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Summary of Doctoral Research Work

The theory of general relativity (GR) is remarkably consistent with observations and experiments and passed all the stringent tests in the weak-field limits. However, in the strong-gravity regimes, it is relatively unexplored, and the rooms to its modifications are still open. The modified theories of gravity (MTG), differing significantly from GR in the strong-field regime, aim to settle the long-standing unresolved issues that the GR could not adequately answer. It is thereof essential to investigate the predictions and test the validity of gravity theory in the conceivable extreme field regimes, particularly around the black hole (BH) horizon. In my doctoral research work, I have focused in four more specific directions connected to this broader goal, which I list below:

Rotating BHs in MTGs: My doctoral thesis is devoted to the rotating BHs arising in MTGs, which usually carry non-trivial *hairs* and encompass the Kerr solution as a particular case. We investigated the rotating BH solutions of $4D$ regularized Einstein-Gauss-Bonnet (EGB) gravity, Einstein gravity with non-minimally coupled spontaneously Lorentz violating tensor field, asymptotically safe gravity, Einstein gravity with non-linear electrodynamics (NED) field, black string in dRGT massive gravity, nonsingular Kerr-Sen BH, and non-conservative Rastall gravity. Besides investigating these BHs over a wide range of contexts and emphasizing their prominent differences from the Kerr BH, we also tested them against the observations to check their viability for astrophysical BH candidates.

Shadows and BH parameter estimation: The current observational facilities for horizon-scaled BH imaging have unprecedented capabilities to test both the MTGs in the extreme-field regime around the horizon and to unravel the astrophysical BHs nature. For this purpose, we proposed a general formalism characterizing a haphazard BH shadow using novel astronomical observables to estimate the precise value of BH's parameters. Our robust method is applicable to arbitrary shadows (irrespective of their shape and size), and most importantly, it can be implemented without knowing the BH center position and thus coordinate independently by different teams analysing the same noisy data. Further addressing the question of testing the no-hair theorem, we have empirically shown that a given Kerr BH shadow can be very-well reconstructed by rotating regular BHs; however, the parameters' values vary in the considered BH models. Our analysis asserts that a given shadow does not correspond to a unique BH. I have also been interested in the observational consequences of exotic spacetimes and firstly established that, in striking contrary to the Kerr-naked singularity, no-horizon rotating regular spacetimes over a finite parameter space cast closed photons ring similar to that of a Kerr BH. Our findings firmly support the idea that the mere existence of a closed photons ring does not by itself confirms a BH.

Testing MTG BHs using lensing and shadows: Testing the validity of the no-hair theorem and MTG's BHs, using gravitational lensing and shadow, through EHT observations has been the central focus of my research work. Although the MTG BHs shadows are found smaller and distorted than that of the Kerr BH, over a limited parameter space they satisfy the M87* BH shadow observables within the 1σ bounds deduced by the EHT. The detailed investigations reveal that modelling Sgr A* as an MTG BH and considering the source star in the Galaxy's bulge, the light deflection angle is smaller, images angular separation is larger and images magnification is smaller than that for the Kerr and Schwarzschild BHs and corrections are feasibly measurable with the current observational outreaches. Our findings did not completely rule out the MTG BH, but tightly constrain them within the existing observational facilities; this is remarkably consistent with the EHT results.

BHs thermodynamical phase transitions: We obtained an exact black string solution in the dRGT massive gravity theory, bypassing the Throne's hoop conjecture and Hawking's uniqueness theorem. The solution has rich features and generalizes the other known solutions in GR. From thermodynamics study, it follows that non-zero graviton mass leads to the Hawking-Page phase transition, which is absent for the usual rotating-AdS/dS black string. In the NED charged $4D$-AdS BH spacetimes the GB coupling instigates double second-order phase transitions. Identifying the van der Waals like small-large BH first-order thermodynamical phase transition in the extended phase space was crucial finding in this research line. The Hawking evaporation eventually leads to the thermodynamically stable remnant, whose size increase with GB parameter.

List of Publications

The thesis is based on the following publications:

1. *Black Hole Parameter Estimation from Its Shadow*
Rahul Kumar, Sushant G. Ghosh
Astrophys.J. **892**, 78 (2020).
2. *Testing Rotating Regular Metrics as Candidates for Astrophysical Black Holes*
Rahul Kumar, Amit Kumar, Sushant G. Ghosh
Astrophys. J. **896**, 89 (2020).
3. *Photon Ring Structure of Rotating Regular Black Holes and No-Horizon Spacetimes*
Rahul Kumar, Sushant G. Ghosh
arXiv:2004.07501 [gr-qc].
4. *Shadow Cast and Deflection of Light by Charged Rotating Regular Black Holes*
Rahul Kumar, Sushant G. Ghosh, Anzhong Wang
Phys. Rev. D **100**, 124024 (2019).
5. *Gravitational Deflection of Light and Shadow Cast by Rotating Kalb-Ramond Black Holes*
Rahul Kumar, Sushant G. Ghosh, Anzhong Wang
Phys. Rev. D **101**, 104001 (2020).
6. *Rotating Black Holes in* 4*D Einstein-Gauss-Bonnet Gravity and Its Shadow*
Rahul Kumar, Sushant G. Ghosh
J Cosmol. Astropart Phys. **07**, 053 (2020).
7. *Rotating Black Strings in de Rham-Gabadadze-Tolley Massive Gravity*
Sushant Ghosh, **Rahul Kumar**, Lunchakorn Tannukij, Pitayuth Wongjun,
Phys. Rev. D **101**, 104042 (2020).

The following publications are not included in this thesis

1. *Gravitational Lensing by Black Holes in* 4*D Einstein-Gauss-Bonnet Gravity*
Shafqat Ul Islam, **Rahul Kumar**, Sushant G. Ghosh
J Cosmol. Astropart Phys. **09**, 030 (2020).
2. *Shadow and Deflection Angle of Rotating Black Hole in Asymptotically Safe Gravity*
Rahul Kumar, Balendra Pratap Singh, Sushant G. Ghosh
Annals Phys. **420**, 168252 (2020).
3. *Gravitational Lensing by Charged Black Hole in Regularized* 4*D Einstein-Gauss-Bonnet Gravity*
Rahul Kumar, Shafqat Ul Islam, Sushant G. Ghosh
arXiv: 2004.12970 [gr-qc]. Accepted in EPJC.
4. *Generating Black Holes in the* 4*D Einstein-Gauss-Bonnet Gravity*
Sushant G. Ghosh, **Rahul Kumar**
arXiv:2003.12291 [gr-qc]. Accepted in CQG.
5. *Bardeen Black Holes in the Novel* 4*D Einstein-Gauss-Bonnet Gravity*
Arun Kumar, **Rahul Kumar**
arXiv:2003.13104 [gr-qc].
6. *Phase Transition of AdS Black Holes in* 4*D EGB Gravity Coupled to Nonlinear Electrodynamics*
Dharm Veer Singh, **Rahul Kumar**, Sushant G. Ghosh, Sunil D. Maharaj
arXiv: 2006.00594 [gr-qc].
7. *Rotating Black Hole in Rastall Theory*
Rahul Kumar, Sushant G. Ghosh
Eur. Phys. J. C **78**, 750 (2018).
8. *Accretion onto a Noncommutative Geometry Inspired Black Hole*
Rahul Kumar, Sushant G. Ghosh
Eur. Phys. J. C **77**, 577 (2017).
9. *Rotating Black Hole Shadow in Rastall Theory*
Rahul Kumar, Balendra Pratap Singh, Md Sabir Ali Sushant G. Ghosh
arXiv:1712.09793 [gr-qc].