Séptima Escuela de Física-Matemáticas

25 Mayo – 29 Mayo 2015

Topological Quantum Matter

From Theory to Applications

Departamento de Matemáticas – Departamento de Física
Universidad de los Andes

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Morning Lectures

Andrei Bernevig (Princeton University, USA)

Topological Superconductors and Category Theory

- Topological Superconductivity, Kitaev wire, p+ip superconductor in $2D$ and relation to projector Chern numbers, Majorana fermions.
- Different kinds of chiral superconductors - the 16 fold way.
- Modular tensor categories, braiding,and topological quantum field theory.

Allan Macdonald (University of Texas at Austin, USA)

Quantum Hall effects through the ages

- Chern Indices and the Quantum Hall Effect (covers Thouless's original paper).
- Fractional Quantum Hall Effect (covers incompressible states, fractional and non-Abelian excitations).
- Quantum Hall Effect in a Periodic Potential (covers Hofstadter butterfly, Chern insulators, QHE for graphene on h-BN).
- Landau Levels and Superconductivity (covers Hall quantization in the presence of a pair-potential and proximity-coupled superconductivity in graphene sheets with well formed Landau levels).

Jiannis Pachos (University of Leeds, United Kingdom)

Why should anyone care about anyons?

- General overview of anyons and topological systems.
- The toric code and quantum error correction (maybe finite temperature effects).
- Anyons, Jones polynomials and quantum algorithms.
- Topological entanglement entropy.

Short Communications

Aiyalam Balachandran
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Edge States, topological insulators and superconductors

On manifolds M with boundaries ∂M, the formulation of quantum field theories for tensor fields requires boundary conditions on the Laplacian Δ such as Dirichlet, Neumann or Robin boundary conditions. They can lead to edge states with a gapped bulk. Examples are quantum Hall effect and the interface ∂M of a superconducting M and a normal metal. We discuss this phenomenon in general terms, give examples and suggest that they are very common.
Such edge states occur for Dirac fields too, but the boundary conditions are those of Atiyah, Pataudi and Singer (APS). The APS approach is explained and shown to lead to edge states by examples. Perhaps these edge states are related to "topological" edge states. They can conserve P and T and lead to spin-momentum locking.

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Classification of Modular Categories

Modular categories are intricate organizing algebraic structures appearing in a variety of mathematical subjects including topological quantum field theory, conformal field theory, representation theory of quantum groups, von Neumann algebras, and vertex operator algebras.
Besides the mathematical interest, a motivation for a classification of modular categories comes from their application in condensed matter physics and quantum computing. Unitary modular categories are algebraic models of anyons in two dimensional topological phases of matter where simple

objects model anyons. In topological quantum computation, anyons give rise to quantum computational models. Modular categories have also been used recently to construct three dimensional topological insulators and superconductors. Therefore, a classification of modular categories is literally a classification of certain topological phases of matter.
In this talk we will present the classification of all modular categories of dimension $4m$, where m is an odd square-free integer. We will use this result to give the classification of rank 6 and rank 7 weakly integral modular categories. This completes the classification of weakly integral modular categories through rank 7. This talk is based on a joint work with P. Bruillard, S-H. Ng, J. Plavnik, E. Rowell and Z. Wang (Prepint: arXiv:1411.2313).

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Arturo Gómez
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Regiones de confinamiento y deconfinamiento a partir de propagadores no perturbativos en modelos 3-dimensionales

Primeramente haremos una breve revisión acerca de las teorías de Yang-Mills y su cuantización a través de la integral de camino. Posteriormente, abordaremos el problema de Gribov, donde se estudia en profundidad la cuestión de la fijación del calibre de la teoría, generalizando la propuesta de Faddeev-Popov. A partir de este análisis es posible obtener modificaciones en la estructura analítica de los propagadores del gluón y del ghost en la región de infrarroja de la teoría, dando lugar a un escenario adecuado para el estudio del confinamiento del gluón. Tomando este escenario para el estudio no-perturbativo de las teorías de Yang-Mills, estudiaremos dos modelos en 3 dimensiones de gran interés físico, a saber, el conocido modelo de Georgi-Glashow (que introduce un campo de Higgs en la representación adjunta) y la llamada teoría de gauge topologicamente masiva, que introduce un término de Chern-Simons en la acción.
En ambos casos, a través del análisis de los propagadores no-perturbativos del campo de calibre es posible determinar en el espacio de los parámetros

de la teoría, regiones de existencia de polos físicos masivos para el gluón, correspondiendo a la fase masiva observable y regiones donde no es posible identificar gluónes como estados físicos pertenecientes a la Matriz S, dando lugar a la fase confinante.

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Quantum physics and transport process in 2D nanostructures by means of special functions

In this paper we analyze quantum transport in a two-dimensional nanostructure where we consider the spin polarization, a physical effect which now has a high performance potential in research and fabricating of basic nano-spintronics devices for implementation and quantum computing operation [1]. We present a physical-mathematical analysis of effects of Dresselhaus $H_D = \beta_D(\widehat{\sigma}_x k_x - \sigma_y k_y)\frac{\partial^2}{\partial z^2}$ and in-plane Rashba $H_R = \alpha_R(\widehat{\sigma}_x k_y - \sigma_y k_x)\frac{\partial^2}{\partial z^2}$ spin-orbit interactions, where β_D and α_R are constants depending on the material, $\widehat{\sigma}_x$ and $\widehat{\sigma}_y$ are Pauli matrices, k_x and k_y indicate the wave vectors in the crystallographic direction [100] and [101]. The effects spin-orbit coupling Schrödinger-Pauli equation given by the Hamiltonian end effects spin-orbit coupling Schrödinger-Pauli equation given by the Hamiltonian

$$\widehat{H} = \frac{\hbar^2}{2m_j^*}(k_z^2 + k_\parallel^2)\widehat{\sigma}_x^T + V_{L,R}(z)\widehat{\sigma}_x^T + \widehat{H}_D + \widehat{H}_R + \widehat{H}_Z$$

[3, 5, 4] with a type potential energy barrier, shaped with a hyperbolic function, known as Pöschl-Teller, $V_{L,R}(z) = V_0 \cosh^{-2}\frac{z-z_0}{a_{L,R}}$ where $a_{L,R}$ refers to the width of the barriers [8]. Furthermore considering the Zeeman energy $\widehat{H}_z = \frac{1}{2}g_j^*\mu_B^j\widehat{\sigma}\cdot\vec{B}$ with the influence of in-plane magnetic field on spin polarization [7, 9]. The study is conducted analytically by confluent hypergeometric functions [6, 2], allowing the resonant tunneling spin model for semiconductor heterostructures multilayer type. The results show spin polarization depending on the energy applied to the electrons, the well width and intensity of the magnetic field.

Keywords. Polarisation, Dresselhaus, Rashba, Pöschl-Teller.

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The Geometry of Quantum Phase Transitions: From Berry Phases to Fredholm Modules

In the last few years, a characterization of the critical point in several spin chain modules in terms of Berry phases and also in terms of the so-called quantum geometric tensor has been extensively studied. This characterization complements the conformal field theory description of the critical point, as well as those based on entanglement properties of the ground state. In this talk I will present an approach based on the study of certain topological invariants that arise naturally from the topology of the parameter space of a modified XY-mode. This, in turn, leads to more general considerations in the context of quasi-free representations of CAR-algebras, for which a connection to noncommutative geometry via Fredholm modules can be exploited in the context of fermionic Gaussian systems.

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Applications of conformal field theory to the fractional quantum Hall states

The fractional quantum Hall states are one of the most amazing quantum phases of matter. Among other mind bending features, they display quasiparticles with fractional charge and non-abelian braiding statistics. In this

talk, I will revisit the use of conformal field theory machinery in the characterization of the ground state order and the edge and bulk quasiparticle excitations with particular emphasis on paired FQHE states.

Posters

Julián Arcila Forero
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Phase transition of anyons confined in one-dimensional optical lattice

Anyons are the third fundamental category of particles, for two anyons under particle exchange the wavefunction acquires a fractional phase $e^{i\theta}$, giving rise to fractional statistics with $0 < \theta < \pi$. The greatest interest for the anyons study emerged when the fractional quantum Hall effect observed experimentally had natural explanation in term of anyons. We study a Hubbard model for anyons equivalent to a variant of the Bose-Hubbard, we established an exact mapping between anyons and bosons in one-dimension. Using the density matrix renormalization group method we studied the system properties, we presented the phase diagram for density $\rho = 1$ with some angles, the quantum transition is from Mott insulator to Superfluid phase, the Mott lobe expands with increasing statistical angle.
We study the block von Neumann entropy, which was used to establish the critical points. For a fixed density we study the critical point evolution vs θ and find that the position of the critical point increasing with the angle. For fixing statistical we showed the dependency between the position of the critical point and the density, also the critical point decreases with increasing of the density, implying that the Mott region decreases.

Keywords. Anyons, phase transition, critical point, block von Neumann entropy.

Joint with R. Franco and J. Silva-Valencia, Universidad Nacional de Colombia, Bogotá, Colombia. .

Óscar Casas
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Topological Insulators in Nanowires

In this work we review the main characteristics of a topological insulator and some applications in the study of nanowires. In particular, we summarize some results obtained for the energy spectrum in nanowires of circular and rectangular cross-section. In these systems the surface states show an energy gap associated with the Berry phase. Finally, we discuss how to control this gap using magnetic or exchange fields and the possible applications in spintronics.

Joint with S. Gomez P., Universidad el Bosque, Bogotá, Colombia and William J. Herrera, Universidad Nacional de Colombia, Bogotá, Colombia.
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Further Explorations of the Parameter Space of $3D$ Lattice Gauge Theories

State sum models can be used to construct the partition functions of $3D$ lattice gauge theories based on involutory Hopf algebras, $\mathcal{A}$, of which the group algebras, $\mathbb{C}G$, are a particular case. Transfer matrices can be obtained from such partition functions by carrying out the state sum construction on a manifold with boundary. The parameter space of these transfer contains various Hamiltonians of physical interest. The $2D$ quantum double Hamitlonians of Kitaev can be obtained from such transfer matrices for specific values of these parameters. A initial study of such models has been carried out in our previous work. In this paper we study other regions of this parameter space to obtain some new and known models. The new model comprise of Hamiltonians which "partially" confine the excitations of the quantum double Hamiltonians which are usually deconfined. The state sum construction is not invariant by translations and thus it is natural to expect to obtain disordered Hamiltonians from the transfer matrices resulting from these constructions. Thus one set of known models consist of the disordered quantum double Hamiltonians. Finally we obtain quantum double Hamiltonians perturbed by magnetic fields which have been considered earlier in the literature to study the stability of topological order to perturbations.

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Faraday rotation in thin metal films bounded by topological insulators

Electromagnetic excitations arising in a metal slab surrounded by an insulator with a non trivial topology associated to time reversal symmetry (topological insulator) are described in the frame of axion electrodynamics. It is shown that the rotation of the polarization plane induced by the non trivial topology is a linear function of the topological term for all slab thicknesses but strongly depends on the dispersion relations of bonding and antibonding surface modes. Numerical calculations show that for the bonding surface modes the presence of the topological term leads to an increasing rotation angle, which becomes more pronounced for thin slabs. On the other hand, the rotation angle of polarization corresponding to antibonding surface modes decreases with the in-plane wave vector and its magnitude is several orders of magnitude greater than that corresponding to bonding modes.

Joint with Juan Carlos Granada, Departamento de Física, Universidad Del Valle, Cali, Colombia.

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Simulation of universal logic quantum gates by using a toric code model

Currently a topic of high scientific interest is the quantum simulation of many-body spin interactions. Toric code model is highlighted, in which the spins are located at the edges of a square lattice on the surface of a torus. In this paper the Hamiltonian of the system is initially identified. If the lattice is of dimension $k \times k$, the Hamiltonian is a matrix of dimension $2^{2k^2} \times 2^{2k^2}$. The many-qubit time evolution operator of the system is then obtained. Further to this, universal logic quantum gates are constructed. This work may have relevance to establish a representation of anyons by using the toric code model, which would simulate topological quantum gates.

Simulación de compuertas lógicas cuánticas universales mediante un modelo de código tórico

En la actualidad un tema de alto interés científico es la simulación cuántica de interacciones de espín de muchos cuerpos. Se destaca el modelo de código tórico, en el cual los espines se ubican en los bordes de una red cuadrada sobre la superficie de un toro. En este trabajo se identifica inicialmente el hamiltoniano del sistema. Si la red es de dimensión $k \times k$, el hamiltoniano será una 2×2 matriz de dimensión $2^{2k^2} \times 2^{2k^2}$. Luego se obtiene el operador de evolución temporal del sistema de varios qubits. Ulterior a esto, se construyen compuertas lógicas cuánticas universales. Este trabajo puede tener importancia para establecer una representación de anyones mediante

el modelo de código tórico, lo cual permitiría simular compuertas cuánticas topológicas.

Joint with Jorge Mahecha, Universidad de Antioquia, Medellín.
Palabras Clave: Many-electron systems, Quantum computation, anyons.

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Density of states of a graphene layer under circularly polarized *ac* field

In this work we study the density of states for a graphene monolayer in presence of circularly polarized ac field. In the effective mass approximation, the presence of photon-dressed electron states within an energy gap favors quantum oscillations in the density of states analogously to quantum magnetic oscillations in presence of quantizing magnetic field. Basically the difference lies in the nature of oscillations, which are driven by the field frequency.

Joint with G. Salazar Cohen and R. Vega Monroy.

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Dirac Fermions without bulk backscattering in rhombohedral topological insulators

The realization of a spintronic device using topological insulators is not trivial, because there are inherent difficulties in achieving the surface transport regime [1]. The majority of 3D topological insulators materials (3DTI) despite of support helical metallic surface states on an insulating bulk, forming topological Dirac fermions protected by the time-reversal symmetry [2, 6], exhibit electronic scattering channels due to the presence of residual continuous bulk states near the Dirac-point [3]. From *ab initio* calculations, we studied the microscopic origin of the continuous bulk states in rhombohedral topological insulators materials with the space group $D_{3d}^5(R\bar{3}m)$, showing that it is possible to understand the emergence of residual continuous bulk states near the Dirac-point into a six bands effective model, where the breaking of the R_3 symmetry beyond the Γ point has an important role in the hybridization of the px, py and pz atomic orbitals, which leads to a band repulsion that depends on only one parameter, as shown in Figure 1.

Within this model, the mechanisms known to eliminate the bulk backscattering, for instance: the stacking faults [4], electric field [5] and alloy [7], generated a similar effect in the effective states of the 3DTI. Finally, we studied the surface electronic transport in the 3DTI with staking faults, showing how the surface electronic transport is modified by perturbations of bulk.

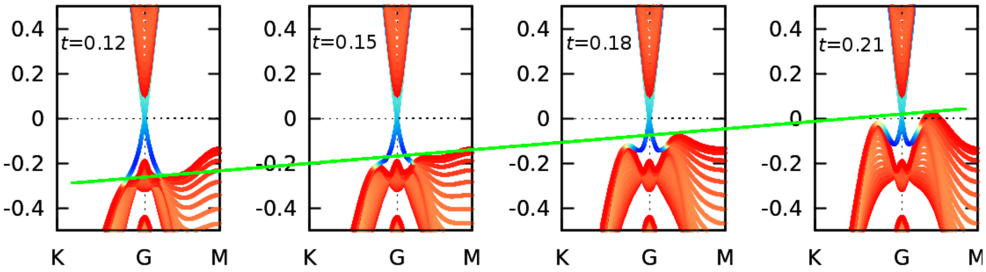

Figure 1: Projected surface band structure for 20 Qls calculated using the six bands effective model varying the repulsion parameter. The color scale is related to the contribution of the Qls in the surface. The blue and red colors indicate the major and null contributions, respectively.

Joint with Antônio J. R. da Silva, Instituto de Física, Universidade de São Paulo y Laboratório Nacional de Luz Síncrotron, Campinas, Brasil y A. Fazzio, Laboratório Nacional de Luz Síncrotron, Campinas, Brasil .

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A Bohmian approach to the non-Markovian non-linear Schrödinger-Langevin equation

The theory of open quantum systems is of fundamental importance to properly describe real systems, which do not exist in complete isolation. Among the main approaches usually considered to incorporate environmental effects in the dynamics of the system under study, non-linear Schrödinger equations and system-plus-bath techniques are two of the most representative ones. In this work, a non-Markovian generalized Schrödinger-Langevin equation is derived from the system-plus-bath approach [2]. Specifically Bohmian mechanics is shown to be of great importance in order to obtain a compact expression for the damping potential, which reduces to the well known situations reported in the literature, where Markovian and/or non-linear effects are considered. Finally, an application regarding the generalized uncertainty principle (GUP) as a quantum gravitational principle is presented [1].

Joint with Pedro Bargueño, Universidad de los Andes, Bogotá, Colombia.

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Edge modes in the single-band Bose-Hubbard model.

Topological phases of matter are nowadays an active field of study and there is special interest in to look for their realization since there exists the possibility of topological superconductivity followed by the promise of a fault free quantum computer. On the other hand, ultra cold atoms have proven to be excellent quantum simulators to mimic the previously mentioned complex condensed matter systems. Therefore, in the present work, we use an already tested simulation of an Ising spin chain by taking advantage of the dipole transitions of the Mott-insulator state when the spins are in presence of a strong electric field. Furthermore, by means of a Jordan-Wigner transformation, the system is fermionized, and finally the unitary transformations introduced by Kitaev are used. The main result is that for a proper set of parameters the initial single-band Bose-Hubbard Hamiltonian can sustain unpaired zero-energy edge-modes.

Joint with Karen Rodriguez and Javier Madroñero, Departamento de Física, Universidad Del Valle, Cali, Colombia.

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Effective Model for Graphene

We employ a simple nonrelativistic model, based on a deformation of the Heisenberg algebra which makes the commutator of momenta proportional to the pseudo-spin, to describe the low energy excitation of graphene.

This model (which reduces in a ceratin limit to the usual linear one employed to describe these excitations as massless Dirac fermions) reproduces

the leading (isotropic) terms in the low energy expansion of the dispersion relation derived from the tight binding model for both nearest and next-to-nearest-neighbor interactions.
We solve the Landau problem for the resulting Hamiltonian and, taking into account the contribution of both Dirac points, we evaluated the Hall conductivity within a ζ-function approach, showing that it is consisten with the *anomalous integer quantum Hall effect* characteristic of graphene.

Palabras Clave: Graphene, Hall conductivity, ζ-function.

Joint with H. Falomir, IFLP - CONICET and Departamento de Física, Facultad de Ciencias Exactas, Universidad Nacional de La Plata, La Plata, Argentina,
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Ramsey interferometer and measurements of quantum topological phases

Ramsey's method of successive oscillatory fields is an accuracy procedure to perform molecular and atom beam resonance experiments. There exist a lot of advantages provided by this method. Between them, measurement of relative phases is the commonly used, this because the required information is available in the transition probability of the interferometer.
Here we describe the Aharonov-Casher effect. Also we do a description of the Ramsey's interferometer and how it is used to measure topological phases. After that, we will describe how this interferometer is used to measure the phase acquired by the Aharonov-Casher effect in an atomic beam experiment.

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Medidas de impedancia del $Dy_2Fe_{17-x}Ga_x$ cerca de la transición de fase Ferromagnética-Paramagnética

Estudio de las propiedades de transporte eléctrico de los compuestos intermetálicos con composición $Dy_2Fe_{17-x}Ga_x$ ($x = 0, 1, 3, 4, 5, 7$) en el rango cercano a la temperatura de transición (Tc) de cada uno de estos compuestos.

Para ello, se llevó a cabo medidas de impedancia como función de la temperatura, en un rango de frecuencia comprendido entre 1 Hz a 1 MHz utilizando la técnica de espectroscopia de impedancia. Además se realizaron medidas de difracción de rayos X (DRX) a temperatura ambiente, como método de caracterización estructural, el cual permitió conocer los parámetros de red del compuesto y confirmar la formación de una sola fase principal. Las estructuras cristalinas se refinaron a partir de sus patrones de difracción empleando el método de Rietveld, revelando que la sustitución de Ga en la serie ocasiona un aumento en los parámetros de red y un cambio en su estructura de la fase hexagonal tipo Th_2Ni_{17} a la fase romboédrica tipo Th_2Zn_{17}.

Transport properties of the intermetallic compounds with $Dy_2Fe_{17-x}Ga_x$ composition ($x = 0, 1, 3, 4, 5, 7$) near to the transition temperature (Tc) were studied for each compounds. For this purpose, impedance measurements as a function of temperature was carried out in the range of 1 Hz to 1 MHz using impedance spectroscopy technique. Moreover, X-ray diffraction (XRD) measuremetns conducted at room temperature, allowed to know the lattice parameters for all compounds and from these results single main phase is confirmed. The crystal structures were refined from diffraction patterns using the Rietveld method, an then showed that Ga substitution in the series increase lattice parameters and produce a change in the structure from hexagonal type Th_2Ni_{17} to rhombohedral phase type Th_2Zn_{17}.

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Monday, May 25th (Room: B-202)

8:00 – 9:00	*Registration*
9:00 – 9:15	*Opening*
9:15 – 10:15	Jiannis Pachos: *Why should anyone care about anyons? I*
10:15 – 11:15	Allan Macdonald: *Quantum Hall effects through the ages I*
11:15 – 11:45	Break
11:45 – 12:45	Andrei Bernevig: *Topological Superconductors and Category Theory I*
12:45 – 14:00	Lunch Break

–	**Afternoon session in Room O-101**
14:00 – 15:00	Problem Session
15:00 – 15:30	Break
15:30 – 16:10	Inti Sodemann: *Applications of conformal field theory to the fractional quantum Hall states*
16:10 – 16:50	Servio Pérez: *Quantum physics and transport process in 2D nanostructures by means of special functions*

Tuesday, May 26th (Room: B-202)

9:00 – 10:00	Jiannis Pachos: *Why should anyone care about anyons? II*
10:00 – 11:00	Allan Macdonald: *Quantum Hall effects through the ages II*
11:00 – 11:30	Break
11:30 – 12:30	Andrei Bernevig: *Topological Superconductors and Category Theory II*
12:30 – 14:00	Lunch Break
14:00 – 14:40	César Galindo: *Classification of Modular Categories*
14:40 – 15:00	Break
15:00 – 16:00	Problem Session
16:00 – 16:30	Break
16:30 –	Poster Session & refreshments

Wednesday, May 27th (Room: O-101)

9:00 – 10:00	Jiannis Pachos: *Why should anyone care about anyons? III*
10:00 – 11:00	Allan Macdonald: *Quantum Hall effects through the ages III*
11:00 – 11:30	Break
11:30 – 12:30	Andrei Bernevig: *Topological Superconductors and Category Theory III*

Thursday, May 28th (Room: B-202)

9:00 – 10:00	Jiannis Pachos: *Why should anyone care about anyons? IV*
10:00 – 11:00	Allan Macdonald: *Quantum Hall effects through the ages IV*
11:00 – 11:30	Break
11:30 – 12:30	Andrei Bernevig: *Topological Superconductors and Category Theory IV*
12:30 – 14:00	Lunch Break
14:00 – 14:40	Arturo Gómez: *Confinement and Deconfinement regimes in 3D gauge systems a la Gribov*
14:40 – 15:20	Andrés Reyes: *The Geometry of Quantum Phase Transitions: From Berry Phases to Fredholm Modules*
15:20 – 15:50	Break
15:50 – 16:50	Problem Session

Friday, May 29th (Room: O-101)

9:00 – 10:00	Jiannis Pachos: *Why should anyone care about anyons? V*
10:00 – 11:00	Allan Macdonald: *Quantum Hall effects through the ages V*
11:00 – 11:30	Break
11:30 – 12:30	Andrei Bernevig: *Topological Superconductors and Category Theory V*
12:30 – 14:00	Lunch Break

–	**Afternoon session in Room B-202**
14:00 – 15:00	Problem Session
15:00 – 15:30	Break
15:30 – 16:30	Aiyalam Balachandran: *Edge States, topological insulators and superconductors*
16:30 –	Entrega de certificados de asistencia

	Monday	Tuesday	Wednesday	Thursday	Friday
8:00 – 9:00	Registration				
9:00 – 10:00	J. Pachos	J. Pachos	J. Pachos	J. Pachos	J. Pachos
10:00 – 11:00	A. Macdonald	A. Macdonald	A. Macdonald	A. Macdonald	A. Macdonald
11:00 – 11:30	*Break*	*Break*	*Break*	*Break*	*Break*
11:30 – 12:30	A. Bernevig	A. Bernevig	A. Bernevig	A. Bernevig	A. Bernevig
12:30 – 14:00	*Break*	*Break*		*Break*	*Break*
	14:00 – 15:00 Problem Session	14:00 – 14:40 C. Galindo		14:00 – 14:40 A. Gómez	14:00 – 15:00 Problem Session
	15:00 – 15:30 *Break*	14:40-15:00 *Break*		14:40-15:20 A. Reyes	15:00 – 15:30 *Break*
	15:30-16:10 I. Sodemann	15:00 – 16:00 Problem Session		15:20 – 15:50 *Break*	15:30-16:30 A. Balachandran
	16:10-16:50 S. Pérez	16:00 – 16:30 *Break*		15:20 – 15:50 Problem Session	
		16:30 Poster Session			