Quasiparticle picture
from the
Bekenstein bound

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Testing Fundamental Physics Principles

Corfu, Greece

Ref: G.Acquaviva, A.I., M.Scholtz, arXiv:1704.00345 (Ann Phys, tbp)

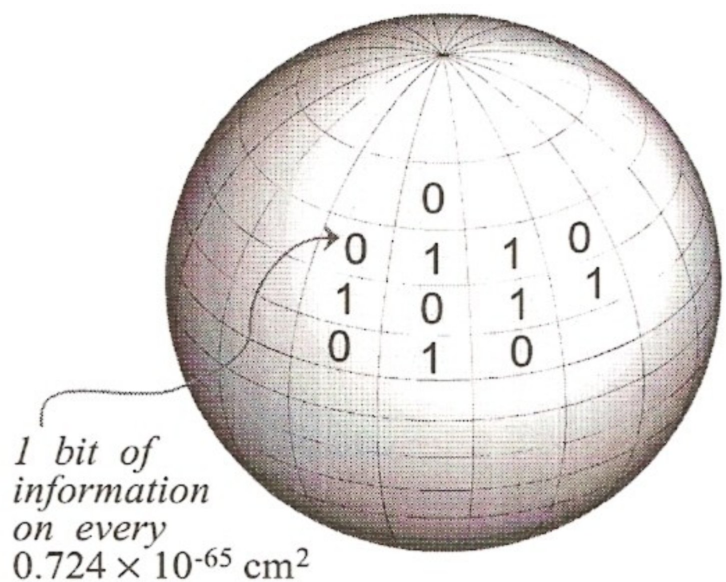
Quasiparticle picture

It is widely accepted

$$S \leq S_{\mathrm{BH}} = \frac{1}{4}\frac{\partial V}{\ell_P^2},$$

where $\partial V \equiv A_{\mathrm{EH}}$.

One possible interpretation is that, when a BH is formed, the "X level" has been reached.



- **If**

$$S \leq S_{BH} = \frac{1}{4}\frac{A}{\ell_P^2}$$

means that fundamental degrees of freedom X exist, then

$$g_{\mu\nu}\text{s} \quad \text{AND} \quad \phi\text{s}$$

both emerge from X

- **Then, in general:**

a) particles we call elementary are, in fact, quasiparticles, and

b) there is field-geometry entanglement

- **Different configurations of X may give rise to the same $g_{\mu\nu}$ but then yield different ϕs**

$$(g_{\mu\nu}, \phi), \ldots, (g_{\mu\nu}, \phi')$$

- **Thus, even if**

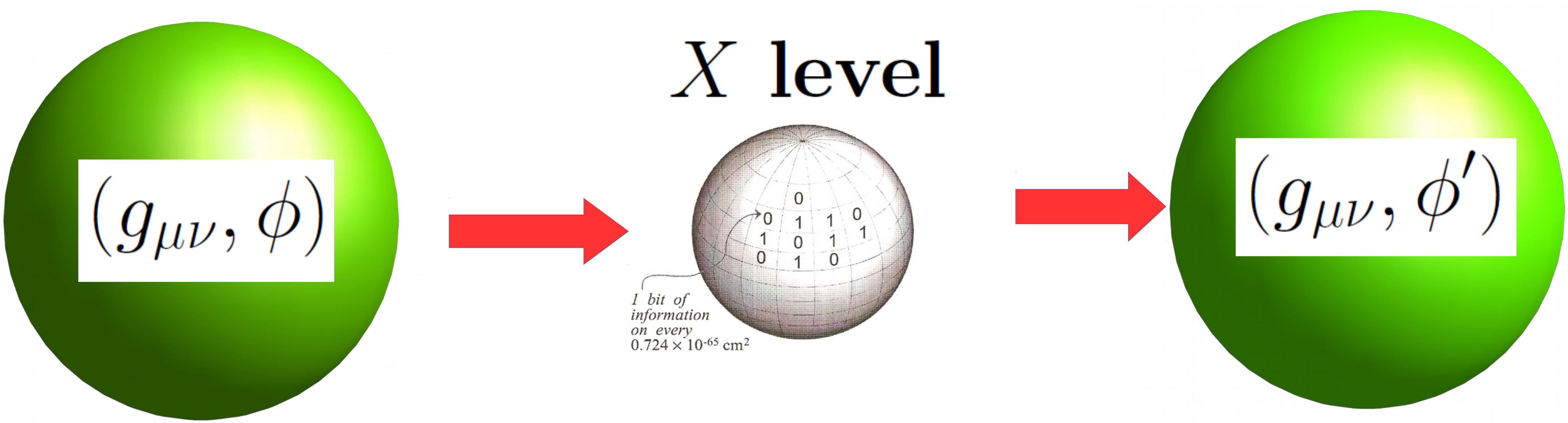
$$g_{\mu\nu}^{<BH} = g_{\mu\nu}^{>BH} \equiv g_{\mu\nu}$$

the emerging quantum fields $\phi \neq \phi'$ and live in different Hilbert spaces.

- **Since the Xs rearrange, even a unitary evolution at the X level leads to information loss for ϕ!**

Thus BHs are (the only!) drivers of phase transitions between different "emergent" arrangements of the X level

Before formation | **After evaporation**



$$S \leq 2\pi \frac{RE}{\hbar c} \longrightarrow S|_{E=E_S} = \pi R_S^2 \frac{c^3}{\hbar G} = \frac{1}{4}\frac{A_{EH}}{\ell_P^2} \longrightarrow S \leq 2\pi \frac{RE}{\hbar c}$$

On the other hand, the following is widely accepted

Take

$$\mathsf{H} = \mathsf{H}_A^m \otimes \mathsf{H}_B^n$$

and $U|\psi_0\rangle \in \mathsf{H}$ **a random state, with associated** $\rho_A(U)$**, and** $S_{m,n}(U)$

The average entanglement entropy of A

$$S_{m,n} = \langle S_{m,n}(U)\rangle$$

and the average information contained in A

$$I_{m,n} = \ln m - S_{m,n}$$

Page conjectured

$$I_{m,n} = \ln m + \frac{m-1}{2n} - \sum_{k=n+1}^{mn} \frac{1}{k}$$

for $m < n$

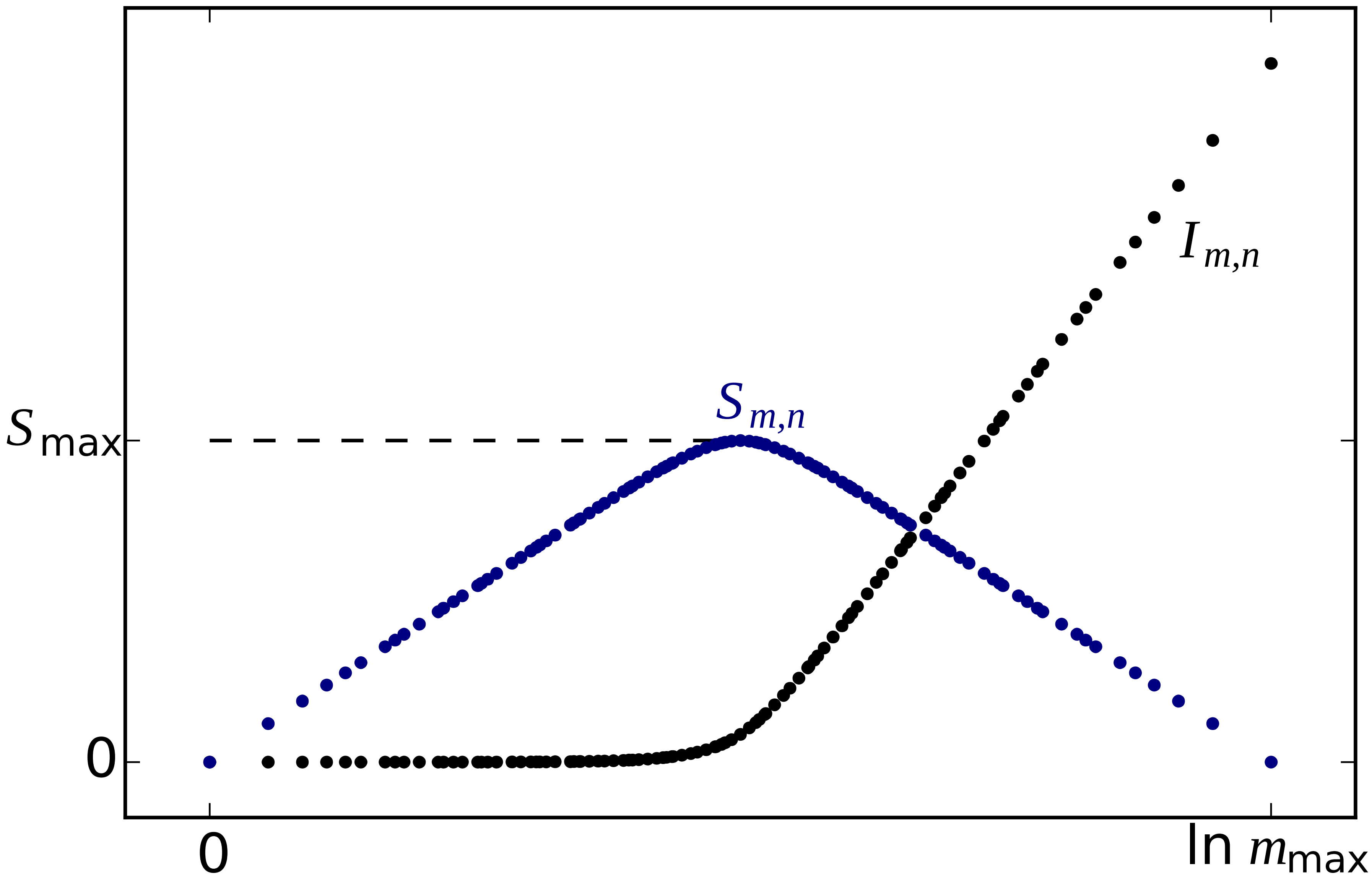
Applied to BH evaporation: A corresponds to the states under the horizon, B corresponds to the radiation

When the BH is formed, $n = 1$ and $m = \dim \mathsf{H}$: $S_{m,n}$ is zero

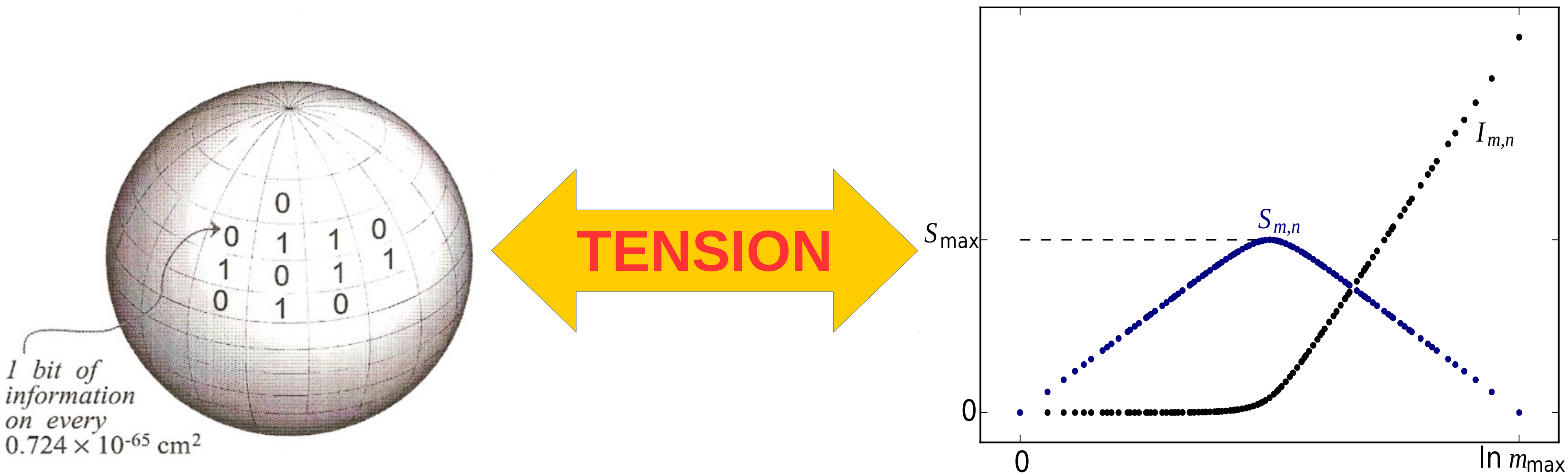
As the BH evaporates, n increases and m decreases ($m\, n$ =const.): $S_{m,n}$ increases

At some stage (approximately half time, t_{Page}) $I_{m,n}$ starts to leak from the BH: $S_{m,n}$ decreases

When the BH fully evaporates, $m = 1$ and $n = \dim \mathsf{H}$: $S_{m,n}$ returns to zero



S_{max}
0
$S_{m,n}$
$I_{m,n}$
0
$\ln m_{max}$


0
0 1 1 0
1 0 1 1
0 1 0
1 bit of
information
on every
0.724 × 10-65 cm2
TENSION
Smax
Sm,n
Im,n
0
0
ln mmax

Modeling BH evaporation

The Hilbert space H for the X level is

$$|\psi\rangle \in \mathsf{H}$$

$$\mathsf{P}_{\mathrm{G}} \swarrow \qquad \searrow \mathsf{P}_{\mathrm{F}}$$

$$|g^{(a)}\rangle \in \mathsf{H}_{\mathsf{G}} \qquad\qquad |\phi\rangle \in \mathsf{H}_{\mathsf{F}}$$

N_G **allowed geometries**

$$|g^{(a)}\rangle, \qquad a = 0, 1, \ldots N_G - 1$$

so $|\psi\rangle = |g^{(a)}, \phi\rangle$

The distribution of the X between geometry and the fields in general changes during the unitary evolution.

Assume

$$\mathsf{H} = \bigoplus_{i=1}^{N_T} T_{(i)}, \qquad \dim \mathsf{H} = N_T\, N$$

where

$$T_{(i)} = \mathsf{H}_{\mathrm{G}}^{p_i} \otimes \mathsf{H}_{\mathrm{F}}^{q_i}, \qquad p_i\, q_i = N$$

A general state $|\psi\rangle \in \mathsf{H}$ admits then the expansion

$$|\psi\rangle = \bigoplus_{i=1}^{N_T} \sum_{I=1}^{p_i} \sum_{n=0}^{q_i-1} c_{In}^{(i)} |I_i\rangle \otimes |n_i\rangle$$

$|I_i\rangle$s and $|n_i\rangle$s bases of $\mathsf{H}_{\mathrm{G}}^{p_i}$ and $\mathsf{H}_{\mathrm{F}}^{q_i}$, resp.

Denote by $\mathsf{P}_{(i)} : \mathsf{H} \mapsto T_{(i)}$ **a projector onto** $T_{(i)}$**. Then**

$$p_{(i)} = \|\mathsf{P}_{(i)}|\psi\rangle\|^2$$

is the probability of finding the system in the state with the topology $T_{(i)}$**.**

In general, a state in $T_{(i)}$ **has entanglement between geometry and field**

$$\mathsf{P}_{(i)}|\psi\rangle = \sum_{I,n} c^{(i)}_{In} |I_i\rangle \otimes |n_i\rangle$$

The associated density matrix representing the state of the field is

$$\rho_{(i)} = \mathrm{Tr}_{\mathsf{H}^{p_i}_{\mathrm{G}}} |\psi\rangle_i \langle\psi|_i$$

where $|\psi\rangle_i = p_{(i)}^{-1/2} \mathsf{P}_{(i)} |\psi\rangle$

The corresponding entanglement entropy

$$S_{(i)} = -\mathrm{Tr}_{\mathsf{H}_{\mathrm{F}}^{q_i}} \rho_{(i)} \ln \rho_{(i)}$$

is the entanglement entropy between the geometry and the fields for a given topology

Since the observer does not distinguish between different topologies, the expected value of the entanglement between the fields and the geometrical dof is

$$\langle S \rangle = \sum_i p_{(i)} S_{(i)}$$

Assume $N_T = 2$**,** $N_G = 30$**,** $\mathsf{P}_{\mathrm{G}}(T_{(1)}) = \mathsf{P}_{\mathrm{G}}(T_{(2)}) = \mathsf{H}_{\mathsf{G}}$ **and** $N = 1500$ **and let us set** $(\dim \mathsf{H} = 3000)$

$$\begin{aligned} T_{(1)} &= \mathsf{H}_{\mathrm{G}}^{30} \otimes \mathsf{H}_{\mathrm{F}}^{50}, \quad p_1 \times q_1 = 30 \times 50 \\ T_{(2)} &= \mathsf{H}_{\mathrm{G}}^{60} \otimes \mathsf{H}_{\mathrm{F}}^{25}, \quad p_2 \times q_2 = 60 \times 25 \end{aligned}$$

Define the "mass operator" M

$$\mathsf{M}|g^{(a)}\rangle = M^{(a)}|g^{(a)}\rangle \equiv \varepsilon\, a\, |g^{(a)}\rangle$$

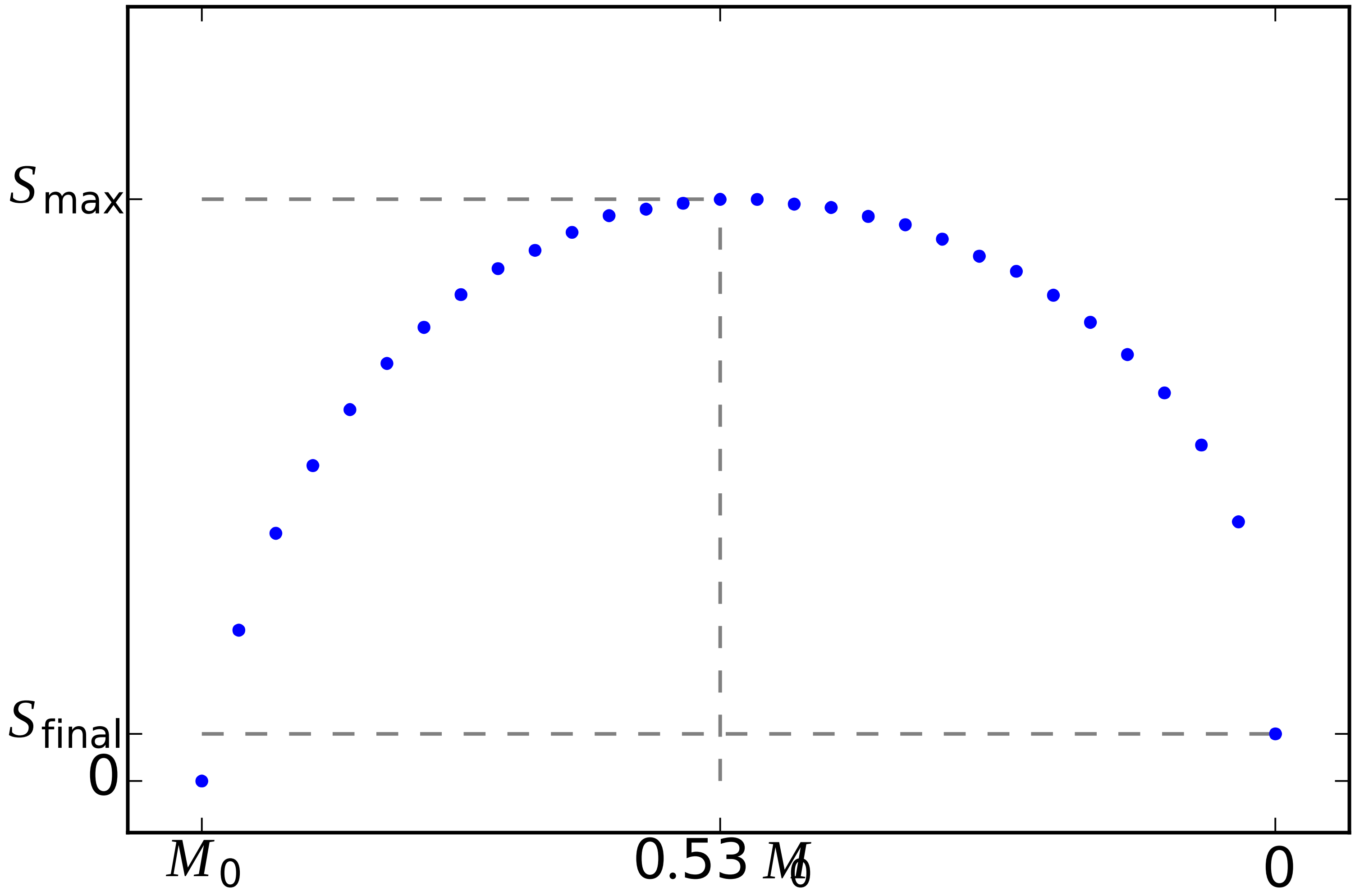
For a BH of $M^{(a)} = a\,\varepsilon$ **one state in** $\mathsf{H}_{\mathrm{G}}^{30}$ **mapped to one** $|g^{(a)}\rangle$ **by** P_{G}**, while in** $\mathsf{H}_{\mathrm{G}}^{60}$ **to two such states**

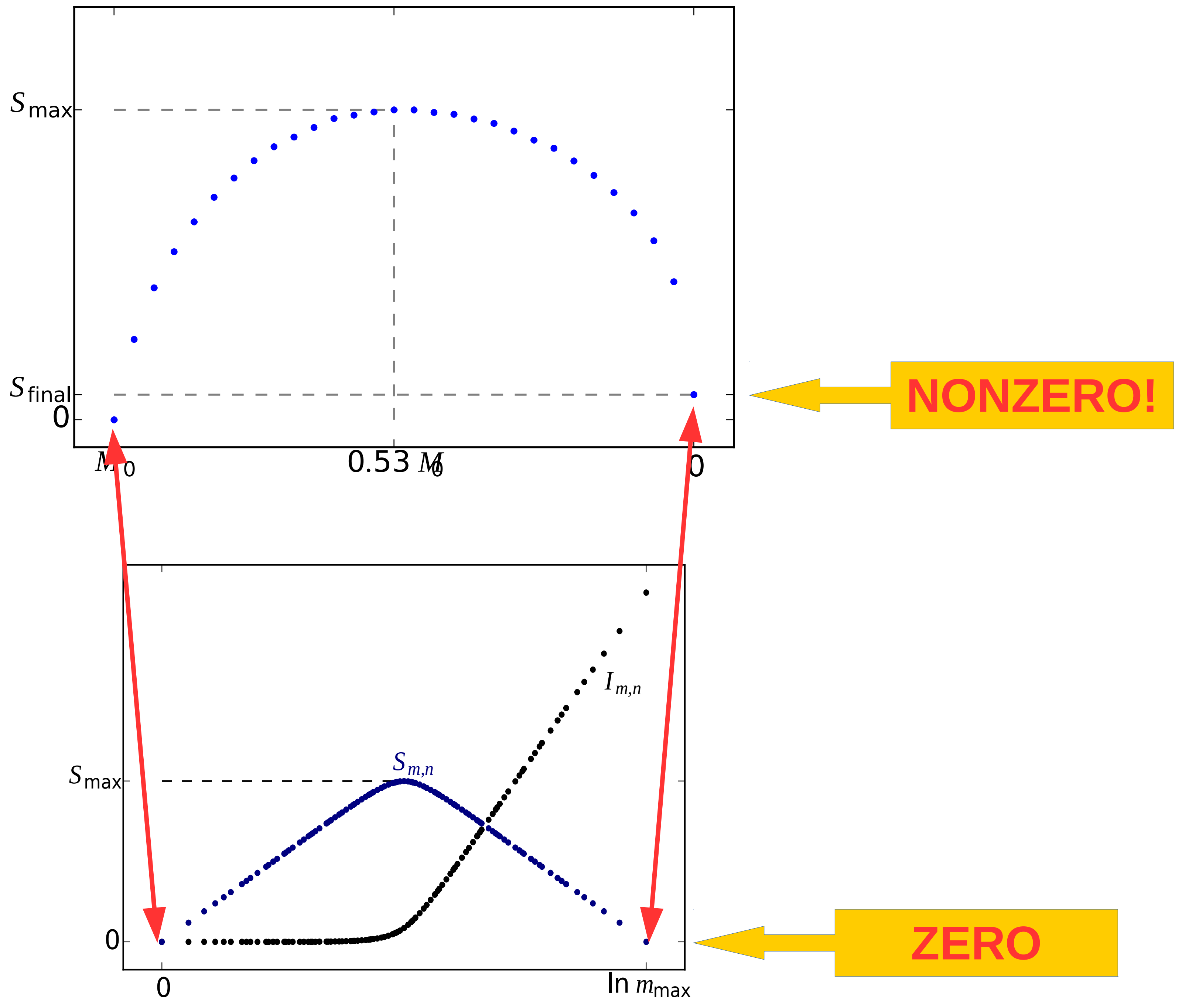
"Snapshots" of the continuous and unitary evolution in H

$$\langle M \rangle = (N_G - 1 - k) \quad \text{and} \quad \langle n \rangle = k\,,$$

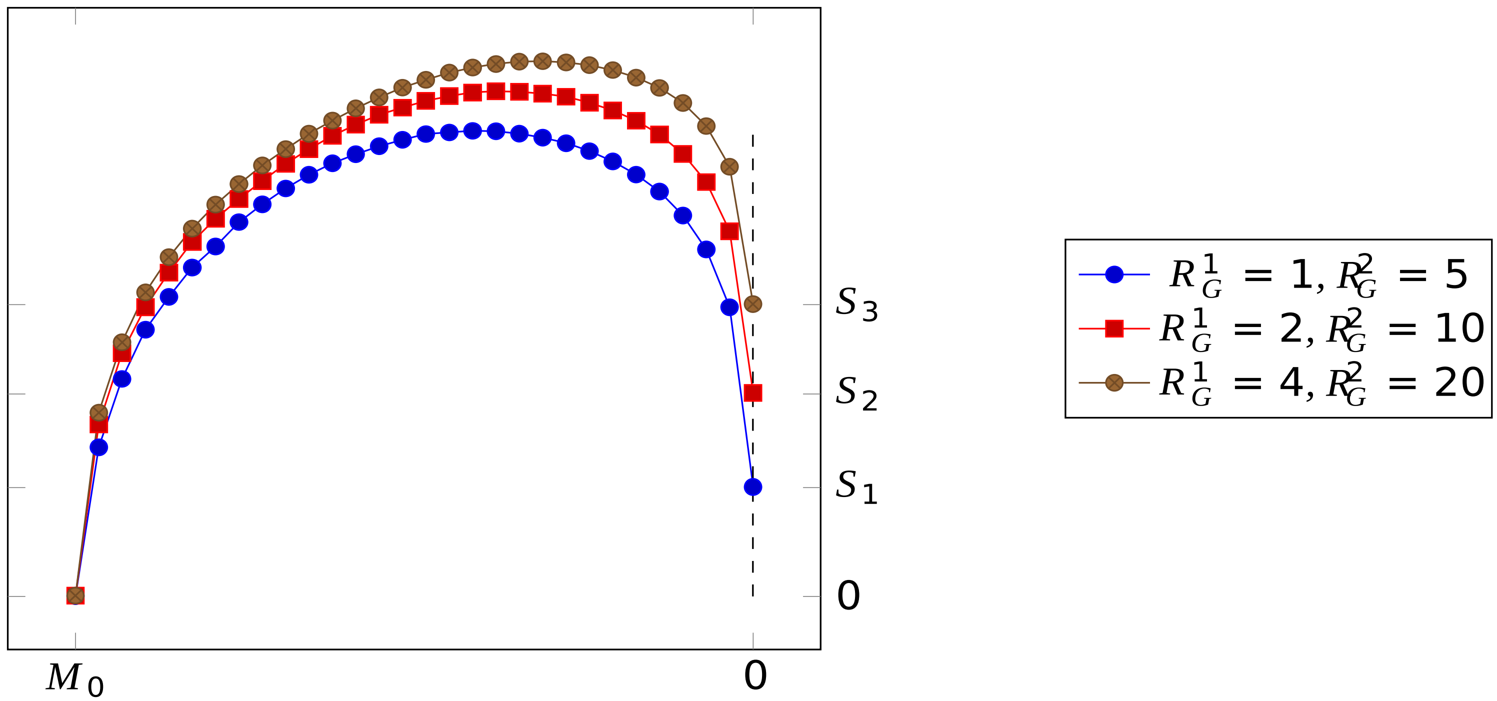
where $k = 0, 1, \ldots N_G - 1$**.**

Making the long story *of the estimate of the expected entanglement entropy for a random state with prescribed expected* $< n >$ *and* $< M >$ short *(a story of Hopf coordinates parametrization on* S^3*, of solving constrains, of generation of sequences and their random phases... done 5000 times)*





S_{max}
S_{final}
0
M_0
0.53 M_0
0
NONZERO!
$I_{m,n}$
$S_{m,n}$
S_{max}
0
0
ln m_{max}
ZERO



Here $p_i = N_G\, R_G^i$ **and** $q_i = N_F^i\, R_F^i$

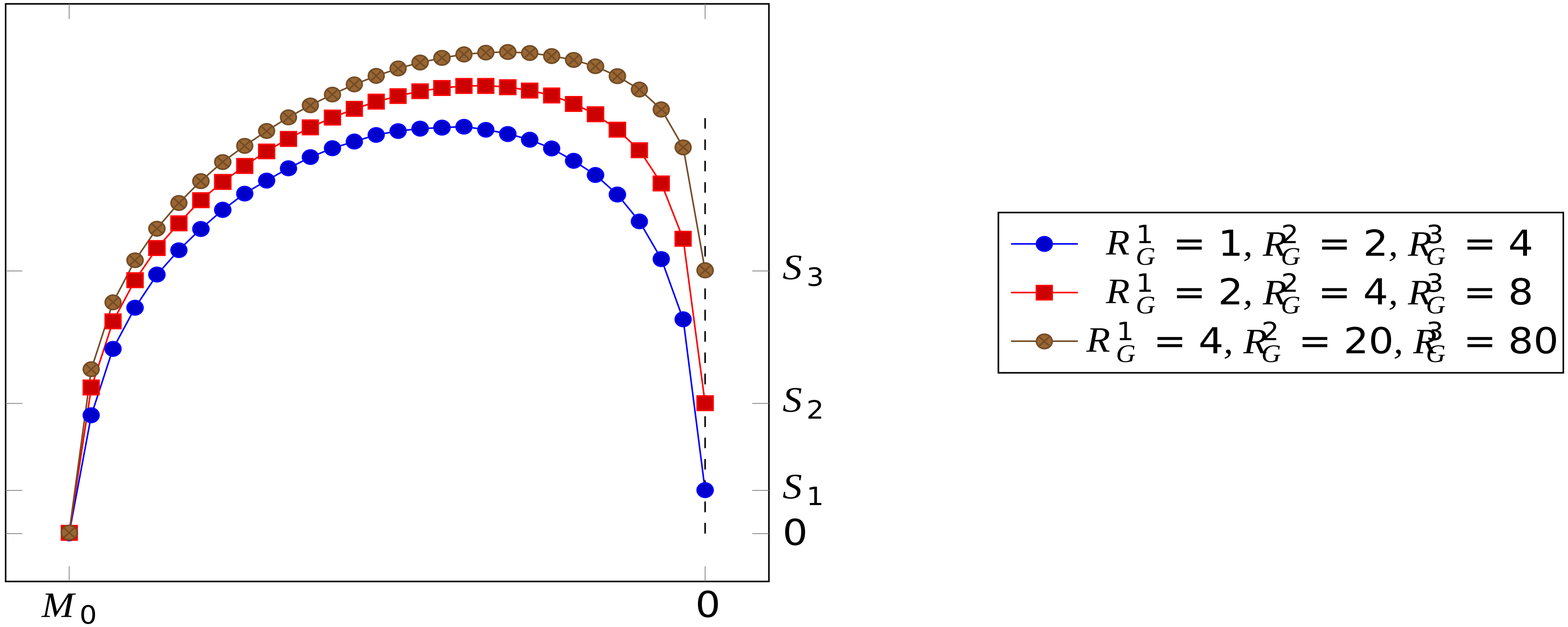
We choose $N_G = 30$**,** $N_T = 2$**, and** $R_F^i = 1$ **for each topology**

We plot three different cases:

$$N_F^1 = 200, R_G^1 = 1, N_F^2 = 40, R_G^2 = 5$$
$$N_F^1 = 200, R_G^1 = 2, N_F^2 = 40, R_G^2 = 10$$
$$N_F^1 = 200, R_G^1 = 4, N_F^2 = 40, R_G^2 = 20$$

The residual entropies are

$$S_1 = 0.77, \quad S_2 = 1.43, \quad S_3 = 2.06$$



Again $p_i = N_G\, R_G^i$ and $q_i = N_F^i\, R_F^i$
As before $N_G = 30$, but $N_T = 3$, and

$$N_F^1 = 120, N_F^2 = 60, N_F^3 = 30 \quad \text{and} \quad R_G^1 = 1, R_G^2 = 2, R_G^3 = 4,$$
$$N_F^1 = 120, N_F^2 = 60, N_F^3 = 30 \quad \text{and} \quad R_G^1 = 2, R_G^2 = 4, R_G^3 = 8,$$
$$N_F^1 = 200, N_F^2 = 40, N_F^3 = 10 \quad \text{and} \quad R_G^1 = 4, R_G^2 = 20, R_G^3 = 80,$$

In this case, the residual entropies are

$$S_1 = 0.34, \quad S_2 = 1.02, \quad S_3 = 2.06$$

What to do with this?

Our quasiparticle picture makes a lot of sense (to us!)

Plenty of further theoretical research (= we still don't understand most of what have done!):

dynamical realizations; more realistic BH evaporation; exact computations of S_{ent}; realistic estimate of the degeneracy; the classical limit; coherent states; new Stone-von Neumann thrm; dark matter; the fundamental nature of oscillating particles; etc.

We shall probably follow that road, but this will not (and cannot) stop the info-loss-yes-or-not story to keep going forever...

Perhaps, one should try to look for something to measure? Is there anything around that resembles this?

First we need quasi-particles

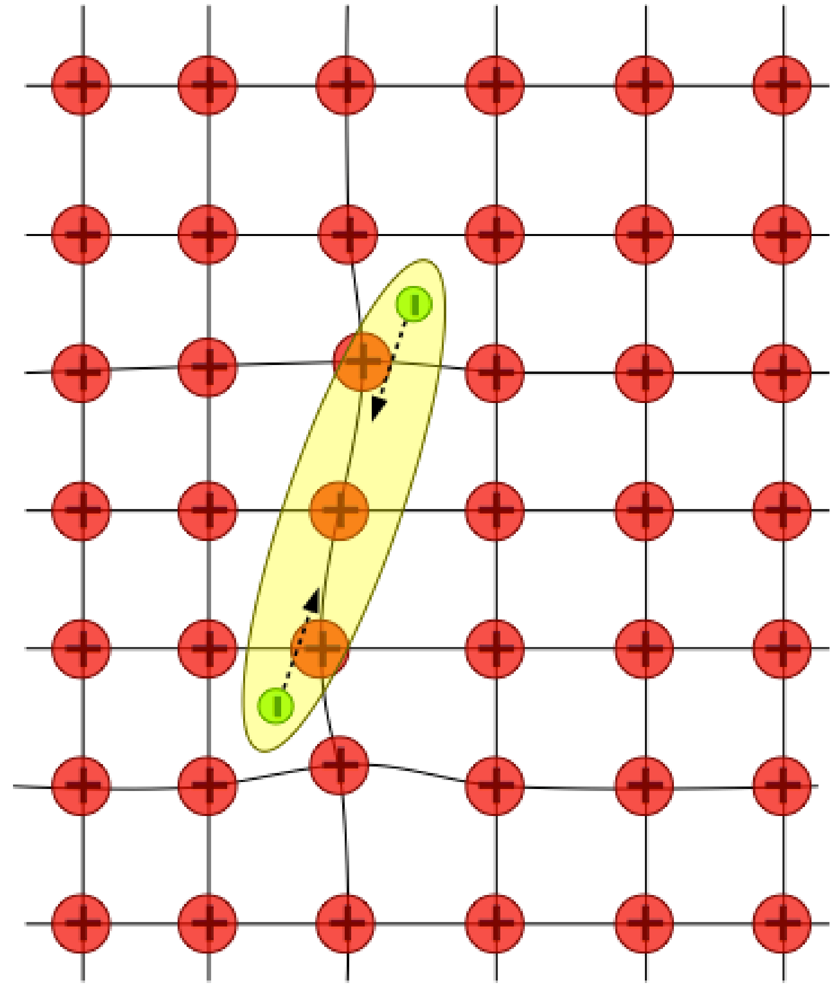
BCS pairs

Plasmons

Phonons

Magnons

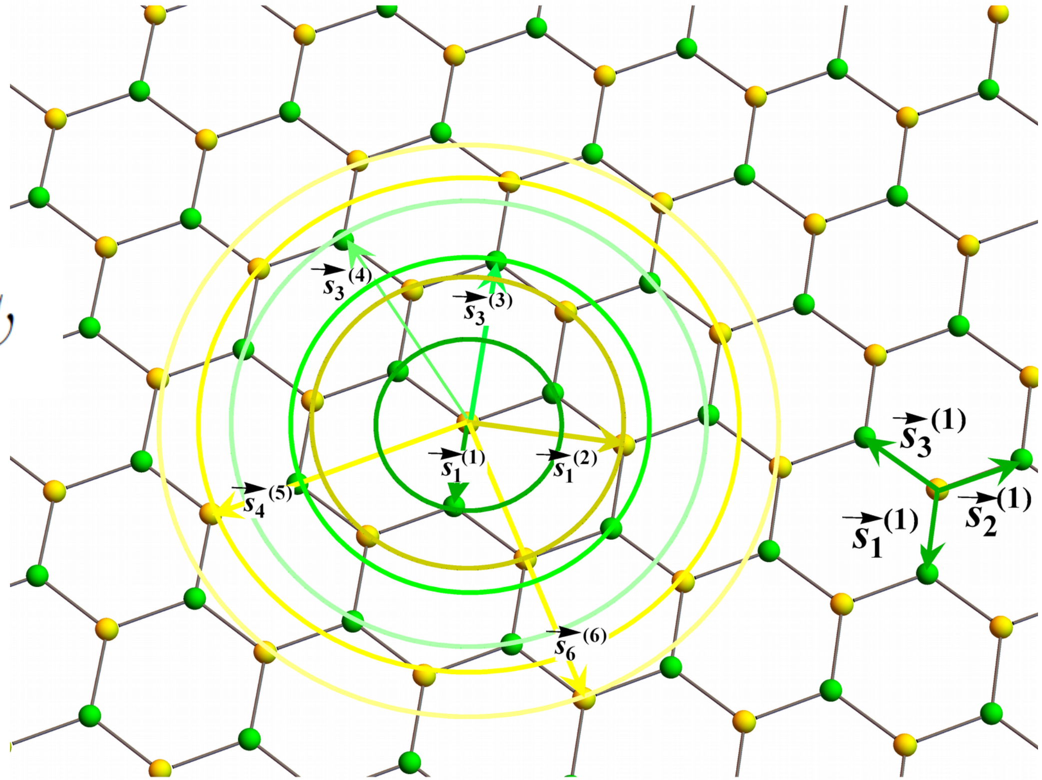
...



Rep of one Cooper pair from Chernodub, M.N. Lect. Notes Phys. 871 (2013) 143

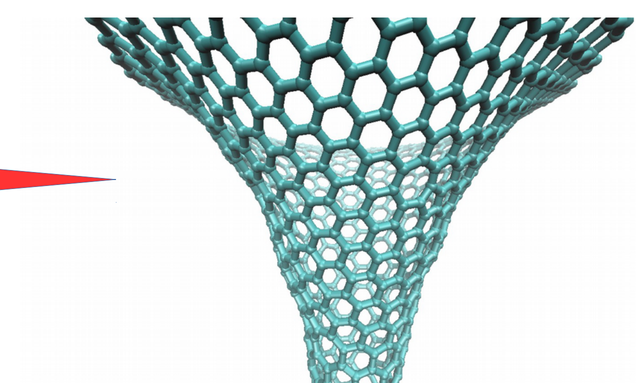
Graphene is unique

$$i\hbar v_F \int d^3x \bar{\psi}\ \partial\!\!\!/ \psi$$



$$ds^2_{\rm graphene} = \frac{r^2}{\tilde{y}^2}\left[\frac{\tilde{y}^2}{r^2}dt^2 - d\tilde{y}^2 - d\tilde{x}^2\right]$$

$$(\eta, \psi)$$



Dispersion relations

$$E_\pm = V_F\left(\pm|\vec{P}| - A\,|\vec{P}|^2\right)$$

with $\vec{P} \equiv (\hbar/\ell)(Re\mathcal{F}_1, Im\mathcal{F}_1)$, $V_F \equiv \eta_1\ell/\hbar$, $A \equiv (\ell/\hbar)\epsilon(\eta_2)/\eta_1$ **and**

$$\mathcal{F}_1 = \sum_{i=1}^{3} e^{i\vec{k}\cdot\vec{s}_i^{(1)}} = e^{-i\ell k_y}[1 + 2e^{i\frac{3}{2}\ell k_y}\cos(\frac{\sqrt{3}}{2}\ell k_x)]$$

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

Henceforth *deformed* Dirac Hamiltonian

$$H(P) = V_F\sum_{\vec{k}}\psi^\dagger_{\vec{k}}(\not{P} - A\ \ \not{P}\ \not{P})\,\psi_{\vec{k}}$$

with *standard* commutation relations, $[X^P_i, P_j] = i\hbar\delta_{ij}$

Or *standard* Dirac Hamiltonian, $\vec{Q} \equiv \vec{P}(1 - A|\vec{P}|)$

$$H(Q) = V_F\sum_{\vec{k}}\psi^\dagger_{\vec{k}}\ \not{Q}\psi_{\vec{k}}$$

with *deformed* commutation relations

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

A.I., P.Pais, I.A.Elmashad, A.F.Ali, et al, arXiv:1706.01332 (sbmtd PRD)

To have nonzero intrinsic curvature $\mathcal{K}$ on an hexagonal lattice we need <u>disclination</u> defects

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

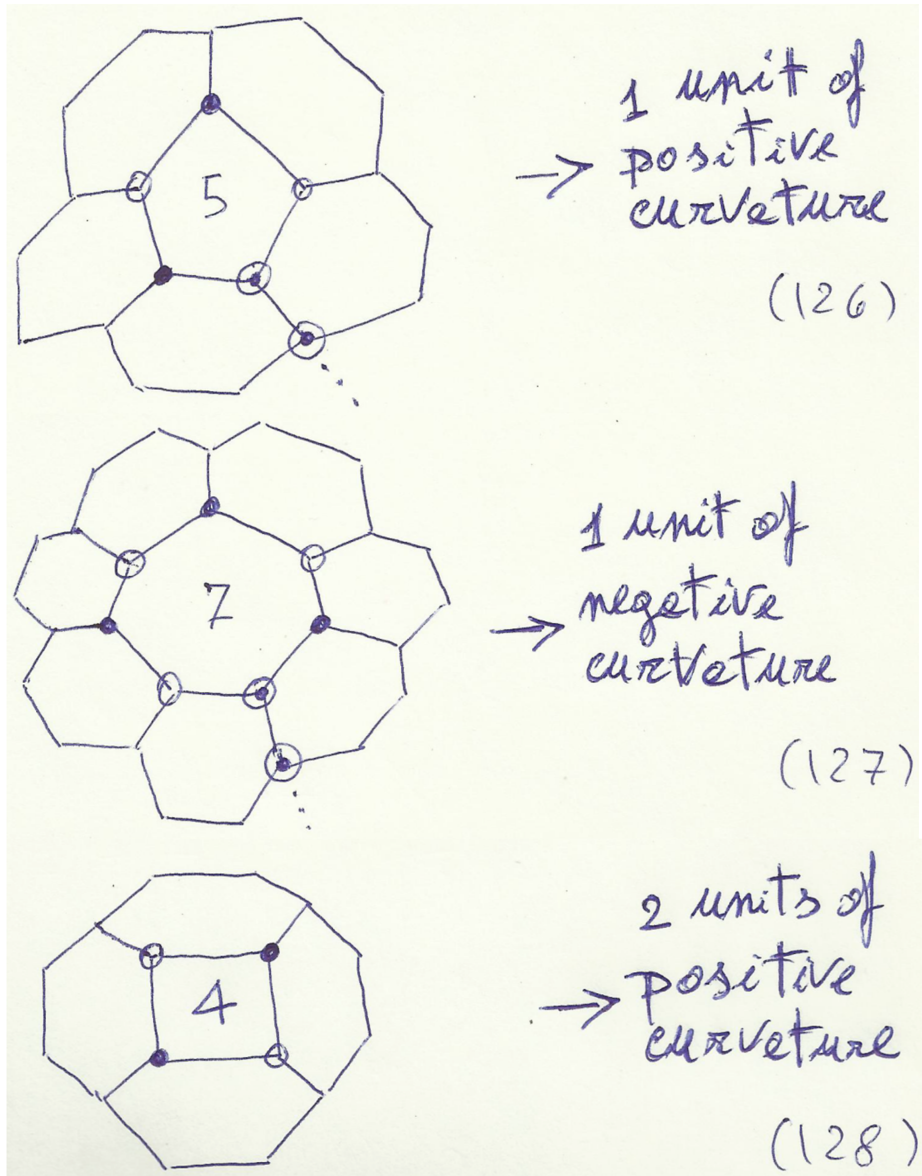
and

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

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

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

Thus, (♣) and (♠) together give



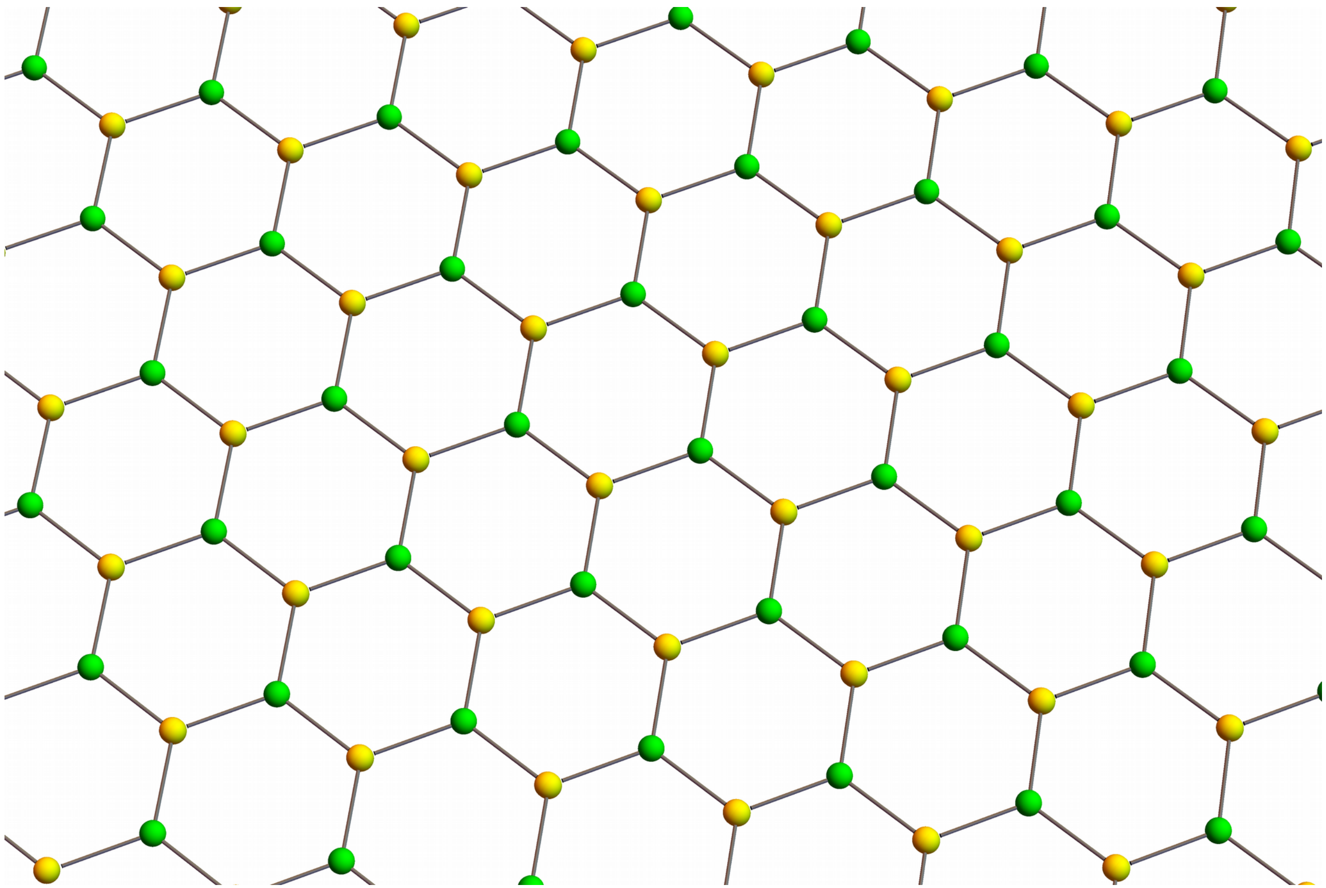
$$\mathcal{K}_5 = +\left(\frac{3}{\pi}\right) \frac{\mathcal{K}_{tot}}{12}$$

and

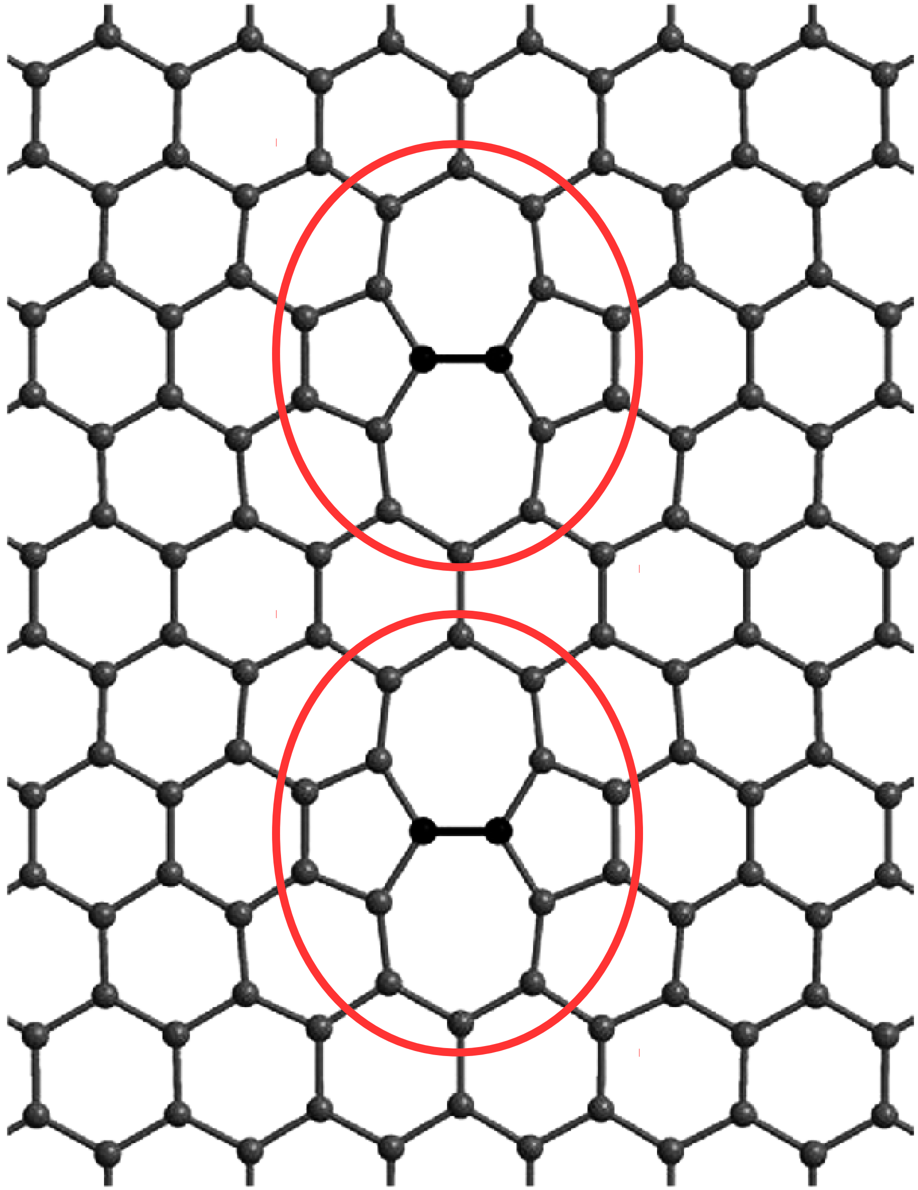
$$\mathcal{K}_7 = -\left(\frac{3}{\pi}\right) \frac{\mathcal{K}_{tot}}{12}$$

and so on

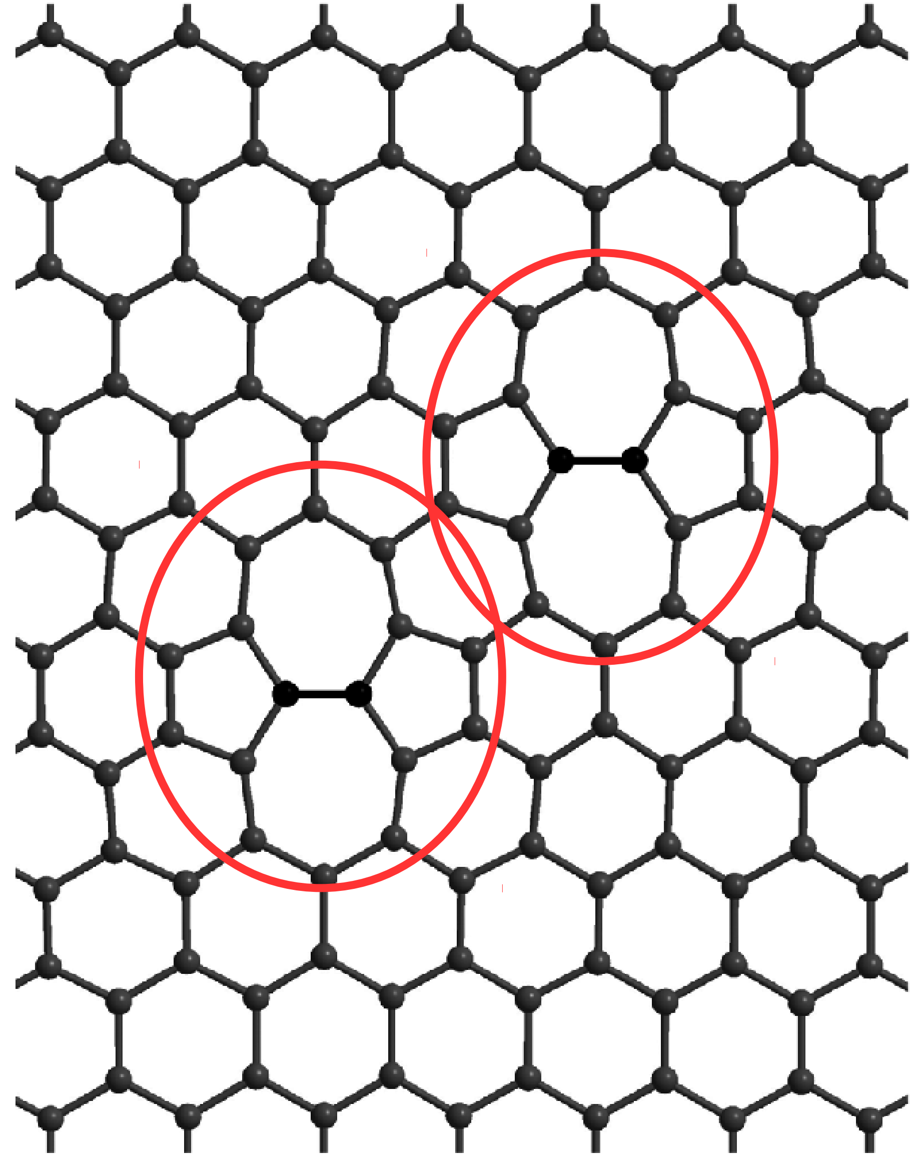
This is behind ω_μ^a



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



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



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

Fig.s adapted from: Openov, Podlivaev, Phys Solid State 57 (2015) 1477

Conclusions and credits

- The Bekenstein bound may imply the existence of the "X level"
- Both fields and geometry need be made of the same "X material"
- Even assuming unitary evolution at the X level, such unitarity is unaccessible
- We (= me) do not understand Page curve
- Should we try to test that on... graphene?

G. Acquaviva, AI, M. Scholtz, (AoP tbp), arXiv:1704.00345; and letter (sbmtd PLB)

AI, P. Pais, I.A. Elmashad, A.F. Ali, et al, arXiv:1706.01332 (sbmtd PRD)

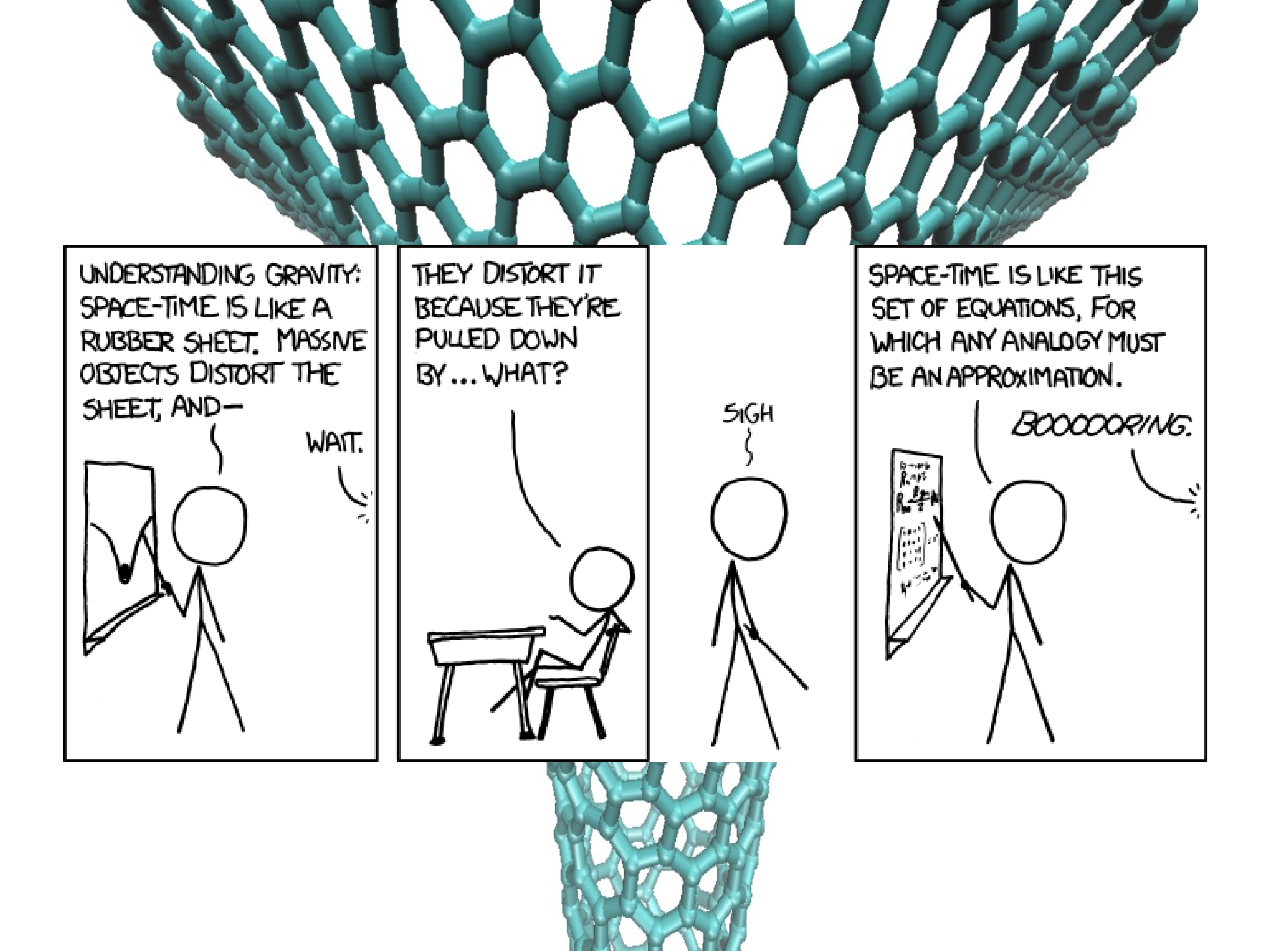
R. Gabbrielli, AI, N.M. Pugno, S. Simonucci, S. Taioli, J Phys: Cond Mat 28 (2016) 13LT01

AI, P Pais, PRD 92 (2015) 125005

AI, IJMPD 24 (2015) 1530013

AI, G. Lambiase, PLB 716 (2012) 334; PRD 90 (2014) 025006

AI, Ann Phys, 326 (2011) 1334


UNDERSTANDING GRAVITY: SPACE-TIME IS LIKE A RUBBER SHEET. MASSIVE OBJECTS DISTORT THE SHEET, AND—
WAIT.
THEY DISTORT IT BECAUSE THEY'RE PULLED DOWN BY... WHAT?
SIGH
SPACE-TIME IS LIKE THIS SET OF EQUATIONS, FOR WHICH ANY ANALOGY MUST BE AN APPROXIMATION.
BOOOOOORING.

Giovanni
Acquaviva

Martin
Scholtz

Georgios
Lukes-Gerakopoulos

Pablo
Pais

Adamantia
Zampeli