Is the Hofstadter energy spectrum observable in far-infrared absorption?

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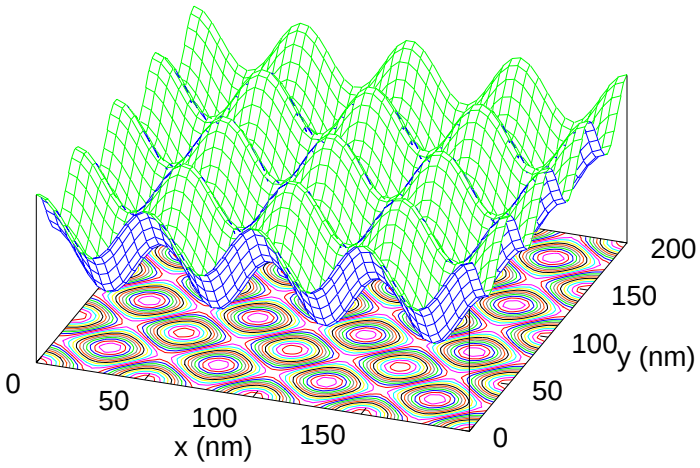
Goals

- Bernstein modes?
- Effects of modulation
- Is the Hofstadter butterfly visible?



Ground state

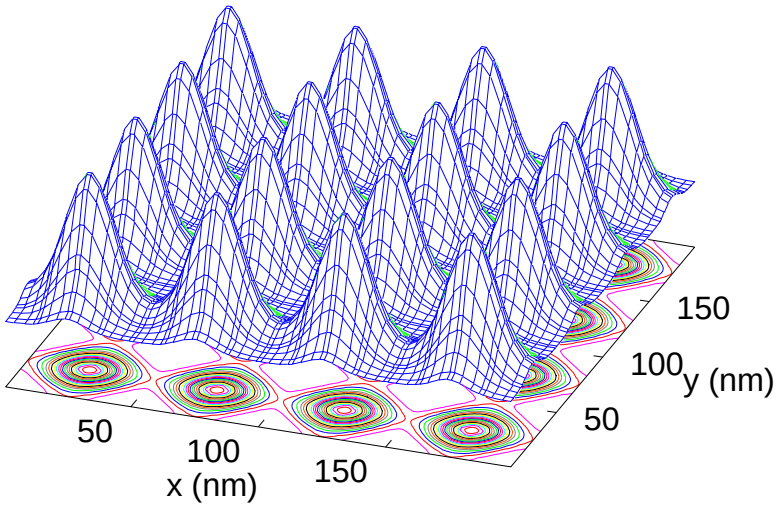
2DEG in a periodic potential

$$V(x,y) = V\left\{\cos(gx) + \cos(gy)\right\}$$

$g = 2\pi/L$, with the periodic length L

Perpendicular magnetic field $\vec{B} = B\hat{z}$

Integer number pq of flux units $\Phi_0 = hc/e$ flows through a lattice unit cell with area $A = L^2 \longrightarrow B = pq\Phi_0/A$



Magnetic length: $l = \sqrt{c\hbar/eB}$

Cyclotron frequency: $\omega_c = eB/m^*c$

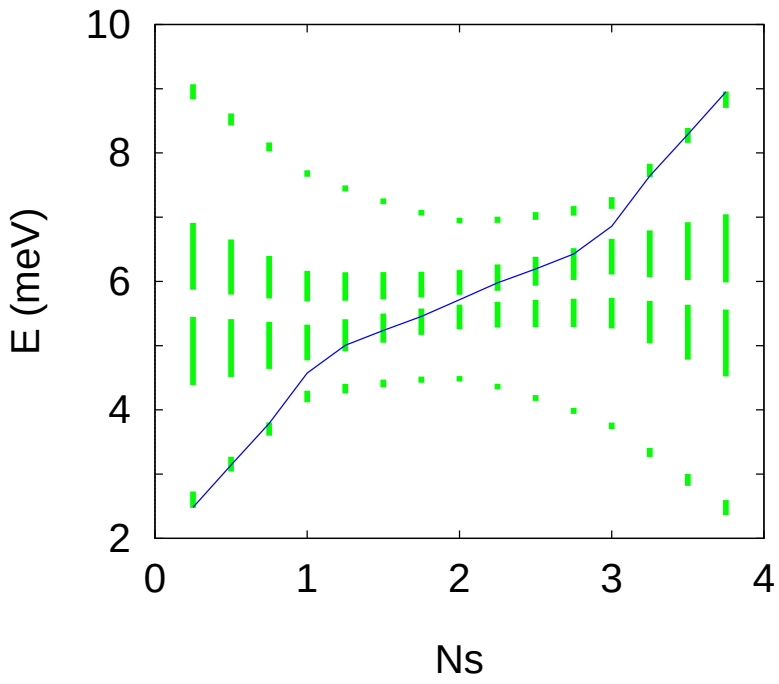
Commensurability between l and L splits each Landau level into pq subbands

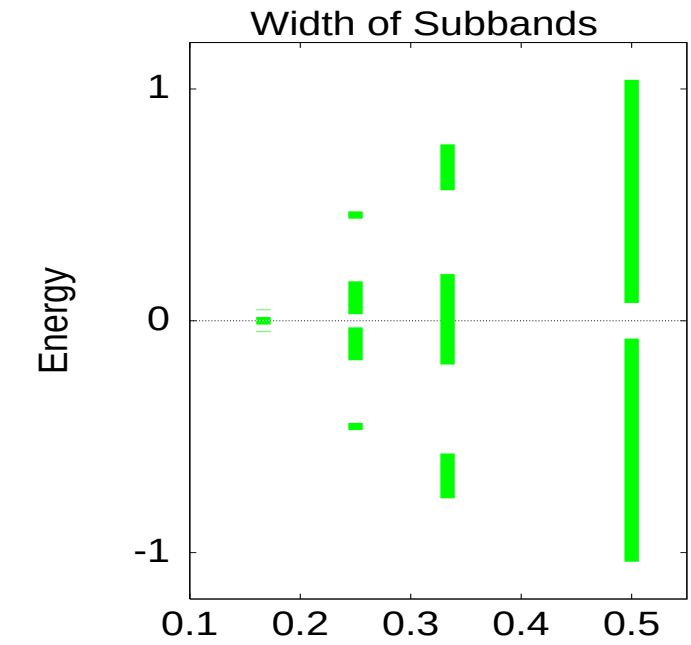
Hartree interacting electrons

Finite temperature T

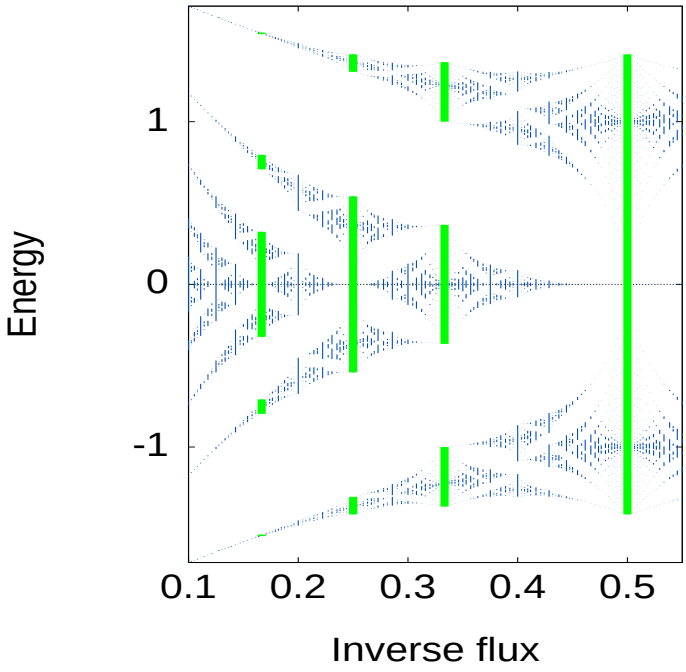
N_s electrons in a unit lattice cell

Filling factor of Landau levels is $\nu = N_s/pq$





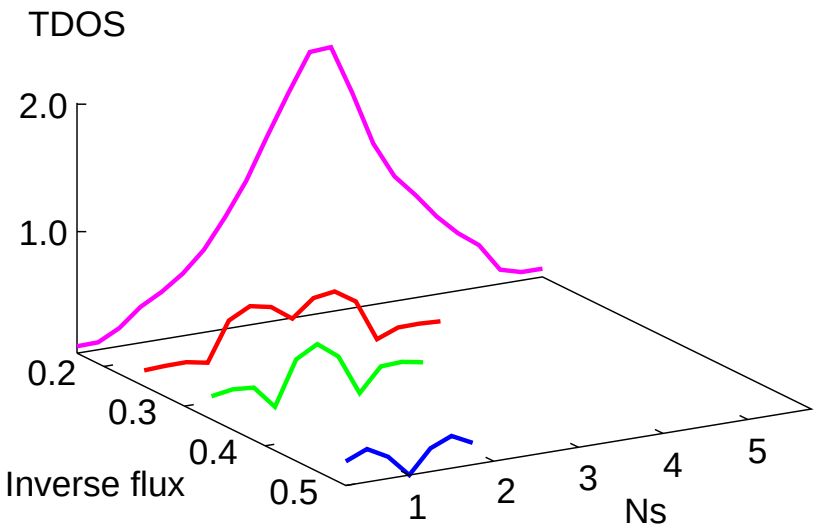
Interacting



Non interacting

L=50nm, V=4meV, T=1K, one Landau level

Subbands can be seen in TDOS!



Can they be seen in FIR?

Is strong modulation and short period needed?

What are the effects of ν?

FIR-absorption

Self-consistent response to the in-field

$$\mathbf{E}_{ext}(\mathbf{r},t) = -i\mathcal{E}_0 \frac{\mathbf{k}+\mathbf{G}}{|\mathbf{k}+\mathbf{G}|} \exp\left\{i(\mathbf{k}+\mathbf{G})\cdot\mathbf{r} - i\omega t\right\}$$

System properties $\rightarrow \epsilon_{\mathbf{G},\mathbf{G}'}(\mathbf{k},\omega) \rightarrow$
self-consistent field $-\nabla\phi_{sc}$

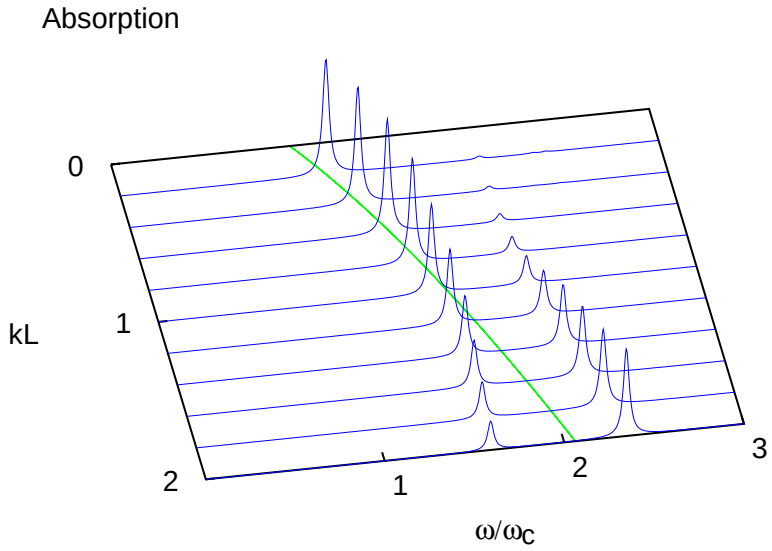
$$\sum_{\mathbf{G}'} \epsilon_{\mathbf{G},\mathbf{G}'}(\mathbf{k},\omega)\phi_{sc}(\mathbf{k}+\mathbf{G}',\omega) = \phi_{ext}(\mathbf{k}+\mathbf{G},\omega)$$

Joule heating $\rightarrow$ power absorption

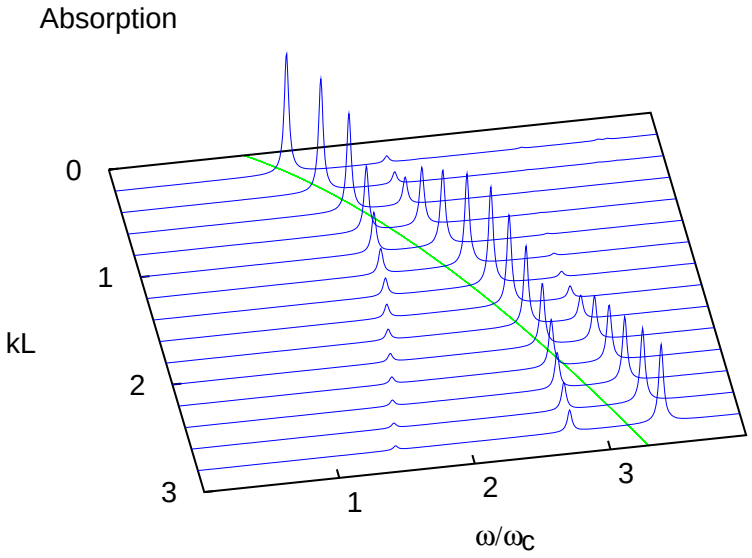
$$P(\mathbf{k}+\mathbf{G},\omega) = -\frac{\omega}{4\pi}\Im\{\mathcal{E}_0\phi_{sc}(\mathbf{k}+\mathbf{G},\omega)\}$$

No modulation, Bernstein modes

L=100nm, pq=1, $h\omega_c$=0.715meV, T=1K, V=0.0meV, Ns=0.25



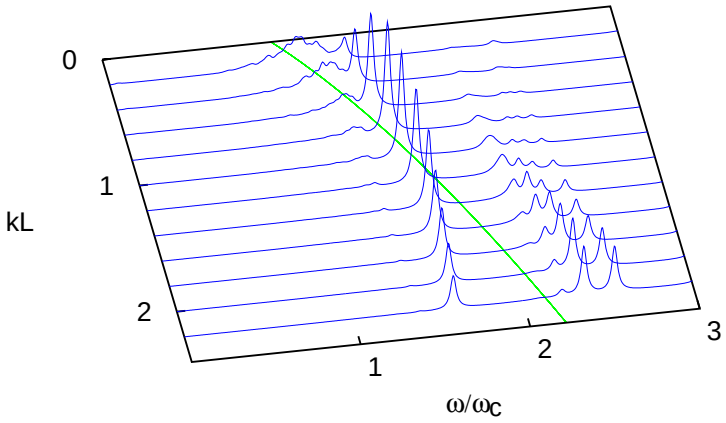
L=200nm, pq=1, $h\omega_c$=0.1786meV, T=1K, V=0.0meV, Ns=1.00

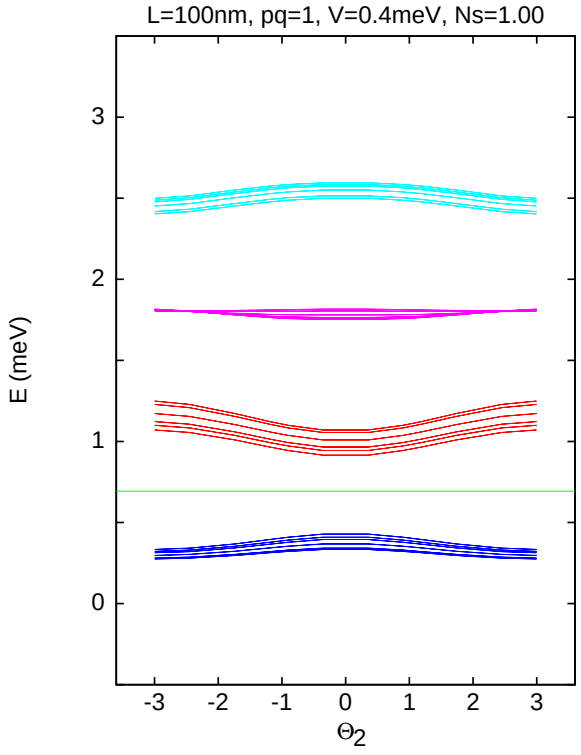


Modulation, $pq = 1$, $\nu = 1$

L=100nm, pq=1, $h\omega_c$=0.715meV, T=1K, V=0.4meV, Ns=1.00

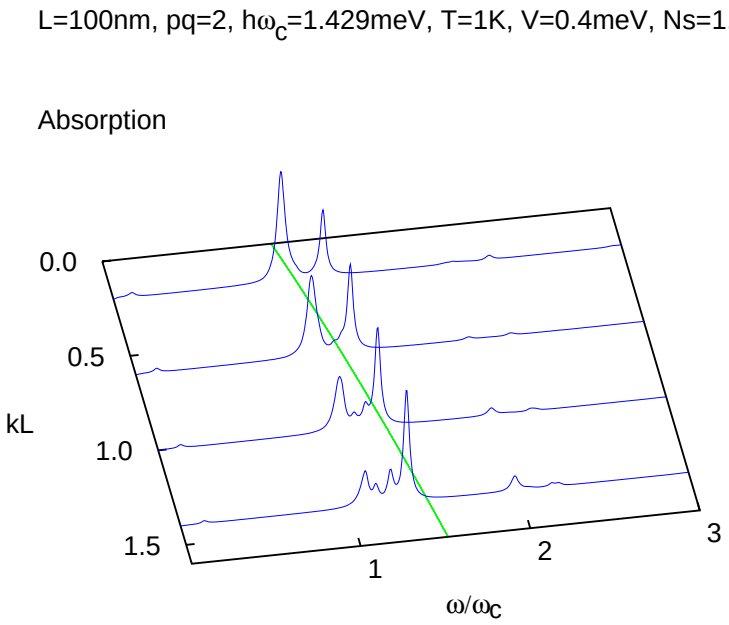
Absorption

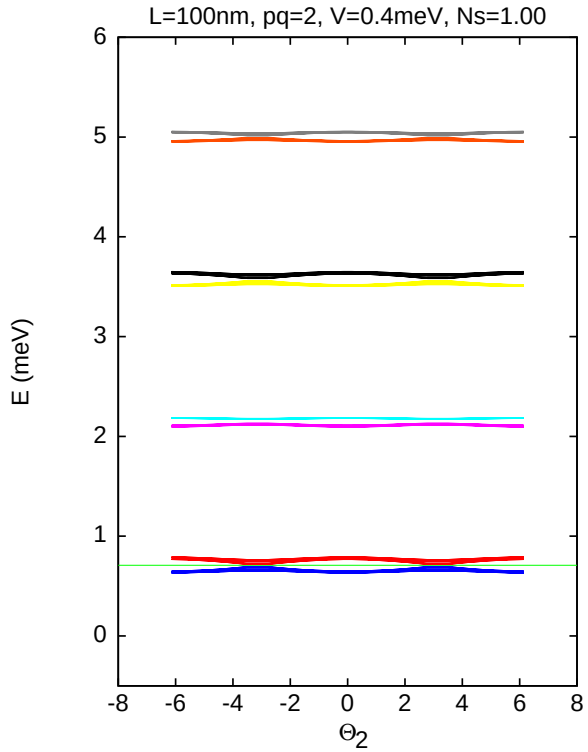




Modulation, $pq = 2$, $\nu = 1/2$

Inter and intra Landau band excitations





Are we seeing the two Hofstadter subbands?

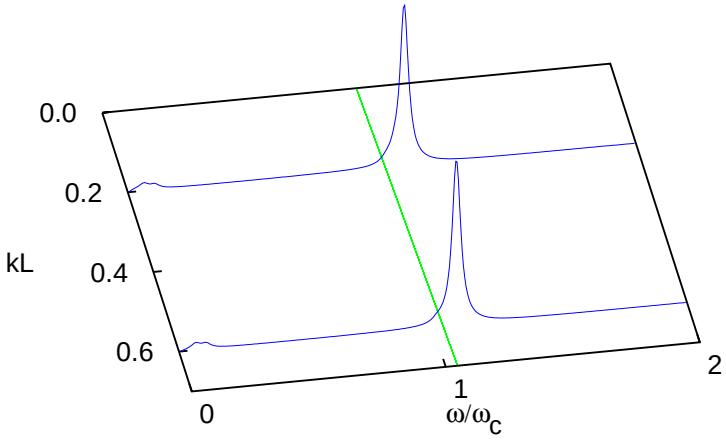
Two peaks or not, for $pq = 2$ are sensitive to modulation strength and filling factor ν

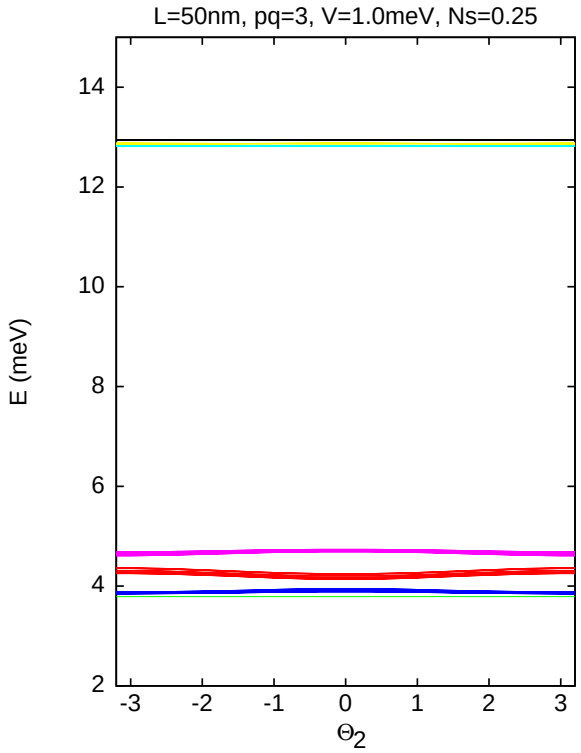
Can we see three peaks for $pq = 3$?

Modulation, $pq = 3$, $\nu = 1/12$

L=50nm, pq=3, $h\omega_c$=8.574meV, T=1K, V=1.0meV, Ns=0.25

Absorption

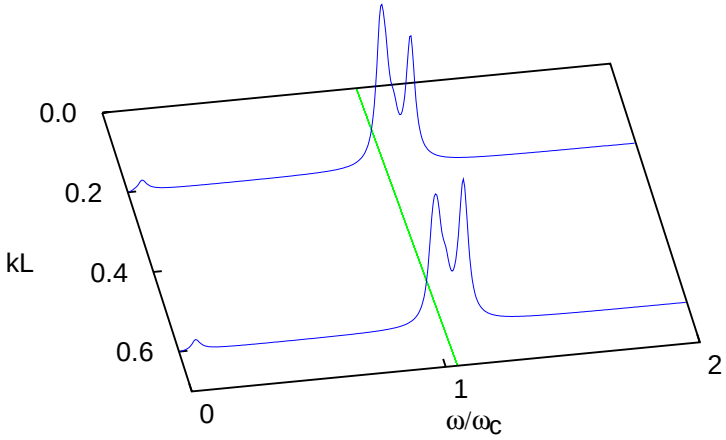


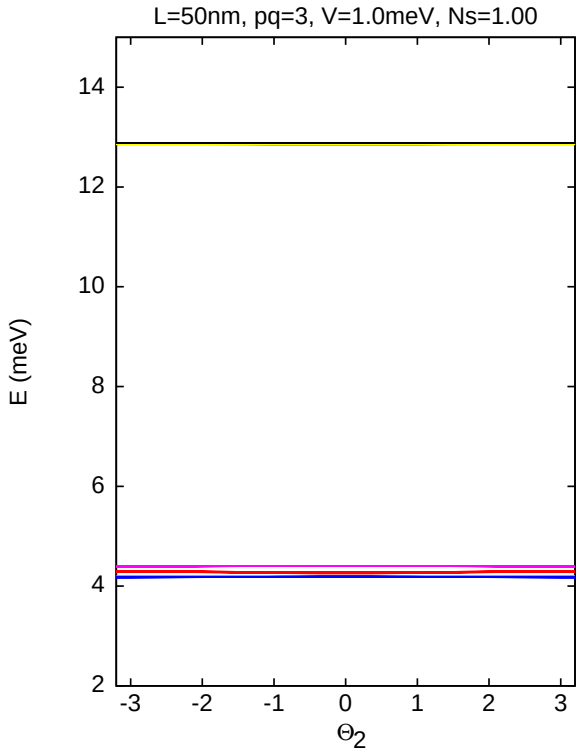


Modulation, $pq = 3$, $\nu = 1/3$

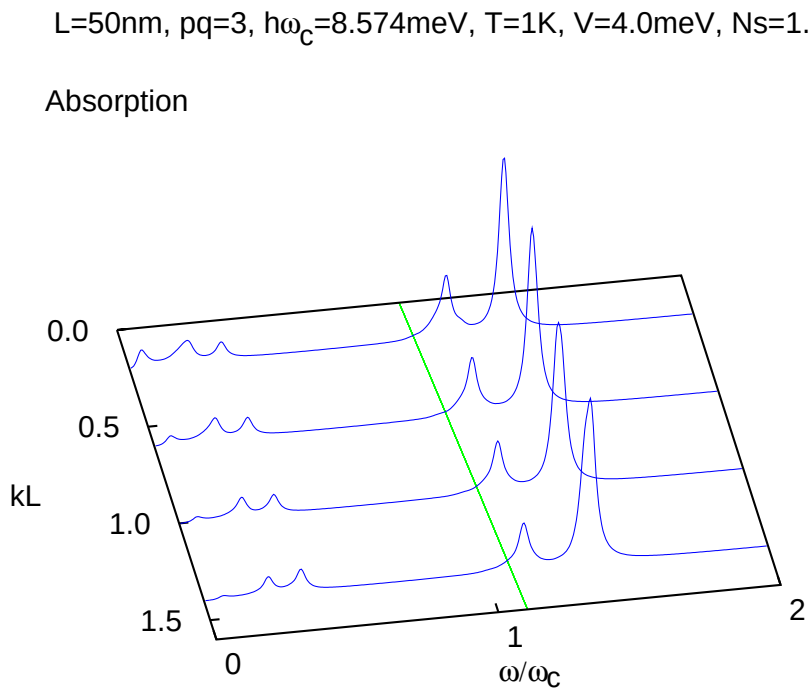
L=50nm, pq=3, $h\omega_c$=8.574meV, T=1K, V=1.0meV, Ns=1.00

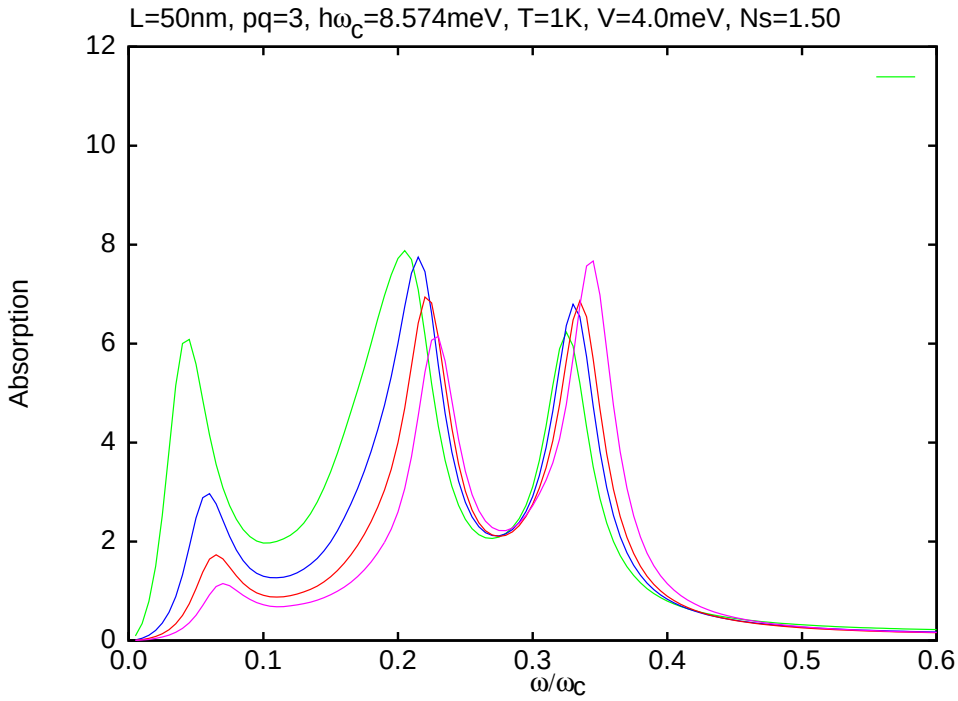
Absorption





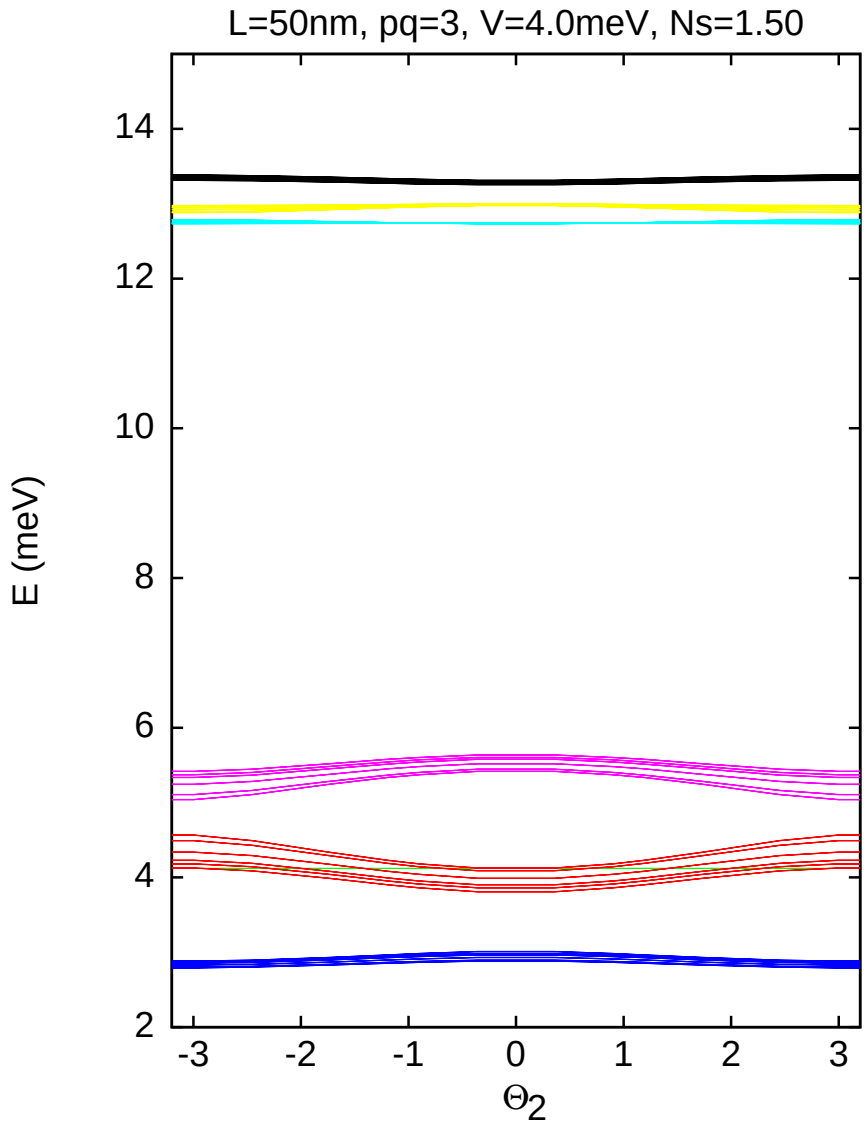
Modulation, $pq = 3$, $\nu = 1/2$





$L = 50\,\mathrm{nm}$, $V = 4\,\mathrm{meV}$, $pq = 3$, and $\nu = 1/2$

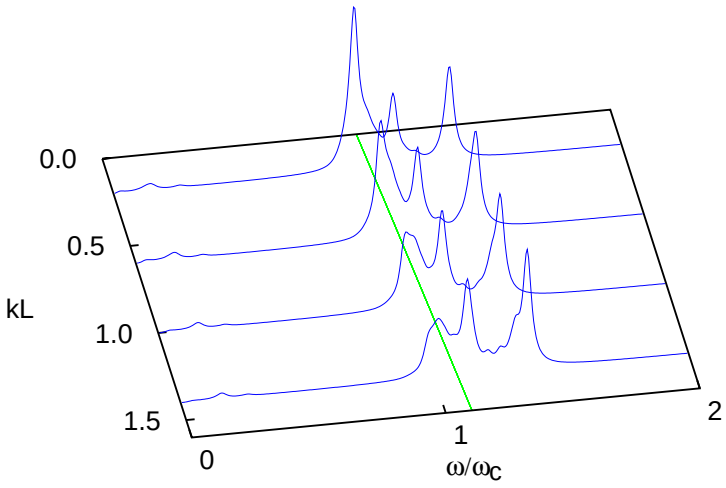
Three intraband excitations



Modulation, $pq = 3$, $\nu = 5/6$

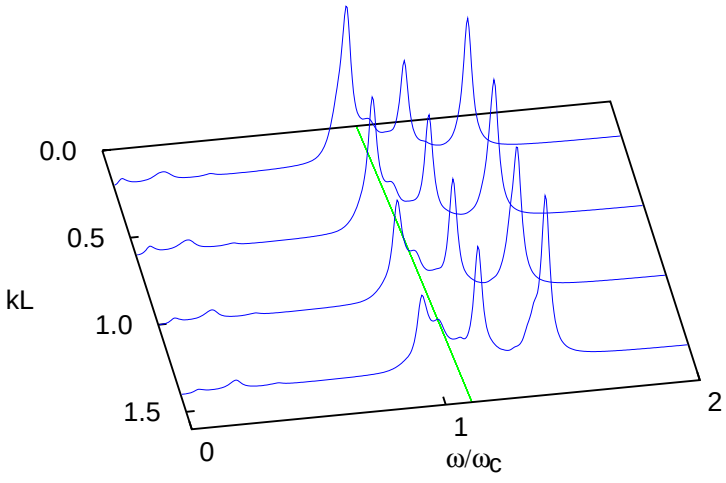
L=50nm, pq=3, $h\omega_c$=8.574meV, T=1K, V=3.0meV, Ns=2.50

Absorption



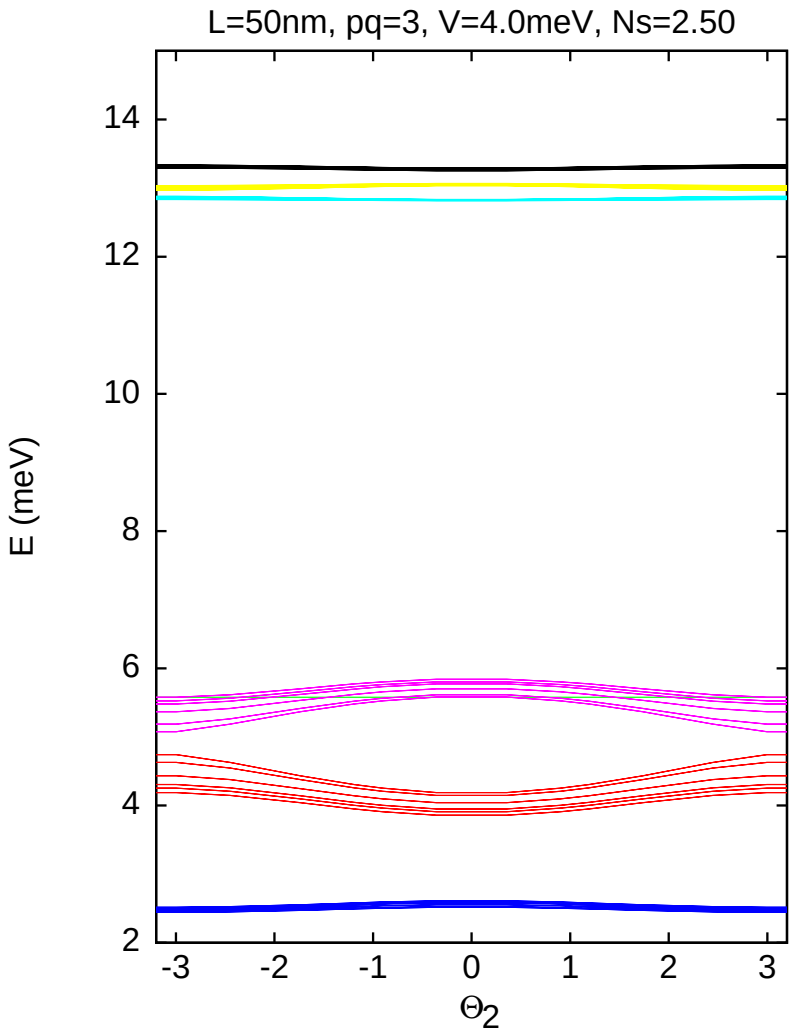
L=50nm, pq=3, $h\omega_c$=8.574meV, T=1K, V=4.0meV, Ns=2.50

Absorption



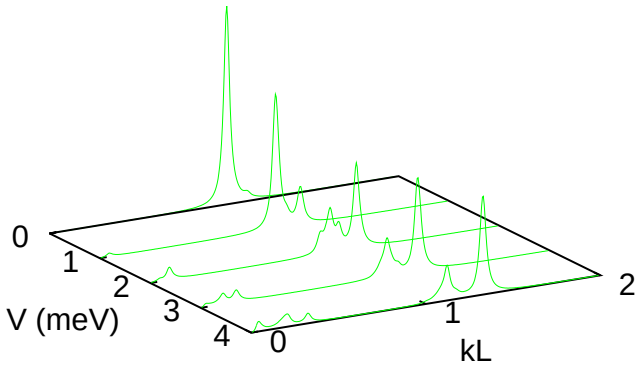
$L = 50\,\mathrm{nm}$, $V = 4\,\mathrm{meV}$, $pq = 3$, and $\nu = 5/6$

Three interband excitations

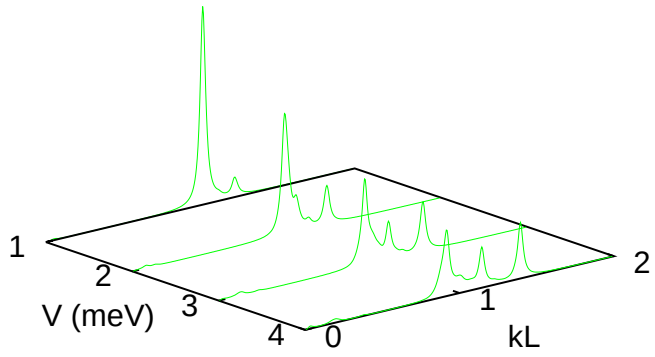


$pq = 3$, $L = 50$nm Splitting as a function of V

$\nu = 1/2$



$\nu = 5/6$



Conclusions

- Bernstein modes
- Hofstadter subband structure is found in absorption due both to inter- and intra-Landau-band magnetoplasmon
- It depends strongly on filling factor ν and modulation strength V
- FIR-absorption has similar "sensitivity" as the TDOS
- Coulomb interaction weakens selection rules when $\nu \neq$ integer