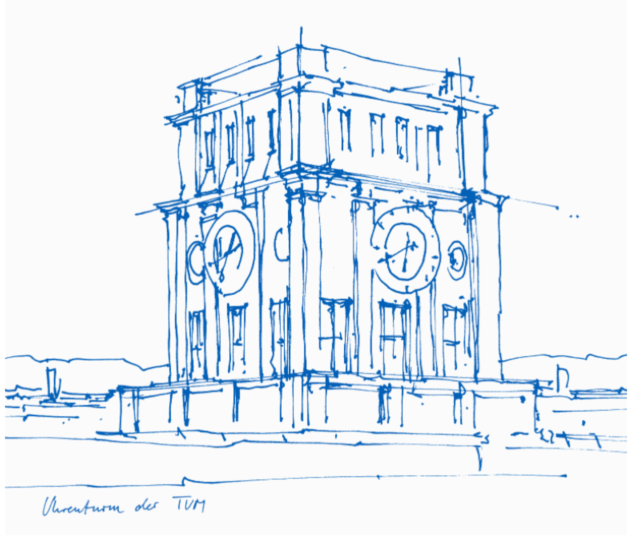
Transient localization from fractionalization: vanishing energy transport in gapless quantum magnets

Shi Feng,

Technical University of Munich

Denver 03/18/2026



DFG Deutsche Forschungsgemeinschaft

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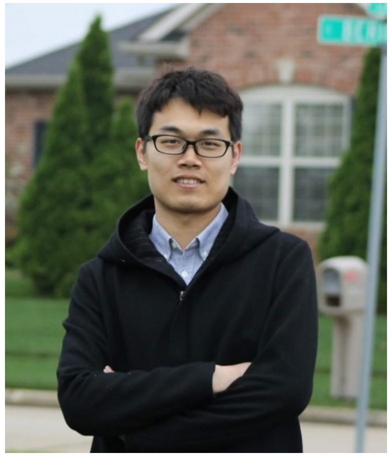
Acknowledgment



Penghao Zhu
Ohio State University

Michael Knap
TU Munich

Johannes Knolle
TU Munich

Puzzle: Vanishing thermal transport in gapless quantum magnets

Linear $C_V(T)$ is a hallmark of
neutral gapless fermion (e.g. Fermi surface):

$$C_V \sim \gamma T$$

Thermal conductivity $\kappa(T)$ is related by
Einstein relation:

$$\kappa \sim DC_V, \quad \kappa_0 \sim \kappa/T \sim D\gamma$$

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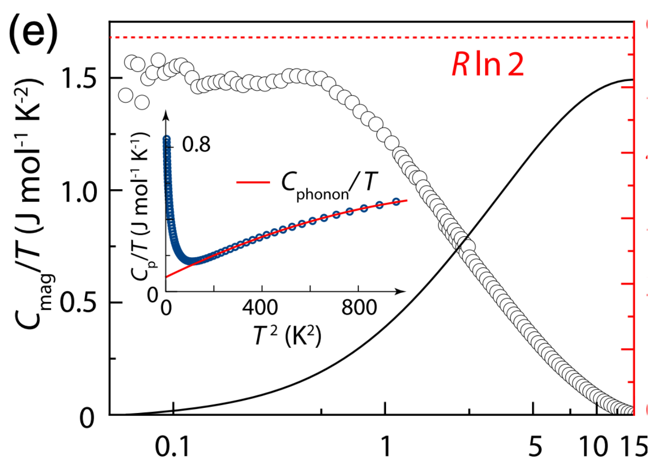

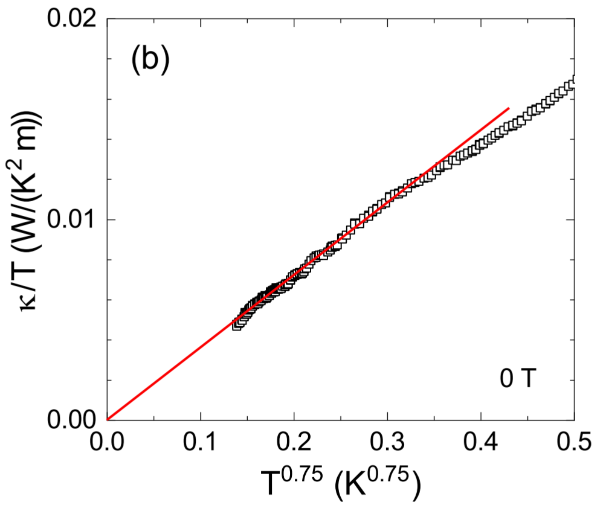

Dai *et al., Phys. Rev. X* ***11****, 021044 (2021)*

Li *et al., Phys. Rev. B 110, 224414 (2024)*

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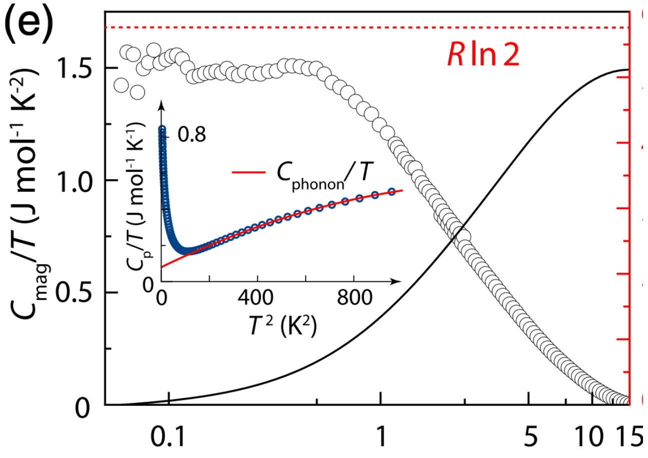

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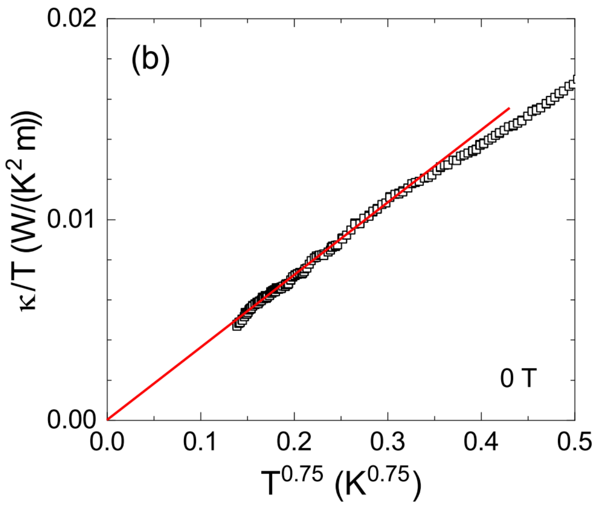
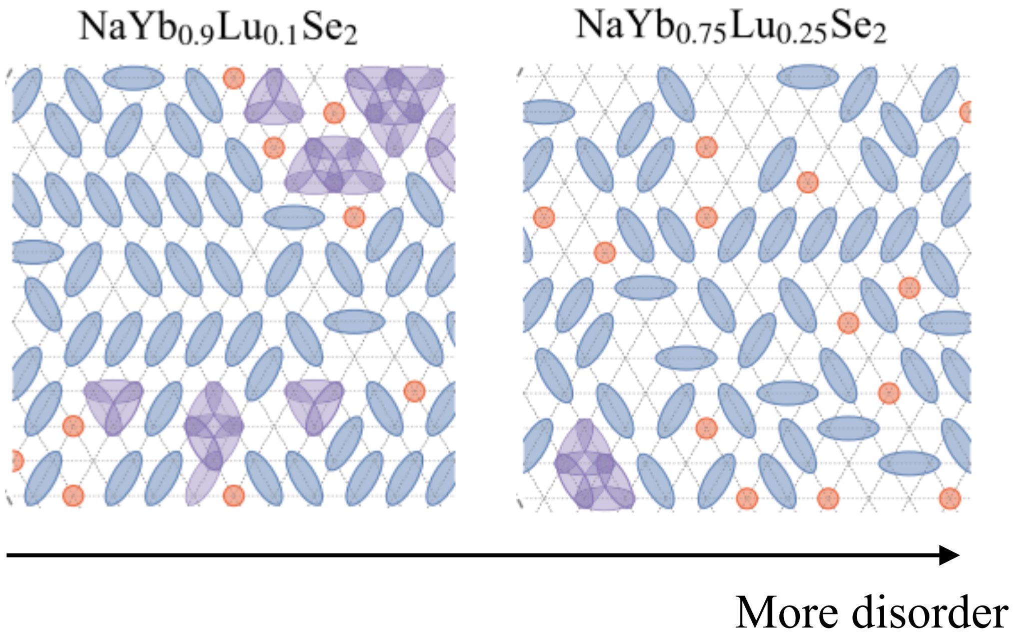


Li *et al., Phys. Rev. B 110, 224414 (2024)*

Possibilities:

- Extrinsic Quenched Defects/Disorder



Lyu, Cairns, Rodriguez et al., *Phys. Rev. X 15, 041035 (2025)*

- Intrinsic self-generated coherent disorder (Translation invariant)

Key Information

- Gapless excitations can coexist with strongly suppressed energy transport even without quench disorder

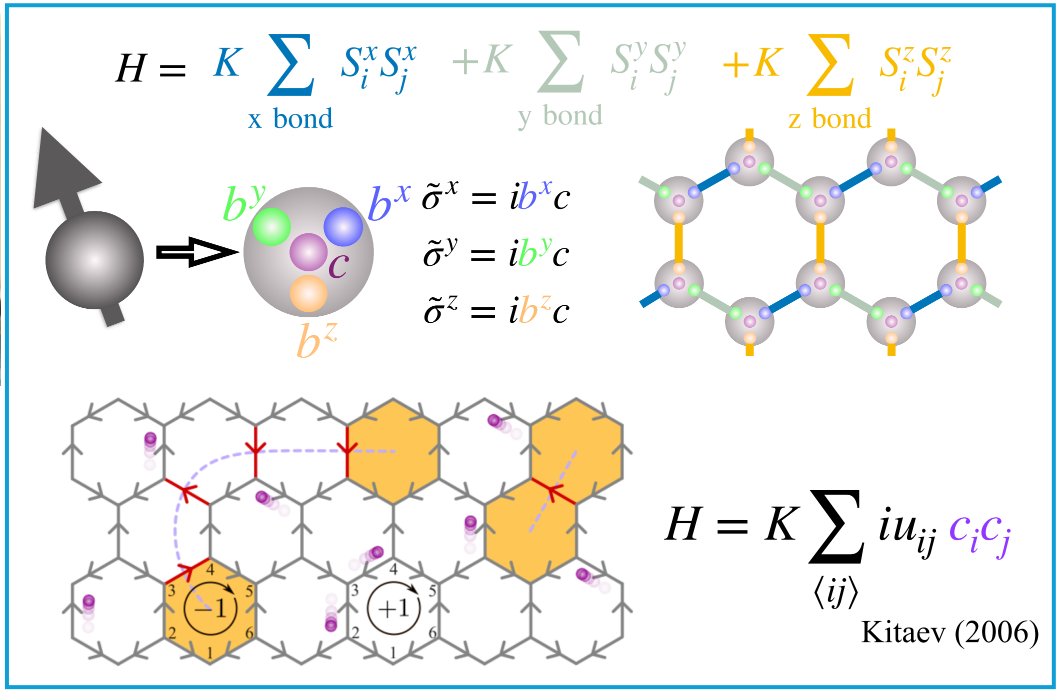
- Translation-symmetric system can localize itself by fractionalization

Overview

1. Fractionalization

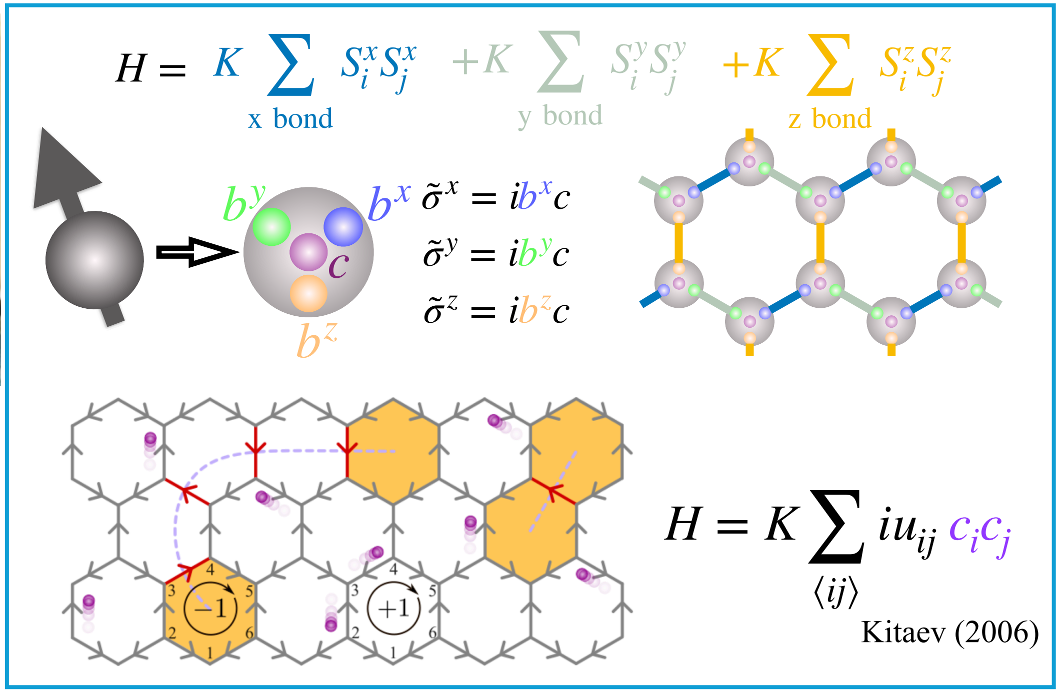
Overview

1. Fractionalization
   - *Kitaev spin liquid*



Overview

1. Fractionalization
   - *Kitaev spin liquid*
2. Gapless
   - *Field-induced gapless Kitaev magnets*



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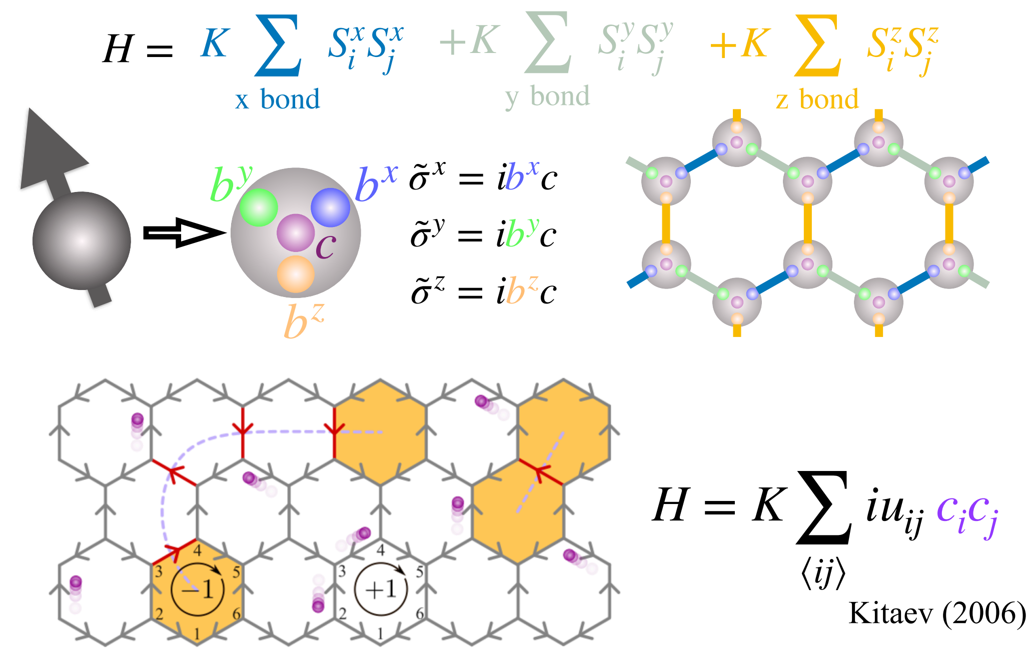

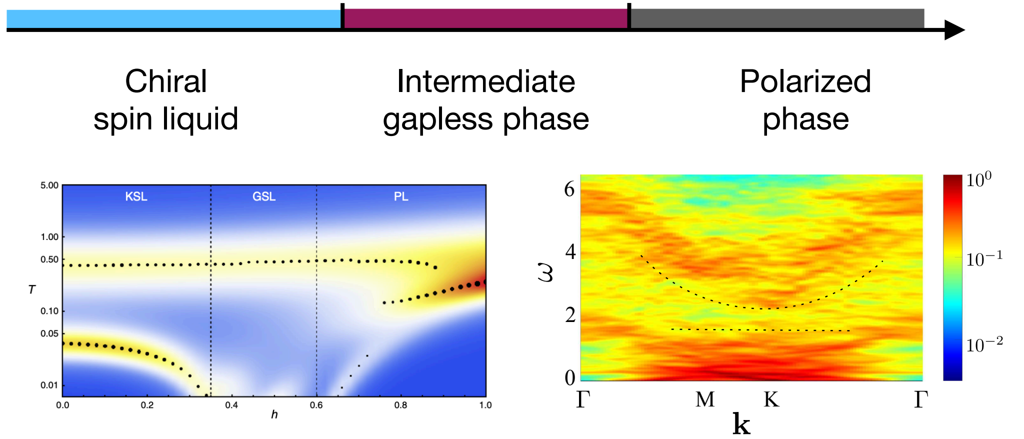

Zhu, Kimchi *et al. Phys. Rev. B 97, 241110 (2018)*

Hickey, Trebst, *Nat. Commun. 10, 530 (2019)*

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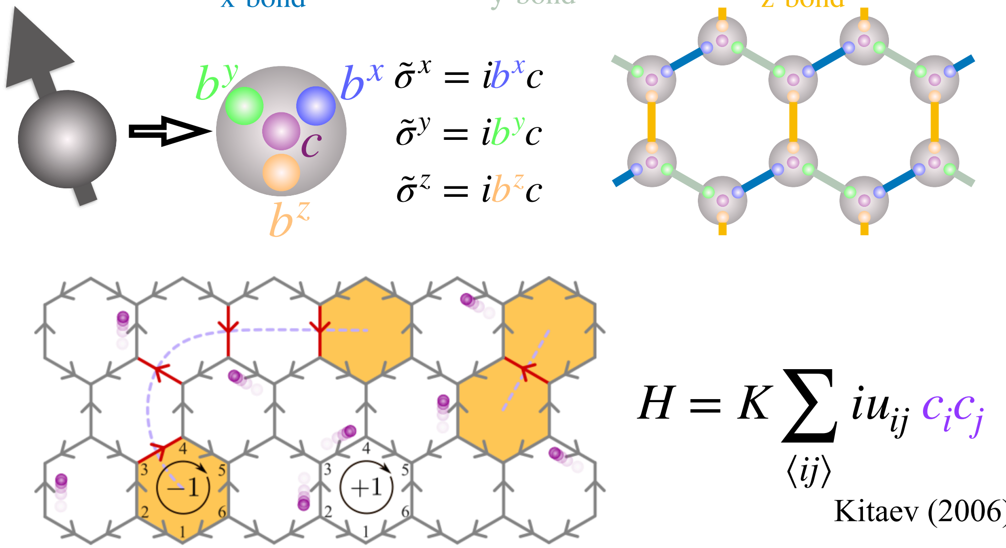
Zhu, **Feng**, *et al.*, *Nat. Commun. 16, 2420 (2025)*

Wang, **Feng**, *et al.*, *Phys. Rev. B 111, L100402 (2025)*

Overview

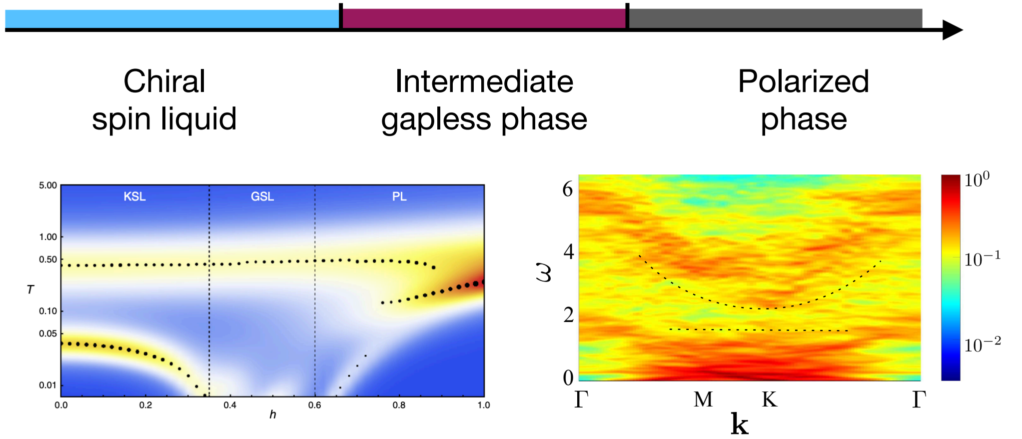
1. Fractionalization
   - *Kitaev spin liquid*
2. Gapless
   - *Field-induced gapless Kitaev magnets*
3. Translation invariant yet localized
4. Suppressed transport

$$H = K \sum_{\text{x bond}} S_i^x S_j^x + K \sum_{\text{y bond}} S_i^y S_j^y + K \sum_{\text{z bond}} S_i^z S_j^z$$



$$H = K \sum_{\langle ij \rangle} iu_{ij} c_i c_j$$

Kitaev (2006)



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Overview

1. Fractionalization
   - *Kitaev spin liquid*
2. Gapless
   - *Field-induced gapless Kitaev magnets*
3. Translation invariant yet localized
   - *Mechanism akin to disorder-free localization at low energy*

   Smith, Knolle *et al.*, *Phys. Rev. Lett.* **118**, *266601 (2019)*
   Oppong, Pasqualetti *et al.*, *Phys. Rev. X* **12**, *031026 (2022)*
4. Suppressed transport
   - *Zero-temperature Energy conductivity*
   - *Finite-temperature thermal conductivity*

Our Focus **Feng**, Zhu, Knolle, Knap, *arxiv:2509.07062*

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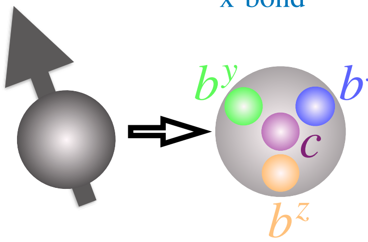

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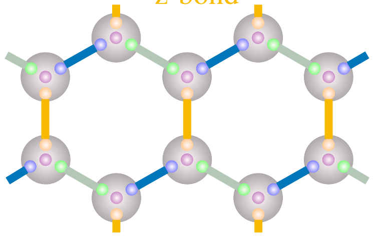

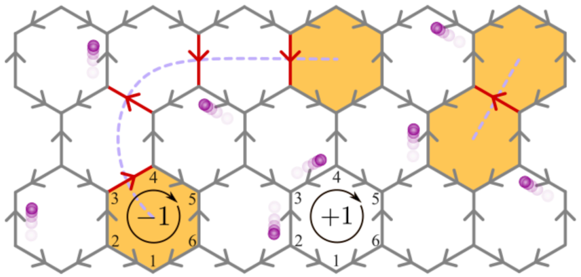

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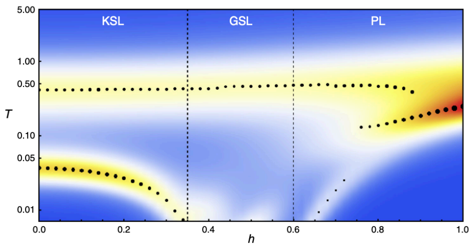

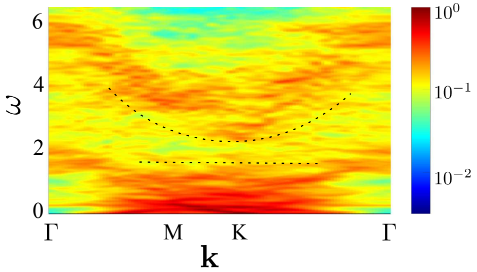

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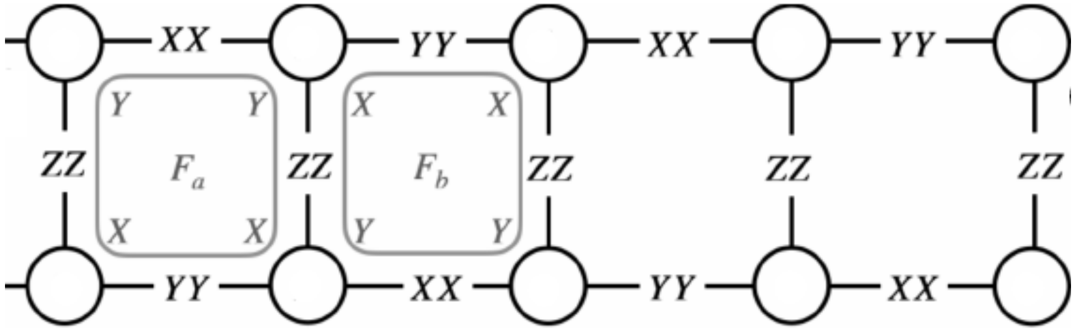
A simplified Model: Kitaev Ladder



$$H_{\text{ladder}} = \sum_{j+l \in \text{even}} \left(X_j^l X_{j+1}^l + Y_{j-1}^l Y_j^l + Z_j^l Z_j^{l+1} \right)$$

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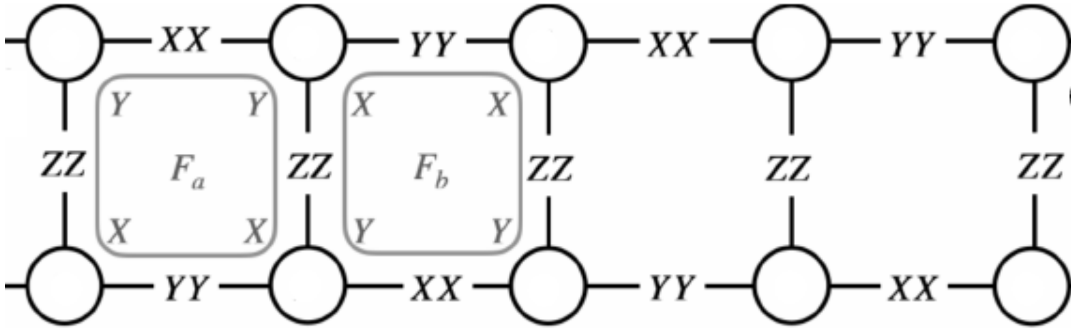

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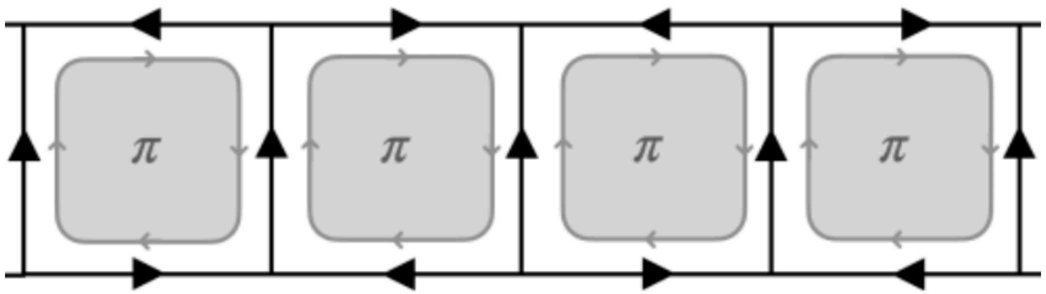
JW

Feng, Zhang, Xiang,
Phys. Rev. Lett. 98, 087204 (2007)



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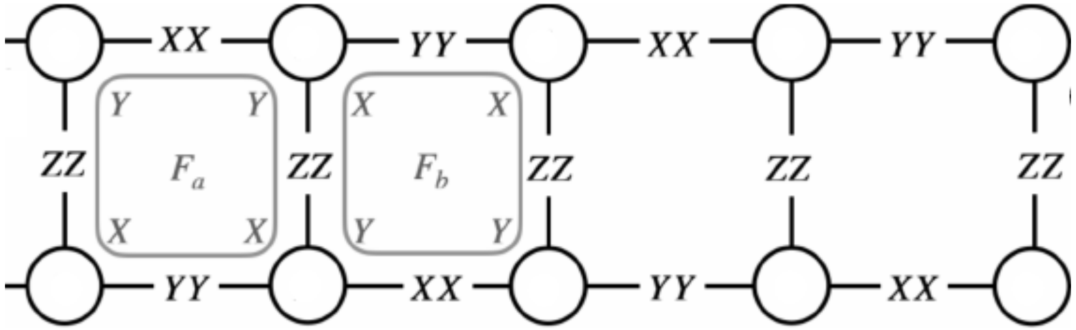

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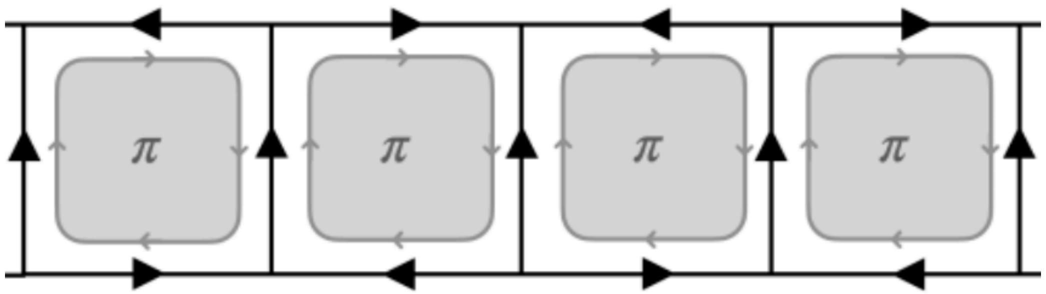

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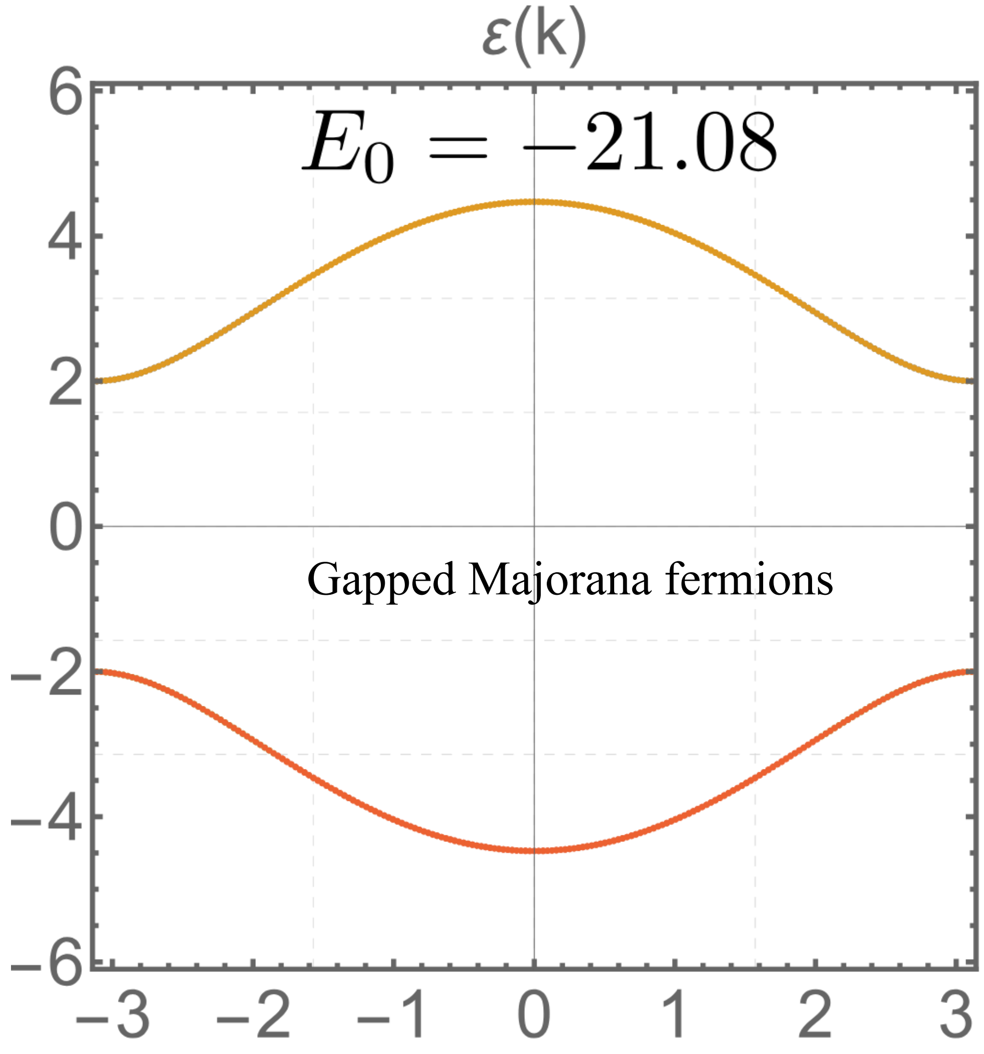
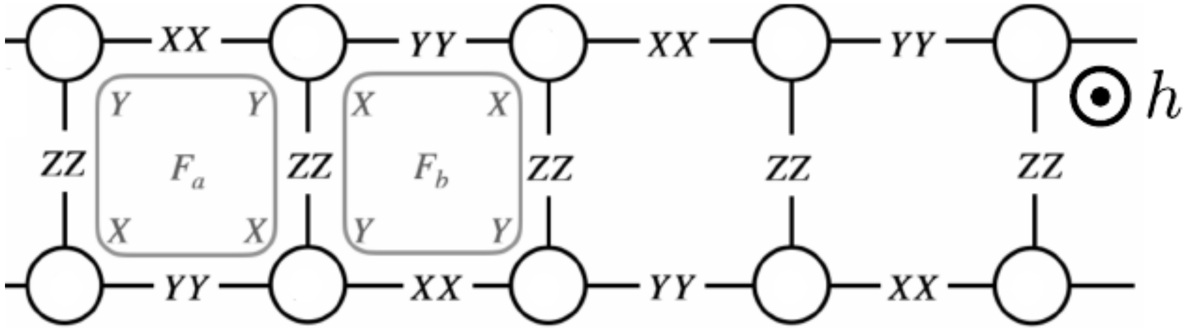


Feng, Zhu, Knolle, Knap, *arxiv:2509.07062*

A simplified Model: Kitaev Ladder under magnetic field



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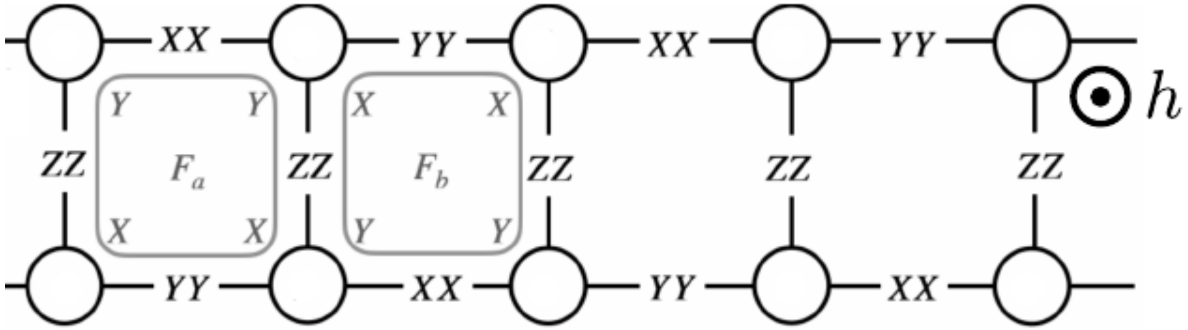

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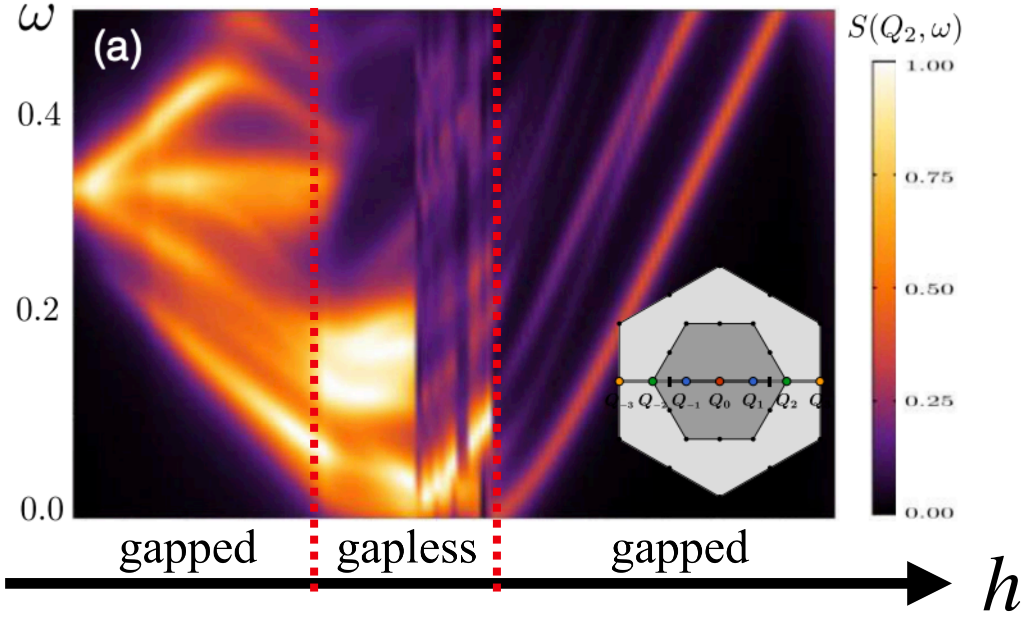
Dynamical spin structure factor, ED
(Fixed momentum)



Sørensen, Catuneanu, Gordon, Hae-Young Kee, *Phys. Rev. X 11, 011013 (2021)*

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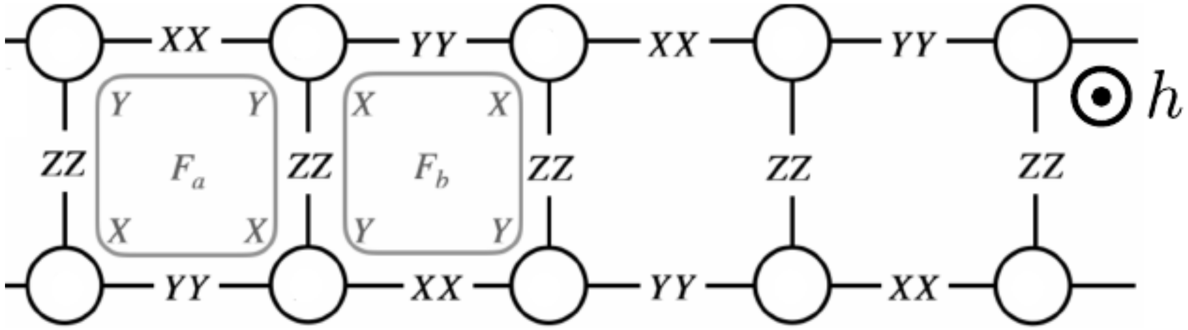

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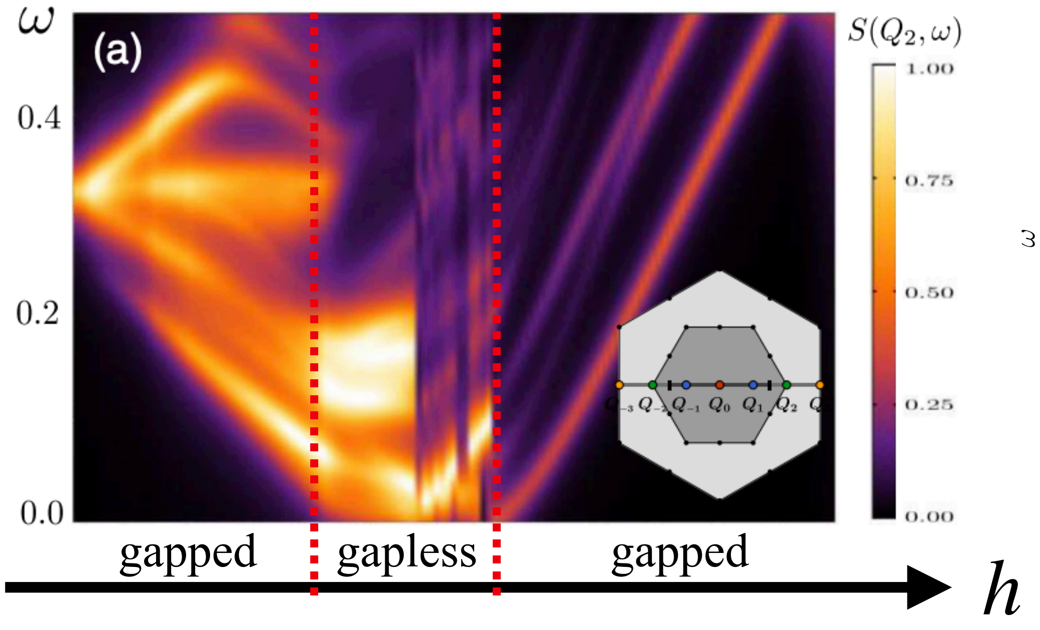
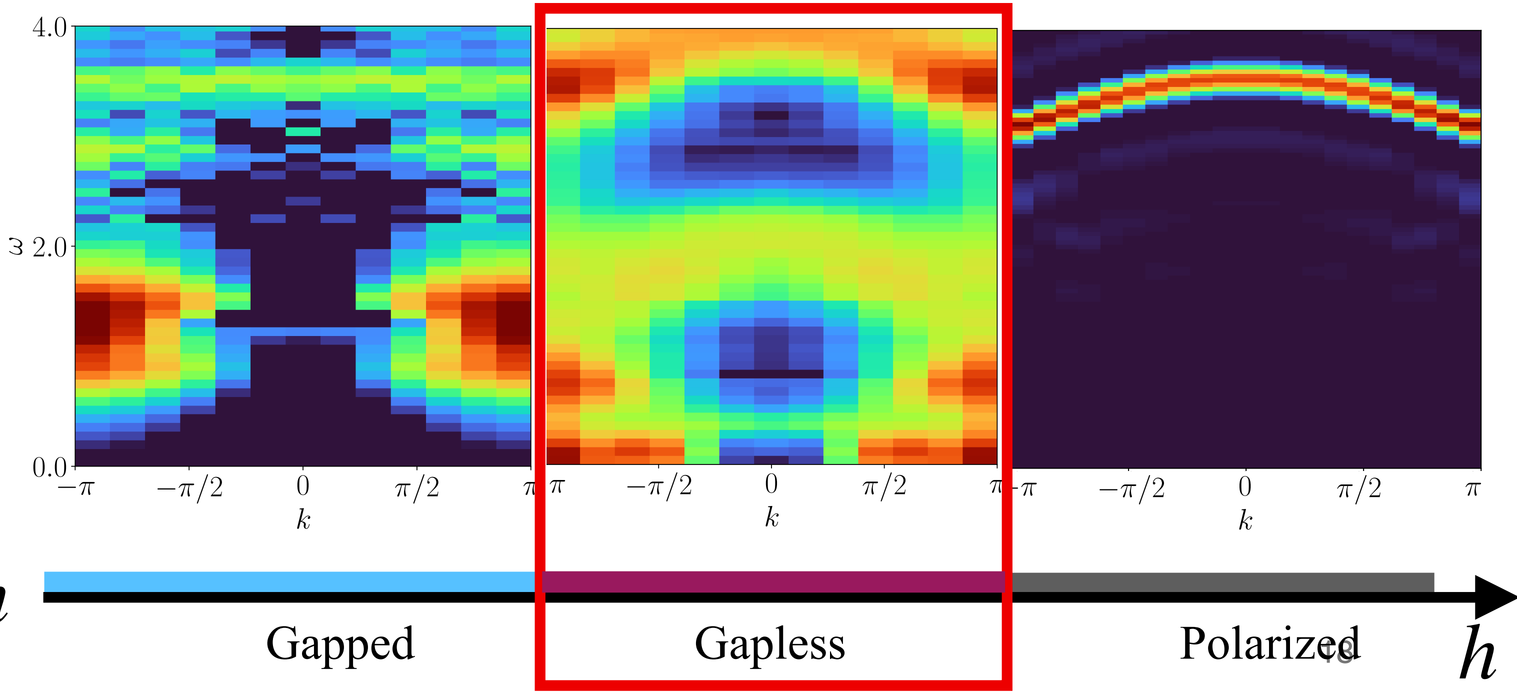


Sørensen, Catuneanu, Gordon, Hae-Young Kee, *Phys. Rev. X 11, 011013 (2021)*

Dynamical spin structure factor, DMRG
(***momentum-resolved***) **Feng**, Zhu, Knolle, Knap, *arxiv:2509.07062*



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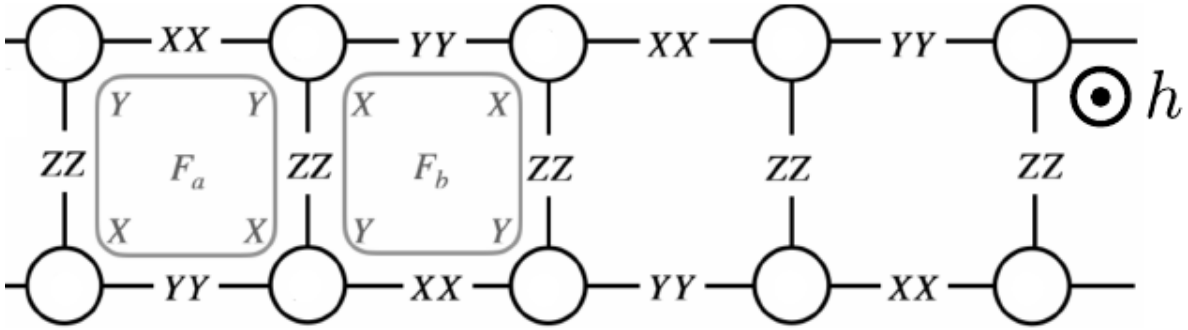

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H has no symmetry at the microscopic level: Frustration gives a floating incommensurate LL

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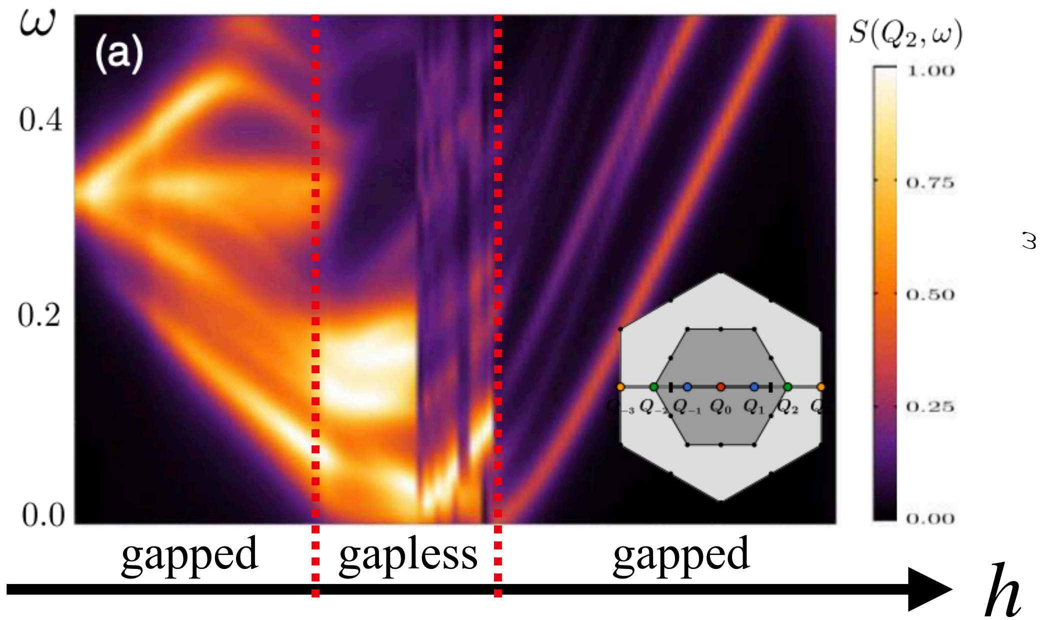

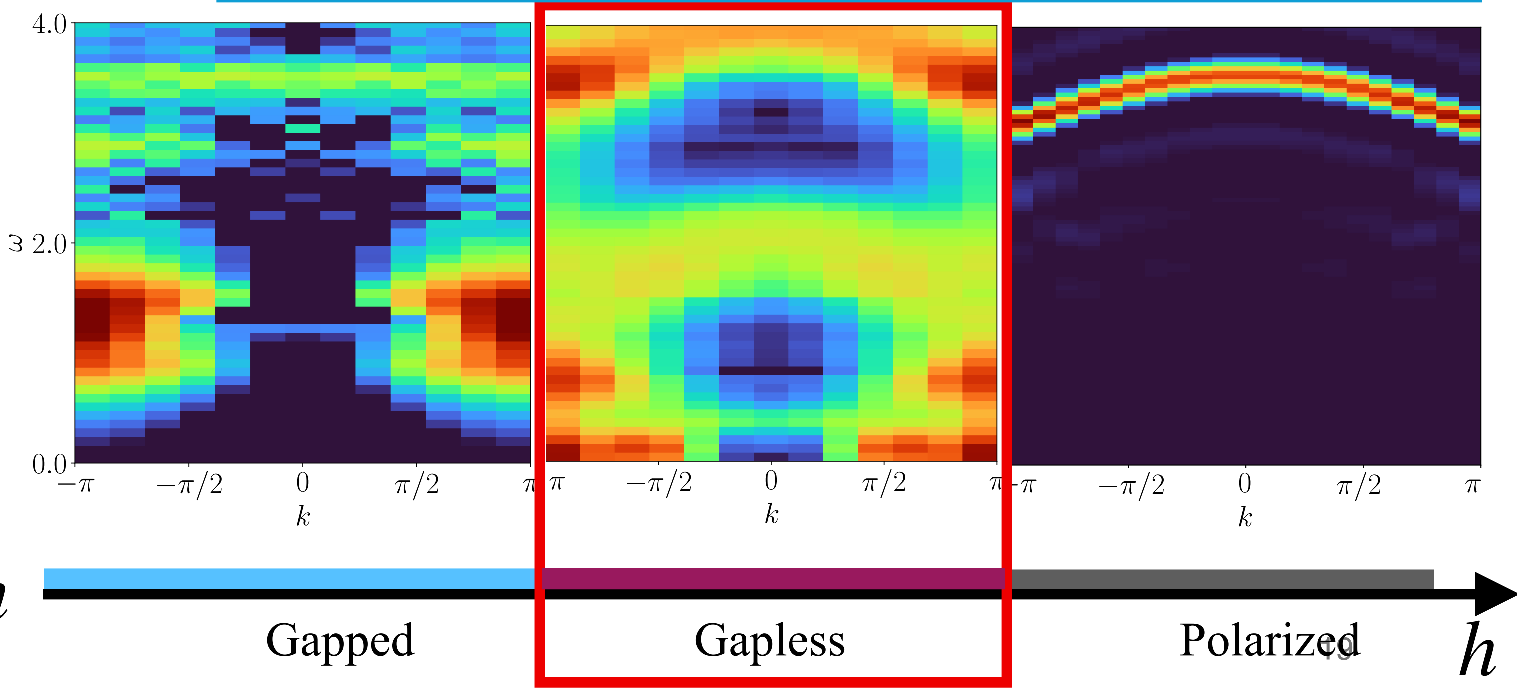

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Quasi-static-flux approximation: a minimal Ansatz

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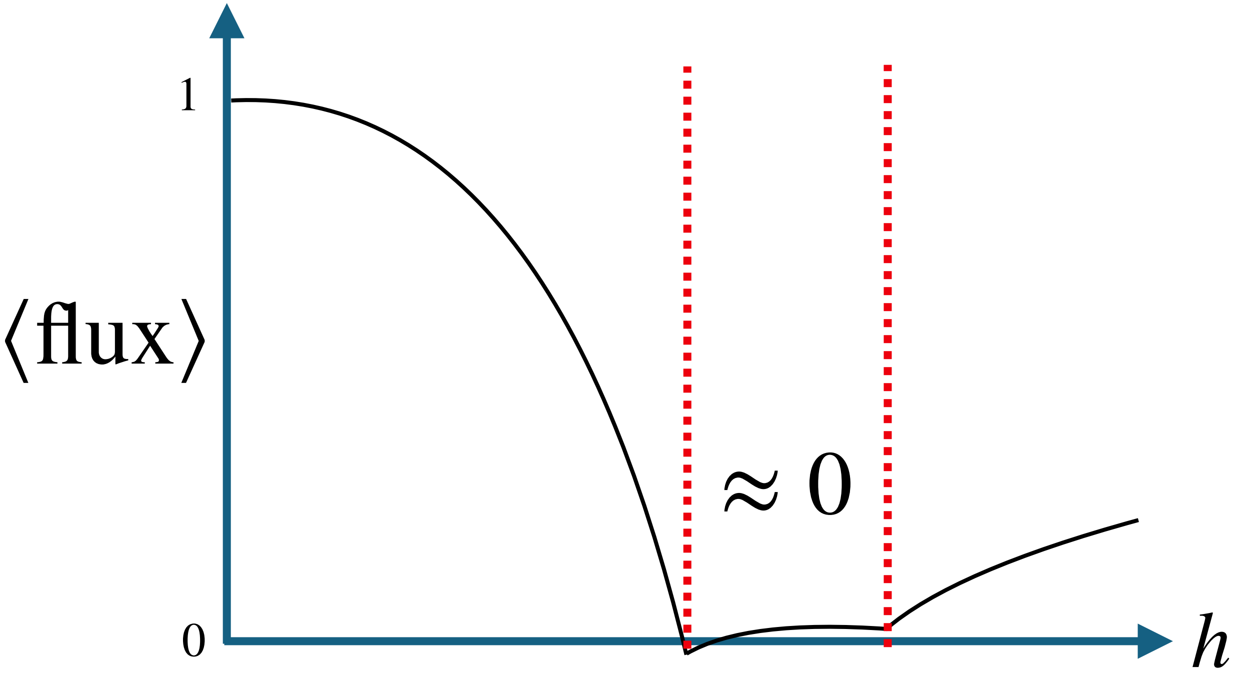

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Yogendra, Das, Baskaran, *Phys. Rev. B 108, 165118 (2023)*

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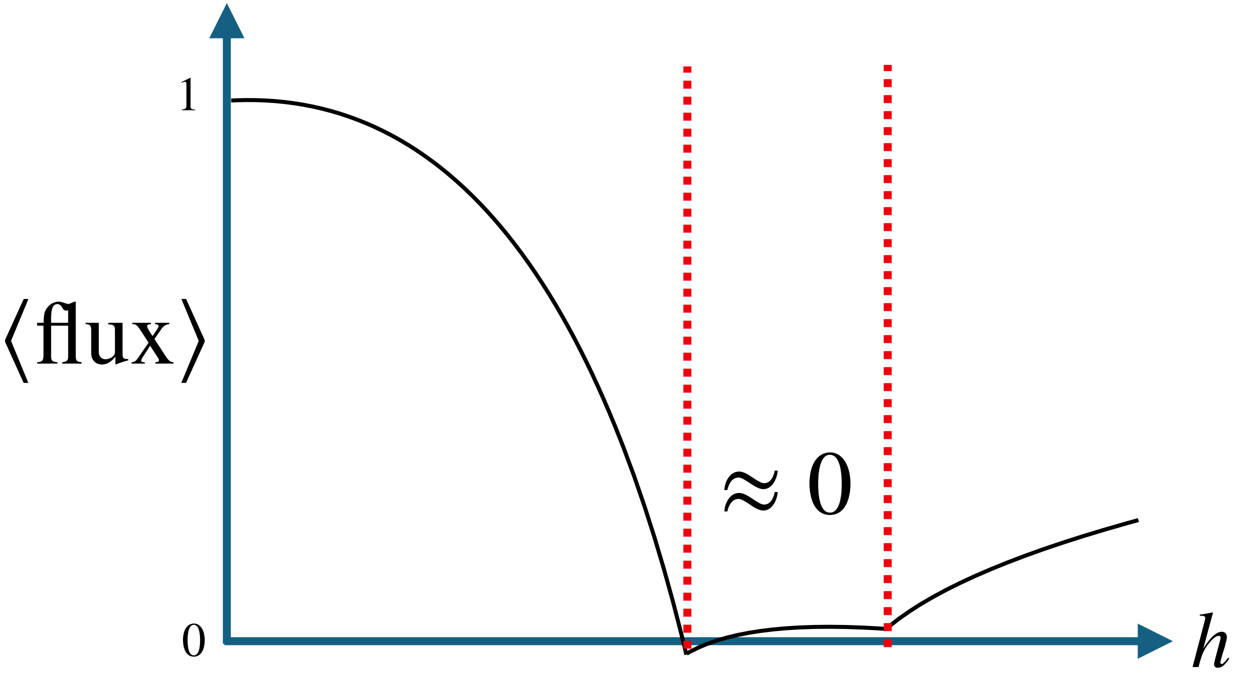

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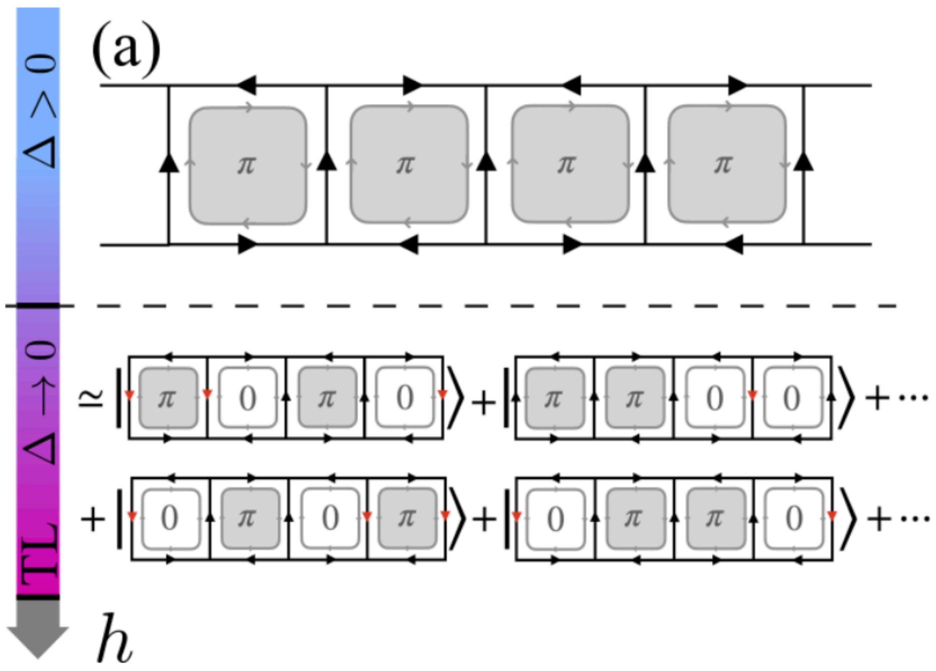

A superposition of fluxes and fermions, capturing the interplay between both sectors while preserving translational invariance:

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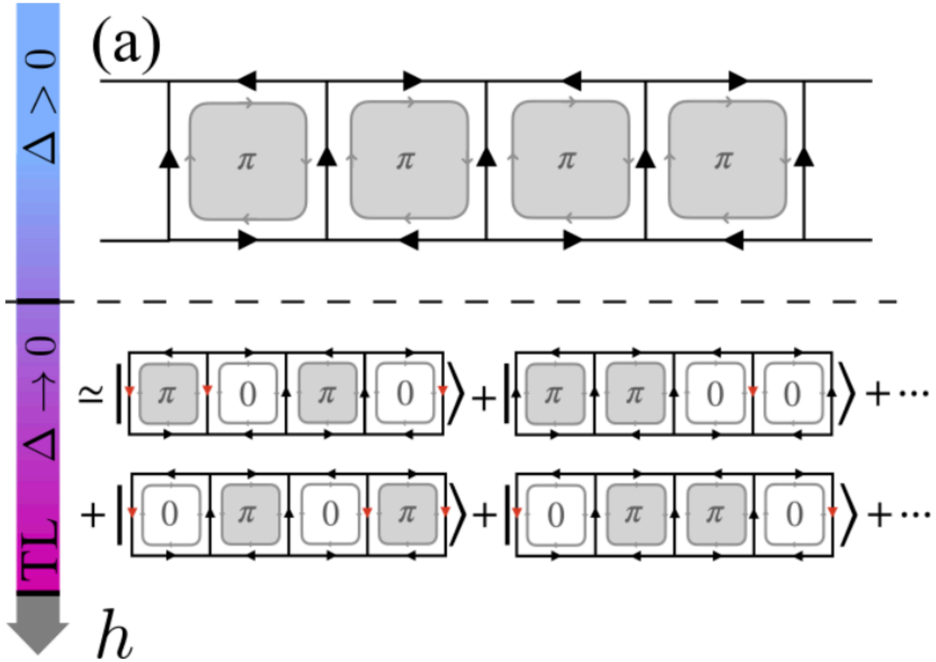

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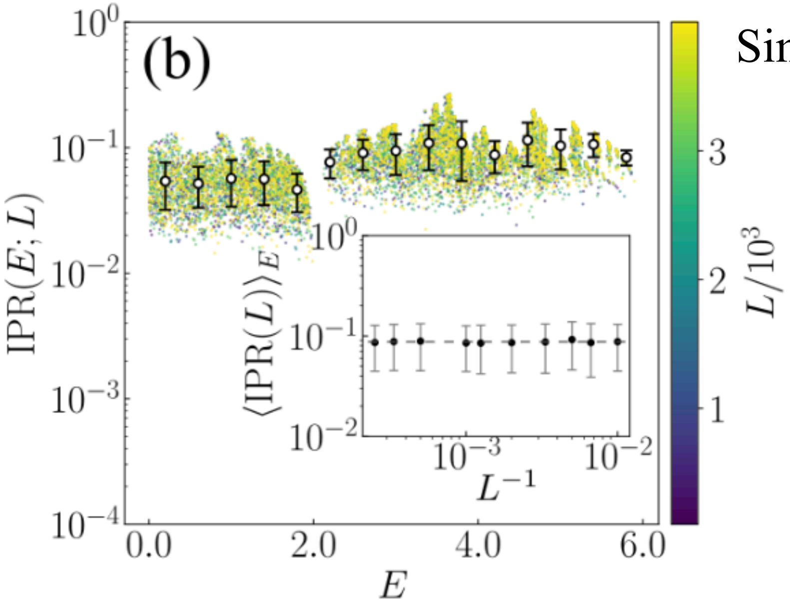
Quantum coherent disorder in flux sector $|D\rangle$ gives

- Localization (natural in quasi-1D)

Inverse Participation Ratio



Similar to disorder-free localization
But in a low-energy context

Yao, Laumann, Cirac *et al.*, *Phys. Rev. Lett. 117, 240601 (2016)*

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- Gapless majorana spectrum by hybridization

Feng, Zhu, Knolle, Knap, *arxiv:2509.07062*

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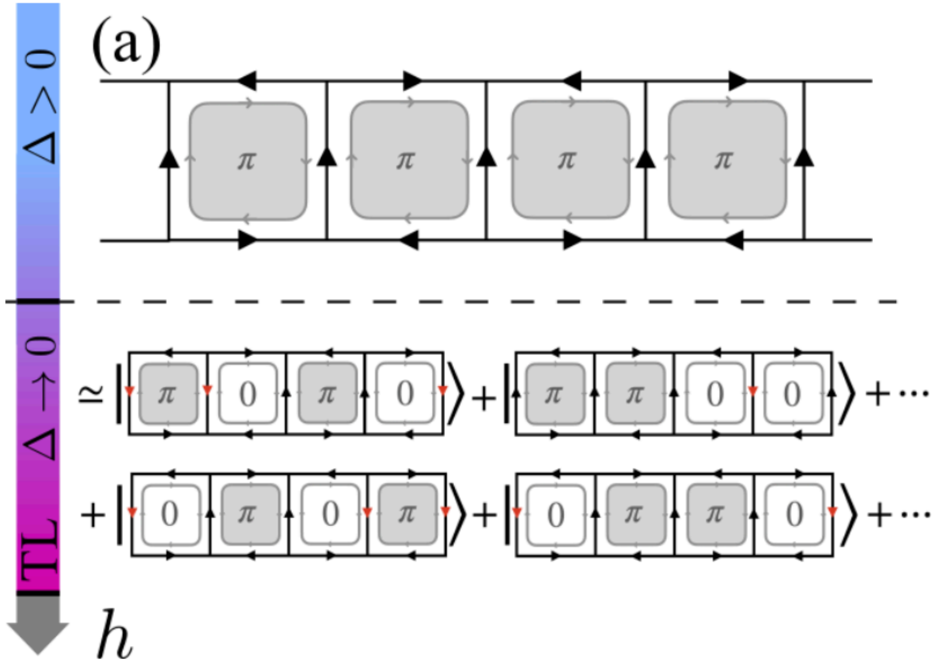

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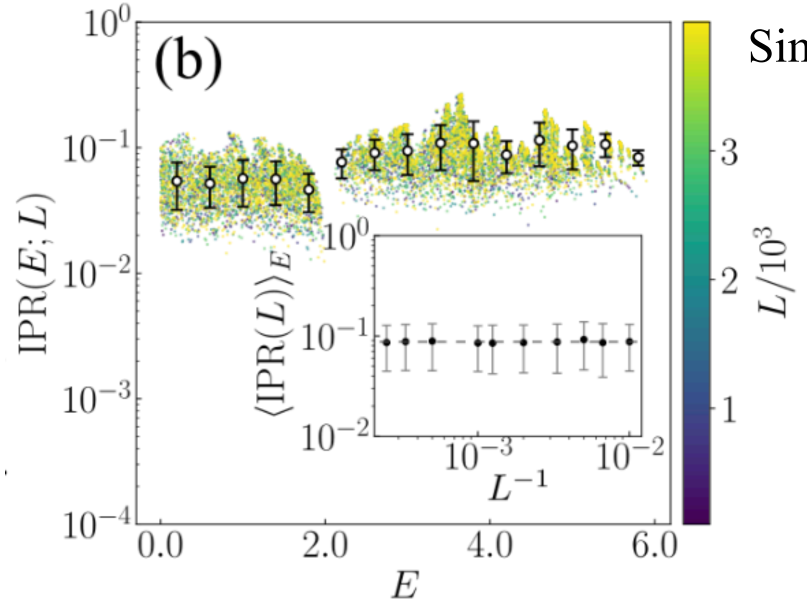

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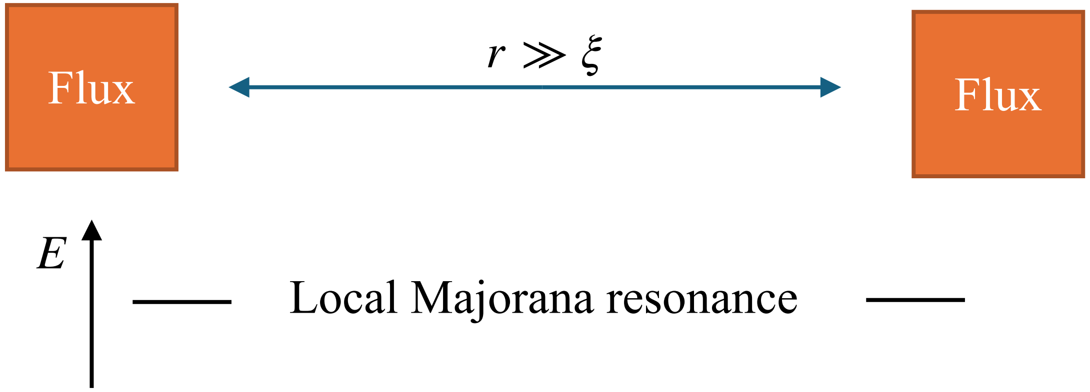
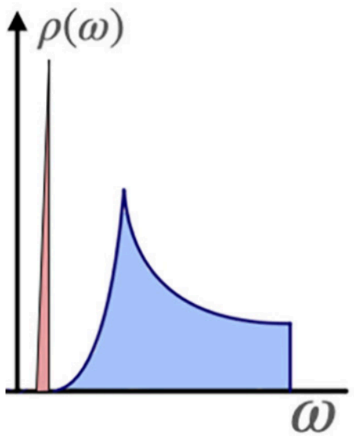
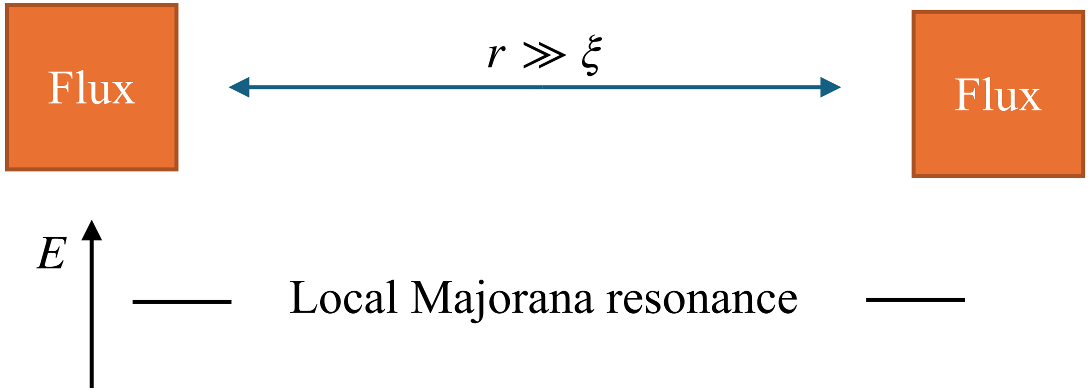
Emergence of gapless modes: The Hybridization of Majorana Resonances

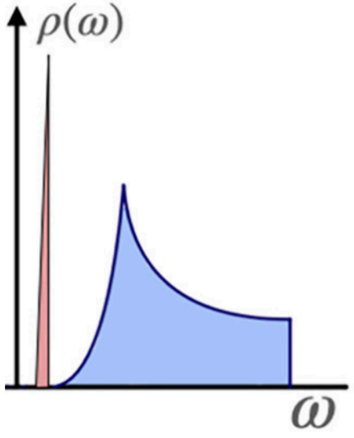




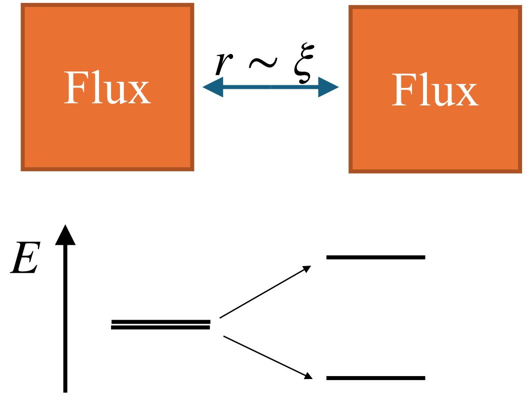
A. Panigrahi *et al.*, *Phys. Rev. B 108, 045151 (2023)*

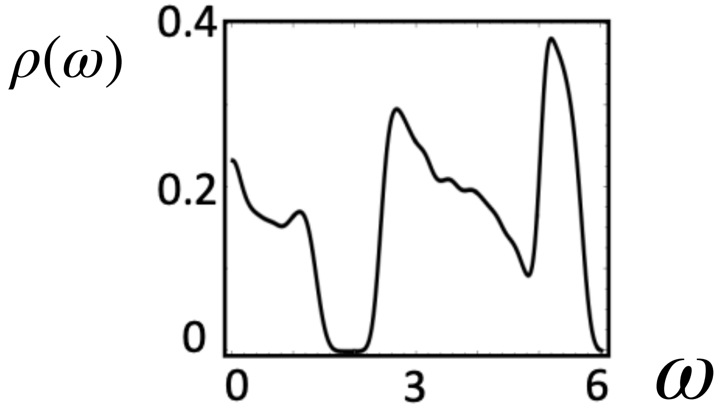
Emergence of gapless modes: The Hybridization of Majorana Resonances





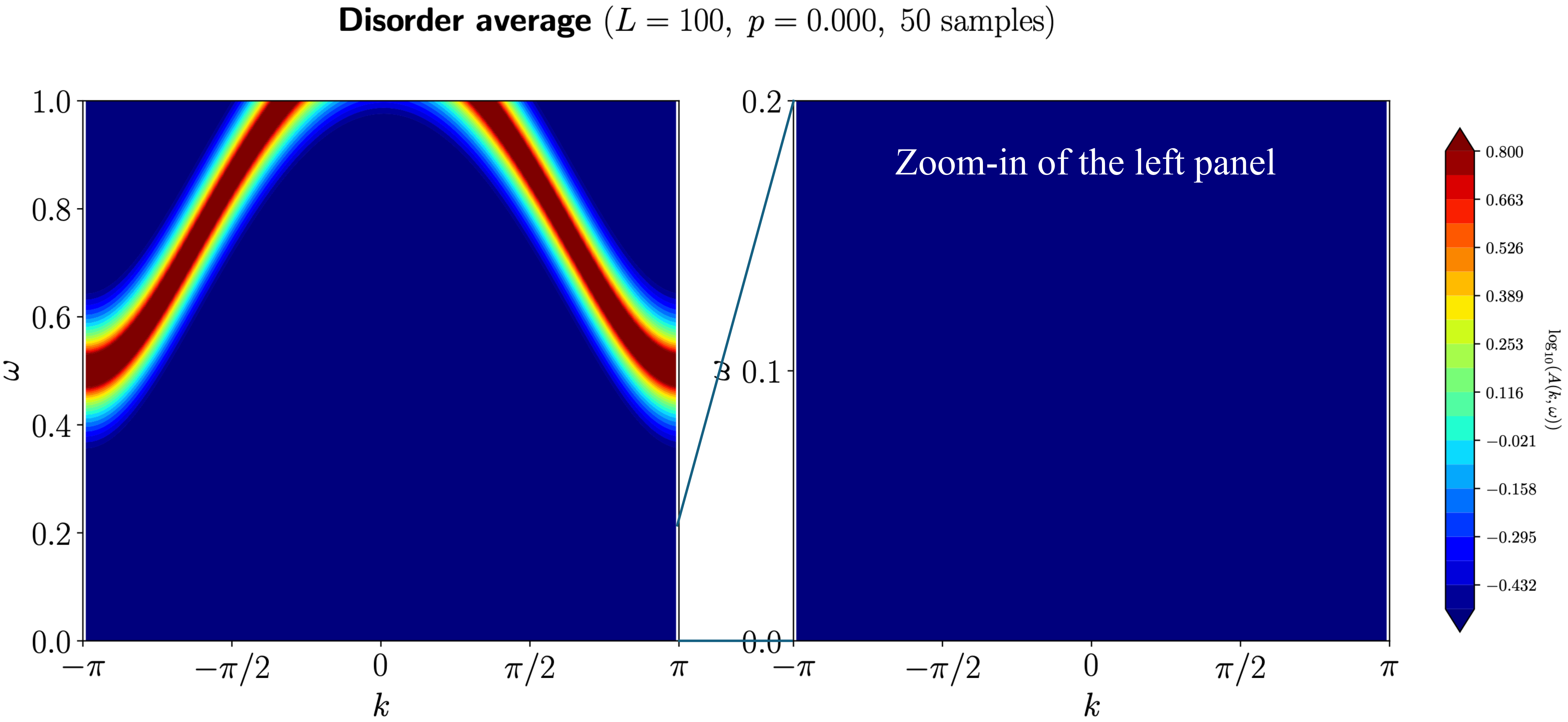
A. Panigrahi *et al.*, *Phys. Rev. B 108, 045151 (2023)*





Zhu, **Feng**, *et al.*, *Nat. Commun. 16, 2420 (2025)*

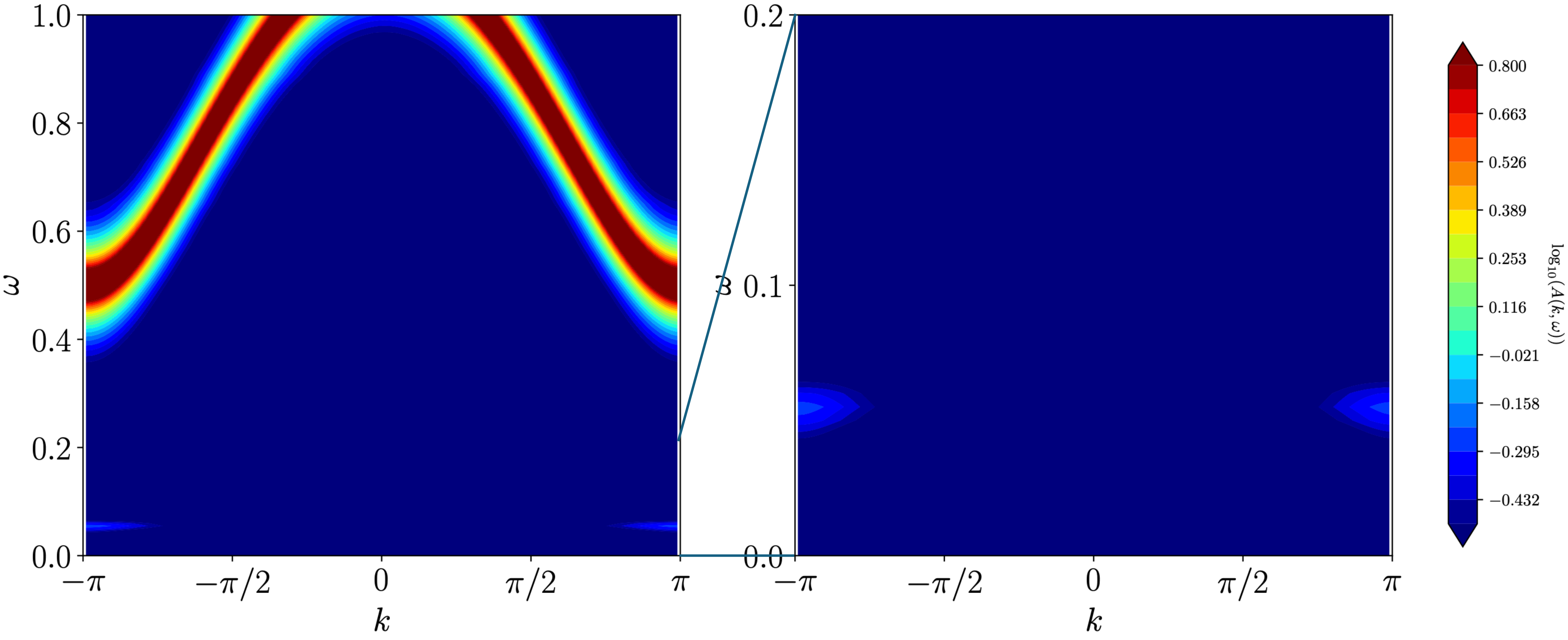
Emergence of gapless modes: The Hybridization of Majorana Resonances



$|\Psi_{\mathrm{IGP}}\rangle = \sum_{\mathcal{F}} \psi_{\mathcal{F}} \, |\mathcal{F}\rangle \otimes |\mathcal{M}_{\mathcal{F}}\rangle$ Average translation invariance, thus average momentum

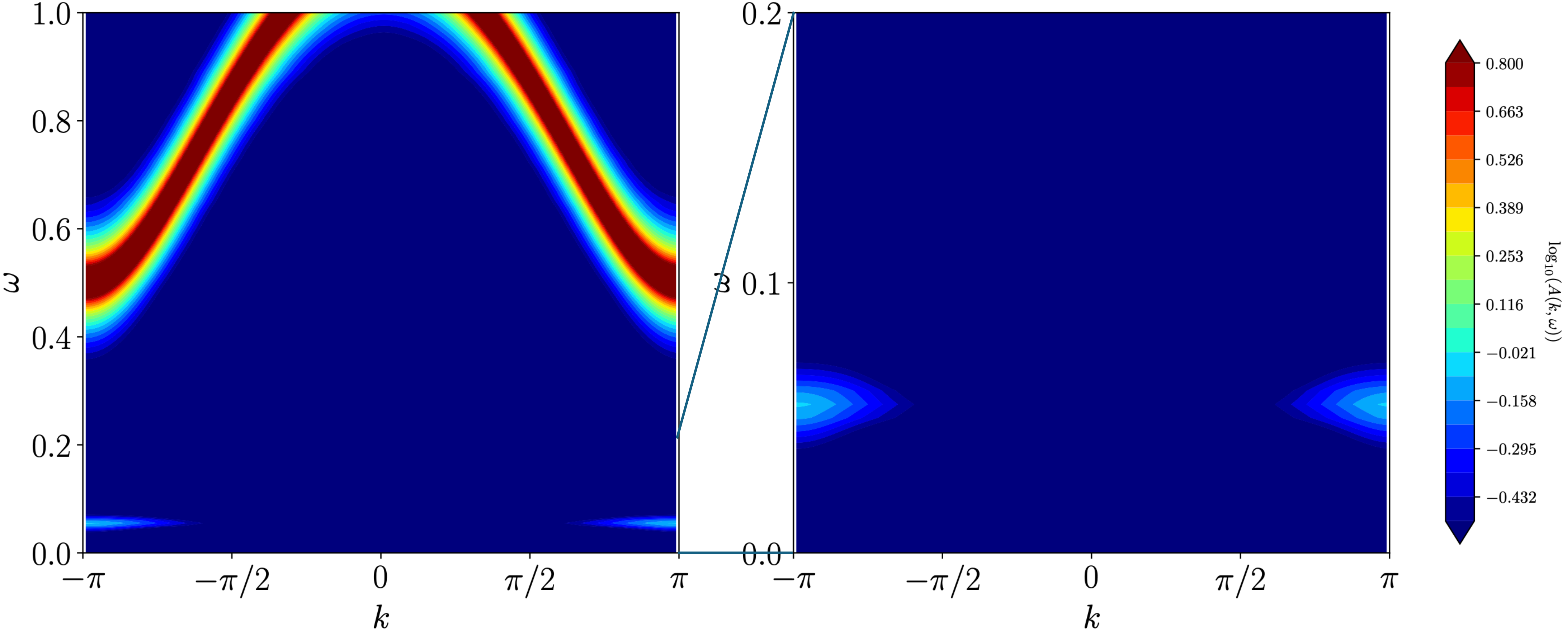
Emergence of gapless modes: The Hybridization of Majorana Resonances

Disorder average $(L = 100,\ p = 0.004,\ 50\ \text{samples})$



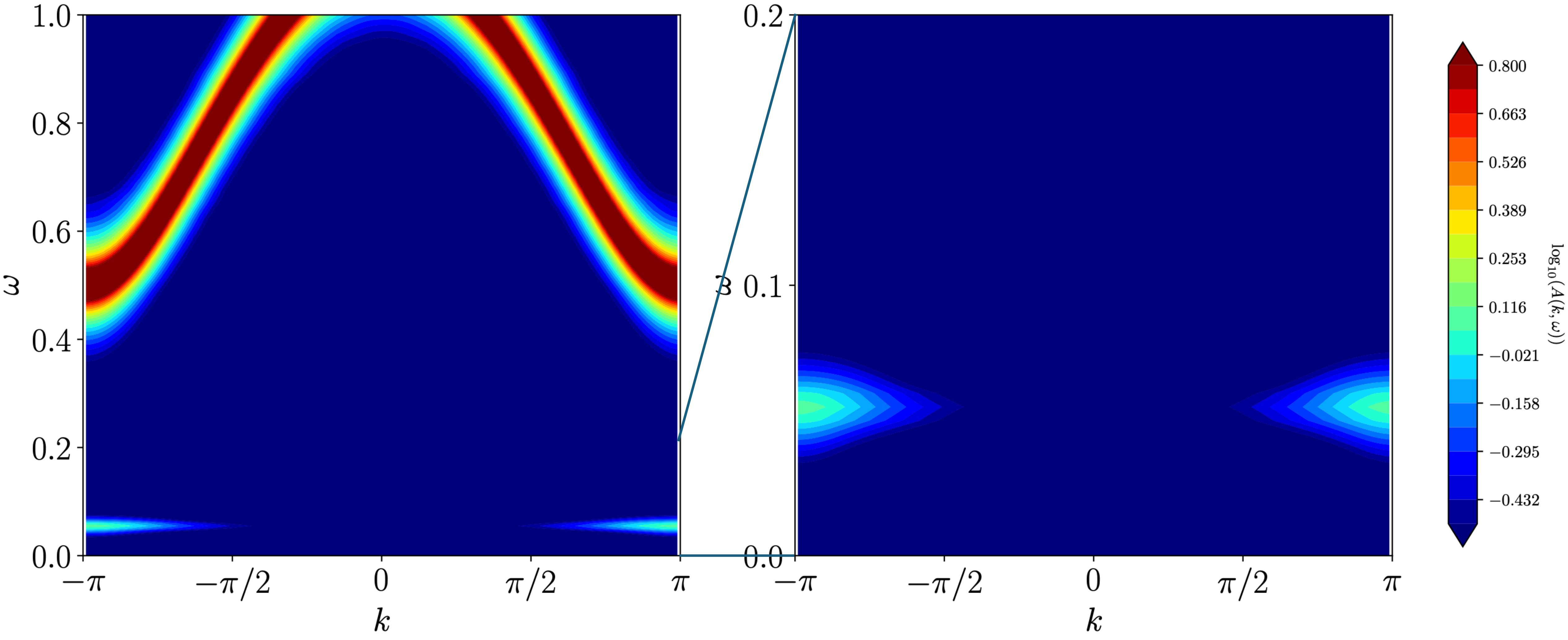
Emergence of gapless modes: The Hybridization of Majorana Resonances

Disorder average $(L = 100,\ p = 0.006,\ 50\ \text{samples})$

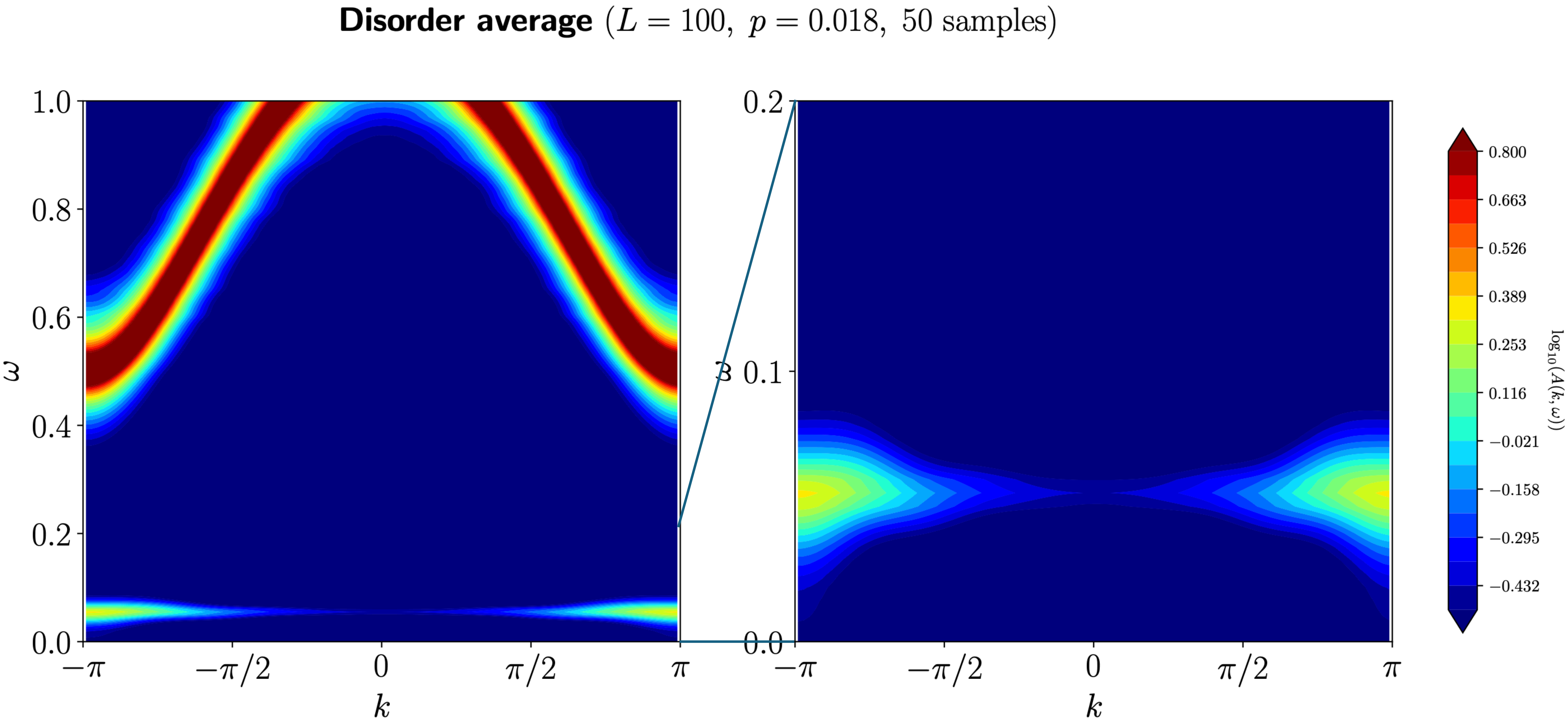


Emergence of gapless modes: The Hybridization of Majorana Resonances

Disorder average $(L = 100,\ p = 0.008,\ 50 \text{ samples})$

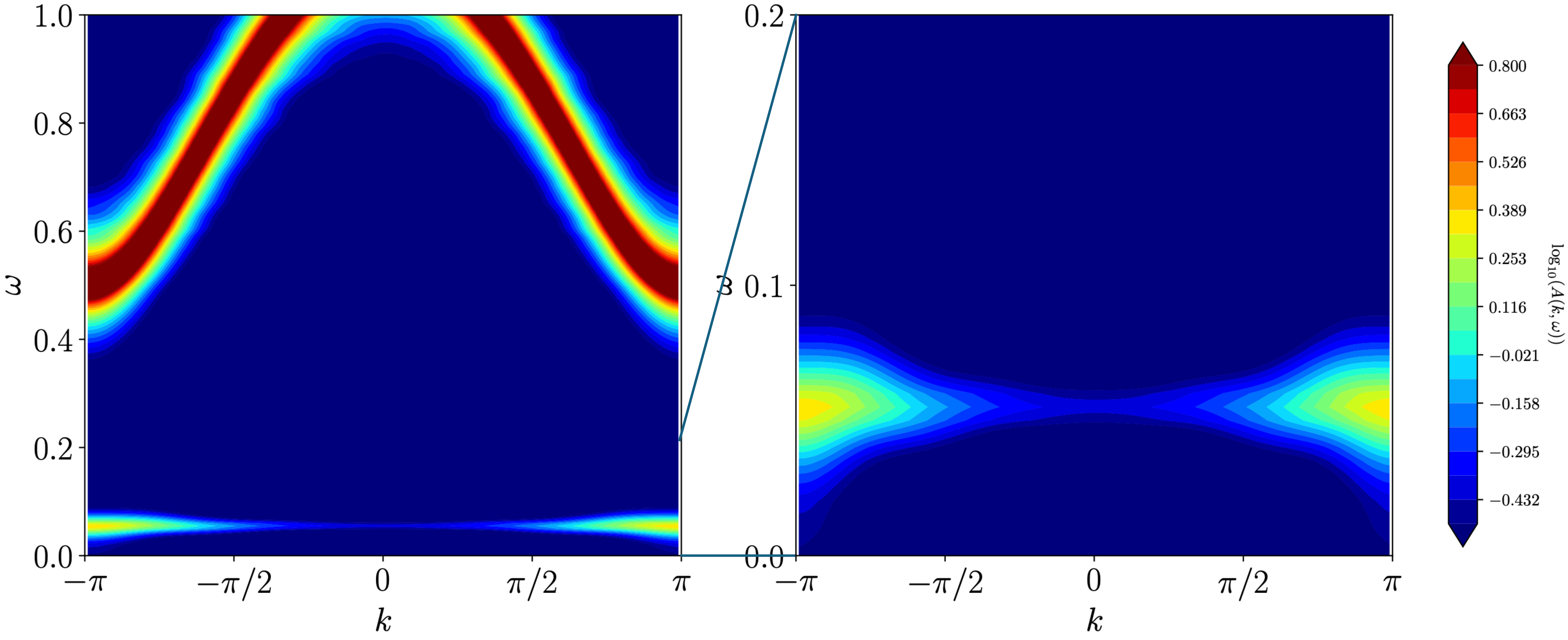


Emergence of gapless modes: The Hybridization of Majorana Resonances



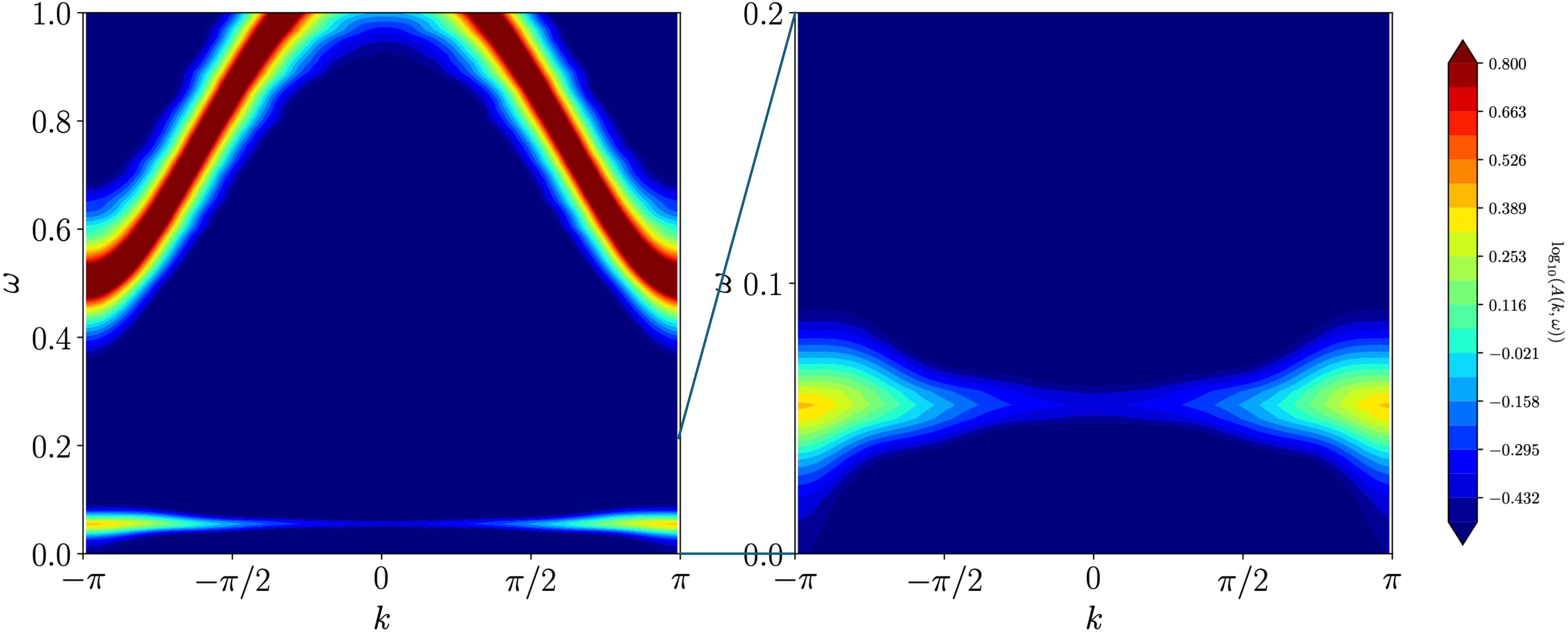
Emergence of gapless modes: The Hybridization of Majorana Resonances

Disorder average $(L = 100,\ p = 0.020,\ 50\ \text{samples})$



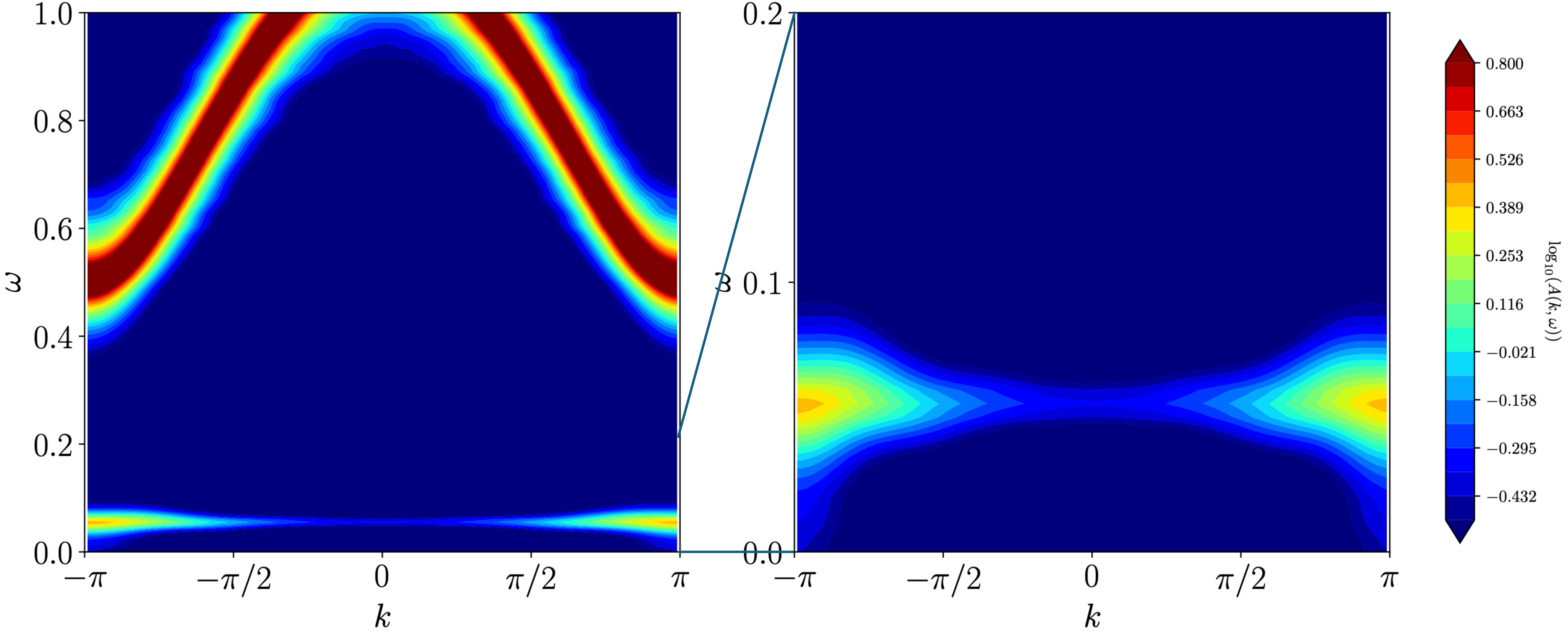
Emergence of gapless modes: The Hybridization of Majorana Resonances

Disorder average $(L = 100,\ p = 0.022,\ 50\ \text{samples})$



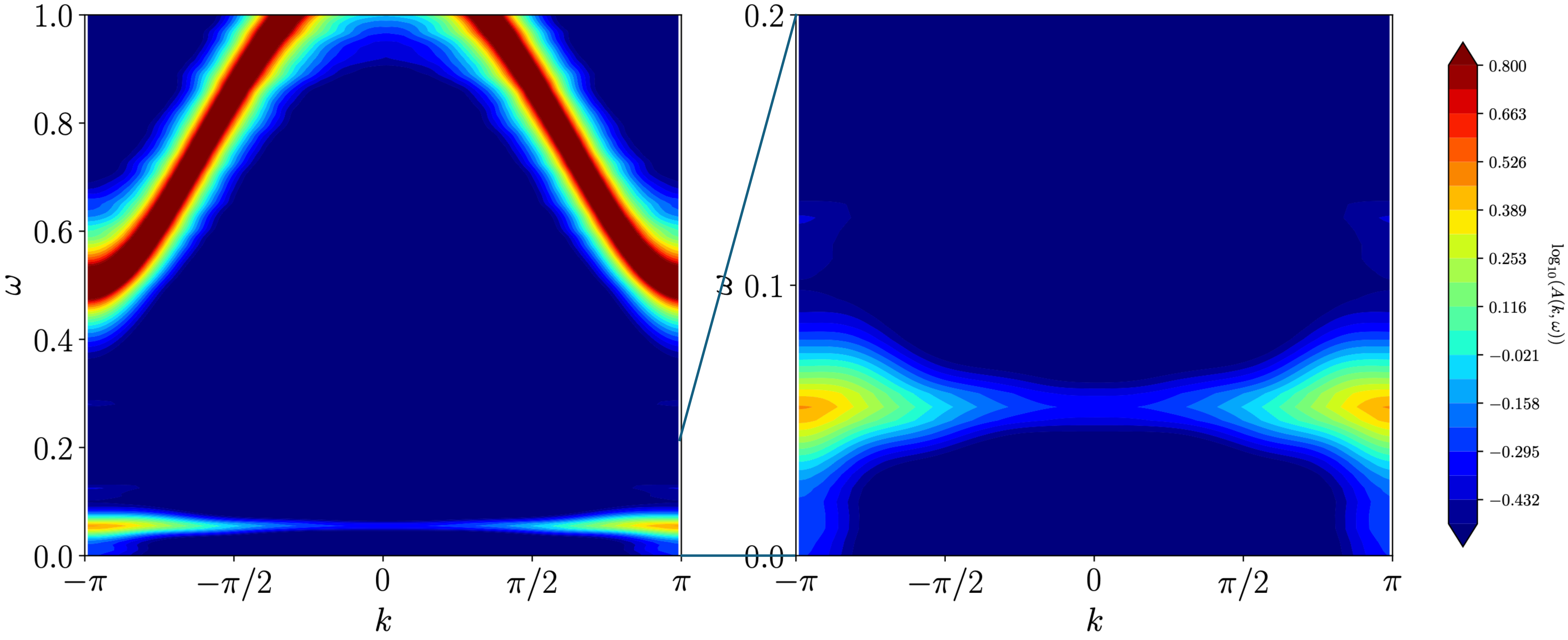
Emergence of gapless modes: The Hybridization of Majorana Resonances

Disorder average $(L = 100,\ p = 0.024,\ 50\ \text{samples})$

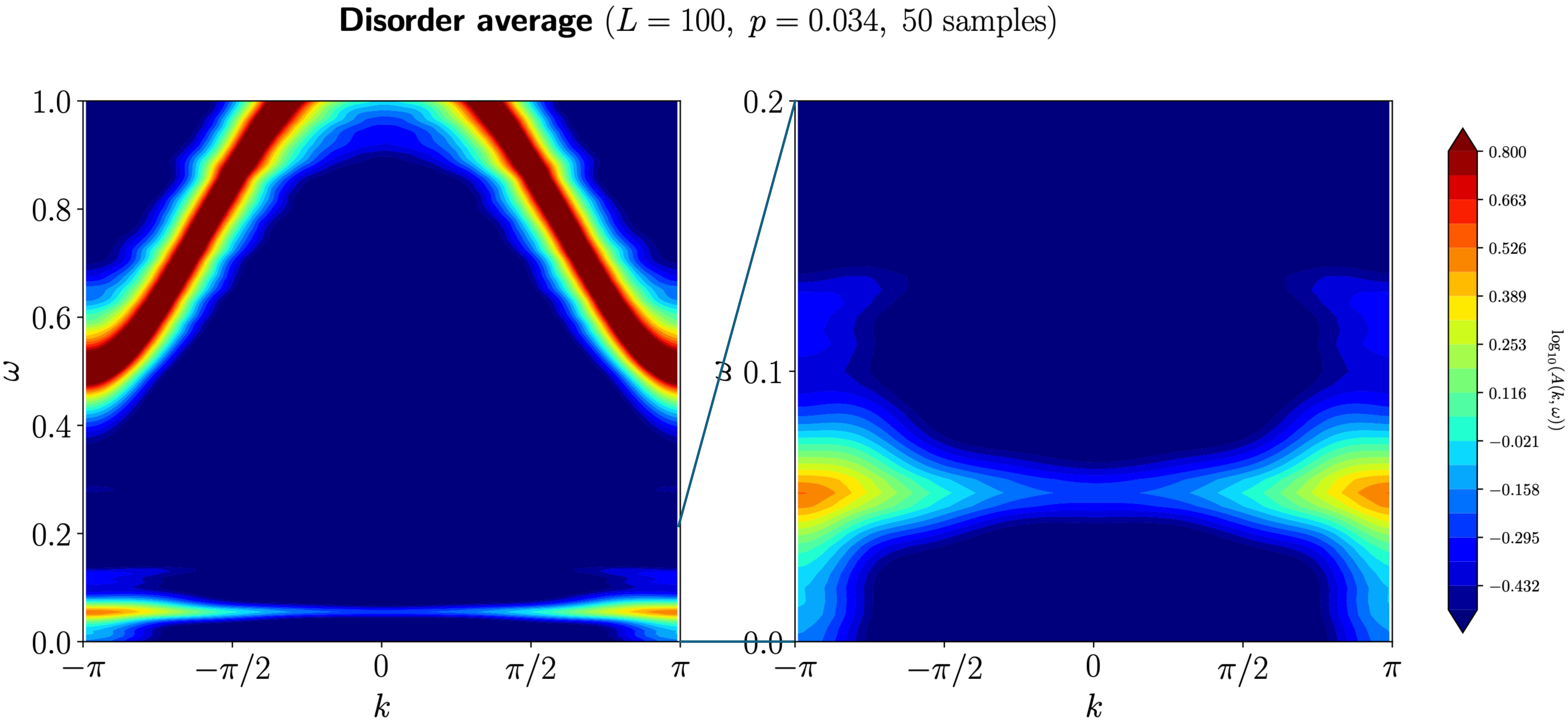


Emergence of gapless modes: The Hybridization of Majorana Resonances

Disorder average $(L = 100,\ p = 0.028,\ 50\ \text{samples})$

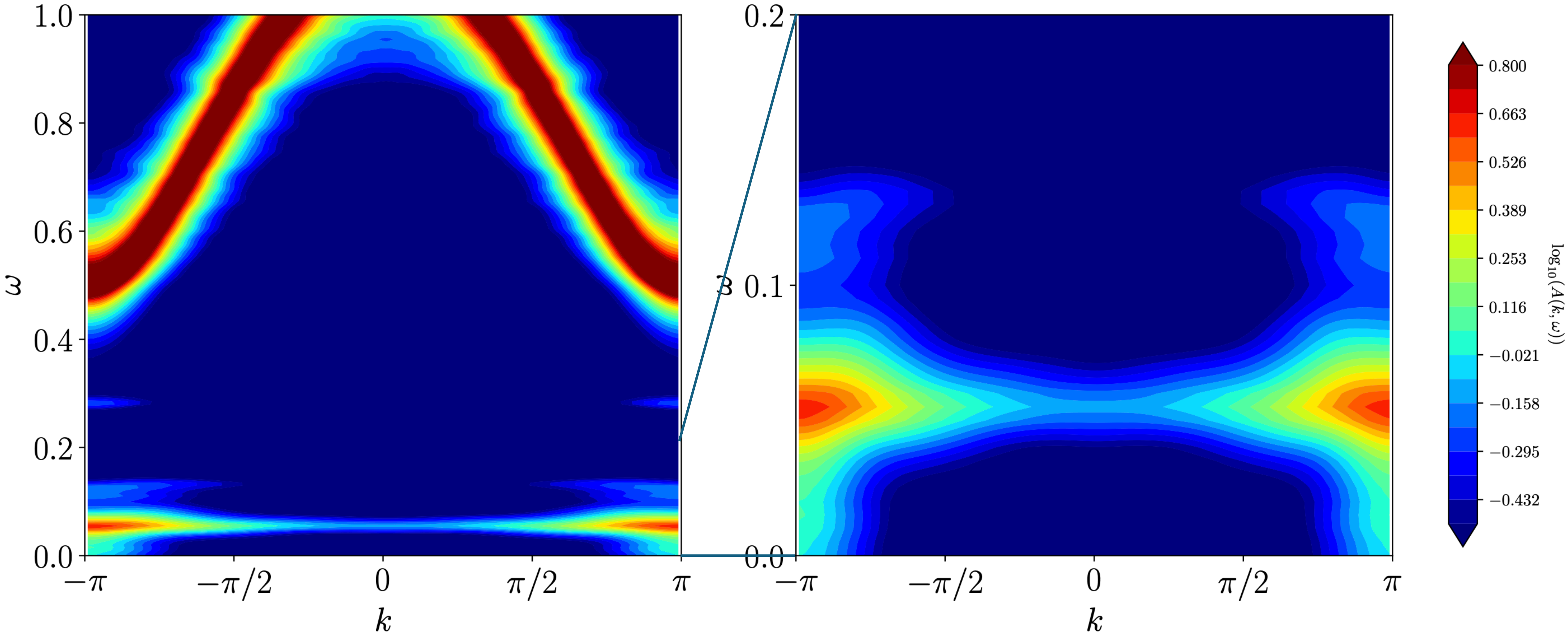


Emergence of gapless modes: The Hybridization of Majorana Resonances



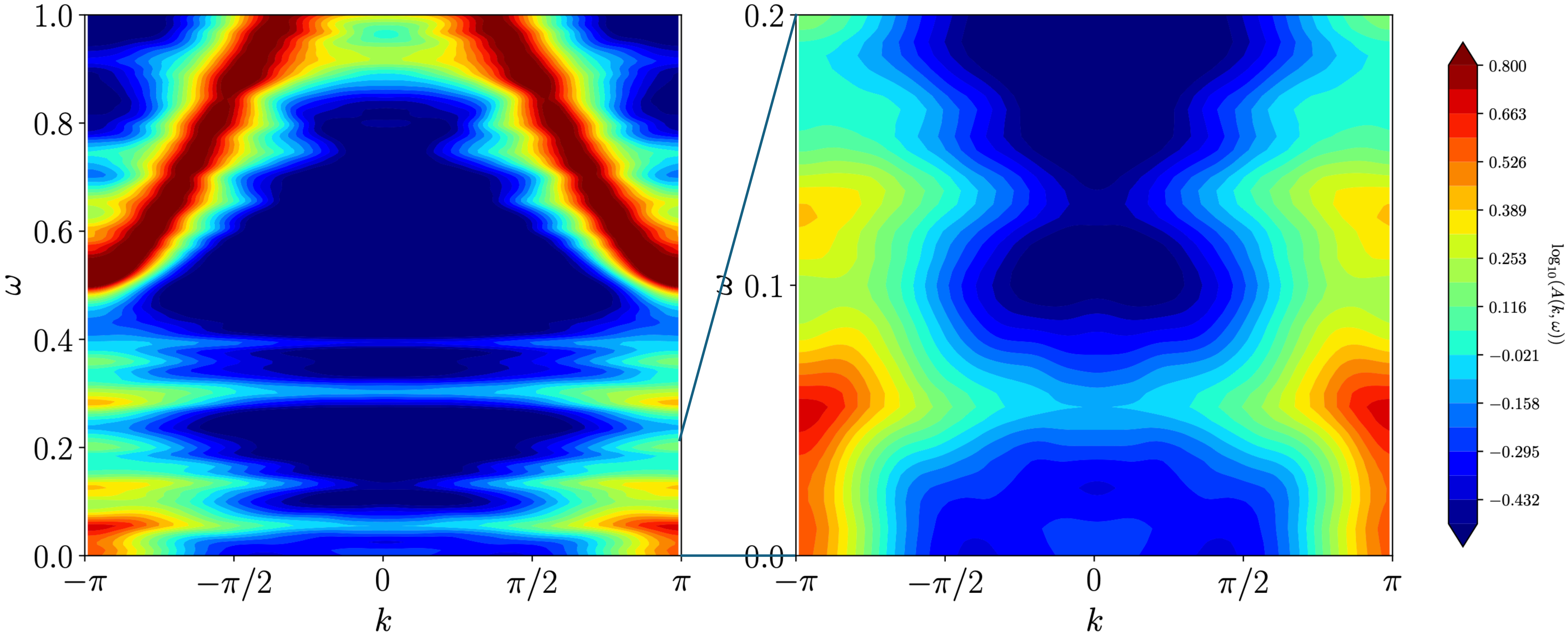
Emergence of gapless modes: The Hybridization of Majorana Resonances

Disorder average $(L = 100,\ p = 0.046,\ 50 \text{ samples})$

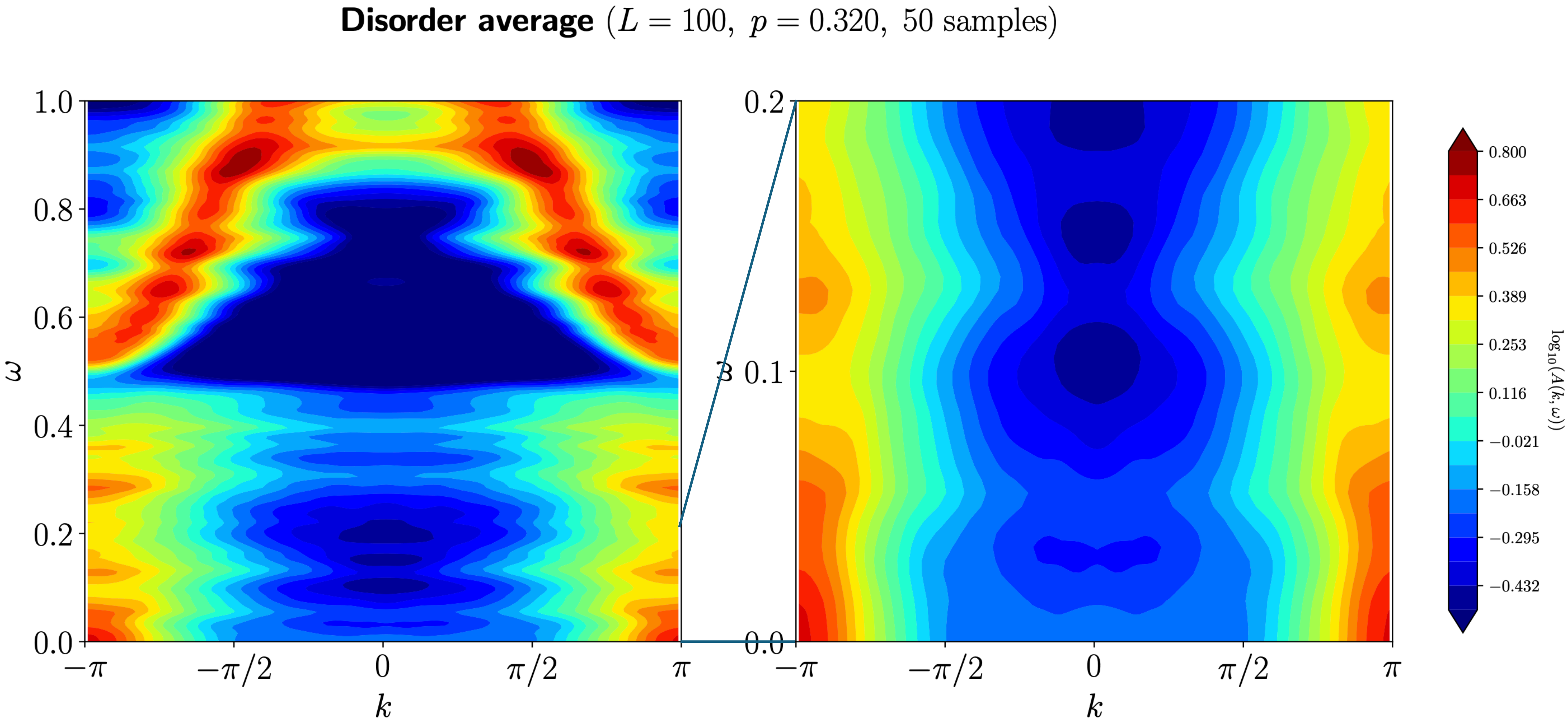


Emergence of gapless modes: The Hybridization of Majorana Resonances

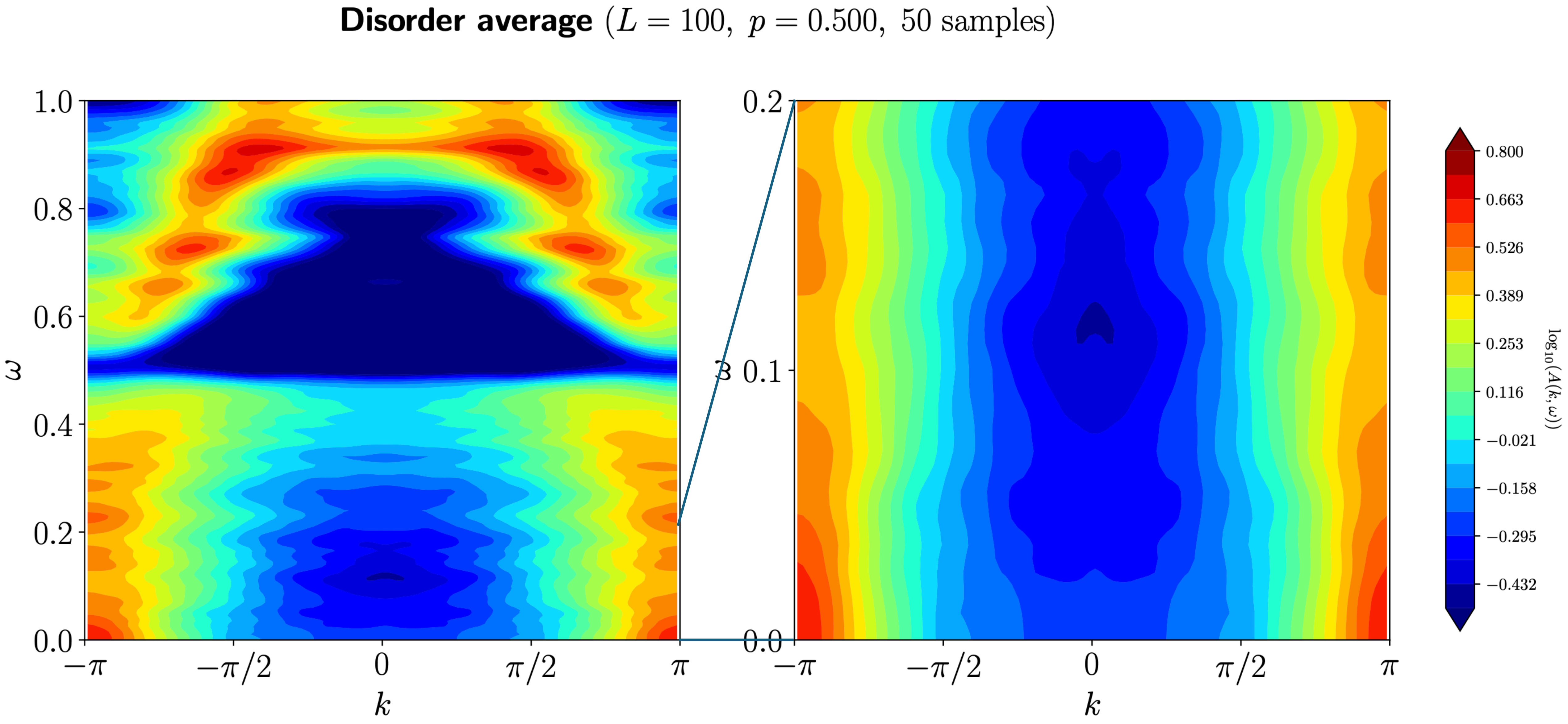
Disorder average $(L = 100,\ p = 0.178,\ 50 \text{ samples})$



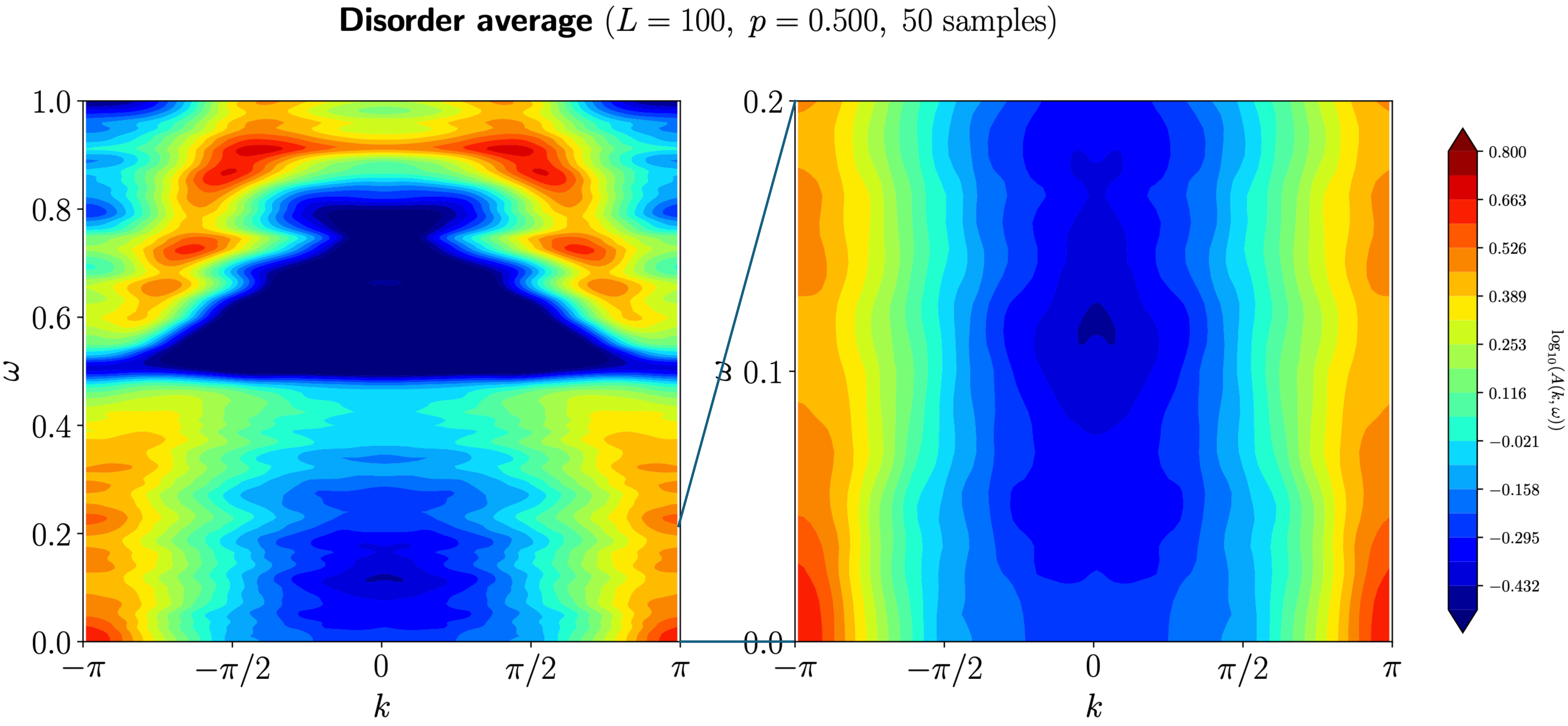
Emergence of gapless modes: The Hybridization of Majorana Resonances



Emergence of gapless modes: The Hybridization of Majorana Resonances

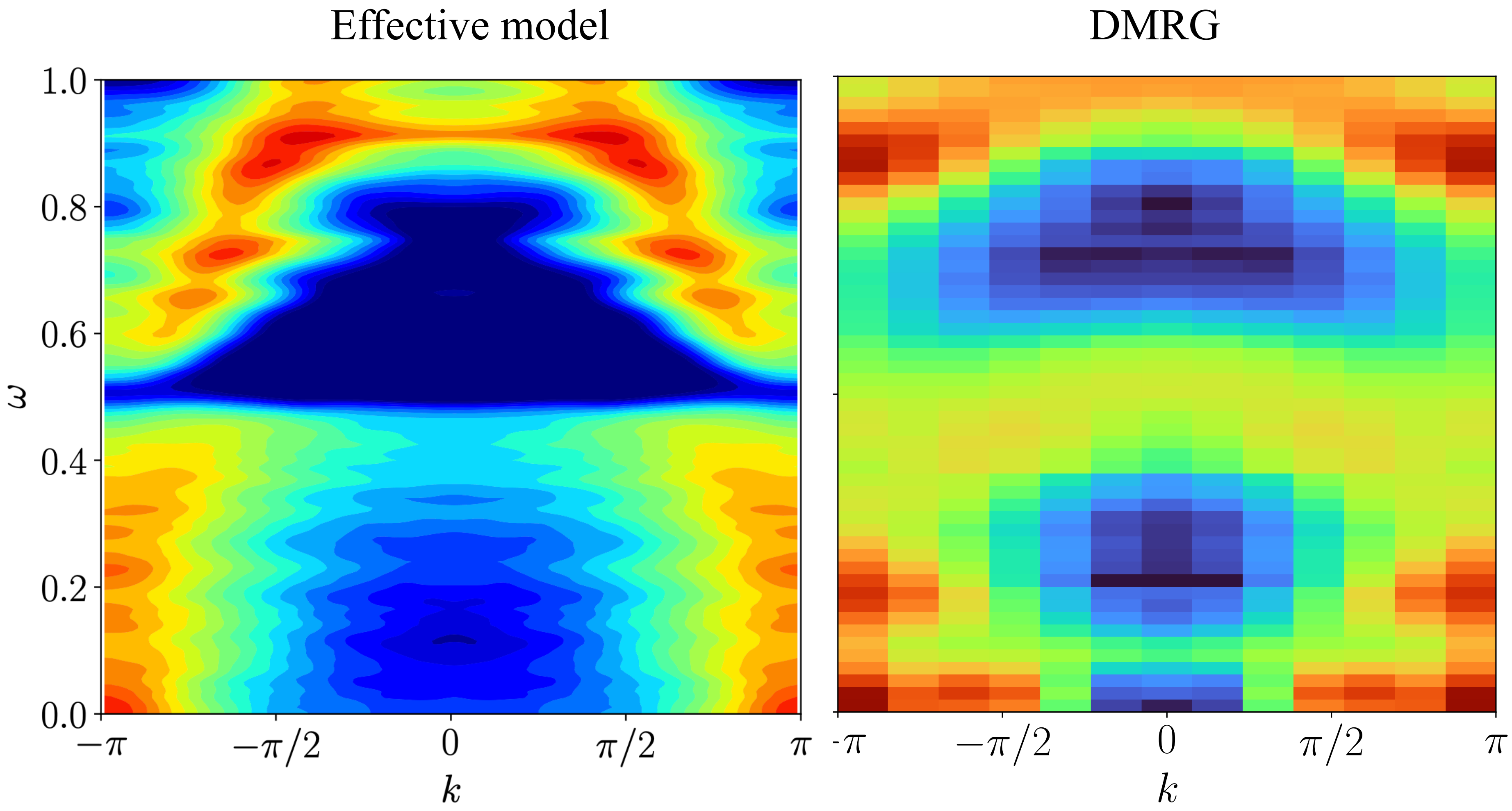


Emergence of gapless modes: The Hybridization of Majorana Resonances

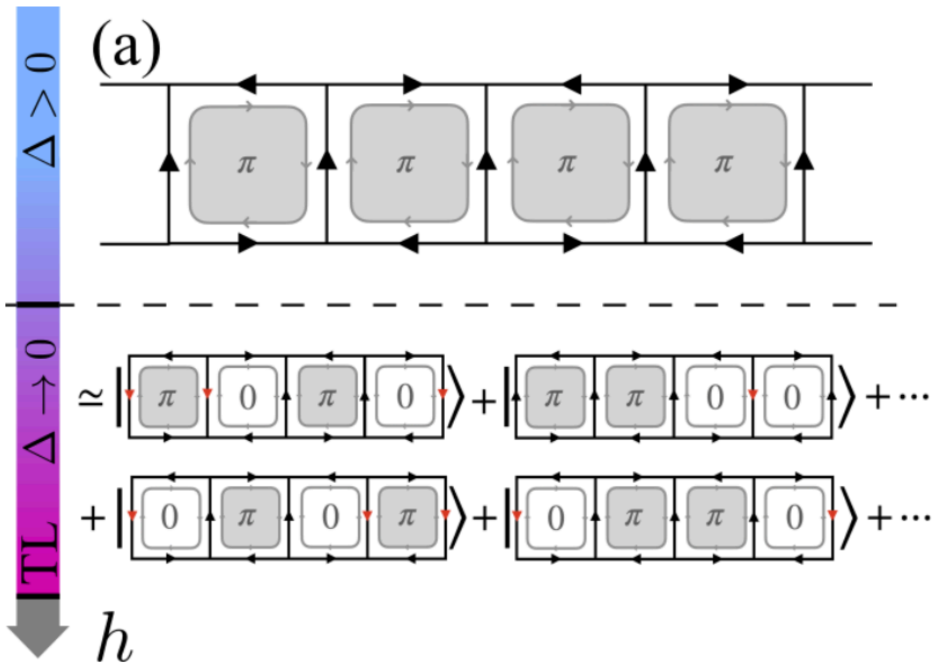


Emergence of gapless modes: The Hybridization of Majorana Resonances

Slow fluxes: Dynamic spin structure factor is covered by Majorana spectrum



Quasi-static-flux approximation: a minimal Ansatz

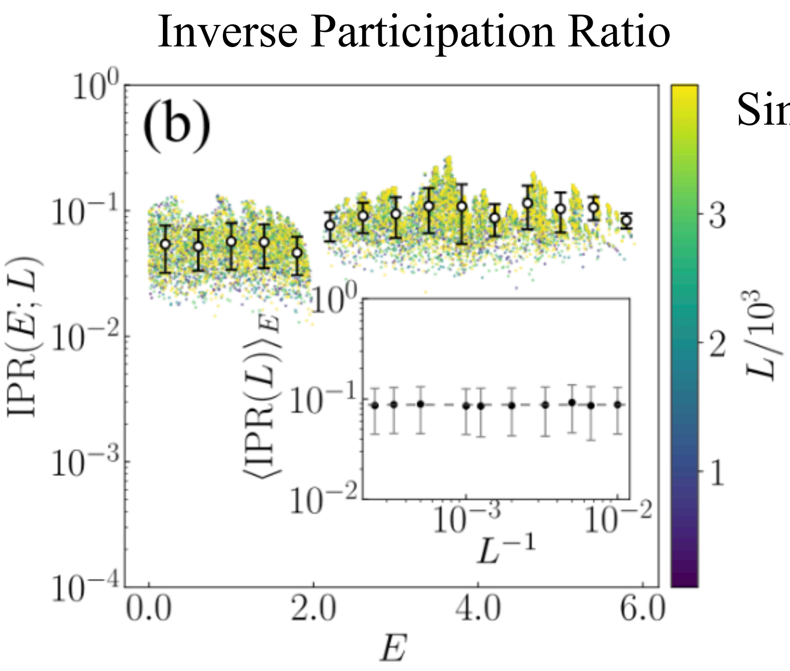


A superposition of fluxes and fermions, capturing the interplay between both sectors while preserving translational invariance:

$$|0\rangle \sim \sum_D w_D |M_D\rangle \otimes |D\rangle$$

Quantum coherent disorder in flux sector $|D\rangle$ gives

- Localization (natural in quasi-1D)



Similar to disorder-free localization
But in a low-energy context

Yao, Laumann, Cirac *et al.*, *Phys. Rev. Lett. 117, 240601 (2016)*

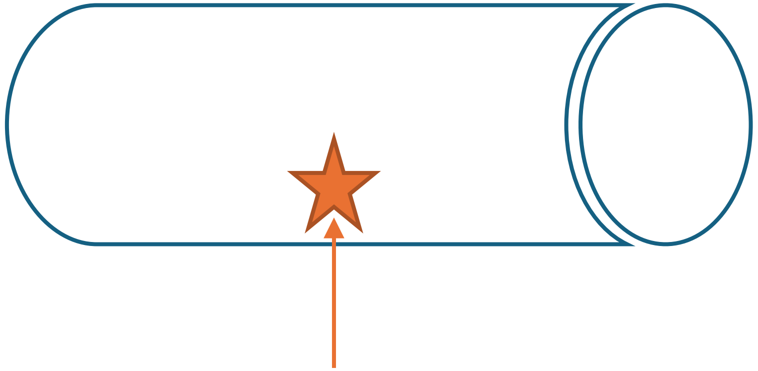
Smith, Knolle *et al.*, *Phys. Rev. Lett.* ***118****, 266601 (2019)*

Oppong, Pasqualetti *et al.*, *Phys. Rev. X* ***12****, 031026 (2022)*

- Gapless majorana spectrum by hybridization

Feng, Zhu, Knolle, Knap, *arxiv:2509.07062*

Quench dynamics



$\hat{P}$ local pert. on $|0\rangle$

Measure **energy density** ε spreading

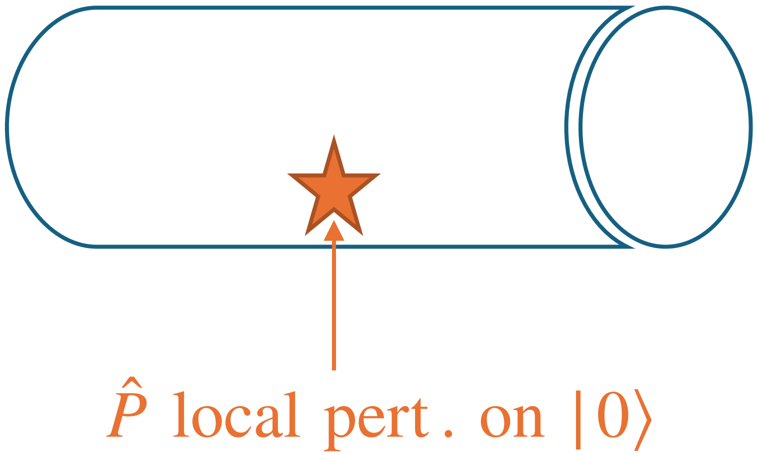
(MPS time evolution)

$$\langle 0|\hat{P}\,\varepsilon(t)\,\hat{P}|0\rangle$$

Feng, Zhu, Knolle, Knap, *arxiv:2509.07062*

Quench dynamics in trivial phase $h \gg K$

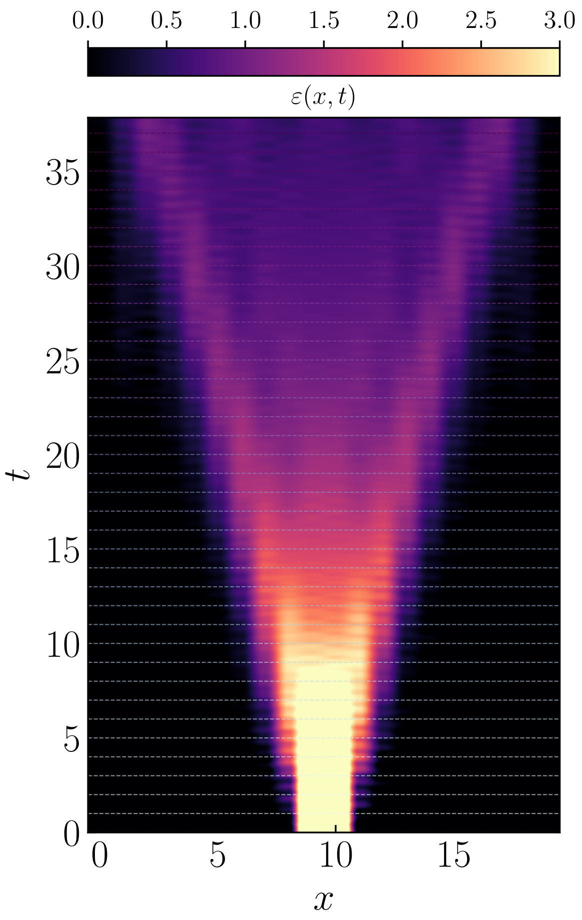
$$H = K \sum_{<jk>_\alpha} \sigma_j^\alpha \sigma_k^\alpha - h \sum_{j,\alpha} \sigma_j^\alpha$$

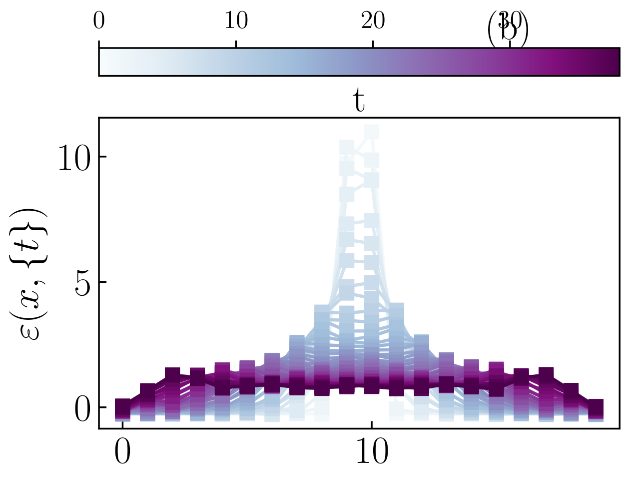


Measure **energy density** ε spreading

(MPS time evolution)

$$\langle 0 | \hat{P}\, \varepsilon(t)\, \hat{P} | 0 \rangle$$





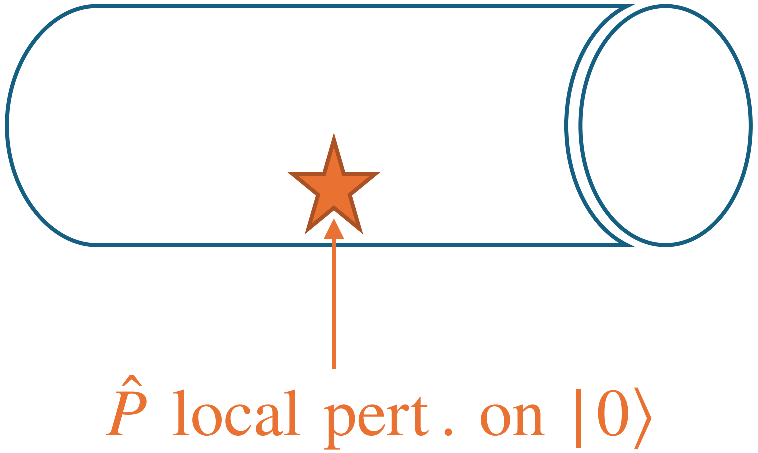
Partially Polarized Phase

(Magnons)

Feng, Zhu, Knolle, Knap, *arxiv:2509.07062*

Quench dynamics in integrable limit $h \sim 0$

Exactly solvable point



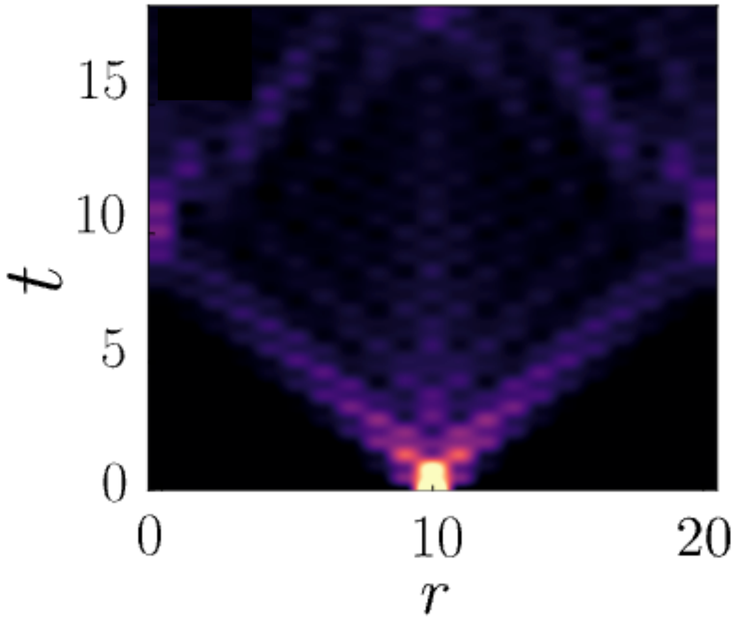
Measure **energy density** ε spreading

(MPS time evolution)

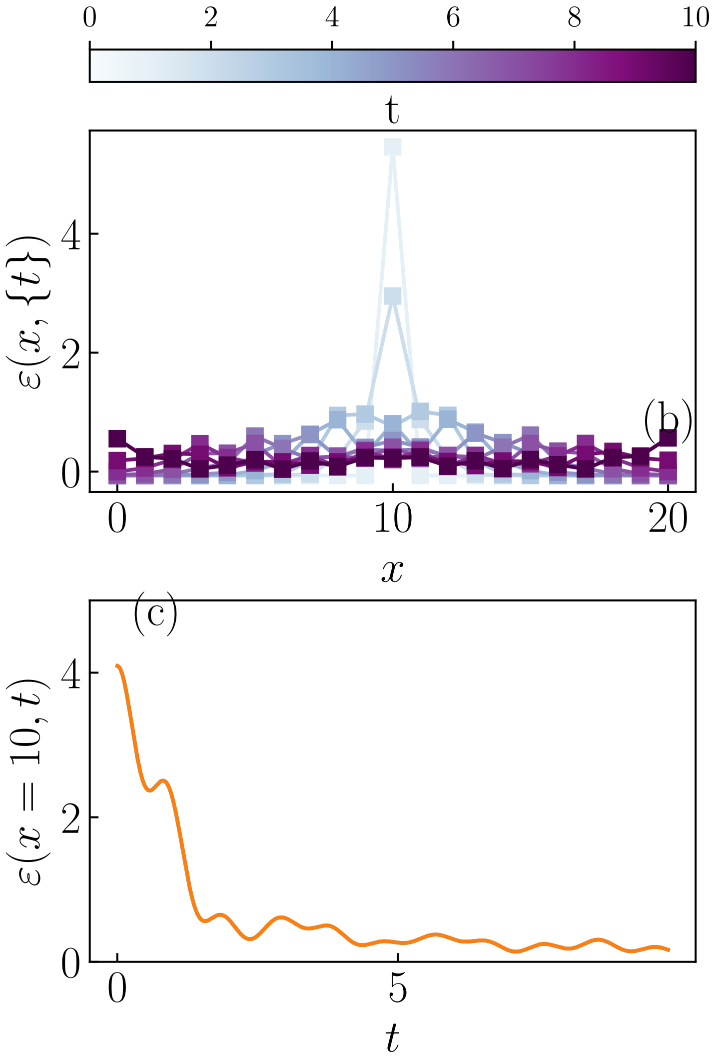
$$\langle 0 | \hat{P}\, \varepsilon(t)\, \hat{P} | 0 \rangle$$

$\hat{P} = Z_i Z_{i+z}$ dimer

Excite only fermions



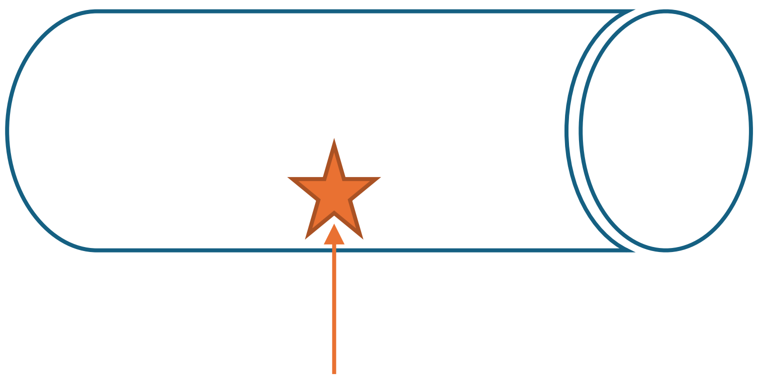
Fast spreading of Majorana fermions



Feng, Zhu, Knolle, Knap, *arxiv:2509.07062*

Transient localization in quench dynamics

Gapless QSL at h/K ~ 0.8

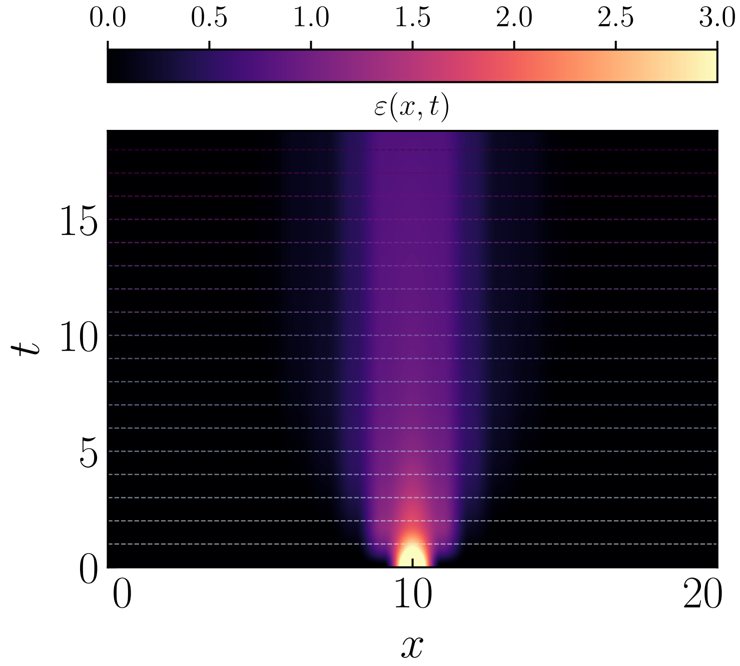


$$|0\rangle \sim \sum_D w_D |M_D\rangle \otimes |D\rangle$$

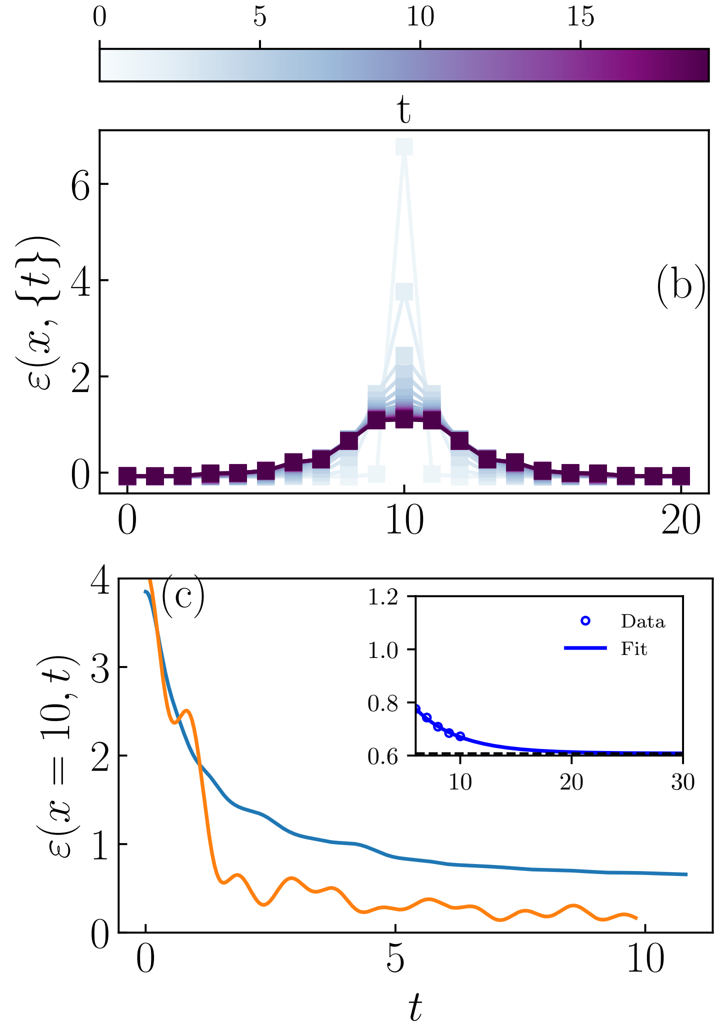
Measure **energy density** ε spreading

(MPS time evolution)

$$\langle 0|\hat{P}\,\varepsilon(t)\,\hat{P}|0\rangle$$



No spreading at transient time



Feng, Zhu, Knolle, Knap, *arxiv:2509.07062*

Transient Localization from energy-current response

Continuity equation:

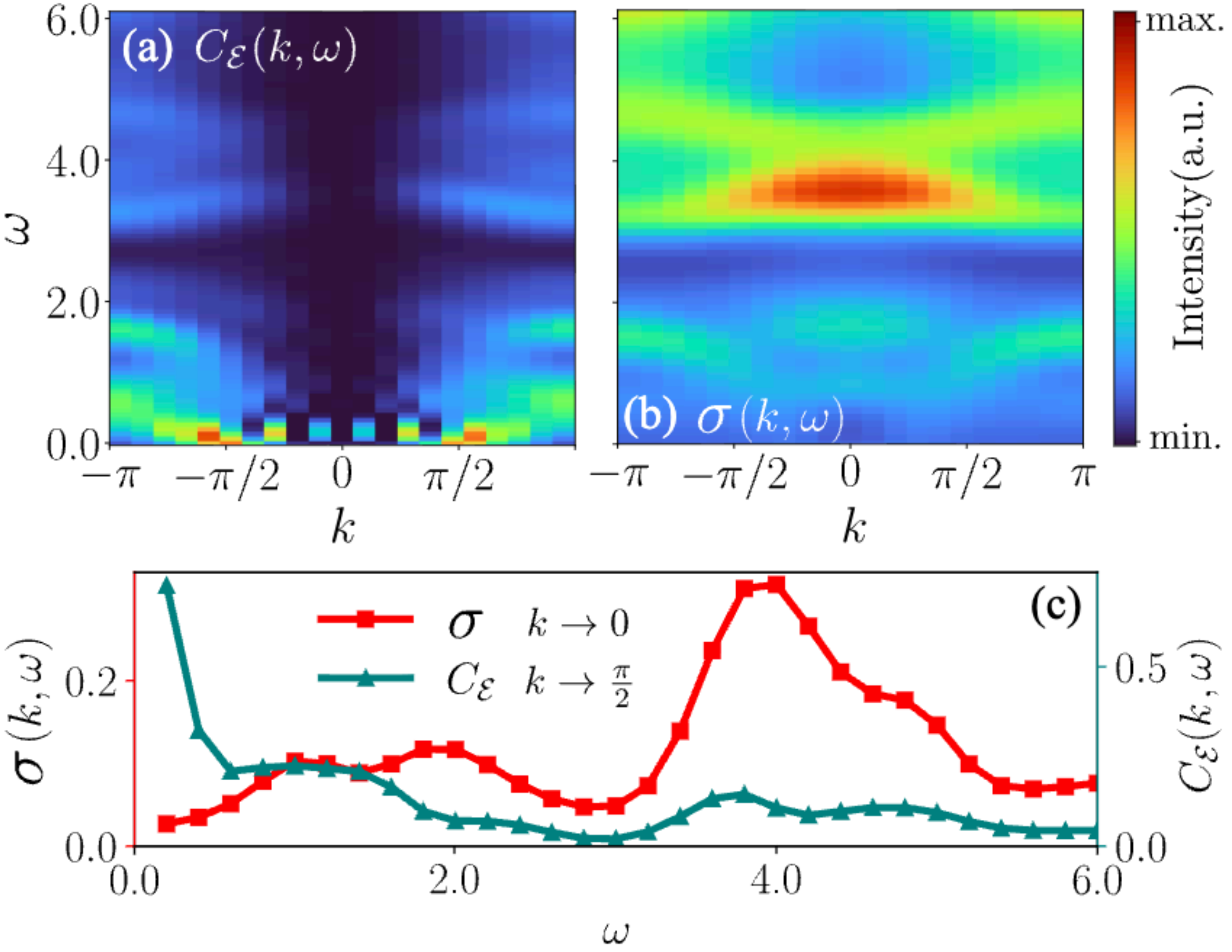
$$\partial_t \varepsilon(x,t) + \nabla \cdot J(x,t) = 0$$

Energy current correlation:

$$C_J(k,\omega) = \frac{\omega^2 C_\varepsilon(k,\omega)}{2 - 2\cos(k)}$$

Dynamical energy conductivity

$$\sigma(k,\omega) \sim \frac{C_J(k,\omega)}{\omega}$$

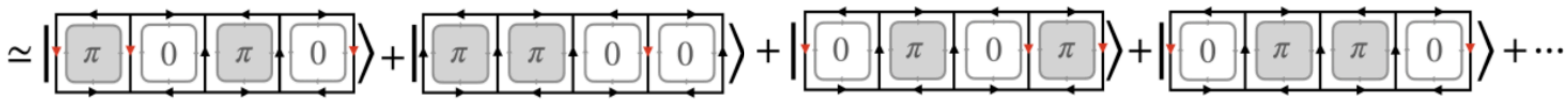


Feng, Zhu, Knolle, Knap, *arxiv:2509.07062*

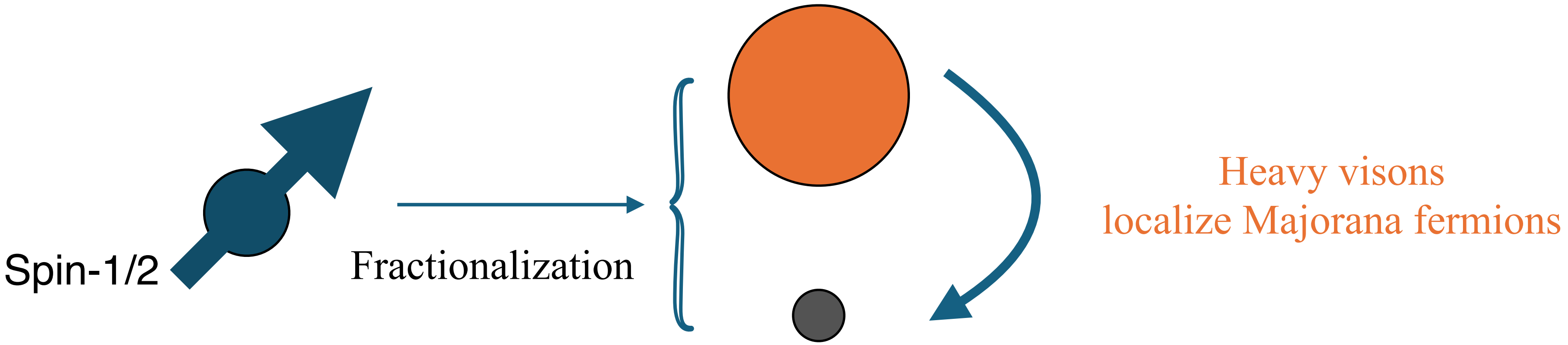
Take Home Message:

- Gapless quantum magnets can have vanishing energy transport **without breaking translation-invariance**; a Hallmark of mass-imbalanced fractionalization in gapless quantum magnets

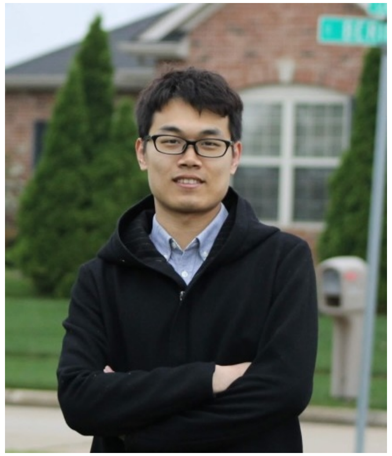
- Mechanism: Transient localization without disorder (or with quantum coherent disorder)



- **No extrinsic disorder is needed; A fraction of spin localizes the other fraction**



Acknowledgment



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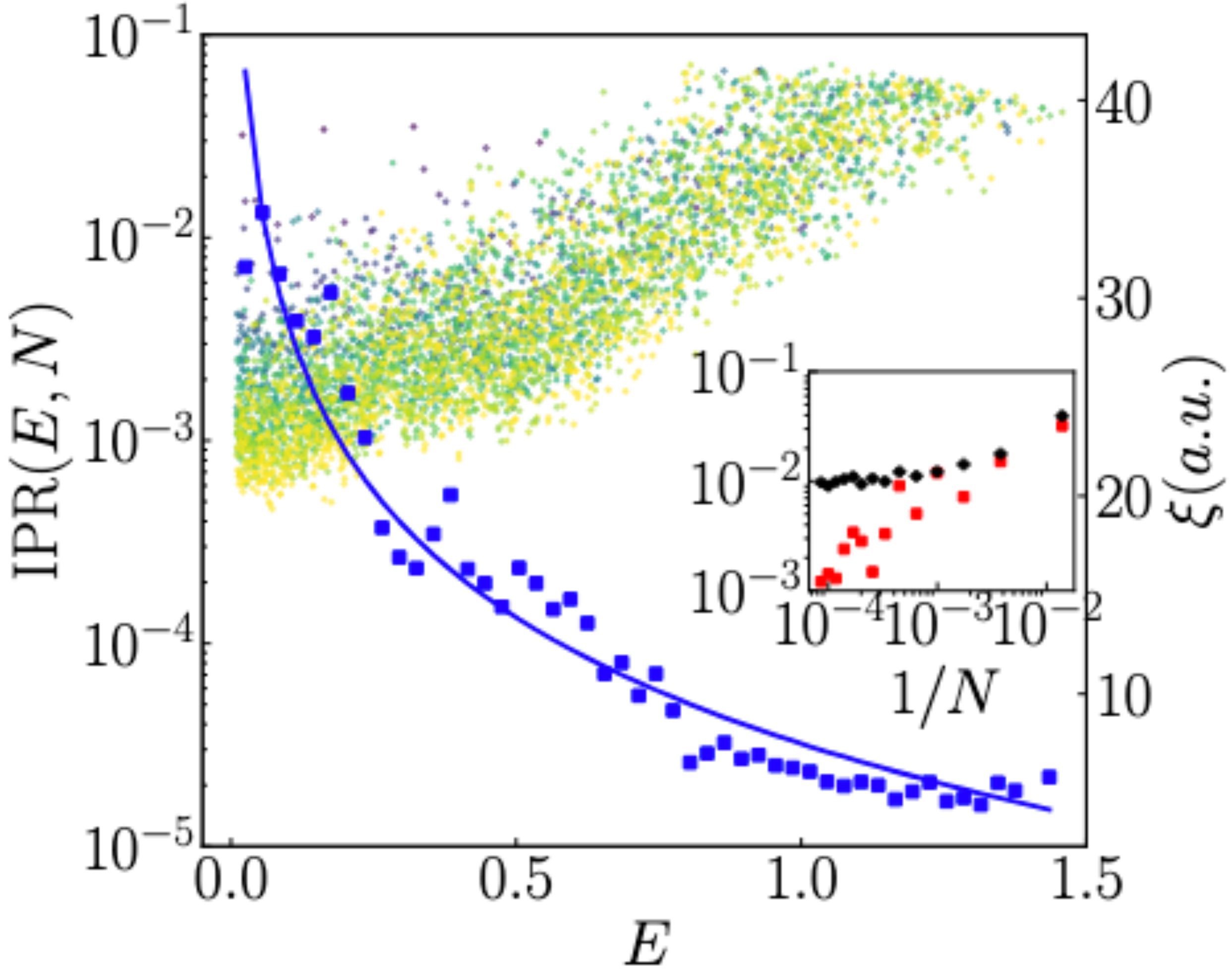
Thank you for your attention !

Backup Slides

2D IPR



$$\xi(E) \sim \frac{1}{\sqrt{E}} \exp\left[\frac{1}{4} \ln^2 E\right]$$

Energy Correlation Function

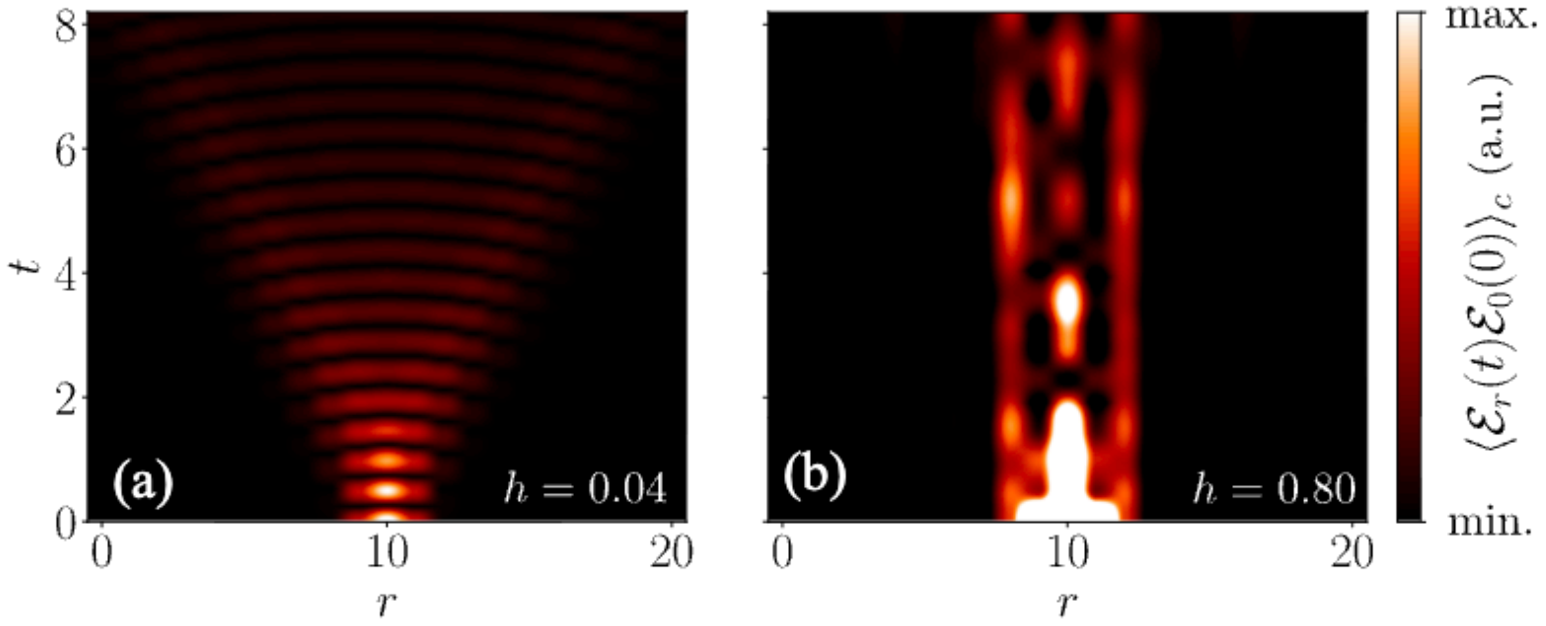
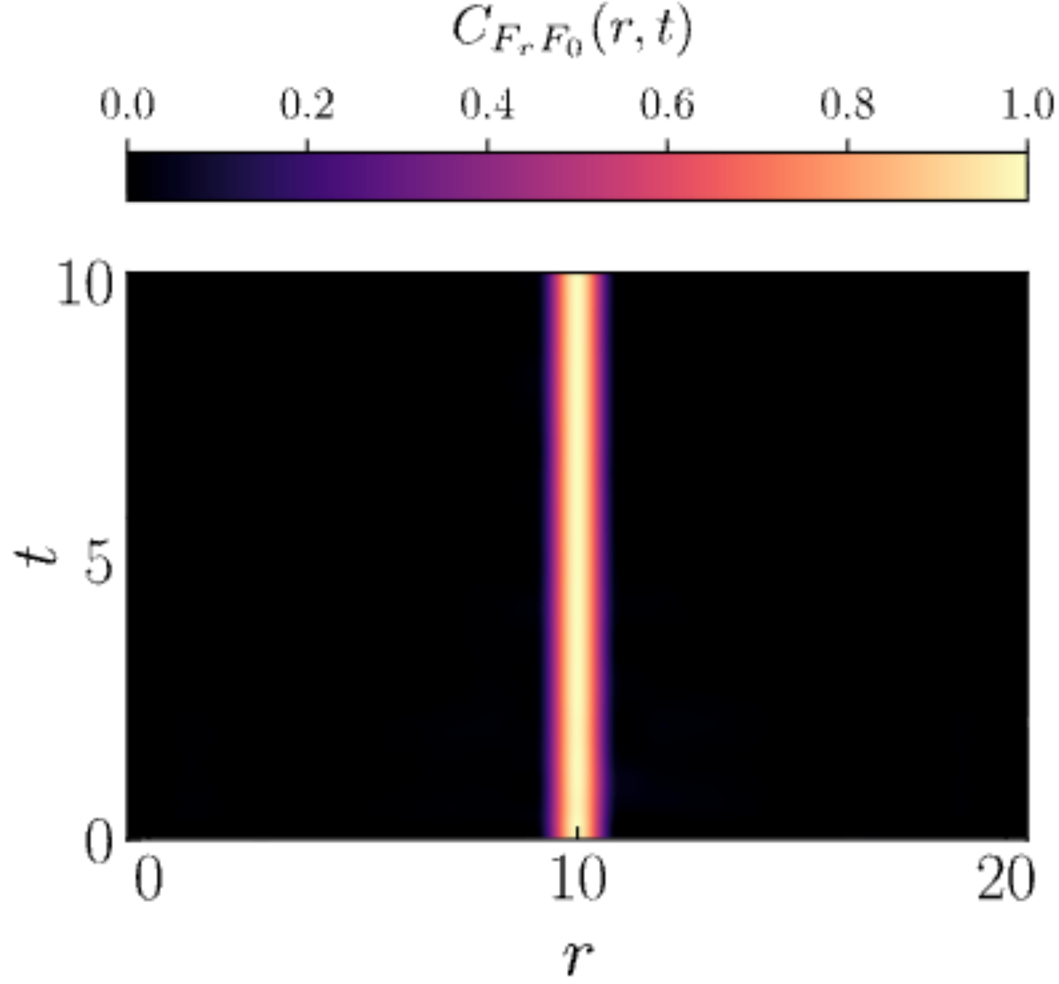


FIG. S4. Absolute value of energy correlation function $\langle 0|\mathcal{E}_r(t)\mathcal{E}_{r_0}|0\rangle$ excluding the disconnected ground-state contribution, computed for (a) the spinon band insulator at $h = 0.04$ and (b) the gapless and transient localized regime at $h = 0.80$.

Slow Spreading of Flux-Flux Correlation



MPS Dynamics