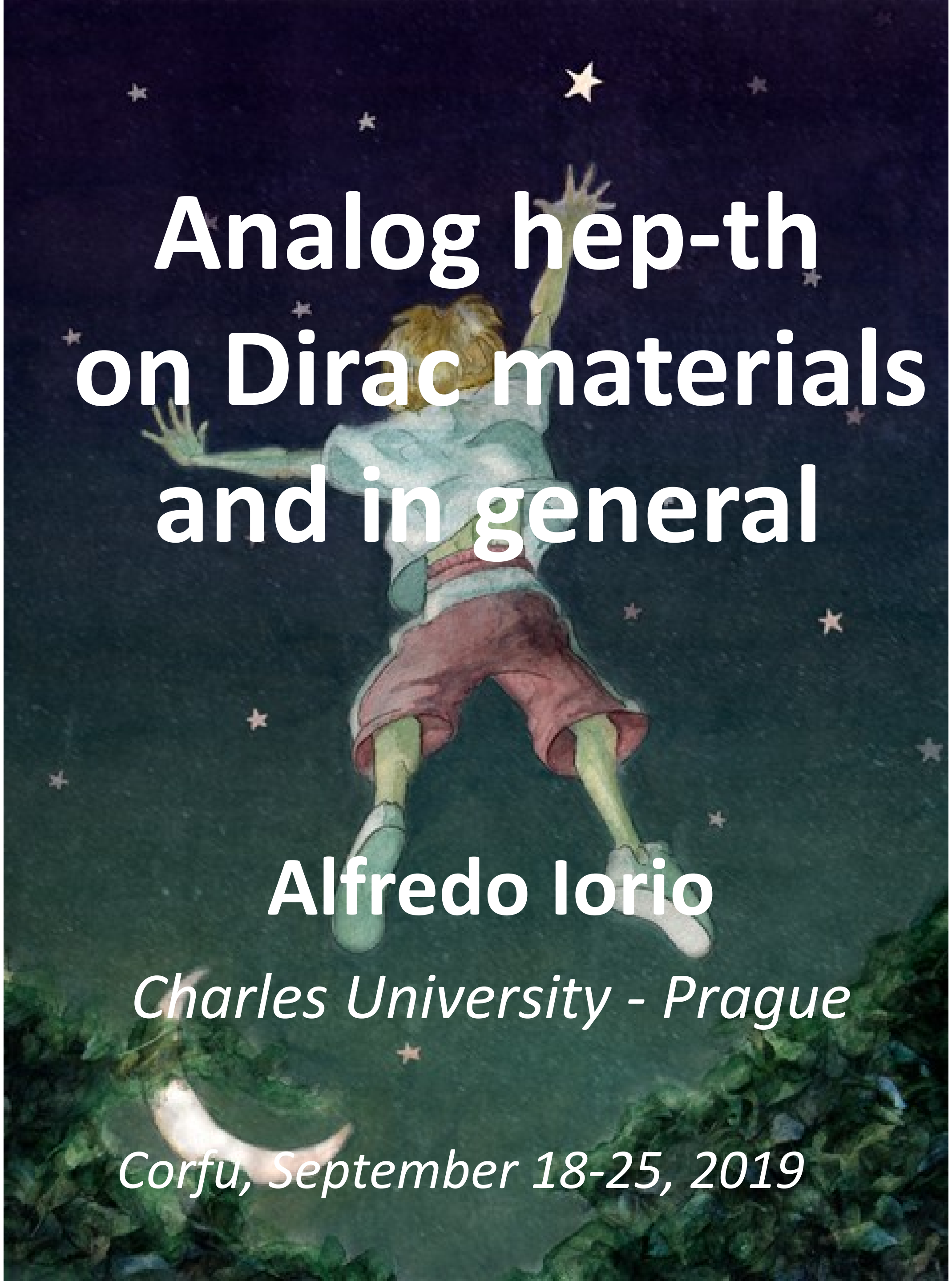


Analog hep-th on Dirac materials and in general

Alfredo Iorio

Charles University - Prague

Corfu, September 18-25, 2019

Emergent fields in Dirac materials

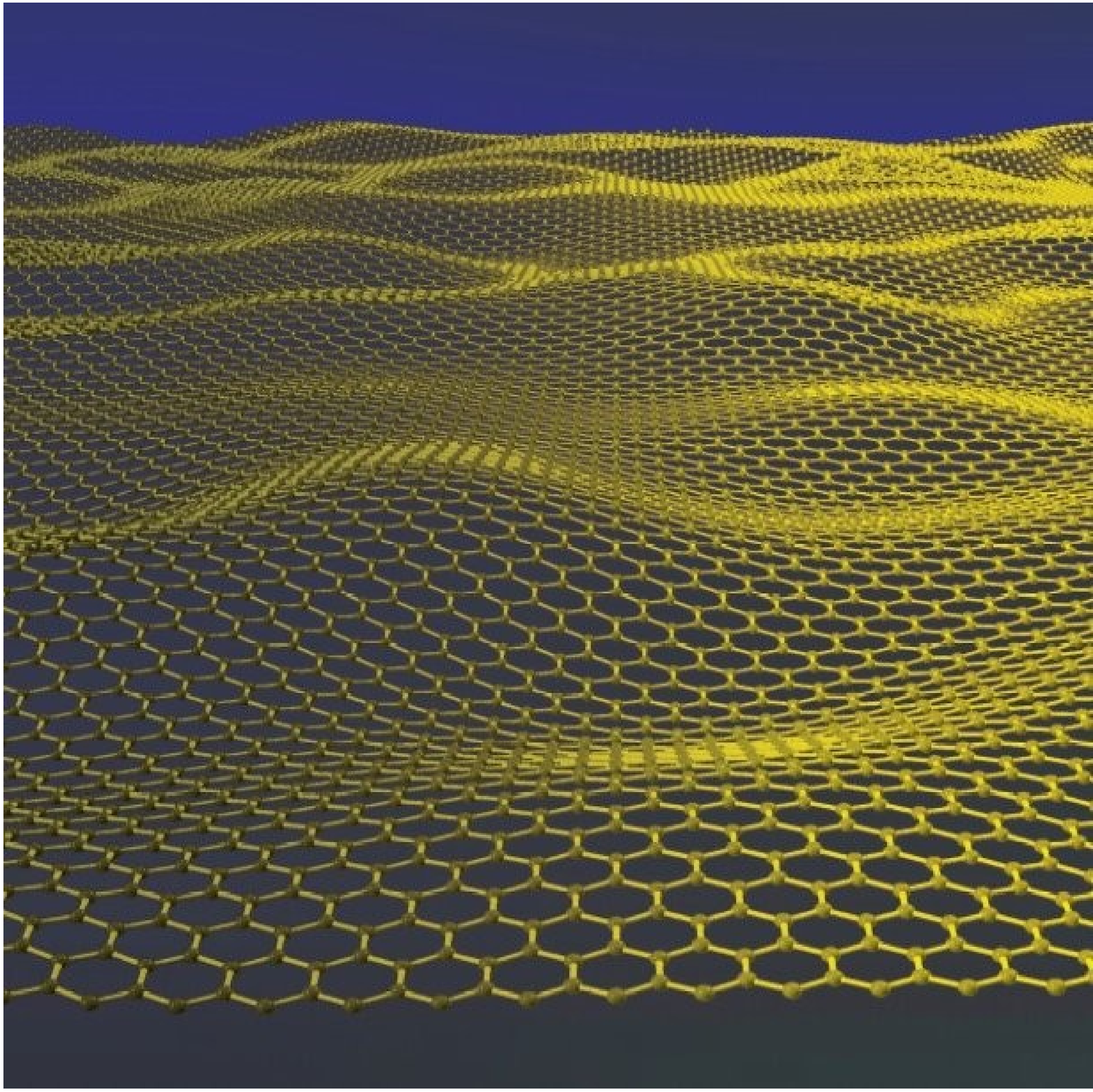
ψ_α

A_μ

ω_μ^a

κ_μ^a

$g_{\mu\nu}$



For conventional metals/semiconductors, the Hamiltonian of the low energy quasiparticles is

$$H_S = \vec{p}^2/2m_*$$

New materials appeared for which

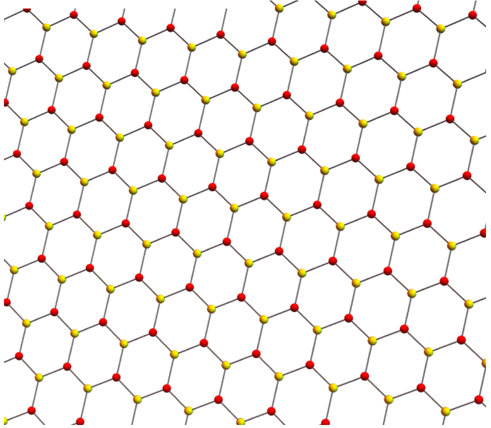
$$H_D = v\vec{\sigma}\cdot\vec{p} + mv^2\sigma_3$$

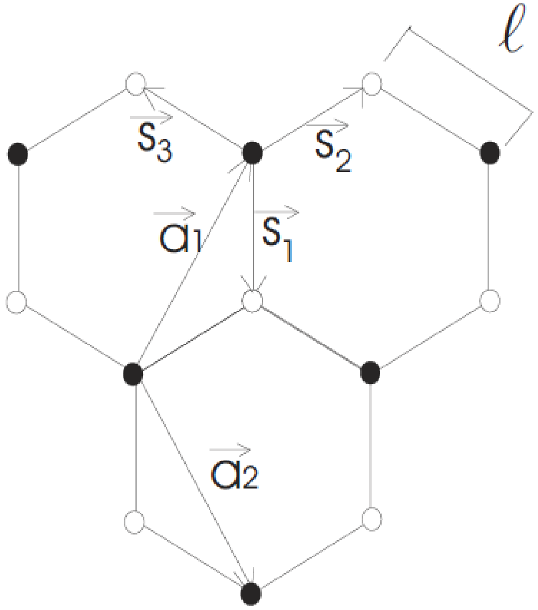
where $\vec{\sigma} = (\sigma_1, \sigma_2)$, and v is speed.

Materials whose low-energy quasi-particles are described by this H_D are called <u>Dirac materials</u>

Material	Pseudo-spin	Energy scale
Graphene, silicene, germanene	Sublattice	$1-3\,\mathrm{eV}$
Artificial graphenes	Sublattice	$10^{-8}-0.1\,\mathrm{eV}$
Hexagonal layered heterostructures	Emergent	$0.01-0.1\,\mathrm{eV}$
Hofstadter butterfly systems	Emergent	$0.01\,\mathrm{eV}$
Graphene–hBN heterostructures in high magnetic fields		
Band inversion interfaces: SnTe/PbTe, CdTe/HgTe, PbTe	Spin–orbit ang. mom.	$0.3\,\mathrm{eV}$
2D topological insulators: HgTe/CdTe, InAs/GaSb, Bi bilayer, …	Spin–orbit ang. mom.	$<0.1\,\mathrm{eV}$
3D topological insulators: $Bi_{1-x}Sb_x$, Bi_2Se_3, strained HgTe, Heusler alloys, …	Spin–orbit ang. mom.	$\lesssim 0.3\,\mathrm{eV}$
Topological crystalline insulators: SnTe, $Pb_{1-x}Sn_xSe$	Orbital	$\lesssim 0.3\,\mathrm{eV}$
d-wave cuprate superconductors	Nambu pseudo-spin	$\lesssim 0.05\,\mathrm{eV}$
^{3}He	Nambu pseudo-spin	$0.3\,\mu\mathrm{eV}$
3D Weyl and Dirac SM Cd_3As_2, Na_3Bi	Energy bands	Unclear

T.O. Wehling, A.M. Black-Schaffer & A.V. Balatsky (2014) Dirac materials, Advances in Physics, 63:1, 1-76,





● = sublattice L_A ○ = sublattice L_B

The electronic properties of these ⬢ materials (physics of the π-bonds) are customarily described by ($\hbar = 1$)

$$H = -\eta \sum_{\vec{r} \in L_A} \sum_{i=1}^{3} \left(a^\dagger(\vec{r}) b(\vec{r} + \vec{s}_i) + b^\dagger(\vec{r} + \vec{s}_i) a(\vec{r}) \right) ,$$

where η the hopping parameter (e.g. $\eta_{graphene} \simeq 2.8$ eV).

If we Fourier transform, $a(\vec{r}) = \Sigma_{\vec{k}} a(\vec{k}) e^{i\vec{k}\cdot\vec{r}}$, etc, then

$$H = \sum_{\vec{k}} (\mathcal{F}_1(\vec{k}) a^\dagger(\vec{k}) b(\vec{k}) + \mathrm{h.c.})$$

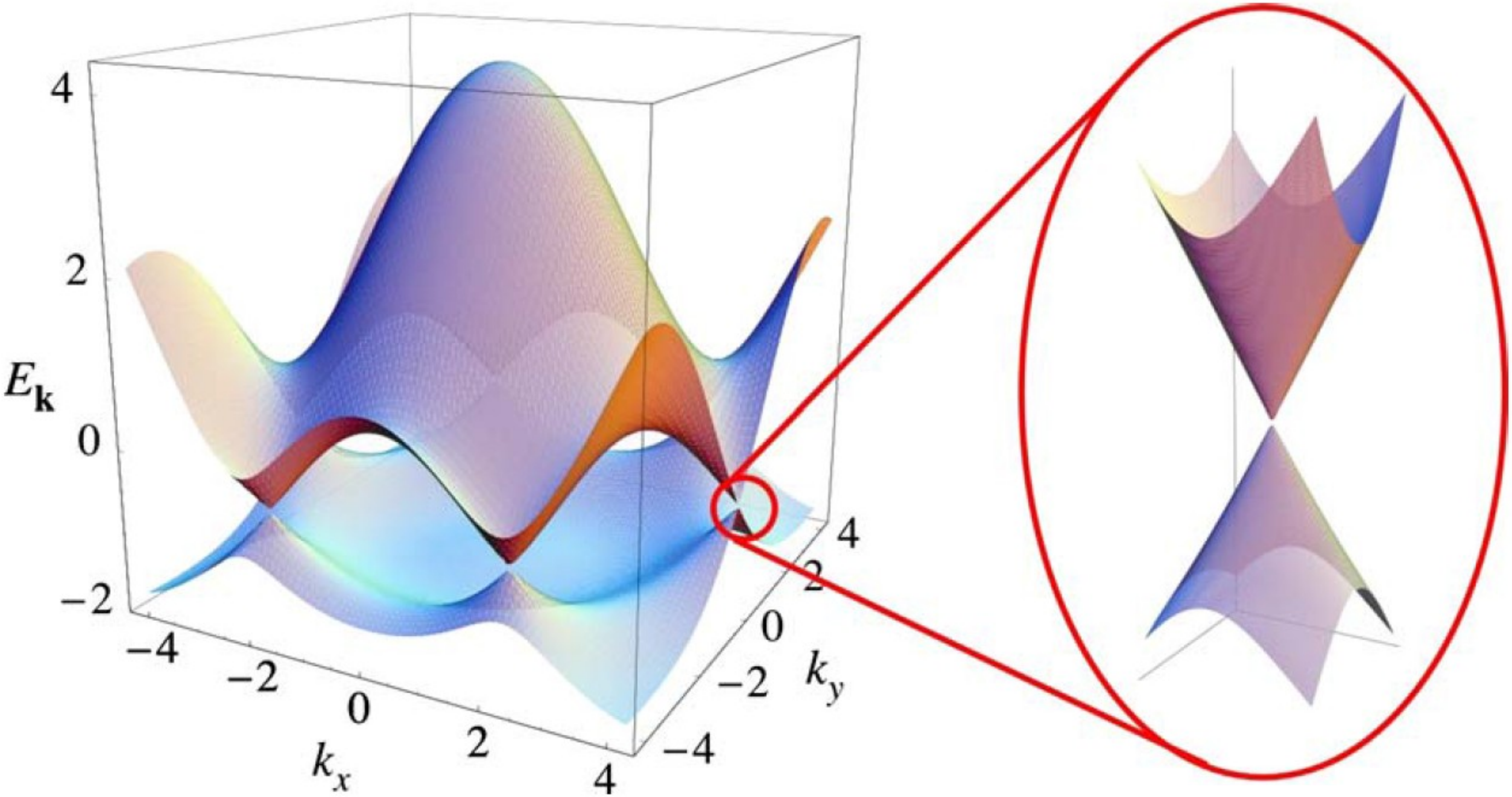
with

$$\mathcal{F}_1(\vec{k}) = -\eta\, e^{-i\ell k_y} \left(1 + 2\, e^{i3\ell k_y/2} \cos(\sqrt{3}\ell k_x/2)\right) \ .$$

Solve

$$E(\vec{k}) = \pm|\mathcal{F}_1(\vec{k})| \equiv 0$$

Electronic properties described by the behavior in the given energy range around $E = 0$



The two Fermi points

$$E_\pm \simeq \pm v_F|\vec{k}|$$

$$(v_F \equiv 3\eta\ell/2)$$

$$\vec{k}^D_\pm = \left(\pm\frac{4\pi}{3\sqrt{3}\ell}, 0\right)$$

Picture taken from A. H. Castro Neto *et al.*, Rev. Mod. Phys. **81** (2009) 109

When

$$E < E_\ell \sim v_F/\ell$$

that is when

$$\lambda = 2\pi/|\vec{p}| \simeq 2\pi v_F/E > 2\pi\ell$$

taking $\vec{p} \to -i\vec{\partial}$, we have

$$H = -iv_F \int d^2x \, \left(\psi_+^\dagger \vec{\sigma} \cdot \vec{\partial} \, \psi_+ - \psi_-^\dagger \vec{\sigma}^* \cdot \vec{\partial} \, \psi_- \, , \right)$$

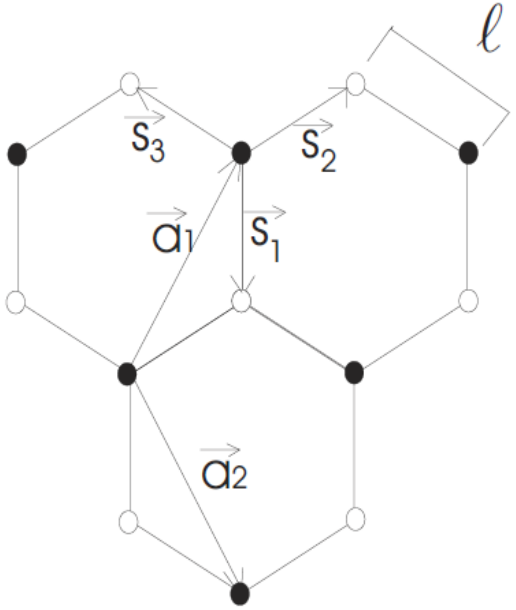
We have a "slower Dirac world", e.g., for graphene $v_F \simeq 9 \times 10^5$m/s, for art. graph. $v_F \simeq 6.5 \times 10^5$m/s, etc.

Control panel

$g_{\mu\nu}$	A_μ	Ψ	$E \sim p - A(\ell)p^2 + \cdots$
Disclinations	Strain	ψ	$(\psi, g_{\mu\nu})$
Dislocations	$U(1)$	$\psi_+ \leftrightarrow \psi_-$	$(\psi, \eta_{\mu\nu})$
Grain Boundaries	$SU(2)$	m	$(\psi(\ell), \eta_{\mu\nu}(\ell))$
Time effects		Dirac/Weyl	only $a(k), b(k)$

Different analogs/emergence $\Rightarrow$ QFT, Curvature, QFT in curved space, Weyl symmetry, Torsion, Internal vs Spatiotemporal symmetries, Quantum gravity, ...

A_μ



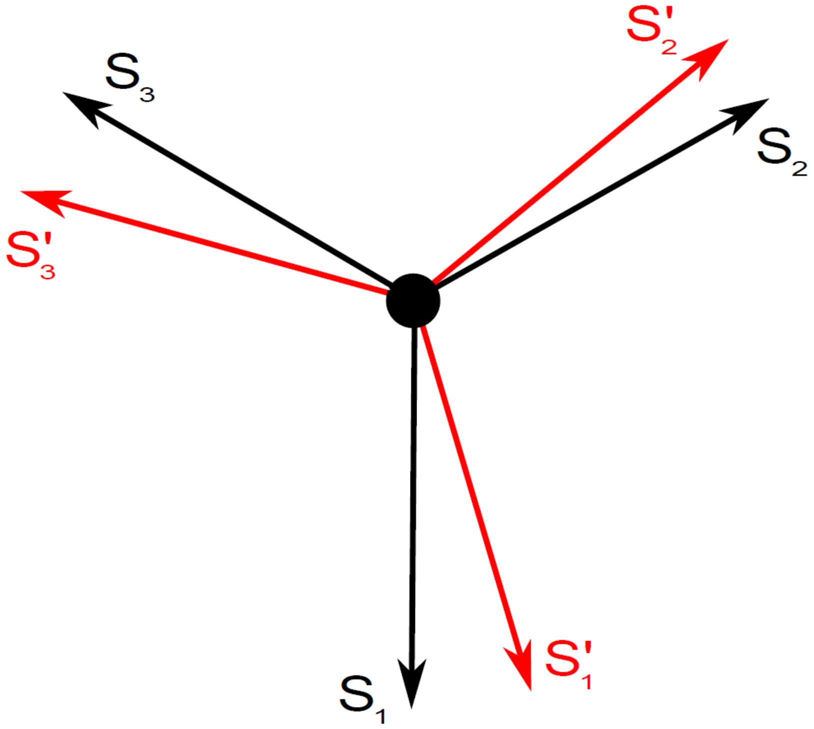
If we strain $x'_i = x_i + u_i$

$s'_{Ii} = (\delta_{ij} + \partial_i u_j) s_{Ij}$

and

$\eta_I = \eta(1 - \beta\delta_I)$

with $\ell^2 \delta_I = \vec{s}_I \cdot \vec{\Delta}_I$**, and** $I = 1, 2, 3$



PRD 92 (2015) 125005

If we start all over again

$$H = \sum_{\vec{k}} \left(\mathcal{G}_1(\vec{k}) a^\dagger(\vec{k}) b(\vec{k}) + c.c. \right) ,$$

where, at first order in u

$$\mathcal{G}_1(\vec{k}) = \mathcal{F}_1(\vec{k'}) + \frac{\eta}{\ell^2} \sum_{I=1}^{3} \left(\vec{s}_I \cdot \vec{\Delta}_I \right) e^{i\vec{k'} \cdot \vec{s}_I} .$$

Expanding $\vec{k} = \vec{k}'^D_\pm + \vec{p}$, going to the continuum, and to configuration space

$$H = -i v_F \int d^2x \left[\psi_+^\dagger \vec{\sigma} \cdot \left(\vec{\partial} + i\vec{A} \right) \psi_+ - \psi_-^\dagger \vec{\sigma}^* \cdot \left(\vec{\partial} - i\vec{A} \right) \psi_- \right]$$

$g_{\mu\nu}$ **For intrinsic curvature $\mathcal{K}$ in an hexagonal lattice, we need <u>disclination</u> defects**

$$\sum_p (6-p) n_p = 6\chi_M \qquad (\clubsuit)$$

and

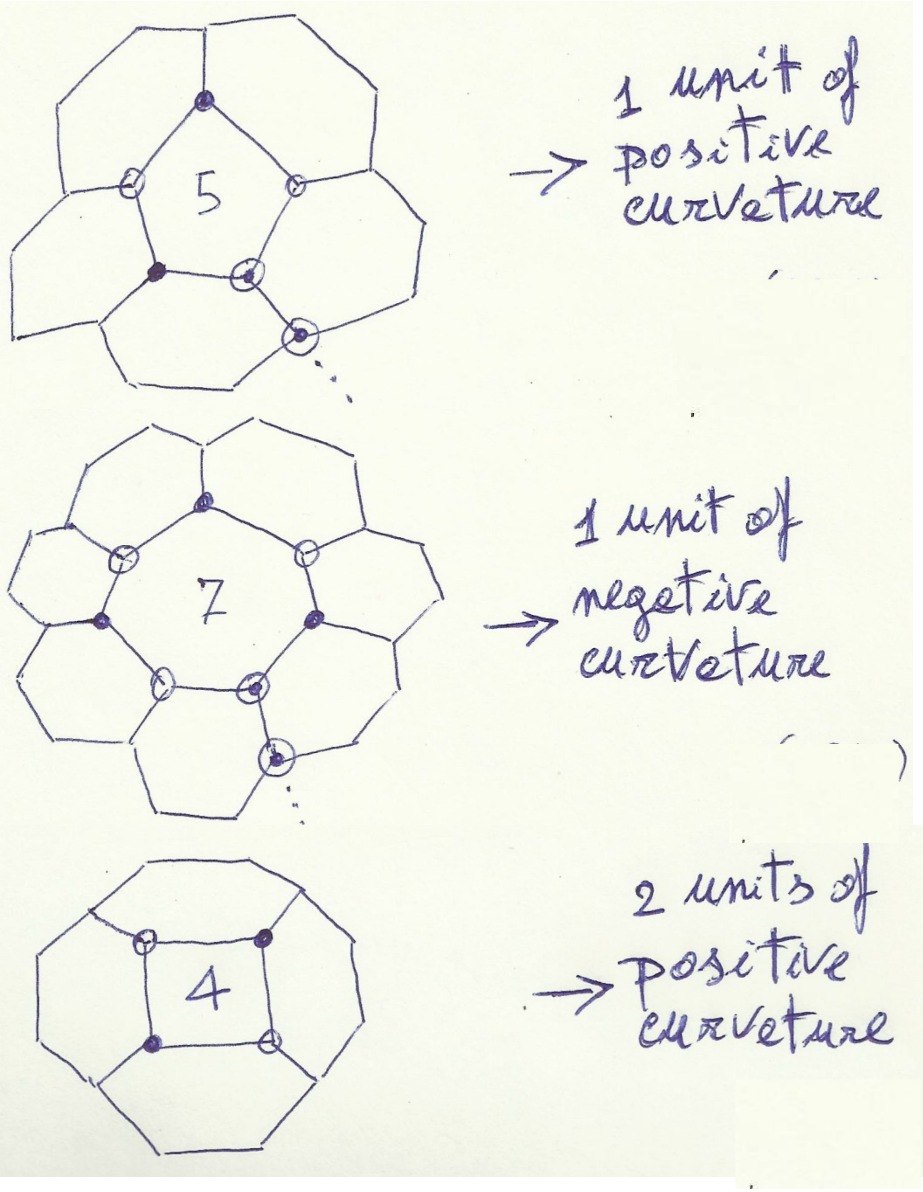
$$\int_M \mathcal{K}(x) \equiv \mathcal{K}_{tot} = 2\pi\chi_M \qquad (\spadesuit)$$

E.g., $M = S^2$ $(\chi_{S^2} = 2)$

$$(6-7)\,n_7 + (6-6)\,n_6 + (6-5)\,n_5 = 12$$

that is: n_6 **irrelevant,** $n_5 = 12 + m$, $n_7 = m$

Thus, (♣) and (♠) together give



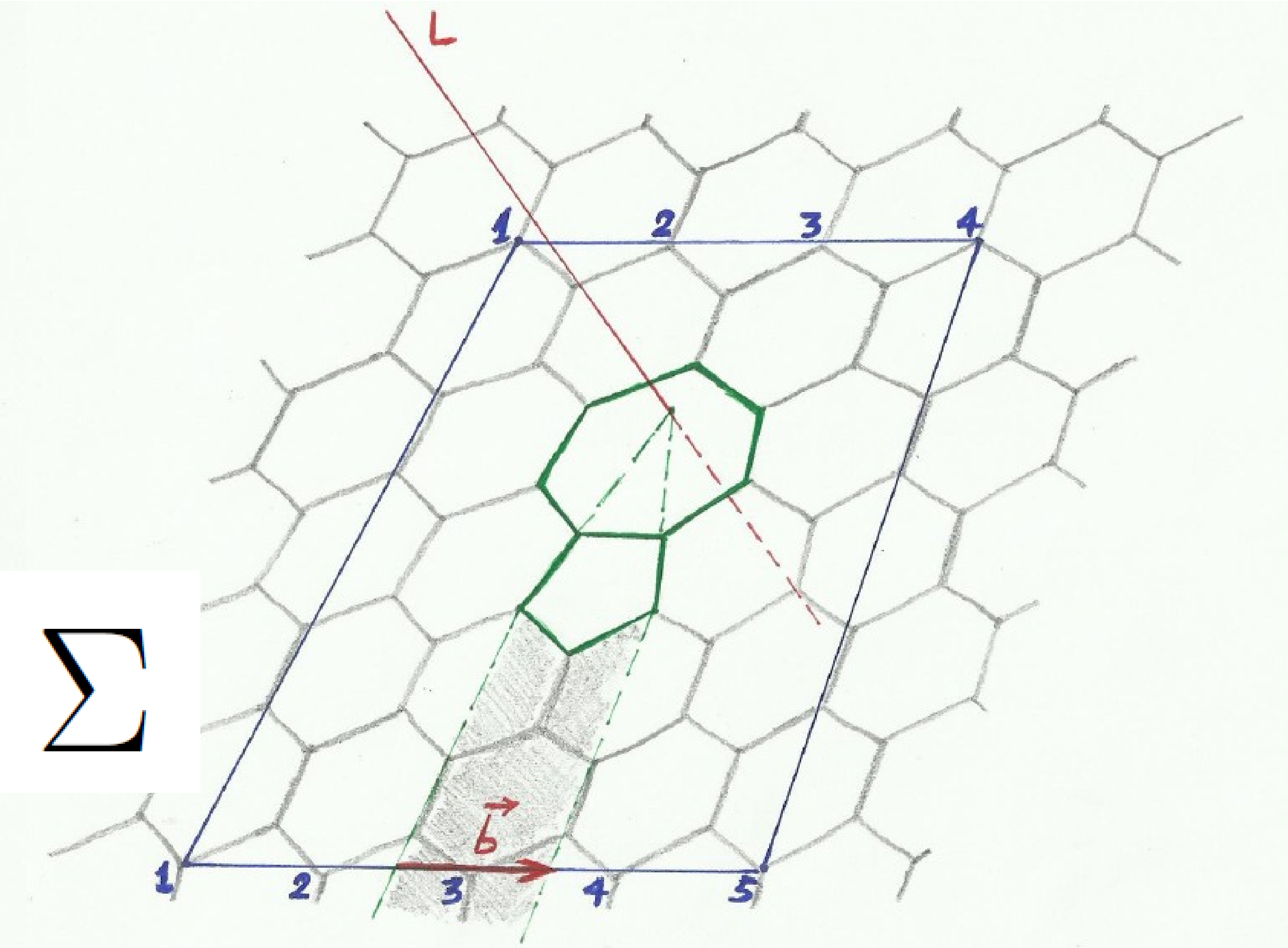
$\mathcal{K}_5 = +(\frac{3}{\pi})\ \frac{\mathcal{K}_{tot}}{12}$

and

$\mathcal{K}_7 = -(\frac{3}{\pi})\ \frac{\mathcal{K}_{tot}}{12}$

and so on

This is behind ω_μ^a



Σ

This is behind κ^a_μ through

$$b^a = \int\int_{\Sigma} e^a_\lambda T^\lambda_{\mu\nu} dx^\mu \wedge dx^\nu$$

Include time as $x^0 = v_F t$, hence turn to

$$\mathcal{S} = i\hbar v_F \int d^3x \overline{\psi} \gamma^a \partial_a \psi$$

$\psi = (\psi_+, \psi_-)^T$, **with** $\psi_\pm = (\alpha_\pm, \beta_\pm)^T$**.**

When torsion is present, standard manipulations lead to

$$\mathcal{S} = i\hbar v_F \int d^3x \; |e| \; \overline{\psi} \left(\gamma^\mu \overset{\circ}{D}_\mu + \frac{i}{4} \gamma^5 \frac{\epsilon^{\mu\nu\rho}}{|e|} T_{\mu\nu\rho} \right) \psi \qquad (*)$$

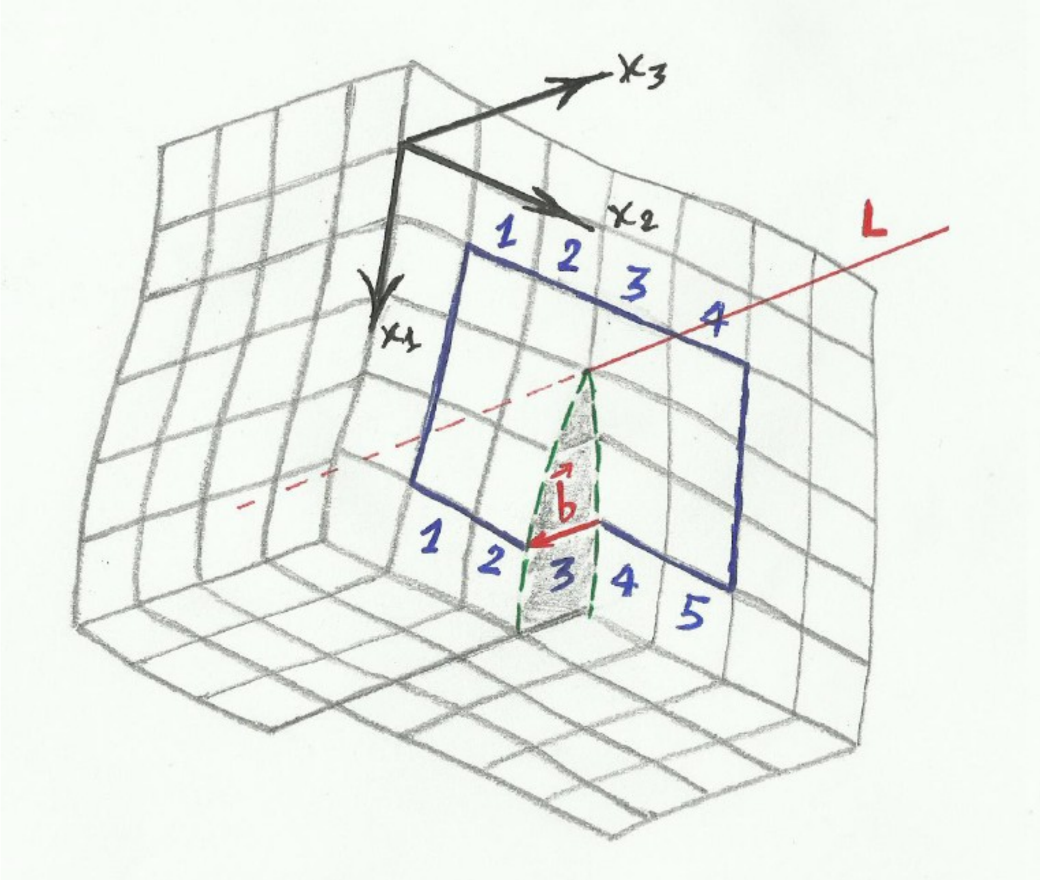
with

$$\omega_\mu^{ab} = \overset{\circ}{\omega}{}_\mu^{ab} + \kappa_\mu^{ab}$$

and

$$T_{\mu\nu}^\lambda = E_a^\lambda \kappa_\nu{}^a{}_b e_\mu^b - E_a^\lambda \kappa_\mu{}^a{}_b e_\nu^b$$

therefore, in (*) $T_{012} \quad \text{or} \quad T_{102} \quad \text{or} \quad T_{210}$



?

arXiv:1907.00023

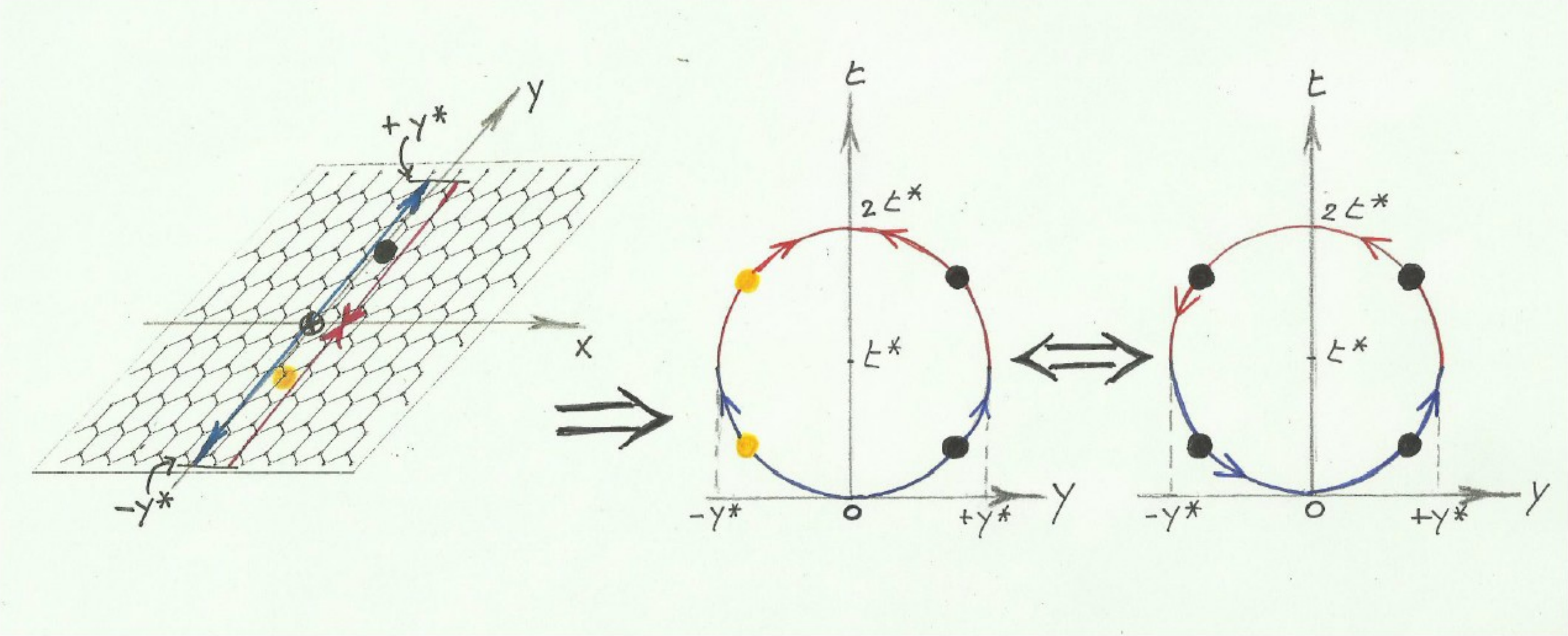
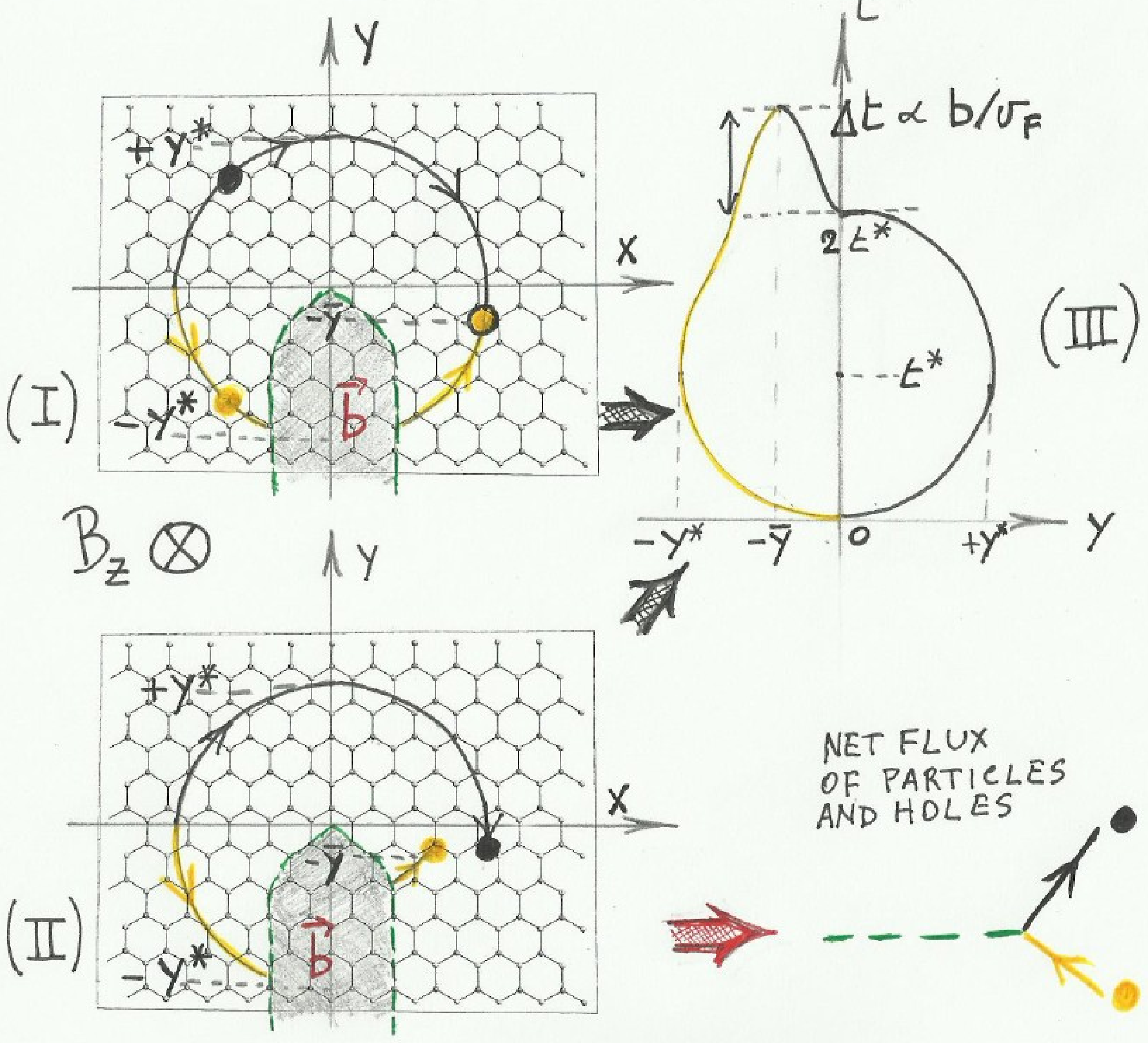
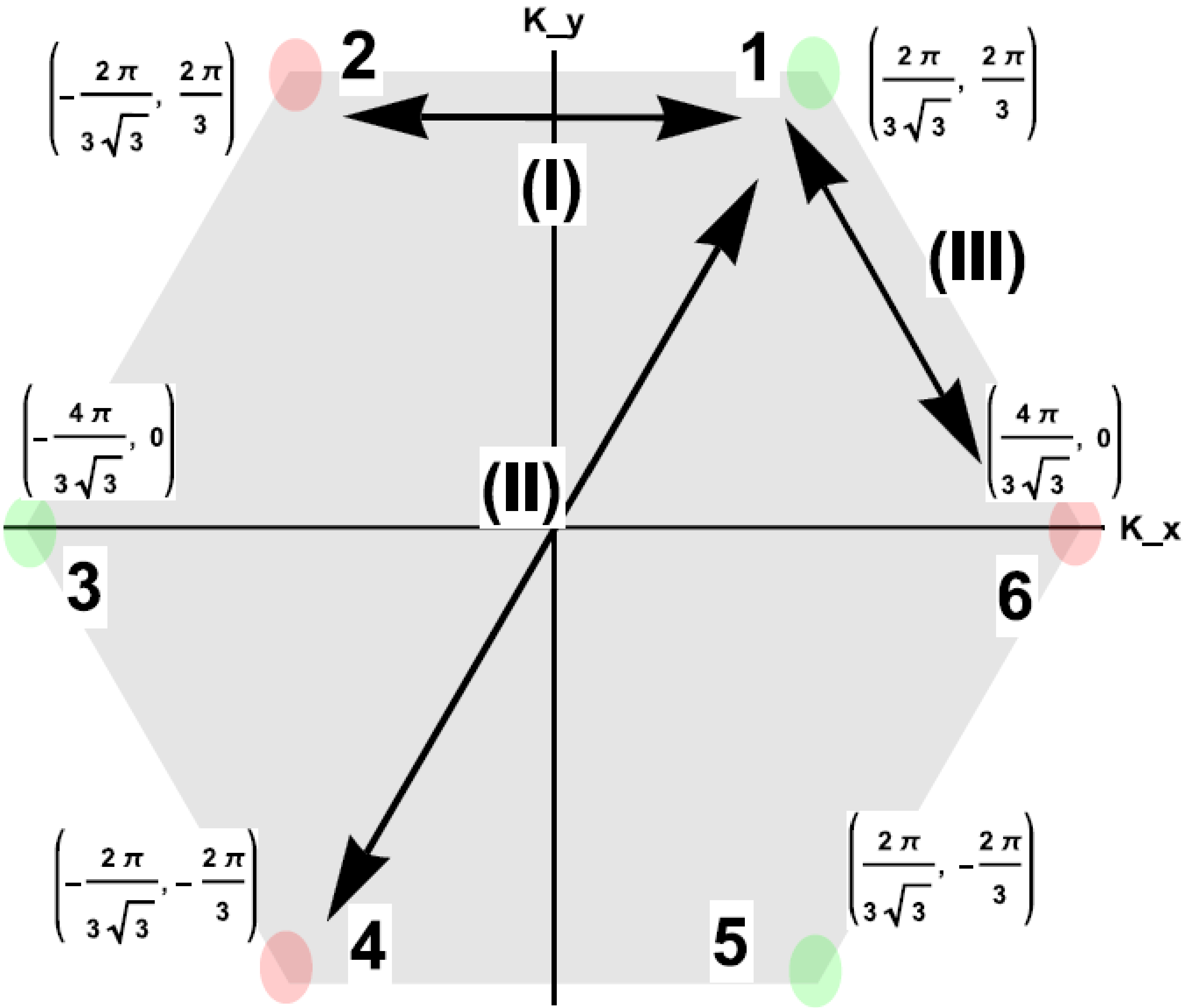


FIG. 2. Idealized *time-loop*. At $t = 0$, the hole (yellow) and the particle (black) start their journey from $y = 0$, in opposite directions. Evolving forward in time, at $t = t^* > 0$, the hole reaches $-y^*$, while the particle reaches $+y^*$, (blue portion of the circuit). Then they come back to the original position, $y = 0$, at $t = 2t^*$ (red portion of the circuit). This can be repeated indefinitely. On the far right, the equivalent *time-loop*, where the hole moving forward in time is replaced by a particle moving backward in time.



(I)
y
x
+y*
−y*
−ȳ
$\vec{b}$
$B_z \otimes$
(II)
y
x
+y*
−y*
−ȳ
$\vec{b}$
(III)
t
$\Delta t \propto b/v_F$
$2t^*$
t^*
y
−y*
−ȳ
0
+y*
NET FLUX
OF PARTICLES
AND HOLES



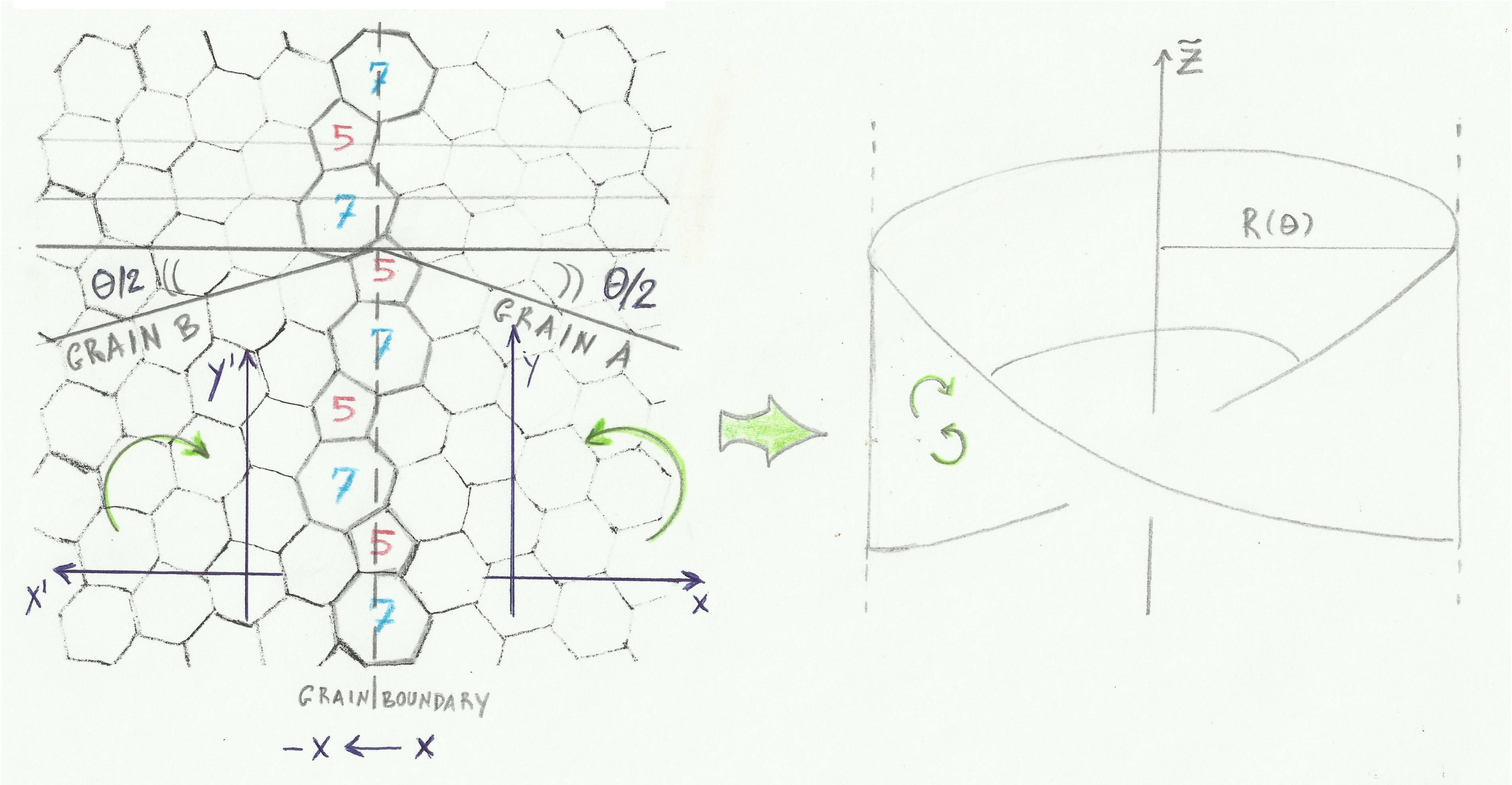
Ann Phys 398 (2018) 265

Table B.2

Possible choices of the two inequivalent Dirac points to write down the Hamiltonian describing the π electrons. Here $\psi = \begin{pmatrix} b \\ a \end{pmatrix}$, $\tilde{\psi} = \begin{pmatrix} e^{i\pi/3}b \\ a \end{pmatrix}$, $\tilde{\tilde{\psi}} = \begin{pmatrix} e^{-i\pi/3}b \\ a \end{pmatrix}$, $\psi' = \begin{pmatrix} a \\ b \end{pmatrix}$, $\tilde{\psi}' = \begin{pmatrix} e^{i\pi/3}a \\ b \end{pmatrix}$, $\tilde{\tilde{\psi}}'' = \begin{pmatrix} e^{-i\pi/3}a \\ b \end{pmatrix}$, and, as usual $\vec{\sigma} = (\sigma_1, \sigma_2)$ and $\vec{\sigma}^* = (\sigma_1, -\sigma_2)$.

Dirac points	*H* structure	Transformation	Suitability
1 - 2	$\tilde{\psi}_+^\dagger \vec{\sigma}^* \cdot \vec{p}\tilde{\psi}_+ - \tilde{\psi}'^\dagger_- \vec{\sigma} \cdot \vec{p}\tilde{\psi}'_-$	*x*-parity	Yes
1 - 4	$\tilde{\psi}_+^\dagger \vec{\sigma}^* \cdot \vec{p}\tilde{\psi}_+ - \tilde{\tilde{\psi}}'^\dagger_- \vec{\sigma} \cdot \vec{p}\tilde{\tilde{\psi}}'_-$	Full inversion	
1 - 6	$\tilde{\psi}'^\dagger_- \vec{\sigma} \cdot \vec{p}\tilde{\psi}'_- + \psi_+^\dagger \vec{\sigma} \cdot \vec{p}\psi_+$	$\pi/3$ rotation	
2 - 3	$-\tilde{\psi}_+^\dagger \vec{\sigma}^* \cdot \vec{p}\tilde{\psi}_+ - \psi'^\dagger_- \vec{\sigma} \cdot \vec{p}\psi'_-$	$\pi/3$ rotation	
2 - 5	$-\tilde{\psi}_+^\dagger \vec{\sigma}^* \cdot \vec{p}\tilde{\psi}_+ + \tilde{\tilde{\psi}}'^\dagger_- \vec{\sigma} \cdot \vec{p}\tilde{\tilde{\psi}}'_-$	Full inversion	
3 - 4	$-\psi_+^\dagger \vec{\sigma}^* \cdot \vec{p}\psi_+ - \tilde{\tilde{\psi}}'^\dagger_- \vec{\sigma} \cdot \vec{p}\tilde{\tilde{\psi}}'_-$	$\pi/3$ rotation	
3 - 6	$-\psi'^\dagger_- \vec{\sigma} \cdot \vec{p}\psi'_- + \psi_+^\dagger \vec{\sigma} \cdot \vec{p}\psi_+$	Full inversion	Yes
4 - 5	$-\tilde{\tilde{\psi}}^\dagger_+ \vec{\sigma}^* \cdot \vec{p}\tilde{\tilde{\psi}}_+ + \tilde{\tilde{\psi}}'^\dagger_- \vec{\sigma} \cdot \vec{p}\tilde{\tilde{\psi}}'_-$	*x*-parity	Yes
5 - 6	$\tilde{\tilde{\psi}}'^\dagger_- \vec{\sigma} \cdot \vec{p}\tilde{\tilde{\psi}}'_- + \psi_+^\dagger \vec{\sigma} \cdot \vec{p}\psi_+$	$\pi/3$ rotation	

Grain Boundaries



$$\overrightarrow{D}_\mu \Psi = \partial_\mu \Psi + \omega^a_\mu \mathbb{J}_a \Psi + i e^a_\mu \mathbb{P}_a \Psi$$

$$[\mathbb{J}_a, \mathbb{J}_b] = i\,\epsilon_{ab}^{c}\,\mathbb{J}_c \ ,$$

$$[\mathbb{J}_a, \mathbb{P}_b] = i\,\epsilon_{ab}^{c}\,\mathbb{P}_c \ ,$$

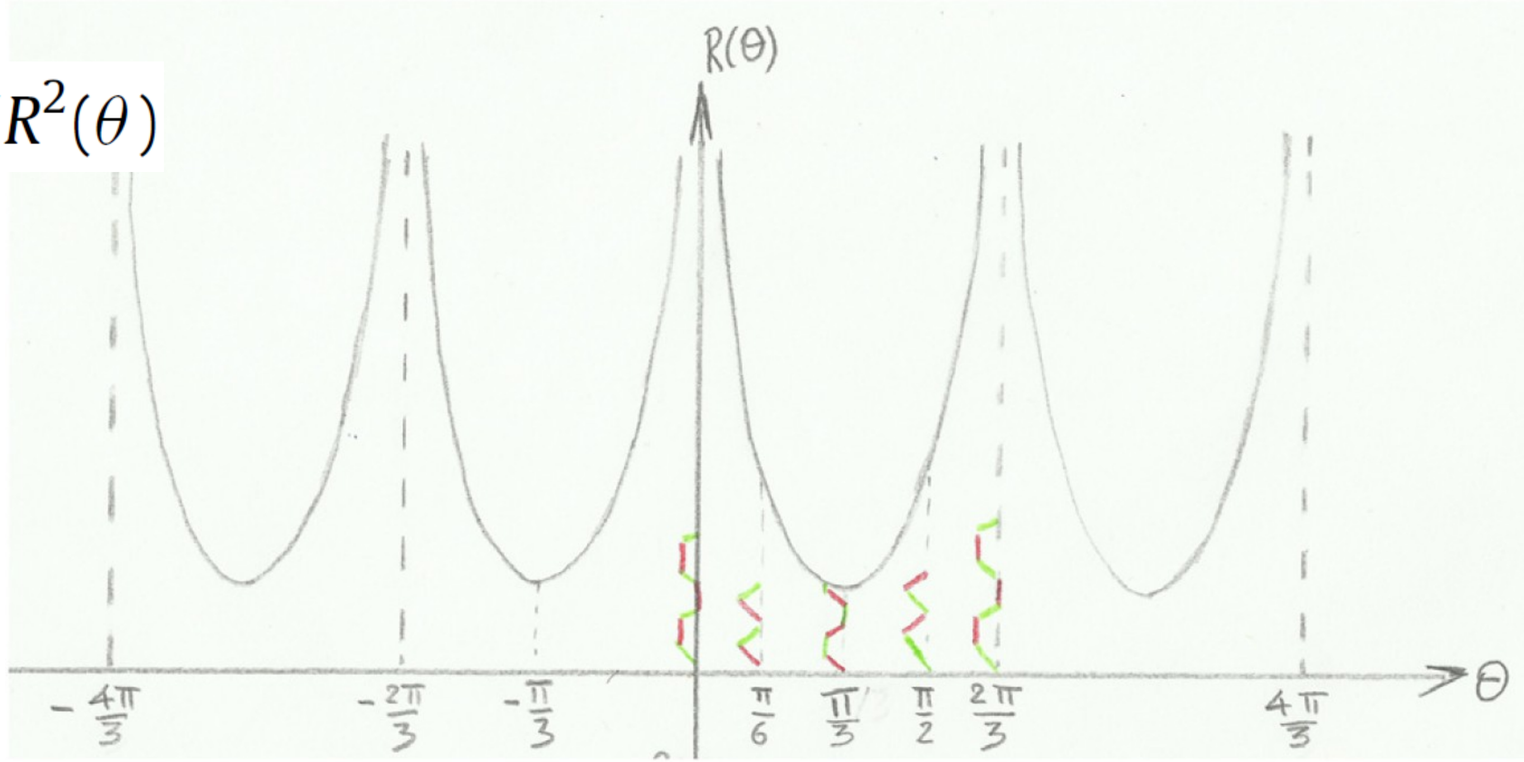
$$[\mathbb{P}_a, \mathbb{P}_b] = i\,\lambda(R)\,\epsilon_{ab}^{c}\,\mathbb{J}_c$$

E. Witten, Nucl. Phys. **B311**, 46 (1988)

and revisit 0706.3359

$$\mathbb{J}_a = \begin{pmatrix} J_a^+ & 0 \\ 0 & J_a^- \end{pmatrix} \qquad \mathbb{P}_a = \begin{pmatrix} 0 & P_a^+ \\ P_a^- & 0 \end{pmatrix}$$

$$\lambda \equiv 1/R^2(\theta)$$



alternatively, internal symmetry

$$(\overrightarrow{D}_{\mu})_i^j\psi_j = \partial_\mu\psi_i + \frac{i}{2}\omega_\mu^{ab}\mathbb{J}_{ab}\psi_i + iA_\mu^I(\sigma_I)_i^j\psi_j$$

$$\mathcal{S} = \frac{i}{2}\hbar v_F\int d^3x|e|\left[\overline{\psi}^i\gamma^\mu(\overrightarrow{\overset{\circ}{D}}_{\mu})_i^j\psi_j - \overline{\psi}^i(\overleftarrow{\overset{\circ}{D}}_{\mu})_i^j\gamma^\mu\psi_j - \frac{1}{2}\epsilon_a^{bc}T^a_{bc}\overline{\psi}^i\psi_i\right]$$

USUSY

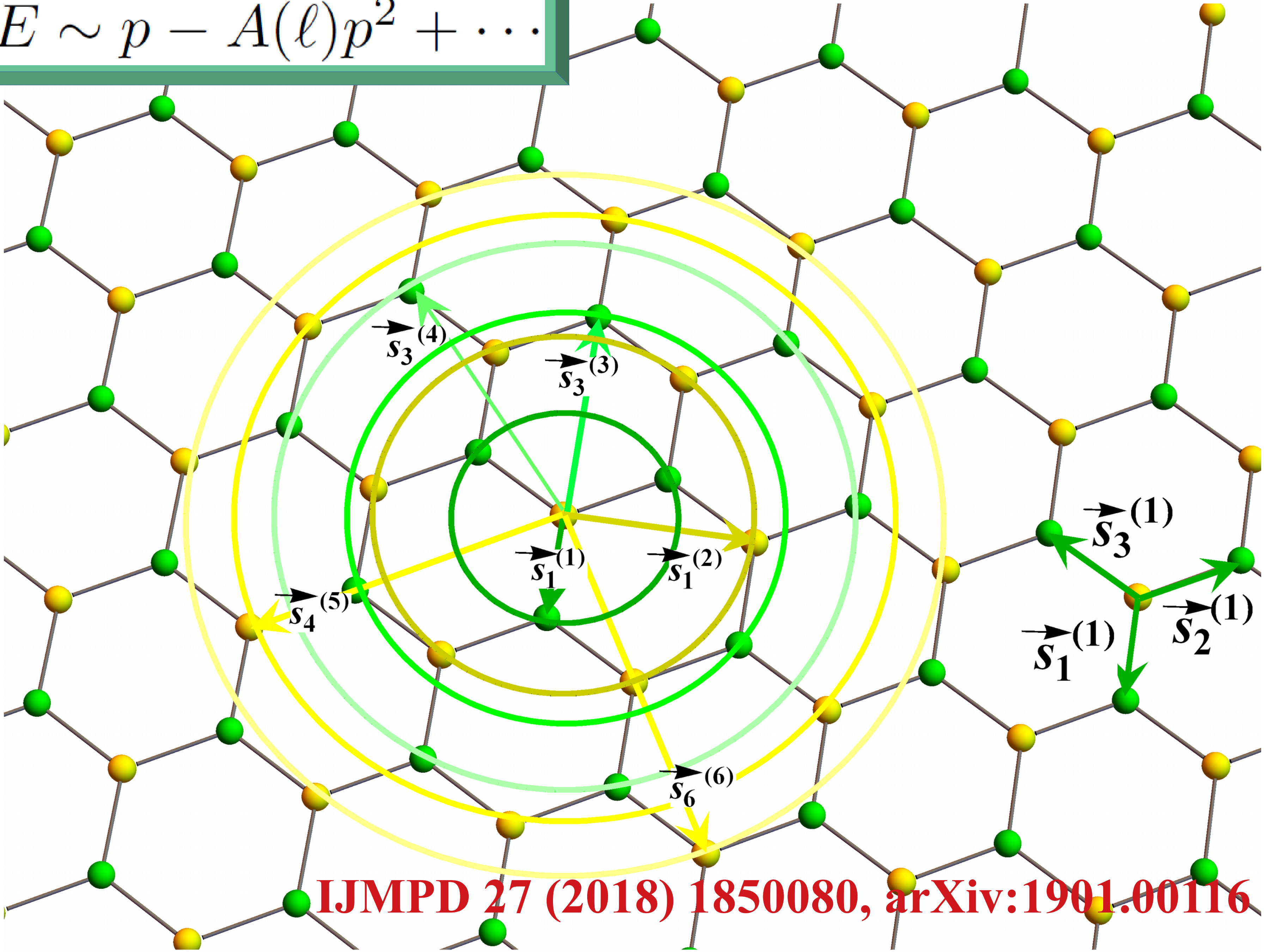
$$L = \frac{\kappa}{2}\langle\mathbb{A}d\mathbb{A} + \frac{2}{3}\mathbb{A}^3\rangle$$

$$\mathbb{A} = A^I\mathbb{T}_I + \overline{\psi}^i\not{e}\mathbb{Q}_i + \overline{\mathbb{Q}}^i\not{e}\psi_i + \omega^a\mathbb{J}_a$$

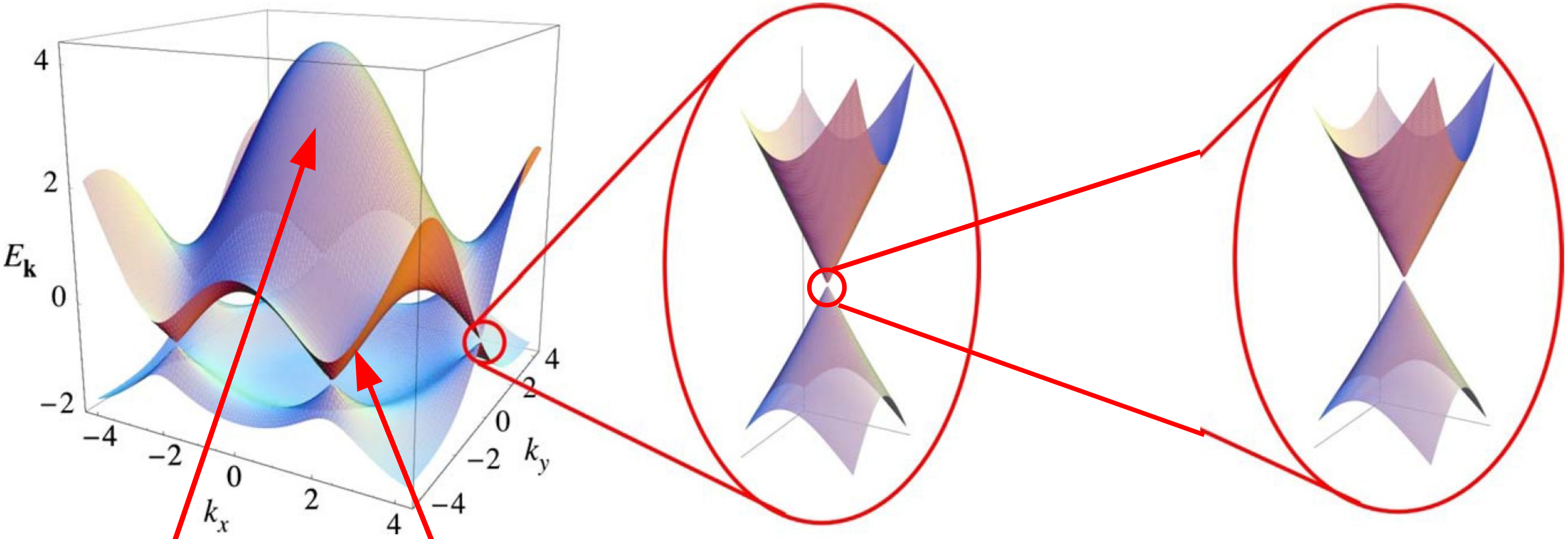
$$\mathcal{S} = \frac{i}{2}\hbar v\int d^3x|e|\left[\overline{\psi}^i\gamma^\mu(\overrightarrow{\overset{\circ}{D}}_{\mu})_i^j\psi_j - \overline{\psi}^i(\overleftarrow{\overset{\circ}{D}}_{\mu})_i^j\gamma^\mu\psi_j - \frac{1}{4}\epsilon_a^{bc}T^a_{bc}\overline{\psi}^i\psi_i\right]$$

P. D. Alvarez, M. Valenzuela, and J. Zanelli JHEP **1204**, 058 (2012)

$$\boxed{E \sim p - A(\ell)p^2 + \cdots}$$



IJMPD 27 (2018) 1850080, arXiv:1901.00116



small $\lambda \sim \ell$

full granular description

only basic constituents

medium $\lambda \sim$ few ℓs

granular effects on

$(\psi, \eta_{\mu\nu})$

large $\lambda > \ell$

smooth description

$(\psi, \eta_{\mu\nu})$

very large $\lambda > r > \ell$

smooth description

$(\psi, g_{\mu\nu})$

$$H = \sum_{m \in \mathbf{diag}} (\epsilon^{(0)} \varsigma_m + \eta_m) \mathcal{F}_m(\vec{k})(a^\dagger_{\vec{k}} a_{\vec{k}} + b^\dagger_{\vec{k}} b_{\vec{k}}) + \left(\sum_{m \in \mathbf{off}} (\epsilon^{(0)} \varsigma_m + \eta_m) \mathcal{F}^*_m(\vec{k}) a^\dagger_{\vec{k}} b_{\vec{k}} + h.c. \right)$$

One has

$$\mathcal{F}_2 = |\mathcal{F}_1|^2 - 3$$

thus

$$E_\pm = \eta_1 \left(\pm |\mathcal{F}_1| - \tilde{A} |\mathcal{F}_1|^2 \right)$$

where $\tilde{A} = \epsilon'{}_1/\eta_1$**. If** $\vec{\tilde{P}} \equiv (Re\mathcal{F}_1, Im\mathcal{F}_1)$ **then**

$$E_\pm = \eta_1 \left[\pm \frac{\ell}{\hbar} \frac{\hbar}{\ell} |\vec{\tilde{P}}| - \tilde{A} \, \left(\frac{\ell}{\hbar} \frac{\hbar}{\ell} \right)^2 |\vec{\tilde{P}}|^2 \right] \equiv V_F \left(\pm |\vec{P}| - A \, |\vec{P}|^2 \right)$$

which leads to the GUP

$$[X^P_i, Q_j] = i\hbar \left[\delta_{ij} - A \left(Q\delta_{ij} + \frac{Q_i Q_j}{Q} \right) \right]$$

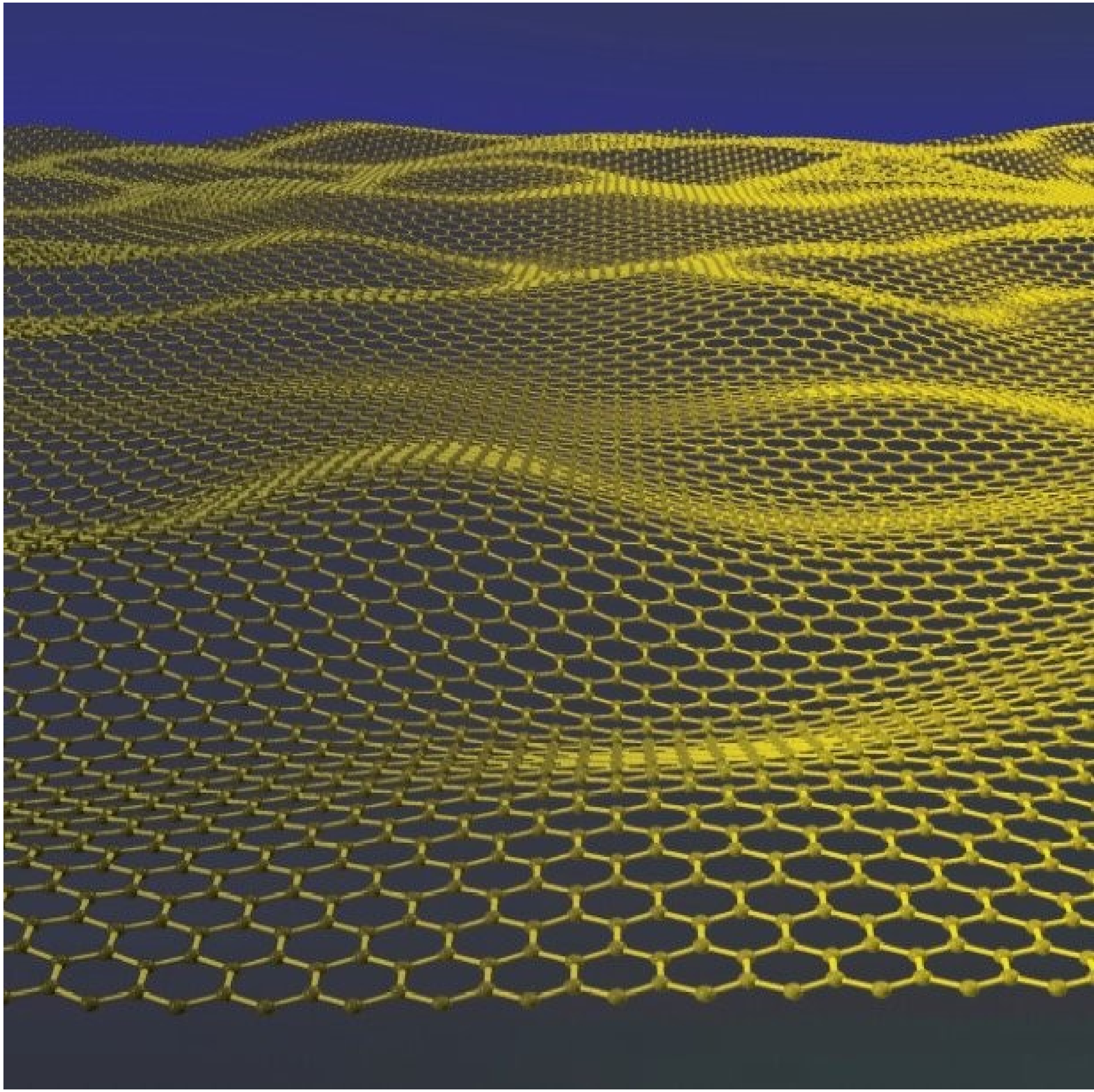
Shortcut to Hawking

$\enclose{circle}{\psi^{\alpha}_{+}}$ $\cancel{\psi^{\alpha}_{-}}$

$\cancel{A_{\mu}}$

$\enclose{circle}{\omega^{a}_{\mu}}$

$\cancel{\kappa^{a}_{\mu}}$



The simplest setting is to go to regimes where only intrinsic curvature counts

$$R^{ij}{}_{kl} = \epsilon^{ij}\epsilon_{kl}\epsilon^{mn}\partial_m\omega_n = \epsilon^{ij}\epsilon_{lk}2\mathcal{K}$$

where $\partial_i\omega \equiv \omega_i$**.**

We include time, in the most gentle way

$$g_{\mu\nu}^{\text{graphene}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & & \\ 0 & g_{ij} & \end{pmatrix}$$

$\partial_t g_{ij} = 0$**.**

SO(2)-valued disclination field → SO(1,2)-valued disclination field, so $R^i{}_{jkl} \to R^\lambda{}_{\mu\nu\rho}$**, etc.**

The action we considered here is

$$\mathcal{S} = i\hbar v_F \int d^3x|e|\left[\overline{\psi}\gamma^\mu\left(\partial_\mu + \mathring{\Omega}_\mu\right)\psi\right]$$

where $\psi \equiv \psi_+$ **or** ψ_-**, hence** $\gamma^\mu = 2 \times 2$**, irreducible.**

Ann Phys 326 (2011) 1334

This *exotic* situation, on the graphene side, is *very meagre*, on the hep-th side

Local Weyl symmetry

$$g_{\mu\nu}(x) \to \phi^2(x) g_{\mu\nu}(x) \quad \text{and} \quad \psi(x) \to \phi^{-1}(x)\psi(x)$$

and

$$\mathcal{S} \to \mathcal{S}$$

This is a huge and powerful symmetry:
Classical physics in $g_{\mu\nu}$ = classical physics in $\phi^2 g_{\mu\nu}$

Important cases are *conformally flat spacetimes*

$$g_{\mu\nu} = \phi^2 \eta_{\mu\nu}$$

How can we make CF *spacetimes* with

$$g_{\mu\nu}^{2+1}(x,y) = \begin{pmatrix} 1 & 0 \\ 0 & g_{\alpha\beta}^{(2)}(x,y) \end{pmatrix}$$

The condition is

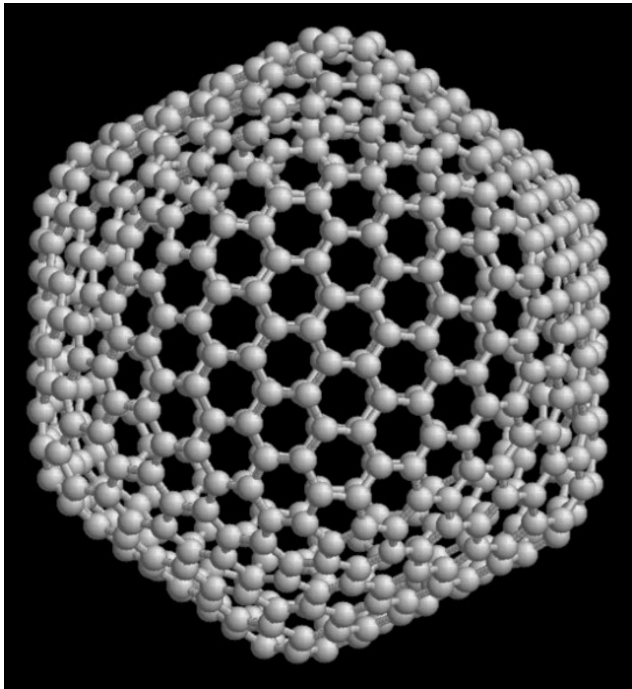
$$C_{\mu\nu} = \epsilon_{\mu\lambda\kappa}\nabla^{\lambda}R^{(3)}{}^{\kappa}_{\nu} + \epsilon_{\nu\lambda\kappa}\nabla^{\lambda}R^{(3)}{}^{\kappa}_{\mu} = 0$$

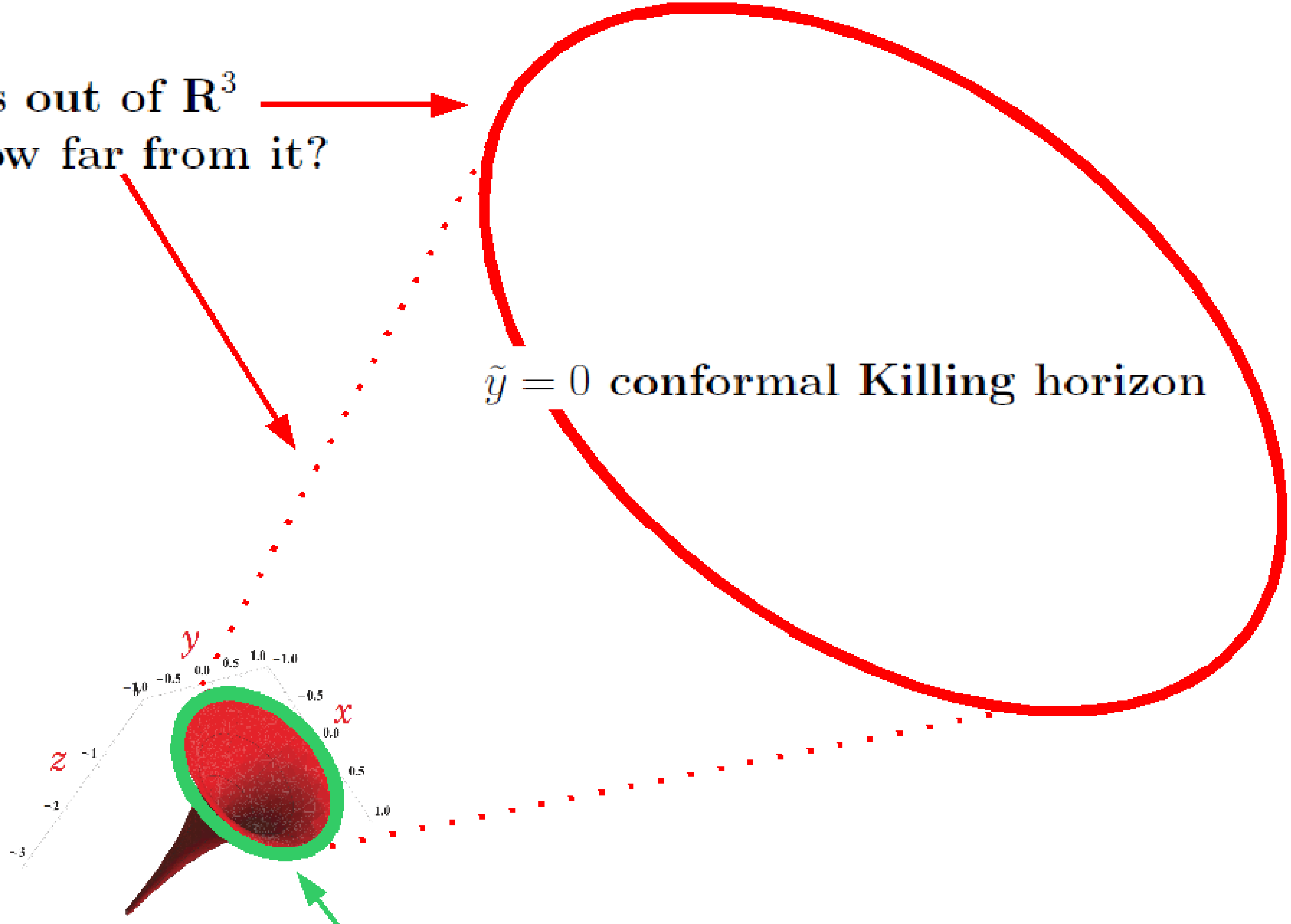
All surfaces of constant Gaussian curvature $\mathcal{K}$, give a CF spacetime!

One immediately thinks of the sphere

$$\mathcal{K} = \frac{1}{r^2}$$

Interesting, but no horizons in sight...



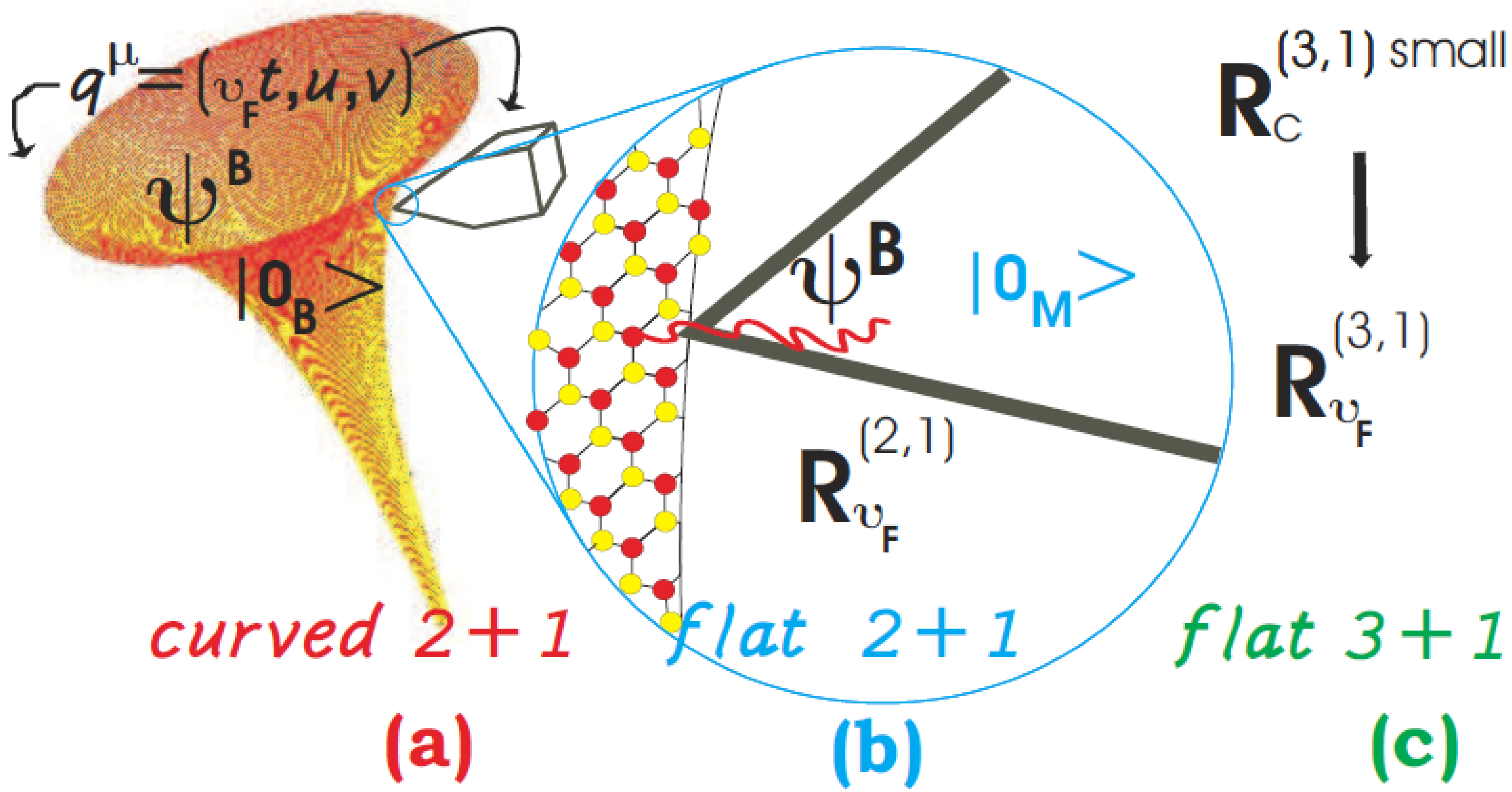


This is out of R^3
but how far from it?

$\tilde{y} = 0$ conformal Killing horizon

Hilbert horizon

PLB 716 (2012) 334; PRD 90 (2014) 025006



The recipe is

$$G^{\rm any}(q_1, ..., q_n) \equiv \langle 0_M|\psi(q_1)...\bar{\psi}(q_n)|0_M\rangle$$

$$\begin{aligned}\rho^{(\mathrm{B})}(E,u,r) &= \frac{4}{\pi(\hbar v_F)^2}\frac{r^2}{\ell^2}e^{-2u/r}\Big[\frac{E}{\exp\left[(2\pi E)/(\hbar v_F\alpha(u,r))\right]-1} \\ &+ \frac{1}{2}\frac{|E|}{b^2-1}\cos\left(\frac{\tilde{b}\,E}{\hbar v_F\alpha(u,r)}\right)\Big]\,.\end{aligned}$$

This a thermal spectrum, with Hawking temperature

$$T_B \equiv \frac{\hbar v_F}{k_B}\,\frac{\alpha}{2\pi} = \frac{\hbar v_F}{k_B}\,\frac{\ell}{2\pi r^2}\,e^{u/r}$$

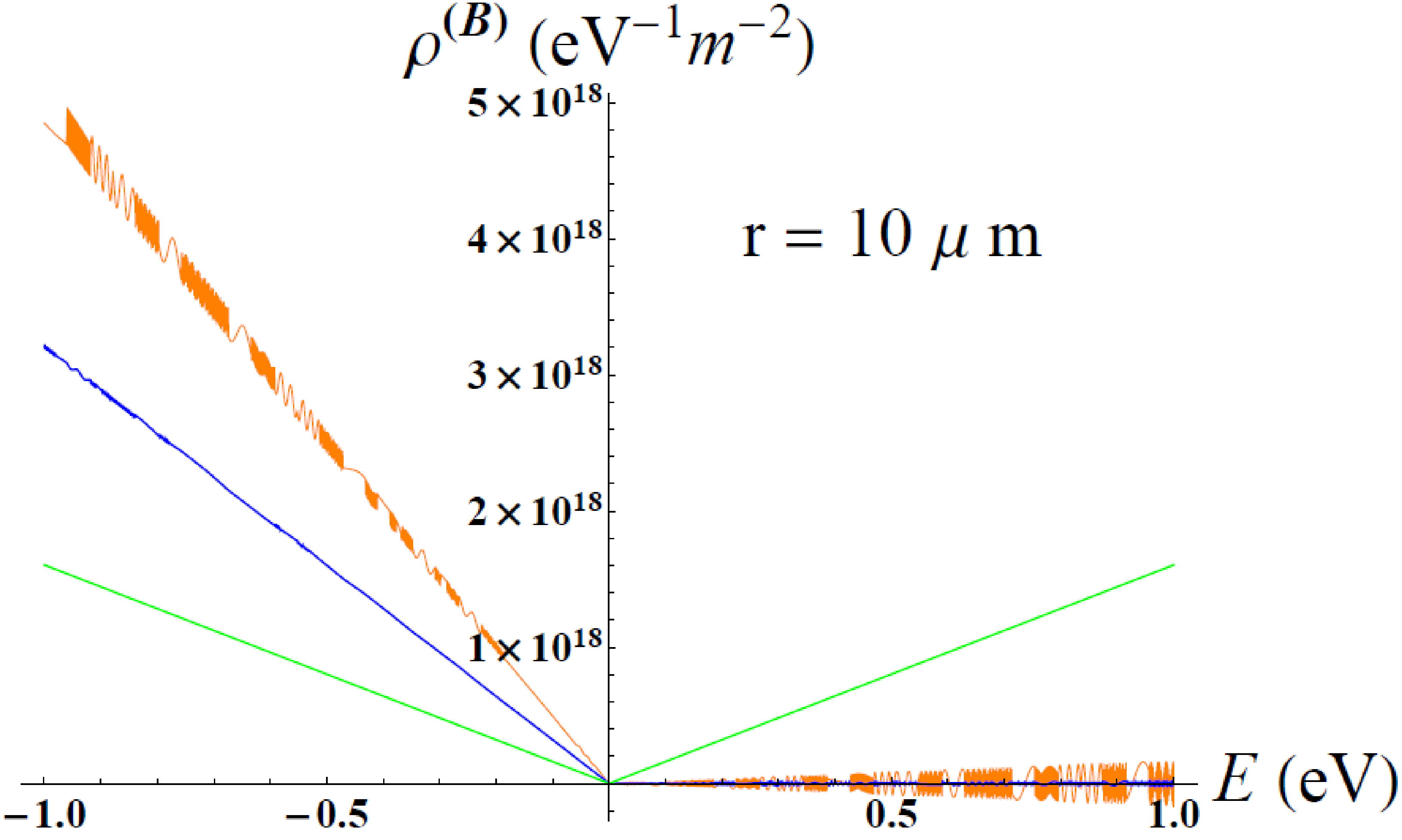
with $u \in [0, r\ln(r/\ell)]$**, that, at the horizon gives**

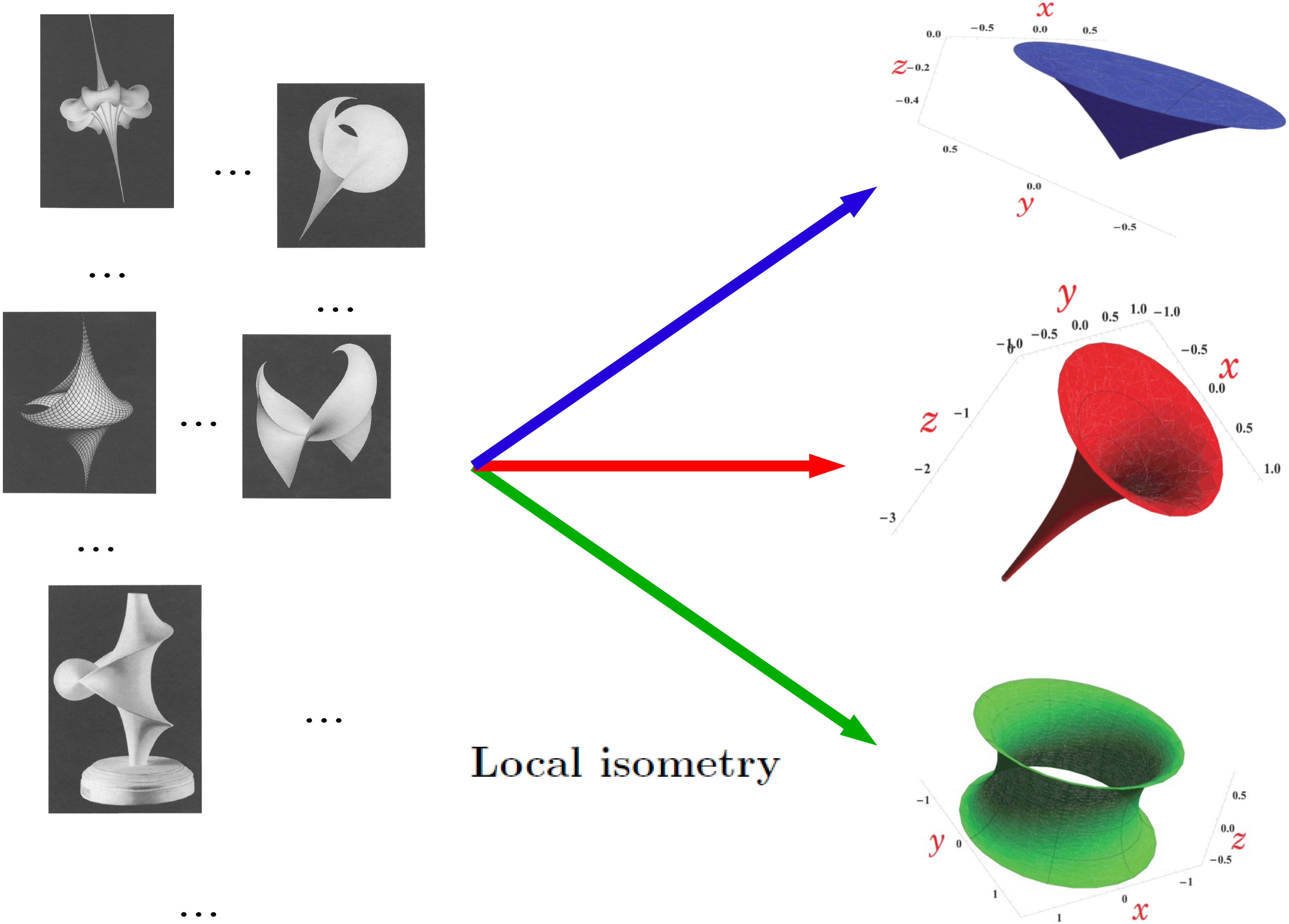
$$T_B(r\ln(r/\ell)) = \frac{\hbar v_F}{k_B}\,\frac{1}{2\pi r}$$

to compare with

$$T_H = \frac{\hbar c}{k_B}\,\frac{1}{4\pi r_S}$$

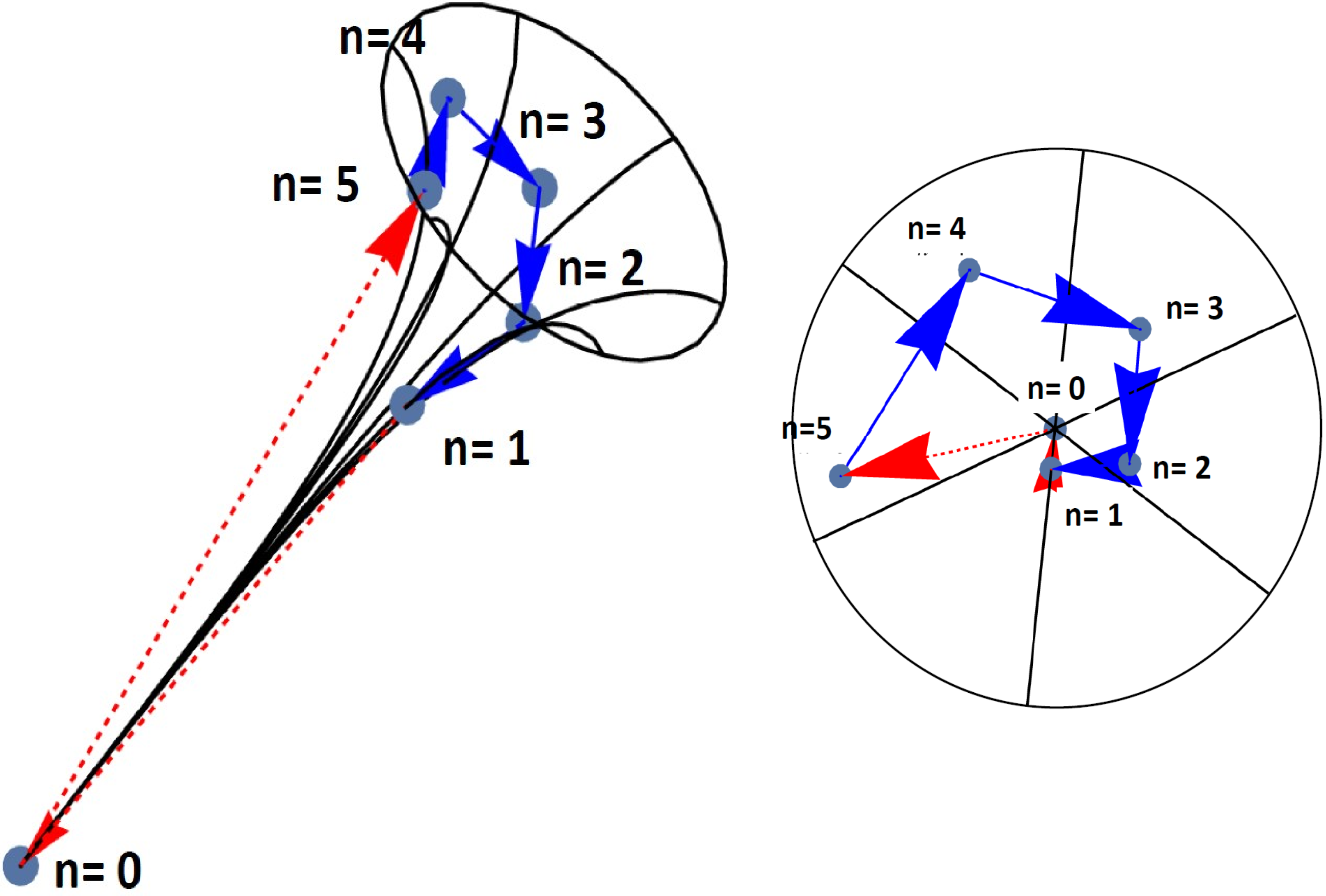
Electronic Local Density of States (LDOS)



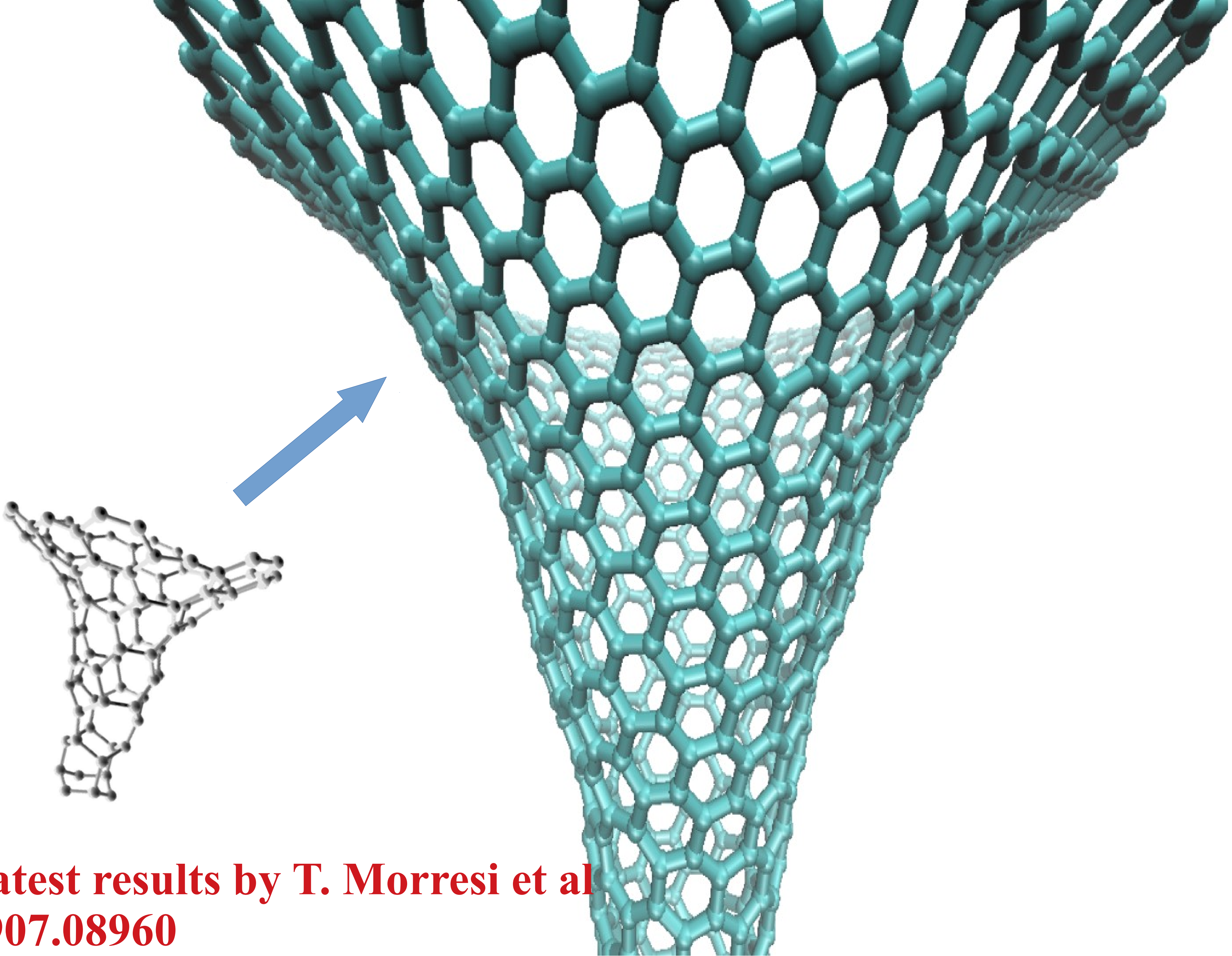


Local isometry

Towards experiments

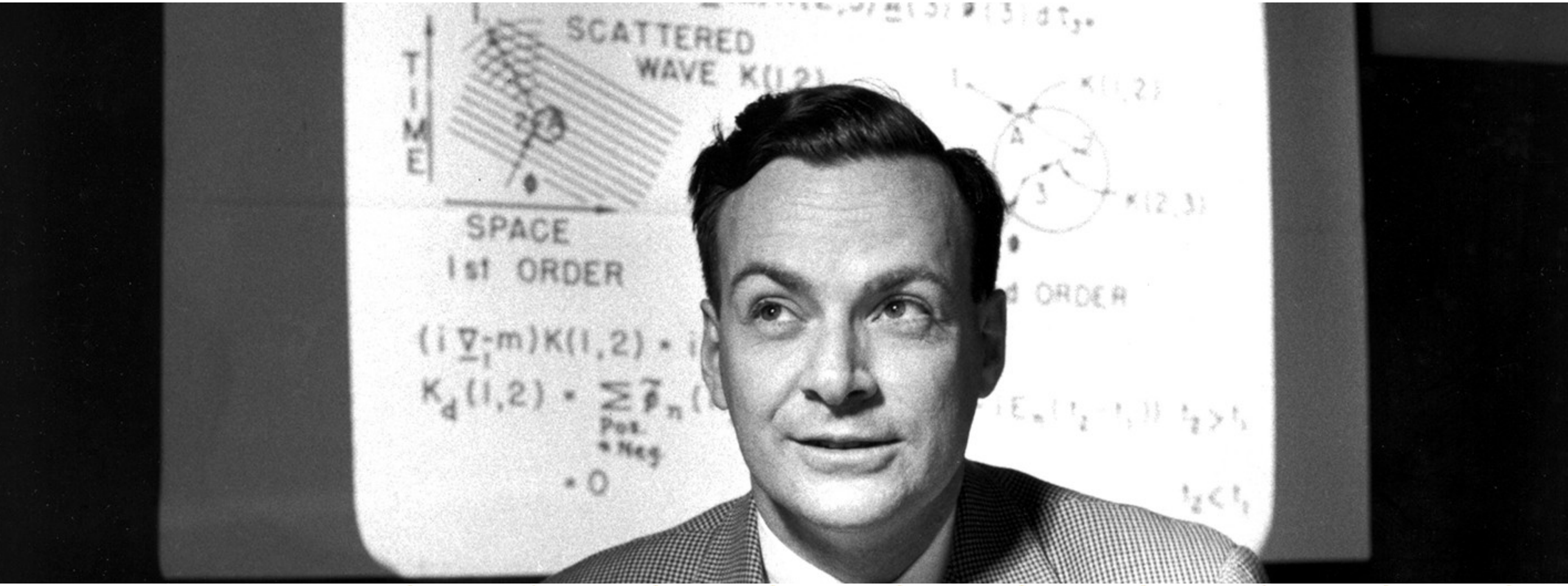


EPJ plus 127 (2012) 156; J Phys: Cond Matt 28 (2016) 13LT01



Latest results by T. Morresi et al
1907.08960

Are analogs tests of hep-th?



1902.07096

Three relations heavily used in physics

1. ***Symmetry***

$$\mathcal{S}(\Phi) \to \mathcal{S}(\Phi') = \mathcal{S}(\Phi)$$

when $\Phi \to \Phi'$.

2. ***Duality***

$$\mathcal{S}(\Phi) \to \mathcal{S}_D(\Phi_D) \neq \mathcal{S}(\Phi)$$

when $\Phi \to \Phi_D$.

3. ***Correspondence***

$$AdS \to CFT$$

Underlying common structure. How about a fourth member?

4. ***Analogy***

$$Equation(1) \to Equation(2)$$

(no underlying common structure considered)

$$\vec{\nabla} \cdot (\kappa \vec{\nabla} \phi) = -\rho_{free}/\epsilon_0$$

“ [...] there are many physics problems whose mathematical equations have the same form. [...] Whatever we know about electrostatics can immediately be carried over into that other subject, and vice versa”

The flow of heat

The stretched membrane

The diffusion of neutrons

Irrotational fluid

Illumination of a plane

"Why are the equations from different phenomena so similar"?

"[...] the thing which is common to all the phenomena is the space, the framework into which the physics is put".

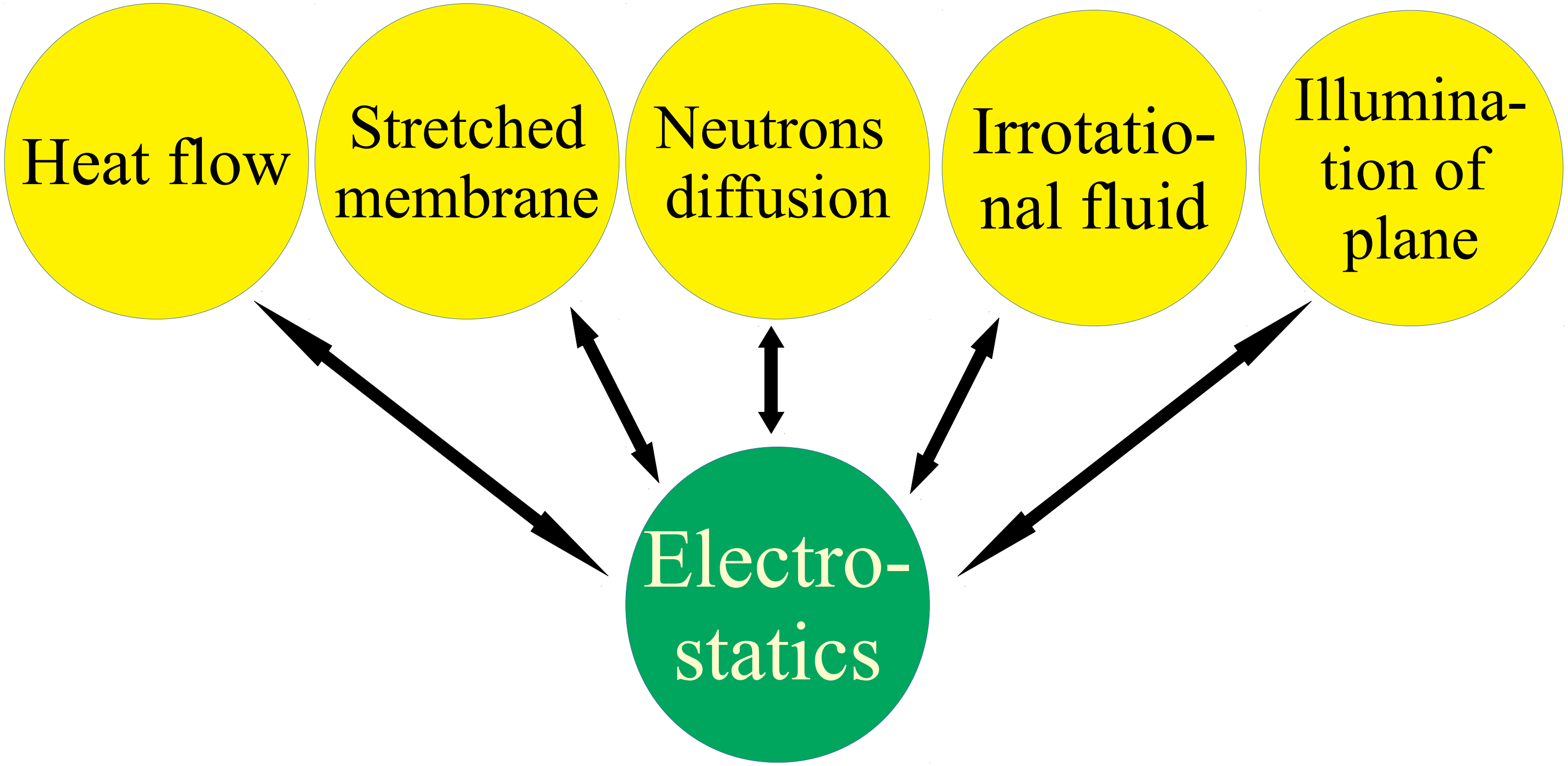
"Are they [the electrostatic equations, ed] also correct only as a smoothed-out imitation of a really much more complicated microscopic world? Could it be that the real world consists of little *Xons* which can be seen only at very tiny distances"?

Many years later Bekenstein proposed

$$S_{\text{anything}} \leq S_{\text{BH}}$$

leading to a ***level X***

$$\dim \mathsf{H}_X \sim e^{S_{\text{BH}}} < \infty$$



Heat flow

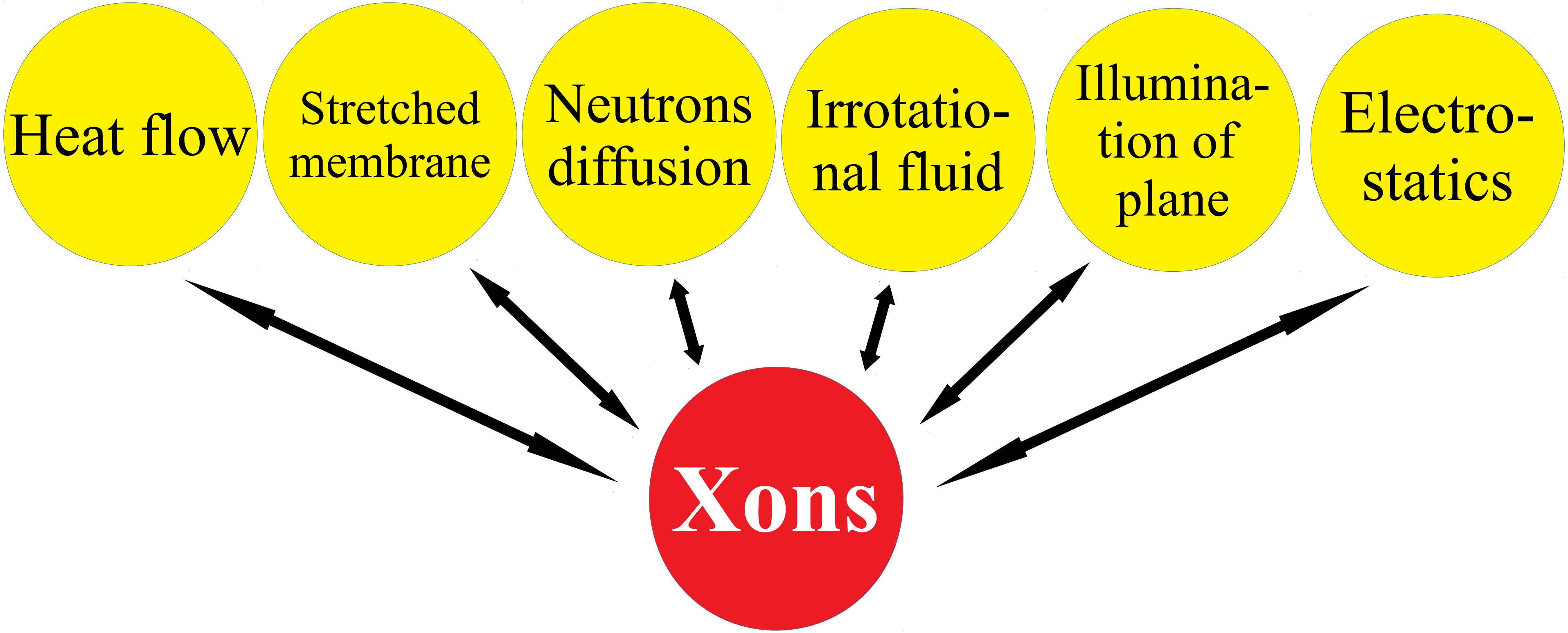
Stretched membrane

Neutrons diffusion

Irrotational fluid

Illumination of plane

Electrostatics



Heat flow

Stretched membrane

Neutrons diffusion

Irrotational fluid

Illumination of plane

Electrostatics

Xons

Further reading:

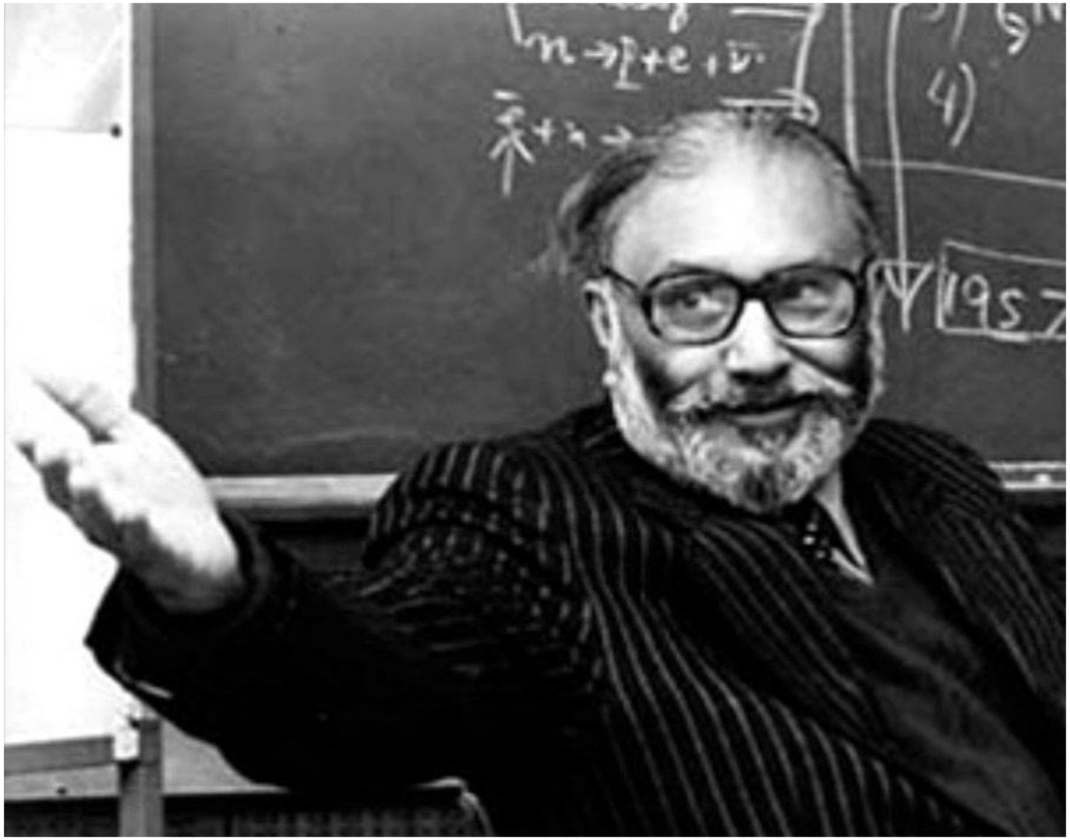
R Feynman, *Electrostatic analogs*, Feynman Lectures on Physics, Vol II, Chp 12

J D Bekenstein, *Information in the holographic universe*, Scientific American 289 (2003) 58

AI, *Two arguments for more fundamental building blocks*, arXiv:1902.07096

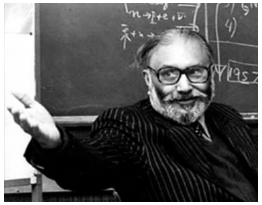
R Dardashti, *Putting analogue experiments on the methodological map*, talk @ Workshop: Analogue Experimentation, Bristol, 16th July 2018

HELIOS (*)



(*) **H**igh **E**nergy **L**ab for **I**ndirect **O**bservation**S**

I "Find the Xons"



I.a Search for the ultimate building blocks

I.b Systematically explore the common underlying structure between analogs, thus *Analogy* will rise at the same level of *Symmetry*, *Duality*, and *Correspondence*.

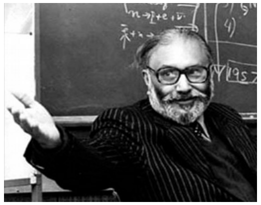
Example: supernova explosions can be simulated in the lab by implosions induced in a plasma by intense lasers *

$$t \to -1/t \quad \vec{x} \to \vec{x}/t \qquad \text{duality}$$

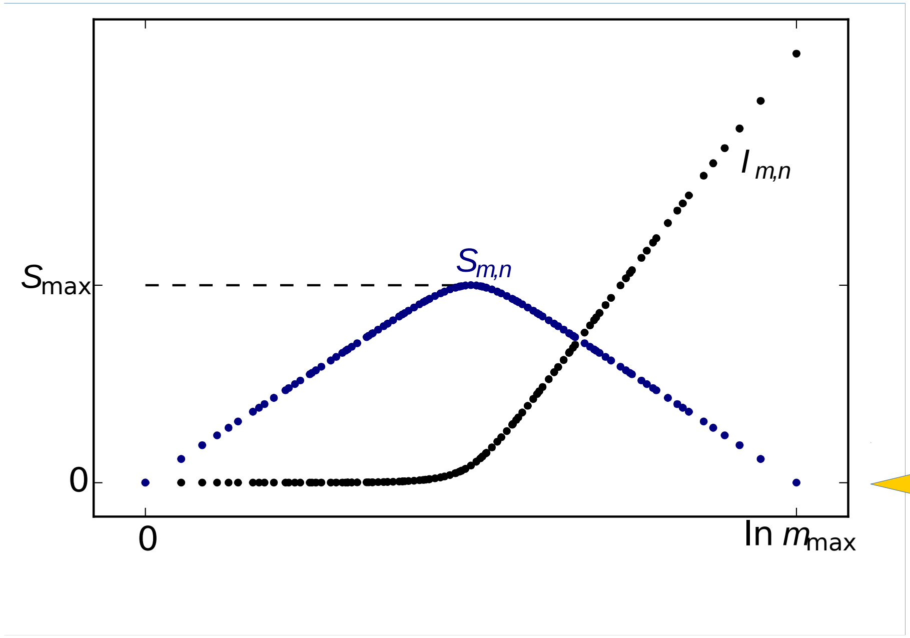
Only this will eventually convince the whole community that analogs are tests of hep-th.

*** L O'Raifeartaigh, V Sreedhar, Ann Phys 293 (2001) 215**

II Solve open theoretical debates with analog experiments



Focus on some few open issues, probably the most important being the info loss. Problem: kinematics → dynamics?



ZERO?

Our research directions

Theory search:

* Promote analogs to a higher status

* Face theory open issues inspired by analogs

- Hunt for analog BH thermodynamics
- Refine the Hawking (time; new results; BTZ; ...)
- Generalized Uncertainty Principle and quantum gravity
- Classical Unruh/Hawking
- Inequivalent quantizations and BHs
- USUSY

...

Experimental search:

- Magnetic field to generate t-loops
- Laser-graphene interaction and $g_{\mu\nu}$
- Look for the refined Hawking

...

Luca Smaldone

PabloPais

Giovanni Acquaviva

Martin Scholtz

Tadzio Levato

Marcelo Ciappina

Gaetano Lambiase

Paolo Castorina

G Lukes-Gerakopoulos, R Gabbrielli, S Taioli, A Zampeli, P Haman, P Kus

AI, Ann Phys 326 (2011) 1334; EPJ plus 127 (2012) 156

AI, G Lambiase, PLB 716 (2012) 334; PRD 90 (2014) 025006
AI, P Pais, 1901.00116; Ann Phys 398 (2018) 265; PRD 92 (2015) 125005; et al, 1907.00023; IJMPD 27 (2018) 1850080
R Gabbrielli, AI, S Taioli, et al J Phys: CM 28 (2016) 13LT01
AI, IJMPD 24 (2015) 1530013 review

AI, 1902.07096; G Acquaviva, AI, M Scholtz, Ann Phys 387 (2017) 317; PoS (CORFU2018) 206

P Castorina, D Grumiller, AI, PRD 77 (2008) 124034;
P Castorina, AI , H Satz, IJMPE 24 (2015) 1550056;
P Castorina, AI, IJMPA 33 (2018) 1850211

9 projects in progress