New Horizons in Primordial Black Hole physics (NEHOP) – ’24

Monday, 17 June 2024 - Thursday, 20 June 2024

National Galleries of Scotland

Book of Abstracts

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Constraining primordial non-Gaussianities with primordial black hole induced gravitational waves

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Ultra-light PBHs with masses $M < 5 \times 10^8 \mathrm{g}$ can dominate transiently the energy budget of the Universe and reheat the Universe through their evaporation taking place before Big Bang Nucleosynthesis (BBN). Interestingly enough, the inhomogeneous distribution of a population of such light PBHs can induce the abundant production of GWs due to second-order gravitational effects. In this talk, we will discuss the effect of primordial non-Gaussianity on the clustering properties of PBHs as well as on the spectral shape of the aforementioned induced GW signal. In particular, focusing on local-type non-Gaussianity we find a distinctive double-peaked GW signal which, depending on the PBH mass M and the initial abundance of PBHs at formation time, i.e. $\Omega_{\mathrm{PBH,f}}$, can lie within the frequency bands of future GW detectors, namely that of LISA, ET, SKA and BBO, hence rendering this signal potentially detectable by GW experiments and promoting it as a novel portal probing primordial non-Gaussianities. Remarkably, by accounting on BBN bounds on the non-Gaussian GW amplitude we set model-independent constraints on the effective τ_{NL} on very small scales $k > 10^5 \mathrm{Mpc}^{-1}$ otherwise inaccessible by CMB and LSS probes.

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θ-vacua, asymmetric Hawking radiation and baryogenesis from primordial black holes

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In empty Minkowski space, the CP-violating electroweak θ-term can be rotated away by the redefinition of quark and lepton states by anomalous B+L phase transformations. I will argue this is no longer true in black hole spacetime, where non-zero θ-term remains on the black hole horizon. This boundary term acts as a source of CP-asymmetric Hawking radiation. The phenomenon may be responsible for cosmological baryogenesis from primordial black holes.

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The Inflationary Butterfly Effect: non-perturbative dynamics from small-scale features

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I will present the first non-perturbative study of a single-field model of inflation with a localized departure from slow-roll. Using lattice simulations, we find that small-scale oscillatory features in the potential can lead to drastic changes in the evolution of the inflationary Universe, with profound phenomenological implications. In certain cases, the entire Universe gets trapped in an eternal de Sitter state. In others, some regions get stuck in a false vacuum within the oscillatory feature, offering an alternative channel for primordial black hole (PBH) formation. Notably, these drastic non-perturbative effects occur when linear perturbation theory predicts $P_\zeta \simeq 10^{-2}$, demonstrating the importance of a fully nonlinear treatment in the regime relevant for PBH formation. Additionally, we compare our fully nonlinear lattice power spectra with perturbative 1-loop calculations.

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Dark Dresses around Primordial Black Holes: Phenomenological Implications

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I will discuss the interplay between the phenomenology of primordial black holes and the dark matter searches. I will focus on how a sub-dominant component of PBHs interacts with the bulk of the DM. In particular, I will describe how a DM "mini-halo"is expected to form around PBHs, with relevant phenomenological consequences. The focus will be on two relevant effects. (i) If the bulk of the DM is composed of WIMPs, the mini-halos would shine in gamma rays. Hence, a hypotetical future detection of a sub-dominant component of PBHs could allow to set very stringent constraints on the WIMP annihilation cross section. (ii) The dark mini-halo can significantly alter the accretion rate of baryonic matter. I will discuss this effect and its impact on the CMB bounds, stressing the importance of the accretion model. I will conclude by carefully reassessing the accretion bounds (both astronomical and cosmological) stressing the relevance of the astrophysical uncertainties.

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Searching for primordial black hole populations with resonant cavities

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The FINUDA magnet for Light Axion SearcH (FLASH) is a large resonant cavity haloscope planned to probe new physics as part of the INFN Frascati National Laboratories near Rome (Italy). The frequency range accessible overlaps with the Very High Frequency (VHF) range of the radio wave spectrum and allows for a search in high frequency gravitational waves (HFGW) in the frequency range (100–300) MHz, allowing to scan for the existence of light primordial black holes in the asteroid mass window. I present the setup of the experiment and the sensitivity forecasts for the detection of HFGWs. The considerations for the astrophysical framework that can be probed are drawn. Based on 2309.00351 and ongoing work.

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Black hole overtones in technicolor

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We present a special property of natural polynomials related to the overtone label of quasi-normal modes for Schwarzschild black holes. The natural polynomials for the radial Teukolsky equation have been the subject of recent, related work. These polynomials, which can be constructed using Gram-Schmidt orthogonalization, produce a basis for the ringdown strain of the black hole mergers. We derive a three-term recurrence relation which allows us to shift overtone peaks using algebraically special frequencies, and to provide insight into the physical significance of the overtone index.

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Classical and stochastic δN formalisms

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The non-Gaussian tail of the PDF of primordial scalar perturbations is a key element to determine the abundance of primordial black holes. These primordial non-Gaussianities arise, at least partly, from the non-linear, super-horizon dynamics of inflationary perturbations. Such non-linear evolution is usually addressed through the stochastic δN formalism. This formalism is based on the deterministic δN formalism, which captures the non-linear relation between curvature and inflaton perturbations, and is then supplemented with the stochastic formalism of inflation, which accounts for the backreaction of quantum fluctuations into large-scale inflaton dynamics. In our work, we reconsider the underlying assumptions and implications of this calculation using both numerical and analytical methods, assessing the validity of several approximations commonly used in the literature.

Based on work in progress with Guillermo Ballesteros, Thomas Konstandin, Mathias Pierre and Julian Rey.

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The mass-distribution of LIGO's events as a probe for dark matter

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Primordial black holes (PBHs) may contribute to the observed abundance of dark matter. We use the black-hole mass distribution obtained from the detected binary black hole merger events by the

LIGO/VIRGO gravitational-wave observatories, with a signal to noise ratio (SNR) > 8. We search for and place limits on PBHs in the stellar-mass range. We also simulate binary black holes following models of formation of two separate populations of merging binaries: stellar-origin binary black holes and PBH binaries. For those we calculate the signal to noise ratio that would result on the LIGO detectors. Selecting only simulated merger events with a SNR > 8, we fit the combination of these two components to the LIGO/VIRGO data. In our work, we rely on a wide range of black-hole mass distributions expected from models of formation of stellar-origin black holes and of PBHs.

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Gravothermalizing into primordial black holes

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Very little is known about the universe's history from after the end of inflation until the Big Bang nucleosynthesis (BBN), which spans more than 10^{39} orders of magnitude in time scales. In this work, we show that if there was a long period of matter domination (at least 10^8 scale factors) in this unknown period, and if the particle causing the matter domination has self-interactions, then the matter particles can undergo gravothermal collapse to form primordial black holes (PBHs). We show that $4 \rightarrow 2$ self-annihilations of the particles can form a 'cannibal star' and inhibit collapse to a black hole for some parameter space. For a range of black hole formation efficiency, we find that CMB and BBN constraints on PBHs can rule out significant regions of EMDE parameter space. Thus, we show how PBHs can offer a new window into a pre-BBN universe.

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Are supermassive black holes primordial?

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Black holes with masses between a million and a billion solar masses are seen in the centres of many galaxies, even at high redshift. Their origin remains unknown and hard to explain, raising the possibility that these black holes are primordial rather than astrophysical. I will discuss the motivation for this scenario and the difficulty in finding a working model, especially due to constraints from CMB spectral distortions which tightly constrain non-standard initial conditions on the relevant length scale for supermassive black holes.

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Light primordial black holes as a viable dark matter candidate

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The energy injection through Hawking evaporation has been used to put strong constraints on primordial black holes as a dark
matter candidate at masses below 1e18 g. However, recent work has shown that Hawking's semi-classical approximation breaks
down at latest after half-decay. Beyond this point, the evaporation could be significantly suppressed. In this work, we review
existing cosmological and astrophysical bounds on primordial black holes. We show that the constraints disappear completely
for a reasonable range of parameters, which opens a new window for light primordial black holes as a dark matter candidate.

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Primordial Black Holes Are True Vacuum Nurseries

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The Hawking evaporation of primordial black holes (PBH) reheats the Universe locally, forming hot spots that survive throughout their lifetime. We propose to use the temperature profile of such hot spots to calculate the decay rate of metastable vacua in cosmology, avoiding inconsistencies inherent to the Hartle-Hawking or Unruh vacuum. We apply our formalism to the case of the electroweak vacuum stability and find that a PBH energy fraction $\beta > 7 \times 10^{-80}(M/\mathrm{g})^{3/2}$ is ruled out for black holes with masses $0.8\,\mathrm{g} < M < 10^{15}$ g.

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Primordial Black Hole probes of Heavy Neutral Leptons

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In this talk, I will discuss possible probes of Heavy Neutral Leptons (HNLs) with Primordial Black Holes (PBHs).
If produced in the early Universe with an initial mass of ~ 10^{15} g, PBHs are expected to evaporate at the present time producing sizable
fluxes of particles in their last instants. These "exploding"black holes will emit bursts of
Standard Model particles as well as new degrees of freedom, if present.
We explore the possibility that HNLs mixing with the active neutrinos
are emitted in the final evaporation stage of PBHs.
We evaluate the active neutrino fluence expected
from such an explosion, to which the decays of the heavy sterile neutrinos contribute through
a secondary emission.
We estimate the expected number of muon-neutrino events at IceCube
and we infer sensitivities on the active-sterile neutrino mixing and the sterile neutrino
mass.

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Signatures of domain wall networks: from gravitational waves to primordial black holes

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The Domain Wall (DW) problem is the fact that DW networks that result from the spontaneous breaking of discrete symmetries tend to dominate the universe's energy budget.
However, if the symmetry is not exact the network annihilates and the problem turns into a virtue, as the network tends to be an abundant component before its collapse, and is thus easier to probe.
In this talk, I will discuss recent progress in the study of the gravitational relics of DW networks - gravitational wave emission and primordial black holes formation - and the interesting possibility that such networks might be behind the recent GW signal observed at Pulsar Timing Arrays.

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Primordial Black Holes from Domain Wall Networks

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Domain Wall Networks are defects of the quantum vacuum which can be generated after phase transition taking place in the early universe. Since we do not observe such objects today, if they form then they must annihilate early on. I will discuss recent advances in our understanding of how Primordial Black Holes can be produced during the annihilation stage. Wormholes to parallel universes can also be generated.

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Uphill inflation

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Primordial black holes (PBH) may form from large cosmological perturbations, produced during inflation when the inflaton's velocity is sufficiently slowed down. This usually requires very flat regions in the inflationary potential. In this talk, I will discuss another possibility, namely that the inflaton climbs up its potential. When it turns back, its velocity crosses zero, which triggers a short phase of "uphill inflation"during which cosmological perturbations grow at a very fast rate. This naturally occurs in double-well potentials if the width of the well is close to the Planck scale. I will discuss the effect of quantum diffusion in this scenario, which plays a crucial role, through the stochastic-δN formalism. Finally, I will discuss the amount of PBH that is expected to be produced in such a model.

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Close Encounters of the Primordial Kind

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Primordial black holes (PBHs) remain a viable dark matter candidate in the asteroid-mass range. I will show that, if PBHs lie within this mass range and make up most or all of the dark matter, the PBH abundance would be large enough for at least one object to cross through the inner Solar System per decade. Since Solar System ephemerides are modeled and measured to extremely high precision, such close encounters could produce detectable perturbations to orbital trajectories with characteristic features. Using a suite of simple Solar System simulations, I will make the case that the abundance of asteroid-mass PBHs can be probed by existing and near-term data, potentially furnishing us with a new direct probe of PBH dark matter.

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Compaction function profiles from stochastic inflation

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Primordial black holes can arise from quantum fluctuations produced during cosmic inflation. Stochastic inflation is a method to compute the fluctuation statistics non-perturbatively, including non-Gaussianities. I discuss recent progress in the numerical implementation of the method, allowing us to compute the radial dependence of the fluctuations' compaction function in random patches of space. These compaction function profiles are needed for accurate black hole predictions. Using example models of ultra-slow-roll inflation, I discuss the spiky, stochastic nature of the profiles, their dependence on the curvature power spectrum, and the implications for the abundance and mass distribution of primordial black holes.

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Relic neutrino decay solution to the excess radio background mystery

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I will first discuss why the excess radio background measured by the balloon borne experiments ARCADE 2 is a mystery and might be an indication of new physics. After having reviewed a few solutions that have been proposed and that are now ruled out I will focus on the possibility that the excess is explained by radiative decays of relic neutrinos, showing how they produce a very nice fit to the data. I will then talk about possible models of neutrino decays able to produced such a solution. I will finally comment on possible links of such a solution with other cosmological anomalies and tensions.

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Timekeepers of the Universe: The recent gravitational wave observation by PTA and PBH.

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The recent data releases by multiple pulsar timing array (PTA) experiments show evidence for Hellings-Downs angular correlations indicating that the observed stochastic common spectrum can be interpreted as a stochastic gravitational wave background. We study whether the signal may originate from gravitational waves induced by high-amplitude primordial curvature perturbations. Such large perturbations may be accompanied by the generation of a sizeable primordial black hole (PBH) abundance. We discuss in which scenarios the inclusion of non-Gaussianities in the computation of the abundance can lead to a signal compatible with the PTA experiments without overproducing PBHs. The talk si based on these papers:
https://inspirehep.net/literature/2759520
https://inspirehep.net/literature/2672979

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Clustering of primordial black holes from quantum diffusion during inflation

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When investigating primordial black hole (PBH) formation scenarios, a central question is to characterise their initial clustering, which then determines their subsequent clustering evolution throughout cosmic history. In this talk I will present how top compute PBH clustering in the presence of non-perturbative non-Gaussianities, making use of the stochastic- δN formalism. To this end, I will show how to derive the two-point statistics of the curvature perturbation in stochastic inflation, consistently including volume-weighting effects. Due to the presence of exponential tails, the joint distribution of large fluctuations is of the form $P(\zeta_{R_1}, \zeta_{R_2}) = F(R_1, R_2, r)P(\zeta_{R_1})P(\zeta_{R_2})$, where ζ_{R_1} and ζ_{R_2} denote the curvature perturbation coarse-grained at radii R_1 and R_2, around two spatial points distant by r. This implies that, on the tail,the reduced correlation function, defined as $P(\zeta_{R_1} > \zeta_c, \zeta_{R_2} > \zeta_c)/[P(\zeta_{R_1} > \zeta_c)P(\zeta_{R_2} > \zeta_c)]-1$, is independent of the threshold value ζ_c. This contrasts with Gaussian statistics where the same quantity strongly decays with ζ_c, and shows the existence of a universal clustering profile for all structures forming in the exponential tails. Structures forming in the intermediate (i.e. not yet exponential) tails may feature different, model-dependent behaviours.

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Cosmological particle production and PBHs

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Among many mechanisms that produce particles via gravitational interactions, the production of particles from the expansion of the universe represents a simple and irreducible source of particles from the early universe, that can account for the present abundance of dark matter. Another feasible and interesting mechanism is to have a population of primordial black holes that, through evaporation, produce the correct amount of dark matter. Since these black holes can alter the cosmological history, inject entropy and emit particles on their own, they can non-trivially impact the graviational production of particles from the expansion and change the predicted fraction of dark matter. In this talk, I will discuss the interplay between these two mechanisms, while highlighting how the final abundance of dark matter changes in the presence of the primordial black holes. We also investigate the possibility of the dark matter produced from the expansion to generate primordial black holes by gravitational collapse, thus providing a novel production mechanism for the latter.

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Gravitational Microlensing of Asteroid Mass PBHs

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Gravitational microlensing is known as a productive method for exoplanet discovery and characterisation, and crucially, it also provides an experimental avenue to constrain the galactic PBH abundance in the mass regime from ~ 10−12 $M_\odot$ (i.e. asteroid-mass scale) to ~ 1000 $M_\odot$. The key to probing the very lowest masses is fast cadence observations on the order of hours to minutes. We previously conducted a 5-night DECam survey of the Large Magellanic Cloud (LMC), monitoring 2 million LMC stars in a single very broad optical filter to a limit of $r \approx 23$ at ≈ 40 second cadence, with the primary motivation being to place constraints on the PBH abundance in the Galactic halo in the asteroid- to Jupiter-mass regime ($-12 \lesssim \log M/M_\odot \lesssim -4$). A galactic halo population of PBHs are a simple solution to the dark matter (DM) problem. Being dark, massive and non-baryonic, the PBH fits the phenological traits defining Cold DM. This talk will present the most stringent results on asteroid-mass PBHs in the Milky Way halo by incorporating considerations of second-order realistic corrections to the microlensing signal, such as finite source effects and wave optics. The main discussion of this talk will be the detection pipeline, a discussion on the pipeline efficiency and 95% C.L on the fraction of PBHs that exist as halo DM within the standard halo model.

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Scalar-Induced Gravitational Waves and its impact in understanding cosmology

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Observations of gravitational waves (GW) from mergers of binary black holes has opened up a new door into cosmology. Due to their weak interaction with matter, we hope to observe Primordial GWs among the various signals that are expected from current and future-generation detectors. This offers a new and exciting opportunity to explore the physics of the early Universe. Quantum vacuum fluctuations are the standard generation mechanism and due to its quantum nature, Primordial GWs come in the form of a stochastic background (SGWB). One contribution to the latter arises from "scalar-induced"GWs (SIGWs), that are produced by second-order effects and coupling of scalar perturbations. Furthermore, the primordial fluctuations which produce SIGWs can additionally collapse to form primordial black holes (PBHs), providing a new channel to study their formations scenario and abundance.

In this talk I will briefly present the motivation to study SIGW. To understand the signature of SIGW that we can observe, I present our computations of the source term, first in a generic gauge and later by imposing the Newtonian gauge. In addition, we discuss how SIGW can be used to understand and probe both standard cosmology and beyond General Relativity, specifically considering modified gravity models. In particular we look at the effect of the modifications in the source term, considering the first-order corrections.

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Superhorizon Spatial Gradients and Implications for PBH Formation

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Accurately predicting primordial black hole (PBH) formation in the early universe requires a knowledge of the full probability distribution function of curvature perturbations. This is typically obtained by employing the δN formalism, a powerful non-perturbative technique which identifies the curvature perturbation with the difference in amounts of logarithmic expansion between perturbed and unperturbed universes. Crucially, the δN formalism relies on the separate universe assumption, which neglects spatial gradients on superhorizon scales. This is a valid approximation during the slow roll phase of single field inflation, but breaks down in models featuring a deviation from slow roll behavior, rendering the δN formalism inapplicable.

Unfortunately such a deviation from slow roll is required for enhancing the comoving curvature perturbation on superhorizon scales, a prerequisite for efficient PBH production. $\mathcal{O}(k^2)$ corrections to the curvature perturbation play a vital role in this enhancement and correspond to $\mathcal{O}(\epsilon^2)$ terms in the gradient expansion, implying the necessity of working to this order in such models. In this talk, we explore the error incurred by using the δN formalism to estimate PBH abundances and non-Gaussianities in such scenarios. For a few tractable examples, we explicitly compare with predictions obtained using the fully non-linear curvature perturbation computed on superhorizon scales working at second order in the gradient expansion.

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Consequence of vorticity in merging black hole prototype

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Vorticity has recently been suggested to be a property of highly-spinning black holes. The connection between vorticity and limiting spin represents a universal feature shared by objects of maximal microstate entropy, so-called saturons. Using Q-ball-like saturons as a laboratory for black holes, we study the collision of two such objects and find that vorticity can have a large impact on the emitted radiation as well as on the charge and angular momentum of the final configuration. As black holes belong to the class of saturons, we expect that the formation of vortices can cause similar effects in black hole mergers, leading to macroscopic deviations in gravitational radiation. This could leave unique signatures detectable with upcoming gravitational-wave searches, which can thereby serve as a portal to macroscopic quantum effects in black holes.

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Gravitational Leptogenesis and Primordial Gravitational Waves during PBH-induced Reheating

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We explore the possibility of dynamically producing the observed matter-antimatter asymmetry of the Universe entirely from the evaporation of primordial black holes (PBH), that are formed in an inflaton-dominated
background. Considering the inflaton (ϕ) to oscillate in a monomial
potential $V(\phi) \propto \phi^n$, we show that it is possible to obtain
the desired baryon asymmetry via vanilla leptogenesis from evaporating
PBHs of initial mass
$lesssim 10$ g. The feasible parameter space is
heavily dependent on the shape of the inflaton potential during reheating
(determined by n), the energy density of PBHs (determined by
β), and the nature of the coupling between the inflaton and the
Standard Model (SM). We further include in our analysis the minimal
gravitational leptogenesis set-up through inflaton scattering via a graviton, that opens up an even larger window for PBH mass, depending on the background equation of state. We finally show that such gravitational leptogenesis scenarios can be tested with upcoming gravitational wave (GW) detectors, courtesy of the blue-tilted primordial GW with inflationary origin, thus paving a way to probe a PBH-induced reheating and leptogenesis era.

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Inflation and primordial black hole production in Starobinsky-like supergravity

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A viable model of large-field (chaotic) inflation with efficient production of primordial black holes is proposed in Starobinsky-like (modified) supergravity leading to the "no-scale-type"Kähler potential and the Wess-Zumino-type ("renormalizable") superpotential. The cosmological tilts are in good (within 1σ) agreement with Planck measurements of the cosmic microwave background radiation. In addition, the power spectrum of scalar perturbations has a large peak at smaller scales, which leads to a production of primordial black holes from gravitational collapse of large perturbations with the masses about 10^{17}g. The masses are beyond the Hawking (black hole) evaporation limit of 10^{15}g, so that those primordial black holes may be viewed as viable candidates for a significant part or the whole of the current dark matter. The parameters of the superpotential were fine-tuned for those purposes, while the cubic term in the superpotential is essential whereas the quadratic term should vanish. The vacuum after inflation (relevant to reheating) is Minkowskian. The energy density fraction of the gravitational waves induced by the production of primordial black holes and their frequency were also calculated in the second order with respect to perturbations.

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How Primordial Black Holes constrain leptogenesis

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The parameter spaces of leptogenesis and ultralight ($M_{\rm PBH} \leq 10^9$g) Primordial Black Holes (PBHs) are notoriously difficult to constrain, but while experiments struggle to probe sterile neutrino masses heavier than a few GeV, the new window into the early universe opened by Gravitational Wave (GW) astronomy offers realistic hopes of detecting GW signals associated with PBHs. Since ultralight PBHs would be born, live and die in or around the era of leptogenesis, even tiny populations can have profound effects on a wide range of leptogenesis models. In particular, for $M_{\rm PBH} \geq 10^6$g, the entropy injection from PBHs has been shown to be highly incompatible with thermal leptogenesis, leading us to draw stringent mutual exclusion limits between the two scenarios. In this talk I discuss how GW observations of PBHs can rule out models of leptogenesis far beyond the reach of direct detection experiments, and how searches for light sterile neutrinos are impacted. I elucidate the fascinating interplay between leptogenesis and PBHs in the early universe, and show how we can glean information about leptogenesis and PBHs from future experimental results. I will also cover some recent and highly interesting developments concerning particle processes in hot-spots.

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Quantum tunneling in the early universe: Stable magnetic monopoles from metastable cosmic strings

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We discuss a novel mechanism for producing topologically stable monopoles (TSMs) from the quantum mechanical decay of metastable cosmic strings in the early universe. For a dimensionless string tension parameter $G\mu \approx 10^{-9} - 10^{-5}$, the monopoles are superheavy with masses of order $10^{15} - 10^{17}$ GeV. The stochastic gravitational wave emission arises from metastable strings with $G\mu \sim 10^{-9} - 10^{-5}$ and should be accessible at HLVK and future detectors, including the Einstein Telescope and Cosmic Explorer. Monopoles with masses of order $10^{8} - 10^{14}$ GeV arise from metastable strings for $G\mu$ values from $\sim 10^{-22}$ to 10^{-10}. We discuss the parameter space for producing these monopoles at an observable level with detectors such as IceCube, KM3NeT, Pierre Auger, and ANITA. This mechanism yields TSMs that carry two units $(4\pi/e)$ of Dirac magnetic charge and some screened color magnetic charge in an $SO(10)$ model.

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Can primordial black holes form without fine-tuning?

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Primordial black holes (PBHs) may form in the early universe, and could have relevance to cosmic evolution, particularly as a dark matter candidate. Forming PBHs requires increased power on small scales, corresponding to some kind of feature in the inflaton potential. I will present a study of the fine-tuning of PBH formation for four representative inflation models, discussing the different sources of tuning and potential mitigation methods

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Evaporating Kerr black holes as probes of new physics

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In the string axiverse scenario, primordial black holes (PBHs) can sustain non-negligible spin parameters as they evaporate. We show that tracking both the mass and spin evolution of a PBH in its final hour can yield a purely gravitational probe of new physics beyond the TeV scale, allowing one to determine the number of new scalars, fermions, vector bosons, and spin-3/2 particles. Furthermore, we propose a multi-messenger approach to accurately measure the mass and spin of a PBH from its Hawking photon and neutrino primary emission spectra, which is independent of putative interactions between the new degrees of freedom and the Standard Model particles, as well as from the Earth-PBH distance.

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Realistic and conservative bounds on primordial black holes from the CMB

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This talk examines the cosmic microwave background (CMB) bounds on solar mass and heavier primordial black holes (PBHs). While the CMB bound is often regarded as the most stringent in this mass regime, its computation relies on several astrophysical assumptions, including accretion geometry, dark matter halo formation, and the treatment of energy injection and deposition. By applying realistic accretion models incorporating ionization fronts and halo effects, we aim to refine these constraints and identify the most conservative bound from current cosmological observations.

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Constraints on Primordial Black Holes From Stars in Ultra-Faint Dwarf Galaxies

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If primordial black holes (PBHs) constitute the dark matter (DM), stars forming in dark-matter dominated environments with low velocity dispersions, such as ultra-faint dwarf galaxies, may capture a black hole at birth. The capture probability is non-negligible for PBHs of masses around 10^{20}g, and increases with stellar mass. Moreover, infected stars are turned into virtually invisible black holes on cosmologically short time-scales. Hence, the number of observed massive main-sequence stars in ultra-faint dwarfs should be suppressed if the DM was made of asteroid-mass PBHs. This would impact the measured mass distribution of stars, making it top-light (i.e. depleted in the high-mass range). Using simulated data that mimic the present-day observational power of telescopes, we show that already existing measurements of the mass function of stars in local ultra-faint dwarfs could be used to constrain the fraction of DM composed of PBHs in the - currently unconstrained - mass range of 10^{19} - 10^{21}g.

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Primordial Black Holes and Induced Gravitational Waves from a Smooth Crossover beyond Standard Model

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GWs induced by primordial fluctuations can be affected by the modification of the sound speed c_s^2 and the equation of state parameter w once the curvature fluctuations reenter the cosmological horizon. That softening can also significantly boost the production of PBHs at the mass scale where the softening arises. In this work, we consider a hypothetical softening of w and c_s^2 caused by a smooth crossover beyond Standard Model theories, for what we numerically compute the secondary induced GWs considering the case of a flat scale-invariant power spectrum. We find that if the amplitude of the power spectrum is sufficiently large, the characteristic feature of the GW signal caused by the smooth crossover can be detected by future space-based gravitational wave interferometers and differentiated from the pure radiation case. At the same time, depending on the mass scale where the crossover occurs, such a scenario can have compatibility with PBHs being all the dark matter when $\mathcal{A} \sim \mathcal{O}(10^{-3})$, with a mass function very sharply peaked around the horizon mass scale of the minimum of the sound speed. Our results show that the GW signal can be used to resolve the

existing degeneracy of sharply peaked mass function caused by peaked power spectrums and broad ones in the presence of softenings of w and c_s^2.

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Numerical First Order QED calculations of Hawking Radiation from Asteroid Mass PBHs

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Asteroid mass primordial black holes (mass $10^{16} - 10^{21}$ grams) are viable candidates to describe the total dark matter content of the universe. One of the interesting features of these primordial black holes (PBHs) being a source of dark matter is their Hawking temperature is greater than 100 keV, meaning that charged particle pairs can easily be created for nontrivial hawking radiation signatures. Because of this generation of particles on Quantum Electrodymanic (QED) energy scales, it is necessary to rigorously investigate the Hawking radiation spectra not just at zeroth order, but also at first order in the coupling constant where electrons and positrons could also interact with emitted photons. Previously, our group has created an analytic expression for the first order Hawking radiation spectra from dissipative effects for a Schwarzschild PBH. This talk will demonstrate the numerical implementation of that result for a range of black hole masses, as well as demonstrate which processes are most impactful at different energy scales. This work is critical in understanding upcoming keV -MeV surveys that will be able to directly search for asteroid mass PBHs, and is part of the first steps towards a complete treatment of QED interactions on black hole spacetimes.

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Primordial black hole formation from a nonspherical density profile with a misaligned deformation tensor

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We perform the numerical simulation of primordial black hole formation from a nonspherical profile of the initial curvature perturbation ζ. We consider the background expanding universe filled with the perfect fluid with the linear equation of state $p = w\rho$ ($w = 1/3$ or $1/5$), where p and ρ are the pressure and the energy density, respectively. The initial condition is set in a way such that the principal directions of the second derivatives of ζ and $\triangle\zeta$ at the central peak are misaligned, where $\triangle$ is the Laplacian. In this setting, since the linearized density is proportional to $\triangle\zeta$, the inertia tensor and deformation tensor $\partial_i\partial_j\zeta$ are misaligned. Thus tidal torque may act and the spin of a resultant primordial black hole would be non-zero in general, although it is estimated to be very small from previous perturbative analyses. As a result, we do not find a finite value of the spin within our numerical precision, giving support for the negligibly small value of the black hole spin for $1/5$
$lesssim w$
$lesssim 1/3$. More specifically, our results suggest that the dimensionless PBH spin s is typically so small that $s \ll 0.1$ for w
$gtrsim 0.2$.

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Cogenesis of baryon and dark matter with PBH and QCD axion

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We study the role of an ultra-light primordial black hole (PBH) dominated phase on the generation of baryon asymmetry of the Universe (BAU) and dark matter (DM) in a type-I seesaw framework augmented by Peccei-Quinn (PQ) symmetry which solves the strong CP problem. While the BAU is generated via leptogenesis from the decay of heavy right-handed neutrino (RHN) at the seesaw scale dictated by the PQ scale, DM can arise either from QCD axion or one of the RHNs depending upon the PQ scale. The ultra-light PBH not only affects the axion DM production via misalignment mechanism, but can also produce superheavy RHN DM via evaporation. Depending upon the PBH parameters and relative abundance of axion DM, axion mass can vary over a wide range from sub-μeV to sub-eV keeping the detection prospects promising across a wide range of experiments. While hot axions produced from PBH evaporation can lead to observable $\Delta N_{\rm eff}$ to be probed at future cosmic microwave background (CMB) experiments, stochastic gravitational waves (GW) produced from PBH density fluctuations can be observed at future detectors like CE, DECIGO, LISA and even future runs of LIGO-VIRGO.

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Primordial black hole formation from cosmological perturbations: recent developments (tentative)

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PBHs may have formed from a sufficiently large amplitude of perturbation in the early Universe. The central aim of the formation studies is to predict the abundance and other properties of PBHs for a given cosmological scenario. Both numerical relativity simulations and analytical investigations play important roles. In this talk I will introduce some of the recent developments, focusing on the dynamics in different situations.

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Observational constraints on the abundance of Primordial Black Holes

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I will overview the current status of observational constraints on the abundance of Primordial Black Holes (PBHs) of all masses, including astrophysical uncertainties on stellar microlensing constraints,

constraints on (more realistic) extended mass functions, and prospects for probing asteroid mass PBHs.

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Determining mass and spin of light PBHs

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We propose methods to determine the mass and spin of PBHs based on measuring specific features of the primary emitted Hawking spectra. In the previous edition of this conference, we focused on masses between 5 × 10^7 and 10^12 kg and adimensional spin parameter a = 0.1–0.5. Now we extend those ranges in distant independent ways.
We investigate values of a ⊠ 0.6, measuring the energy and emission rate at the dipolar and quadrupolar peaks in the primary photon spectrum. This method is valid for any mass of the PBH.
We propose a multi-messenger approach to accurately measure the mass and spin of a PBH from its Hawking photon and neutrino primary emission spectra. This is of particular interest for temperature beyond the TeV scale since it is independent of putative interactions between new possible degrees of freedom and the Standard Model particles.

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Early structure and binary formation with primordial black holes

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Partially due to the detection of gravitational waves LIGO, Virgo and KAGRA (LVK), there has been renewed interest in the possibility that primordial black holes (PBHs) make up all, or a fraction of, dark matter. However, the origin of the LVK black holes is still not well understood. To explore the possibility that (at least some) of the LVK black holes are primordial in nature requires an understanding of the environments in which binary PBHs might and evolve, and how PBHs can affect structure formation. In this talk, I will present the first results from a new suite of fully collisional cosmological simulations with PBH dark matter, looking at how early structure formation is affected, and how this affects the formation and evolution of binary PBHs.

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Primordial black hole formation during preheating?

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One of the main difficulties in scenarios involving primordial black holes (PBHs) are the rather special conditions required to produce them, typically demanding major tunings in the inflationary potential or very specific conditions following phase transitions. Some authors have found a promising alternative in the preheating epoch, just after inflation, when metric feedback would resonantly boost the growth of perturbations to the point of generically creating PBHs. This phenomenon could be followed by simply studying a quadratic approximation for the (post-accelerated expansion) inflaton potential. We revisit this issue, discussing the extent to which: i) This framework effectively eases the formation of PBHs. ii) The quadratic approximation for the inflaton potential generically captures the quantitative dynamics. iii) The inflaton self-potential beyond the quadratic approximation can be used to boost PBH formation.

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Primordial Black Holes: formation and cosmological impact in the current Universe

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Primordial black holes (PBHs) could have been formed in the very early Universe from large amplitude perturbations of the metric. Their formation is naturally enhanced during phase-transitions, because of the softening of the equation of state, from the electron weak transition, corresponding to PBHs as CDM candidate, till the Nucleosynthesis, when the PBHs formed could be the seeds of SMBHs. The quark-hadron phase in particular has received lots of attention recently, with a characteristic scale between 1 and 3 solar masses and the abundance of PBHs significantly increased. Performing detailed numerical simulations we have computed the modified mass function for such black holes, showing that the minimum of the QCD transition works as an attractor solution. Making then a confrontation with the LVK phenomenological models describing the GWTC-3 catalog, we have found that a sub-population of such PBHs formed in the solar mass range is compatible with the current observational constraints and could explain some of the interesting sources emitting gravitational waves detected by LIGO/VIRGO in the black hole mass gap, such as GW190814, and other light events.

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Curvature Perturbations Protected Against One Loop

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I examine one-loop corrections from small-scale curvature perturbations to the superhorizon-limit ones in single-field inflation models, which have recently caused controversy. I consider the case where the Universe experiences transitions of slow-roll (SR) $\longrightarrow$ intermediate period $\longrightarrow$ SR. The intermediate period can be an ultra-slow-roll period or a resonant amplification period, either of which enhances small-scale curvature perturbations. I assume that the superhorizon curvature perturbations are conserved at least during each of the SR periods. Within this framework, I show that the superhorizon curvature perturbations during the first and the second SR periods coincide at one-loop level in the slow-roll limit.

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Black Holes as New Dark Matter Factories

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We present a new general paradigm for the production of dark matter (DM) relic abundance, regurgitated DM, based on the evaporation of early Universe primordial black holes (PBHs) themselves formed from DM particles. We discuss a minimal realization of the model with dark sector in which a first-order phase transition results in the formation of Fermiball remnants that collapse to PBHs, which then emit DM particles. We show that the regurgitated DM scenario allows for DM over many decades in mass, including parameter space considered excluded. Further, we highlight how evaporating PBHs can serve as unique factories of sterile neutrinos in PBH sterile neutrinogenesis, which minimally couple only to active neutrinos. Contrary to the conventionally studied sterile neutrino production mechanisms, this novel mechanism does not depend on the active-sterile mixing. A unique signal is coincidence of induced gravitational waves associated with PBH evaporation and X-rays from sterile decays.

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Characterising spacetime during cosmological collapse

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We look into whether the spherical collapse model is a good approximation in a numerical relativity cosmological simulation and describe the spacetime's evolution during nonlinear collapse. In the simulation, we evolve a quasi-spherical structure, where fully nonlinear initial conditions are provided by perturbing the ΛCDM model with the comoving curvature perturbation, defined as a 3D sinusoidal. Then it is fully evolved with the Einstein Toolkit code. This is compared to the spherical collapse model, and the spacetime's evolution is described with both gravito-electromagnetism and the Petrov classification.

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The inflation trilogy and primordial black hole dark matter

Authors: Paulo Ferraz[1]; João Rosa[1]

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We propose an inflation scenario with three independent stages of cold, warm and thermal inflation, respectively, driven by different scalar fields, motivated by the large number of such fields predicted by most extensions of the Standard Model. We show, in particular, that the intermediate period of warm inflation naturally leads to large density fluctuations on small scales, which can lead to primordial black hole formation in the mass window where they may account for all dark matter. This type of scenario yields a distinctive primordial black hole mass function due to the final period of thermal inflation, which dilutes the abundance of very light black holes.

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Limits on the Burst Rate of Exploding Black Holes

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Primordial Black Holes (PBHs) could play a relevant role in several physical phenomena. They are particularly attractive as a candidate for dark matter, seeds of supermassive black holes, sources of gravitational waves, etc. In addition, the observation of an evaporating black hole would provide definitive information on the elementary particles present in nature, including new degrees of freedom beyond the Standard Model. VHE gamma-ray observatories such as HAWC and LHAASO, among others, provide the technology to potentially detect such an extraordinary and unprecedented event. Although the PBH abundance is tightly constrained in the mass range of interest, we critically revisit the assumptions underlying the bounds and study how they are modified in alternative scenarios where a large number of degrees of freedom are introduced. We also provide a realistic assessment of the capacity of current and future VHE gamma-ray telescopes to detect an exploding PBH in the coming years.

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Constraining Primordial Black Holes through Big Bang Nucleosynthesis

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In this analysis, we investigate the scenario wherein Primordial Black Holes (PBHs) with very low masses ($M_{\rm PBH}$
$lesssim 10^9$ g) undergo evaporation during the Big Bang Nucleosynthesis (BBN) epoch. This evaporation process leads to a non-standard behavior in the expansion rate of the Universe, which plays a crucial role in determining the freeze-out of nuclear reactions. This non-standard expansion rate may have implications for the asymptotic primordial abundance of light nuclei. We present numerical solutions for the background metric, considering different values of PBH mass and abundance at their formation. Subsequently, we share results for the abundances of light nuclei, obtained by incorporating the non-standard Hubble rate into the BBN code Parthenope3.0, such results are then used to obtain upper bounds at 95\% confidence level for the PBHs relative abundance at formation in the range 4×10^8 g
$lesssim M_{\rm PBH}$
$lesssim 10^9\, g$.

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Primordial Black Holes with a Spectator Field

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This presentation introduces a cosmological mechanism featuring a spectator field and investigates its connection to the formation of primordial black holes (PBHs) and dark matter. By considering fluctuations during inflation, we study a natural PBH formation process that doesn't rely on exotic physics in the potential and the fine-tuning issue can be avoided. Observational constraints demonstrate the mechanism's ability to reproduce PBH abundance and mass distribution. This mechanism can be applied in a variety of theoretical framework and it can give us remarkable results.

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Primordial Black Holes - Positivist Perspective and Quantum Quiddity

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I review the observational evidence for primordial black holes from a variety of lensing, dynamical, accretion and gravitational-wave effects. As I will show, all of these (over 20) may be explained by a single and simple unified model, naturally shaped by the thermal history of the Universe. In the second part of my talk, I will comment on the novel feature of vorticity in black holes, which may yield the very first astrophysical observable for quantum effects in these compact bodies.

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Can primordial black holes explain LIGO/Virgo observations?

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The current merger rate prescriptions for primordial black holes (PBHs) only apply to peaked mass distributions. For an extended mass distribution that includes features from the QCD epoch, additional effects must be taken into account that can importantly change these rates. Based on new estimations of the merger rates of early and late PBH binaries, I will present an update of the status of PBHs to explain the LIGO/Virgo observations of compact binary coalescences, and of the allowed dark matter fraction made of stellar-mass PBHs based on gravitational-wave observations.

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Black Holes in the Early Universe

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Cosmology textbooks typically assume that the early universe was dominated by relativistic particles. But if even a relatively small number of black holes were created after inflation, they would have constituted an increasingly large fraction of the total energy density as the universe expanded. I' ll argue that it is well-motivated to scenarios in which the early universe included an era in which low-mass ($< 10^9$ grams) primordial black holes dominated the total energy density. Within this context, I'll discuss Hawking radiation as a mechanism to produce both dark radiation and dark matter. I'll also talk about the possibility that these black holes may have undergone mergers before evaporating, leading to potentially detectable gravitational waves signals, and to the production of a "hot graviton background". Such black holes could have also played an important role in the process of baryogenesis.

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Primordial monopoles, black holes and gravitational waves

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TBC

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Primordial black hole formation from a massless scalar field

Author: Gabriele Palloni[1]

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We consider primordial black holes formation from adiabatic cosmological perturbation of the Early Universe dominated by a massless scalar field. These are sourced by a time independent curvature profile imposed on super horizon scale, corresponding to pure growing modes of the scalar field. Assuming spherical symmetry we study the collapse of these cosmological perturbations using the comoving and the constant mean curvature gauge, showing that the behaviour of a massless scalar field is equivalent to a perfect fluid where the pressure is equal to the total energy density (i.e. equation of state $p = \rho$). Using a numerical code based on the BSSN conformal decomposition, developed specifically for this problem, we computed the threshold δ_c, defined as the peak of the compaction function $\mathcal{C}(r)$ measured on super horizon scales. This is equivalent to the relative mass excess measured at the cosmological horizon crossing.

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Primordial Black Hole Relics as Dark Matter Candidates

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During the talk, I will delve into the unique candidate of Planck mass Primordial Black Hole (PBH) relics as dark matter. These relics, arising from the evaporation of light PBHs with initial masses ranging from 1g to approximately 10^6g, possess the potential to account for the entirety of dark matter in our universe. My presentation will encompass a thorough review of existing constraints on PBH abundance, incorporating the consideration of Planck mass relics. Additionally, I will provide visual representations, such as plots, illustrating the new perspective on dark matter as PBH relics.

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PBH from Numerical Relativity

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We simulated the formation of spinning and non-spinning PBH from the collapse of superhorizon density fluctuations using full numerical relativity in the case of the approximately matter dominated case. We showed that there are two formation mechanism (1) direct collapse where the perturbation itself forms a BH and (2) accretion collapse where the perturbation generate a potential well which causes subsequent BH formation due to accretion. We argue that the dynamics of formation matters in the final properties of the PBH, which is not captured by the usual "kinematics" threshold arguments

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Supermassive primordial black holes for nano-Hertz gravitational waves

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We investigate the formation of primordial black holes (PBHs) during the inflation by nucleation of supercritical bubbles in a multiverse scenario. We find that when the inflaton slowly passes by a neighboring vacuum, the nucleating rate of supercritical bubbles would inevitably attain a peak, so the mass distribution of multiverse PBHs, and the mass of peak can be up to $10^{18} M_{\odot}$. We also present a mechanism for the origin of initial clustering of such supermassive PBHs (SMPBHs), which can significantly magnify the merger rate of SMPBH binaries, and show the possibility that the merging of such SMPBH binaries explains recent NANOGrav signal.

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Dark Matter, Black Holes and Phase Transitions

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Phase transitions can have a dramatic impact on physics in the early universe. We illustrate this by discussing a novel mechanism of dark matter production and a related novel mechanism of primordial black hole production, both of which hinge on cosmological phase transitions.

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The detection of a population of stellar mass primordial black holes

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After many years where the belief that dark matter is in the form of elementary particles has been the dominant paradigm, there is now growing support for the idea that at least in part dark matter is made up of primordial black holes. Although there have been a number of observational and theoretical pointers in this direction, there are two areas where a strong case has been made that primordial black holes have actually been detected. Recently, the detection of gravitational waves from black hole mergers has opened up the possibility that the merging objects are promordial black holes and not stellar remnants. The other area where claims for the detection of primordial black holes have been made is from the microlensing of compact bodies such as stars and quasars. This is the subject of my talk, where I shall present evidence that the population of compact bodies responsible for the observed microlensing is made up of stellar mass primordial black holes, and that these bodies must make up at least a substantial fraction of the dark matter.

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One-loop power spectrum in ultra slow-roll inflation and implications for primordial black hole dark matter

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A possible way to generate primordial black holes as candidates for the entirety of dark matter is a large power spectrum of inflationary curvature fluctuations. Recently, questions have been raised regarding the validity of perturbation theory in this context. We compute the one-loop power spectrum in ultra-slow roll inflation, including all relevant interactions for such analysis, along with counterterms that absorb the ultraviolet divergences. We compare the one-loop and tree-level contributions to the power spectrum, finding that perturbation theory remains valid in realistic ultra-slow roll models.

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Assembling PBH Dark Matter from Evaporating PBH Mergers

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We introduce a novel mechanism for making primordial black hole (PBH) dark matter from the mergers of unstable PBH progenitors.
Since PBH redshift like non-relativistic matter, they can
dominate the energy density of the early universe even if produced with only a tiny initial abundance. Once established, this era of black hole domination (BHD) is only empirically viable if PBH evaporates via Hawking radiation to restore a radiation-dominated universe before big bang nucleosynthesis, corresponding to PBH masses $m < 10^9$ g (lifetimes < 1s). Since cosmological perturbations grow appreciably during BHD, the PBHs form halos and merge to change the initial PBH mass distribution. We find that some BHD halos enter a runaway merger regime during which their constituent PBHs merge many times to become cosmologically stable dark matter candidates.

Registration / **70**

Arrival / Registration

Registration / **71**

Welcome