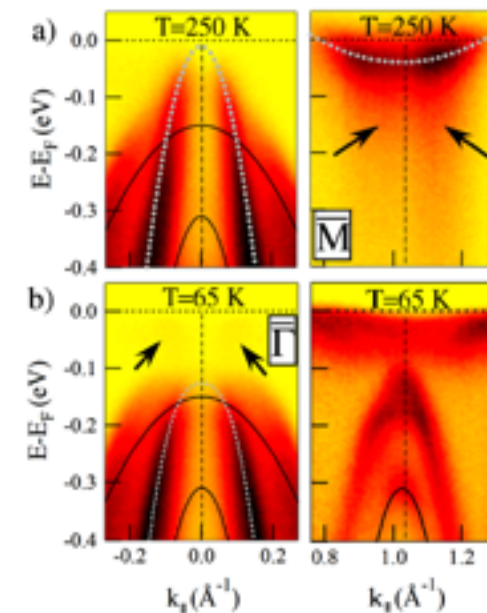


Excitonic Insulator in real materials

Excitonic transition coupled to other types of symmetry breaking

charge ordering TiSe_2

Cercellier & al *PRL* '07
Kogar & al *Sci* '17



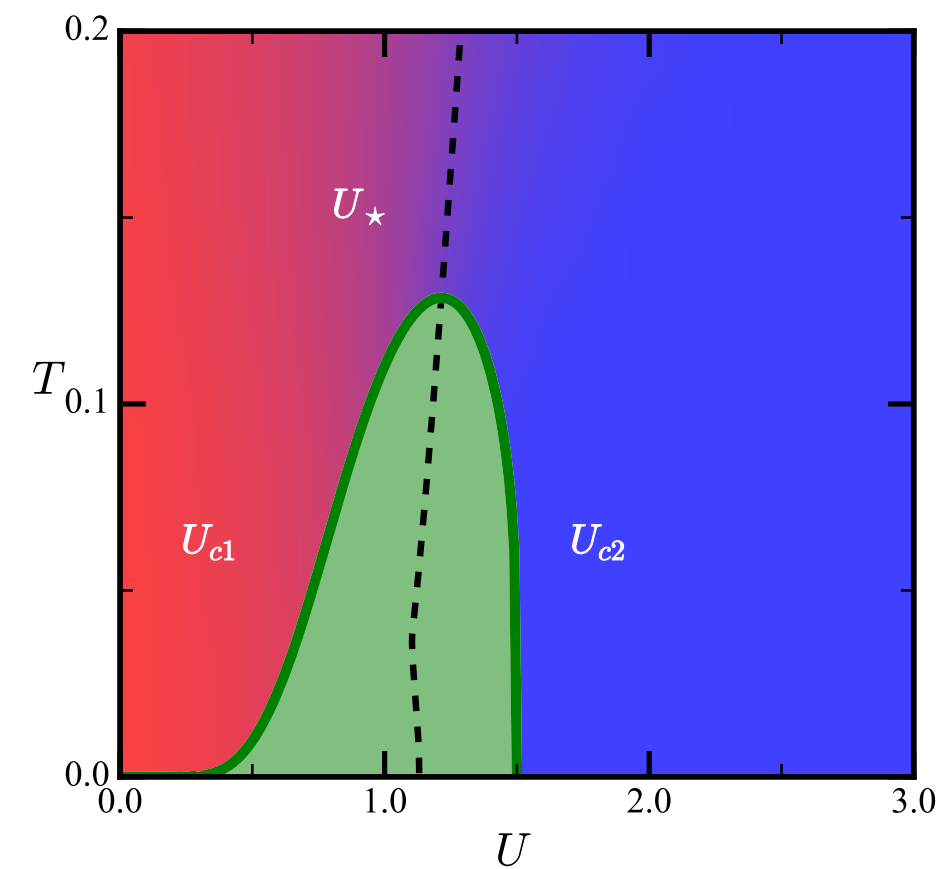
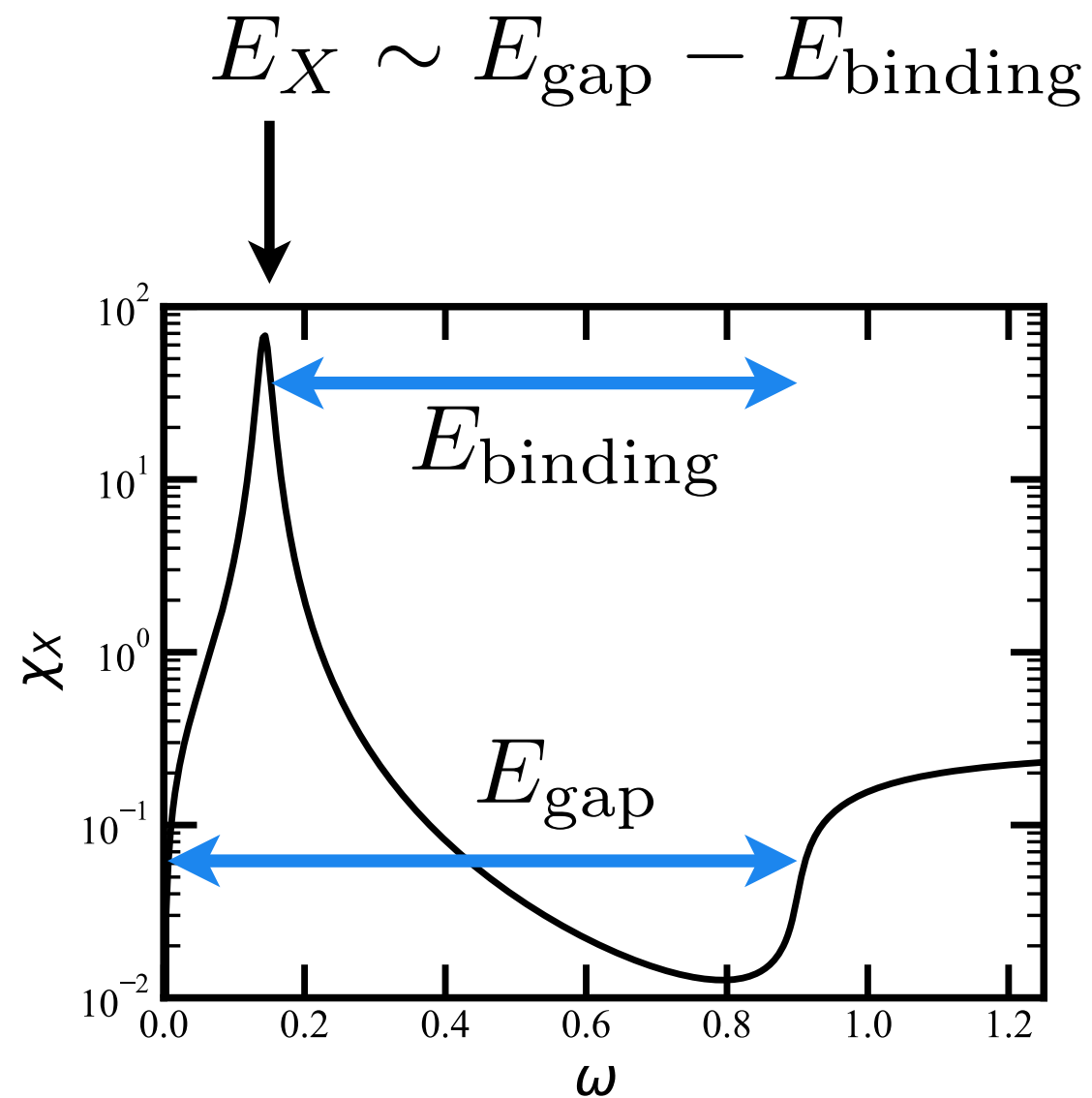
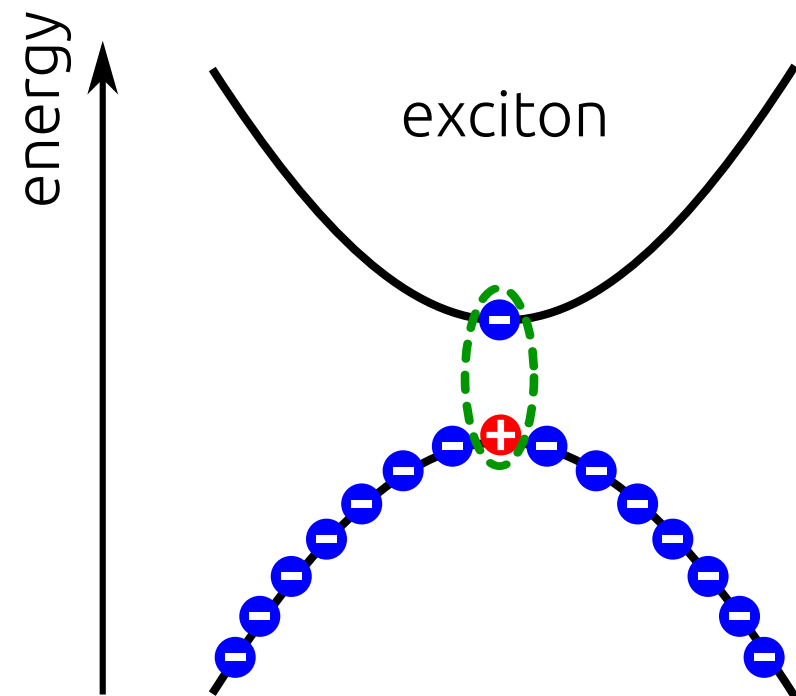
Discrete symmetry of the lattice

Kaneko & al *PRB* '13

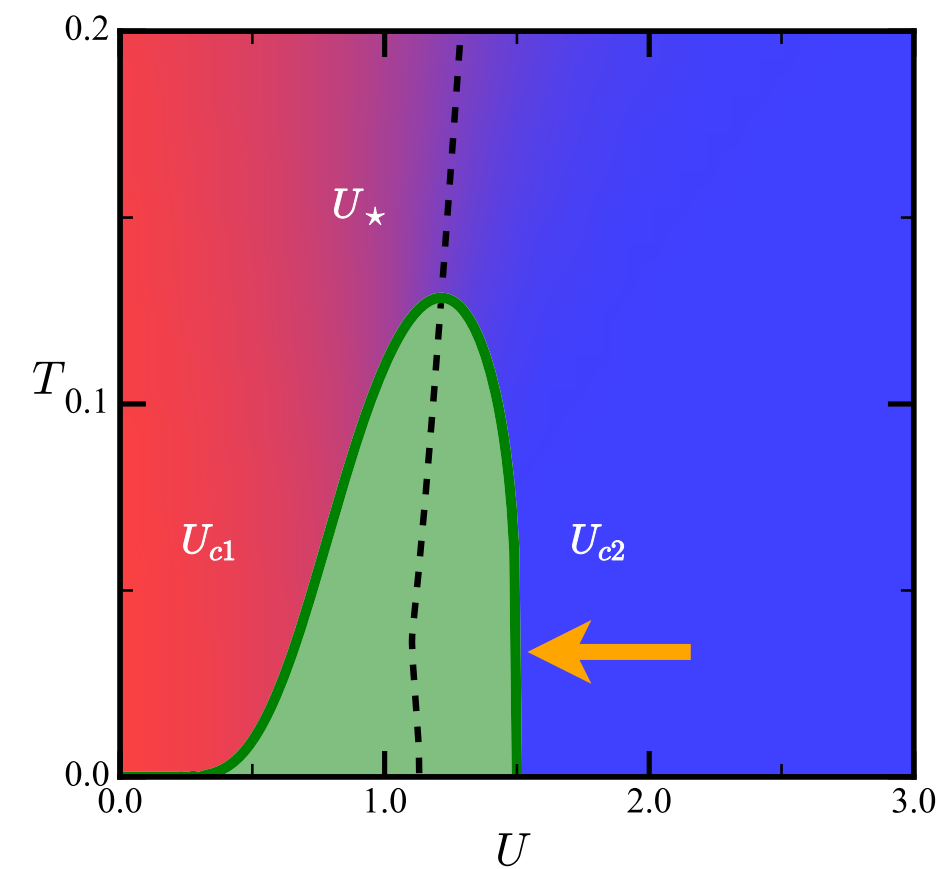
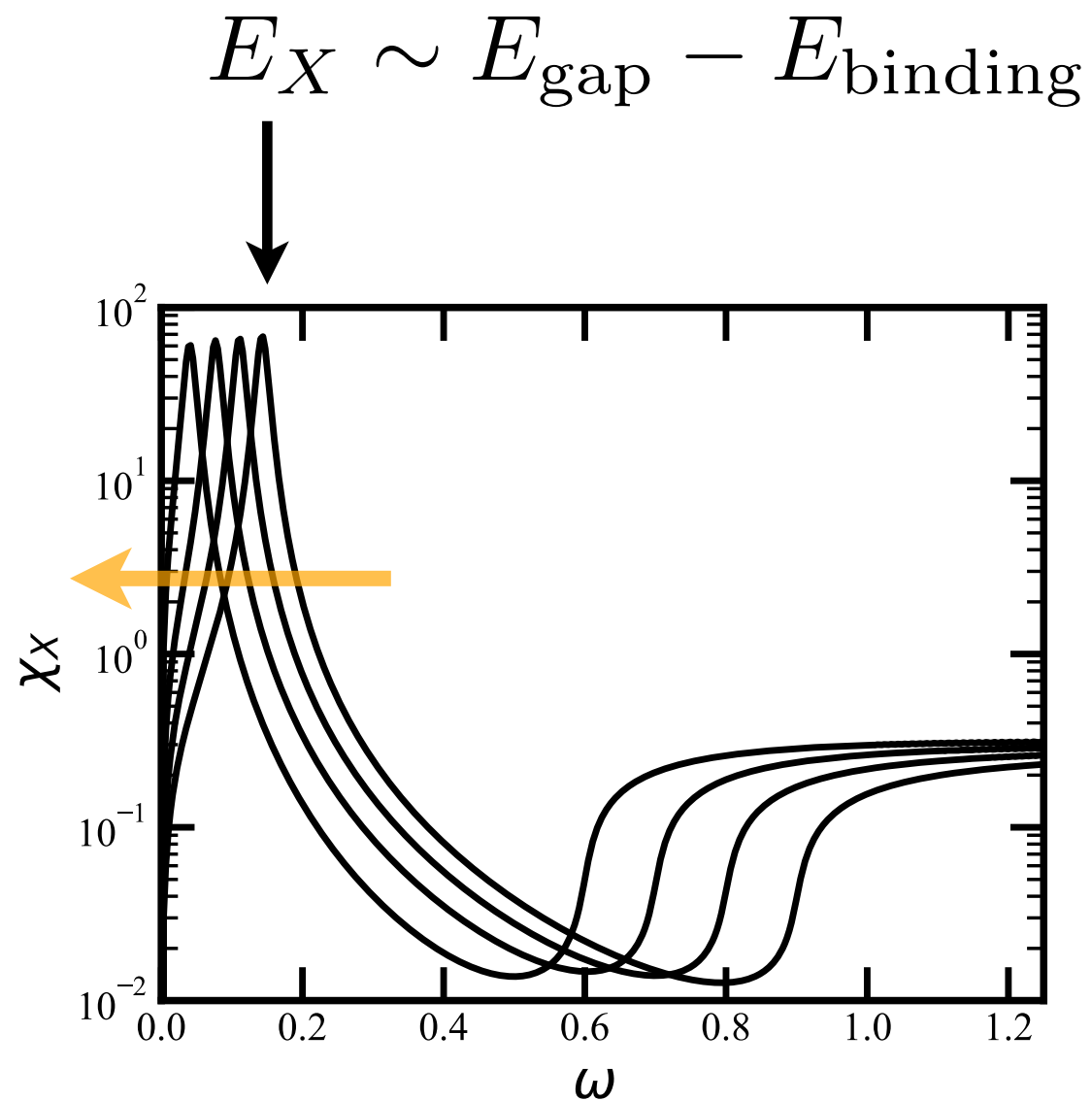
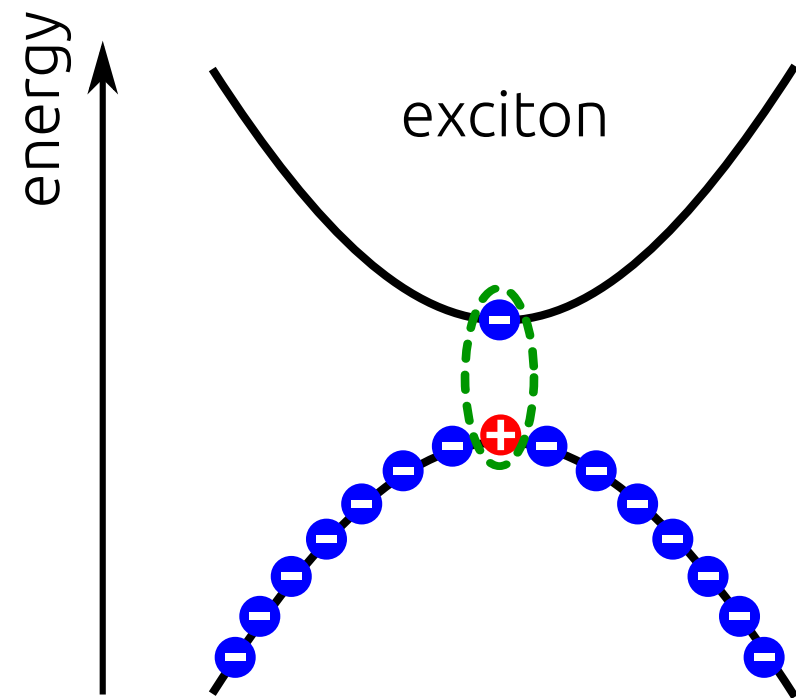
Lu & al *NatComm* '17

Talk by M. Roesner

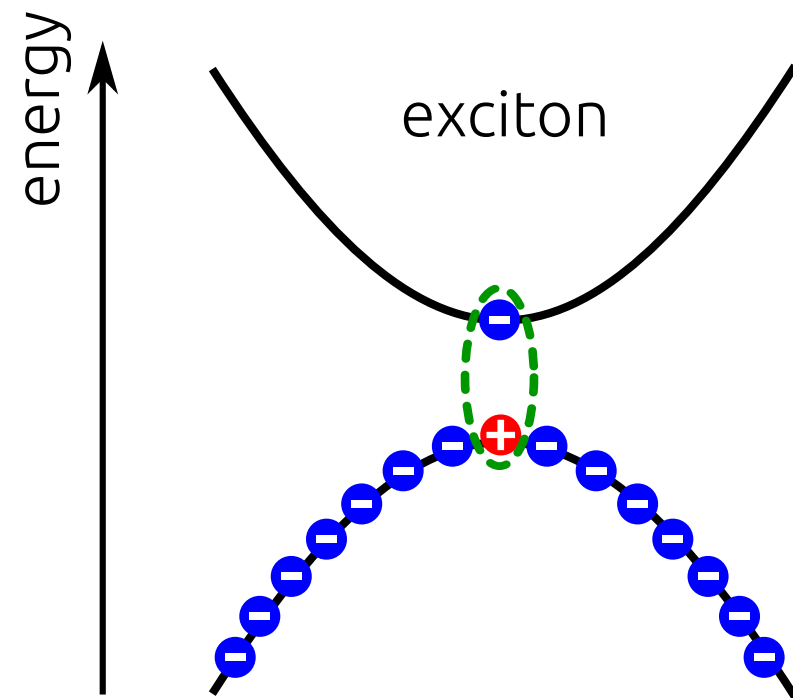
Excitonic soft mode



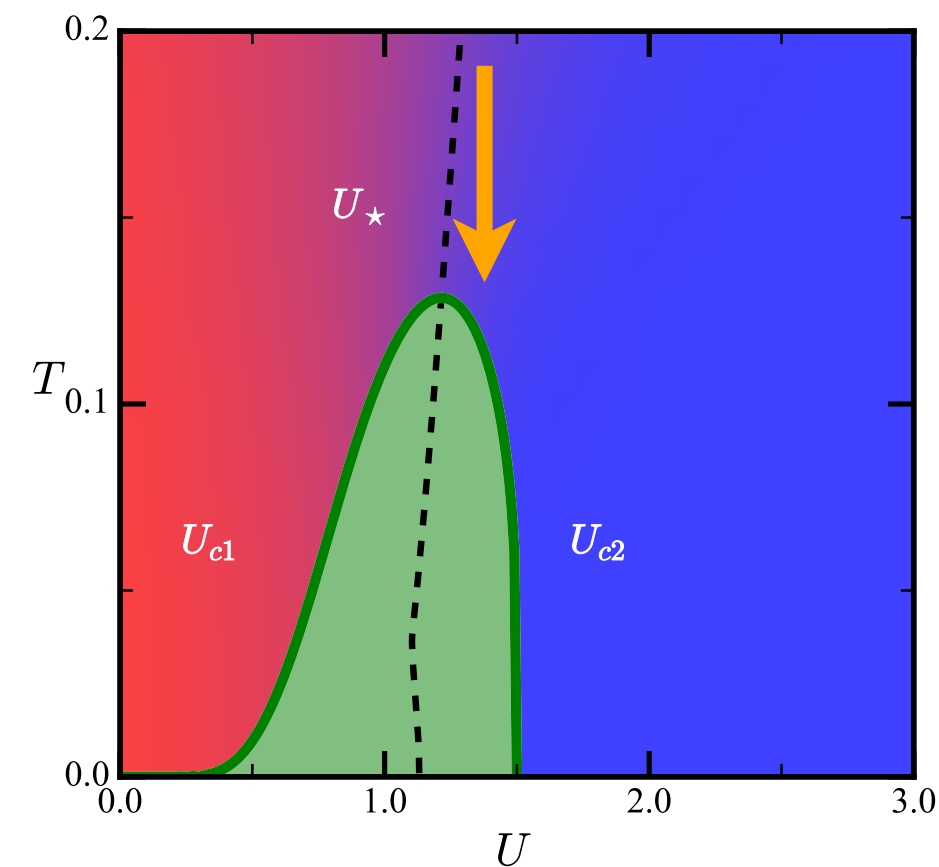
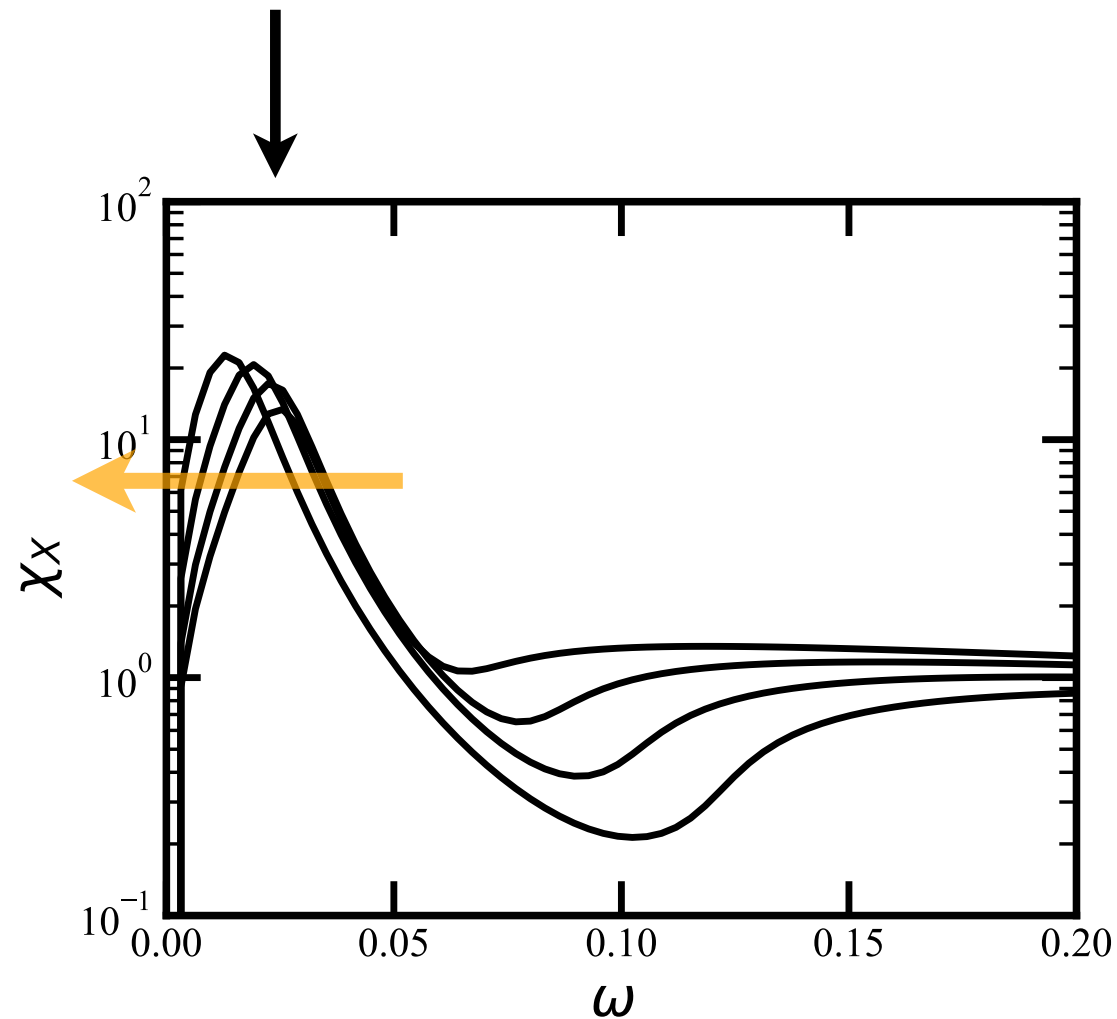
Excitonic soft mode



Excitonic soft mode



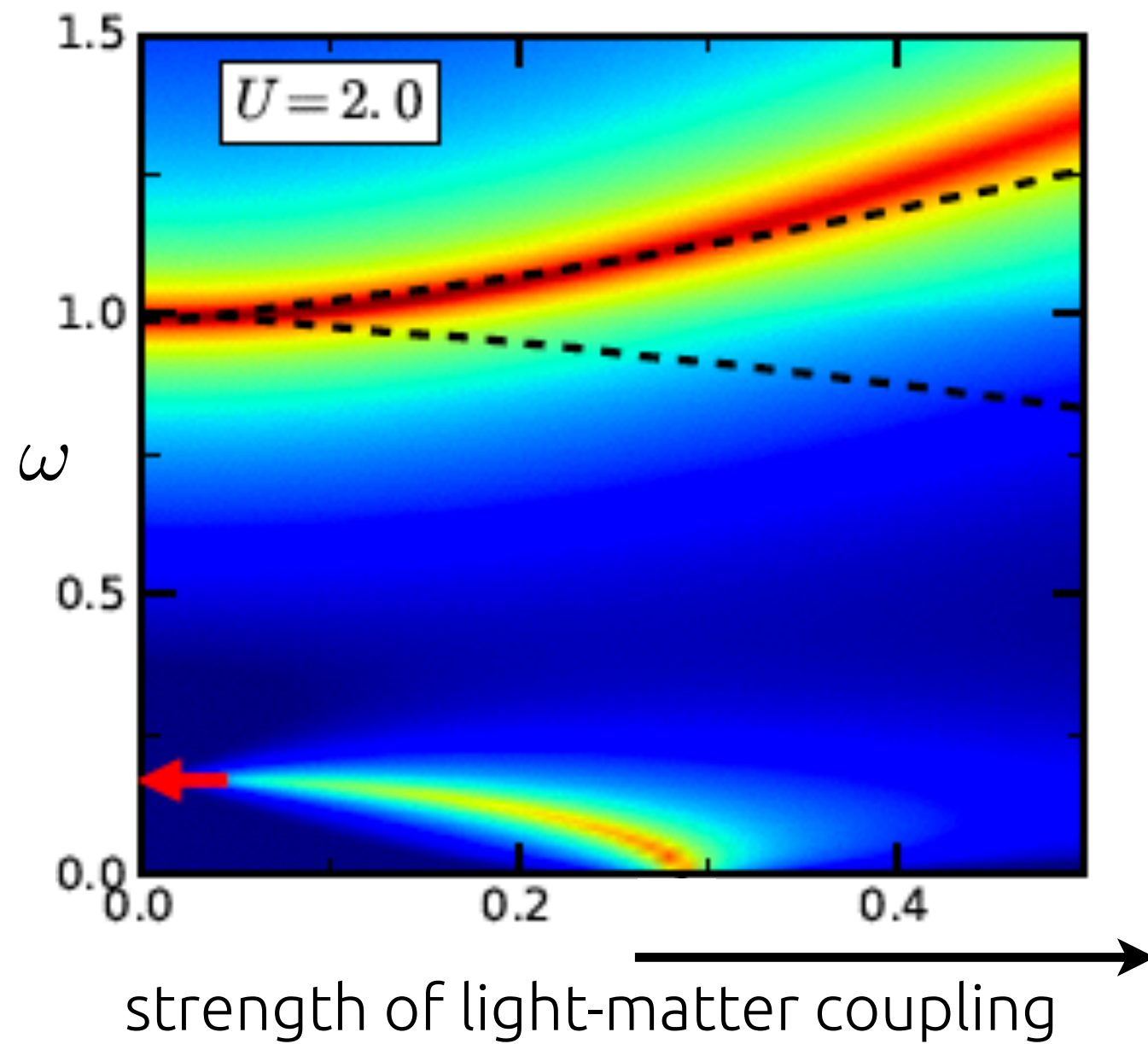
$$E_X \sim E_{\text{gap}} - E_{\text{binding}}$$



Form polaritons to stimulate the softening of the mode?

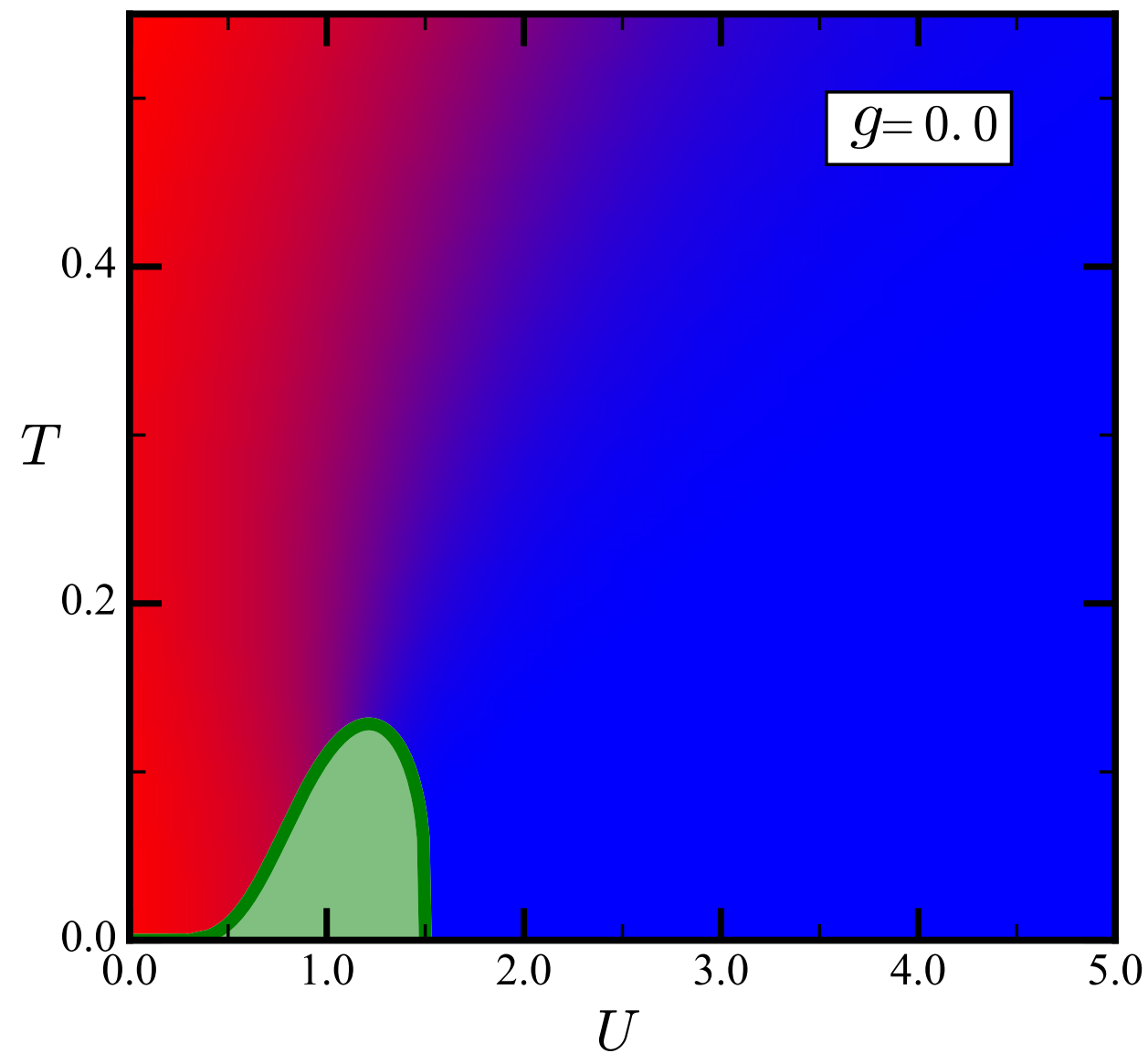
Excitonic insulators in cavities

G.Mazza&A.Georges *PRL*(2019)



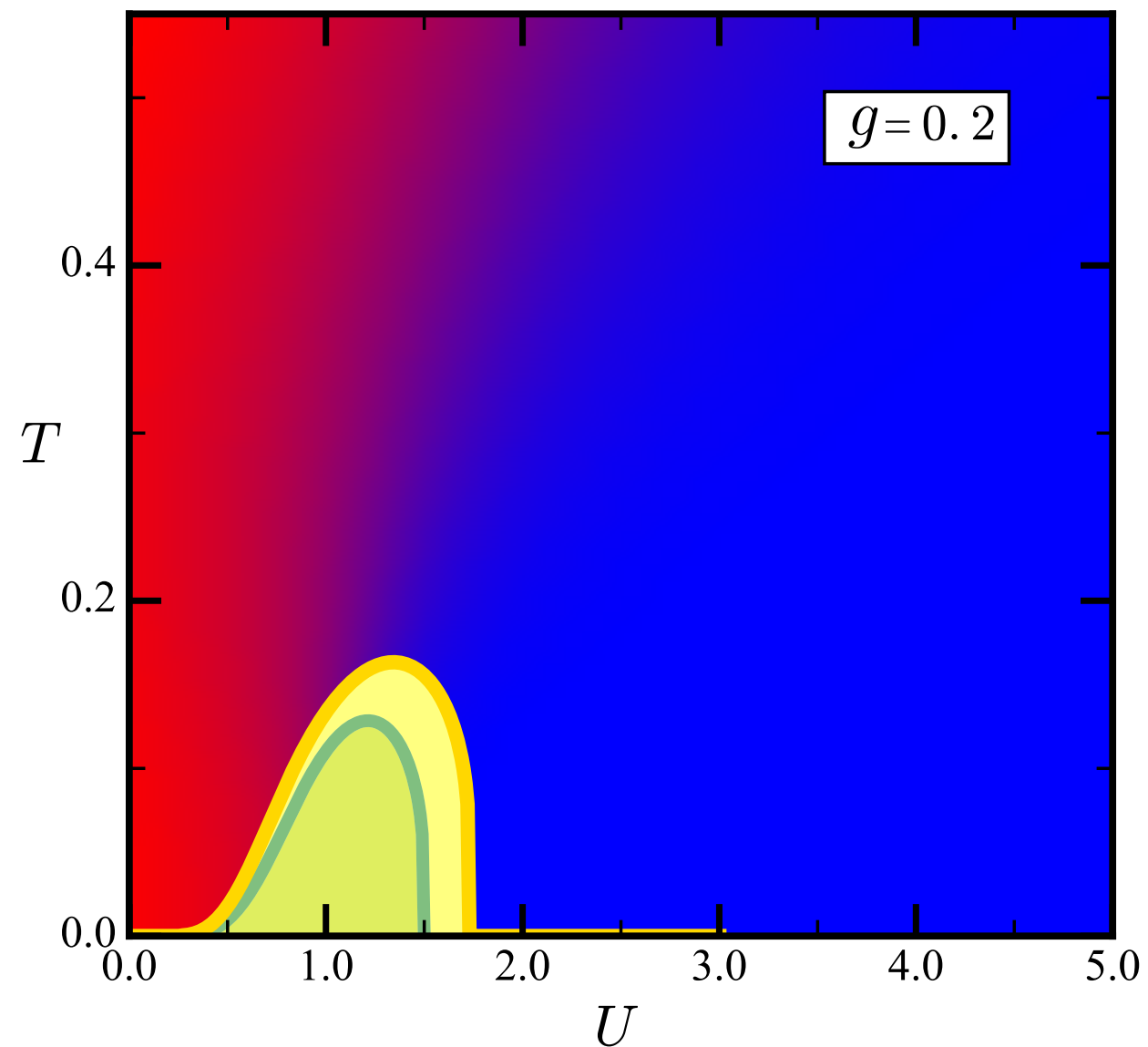
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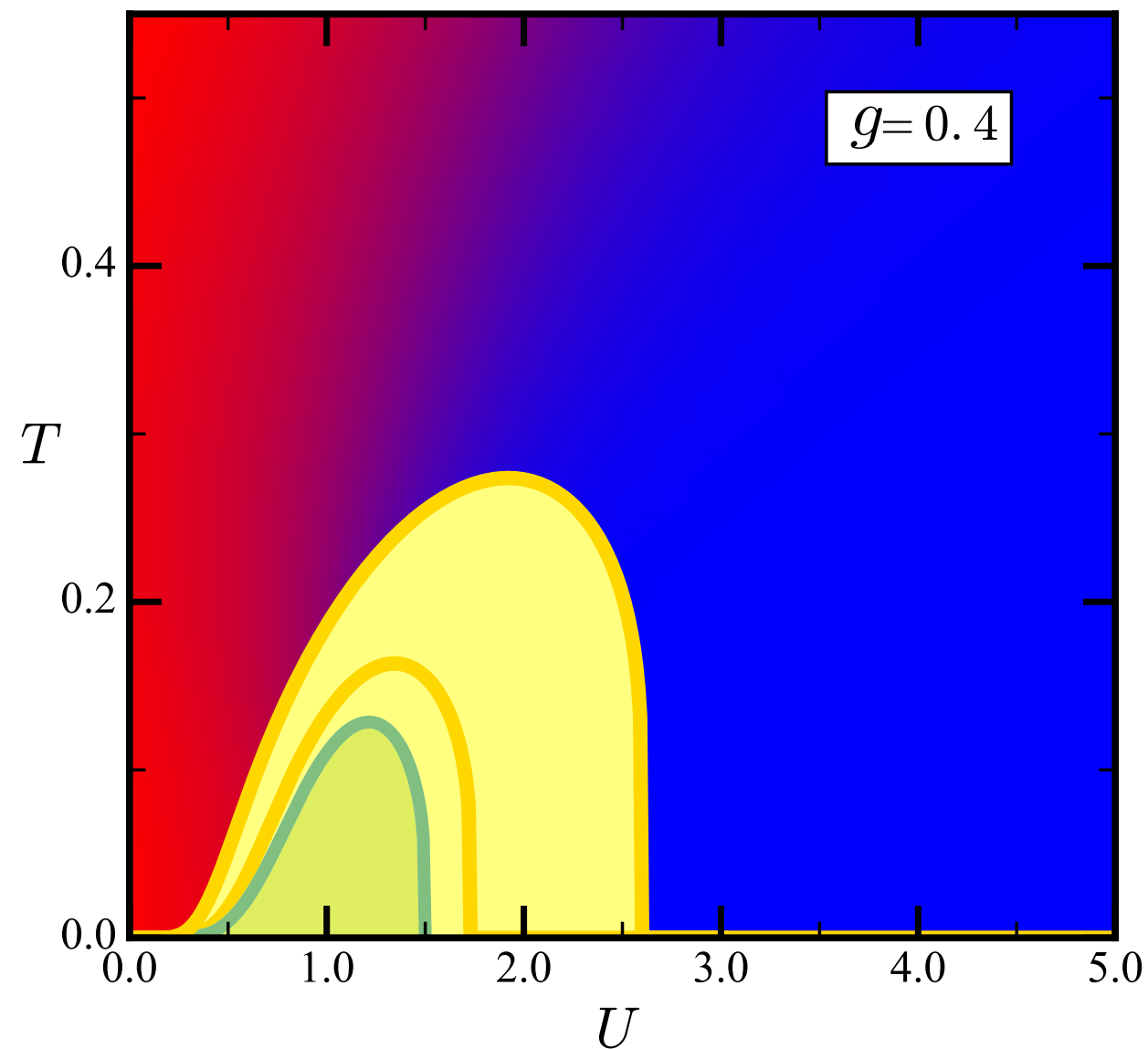
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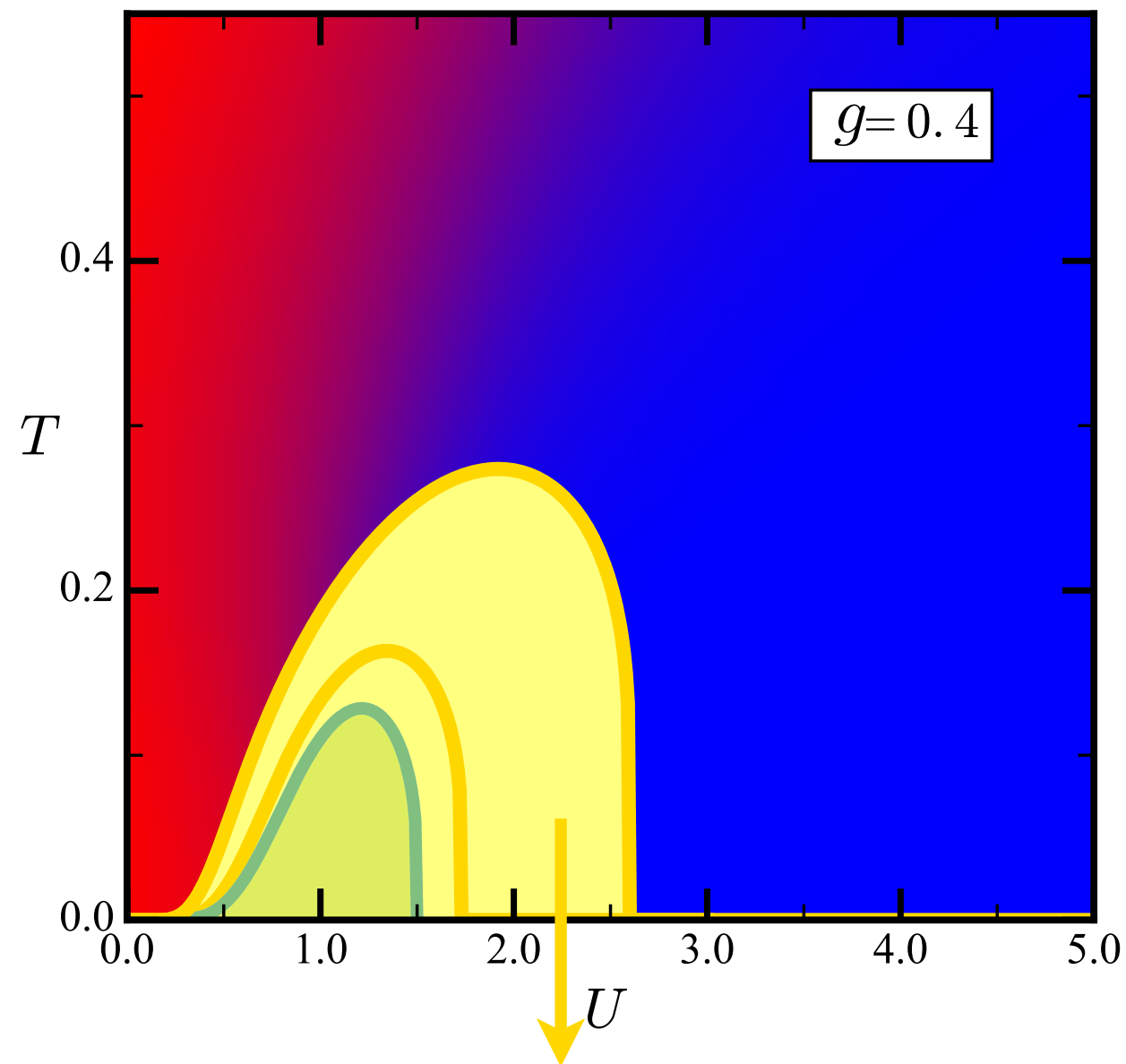
Excitonic insulators in cavities

G.Mazza&A.Georges *PRL*(2019)



Excitonic insulators in cavities

G.Mazza&A.Georges *PRL*(2019)



$$\Phi = \langle c_{i1}^\dagger c_{i2} \rangle \neq 0 \quad \& \quad \alpha = \langle a \rangle \neq 0$$

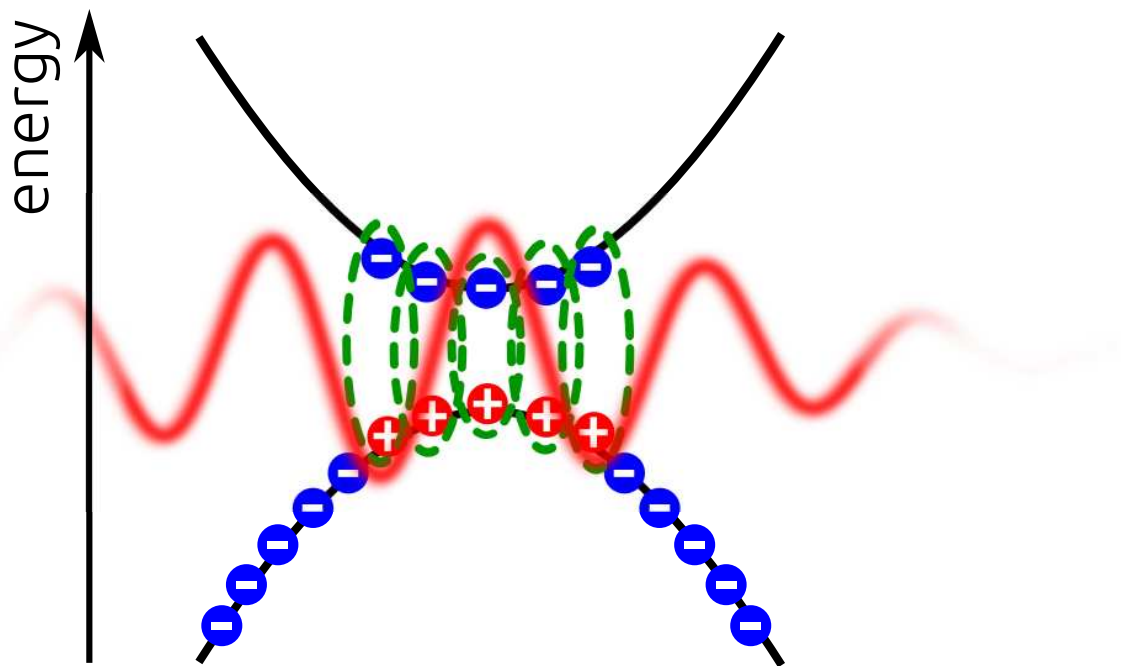
Simultaneous instability of matter and light

$$\Phi = \langle c_{i1}^\dagger c_{i2} \rangle \quad \alpha = \langle a \rangle$$

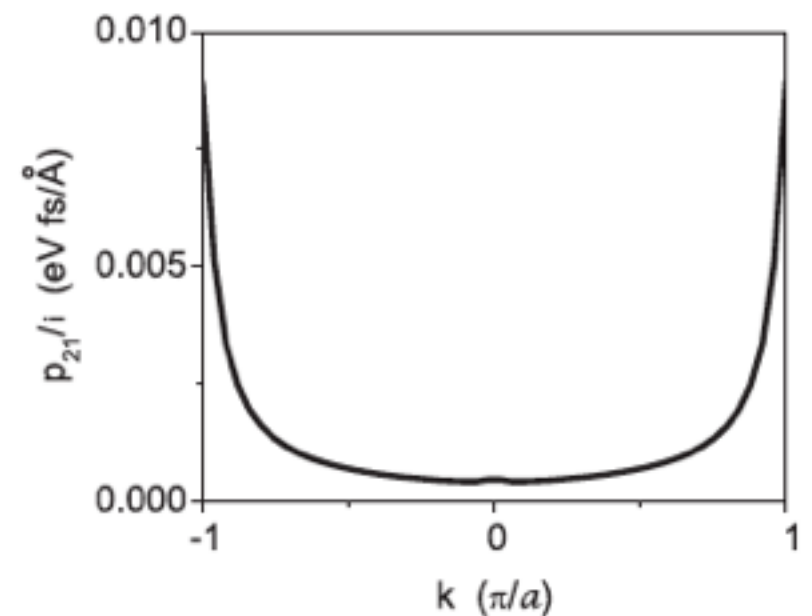
$$F[\alpha, \Phi] = a_\alpha \alpha^2 + a_\Phi \Phi^2 + 2k\alpha\Phi + b\Phi^4 + \dots$$

“Superradiant excitonic insulator”

$$k \sim g \sum_{\mathbf{k}} p_{12}(\mathbf{k})$$



See also Zhu and Littelwood '94



ex. Kronig-Penney model

Gu&al *PRB* '13

Superradiance - a misleading terminology-

$$H = \omega_0 a^\dagger a + \frac{\omega_{12}}{2} \sum_i \sigma_i^z + \frac{g}{\sqrt{N}} (a + a^\dagger) \sum_i (\sigma_i^+ + \sigma_i^-)$$

Hepp, Lieb *Annals of Physics* '73

Wang, Hioe *PRA* '73

GROUND STATE PHASE TRANSITION:
NOTHING RADIATES!

$$g < g_c$$

$$\langle a \rangle = 0$$

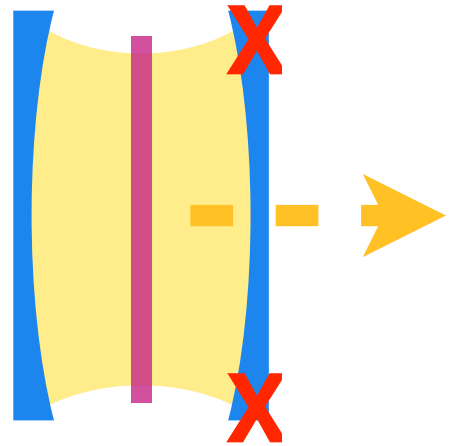
$$\langle \sigma^x \rangle = 0$$

$$g > g_c$$

$$\langle a \rangle \sim \sqrt{N}$$

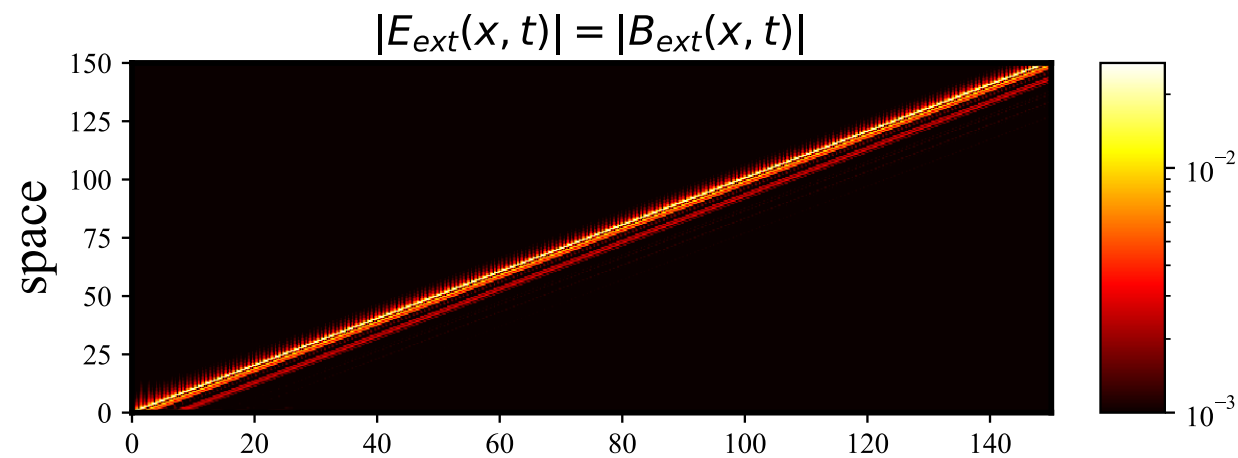
$$\langle \sigma^x \rangle \neq 0$$

Light emitted by opening the cavity

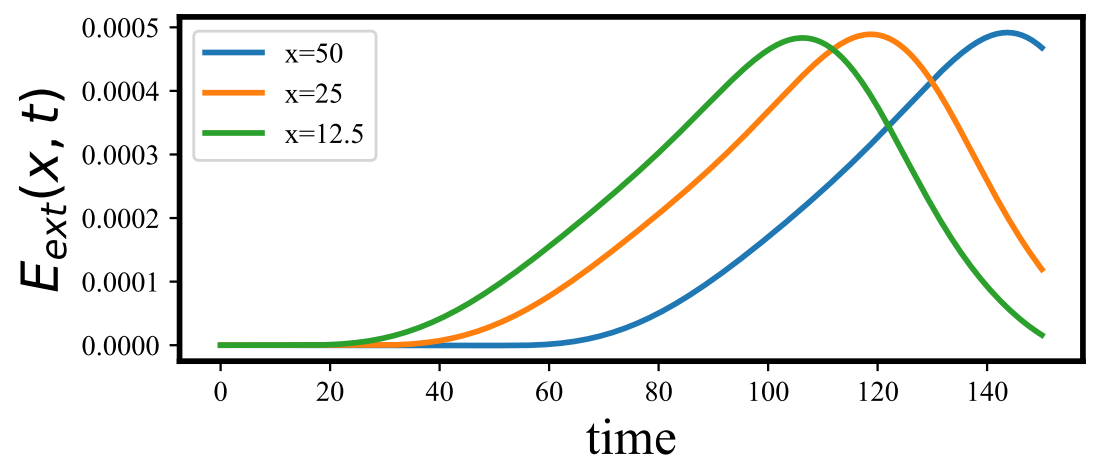
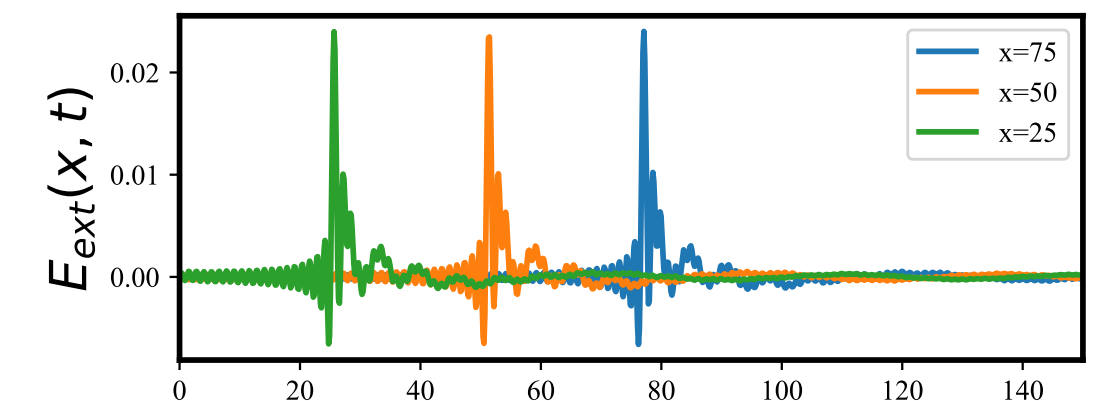
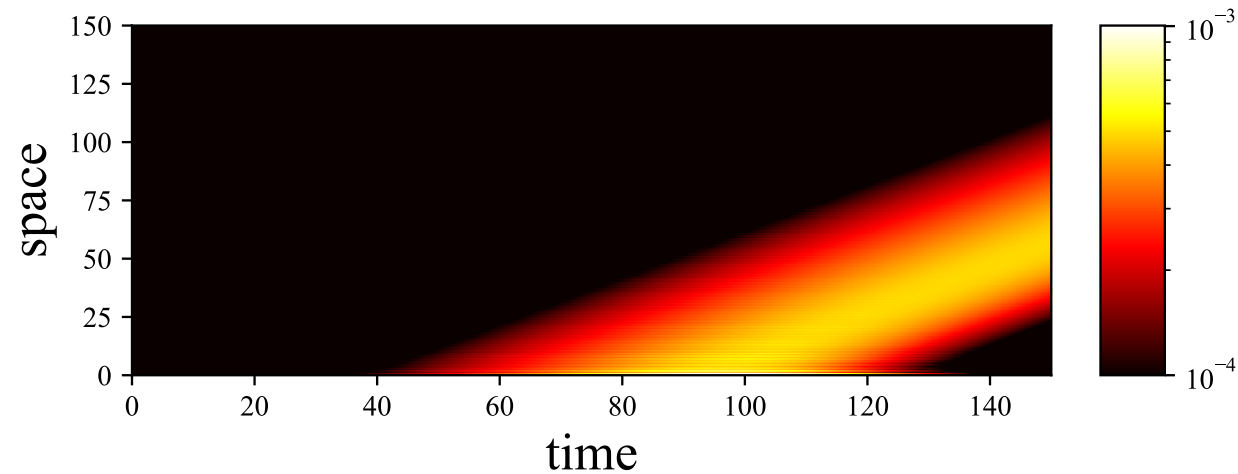


w/ Ivan Amelio and Iacopo Carusotto (Trento)

QUENCH



ADIABATIC



Superradiance - a misleading terminology-

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Hepp, Lieb *Annals of Physics* '73

Wang, Hioe *PRA* '73

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!! No-go's !!

Rzazewski et al PRL 1975

Birula, Rzazewski PRA 1979

Nataf, Ciuti NatComm 2010

Viehmann et al PRL 2011

Andolina et al 2019

Superradiance - a misleading terminology-

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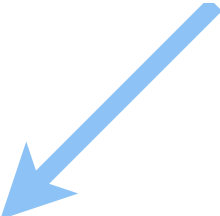
GROUND STATE PHASE TRANSITION:
NOTHING RADIATES!

$$\begin{aligned} g &< g_c \\ \langle a \rangle &= 0 \\ \langle \sigma^x \rangle &= 0 \end{aligned}$$

$$\begin{aligned} g &> g_c \\ \langle a \rangle &\sim \sqrt{N} \\ \langle \sigma^x \rangle &\neq 0 \end{aligned}$$

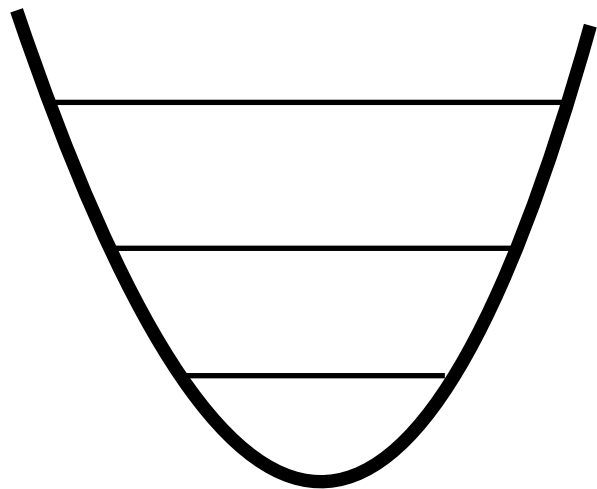
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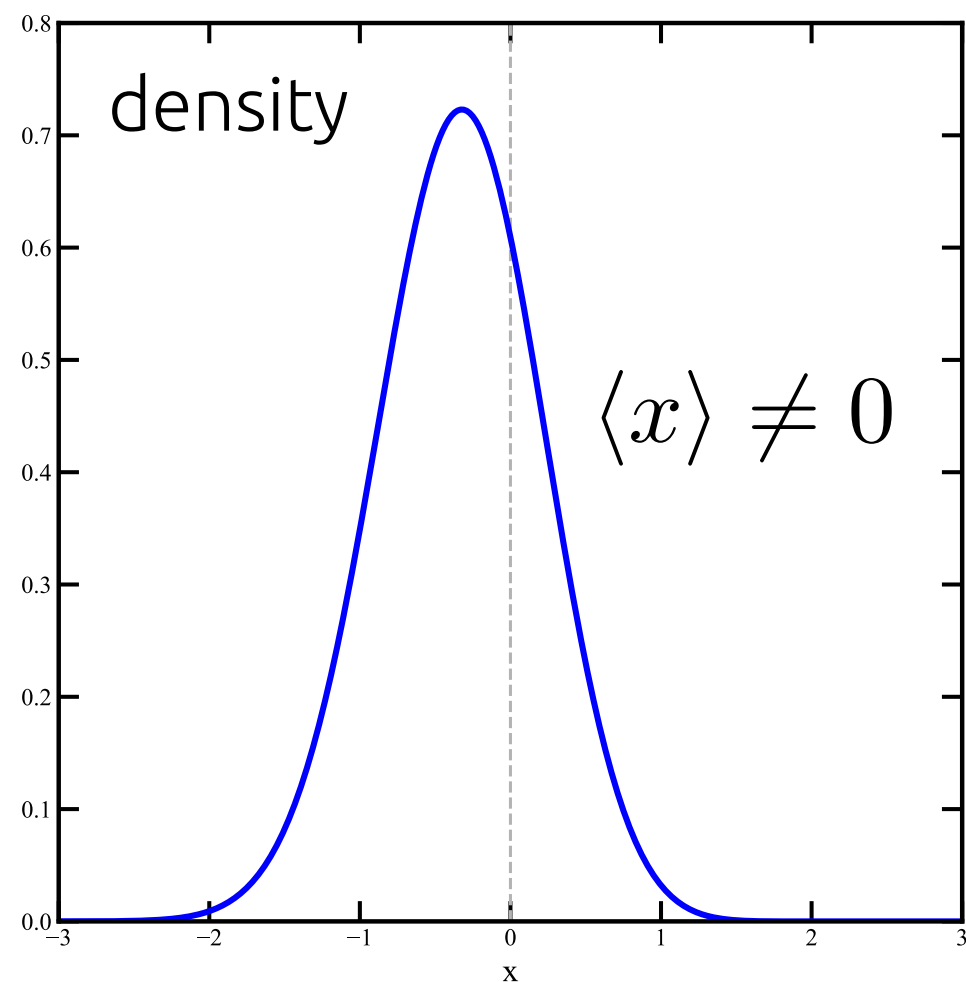
This is an excitonic insulator!

Level hybridization in an single dipole

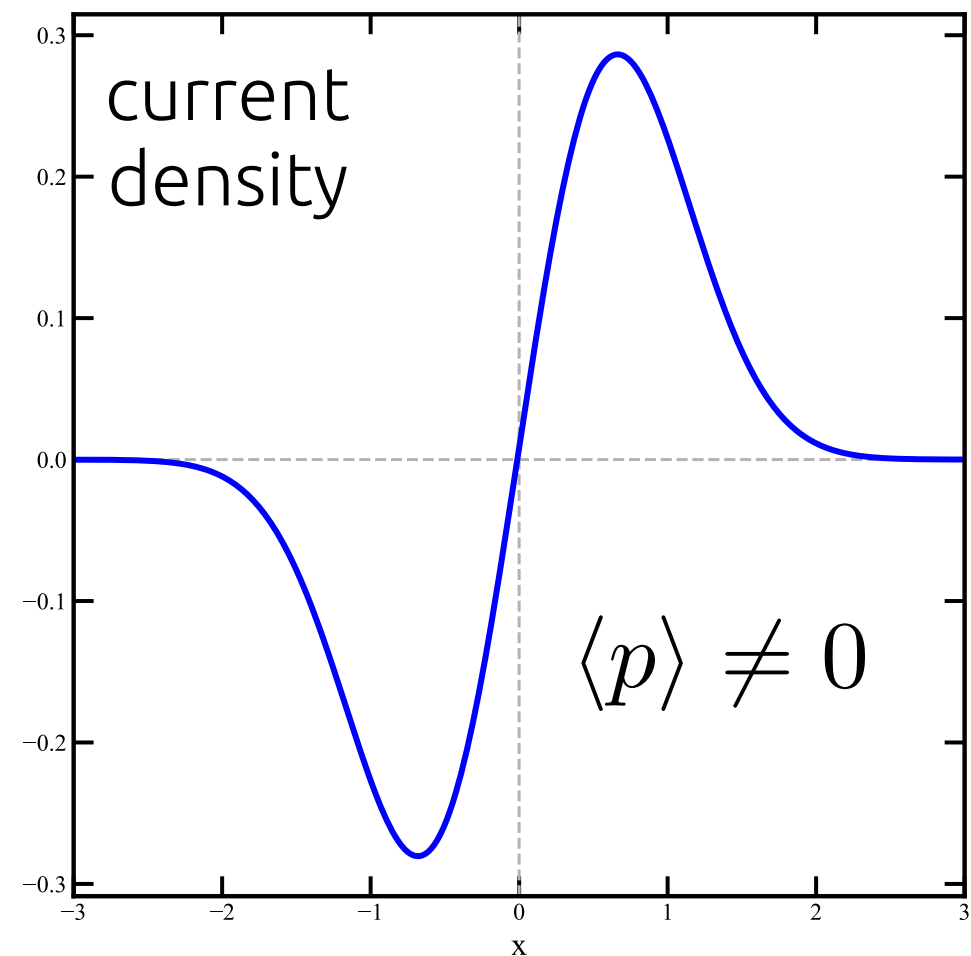


$$H_0 \rightarrow H_0 + \lambda |1\rangle \langle 2| + \lambda^* |2\rangle \langle 1|$$

λ real



λ imaginary



Degenerate phases of the excitonic insulator

The phase of the order parameter determines the macroscopic state of the system

$$\Phi = |\Phi|e^{i\varphi}$$

$$\varphi = 0$$



CDW / Ferroelectric

$$\varphi = \pi/2$$



"Ferrocurent"

Degenerate phases of the excitonic insulator

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CDW / Ferroelectric

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"Ferrocurent"

Coupling with light lowers the energy of the "ferrocurent" state

Ferrocurrent excitonic insulator ?

Dielectric phase transition into a current state

B. A. Volkov and Yu. V. Kopaev

P. N. Lebedev Physics Institute, USSR Academy of Sciences

(Submitted 20 October 1977)

Pis'ma Zh. Eksp. Teor. Fiz. **27**, No. 1, 10–13 (5 January 1978)

Volkov&al '78/Volkov&al '81/Gorbatsevich&al '80

Breaking down in domain walls
and creation of current patterns

see also

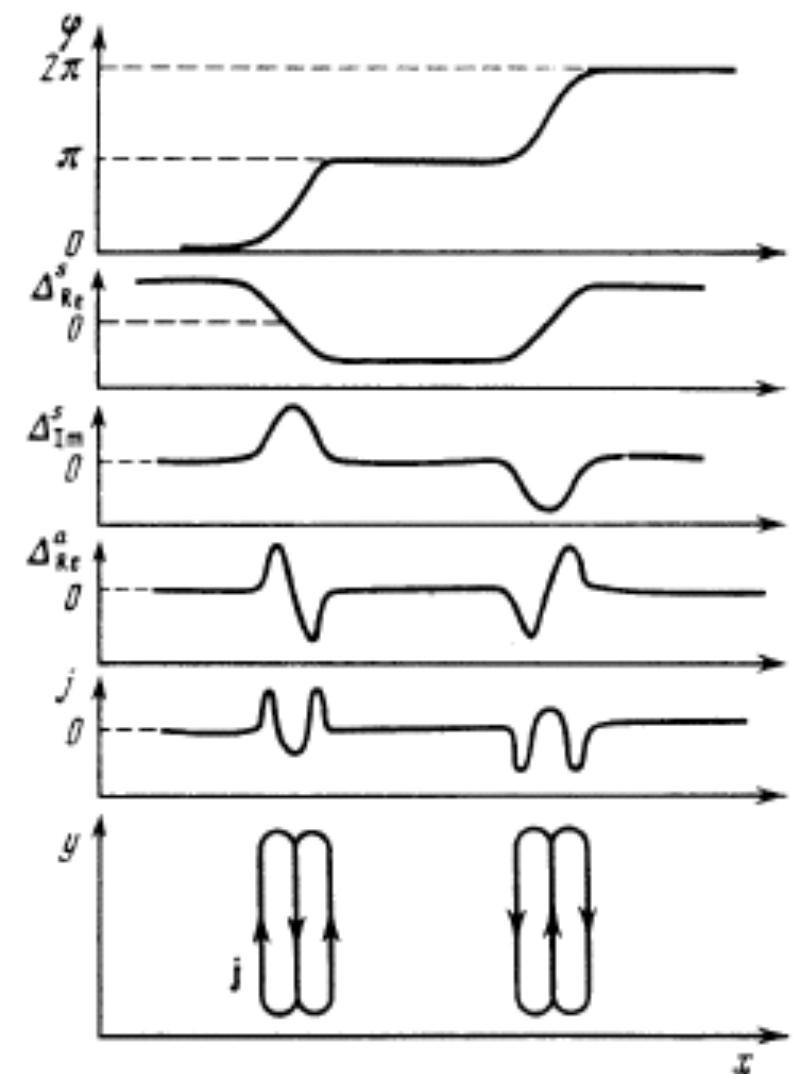
spin current in excitonic magnets

Geffroy&al PRB 2018 (DMFT)

Nishida&al PRB 2019

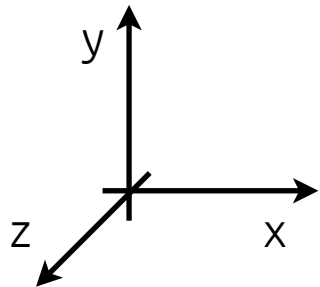
periodic(or infinite) system

$$p \neq \dot{x}$$

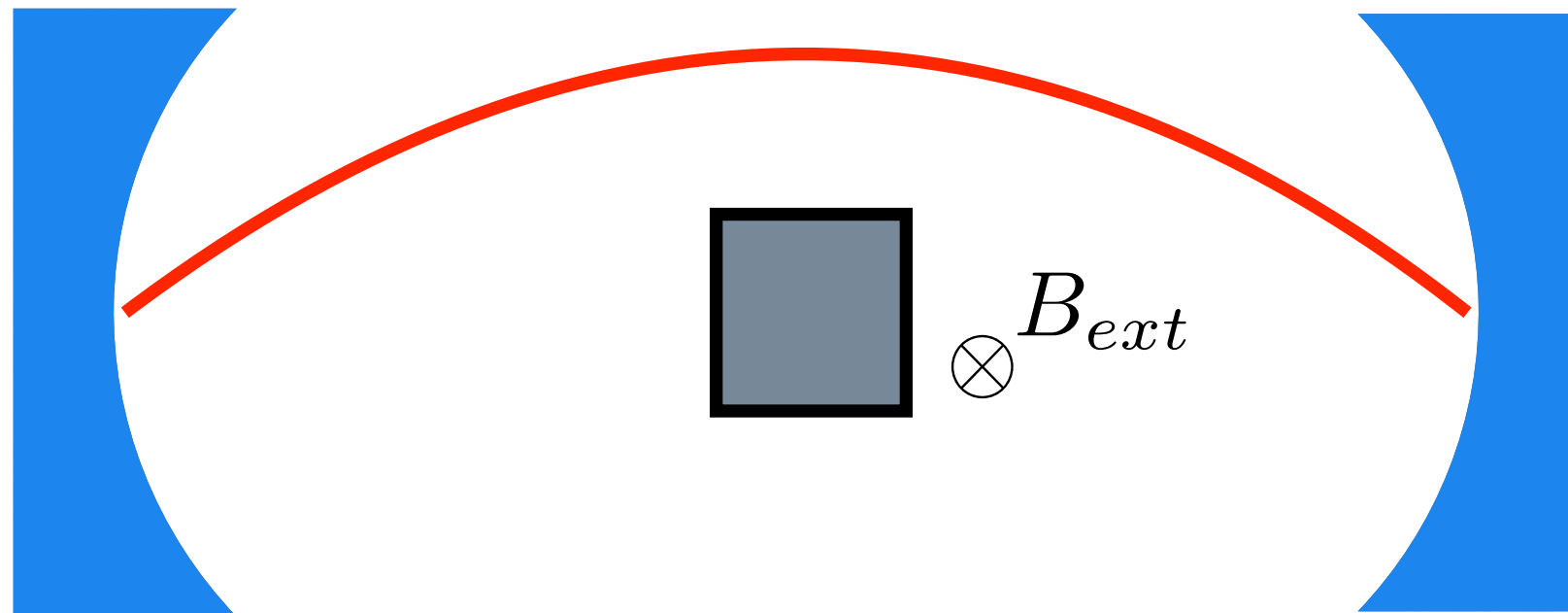


Polarized dipole in a cavity

$$H = \frac{p_x^2 + p_y^2}{2m} + V(x, y) + \frac{e}{m} A_y(x) p_y + \frac{e^2}{2m} A_y^2(x)$$

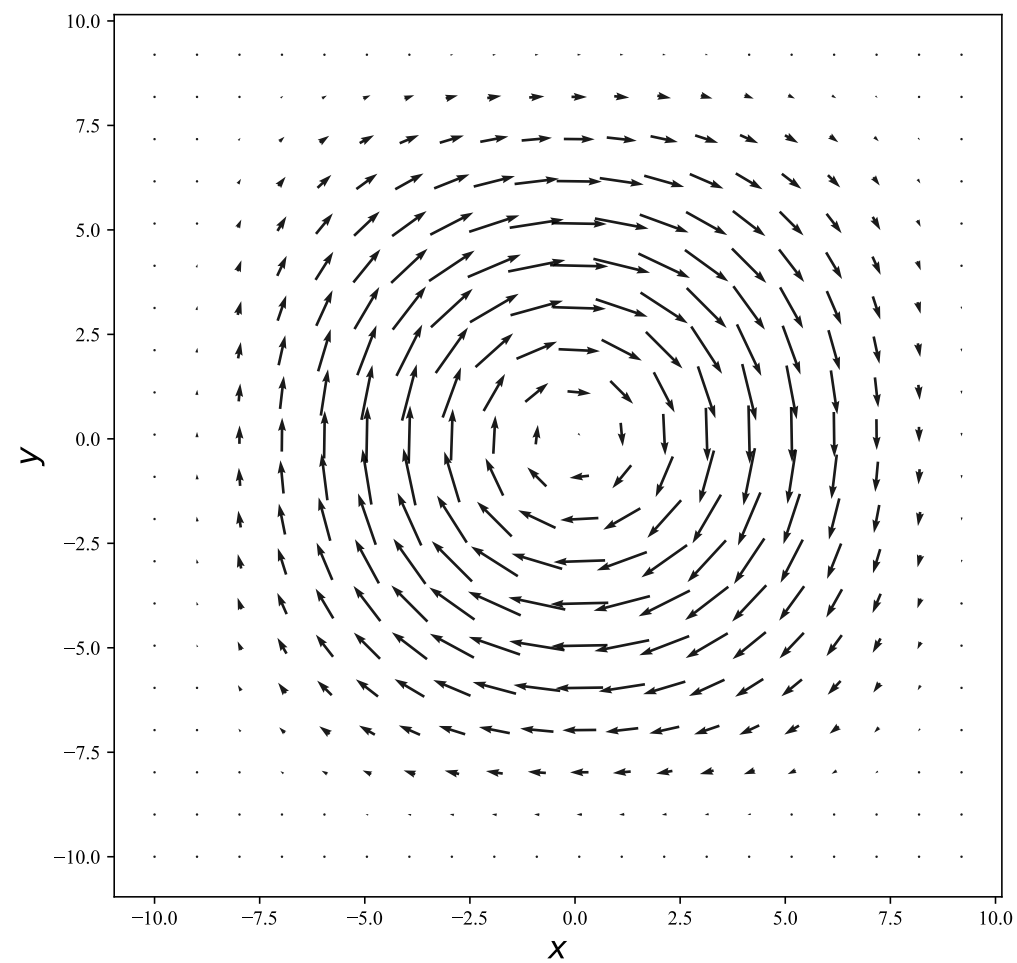


$$A_y(x) = A_0 \sin(\pi/Lx) (a^\dagger + a)$$



Polarized dipole in a cavity

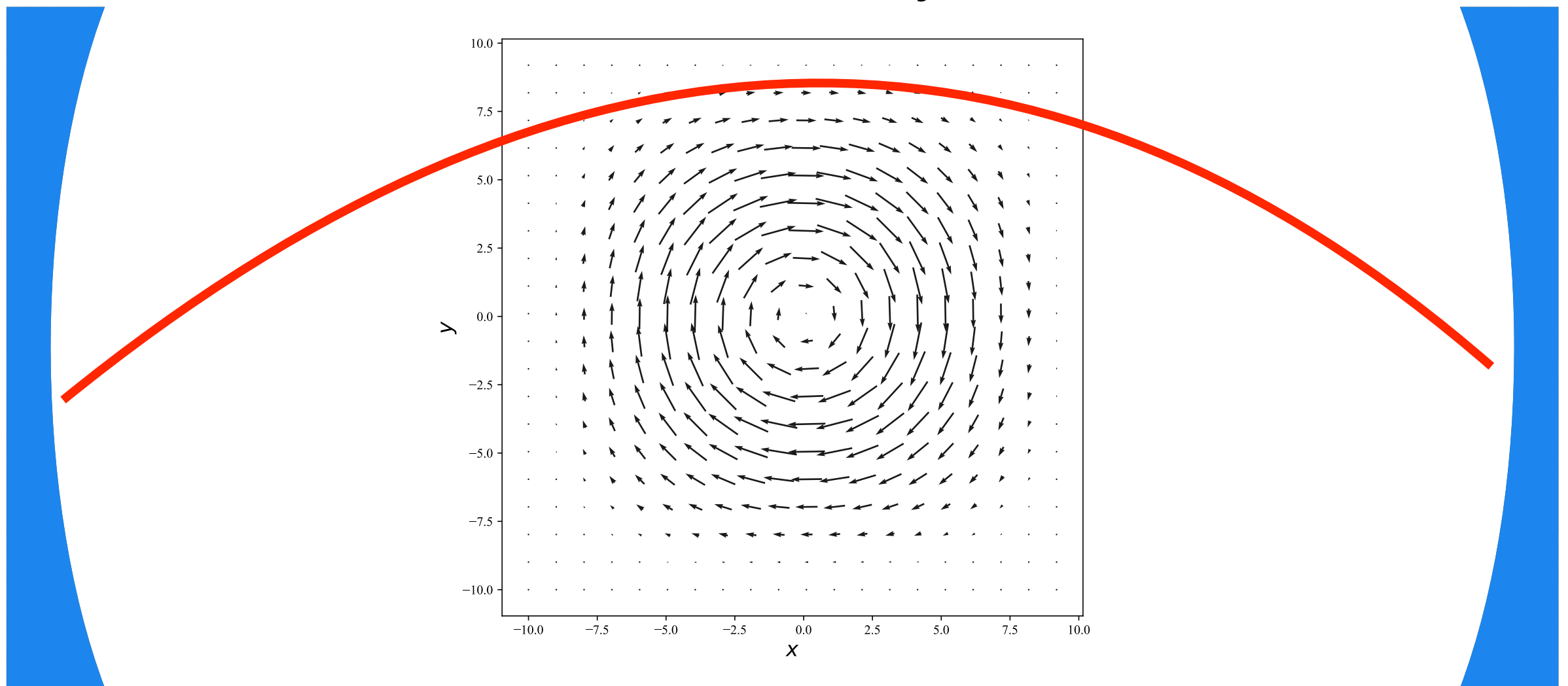
current density



Polarized dipole in a cavity

$$H_{l-m} \sim j_y(x) \sin(\pi/Lx)(a + a^\dagger)$$

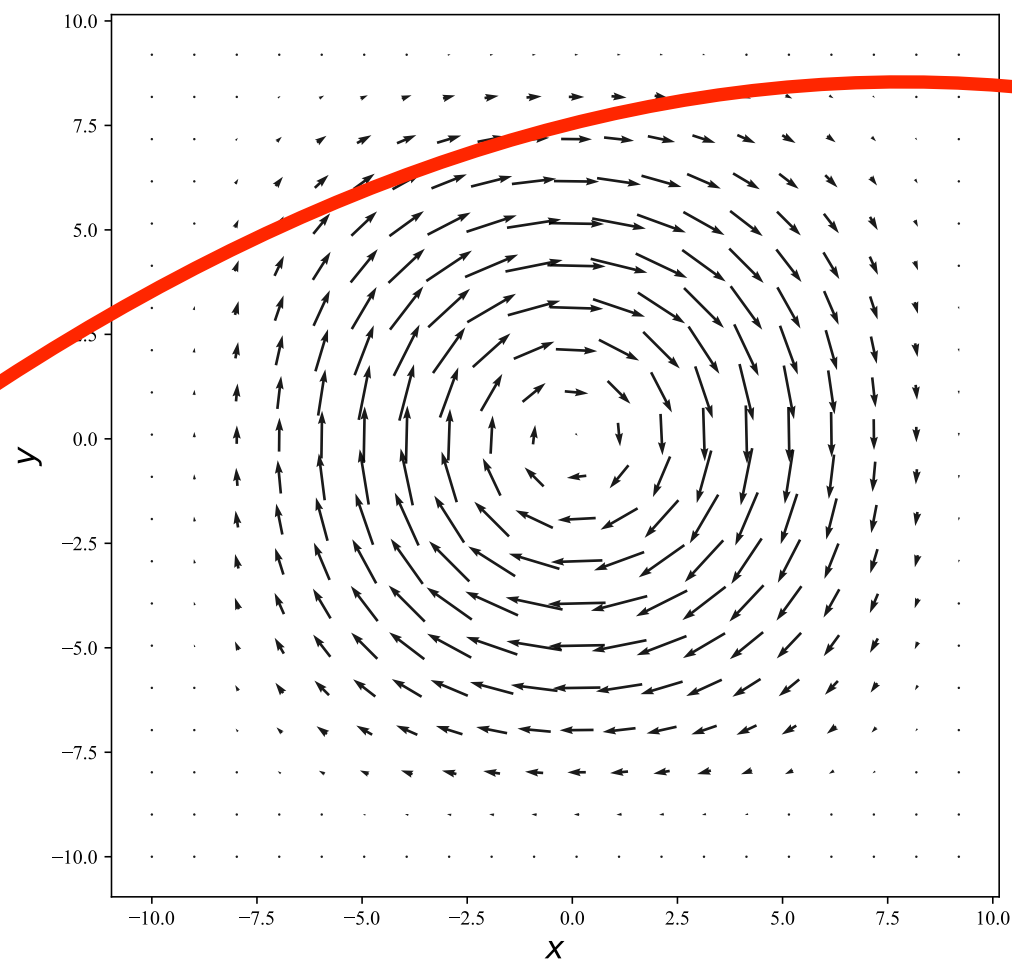
current density



Polarized dipole in a cavity

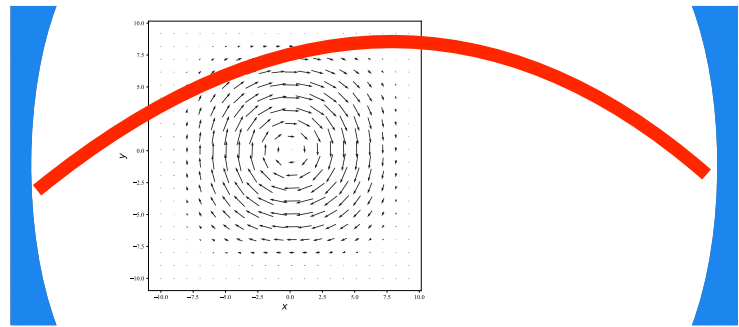
$$H_{l-m} \sim j_y(x) \sin(\pi/Lx)(a + a^\dagger)$$

current density

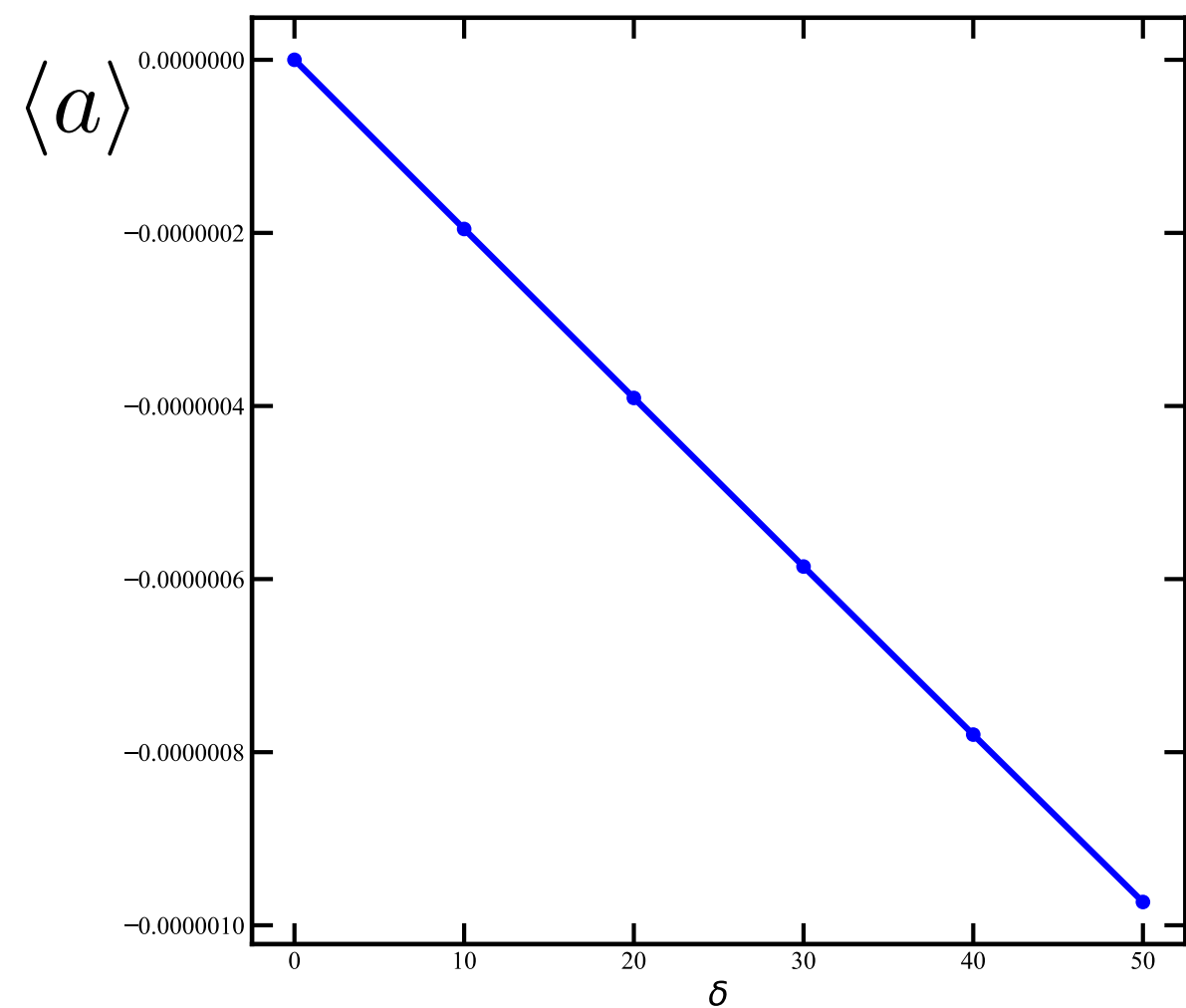


Polarized dipole in a cavity

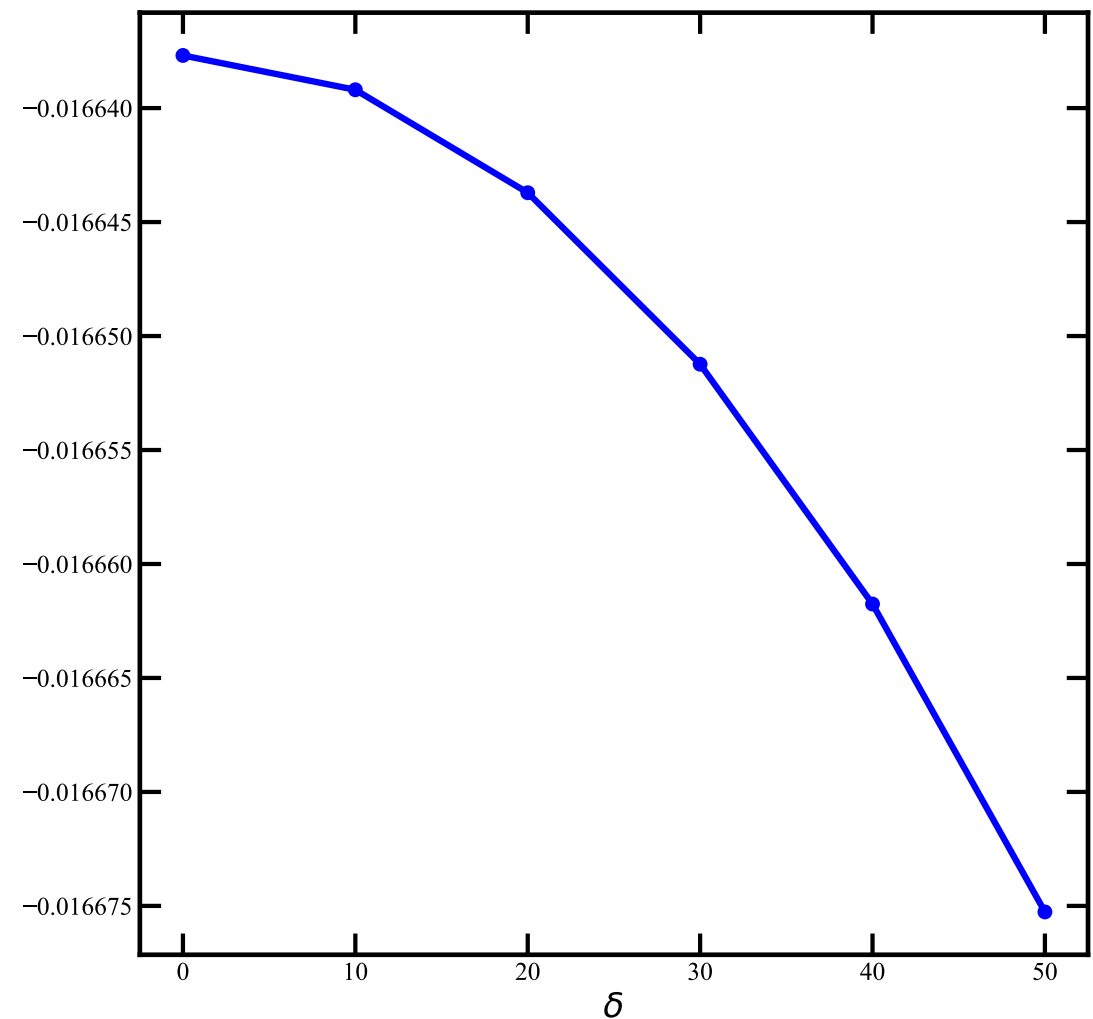
$$H_{l-m} \sim j_y(x) \sin(\pi/Lx)(a + a^\dagger)$$



photon expectation value



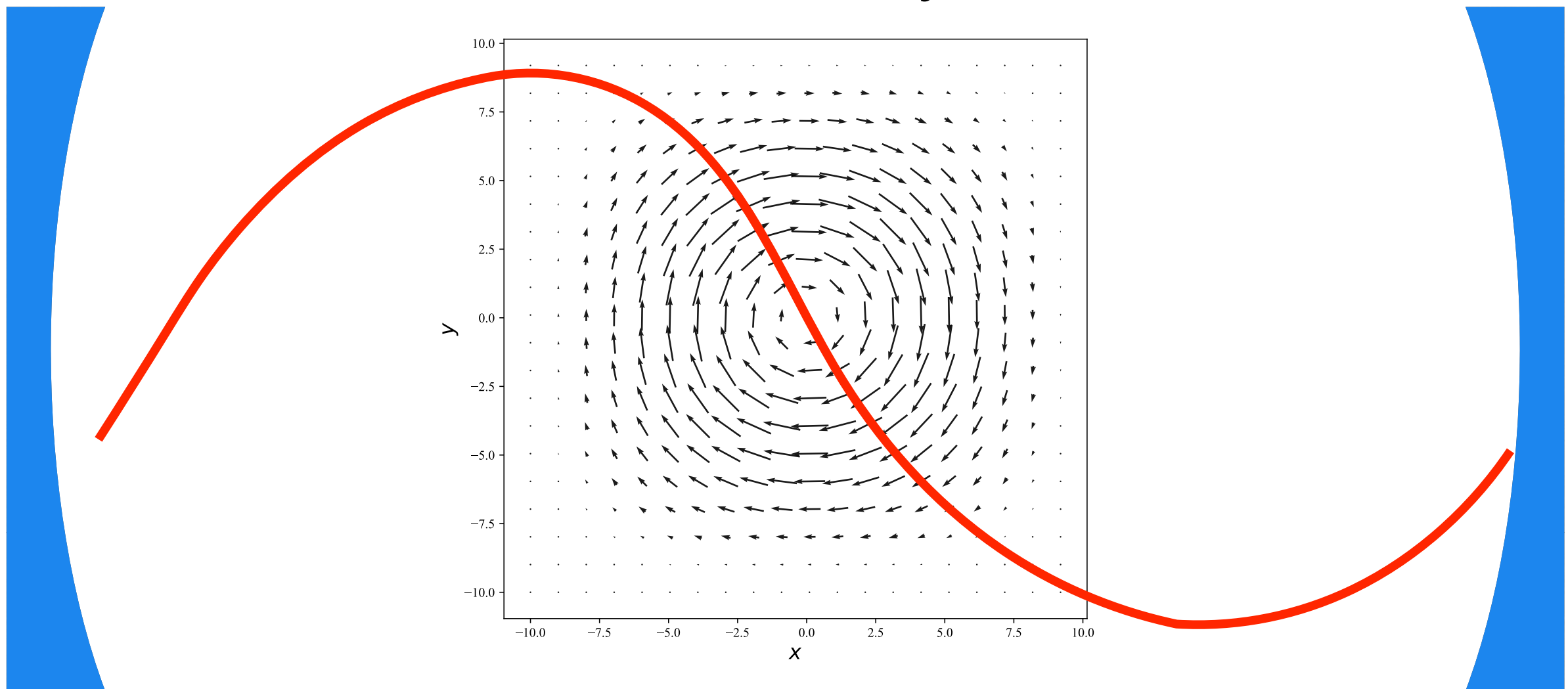
magnetic moment



Polarized dipole in a cavity

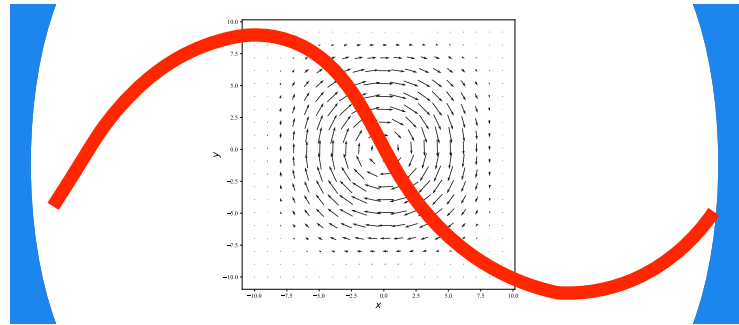
$$H_{l-m} \sim j_y(x) \sin(2\pi/Lx)(a + a^\dagger)$$

current density

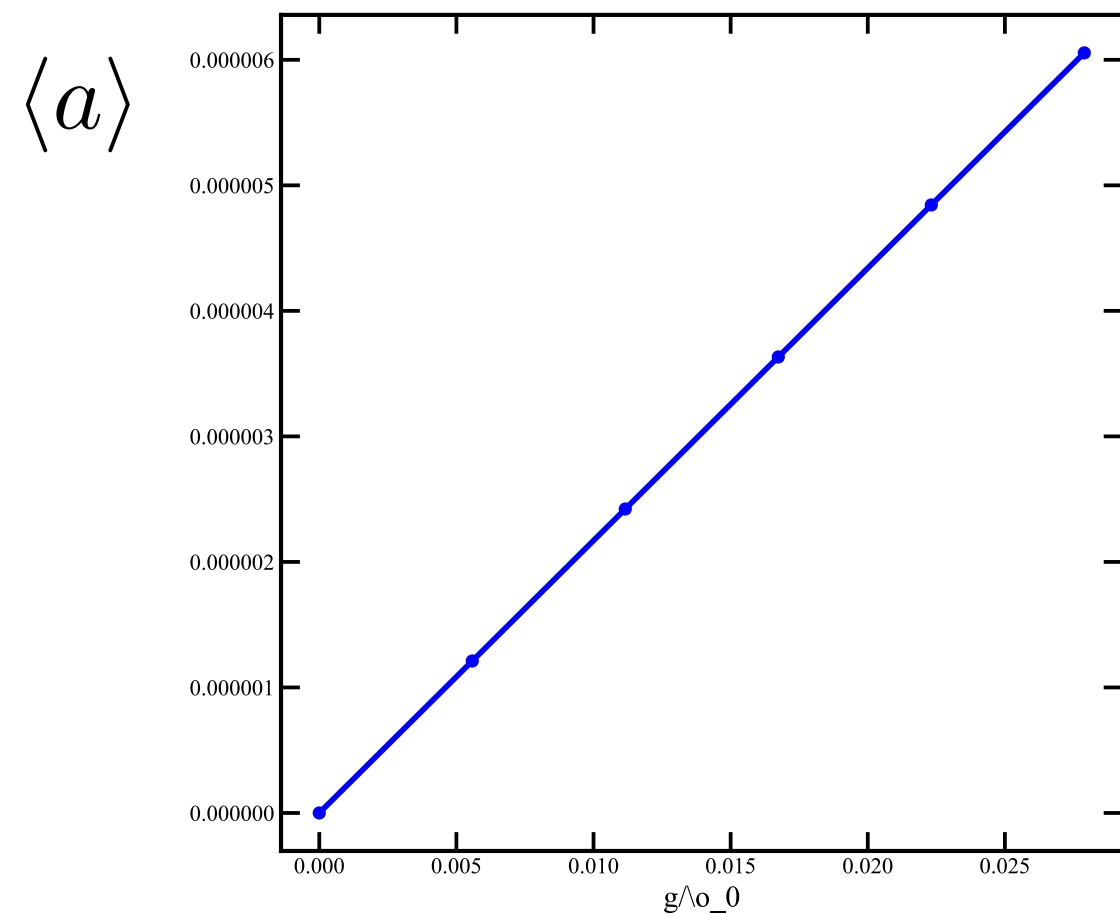


Polarized dipole in a cavity

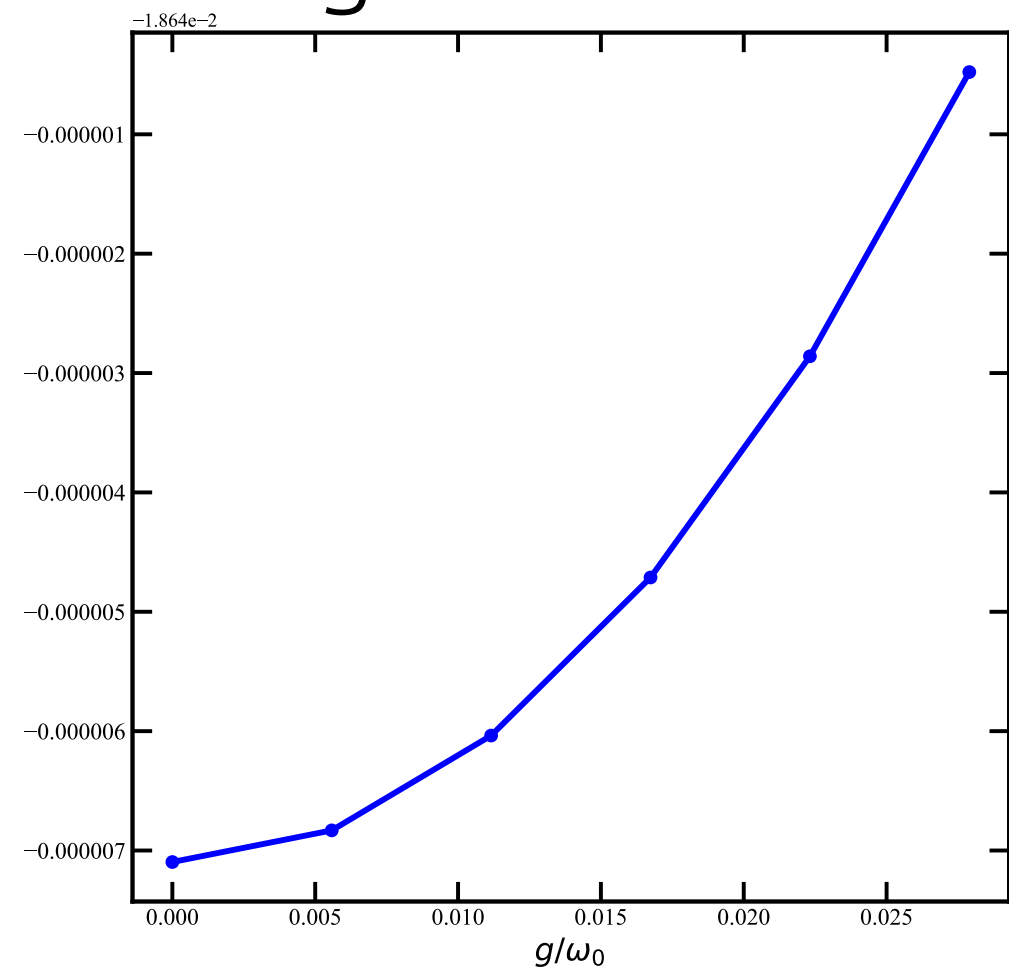
$$H_{l-m} \sim j_y(x) \sin(2\pi/Lx)(a + a^\dagger)$$



photon expectation value



magnetic moment



Outlook

Excitonic Insulators in Cavities

Polarization of excitonic insulator materials
(e.g. current pattern)

Coupling with vacuum fluctuations

Interaction with external fields