Indian Association for General Relativity and Gravitation

First IAGRG School on Gravitation and Cosmology

Causal Structure of Black Holes and Quasi-Normal Modes

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1 Main points to remember

- **Course Webpage**: I have created a webpage, where all the details regarding this course will be posted. You are encouraged to check the webpage in regular intervals. You can access it by clicking here. Or, copy paste the following url to your browser: *https://sumantachakraborty.weebly.com/iagrg-school-2022.html*.
- **Class Schedule and Tutorials**: There will be **six** lectures and **four** tutorials, each having length of one and a half hours over the duration of the school.
- **Communications**: The mode of communication outside class will be through emails. Thus I would request all of you to check emails at least once everyday during the school. The assignments as well as other instructions will be handed over through emails only.

2 Plan for the lectures and Timeline

I provide below the plan for each lectures and their timeline. This course will start from the black holes and their causal structure and eventually expand to the study of their perturbations under scalar, electromagnetic and gravitational influences. Finally, various characteristics of the Quasi-Normal modes and their implications for the nature of compact objects will be presented.

- **Lecture 1 (11:45 AM — 1:15 PM) [16.05.2022]**: Gravity as geometry, Principle of equivalence, Geodesic equation, Einstein's equations, Black holes in general relativity and beyond, Penrose Diagram of Schwarzschild spacetime.
- **TA 1 (11:45 AM — 1:15 PM) [17.05.2022]**: This will be based on parts of the questions in the project - I. Broadly, some part regarding the geometry and causal structure of dS and AdS spacetimes will be discussed.
- **Lecture 2 (10:00 AM — 11:30 PM) [18.05.2022]**: Perturbation of static and spherically symmetric black hole spacetimes, Scalar and electromagnetic perturbations, Obtaining the master equation and resemblance with the Schrödinger equation.
- **TA 2 (11:45 AM — 1:15 PM) [18.05.2022]**: This will be based on parts of the questions in the project - I. Broadly, some part regarding the geometry and causal structure of dS and AdS spacetimes will be discussed.
- **Lecture 3 (10:00 AM — 11:30 PM) [19.05.2022]**: Gravitational perturbation of static and spherically symmetric black holes. Axial and Polar perturbations. The Regge-Wheeler gauge and associated master equation.
- **TA 3 (11:45 AM — 1:15 PM) [19.05.2022]**: Project on WKB analysis will be discussed. In particular, the project will involve possible connection of the WKB modes in the eikonal limit with properties of the photon sphere,
- **Lecture 4 (10:00 AM — 11:30 PM) [20.05.2022]**: Solving for the Quasi-Normal Modes using the WKB approximation.
- **Lecture 5 (10:00 AM — 11:30 PM) [21.05.2022]**: Method of continued fraction in order to determine the Quasi-Normal modes for static and spherically symmetric black hole.

- **Lecture 6 (11:45 AM — 1:15 PM) [21.05.2022]**: Quasi-Normal modes for exotic compact objects, wormholes and quantum black holes, Method of matching coefficients, emergence of echoes, Signatures of non-black hole nature of compact objects in observational avenues other than Quasi-Normal modes.
- **TA 4 (3:00 PM — 4:30 PM) [21.05.2022]**: Associated caveats with the photon sphere modes and the connection with the Strong Cosmic Censorship Conjecture.

3 Basic References

I list below the basic references necessary for this course. More advanced references will be provided at the end of each lectures.

- *Gravitation: Foundation and Frontiers* — T. Padmanabhan — Cambridge University Press.
- *A Relativists Toolkit* — E. Poisson — Cambridge University Press.
- *General Relativity* — R.M. Wald — Chicago University Press.
- *The large scale structure of spacetime* — S.W. Hawking and G.F.R. Ellis — Cambridge University Press.
- *The Mathematical Theory of Black Holes* — S. Chandrasekhar — Oxford University Press.
- *Gravitation* — C. Misner, K.S. Thorne and J.A. Wheeler — Freeman Publishers.
- *Exploring Black Holes* — E.F. Taylor and J.A. Wheeler — Freeman Publishers.
- *The Nature of Space and Time* — S.W. Hawking and R. Penrose — Princeton University Press.
- *Gravity* — E. Poisson and C. Will — Cambridge University Press.
- *Gravitational Waves: Volume 1: Theory and Experiments* — M. Maggiore — Oxford University Press.
- *Black Holes* — P.K. Townsend — arXiv:gr-qc/9707012.
- *Black Holes* — H. Reall — Link: http://www.damtp.cam.ac.uk/user/hsr1000.
- *Geometry and Physics of Black Holes* — E. Gourgoulhon — Link: https://luth.obspm.fr.
- *Introduction to The Theory of Black Holes* — G. 't Hooft — Link: http://www.staff.science.uu.nl.