Why `pseudobands` works?

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A review at GW

To be very concise... $-\mathrm{i}\,\Sigma \approx GW^{\text{RPA}} =$  .

Assuming quasiparticles... $v(\mathbf{q}+\mathbf{G})=\frac{4\pi}{V|\mathbf{q}+\mathbf{G}|^2}$. $\Sigma \overset{\int\text{contour}}{=} \Sigma^{\text{CH}}+\Sigma^{\text{SX}}$,
$\epsilon_{\mathbf{G}\mathbf{G}'}(\mathbf{q},\omega)=\delta_{\mathbf{G}\mathbf{G}'}-v(q+\mathbf{G})\chi_{\mathbf{G}\mathbf{G}'}(\mathbf{q},\omega)$, $M_{nn'}(\mathbf{k},\mathbf{q},\mathbf{G})=\langle n\mathbf{k}+\mathbf{q}|\mathrm{e}^{\mathrm{i}(\mathbf{q}+\mathbf{G})\cdot\mathbf{r}}|n'\mathbf{k}\rangle$

$$\begin{aligned}\left\langle n\mathbf{k}\middle|\Sigma^{\text{SX}}(\omega)\middle|n'\mathbf{k}\right\rangle = -\sum_{n''}^{\text{occ}}\sum_{\mathbf{q}\mathbf{G}\mathbf{G}'} & M^*_{n''n}(\mathbf{k},-\mathbf{q},-\mathbf{G})M_{n''n'}(\mathbf{k},-\mathbf{q},-\mathbf{G}') \\ & \times \epsilon^{-1}_{\mathbf{G}\mathbf{G}'}(\mathbf{q},\omega-E_{n'',\mathbf{k}-\mathbf{q}})v(\mathbf{q}+\mathbf{G}'),\end{aligned}$$

$$\begin{aligned}\left\langle n\mathbf{k}\middle|\Sigma^{\text{CH}}(\omega)\middle|n'\mathbf{k}\right\rangle = \frac{\mathrm{i}}{2\pi}\sum_{n''}\sum_{\mathbf{q},\mathbf{G},\mathbf{G}'} & M^*_{n''n}(\mathbf{k},-\mathbf{q},-\mathbf{G})M_{n''n'}(\mathbf{k},-\mathbf{q},-\mathbf{G}') \\ & \times \int_0^\infty \mathrm{d}\omega'\,\frac{[\epsilon^{\mathrm{r}}_{\mathbf{G}\mathbf{G}'}]^{-1}(\mathbf{q},\omega')-[\epsilon^{\mathrm{a}}_{\mathbf{G}\mathbf{G}'}]^{-1}(\mathbf{q},\omega')}{\omega-E_{n\mathbf{k}}-\omega'+\mathrm{i}\,0^+\,\mathrm{sgn}(E_{n\mathbf{k}})}v(\mathbf{q}+\mathbf{G}').\end{aligned}$$

$$\begin{aligned}\chi^{\mathrm{r/a}}_{\mathbf{G}\mathbf{G}'}(\mathbf{q},\omega) = \sum_{\mathbf{k}}\sum_{n}^{\text{occ}}\sum_{n'}^{\text{emp}} & M_{nn'}(\mathbf{k},\mathbf{q},\mathbf{G})M^*_{nn'}(\mathbf{k},\mathbf{q},\mathbf{G}') \\ & \times\left(\frac{1}{\omega+E_{n,\mathbf{k}+\mathbf{q}}-E_{n'\mathbf{k}}\pm\mathrm{i}\,0^+}+\frac{1}{-\omega+E_{n,\mathbf{k}+\mathbf{q}}-E_{n'\mathbf{k}}\mp\mathrm{i}\,0^+}\right).\end{aligned}$$

GW in momentum space

Note that χ and $\Sigma^{\mathrm{CH}}_{nn'}$ involve summation over high energy states (with or without GPP)

One bottleneck of GW in momentum space

The problem of summing over many empty bands

One further simplification trick: `pseudobands`. For $E_{n\mathbf{k}} \gg E_{\mathrm{F}}$:

$$\{\phi_{n\mathbf{k}}\}_{\text{adjacent energy block } n_{\mathrm{b}}} \to \sum_{n \in \text{block } n_{\mathrm{b}}} \phi_{n\mathbf{k}},$$

$$\{E_{n\mathbf{k}}\}_{\text{adjacent energy block } n_{\mathrm{b}}} \to \frac{1}{|n_{\mathrm{b}}|} \sum_{n \in \text{block } n_{\mathrm{b}}} E_{n\mathbf{k}}.$$

4000 bands $\to \sim 400$ to ~ 1000 bands.

. . . but is this snake oil? It makes no sense!!!

`pseudobands`, and when it works

Understanding `pseudobands`: energy averaging

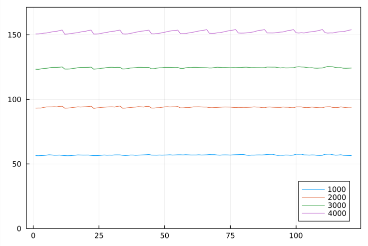
Observation

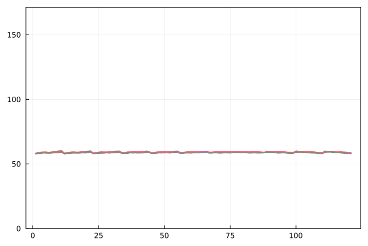
- $\chi \sim MM^* \times \text{some-function}(E_{\text{emp}} - E_{\text{occ}})$;
- $\Sigma^{\text{CH}} \sim MM^* \times \text{some-function}(\omega - E), \quad \omega \sim E_{\text{F}}$.

☛For $E_{n\mathbf{k}} \gg E_{\text{F}}$ (ω): energy-dependent factors $\sim$ const. for all $\mathbf{k}$.

Thus for both χ and Σ^{CH} involving summation over empty bands:

$$\sum_{n''}^{\text{high emp. bands}} M^*_{n''n} M_{n''n'} \times f(E_{n''\mathbf{k}}) = \sum_{\text{block } n_{\text{b}}} f(\bar{E}_{n_{\text{b}}}) \sum_{n''}^{\text{block } n_{\text{b}}} M^*_{n''n} M_{n''n'}.$$

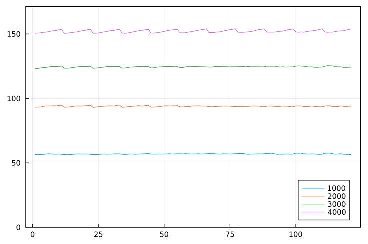


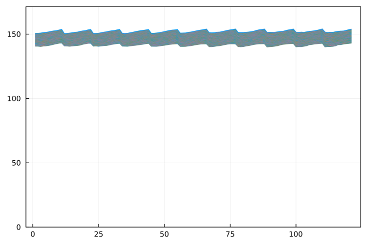


Example High-energy DFT bands of WTe_2 monolayer (ONCV-SG15, 120 electrons; 80 Ry cutoff, $20 \times 20 \times 1$ grid). x axis = $\mathbf{k}$ index in irreducible 1BZ; fastest varying coordinate = k_y

👉 $n \sim 1000$: bands are generally flat

Understanding `pseudobands`: energy averaging





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👉High-lying bands are more dispersive but since they are high, $1/(E_{\mathrm{emp}} - E_{\mathrm{occ}})$ is still flat

Understanding `pseudobands`: wave function averaging?

For `pseudobands` to work, we need

$$\begin{aligned}\underbrace{\sum_{n'' \in \text{block } n_\text{b}} M^*_{n'' n} M_{n'' n'}}_{\text{normal}} &\sim M^*_{\text{averaged band}, n} M_{\text{averaged band}, n'} \\ &= \underbrace{\sum_{n''_1, n''_2 \in \text{block } n_\text{b}} M_{n''_1 n'} M^*_{n''_2 n}}_{\text{pseudobands}} .\end{aligned} \tag{1}$$

The question: is $[M_{n''_1 n'} M^*_{n''_2 n}]_{n''_1 n''_2}$ **diagonal?** Easy to verify: it's not.

Then in which case is (1) **correct in some sense?**

Technical issues in calculating $M_{nn'}(\mathbf{k}, \mathbf{q}, \mathbf{G})$

The structure of $\phi_{n\mathbf{k}}$

Plane wave basis In BerkeleyGW `WFN.h5`,

$$\phi_{n\mathbf{k}}(\mathbf{r}, \sigma) = \frac{1}{\sqrt{V}} \sum_{\mathbf{G}} \mathrm{e}^{\mathrm{i}(\mathbf{k}+\mathbf{G})\cdot\mathbf{r}} \, c_{n\mathbf{k},\mathbf{G}\sigma}.$$

Thus

$$M_{nn'}(\mathbf{k}, \mathbf{q}, \mathbf{G}) = \langle n\mathbf{k} + \mathbf{q} | \mathrm{e}^{\mathrm{i}(\mathbf{q}+\mathbf{G})\cdot\mathbf{r}} | n'\mathbf{k} \rangle = \sum_{\mathbf{G}', \sigma} c^*_{n\mathbf{k}+\mathbf{q},\mathbf{G}+\mathbf{G}'\sigma} c_{n\mathbf{k},\mathbf{G}'\sigma}.$$

Cutoff Each $\mathbf{k}$ has its own $\mathbf{G}$-grid (~ 30000 vectors for $80\,\mathrm{Ry}$).

Input

- indices of $\mathbf{k}, \mathbf{q}$ in $\mathbf{k}$-grid;
- index of $\mathbf{G}$ in $\mathbf{G}$-grid of $\mathbf{k}$ (expect a $\mathbf{G}$ in GW $\mathbf{G}$-grid, cutoff $=$ say 30 Ry, not 80 Ry);
- n, n'.

Procedure

1. find index of $\mathbf{k}$
2. find index of $\mathbf{G} + \mathbf{G}'$ in $\mathbf{G}$-grid of $\mathbf{k} + \mathbf{q}$, for each $\mathbf{G}'$ in $\mathbf{G}$-grid of $\mathbf{k}$
3. do summation $\sum_{\mathbf{G}', \sigma} c^{*}_{n\mathbf{k}+\mathbf{q}, \mathbf{G}+\mathbf{G}'\sigma} c_{n\mathbf{k}, \mathbf{G}'\sigma}$.

Performance Main bottleneck: finding $\mathbf{G} + \mathbf{G}'$. Using `StaticArrays.jl` helps a lot!

`pseudobands` **for** χ

χ revisited

Under GPP:

$$\chi_{\mathbf{G}\mathbf{G}'}(\mathbf{q}, \omega = 0)^{\text{high band terms}} \approx \sum_{\mathbf{k}} \sum_{\text{block } n_{\text{b}}}^{\text{emp}} \frac{2}{E_{n,\mathbf{k}+\mathbf{q}} - E_{\text{average in block } n_{\text{b}}}} \times \sum_{n' \in \text{block } n_{\text{b}}} \sum_{n}^{\text{occ}} M_{nn'}(\mathbf{k}, \mathbf{q}, \mathbf{G}) M^*_{nn'}(\mathbf{k}, \mathbf{q}, \mathbf{G}')$$

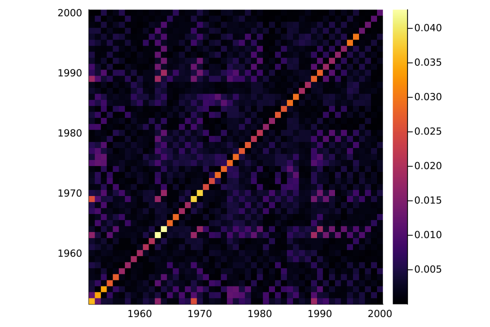
Our goal *Finding how diagonal is*

$$\sum_{n}^{\text{occ}} M_{nn'_1}(\mathbf{k}, \mathbf{q}, \mathbf{G}) M^*_{nn'_2}(\mathbf{k}, \mathbf{q}, \mathbf{G}')$$

It should be diagonal for `pseudobands` to work.

Numerical charaterization of $\sum_n^{\mathbf{occ}} M_{nn'_1}(\mathbf{k},\mathbf{q},\mathbf{G}) M^*_{nn'_2}(\mathbf{k},\mathbf{q},\mathbf{G}')$

Case 1: $\mathbf{G} = \mathbf{G}'$ In this case $\sum_n^{\text{occ}} M_{nn'_1}(\mathbf{k},\mathbf{q},\mathbf{G}) M^*_{nn'_2}(\mathbf{k},\mathbf{q},\mathbf{G}')$ is large and fairly diagonal



Parameters $\mathbf{G} = (0, 1, -14), \mathbf{k} = \mathbf{k}_2 = (0, 0.00, 0), \mathbf{q} = (0, 0.00, 0)$

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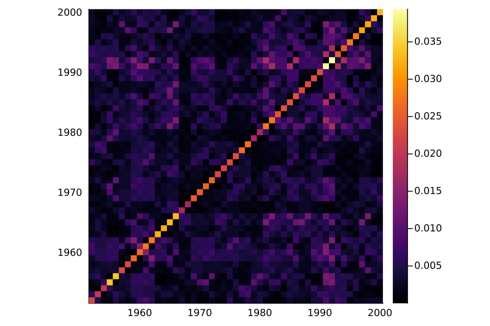

Parameters $\mathbf{G} = (0, 1, -14), \mathbf{k} = \mathbf{k}_2 = (0, 0.05, 0), \mathbf{q} = (0, 0.10, 0)$

Numerical charaterization of $\sum_n^{\mathrm{occ}} M_{nn_1'}(\mathbf{k},\mathbf{q},\mathbf{G}) M^*_{nn_2'}(\mathbf{k},\mathbf{q},\mathbf{G}')$

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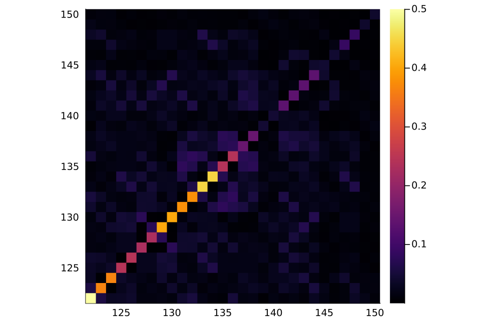
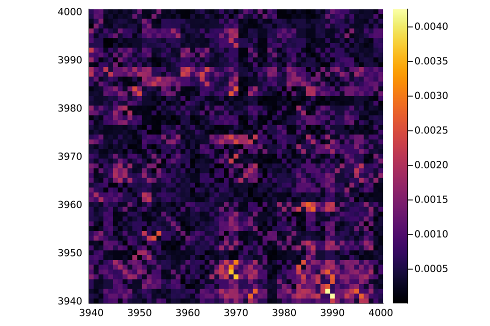


Strikingly, $\sum_n^{\mathrm{occ}} M_{nn_1'}(\mathbf{k},\mathbf{q},\mathbf{G}) M^*_{nn_2'}(\mathbf{k},\mathbf{q},\mathbf{G}')$ is still very diagonal for bands near Fermi surface!

Case 2: $\mathbf{G} \neq \mathbf{G}'$ $\sum_n^{\text{occ}} M_{nn'_1}(\mathbf{k},\mathbf{q},\mathbf{G}) M^*_{nn'_2}(\mathbf{k},\mathbf{q},\mathbf{G}')$ is very non-diagonal, but since the terms's random phases cancel each other so the overall sum after $\sum_{n'}^{\text{emp}}$ is small



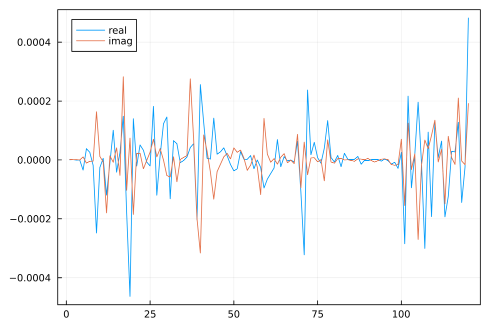
Half-way generalization about `pseudobands` in χ

- `pseudobands` works when it's necessary to do so
- What prevents `pseudobands` from working around Fermi surface is the energy dispersion

...but do we have any theoretical explanation for this?

Cancellation of cross-terms in χ

$M_{nn_1'}(\mathbf{k},\mathbf{q},\mathbf{G})M^*_{nn_2'}(\mathbf{k},\mathbf{q},\mathbf{G}')$ and n (occupied band index), when $n_1' \neq n_2'$:



👉Although for a single n, the value can be large, as we sum over n the terms cancel each other ⇒ diagonal $\sum_n^{\text{occ}} M_{nn_1'}(\mathbf{k},\mathbf{q},\mathbf{G})M^*_{nn_2'}(\mathbf{k},\mathbf{q},\mathbf{G}')$

pseudobands **for** Σ

Σ^{CH} revisited

Only Σ^{CH} involves $\sum^{\text{emp}}$:

$$\langle n\mathbf{k}|\Sigma^{\text{CH, GPP}}|n'\mathbf{k}\rangle = \frac{1}{2}\sum_{n''}\sum_{\mathbf{qGG}'} M^*_{n''n}(\mathbf{k},-\mathbf{q},-\mathbf{G})M_{n''n'}(\mathbf{k},-\mathbf{q},-\mathbf{G}')\times$$

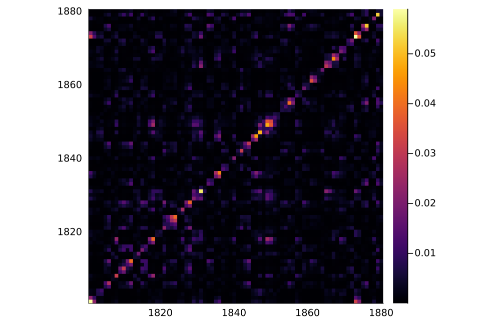
$$\text{something about } \mathbf{q},\mathbf{k},\mathbf{G},\mathbf{G}'$$

Problems

- No summation over occupied states $\Rightarrow$ ✗the aforementioned cancellation mechanism
- Summation over $\mathbf{G}$ very complicated $\Rightarrow$ analysis based on $\mathbf{G}$ very hard.

Some tentative ideas

- It has been verified that a single $M^*_{n''_1 n} M_{n''_2 n}$ term is never diagonal
- But it seems naively summing over $\mathbf{G} = \mathbf{G}'$ (without considering the weight factor) makes it diagonal...



Some tentative ideas

- $M^*_{n_1'' n}(\mathbf{G}_1) M_{n_2'' n}(\mathbf{G}_2)$ is not diagonal at all when $\mathbf{G}_1 \neq \mathbf{G}_2$;
- but probably only the $\mathbf{G}_1 = \mathbf{G}_2$ terms matter?

Comments from Felipe H. Jornada's recent paper

“Stochastic” pseudobands

Energy averaging is also done in their paper:

$$G = \sum_{n \text{ near F.S.}} \frac{|\phi_{n\mathbf{k}}\rangle\langle\phi_{n\mathbf{k}}|}{\omega - E_{n\mathbf{k}}} + \sum_{\text{pseudobands block}} \frac{1}{\omega - \bar{E}} \sum_{n \in \text{block}} |\phi_{n\mathbf{k}}\rangle\langle\phi_{n\mathbf{k}}| \, .$$

Their procedure Replace each pseudobands block by *several bands*:

$$\{\phi_{n\mathbf{k}}\}_{n \text{ in block}} \longrightarrow \left\{ |\phi_{\xi\mathbf{k}}\rangle = \sum_{n \text{ in block}} \mathrm{e}^{\mathrm{i}\,\theta_{n\xi}} \, |\phi_{n\mathbf{k}}\rangle \right\}_{\xi}$$

Justification When $N_\xi \to \infty$, $\left\langle \mathrm{e}^{-\mathrm{i}\,\theta_{n'\xi}} \, \mathrm{e}^{\mathrm{i}\,\theta_{n\xi}} \right\rangle_\xi = \delta_{nn'}$

Comparison with the current script When $N_\xi = 1$, $\mathrm{e}^{\mathrm{i}\,\theta_{n\xi}}$ comes from DFT diagonalization

FHJ's justification of pseudobands

Convergence conditions When $N_{\text{pseudobands blocks}} \to \infty$ and in each block $N_\xi \to \infty$,

- the expectations of χ and Σ goes to the true value;
- the standard error goes to zero.

Is this result enough as a justification? My answer: no; because the limits = not doing pseudobands at all. (And their recommended values are not large enough anyway.)

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Additional justification "the polarizability tends to converge much faster than G, partially due to the *rapidly oscillating nature* of the matrix elements involving Kohn-Sham states used in the evaluation of the polarizability"

Compressing the bands even harder: size of blocks

Recall that band dispersion is the main problem...

$$\Delta\chi \sim \frac{\Delta E}{E^2}, \quad \chi \sim \frac{1}{E} \Rightarrow \frac{\Delta\chi}{\chi} \simeq \frac{\Delta E}{E}$$
$$\Rightarrow \frac{\Delta\chi}{\chi} \lesssim \mathrm{const} \Leftrightarrow \boxed{\frac{\Delta E}{E} \lesssim \mathrm{const}}$$

Exponential growth of the energy spread of blocks!

Compressing the bands even harder: pseudobands near E_F?

They claim that for `epsilon`, bands near Fermi surface can also be pseudo-ized

It somehow goes against my own numerical experiments; but they are quite sure about that hmm...

They also claim that for `sigma`, only the bands near Fermi surface shouldn't be pseudo-ized.

Important claim: protection window is not a convergence parameter.