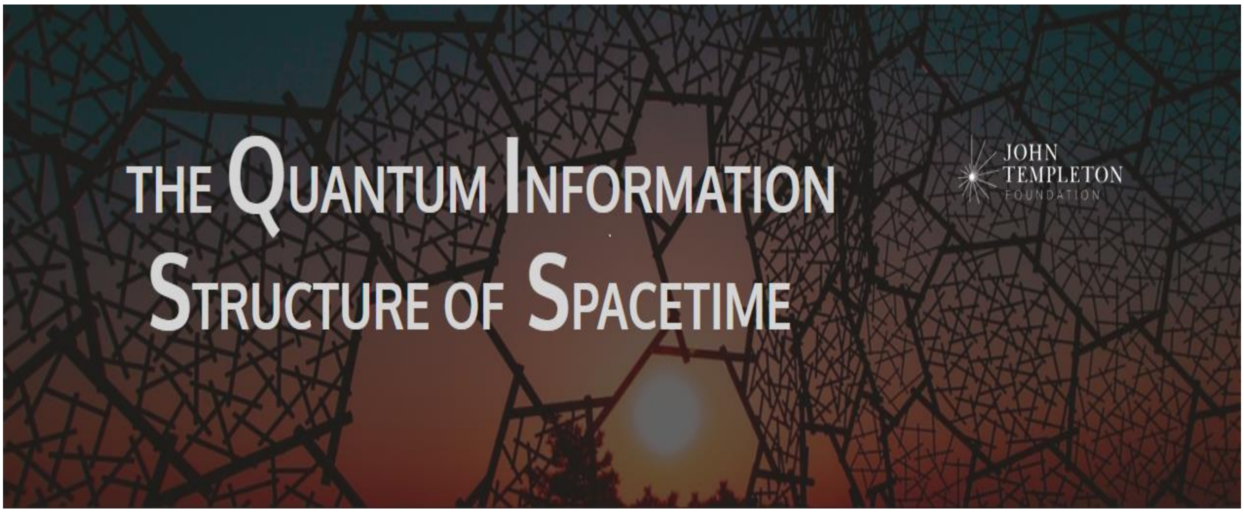

QISS HKU Workshop 2020

13th-17th January 2020

Island Pacific Hotel
Hong Kong

Contents

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COMPUTER SCIENCE

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Host Programme

QICi
Quantum Information and Computation Initiative

About

QISS

QISS (Quantum Information Structure of Spacetime) is an interdisciplinary research consortium founded by the John Templeton Foundation.

QISS explores and connects the exciting fields of Quantum Information and Quantum Gravity, aiming to develop the physics of quantum spacetime on a information-theoretic basis, to bring within reach empirical access to quantum gravity in 'table-top' laboratory conditions, and to promote an extensive interaction between physicists and philosophers.

The central goal of the collaboration is to deepen the current understanding of the role of foundational role of information, a slippery but yet crucial notion that is rapidly taking a central role in our understanding of the structure of reality.

QICI

QICI is the Quantum Information and Computation Initiative at the Department of Computer Science, The University of Hong Kong. Its mission is to promote and accelerate the growth of the quantum information area in Hong Kong, and to promote Hong Kong as an international research hub for quantum information and foundations.

QICI has been established in November 2018 under the auspices of the HKU Department of Computer Science. Its research platform consists of research in quantum information theory, quantum cryptography, quantum metrology, and quantum foundations.

An important component of QICI is a strong collaboration with the Quantum Group, at the Computer Science Department of the University of Oxford. The collaboration includes the joint supervision of PhD students, establishment of joint postdoctoral positions, exchanges of visits for research and education in the quantum information area, and joint organization of scientific events. These activities have been recently included in a Memorandum of Understanding (MoU) between the Computer Science Departments of HKU and Oxford.

For more information about QICI, see https://qift.weebly.com/

Programme

	Mon 13	Tue 14	Wed 15	Thu 16	Fri 17
9:30 – 10:10	**Reception** 10:00-10:10 **Welcoming Remarks and QISS Introduction**	**Giulio Chiribella** Ten Years of the Quantum SWITCH	**Lucien Hardy** The Quantum Equivalence Principle	**Bob Coecke** Causality in Pictures	**David Rideout** Causal Sets As Quantum Spacetime
10:10 – 10:30 ---------- **10:30-10:50**	**Carlo Rovelli** The Strange Fate of Time-Reversal Invariance in the Instrumentalists Takes on Quantum Theory and Its Relevance For Non-Trivial Causal Structures	**Cyril Branciard** Quantum Circuits with Classical or Quantum Control of Causal Orders	**Nitica Sakharwade** Revisiting the Causaloid Framework ———— **Lucas Hackl** Energy Cost of Extracting Entanglement from Relativistic Fields	**Nicola Pinzani** On the Operational Nature of Causality ———— **Maria Stasinou** Functorial Evolution of Quantum Fields in Discretised Spacetime	**Ravi Ramanathan** Relativistic causality versus no-signaling
10:50 – 11:20	**Coffee Break**	**Coffee Break**	**Coffee Break**	**Coffee Break**	**Coffee Break**
11:20– 12:00	**Pietro Donà** Quantum Information of Loop Quantum Gravity States	**Marko Vojinovic** Definite vs Superposed Causal Orders and Quantum Gravity	**Caslav Brukner** Timeless Formulation of Wigner's Friend Scenarios	**Pablo Arrighi** What is Discrete Covariance?	**Jakub Mielczarek** SU(2) Gauge Fields and Quantum Entanglement
12:00– 12:20	**Pierre Martin-Dussaud** Relational Features Between Gravity and the Quantum	**Giulia Rubino** Experimental Entanglement of Temporal Orders	**Kaumudibikash Goswami** Generalised Holevo Bound for a Bipartite Process Matrix	**Lautaro Amadei** The Role of Discreteness in the Black Hole Information Loss Puzzle	**Jakub Bilski** General Covariance of Quantum Corrections in Mini-Superspace Models
12:20 – 14:00	**Lunch Break**	**Lunch Break**	**Lunch Break**	**Lunch Break**	**Lunch Break**

	Mon 13	Tue 14	Wed 15	Thu 16	Fri 17
14:00 – 14:40	**Mischa Woods** General Relativistic Time Dilation and Increased Uncertainty in Generic Quantum Clocks	**Alastair Abbott** Coherent Control of Quantum Channels	**Oxford-HKU MoU Ceremony** **(HKU, Room 328, Chow Yei Ching Building)**	**Excursion to Lamma Island**	**Michal Studzinski** Multiport quantum teleportation protocols and their performance
14:40 – 15:00	**Marios Christodolou** The Possibility to Experimentally Detect Time Discreteness	**Hlér Kristjánsson** Quantum Interference of Latent Time-Correlations	**Free Time**		**Yadong Wu** Relativistic Quantum Summoning
15:00 – 15:30	**Coffee Break**	**Coffee Break**	**Coffee Break**		**Coffee Break**
15:30 – 16:10	**Philipp Hoehn** A Perspective-Neutral Approach to Quantum General Covariance	Transfer and Reception at HKU **(Foyer of Lecture Theatre A,** **Chow Yei Ching Building)**	**Richard Howl** Quantum Gravity in Continuous-Variable Quantum Information Theory		**Marco Túlio Quintino** Reversing Unknown Quantum Transformations: a Universal Quantum Circuit For Inverting General Unitary Operations
16:10 – 16:50	**Vladko Vedral** Quantum Nature of the Gravitational Field and the Quantum Sagnac Effect	**Carlo Rovelli** QICI Distinguished Lecture “What is Time?” **(HKU, Lecture Theatre A,** **Chow Yei Ching Building)**	**Jonathan Oppenheim** A Post-Quantum Theory of Classical Gravity?		**Ding Jia** Marrying Information and Spacetime Through Correlation Diagrams ---------------------- **Sebastian Murk** Probing Quantum Geometries with Correlated Photon Pairs

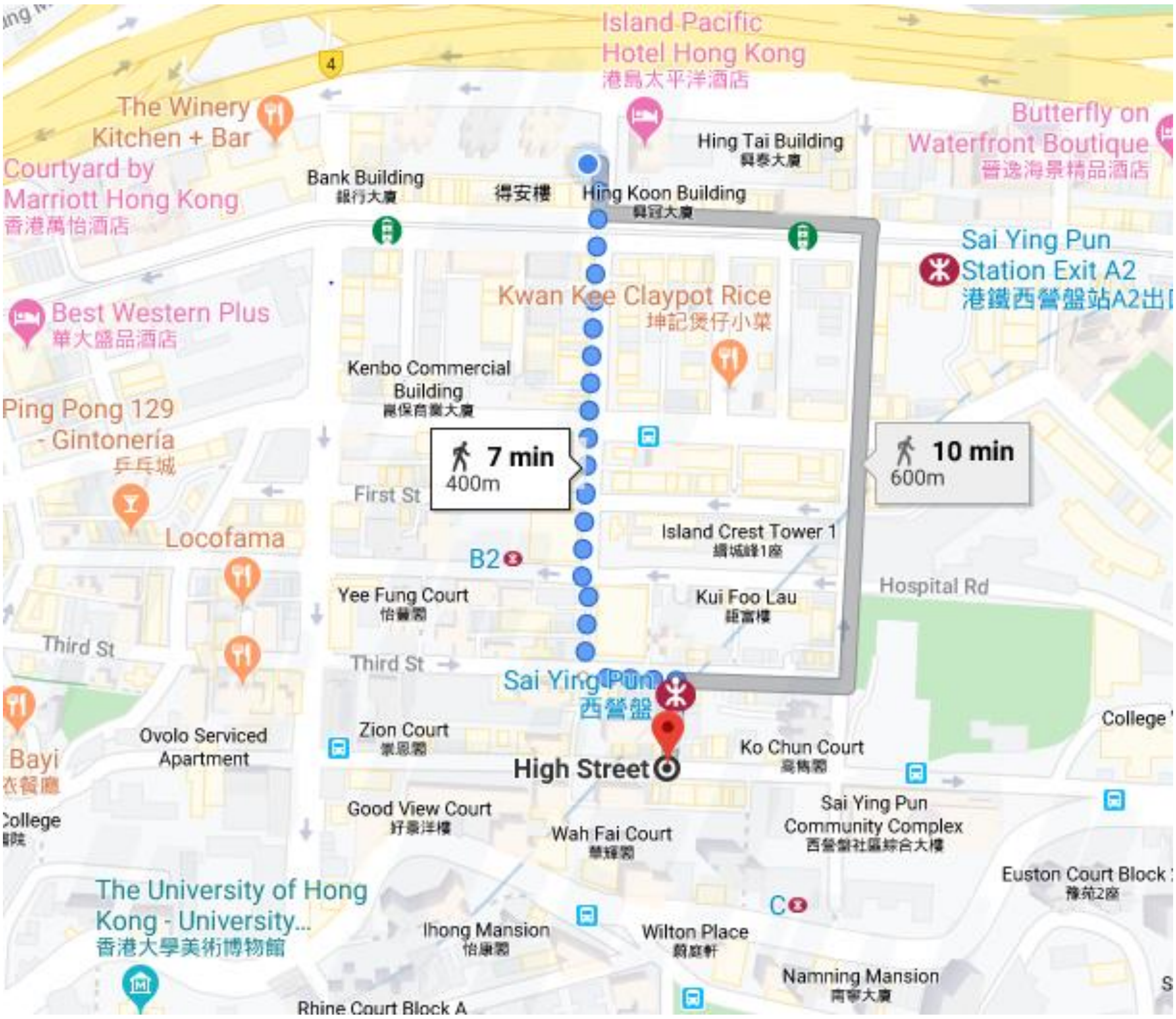
Refreshments and Meals

Refreshments and lunches are provided throughout the Workshop. In addition, there will be an arrival refreshment on Monday 13th January.

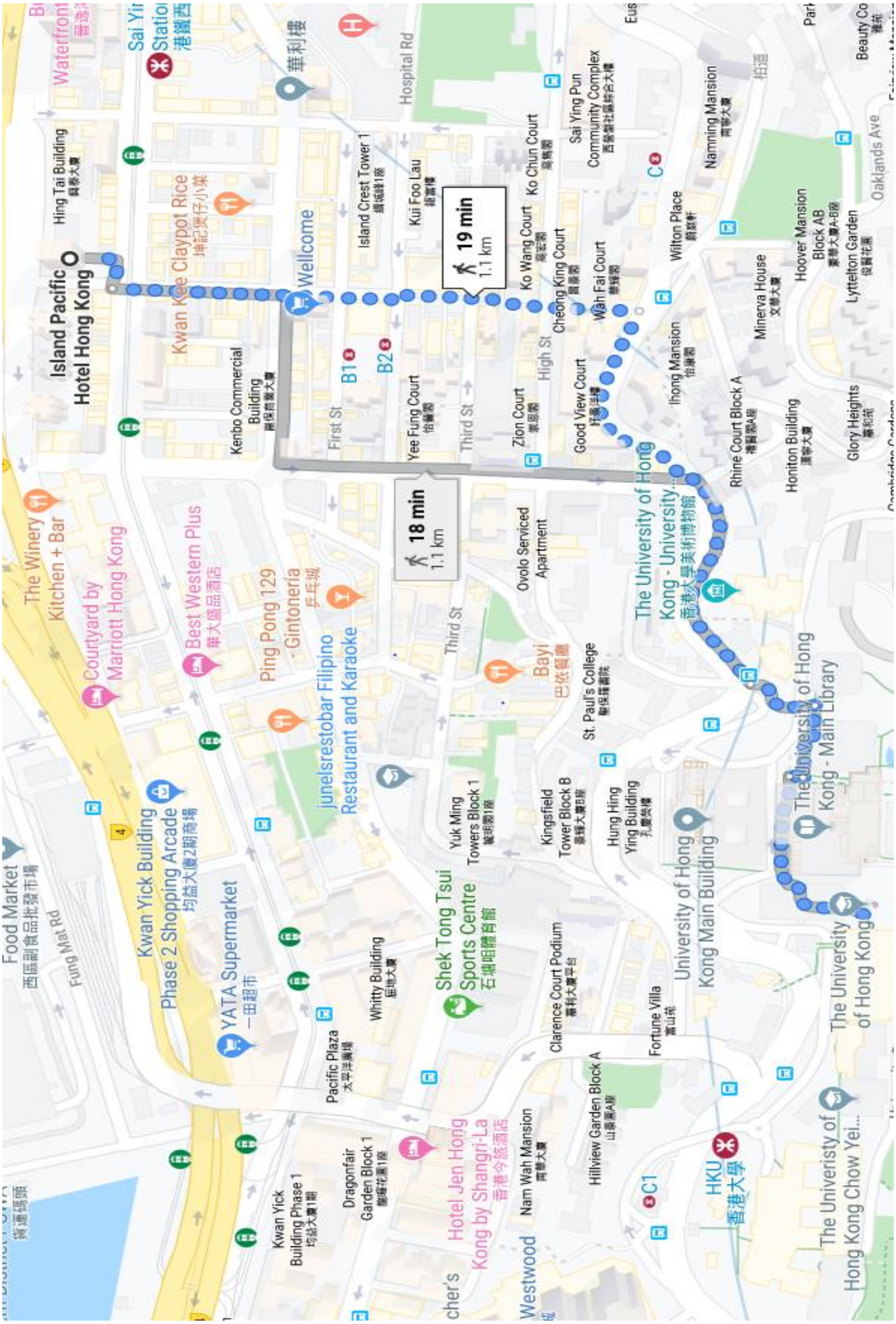
For those participants who are staying at the Island Pacific Hotel, buffet breakfasts are included in the room rate.

Dinners are not provided. There is an array of cafés, restaurants and bars around the conference venue, particularly along High Street.

A walking map to eateries:



A walking map between the Island Pacific Hotel and Hong Kong University



QICI Distinguished Lecture by Carlo Rovelli

Tuesday 14th January at Lecture Theatre A, Ground Floor of Chow Yei Ching Building, The University of Hong Kong

4:00 PM - 4:45 PM: Reception in the foyer of Lecture Theatre A
4:45 PM - 5:45 PM: QICI Distinguished Lecture "What is Time?", by Carlo Rovelli
5:45 PM - 6:00 PM: Book signing

HKU–Oxford Joint Lab Inauguration Ceremony

Wednesday 15th January at Room 328, 3rd floor of Chow Yei Ching Building, The University of Hong Kong

2:00 PM - 2:05 PM: Speech by Prof. Bob Coecke, Head of Quantum Group, Department of Computer Science, University of Oxford
2:05 PM - 2:10 PM: Speech by Prof. Christopher Chao, Dean of HKU Engineering Faculty
2:10PM - 2:15PM: Speech by Prof. Alfonso Ngan, Acting-Designate HKU Pro-Vice-Chancellor (Research)
2:15PM - 2:20PM: Photo taking
2:20PM – 2:40PM: Refreshments

Hike and Seafood Dinner on Lamma Island

Thursday 16th January

After lunch at IPH, for those who are interested, we will take a ferry with Marios to Yung Shue Wan on Lamma Island. People can walk along the beach and the village there. Afterwards, they can choose to do a one-hour hike to Sok Kwu Wan, followed by a seafood dinner (costs not covered by the Workshop). From Sok Kwu Wan, either they can hike back to Yung Shue Wan to take a ferry back to the Hotel, or they can take a ferry from Sok Kwu Wan back to the Hotel.

Alternatively, people can make their own way there after the Ceremony, or on another day, using the ferries below.

Ferry Timetable to Yung Shue Wan

http://www.hkkf.com.hk/index.php?op=timetable&style=en

This ferry links between Pier 4 (10 minutes' walk from IPH) and the main village, also a historical fishing village, with a stretch of beach.

Central - Yung Shue Wan

With effect from 1 July 2017 Amended on 1 July 2018

Monday to Saturday				Sunday and Public Holidays			
From Central		From Yung Shue Wan		From Central		From Yung Shue Wan	
{02:30}	*15:15	05:30	*15:15	02:30	15:00	05:30	15:30
*06:30	#15:50	06:20	*16:00	07:30	16:00	06:40	16:00
07:00	*16:30	*07:00	#16:30	08:00	@16:30	07:30	16:30
*07:30	17:20	*07:20	*17:15	08:30	17:00	@08:00	17:00
*07:50	*17:40	07:40	17:50	09:00	@17:30	08:30	17:30
08:10	*18:00	*08:00	*18:10	09:30	18:00	@09:00	18:00
*08:30	18:20	*08:20	*18:30	10:00	@18:30	09:30	18:30
*08:50	#18:40	08:40	18:50	10:30	19:00	10:00	19:00
09:10	*19:00	*09:00	#19:20	11:00	@19:30	10:30	19:30
*09:30	19:30	*09:20	20:00	11:30	20:00	11:00	20:00
*10:10	*20:00	09:40	#20:30	12:00	20:30	11:30	20:30
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*12:00	#21:30	*11:20	#22:30	13:00	22:30	12:30	22:30
#13:00	22:30	#12:00	^23:30	13:30	23:30	@13:00	^23:30
*13:45	#23:30	*13:00		14:00	^00:30	13:30	
#14:30	^00:30	#13:45		14:30		@14:00	
		*14:30				14:30	

Remarks:

{ } Only available on Saturdays, no freight service
* Only small quantity of freight can be carried
# Advanced booking is required for carriage of large quantity of freight
@ Optional Service
^ Last sailing

Fare Table ($HKD)	Monday to Saturday	Sunday and Public Holidays
Adult	$17.80	$24.70

Ferry Timetable to Sok Kwu Wan

http://www.hkkf.com.hk/index.php?op=timetable&page=sokkwuwan&style=en

This Ferry links between Pier 4 and Sok Kwu Wan, famous for its seafood cuisines, where we plan to take our dinner there.

Central - Sok Kwu Wan

With effect from 1 July 2017 — Amended on 1 July 2018

Monday to Saturday		Sunday and Public Holidays	
From Central	From Sok Kwu Wan	From Central	From Sok Kwu Wan
07:20	06:45	07:20	06:45
08:35	08:00	08:35	08:00
10:20	09:35	10:20	09:35
11:50	11:05	11:50	11:05
13:50	12:40	@12:50	12:40
15:20	14:35	13:50	@13:50
16:50	16:05	@14:35	14:35
18:45	17:35	15:20	@15:20
20:20	19:35	@16:05	16:05
21:50	21:05	16:50	@16:50
^23:30	^22:40	@17:35	17:35
		18:45	@18:35
		@19:20	19:35
		20:20	@20:20
		21:50	21:05
		^23:30	^22:40

Remarks:

^ Last sailing and no freight service

@ Optional Service

Fare Table ($HKD)	Monday to Saturday	Sunday and Public Holidays
Adult	$22.00	$31.00

Talk Titles and Abstracts

Alastair Abbott (University of Geneva)

Title: Coherent Control of Quantum Channels

Abstract: A string of recent results have shown advantages arising from the coherent control of the order in which quantum channels are applied in a quantum switch. Is causal indefiniteness a necessary resource for such results? In a recent result we showed that one such advantage – the causal activation of capacity when communicating through noisy channels – can be obtained if one coherently controls between which channel to use, rather than their order. This raises several questions about how these two types of coherent control should be compared and what we should require to claim causal indefiniteness provides an advantage. I will discuss some of these questions in the context of our result, as well as the possibility of using coherently controlled channels as a more general resource.

Lautaro Amadei (Centre de Physique Théorique, Marseille)

Title: The role of discreteness in the black hole information loss puzzle

Abstract: In approaches to quantum gravity where smooth spacetime is emergent from a fundamentally discrete Planckian structure, any standard effective smooth field theoretical description will miss part of the degrees of freedom and thus break unitarity. In this talk I will show that these expectations can be made precise in loop quantum cosmology. Concretely, even when loop quantum cosmology is unitary at the fundamental level, when microscopic degrees of freedom, irrelevant to low-energy cosmological observers, are suitably ignored, pure states in the effective description evolve into mixed states due to decoherence with the Planckian microscopic structure. When extrapolated to black hole formation and evaporation, this concrete example provides a key physical insight for a natural resolution of Hawking's information paradox.

Pablo Arrighi (Aix-Marseille University)

Title: What is Discrete Covariance?

Abstract: Covariance is the mother of all Physics symmetries. Whilst its meaning in the continuum is clear enough, it does lack a consensual discrete counterpart. I will give my understanding of different meanings attached to "Discrete Covariance".

Jakub Bilski (Zhejiang University of Technology)

Title: General covariance of quantum corrections in mini-superspace models

Abstract: The mini-superspace models (for instance all variants of loop quantum cosmology, quantum reduced loop gravity, cosmological complexifier coherent quantum gravity, etc.) are symmetry-reduced formulations of canonical quantum general relativity (CQGR) based on loop quantum gravity (LQG). These theories were constructed to capture a finite number of gravitational degrees of freedom of CQGR, which corresponds to phenomenological models (usually representing cosmological symmetries of spacetime). Precise study of the structure of all quantum corrections corresponding to gravitational degrees of freedom reveals whether the matter sector of a chosen model satisfies or breaks general covariance. Assuming that the general covariance has to be satisfied also at the quantum level, one finds constraints on the formulation of the matter sector. These constraints not only select the quantum generally covariant mini-superspace models, but also provide a recipe for the quantum generally covariant coupling of matter to LQG.

Cyril Branciard (Institut Néel - CNRS)

Title: Quantum circuits with classical or quantum control of causal orders

Abstract: A standard model for quantum computers is that of quantum circuits, where quantum gates are applied to some quantum systems one after the other, in a well-defined order. It has however been realized in the last decade that quantum theory also allows for quantum operations to be applied in some indefinite order: the paradigmatic example being the so-called « quantum switch », where the state of a « control qubit » controls the order of two operations applied on a « target system ».

Here we generalize the idea of the quantum switch; we describe and characterize new classes of quantum circuits, with both classical and quantum control of causal orders. This allows us to investigate new types of quantum processes with indefinite causal order and their potential applications, beyond the quantum switch.

Caslav Brukner (University of Vienna)

Title: Time reference frames and indefinite causal order

Abstract: The standard formulation of quantum theory relies on a fixed space-time metric determining the localisation and causal order of events. In general relativity, the metric is influenced by matter, and it is expected to become indefinite in the presence of gravitating quantum systems. I will introduce “time reference frames” according to which events are defined operationally in terms of quantum operations with respect to a quantum clock. I will show that, when clocks and quantum systems interact gravitationally, the temporal localisability of events becomes relative, depending on the time reference frame. The impossibility to find a reference frame in which all events are localised is a signature of an indefinite metric, which might yield an indefinite causal order of events. Even if the metric is indefinite, for any event one can find a time reference frame with respect to which the event is localised in time, while other events may remain delocalised. In this frame, time evolution takes its standard (Schrödinger) form. This form is preserved when moving from the frame localising one event to the frame localising another one, thereby implementing a form of covariance with respect to quantum reference frame transformations.

Joint work with with Veronika Baumann, Flavio Del Santo, Alexander R. H. Smith, Flaminia Giacomini, and Esteban Castro-Ruiz

Giulio Chiribella (QICI, University of Hong Kong)

Title: Ten years of the quantum SWITCH

Abstract: The quantum SWITCH is the simplest example of indefinite causal structure. Technically, it is a higher-order transformation that takes two physical processes A and B in input and combines them in a coherent superposition of two alternative orders, AB and BA. In the past decade, the quantum SWITCH has been the object of active research, both theoretically and experimentally. In this talk, I will review the state of the art on the quantum SWITCH, and outline some of its applications in quantum information.

Marios Christodoulou (QICI, University of Hong Kong)

Title: The Possibility to Experimentally Detect Time Discreteness

Abstract: The general relativistic analysis of the experimental proposals to detect gravity mediated entanglement growth reveal an immense amplification of minuscule proper time dilations. The physical regime is seen to be controlled by the planck mass: when the superposed masses are planckian, the time dilation that is being probed by the experiment is of order of planck time. This reveals the role of the planck mass in order to probe quantum qravity in laboratory conditions and opens the possibility to probe the structure of time at the planckian level.

Bob Coecke (University of Oxford)

Title: Causality in Pictures

Pietro Donà (Centre de Physique Théorique, Marseille)

Title: Quantum information of loop quantum gravity states

Abstract: Correlations of quantum observables play a central role in the study of physical states of any quantum gravity theory. Correlations and entanglement entropy are among the leading research topic of quantum information while they are relatively unexplored in loop quantum gravity. In this talk, I will present new analytic and numerical results on the computation of information-theoretic bounds on correlations in loop quantum gravity.

Kaumudibikash Goswami (University of Queensland)

Title: Generalised Holevo bound for a bi-partite process matrix

Abstract: The conventional quantum communication protocols AKA quantum Shannon theory, presumes a fixed underlying causal between the communicating parties. However, recently quantum processes with indefinite causal order has invoked a considerable attention, ranging from the foundational aspects like quantum gravity to more applied areas like quantum communication and quantum computation. One of the several available frameworks for such processes is the process-matrix. With that in mind, we explore a classical communication protocol through a bi-partite process matrix. In the conventional quantum Shannon theory, the maximum amount of classical information possible to transfer through a quantum channel is quantified by the Holevo quantity. It is natural to look for more general information theoretic measures in terms of indefinitely ordered quantum processes. Motivated by this investigation, we generalised the Holevo quantity for an arbitrary bi-partite process. We also consider the situation of a bi-directional communication through a process matrix and found an interesting information theoretic inequality.

Lucas Hackl (University of Copenhagen)

Title: Energy cost of extracting entanglement from relativistic fields

Abstract: In quantum information science, entanglement provides a valuable resource that can be used for communication, cryptography and quantum teleportation. The ground state of relativistic field theories is spatially highly entangled, so it is natural to ask if two separated parties, Alice and Bob, can extract some of this entanglement for their own use. Indeed, this can be accomplished by interacting locally with the field and thereby inevitably increasing the energy of the state. In this talk, I present lower bounds for the energy cost of entanglement extraction (measured in entropy) per mode in scalar quantum field theories and compare them to a concrete scenario where Alice and Bob are both localized in spacetime.

Lucien Hardy (Perimeter Institute)

Title: The Quantum Equivalence Principle

The quantum equivalence principle says that, for any given point, it is possible to find a quantum coordinate system with respect to which we have definite causal structure in the vicinity of that point. It is conjectured that this principle will play a similar role in the construction of a theory of Quantum Gravity to the role played by the equivalence principle in the construction of the theory of General Relativity. I will discuss how this might play out.

Philipp Hoehn (University College London)

Title: A perspective-neutral approach to quantum general covariance

Abstract: General covariance posits that "all the laws of physics are the same in every reference frame." While this is an established pillar of general relativity, its fate in the quantum realm remains an open question, in particular in quantum gravity where reference frames are dynamical systems and thus subject to the laws of quantum theory themselves. I will summarize a perspective-neutral approach to both spatial and temporal quantum reference frames aimed at addressing this question. This approach permits one to switch from the description of physics relative to one quantum frame (a perspective) to that relative to another. Such perspective changes work in analogy to coordinate changes on a manifold, except that these "quantum coordinate changes" proceed between different Hilbert spaces. I will then apply this framework to relational dynamics and show how it has revealed a previously unknown equivalence between three different approaches to the problem of time, namely relational observables, the Page-Wootters formalism and deparametrizations. This equivalence leads to various interesting implications for relational quantum dynamics.

Richard Howl (University of Nottingham)

Title: Quantum gravity in continuous-variable quantum information theory

Abstract: Recently, S. Bose et al., and C. Marletto and V. Vedral have proposed table-top experiments that would test quantum gravity using tools from quantum information theory. In these proposals, it was shown that any sign of entanglement between two spatially separated microspheres, each in a superposition of two locations, would provide evidence for a quantum theory of gravity. Inspired by these works, we analyse how tools specific to continuous-variable quantum information theory can be used to find evidence of quantum gravity. These tools are not based on entanglement, providing an alternative testing method to the Bose-Marletto-Vedral (BMV) proposal and opening up new systems to tests of quantum gravity.

Ding Jia (Perimeter Institute)

Title: Marrying information and spacetime through correlation diagrams

Abstract: I introduce correlation diagrams as a unifying language for quantum information theory, quantum field theory, and quantum gravity. This leads to an approach to quantum gravity based on the invariant distance as a dynamical variable. Connections to loop quantum gravity, lattice theories, quantum causal structure, compositional/boundary/pictorial/spacetime formulations of quantum theory are abundant. (Partially based on arXiv: 1909.05322)

Hlér Kristjánsson (University of Oxford)

Title: Quantum interference of latent time correlations

Abstract: When a noisy transmission line is used multiple times in succession, the noisy processes occurring at consecutive time-steps generally exhibit correlations in time, resulting in non-Markovian dynamics. Here we show a counterintuitive property of these correlations, namely that they affect the amount of information that a single particle can communicate, even if the particle only traverses the transmission line once. We characterise the time-correlations compatible with a given communication channel and identify those that give rise to the maximum communication enhancement. In a scenario involving multiple transmission lines, time-correlations within each line can be used to simulate quantum channels in a superposition of alternative orders. Remarkably, the correlations that simulate the superposition of orders are not the ones that achieve the highest communication capacity.

Pierre Martin-Dussaud (Centre de Physique Théorique, Marseille)

Title: Relational features between Gravity and the Quantum

Abstract: Both general relativity and quantum theory exhibit strong relational aspects of Nature. In general relativity it takes the form of diffeomorphism invariance, while in quantum theory it was first noticed by Everett, and later emphasised by Rovelli, with the concept of relative state. It is reasonable to expect these two features to be characteristic of the quantum structure of space-time, but the question remains open whether or not they are two aspects of the same kind of fundamental relationalism. In this talk, we will propose a clarification of the conceptual issues at stake and illustrate the discussion in the context of covariant loop quantum gravity.

Jakub Mielczarek (Jagiellonian University, Poland)

Title: SU(2) gauge fields and quantum entanglement

Abstract: The purpose of this talk is to explore relation between gauge fields, which are at the basis of our understanding of fundamental interactions (including gravity), and the quantum entanglement. The relation is investigated for the case of SU(2) gauge fields. I will shown that holonomies of the SU(2) gauge fields are naturally associated with maximally entangled two-particle states. Furthermore, the notion of gauge fields can be deduced from considerations of maximally entangled states. This new insight unveils a possible relation between gauge fields and spin systems, which contributes to our understanding of the relation between tensor networks (such as MERA) and spin network states considered in loop quantum gravity approach to quantum gravity. In consequence, the results are relevant in the context of the emerging Entanglement/Gravity duality.

Sebastian Murk (Macquarie University)

Title: Probing quantum geometries with correlated photon pairs

Abstract: Many theories of quantum gravity predict spacetime to be fundamentally discrete at the Planck scale. Due to the extremely small length scales involved, this prediction is notoriously difficult to confirm and has so far evaded all attempts of experimental corroboration. We propose a new empirical approach that allows to probe some aspects of the superposition of quantum geometries in an experiment involving correlated pairs of photons. More specifically, we study superpositions of the volume operator associated to a quantum geometry comprised of tetrahedra using an eight photon state spin network created via second order spontaneous parametric down-conversion. The distinguishing feature of the eight photon state spin network is that it allows one to perform measurements of a fluctuating volume. This is the first experimental test of a physical observable associated to a quantum geometry.

Jonathan Oppenheim (University College London)

Title: A post-quantum theory of classical gravity?

Abstract: Can we have a consistent theory of classical systems coupled to quantum ones? Would I be giving this talk if it wasn't the case? We construct a theory of classical gravity coupled to quantum field theory. The theory doesn't suffer the pathologies of semi-classical gravity and reduces to Einstein's equations in the appropriate limit. The assumption that gravity is classical necessarily modifies the dynamical laws of quantum mechanics -- the theory must be fundamentally information destroying involving finite sized and stochastic jumps in space-time and in the quantum field. The measurement postulate of quantum mechanics is not needed since the interaction of the quantum degrees of freedom with classical space-time necessarily causes collapse of the wave-function. The theory can be regarded as fundamental, or as an effective theory of the backreaction of quantum fields on space-time. We discuss why several well-known no-go results on both local information destruction and leaving gravity unquantised don't apply.

Nicola Pinzani (University of Oxford)

Title: On the Operational Nature of Causality

Abstract: When considering the information-theoretical structure of spacetime, it is of a fundamental importance to stick to an operational perspective, within which the notion of `information' can be consistently and univocally defined. In this talk, we introduce a mathematical framework enabling us to rigorously describe definite and indefinite causality from such an operational perspective: whether a given scenario satisfies specific causal assumptions will be directly detectable in the empirical correlations between inputs and outputs, in a theory-independent way. We exemplify the framework by presenting a number of numerical experiments, including versions of the much-discussed quantum switch.

Marco Túlio Quintino (University of Tokyo)

Title: Reversing unknown quantum transformations: A universal quantum circuit for inverting general unitary operations

Abstract: Given a quantum gate implementing a d-dimensional unitary operation, without any specific description but d, and permitted to use k times, we present a universal probabilistic heralded quantum circuit that implements the exact inverse, whose failure probability decays, exponentially in k. The protocol employs an adaptive strategy, proven necessary for the exponential performance. It requires $k \geq d-1$, proven necessary for exact implementation of the inverse with quantum circuits. Moreover, even when quantum circuits with indefinite causal order are allowed, $k \geq d-1$ uses are required. We then present a finite set of linear and positive semidefinite constraints characterizing universal unitary inversion protocols and formulate a convex optimization problem whose solution is the maximum success probability for given k and d. The optimal values are computed using semidefinite programming solvers for $k \leq 3$ when $d=2$ and $k \leq 2$ for $d=3$. With this numerical approach we show for the first time that indefinite causal order circuits provide an advantage over causally ordered ones in a task involving multiple uses of the same unitary operation.

Ravi Ramanathan (QICI, The University of Hong Kong)

Title: Relativistic causality versus no-signaling

Abstract: The no-signaling constraint is that the probability distributions of outputs of any subset of parties in a Bell experiment are independent of remaining parties' inputs. This constraint imposes fundamental limits on physical correlations and led to the fields of post-quantum cryptography, randomness generation besides identifying information-theoretic principles underlying quantum theory. Here we show that while the no-signalling constraints are sufficient, they are not necessary to enforce relativistic causality in multi-party correlations, i.e., the rule that correlations do not allow casual loops. Depending on the space-time coordinates of the measurement events, causality only imposes a subset of no-signaling conditions. We first consider the n-party Bell experiment ($n > 2$) and identify all configurations where subsets of the constraints suffice. Secondly, we examine the implications for device-independent cryptography against an eavesdropper constrained only by relativity, detailing among other effects explicit attacks on well-known randomness amplification and key distribution protocols.

David Rideout (University of California)

Title: Causal sets as quantum spacetime

Abstract: Causal sets can be seen as a quantum protostructure to spacetime, which can give rise to spacetime at macroscopic scales. I will briefly describe the approach and highlight some interesting results.

Carlo Rovelli (Centre de Physique Théorique, Marseille)

Title: The strange fate of time-reversal invariance in the instrumentalists takes on quantum theory and its relevance for non-trivial causal structures. Reflections and possible lessons.

QICI Distinguished Lecture: What is time?

Abstract: `Time' is something very familiar to all of us. But the physics of the XX century has discovered that time works quite differently from what we usually think.
In this conference I will review what have learned a lot about the nature of time, but also the mysteries surrounding this notion that are still open. These mysteries are connected with many questions about the universe that are still open, like the fate of black holes, the nature of heat, the reason past is different from the future, and the nature of our consciousness.

Giulia Rubino (University of Vienna)

Title: Experimental Entanglement of Temporal Orders

Abstract: The study of causal relations has recently been applied to the quantum realm, leading to the discovery that not all quantum processes have a definite causal structure. While such processes have previously been experimentally demonstrated, these demonstrations relied on the assumptions that quantum theory can be applied to causal structures and laboratory operations. In this talk, I present the first demonstration of entangled temporal orders independent of any such assumptions, by illustrating the incompatibility of our experimental outcomes with a class of generalized probabilistic theories which satisfy the assumptions of locality and definite temporal orders. To this end, I derive physical constraints (in the form of a Bell-like inequality) on experimental outcomes within such a class of theories. I then show experimental results which invalidate these theories by violating the inequality, thus providing an experimental proof, outside the quantum formalism, that nature is incompatible with the assumption that the temporal order between events is definite locally.

Nitica Sakharwade (Perimeter Institute)

Title: Revisiting the Causaloid Framework

Abstract: One way to study physical theories is through quantifying the way in which it relates quantities, and by focussing on studying the minimum set of quantities required to perform any calculation. The Causaloid framework introduced by Lucien Hardy in 2005 (arxiv: 0608043) pursued this route by focussing on physical compression as a method to classify physical theories, using three levels of compression. While the first level of compression is related with local tomography that gives us the space of GPTS, the second level of compression applies on composite regions and classifies the causal relations between these regions. Finally, the third level compression applies on all such composite regions to completely classify the physical theory at hand, and gives us the space of theories admitting

indefinite causal structures. In this talk, I present ongoing work in which we revisit this framework to further study the third compression and find an ansatz that helps us classify theories with indefinite causal structures.

Maria Stasinou (University of Oxford)

Title: Functorial evolution of quantum fields in discretised spacetime

Abstract: We present a compositional framework to describe the evolution of quantum fields in descritized spacetimes with applications to quantum cellular automata. We investigate the different behavior of regular and irregular lattices, as well as the effect of large scale spacetime topology on the models. We build connections with topological and algebraic quantum field theories via their respective categorical formulations. We prove that our approach remains sound in the limit of infinite extent and infinitesimal mesh.

Michal Studzinski (University of Gdansk)

Title: Multiport quantum teleportation protocols and their performance.

Abstract: Quantum teleportation is one of the earliest and most widely used primitives in the Quantum Information Science which performs an arbitrary quantum state transfer between two spatially separated systems. This involves pre-sharing entangled resource state and consists of three simple stages (joint measurement, classical communication, correction operation). Already except standard quantum teleportation protocol presented by Bennet et al. we distinguish Knill-Laflamme-Milburn schme based soley on linear optical tools and so called Port-based Teleportation (PBT) scheme, where in the last step the unitary correction is absent. The lack of the correction in the last step extends the spectrum of possible applications to position-based cryptography, communication complexity or theory of the universal quantum processors and simulators. In our work we propose a family of PBT schemes, allowing for transmitting more than one unknown quantum state in one go. We investigate the efficiency of our protocols by presenting expression for entanglement fidelity. It turns out that our schemes have better performance than standard PBT with respective dimension with the same amount of resource consumption. Results are obtained by using tools coming from representation theory of the symmetric group and connection with Walled-Brauer Algebra, which plays a role in some aspects of anti-branes and gauge-gravity duality.

Joint work with Michal Horodecki, Mark Mozrzymas, and Piotr Kopszak

Vladko Vedral (University of Oxford)

Title: Quantum nature of the gravitational field and the quantum Sagnac effect

Abstract: I will discuss the recently proposed experiment to witness indirectly non-commuting degrees of freedom in gravity, in the light of the analogy between the

electromagnetic and the gravitational field. I will identify the non-commuting gravitational degrees of freedom in the linear regime of Einstein's General Relativity. They are the electric-like and the magnetic-like components of the Christoffel symbol, in the weak limit of gravity. The equivalence principle can then be used to suggest further experiments of the quantum nature of gravity, exploiting acceleration only. use a quantum variant of the Sagnac interferometer to argue for the quantum nature of gravity as well as to formulate a quantum version of the equivalence principle. Here, if the radial and angular degrees of freedom of the matter wave become entangled through this experiment, then, via the equivalence principle, the gravitational field must be non-classical.

Marko Vojinovic (University of Belgrade)

Title: Definite vs superposed causal orders and quantum gravity

Abstract: We will discuss the realisations of the quantum switch using 4 and 3 gates in classical spacetimes with fixed causal orders, and a realisation of a gravitational switch with only 2 gates that features superpositions of different gravitational field configurations and their respective causal orders. An observable will be constructed that can distinguish between the quantum switch in classical spacetime, and the gravitational switch in superposed spacetimes. Using this observable, we will argue that the current experimental implementations of the quantum switch do not feature superpositions of causal orders, and that these superpositions can only occur in the case of a gravitational switch. Finally, we will shortly reflect on the limits of the modern relational approach to physics. Based on arXiv:1905.09682.

Mischa Woods (ETH Zurich)

Title: General relativistic time dilation and increased uncertainty in generic quantum clock

Abstract: The theory of relativity associates a proper time with each moving object via its world line. In quantum theory however, such well-defined trajectories are forbidden. After introducing a general characterisation of quantum clocks, we demonstrate that, in the weak-field, low-velocity limit, all "good" quantum clocks experience time dilation as dictated by general relativity when their state of motion is classical (i.e. Gaussian). For nonclassical states of motion, on the other hand, we find that quantum interference effects may give rise to a significant discrepancy between the proper time and the time measured by the clock. We also show how ignorance of the clock's state of motion leads to a larger uncertainty in the time measured by the clock --- a consequence of entanglement between the clock time and its center-of-mass degrees of freedom. We demonstrate how this lost precision can be recovered by performing a measurement of the clock's state of motion alongside its time reading.

arXiv preprint: https://arxiv.org/abs/1904.02178v2

Yadong Wu (QICI, University of Hong Kong)

Title: Relativistic Quantum Summoning

Abstract: Summoning retrieves quantum information, prepared somewhere in spacetime, at another specified point in spacetime, but this task is limited by the quantum no-cloning principle and the speed-of-light bound. We develop a thorough mathematical framework for summoning quantum information in a relativistic system and formulate a quantum summoning protocol for any valid configuration of causal diamonds in spacetime. For single-qubit summoning, we present a protocol based on a Calderbank– Shor–Steane code that decreases the space complexity for encoding by a factor of two compared to the previous best result and reduces the gate complexity from scaling as the cube to the square of the number of causal diamonds. Our protocol includes decoding whose gate complexity scales linearly with the number of causal diamonds. Our thorough framework for quantum summoning enables full specification of the protocol, including spatial and temporal implementation and costs, which enables quantum summoning to be a well posed protocol for relativistic quantum communication purposes.