Quantum Criticality in Non-Hermitian Dirac Matter

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FONDECYT

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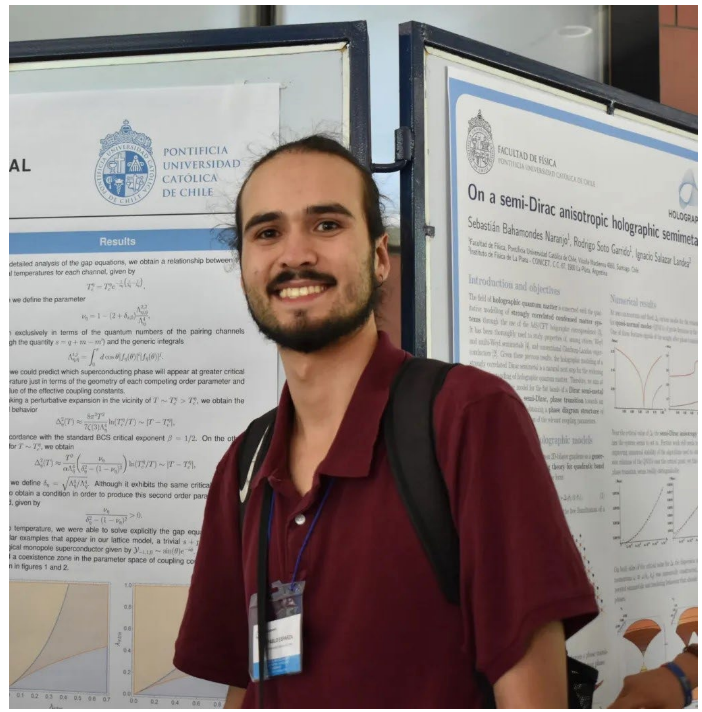
Collaborators

Bitan Roy
(Lehigh University)



Juan Pablo Esparza
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Outline

- Introduction
- Non-Hermitian Dirac fermions: A general principle of construction
- Strongly-coupled non-Hermitian Dirac semimetal: Yukawa-Lorentz symmetry
- Tilted NH Dirac semimetals
- Observables detecting non-Hermiticity
- Summary

- V. J. & B. Roy, Communications Physics **7**, 169 (2024)
- S. Pino-Alarcón & V. J., PRB **111**, 195126 (2025)
- S. Pino-Alarcón, J. P. Esparza & V. J., in preparation.

Biorthogonal QM

Mostafazadeh, Journal od Mathematical Physics (2002)
Review on biorthogonal QM: Brody 2014

- QM: Observables are represented by Hermitian operators

$$A = A^{\dagger} \Rightarrow Spectrum(A) \in \mathbb{R}$$

- Hermiticity is not a necessary condition for a real spectrum.

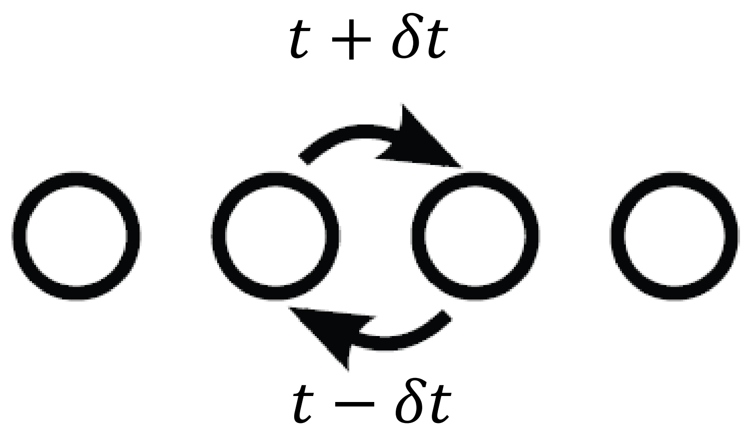
- Any pseudo-Hermitian operator $A^{\dagger} = \eta\, A\, \eta^{\dagger}$ has a real spectrum if (unitary) η is positive-definite

$$\langle \psi | \eta | \phi \rangle \equiv \langle \psi_L | \phi_R \rangle \geq 0$$

$$A|\phi_R\rangle = \lambda|\phi_R\rangle \qquad A^{\dagger}|\phi_L\rangle = \lambda^{*}|\phi_L\rangle$$

Pseudo-Hermiticity generalizes PT symmetry condition introduced in Bender & Boettcher, PRL 1998

Non-Hermitian systems: Nonreciprocity



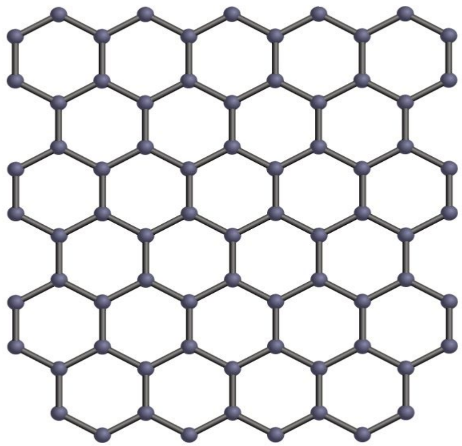
Canonical example: Hatano-Nelson model   Hatano, Nelson, PRL 1996

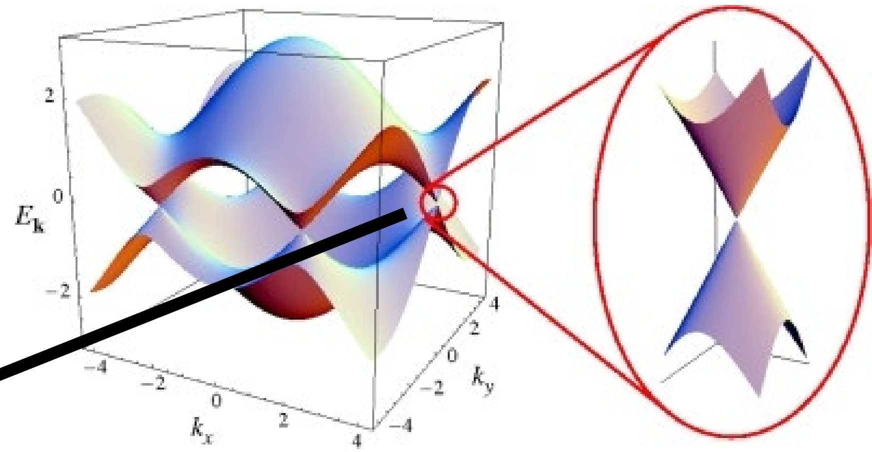
NH skin effect: accumulation of a microscopic number of states at edge
– breaking of the usual topological bulk-boundary correspondence

V. M. Martinez Alvarez et al., PRB **97**, 121401(R) (2018).
S. Yao and Z. Wang, PRL **121**, 086803 (2018).
S. Yao, F. Song, and Z. Wang, PRL **121**, 136802 (2018).

Hermitian Dirac(-like) fermions

Two-dimensional membrane of C atoms





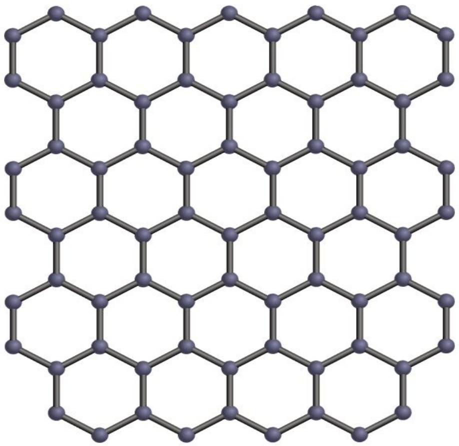
Dirac Hamiltonian

$$H(\boldsymbol{k}) = v_0\, \boldsymbol{\sigma} \cdot \boldsymbol{k}$$

$v_0 \sim c/300 \sim 10^6$m/s

Density of states $\rho(E) \sim \dfrac{|E|}{v_0^2}$

Hermitian Dirac(-like) fermions



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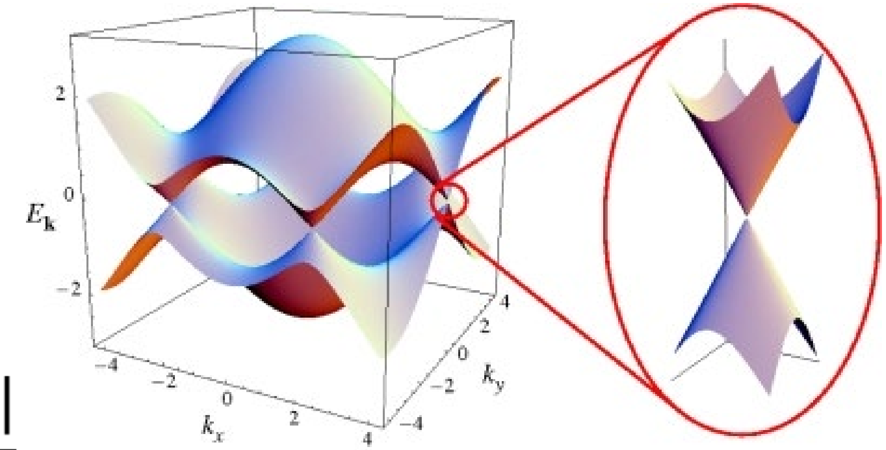
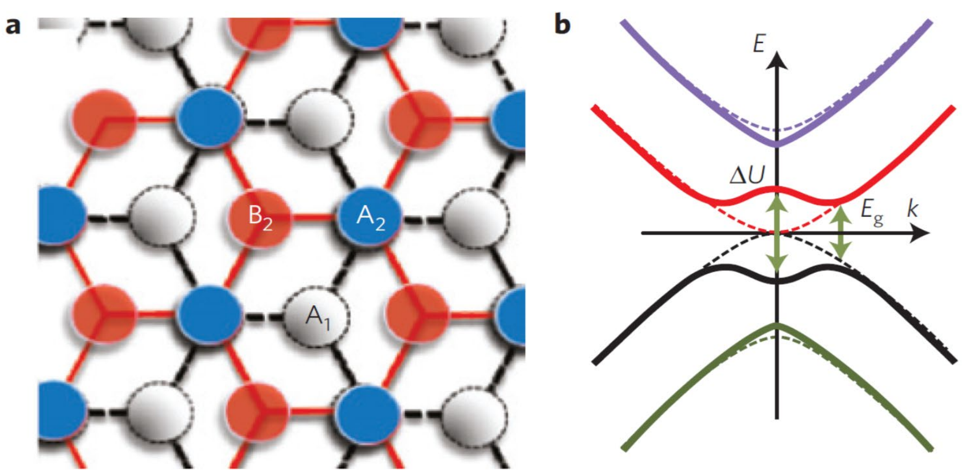


Density of states $\rho(E) \sim \dfrac{|E|}{v_0^2}$

Bilayer graphene – Bernal stacking



$$H(\boldsymbol{k}) = \sigma_1 \frac{k_x^2 - k_y^2}{2m} + \sigma_2 \frac{2k_x k_y}{2m}$$

Quadratic chiral fermions!

Constant density of states

Ordering @ B=0

Velasco et al., Nat Nano 7, 156 (2012)
Freitag et al., PRB 87, 161402 (2013)

ABC trilayer graphene → **diverging DoS!**

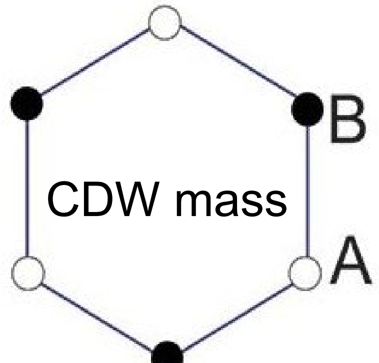
Non-Hermitian Dirac operator

- Dirac theory allows two Lorentz invariant operators: (1) Dirac kinetic energy
  (2) Dirac mass

These two Hermitian operators mutually ***<u>anticommute</u>***

Anti-Hermitian operator : $H_{\mathrm{Dirac}}\ M$

Proof : $(H_{\mathrm{Dirac}}\ M)^\dagger = M^\dagger\ H_{\mathrm{Dirac}}^\dagger = M\ H_{\mathrm{Dirac}} = -H_{\mathrm{Dirac}}\ M$



Semenoff, PRL 1984

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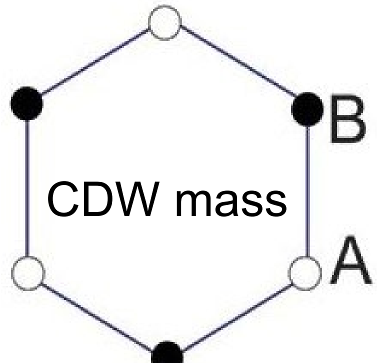

Semenoff, PRL 1984

Proof : $(H_{\rm Dirac}\, M)^\dagger = M^\dagger\, H^\dagger_{\rm Dirac} = M\, H_{\rm Dirac} = -H_{\rm Dirac}\, M$

- General construction of Lorentz invariant NH Dirac operator :

$$H_{\rm NH}(\boldsymbol{k}) = v_{\rm H} \left(\sum_{j=1}^{d} \Gamma_j k_j \right) + v_{\rm NH} \left(M \sum_{j=1}^{d} \Gamma_j k_j \right)$$

V. J. & B. Roy, Comm Phys 2024

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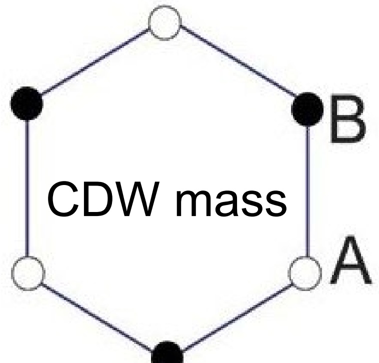

Semenoff, PRL 1984

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V. J. & B. Roy, Comm Phys 2024

- Eigenvalues: $E_{\rm NH}(\boldsymbol{k}) = \pm\sqrt{v_{\rm H}^2 - v_{\rm NH}^2}\,|\boldsymbol{k}| \equiv v_{\rm F}\,|\boldsymbol{k}|$: Real for $v_{\rm H} > v_{\rm NH}$

  Both 2D & 3D Dirac materials host a plethora of mass orders (*M*)
  Any mass order can be used to define NH Dirac operator

Ryu et. al. PRB **80**, 205319 (2009), Szabo & Roy, PRB **103**, 205135 (2021), JHEP **2021** (4), 27

Non-Hermitian monolayer graphene

- Tight-binding Hamiltonian → Hermitian Dirac system: $h_0^{\rm lat}(\boldsymbol{k}) = t_0 \begin{pmatrix} 0 & \Delta_{\boldsymbol{k}} \\ \Delta_{\boldsymbol{k}}^\star & 0 \end{pmatrix}$

- Sublattice symmetry breaking Dirac mass (CDW): $h_{\rm CDW}^{\rm lat} = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$

- NH Dirac fermions on honeycomb lattice: $\{h_0^{\rm lat}(\boldsymbol{k}), h_{\rm CDW}^{\rm lat}\} = 0$

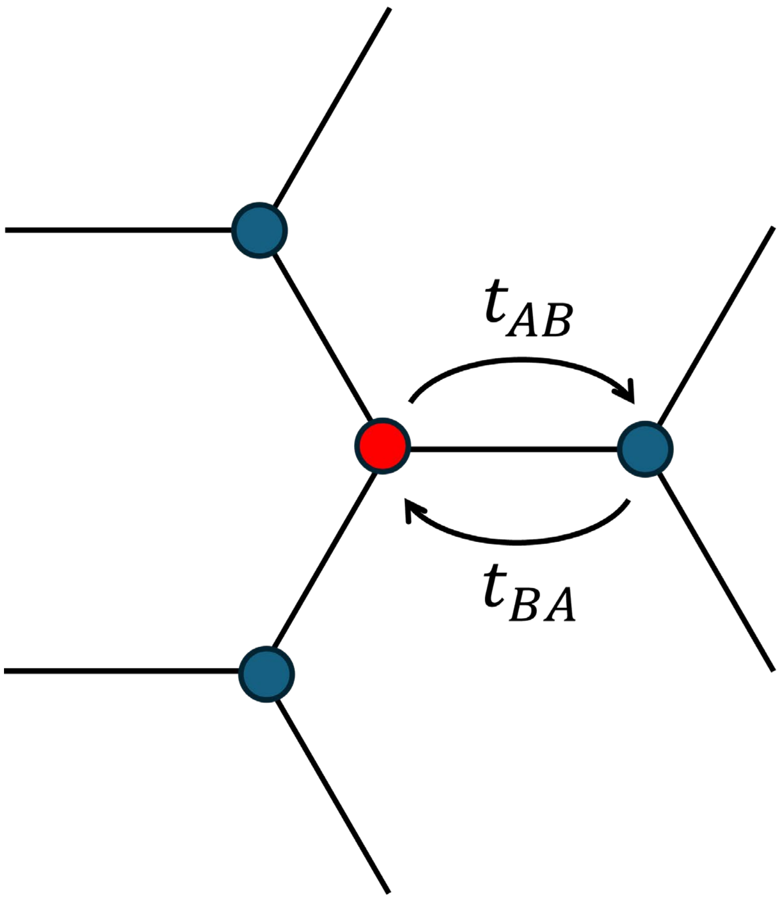
$$h_{0,\rm NH}^{\rm lat}(\boldsymbol{k}) = h_0^{\rm lat}(\boldsymbol{k}) + \alpha h_0^{\rm lat}(\boldsymbol{k}) h_{\rm CDW}^{\rm lat} = t_0 \begin{pmatrix} 0 & (1+\alpha)\Delta_{\boldsymbol{k}} \\ (1-\alpha)\Delta_{\boldsymbol{k}}^\star & 0 \end{pmatrix}$$

Non-Hermiticity in single-layer graphene: Hopping imbalance between sublattices

Z. Gong, et. al. PRX 8, 031079 (2019): Appendix F

1D chain: Hatano & Nelson, PRL 1996

Non-Hermitian monolayer graphene



Effective NH Hamiltonian

$$h_{\boldsymbol{k}} = (v_H + v_{NH}\sigma_3)\boldsymbol{\sigma}\cdot\boldsymbol{k}$$

Spectrum: $\epsilon_{\boldsymbol{k}} = v_F\, k$

Fermi velocity

$$v_F = v_H\sqrt{1-\beta^2}$$

$$\beta = v_H/v_{NH}$$

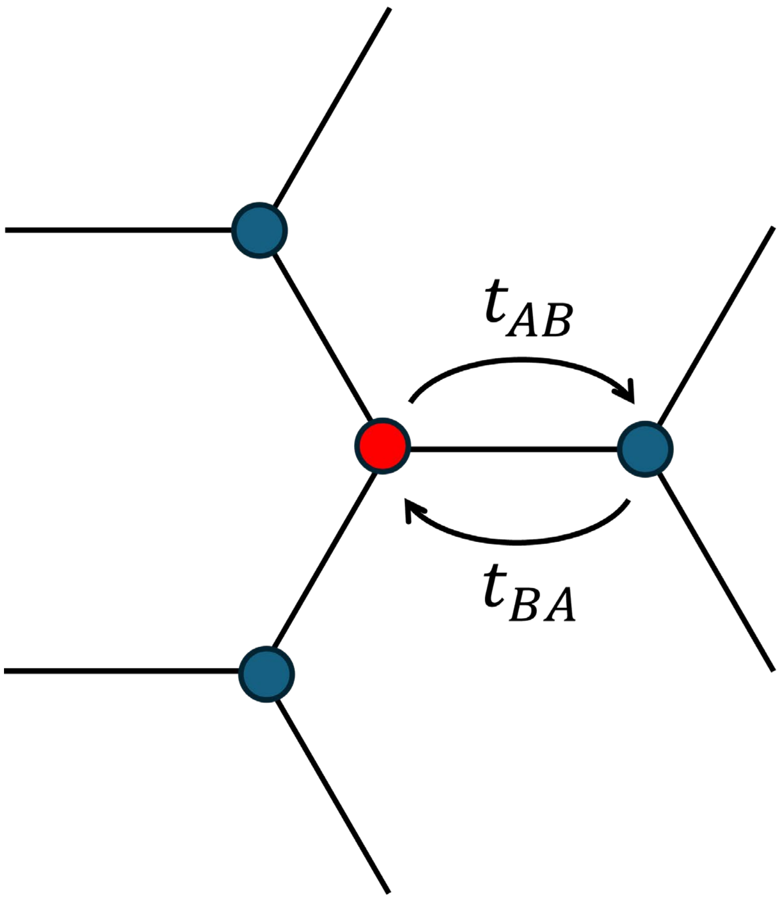
TB model with nonreciprocal hoppings: $|\beta| < 1$

v_H ~ average hopping amplitude

v_{NH} ~ hopping imbalance ($\delta t \sim t_{AB} - t_{BA}$)

Expt - ultracold atoms: NH Aharonov-Bohm chain
Liang et al., Phys. Rev. Lett. **129**, 070401 (2022).

Non-Hermitian monolayer graphene



Effective NH Hamiltonian

$$h_{\boldsymbol{k}} = (v_H + v_{NH}\sigma_3)\boldsymbol{\sigma}\cdot\boldsymbol{k}$$

Spectrum: $\epsilon_{\boldsymbol{k}} = v_F\, k$

Density of states

$$\rho(\epsilon) = \frac{N_f}{2\pi v_F^2}\{|\epsilon|\Theta(1-|\beta|) + \Lambda^2\delta(\epsilon)\Theta(|\beta|-1)\}$$

TB model with nonreciprocal hoppings: $|\beta| < 1$

v_H ~ average hopping amplitude

v_{NH} ~ hopping imbalance ($\delta t \sim t_{AB} - t_{BA}$)

Expt - ultracold atoms: NH Aharonov-Bohm chain
Liang et al., Phys. Rev. Lett. **129**, 070401 (2022).

NH Dirac operator: Symmetry protection

- Non-spatial discrete symmetries of NH operator ($H_{\rm NH}$) : (1) Time-reversal (T_+ & C_+),
  (2) Anti-unitary particle-hole (T_- & C_-)
  (3) Unitary particle-hole (PH)
  (4) Pseudo-Hermiticity (PSH)

D. Bernard & A. LeClair, A Classification of Non-Hermitian Random Matrices (Springer, 2002)
Kawabata, Shiozaki, Ueda, Sato, Phys. Rev. X 9, 041015 (2019).

- Symmetries operations:

$$\mathcal{T}_{\pm} H_{\rm NH} \mathcal{T}_{\pm}^{-1} = \pm H_{\rm NH} \qquad \mathcal{C}_{\pm} H_{\rm NH}^{\dagger} \mathcal{C}_{\pm}^{-1} = \pm H_{\rm NH}$$

$$\mathrm{PH}_{1,2} H_{\rm NH} \mathrm{PH}_{1,2}^{-1} = -H_{\rm NH} \qquad \mathrm{PSH}_{1,2} H_{\rm NH}^{\dagger} \mathrm{PSH}_{1,2}^{-1} = H_{\rm NH}$$

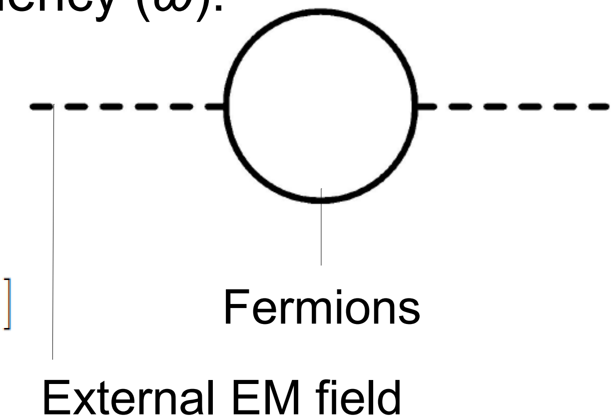
Mass terms	Symmetries										
	$\mathcal{T}_+$		$\mathcal{C}_+$		$\mathcal{T}_-$	$\mathcal{C}_-$		PH_1	PH_2	PSH_1	PSH_2
	$\mathcal{K}$	$iM_2M_3\,\mathcal{K}$	$iM_1M_2\,\mathcal{K}$	$iM_1M_3\,\mathcal{K}$	$M_1\,\mathcal{K}$	$M_2\,\mathcal{K}$	$M_3\,\mathcal{K}$	M_1	$i\Gamma_1\Gamma_2$	iM_1M_2	iM_1M_3
M_1	✓	✓	×	×	×	✓	✓	×	×	×	×
M_2	✓	×	×	✓	✓	×	✓	✓	×	×	✓
M_3	✓	×	✓	×	✓	✓	×	✓	×	✓	×
$i\Gamma_1\Gamma_2$	×	×	✓	✓	✓	×	×	×	×	✓	✓

V. J. & B. Roy, Comm Phys 2024

No constant mass term can be added without breaking at least one symmetry!!

Responses of NH Dirac materials

Optical conductivity (OC) @ zero temperature & finite frequency (ω):



Polarization tensor

$$\Pi_{jj}(i\omega) = -\mathrm{Tr} \int_{-\infty}^{\infty} \frac{d\nu}{2\pi} \int \frac{d^d\mathbf{k}}{(2\pi)^d} \left[J_j \, G_{\mathrm{F}}(i\omega + i\nu, \mathbf{k}) \, J_j \, G_{\mathrm{F}}(i\nu, \mathbf{k}) \right]$$

Current operator in *j* th direction: $J_j = (v_{\mathrm{H}} + v_{\mathrm{NH}} M)\, \Gamma_j$

OC in *d*=2: $\sigma(\omega) = \left. \dfrac{\mathrm{Im}\, \Pi(i\omega \to \omega + i\eta)}{\omega} \right|_{\eta \to 0} = N_f \dfrac{\pi}{4} \sigma_0$

OC in *d*=3: $\sigma(\omega) = \left. \dfrac{\mathrm{Im}\, \Pi(i\omega \to \omega + i\eta)}{\omega} \right|_{\eta \to 0} = \dfrac{N_f \omega}{6 v_{\mathrm{F}}} \sigma_0$

Same as in Hermitian systems with $v_{\mathrm{F}} \longrightarrow v_{\mathrm{H}}$

N_f: Number of 4-component Dirac flavors & $\sigma_0 = e^2/h$

V. J. & B. Roy, Comm Phys 2024

Interaction effects in NH Dirac semimetal

Local interaction: Dynamic mass generation

- Dirac fermions → Vanishing density of states: $\rho(E) \sim |E|$ in 2D or $|E|^2$ in 3D
- Local four-fermion interaction → Spontaneous symmetry breaking (sublattice, chiral, TRS, spin-rotational, ….)

Dynamic generation of Dirac mass → Insulator (electric or thermal)

Ordered phase → Nontrivial expectation value of mass bilinear: $\langle \Psi^\dagger N \Psi \rangle \neq 0$

Hermitian matrix operator *N*: Must *anticommute* with the Dirac Hamiltonian

Local interaction: Dynamic mass generation

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  Hermitian matrix operator *N*: Must *anticommute* with the Dirac Hamiltonian

- Scaling dimension of local four-fermions interaction: $g_{\mathrm{N}} \left(\Psi^\dagger N \Psi\right)^2$

  $[g_N]$ = -1 in 2D & -2 in 3D → (a) Weak interactions: Irrelevant

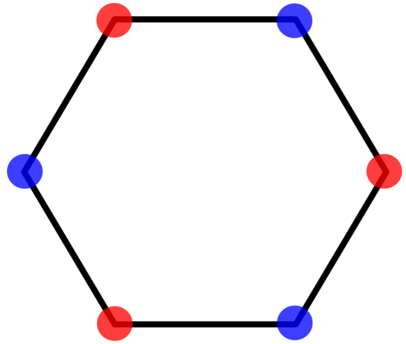
  (b) Broken symmetry phase @ strong coupling via quantum phase transition

I.F. Herbut, V.J., B. Roy, PRB 2009
I.F. Herbut, V.J., O. Vafek, PRB 2009

QMC: Herbut, Assaad, PRX 2013;
Otsuka, Yonuki, Sorella, PRX 2016

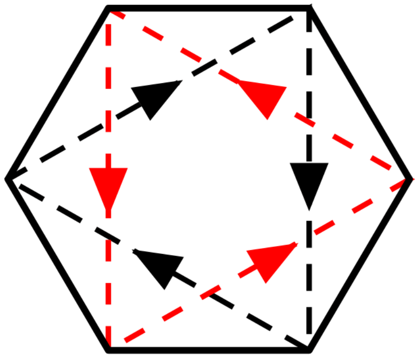
Examples of Dirac masses

- Charge density wave (CDW): Breaks sublattice symmetry
  Semenoff PRL **53**, 2449 (1983)

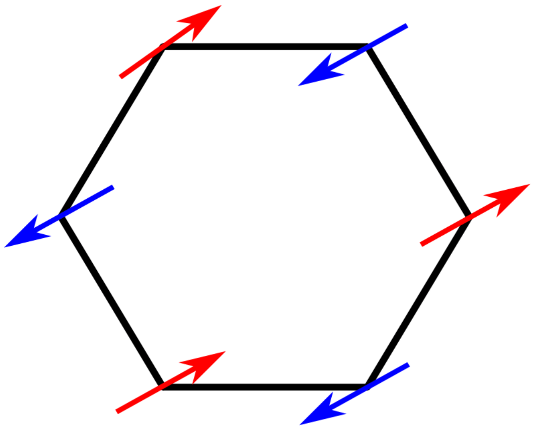


Each mass: Represented by unique mass matrix (*N*)

- Quantum anomalous Hall insulator (QAHI): Breaks sublattice & time reversal symmetries
  Haldane PRL **61**, 2015 (1988)



- Antiferromagnet (AFM): Breaks sublattice & spin rotational symmetries



Other examples of masses: translational symmetry breaking valence bond order, *s*-wave and *f*-wave pairings, Kekule pair-density-wave etc.

S. Ryu, C. Mudry, C.-Y Hou & C. Chamon, PRB **80**, 205319 (2010)
A. L. Szabo & B. Roy, PRB **103**, 205319 (2019)

Mass: Fragmentation in NH Dirac systems

V. J. & B. Roy, Comm Phys 2024

- Lorentz invariant construction of NH Dirac operator :

Selects a mass matrix M from the set of all Ns

↓

Causes fragmentation among all Ns, depending on algebra between M and N

↓

Two classes of mass orders in NH Dirac systems

- Commuting class mass (CCM): $[N, M] = 0$
- Anti-commuting class mass (ACM): $\{N, M\} = 0$

Effective field theory: Gross-Neveu-Yukawa theory

Scalar bosons: NH Yukawa theory

- Dynamic mass generation → Condensation of bosonic order-parameter field: Composite of fermionic fields

V. J. & B. Roy, Comm Phys 2024

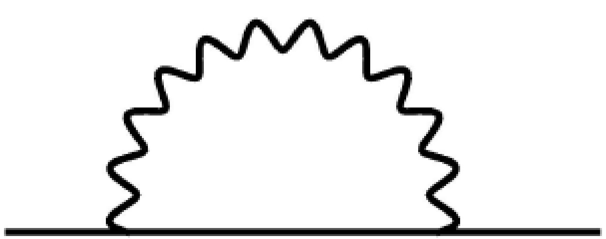
Yukawa interaction between bosonic & fermionic degrees of freedom

$$S_Y = g \int d\tau \int d^d\mathbf{x} \sum_{j=1}^{n} \Phi_j(\tau, \mathbf{x}) \; \Psi^\dagger(\tau, \mathbf{x}) N_j \Psi(\tau, \mathbf{x})$$

Marginal in *d=3+1*

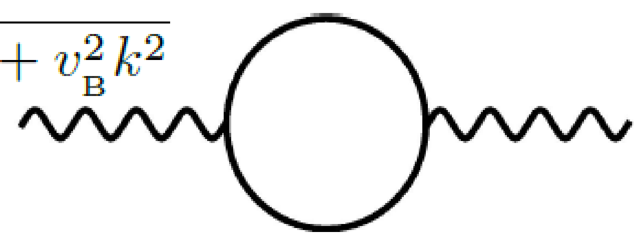
- Fermions: Two velocity parameters (v_H , v_{NH}) & effective Fermi velocity (v_F)
- Bosons: Unique bosonic velocity (v_B) → Bosonic Green's function:

$$G_B(i\omega, \mathbf{k}) = \frac{1}{\omega^2 + v_B^2 k^2}$$



Fermionic self-energy

Lorentz symmetry?



Bosonic self-energy

CCM: Emergent NH Lorentz symmetry

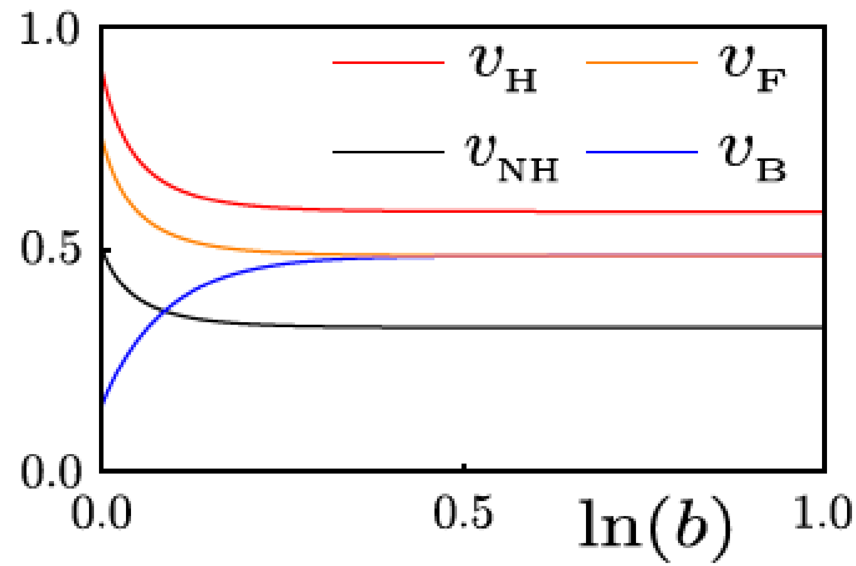
- RG Flow equations: Hermitian & anti-Hermitian velocity components of Dirac fermions

$$\beta_{v_{\mathrm{H}}} = -\frac{4g^2 n}{3v_{\mathrm{B}}(v_{\mathrm{F}}+v_{\mathrm{B}})^2}\left(1-\frac{v_{\mathrm{B}}}{v_{\mathrm{F}}}\right)v_{\mathrm{H}} \quad \& \quad \beta_{v_{\mathrm{NH}}} = -\frac{4g^2 n}{3v_{\mathrm{B}}(v_{\mathrm{F}}+v_{\mathrm{B}})^2}\left(1-\frac{v_{\mathrm{B}}}{v_{\mathrm{F}}}\right)v_{\mathrm{NH}}$$

- RG Flow equation: Bosonic velocity $\beta_{v_{\mathrm{B}}} = -N_f \frac{g^2 n}{2v_{\mathrm{F}}^3}\left(1-\frac{v_{\mathrm{F}}^2}{v_{\mathrm{B}}^2}\right)v_{\mathrm{B}}$

RG fixed point

The system acquires a unique terminal velocity for fermionic & bosonic degrees of freedom $\rightarrow v_{\mathrm{F}} = v_{\mathrm{B}}$ with both v_{H} & v_{NH} being non-zero!!



Emergent Yukawa-Lorentz symmetry (Non-Hermiticity: retained)

ACM: Emergent Hermitian Lorentz symmetry

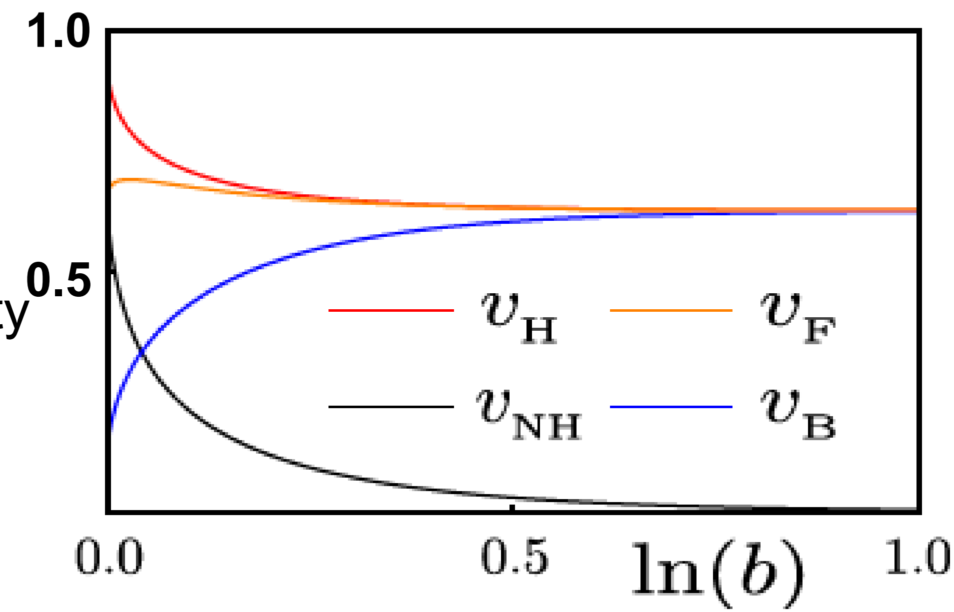
- RG Flow equations: Hermitian & anti-Hermitian velocity components of Dirac fermions

$$\beta_{v_{\rm H}} = -\frac{4g^2 n}{3v_{\rm B}(v_{\rm F}+v_{\rm B})^2}\left(1-\frac{v_{\rm B}}{v_{\rm F}}\right)v_{\rm H} \quad \& \quad \beta_{v_{\rm NH}} = -\frac{8g^2 n}{3v_{\rm B}(v_{\rm F}+v_{\rm B})^2}\left(1+\frac{v_{\rm B}}{2v_{\rm F}}\right)v_{\rm NH}$$

- RG Flow equation: Bosonic velocity $$\beta_{v_{\rm B}} = -N_f \frac{g^2 n}{2v_{\rm F}^3}\left(\frac{v_{\rm H}^2}{v_{\rm F}^2}-\frac{v_{\rm H}^2}{v_{\rm B}^2}-\frac{2v_{\rm NH}^2}{3v_{\rm B}^2}\right)v_{\rm B}$$

RG fixed point

The system acquires a unique terminal velocity for fermionic & bosonic degrees of freedom
$\rightarrow v_{\rm F} = v_{\rm H} = v_{\rm B}$ with $v_{\rm NH} = 0$!!



Emergent Hermitian Lorentz symmetry (Hermiticity: restored)

Tilted NH Dirac Semimetal

NH tilted strongly-coupled DSM:

S. Pino-Alarcon & V. J., PRB **111**, 195126 (2025)

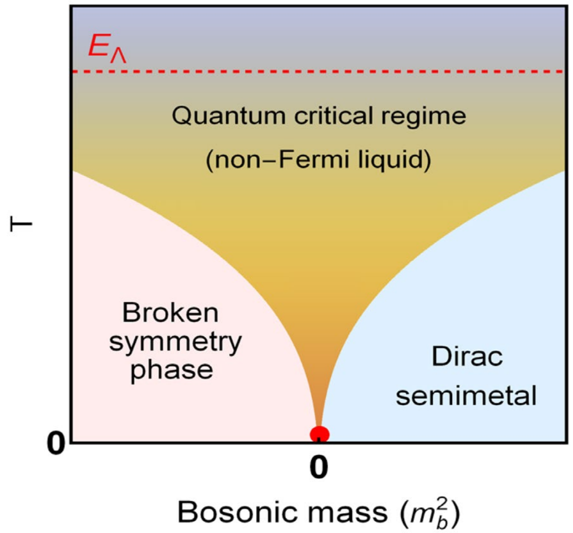
Hermitian tilted strongly-coupled DSM:

H. Rostami & V. J., PRR **2**, 013069 (2020).
P. Reiser & V. J., JHEP **2024**, 1 (2024).

$$H_{\mathrm{NH}} = (v_{\mathrm{H}} + v_{\mathrm{NH}} M) h_0 + \alpha v_{\mathrm{H}} T k_x$$

$$\{M, H_{\mathrm{D}}\} = 0 \quad v_{\mathrm{F}} = \sqrt{v_{\mathrm{H}}^2 - v_{\mathrm{NH}}^2}$$

Tilt matrices - Symmetric & Asymmetric $T_{\mathrm{S}} = \sigma_1 \otimes \tau_0$ and $T_{\mathrm{AS}} = \sigma_0 \otimes \tau_0$



Lorentz symmetry close to the QCP:
Velocities are not neccesarily equal

The Density of States

S. Pino-Alarcon & V. J., PRB 2025

$$\rho(E) = -\frac{1}{\pi} \lim_{\eta \to 0^+} \mathrm{Im}\left\{ \mathrm{Tr}\, G_F(i\omega \to \omega + i\eta, \mathbf{k}) \right\}$$

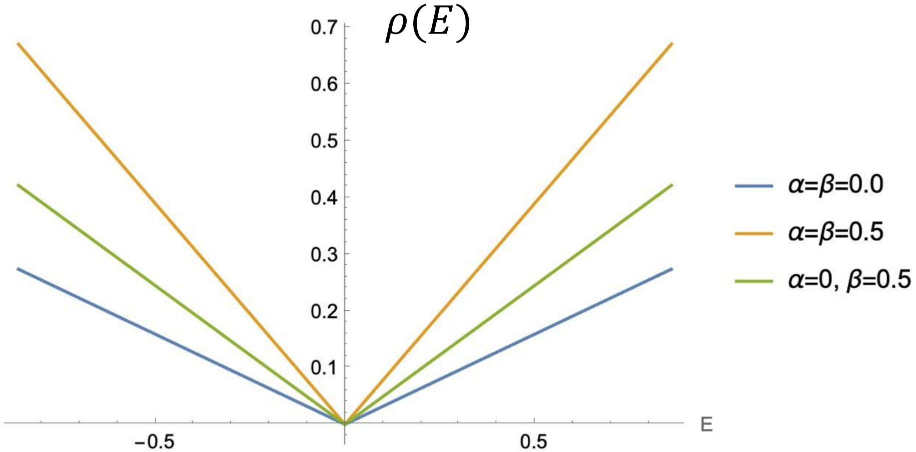
$$\beta = v_{\mathrm{NH}}/v_{\mathrm{H}}$$

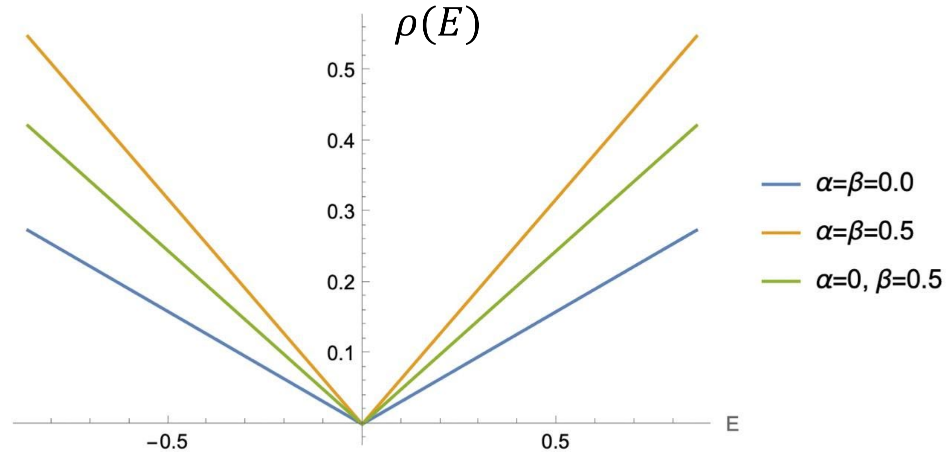
Asymmetric tilt

$$\rho_{\mathrm{AS}}(E) = \frac{\sqrt{1-\beta^2}\,|E|}{\pi(1-\alpha^2-\beta^2)^{3/2} v_{\mathrm{H}}^2}$$

Symmetric tilt

$$\rho_{\mathrm{S}}(E) = \frac{|E|}{\pi(1-\alpha^2-\beta^2) v_{\mathrm{H}}^2}$$





$\alpha^2 + \beta^2 < 1 \longrightarrow \rho(E \to 0) \to 0$

Weak interactions irrelevant

Zero-frequency optical conductivity: Tilt probes non-Hermiticity

S. Pino-Alarcon, J.P. Esparza & V. J., in preparation.

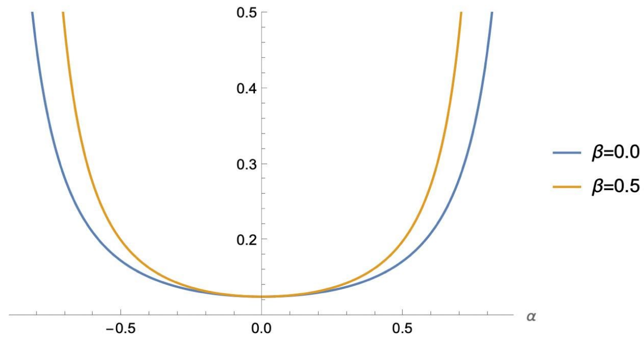
Kubo formula

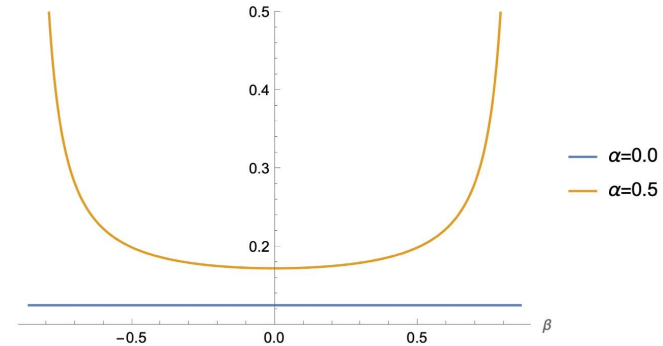
$$\sigma(\omega) = \left.\frac{\mathrm{Im}\,\Pi(i\omega \to \omega + i\eta)}{\omega}\right|_{\eta \to 0}$$

$$\Pi_{lm}(i\omega) = -\,\mathrm{Tr}\int_{-\infty}^{\infty}\frac{d\nu}{2\pi}\int\frac{d^2\mathbf{k}}{(2\pi)^2}[J_l G_F(i\omega + i\nu, \mathbf{k}) J_m G_F(i\nu, \mathbf{k})]$$

Symmetric tilt

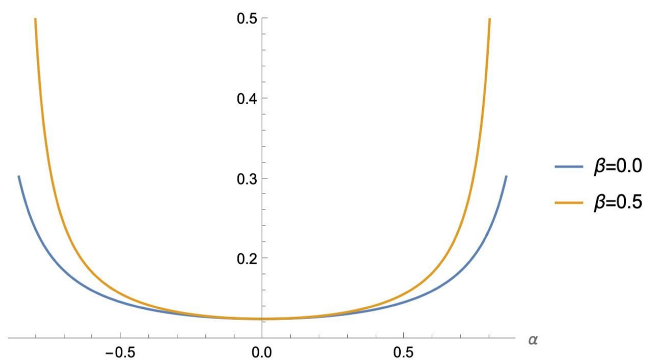
$$\sigma_{\mathrm{S}}(\omega) = \frac{N_f}{8}\left(1 + \frac{\alpha^2}{2\left(1 - \alpha^2 - \beta^2\right)}\right)$$

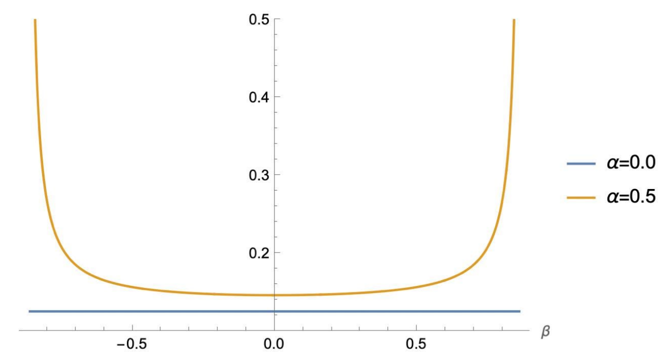




Asymmetric tilt

$$\sigma_{\mathrm{AS}}(\omega) = \frac{N_f}{32}\left(\frac{\alpha^2\left(-2\alpha^2 + \beta^2 - 1\right)\left(\alpha^2 + 2\beta^2 - 2\right)}{\left(1 - \beta^2\right)^{3/2}\left(-\alpha^2 - \beta^2 + 1\right)^{3/2}} + \frac{2\left(\alpha^2 - 2\beta^2 + 2\right)}{1 - \beta^2}\right)$$





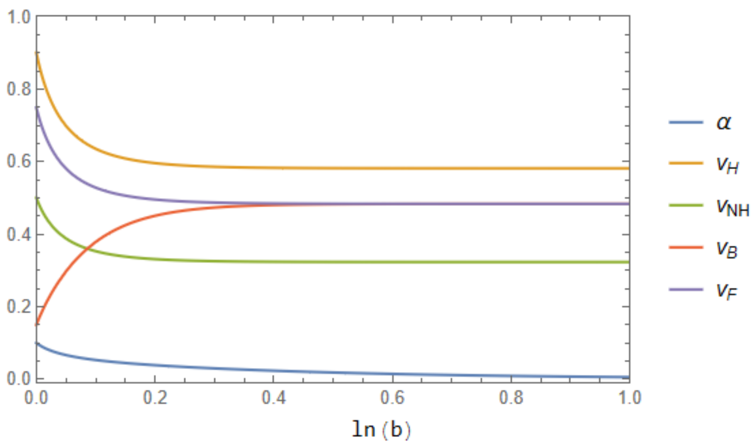
Strongly-coupled tilted NH Dirac Semimetal

S. Pino-Alarcon & V. J., PRB 2025

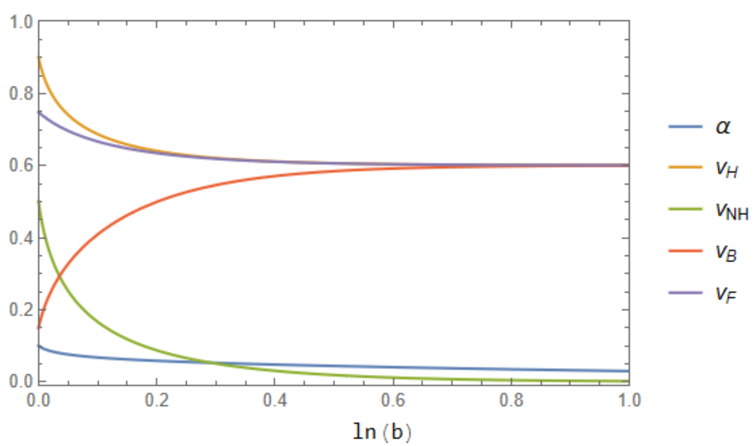
$\epsilon -$ expansion close to $d = 3$ spatial dimensions near CDW QCP

Asymmetric tilt

CCM: NH Lorentz

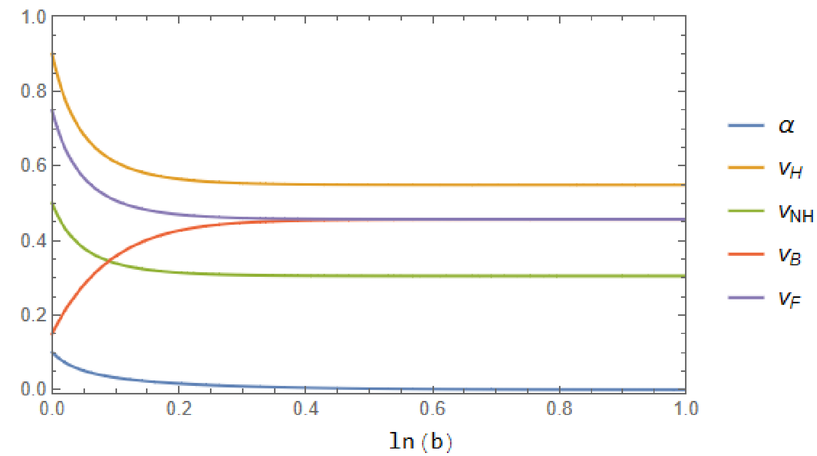


ACM: Hermitian Lorentz

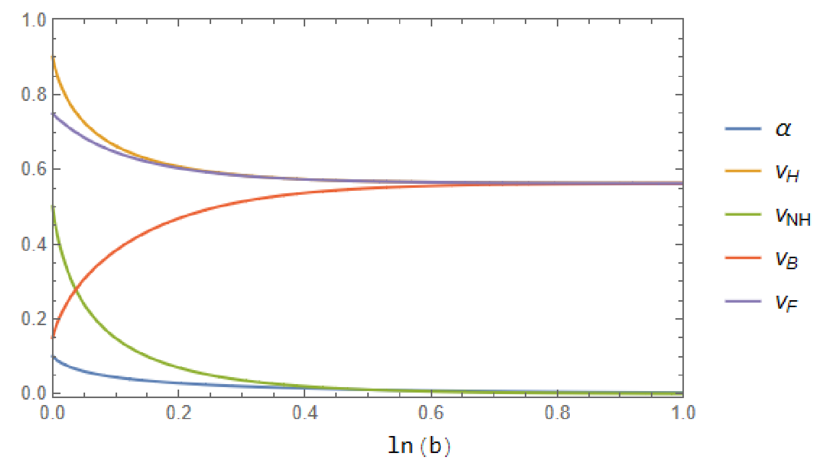


Symmetric tilt

CCM



ACM



In all cases: Restoration of the Lorentz symmetry – *CCM: Yukawa-Lorentz symmetry*

Conclusions

- General principle of construction for NH Dirac Hamiltonians

- Strongly coupled NH Dirac fermions: Emergent Lorentz symmetry in NH or open quantum systems (system-to-environment coupling)

- Tilted NH Dirac semimetals: Tilt can probe non-Hermiticity (OC)

- Lorentz symmetry restores at strong coupling – tilt irrelevant at QCP: CCM – non-Hermiticity retained