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Interaction-driven symmetry protected exceptional torus with many-body chiral symmetry

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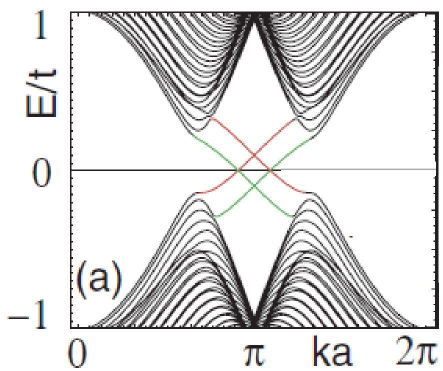
K. Kimura, T. Yoshida, & N. Kawakami,
PRB 100, 115124 (2019)

Introduction

Topology has become a ubiquitous issue in condensed matter physics !

Hermitian topological phases

Topological insulator (TI)



C. L. Kane, PRL **95** 146802 (2005).

- insulating Bulk
- metallic Edge

Protected by local symmetry

Extension of TIs.

- metallic (gapless) phase

⇒topological semi-metals

S. Murakami, NJP **9** 356 (2007).

- crystalline (non-local) symmetry

⇒topological crystalline insulators

L. Fu, PRB **106** 106802 (2011).

They have been of intense interest !

Non-Hermitian topological phases

The notion of band topology extended to non-Hermitian matrix

⇒New type topological phenomena!

- Open quantum system

  Cold atom w/ dissipation

- Classical optics

  Photonic crystal w/ gain & loss

- **Another aspect of Equilibrium**

  Lifetime effect

We focus on it in strongly correlated system.

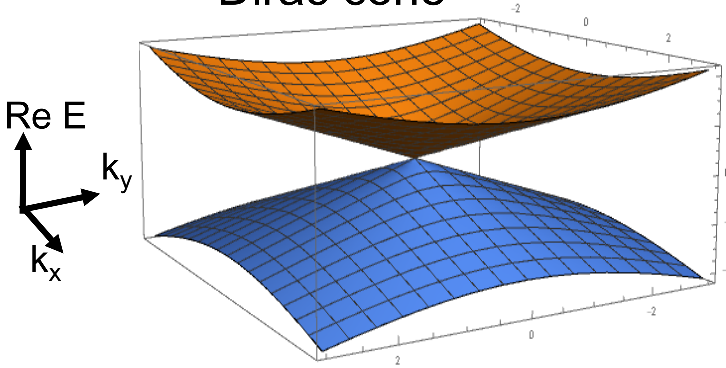
Introduction

Non-Hermitian Band theory

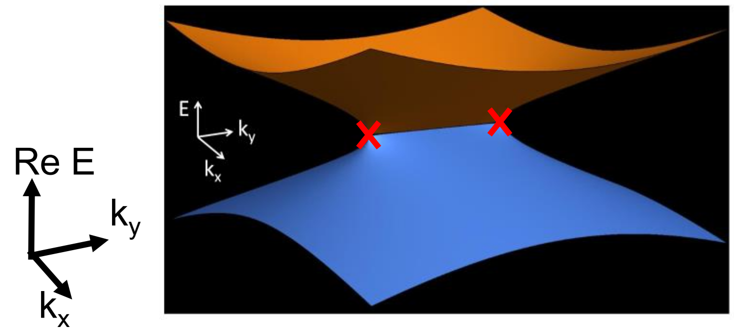
Non-Hermiticity

$$H(\mathbf{k}) = (k_x + i\kappa_x)\sigma_x + (k_y + i\kappa_y)\sigma_y + (m + i\delta)\sigma_z,$$

Dirac cone

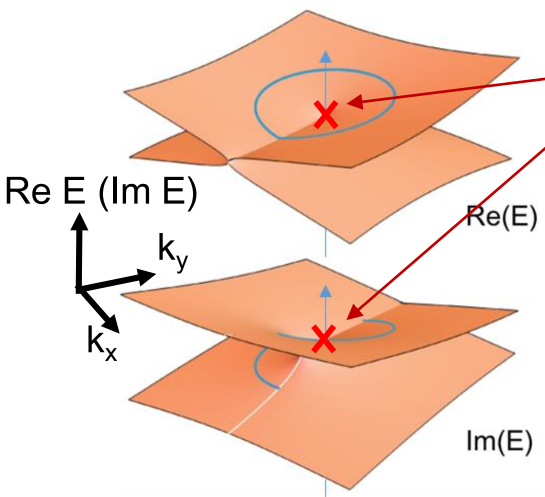


A pair of Exceptional Points



Topological number on complex energy plane

H. Shen, PRL **120**, 146402 (2018)



Exceptional point

Winding number on the complex E plane

$$\nu_{mn}(\Gamma) = -\frac{1}{2\pi}\oint_{\Gamma} \nabla_{\mathbf{k}} \arg\left[E_m(\mathbf{k}) - E_n(\mathbf{k})\right] \cdot d\mathbf{k},$$

Topologically stable band degeneracies appear

Non-Hermitian topological phenomena in equilibrium

Non-Hermiticity induced by the lifetime effect !!

V. Kozii and L. Fu arXiv (2017)

Effective Hamiltonian

$$H_{\mathrm{eff}}(\boldsymbol{k},\omega) = H_0(\boldsymbol{k}) + \Sigma(\omega)$$

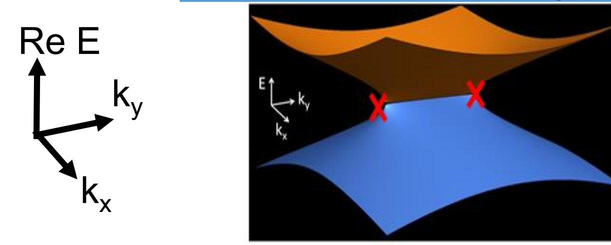
$$i\,\mathrm{Im}\,\Sigma(\omega) = \begin{pmatrix} i\Gamma_1(\omega) & 0 \\ 0 & i\Gamma_2(\omega) \end{pmatrix}$$

Spectral function

$$A_{\boldsymbol{k}}(\omega) = -\frac{1}{\pi}\mathrm{Im}[\mathrm{tr}G_{\boldsymbol{k}}(\omega)]$$

$$G_{\boldsymbol{k}}(\omega) = [(\omega + i\delta)1 - H_{\mathrm{eff}}(\boldsymbol{k},\omega)]^{-1}$$

Dispersion of $H_{\mathrm{eff}}(\boldsymbol{k},0)$



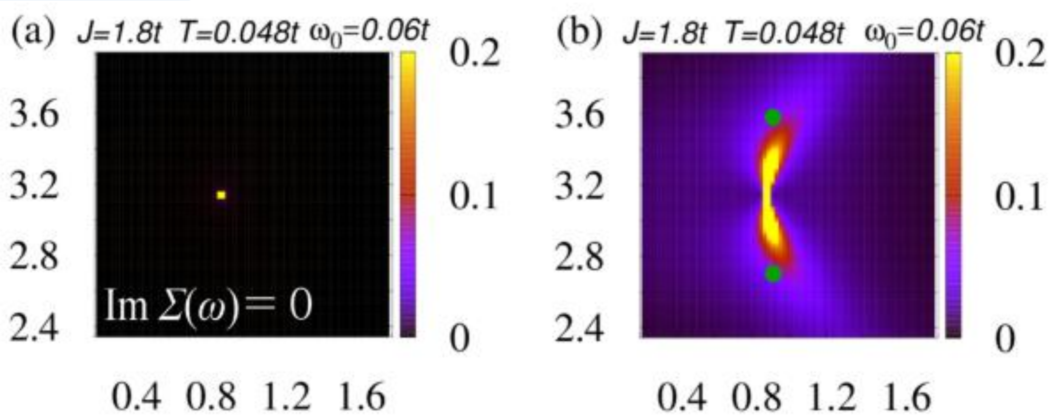
$A_{\boldsymbol{k}}(\omega = 0)$

open Fermi surface

V. Kozii & L. Fu arXiv (2017)

Heavy-Fermions (DMFT)

$A_{\boldsymbol{k}}(\omega = 0)$



Y. Nagai, (JPS Meeting 2018). T. Yoshida, PRB 98, 035141 (2018).

NH band degeneracy & symmetry protection

2×2 Non-Hermitian Hamiltonian

$$H_{\mathrm{eff}} = (d_0 + i b_0)\cdot\tau_0 + (\boldsymbol{d} + i\boldsymbol{b})\cdot\boldsymbol{\tau}$$

$$E_{\pm} = d_0 + i b_0 \pm \sqrt{\boldsymbol{d}^2 - \boldsymbol{b}^2 + 2i\boldsymbol{b}\cdot\boldsymbol{d}}$$

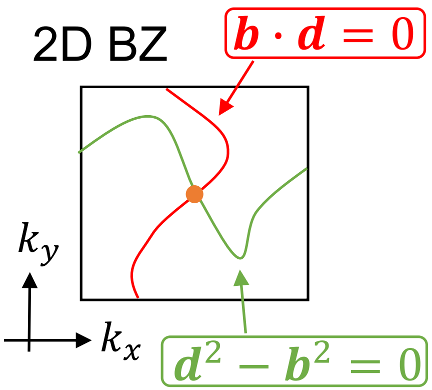
Condition of Band degeneracy

$$\boldsymbol{d}^2 - \boldsymbol{b}^2 = 0, \qquad \boldsymbol{b}\cdot\boldsymbol{d} = 0$$

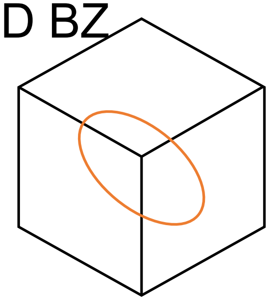
$+\ \boldsymbol{b} \neq 0 \Rightarrow$ **H is defective**

Defective manifold & dimension

2D BZ



3D BZ



Defective region
= system dim−constraint cond.

0=2-2 ⇒ point 1=3-2 ⇒ ring

Symmetry (Ex. parity & time-reversal)

$$(PT)H_{\mathrm{eff}}(k)(PT)^{-1} = H_{\mathrm{eff}}(k)$$

$PT = K\sigma_0$ K:complex conjugation

R. Okugawa, PRB2019

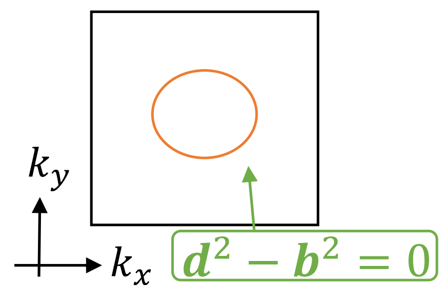
$\boldsymbol{b}\cdot\boldsymbol{d} = 0$ **is automatically satisfied**

Condition of Band degeneracy

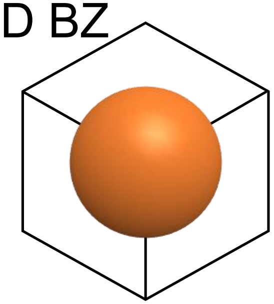
$$\boldsymbol{d}^2 - \boldsymbol{b}^2 = 0,$$

Defective manifold

2D BZ



3D BZ

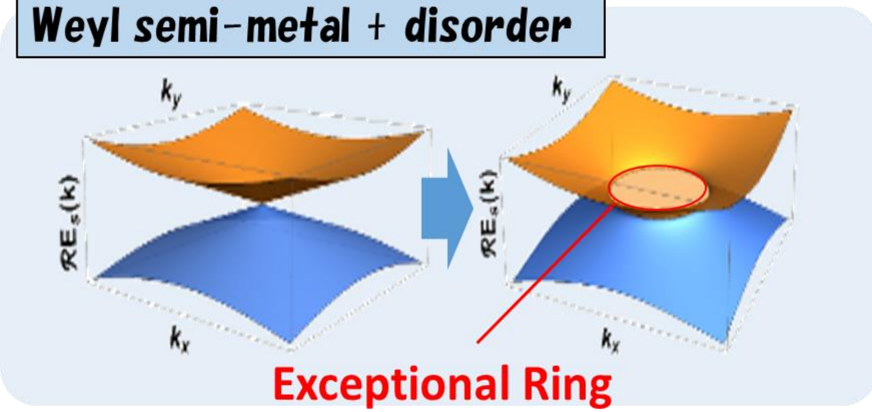


1=2-1 ⇒ ring

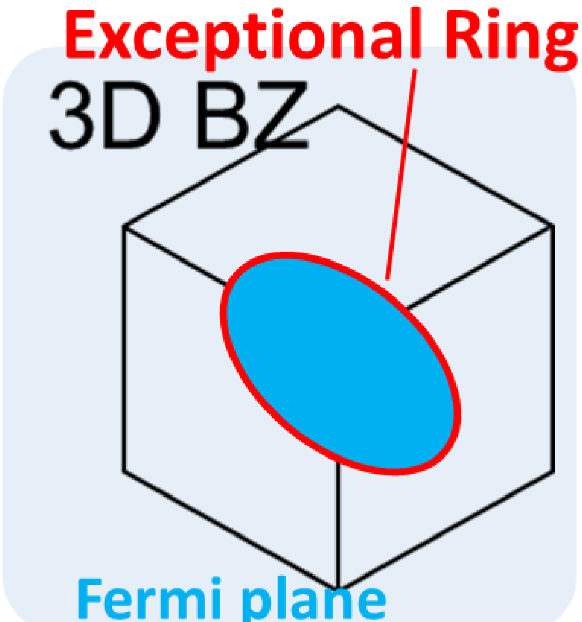
2=3-1
⇒ surface/torus

Without Symmetry protection

Weyl semi-metal + disorder

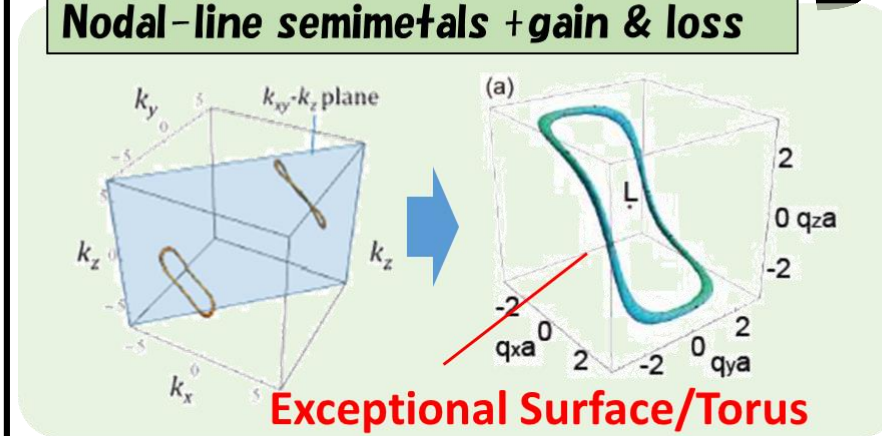


Y. Xu, PRL **118**, 045701 (2017),
A. A. Zyuzin, PRB **97**, 041203(R) (2018)

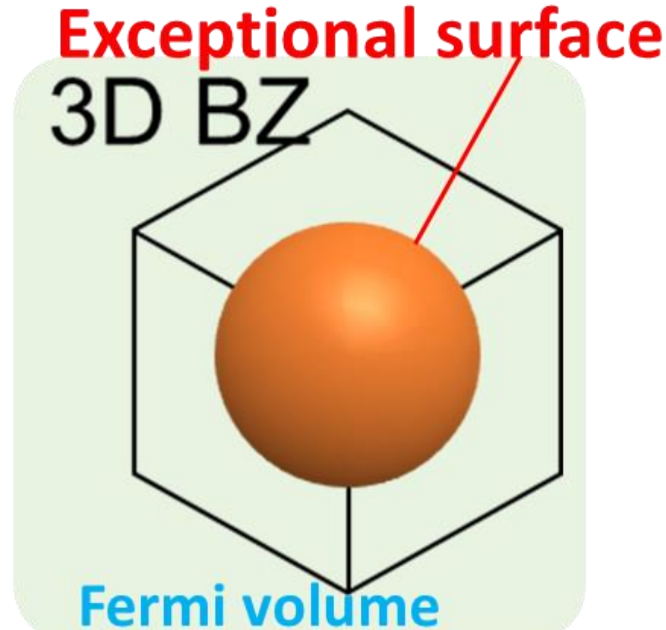


With Symmetry Protection

Nodal-line semimetals +gain & loss



R. Okugawa, PRB **99**, 041202 (2019)



But almost all studies have been discussed about energy dispersion so far…

Motivation

Previous study: Symmetry-protected NH band degeneracy

R. Okugawa & T. Yokoyama, PRB 99, 041202 (2019)
J. C. Budich, et. al., PRB 99, 041406 (2019)
T. Yoshida, et. al., PRB 99, 121101 (2019)
K. Kawabata, T. Bessho, & M. Sato, PRL 123, 066405 (2019)
T. Yoshida & Y. Hatugai, PRB 100, 054109 (2019)

Our study

Can the Symmetry-Protected Exceptional Torus emerge in strongly correlated system ?

We focus on **nodal-line semimetals** with many-body chiral symmetry.

Effect of many-body chiral symmetry ?

Emergence of 3D open Fermi surface enclosed by ET !
EP locked on the Fermi level

How physical properties affected by NH structure ?

NH structure on the Fermi level increase the Spin susceptibility !

The main idea: Many-body chiral symmetry

Many-body chiral symmetry

$$\hat{U}_\Gamma^\dagger \hat{H}^* \hat{U}_\Gamma = \hat{H}$$

$$\hat{U}_\Gamma^\dagger \hat{c}_{is\sigma}^\dagger \hat{U}_\Gamma = \mathrm{sgn}(s)\hat{c}_{is\sigma}$$

sgn(s) takes 1 & -1 for s=A & s=B

Green's function

$$G(\omega + i\delta) = -U_\Gamma^\dagger G^\dagger(-\omega + i\delta)U_\Gamma,$$

chiral matrix $U_\Gamma = \tau_z$

$$G(\boldsymbol{k}, \omega) = [\omega \mathbb{1} - h(\boldsymbol{k}) - \Sigma^R(\boldsymbol{k}, \omega)]^{-1},$$

Effective Hamiltonian

$$H_{\mathrm{eff}}(\omega, \boldsymbol{k}) = -U_\Gamma^\dagger H_{\mathrm{eff}}^\dagger(-\omega, \boldsymbol{k})U_\Gamma$$

$$G^{-1}(\omega + i\delta) = \omega \mathbb{1} - H_{\mathrm{eff}}(\omega, \boldsymbol{k}).$$

Focus on the Fermi level

Many-body chiral symmetry

$$H_{\mathrm{eff}}(k, 0) = -\tau_z H_{\mathrm{eff}}^\dagger(k, 0)\tau_z$$

T. Yoshida, PRB 99, 121101 (2019)

2×2 Non-Hermitian Hamiltonian

$$H_{\mathrm{eff}}(k, 0) = (d_0 + ib_0)\tau_0 + (\boldsymbol{d} + i\boldsymbol{b}) \cdot \boldsymbol{\tau}$$

$$E_\pm = d_0 + ib_0 \pm \sqrt{\boldsymbol{d}^2 - \boldsymbol{b}^2 + 2i\boldsymbol{b} \cdot \boldsymbol{d}}$$

$$\Rightarrow d_0 = 0, \boldsymbol{d} = \begin{pmatrix} d_1 \\ d_2 \\ 0 \end{pmatrix}, \boldsymbol{b} = \begin{pmatrix} 0 \\ 0 \\ b_3 \end{pmatrix}$$

$\boldsymbol{b} \cdot \boldsymbol{d} = 0$ **is satisfied**

on the Fermi level !!

Symmetry-protected EPs are locked on $\omega = 0$!

Model & Method

Hubbard model on diamond lattice @ half-filling

with spatially modulated on-site interaction $U_A \neq U_B$

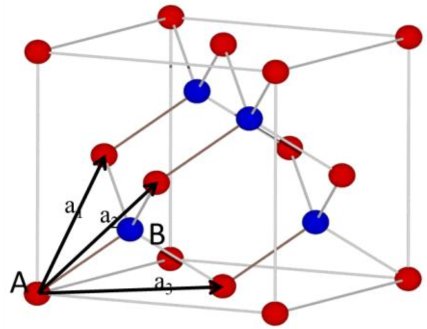
$$\hat{H} = \sum_{\langle i\alpha, j\alpha' \rangle \sigma} t_{ij} \hat{c}^{\dagger}_{i\alpha\sigma} \hat{c}_{j\alpha'\sigma} + \sum_{i\alpha} U_\alpha (\hat{n}_{i\alpha\uparrow} - \frac{1}{2})(\hat{n}_{i\alpha\downarrow} - \frac{1}{2}),$$

Noninteracting part

$$h(\boldsymbol{k}) = \begin{pmatrix} 0 & D_{\boldsymbol{k}} \\ D^*_{\boldsymbol{k}} & 0 \end{pmatrix} \otimes \sigma_0$$

Spin

$$D_{\boldsymbol{k}} = t_0 + \sum_{j=1,2,3} t_j e^{i\boldsymbol{k}\cdot\boldsymbol{a}_j}$$



DMFT

Impurity solver :Iterated perturbation theory (IPT)

$$\Sigma^{(2)}_\alpha(\omega) = U^2 \int_{-\infty}^{\infty} dx \int_{-\infty}^{\infty} dy \int_{-\infty}^{\infty} dz \rho^0_\alpha(x)\rho^0_\alpha(y)\rho^0_\alpha(z) \frac{f(-x)f(-y)f(z) + f(x)f(y)f(-z)}{\omega - x - y + z + i\delta},$$

DMFT-Random Phase Approximation

$$\chi^0_{\alpha\beta}(\boldsymbol{q}, i\epsilon_m) = -\frac{T}{N} \sum_{\boldsymbol{k},n} \underline{G_{\alpha\beta}(\boldsymbol{q}+\boldsymbol{k}, i\omega_n + i\epsilon_m) G_{\beta\alpha}(\boldsymbol{k}, i\omega_n)},$$

Green's function from DMFT

$$\boldsymbol{\chi}^{\mathrm{RPA}}(\boldsymbol{q}, i\epsilon_m) := (\boldsymbol{1} - \boldsymbol{\chi}^0 \boldsymbol{U})^{-1} \boldsymbol{\chi}^0, \qquad \boldsymbol{U} := \mathrm{diag}(U_A, U_B),$$

Result: Interaction driven SPETs

Emergence of Chiral-Symmetry Protected Exceptional Torus

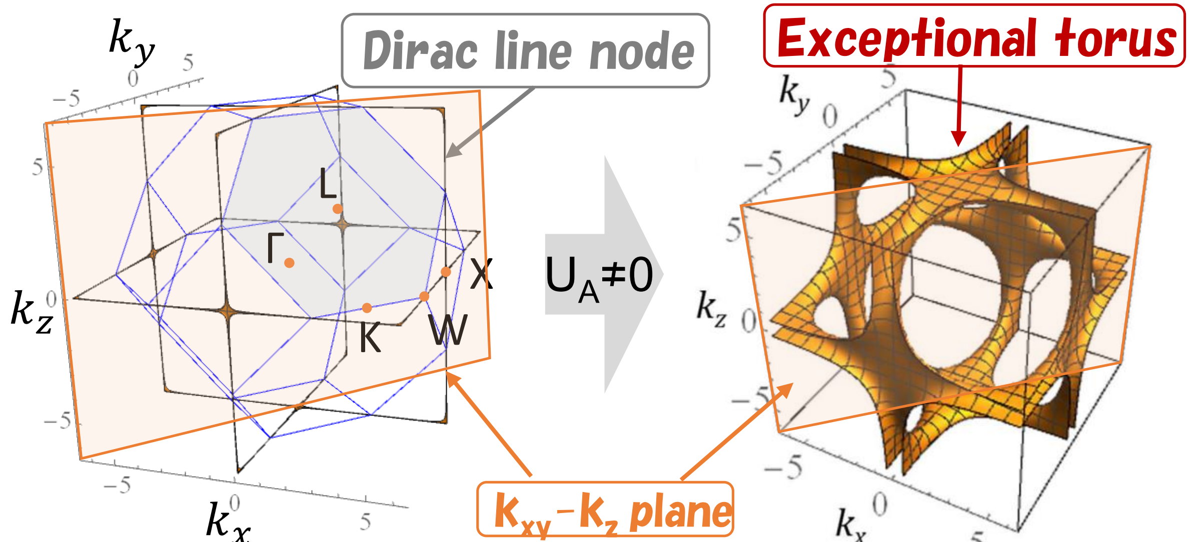
Effective Hamiltonian

$$H_{\mathrm{eff}}(\boldsymbol{k},\omega) = H_{\boldsymbol{k}} + \Sigma^R(\omega)$$

from DMFT-IPT

$$= \begin{pmatrix} 0 & D_k \\ D_k^* & 0 \end{pmatrix} + \begin{pmatrix} \Sigma_A(\omega) & 0 \\ 0 & 0 \end{pmatrix}$$

@T=0.8t, U_A=8t, U_B=0



Fermi surface (U_A=0)

$H_{\mathrm{eff}}(\boldsymbol{k},0)$ is defective

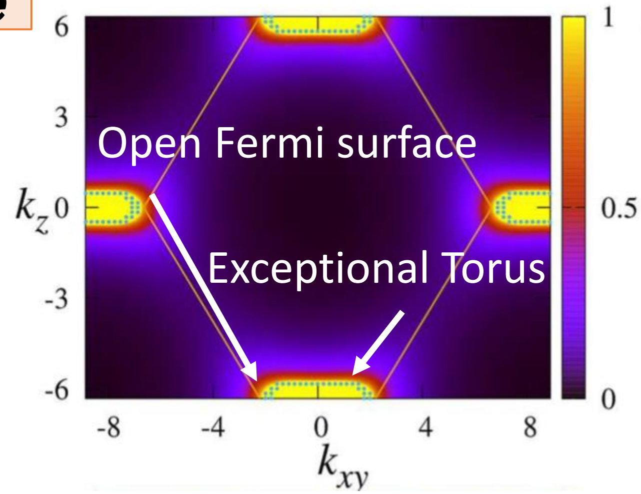
Spectral function on k_{xy}-k_z plane

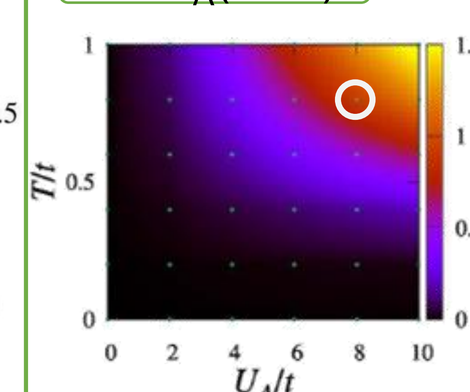
Spectral function

$$A_{\boldsymbol{k}}(\omega=0) = -\frac{1}{\pi}\mathrm{Im}[\mathrm{tr}G_{\boldsymbol{k}}(0)]$$

$$G_{\boldsymbol{k}}(\omega) = [(\omega + i\delta)1 - H_{\mathrm{eff}}(\boldsymbol{k},\omega)]^{-1}$$

@T=0.8t, U_A=8t, U_B=0



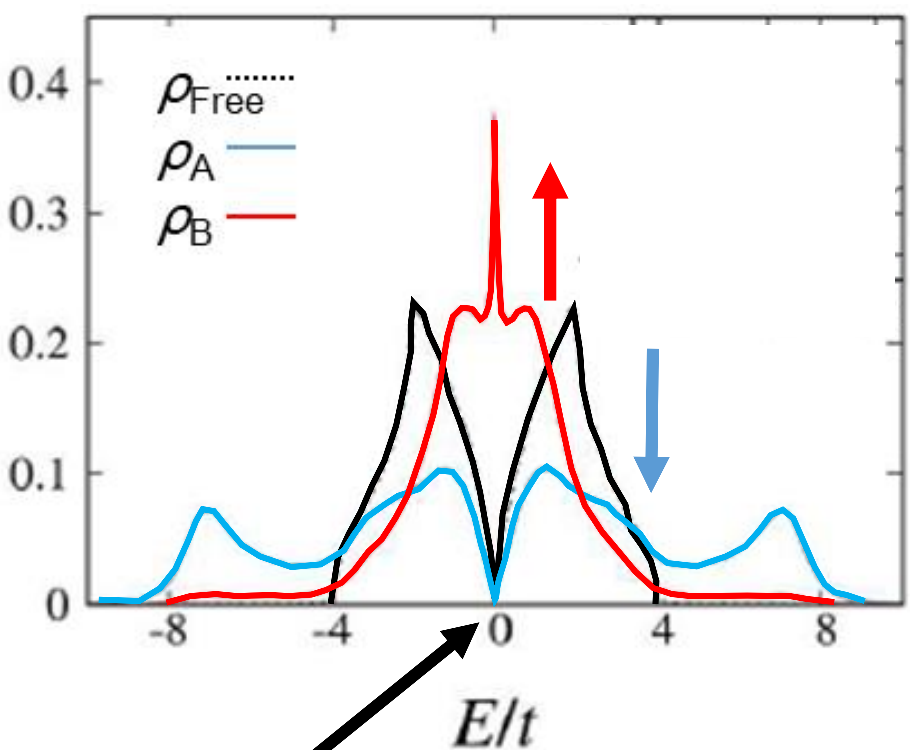


Result: The peak structure of LDOS

Local Density of State

@T=0.8t, U_A=8t, U_B=0

$$\rho_\alpha(\omega) = -\frac{1}{\pi}\mathrm{Im}[G_{\boldsymbol{k}}(\omega)]_{\alpha\alpha}$$



Topological semimetal

DOS of A is suppressed (renormalization)

But the DOS of B is enhanced with increasing U_A(& T) !!

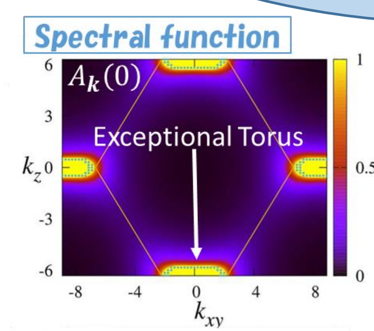
not renormalization factor but lifetime effect of $\Sigma(\omega)$!!

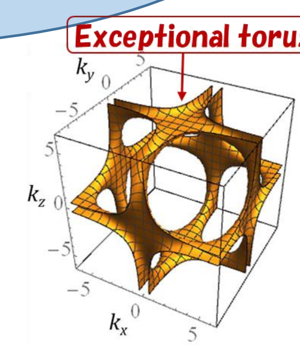
non-Hermitian effect

Strange !? But we recall ETs!!

Peak structure is formed by ET

@ω=0 locked by Chiral symmetry





Result: Magnetic susceptibilities

Scenario

LDOS of B is enhanced by Chiral-symmetry protected ET

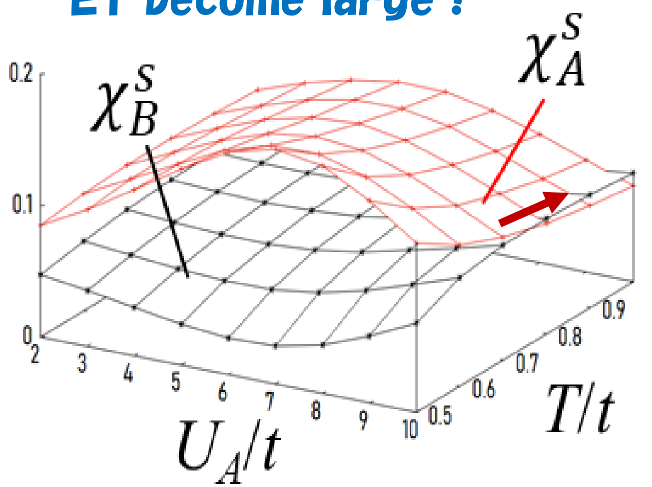
Does the magnetic response for B-sublat. become large?

$$\chi_{\mathrm{B}} = \frac{M_B}{B}\Big|_{B\to 0}$$

Numerical data form DMFT-RPA

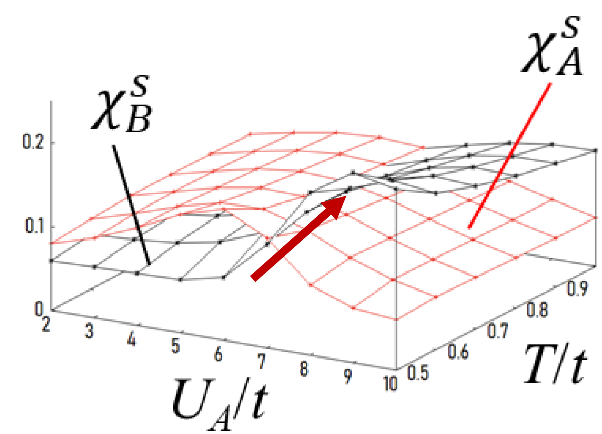
With increasing U_A(& T),

ET become large !



χ_{B} weakly enhanced !

Another parm. $U_B = U_A/2$



χ_{B} enhanced by forming of ET!

Magnetic susceptibility $\chi_B^S > \chi_A^S$ although Interaction is opposite $U_B < U_A$.

Summary

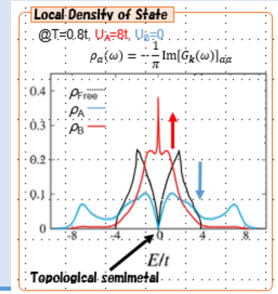
Interaction-driven Chiral-Symmetry Protected Exceptional Torus

- The low-energy excitations are locked on the Fermi level.

  "Fermi volume" enclosed by ET

- The unusual peak structure of LDOS induced by ET with increasing T & U_A.

  This is not usual renormalization effect but the lifetime effect !!



- How is the physical properties affected by ET ?

  The magnetic response for B-sublat. becomes large.

K. Kimura, T. Yoshida, & N. Kawakami, PRB **100**, 115124 (2019)