Casimir effect in magnetized dense QCD

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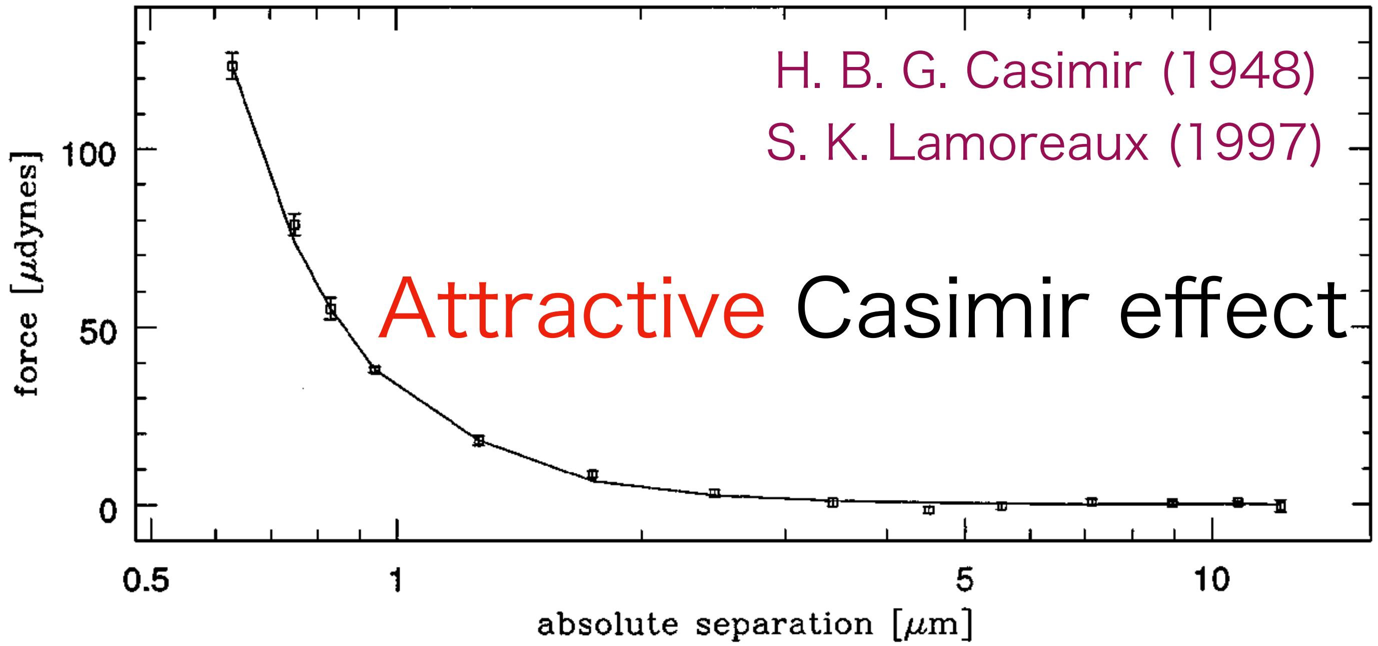
ASRC (JAEA) Daisuke Fujii

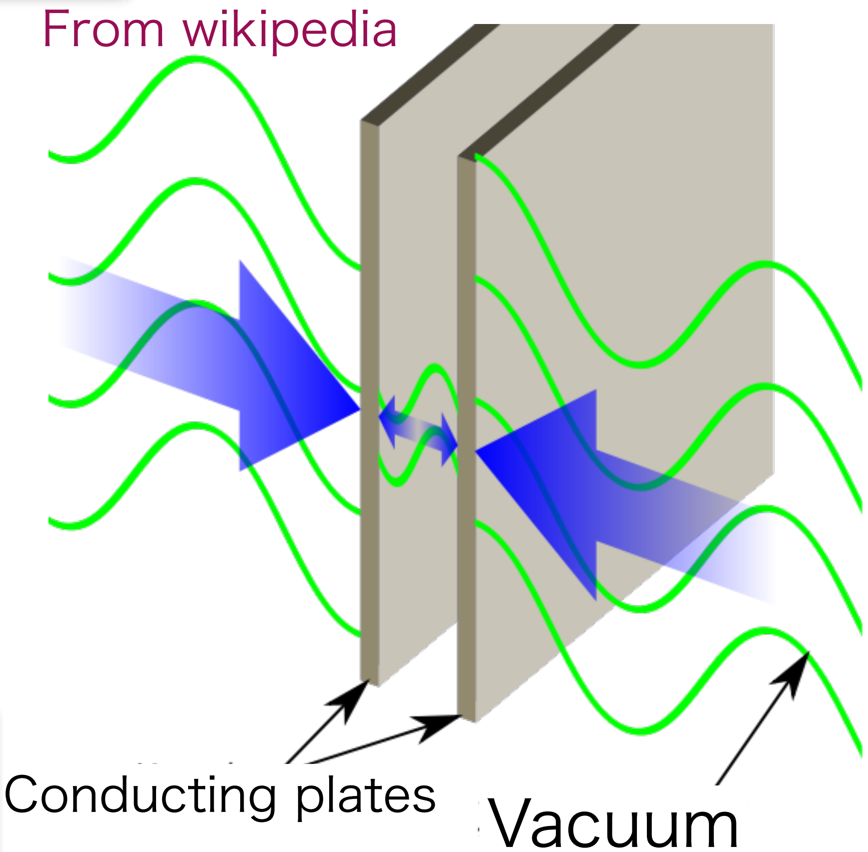
先端基礎研究センター（原子力研究開発機構）

Collaborators:

K. Nakayama (RIKEN-CCS), K. Suzuki (ASRC, JAEA)

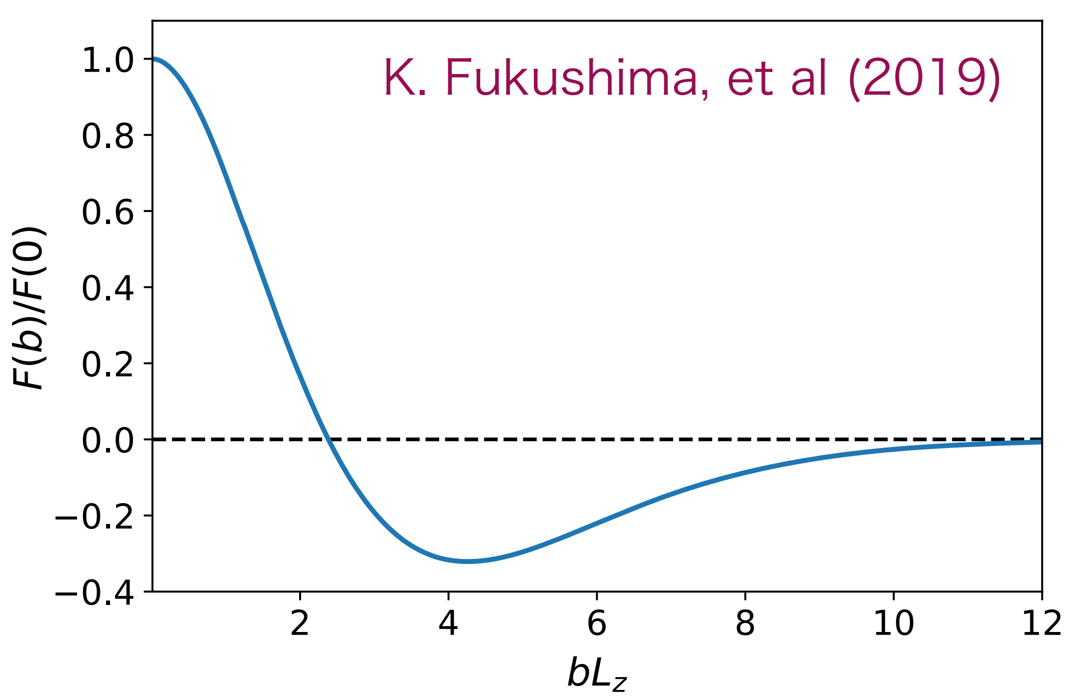
Casimir effect



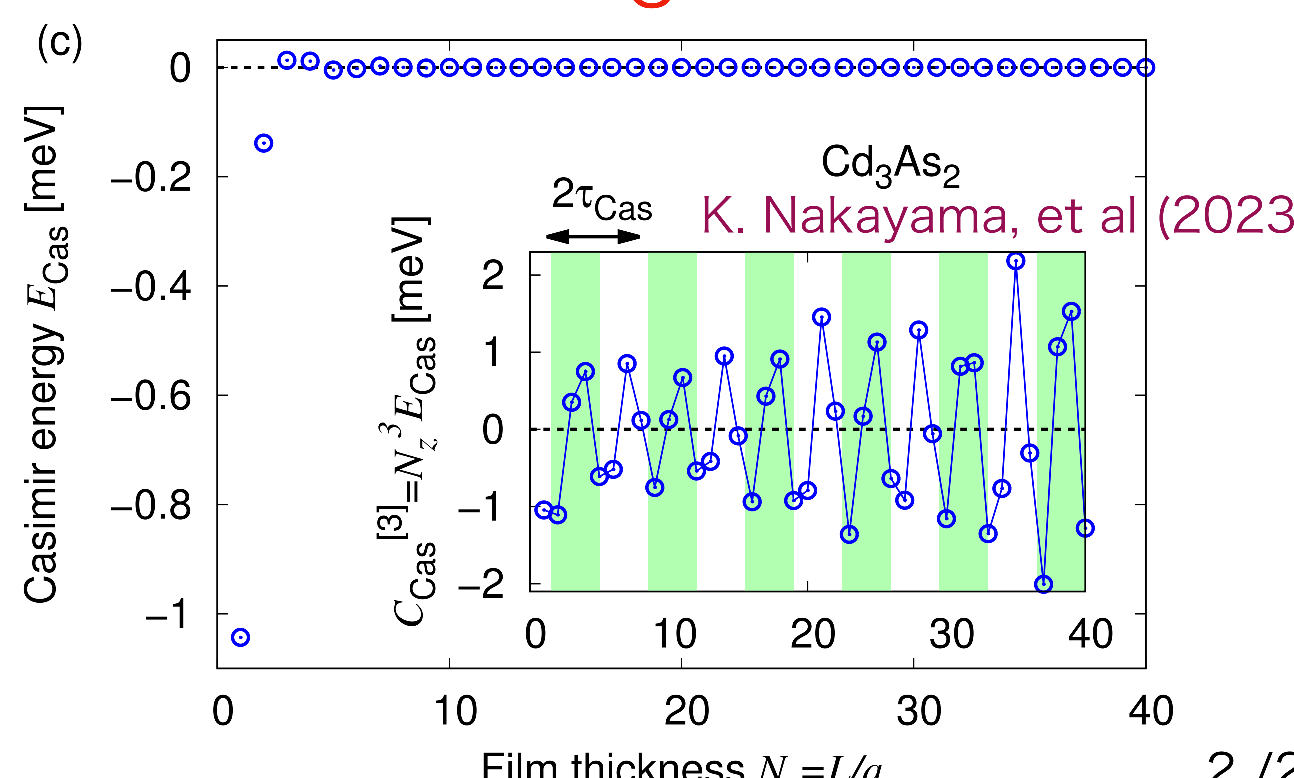


Some types of Casimir effect

- Sign-flipping Casimir effect

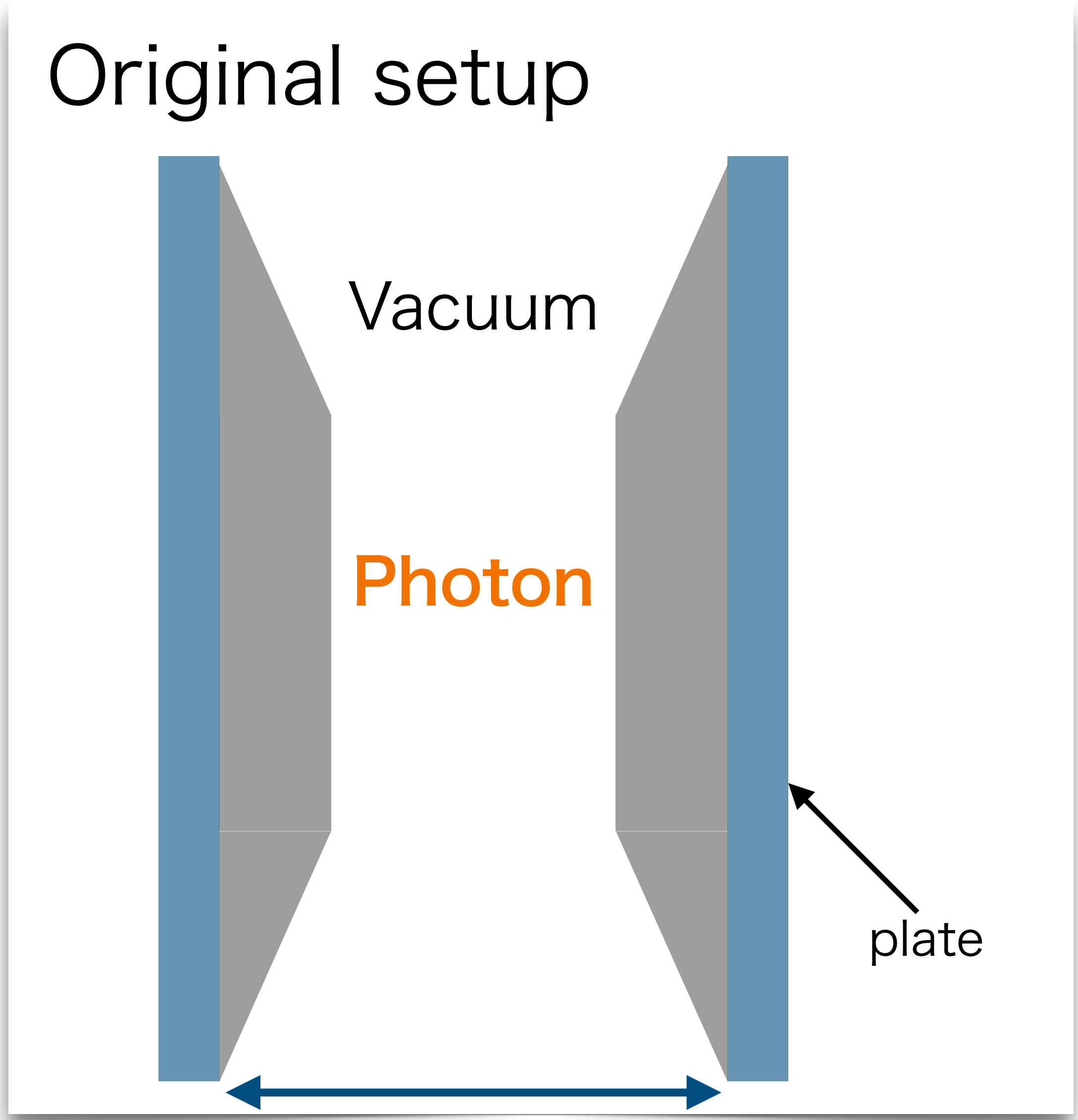


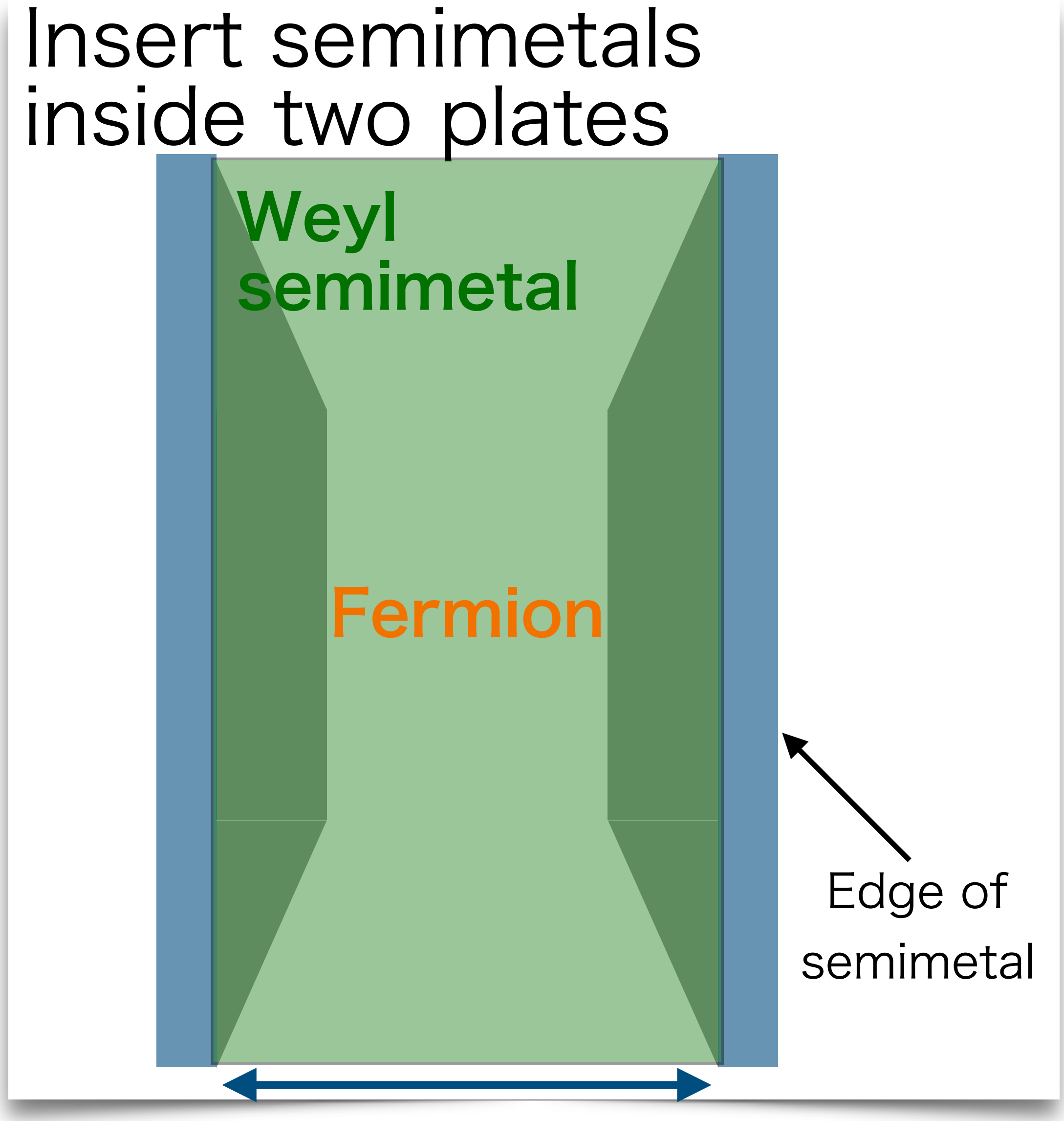
- Oscillating Casimir effect



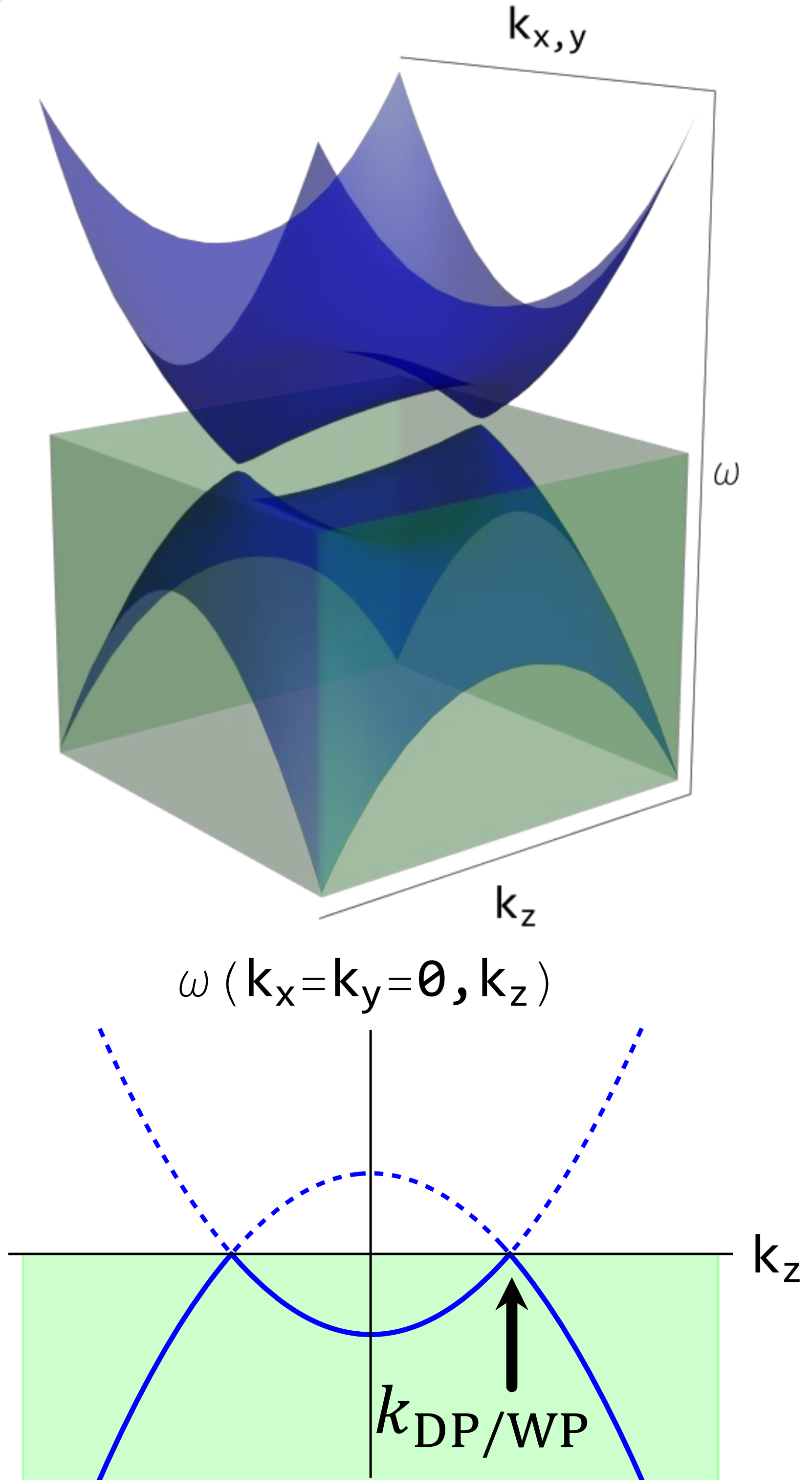
Oscillating Casimir effect

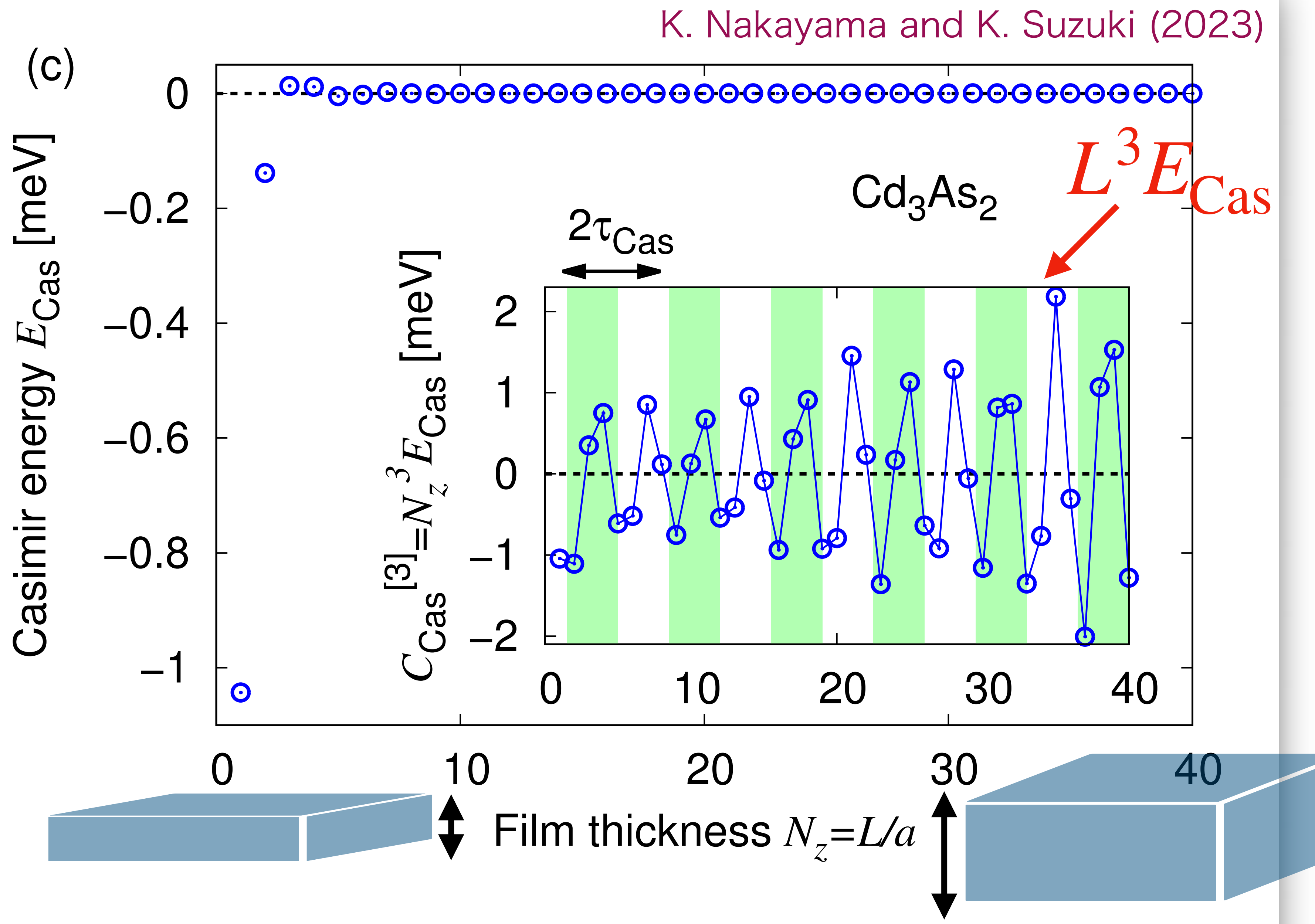
- **Casimir effect** from **Dirac/Weyl** electron fields in **Semimetals**
  - Thin films of Dirac semimetal Cd_3As_2 and Na_3Bi
  - **Oscillating** attractive/zero/repulsive Casimir forces





Oscillating Casimir effect

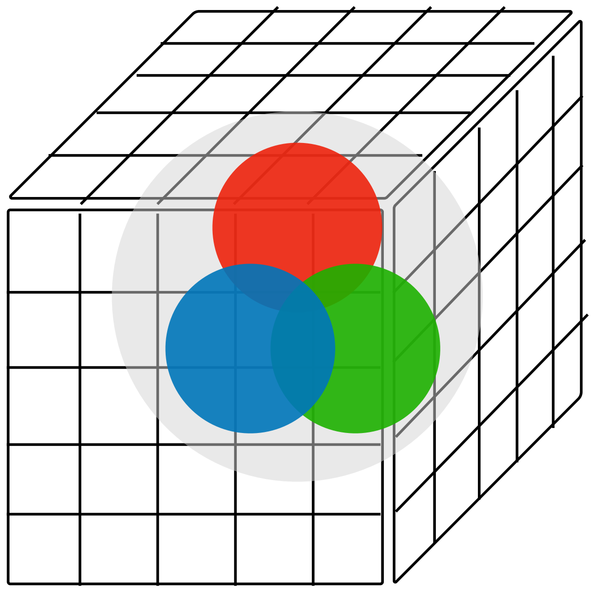




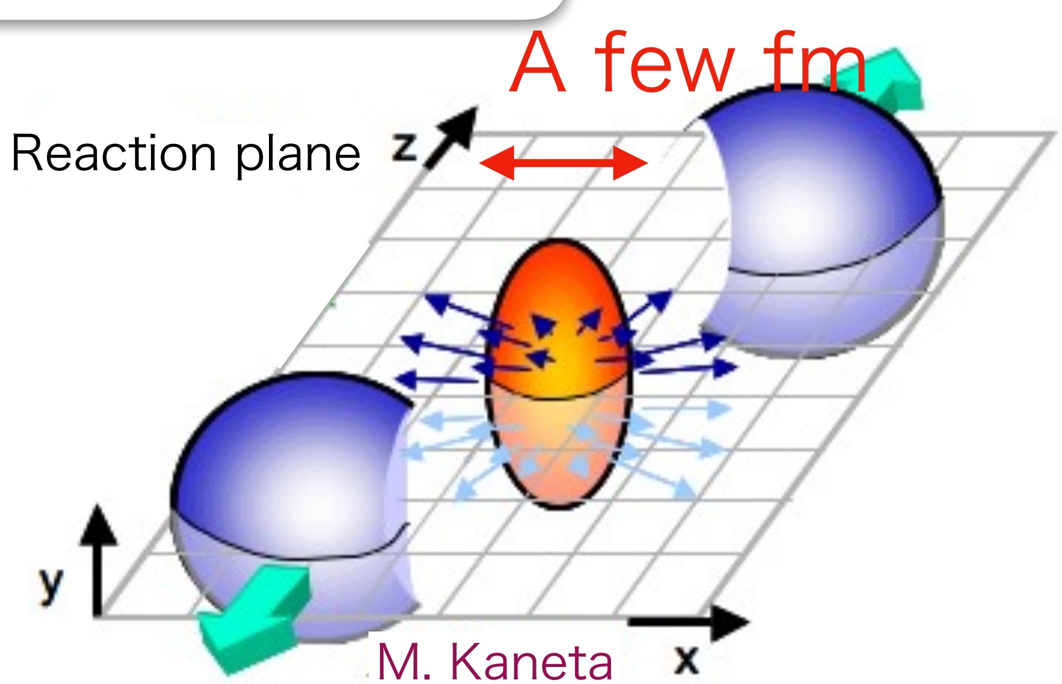
Oscillating due to the Weyl point

Small volume physics in QCD

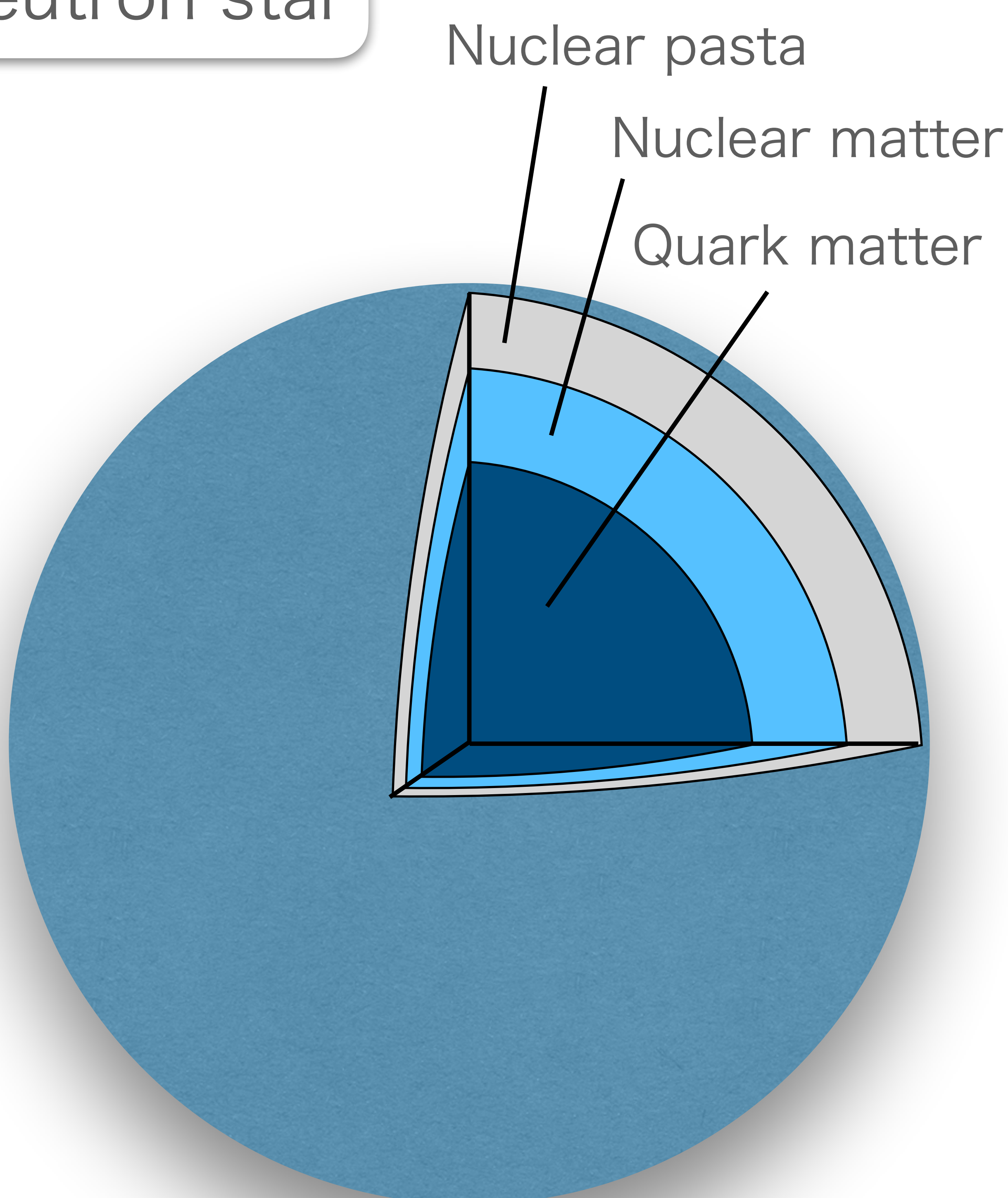
Lattice QCD



Fire ball of QGP

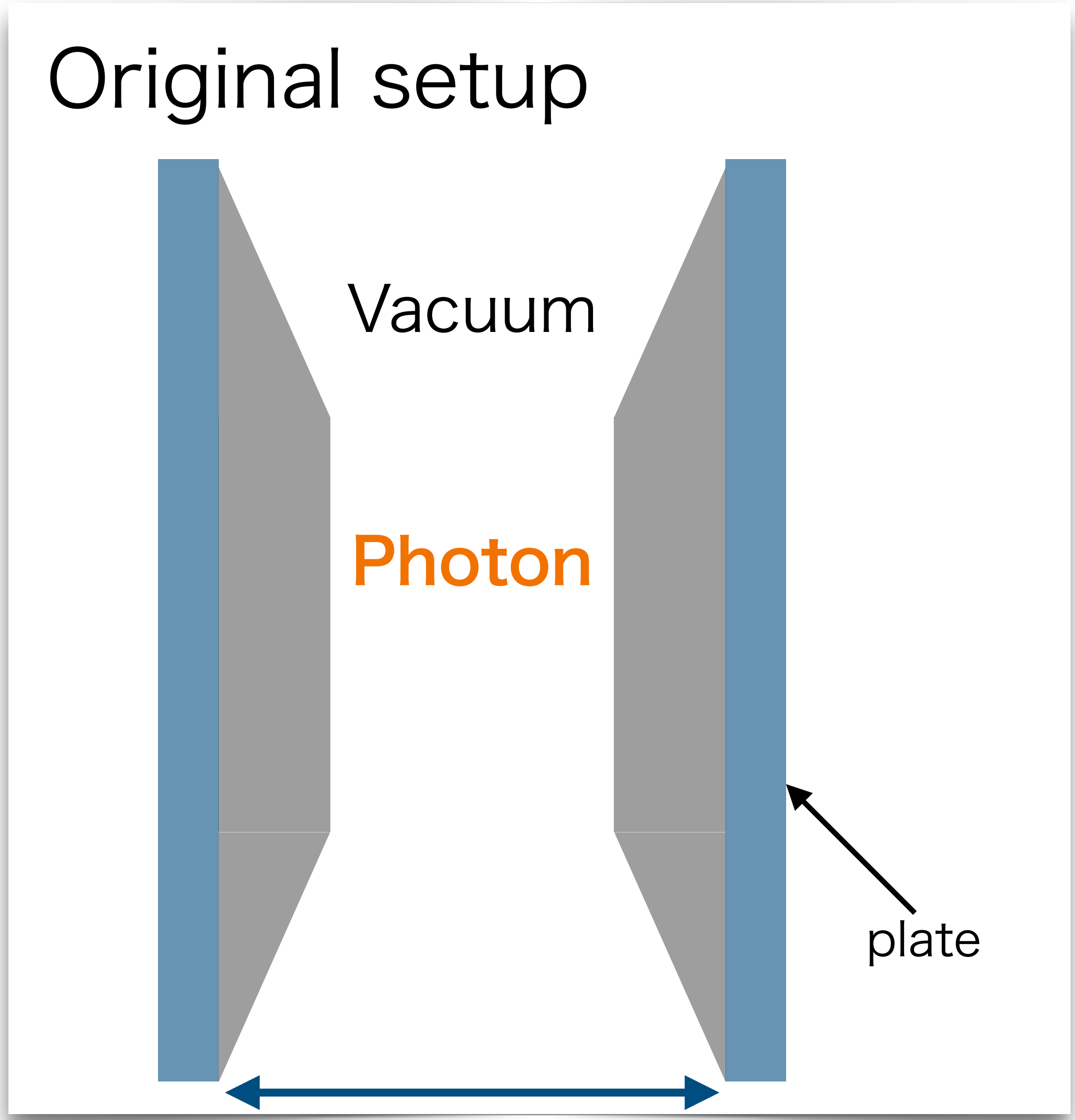


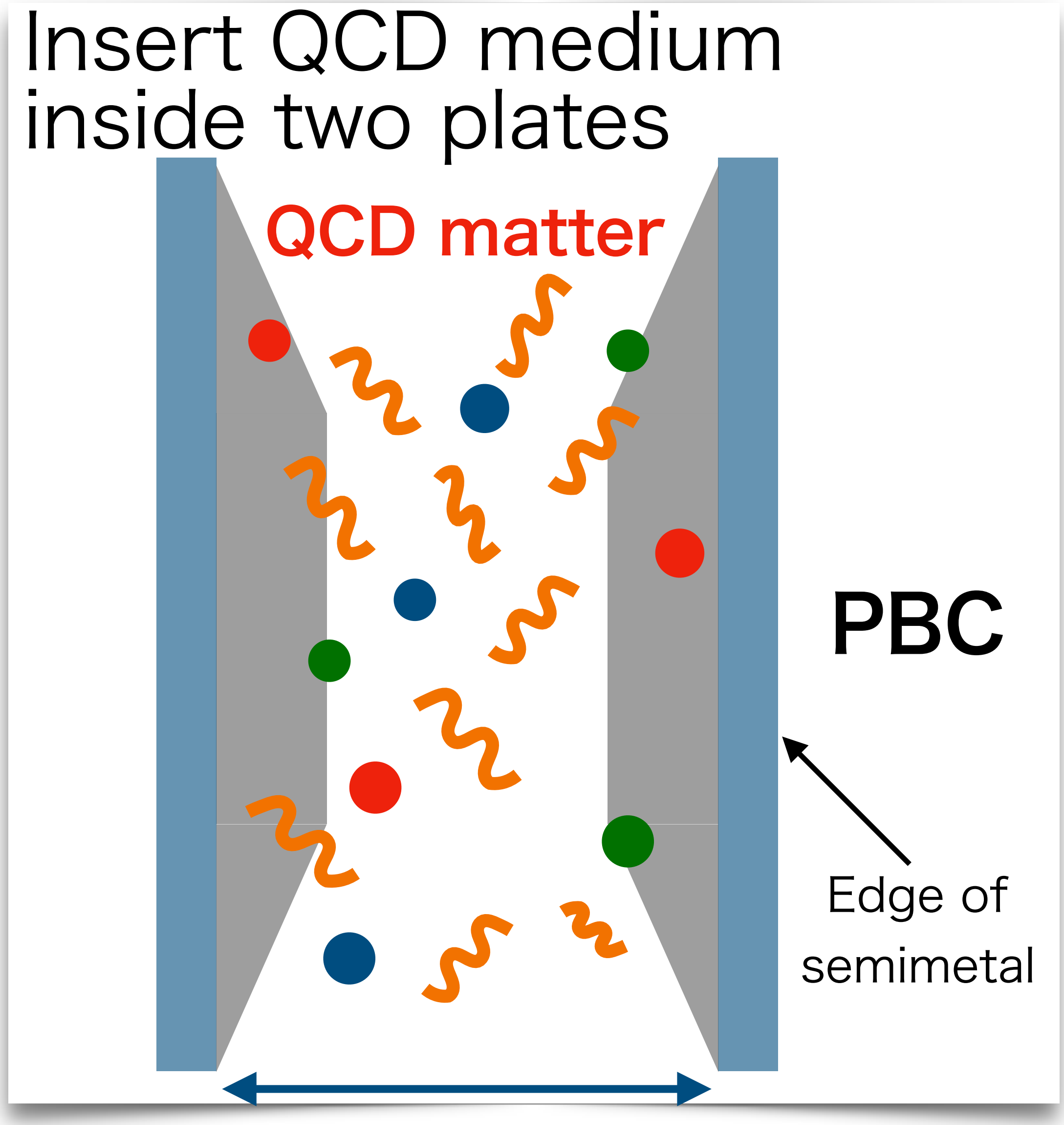
Neutron star



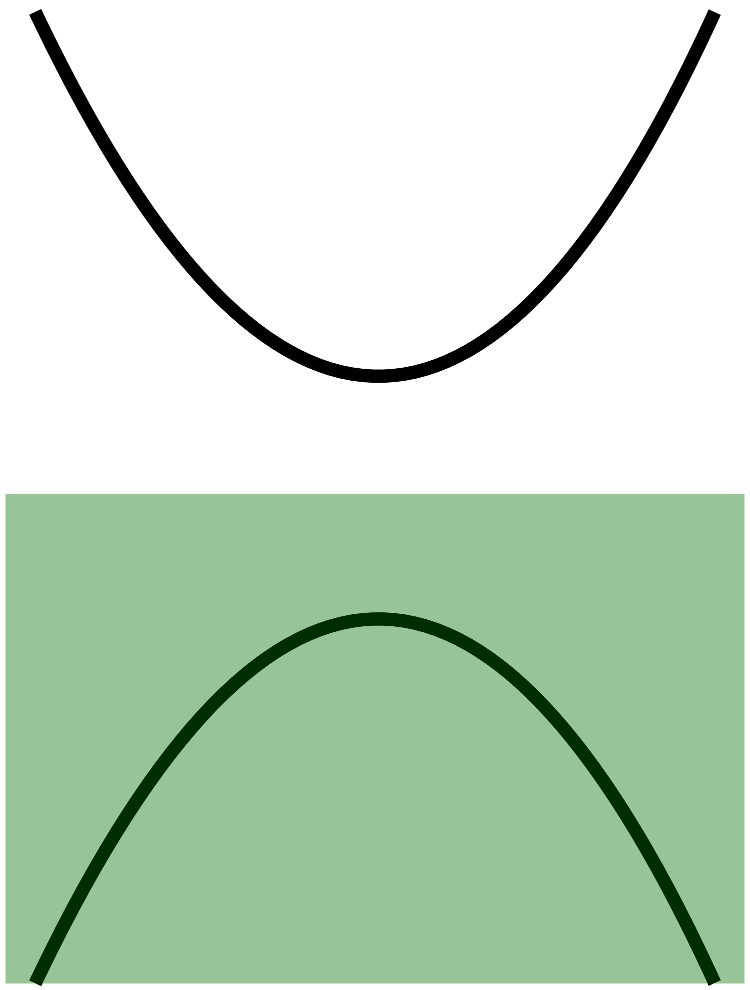
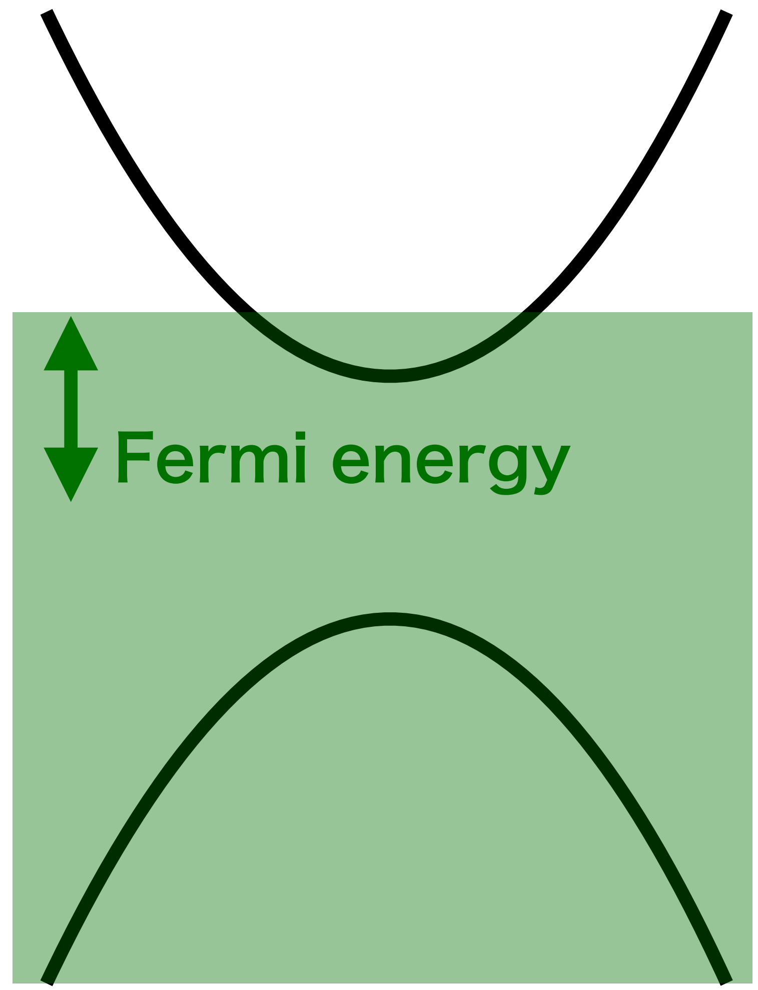
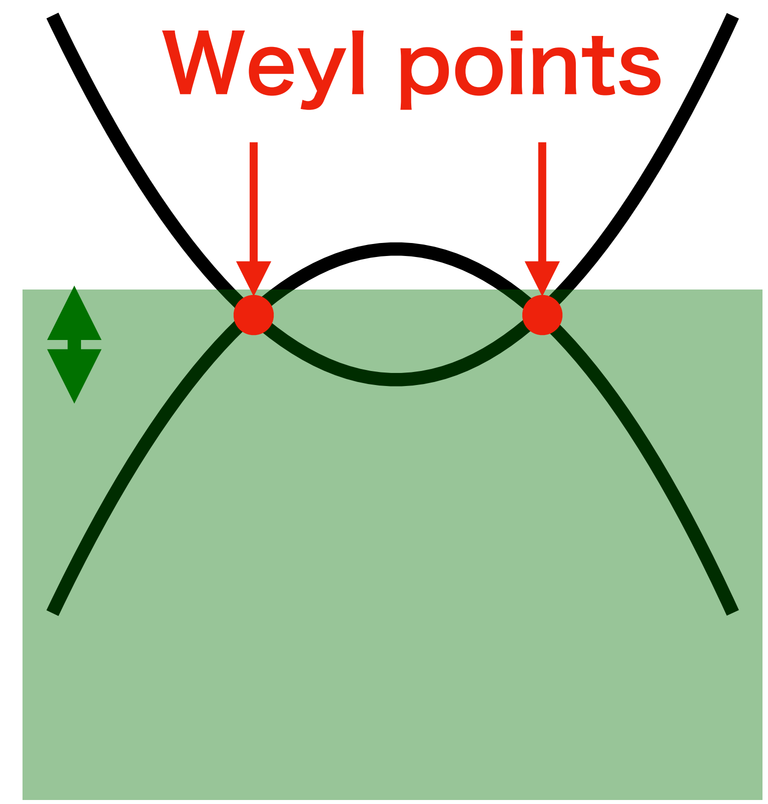
Oscillating Casimir effect

- Consider **counterparts** of several Casimir effect **in NJL model**





What is a counterpart in QCD (NJL) ?

Insulator	Metals	Weyl (semi)metals
		
QCD vacuum with chiral cond.	Dense QCD with chiral cond.	?

What is a counterpart in QCD ?

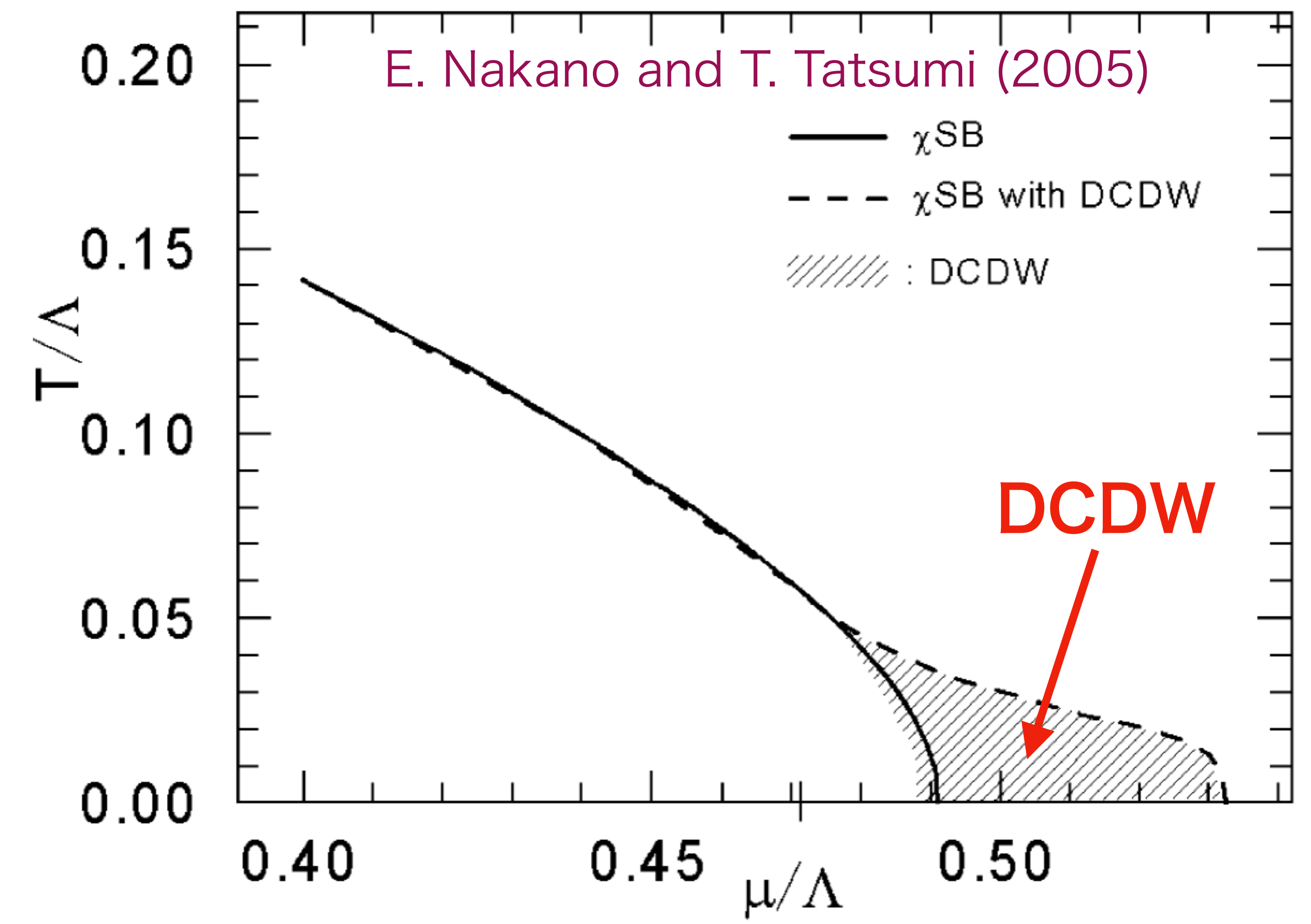
Dual Chiral Density Wave (DCDW)

- A candidate for **ground state** near **chiral phase transition** of density QCD (NJL)
- Order parameter with **spatially inhomogeneous** chiral condensate
- The spiral structure of **scalar** (σ) and **pseudoscalar** (π_0) condensates

$$\langle \bar{q}q \rangle \rightarrow M\cos(\vec{q}\cdot\vec{r})$$

$$\langle \bar{q}i\gamma_5 q \rangle \rightarrow M\sin(\vec{q}\cdot\vec{r})$$

Prediction from NJL



Dispersion relations in DCDW

- Four eigenvalues of Dirac field at $q = (0,0,q)$

$$\omega_\pm = \sqrt{k_x^2 + k_y^2 + \left(\sqrt{k_z^2 + M^2} \pm \frac{q}{2}\right)^2} \qquad \tilde{\omega}_\pm = -\sqrt{k_x^2 + k_y^2 + \left(\sqrt{k_z^2 + M^2} \pm \frac{q}{2}\right)^2}$$

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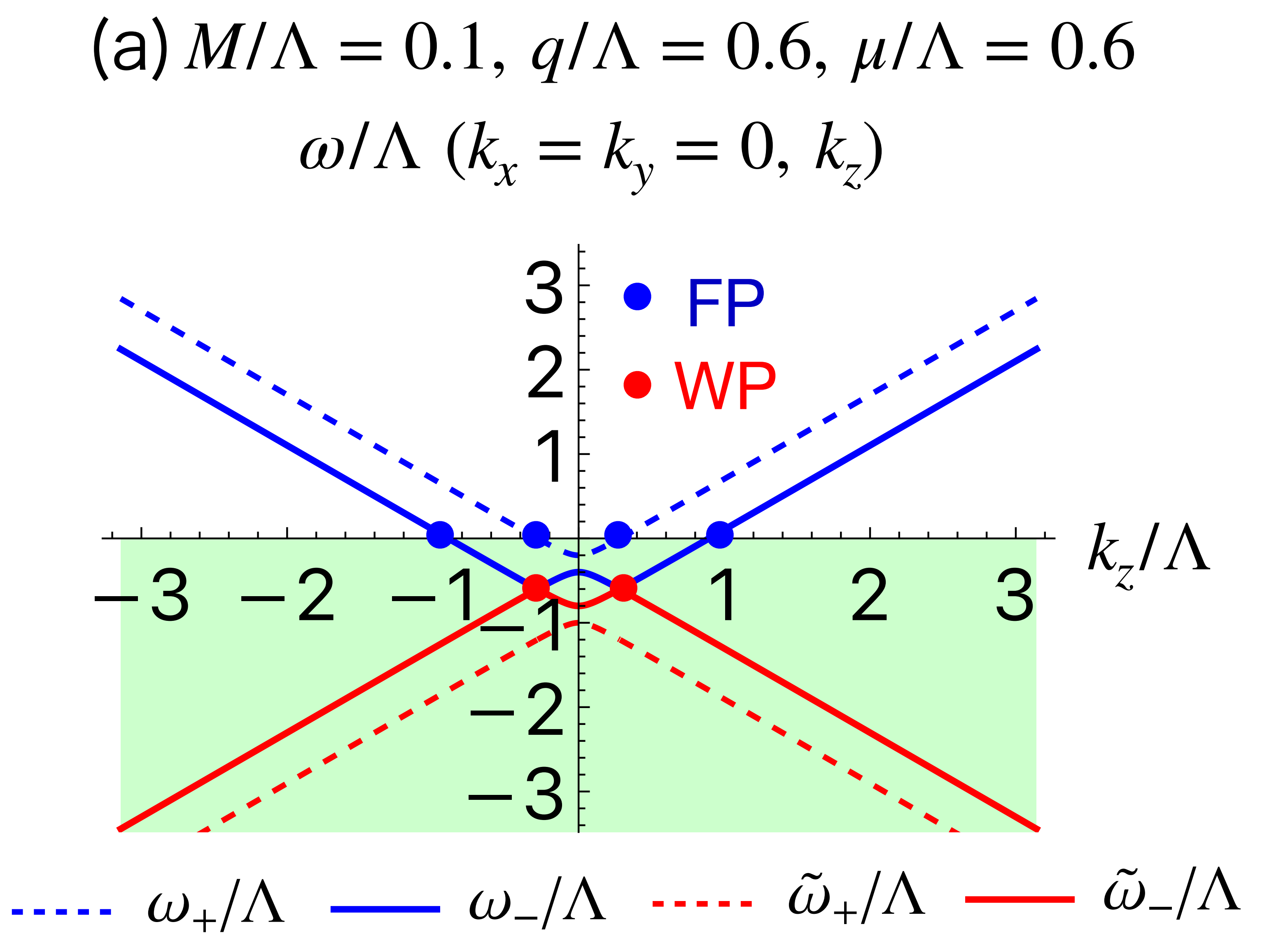


Wavenumber :

Splitting of L/R (±)

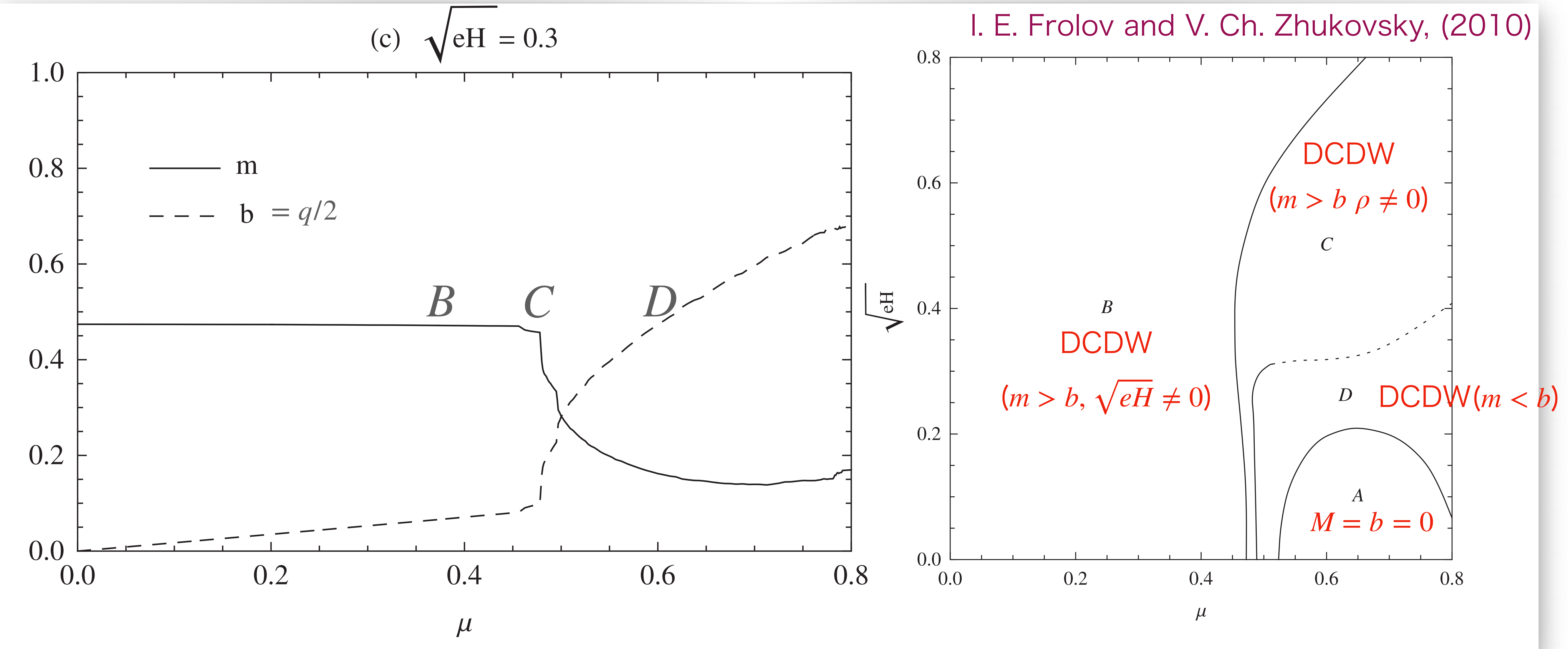
Amplitude of DCDW (Chiral cond.) :

Gap of $\omega_\pm$ and $\tilde{\omega}_\pm$

DCDW under Magnetic fields

Magnetic Dual Chiral Density Wave (MDCDW)

- The **magnetic field** makes the DCDW phase more **robust** because of the effective 1dim space.
- MDCDW is realized in the interior of a **neutron star**



Dispersion relations in MDCDW

- Four eigenvalues of Dirac field at $q = (0,0,q)$

Lowest Landau Levels (LLLs)

$$\omega_{l=0} = \sqrt{M^2 + k_z^2} + \frac{q}{2} \qquad \tilde{\omega}_{l=0} = -\sqrt{M^2 + k_z^2} + \frac{q}{2}$$

Higher Landau Levels (HLLs)

$l = 1,2,\ldots$

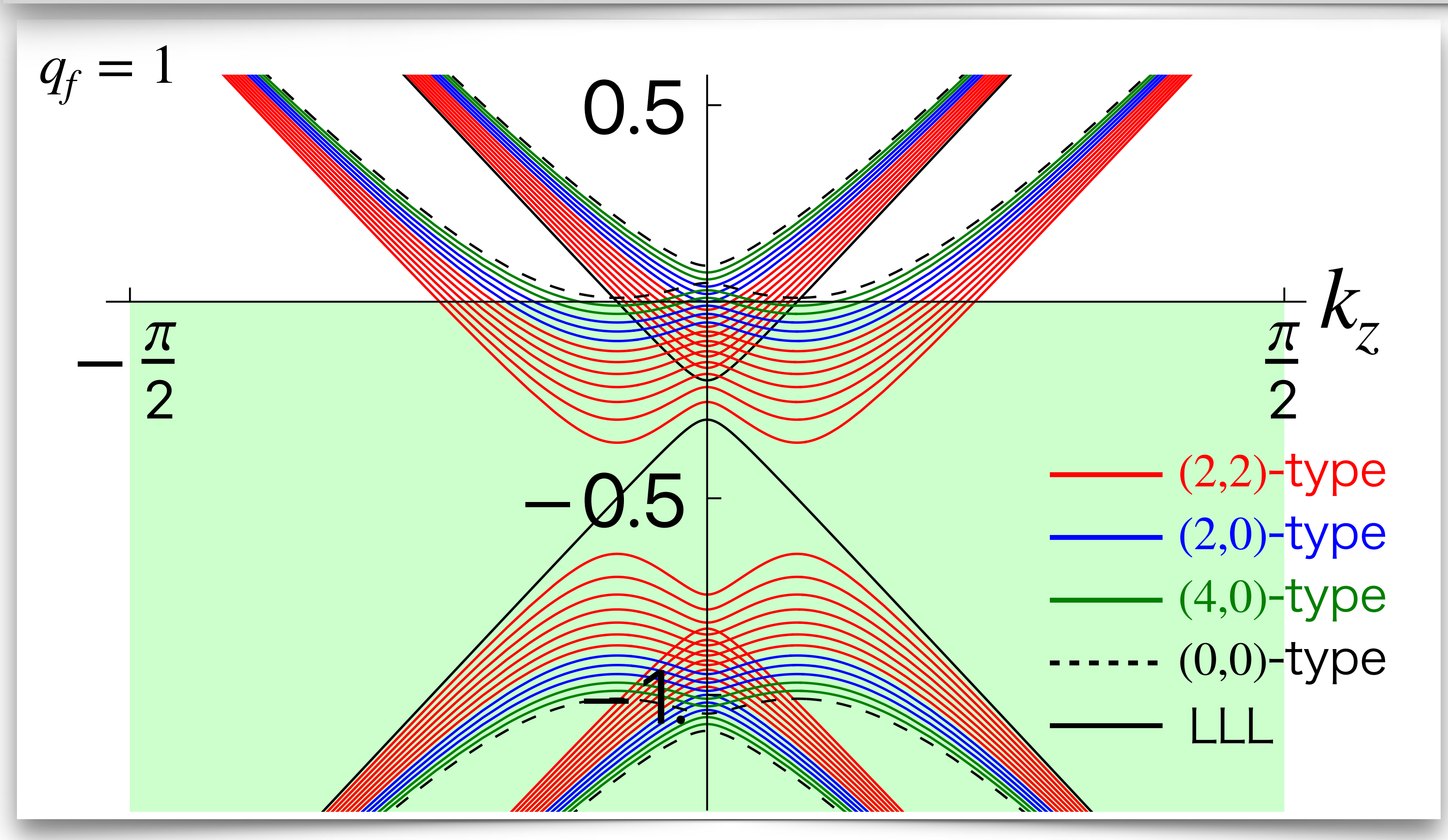
$$\omega_{\pm,l} = \sqrt{2|q_f B|l + (\sqrt{k_z^2 + M^2} \pm \frac{q}{2})^2} \qquad \tilde{\omega}_{\pm,l} = -\sqrt{2|q_f B|l + (\sqrt{k_z^2 + M^2} \pm \frac{q}{2})^2}$$

u, d quark charge (q_f)

Magnetic fields (B)

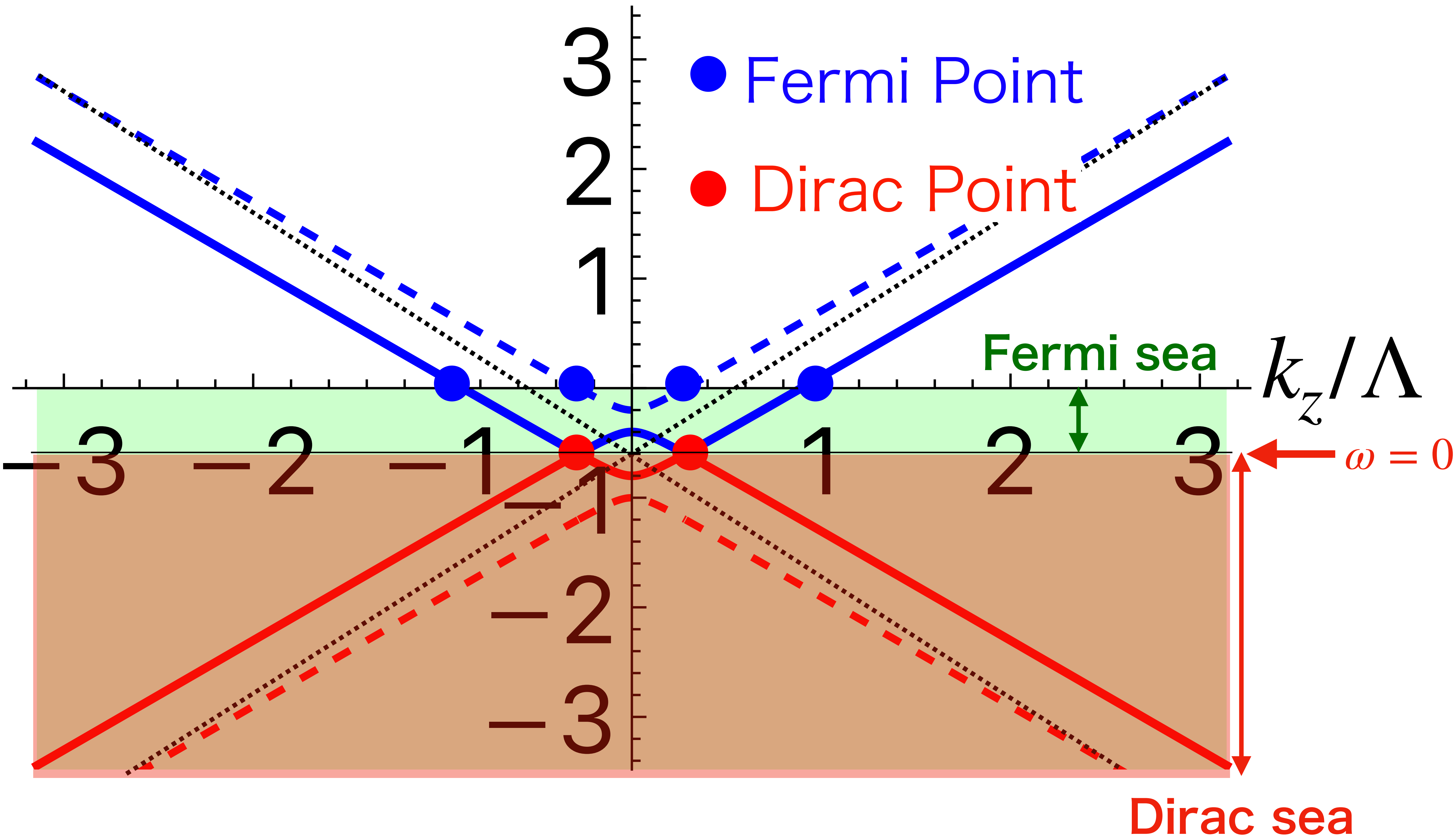
Amplitude of DCDW (Chiral cond. like) : Gap of $\omega_\pm$ and $\tilde{\omega}_\pm$ (M^2)

Wavenumber : Splitting of L/R (±) ($\frac{q}{2}$)



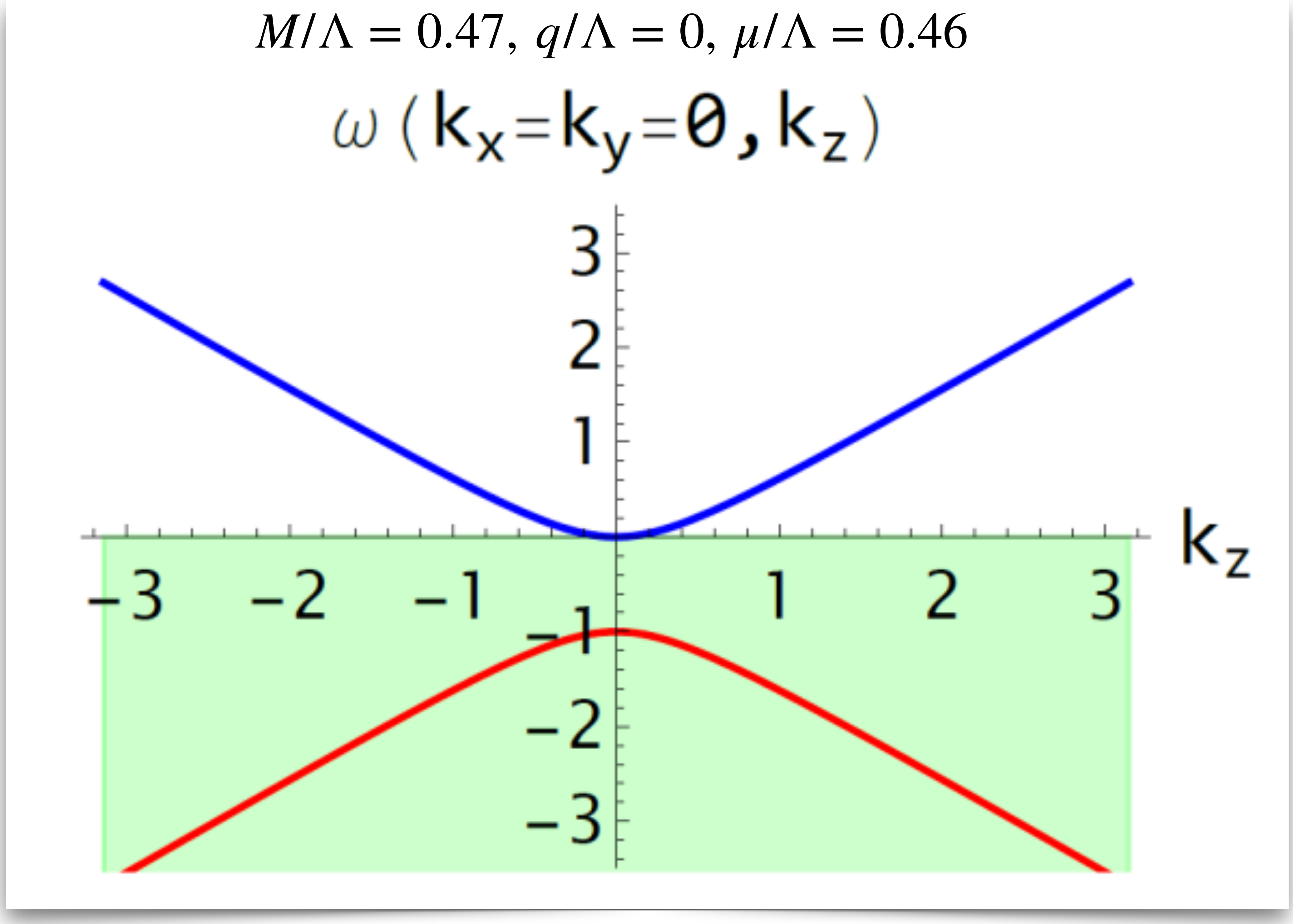
Results

Definition of Fermi/Dirac sea



Zero baryon number density ρ_B (Low μ)

No Dirac and Fermi point



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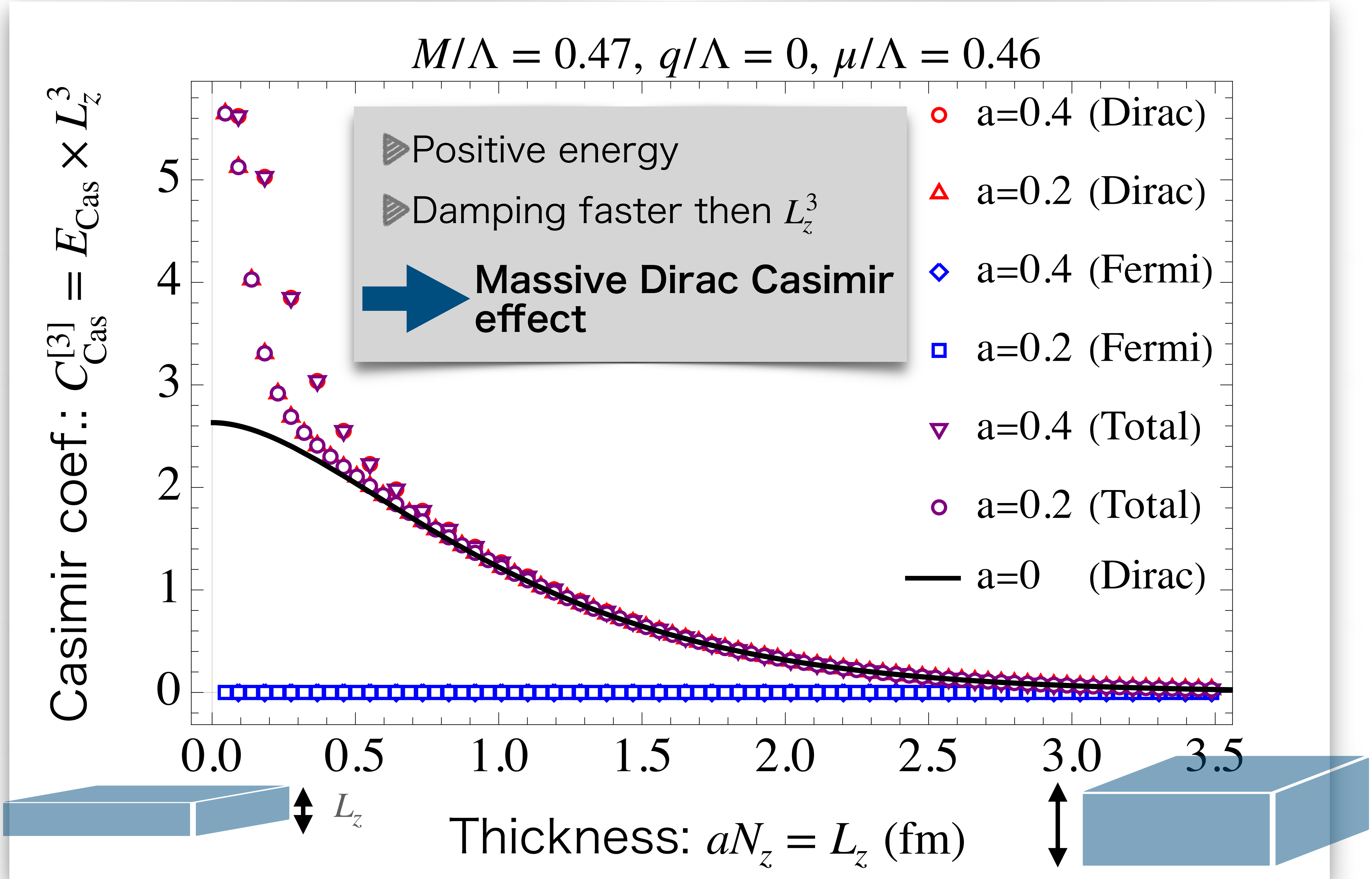
Zero baryon number density ρ_B (Low μ)



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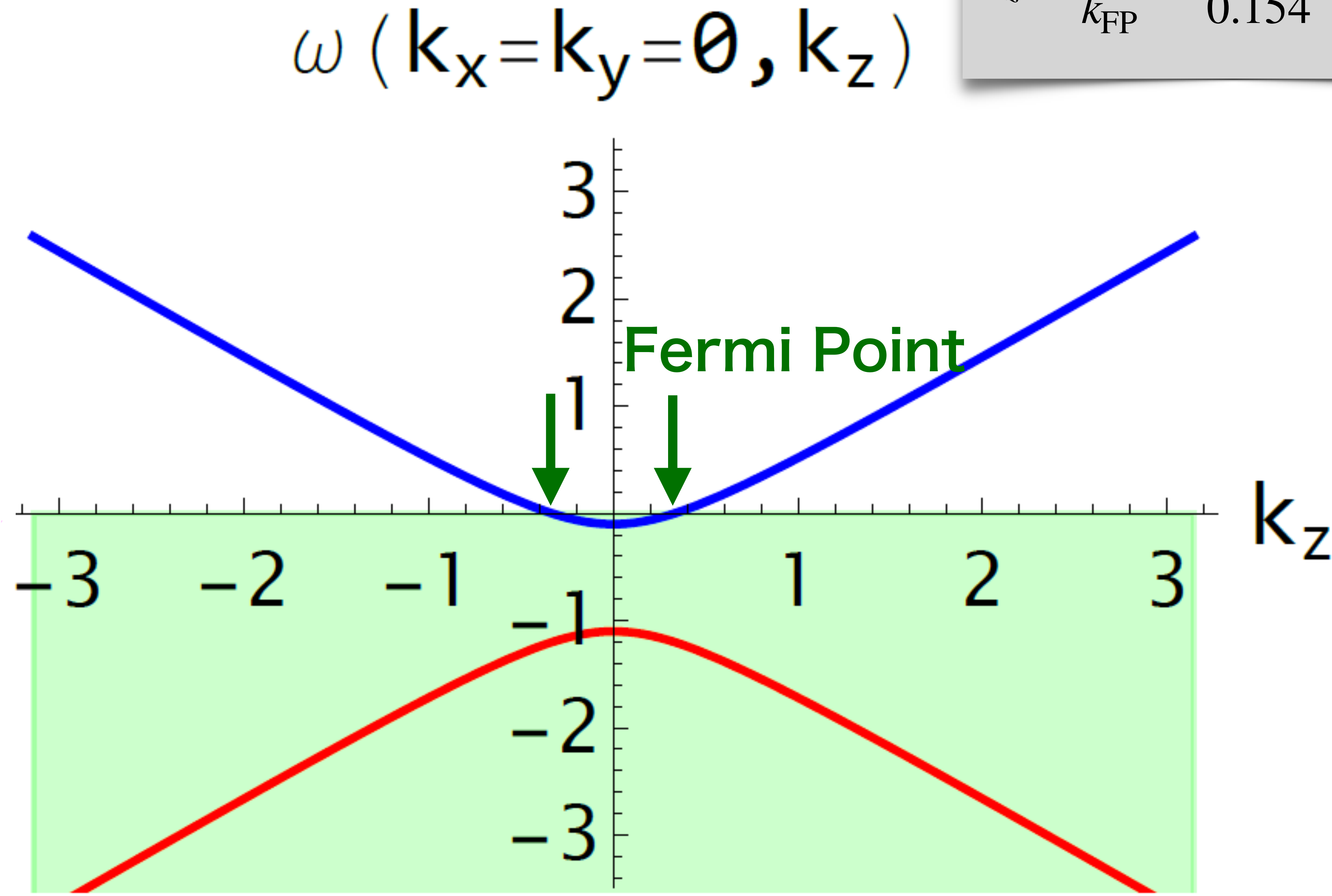
Finite baryon number density ρ_B (Intermediate μ)

- Oscillation occur by Fermi point

Oscillation period:

$$L_z = \frac{\pi}{k_{\mathrm{FP}}} \sim \frac{2\pi}{0.154} \sim 9.4\mathrm{fm}$$

$M/\Lambda = 0.46,\ q/\Lambda = 0,\ \mu/\Lambda = 0.485$



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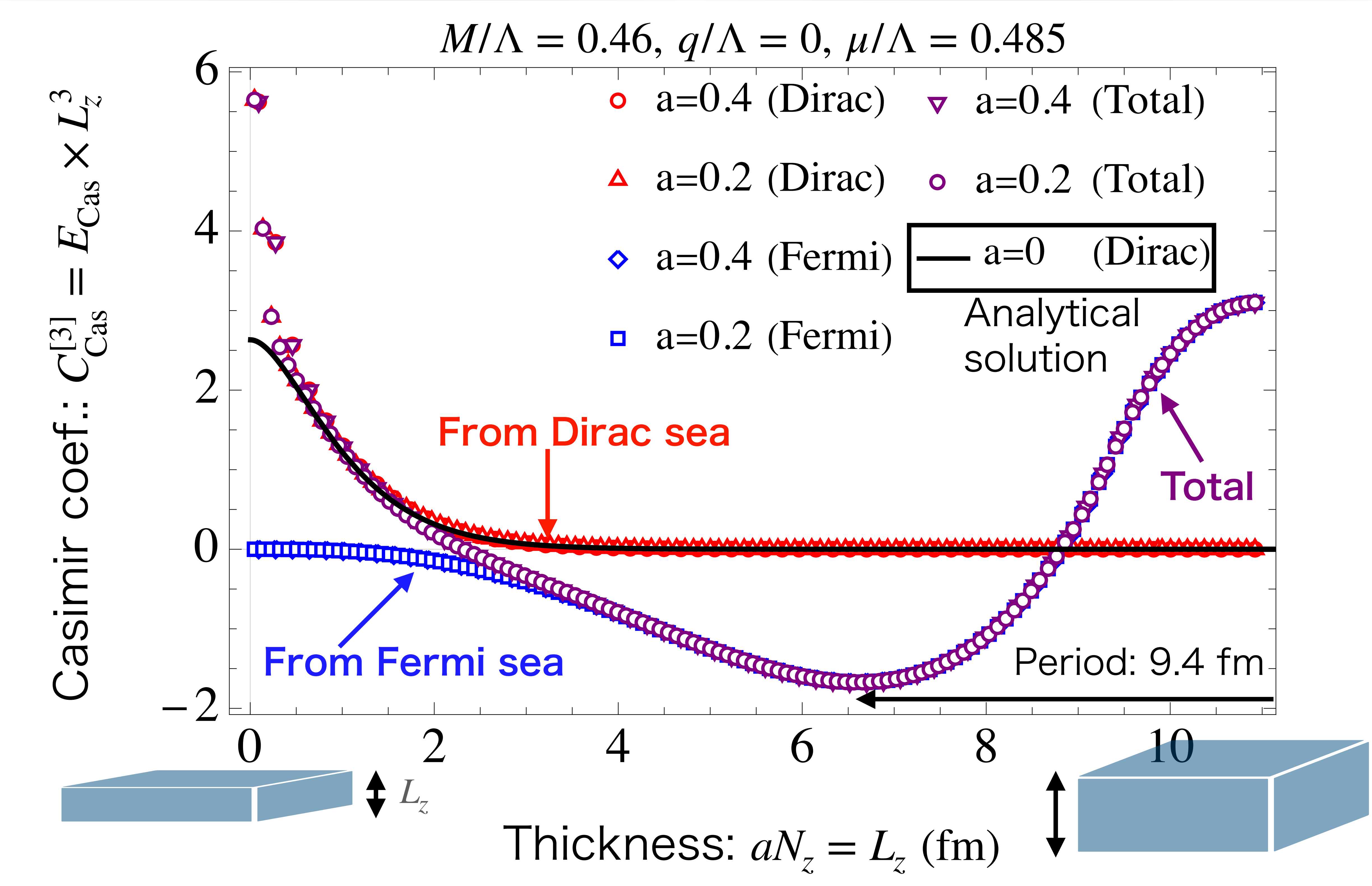
Finite baryon number density ρ_B (Intermediate μ)



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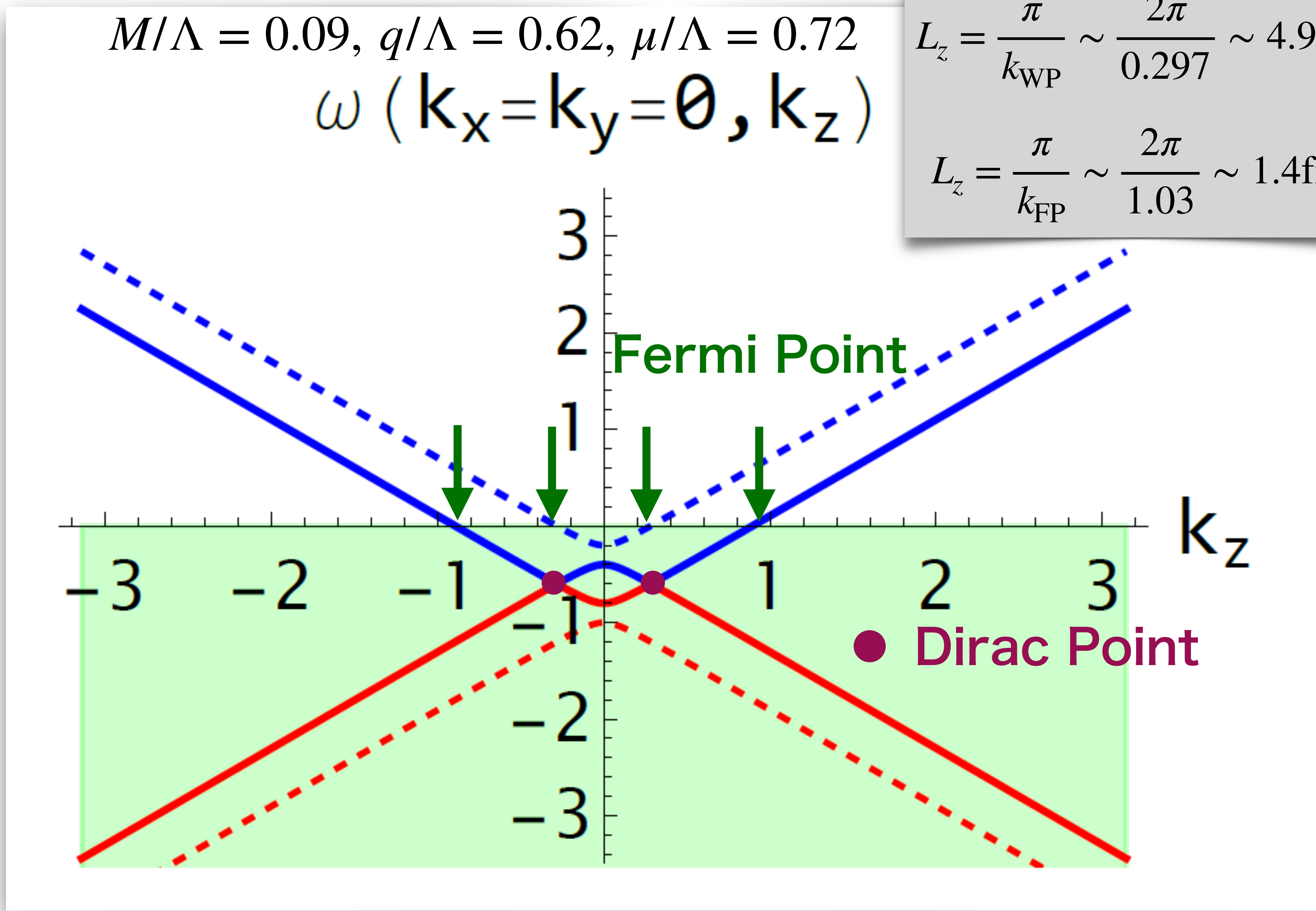
DCDW phase (high μ)

- Oscillations by DCDW phase

Oscillation period:

$$L_z = \frac{\pi}{k_{\rm WP}} \sim \frac{2\pi}{0.297} \sim 4.9\text{fm}$$

$$L_z = \frac{\pi}{k_{\rm FP}} \sim \frac{2\pi}{1.03} \sim 1.4\text{fm}$$



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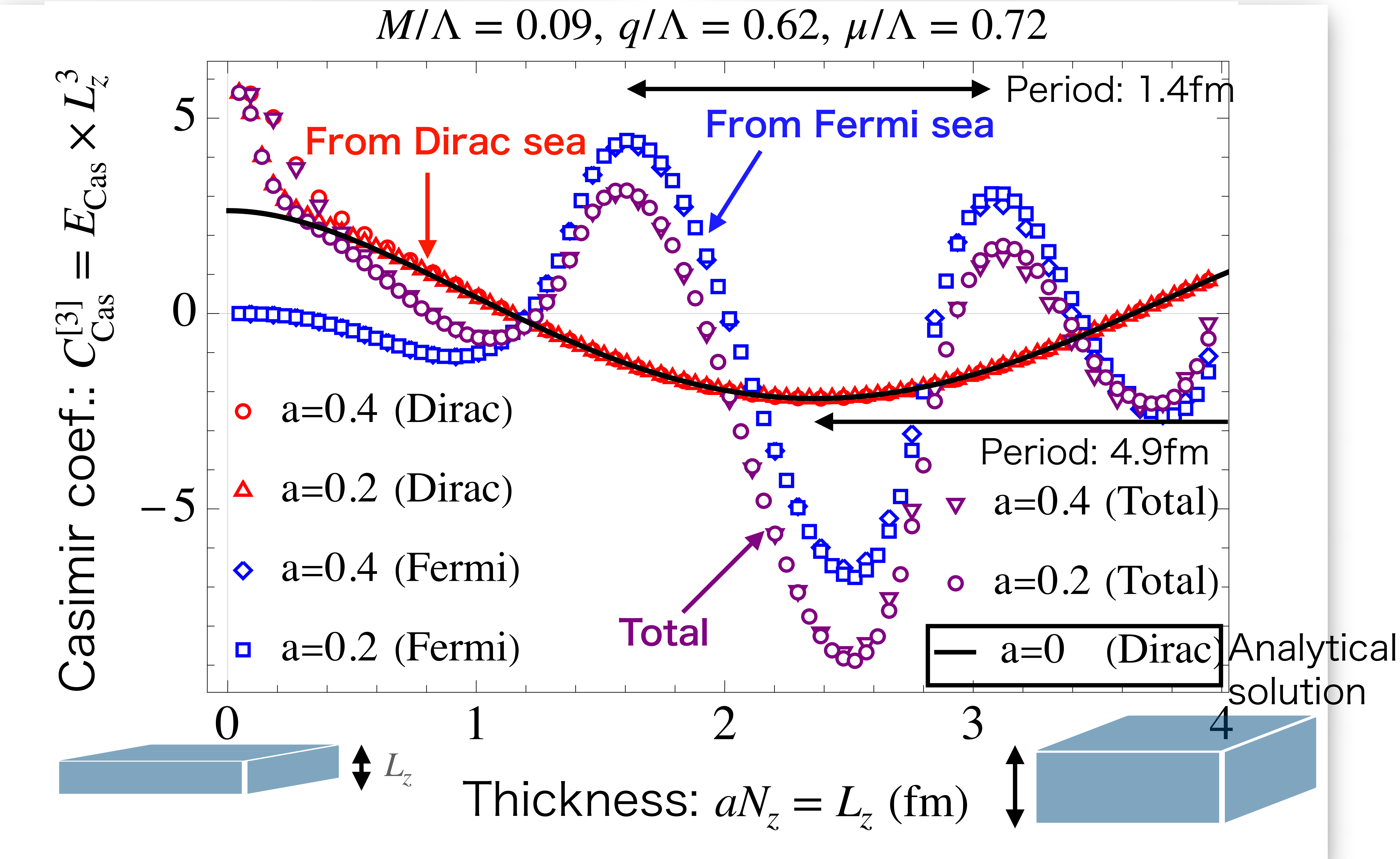
DCDW phase (high μ)



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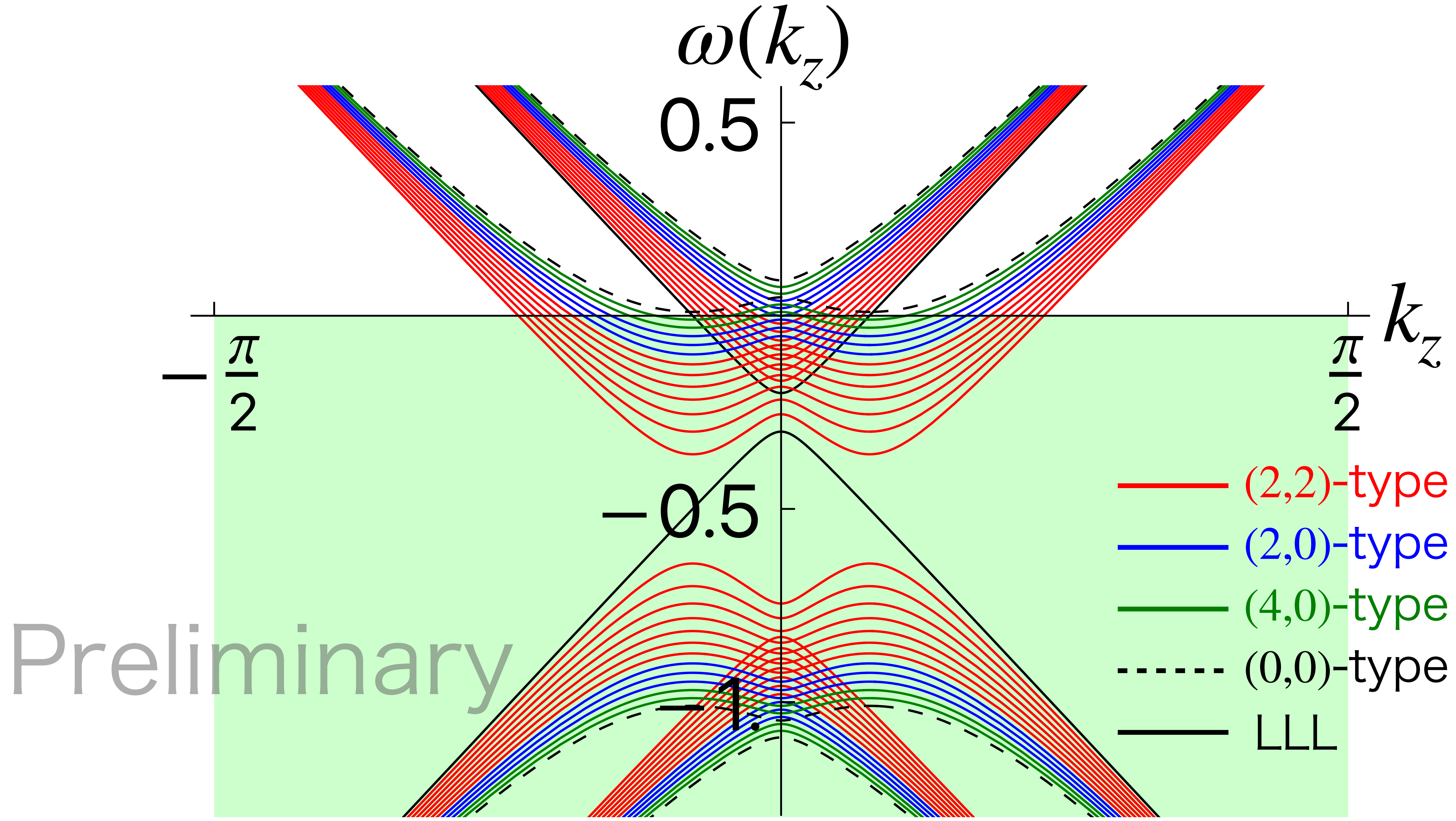
DCDW phase (high μ)

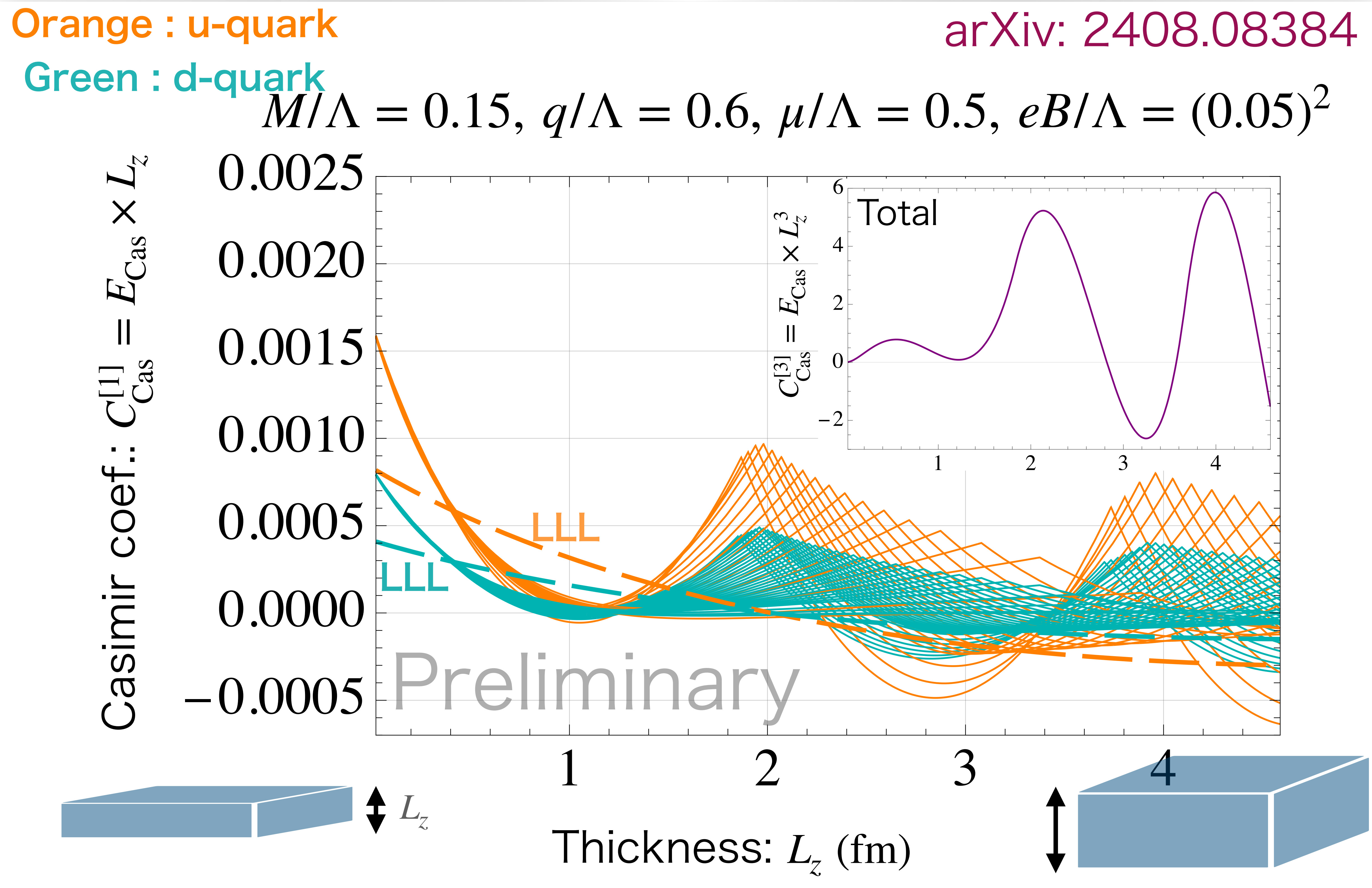
- Oscillations by MDCDW phase

$q_f = 1$

$M/\Lambda = 0.15,\ q/\Lambda = 0.6,\ \mu/\Lambda = 0.5,\ eB/\Lambda = (0.05)^2$



MDCDW phase



Orange : u-quark
Green : d-quark
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$M/\Lambda = 0.15,\ q/\Lambda = 0.6,\ \mu/\Lambda = 0.5,\ eB/\Lambda = (0.05)^2$
Casimir coef.: $C^{[1]}_{\mathrm{Cas}} = E_{\mathrm{Cas}} \times L_z$
0.0025
0.0020
0.0015
0.0010
0.0005
0.0000
−0.0005
LLL
LLL
Preliminary
Total
$C^{[3]}_{\mathrm{Cas}} = E_{\mathrm{Cas}} \times L_z^3$
6
4
2
0
−2
1
2
3
4
L_z
Thickness: L_z (fm)

Summary and Outlook

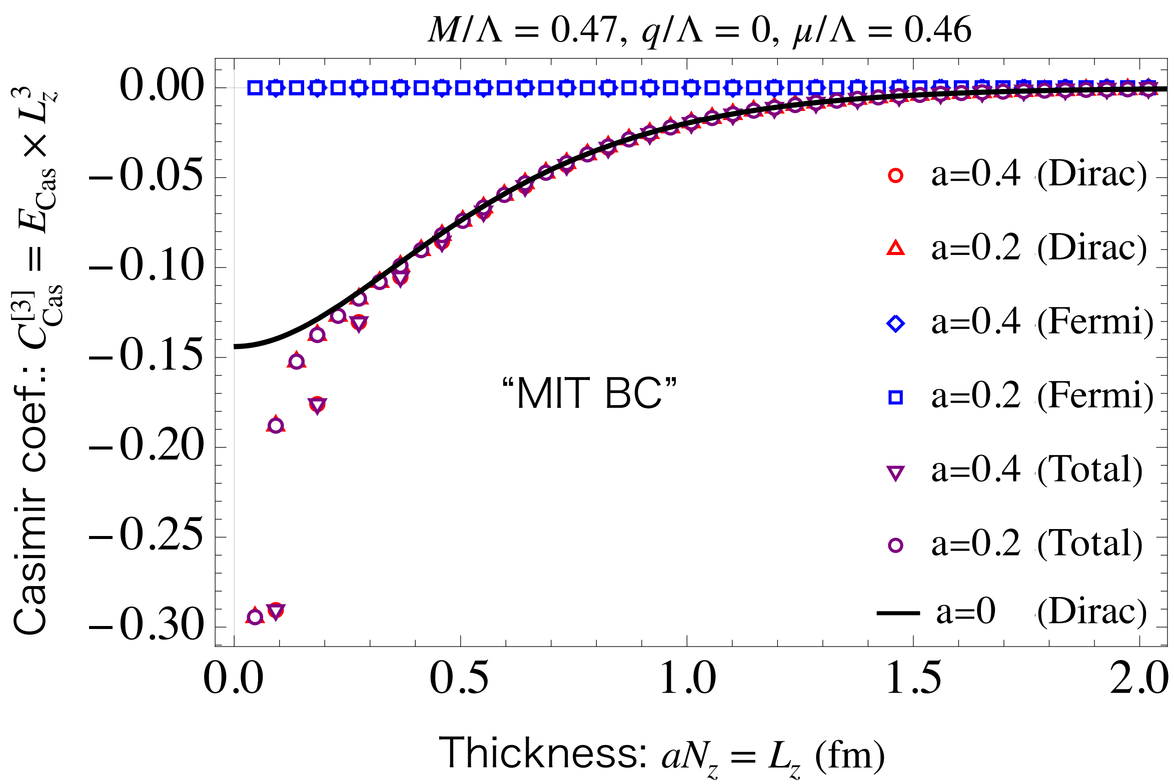
- Casimir effect in dense QCD (NJL)
  - Low μ : **Massive Dirac** Casimir effect
  - Intermediate μ : **Oscillating** Casimir effect from **Fermi sea**
  - High μ : **Oscillating** Casimir effect by **DCDW**
  - Under B : **Oscillating** Casimir effect from **each LL**

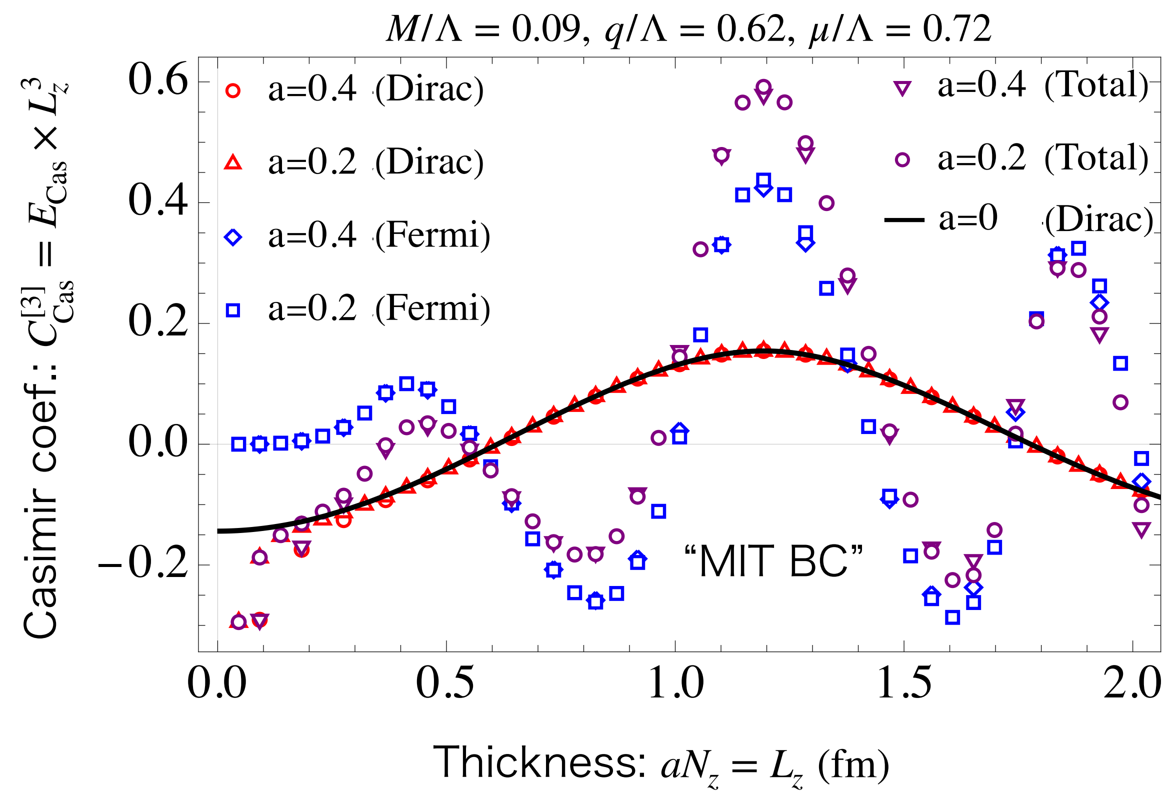
- Color superconducting phase or kink crystal phase
- Lattice QCD simulations
- ・・・・

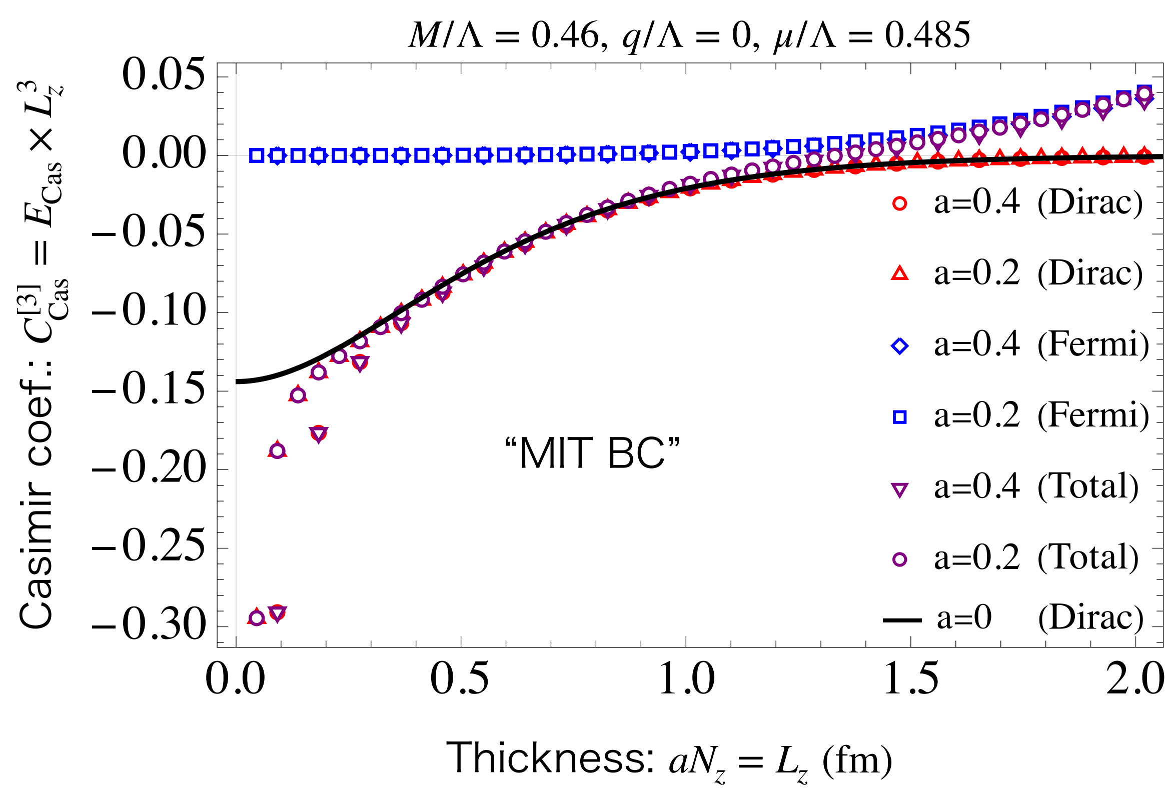
Thank you for your attention

Buck up

Buck up

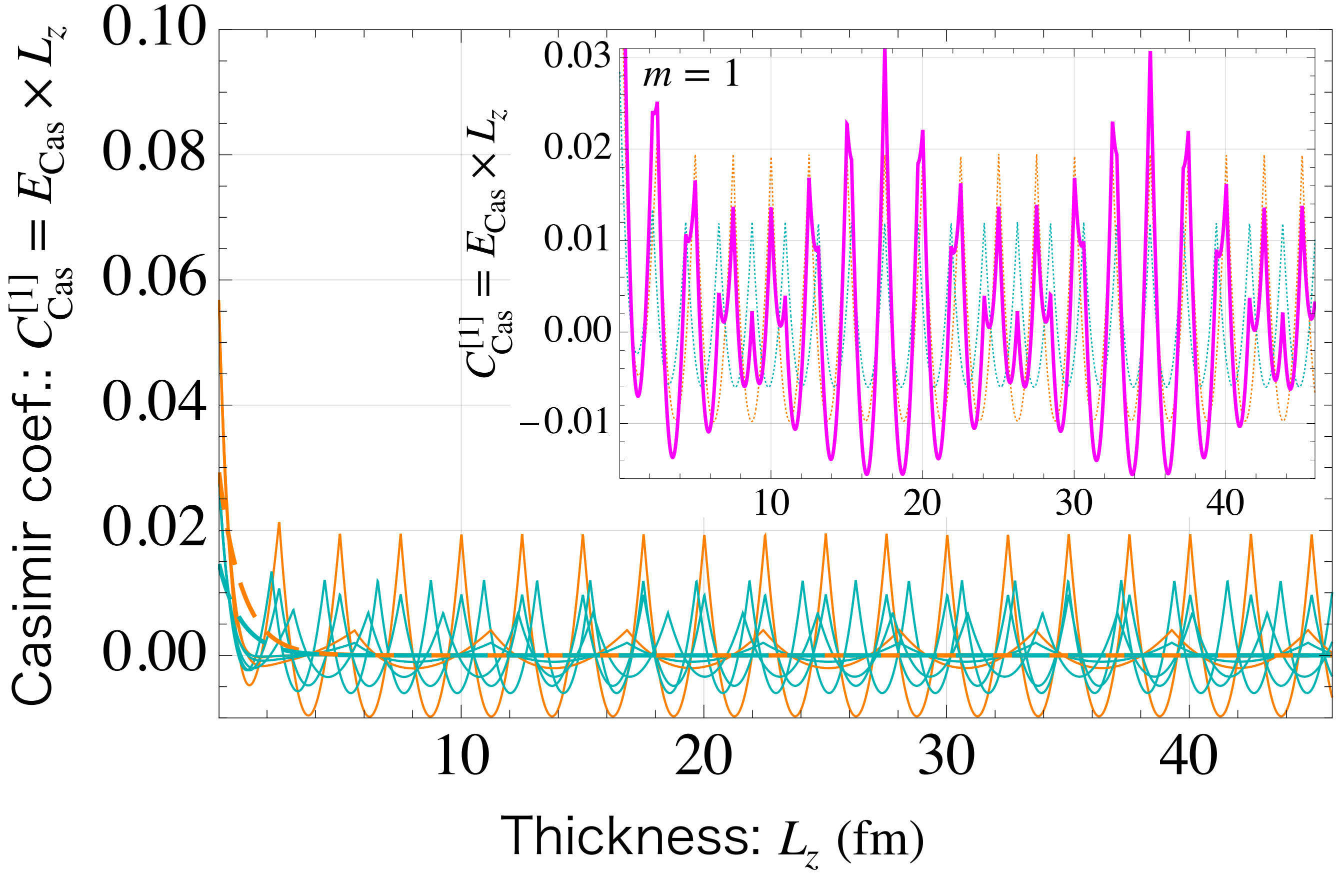

$M/\Lambda = 0.47$, $q/\Lambda = 0$, $\mu/\Lambda = 0.46$
Casimir coef.: $C_{\rm Cas}^{[3]} = E_{\rm Cas} \times L_z^3$
Thickness: $aN_z = L_z$ (fm)
"MIT BC"
a=0.4 (Dirac)
a=0.2 (Dirac)
a=0.4 (Fermi)
a=0.2 (Fermi)
a=0.4 (Total)
a=0.2 (Total)
a=0 (Dirac)


$M/\Lambda = 0.09$, $q/\Lambda = 0.62$, $\mu/\Lambda = 0.72$
Casimir coef.: $C_{\rm Cas}^{[3]} = E_{\rm Cas} \times L_z^3$
Thickness: $aN_z = L_z$ (fm)
"MIT BC"
a=0.4 (Dirac)
a=0.2 (Dirac)
a=0.4 (Fermi)
a=0.2 (Fermi)
a=0.4 (Total)
a=0.2 (Total)
a=0 (Dirac)

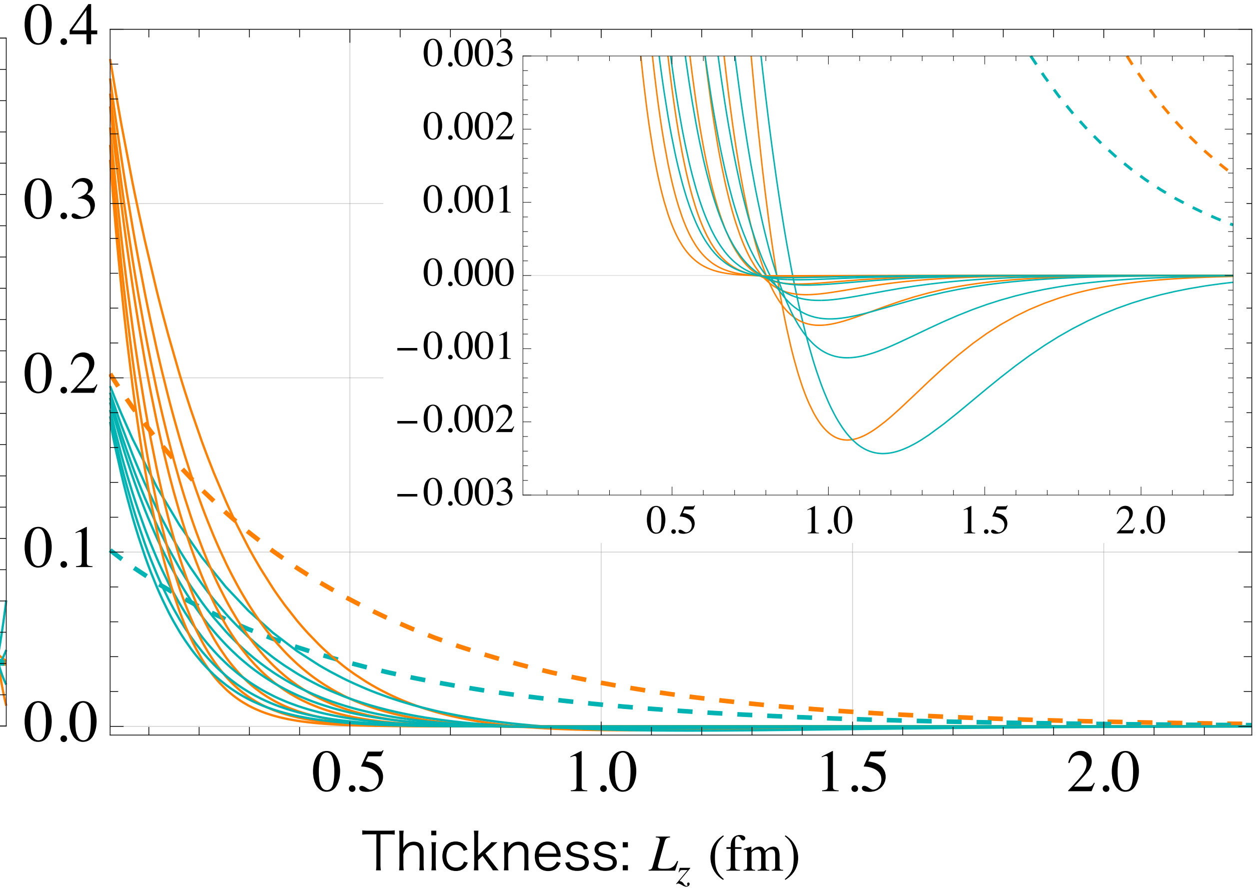

$M/\Lambda = 0.46$, $q/\Lambda = 0$, $\mu/\Lambda = 0.485$
Casimir coef.: $C_{\rm Cas}^{[3]} = E_{\rm Cas} \times L_z^3$
Thickness: $aN_z = L_z$ (fm)
"MIT BC"
a=0.4 (Dirac)
a=0.2 (Dirac)
a=0.4 (Fermi)
a=0.2 (Fermi)
a=0.4 (Total)
a=0.2 (Total)
a=0 (Dirac)

Buck up

Intermediate magnetic fields



Strong magnetic fields



Buck up

E. Nakano and T. Tatsumi (2005)