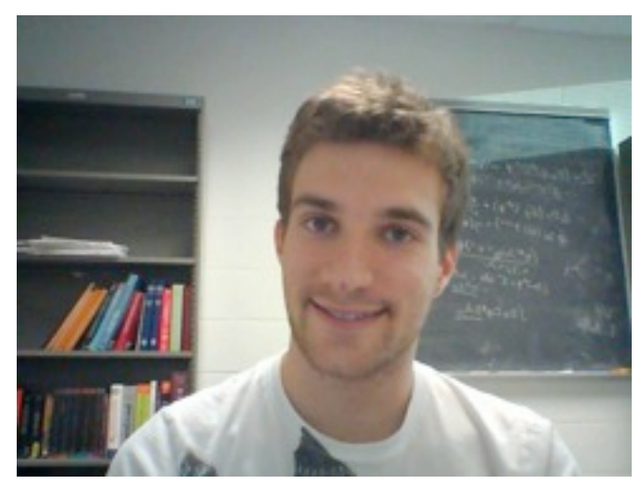
Unparticles and Superconductivity

Thanks to: NSF, EFRC (DOE)

Kiaran dave

Charlie Kane



Brandon Langley

J. A. Hutasoit

Properties all particles share?

Properties all particles share?

charge

fixed mass!

Properties all particles share?

charge

fixed mass!

conserved (gauge invariance)

Properties all particles share?

charge

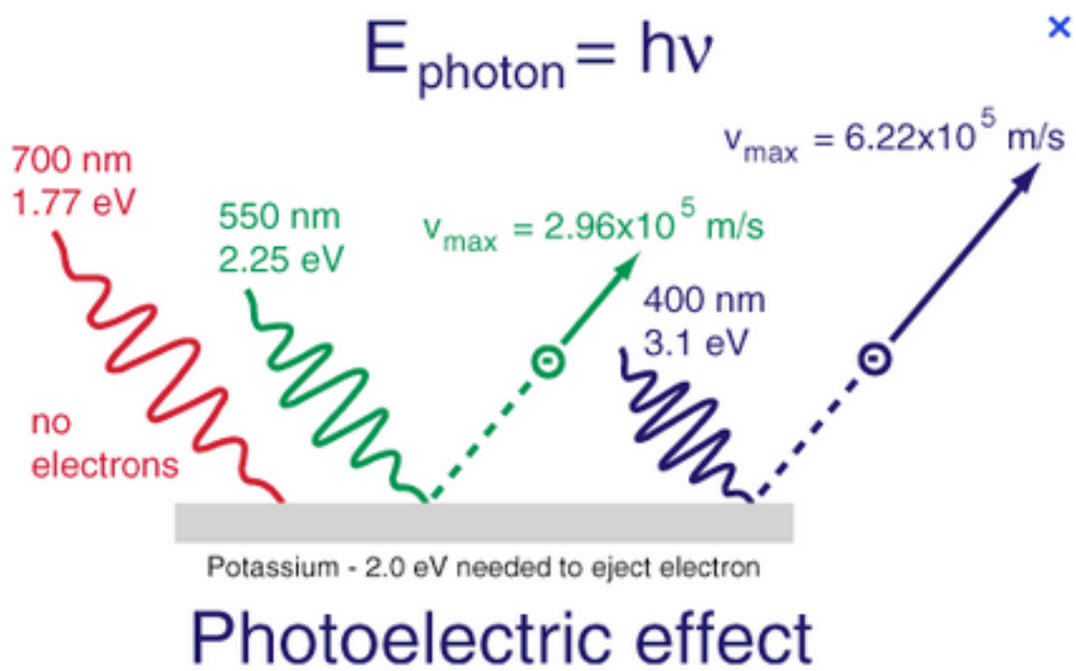
fixed mass!

conserved (gauge invariance)

not conserved

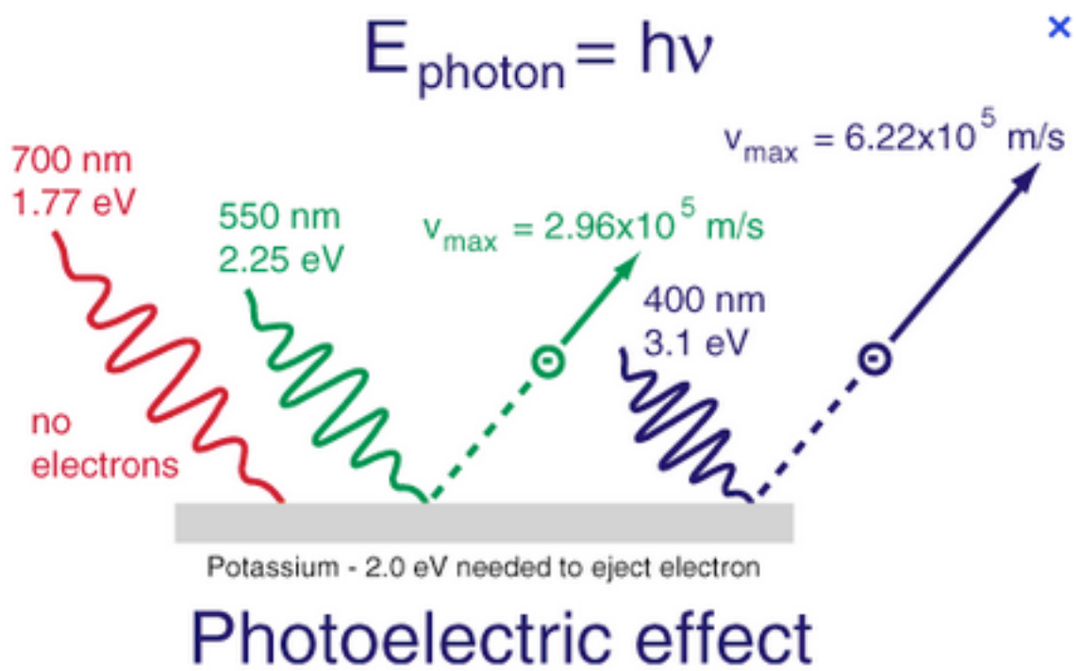
mass sets a scale

particles



energy $E = \varepsilon_p$

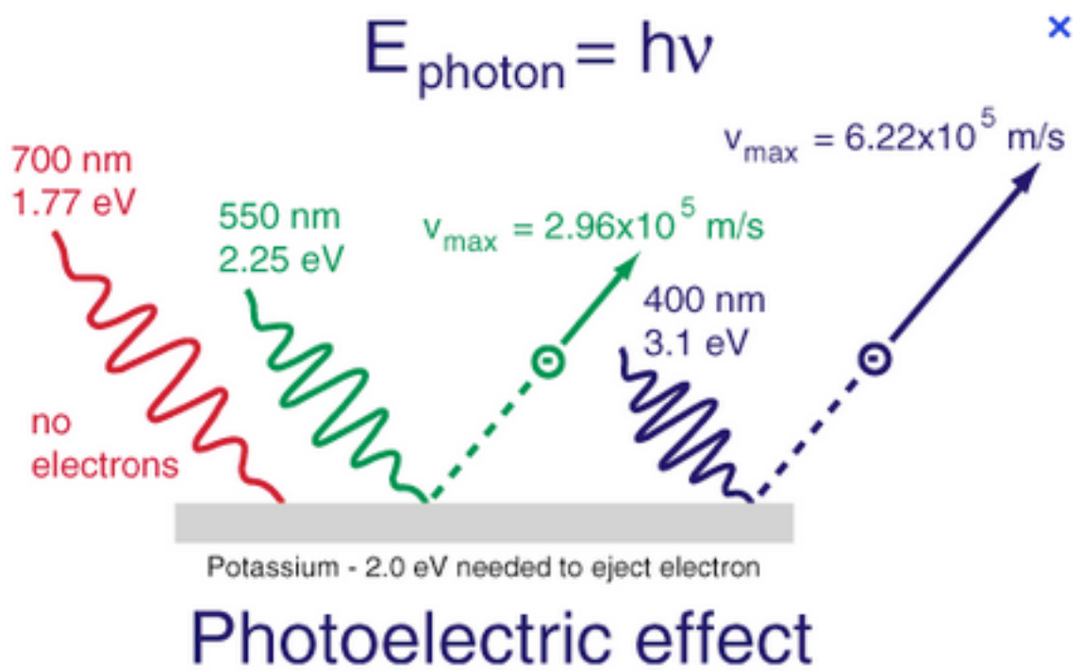
particles



energy $E = \varepsilon_p$

$$G(E) = \frac{1}{E - \varepsilon_p}$$

particles

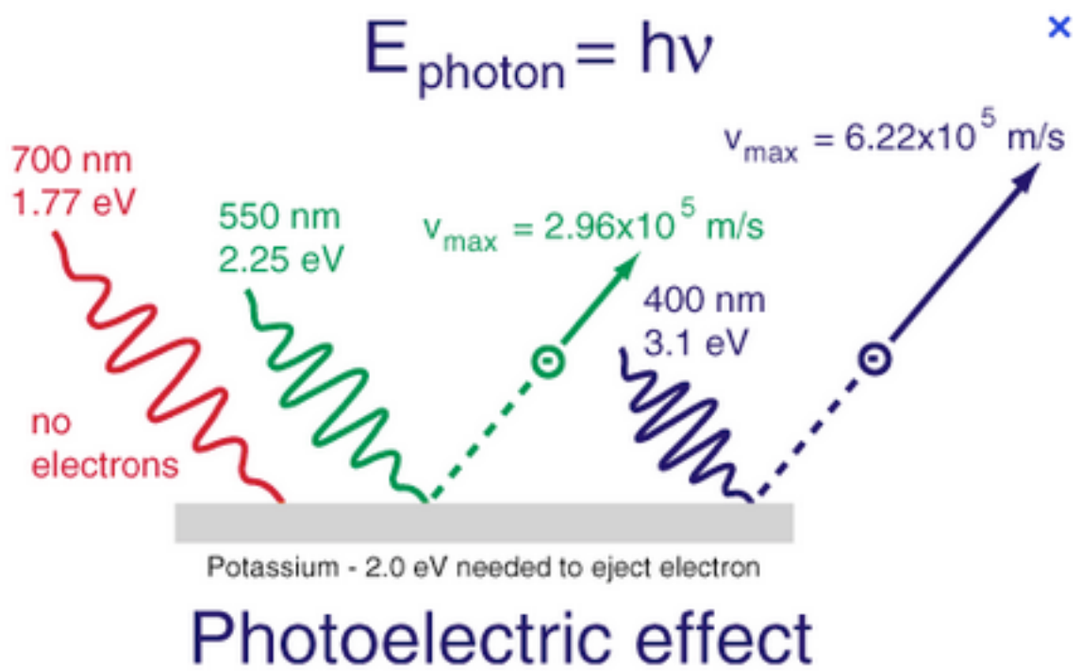


energy $E = \varepsilon_p$

$$G(E) = \frac{1}{E - \varepsilon_p}$$

particle=infinity

particles



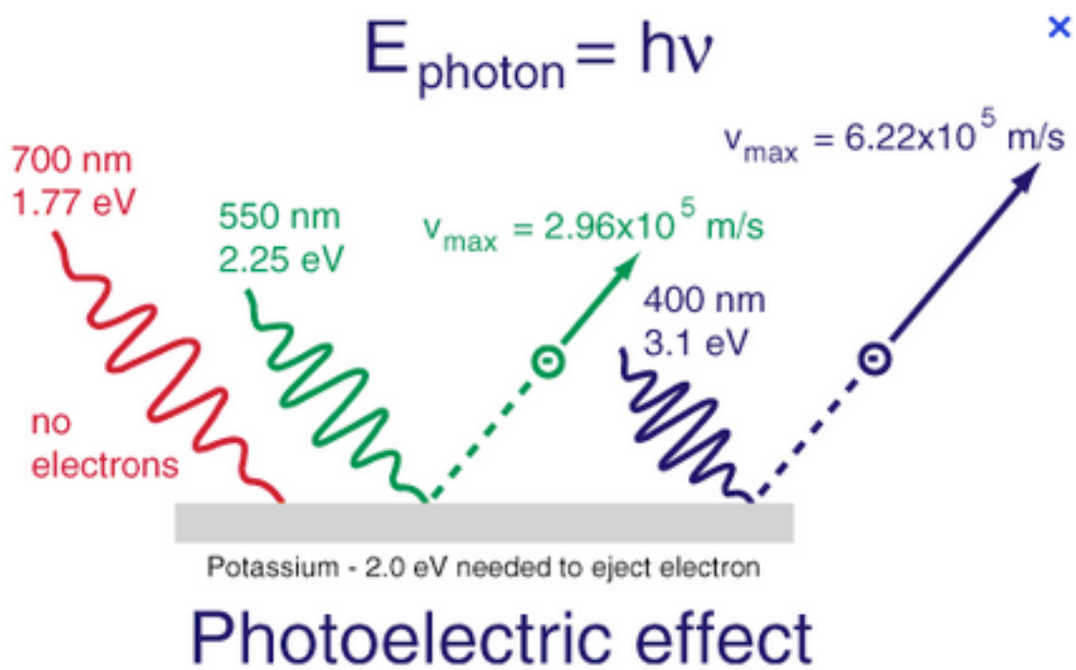
energy $E = \varepsilon_p$

Green function (propagator)

$$G(E) = \frac{1}{E - \varepsilon_p}$$

particle=infinity

particles =poles in Green function



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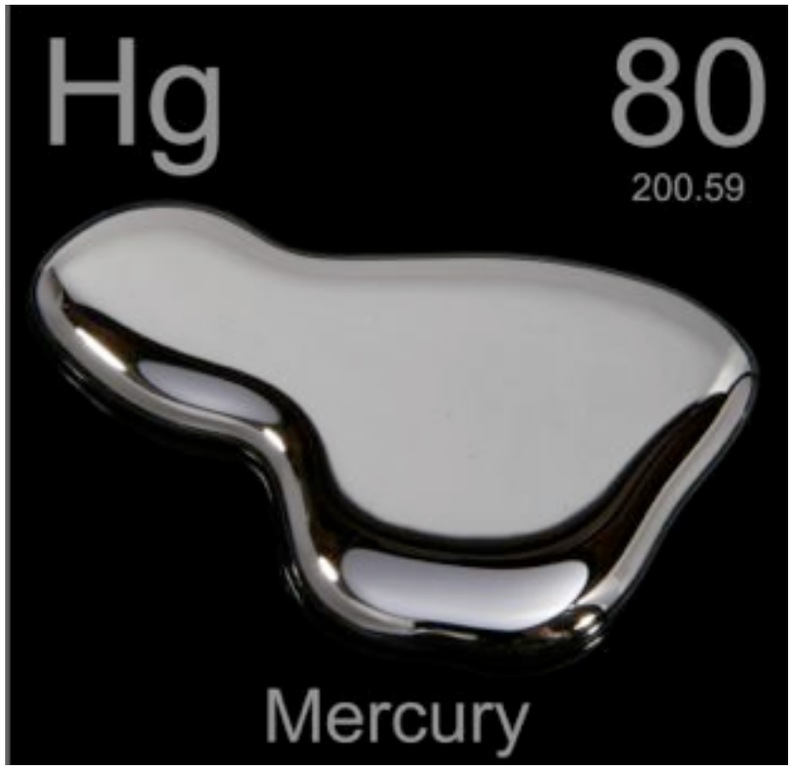

what would you see in a metal?

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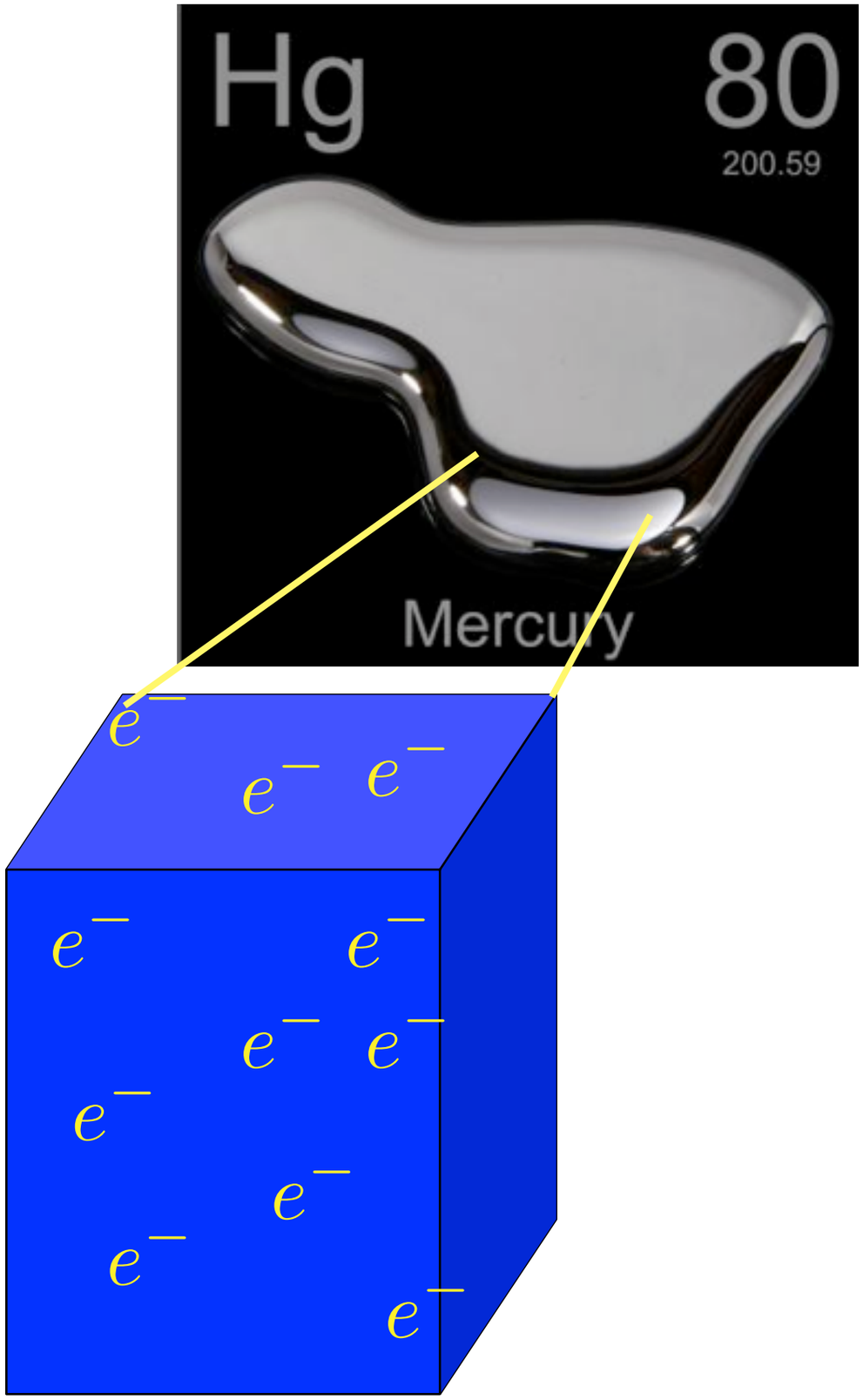

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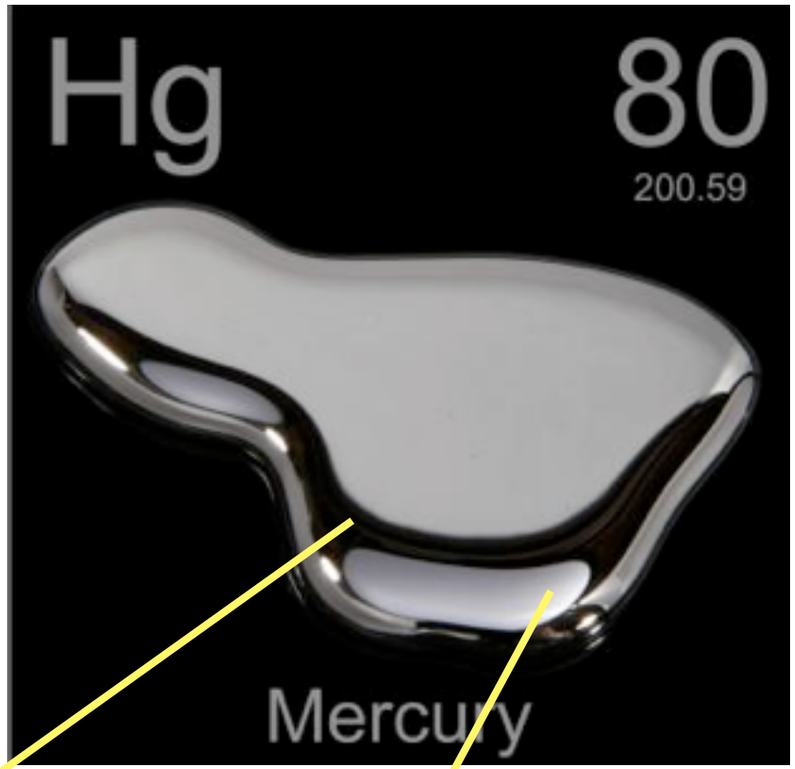

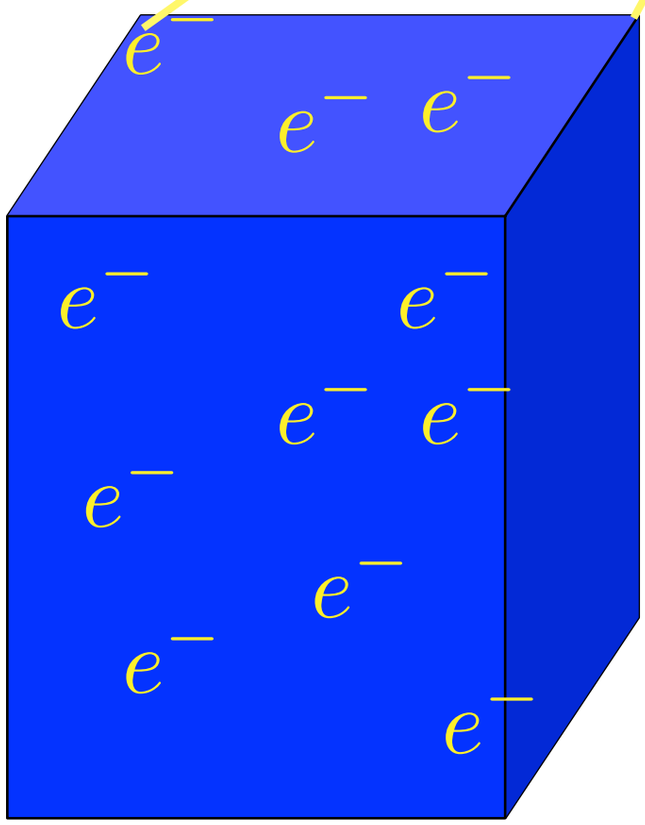

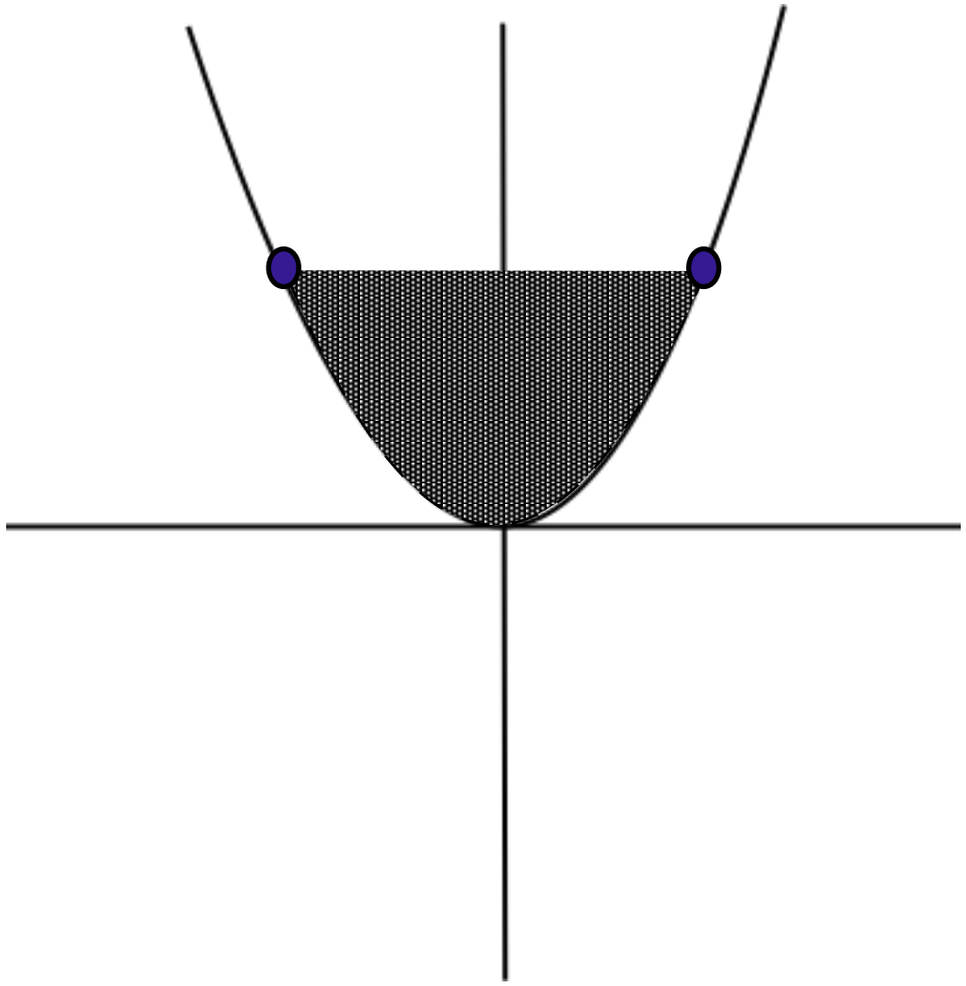

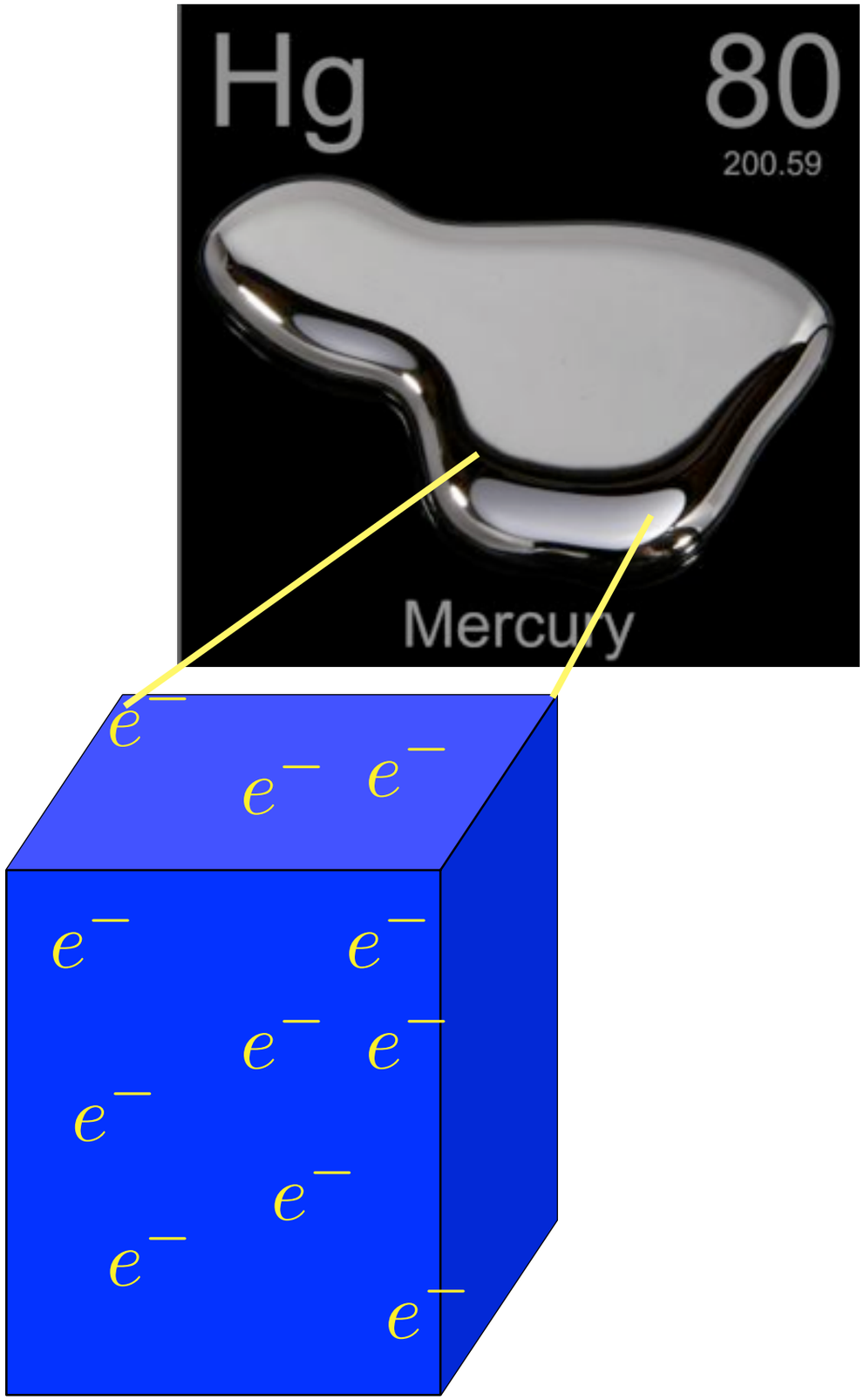

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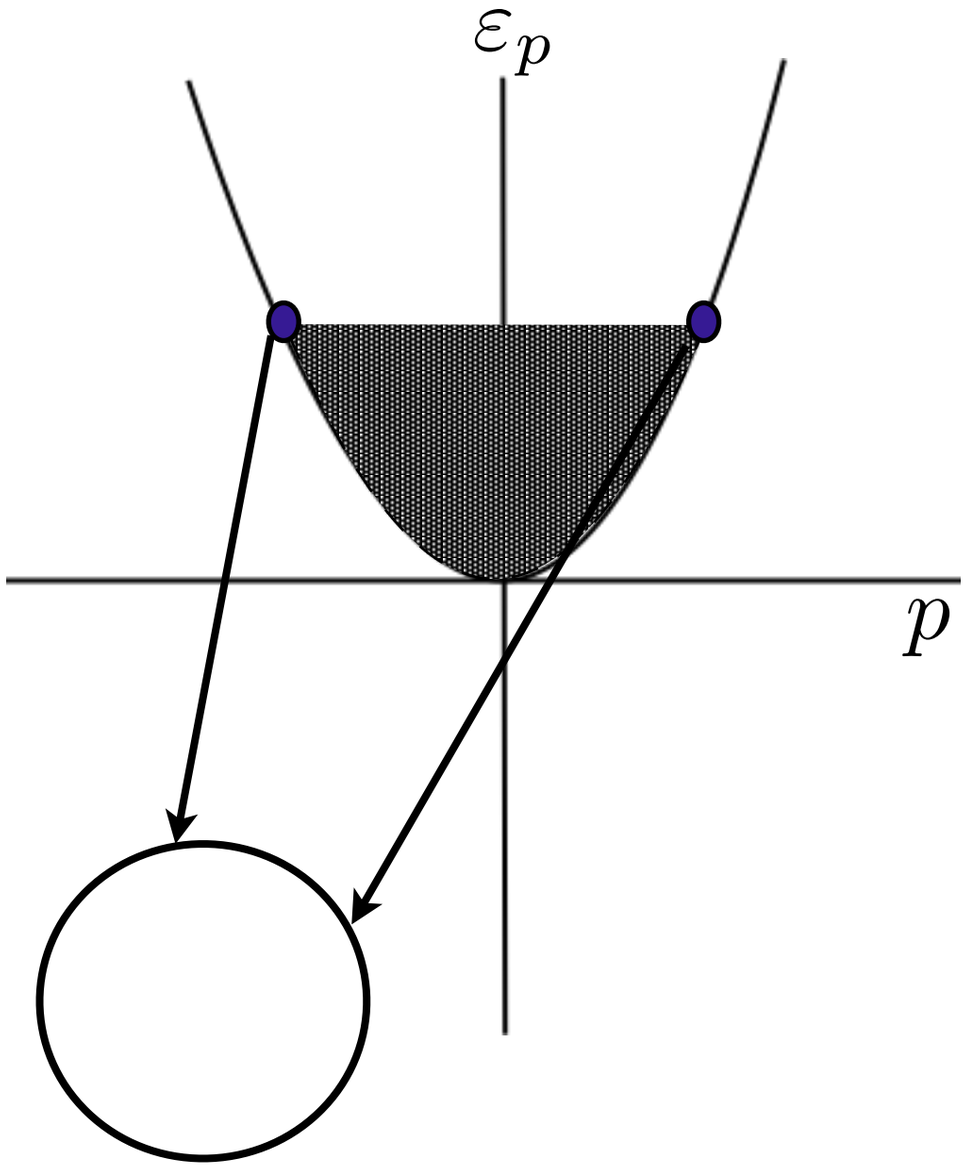
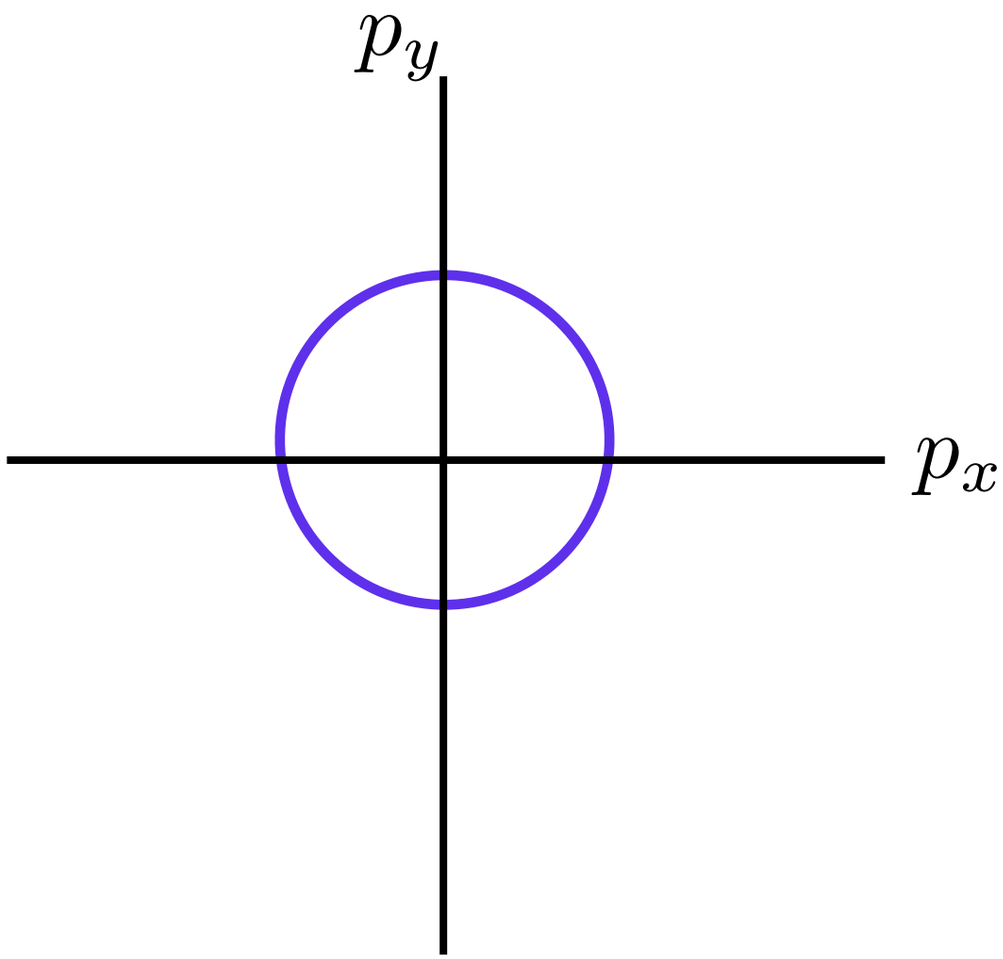


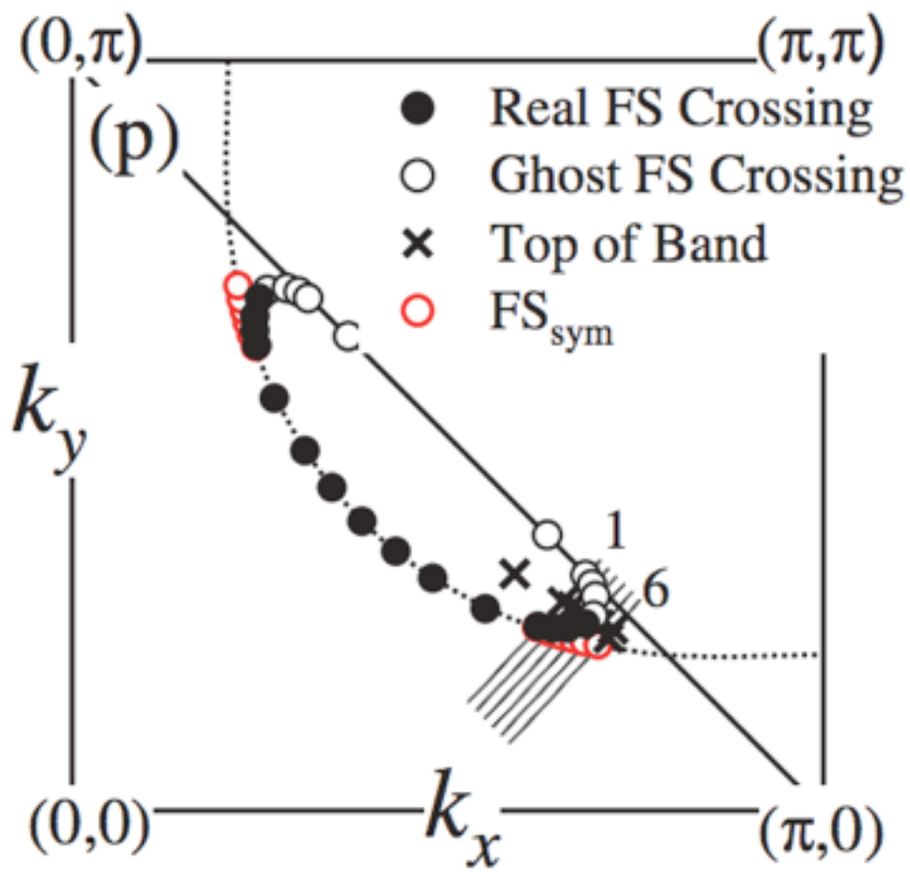
two crossings:
closed surface of excitations

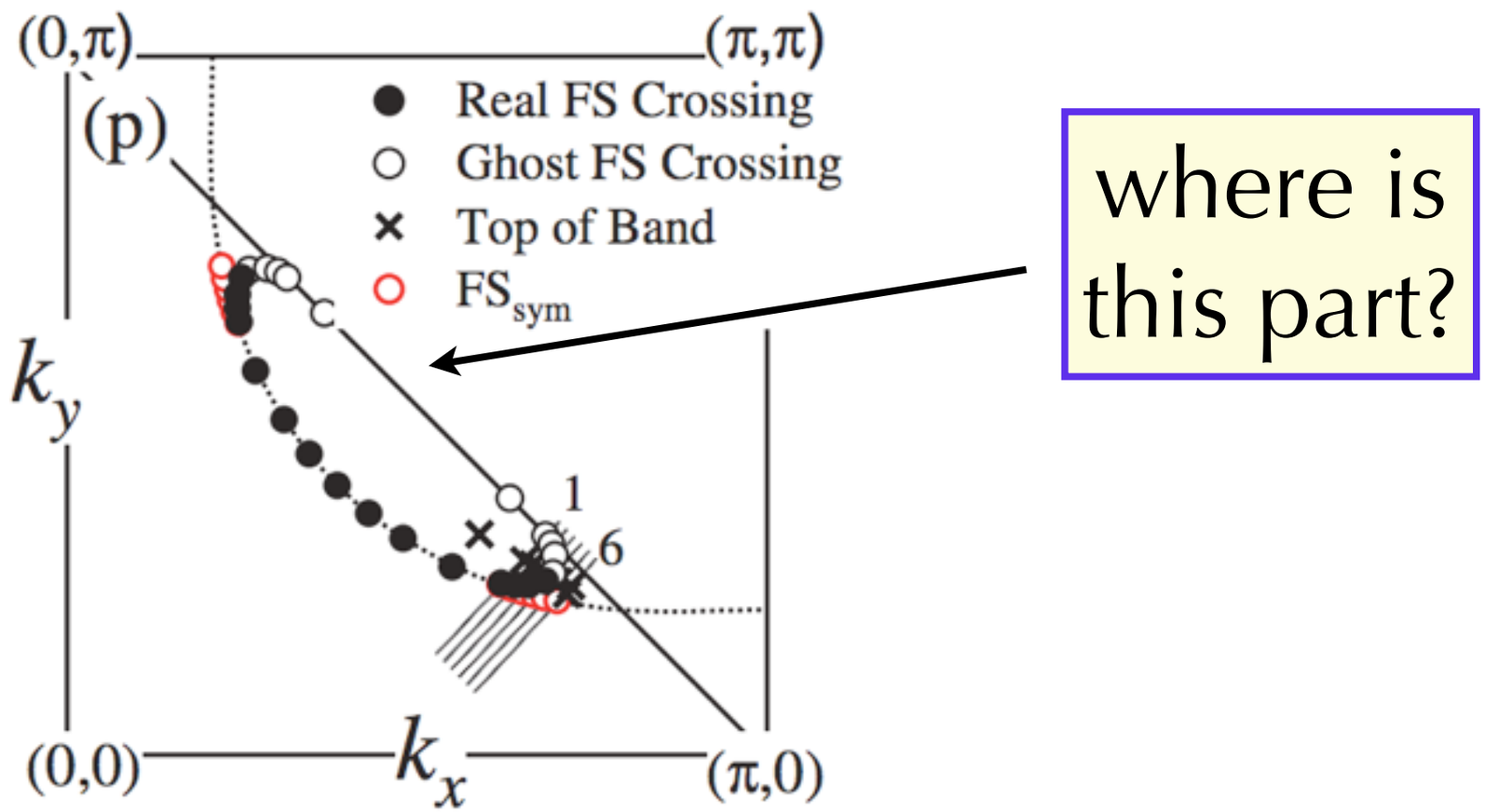
expect to see



closed surface

are there any exceptions?


(0,π)
(π,π)
(p)
Real FS Crossing
Ghost FS Crossing
Top of Band
FS$_{sym}$
k_y
1
6
(0,0)
k_x
(π,0)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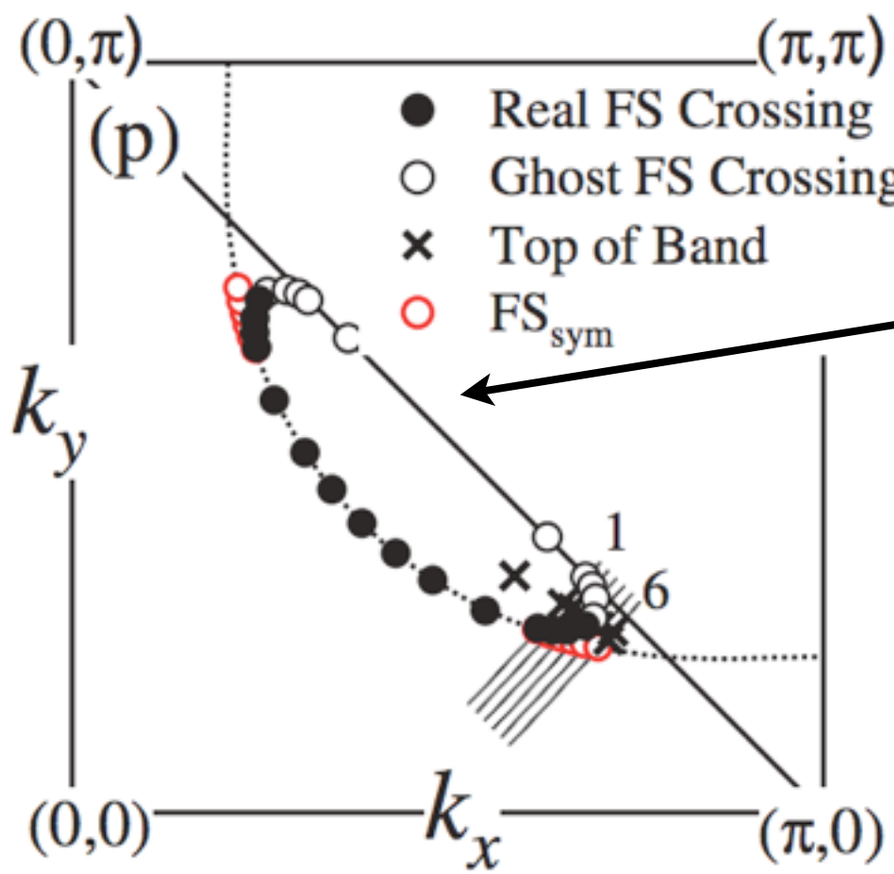
k_x
(π,0)
where is this part?

Fermi Arcs

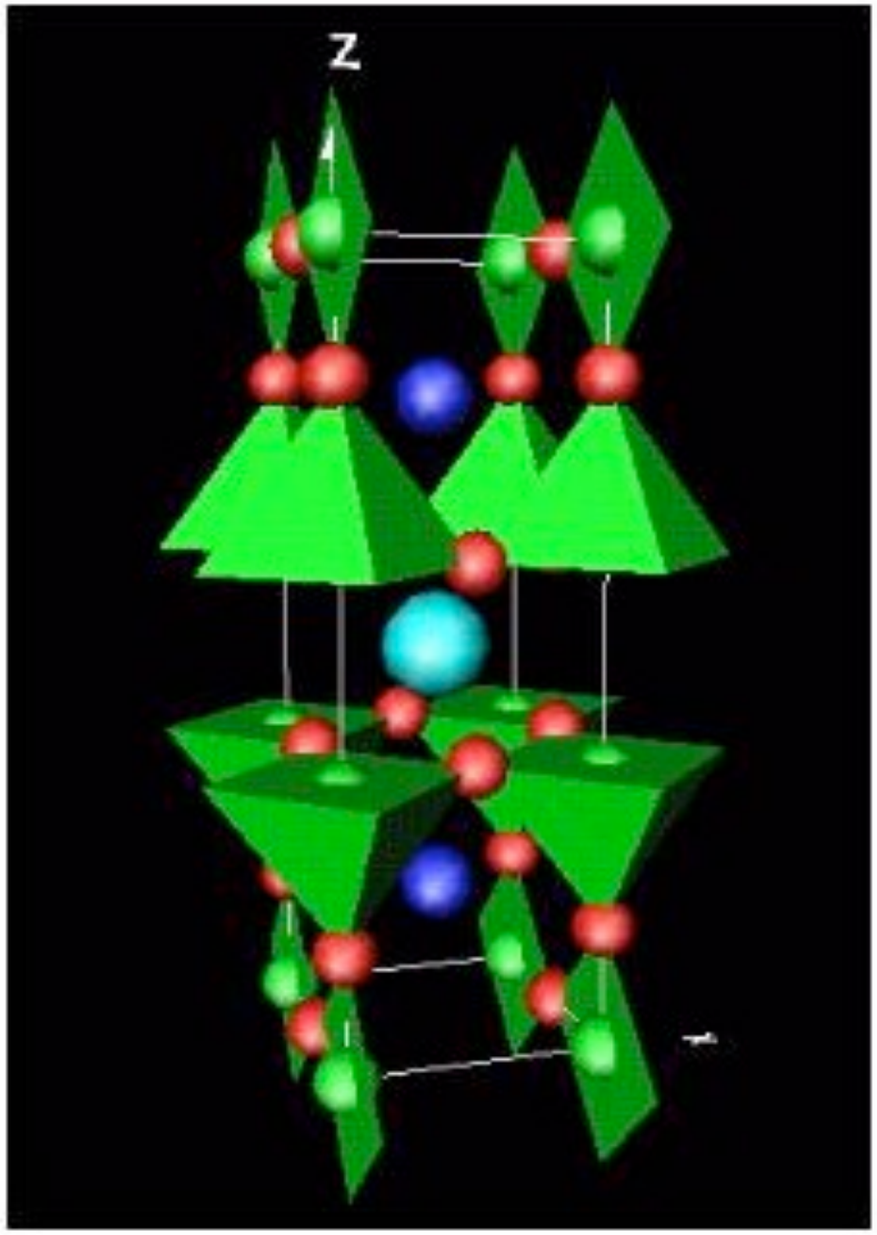


where is this part?

Fermi arcs:
(PDJ,JCC,ZXS)

where are arcs seen?

normal state

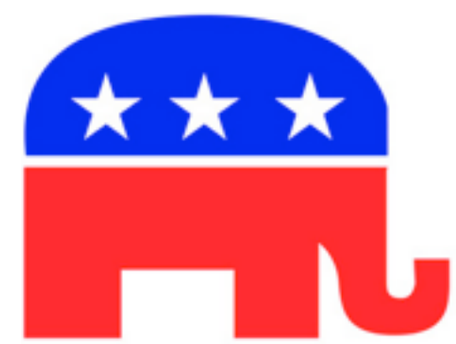


$YBa_2Cu_3O_7$
Cuprate Superconductors

ceramics

what's the explanation?

Two opposing Views on Fermi arcs

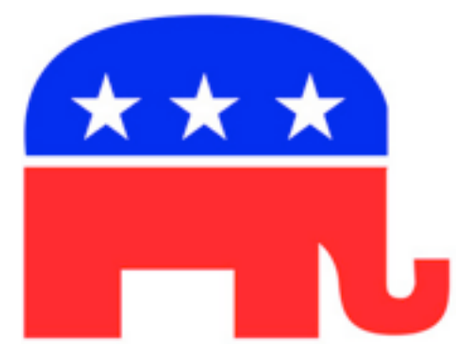


strange

not strange

what's the explanation?

Two opposing Views on Fermi arcs



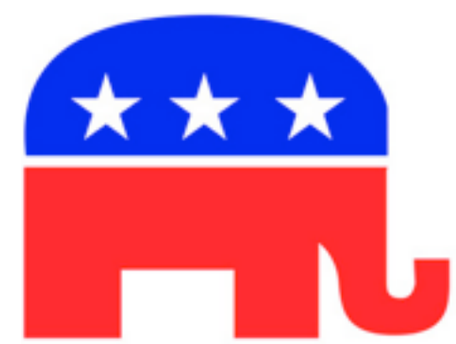
strange

not strange

this dispute has an answer!

what's the explanation?

Two opposing Views on Fermi arcs



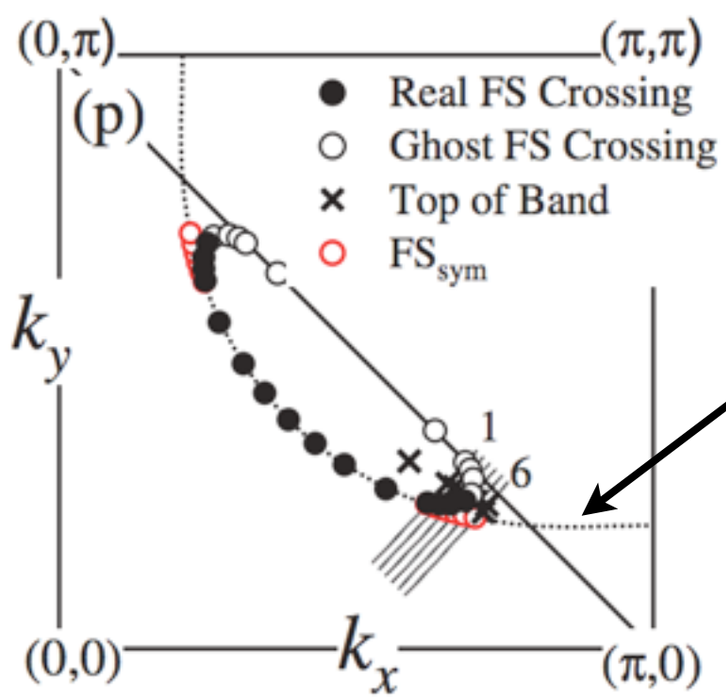
strange

not strange

unparticles

this dispute has an answer!

Right Wingers: Fermi Arcs are not Strange

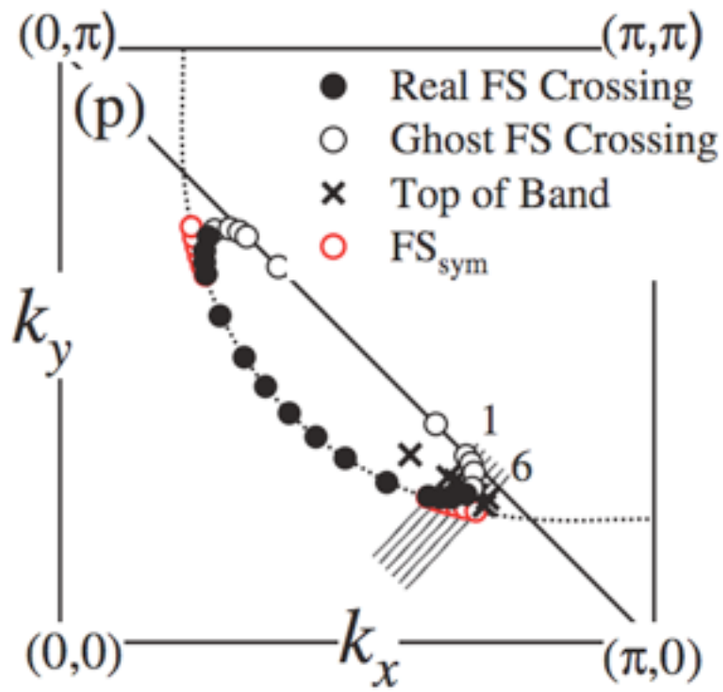


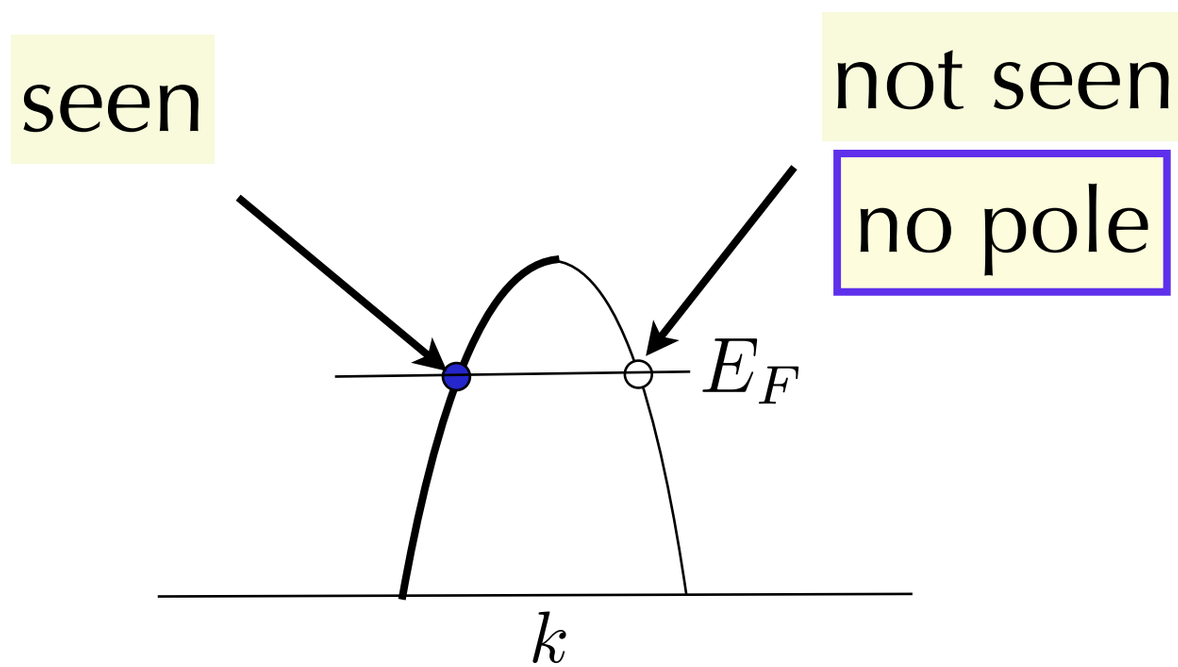
intensity too small to be seen

$$G(E) = \frac{Z_p}{\omega - \varepsilon_p}$$

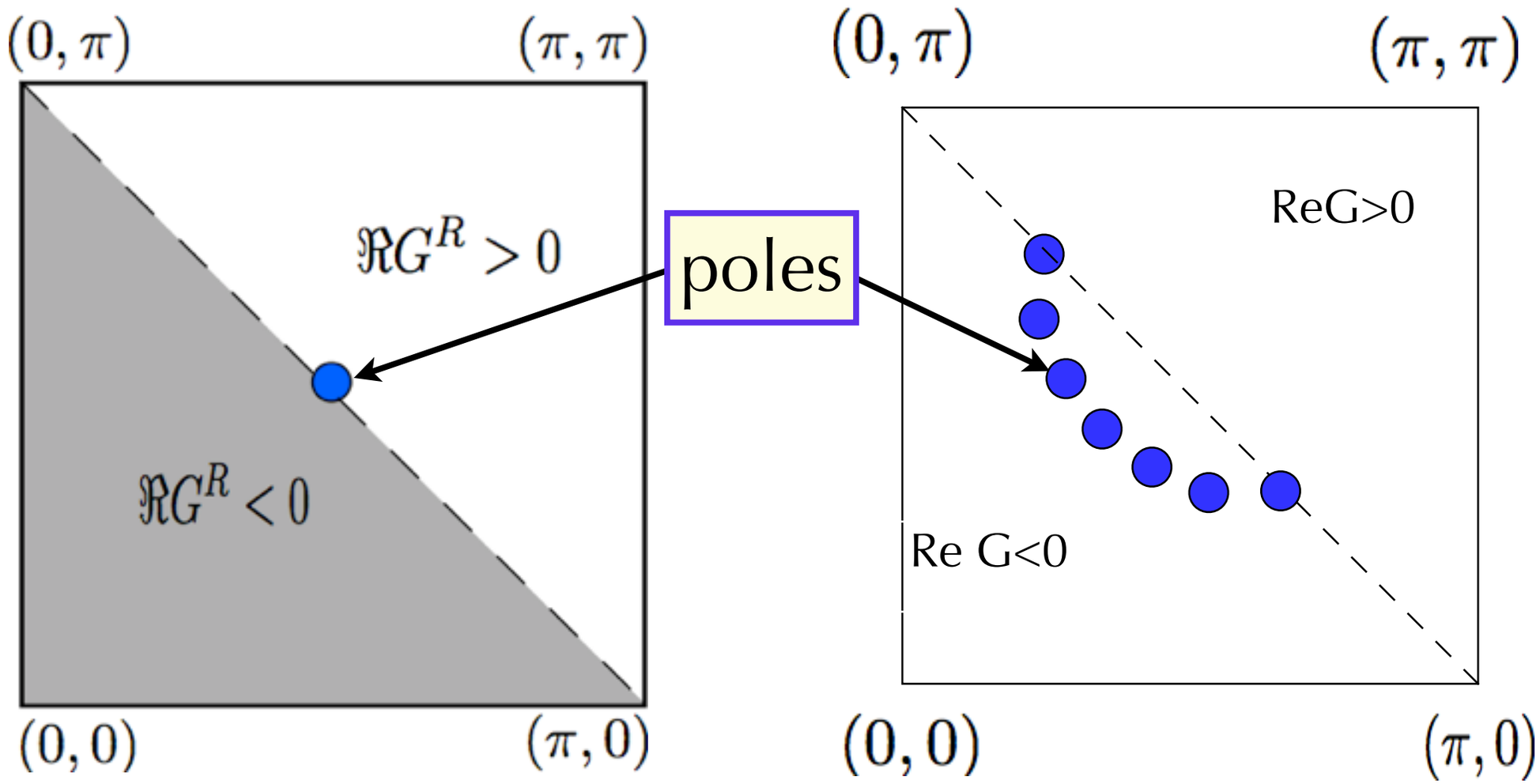
pole (particle) exists but $Z_p \to 0$

Fermi Arcs are Strange

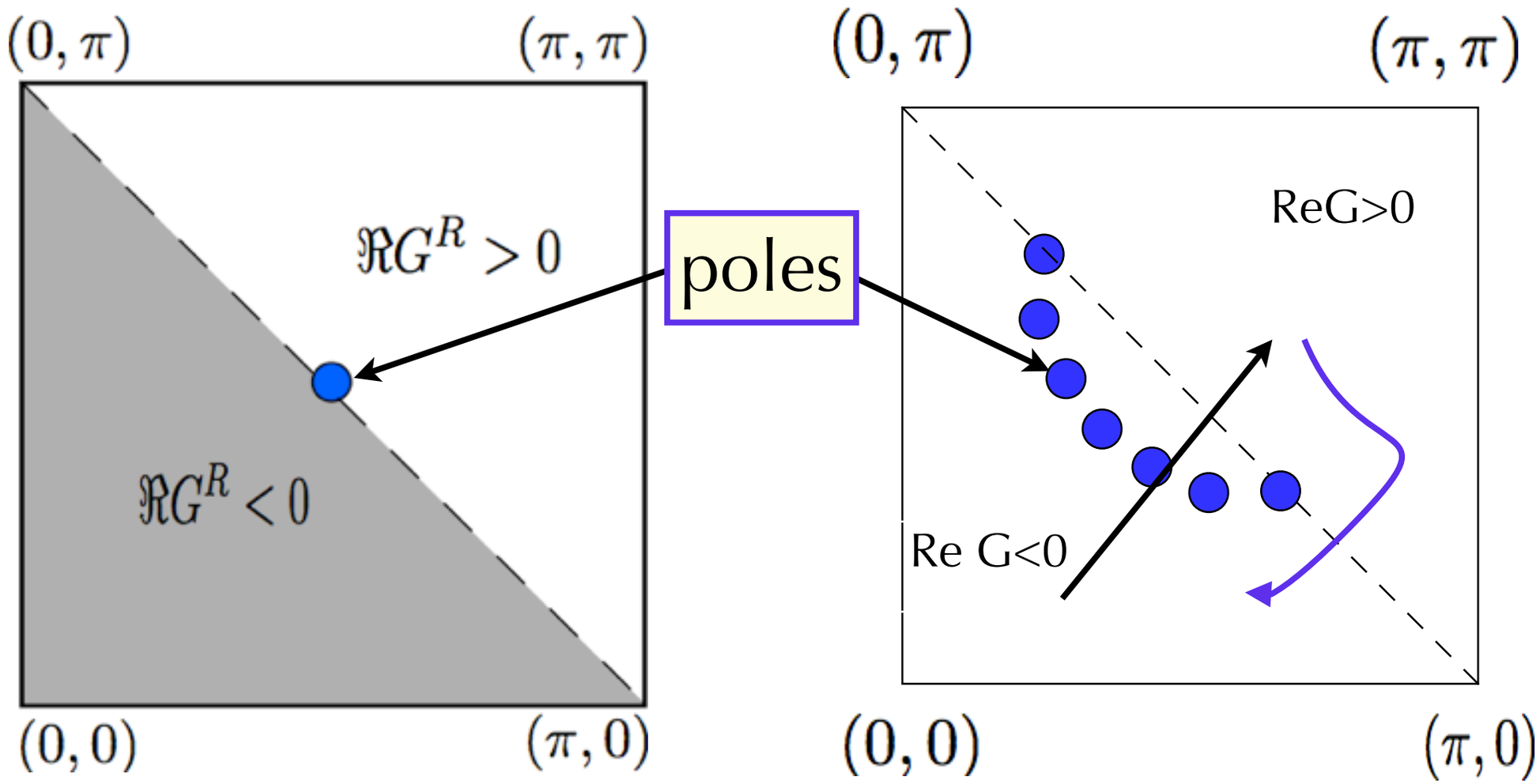




Problem for left-wingers (me)

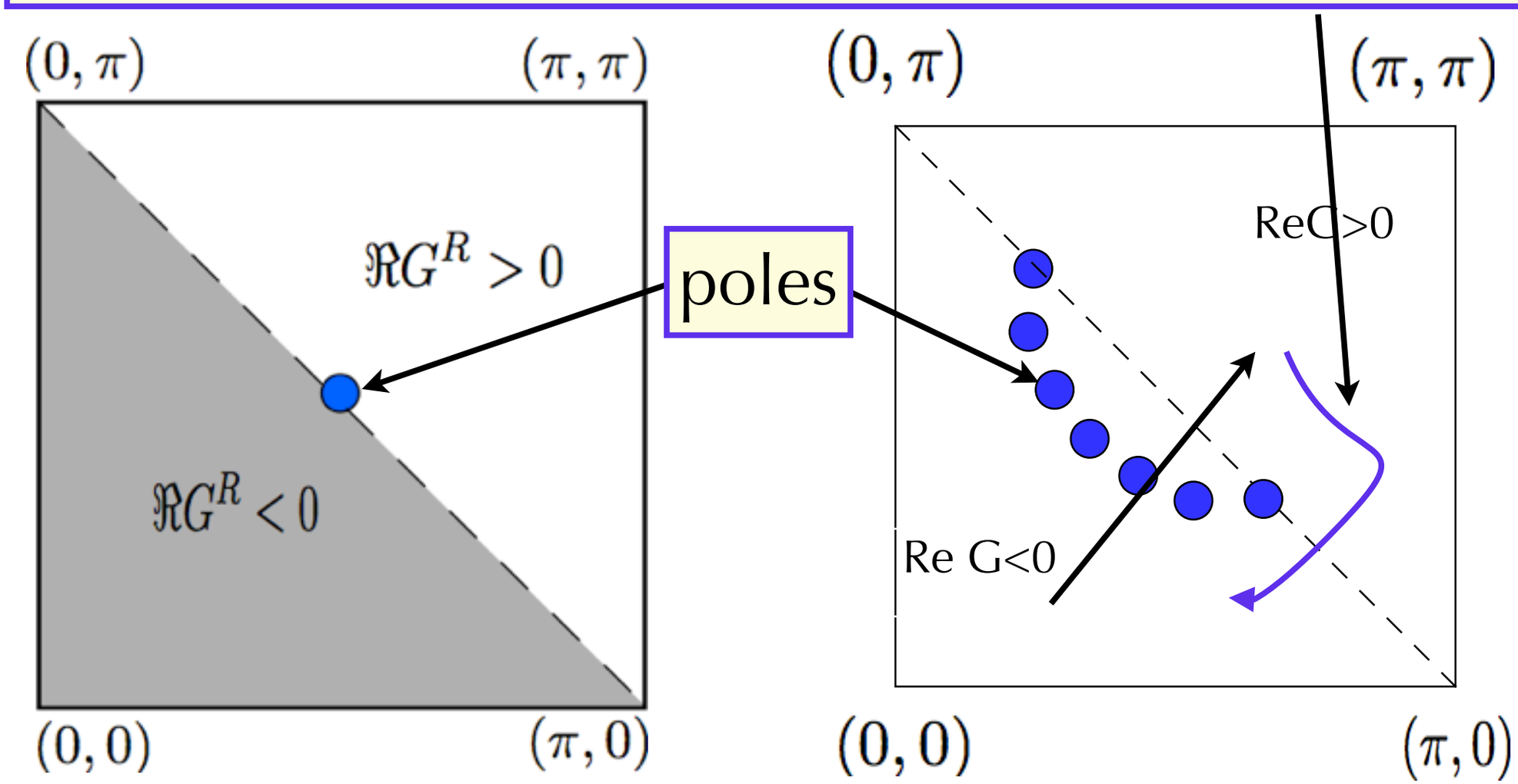


Problem for left-wingers (me)



Problem for left-wingers (me)

How to account for the sign change without poles?



Fermi arcs

pole

no pole

$$\frac{0}{\#}$$

$$\frac{\#}{E - \epsilon_p - \infty} = 0$$

do poles account for all the charged stuff?

if not?

if not?

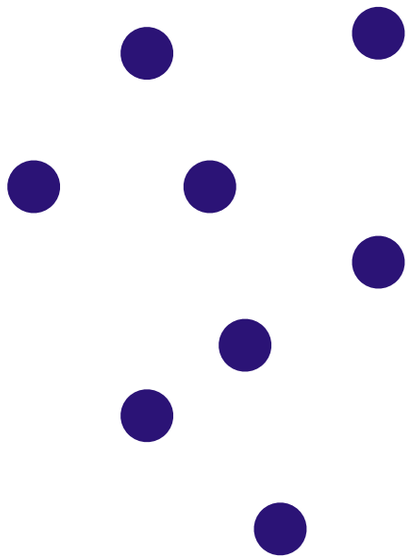
charge stuff= particles + other stuff

if not?

charge stuff= particles + other stuff

unparticles!

counting particles



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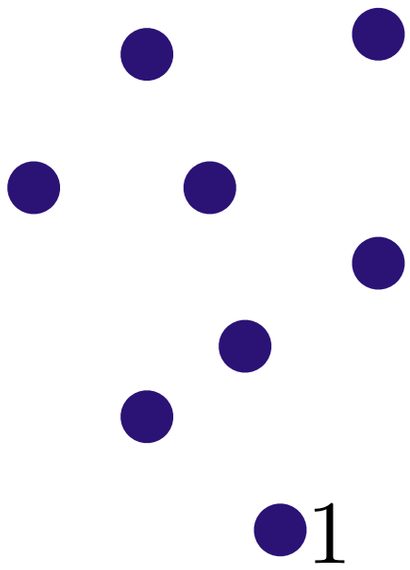

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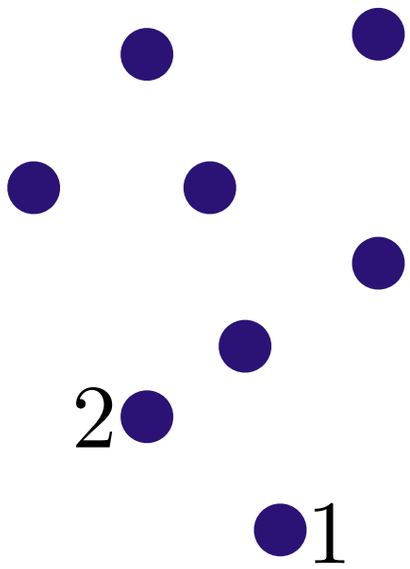

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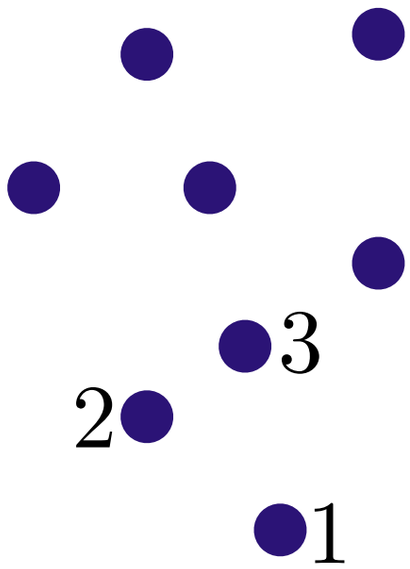

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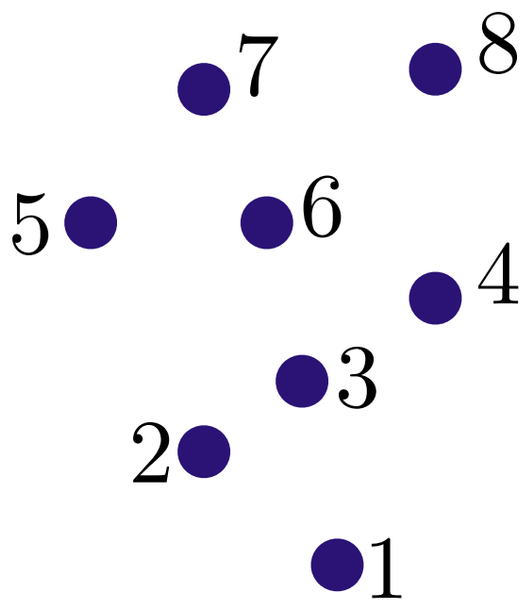

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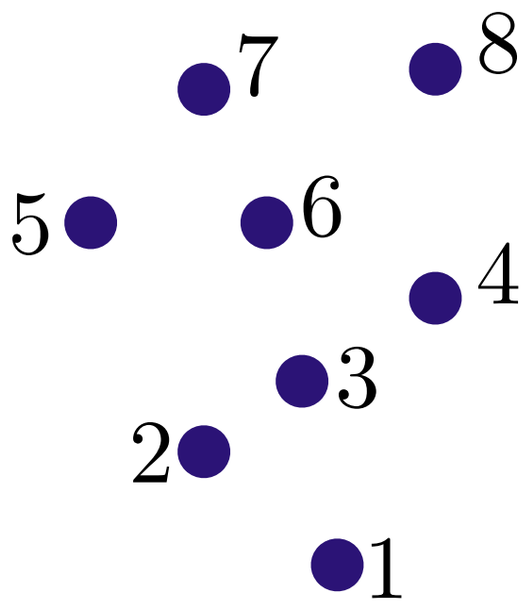
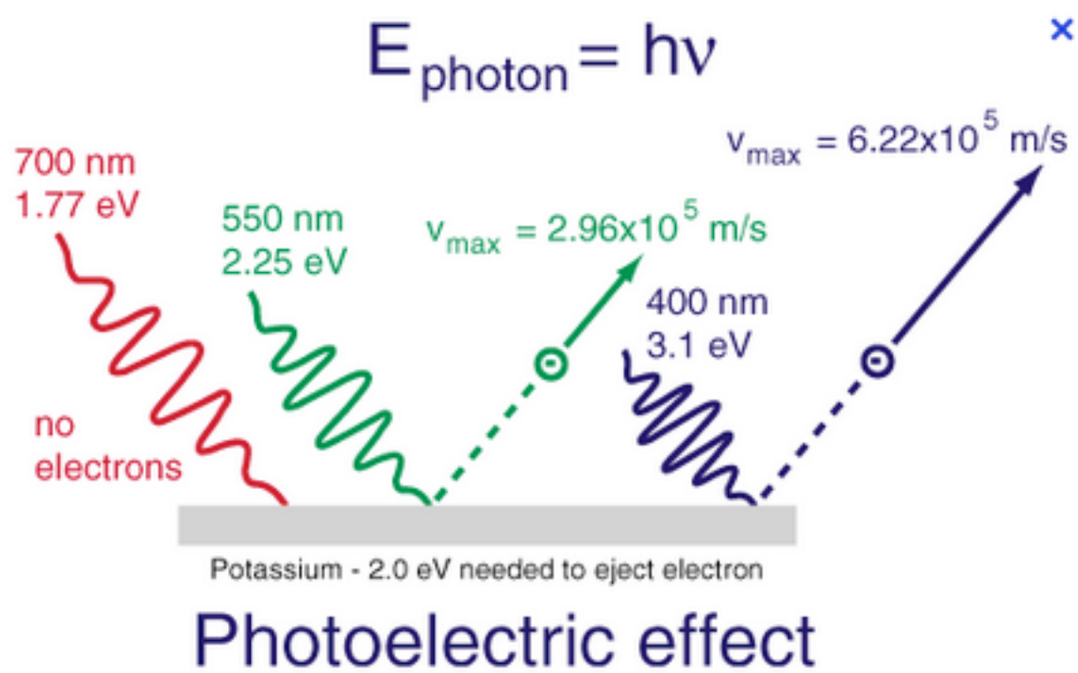


is there a more efficient way?

Each particle has an energy

particles



energy $E = \varepsilon_p$

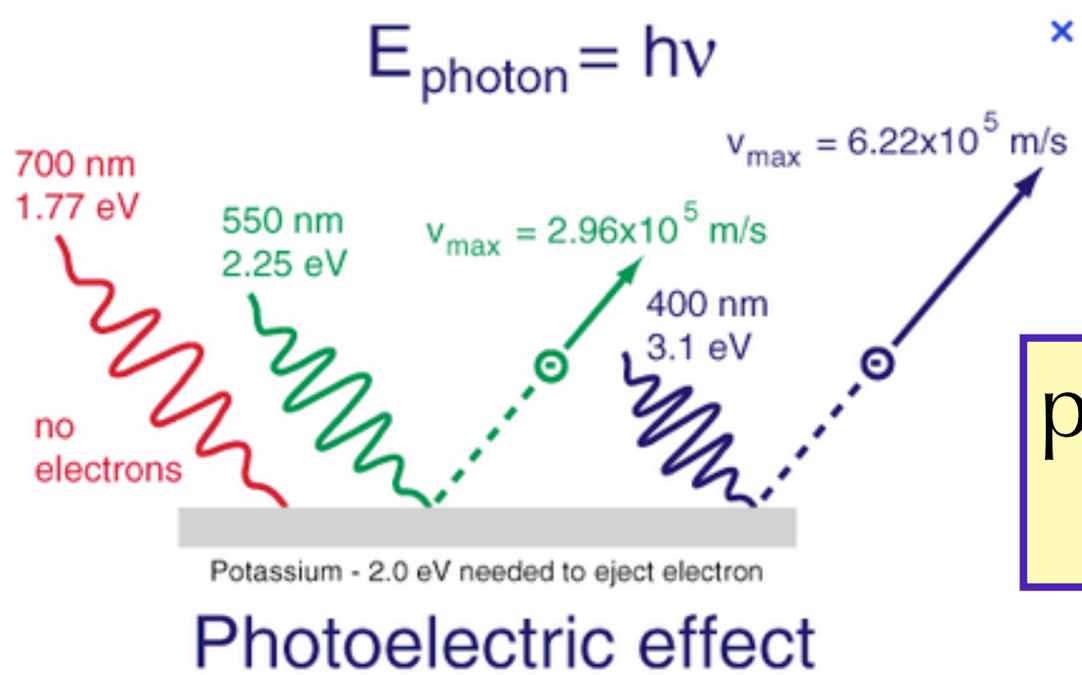
Green function (propagator)

$$G(E) = \frac{1}{E - \varepsilon_p}$$

particle=infinity

Each particle has an energy

particles



particle count is deducible from Green function

energy $E = \varepsilon_p$

Green function (propagator)

$$G(E) = \frac{1}{E - \varepsilon_p}$$

particle=infinity

Luttinger's Theorem

Green function (propagator)

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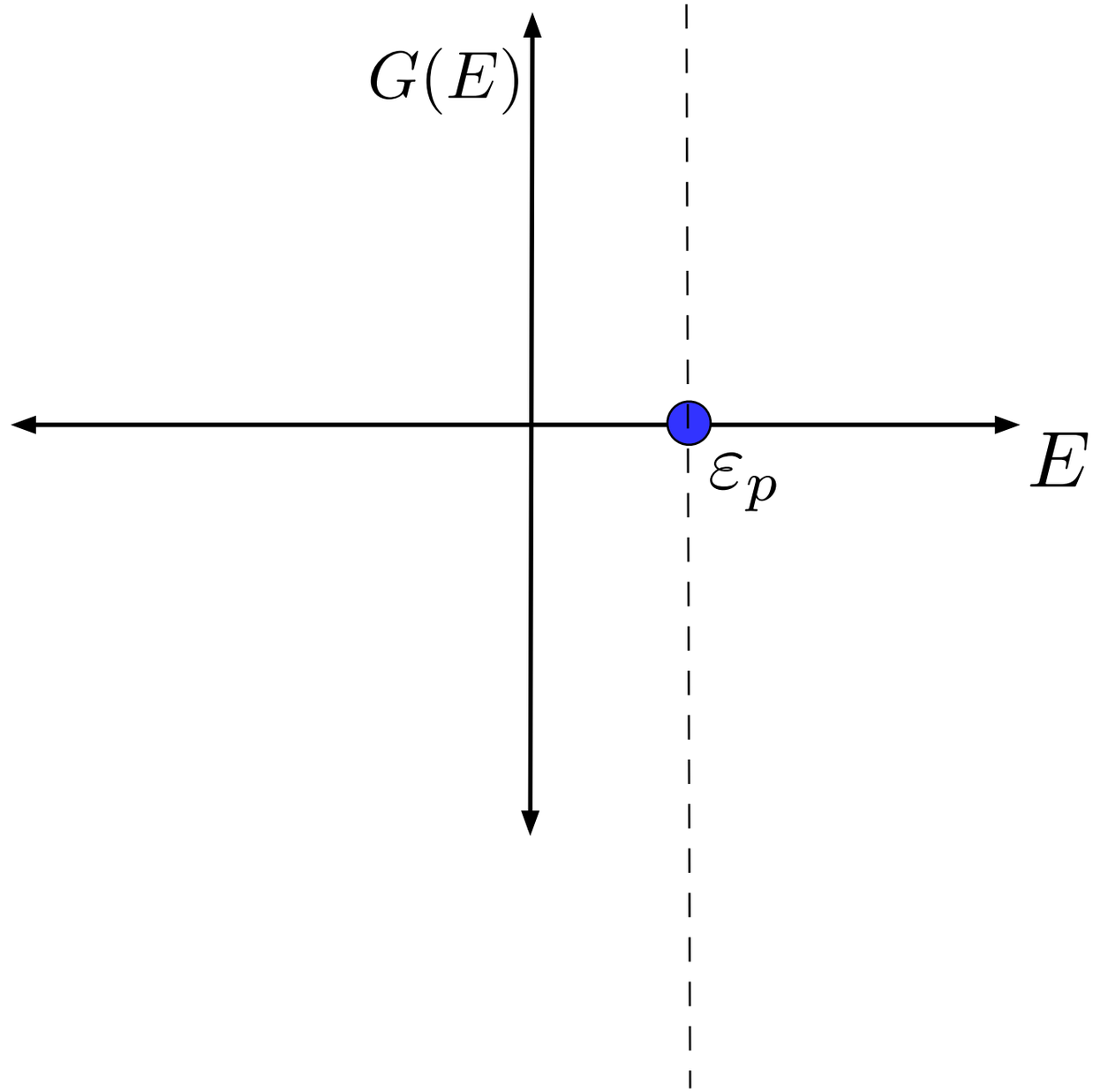

Luttinger's Theorem

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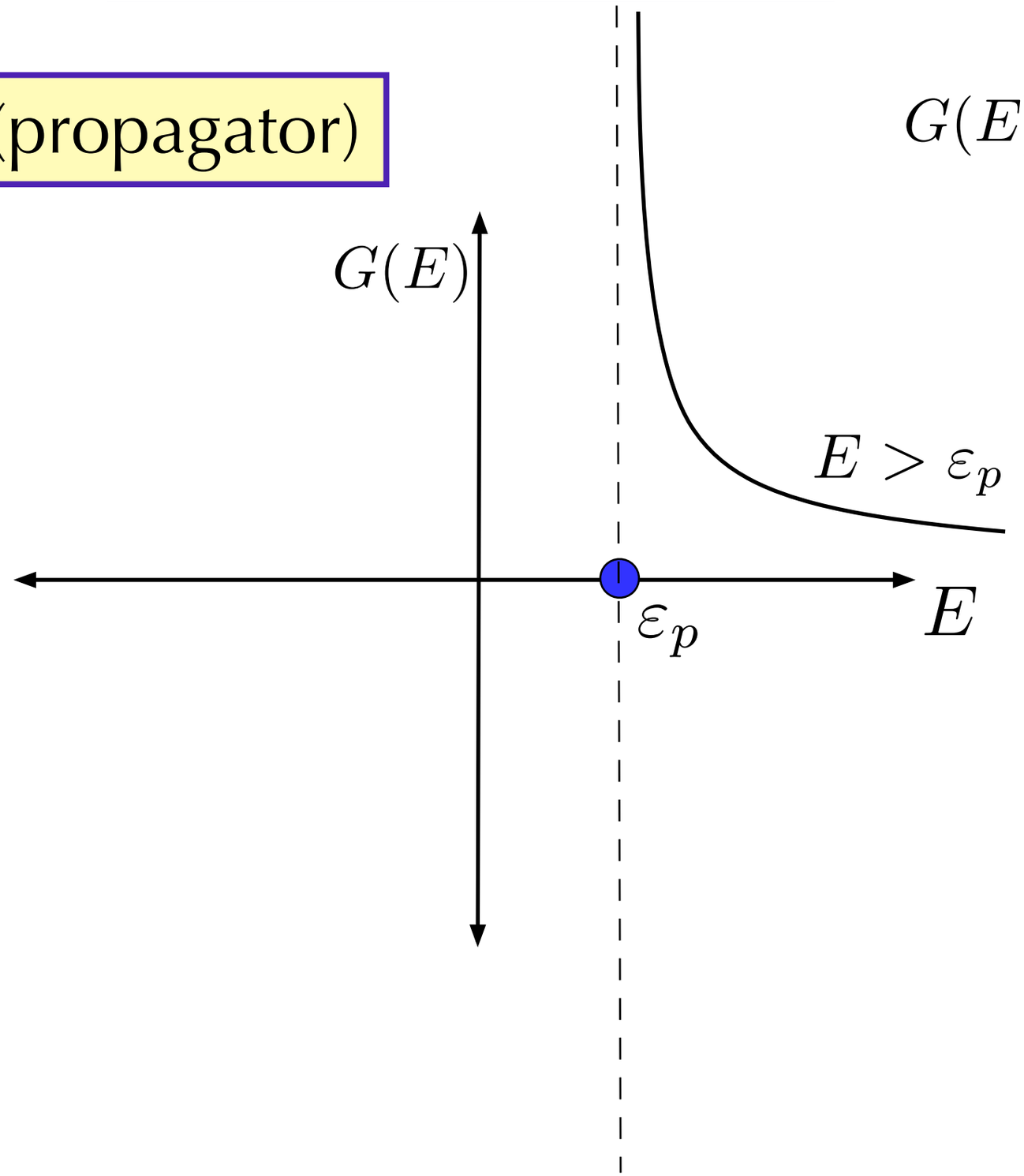

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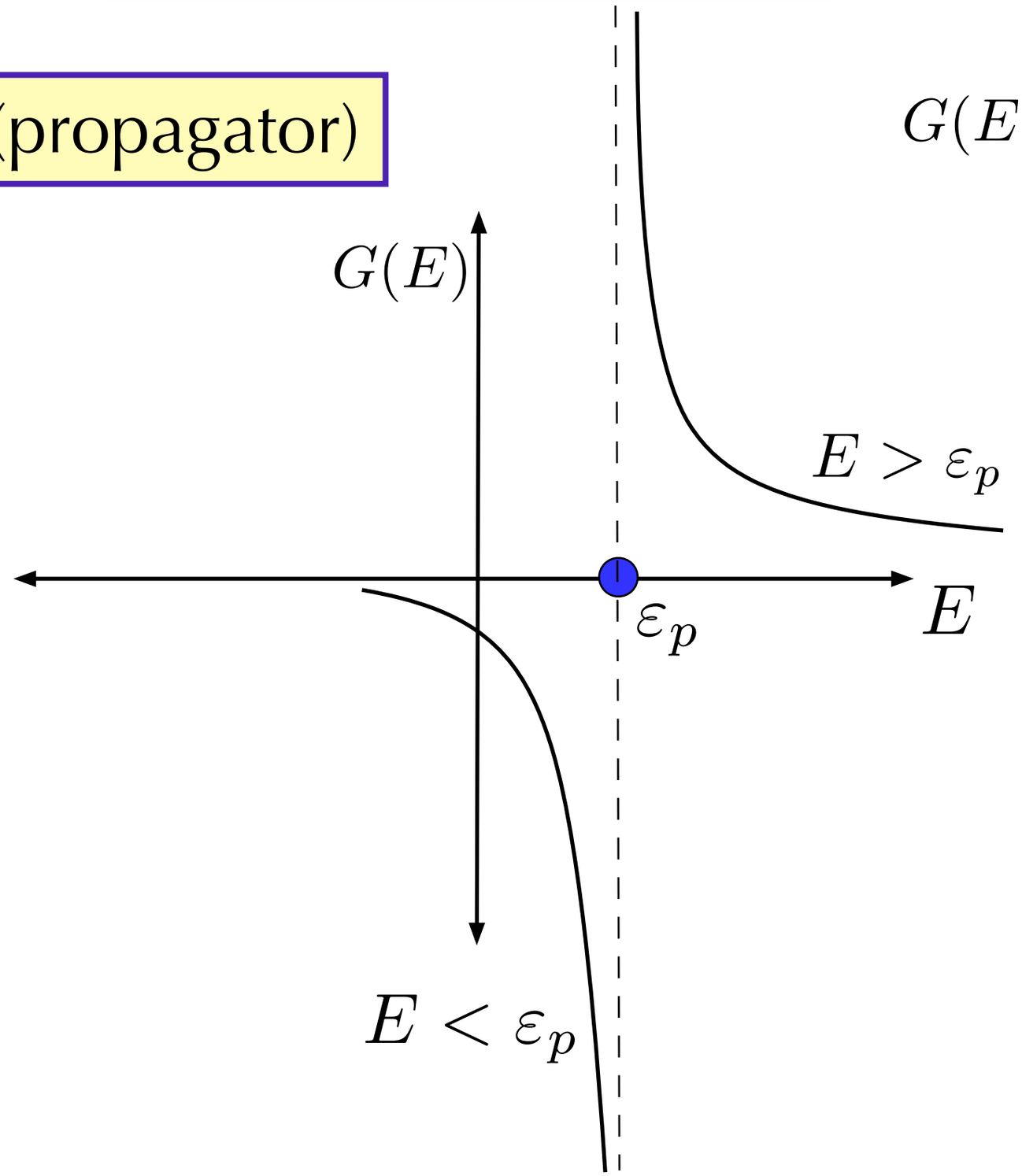

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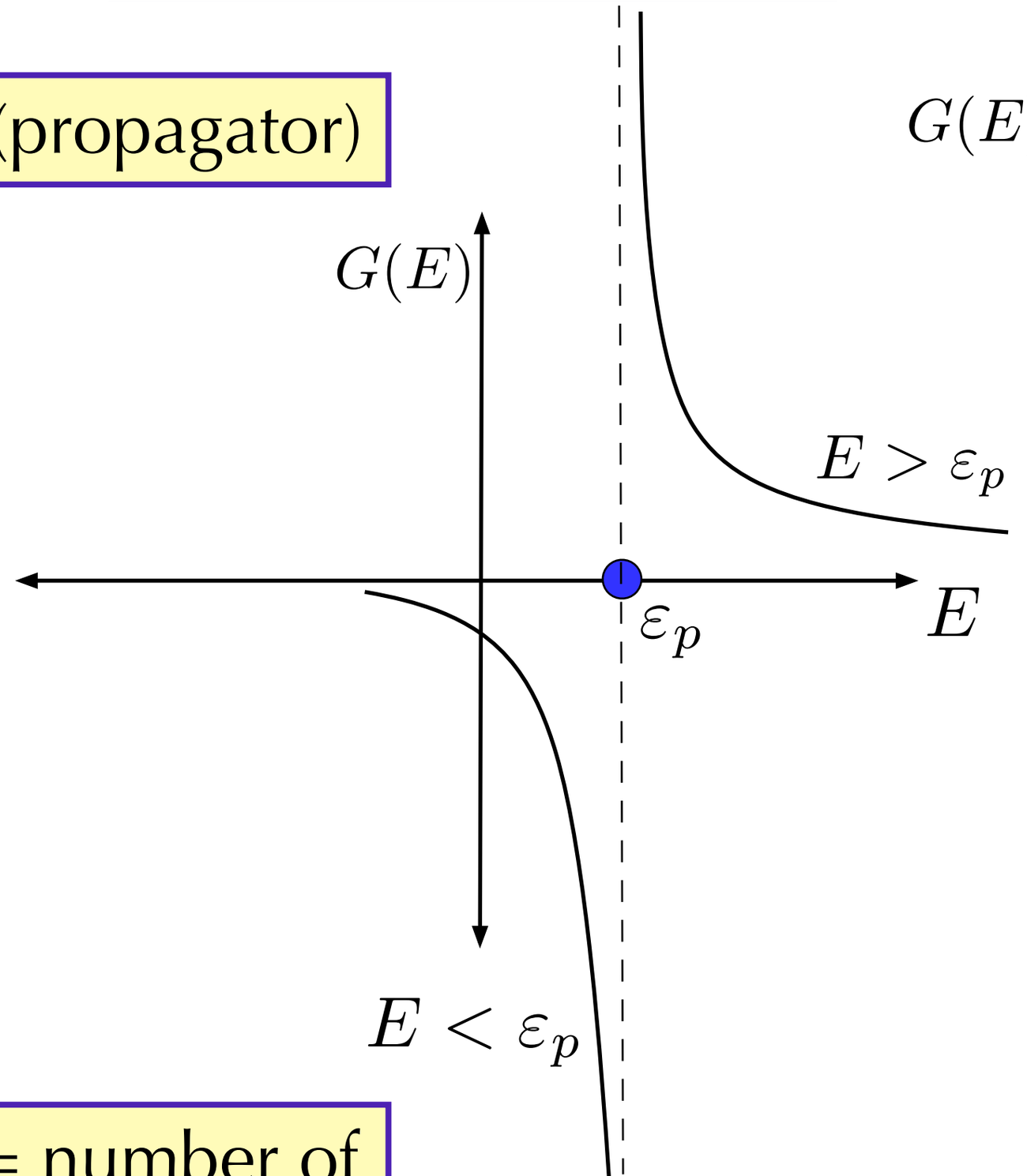

particle density= number of sign changes of G

Counting sign changes?

Counting sign changes?

$$\Theta(x)$$

Counting sign changes?

$$\Theta(x) = \begin{cases} 0 & x < 0 \\ & \end{cases}$$

Counting sign changes?

$$\Theta(x) = \begin{cases} 0 & x < 0 \\ 1 & x > 0 \end{cases}$$

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counts sign changes

Counting sign changes?

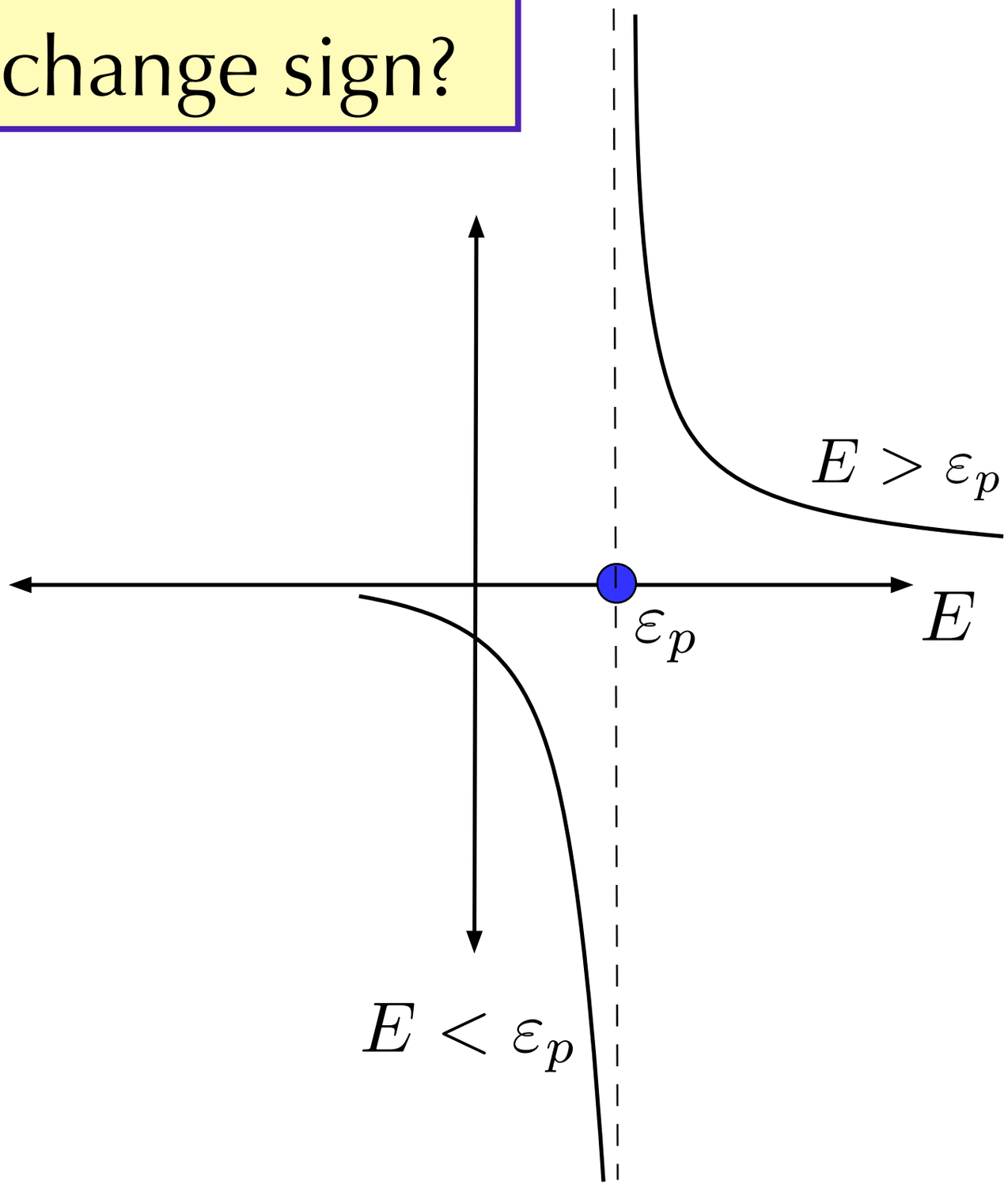
$$\Theta(x) = \begin{cases} 0 & x < 0 \\ 1 & x > 0 \\ 1/2 & x = 0 \end{cases}$$

counts sign changes

$$n = 2 \sum_{\mathbf{k}} \Theta(\Re G(\mathbf{k}, \omega = \mathbf{0}))$$

Luttinger Theorem for electrons

How do functions change sign?



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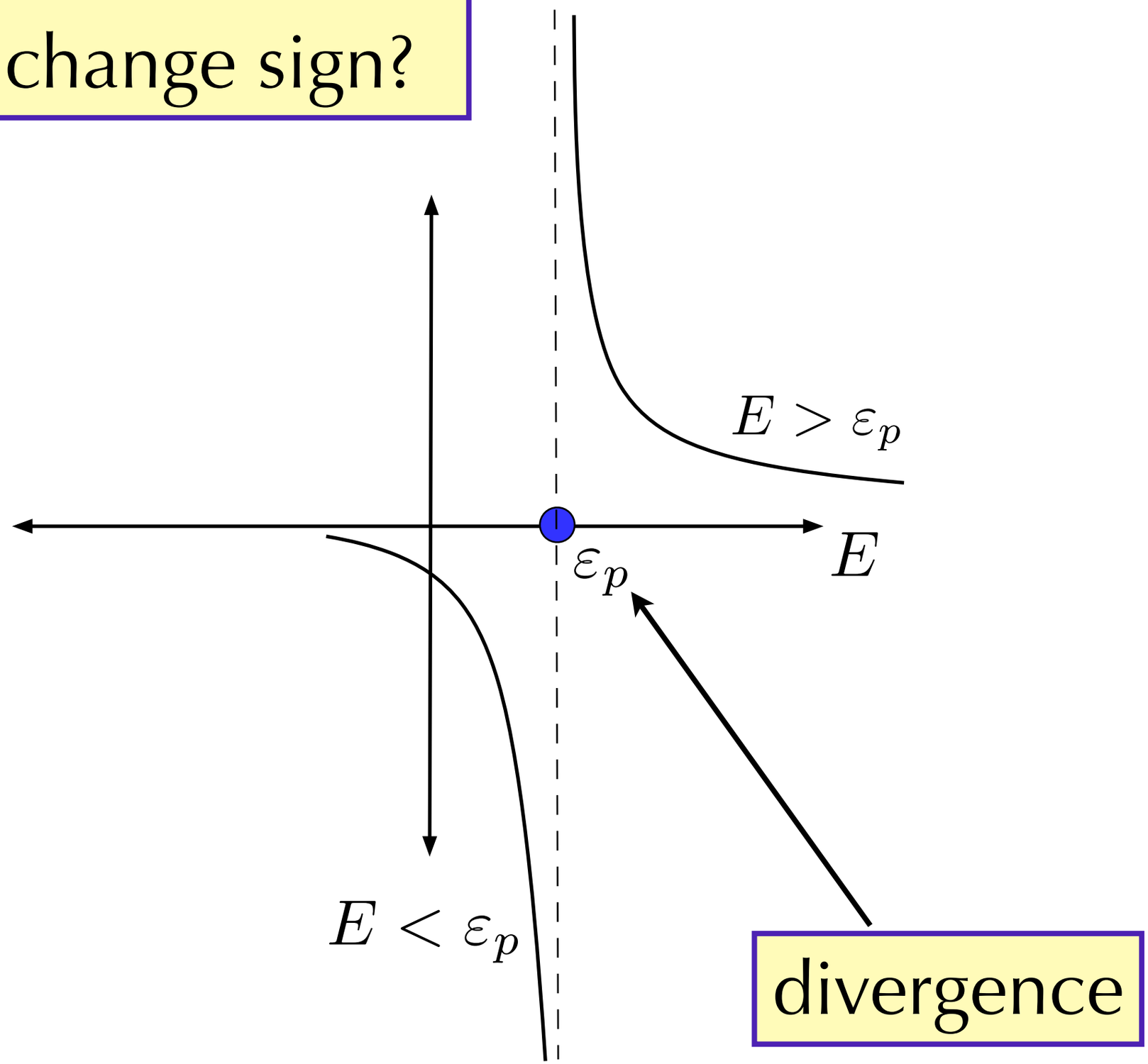

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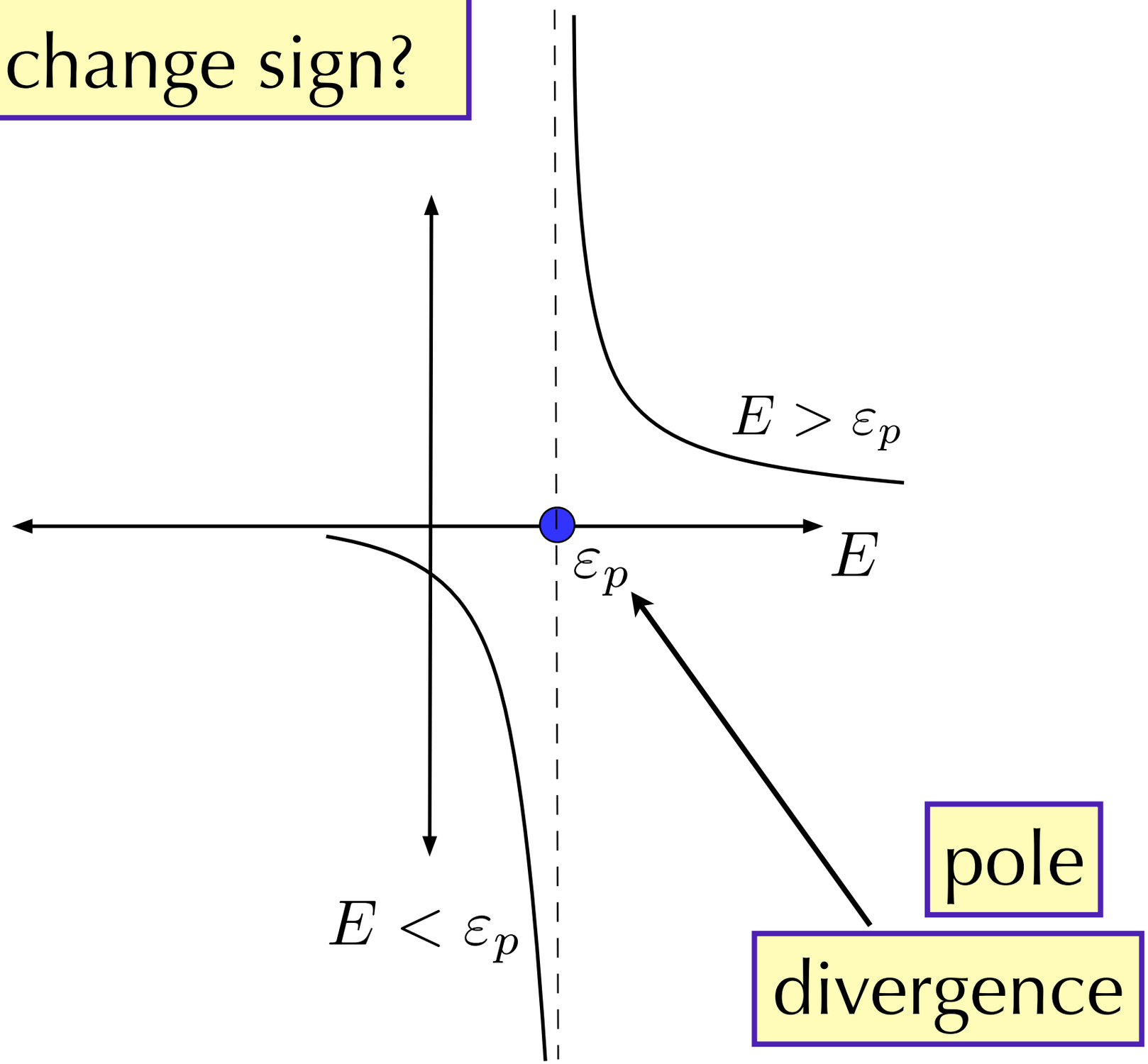
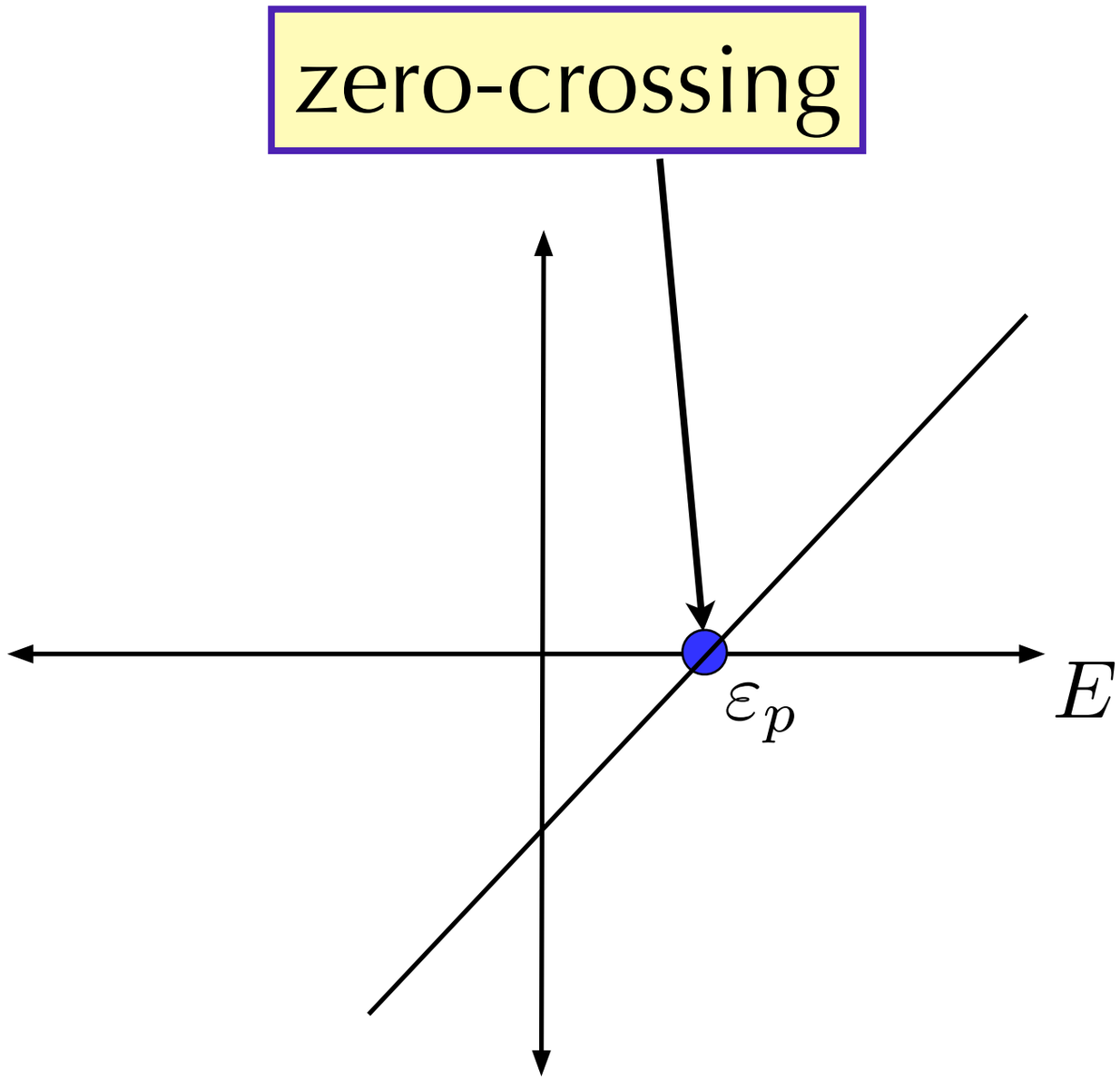
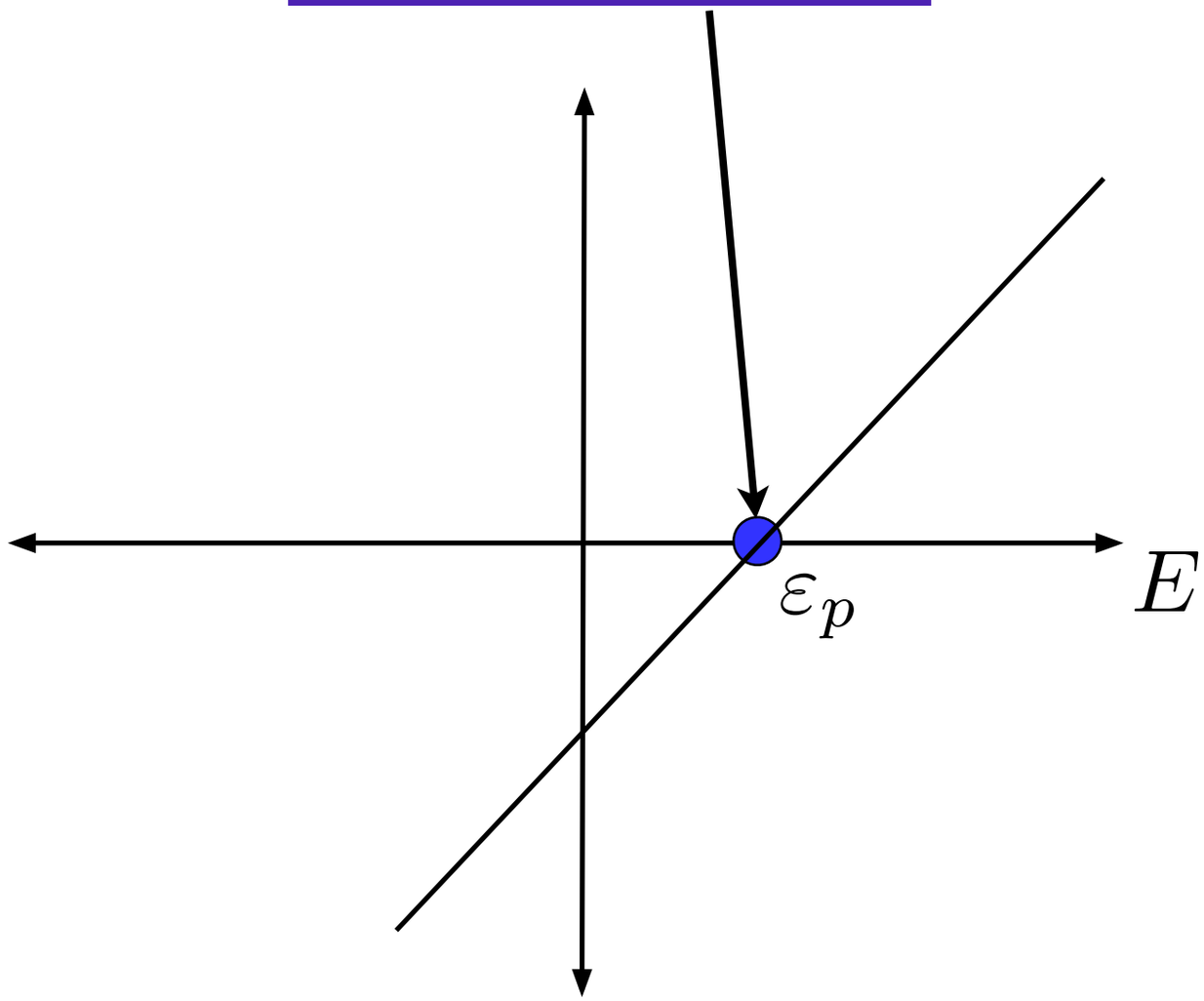


Is there
another way?

Yes


zero-crossing
ε_p
E

zero-crossing



no divergence is necessary

closer look at Luttinger's theorem

$$n = 2\sum_{\mathbf{k}} \Theta(\Re G(\mathbf{k}, \omega = \mathbf{0}))$$

closer look at Luttinger's theorem

$$n = 2\sum_{\mathbf{k}} \Theta(\Re G(\mathbf{k}, \omega = \mathbf{0}))$$

divergences (poles)+ zeros

closer look at Luttinger's theorem

$$n = 2\sum_{\mathbf{k}} \Theta(\Re G(\mathbf{k}, \omega = \mathbf{0}))$$

divergences (poles)+ zeros

how can zeros affect the particle count?

what are zeros?

are they (like poles) conserved?

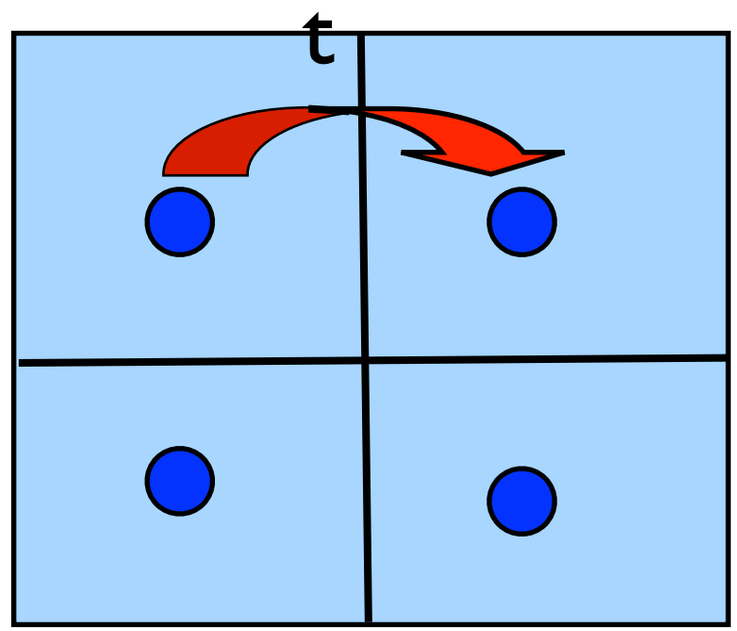
what models have zeros?

Mott mechanism

NiO insulates

d^8 ?

Sir Neville



Mott mechanism

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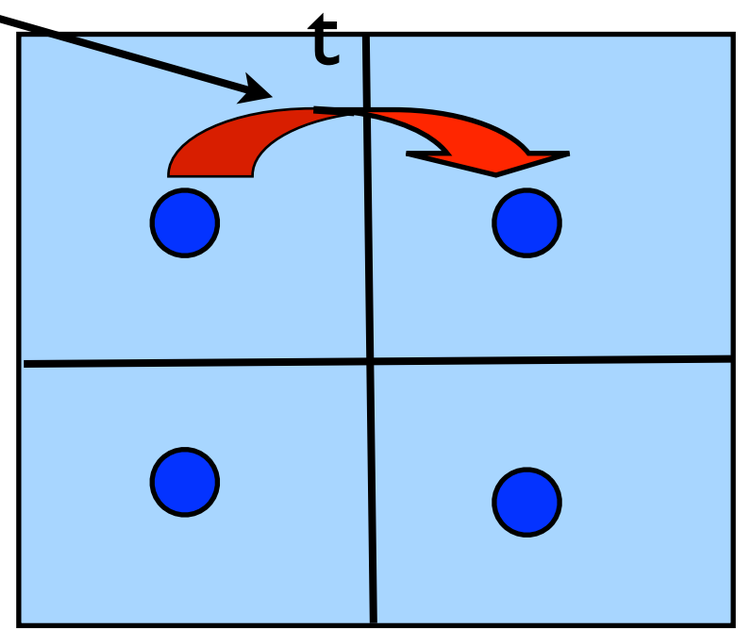
perhaps this costs energy



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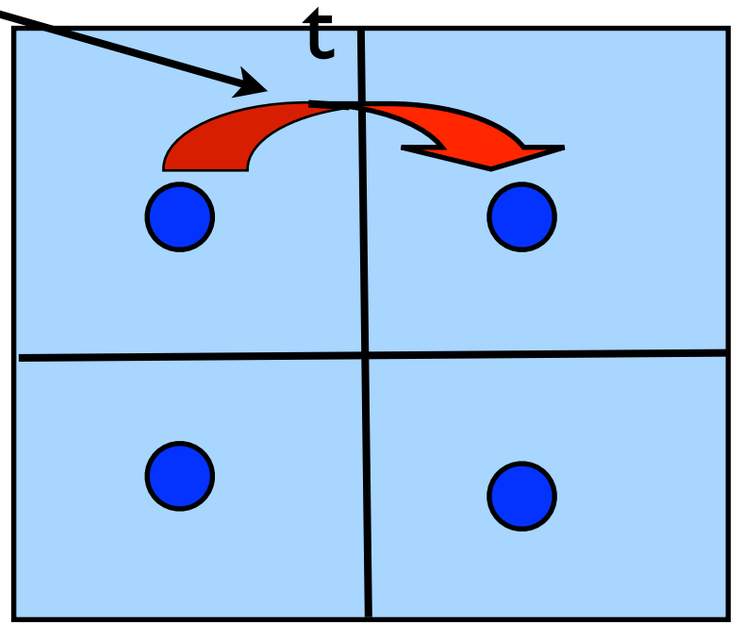

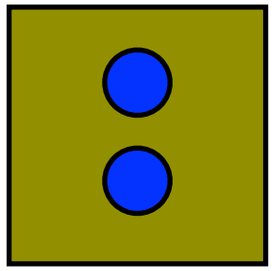

$U \gg t$

Sir Neville

Mott mechanism

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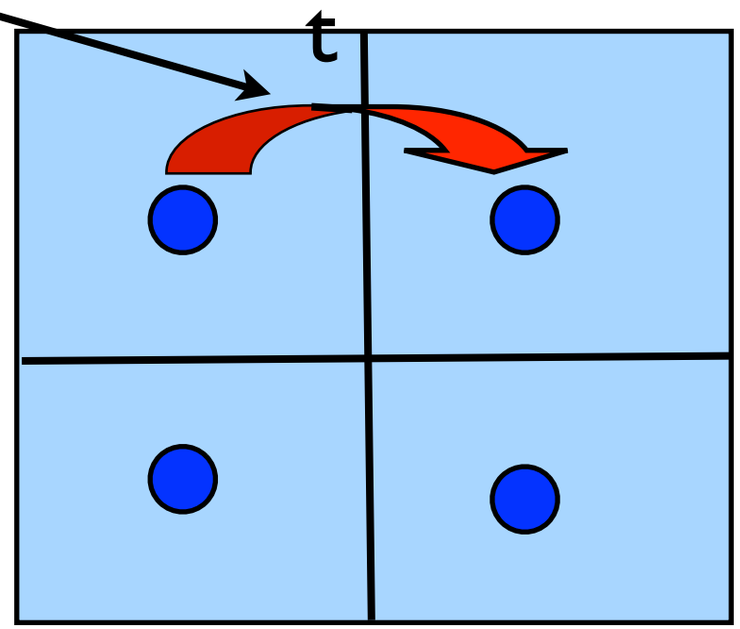
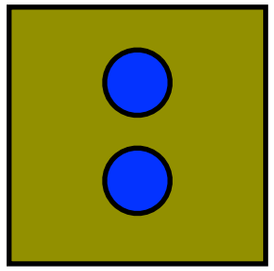
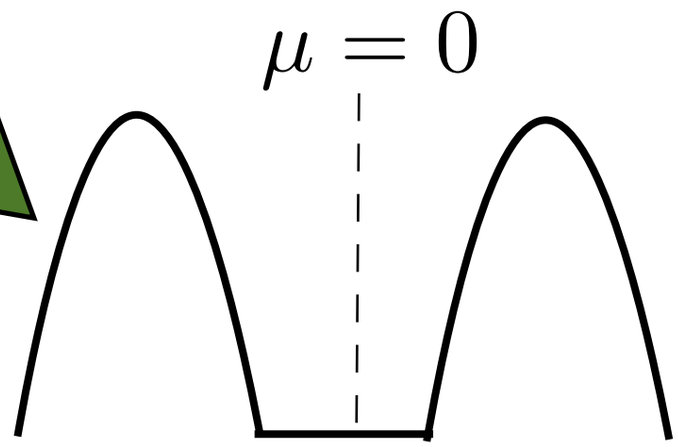
perhaps this costs energy





$U \gg t$

Sir Neville

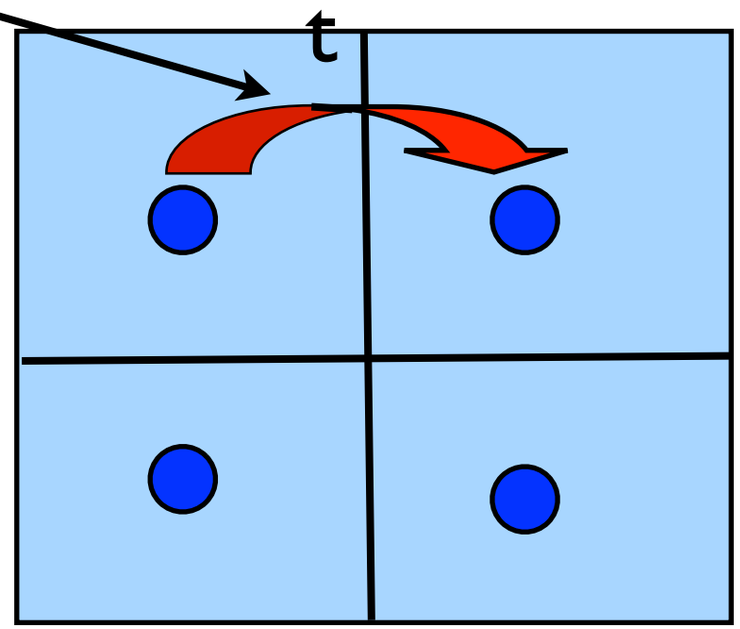


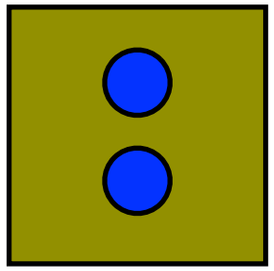
Mott mechanism

NiO insulates

d^8 ?

perhaps this costs energy





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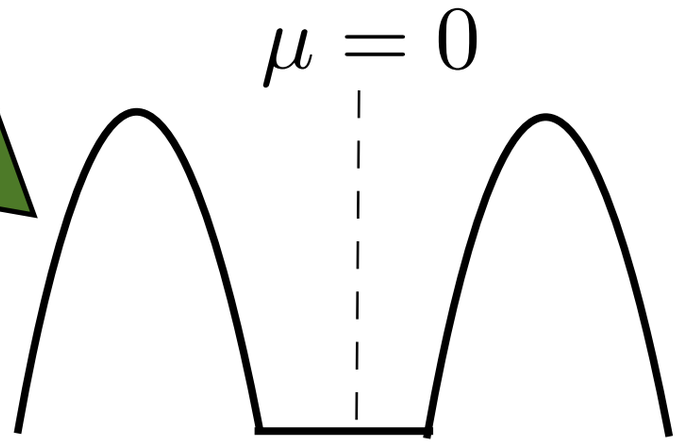


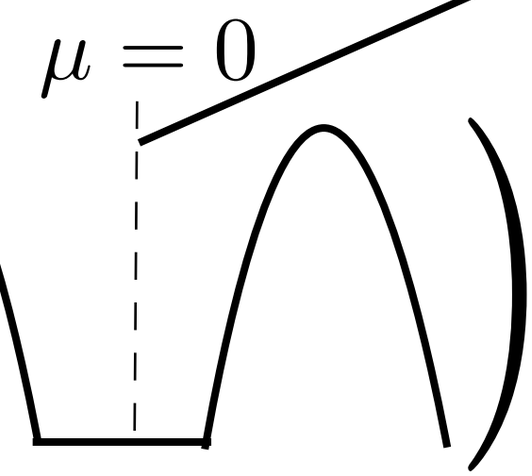
no change in size of Brillouin zone

Mott Problem

Mott Problem

Im G=0

$$\mathrm{Re}G(0,p) = \int_{-\infty}^{\infty} \frac{\left(\quad \right)}{\omega} d\omega$$

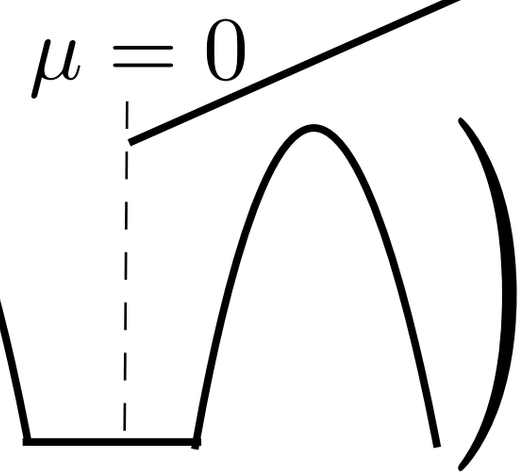


Kramers -Kronig

Mott Problem

Im G=0

$$\mathrm{Re}G(0,p) = \int_{-\infty}^{\infty} \frac{\left(\quad \right)}{\omega} d\omega$$



Kramers -Kronig

= below gap+above gap

Mott Problem

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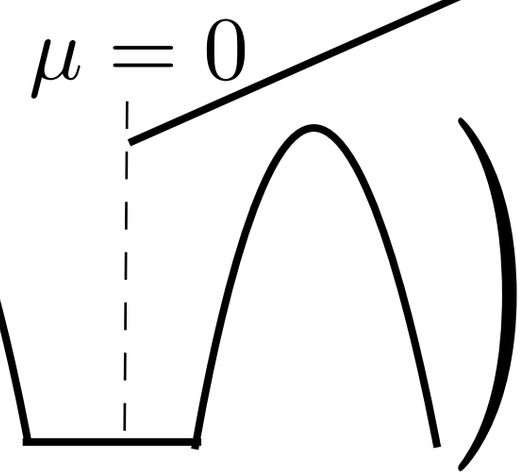

Kramers -Kronig

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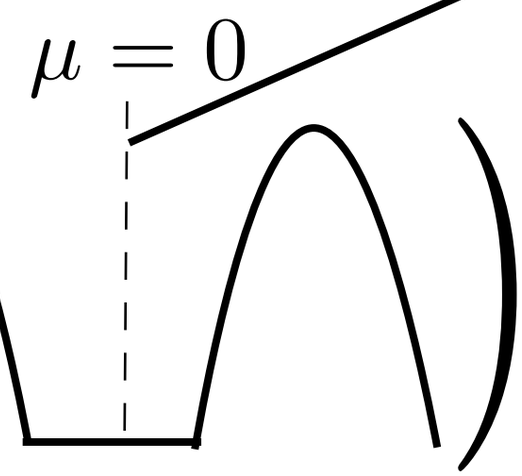


Kramers -Kronig

= below gap+above gap = 0

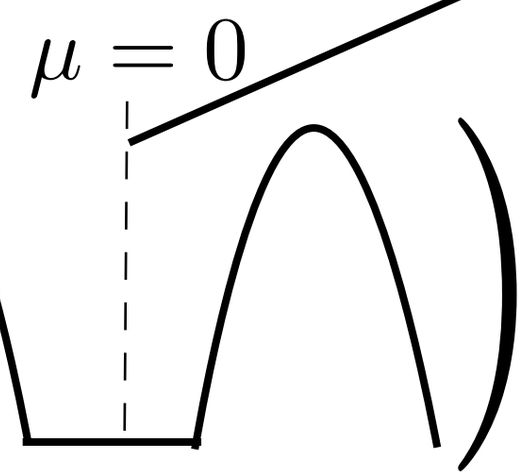
$$\mathrm{Det}G(\mathbf{k}, \omega = \mathbf{0}) = \mathbf{0}$$

(single band)

Mott Problem

Im G=0

$$\mathrm{Re}G(0,p) = \int_{-\infty}^{\infty} \frac{\left(\quad \right)}{\omega} d\omega$$



Kramers -Kronig

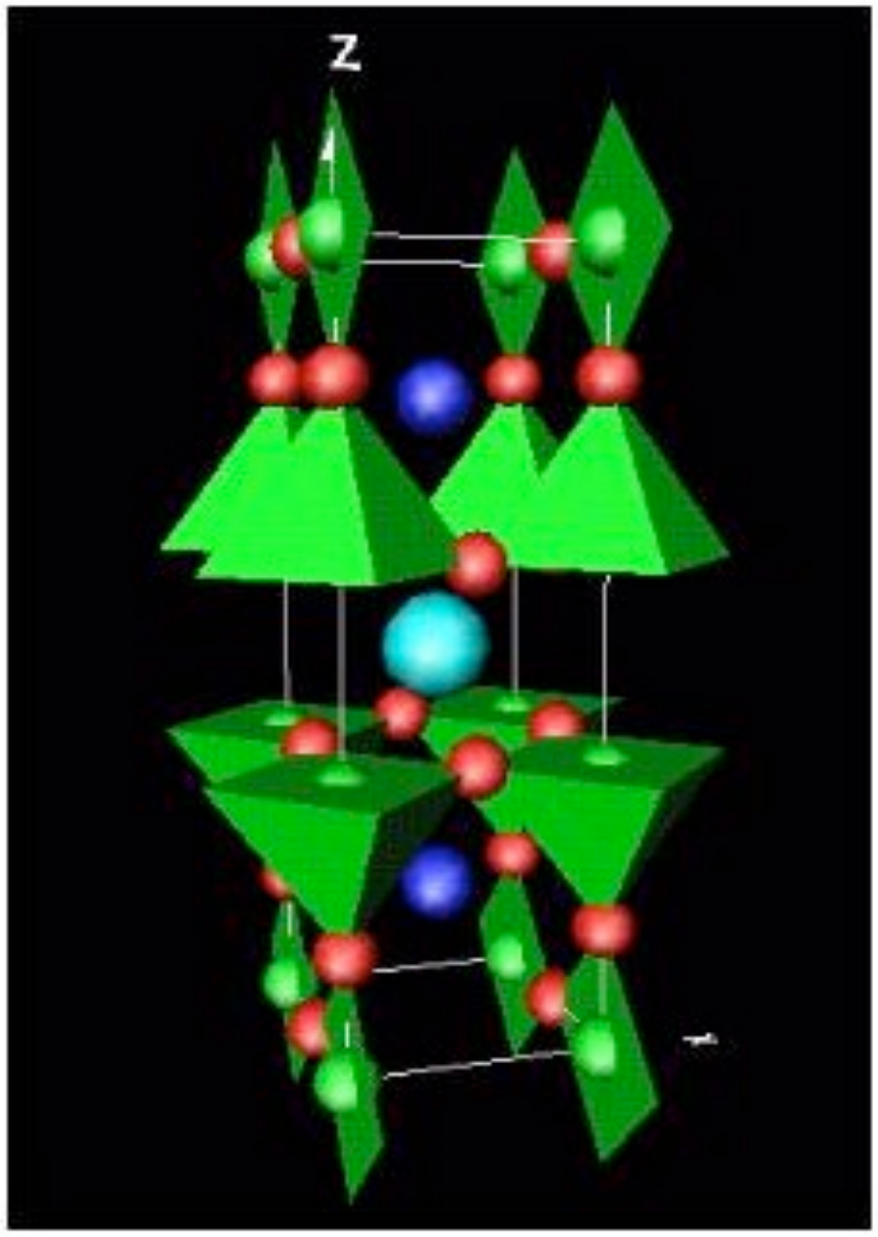
= below gap+above gap = 0

$$\mathrm{Det}G(\mathbf{k}, \omega = \mathbf{0}) = \mathbf{0}$$

(single band)

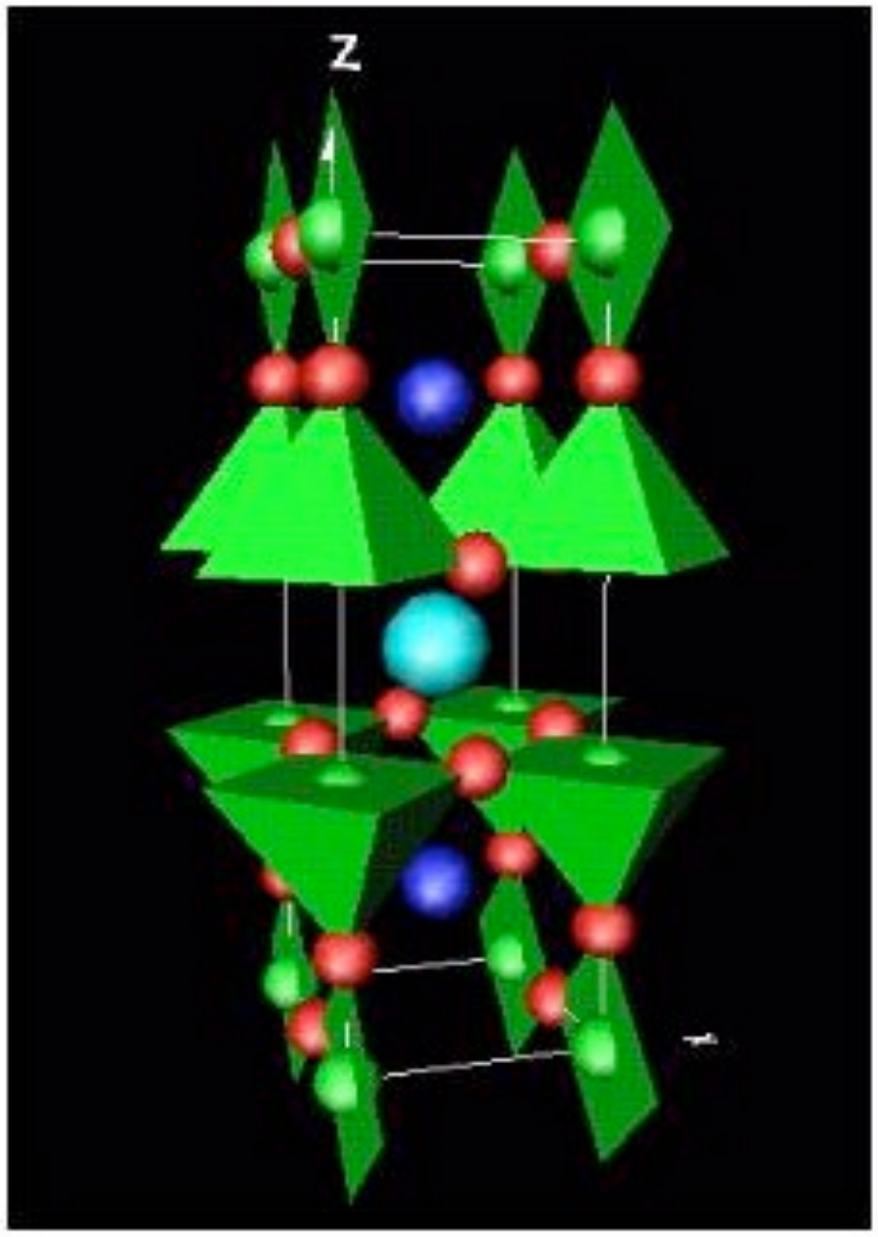
DetReG(0,p)=0

Mottness



$YBa_2Cu_3O_7$

Cuprate Superconductors



$Y\,Ba_2Cu_3O_7$
Cuprate Superconductors

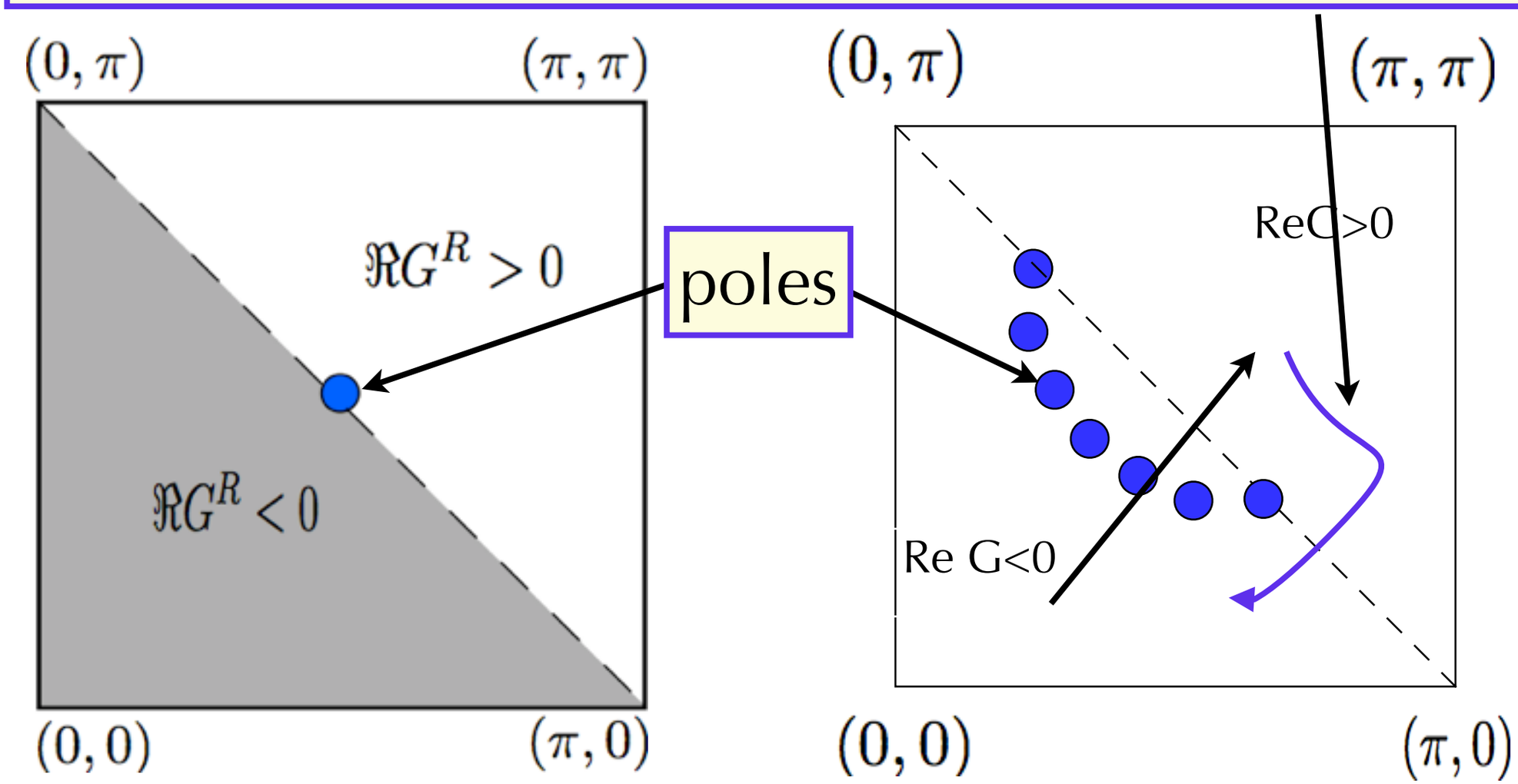
$$U/t = 10 \gg 1$$

interactions dominate:
Strong Coupling Physics

how do zeros show up?

Problem for left-wingers (me)

How to account for the sign change without poles?



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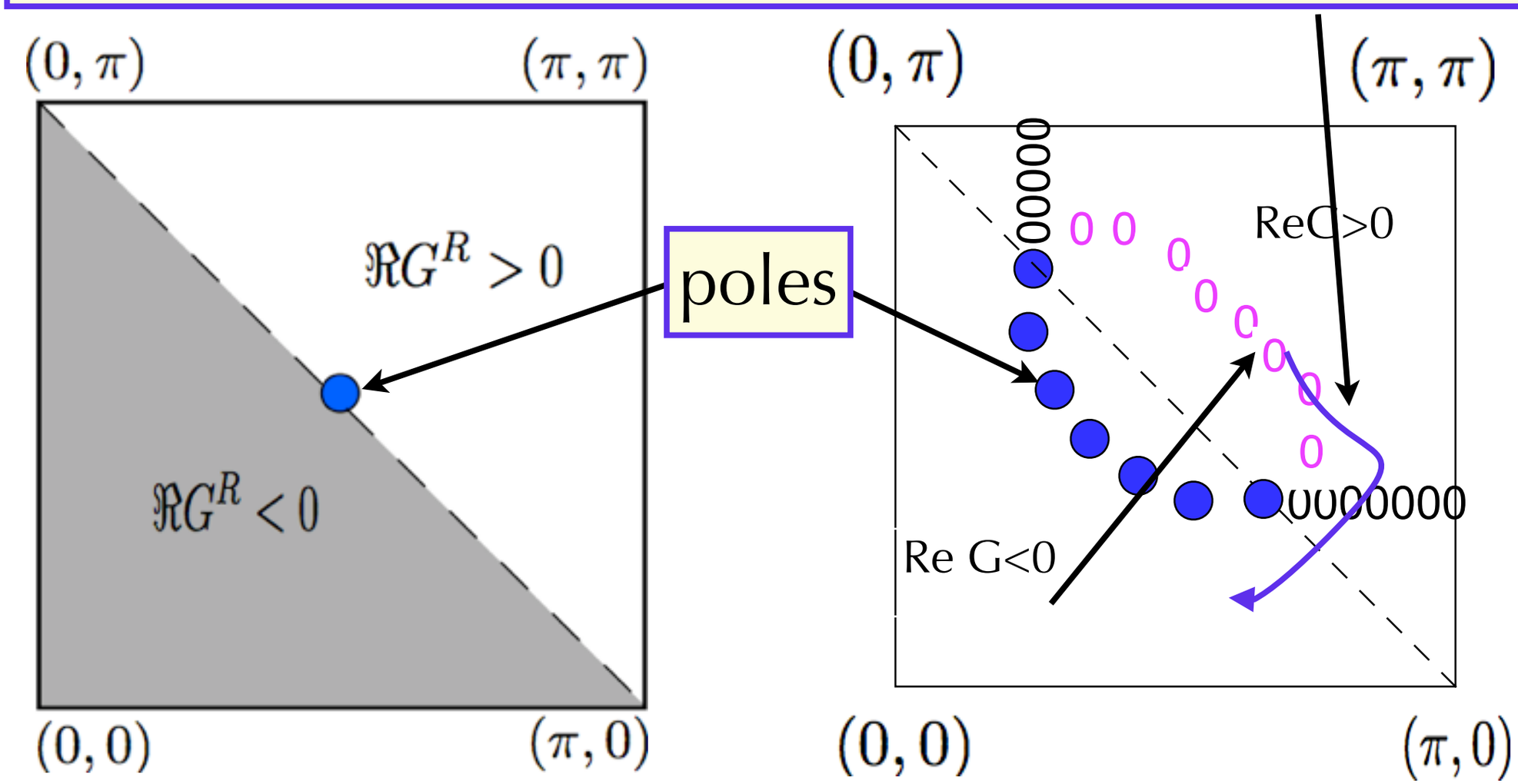
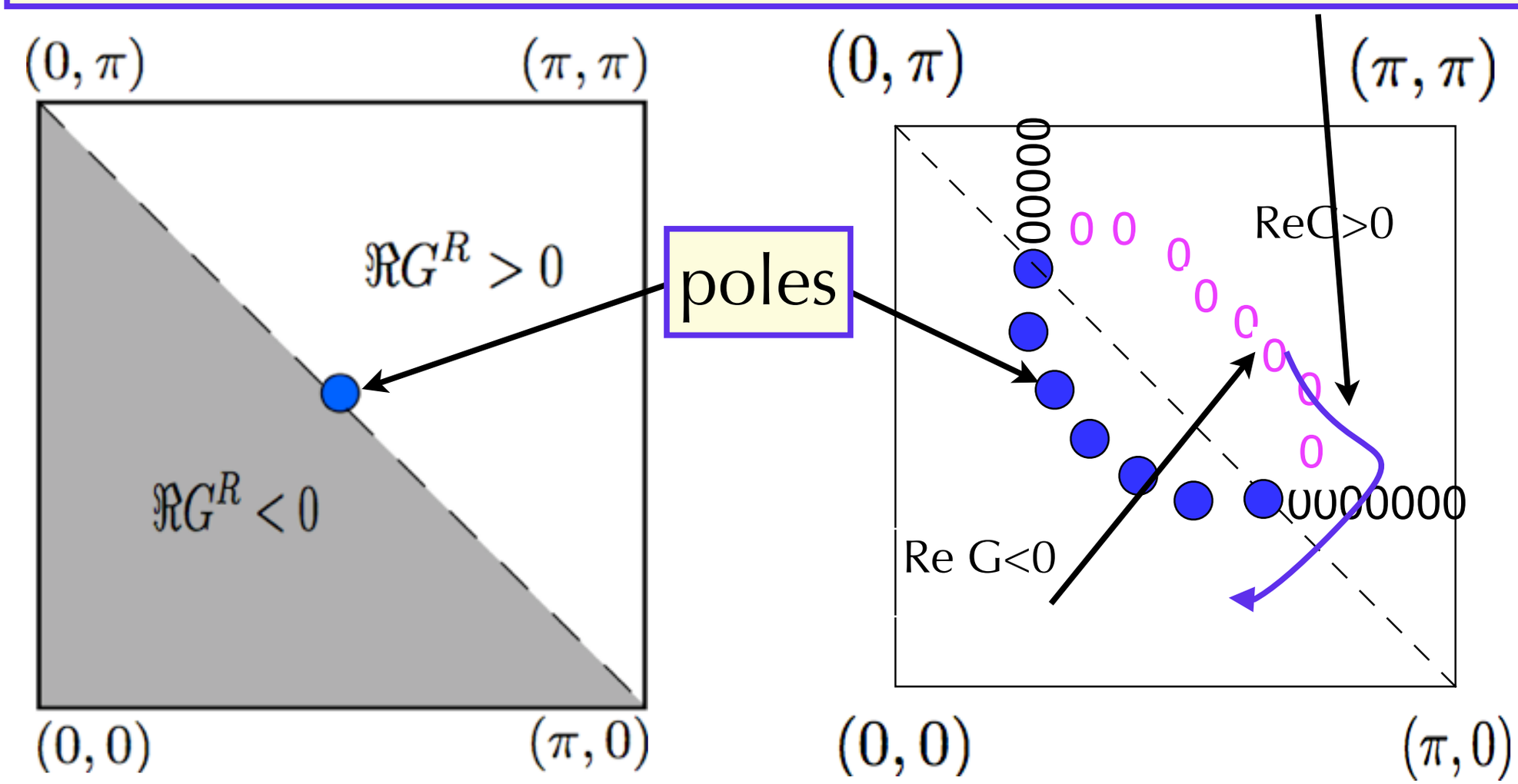


Problem for left-wingers (me)

How to account for the sign change without poles?



Only option: DetG=0! (zeros)

Fermi Arcs

zeros + poles

Luttinger, Dzyaloshinskii, Yang, Rice, Zhang,Tsvelik, Anderson (lots of smart people)...

n=zeros + poles

PHYSICAL REVIEW B **68**, 085113 (2003)

Some consequences of the Luttinger theorem: The Luttinger surfaces in non-Fermi liquids and Mott insulators

Igor Dzyaloshinskii
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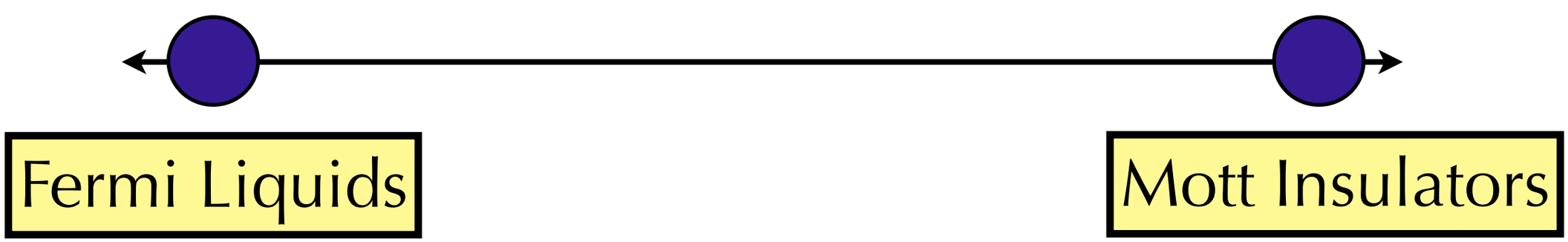
(Received 30 January 2003; published 27 August 2003)

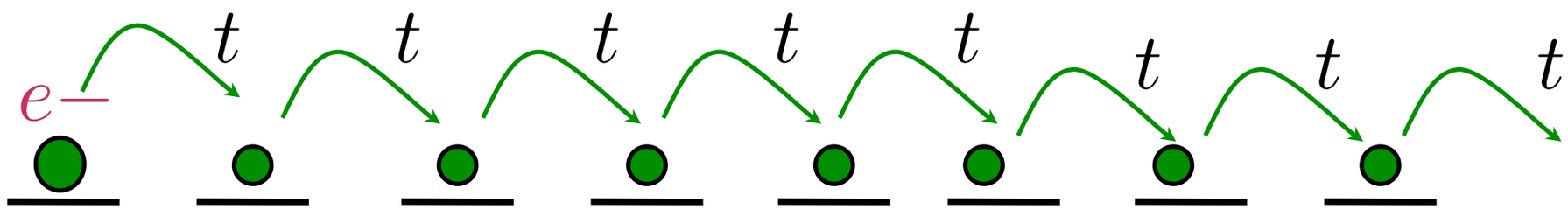
The proof just presented is good for any state of our system: FL, NFL, or MI [in other words, either of poles or zeros can be used to change the sign of G_r in Eq. (1)]. The only way to incapacitate the Luttinger theorem in form (1) is to assume that the limit $T \to 0$ is discontinuous. Actually, one has to require that the whole line $T=0$ is a line of phase transitions.



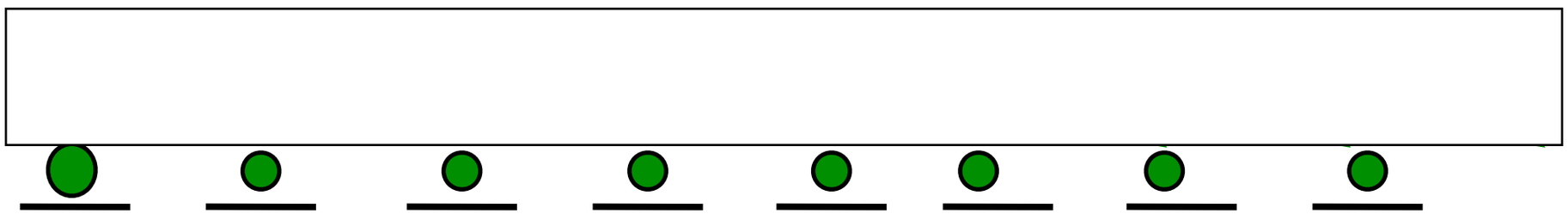
Is this famous theorem from 1960 correct?

A model with zeros but Luttinger fails

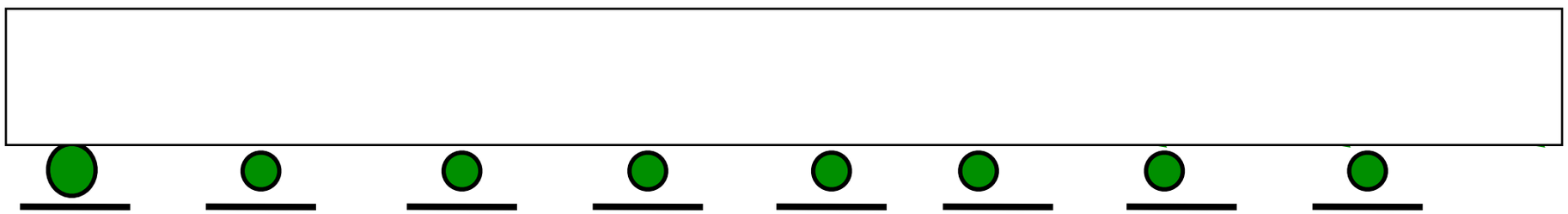
A model with zeros but Luttinger fails



A model with zeros but Luttinger fails

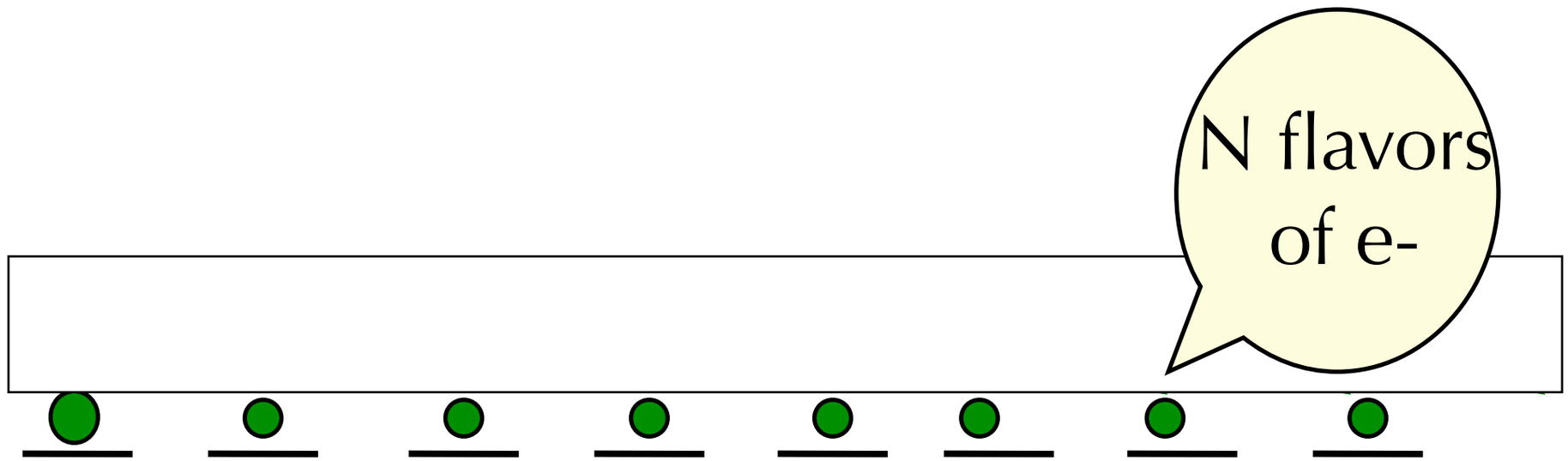


A model with zeros but Luttinger fails



no hopping=> no propagation (zeros)

A model with zeros but Luttinger fails



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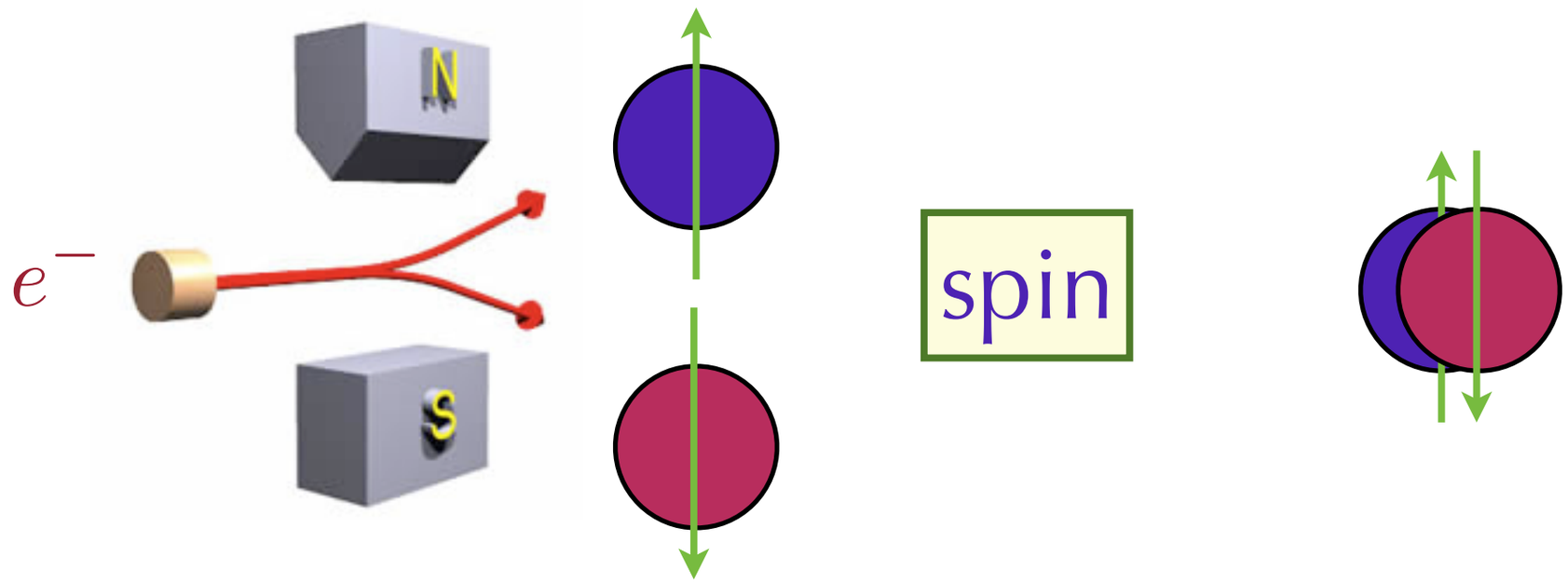
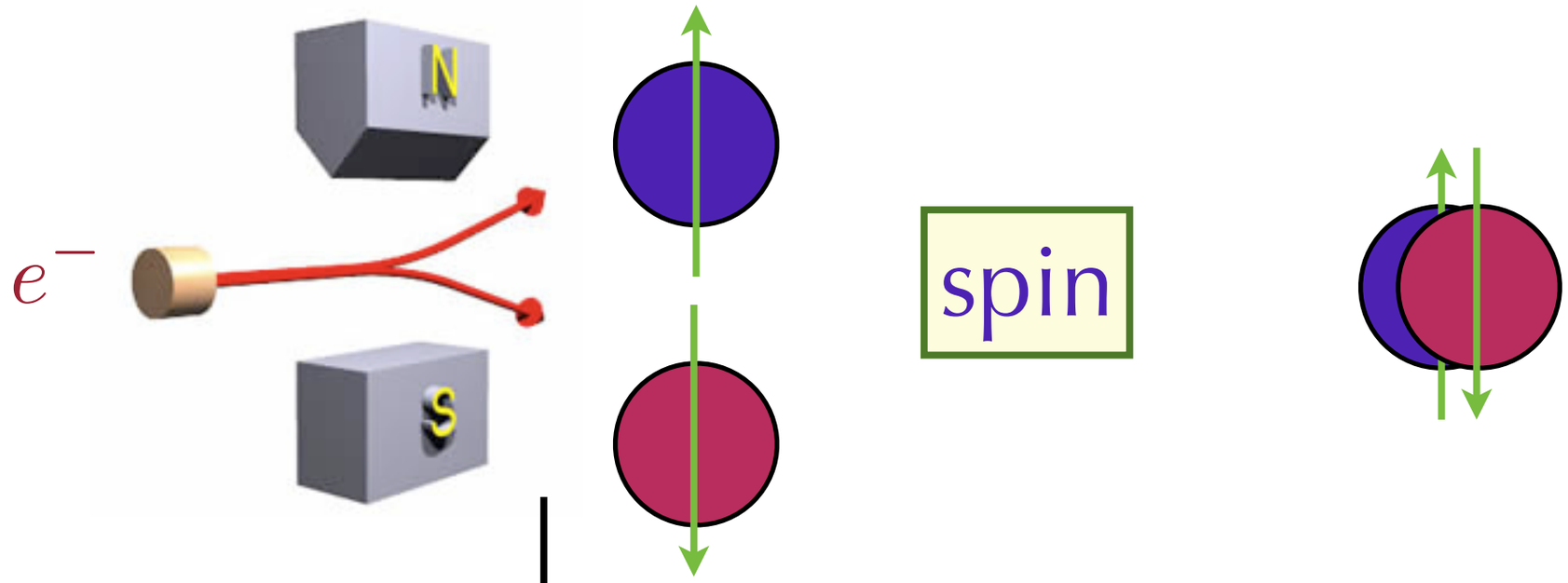
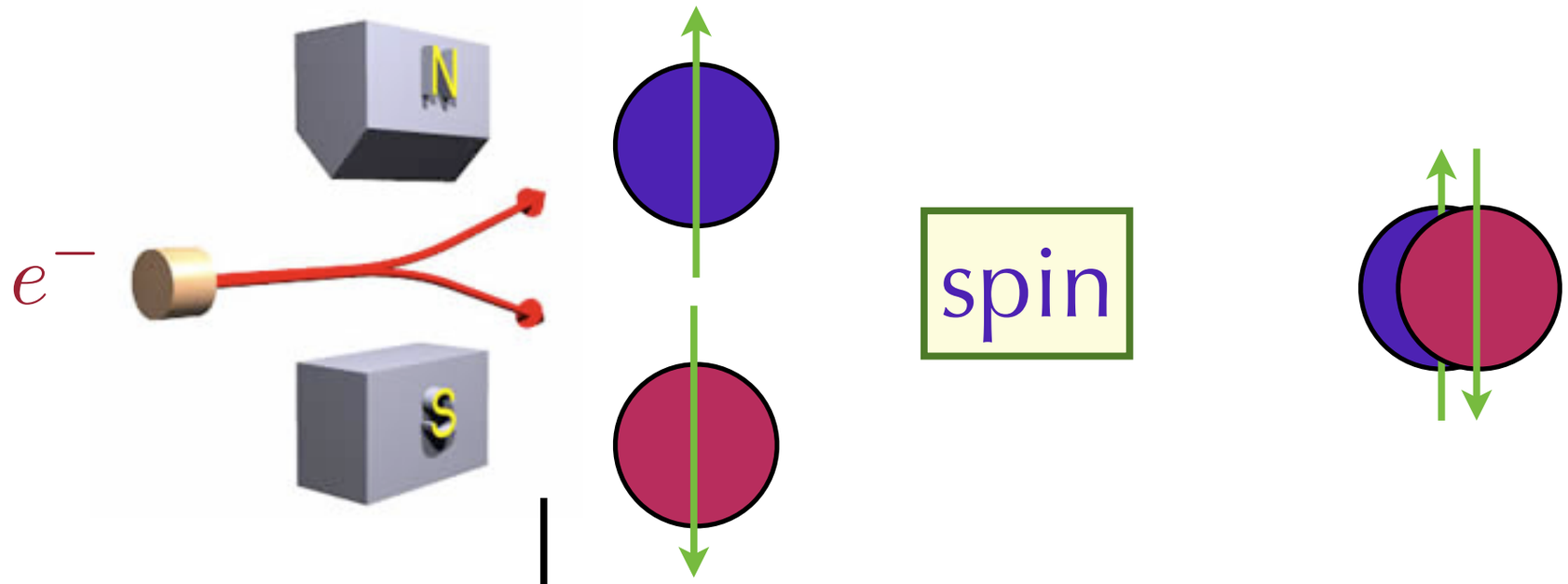

N
S
e^-
spin



generalization

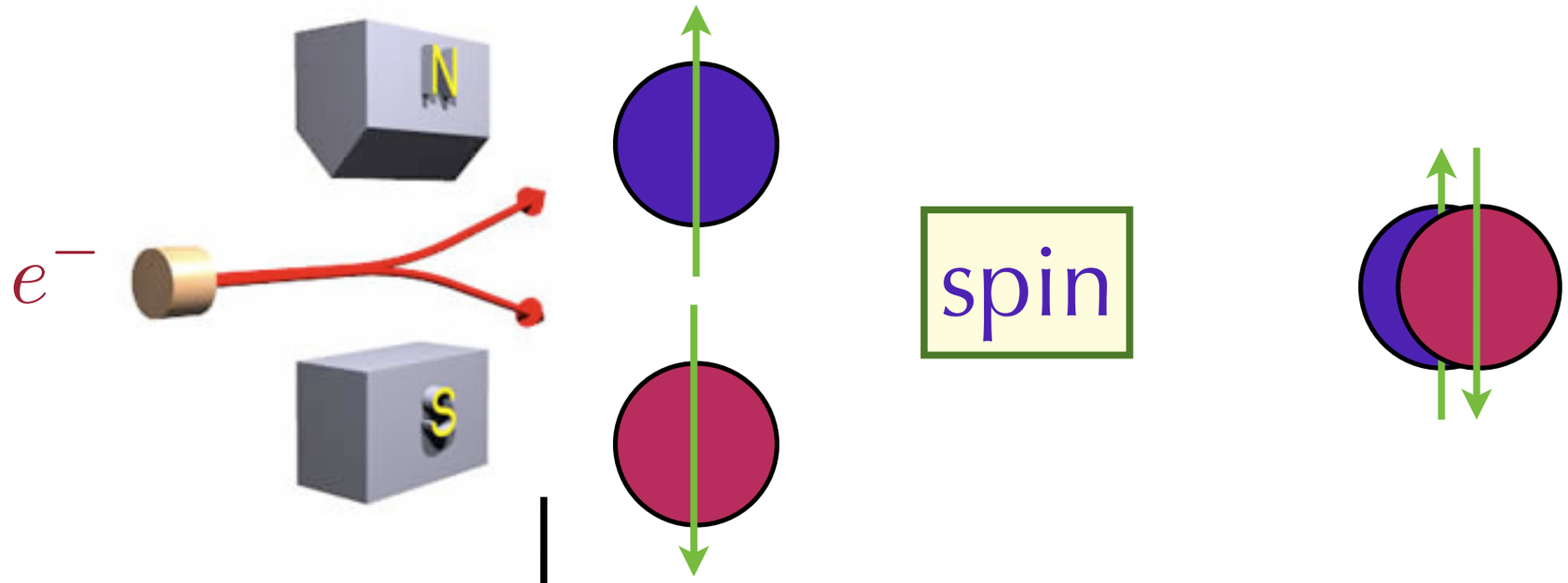
N flavors of spin



generalization

N flavors of spin

$N = 5$



generalization

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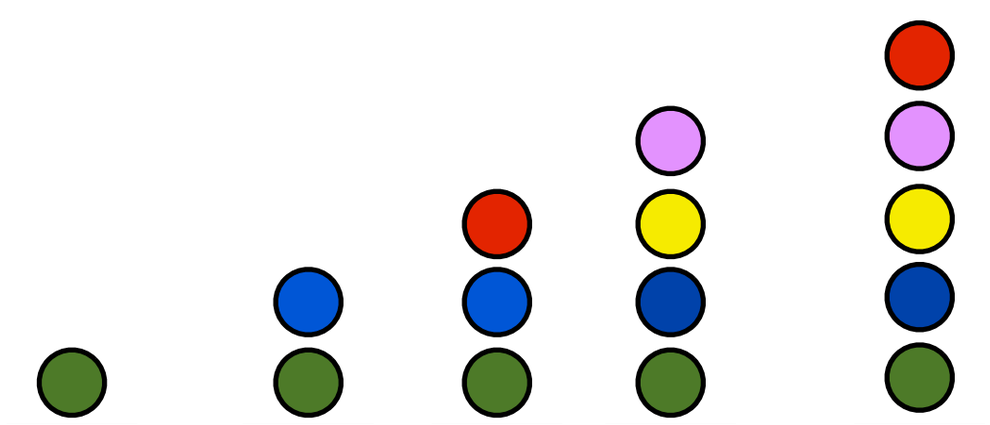

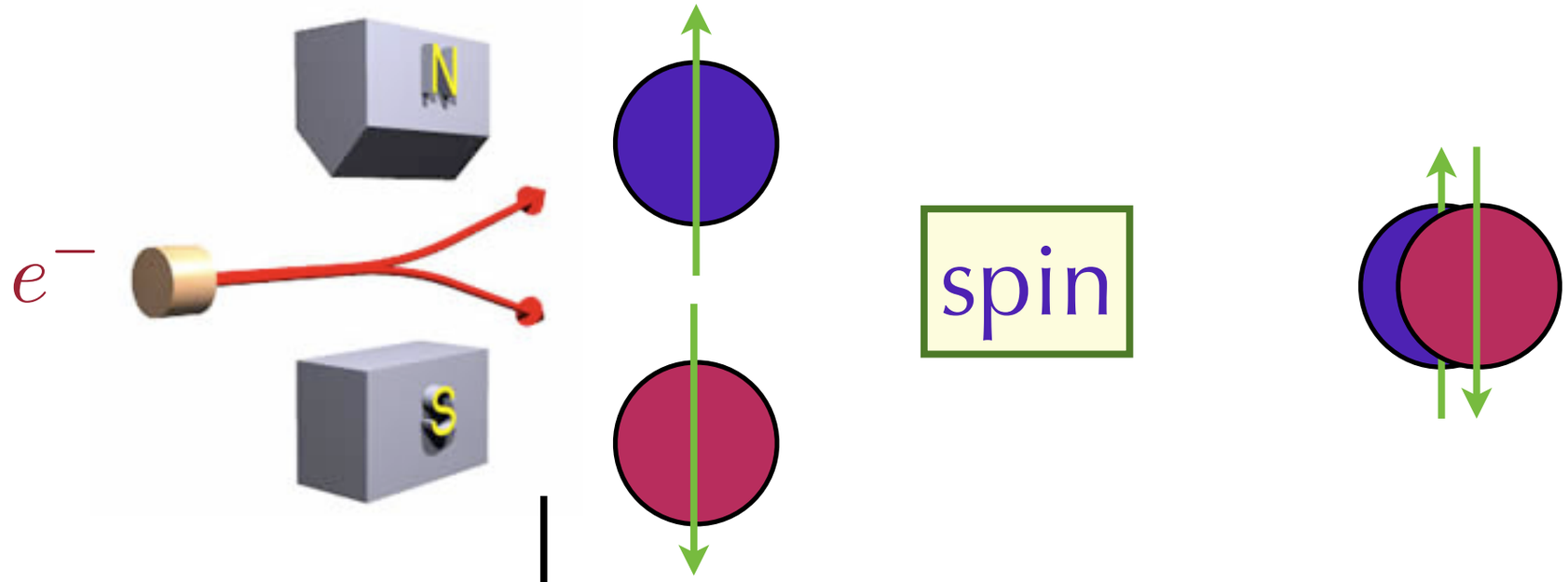

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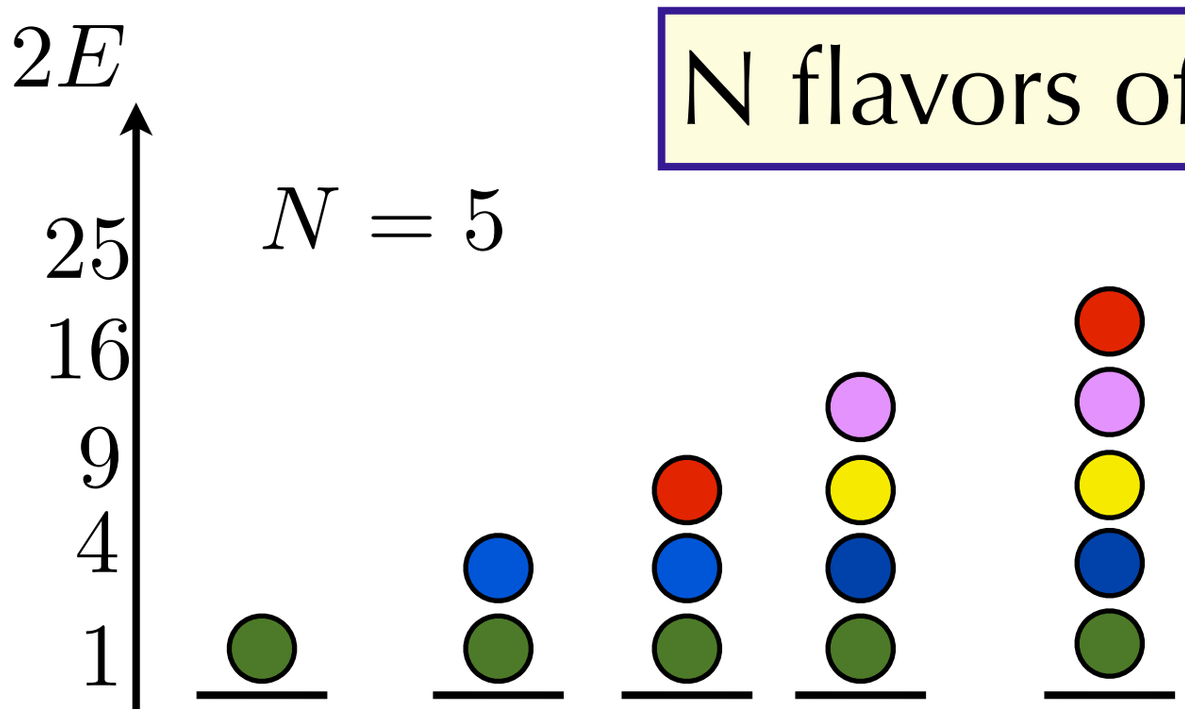
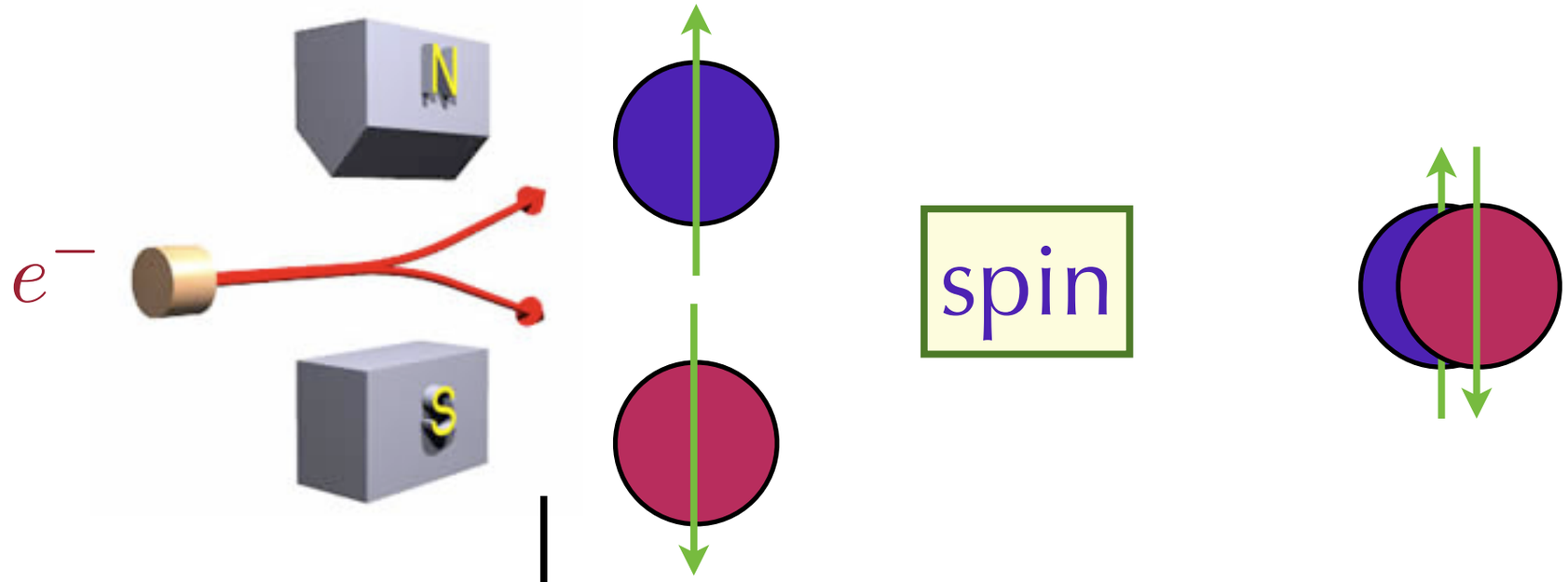
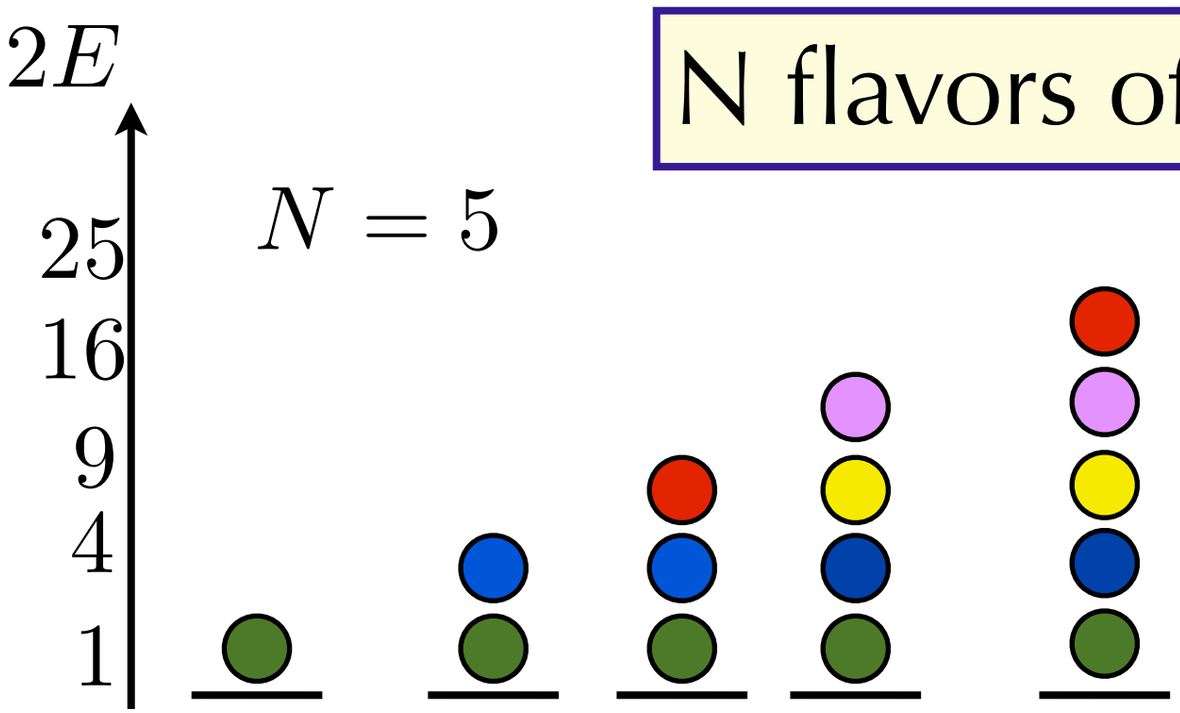
N flavors of spin





generalization

N flavors of spin



$$H = \frac{U}{2}(n_1 + \cdots n_N)^2$$

$$G_{\alpha\beta}(\omega = 0) = \# \left(\frac{2n - N}{N} \right)$$

$$G_{\alpha\beta}(\omega = 0) = \# \binom{2n - N}{N}$$

Luttinger's theorem

$$n = N\Theta(2n - N)$$

Luttinger's theorem

$$n = N\underbrace{\Theta(2n - N)}_{0,\,1,\,1/2}$$

Luttinger's theorem

$$n = N\underbrace{\Theta(2n - N)}_{0,\,1,\,1/2}$$

$n = 2$

$N = 3$

Luttinger's theorem

$$n = N\underbrace{\Theta(2n - N)}_{0,\,1,\,1/2}$$

$$n = 2$$

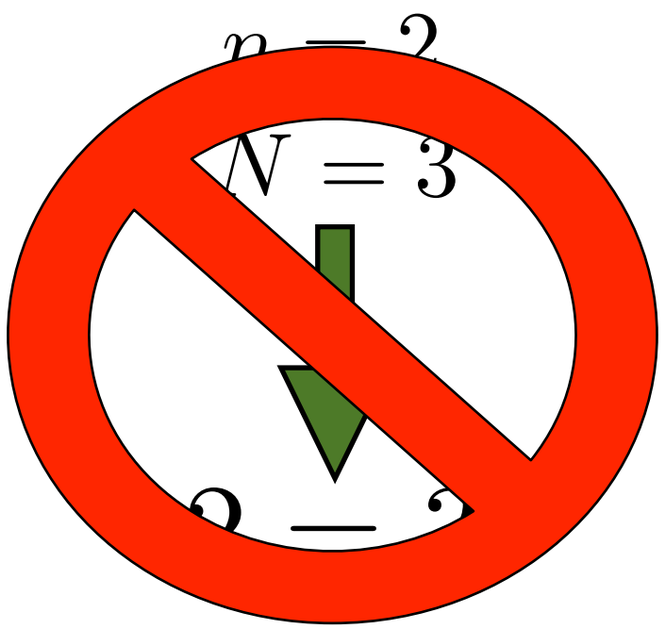
$$N = 3$$

$$\Downarrow$$

$$2 = 3$$

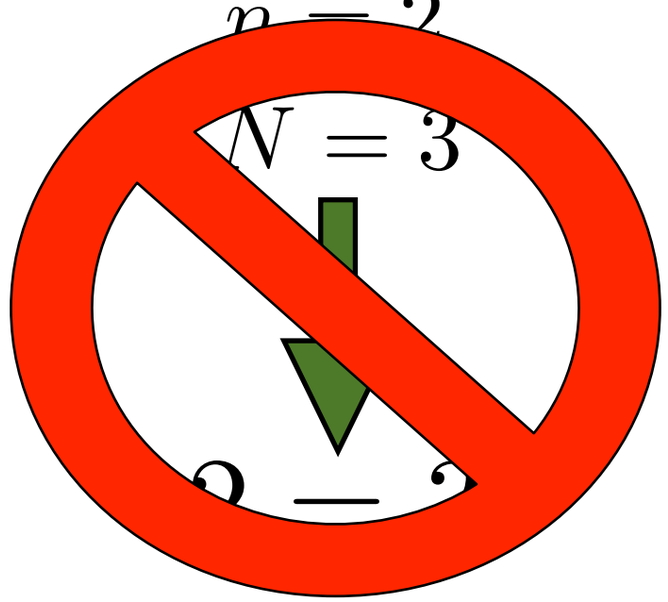
Luttinger's theorem

$$n = N\underbrace{\Theta(2n - N)}_{0,\,1,\,1/2}$$



Luttinger's theorem

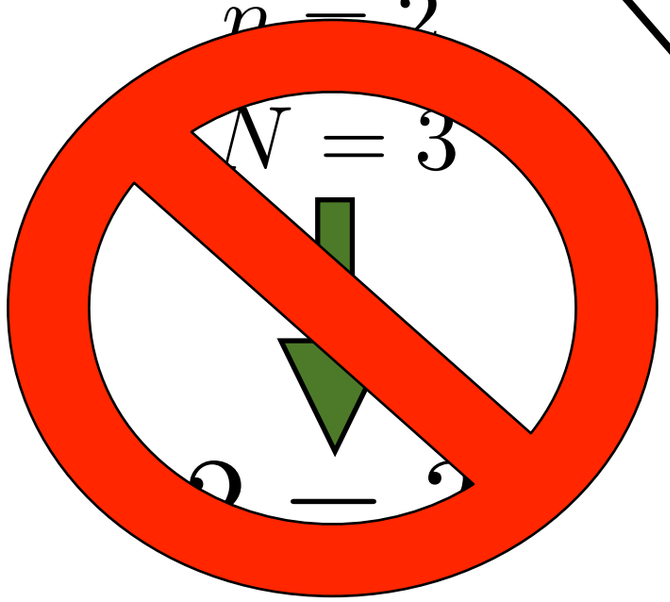
$$n = N\underbrace{\Theta(2n - N)}_{0,\,1,\,1/2}$$



even

Luttinger's theorem

$$n = N\underbrace{\Theta(2n - N)}_{0,\,1,\,1/2}$$

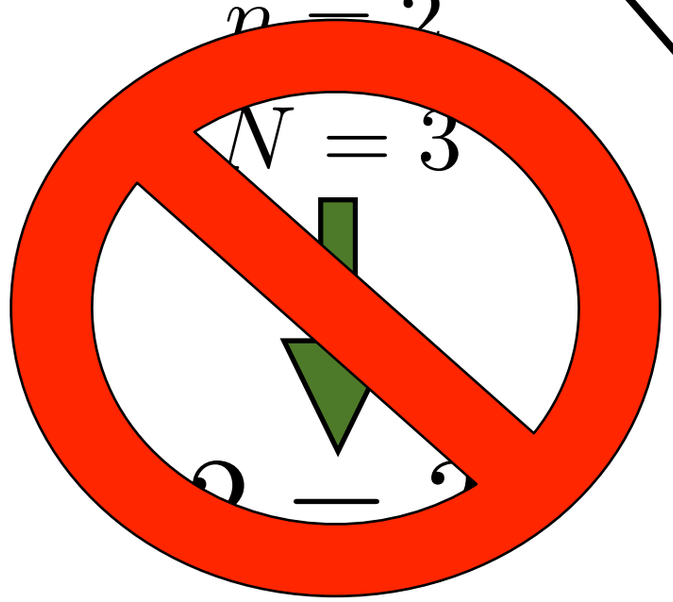


even

odd

Luttinger's theorem

$$n = N\underbrace{\Theta(2n - N)}_{0,\,1,\,1/2}$$



even

odd

no solution

Problem

G=0

Problem

G=0

$$G = \frac{1}{E - \varepsilon_p - \Sigma} \rightarrow \infty$$

Problem

G=0

$$G = \frac{1}{E - \varepsilon_p - \Sigma} \rightarrow \infty$$

lifetime of a particle vanishes

Problem

G=0

$$G = \frac{1}{E - \varepsilon_p - \Sigma}$$

$\Sigma \to \infty$

$\Im\Sigma < \epsilon_p$

lifetime of a particle vanishes

Problem

G=0

$$G = \frac{1}{E - \varepsilon_p - \Sigma}$$

$\Sigma \to \infty$

$\Im\Sigma < \epsilon_p$

lifetime of a particle vanishes

no particle

what went wrong?

what went wrong?

$$\delta I[G] = \int d\omega \Sigma \delta G$$

what went wrong?

$$\delta I[G] = \int d\omega \Sigma \delta G$$

$$\Big\Downarrow \text{ if } \Sigma \to \infty$$

what went wrong?

$$\delta I[G] = \int d\omega \Sigma \delta G$$

$$\Big\Downarrow \text{ if } \Sigma \to \infty$$

integral does not exist

what went wrong?

$$\delta I[G] = \int d\omega \Sigma \delta G$$

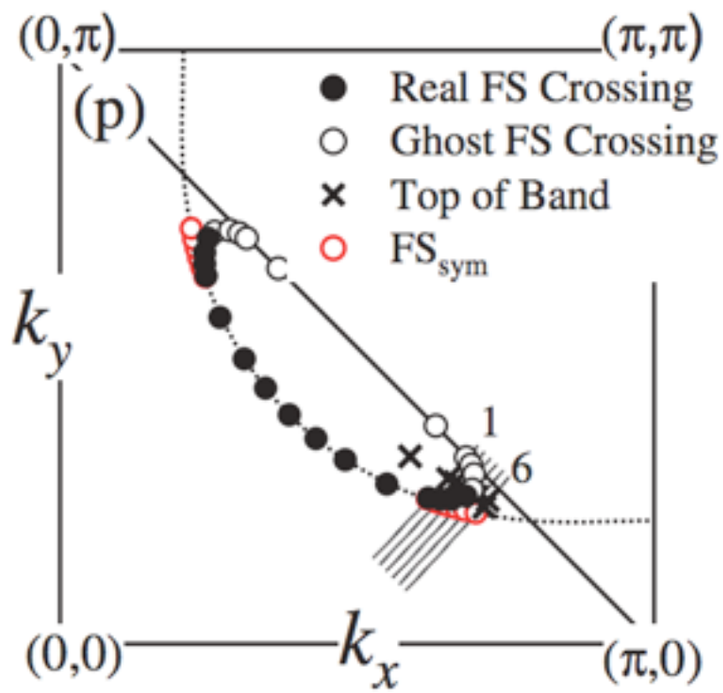
if $\Sigma \to \infty$

integral does not exist

No Luttinger theorem!

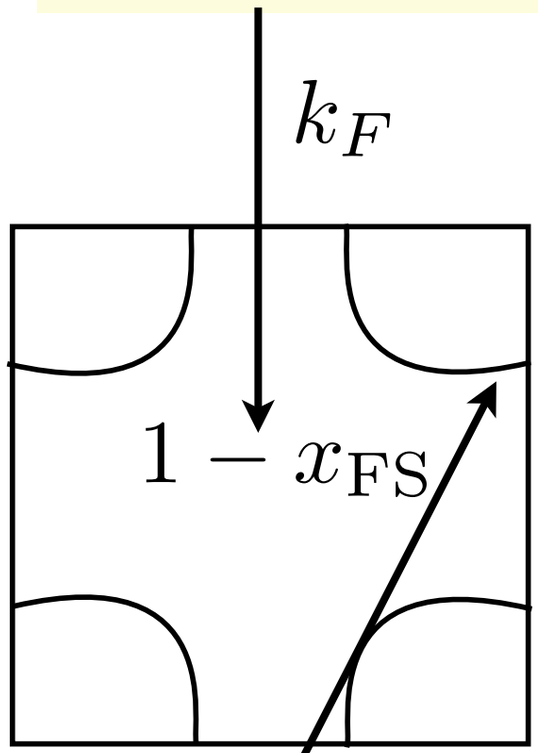
Luttinger's theorem

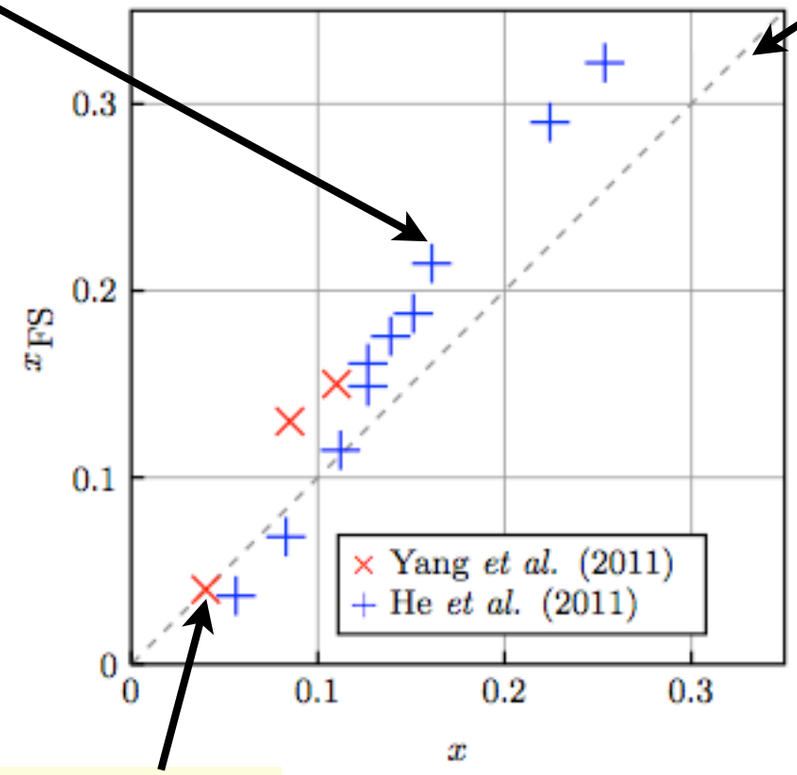
experimental confirmation of violation?


(0,π)
(π,π)
(p)
Real FS Crossing
Ghost FS Crossing
Top of Band
FS$_{sym}$
k_y
1
6
(0,0)
k_x
(π,0)

experimental data (LSCO)

`Luttinger' count



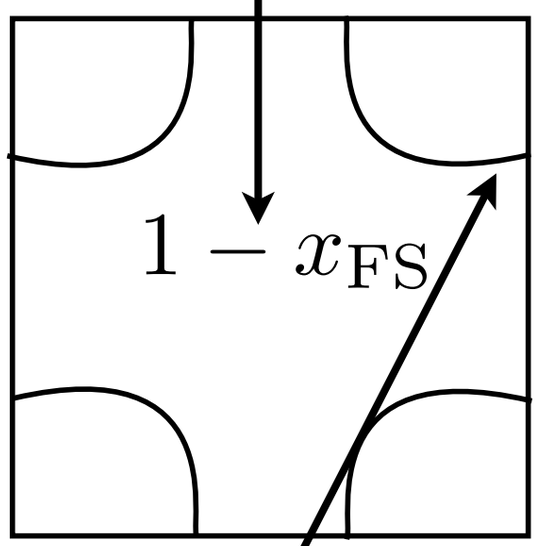


Bi2212

experimental data (LSCO)

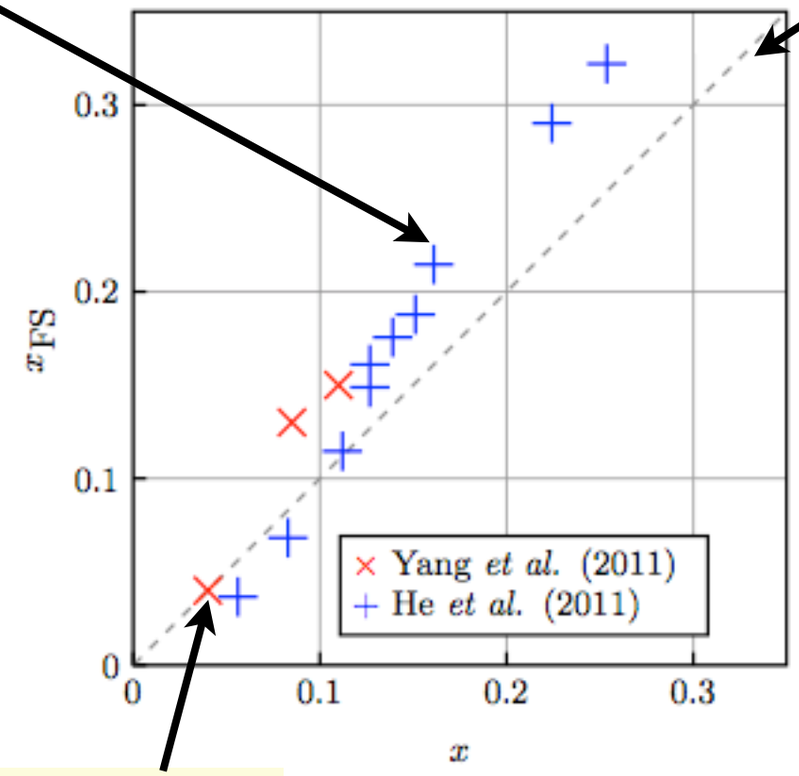
`Luttinger' count

k_F



$1 - x_{\mathrm{FS}}$

$Z_p \to 0$



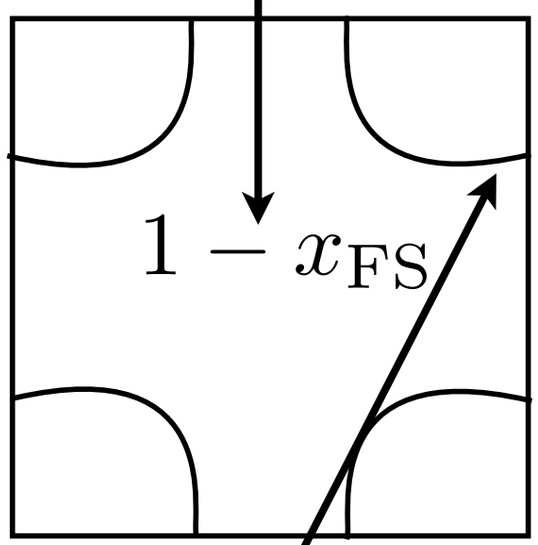
Bi2212

violation=> zeros are present

experimental data (LSCO)

`Luttinger' count

k_F



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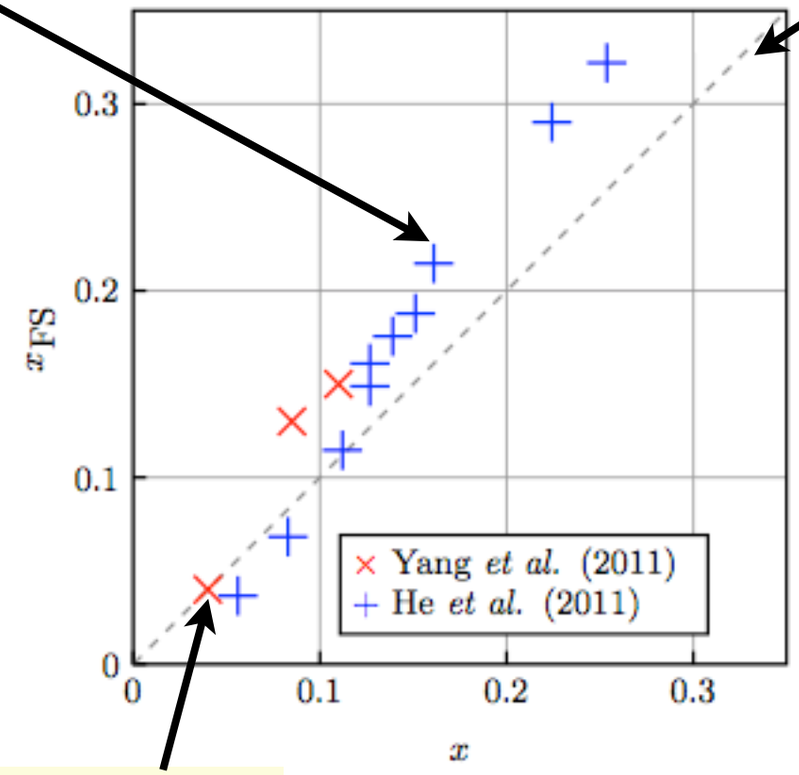


Bi2212

violation=> zeros are present

each hole $\neq$ a single k-state

Two opposing Views on Fermi arcs

strange

not strange

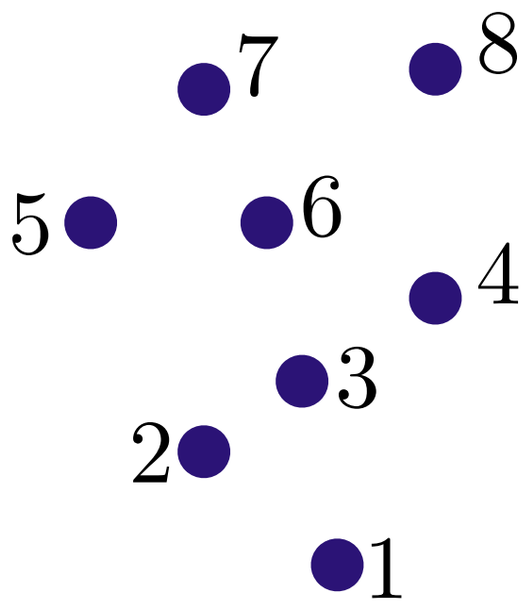
this dispute has an answer!

Two opposing Views on Fermi arcs

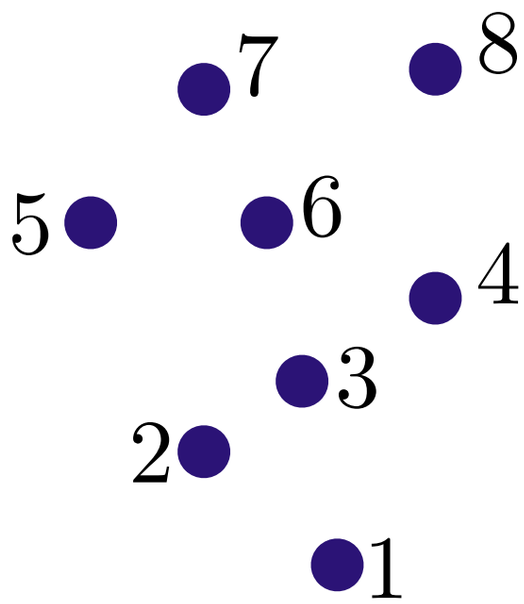
strange

this dispute has an answer!

how to count particles?

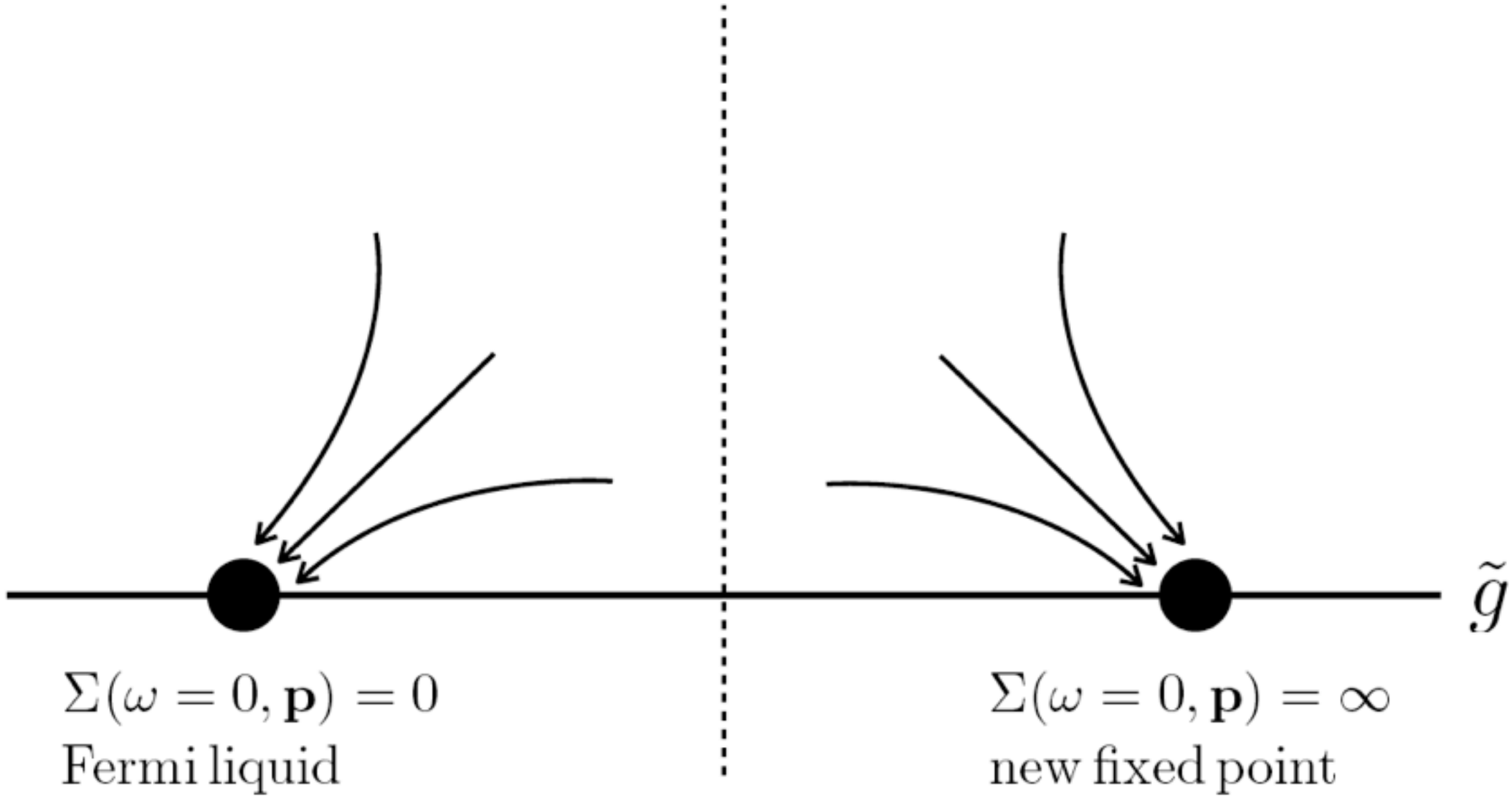


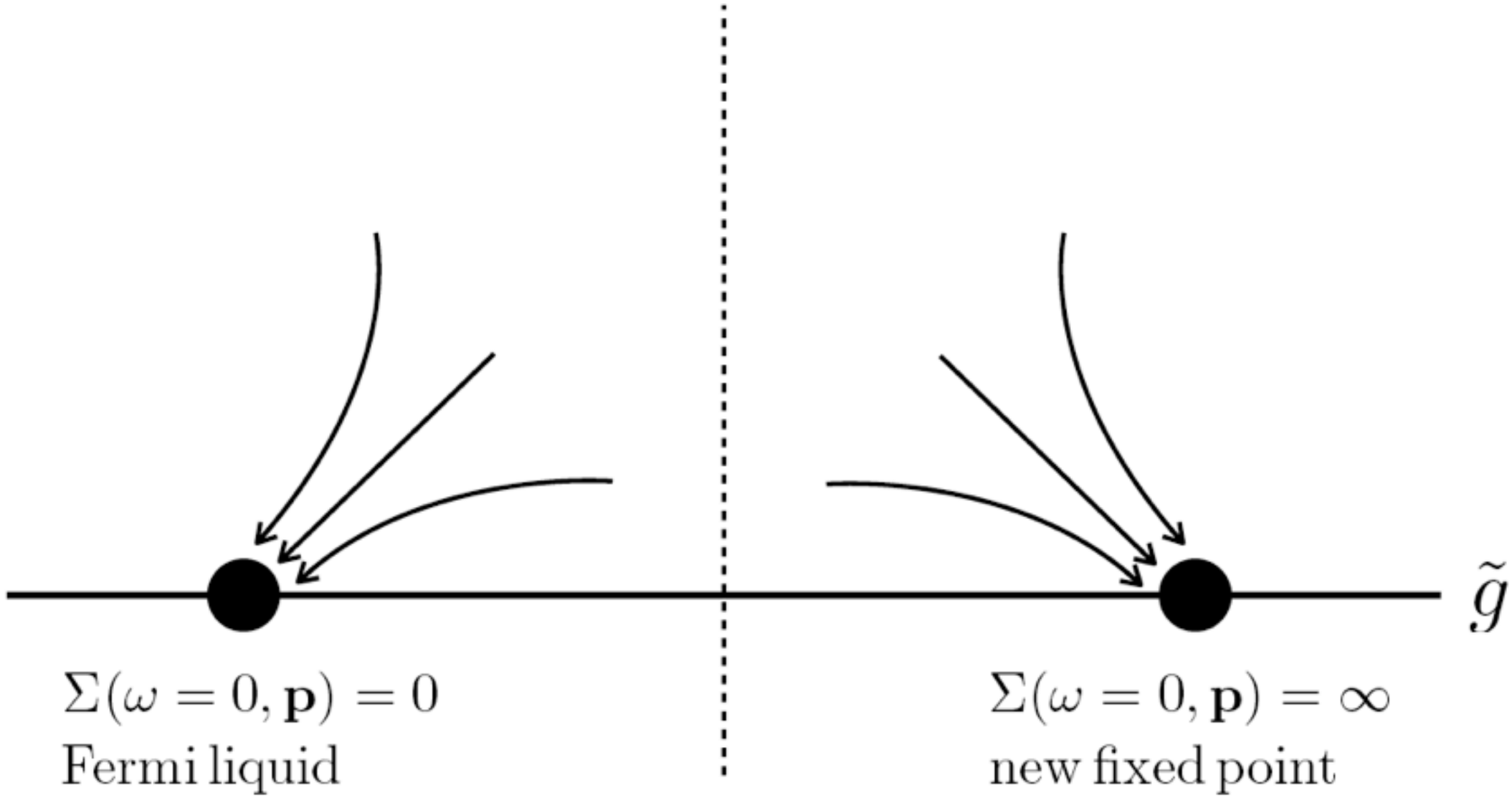
how to count particles?



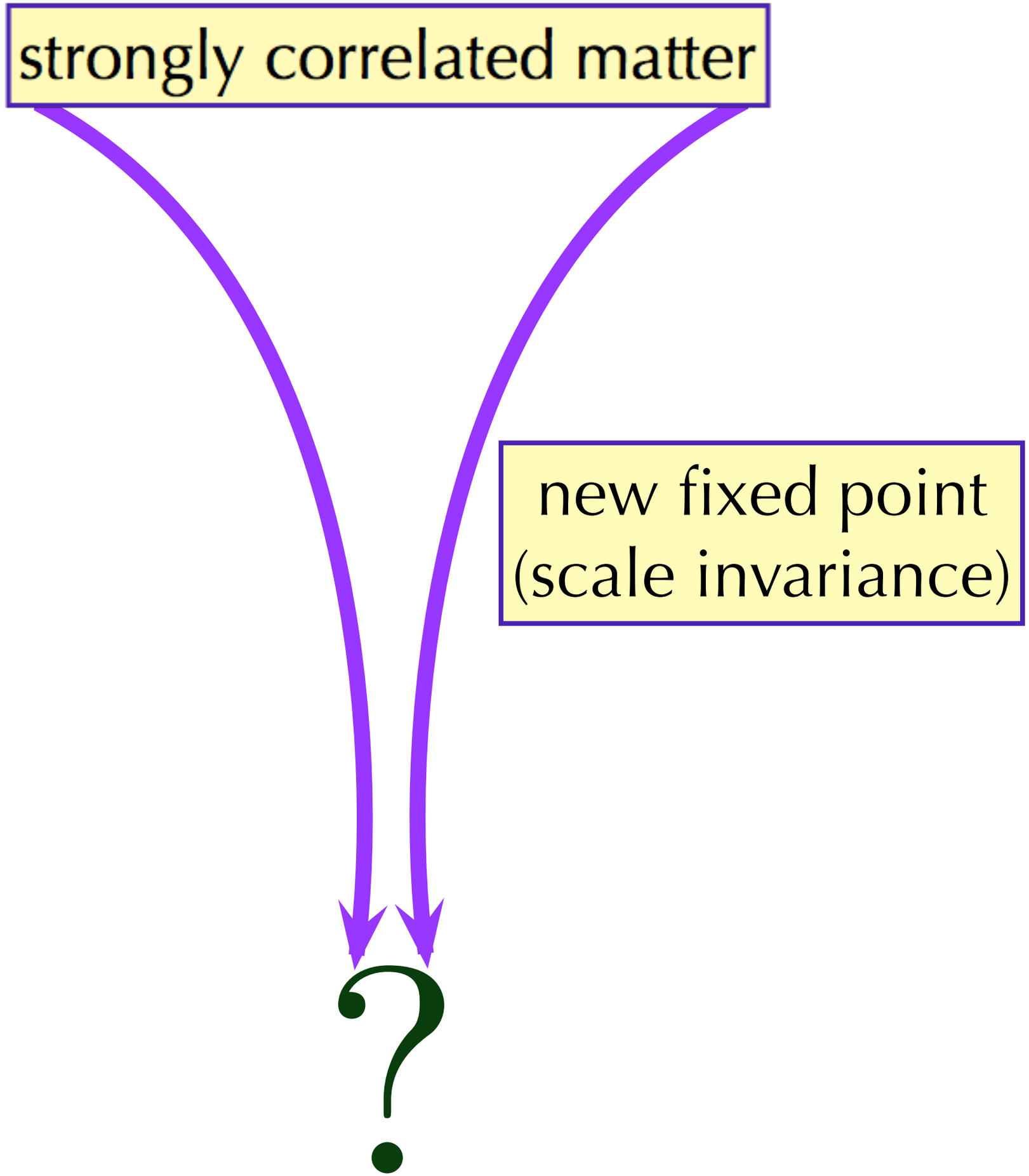
some charged stuff
has no particle interpretation

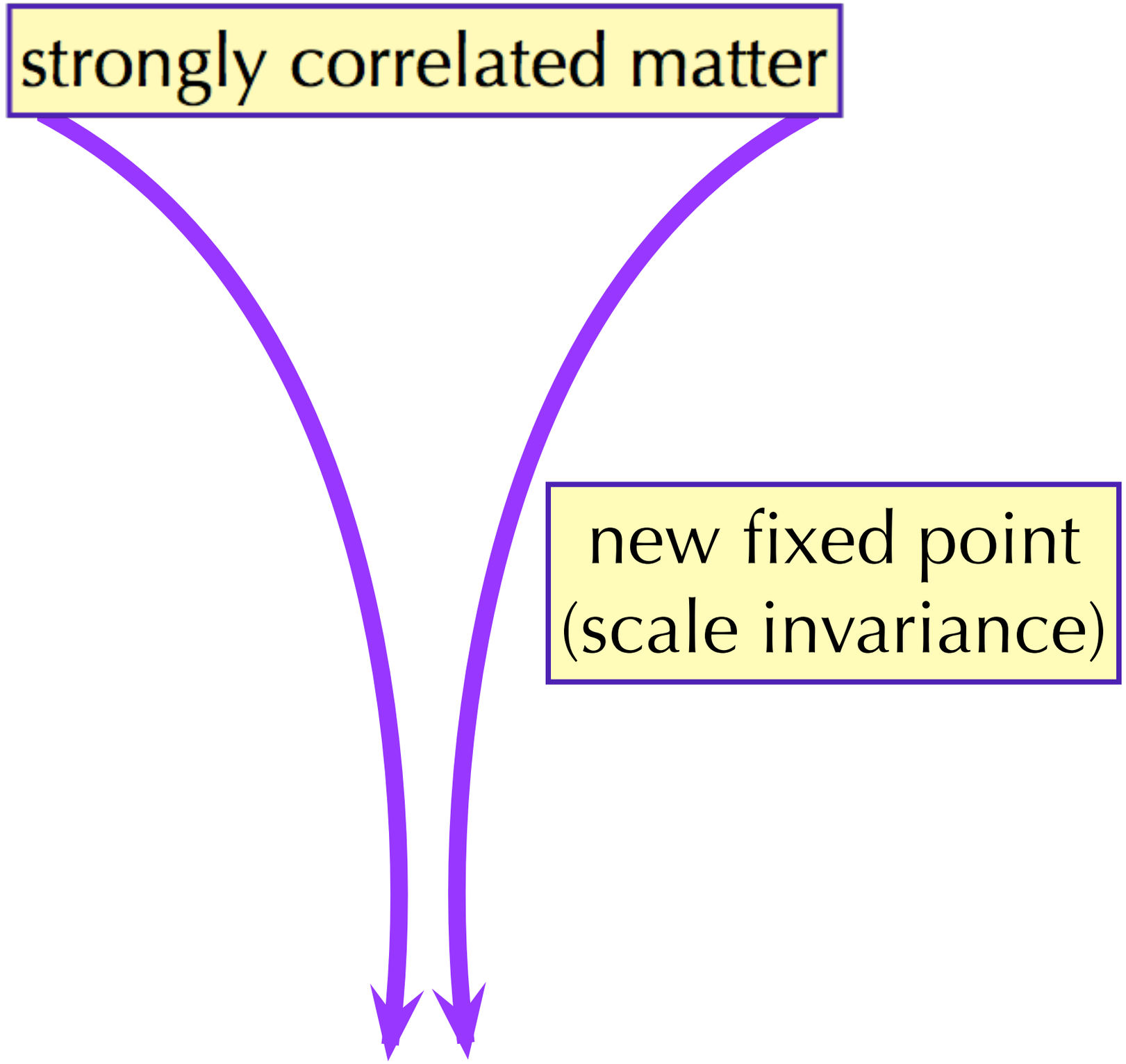
what is the extra stuff?

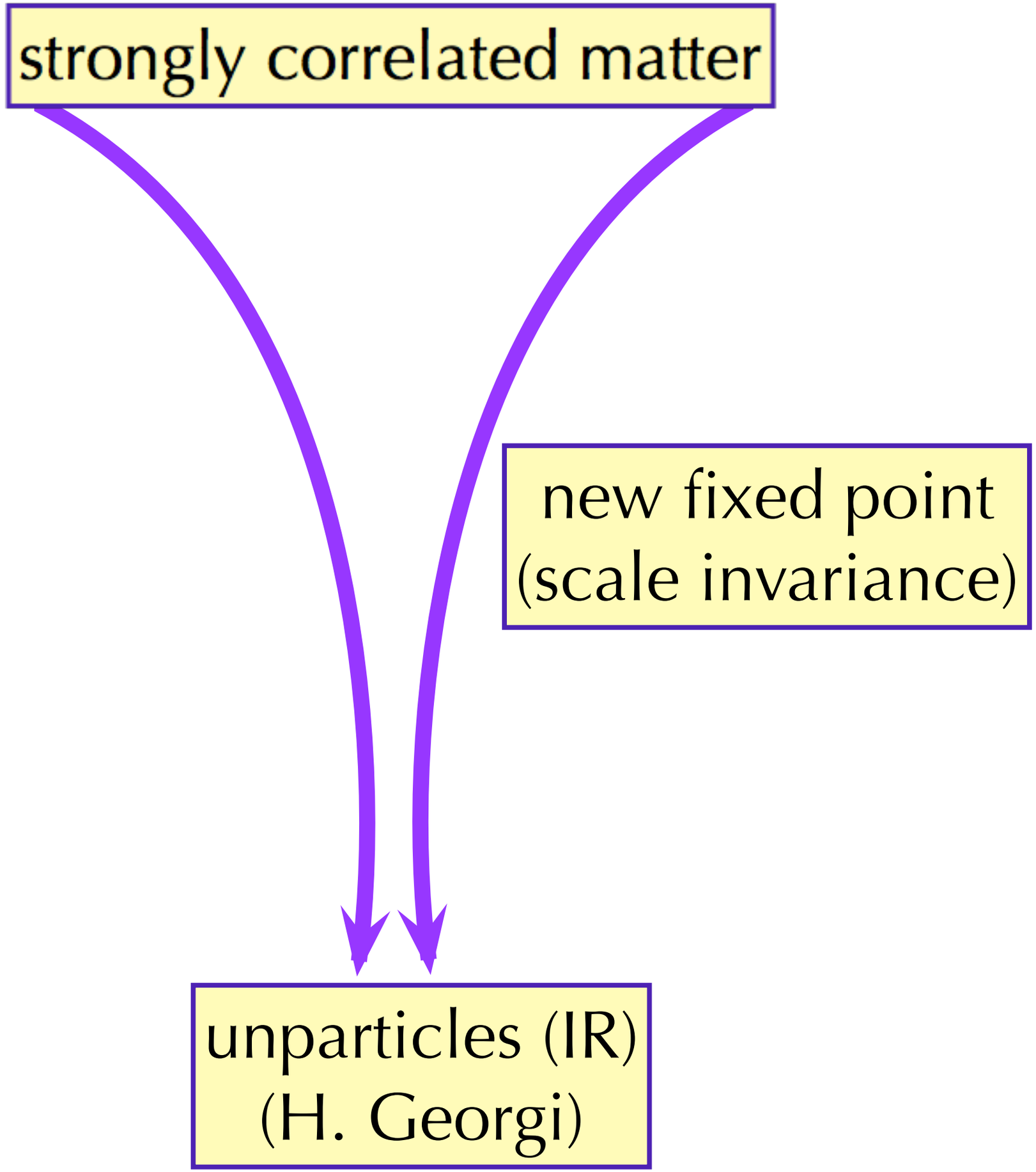

$\tilde{g}$
$\Sigma(\omega = 0, \mathbf{p}) = 0$
Fermi liquid
$\Sigma(\omega = 0, \mathbf{p}) = \infty$
new fixed point



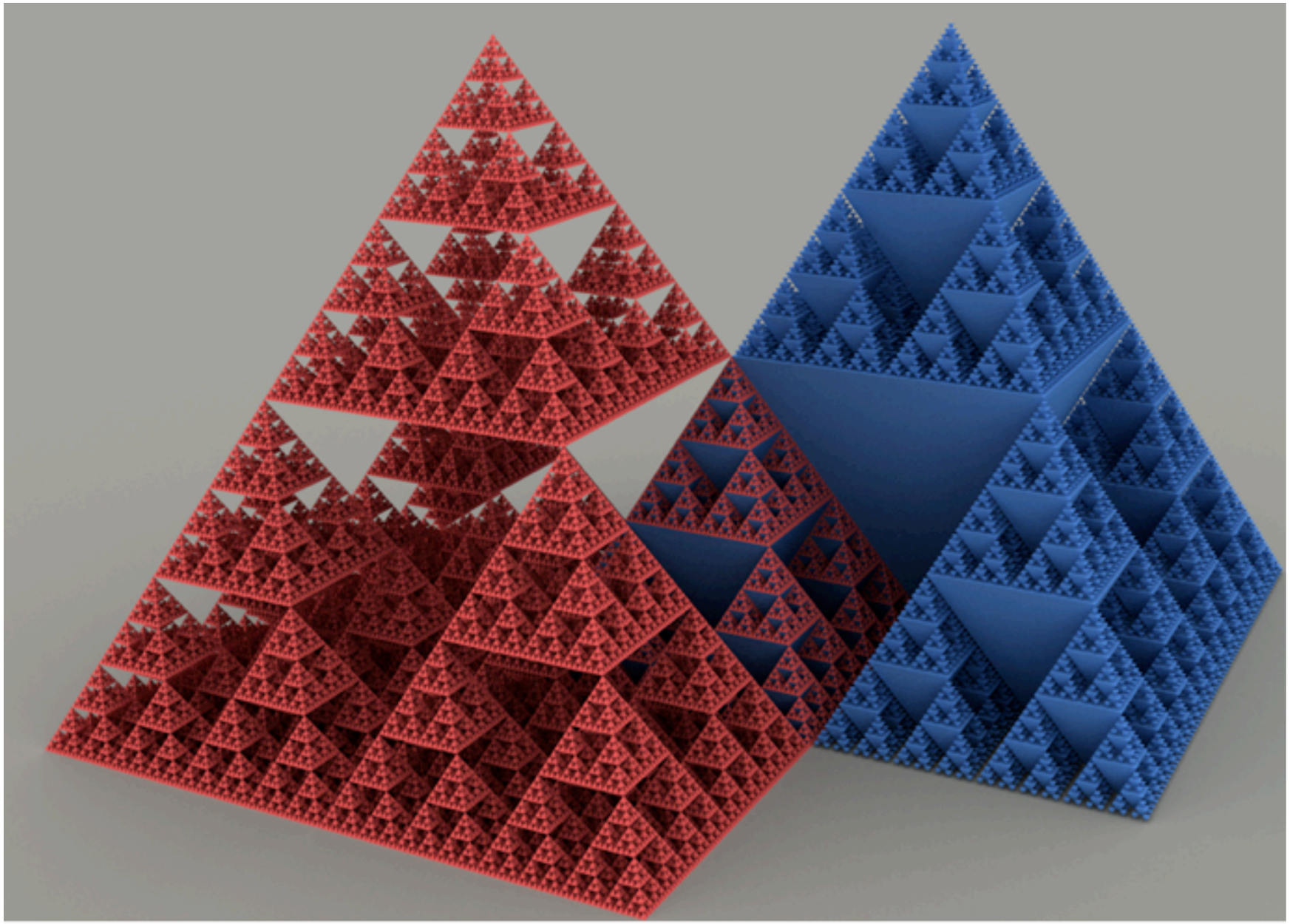
scale invariance


strongly correlated matter
new fixed point
(scale invariance)
?


strongly correlated matter
new fixed point
(scale invariance)

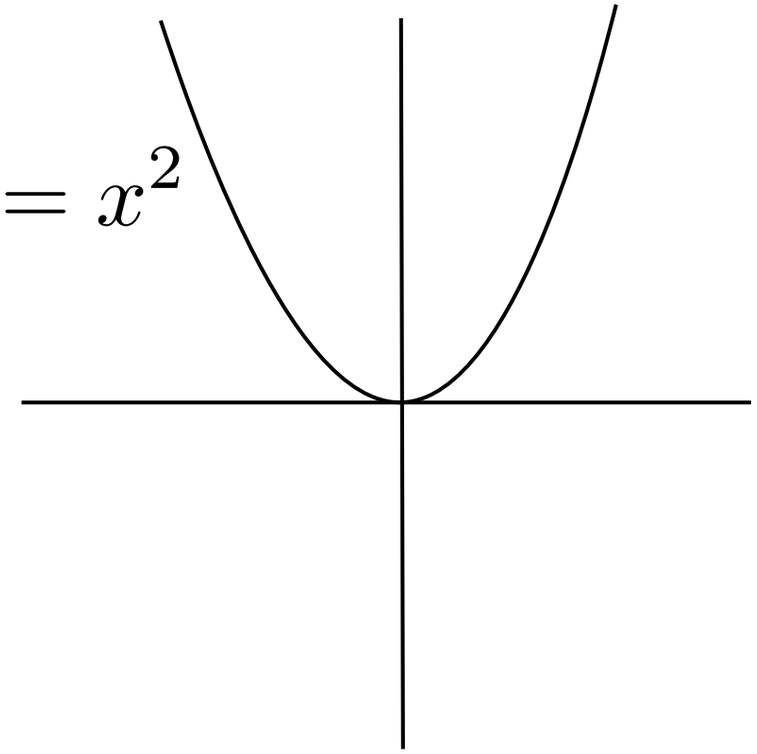

strongly correlated matter
new fixed point
(scale invariance)
unparticles (IR)
(H. Georgi)

what is scale invariance?



invariance on all length scales

$$f(x) = x^2$$



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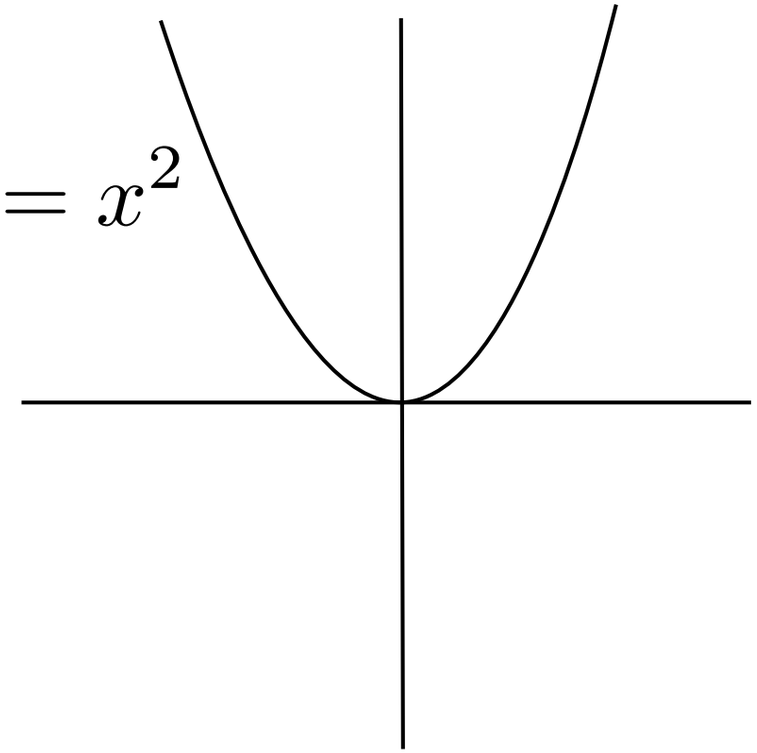
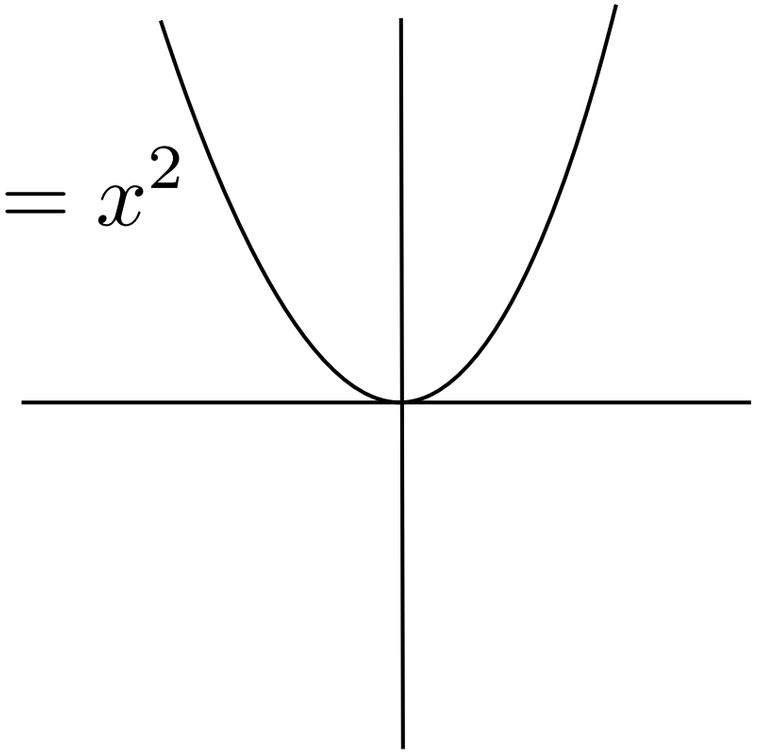


$$f(x/\lambda) = (x/\lambda)^2$$

scale change

$$f(x) = x^2$$



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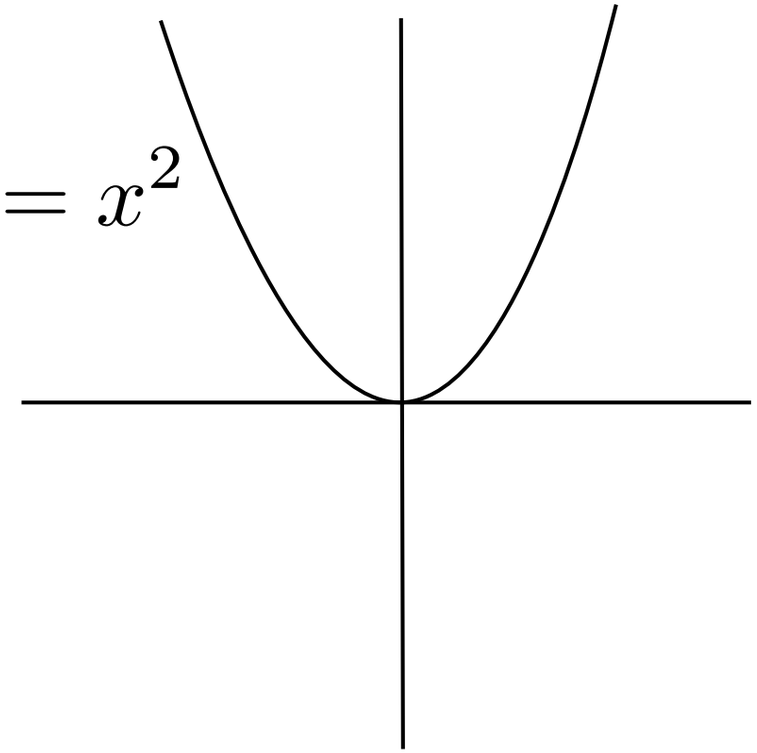


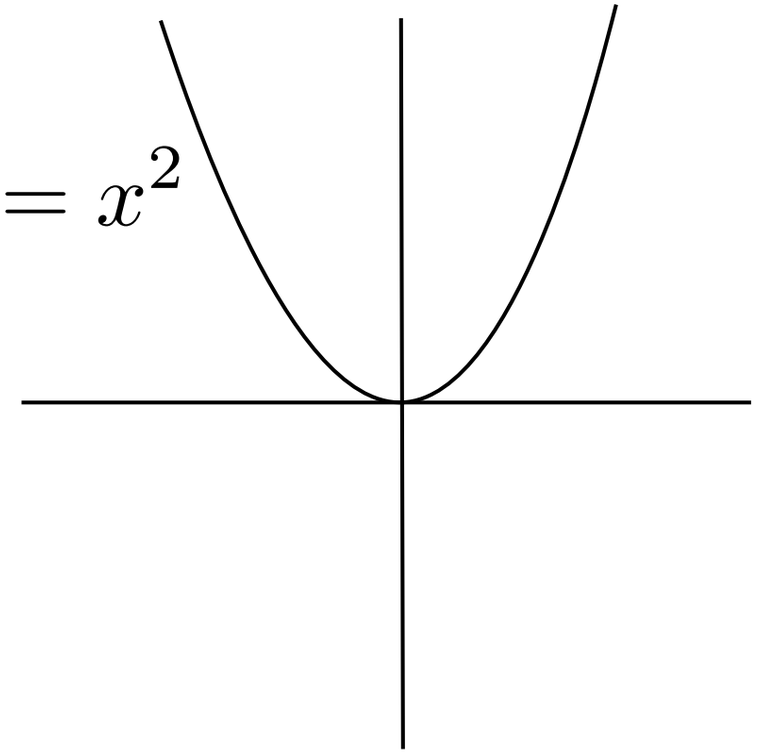
$$f(x/\lambda) = (x/\lambda)^2$$

scale change

scale invariance

$$f(x) = x^2 \underbrace{\lambda^{-2} g(\lambda)}_{\longrightarrow\ 1}$$

$$f(x) = x^2$$



$$f(x/\lambda) = (x/\lambda)^2$$

scale change

scale invariance

$$f(x) = x^2 \underbrace{\lambda^{-2} g(\lambda)}$$

$$g(\lambda) = \lambda^2$$

$$1$$

what's the underlying theory?

free field theory

$$\mathcal{L} = \frac{1}{2}\partial^\mu \phi \partial_\mu \phi$$

$$\Big\downarrow \quad \begin{array}{l} x \to x/\Lambda \\ \phi(x) \to \phi(x) \end{array}$$

$$\mathcal{L} \to \Lambda^2 \mathcal{L}$$

free field theory

$$\mathcal{L} = \frac{1}{2}\partial^\mu \phi \partial_\mu \phi$$

$$\downarrow \quad x \to x/\Lambda$$

$$\phi(x) \to \phi(x)$$

$$\mathcal{L} \to \Lambda^2 \mathcal{L}$$ scale invariant

massive free theory

mass

$$\mathcal{L} = \frac{1}{2}\partial^\mu \phi \partial_\mu \phi + m^2 \phi^2$$

massive free theory

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$$m^2\phi^2$$

no scale invariance

unparticles
from a massive theory?

$$\mathcal{L} = \quad \left(\partial^\mu \phi(x,m)\partial_\mu \phi(x,m) + m^2\phi^2(x,m)\right)$$

$$\mathcal{L} = \int_0^\infty \left(\partial^\mu \phi(x,m)\partial_\mu \phi(x,m) + m^2 \phi^2(x,m)\right) dm^2$$

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theory with all possible mass!

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theory with all possible mass!

$$\phi \to \phi(x, m^2/\Lambda^2)$$
$$x \to x/\Lambda$$
$$m^2/\Lambda^2 \to m^2$$

$$\mathcal{L} = \int_0^\infty \left(\partial^\mu \phi(x,m)\partial_\mu \phi(x,m) + m^2\phi^2(x,m)\right) dm^2$$

theory with all possible mass!

$$\phi \to \phi(x, m^2/\Lambda^2)$$
$$x \to x/\Lambda$$
$$m^2/\Lambda^2 \to m^2$$

$$\mathcal{L} \to \Lambda^4 \mathcal{L}$$

scale invariance is restored!!

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not particles

unparticles

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theory with all possible mass!

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not particles

propagator

$$\left(\int_0^\infty dm^2 m^{2\gamma} \frac{i}{p^2 - m^2 + i\epsilon}\right)^{-1} \propto p^{2|\gamma|}$$

propagator

$$\left(\int_0^\infty dm^2 m^{2\gamma} \frac{i}{p^2 - m^2 + i\epsilon}\right)^{-1} \propto p^{2|\gamma|}$$

$$\downarrow$$

$$d_U - 2$$

n massless particles

$$G \propto (E - \varepsilon_p)^{n-2}$$

n massless particles

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$$G \propto (E - \varepsilon_p)^{d_U - 2}$$

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unparticles=fractional number of massless particles

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unparticles=fractional number of massless particles

$d_U > 2$

zeros

n massless particles

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$$G \propto (E - \varepsilon_p)^{d_U - 2}$$

unparticles=fractional number of massless particles

$d_U > 2$

zeros

no simple sign change

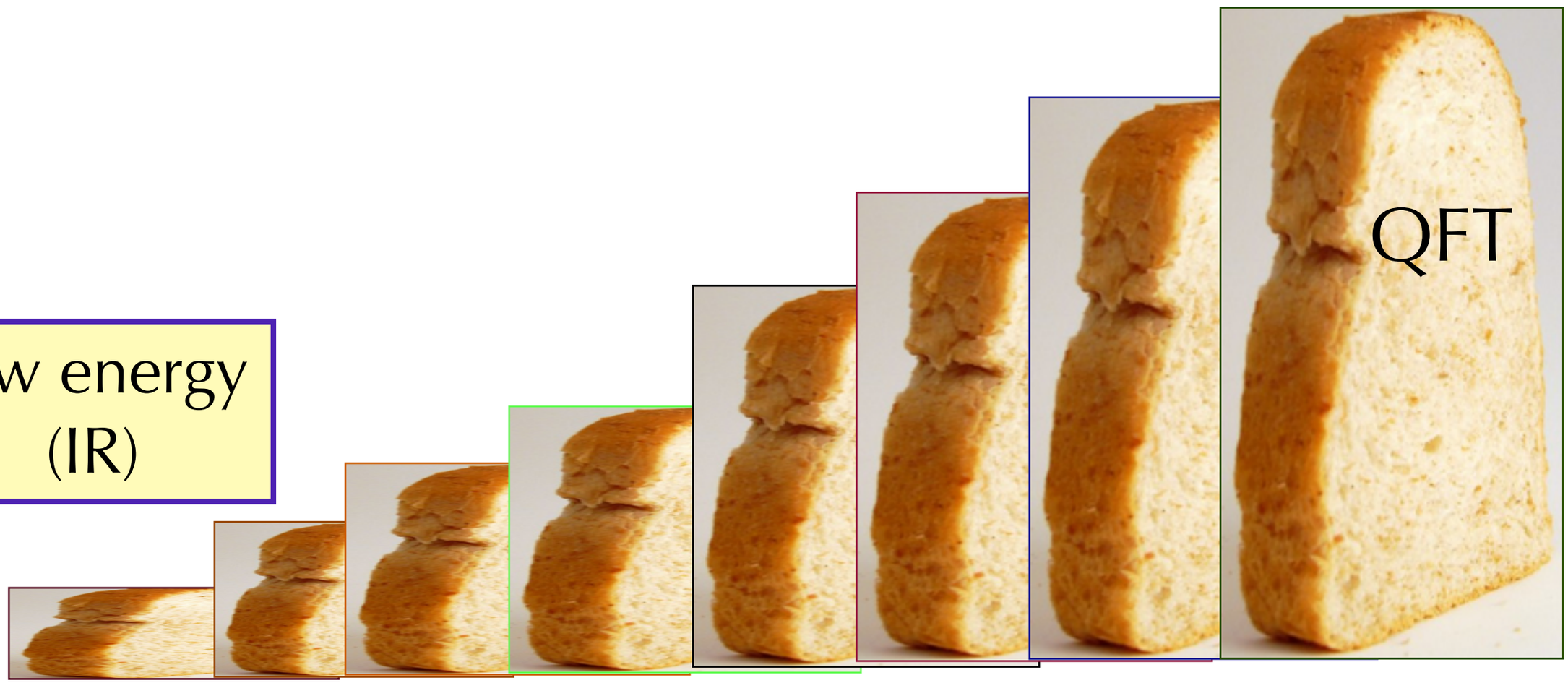
$$d_U\,?$$

what really is the summation over mass?

what really is the summation over mass?

mass=energy

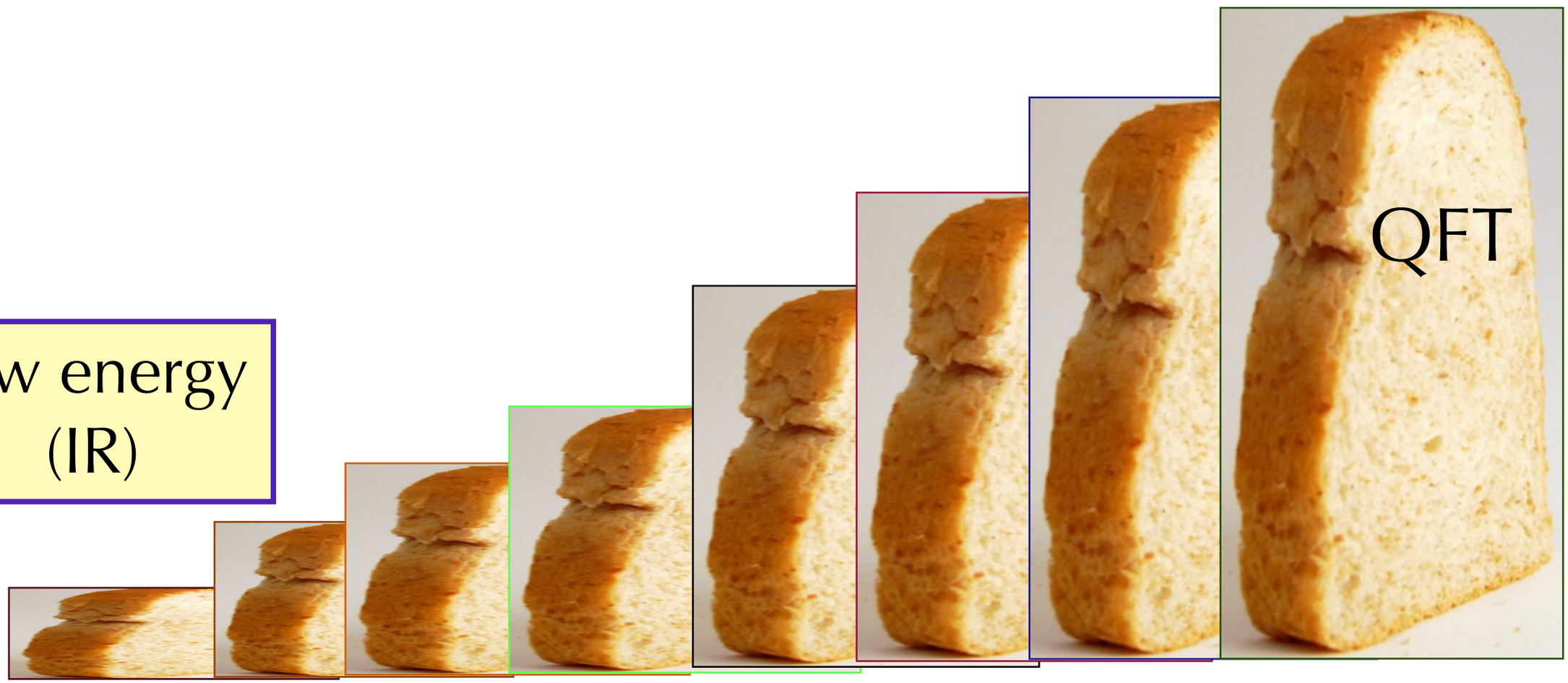
high energy
(UV)



low energy
(IR)

related to sum
over mass

high energy
(UV)



low energy
(IR)

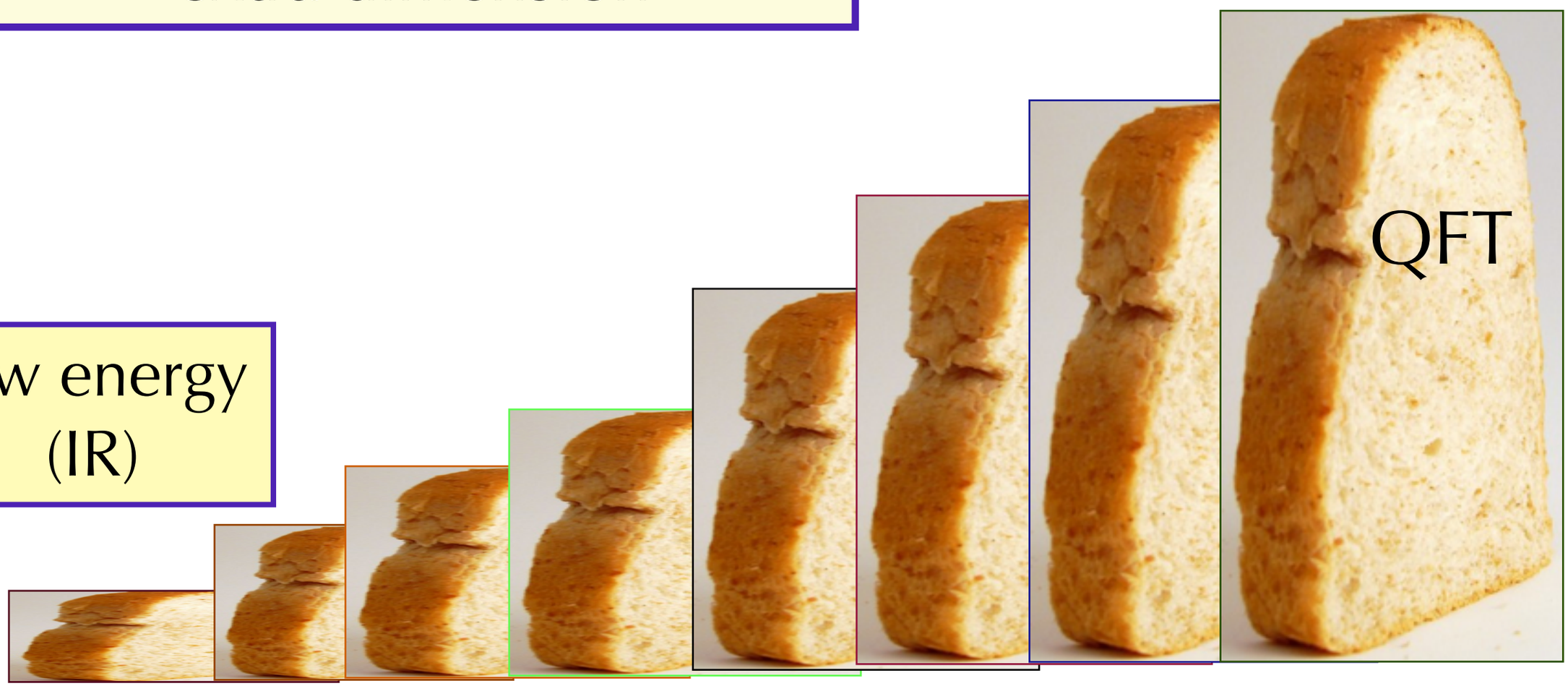
$$\frac{dg(E)}{dlnE} = \beta(g(E))$$

locality in energy

related to sum
over mass

implement E-scaling with an extra dimension

high energy (UV)



low energy (IR)

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locality in energy

implement E-scaling with an extra dimension

QFT

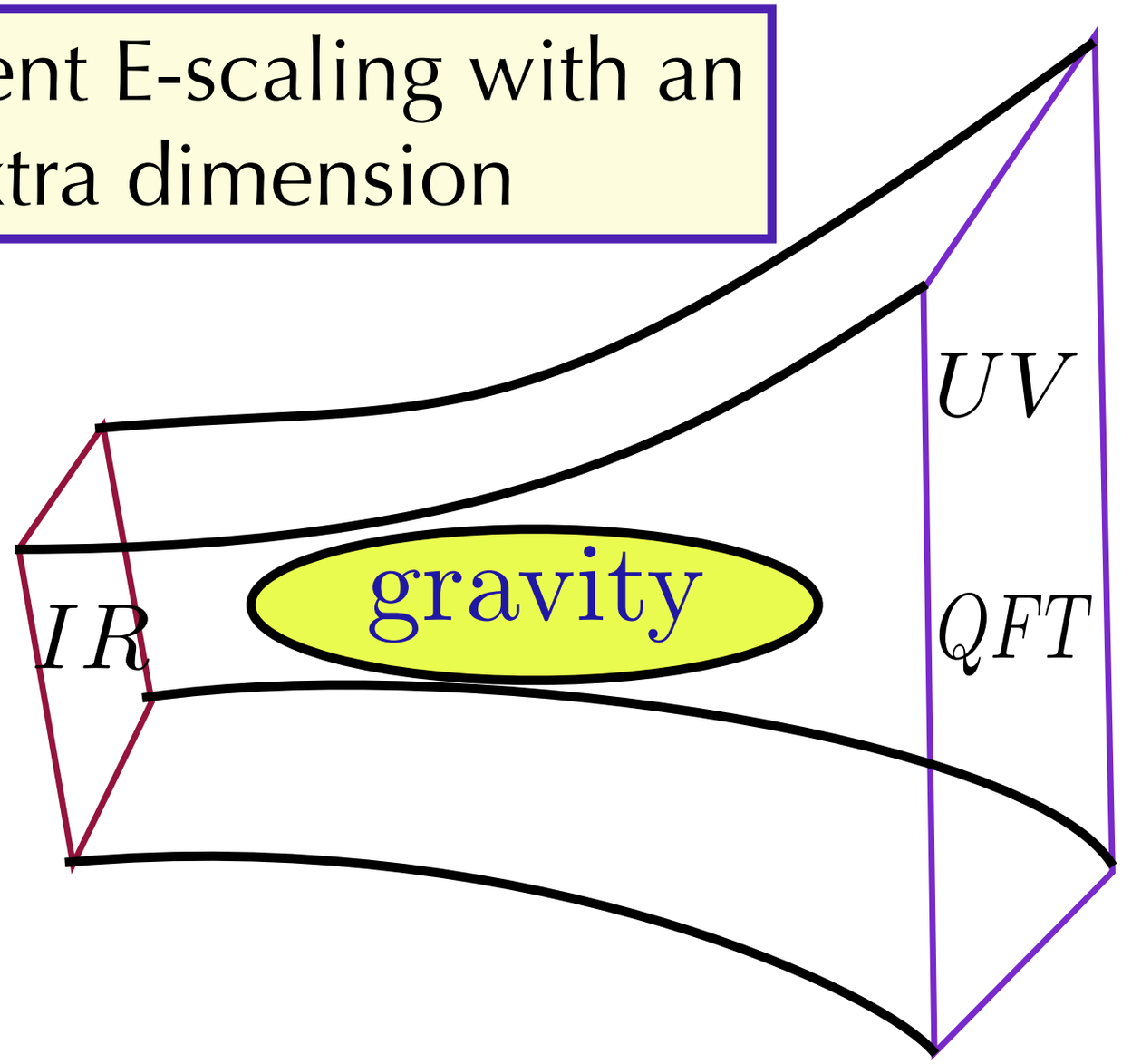
$$\frac{dg(E)}{dlnE} = \beta(g(E))$$

related to sum over mass

locality in energy

gauge-gravity duality
(Maldacena, 1997)

implement E-scaling with an extra dimension



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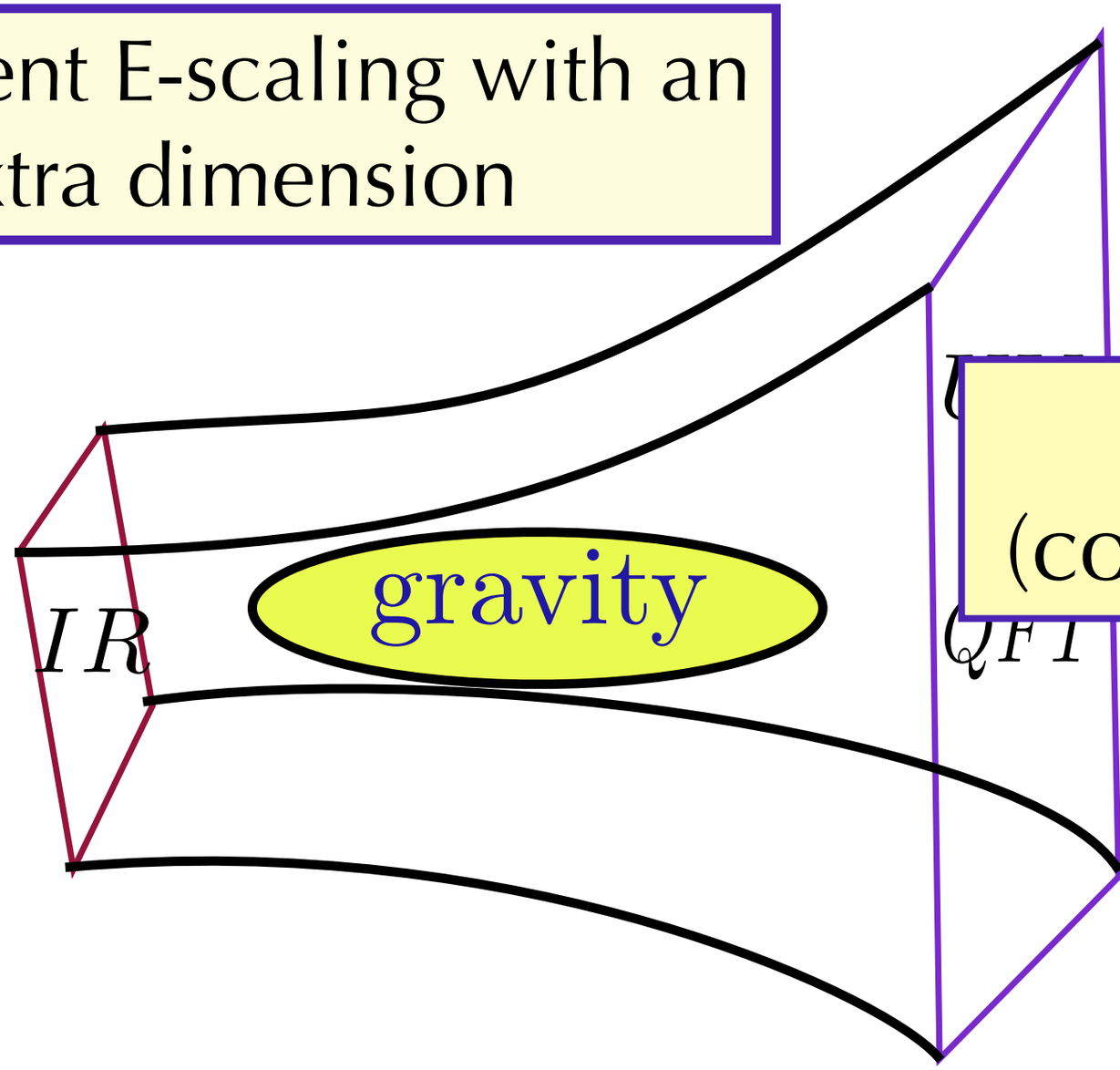

no particles
(conserved currents)

$$\frac{dg(E)}{dlnE} = \beta(g(E))$$

related to sum over mass

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gauge-gravity duality
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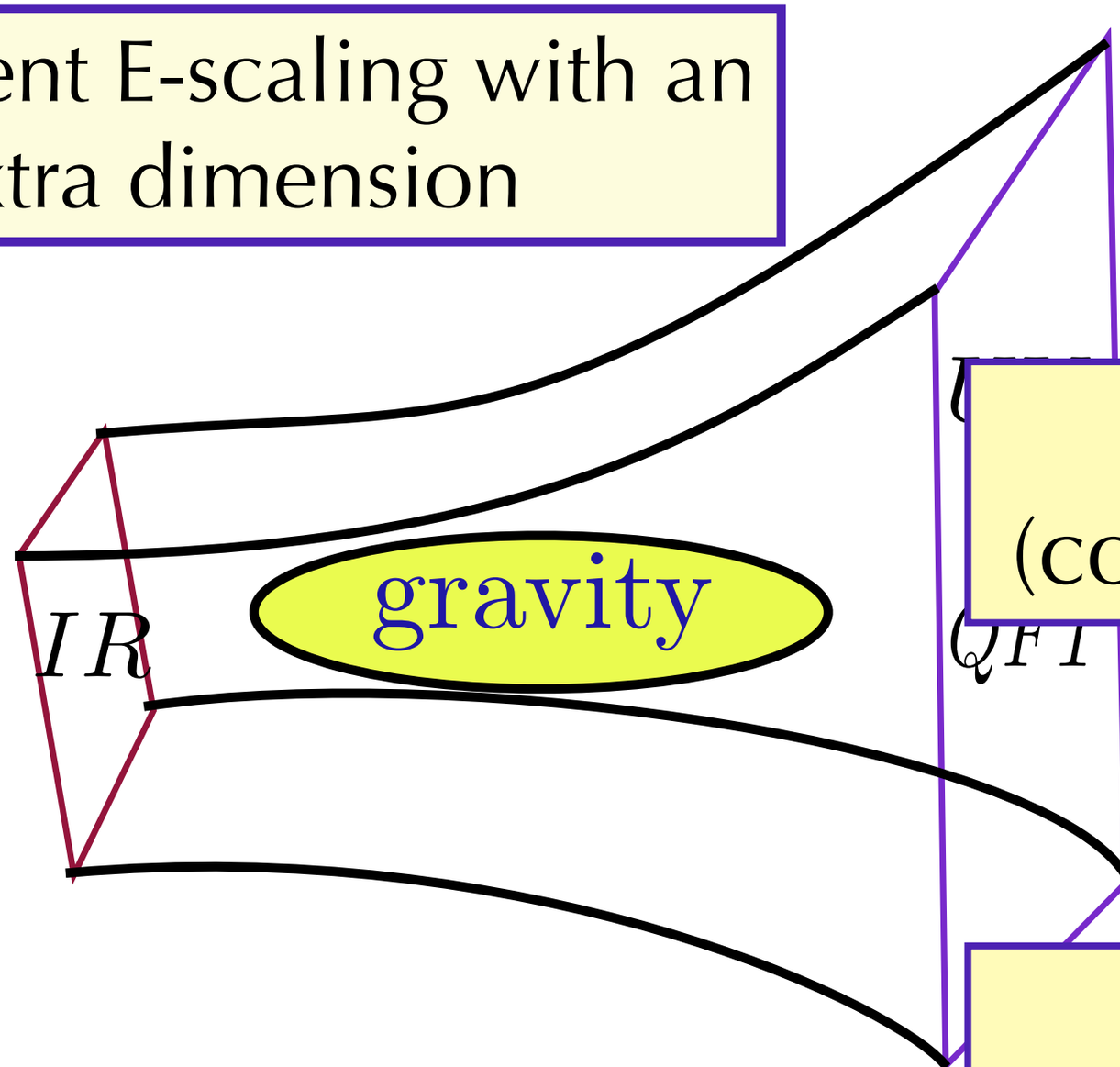
implement E-scaling with an extra dimension



no particles
(conserved currents)

unparticles?

$$\frac{dg(E)}{dlnE} = \beta(g(E))$$

related to sum over mass

locality in energy

mass=extra dimension

↓

fixed by metric

rewriting the action

rewriting the action

$$\mathcal{L} = \int_0^\infty \left(\partial^\mu \phi(x,m)\partial_\mu \phi(x,m) + m^2\phi^2(x,m)\right) m^{2\delta} dm^2$$

rewriting the action

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$$m = z^{-1}$$

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$$m = z^{-1}$$

$$\mathcal{L} = \int_0^\infty dz \frac{2R^2}{z^{5+2\delta}} \left[\frac{1}{2}\frac{z^2}{R^2}\eta^{\mu\nu}(\partial_\mu\phi)(\partial_\nu\phi) + \frac{\phi^2}{2R^2}\right]$$

rewriting the action

$$\mathcal{L} = \int_0^\infty \left(\partial^\mu \phi(x,m)\partial_\mu \phi(x,m) + m^2\phi^2(x,m)\right) m^{2\delta} dm^2$$

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can be absorbed with AdS metric

generating functional for unparticles

action on $AdS_{5+2\delta}$

$$S = \frac{1}{2}\int d^{4+2\delta}x\, dz\, \sqrt{-g}\left(\partial_a\Phi\partial^a\Phi + \frac{\Phi^2}{R^2}\right)$$

generating functional for unparticles

action on $AdS_{5+2\delta}$

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$$ds^2 = \frac{L^2}{z^2}\left(\eta_{\mu\nu}dx^\mu dx^\nu + dz^2\right) \qquad \sqrt{-g} = (R/z)^{5+2\delta}$$

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unparticle lives in

$$d = 4 + 2\delta \qquad \delta \leq 0$$

scaling dimension is fixed

$$m = \frac{1}{z}$$

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$$m^2_{\mathrm{AdS}} = \frac{d_U\,(d_U - d)}{R^2}$$

scaling dimension is fixed

$$m = \frac{1}{z}$$

$$1 = d_U(d_U - d)$$

scaling dimension is fixed

$$m = \frac{1}{z}$$

$$1 = d_U(d_U - d)$$

$$d_U = \frac{d}{2} + \frac{\sqrt{d^2+4}}{2}$$

$$G_U(p) \propto p^{2(d_U - d/2)}$$

$$\downarrow$$

$$G_U(0) = 0$$

unparticle (AdS) propagator has zeros!

$$G_U(p) \propto p^{2(d_U - d/2)}$$

$$\downarrow$$

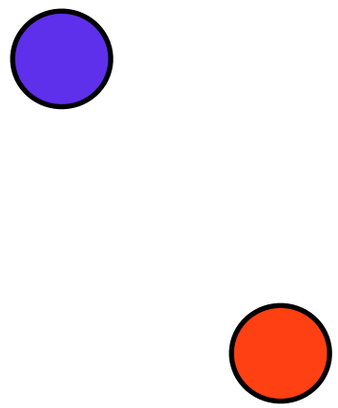
$$G_U(0) = 0$$

interchanging unparticles

fractional (d_U) number of massless particles

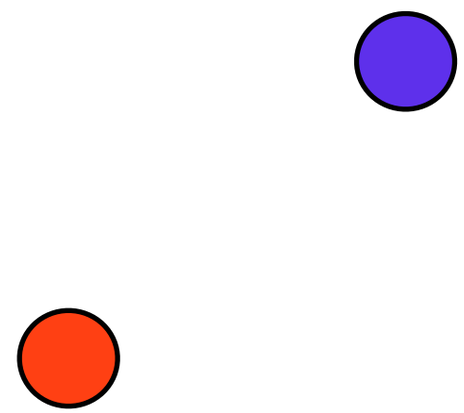
interchanging unparticles

fractional (d_U) number of massless particles



interchanging unparticles

fractional (d_U) number of massless particles



interchanging unparticles

fractional (d_U) number of massless particles

interchanging unparticles

fractional (d_U) number of massless particles

$$e^{i\pi d_U} \neq -1, 0$$

interchanging unparticles

fractional (d_U) number of massless particles

$$e^{i\pi d_U} \neq -1, 0$$

fractional statistics in d=2+1

$$d_U = \frac{d}{2} + \frac{\sqrt{d^2+4}}{2} > \frac{d}{2}$$

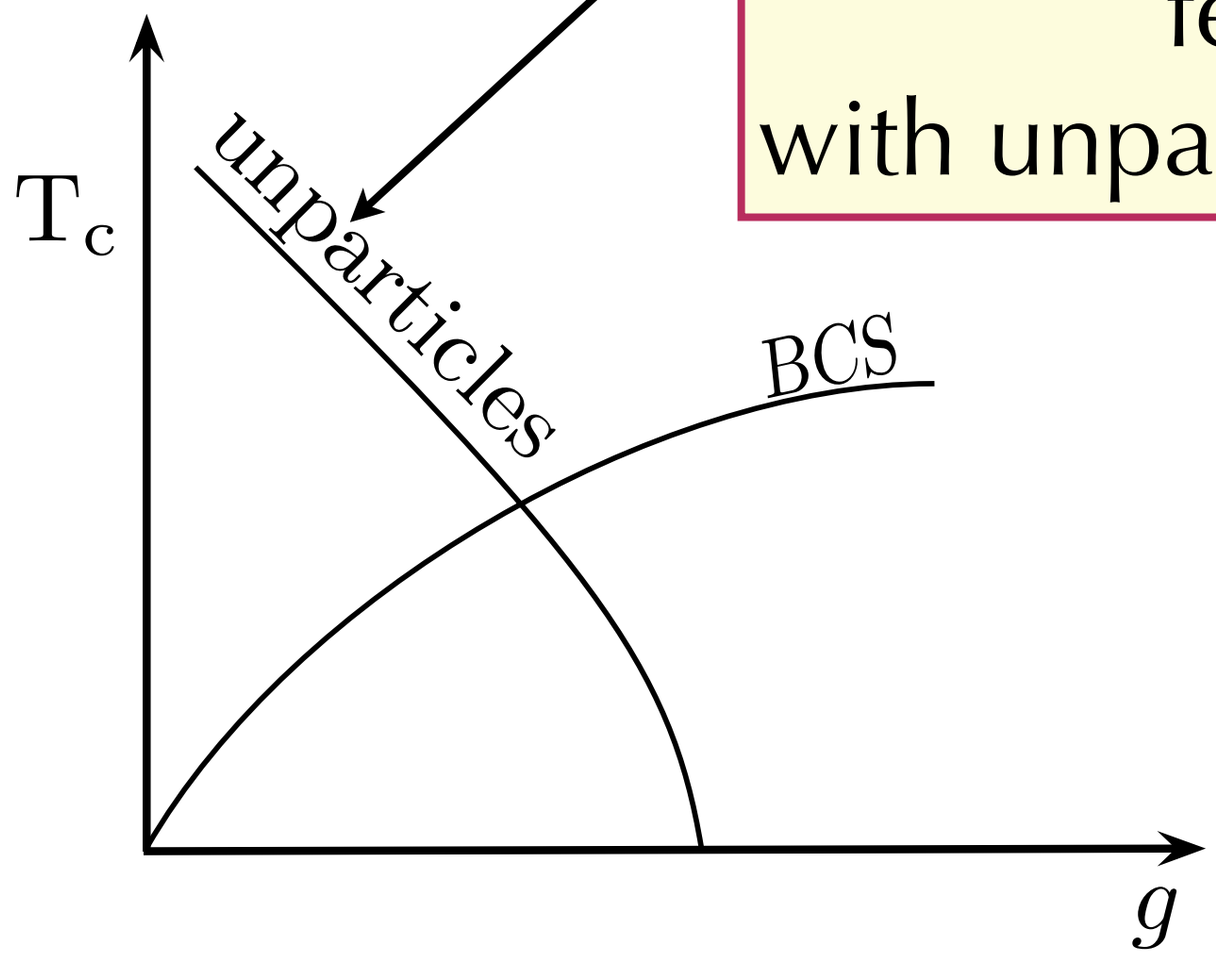
$$e^{i\pi d_U} \neq e^{-i\pi d_U}$$

$$\Downarrow$$

time-reversal symmetry breaking
from unparticle (zeros=Fermi arcs) matter

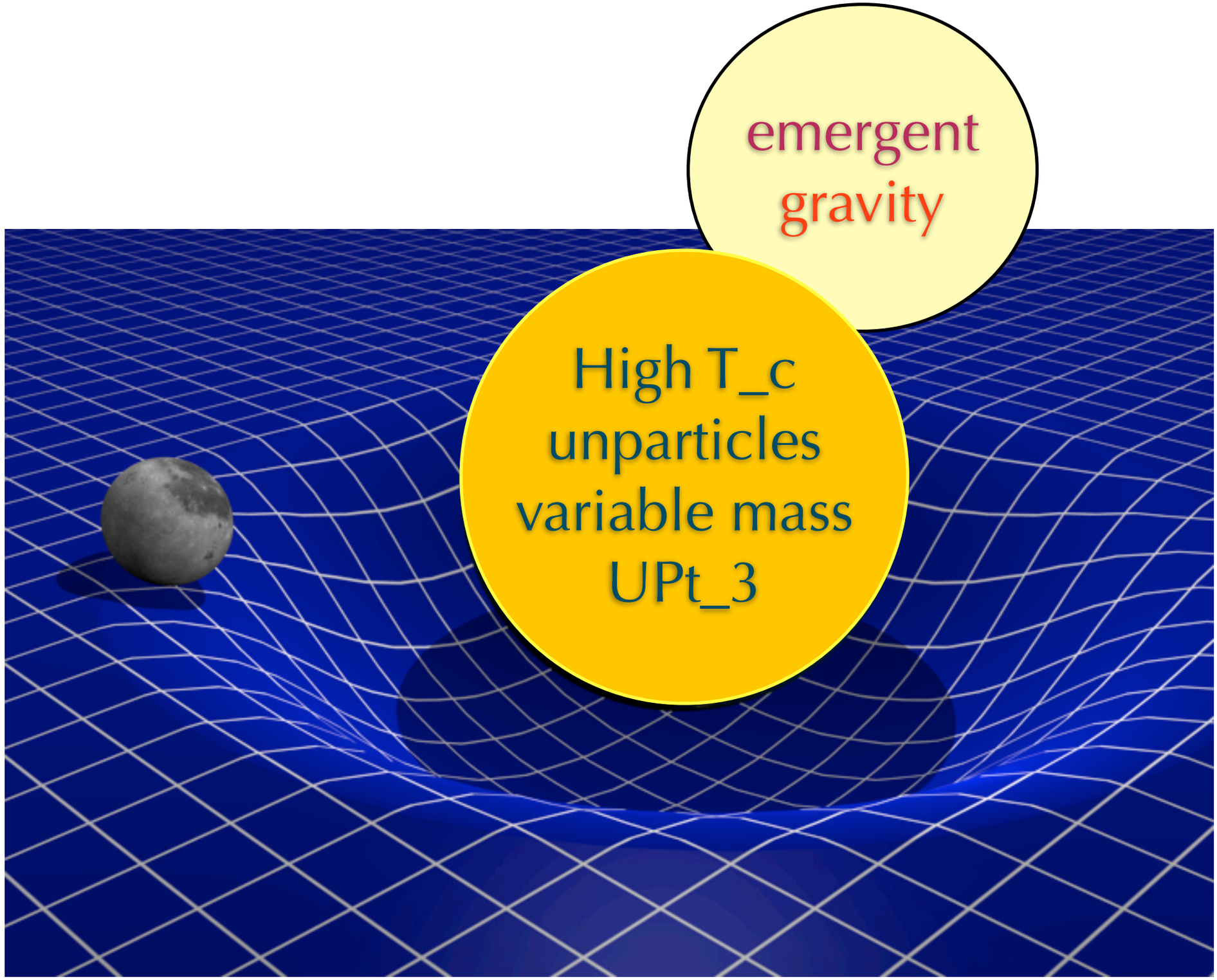
$$\frac{d \ln g}{d \ln \beta} = 4d_U - d > 0$$

fermions
with unparticle propagator



tendency towards pairing (any instability which establishes a gap)

High T_c
unparticles
variable mass
UPt_3


emergent
gravity
High T_c
unparticles
variable mass
UPt_3