UK Cosmology Meeting / Ruth Fest

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Book of Abstracts

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Stochastic Ultra-slow-roll Inflation

Corresponding Author: david.wands@port.ac.uk

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Stochastic inflation in full general relativity

In the context of inflation, we show how to account for quantum modes in general and numerical relativity on scales bigger than the Hubble radius, from where they behave classically and can grow non-perturbatively.

We provide a formulation of Stochastic Inflation in full general relativity that goes beyond the slow-roll and separate universe approximations. Starting from the initial conditions problem in numerical relativity, we show how gauge invariant Langevin source terms can be obtained for the complete set of Einstein equations in their ADM formulation by providing a recipe for coarse-graining the spacetime in any small gauge. These stochastic source terms are defined in terms of the only dynamical scalar degree of freedom in single-field inflation and all depend simply on the first two time derivatives of the coarse-graining window function, on the gauge-invariant mode functions that satisfy the Mukhanov-Sasaki evolution equation, and on the slow-roll parameters. Stochastic gravitons sources can also be accounted for.

We validate the efficacy of these Langevin dynamics directly using an example in uniform field gauge, obtaining the stochastic e-fold number without the need for a first-passage-time analysis. As well as investigating the most commonly used gauges in cosmological perturbation theory, we also derive stochastic source terms for the coarse-grained first-order BSSN formulation of Einstein's equations, which enables a well-posed implementation for 3+1 numerical relativity simulations.

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Quantum Fields in the Early Universe Sky

Corresponding Author: azadeh.maleknejad@cern.ch

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Bounding Effective Field Theories in Cosmological Spacetimes

Author: Mariana Carrillo Gonzalez[1]

[1] *Imperial College London*

In this talk, I will present a novel method for obtaining bounds on the Wilson coefficients of EFTs living in cosmological backgrounds by requiring that their physical modes do not propagate further than a minimally coupled photon by a resolvable amount. In analogy with causality bounds for flat spacetimes which are based on the time delay, I will explain how the cosmological version arises by computing spatial shifts. I will show explicit examples of the bounds on shift symmetric scalars and generalized Galileon theories.

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Renormalization of the primordial inflationary power spectra

It has been suggested that the effects of renormalization significantly reduce the amplitude of the inflationary spectra at scales measurable in the cosmic microwave background. Via a gauge-invariant analysis, we compute the renormalized scalar and tensor power spectra and follow their evolution in an inflating universe that undergoes a transition to an FRW phase with a growing horizon. For perturbations originating from Minkowski vacuum fluctuations, we show that the standard prediction for the spectra on superhorizon scales is a late-time attractor, while they are UV finite at all times. Our result is independent of the equation of state after inflation, showing that the standard prediction is fully robust.

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GR extensions and cosmological dark matter

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Large non-Gaussianity from vacuum decay during inflation

We present a general formalism to calculate the non-Gaussianity arising from vacuum decay during inflation in the presence of a light spectator field. This is shown to generate large, potentially detectable non-Gaussianity when applied to an observationally-viable model of inflaton non-minimally coupled to gravity.

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Production of Solar Chameleons: Novel Channels

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Hairy black holes

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Scalar field dark matter with time–varying equation of state

We propose a new model of scalar field dark matter interacting with dark energy. Adopting a fluid description of the dark matter field in the regime of rapid oscillations, we find that the equation of

state for dark matter is non-zero and even becomes increasingly negative at late times during dark energy domination. Furthermore, the speed of sound of dark matter is non-vanishing at all length scales, and a non-adiabatic pressure contribution arises.
The results indicate that there are still unexplored possible interactions within the dark sector that lead to novel background effects and can impact structure formation processes.

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Gravity Simulators

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Squeezing 21cm intensity: the multi-modal bispectrum

21cm intensity surveys in interferometer mode can directly measure the small-scale post-reionisation temperature fluctuations in Fourier space. In single-dish mode, these surveys can measure the modes on larger scales.

We show that this complementarity provides a new way to measure the squeezed bispectrum. The interferometer/ single-dish combination can deliver a high signal-to-noise measurement of the squeezed bispectrum, which in turn can be used to constrain local primordial non-Gaussianity. We find that surveys similar to those planned for HIRAX (interferometer) and SKAO (single-dish) can deliver constraints that are competitive with Planck and outperform a Euclid-like survey.

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Can a stochastic cosmology mimic Lambda and CDM?

A key prediction of consistent theories of classical gravity coupled to quantum matter is that the metric has to evolve stochastically. Motivated by these considerations,
we study a stochastic Einstein-de Sitter Universe, in order to explore whether a random source in Einstein's equations can reproduce the phenomenology of Λ. We find two interesting effects. At early times, we argue that violation of the Hamiltonian constraint of GR manifests itself as phantom extra matter, possibly playing the role of cold dark matter in structure formation. At late times, instead, we show that diffusion away from Friedmann equations mimics qualitatively the redshift-luminosity distance curves of ΛCDM universes with non-zero cosmological constant. To test the latter observation quantitatively, we conclude by placing bounds on the diffusion coefficient using supernovae data from the Pantheon+ and SH0ES datasets. In particular, we show that, in this simple toy model, the hypothesis of an effective cosmological constant coming entirely from stochasticity in the evolution of the scale factor is strongly disfavoured with respect to ΛCDM models. The tension can be relaxed by introducing a non-zero Λ in the equations of motion directly, representing either a bare cosmological constant or an effective one arising from unrelated phenomena.

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Cosmic inflation with fast roll initial conditions

The aim of this talk is to give a motivation of why one should consider inhomogeneous initial condition for inflation and an account for our relevant recent work. We consider single scalar field inflation and we use Numerical Relativity simultationso study inflation with generic fast-roll, inhomogeneous initial conditions for different inflationary models. Specifically, we investigate the effects of large scalar perturbations of the inflaton field as well as large kinetic perturbations. We find that, large kinetic pertubations reduce the number of e-folds of inflation. In particular, small field inflationary models, namely those where the slow roll region is subplanckian are not robust to kinetic perturbations. This strengthens the results of previous work that suggested that small field inflation is not robust to generic inhomogeneities. In large field inflation, despite reducing the number of e-folds overall, inflation is resilient. In the cases we study, the robustness of inflation depends strongly on whether or not the scalar inflaton field is driven by scalar dynamics into the reheating phase by the inhomogeneities.

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Stochastic inflation and primordial black holes

Quantum fluctuations from cosmic inflation give rise to the macroscopic structures of the universe. The strongest fluctuations collapse into primordial black holes, a dark matter candidate. Stochastic inflation is a tool to compute the fluctuation statistics non-perturbatively, needed for accurate black hole predictions. I discuss recent progress in these computations, their numerical implementation and analytical approximations, and the implications for black hole abundance in single-field models of inflation.

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KiDS-SBI: Simulation-Based Inference Analysis of KiDS-1000 Cosmic Shear

Cosmic shear, the weak gravitational lensing effect on distant galaxies due to matter in the foreground, is a powerful tool to study the distribution of matter, to probe its large-scale structure, and infer the cosmological model of the Universe. Standard analyses are typically based on the assumption of a Gaussian likelihood with a parameter-independent covariance, but these assumptions may not hold for all observables, scales and/or all systematics. Simulation-based inference (SBI) addresses this by evaluating an effective likelihood from forward-simulations which map parameters to data vectors. To this end, I will present a novel application of SBI to a cosmic shear analysis of the Kilo-Degree Survey's KiDS-1000 data release. The forward model is based on lognormal random fields which take into consideration systematics which are typically not modelled in standard inference, such as variable depth, point-spread function variations, shear biases, etc. I will also describe how the simulated galaxy catalogues are compressed to shear-shear angular two-point statistics which are further compressed using score compression. I will show how we train a 12-dimensional neural likelihood estimation to obtain a converged and unbiased posterior of the cosmological parameters within LambdaCDM. We achieve this with only 10,000 model evaluations which run in a time comparable to a standard MCMC. We find that our constraints on the weak lensing parameter, S8, are similar to constraints from previous analyses of KiDS-1000. We note a non-negligible parameter-dependence in the learnt likelihood which is consistent with cosmic variance. At the same time, we find that systematics such as variable depth can have significant impacts on the posterior estimates. Lastly, I will highlight how these findings and SBI will help address the modelling/inference challenges facing upcoming stage IV galaxy surveys.

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Induced gravitational waves: the effect of first order tensor perturbations

Gravitational waves provide a new observational tool to study the universe. Second-order cosmological perturbation theory allows to study gravitational waves sourced by terms quadratic in first order quantities. For example, so-called scalar induced gravitational waves are sourced by first order scalar fluctuations and have been studied extensively. In this presentation I discuss the implications and possibilities of including tensor fluctuations at first order in the source term. I will show how the first order tensor fluctuations change the spectral energy density of the induced waves, particularly on small scales, and will discuss implications for their detectability and observational constraints for models of inflation.

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Testing Beyond-LCDM Cosmologies with Machine Learning

Forthcoming stage-IV cosmological surveys will perform measurements with unprecedented accuracies up to non-linear scales. At this level of accuracy, limitations of our theoretical prescriptions lead to biased predictions for cosmological models. We have developed a novel machine learning approach to detect beyond-standard-model physics in the data using a Bayesian Neural Network and investigate the treatment of theoretical errors that allow the trained network to generalise to different power spectrum prescriptions. Our modelling includes baryonic effects and massive neutrinos to increase the accuracy on non-linear scales and enhance our ability to detect deviations from LCDM.

Based on the halo model reaction framework, we create non-linear dark matter power spectra for a variety of modified gravity and dark energy theories. We use these matter power spectra to train the Bayesian Cosmological Network (BaCoN) that can classify spectra into one of 5 classes: LCDM, f(R), wCDM, Dvali-Gabadaze-Porrati (DGP) gravity and a 'random' class.

Our fiducial classifier with the optimal theoretical error model achieves a total classification accuracy of ˜95%. This greatly bolsters the promise of this method to glean the maximal amount of unbiased gravitational and cosmological information from forthcoming Stage-IV galaxy surveys.

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Nonlinear mixing of vacuum tensor modes during inflation

The recent observation of a gravitational wave background by the NANOGrav collaboration has generated excitement about the possible future detection of primordial gravitational waves. Gravitational waves can be generated by a number of processes during inflation, and their correlation functions can be used to tightly constrain the vast space of inflationary models. But in order to calculate correlation functions for the most chaotic generation mechanism, we must include higher-order dynamics in our analysis. I use the numerical relativity code GRChombo code to study nonlinear mixing between scalar and tensor modes during inflation. We will initialise both the inflaton and the metric with vacuum fluctuations, evolve these fields forward to the freeze-out time and extract their two and three point correlation functions. These results can then be used to study the effect of enhanced gravitational-wave production on the shape of the primordial bispectrum.

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Extremal Black Holes and Quantum Gravity

Extremal black holes are black holes of which the asymptotic charges saturate certain inequalities that ensure weak cosmic censorship. As theoretical playgrounds, they have proven to be instrumental in our understanding of quantum gravity through e.g. microstate counting and swampland conjectures.

Recently, it was noted that extremal black holes generically suffer from singularities on their event horizons. Particular deformations of asymptotically extremal black holes were shown to be marginal, causing the existence of these divergences to strongly depend on even small higher-derivative effective field theory (EFT) corrections, i.e. quantum gravity effects.

In this talk, I will re-examine these singular deformations with a particular focus on the extremal limit and breakdown of perturbation theory. I will then study EFT corrections to a tower of marginally deformed extremal charged black holes in AdS and speculatively derive bounds on EFT coefficients from them. These are closely related to otherwise known bounds from causality, positivity, and the swampland programme, and would provide direct insight into UV completions to GR.

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Constraining the time evolution of gravitational couplings with the CMB

The idea that the strength of gravity may have evolved over cosmic history has attracted considerable attention for several decades. This possibility is often thought of in terms of modified theories of gravity, where, for example, the gravitational coupling is controlled by some new fundamental field. The best constraints to date on the present-day time variation of Newton's constant are obtained from Solar System experiments. They correspond to specific parameters, called the parameterised post-Newtonian (PPN) parameters, that are defined to test gravity in astrophysical settings. Some attempts have been made to study the cosmological evolution of G, but it is not clear that they refer to the PPN parameters rather than to some other coupling. I will present novel constraints on the time variation of the PPN parameters over cosmic history, using data from the cosmic microwave background. These constraints can be combined directly with astrophysical constraints.

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The Cosmic Graph: Optimal Information Extraction from LargeScale Structure using Catalogues

The cosmic web, or Large-Scale Structure (LSS) is the massive spiderweb- like arrangement of galaxy clusters and the dark matter holding them together under gravity. The lumpy, spindly universe we see today evolved from a much smoother, infant universe. How this structure formed and the information embedded within is considered one of the "Holy Grails"of modern cosmology, and might hold the key to resolving existing "tensions"in cosmological theory. But how do we go about linking this
data to theory? Cosmological surveys are comprised of millions of pixels, which can be difficult for samplers and analytic likelihood analysis. This also poses a problem for simulation- based inference: how can we best compare simulations to observed data? Information Maximising Neural Networks (IMNNs) offer a way to compress massive datasets down to (asymptotically) lossless summaries that contain the same cosmological information as a full sky survey, as well as quantify the information content of an unknown distribution. We will look at LSS assembled as a graph (or network) from discrete catalogue data, and use graph neural networks in the IMNN framework to optimally extract information about cosmological parameters (theory) from this representation. We will make use of the modular graph structure as a way to open the "black box"of simulation-based inference and neural network compression to show where cosmological information is stored.

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Spinning up Spinflation

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From number theory to QFT (and beyond)

Inspired by the method of smoothed asymptotics developed by Terence Tao, we introduce a new ultra-violet regularisation scheme for loop integrals in quantum field theory which we call ηeta regularisation. This allows us to reveal a surprising connection between the elimination of divergences in divergent series of powers and the preservation of gauge invariance in the regularisation of loop integrals in quantum field theory. In particular, we note that a method for regularising the series of natural numbers so that it converges to minus one twelfth inspires a regularisation scheme for non-abelian gauge theories coupled to Dirac fermions that preserves the Ward identity for the vacuum polarisation tensor.

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The hot big bang in a cold gas

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Never ending adventures with C-metric thermodynamics

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Stringing Gregory (and Laflamme) along