Scientific report 2019

Title: Analysis of Time series using a Network Science approach
Postdoc: José Luis Herrera diestra
Supervisor: Nathan Jacob Berkovits
Fapesp: 2017/00344-2
Period: June 1, 2017 to August 31, 2019

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Nath Berkovits

Scientific report (2019)
Dr. Jose Luis Herrera D.
Postdoctoral researcher

<u>Summary:</u>

During postdoctoral appointment at ICTP - SAIFR, I have had the opportunity to attend multiple conferences, publish and submit research papers, as well as establish new collaborations, along with the ones I was already working on. I interacted with renowned researchers in the field and hosted the visit of scientific collaborators. As part of my postdoctoral responsibilities, my research is focused in several applications of Network Science and Time series analysis to study propagation, containment and surveillance of diseases; intermittent spatiotemporal intervention on dynamical systems; detection of dynamical transitions in Electroencephalographic signals, characterization of speeches, as well as evaluation in individual and team performance in sports (particularly soccer) using complex networks approaches.

In the following I briefly describe the projects I am/was involved and the resulting outcome of these collaborations: seminar talks and published/submitted articles.

<u>Progress:</u>

Characterization of diseases using symbolic patterns.

We studied the transfer of information along temporal segments of epidemic time series. We transform them into ordinal patterns, which are then projected into nodes of a network whose links are based on consecutive appearances along the time series. In particular, we construct symbolic networks from epidemic time series of vector-borne (Dengue, Malaria) and air-borne (Influenza) diseases reported at different countries. We also introduced a family of five novel parameters that characterize the role of the nodes (patterns) of the network. Using these five metrics we are able to identify differences between diseases and assign specific roles to the different patterns of the time series. We compare our results with a set of synthetic outputs of different complexity in order to infer the closeness similarities of these diseases with synthetic models. Our results demonstrate that this methodology unveils differences among air-borne and vector-borne diseases, and evidences how these outbreaks share similarities with autoregressive processes of linear and nonlinear nature.
Additionally, we proposed the Time Reversibility from Ordinal Patterns method (TiROP) to assess time-reversibility from an observed finite time series. TiROP captures the information of scalar observations in time forward as well as its time-reversed counterpart by means of ordinal patterns. The method compares both underlying information contents by quantifying its (dis)-similarity via the Jensen-Shannon divergence. We tested TiROP in different synthetic and real, linear, and non-linear time series, juxtaposed with results from the classical Ramsey's time reversibility test. Our results depict a novel, fast-computation, and fully data-driven methodology to assess time-reversibility with no further assumptions over data.

Estimation of dengue's burden in Venezuela using neighboring and internet-based data.

Humanitarian crises, such as those unfolding in Venezuela due to amid civil unrest, often elevate the risk of and are exacerbated by infectious disease outbreaks. Rapid and efficient responses are paramount in such emergencies. To address this challenge, we develop multivariate early warning and situational awareness surveillance systems for arboviruses. Colombia and Venezuela, with populations over 48 and 31 million, respectively, share a vast border with more than 30,000 crossings daily. Given their proximity, border fluidity, and similar environmental characteristics (weather, altitude, etc), we hypothesize that Colombian infectious disease data might provide situational awareness for Venezuela at a time when political unrest is undermining public health. We use weekly dengue reports for every state in Venezuela and Colombia back to 2001, with which we initially fit a dengue model to determine spatiotemporal patterns, as well as possible environmental and geopolitical predictors. We then apply our surveillance optimization methods to identify combinations of state-level Colombian surveillance data, dengue-related Spanish Google Trends data (at the state and national scale), and other internet-source and environmental data that yield robust, real-time indications of dengue emergence and prevalence in individual states of Venezuela and nationwide.

Characterization of epileptic seizures using complex networks.

In this ongoing project, we aim to characterize the onset of epileptic seizures in patients, using EEGs from the platform Physionet. We intend on defining a new methodology that could be used to anticipate the seizure onset, with tools borrowed from nonlinear dynamics. Additionally, we use symbolic transformations of the time series, visibility graph algorithms, as well as the construction of recurrence matrices, to study dynamical similarities/differences in ill and healthy patients. Additionally,

Design and evaluation of surveillance/immunization strategies on complex networks.

As infectious disease outbreaks emerge, public health agencies often enact vaccination and social distancing measures to slow transmission. Their success depends on not only strategies and resources, but also public adherence. Individual willingness to take precautions may be influenced by global factors, such as news media, or local factors, such as infected family members or friends. We compared three modes of epidemiological decision-making in the midst of a growing outbreak. Individuals decide whether to adopt a recommended intervention based on overall disease prevalence, the proportion of social contacts infected, or the number of social contacts infected. While all strategies can substantially mitigate transmission, vaccinating (or self isolating) based on the number of infected acquaintances is expected to achieve the greatest herd immunity and number of infections averted, while requiring the fewest intervention resources.

Additionally, we approach the problem of surveillance of diseases in temporal networks based on the idea that vaccination strategies can serve as a method to identify sentinels. The vaccination problem is a related question that is much more well studied for temporal networks. To assess the ability to detect epidemic outbreaks early, we calculate the time difference (lead time) between the surveillance set and whole population. We find that the optimal selection of sentinels depends on both the network's temporal structures and the infection probability of the disease. We find that, for a mild infectious disease (low infection probability) on a temporal network in relation to potential disease spreading (the Prostitution network), the strategy of selecting latest contacts of random individuals provide the most amount of lead time. And for a more uniform, synthetic network with community structure the strategy of selecting frequent contacts of random individuals provide the most amount of lead time.

Complex network's approach to evaluate game performance in soccer.

During the last decade, Network Science has become one of the most active fields in applied physics and mathematics [1]. From all its possible applications, we are concerned about the analysis of one of the most extended sports, football (soccer in U.S. terminology), since it allows addressing different aspects of the team organization and performance not captured by classical analyses based on the performance of individual players. The reason behind relies on the complex nature of the game, which, paraphrasing the foundational paradigm of complexity sciences “can not be analyzed by looking at its components (i.e., players) individually but, on the contrary, considering the system as a whole” or, in the classical words of after-match interviews “it's not just me, it's the team.” The recent ability of obtaining datasets of all events occurring during a match allows analysing and quantifying the behavior of a team as a whole, together with the role of each single player. Under this framework, the organization of a team can be considered as the result of the interaction between its players, creating passing networks, which are directed (i.e., links between players go in one direction), weighted (the weight of the links is based on the number of passes between players), spatially embedded (i.e., the Euclidean position of the ball and players is highly relevant) and time evolving (i.e., the network continuously changes its structure).

Furthermore, at the moment we are analyzing the temporal changes of networks measures, treating them as time series, to characterize potential transitions at the match level.

Invited oral presentation:

“Estimation of dengue’s burden in Venezuela using neighboring and internet-source data”. Conference on Perspectives on Non Linear Dynamics. 16 - 19 of July 2019. ICTP - SAIFR, São Paulo - Brazil.

Invited panelist for the discussion of diversity. Diversify NetSci Satellite. NetSci 2019. May 27 - 31, 2019. Burlington - Vermont, University of Vermont. USA.

“Spatio-temporal intermittent interventions in social and dynamical systems”. Dynamics Days Latin America and the Caribbean. 26 - 30 of November 2018. Punta del Este - Uruguay.

“Dynamical and topological characterization of the symbolic networks of disease outbreaks”. International school and conference on Network Science - NetSci 2018. June 11 - 15, 2018. Paris - France.

“Analyzing disease outbreaks by means of symbolic networks”. 15h Experimental Chaos and Complexity Conference. June 4 - 7, 2018. Madrid - Spain.

“Disease surveillance on social complex networks”. 1st Latin American Conference on Complex Networks (LANET 2017). September 25-29, 2017, at Benemérita Universidad Autónoma de Puebla, Puebla - México.

“Information-based immunization strategies on complex networks”. 1st Latin American Conference on Complex Networks (LANET 2017). September 25-29, 2017, at Benemérita Universidad Autónoma de Puebla, Puebla, México.

Scientific visits:

Grupo de Caos y Sistemas Complejos. Universidad de Los Andes. Mérida - Venezuela. Collaboration with Dr. Mario Cosenza. Synchronization, chimera states, opinion formation, among others. June 29 - July 18, 2017.

MeyersLab. University of Texas at Austin. Austin, Texas -USA. Collaboration with Dr. Lauren Meyers. Epidemic spreading of diseases in networks. 6 - 31 of August, 2018.

Centro de Tecnologia Biomedica. Universidad Rey Juan Carlos. Madrid - Espana. Collaboration with Dr. Javier M. Buldu. Characterization of disease's time series using symbolic representation. May 26 - June 3, 2018.

MeyersLab. University of Texas at Austin. Austin, Texas - USA. Collaboration with Dr. Lauren Meyers. Theoretical study of immunization strategies in social networks. 24 April - 22 May, 2019

Articles published and submitted:

Disease Surveillance with Page Rank and Dissimilarity.
Zeynep Ertem, Zhanwei Du, **J.L. Herrera-Diestra**
Submitted to Physica A (2019)

Complex network approach to estimate the loss of information by Google translations.
J.L. Herrera-Diestra
Submitted to Scientific Reports (2019)

Estimation of dengue's burden in Venezuela using neighboring and internet-source data.
J.L. Herrera-Diestra, Remy Pasco, Kai Liu and Lauren A. Meyers
Submitted to Plos Computational Biology (2019)

Using symbolic networks to analyze dynamical and statistical properties of disease outbreaks.
J.L. Herrera-Diestra, Javier M. Buldu, Mario Chavez, Johann H. Martinez.
Submitted to the Royal Society A (2019).

Local risk perception enhances epidemic control.
J.L. Herrera-Diestra, Lauren Ancel Meyers.
Under revision PLoS One (February 2019).

Damping and clustering into crowded environment of catalytic chemical oscillators.
Carlos Echeverria, **Jose L. Herrera**, Kay Tucci, Orlando Alvarez, Miguel Morales.
Volume 517, 1 March 2019, Pages 297-306

Using network science to analyze football passing networks: dynamics, space, time and the multilayer nature of the game.
J. M. Buldú, J. Busquets, J. H. Martínez, **J. L. Herrera-Diestra**, I. Echegoyen, J. Galeano, J. Luque.
Frontiers in Psychology 9, 1900 (2018).

Detection of time reversibility in time series by ordinal patterns analysis.
J. H. Martínez, **J.L. Herrera-Diestra** and M. Chavez.
Chaos 28, 123111 (2018)

Optimizing sentinel surveillance in temporal network epidemiology
PH Yuan Bai, Bo Yang, Lijuan Lin, **Jose L. Herrera**, Zhanwei Du
Scientific Reports 7 (4804) 2017

References:

1. Newman, M. E. J. Networks: An Introduction. (Oxford University Press, Oxford, 2010)

Scientific Report

Title: Quantum measurement simulability and applications to Bell nonlocality
Postdoc: Leonardo Guerini
Supervisor: Nathan Jacob Berkovits
Period: 01/Apr/2018 - 30/Nov/2019
Fapesp 2016/01343-7 and 2018/04208-9

Leonardo Guerini

Nathan Jacob Berkovits

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1 Project and previous work

Entanglement, measurement incompatibility, and intrinsic randomness lie among the most remarkable and counter-intuitive features of quantum theory. While entanglement is well-established as a key concept for quantum advantages over classical resources, measurement incompatibility also offers a rich collection of properties that remain to be investigated. The typical context to investigate these concepts is the Bell scenario, a causal structure that conveys bipartite experiments. The initial goal of this project was to extend previous works on properties of quantum measurements [1, 2] and derive a more complete resource theory for these objects, together with applications to Bell nonlocality.

Already in the beginning, a few works appeared answering some of the questions we posed [3, 4]. Reinforced by a better understanding of the problem, we modified the direction of our research towards the connection between measurement's features and quantum communication. We reviewed the literature of the so-called prepare-and-measure scenario, a well-known stage for comparing quantum and classical resources for communication tasks such as random access codes, dimension witnessing, and self-testing. In this scenario, our initial results uncovered a close connection between incompatibility and the usefulness of quantum communication for a specific task denoted distributed sampling.

Also, side projects on different topics naturally emerged from interactions with colleagues. Motivated by properties of the set of compatible measurements, we proposed a generalisation of Birkhoff-von Neumann's theorem, characterizing the set of doubly-normalized tensors in terms of incompatibility. The corresponding article was finished and submitted to the Journal of Mathematical Physics [5]. With respect to causal models alternative to Bell's, we investigated the certification of private randomness in the instrumental scenario, exploiting a classical-quantum gap recently reported in this framework.

2 Research activities

We now present the activities done along the period contemplated in this report. Firstly, we finished the work on incompatibility and quantum communication, whose final outcome was an equivalence between restricted compatibility and the certification of quantum channels [6]. More specifically, we showed that the statistics of a quantum experiment can be sampled in a distributed fashion without quantum communication if and only if the measurements implemented are compatible when restricted to the quantum states being measured. This provides a strategy for attesting the quantumness of a communication channel in a practical experiment, given that the preparation of the system is trustworthy. In other words, we presented semi-device independent quantum communication witnesses based on incompatibility. When compared to recent channel-certification experimental works [7, 8], our techniques happen to require less assumptions and simpler set-ups, to the cost of not certifying all quantum channels. This work was published in Physical Review A.

Therefore, distributed sampling is a communication task that captures precisely the notion of measurement incompatibility in a prepare-and-measure scenario, allowing for discriminating cases where classical and quantum communication are decisively inequivalent. The next step we are developing is the quantification of resources for this task. In this context, the main question is how much noise is required for some set of statistics to be samplable with a given (i) a limited amount of classical communication, and (ii) unlimited classical communication assisted by a fixed amount of entanglement shared between the parties. Currently, we have the computational codes to calculate the noise robustness in both cases (i) and (ii), and are trying to prove analytically a bound for this it suggested by our computations. We plan to finish this work by the beginning of 2020.

As for the generalized Birkhoff-von Neumann theorem, after receiving valuable criticisms from the referees, we revisited the paper and improved our results. Also, we have added a direct connection to quantum-classical channels, bringing our rather mathematical results closer to quantum theory. The paper was therefore resubmitted to the journal and is currently under review.

Following the other side project, we performed a careful cryptographic analysis of our protocol for private randomness certification. By verifying that the Entropy Accumulation Theorem can be safely extended to the instrumental scenario, we proved the security of our strategy against the most general adversary (that could be quantum-correlated to the system). In comparison with the Bell scenario, we showed that for experiments with low levels of noise the instrumental scenario can present a randomness generation gain due to the smaller randomness investment. The paper containing these theoretical and experimental results is currently under review on Physical Review X [9].

Finally, in these last months we have devoted time to learn about paradigmatic quantum computation techniques and their advantages over classical computation. The most common quantum circuit model is composed of a number of qubits over which is implemented a series of quantum gates, hence updating their joint state until a final step where they are measured. We are presently investigating efficient quasi-probabilistic representations (i.e. normalized distributions whose positivity is relaxed) of quantum gates. These would allow us to simulate the circuit dynamics by means of a classical Markov chain. The drawback is that the negativity of the representation is reflected by an increased number of samples required to approximate the target-value of the computation. However, in the reality of the NISQ (noisy intermediate-scale quantum) devices available today, these representations can still provide a valuable classical simulation of some quantum circuits. Our initial results points that this is the case for the swap-test, a celebrated quantum circuit that can be used to calculate the fidelity between two uncharacterised quantum states. Our idea is to test this classical simulation method to more general circuits and, eventually, integrate it in quantum machine learning optimization methods.

3 Attended conferences and scientific meetings

- Universidade Federal do Rio de Janeiro. Scientific visit to Prof. Leandro Aolita. November, 2019.
- Universidade Federal do Rio de Janeiro. Scientific visit to Prof. Leandro Aolita. October, 2019.
- Universidade Federal do Rio de Janeiro. Scientific visit to Prof. Leandro Aolita. September, 2019.
- VII Paraty Quantum Information School and Workshop. Measurement incompatibility and quantum communication witnesses. Contributed talk, August 2019.
- Benasque Quantum Information. Measurement incompatibility in prepare-and-measure scenarios. Contributed talk, July 2019.
- Q-turn: changing paradigms in quantum science. Joint measurability: from simulability to Birkhoff-von Neumann. Contributed talk, 2018.
- ICFO - The Institute of Photonic Sciences. Scientific visit to Prof. Antonio Acin. June, 2019.
- University of Düsseldorf. Scientific visit to Dr. Gláucia Murta, June 2019.

- Universidade Federal do Rio de Janeiro. Scientific visit to Prof. Leandro Aolita. April, 2019.

- Centro Brasileiro de Pesquisas Físicas. Scientific visit to Prof. Fernando de Melo. April, 2019.

4 Future activities

- December: calculations on noise robustness and communication cost of distributed sampling; translation of Matlab codes for classical simulation of quantum circuits to Python language.

- January: analytical investigation and writing of the draft on communication cost of distributed sampling; codes for quasi-probabilistic approach to general quantum circuits.

- February: final details of communication cost of distributed sampling; codes for quasi-probabilistic approach to general quantum circuits.

- March: Writing of the draft on classical simulation of quantum circuits and review of machine learning literature.

References

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[9] Iris Agresti, Davide Poderini, Leonardo Guerini, Michele Mancusi, Gonzalo Carvacho, Leandro Aolita, Daniel Cavalcanti, Rafael Chaves, and Fabio Sciarrino. Experimental device-independent certified randomness generation with an instrumental causal structure, (2019). [arXiv: 1905.02027].

Scientific Report

Bootstrap não-perturbativa e a matriz S

Posdoc: Andrea Leonardo Guerrieri
Supervisor: Nathan Berkovits
Fapesp process: 2017/02303-1
Period: 01/06/2017 to 30/11/2019

1 Introduction

In the early days of particle physics, the self-consistent Bootstrap approach based on sound physical principles as causality, crossing and unitarity seemed to be the only way to describe the myriads of resonances produced in nuclear collisions. Those first attempts, culminated with the rigorous proof of the Froissart-Martin bound and with the Veneziano amplitude, have given a crucial boost both to the birth of string theory and to provide a solid framework to fit experimental data. Despite the many non-perturbative methods developed to tackle them, determining scattering amplitudes in strongly coupled gauge theories, and in particular in QCD, still remains a challenge for theoretical physics.

2 The S-matrix bootstrap program

During the period that goes from the 01/06/2017 to the 30/11/2019 I devoted my efforts developing the new S-matrix bootstrap approach. This approach, inspired by the success of the Conformal Bootstrap program, aims at bounding the space of possible S-matrices compatible with basic QFT assumptions using new efficient numerical algorithms for convex optimization. [1] The program was initiated by the study of $2 \to 2$ boson scattering in $1+1$-dimensions [2], and then extended to the generic D-dimensional case [3]. My research work has contributed to improve the bootstrap setup adding to the S-matrix principles inputs from the low-energy effective field theory and soft theorems. As I explain below, those researches lead to new numerical and analytic bounds in the space of massive and massless QFTs and, possibly, to new unexplored directions.

2.1 Bootstrapping QCD using pion amplitudes [4]

In collaboration with J. Penedones and P. Vieira [4] I have studied the scattering of pseudo-Goldstone scalars with $O(3)$ global symmetry in 3+1-dimensions. To single out the sub-space of QCD-like theories from the generic non-linear sigma models, I have imposed the Ward identities of the spontaneous chiral symmetry breaking in the bootstrap ansatz. The low energy theorems, consequence of these Ward identities, predict the existence of zeros in the amplitude, often called *chiral zeros*. I have found an exclusion region in the space of the latter zeros, named the "Pion Lake", and I have bounded the space of the threshold low energy constants in the chiral effective field theory, in short *scattering lengths*. I have also discovered that imposing a chiral zero in the bootstrap ansatz at the position of the physical $\pi-\pi$ scattering produces a kink in the space of the scattering lengths. The S-matrix at the boundary of the allowed region possesses a resonance spectrum that approaches the experimental one as one moves closer to the kink.

2.2 Bootstrapping flux-tube theories

To understand why such intricate structures in the space of S-matrices arise, I have studied a simplified model of QCD: the scattering of massless Yang-Mills flux-tube excitations (branons) [5]. Assuming the UV completion of the effective theory of long strings, I found that the low-energy expansion of their branon S-matrix is strongly constrained by analyticity and unitarity. This allowed me to put analytic bounds on the Wilson coefficients of many irrelevant operators in the effective action. These, in turn, imply bounds on the ground state energy and the level splitting of flux tubes that can be probed using lattice simulations. Again, at the boundary of the allowed region of Wilson coefficients I found a point where the resonance pattern matches the one observed in numerical simulations.

To the best of my knowledge this is the first time that the non-universal coefficients in an effective field theory are bounded rigorously. Without imposing additional model-dependent assumption, this is the best one can get from the consistency of the $2 \to 2$ scattering and the QFT basic assumptions.

Moreover, this research serves also as a starting point to systematically bound the space of UV completed effective field theories matching a specific low energy behavior as I am going to explain momentarily.

3 Organization of events

- I have organized the S-matrix Bootstrap Workshop 2019, held in Sao Paulo at the ICTP-SAIFR from September 9 to 13 2019.

  It is the third workshop of this kind focused on S-matrix related topics. Its main purpose is to gather experts on several different research fields related to the S-matrix and trigger their discussion. The topics covered spanned from String S-matrix, to QCD phenomenology. We have managed to invite top researchers in many related fields.

- I am organizer of the S-matrix Bootstrap Workshop 2020, to be held in Pollica (IT) on September 2020.

4 Conferences and Seminars

4.1 Conference Talks

Invited Talk: "Bootstrapping Flux-Tubes" – video
Workshop on S-matrix Bootstrap, ICTP-SAIFR, São Paulo, BR 11 Sep. 2019

Invited Talk: "Flux Tube S-matrix Bootstrap" – video
Bootstrap 2019, Perimeter Institute, Waterloo, ON–CA 19 Jul. 2019

Invited Talk:"Bootstrapping the QCD Flux-Tube"
Nonperturbative methods for conformal theories, IIP, Natal, BR 4 Apr. 2019

Invited Talk:"The pion lake"
Bootstrap 2018,Caltech, Pasadena, US 16 Jul. 2018

Invited Talk:"Bounding the space of S-matrices: Rebooting the Bootstrap" – slides
Joint Rome Seminar, Dip. di Fisica, La Sapienza, Rome, IT 21 Dec. 2017

4.2 Seminars

"Bootstrapping QCD: the Lake, the Peninsula and the Kink"
Particle Physics journal club, ICTP-SAIFR, São Paulo, BR — 2 May 2019

"Bootstrapping QCD: the pion lake and the peninsula"
Purdue University, West Lafayette, IN–US — 13 Nov. 2018

"The pion lake and the peninsula" – video
Perimeter Institute, Waterloo, ON–CA — 1 Nov. 2018

5 Publications

- A. L. Guerrieri, J. Penedones and P. Vieira, "Bootstrapping QCD Using Pion Scattering Amplitudes," Phys. Rev. Lett. **122**, no. 24, 241604 (2019), arXiv:1810.12849 [hep-th].
- J. Elias Miro, A. L. Guerrieri, A. Hebbar, J. Penedones and P. Vieira, "Flux Tube S-matrix Bootstrap," accepted for publication in PRL, arXiv:1906.08098 [hep-th].

6 Citations

The papers I have published had a large impact on the Community according to feedback received during the talks I recently did on the same subject. They have collected 11 citations, but my expectation is that their number will become important in the upcoming years.

7 Ongoing projects

At the moment I am involved in two projects that are a logical extension of the two papers mentioned above.

7.1 Bootstrapping massless pion amplitudes

The first one aims at bounding the space of $2 \to 2$ amplitude of massless pions or in general Goldstones of the non-linear sigma model in 3+1 dimensions. Using the non-perturbative S-matrix bootstrap for massless particles we aim at bounding optimally the Wilson coefficients of the first non-universal irrelevant operators. It is the first time that the scattering amplitude of massless particles is setup in dimensions $D > 2$. Preliminary results show interesting resonance features along the boundary of the allowed region.

7.2 Bootstrapping multi-branon amplitudes

The second project examines the scattering of multiple (more than four) flux-tube branons in $D = 3$ target space. This system exhibits the simplest non-trivial spontaneous symmetry breaking pattern. For this reason, it seems the perfect ground to explore the possibility of bootstrapping a system of S-matrices, including for the first time not only $2 \to 2$, but also $2 \to 4$ and $3 \to 3$ processes. Given this premise, it is clear that this is the most ambitious project I am pursuing. It is challenging both from theoretical and technological aspects, and a positive outcome is not guaranteed. However, the recent history of the Conformal Bootstrap shows that including multiple correlators is crucial to turn bounds into "islands". As anticipated in [6], it is possible that the theory of large-N_c QCD flux-tube might be single out using the S-matrix Bootstrap including multiple correlators or refining the analytic properties we assume. I believe that such possibility is worth the effort and I plan to push forward this program in the near future.

8 Progress

As mentioned in the research statement, during the entire year 2017/2019 I put my efforts in developing the S-matrix Bootstrap for QCD and flux-tube branon scattering. To achieve that goal I needed to develop a plethora of different skills: analytical, numerical, physical and informatics.

I studied in detail the analytic structure of the S-matrix, that in 3+1 dimensions it is an analytic functions of 2 variables which has, at very least, square root branch points corresponding to the minimal energy for particle to scatter. In order to study resonances I had to understand the structure of the second Riemann-sheet and their consequences on the physical sheet.

An analytic solution to the QCD bootstrap equation seems way beyond our current mathematical skills. For this reason, I decided to tackle this problem numerically. The bootstrap problem is recast into a Semidefinite Optimization Program that I efficiently solved using one of the best algorithms available, SDPB [1].

Moreover, to zoom in on QCD and Pion physics in particular, I studied the experimental literature and the various low energy effective field theory descriptions as the Chiral Perturbation Theory. In particular, the success of my approach heavily relies on the knowledge of the effective field theories.

To put in practice all the idea I used two different clusters for one entire year: one at the EPFL in Lausanne, the other at the Perimeter Institute. Future developments will rely even more heavily on cluster force.

9 Future direction

I truly believe the numerical S-matrix bootstrap explorations have something to teach us about the UV completion of effective field theories that might call for more sophisticated analytical methods. For this reason, I plan to study other phenomenologically relevant effective field theories and to develop more efficient numerical techniques. Here I report a list of possible future projects I plan to start.

- As my research has highlighted, one of the most promising applications to test the effectiveness of the novel bootstrap approach is low energy QCD. In my first paper I have explored somehow qualitative features of the space of low energy constants in $\pi-\pi$ scattering. [4] However, it is certainly possible to bound the low energy constants quantitatively matching the low energy expansion of the bootstrap ansatz with the chiral lagrangian prediction. Moreover, it is easy to input the information on the physical spectrum and fix the values of some of the better known low energy constants to put even more strict bounds on the ones that are known less. In this way I may show how the S-matrix bootstrap can be of immediate help to a better determination of fundamental QCD parameters.

- At the same time I plan to tackle also other effective field theories. It is well known that the consistency of graviton scattering can be used to bound corrections to the Einstein-Hilbert term in general relativity. [7] It is then tempting to ask which bounds it would be possible to derive using the full non-perturbative S-matrix bootstrap. However, there are some difficulties in facing this problem. The first and most severe is about IR divergences. There are several recent attempts to define an infrared safe S-matrix for particles with long-range interactions. One possibility is to work on the subject. Another possibility is to consider scattering of gravitons in $D \geq 5$ where the S-matrix is infrared safe. This last possibility is still challenging because one would consider the scattering of spinning particles, but certainly would be only a technical difficulty, easy to overcome.

- As a last possible application I would like to mention the coupled system of a flux-tube and a glueball. This system would mix the S-matrix of branons with the form factor of the glueball coupled to the brane. This problem has been already studied in the context of the scattering of closed strings off a branon. It would represent a first attempt to generalize the positivity ideas on a mixed system of correlators and explore the possible phenomenological implications for the flux tube dynamics.

- The projects proposed above have many possible extensions. For instance, one could consider multiple-channels in higher dimensions either including different species of particle or many-particle inelastic amplitudes. However, they all suffer of the proliferation of independent variables needed to fully take into account the analyticity and crossing properties. One possible strategy to overcome these issues in the near future is based on the dual space formulation of the bootstrap problem [8]. In the dual formulation the bootstrap is recasted into an unconstrained optimization problem in a non-linear space. In principle, these problems are easier to solve and working in this direction will certainly speed up the progress in this field and open more possibilities in the future.

10 Schedule

Many of the ongoing projects described in one of the previous sections have already been started or already reached an advanced point. I plan to complete all of them for the end of the extension. About the future direction I plan to start them in the near future.

References

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Scientific Report 2019

Title: Beyond Standard Model Physics under the ground and in the sky
Postdoc: Bithika Jain
Supervisor: Nathan Jacob Berkovits
Fapesp: 2017/05770-0
Period: 1/Sep/2017 - 31/Aug/2019

ICTP SAIFR

INTERNATIONAL CENTER FOR THEORETICAL PHYSICS
SOUTH AMERICAN INSTITUTE FOR FUNDAMENTAL RESEARCH

SUMMARY

My research interests are focused on deepening our understanding of the nature of fundamental particles and their interactions via electroweak forces. The standard model (SM) is the mathematical framework that encapsulates our current understanding of these elementary particles and fields. The last particle predicted by SM - the Higgs boson, was recently discovered. However, much remains to be understood about the dynamics of the Higgs mechanism. Solutions aimed at explaining the origin and nature of Higgs often require new physics. The top-down solutions predict new physics possibly accessible at TeV scale energies, while the bottom-up perspective helps scrutinize available experimental data and suggest new search strategies. The lack of experimental evidence for new physics begs for rigorous investigation strategies and theoretical input. I have used both analytical and computational techniques to investigate various new physics scenarios and the particles they predict with the aim of the understanding universe in time scales of few nanoseconds till ~10 seconds after Big bang.

DARK MATTER PHENOMENOLOGY

Dark matter at the colliders: Competitive bounds from collider searches, direct detection, and indirect detection have made the DM puzzle enticing. Extensions of the Standard Model which address the hierarchy problem and dark matter (DM) often contain top partners and additional resonances at the TeV scale. We explored the phenomenology of a simplified effective model with a vector resonance Z', a fermionic vector-like colored partner of the top quark T' as well as a scalar DM candidate ϕ and provide publicly available implementations in CalcHEP and MadGraph. We studied the $pp \to Z' \to T'\overline{T'} \to t\bar{t}\varphi\varphi$ process at the LHC and found that it plays an important role in addition to the $T'\overline{T'}$ production via strong interactions. It turns out that the presence of the Z' can provide a dominant contribution to the $t\bar{t}$+MET signature without conflicting with existing bounds from Z 0 searches in di-jet and di-lepton final states. We also found that through this process, the LHC is already probing DM masses up to about 900 GeV and top partner masses up to about 1.5 TeV, thus exceeding the current bounds from QCD production alone almost by a factor of two for both particles [1]

Electroweak Symmetric Dark Matter Balls: Cosmological data show that only about 5% of the energy density in the Universe is made from visible matter, while about 95% of the energy density is of unknown nature and origin. Roughly 68% of the total energy density is contributed by Dark Energy and 27% by Dark Matter. After a few decades of searching for electroweak-sector-related dark matter particles with a mass around 100 GeV and with a null result, we have started to enlarge the scope of dark matter masses from both the theoretic model and the experimental search sides. Under certain circumstances, the majority of dark matter could be in a form of macroscopic state instead of free particle states. The well-known example is the primordial black hole dark matter. We explored another type of macroscopic dark matter with a bosonic constituent or "non-topological soliton" as named in the literature. We call them Electroweak Symmetric Dark Matter Balls. We worked on their formation in the early universe, its properties and possible ways to detect them. This work has been accepted for publication in JHEP [2].

UNDERSTANDING THE STRUCTURE OF HIGGS POTENTIAL

Effective Potential and the Precision of Higgs Self Couplings

Determining the structure of Higgs potential is also important to understand the features of EW phase transition, whose properties can have significant implications for cosmology. Inflation predicts that the early universe was baryon-symmetric. However, one extra quark per 10 billion quark-antiquark pairs was created. This tiny excess is responsible for baryonic matter in the current universe. A dynamical mechanism for baryon asymmetry generation is needed. A strong first order phase transition (SFOPT) could provide a viable scenario to realize baryogenesis at the EW scale. Such a transition proceeds when the bubbles of the broken phase nucleate within the surrounding plasma in the symmetric phase. These bubbles expand, collide and coalesce until broken phase remains. Particles scatter with the bubble walls to generate Charge (C) and Charge-Parity(CP) asymmetries. These asymmetries help produce more baryons than antibaryons as laws of physics can change when particle is interchanged with its antiparticle while its spatial coordinates are inverted. Some of the net baryon charge created outside the bubble wall enters the broken phase. The higgs mass of 125 GeV does not allow SM electroweak phase transition to be first order and the CP violation induced is not large enough to generate baryon asymmetry. An essential feature of all viable realizations of electroweak baryogenesis (EWBG) is new physics. BSM physics needs to be coupled to SM with moderate strength and must be abundant in thermal plasma during the electroweak phase transition. This implies that new particles of masses around electroweak scale and with direct couplings to SM should exist. These should be discoverable at the collider and precision experiments like LHC. I examined the validity of the so-called Parwani method with Arnold-Espinosa method in computing the Higgs effective potential and investigated the precision of the Higgs couplings required for verifying the strong first order phase transition in Higgs Portal models and effective field theories [3].

Vacuum Stability in Holographic Models

There exists the problem of the ElectroWeak (EW) vacuum in the SM. The true vacuum is at $\phi \sim 10^{11}$ GeV, much deeper than the EW one. When compared with the Hubble expansion of the universe the EW vacuum turns out to be metastable. In SUSY the SM Higgs quartic, $\lambda \propto g^2 + g'^2$. The gauge couplings never get negative values. This is how the stability problem is resolved. How do the Warped Extra dimensions solve the stability problem? We are also currently working on vacuum stability in Randall Sundrum Models by looking at the running of the Higgs quartic. [4] We recently computed the effective potential for the Higgs using the tadpole method as part of this project. Our next step is to identify the running of the higgs quartic.

EARLY UNIVERSE PHASE TRANSITIONS

Cosmological Phase Transition in extra-dimension

I worked on a 5D model where the dynamical generation of electroweak potential occurs and suppressed cosmological constant exists. We focussed on the cosmology of this setup, with detailed numerical analysis to explore the parameter space which allows for successful strong phase transition detectable at the future gravitational wave detector [5]

PROGRESS

As part of my two-year postdoctoral fellowship, I have worked on several projects. These have covered investigating particle physics models that provide dark matter candidates, understanding the structure of Higgs' potential and explore early universe phase transitions. As part of this, three papers have been published and the fourth has been accepted. There is an ongoing project on vacuum stability in Randall Sundrum models which we intend to finish this year. I participated in several conferences and workshops. I have also given invited seminars in few institutes.

TALKS AT CONFERENCE, WORKSHOPS, AND SEMINARS

1. 6th Nov - 17th Nov 2017, LHC Chapter II: The run for new physics, International Institute of Physics, Federal University of Rio Grande do Norte, Natal, Brazil
    a. Topic: On the Validity of the Effective Potential and the Precision of Higgs Self Couplings
2. 4th Dec - 15th Dec 2017, 25th International Conference on Supersymmetry and the Unification of Fundamental Interactions (SUSY17) and the Pre-SUSY school, Tata Institute of Fundamental Research, Mumbai, India
    a. Topic: A Perturbative RS I Cosmological Phase Transition
    b. Topic: On the Validity of the Effective Potential and the Precision of Higgs Self Couplings
3. 6th May - 12th May 2018, Cosmological probes of BSM - from the Big Bang to the LHC, Centro de Ciencias de Benasque Pedro Pascual Benasque, Spain
4. 29th July - 2nd Aug 2019, Meeting of the Division of Particles and Fields of the American Physical Society (DPF 2019), Northeastern University, Boston, MA, USA
    a. Topic: Electroweak Symmetric Dark Matter Balls
5. 27th Nov 2017 - Seminar at Department of Physics, I.I.T Powai, Mumbai, India
    a. Topic: On the Validity of the Effective Potential and the Precision of Higgs Self Coupling
6. 23rd Nov 2017 - Seminar at Department of Theoretical Physics, T.I.F.R, Mumbai, India
    a. Topic: On the Validity of the Effective Potential and the Precision of Higgs Self Coupling
7. 17th May 2018- Seminar at Department of Physics, IISER, Pune, India
    a. Topic: On the Validity of the Effective Potential and the Precision of Higgs Self Coupling
8. 12th June 2018 - Seminar at Centre For High Energy Physics, Indian Institute of Science, Bangalore, India
    a. Topic: On the Validity of the Effective Potential and the Precision of Higgs Self Coupling

SCIENTIFIC VISITS

1. 26th Nov - 1st Dec 2017, Department of Physics, I.I.T Powai, Mumbai, India
2. 20th Nov - 24th Dec 2017, Department of Theoretical Physics, T.I.F.R, Mumbai, India
3. 16th May - 18th May 2018, Department of Physics, IISER, Pune, India
4. 11th June - 13th June, 2018Centre for High Energy Physics, Indian Institute of Science, Bangalore, India

ACADEMIC ORGANIZER

August 2018 - August 201, Organizer of the Particle Physics Journal Club, ICTP-SAIFR/IFT, UNESP, Sao Paulo, Brazil

PUBLICATIONS

[1] A. Belyaev, T. Flacke, B. Jain, P. Schaefers, *LHC Dark Matter Signals from Vector Resonances and Top Partners*, **Phys.Rev. D98 (2018) no.3, 035019,** arXiv:1707.07000

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Scientific report 2019

Title	Matéria Escura nas Galáxias
Postdoc	Ekaterina Karukes
Supervisor	Nathan Jacob Berkovits
Fapesp process	2016/26288-9
Period	01/Feb/2017 - 28/Feb/2019

International Center for Theoretical Physics
South American Institute for Fundamental Research

Kkarukes

Nathan Berkovits

Summary

The proposal of my posdoctoral fellowship addresses the following topics:

- Small scale problems of the ΛCDM paradigm. In particular, the core-cusp problem in dwarf rotationally supported galaxies;
- Dark matter content and its distribution in the Milky Way galaxy;
- Indirect dark matter searches.

Small scale problems of the ΛCDM paradigm

Only 15.5% of the total matter in the Universe is in the form of ordinary baryonic matter, while the other 84.5% is provided by dark matter (DM) [1]. Its existence has long been inferred from its gravitational interactions with ordinary luminous matter on scales ranging from galaxies to the Universe as whole. Although the exact nature of the DM remains unknown, theoretically motivated candidates are the Weakly Interacting Massive Particles (WIMPs) that naturally provide the measured relic density (e.g. [2, 3]). Our current understanding of the Universe is embedded in the well-established concordance cosmological model, the Λ-Cold Dark Matter (ΛCDM). In this theoretical framework, the virialized structures obtained by N-body DM-only simulations are well described by the Navarro-Frenk-White (NFW) profile [4]. On the one hand, the ΛCDM model successfully describes the observed large scale structures of the Universe. On the other hand, on the galactic and sub-galactic scales ΛCDM predictions seem to disagree with current observations. In particular, one of the small-scale problems, the core-cusp problem, is the best documented in dwarf rotationally supported galaxies. This is because their baryonic fraction is low (they are believed to be DM dominated at any radii) and their kinematics is rather simple. In our work we studied the kinematics of a sample of dwarf rotationally supported galaxies (or how we called them dwarf disk galaxies), which are members of Local Volume, with an average optical velocity $< V_{\rm opt} >$=35 km/s. This was done in order to extend the relationships between the global luminous properties of normal spiral galaxies and its dark matter properties down to dwarf disk galaxies in the context of URC. The results of this study are extremely interesting, because they can greatly improve our knowledges about the standard model of galaxy formation and evolution. At the same time, it could also help us to have a better understanding of the nature of DM itself. I have published one paper about small scale ΛCDM problems in dwarf disk galaxies during my postdoc [5].

Dark matter content and its distribution in the Milky Way galaxy

The Milky Way (MW) system also represents a challenge for the ΛCDM theory. In particular, there is a long-standing tension between the number of detected satellite galaxies around the MW and the predictions of the pure dark matter structure formation simulations within the standard ΛCDM theory, known as the "missing satellite problem" [6]. Nonetheless, in the last few years there is a growing evidence that by involving baryonic physics in the hydrodynamical simulations we are able to finally solve the problem [7]. In light of that, one of the key parameter that enters in the solution of the "missing satellite problem" is the total MW mass. Therefore, it is important to have a robust determination of that. Furthermore, understanding the distribution of DM in the MW is important in order to properly interpret direct and indirect DM searches (see e.g. [8]), and to probe more exotic DM models (see e.g. [9]).

Typically the direct way to estimate the mass distribution of the MW, or any other galaxies, is to measure the kinematics of different dynamical tracers such as stars, gas, globular clusters, and satellite galaxies. Then the derived rotation curve can be used to mass model the Galaxy, i.e. fitting the multicomponent model to it (see e.g. [10]). Furthermore, before mass modelling one usually needs to assume a parametric form for the DM distribution (however see [11]). The latter along with the uncertain measurements of the baryonic content of the MW and the uncertain measurement of the galactic parameters makes the estimation of the MW DM content to be uncertain.

The goal of this work is to use recent MW kinematical measurements in order to reconstruct the DM density profile of the MW assuming a gNFW profile [12] and by means of the rotation curve (RC) mass modelling. We use a Markov Chain Monte Carlo approach in order to perform the three parameter gNFW model fitting. We further validate the accuracy of the result on a suite of mock RC where we a priori know the parameters of the underlying gNFW DM density profile. We show that the local DM density ρ_0 values are recovered with a very good accuracy (within uncertainties < 20 %). We also find degeneracy between the scale radius r_s and the inner dark matter density slope γ. Besides, we demonstrate an important dependence of the quality of the gNFW parameters reconstruction on the underlying baryonic morphology. This work was done together with people from ICTP-SAIFR/IFT UNESP and some other collaborators from Imperial College London (United Kingdom), the paper is submitted to the JCAP and it is already on arXive, see [13].

Indirect dark matter searches

Usually as the prime targets for indirect DM searches are considered to be dwarf spheroidal galaxies. This is because they are thought to be DM dominated objects and the contamination from intrinsic astrophysical sources is negligible in them. Besides dwarf galaxies, the Galactic Center region is also a good target for the DM searches, both because of its proximity and its predicted large DM concentration.

Whereas in our work we propose to investigate dwarf irregular galaxies as new targets for indirect searches of DM with gamma-ray telescopes. Main motivations for that are

- the kinematics and therefore the DM content of these galaxies are very well defined;
- beyond the sphere of ~ 4 Mpc the number of rotationally supported dwarf irregular galaxies starts to dominate on pressure-supported objects or dwarf spheroidal galaxies.

We were able to put prospective constraints on the particle DM mass and annihilation cross section that were obtained by the analysis of a sample of 36 dwarf irregular galaxies. We further calculated constraints for the combined analysis of the 7 most promising dIrr galaxies of our sample. During the period of my postdoc I have published one paper and one proceedings about indirect detection of dwarf irregular galaxies together with my collaborators from SISSA (Italy) and people from HAWC collaboration [14, 15].

Additionally, since November 2017, I am a member of the CTA collaboration, where I participate in the DM group. In particular, we are working on characterization of the Large Magellanic Cloud at TeV energies. This is an ongoing work.

Progress

Here I would like shortly summarise the progress of the projects that I have mentioned in the first part of the scientific report. During my two years of postdoc I have been working on several projects. All the projects are related to either determination of the dark matter properties in galaxies or to the indirect searches of the dark matter. As the result of nearly two years work I have published two papers and one proceeding [5, 14, 15] and I am currently working on two other projects. One is related to the DM in the Galaxy, while the other is related to the indirect DM searches with the future Cherenkov Telescope Array Observatory (CTA). I think two finish these project by the end of February.

Furthermore, I have also participated in many conferences and workshop that I am going to mention in the section, and I was involved in the paper reviewing for the Journal of Monthly Notices of the Royal Astronomical Society (MNRAS).

Talks at conferences, workshops and seminars

I have presented my work at the following conferences, workshops and seminars

- May 2017, South American Dark Matter Workshop, ICTP-SAIFR, São Paulo (Brazil), Dark matter distribution in dwarf disk galaxies;
- May 2017, University of Campinas (UNICAMP), São Paulo (Brazil), The nature of Dark Matter from properties of galaxies (invited seminar);
- October 2017,Workshop: Amsterdam-Paris-Stockholm, 7th Meeting, Kasteel Woerden (The Netherlands), Prospects for dark matter detection in dwarf irregular galaxies;
- May 2018, Workshop: Tensions in the LCDM paradigm, MTP, Mainz (Germany), Determination of the DM density profile of the MW (and how much to trust it);
- November 2018, Workshop: II South American Dark Matter Workshop, ICTP-SAIFR, São Paulo (Brazil), Milky Way dark matter density profile and its reconstruction;
- December 2018, Nicolaus Copernicus Astronomical Center (CAMK), Warsaw (Poland), Milky Way dark matter density profile and its reconstruction (seminar).

Scientific visits

- July 2017, Fermilab (USA)
- May June 2018, Deutsches Elektronen-Synchrotron (DESY) (Zeuthen, Germany)
- December 2018, Nicolaus Copernicus Astronomical Center (CAMK) (Warsaw, Poland)

Academic organizer

- February 2017 – February 2019, Organizer of the Astro/Cosmo Journal Club, ICTP-SAIFR/IFT-UNESP, São Paulo, Brazil.

Publications

- *The universal rotation curve of dwarf disk galaxies.*, E.V. Karukes & P. Salucci., 2017, MNRAS 465 (2017) no.4, 4703-4722, [5]
- *Searching for TeV DM evidence from Dwarf Irregular Galaxies with the HAWC Observatory*, S. Hernandez Cadena, R. Alfaro, A. Sandoval, A. Belmont, V. Gammaldi, E.V. Karukes, P. Salucci for the HAWC Collaboration, 2018, PoS ICRC2017 (2018) 897, [15]

- *Theoretical predictions for dark matter detection in dwarf irregular galaxies with gamma rays*, V. Gammaldi, E.V. Karukes, P. Salucci, 2018, Phys. Rev. D 98, 083008, [14]
- *Dark Matter distribution in the Milky Way*, E.V. Karukes, M. Benito, F. Iocco, R. Trotta & A. Geringer-Sameth submitted, [13]
- *Characterization of the Large Magellanic Cloud at TeV energies, for CTA*, M. Benito, M. I. Bernardos, E. Fedorava, F. Iocco, E. Karukes, S. Mangano & O. Sergijenko in prep.

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Scientific Report 2019

Machine Learning techniques applied to Cosmological Problems

Postdoc: Martin Emilio de Los Ríos

Supervisor: Nathan Berkovits

FAPESP process: 2019/08852-2

Reporting period: 1/6/2019 to 30/11/2019

FAPESP Process Number: 2019/08852-2

1 Introduction.

Machine learning techniques represents a new way of analysing big datasets in an agnostic and homogeneous way. These methods are very useful and powerful tolls to find patterns and relations between the variables that are involved in an specific problem. These techniques have been applied with a lot of success in technological problems and in other different areas of science, including astronomy and physics.

2 Research.

- **Merging clusters analysis**:

  In this project we continue studying in an individual way the candidates to merging clusters found previously [2] with the Machine Learning technique developed during my PhD. Specifically I am working, in collaboration with colleagues from Argentina and Chile, in the analysis of the galaxy cluster A267. In May 2019 we submitted our results to the international journal Astronomy & Astrophysics and now we are working on the corrections suggested by the referee.

- **Reconstruction of cosmological parameters through machine learning techniques**:

  In this project I started working in collaboration with Dr. Antonino Troja on the measurement of the masked bispectra of the Cosmic Microwave Background (CMB) using machine learning techniques to deconvolve the effect of the mask. Specifically we build 10000 CMB mock maps using the non-gaussian multipoles estimated by *Elsner & Wandelt* [3] and varying the amplitud of these multipoles. For each one of these maps, we measure the full-sky bispectra and the masked bispectra. Now we are investigating the performance of machine learning techniques, originally developed for the denoising of temporal signals, on the deconvolution of the masked bispectra to obtain the full-sky one.

- **Merging clusters identification**:

  In this project I build a new R package that is publicly available through my github repository. This package is an implementation of the method that I developed during my PhD for the automatic identification of merging clusters.

- **Back-splash galaxies classification**:

  In this project I am working in collaboration with colleagues from Argentina and Chile. The main goal is to identify back-splash galaxies in phase-space (distance to the cluster center vs relative line of sight velocity between the galaxy and the cluster). Specifically we build a data-set of simulated galaxies using the semi-analytical model developed by *Cora et al.* [1] applied to the Multi-Dark cosmological simulations [4]. Using this data-set we trained different machine learning methods finding better results that the obtained using the traditional methods for the classification of this kind of galaxies.

- **Estimation of dark matter in spiral galaxies:**

  The main goal of this project is to estimate the dark matter distribution in spiral galaxies using deep learning techniques applied to the photometric image of the galaxies and the velocity field map of the galaxy gas. During the first part of this project we build a data-set of simulated photometric images and velocity fields of spiral galaxies using the publicly available data of the hydrodynamical cosmological simulation Illustris [5]. In the next months we will trained deep learning methods to estimate the dark matter distribution and compare this results with the traditional techniques. Is important to remark that this work is in collaboration with Dr. Fabio Iocco, Dra. Francesca Calore, Dr. Bryan Zaldivar and Dr. Mihael Petac.

3 Conferences and seminars.

- The dark side of the Universe. From 15/07/2019 to 19/07/2019. (Buenos Aires-Argentina)
- III Joint ICTP Trieste-ICTP-SAIFR School on observational cosmology. From 22/07/2019 to 02/08/2019. ICTP-SAIFR (Sao Paulo-Brazil).
- School on High Energy Astrophysics. From 05/08/2019 to 16/08/2019. ICTP-SAIFR (Sao Paulo-Brazil).
- Linea Bootcamp. From 02/09/2019 to 06/09/2019. Observatório Nacional (Rio de Janeiro-Brazil).
- Dark Universe Workshop – Early Universe Cosmology, Baryogenesis and Dark Matter. From 21/10/2019 to 25/10/2019. ICTP-SAIFR (Sao Paulo-Brazil).

4 Other Activities.

During this semester Dr. Antonino Troja and myself organized the weekly Journal Club on Cosmology and Astrophysics of the ICTP-SAIFR/IFT-UNESP.

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Scientific Report 2019

Modern Methods for Scattering Amplitudes in Field (Gauge Theories and Gravity) and String Theory

Postdoc: Diego Medrano Jimenez

Supervisor: Nathan Berkovits

FAPESP process: 2019/07286-3

Reporting period: 1/10/2019 to 30/11/2019

1 Research

My research is taking place in general terms inside the field of 'Scattering Amplitudes'. In particular, these are some of the topics I have been lately working on:

- Study of gauge theories and gravity in the context of the **Cachazo-He-Yuan (CHY) formalism**. In this set-up, the Scattering Equations (SE) turn out to be a crucial theory-independent object but a complete analytic description for their solutions is still missing. Following some of the results in [1], I am trying to unveil any hierarchy or internal structure of these solutions by means of Sudakov parameters and translating the problem to the study of the critical points of an electrostatic potential on the sphere [2]. Multi-Regge-kinematics (MRK) can also be used to simplify the analytic structure of the punctures in the Riemann sphere and to study the factorizability properties of both gauge and gravity amplitudes [3].

- **Planar radiation zeros**. They are a feature of scattering amplitudes that may allow to extract information about the asymptotic behavior of a particular theory when characterized inside some projective space of the kinematic variables. Already studied in scalar-Yang-Mills and Einstein-Hilbert gravity for MHV tree-level amplitudes in [4, 5], it would be interesting to generalize the obtained results at loop-level and for the remaining N^kMHV helicity sectors.

- **S-matrix bootstrap**. I started working on the field of 'Scattering Amplitudes' from the point of view of 'integrability', where the S-matrix turns out to be one of the most fundamental objects in quantum integrable theories. Being one of the strongest topics in the ICTP-SAIFR collaboration group, I started reviewing the basics in [6, 7] and reproducing different computations and plots from [8, 9]. We have also started some discussions to generalize the results in [10], where the assumption of no tree-level particle production allows to completely constrain the Lagrangian of various relativistic quantum field theories in 1+1 dimensions.

2 Talks

- ICTP-SAIFR String Theory Jounal Club (October 08, 2019): *Sudakov Representation of the Cachazo-He-Yuan Scattering Equations Formalism.* Based on [1].

3 Workshops

- Simons Collaboration on the Nonperturbative Bootstrap Annual Meeting 2019 (New York – November 7-8, 2019).

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Scientific Report 2019

Title	Angular Power Spectrum and Angular Bispectrum of Large Scale Structure
PostDoc	Antonino troja
Supervisor	Nathan Jacob Berkovits
FAPESP process	2017/05549-1
Period	01/Oct/2017 - 30/Nov/2019

ICTP
SAIFR

International Center For Theoretical Physics
South American Institute for Fundamental Research

Research Report

Antonino Troja

Academic activities

Summary

Observations of the Cosmic Microwave Background (CMB) and Large Scale Structure (LSS) of the Universe allow us to better understand the physics that drives the evolution of the primordial perturbation, generated after the Big Bang, all the way to the large-scale distribution of galaxies we see today, leaving, however, important open problems. The latest Planck results show that the Universe is composed only for the $\approx 4\%$ of the total energy density by ordinary baryonic matter. The remaining 96% is unknown, composed by non-baryonic matter (the so-called dark matter $\approx 26\%$) and the mysterious dark energy ($\approx 70\%$).
It is impossible to directly observe dark matter, since it interacts only gravitationally. However, it is possible to relate the distribution of the visible matter (galaxies) with the distribution of the total matter content by writing

$$\delta_m \approx b_1 \delta_g + \frac{1}{2} b_2 \delta_g^2,$$

where δ_m is the total matter density distribution, δ_g is the galaxy density distribution, b_1 and b_2 are the linear and quadratic bias parameters respectively. This relation is local and it is satisfied by the galaxy distribution only on average, since there is a significant scatter among different regions of the Universe.
Since the galaxy distribution is the only observable in photometric and spectroscopic surveys, we need to know as precisely as possible the relation between dark matter and galaxies. To this end, it is crucial to understand the statistical properties of the galaxy distribution. At first order, the galaxy distribution is analyzed by taking its power spectrum, i.e. the Fourier transform of the 2-point correlation function, which parametrizes the excess probability of finding two galaxies at a certain distance. Unfortunately, the amplitude of the power spectrum (parametrized by the amplitude of dark matter fluctuations at $8h^{-1}$Mpc, σ_8) is degenerate with the bias parameters, leading to weak constraints. For this reason, the bispectrum is now one of the main tools in constraining cosmological parameters. The bispectrum is the Fourier counterpart of 3-points correlation function, which parametrizes the excess probability of finding three galaxies in a given triangular configuration. The dependence of the cosmological parameters on a particular triangular configuration (equilateral, isosceles, squeezed, etc...) allows to constrain different parameters by taking different bispectrum configuration, thus removing the degeneracy.

Activity performed

Measurement of the Galaxy Angular Power Spectrum

In colloboration with Prof. Rogerio Rosenfeld, Dr. Hugo Camacho and Dr. Felipe Oliveira

We use data from the first-year (Y1) observations of the DES collaboration to measure the galaxy angular power spectrum (APS), and search for its BAO feature using a template-fitting method. We test our methodology in a sample of 1800 DES Y1-like mock catalogs. The APS is measured with the pseudo-C_l method, using pixelized maps constructed from the mock catalogs and the DES mask. The covariance matrix of the C_l's in these tests are also obtained from the mock catalogs. We use templates to model the measured spectra and estimate template parameters firstly from the C_l's of the mocks using two different methods, a maximum likelihood estimator and a MCMC, finding consistent results with a good reduced chi^2. Robustness tests are performed to estimate the impact of different choices of settings used in our analysis. After these tests on mocks, we apply our method to a galaxy sample constructed from DES Y1 data specifically for LSS studies. This catalog comprises galaxies within an effective area of 1318 deg^2 and 0.6<z<1.0. We fit the observed spectra with our optimized templates, considering models with and without BAO features. We find that the DES Y1 data favors a model with BAO at the 2.6σ C.L. with a best-fit shift parameter of α=1.023±0.047. However, the goodness-of-fit is somewhat poor, with $chi^2/(\mathrm{dof}) = 1.49$. We identify a possible cause of this issue and show that using a theoretical covariance matrix obtained from C_l's that are better adjusted to data results in an improved value of $chi^2/(\mathrm{dof}) = 1.36$ which is similar to the value obtained with the real-space analysis. Our results correspond to a distance measurement of DA(zeff=0.81)/rd=10.65±0.49, consistent with the main DES BAO findings. This is a companion paper to the main DES BAO article showing the details of the harmonic space analysis.

State of the art: Paper written and published (see Publications section).

Non-Gaussian likelihood in harmonic space

In colloboration with Prof. Rogerio Rosenfeld and Vinicius Terra

Usually, the large-scale structures analysis is performed using Bayesian Inference assuming a Gaussian likelihood, requiring a robust and precise Covariance Matrix. Recently some papers showed the necessity of Non-Gaussian Likelihoods in order to improve the strength of power spectrum statistics. Let's consider the angular power spectrum C_ℓ:

$$\hat{C}_\ell = \frac{1}{2\ell+1}\sum_{m=-\ell}^{\ell} |a_{\ell m}|^2, \tag{0.1}$$

where $a_{\ell m}$ are the harmonic coefficients, described by a Gaussian Probability Distribution Function (PDF) with zero mean and variance C_ℓ.
Since the power spectrum is the product of two Gaussian variables, its PDF is described by the so called Gamma distribution:

$$\forall\ell : \hat{C}_\ell \sim Gamma\left[\frac{\nu(\ell)}{2}, \frac{2C_\ell}{\nu(\ell)}\right] \tag{0.2}$$

where C_ℓ and ν are the theoretical angular power spectrum and its number of degrees of freedom respectively. For a full-sky observation, we have $\nu(\ell) = 2\ell + 1$. But, for a fractional area of a full-sphere, the degrees of freedom are affected by the geometry of the un-observed sky and the discretization of the measured field. In this case, we can write the number of degrees of freedom as

$$\nu(\ell) = f_{sky} \frac{(2\ell + 1)}{\ell_{pix}} g_{eff}(\ell), \tag{0.3}$$

where f_{sky} is the observed fraction of the sky, ℓ_{pix} is the parameter due to the pixelization of the field and g_{eff} parametrizes the quality of our measurements.
We calibrate $g_{eff}(\ell)$ using 150 FLASK mocks for a full-sky observation with 5 redshift bins equally spaced between 0.15 and 0.90, with resolution $N_{side} = 1024$.
Once g_{eff} is computed, next step is to run Monte Carlo Markov Chains (MCMC) in order to infer the cosmological parameters from our data.

State of the art: First draft written, we are waiting for the results on g_{eff} in order to run MCMC and infer cosmological parameters from data.

Optimal Multi-Tracer Bispectrum Estimators for the Large-Scale Structure

In colloboration with Prof. Raul Abramo (USP) and Carol Guandalin (USP)

Aiming at the maximal extraction of information from the bispectrum of large-scale structure (LSS) surveys, hence in the smallest variance possible for the estimators, we have found a weighting scheme, to be applied to the data from those surveys, which saturates the Cramér-Rao lower bound (CRLB). Thus, in theory this gives us the best possible estimators. We accomplished it by considering a cubic form to estimate the amplitude of the bispectrum, which combines the data (e.g. the density contrast of a certain type of galaxy) of multiple tracers of the LSS to minimize shot-noise and cosmic variance, and by imposing the CRLB from the Fisher matrix obtained from the data covariance. We compared the error bars estimated from the Fisher matrix with other estimators available in the literature. of large-scale structure (LSS) surveys, hence in the smallest variance possible for estimators $\hat{B}_{\mu\nu\sigma}$ of $B_{\mu\nu\sigma}$, we have found a weighting scheme, to be applied to the data from those surveys, which saturates the Cramér-Rao lower bound (CRLB). Thus, in theory this gives us the best possible estimators. We accomplished it by considering a cubic form $\hat{\Gamma}_{\mu\nu\sigma}$ to estimate the amplitude of the bispectrum, which combines the data (e.g. the density contrast, δ_μ, of a galaxy of type μ) of multiple types of tracers of LSS to minimize shot-noise and cosmic variance, and by imposing the CRLB from an analytical Fisher matrix obtained from the data covariance. Now, we are comparing the error bars estimated for $\hat{B}_{\mu\nu\sigma}$ with other estimators available in the literature.

State of the art: First draft written, actually the project is in stand-by because of other commitments, we hope to submit the paper before half next year.

Analysis of LSS on the Disc

In colloboration with Rodrigo Voivodic (USP)

In general we want to compute the power spectrum for some projection of the contrast density field δ. The first step to compute the Fourier expansion of the density field is to look for a appropriated basis in spherical coordinates. As in the Cartesian case this basis will be the solution of the Helmholtz equation

$$(\nabla^2 + k^2)\Psi = 0\,, \tag{0.4}$$

where $\Psi = \Psi(r, \theta, \phi)$ is a scalar field, our basis.
The main application of the expansion of a scalar field in spherical coordinates is the possibility to compute the correlation function of some scalar field in less dimension construct as some projection of the original one. The main example of this is the computation of the angular power spectrum. The angular scalar field is defined as a projection of the 3D field along the radial coordinate

$$x(\theta, \phi) = \int_0^\infty dr W(r) f(r, \theta, \phi)\,, \tag{0.5}$$

where $W(r)$ is some window function. We have

$$\left\langle x(\theta, \phi) x^*(\theta', \phi') \right\rangle = \sum_{l=0}^{\infty} C_l \, P_l(\hat{n} \cdot \hat{n}')\,, \tag{0.6}$$

. The two point correlation function of a field in a spherical shell only depends of the angle between the two vectors ($\hat{n} \cdot \hat{n}' = \cos\theta$).
In the case of a field defined on a disc, we want to consider a projection of the 3D field along the θ direction

$$x(r, \phi) = \int_0^\pi d\theta \, \sin\theta \, W(\theta) f(r, \theta, \phi)\,, \tag{0.7}$$

where $W(\theta)$ is some window function. Our calculations showed that:

$$\left\langle x(r, \phi) x^*(r', \phi') \right\rangle = \sum_{m=0}^{\infty} D_m(r, r') e^{im(\phi - \phi')}\,, \tag{0.8}$$

where the coefficients D_m are given by

$$D_m(r, r') = \frac{2}{\pi} \sum_{l \geq m} (A_l^m)^2 \int_0^\infty dk \, k^2 P(k) j_l(kr) j_l(kr') \tag{0.9}$$

Next step is to compute the polar power spectrum as defined above on real data, for example, the data from VIPERS survey.

State of the art: First draft written with all the theory needed. We are waiting for VIPERS data in order to start the analysis.

Exploring the Needlet Trispectrum

In colloboration with Prof. Domenico Marinucci (Università Roma Tor Vergata)

We exploit the properties of the Needlet trispectrum in order to obtain constraints on g_{NL}. The result of our analysis shows that it is possible to constrain both g_{NL} and $\sigma_{g_{NL}}$ using a small sample of trispectra measured from simulated skies, almost saturating the Cramer-Rao bound. This is made possible with a simple parametrization of the covariance matrix. This makes the trispectrum evaluated by means of Needlets a powerful tool in order to constrain primordial non-Gaussianity parameters from CMB data, in terms of both statistical strength and computational power.

State of the art: Last draft written, waiting for submission.

Dark Energy Survey Year 3 Results: Covariance Methods

In colloboration with Dark Energy Survey (DES) collaboration

A key ingredient in the estimation of cosmological parameters in a given model using data is the covariance matrix that describes the correlated uncertainties in the data.
There are several methods to estimate covariance matrices that can be divided in three main categories: from data itself (in methods such as subsampling, jackknife and bootstrap), from simulations and from theory. In this paper we will follow the methodology used in the analysis of the first year of DES data and adopt a theoretical covariance for the Y3 analyses that combine data from galaxy clustering and weak gravitational lensing in real space in three different two-point correlation functions, the so-called 3x2pt data vector. Several improvements were implemented with respect to the Y1 methods and will be discussed below.
We test and validate different theoretical covariance matrices against lognormal simulations using as a measure of performance the χ^2 distribution from the simulations. We also run Markov Chain Monte Carlo (MCMC) to check biases in the estimation of the cosmological parameters.

State of the art: First draft written, test on covariance are still on-going.

Modeling the Angular Bispectrum in Photometric Galaxy Surveys

In colloboration with Dr. Emiliano Sefusatti (INAF) and Dr. Martin Crocce (ICEE)

We measure the angular bispectrum of the matter density fields from numerical simulations and compared the result with the leading-order prediction in Perturbation Theory and the one derived from available fitting functions of the three-dimensional bispectrum. We also compare an estimate of the bispectrum variance based on the simulations results with the simple Gaussian theoretical expectation. This is a first step toward assessing the information content of higher-order angular correlation functions with the specific goal of possible applications to the analysis of photometric redshift surveys.

State of the art: Last written, waiting for submission.

Future Activity

My idea is to analyze the photometric distribution of the Large Scale Structure of the galaxies (LSS), in order to constrain its *angular spectrum* and *bispectrum*. We can indeed treat the photometric galaxy distribution as a spherical field, allowing us to use angular statistics. Due to its power in removing degeneracy, in view of present and forthcoming photometric surveys like Dark Energy Survey (DES), Large Synoptic Survey Telescope (LSST) and Euclid, the angular bispectrum is likely to become one of the main tools in the analysis of photometric of datasets.

Activities within institute

I organized and run:

- AC/JC Journal Club, in collaboration with Fabio Iocco and Ekaterina Karukes, at IFT;
- Weekly meeting group, within the cosmology group here at IFT.

Scientific visits

15-20/01/2018 - Visiting ICTP at Trieste, Italy;
05-11/11/2017 - Visiting LIneA at Observatorio de Rio de Janeiro.

Observing Experience

December 2018 - Blanco Telescope, Cerro Tololo, DECAM photometric instrument.

Conferences, workshops and meeting attended

04-08/12/2017 - LSST DESC 2017 Fall/Winter Sprint Week, Argonne National Laboratory, Lemont, IL;
18-20/04/2018 - SCLSS, Oxford, UK;
16-20/07/2018 - DES Y3KP Workshop, CMU Pittsburgh, PA;
20-22/07/2018 - LSST DC2 Fest, CMU Pittsburgh, PA;
23-27/07/2018 - LSST DESC meeting, CMU Pittsburgh, PA;
15-18/10/2018 - DES Michigan Workshop, Michigan University, Ann Arbor, MI;
03-07/12/2018 - DES Meeting, UNICAMP, Campinas, SP;
17-21/12/2018 - South American Workshop on Cosmology in the LSST Era, ICTP-SAIFR, Sao Paulo, SP;
25-29/03/2019 - DES Y3KP Meeting, ICE, Barcelona, Spain;
17-21/06/2019 - DES Meeting, UPenn, Philadelphia, PA;
15-19/07/2019 - LSST-DESC Meeting, Paris, France;
04-08/11/2019 - DES Meeting, Brighton, Sussex, UK.

Publications

- Dark Energy Survey Year 1 results: measurement of the galaxy angular power spectrum, Camacho H., et al., 2019, MNRAS, 487, 3870, doi:10.1093/mnras/stz1514;
- Modeling the Angular Bispectrum in Photometric Galaxy Surveys, Troja A., et al., In Prep., DRAFT AVAILABLE UPON REQUEST;
- Exploring the Needlet Trispectrum, Troja A., et al., In Prep.,DRAFT AVAILABLE UPON REQUES
- Optimal Multi-Tracer Bispectrum Estimators for Large-Scale Structure, Troja A., et al.,In Prep.,DRAFT AVAILABLE UPON REQUEST;
- DES Y3: Covariance methods,Troja A., et al.,In Prep.,DRAFT UNAVAILABLE BECAUSE OF DARK ENERGY SURVEY POLICY ON DATA AND RESULTS;
- Analysis of LSS on the Disc: The Vipers Case,Troja A., et al.,In Prep.,DRAFT YET UNAVAILABLE;
- Non-Gaussian Likelihood in Harmonic space,Troja A., et al.,In Prep.,DRAFT YET UNAVAILABLE.