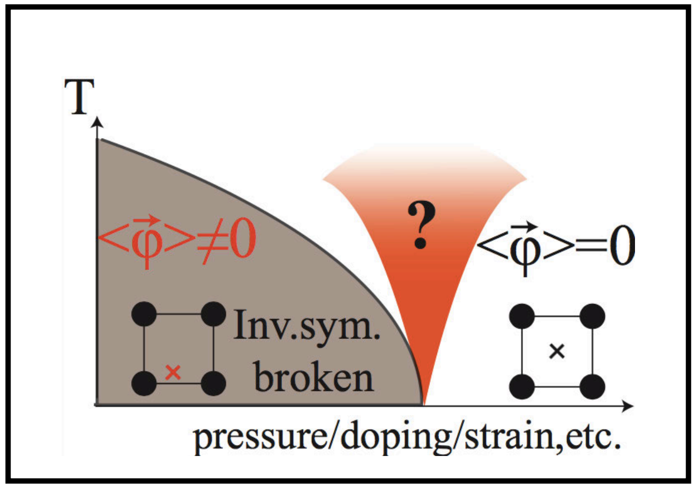
Polar Quantum Criticality

P. Chandra
(Rutgers)

Julich
Sept. 2024

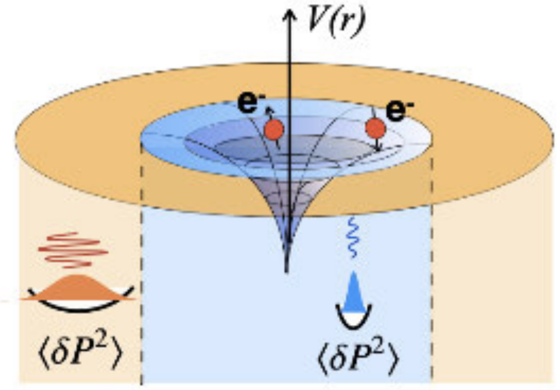
Polar Materials + Quantum Criticality ??



Quantum Annealed Criticality

Novel Metallicity

Enigmatic Superconductivity



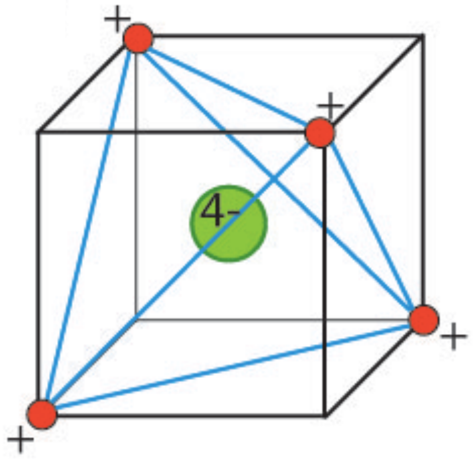
Summary and Outlook

Polar Material ?

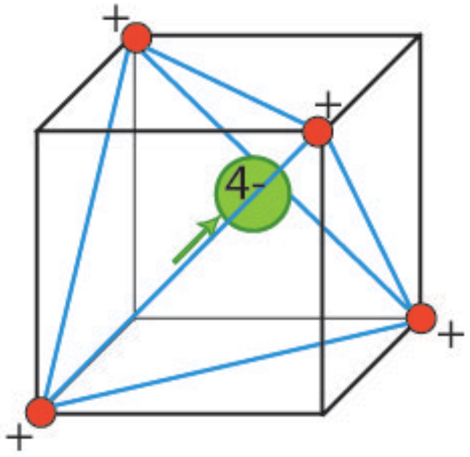
Net Dipole Moment/ Volume

$$P = \frac{\sum \mu}{V}$$

Polarization

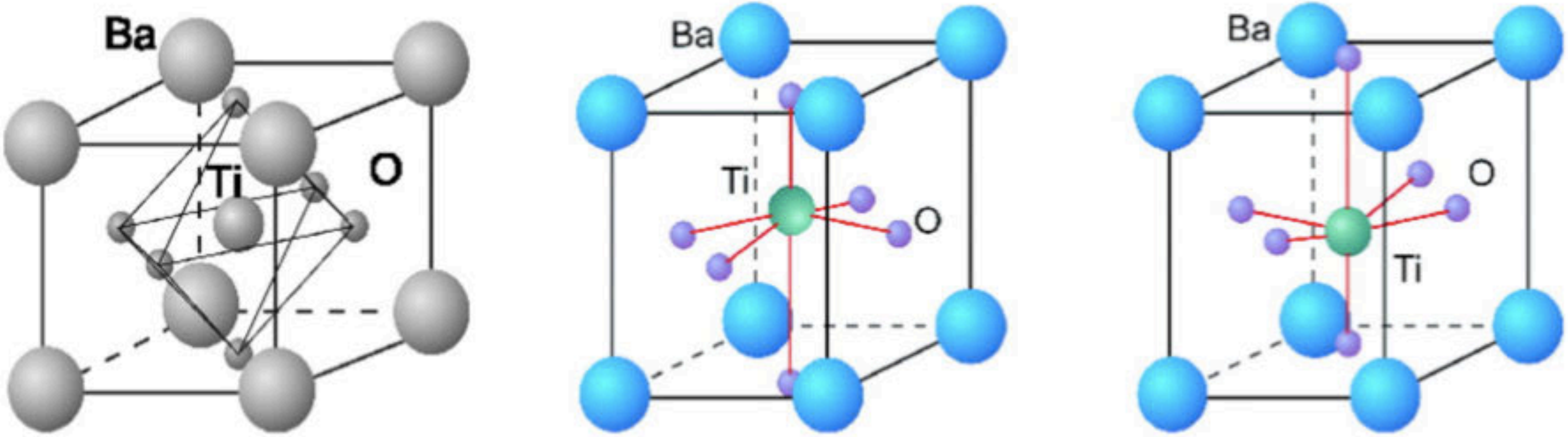


No !! (Centrosymmetric)



Yes !! (Non-Centrosymmetric)

Example: $BaTiO_3$

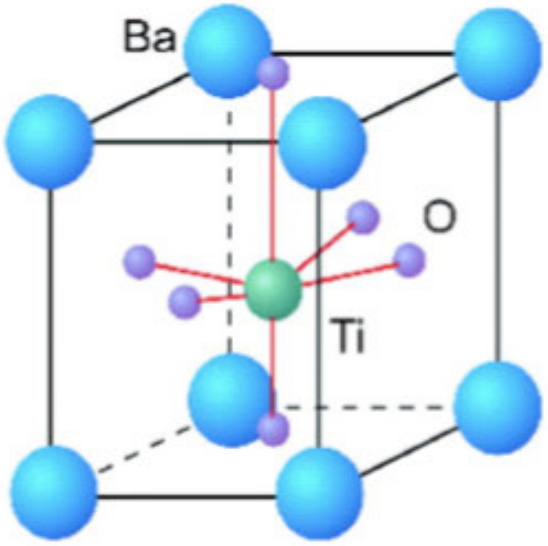


Cubic phase

P_{up}

P_{down}

Polar Materials ? (Simplest Case: Insulators)



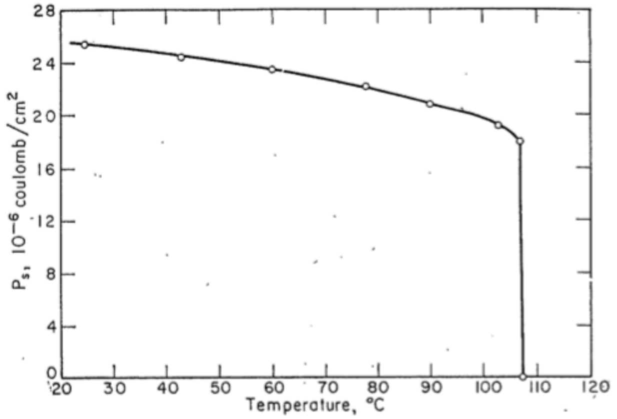
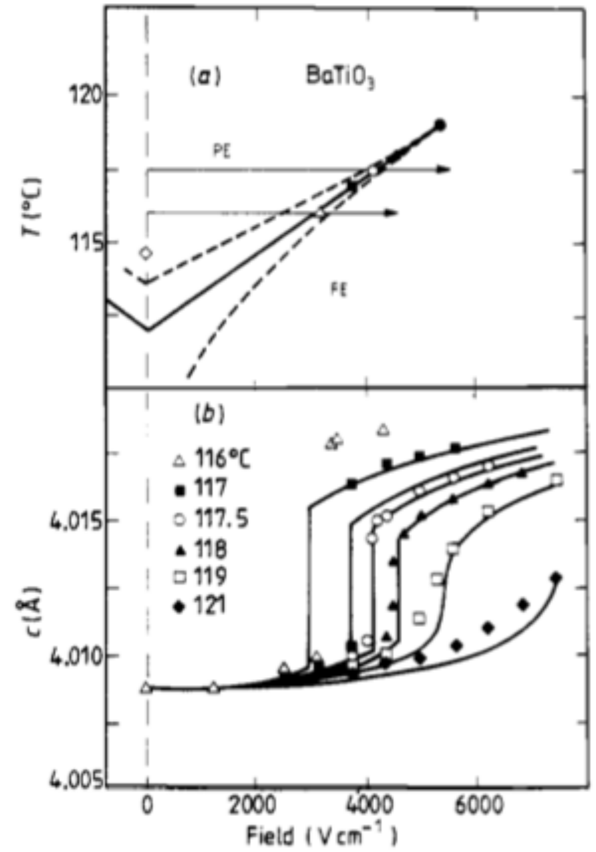


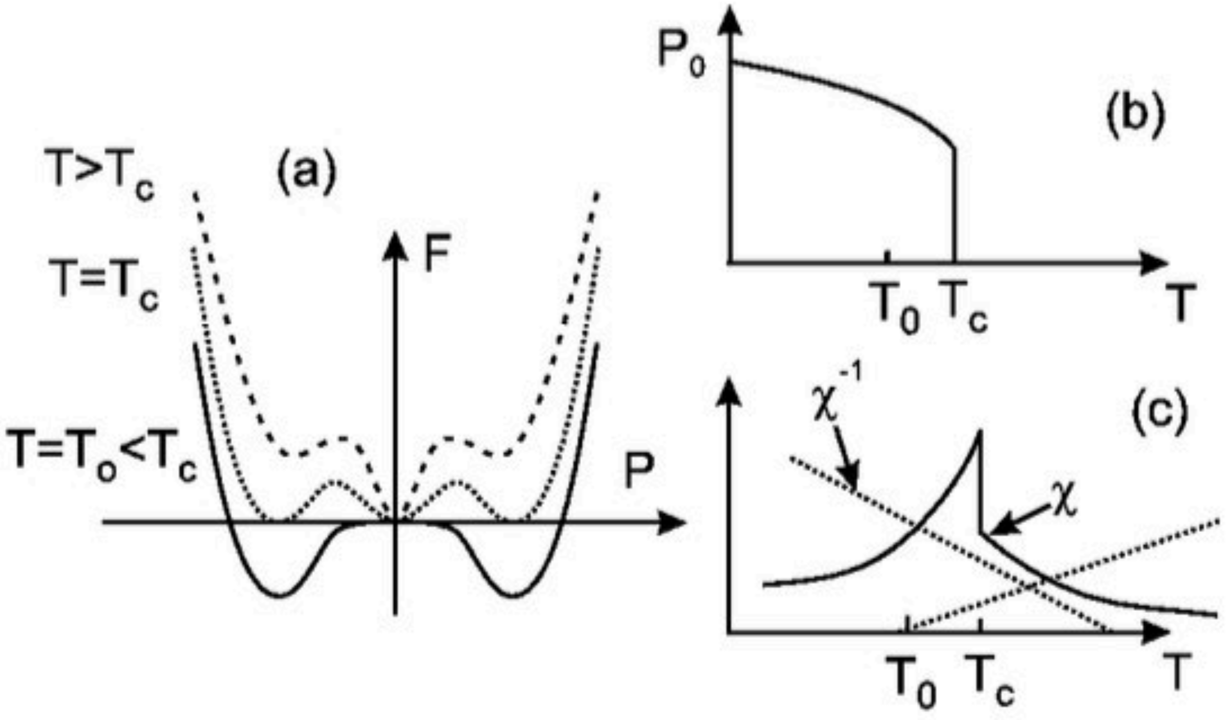
FIG. IV-7. Spontaneous polarization of tetragonal $BaTiO_3$ as a function of temperature (according to Merz (M 2)).

Jona and Shirane, FE Crystals (1962)



McWhan et al., J.Phys. C (1985)

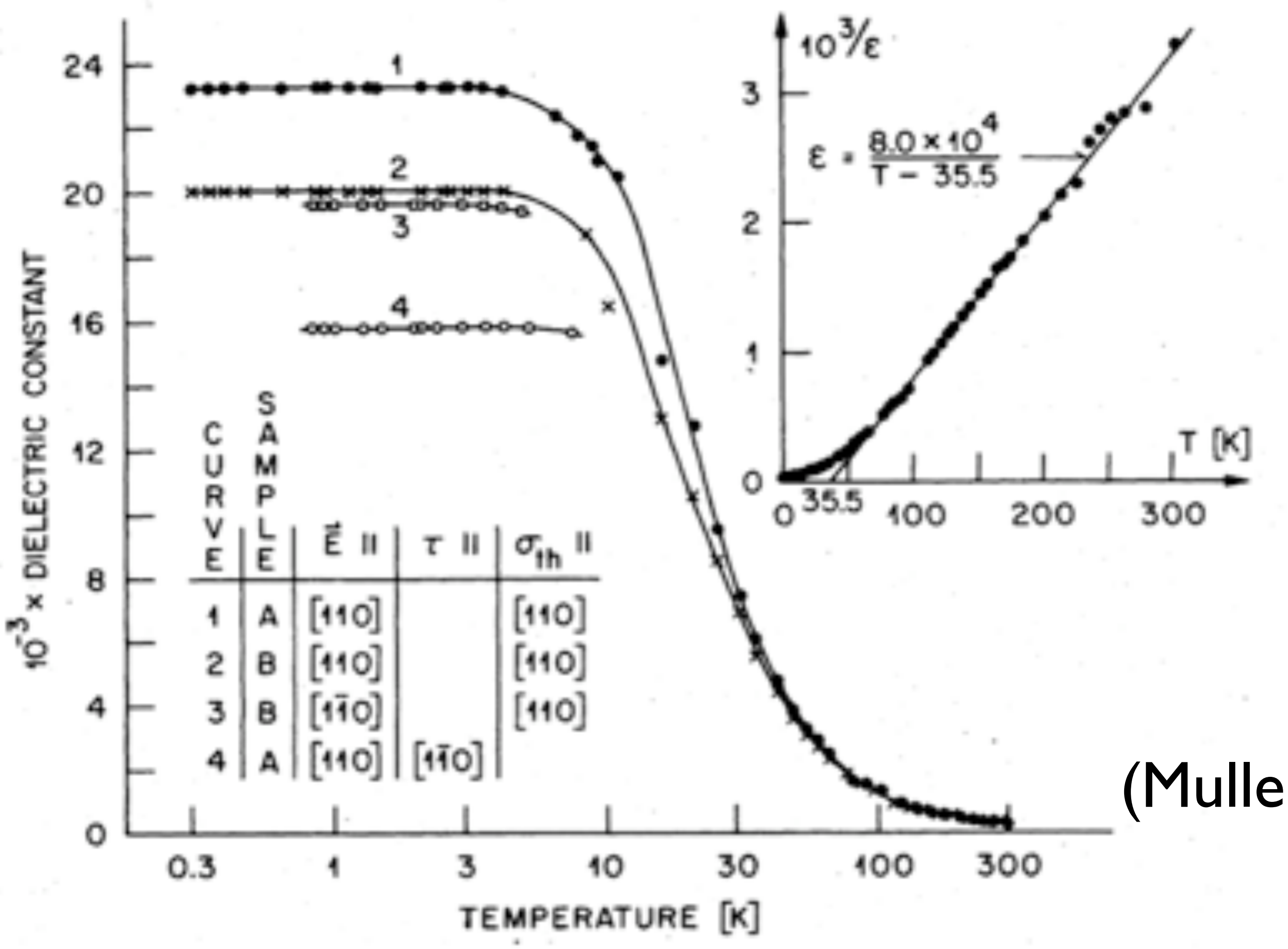
Figure 1. (*a*) Phase diagram of $BaTiO_3$ showing line of first-order transitions terminating at a critical point (full circle). (*b*) Lattice constant against electric field at different temperatures. Full and broken curves in 1(*a*) and 1(*b*) are calculated by minimising the free energy and they correspond to the equilibrium and spinodal boundaries.

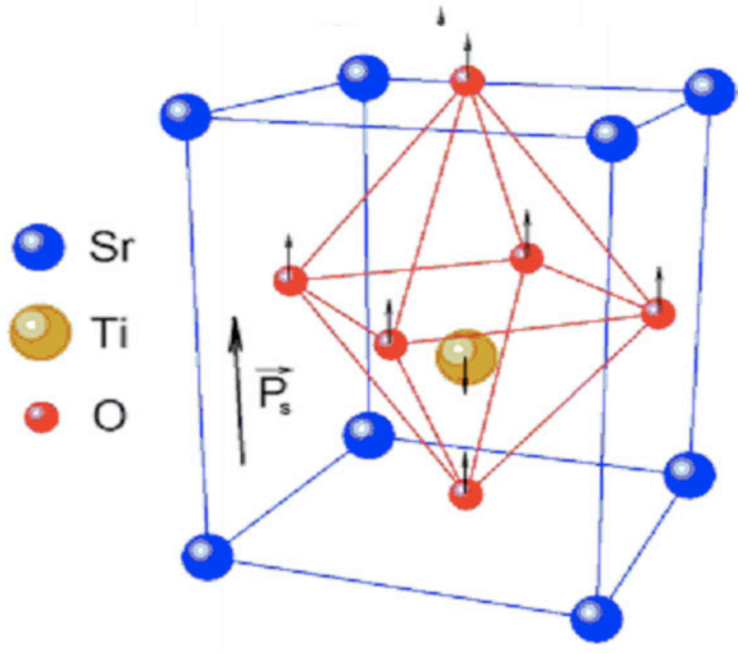


Classically First-Order !

Strong Electromechanical Coupling !

SrTiO$_3$ - Almost a Ferroelectric

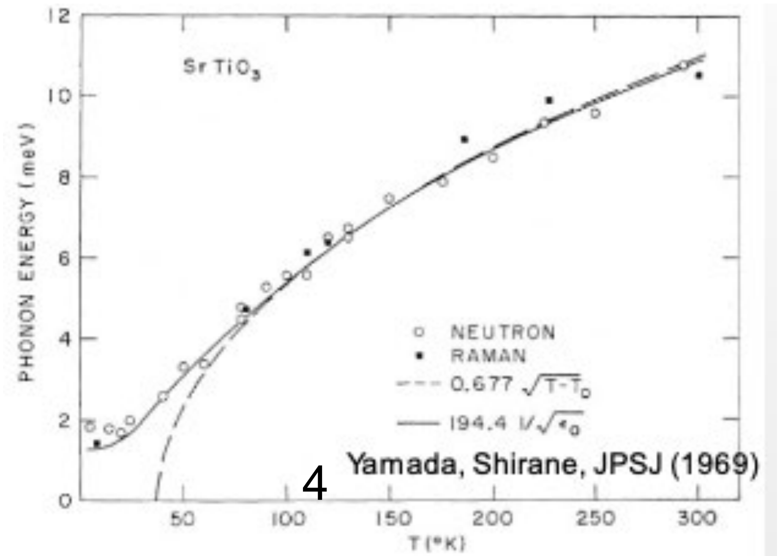




(Muller and Burkhard 79)

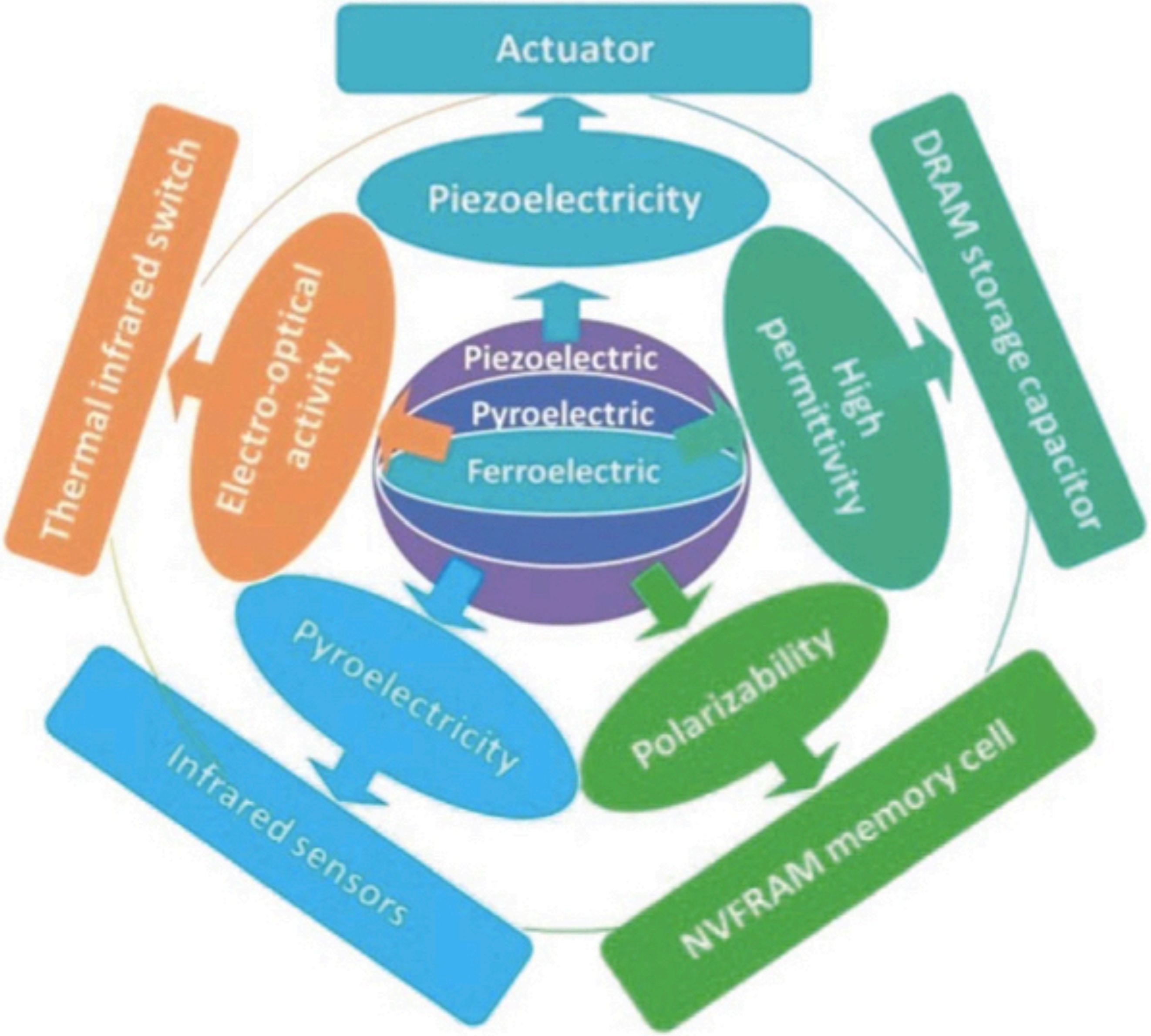
Ferroelectricity induced by
Uniaxial Stress, Ca and O-18 Substitution

Critical mode: Optical Phonon $\epsilon(T) \approx \dfrac{\Omega_0^2}{\omega_{TO}(T)^2}$



Yamada, Shirane, JPSJ (1969)

Polar Materials ?



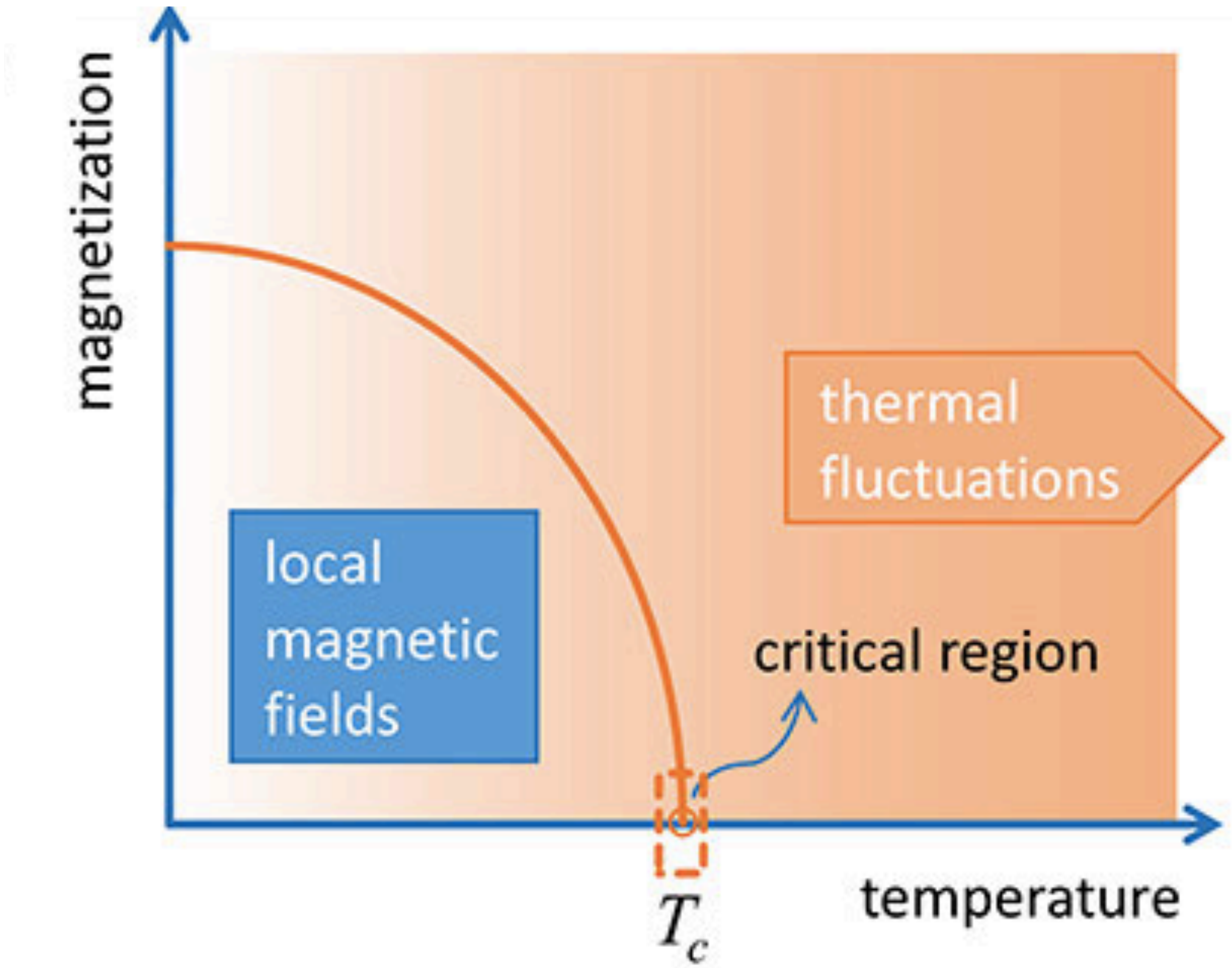
Important for Many

Room-Temperature

Applications

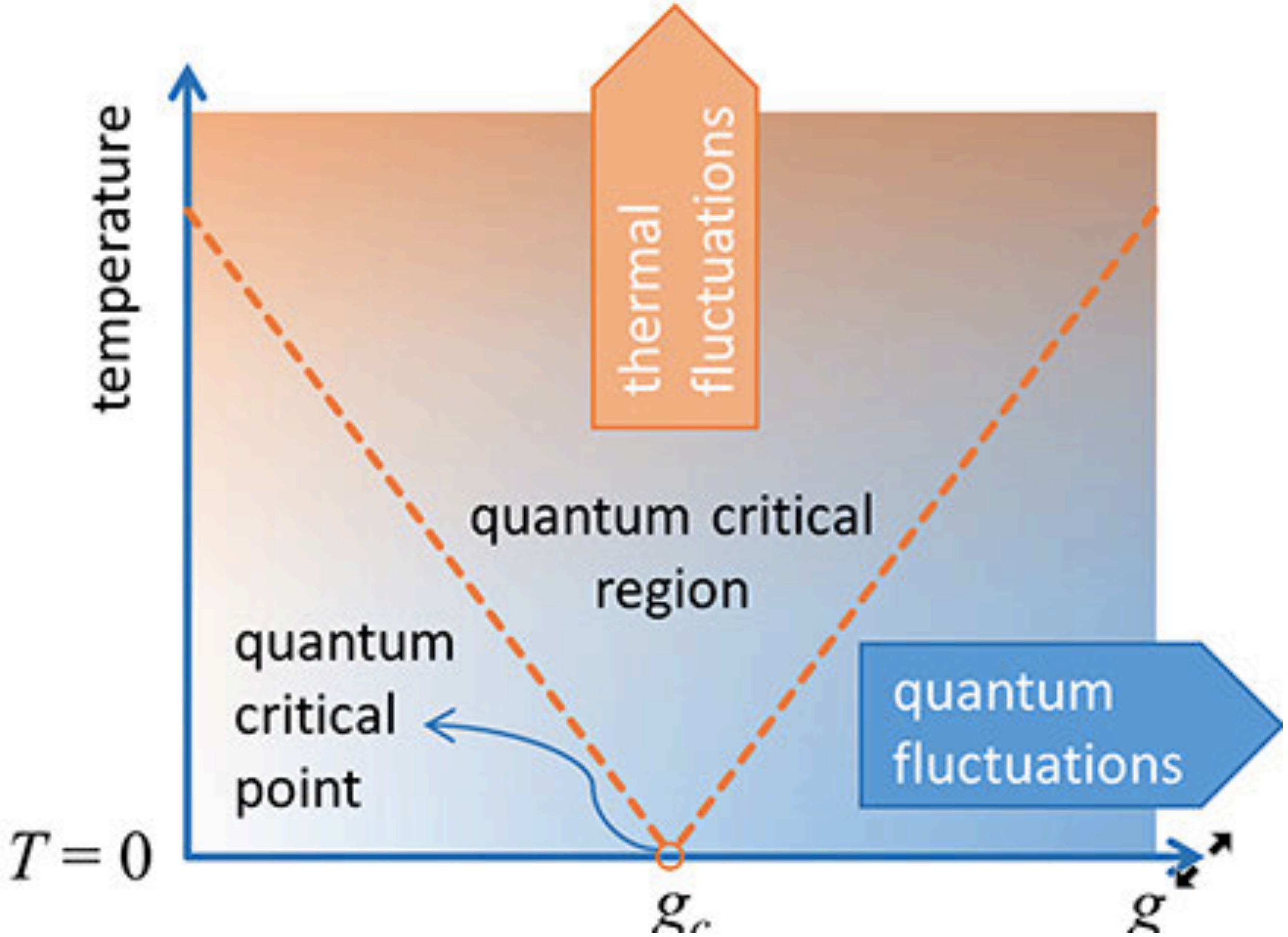
Can these functional materials “teach” us about some fundamental physics in Nature?

Classical Criticality



k_BT

Quantum Criticality



$\hbar\Omega$

Quantum Fluctuations at Finite Temperature ??

Heisenberg Uncertainty Principle

$$\Delta t \propto \frac{\hbar}{\Delta E}$$

Decoherence Time-Scale (Planck time)

$$t_P \propto \frac{\hbar}{k_B T}$$

Fluctuations purely Quantum up to the Planck time
Classical beyond

T = 0 Quantum Critical Point,
Fluctuations are Purely Quantum

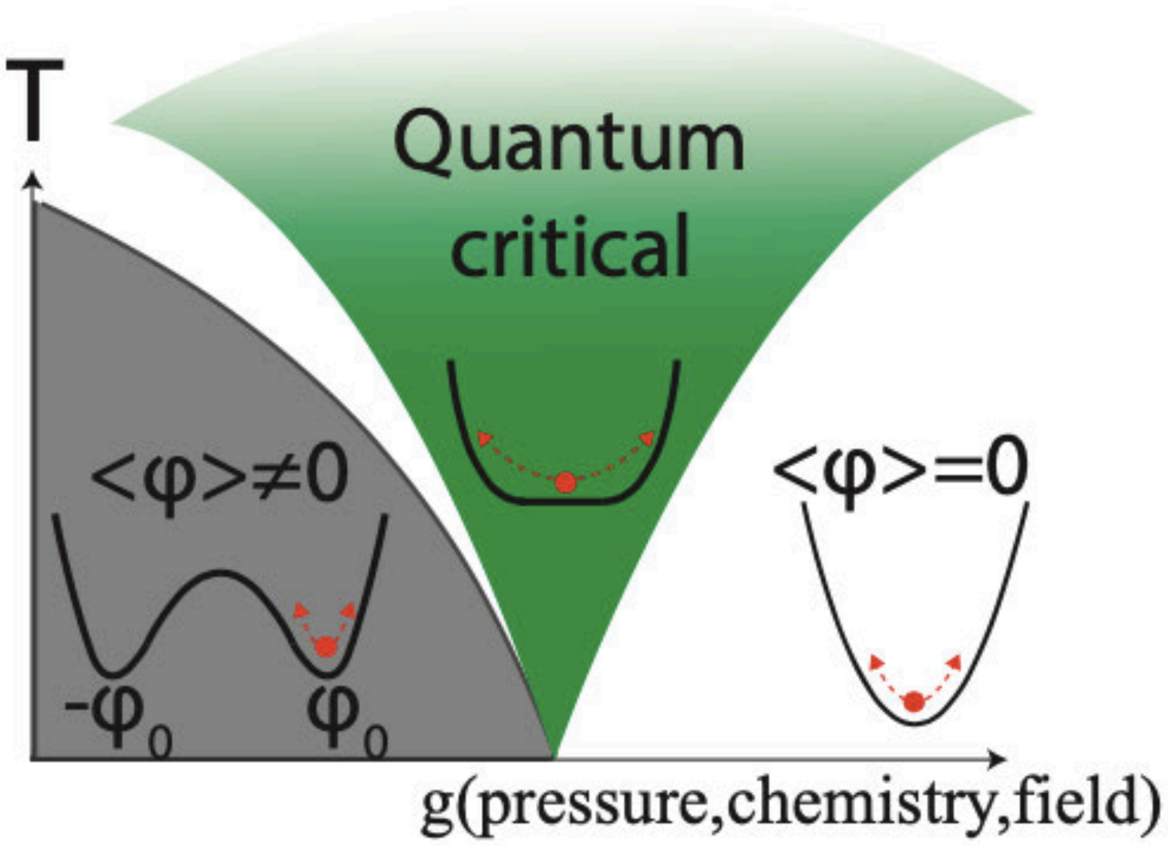
Quantum Criticality: Key Concepts

Symmetry-Breaking
Phase Transition at T=0

Tuning Parameter is
NOT Temperature

Physics determined by
Nature of Critical Soft
Mode

Importance of Dynamics



State of Matter with Quantum
Fluctuations on All Scales

Novel Quantum Phases ??!!

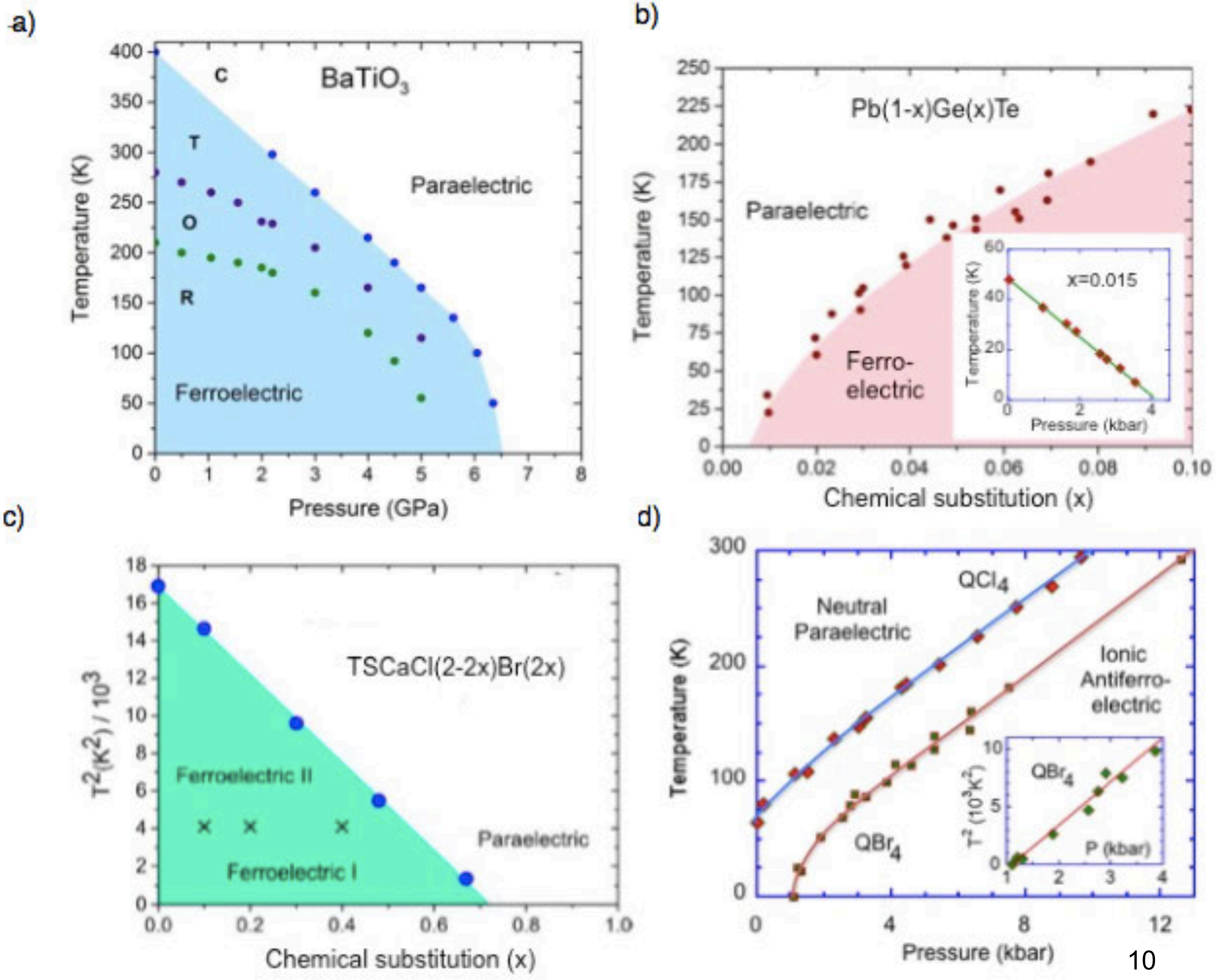
Motivation:
Exotic Metallicity
particularly
Unconventional Superconductivity

Polar Materials
and
Quantum Criticality ?

Classical Polar Transitions Usually
First Order !?

Mostly Insulators !?

(links to novel metallicity??)


a)
BaTiO$_3$
C
T
O
R
Paraelectric
Ferroelectric
Temperature (K)
Pressure (GPa)
0
50
100
150
200
250
300
350
400
0
1
2
3
4
5
6
7
8
b)
Pb(1-x)Ge(x)Te
Paraelectric
Ferro-
electric
Temperature (K)
Chemical substitution (x)
0
25
50
75
100
125
150
175
200
225
250
0.00
0.02
0.04
0.06
0.08
0.10
x=0.015
Temperature (K)
Pressure (kbar)
0
20
40
60
0
2
4
c)
TSCaCl(2-2x)Br(2x)
Ferroelectric II
Ferroelectric I
Paraelectric
T^2(K^2) / 10^3
Chemical substitution (x)
0
2
4
6
8
10
12
14
16
18
0.0
0.2
0.4
0.6
0.8
1.0
d)
Neutral
Paraelectric
QCl$_4$
Ionic
Antiferro-
electric
QBr$_4$
Temperature (K)
Pressure (kbar)
0
100
200
300
0
4
8
12
QBr$_4$
T^2 (10^{3}K^2)
P (kbar)
0
5
10
1
2
3
4

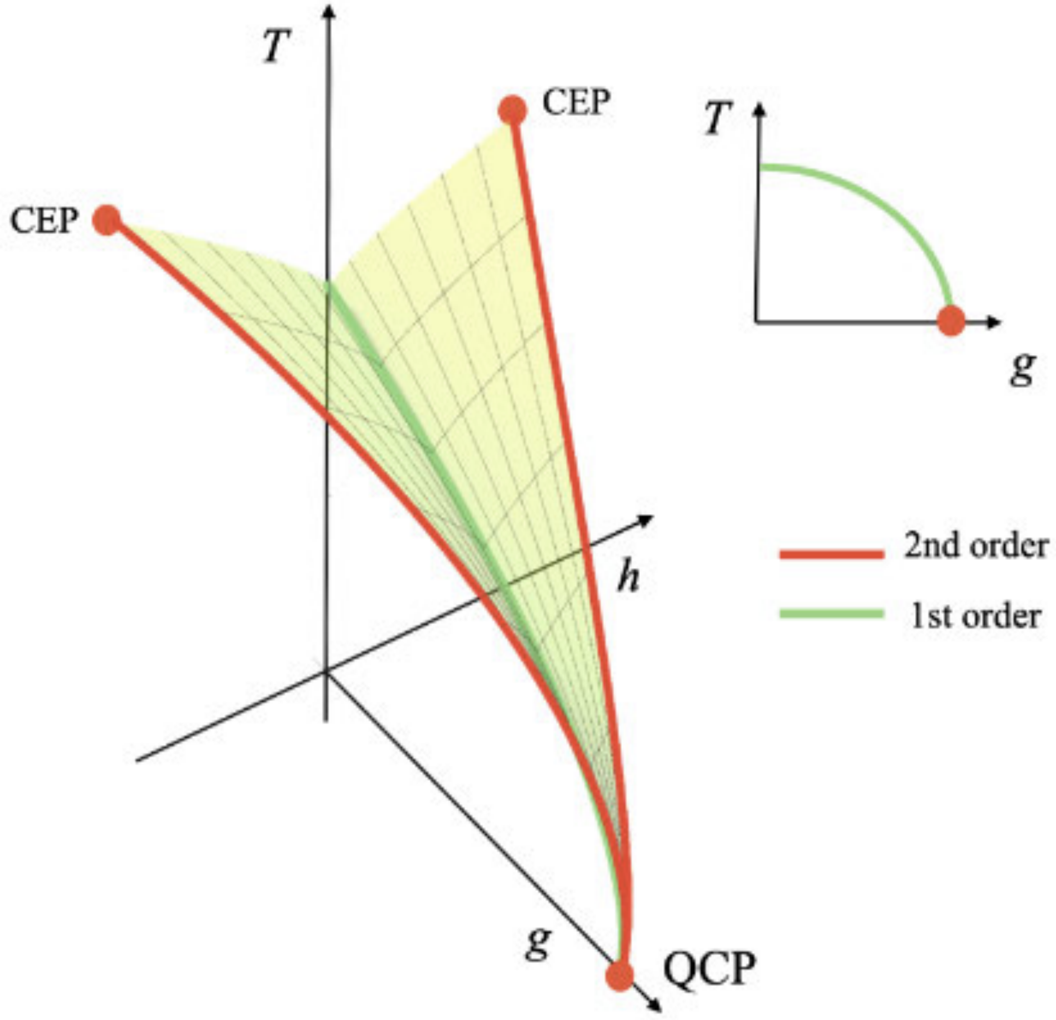
How can Systems that Have Classical First-Order Transitions display Quantum Criticality ??

Interplay of Classical and Quantum Fluctuations ??

Classically Strain-Energy Density Coupling
known to drive 1st Order Transitions
in Compressible Systems
(that are Critical when Clamped)

↓

T=0 ??



Quantum Annealed Criticality

PC, P. Coleman, M.A. Continentino, G. G. Lonzarich, Phys. Rev. Res. 2, 043440 (2020)

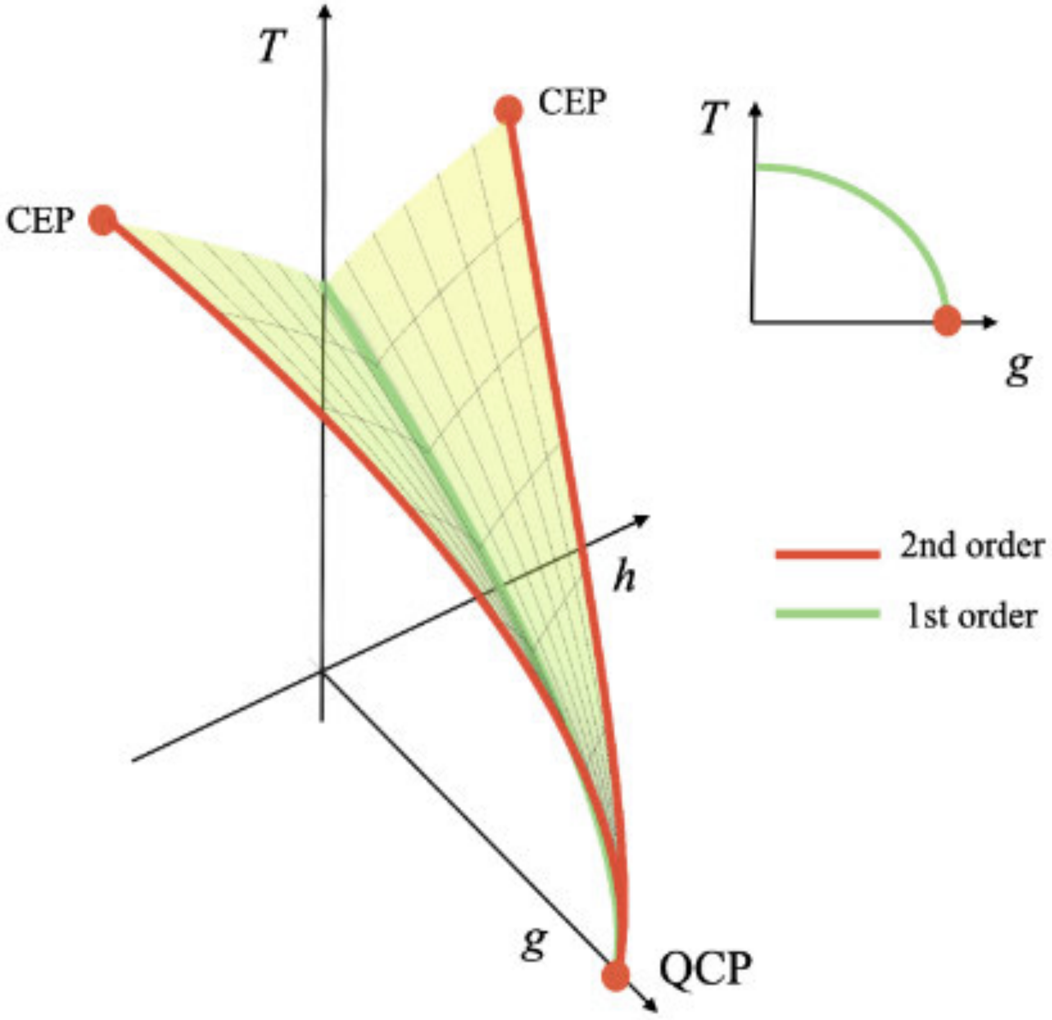
How can Systems that Have Classical First-Order Transitions display Quantum Criticality ??

Interplay of Classical and Quantum Fluctuations ??

Decrease in T

Quantum fluctuations reduce the amplitudes of thermal fluctuations, weakening the first-order transition

T=0 “Quantum Annealed” Critical Point



Quantum Annealed Criticality

PC, P. Coleman, M.A. Continentino, G. G. Lonzarich, Phys. Rev. Res. 2, 043440 (2020)

(Classical) Larkin-Pikin Mechanism

(A. I. Larkin and S. Pikin, Sov. Phys. JETP 29, 891 (1969))

Interaction of strain with squared amplitude of the critical order parameter

Diverging Specific Heat in a Clamped System

↓

1st Order Transition in the Unclamped System

LP Criterion for 1st Order Transition

$$\kappa \ < \ \frac{\Delta C_V}{T_c}\left(\frac{dT_c}{d\ln V}\right)^2$$

$$\kappa^{-1} = K^{-1} - (K + \frac{4}{3}\mu)^{-1} \qquad \kappa \sim K\frac{c_L^2}{c_T^2}$$

Shear Strain Crucial

Coupling of the uniform strain to the energy density

$$\tilde{\kappa} \equiv \kappa - \Delta\kappa$$

↓

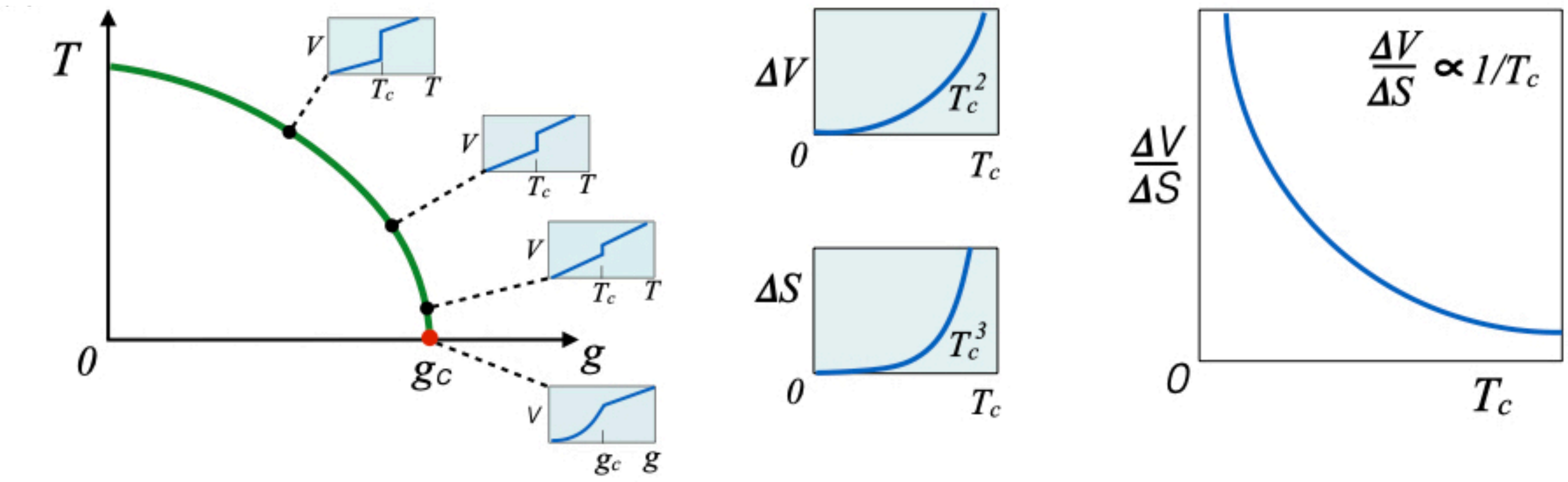
Macroscopic Instability of the Critical Point

↓

Discontinuous Phase Transition

Generalization for the Quantum Case ???

Schematic Flavor of Results



$(g \to P)$

$$\frac{dT_c}{dP} = \frac{\Delta V}{\Delta S}\bigg|_{T=T_c}$$

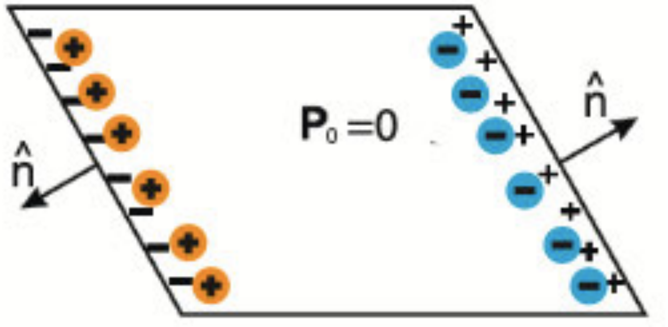
$$\lim_{T_c \to 0^+} \Delta V \to 0$$

No Latent Work

Continuous Quantum Transition!

PC, P. Coleman, M.A. Continentino, G. G. Lonzarich, Phys. Rev. Res. 2, 043440 (2020)

Polar Metal ?



Screening of Dipole Moments

Inversion Symmetry-Breaking Transition Remains
(Anderson and Blount PRL 12, 217 (1965))

Intrinsic and “Engineered”
Polar Metals Exist

Search for Weyl semimetals

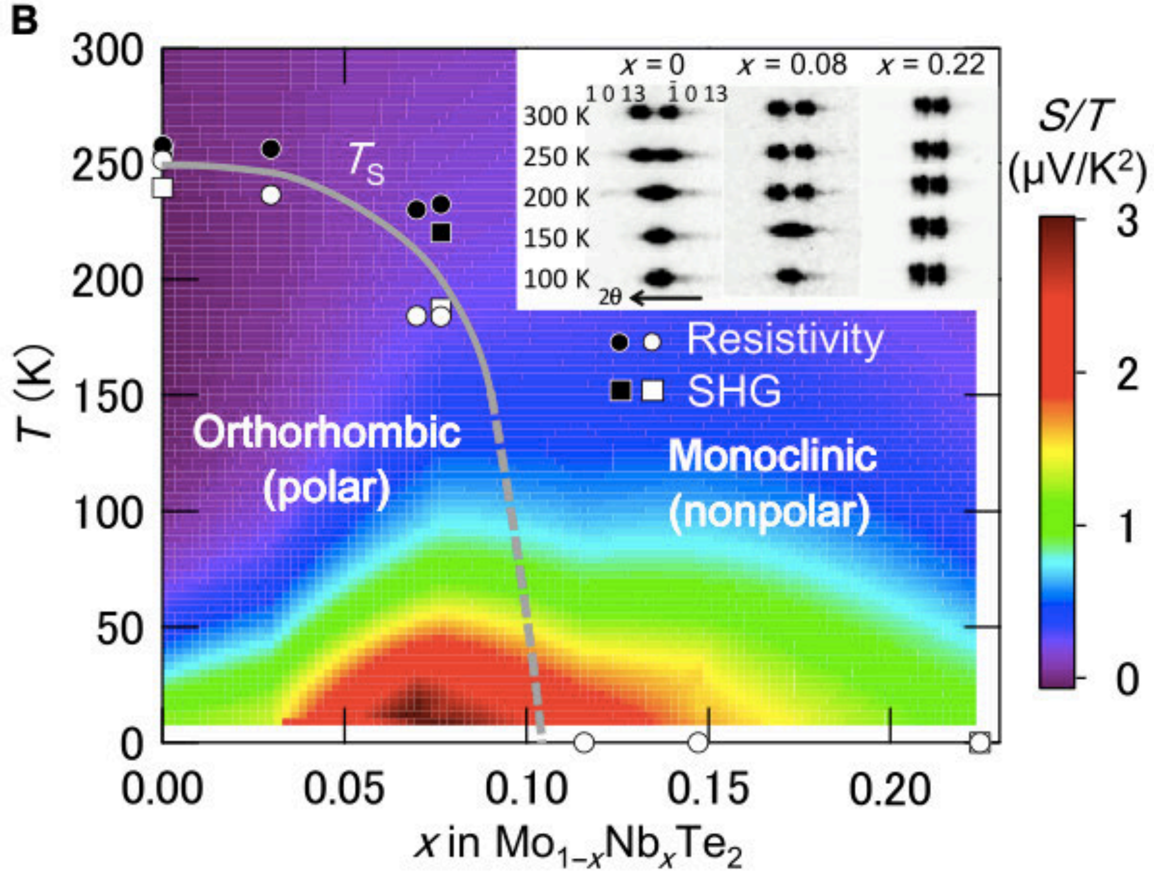
↓

Polar Semimetals

Tuning of the Polar Transition

Chemical Substitution

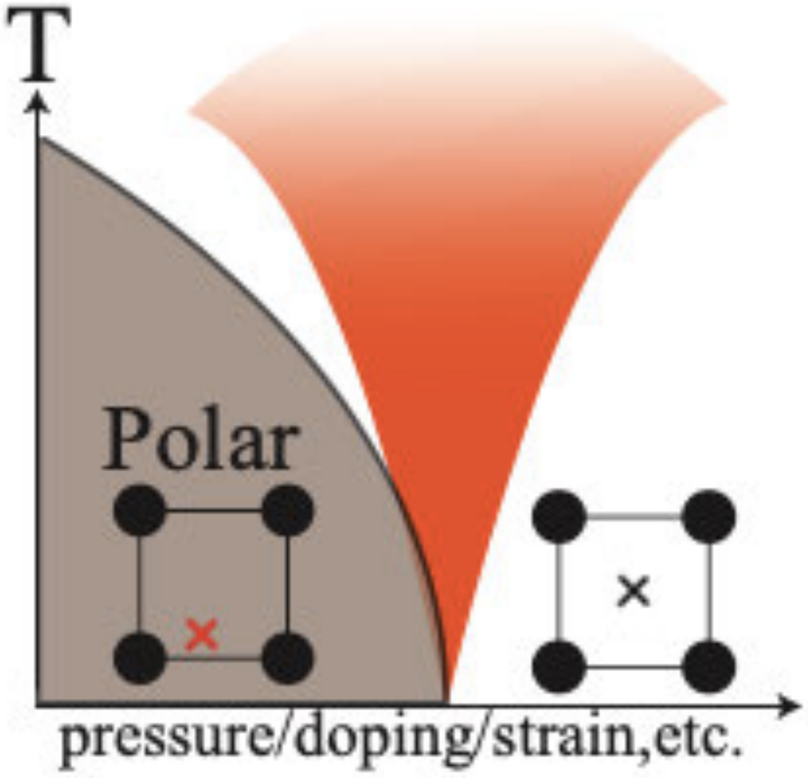
Strain/Pressure



Sakai *et al. Sci. Adv.* 2016;**2**:e1601378

Exotic Phases ??

Novel Quantum Critical Polar Metallic Phases ??



Can metals near polar quantum critical points host strongly correlated phases?

Can Polar Criticality Drive Dilute Superconductivity ??

Polar Quantum Critical Metals

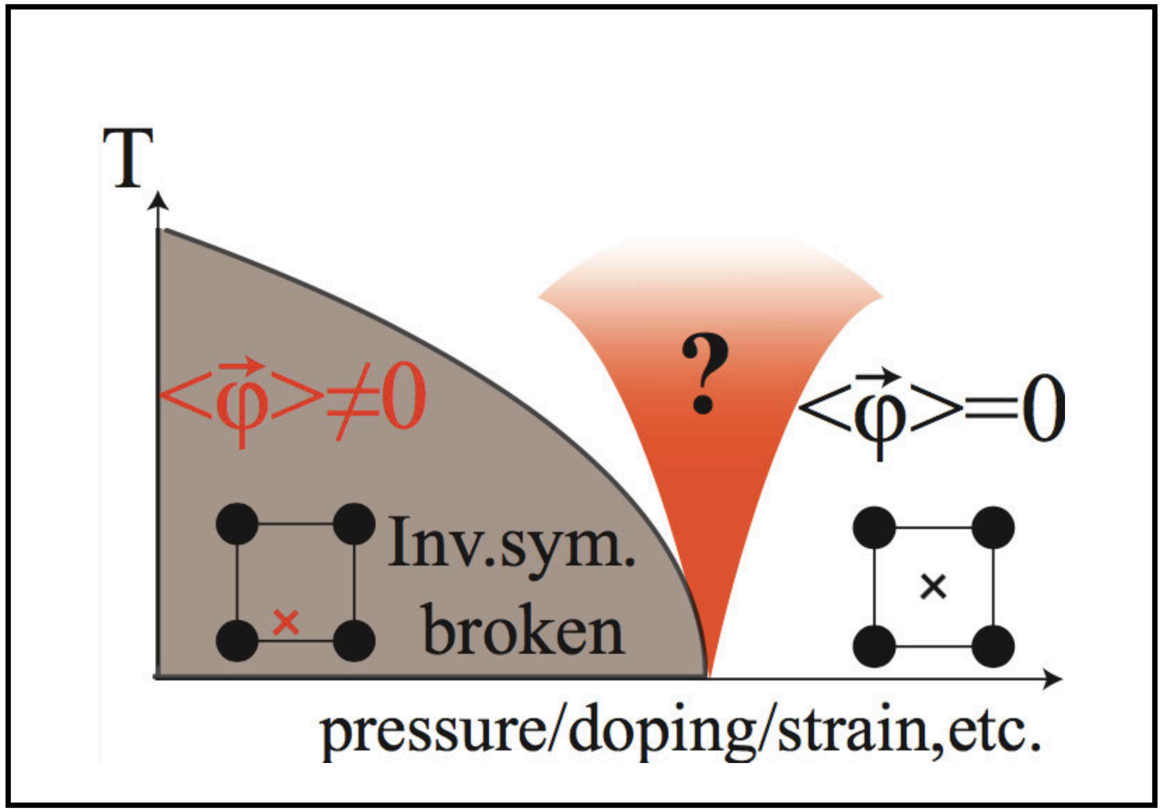
Critical Mode

Polar Optical Phonon

Breaks Inversion Symmetry

q = 0

No direct coupling to the charge density (without spin-orbit)



Usual Frohlich electron-phonon interaction

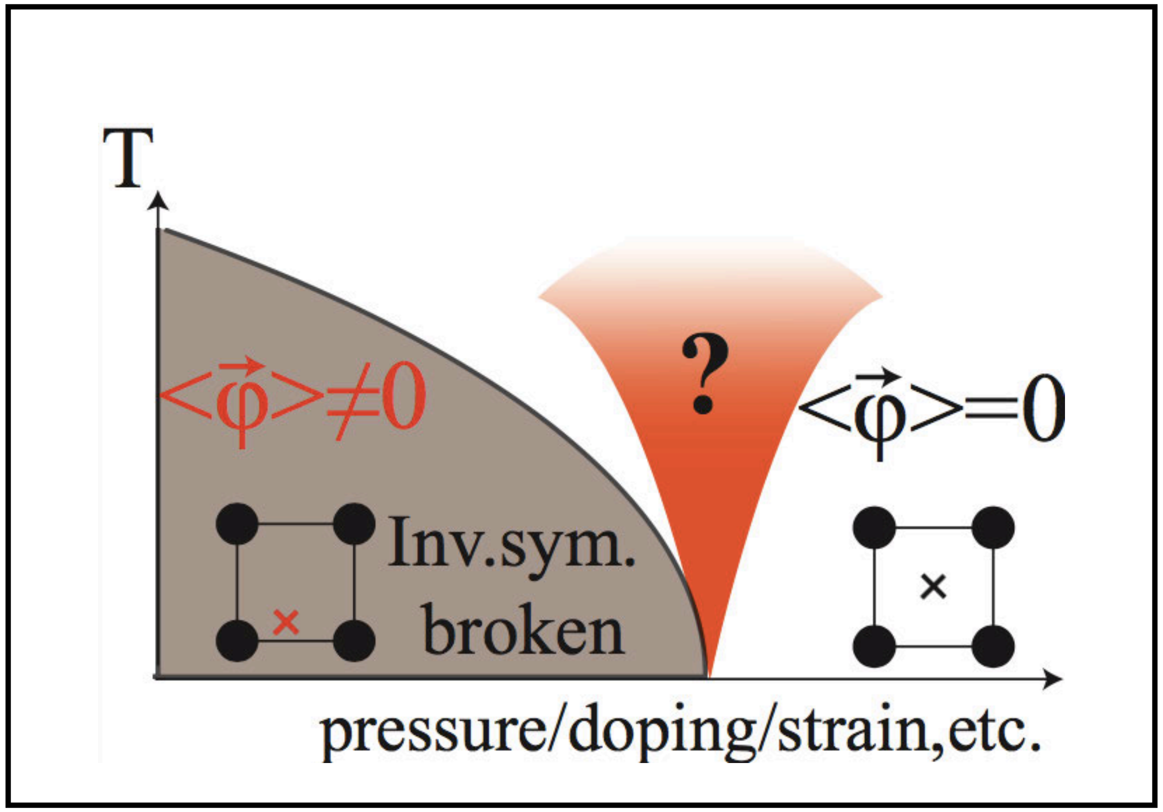
$$H_{e-ph} = \int d\mathbf{r}\ \nabla \cdot \tilde{\varphi}(\mathbf{r})\ \hat{\mathbf{n}}(\mathbf{r})$$

$$\lim_{q \to 0} \frac{|\nabla \vec{\varphi}|}{|\varphi|} \to 0$$

Irrelevant for the critical phonon!

Challenge: Strong Electronic Coupling to the Critical Polar Mode ?

Polar Quantum Critical Metals



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$$\lim_{q \to 0} \frac{|\nabla \vec{\varphi}|}{|\varphi|} \to 0$$

Irrelevant
for the
critical phonon!

Opportunity:

Setting to Study New Collective Electronic Behavior induced by Unconventional Lattice Dynamics

Challenge: Strong Electronic Coupling to the Critical Polar Mode ?

Coulomb Interactions
(in weak screening limit lead to LO/TO splitting)

Yukawa Coupling

$$H_Y = \lambda \int d\mathbf{r}\varphi(\mathbf{r})c^\dagger(\mathbf{r})c(\mathbf{r})$$

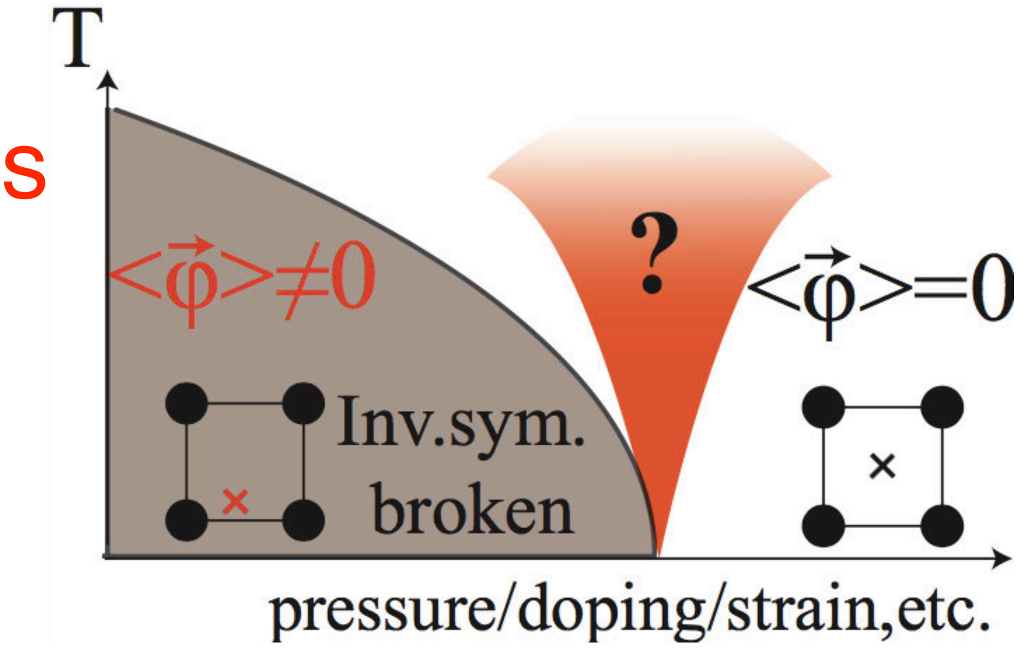
known to produce strong correlations for other QCPs

Is such a Yukawa-type coupling
possible near a Polar QCP ??

Yukawa Coupling to the Polar Mode

How do the electrons couple to an inversion symmetry-breaking field?

Wanted: Fermionic bilinear that breaks Inversion Symmetry (but not Time-Reversal Symmetry)



$$H_{coupling} = \lambda \int d\mathbf{k}\ \varphi(\mathbf{k})\ \hat{O}^i(\mathbf{k})$$

Single Conduction Band (without SOC)

$$\hat{O}(\mathbf{k}) = \hat{c}^\dagger_{\mathbf{k}} f_0(\mathbf{k}) \hat{c}_{\mathbf{k}} \qquad \mathcal{P}, \mathcal{T} \ \rightarrow \ f_0 \quad \text{even}$$

No ISB without TRSB !!

Yukawa Coupling to the Polar Mode

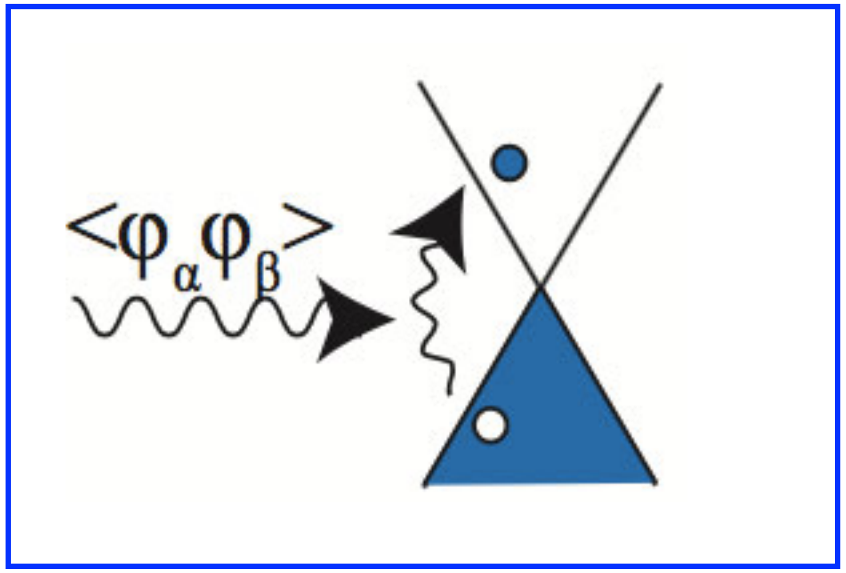
Polar Mode Couples to an Interband Bilinear
(no SOC required)

$$H^{(a)}_{coupl} = \lambda \sum_{i,\mathbf{q},\mathbf{k}} f^i_a(\mathbf{k}) \varphi^i_{\mathbf{q}} c^\dagger_{\mathbf{k}+\mathbf{q}/2} \sigma_1 c_{\mathbf{k}-\mathbf{q}/2},$$

$\mathcal{P} \sim \sigma_3$ (different parity bands)

$$H^{(b)}_{coupl} = \lambda \sum_{i,\mathbf{q},\mathbf{k}} f^i_b(\mathbf{k}) \varphi^i_{\mathbf{q}} c^\dagger_{\mathbf{k}+\mathbf{q}/2} \sigma_2 c_{\mathbf{k}-\mathbf{q}/2},$$

$\mathcal{P} \sim \sigma_0$ (same parity bands)



$f^i_{a(b)}(\mathbf{k})$ even (odd) $\mathbf{k}$

Yukawa Coupling to the Polar Mode: Physical Mechanism

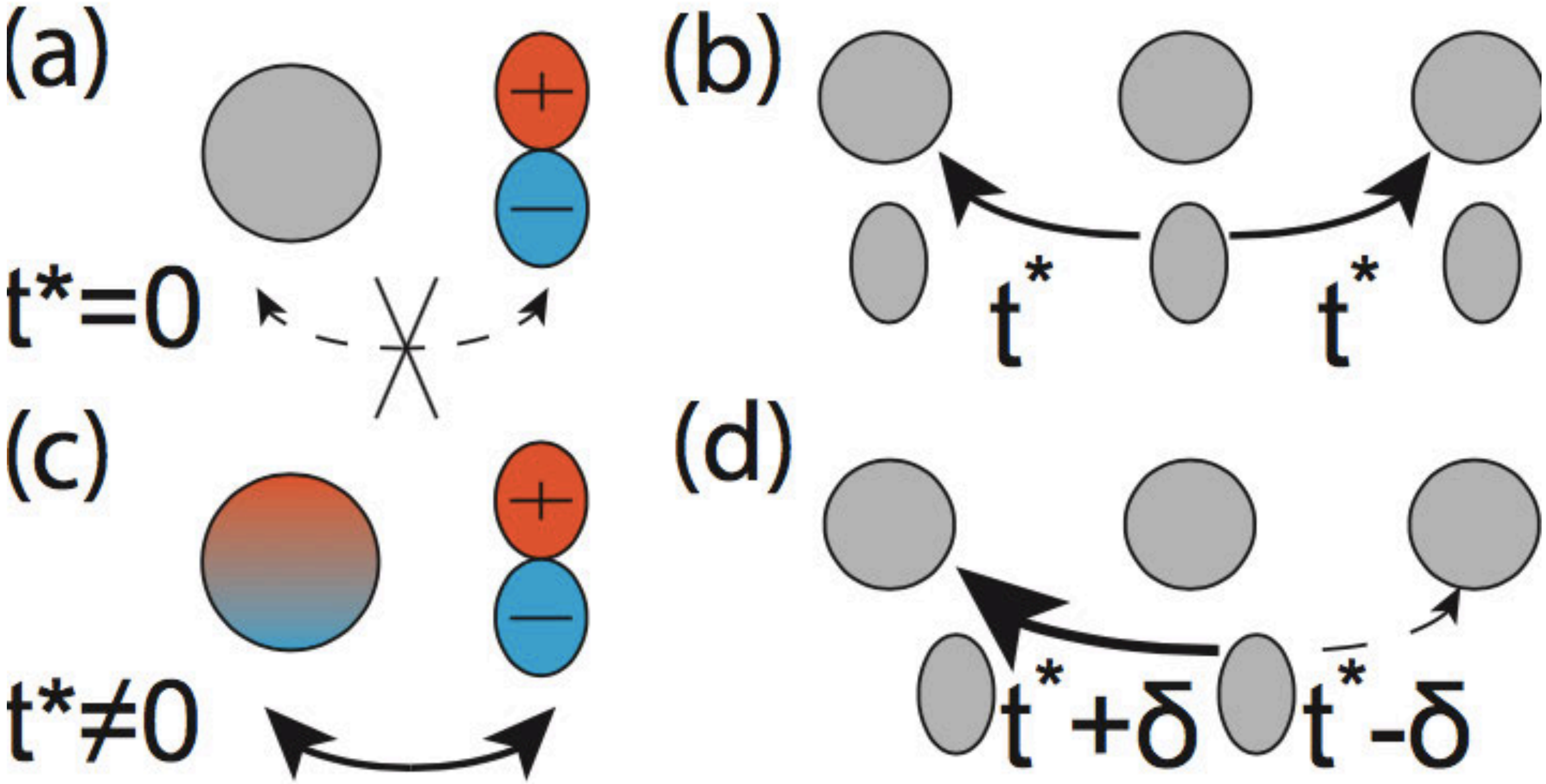
(assuming bands arise from two distinct orbitals)

Different Parity

Same Parity

$\varphi^i = 0$

$\varphi^i \neq 0$



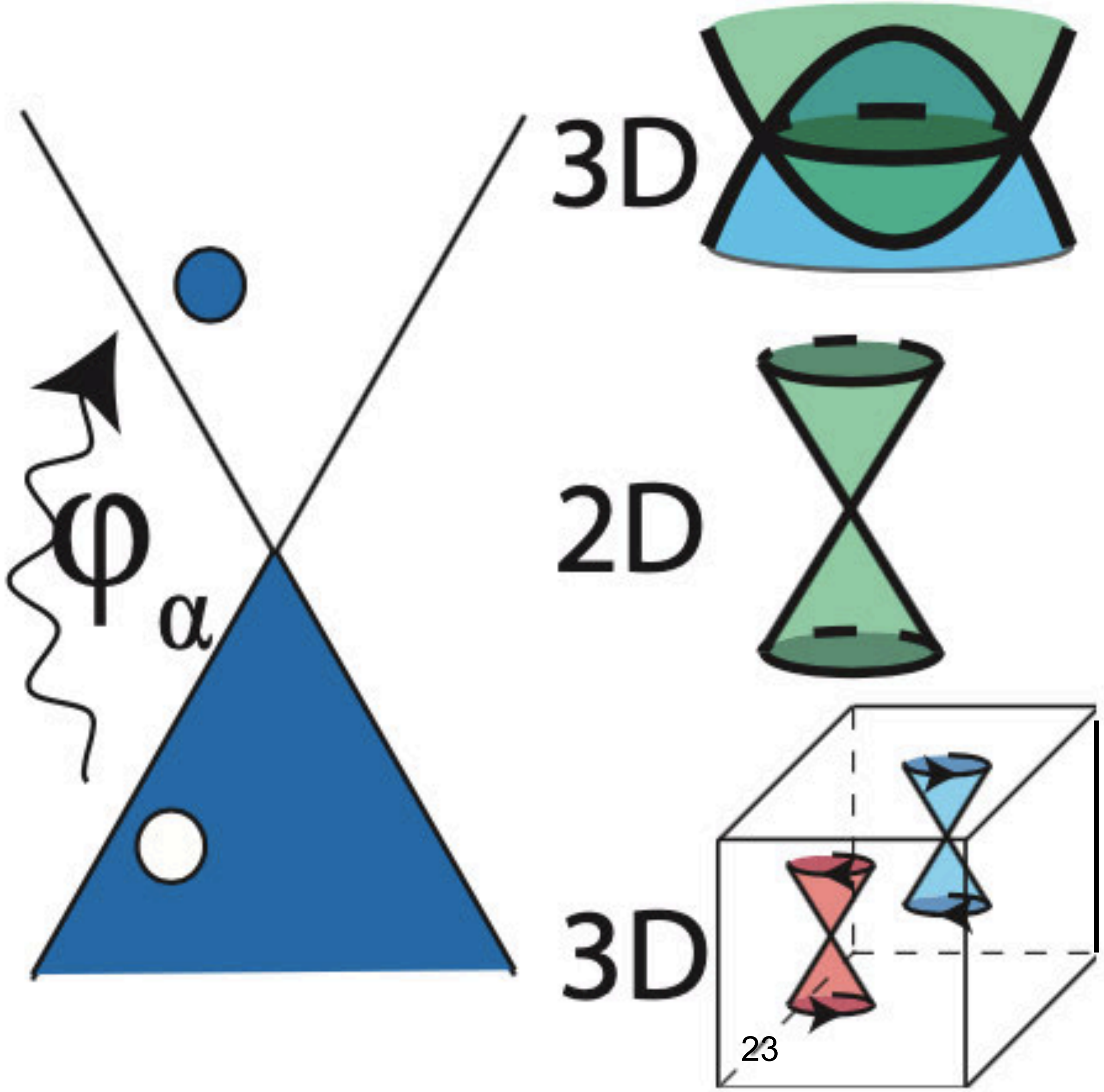
Interorbital Hopping Changes in Both Cases !!

Gapless Particle-Hole Excitations Needed to Drive Novel Metallic Behavior

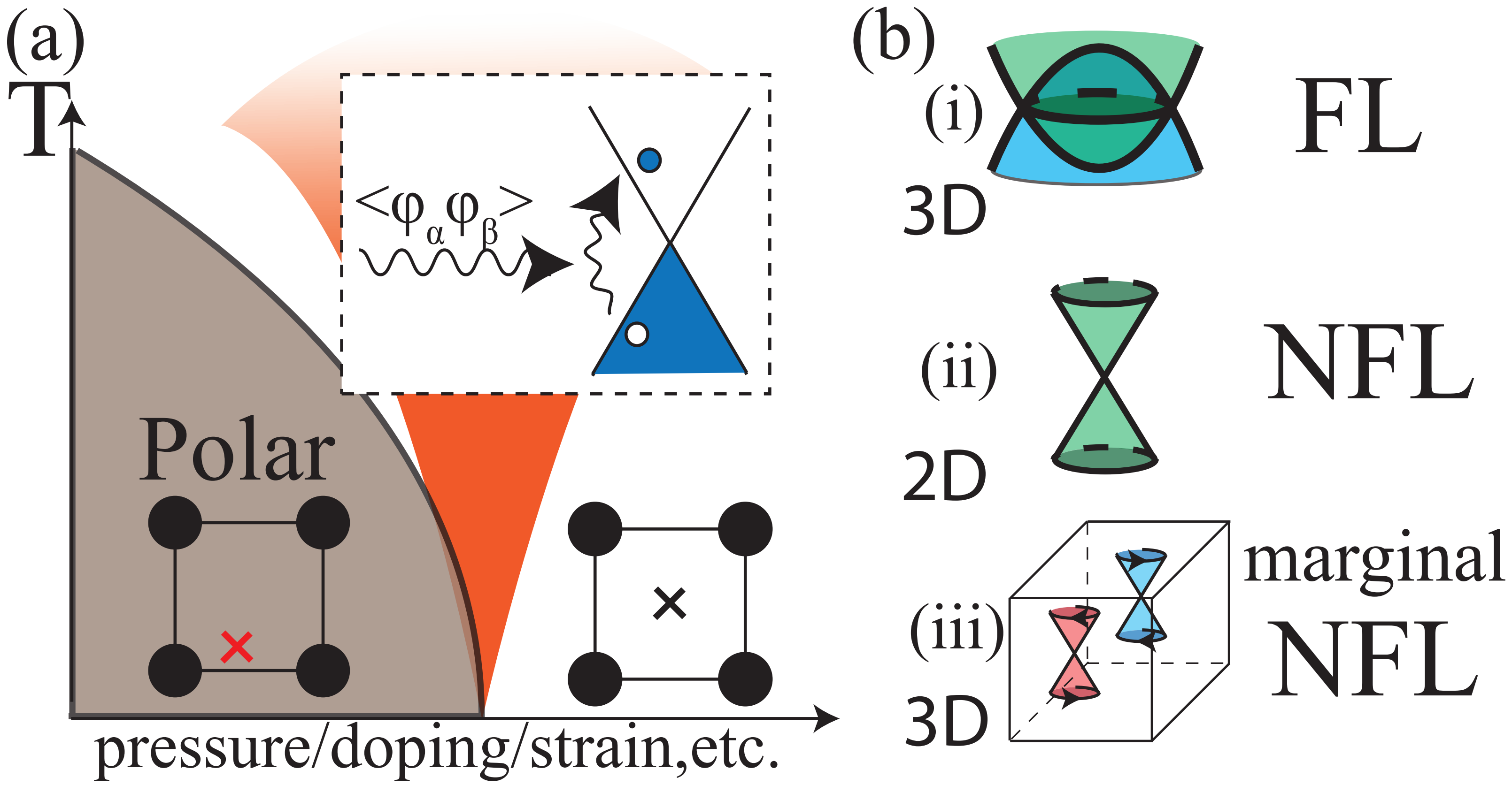
Order Parameter Couples to Interband Particle-Hole Excitations

Best Case Scenario:

Band Crossings
close to the Fermi Level



Can metals near polar quantum critical points host strongly correlated phases? ✓



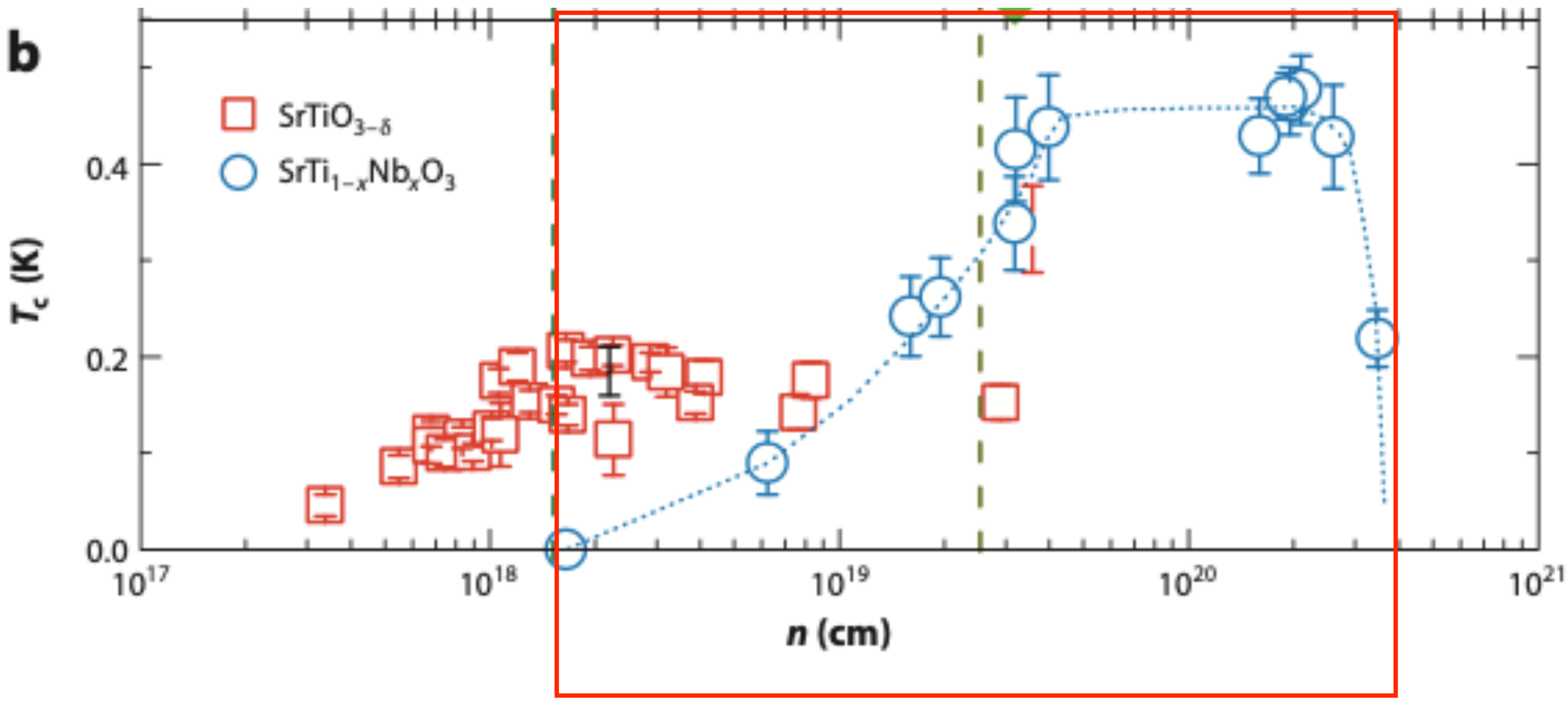
Unconventional Phonon Spectrum ($LiOsO_3$)

Anisotropy induced by Coulomb interactions

Logarithmic NFL Corrections

What about Superconductivity ??

An Old Tale of Unconventional Superconductivity that Remains a Mystery



$$T_F \sim 13K$$

$$T_F \ll T_D$$

$$T_D \sim 400K$$

Slow Electrons and Fast Phonons !

$$\left(\frac{2\Delta}{T_c} \approx 3.5\right) \qquad (E_F << \omega_{LO})$$

C. Collignon, X. Lin, C.W. Richau, B. Fauque and K. Behnia, Ann. Rev. Cond. Mat. Phys. 1025 (2019).

Superconductivity in Dilute QC Polar Metals

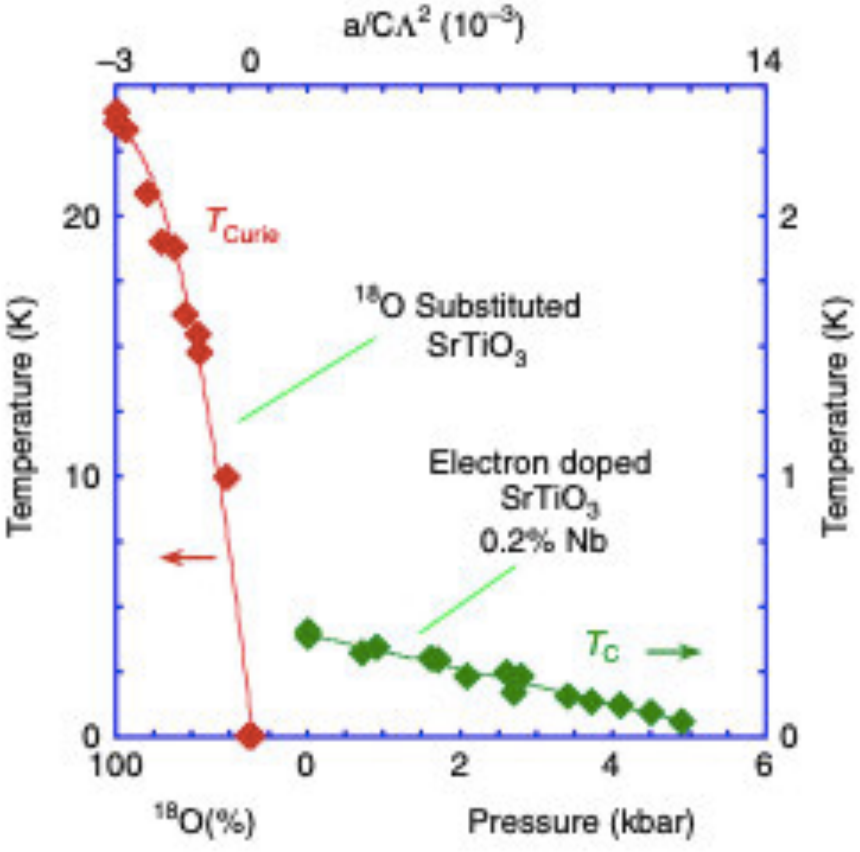
Challenges:

How to Overcome Coulomb Repulsion ??

No retardation

Isotropic (s-wave)

T_c Increases with Proximity to Polar QCP !!



Enderlein et al. Nat. Comm. (2020)

Critical Mode = Transverse Optical Phonon

Negligible Direct Coupling between Electrons and Soft Mode (unless there is spin-orbit coupling)

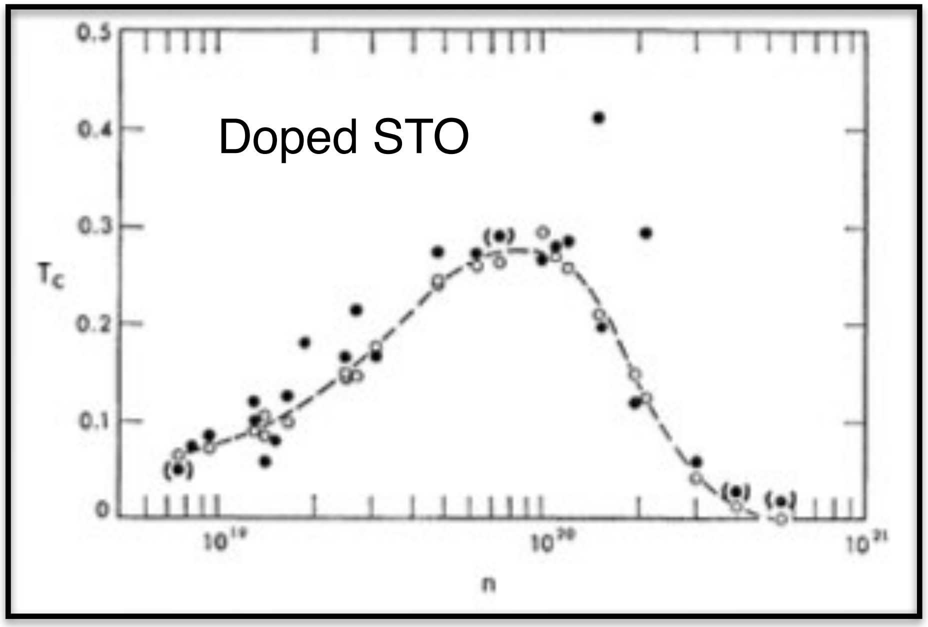
Can Polar Criticality Drive Dilute Superconductivity ??

Superconductivity in Dilute QC Polar Metals: Context

Extension of conventional BCS

- Multivalley
- Plasmons
- Two-Phonon Processes

$$\mathcal{S}^{2ph} = \sum_{\mathbf{kq}} g_{2ph}\ c^{\dagger}_{s,\mathbf{k+q}} c_{s,\mathbf{k}}\ \mathbf{u}^{2}_{\mathbf{q}}$$



Koonce et al., PR (1967)

Quantum criticality important

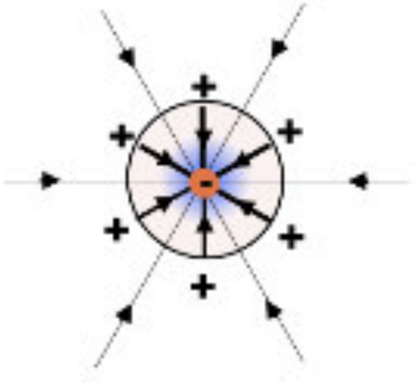
- Multiband Effects
- Spin-Orbit Coupling

$$\mathcal{S}^{2ph} = \sum_{\mathbf{kq}} g_{SOC} \left[c^{\dagger}_{s,\mathbf{k}+\frac{\mathbf{q}}{2}} (\mathbf{k} \times \sigma_{ss'}) c_{s',\mathbf{k}-\frac{\mathbf{q}}{2}} \right] \cdot \mathbf{u}_{\mathbf{q}}$$

M.N. Gastiasoro, J. Ruhman and R. M Fernandes, Annals of Physics 417, 168107 (2020)

Guiding Observations

Strong Ionic Screening ⟶ Weak Coulomb Interaction between Electrons



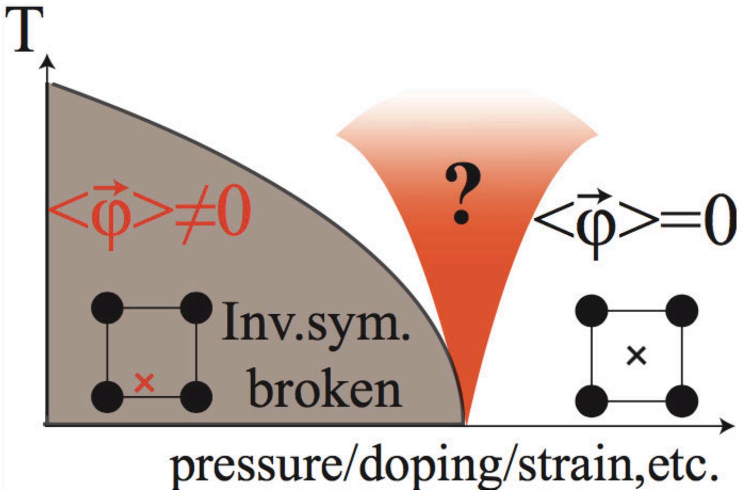
Dielectric Constant Very Large
Near Polar QCP

Critical mode = inversion symmetry-breaking transverse optical phonon

↓

No linear coupling to the charge density.

(Assumption: Negligible Spin-Orbit Coupling)



Electrons do not directly interact with zero-point fluctuations

Electrons Interact with the Energy Density of the Critical TO Phonons

Model for this Coupling

$$H_{\rm En} = g \int d^3x \; \rho_e(\mathbf{x})(\vec{P}(\mathbf{x}))^2$$

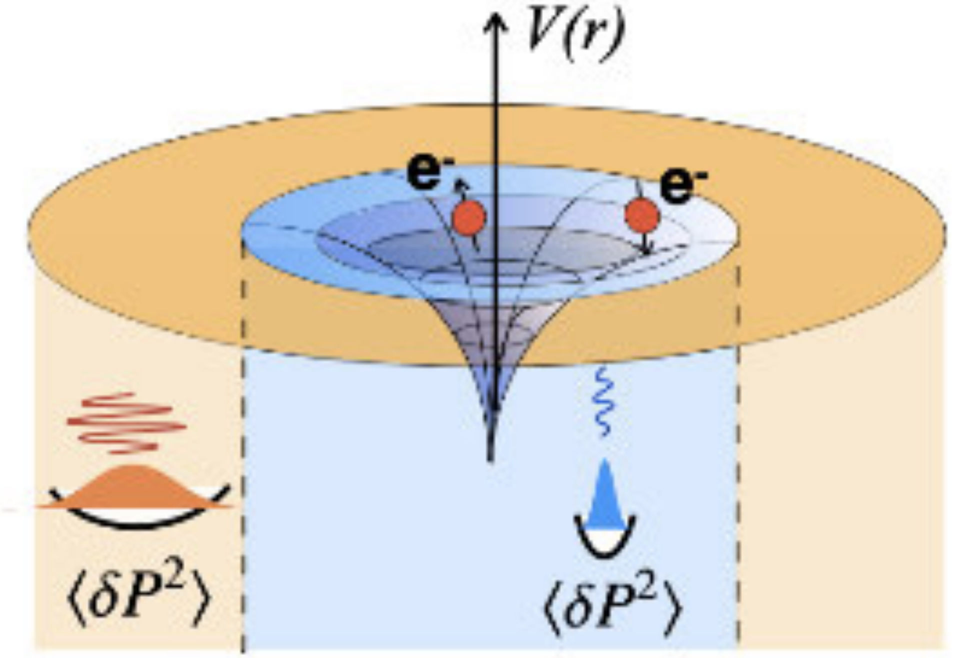
coupling constant

$$[g] = V$$

local electron density

$$\psi^\dagger(\mathbf{x})\psi(x)$$

proportional to energy density of the local polarization



Suppression of the zero-point fluctuations of the critical phonons near the electrons

Reduction of chemical potential of nearby electrons

Fluctuations of the critical phonon energy density near the electrons result in an attractive potential

Weak vs. Strong Coupling ?

Coulomb/Kinetic Energy

$$r_s = 1/(k_F a_B)$$

$$k_F \sim n^{\frac{1}{3}}$$

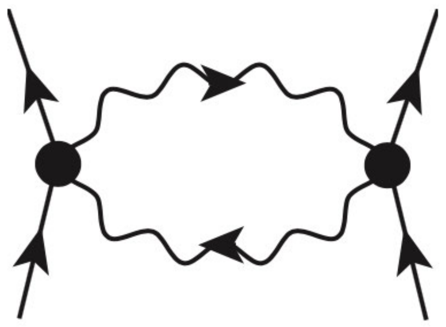
Dilute Quantum Critical Polar Metals

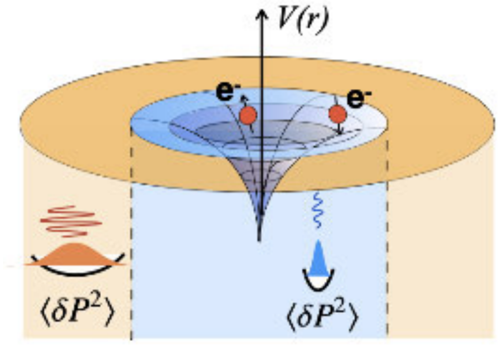
$$a_B = \frac{4\pi\varepsilon\hbar^2}{m^* e^2}$$

$$\varepsilon \sim \varepsilon(\vec{q},\omega)|_{q=2k_F,\omega=E_F} \approx \frac{\Omega_0^2}{(2c_s k_F)^2} \gg 1$$

$r_s << 1$ Weakly Interacting !!

To lowest order, virtual exchange of critical phonon pairs





Electron-electron interaction
from two-phonon exchange

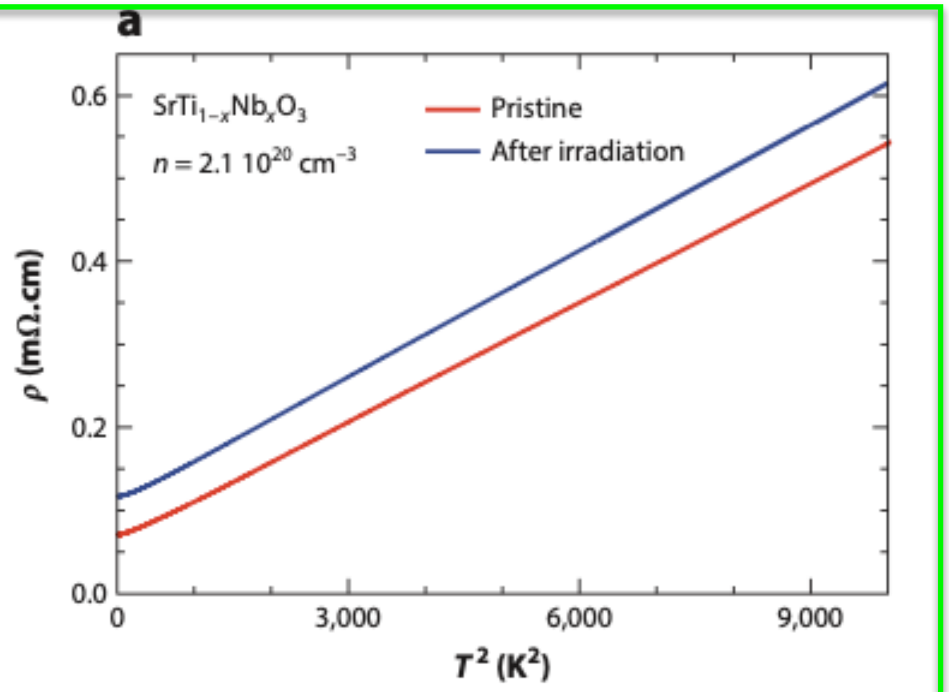
Attractive Potential

Link with prior work: Two-phonon exchange

Important in describing anomalous high temperature transport in polar metals

$\rho \propto T^2$ $T >> T_F$ A. Kumar et al. PRL (2021)

Proposed as a mechanism for superconductivity



Collignon et al. (2019)

D. van der Marel et al. PRB (2011)

K.L. Ngai, PRL (1974)
D. van der Marel et al. PRR (2019)

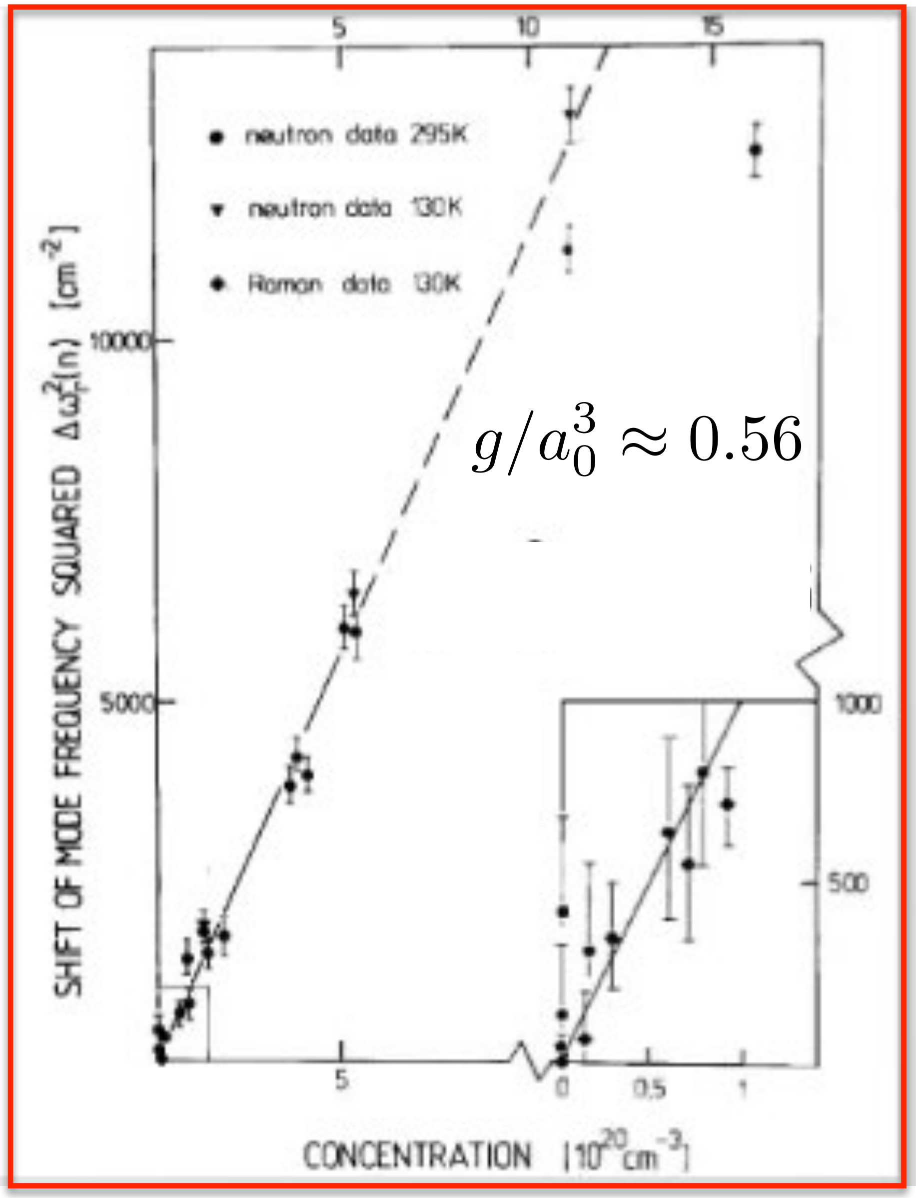
Dilute Quantum Critical Polar Metals ??

Coupling to Energy Fluctuations (g finite)

Finite Electron

$$n = \langle \rho_e(x) \rangle \longrightarrow \omega_T^2(n) = \omega_{T0}^2 + gn\varepsilon_0\Omega_0^2$$

Suppression of Polar State
by Charge Doping



$g/a_0^3 \approx 0.56$

Bauerle et al.
(1980)

Consistent with
Observation

Coupling to Energy Fluctuations (g finite)

Finite Electron Density

$$n = \langle \rho_e(x) \rangle \longrightarrow \omega_T^2(n) = \omega_{T0}^2 + g n \varepsilon_0 \Omega_0^2$$

Suppression of Polar State
by Charge Doping

Shift of the Quantum Critical Point

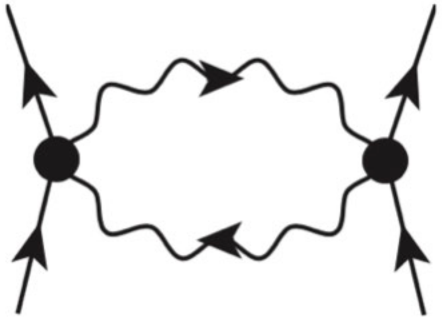
Energy Fluctuation Coupling Cannot be Integrated Out Exactly

✓ Stability of Fermi Liquid

Perturbative Effects (Weak Coupling)

Effective Electron-Electron Interaction

$$V_{En}^{Pair}(x) \sim -g^2[D_T(x)]^2 \sim -\frac{g^2}{x^4}$$



Quantum Critical Point (QCP)

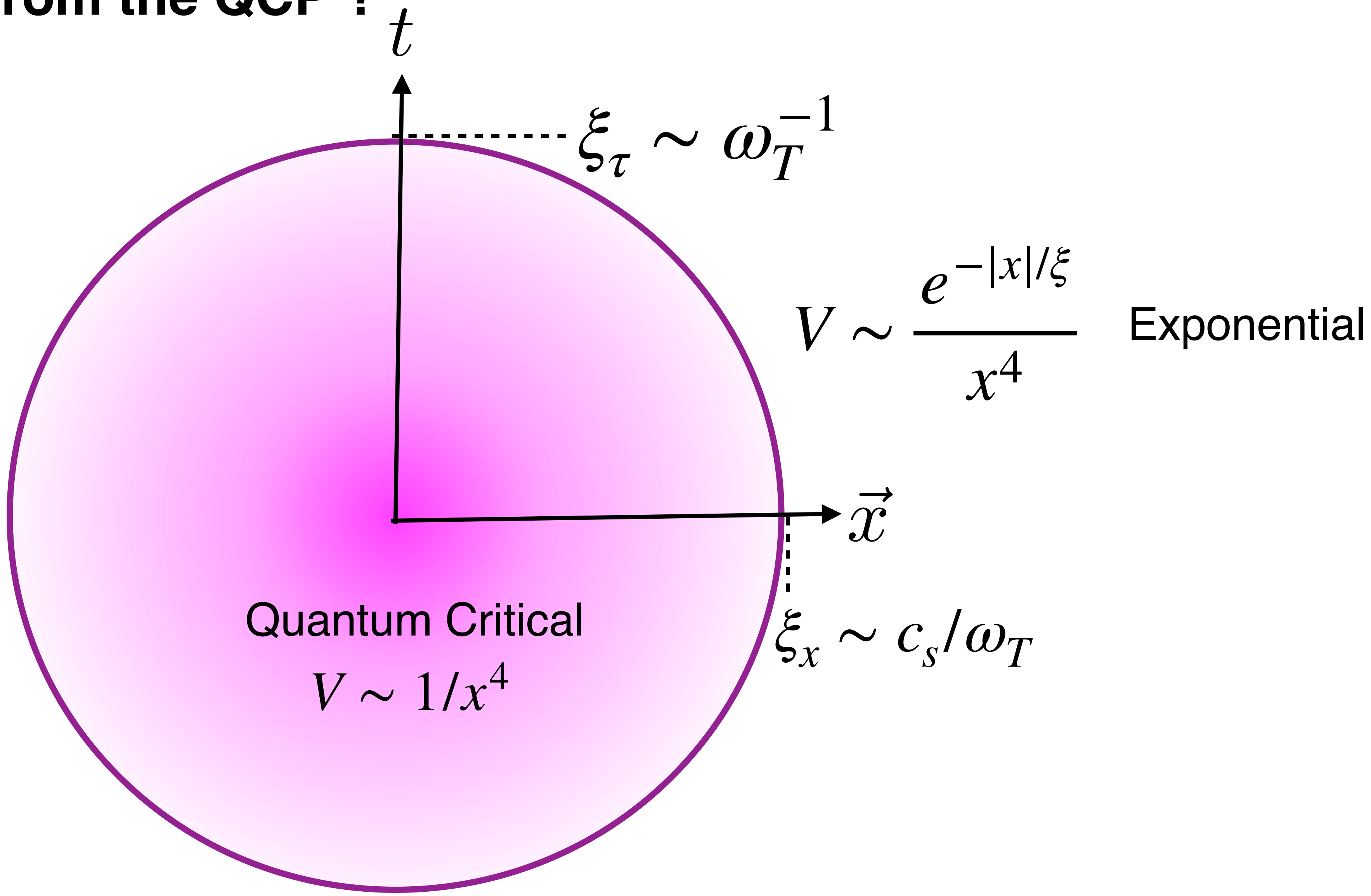
$$(\omega_T(n) = 0)$$

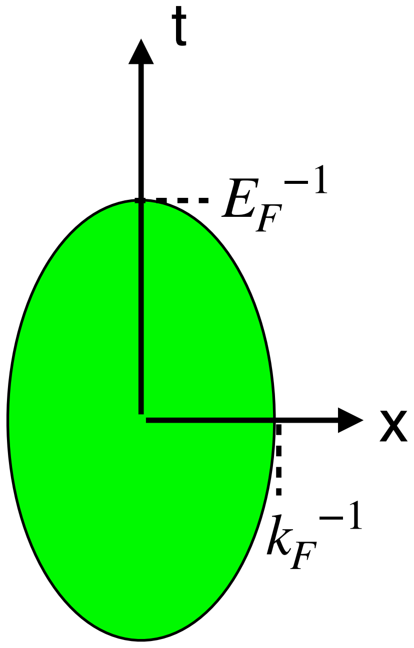
$$x^2 = \vec{x}^2 + c^2\tau^2$$

Effective Electron-Electron Interaction

$$V_{En}^{Pair}(x) \sim -g^2[D_T(x)]^2 \sim -\frac{g^2}{x^4}$$ QCP

Away from the QCP ?





What do the electrons sample ??

Important Scales $(\underset{\overset{\downarrow}{n^{-\frac{1}{3}}}}{k_F^{-1}}, \underset{\overset{\downarrow}{n^{-\frac{2}{3}}}}{E_F^{-1}})$

$(a)\quad \frac{1}{k_F}, \frac{1}{E_F} << \xi$

Quantum Critical in Space and Time
(High Density)

$$V \sim \frac{1}{x^4}$$

$(b)\quad \frac{1}{k_F} << \xi << \frac{1}{E_F}$

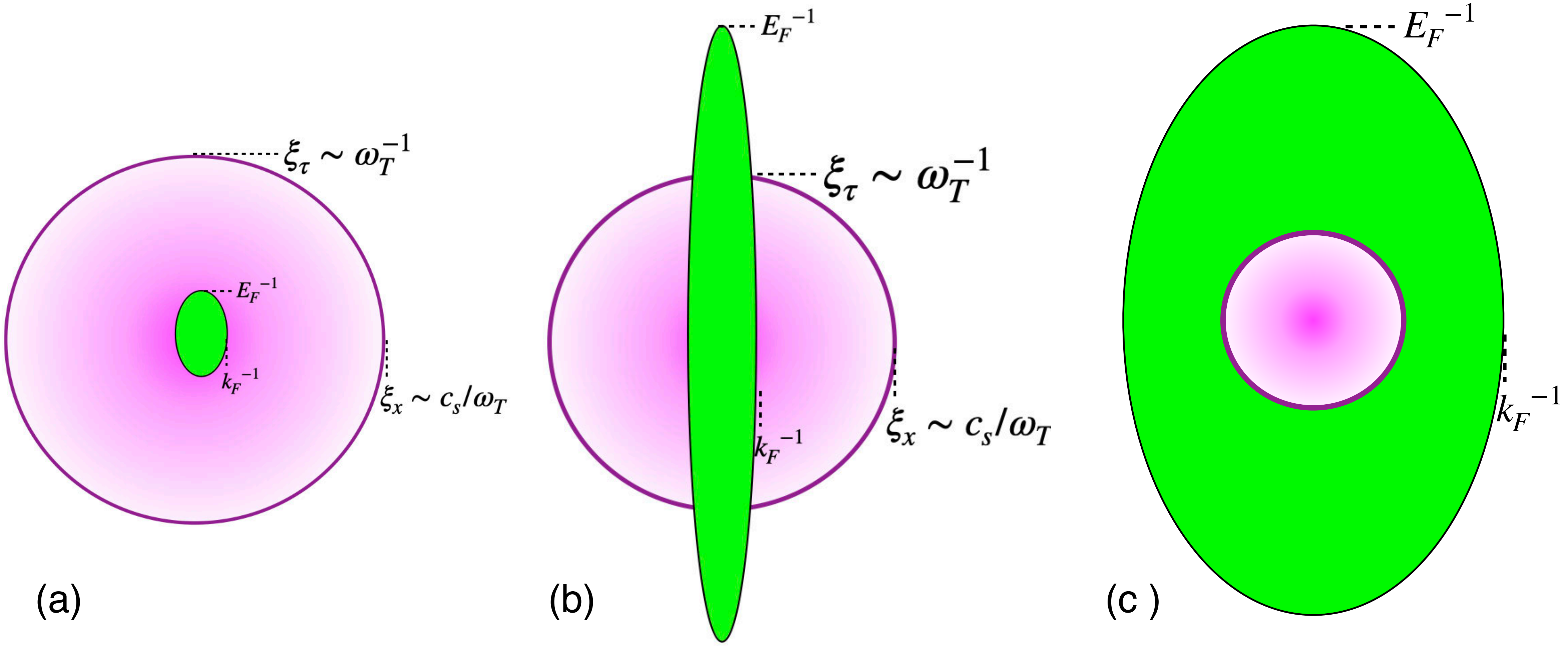
Quantum Critical in Space
Local in Time
(Low Density)

$$V \sim \frac{\delta(\tau)}{|\vec{x}|^3}$$

$(c)\quad \xi << \frac{1}{k_F}, \frac{1}{E_F}$

Local in Space and Time
(Ultralow Density)

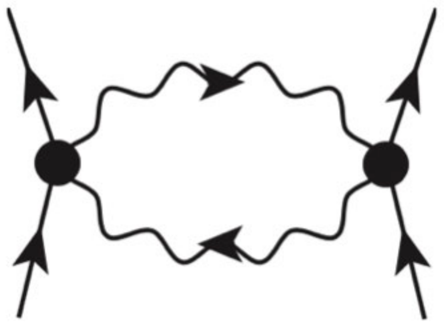
$$V \sim \delta^4(x)$$



(a) (b) (c)

Effective Electron-Electron Interaction

$$V_{En}^{Pair}(x) \sim -g^2[D_T(x)]^2 \sim -\frac{g^2}{x^4}$$



Quantum Critical Point (Q.C.P.)

$$(\omega_T(n) = 0)$$

$$x^2 = \vec{x}^2 + c^2\tau^2$$

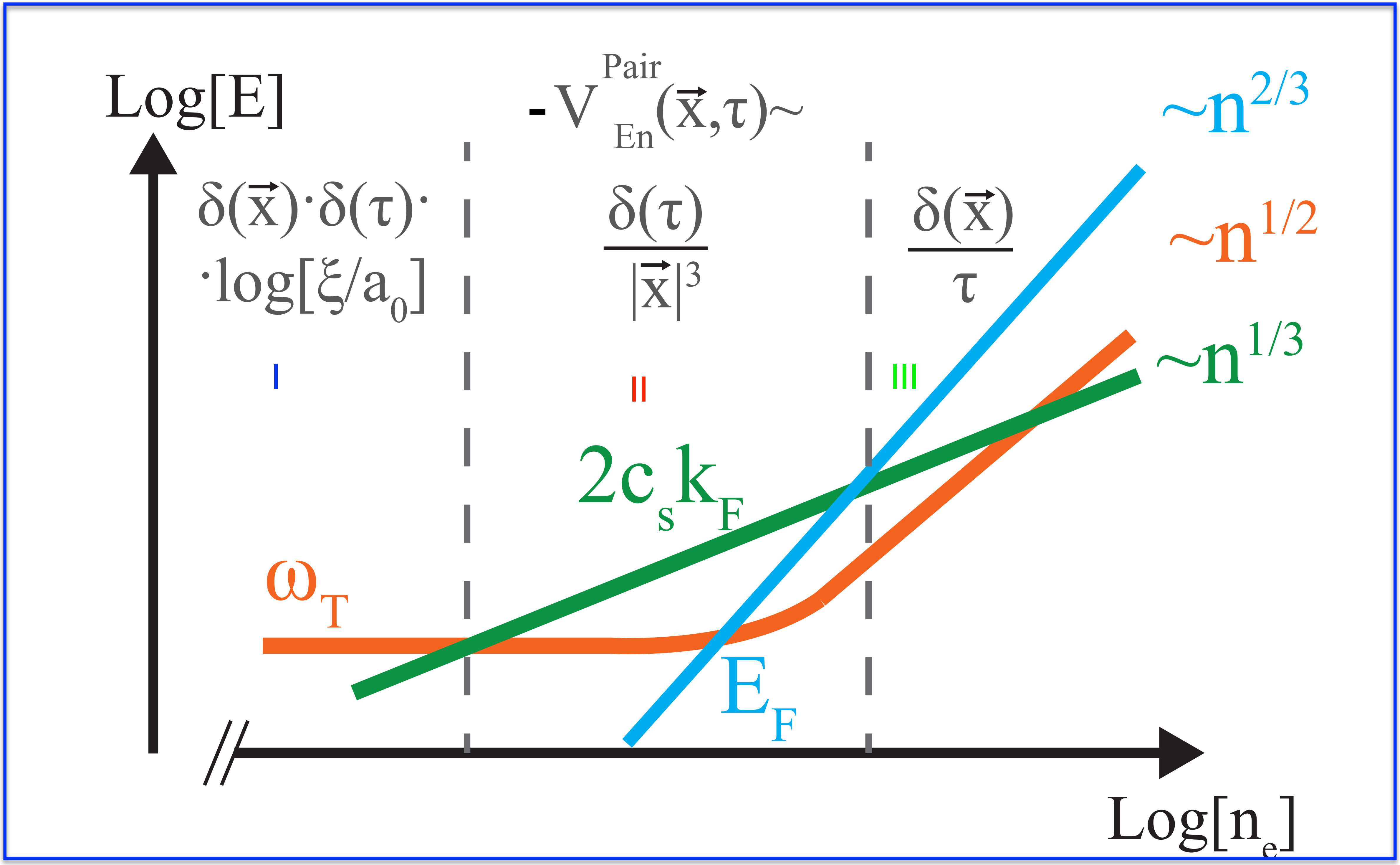
Interaction relevant for electron pairing

$$\langle V(k-k')\rangle = \langle V(k_F,\theta)\rangle_\theta \sim -\frac{g^2}{{c_s}^3}\log\left[\frac{\Omega_T}{\max\ (\omega_T, c_s k_F, E_F)}\right]$$

$\Omega_T = \max_{\vec{q}}\ \omega_T(\vec{q})$ cutoff

large momenta contribute

Density-Dependence of the Effective Attraction



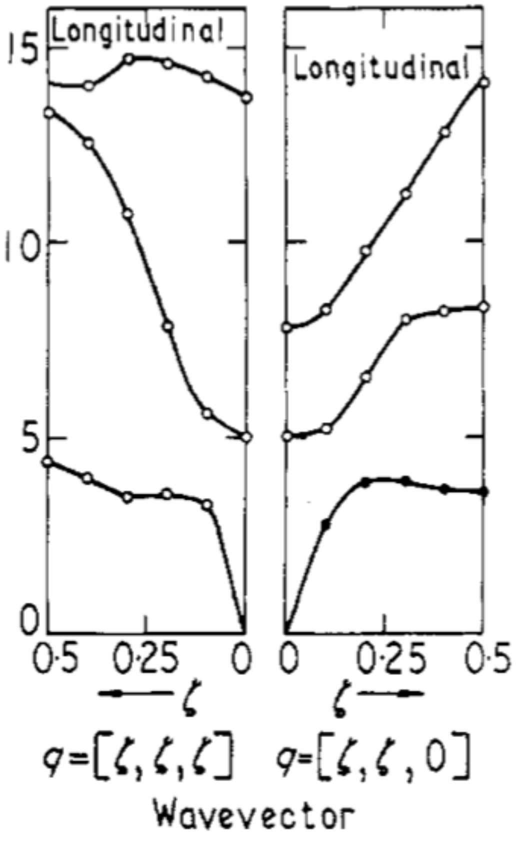
I $\quad$ **No** $q-$dependence, **No** $\omega-$dependence (Kiselov and Feigel'man, PRB (2021))

II $\quad$ **No** $\omega-$dependence ← Our Work

III $\quad$ **No** $q-$dependence

Superconductivity

For low carrier density close to the polar QCP, the attractive electron-electron interaction will overcome Coulomb repulsion leading to superconductivity.



Stirling (1972)

$$\left(\bar{c}_s = \frac{\Omega_T}{((6\pi^2)^{\frac{1}{3}}/a_0)}\right)$$

Attractive part of the effective electron coupling

$$\lambda_{\text{att}} \sim k_F \left[\log\left(\frac{\Omega_T}{2c_s k_F}\right) + 1\right]$$

$$n_{max} = \frac{1}{3\pi^2}\left(\frac{\Omega_T}{2c_s}\right)^3 \approx \frac{(\bar{c}_s/c_s)^3}{4a_0^3}$$

Independent of the coupling constant g

Phonon Dispersion Flattens near BZ edge $\bar{c}_s < c_s$

$$\longrightarrow$$

$$n_{max}a_0^3 << 1$$

Superconductivity

For low carrier density close to the polar QCP, the attractive electron-electron interaction will overcome Coulomb repulsion leading to superconductivity.

$$\lambda \sim k_F \left\{ \left[\log\left(\frac{\Omega_T}{2c_s k_F} \right) + 1 \right] - \frac{C}{\epsilon_0} \right\}$$

Attractive e-e interaction

Coulomb repulsion

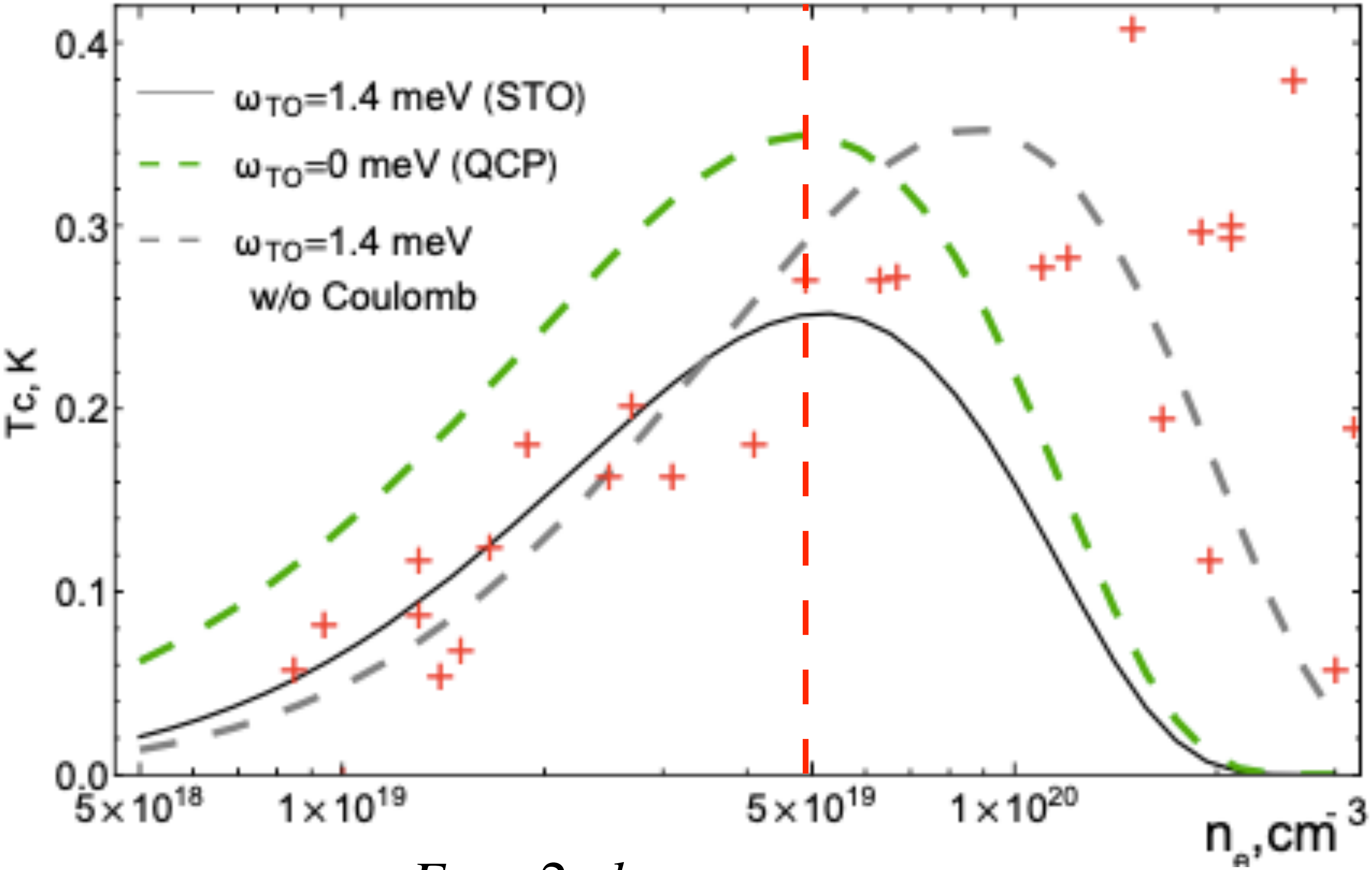
$$T_c \propto E_F \; e^{-\frac{1}{\lambda}} \qquad \left(\frac{2\Delta}{T_c} \right) = 3.5$$

Gorkov and Melik-Barkhudarov (1961)
Gorkov (2016)

T_c has dome-behavior as a function of the carrier density n

Superconductivity in Doped $\mathrm{SrTiO_3}$

$$g/a_0^3 = .68$$



$$E_F < 2c_s k_F$$

Dynamical Effects Must be Included !!

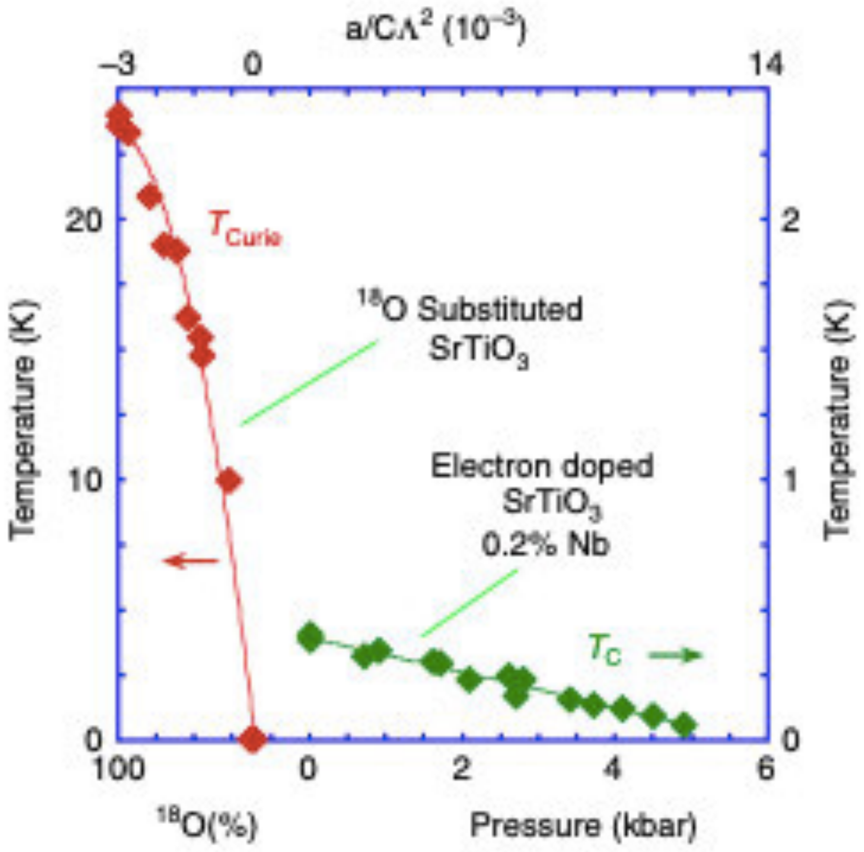
Superconductivity in Doped $SrTiO_3$

✓

$$\frac{2\Delta}{T_c} = 3.53$$

STM Measurements

Hwang et al. (2018)



Enderlein et al. Nat. Comm. (2020)

$$E_F \rightarrow \lambda \approx 0.25$$

$$\downarrow$$

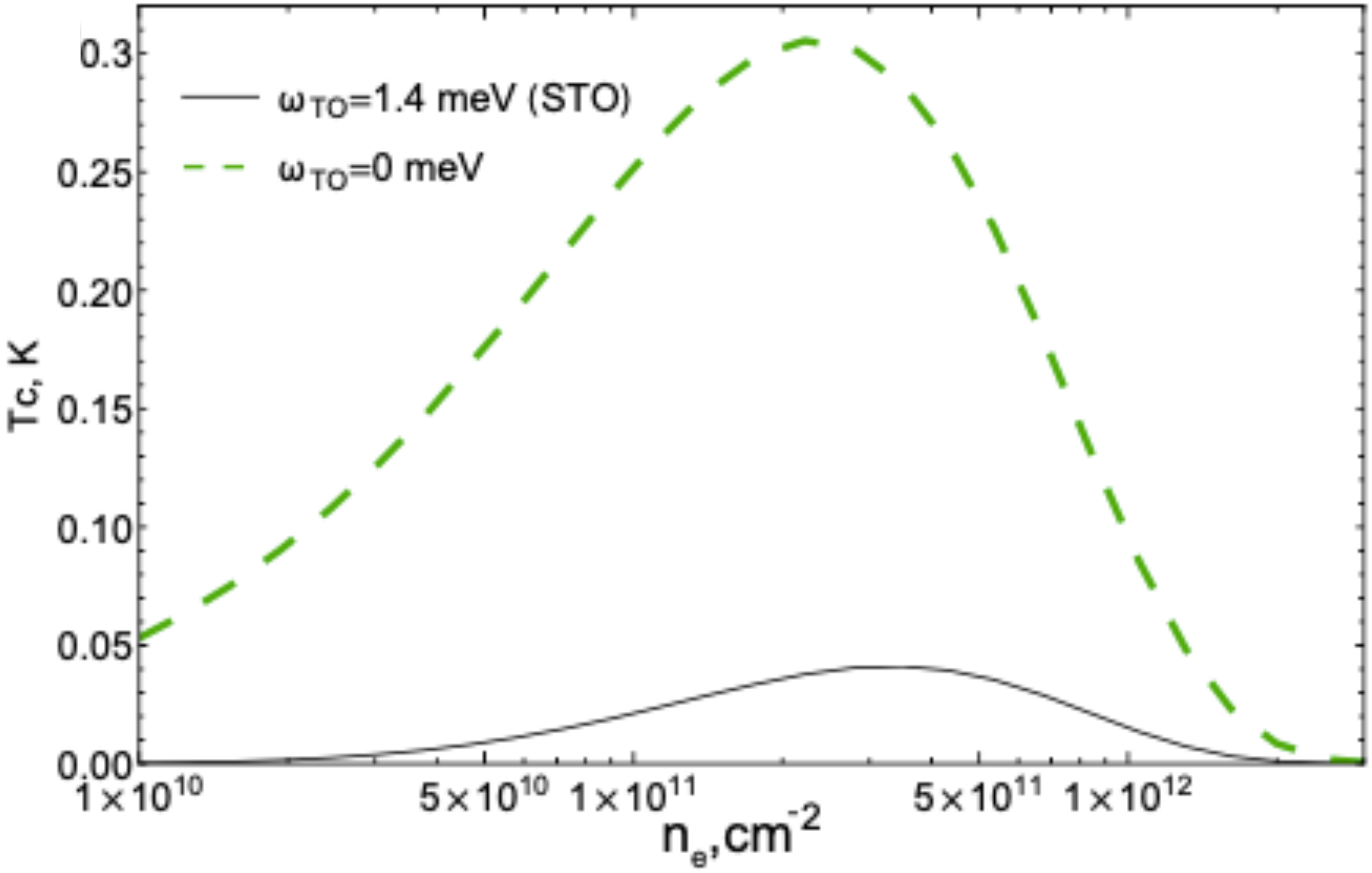
$$\frac{dT_c}{dP} \approx 0.1K/\text{kbar}$$

Experimental Value ☺

✓

$$\frac{dT_c}{dP} = 0.06K/\text{kbar}$$

Superconductivity in Doped 2D $SrTiO_3$



Proximity to QCP leads to
stronger enhancement
than in 3D

Distinguishing Features of the Energy Fluctuation Mechanism

$\rho \propto T^2$ Dominant Coupling to Energy Fluctuations

$\omega_T^2(n_e) - \omega_{TO}^2 \propto g n_e$ Suppression of Polar State with Doping

$0.5 < g/a_0^3 < 0.7$ (n-doped STO) ✓

Unified Approach to Different Properties

Scaling of T_c with phonon frequency and sensitivity to carrier density at low doping concentrations

Normal State near the Polar QCP = Fermi liquid

Distinguishing Features of the Energy Fluctuation Mechanism

$\rho \propto T^2$ Dominant Coupling to Energy Fluctuations

$\omega_T^2(n_e) - \omega_{TO}^2 \propto g n_e$ Suppression of Polar State with Doping

$0.5 < g/a_0^3 < 0.7$ (n-doped STO) ✓

Unified Approach to Different Properties

Take-Home Message: Unconventional Superconductivity can be Driven by Multiple Critical Transverse Phonons

New Channel for Superconductivity in Materials with Large Anharmonicity

Polar Quantum Criticality

Setting to Study Nontraditional Electron-Phonon Interactions

Novel Metallic Phases

Enigmatic Superconductivity Driven by Multiple Transverse Phonons

Future Directions

Mixed parity polar superconducting states?

Polarization Textures ?

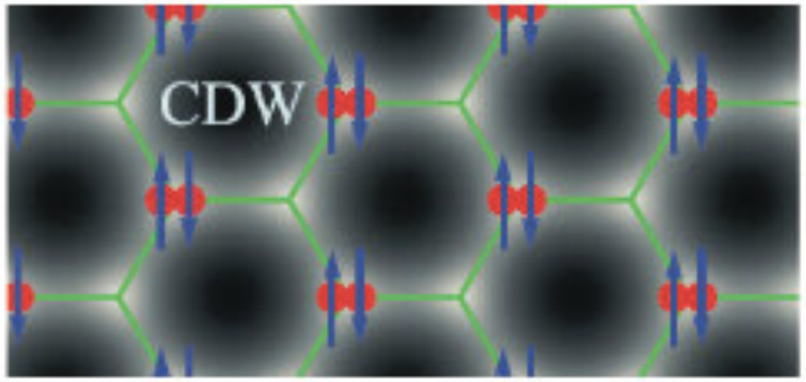
Light-Induced Dynamical Quantum Criticality ?

Please come and join in the good fun !!


thank you
danke
謝謝
teşekkür ederim
gracias
merci
obrigado
спасибо
dziękuję
go raibh maith agat
mochchakkeram
sukriya
kop khun krap
terima kasih
grazie
arigatō
dakujem
takk
bedankt
hvala
mauruuru
sagolun
tapadh leat
dank je
ngiyabonga
taiku
ευχαριστώ
мерси
감사합니다
ありがとう
Баярлалаа
рахмат
хвала
asante
mersi
tack
blagodaram
dankie
dhanyavad
kiitos
enkosi
sobodi
dekuji
mesi
najis tuke
rahmet
tanemirt
diolch
dhanyavadagalu
shukriya
trugarez
djere dieuf
paldies
misaotra
mahalo
ynaka
chnorakaloutioun
gracies
grazas
mamnun
welalin
köszönöm
gracie
taafetai lava
xiexie
nandri
kam sah hamnida

A Technical Flavor for the 2D Dirac Point Results

Example: CDW in graphene



No Coulomb Interactions:

Gross-Neveu-Yukawa Model

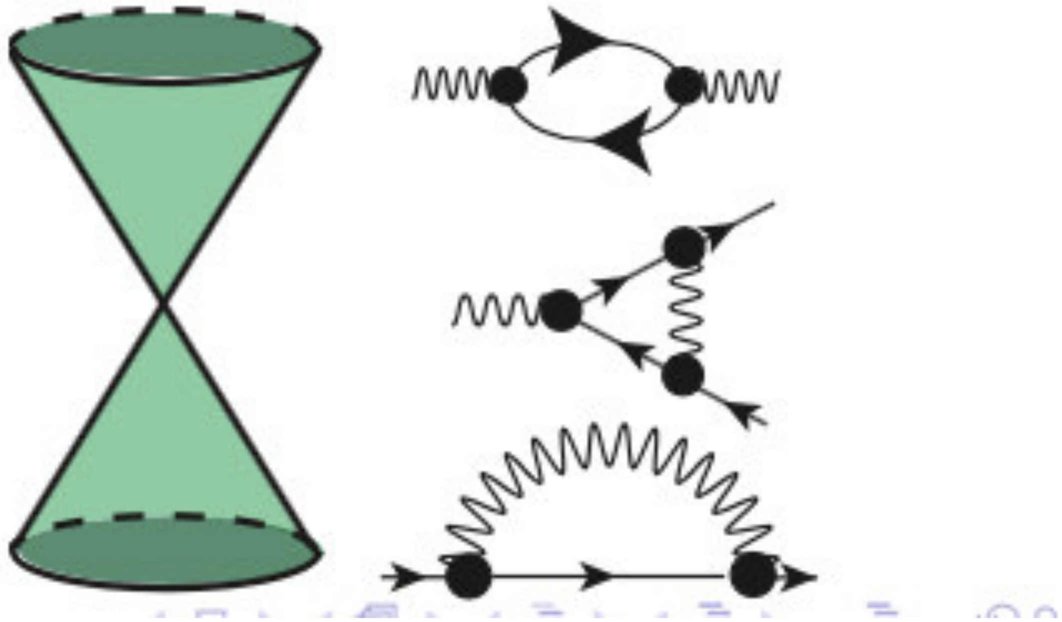
↓

NFL

$$H_{Dir} = v_F(k_x\sigma_x + k_y\sigma_y)$$

$$H_{coupl} = \lambda \sum_{\mathbf{q},\mathbf{k}} \varphi_{\mathbf{q}} c^{\dagger}_{\mathbf{k}+\mathbf{q}/2}\sigma_3 c_{\mathbf{k}-\mathbf{q}/2}$$

Emergent Lorentz invariance
z = 1

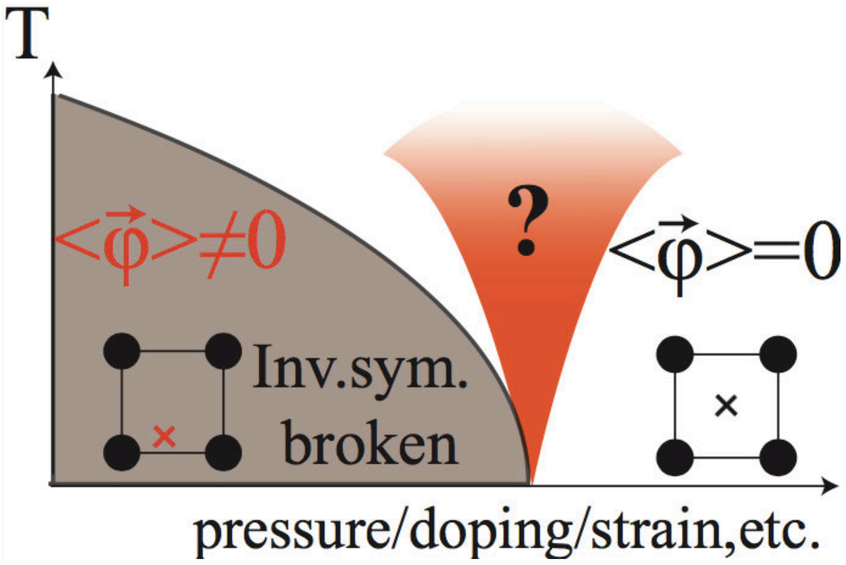


Renormalization of critical
phonon velocity $c_s \to v_F$

Mihaila et al. PRB 96, 165133 (2017); Lang and Lauchli PRL 123, 137602 (2019)

Yukawa Coupling to the Polar Mode

How do the electrons couple to an inversion symmetry-breaking field?



Wanted: Fermionic bilinear that breaks Inversion Symmetry
(but not Time-Reversal Symmetry)

$$H_{coupling} = \lambda \int d\mathbf{k}\ \varphi(\mathbf{k})\ \hat{O}^i(\mathbf{k})$$

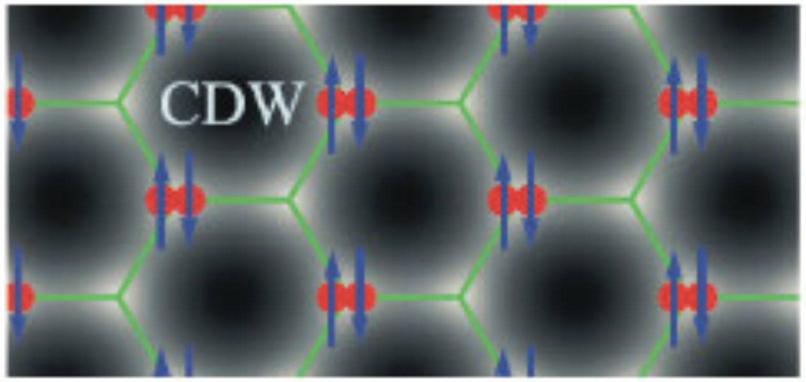
Single Conduction Band (without SOC)

$$\hat{O}(\mathbf{k}) = \hat{c}^\dagger_{\mathbf{k}} f_0(\mathbf{k}) \hat{c}_{\mathbf{k}} \qquad \mathcal{P}, \mathcal{T} \ \rightarrow \ f_0 \quad \text{even}$$

No ISB without TRSB !!

A Technical Flavor for the 2D Dirac Point Results

Example: CDW in graphene



Include Coulomb Interactions:

$$[q_x] = [\omega, q_y]^{3/2}$$

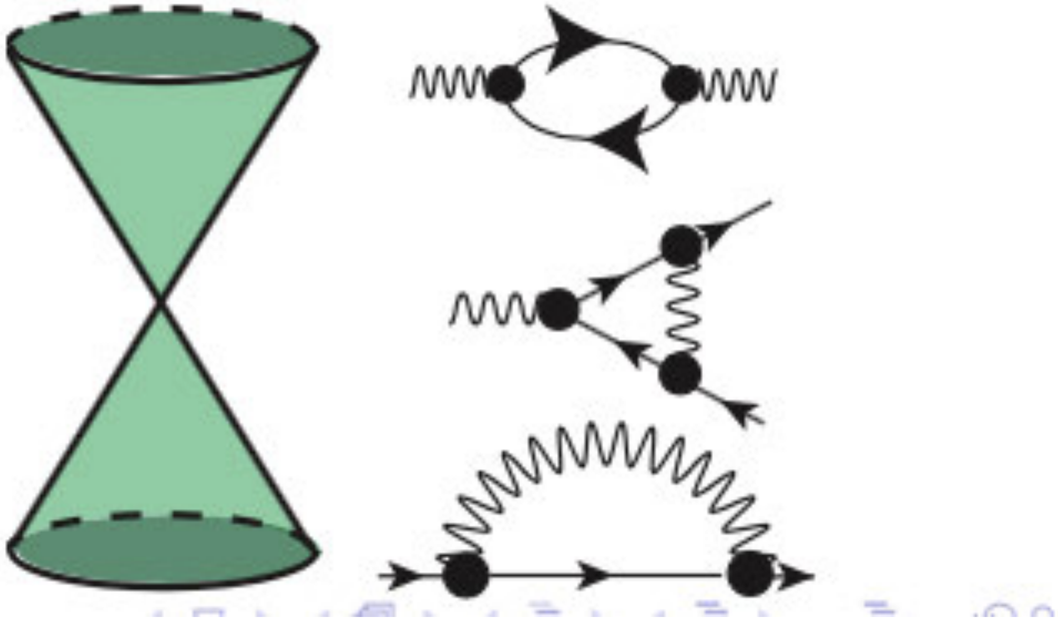
$$H_{Dir} = v_F(k_x\sigma_x + k_y\sigma_y)$$

$$H_{coupl} = \lambda \sum_{\mathbf{q},\mathbf{k}} \varphi_{\mathbf{q}} c^{\dagger}_{\mathbf{k}+\mathbf{q}/2}\sigma_3 c_{\mathbf{k}-\mathbf{q}/2}$$

One-Loop RG

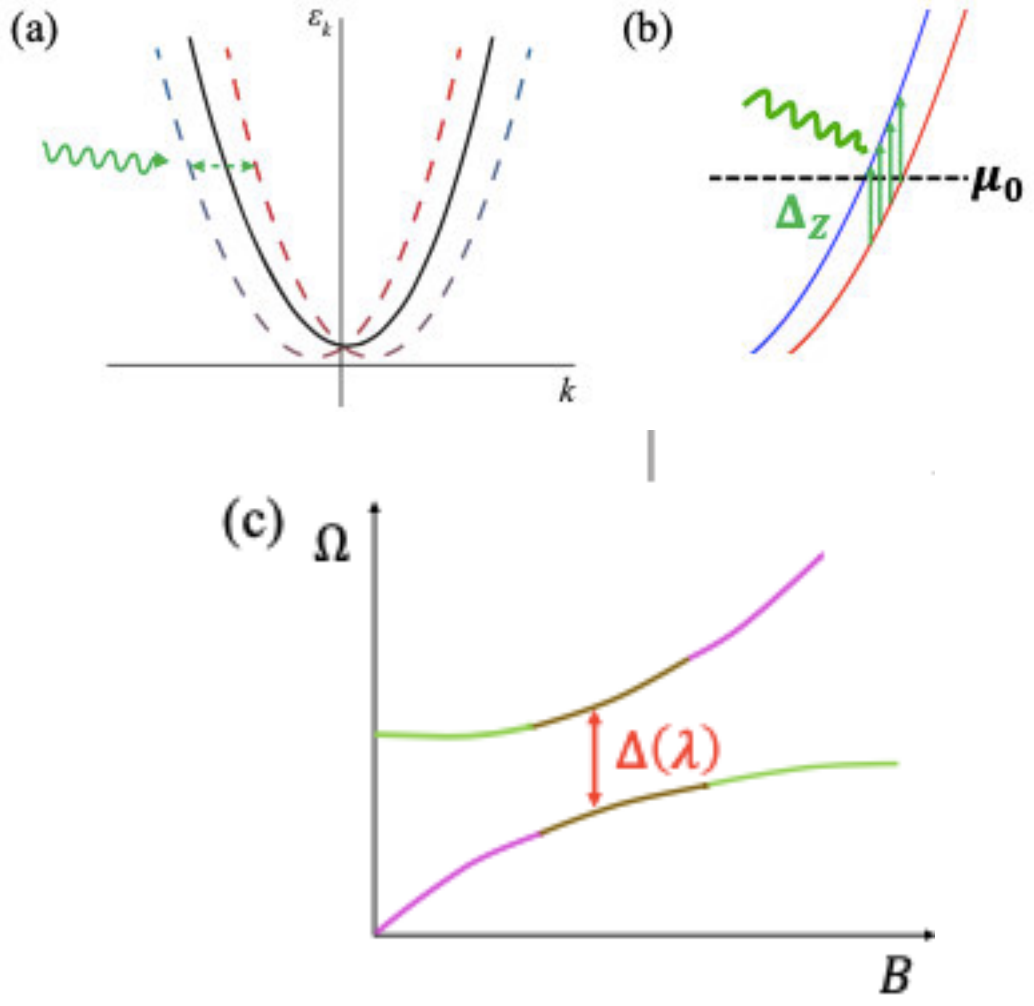
↓

Anisotropic NFL



Mihaila et al. PRB 96, 165133 (2017); Lang and Lauchli PRL 123, 137602 (2019)

Can the strength of the spin-orbit mediated coupling to soft polar modes be probed experimentally ??



Abhishek Kumar
(Rutgers)

Pavel Volkov
(Rutgers)

Accessible with Current Experimental
Techniques with Reasonable Fields

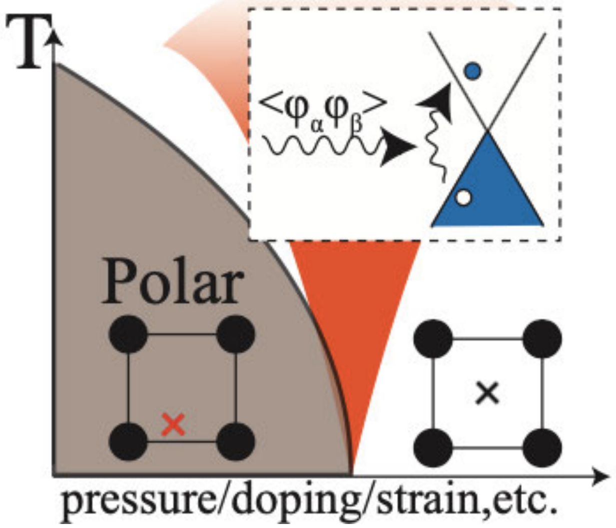
A. Kumar, PC and P.A. Volkov, PRB 105, 125142 (2022).

DFT Studies with Rutgers colleagues also in Progress…

Novel phases in quantum critical polar metals ?? ✓

Yukawa coupling to critical (TO) phonon

Possible in multiband systems without SOC
Strong correlations near Band Crossings



3D Nodal Line ($LiOsO_3$)

Fermi Liquid
Unconventional Phonon Spectrum

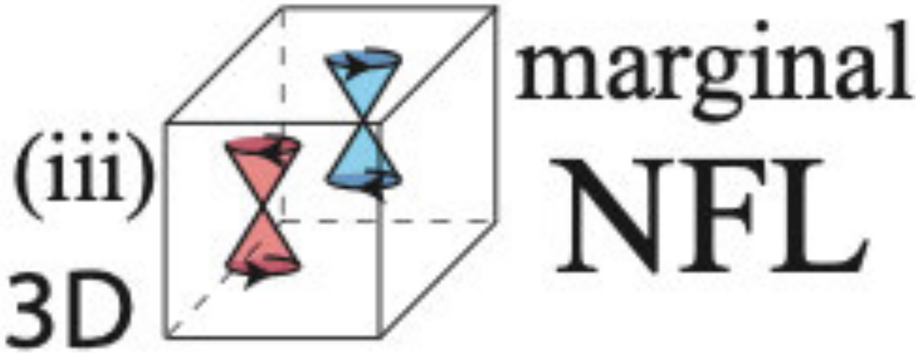
2D Nodal Point

Non-Fermi Liquid (NFL)
Anisotropy induced by Coulomb interactions

3D Weyl Point

Logarithmic NFL corrections

P.A. Volkov and PC, PRL 124, 237601 (2020)

Band Crossing Type	$\lim_{T\to 0+}\rho(T)$
	T^3
	ρ_0
	T^{-1}

In all three cases the critical polar mode is strongly affected by interactions close to the polar QCP (dispersion renormalization and smearing of the spectral weight)