Day 1:

Phil Armitage (CCA)

The Athena / Zeus contribution to planet formation

As pioneering examples of open science, Jim's Athena and Zeus families of codes have enabled multiple advances in planet formation. The talk will highlight the progress that has been made in understanding the physics of protoplanetary disks, the formation of planetesimals, and the accretion of planetary envelopes. I will also discuss some of the areas where further computational and theoretical advances are needed.

Matt Kunz (Princeton University)

Looking in the (magnetic) mirror: lessons in life and anisotropic transport with Jim

Omer Blaes (University of California, Santa Barbara)

Radiation MHD in Accretion Flows: The Debt We Owe to Jim

I will review the role that radiation MHD plays in a number of astrophysical accreting systems, and how Jim Stone's contributions over his illustrious career have been critical in achieving much of what we now understand.

Shane Davis (University of Virginia)

Radiation Magnetohydrodynamics of Black Hole Accretion

I will review some of the highlights of working with Jim (and Yan-Fei and several others!) on the development of (general relativistic) radiation hydrodynamics methods in Athena, Athena++, and AthenaK. I will particularly focus on applications to studying accreting black holes, discussing recent results on the winds and/or accretion flows in X-ray binaries, AGN, and ultraluminous X-ray sources.

Eliot Quataert (Princeton)

Polarimetric signatures of energy extraction from a spinning black hole

I will describe ideas on how the interplay of computation, theory and observations can be used to test the long-standing prediction that the rotational energy of black holes can be extracted to power astrophysical jets. Most of this is based on analytical reasoning but simulations are useful too.

Tom Gardiner (Sandia National Laboratories)

Athena in the Beginning (Numerics, Principles, Science & Lessons Learned)

The development of Athena began around 2001 as an effort to develop a multidimensional, Godunov MHD code and share it with the astrophysics community. Since then, Athena has grown substantially in the physical systems that it models and numerical techniques employed. This conference, scientific community and the steadfast technical progress made with Athena demonstrate success of the original vision. In the beginning, however, this success was far from assured. In this talk I'll share some early history of developing Athena, the challenges we faced and lessons learned along the way.

Lunch

Takayoshi Sano(Osaka University)

TBD

Daniel Proga (University of Nevada, Las Vegas)

A personal view of the scientific career of Jim Stone - a computer charmer who has been figuring out the physics of fluid flows in the heavens.

I present my view of Jim Stone's career achievements of which there are very many. In this presentation, I shall be able to refer to but just two of them: 1) solving hard problems where few simplifications are justified and an exact treatment of physical processes is needed, e.g., where neither the streaming limit nor the diffusive limit applies as in black hole accretion disks and pioneering computational radiation hydro or where non-ideal MHD effects are important as in protoplanetary disks; 2) designing, developing, and extending codes that take full advantage of the most advanced computational hardware and software practices. For over three decades, Jim has been generously sharing with our community his insights and his tools. The latter become very quickly the 'industry standards' and allow very many researchers of all ages to make their own scientific achievements, myself included.

Eve Ostriker (Princeton University)

Building a dynamic model of the ISM with Zeus, Athena, and Jim

Jianjun Xu(Amazon Web Services)

Running Athena++ in the Cloud

A brief demo of how to run Athena++ on AWS ParallelCluster using Jupyter Notebook and Slurm REST API.

Steve Balbus (Oxford University)

Recalcitrant problems of classical disc theory

Despite a half-century of development, our understanding of even relatively simple disc models remains incomplete in important ways. In particular, black hole accretion discs are marked by a transition from a slow, inward drift velocity arising from turbulent diffusion to a ballistic inspiral at the innermost stable circular orbit (ISCO) radius. A detailed understanding of ISCO dynamics and emission is essential for modelers seeking to extract the mass and angular momentum of the host black hole. I will review recent theoretical progress that has been made on this problem, and discuss the future role that will be played by Athena ++ in allowing these ideas to be rigorously tested.

Charles Gammie(University of Illinois)

Inspiring Convergence

I will review 30 years of collaborations in computational astrophysics with Jim and his codes, from ZEUS to athena++.

Peter Teuben (University of Maryland)

Stoneware through the ages

I will highlight Jim's contributions through the software ages, and contrast with other related software. Software is establishing mature roots in the triad of paper, data and software, and I will discuss its ecosystem and where this might lead to in the future.

Day 2:

Sean Ressler(CITA - University of Toronto)

Multi-Scale Wind-Fed Simulations of Sagittarius A*

I will present results from nested, multi-scale MHD/GRMHD simulations of the accretion flow around Sagittarius A* (Sgr A*). These simulations track the gas emitted by massive stellar winds orbiting the black hole and include radiative cooling, electron thermodynamics, and nonzero electron spin. The results can provide insight into tilted disks, jet propagation, and more for Sgr A* and other accreting black holes.

Minghao Guo(Princeton University)

Toward Horizon-scale Accretion onto Supermassive Black Holes in Elliptical Galaxies

We present high-resolution, three-dimensional hydrodynamic simulations of the fueling of supermassive black holes in elliptical galaxies from a turbulent medium on galactic scales, taking M87* as a typical case. The simulations use a new GPU-accelerated version of the \texttt{Athena++} AMR code, and span more than 6 orders of magnitude in radius, reaching scales similar to the black hole horizon. The key physical ingredients are radiative cooling and a phenomenological heating model. We find that the accretion flow takes the form of multiphase gas at radii less than about a kpc. The cold gas accretion includes two dynamically distinct stages: the typical disk stage in which the cold gas resides in a rotationally supported disk and relatively rare chaotic stages ($\lesssim 10\%$ of the time) in which the cold gas inflows via chaotic streams. Though cold gas accretion dominates the time-averaged accretion rate at intermediate radii, accretion at the smallest radii is dominated by hot virialized gas at most times. The accretion rate scales with radius as $\dot{M}\propto r^{1/2}$ when hot gas dominates and we obtain $\dot{M}\simeq10^\mathrm{-4}-10^\mathrm{-3}\,M_\odot\,\mathrm{yr^{-1}}$ near the event horizon, similar to what is inferred from EHT observations. The orientation of the cold gas disk can differ significantly on different spatial scales. We propose a subgrid model for accretion in lower-resolution simulations in which the hot gas accretion rate is suppressed relative to the Bondi rate by $\sim (r_\mathrm{g}/r_{\rm Bondi})^{1/2}$. Our results can also provide more realistic initial conditions for simulations of black hole accretion at the event horizon scale.

Prasun Dhang (CU Boulder)

How make an accretion disk MAD?

It is proposed that the presence of a radiatively inefficient accretion flow (RIAF), saturated with large-scale poloidal magnetic flux, popularly known as a magnetically arrested disk (MAD) close to the black hole (BH) is conducive for jet formation. However, its origin remains poorly understood. Two plausible sources of the large-scale magnetic fields are i) in-situ generation of the magnetic field by dynamo action and ii) advection of the large-scale field from an external source (e.g., e.g. the companion star in X-ray binaries, magnetized ambient medium in AGNs). We studied the efficiency of both processes in a RIAF using 3D global general relativistic magnetohydrodynamic (GRMHD) simulations. We first re-confirm that the MRI dynamo is inefficient in generating a strong large-scale magnetic field in the RIAF and does not spontaneously form a magnetically arrested disk (MAD). We next investigate the other possibility- the accumulation of the large-scale magnetic field due to its inward advection from external sources. Although the geometry of the external fields is quite uncertain, they are likely to be closed. As a first study, we treat them as closed field loops of different sizes, shapes and field strengths. Unlike earlier studies of flux transport, where magnetic flux is injected in the initial laminar flow, we injected the magnetic field loops in the quasi-stationary turbulent RIAF in inflow equilibrium and followed their evolution. We found that a substantial fraction (~15-40%) of the flux injected at the large radii reaches the BH with a weak dependence on the loop parameters except when the loops are injected at high latitudes, away from the mid-plane. The relatively high efficiency of flux transport observed in our study hints that a MAD might be formed relatively easily close to the BH, provided that a source of the large-scale field exists at the larger radii.

Wenrui Xu (Flatiron Institute, CCA)

A new model for 3D radiatively inefficient accretion flows

In recent years, global 3D simulations of radiatively inefficient accretion flows show an interesting trend. The accretion flows are often highly turbulent and diskless, with a power-law radial density scaling with slope ≈ -1. These results are consistent with observational constraints, but do not match existing theories of self-similar accretion flows which generally assume a disk-like geometry and/or predict different slopes. We develop a theory for this new class of accretion flow, which we dub simple convective accretion flows (SCAFs). We start from a simple example of a SCAF in hydrodynamic athena++ simulations, and develop a theory to explain and predict key flow properties. We also argue that the properties of SCAFs are relatively insensitive to additional physical ingredients such as cooling and magnetic field, which explains its common appearance in simulations with different setups and makes SCAFs a potentially important component in the theory of compact object accretion flows.

Christopher Bambic (Princeton University)

Local shearing-box models of two-temperature AGN coronae: Structure, outflows, energetics, and conduction

We use local stratified shearing-box simulations to elucidate the impact of two-temperature thermodynamics on the thermal structure of coronae in radiatively efficient accretion flows. Rather than treating the coronal plasma as an isothermal fluid, we use a simple, parameterized cooling function which models the collisional transfer of energy from the ions to the rapidly cooling leptons. Two-temperature models naturally form temperature inversions, with a hot, magnetically dominated corona surrounding a cold disc. Simulations with net vertical flux (NF) launch powerful magnetocentrifugal winds that would enhance accretion in a global system. The outflow rates are much better converged with increasing box height than analogous isothermal simulations, suggesting that the winds into two-temperature coronae may be sufficiently strong to evaporate a thin disc and form a radiatively inefficient accretion flow under some conditions. Field-aligned thermal conduction from the hot corona into the cold disc may aid in this evaporation process, and we provide estimates for the field-aligned free-streaming heat flux into the disc. These estimates can be compared to our most recent work, which implements conduction into the shearing-box framework. We find evidence for multiphase structure in the corona, with broad density and temperature distributions, and we propose criteria for the formation of a multiphase corona. The fraction of cooling in the surface layers of the disc is substantially larger for net-flux (NF) fields compared to zero net-flux configurations, with moderate NF simulations radiating >~30 per cent of the flow's total luminosity above 2 midplane scale-heights. Our work shows that NF fields may efficiently power the coronae of luminous Seyfert galaxies and quasars, providing compelling motivation for future studies of the heating mechanisms available to NF fields and the interplay of radiation with two-temperature thermodynamics.

Coffee

Bri Mills (University of Virginia)

Monte Carlo spectral calculations of Athena++ simulations with multi-group for super-Eddington accretion onto a stellar mass black hole

We provide a comparison between the MC and RMHD simulations showing that the treatment of Compton scattering in the grey RMHD simulations underestimates the gas temperature in the funnel regions above and below the accretion disk. The multi-group approach provides a better estimate of the radiation field, resulting in post-processed spectra with harder X-ray power law tails compared to their grey snapshot counterparts. We show that the MC post-processed spectra are qualitatively similar in shape to some observed ultraluminous X-ray sources, but deviate slightly at harder energies in the case of the ULX NGC 1313 X-1. Nevertheless, considering the limitations of these spectra, they provide an approximate fit to the combined XMM-Newton and NuSTAR observations of NGC 1313 X-1 and shows a promising direction for physically motivated ULX spectral modeling.

Amy Secunda (Princeton University)

Simulating Reprocessed AGN Light Curves Using Multi-Frequency Radiation in Athena++

Reverberation mapping has been widely used to study the size and thermal structure of active galactic nuclei (AGN) disks by measuring the lags of variations in AGN photometry from high frequency to low frequency wavebands. These lags are thought to be a result of the reprocessing of light in different temperature regions of the disk, and occur on the light-crossing timescale, of order a few days. However, the transfer function of this reprocessing and how it can be affected by local variability in the AGN disk is not well understood. Radiation magnetohydrodynamic codes, such as Athena++, make it possible to study how radiation pressure and magnetic fields drive convection and the magnetorotational instability in AGN disks leading to variability. Furthermore, it is also possible to directly study how higher frequency light injected into a cooler region of an AGN disk is reprocessed and re-emitted as lower frequency light by using a recently developed multi-frequency radiation module for Athena++. I will present light curves from new radiation Athena++ simulations and discuss how they can be directly compared to observations to better understand the structure and internal physics of AGN disks.

Sergei Dyda (University of Virginia)

Time Dependent Line Driven Disc Winds - X-ray Irradiation

Line driving is a promising explanation for AGN winds as it provides both a launching mechanism and an explanation for the absorption and emission lines in spectra. As the community moves towards multi-wavelength and multi-epoch observations, our modeling of AGN systems must likewise follow suit to leverage these new capabilities. For line driving to be a viable acceleration mechanism two conditions must exist in the wind 1) The gas must be sufficiently, though not overly ionized by soft X-rays, so that the gas can interact with the UV 2) The UV flux incident on the gas must be high enough to transfer sufficient momentum to overcome gravity. We present novel simulations of AGN disc winds using time-dependent, multi-frequency radiation hydrodynamics focusing on the problem of gas ionization, where we model both the X-ray and UV radiation fields. We consider a suit of models for gas/X-ray interactions and identify the conditions on scattering and absorption opacities where wind self-shielding can operate and allows line driving to launch and robustly accelerate winds.

Yixian Chen (Princeton University)

Radiation Hydrodynamics Simulation of Gravitational Instability in AGN Disks: Radiation Pressure Enhances Star Formation

We perform 3D radiation hydrodynamic local shearing box simulations to study the outcome of gravitational instability (GI) in optically thick Active Galactic Nuclei (AGN) accretion disks. GI develops when the Toomre parameter QT ~ 1, and may lead to turbulent heating that balances radiative cooling. However, when radiative cooling is too efficient, the disk may undergo runaway gravitational fragmentation. In the fully gas-pressure-dominated case, we confirm the classical result that such a thermal balance holds when the Shakura-Sunyaev viscosity parameter alpha due to the gravitationally-driven turbulence is <~ 0.2, corresponding to dimensionless cooling time >~ 5. As the fraction of support by radiation pressure increases, the disk becomes more prone to fragmentation, with an increased critical value of dimensionless cooling time. The effect is already significant when the radiation pressure exceeds 10% of the gas pressure, while fully radiation-pressure-dominated disks fragment at cooling time >~50. Our results suggest that gravitationally unstable outer regions of AGN disks with significant radiation pressure (likely for high/near- Eddington accretion rates) should always fragment into stars, and perhaps black holes.

Tim Waters (LANL)

Simulations of thermal instability using Athena++'s implicit RHD module

The theory of local thermal instability (TI) has recently been extended to radiation hydrodynamics. This modified theory shows just how easy it is for a column of gas irradiated by X-rays to become thermally unstable. All it takes is for the irradiating spectrum to significantly harden. We demonstrate this by presenting local Athena++ simulations run with the implicit radiation hydrodynamics module. When the input spectrum hardens on timescales shorter than the cooling timescale, it becomes possible to study cloud formation occurring in states of thermal nonequilibrium (TNE). We separately discuss our progress on understanding the saturation mechanism of TI analytically, and whether RHD effects modify this understanding.

Lunch

Lizhong Zhang (UCSB)

Magnetic Opacity Effects in Neutron Star Accretion Columns - Results and New Numerical Algorithm

The accretion column can form on a strongly magnetized neutron star at a sufficiently high accretion rate. The column structure is vertically supported by the radiation pressure due to the accretion process and transversely maintained by the strong magnetic field of the neutron star. The physics of the accretion column plays an important role in understanding the observations of accretion-powered X-ray pulsars, including pulsating ultraluminous X-ray sources (ULXs). We perform radiative relativistic MHD simulations to study the nonlinear dynamics of the accretion column with the polarization- and angle-averaged magnetic opacity. The column structure is extremely dynamical and exhibits kHz quasi-periodic oscillations as in the simulations using Thomson opacity. The temperature dependency of the magnetic scattering opacity can alter the column structure and variability. It can also introduce an extra unstable mechanism in accretion column dynamics. To further investigate this problem, we propose to extend the radiation module with the magnetic polarization based on the current numerical framework.

Goni Halevi (Princeton University / IAS)

Magnetic field amplification in post-merger accretion disks

We use AthenaK to study the evolution of tori with realistically complex, rather than purely poloidal, initial magnetic field structures. We initialize tori with either purely toroidal or mixed toroidal and poloidal fields, inspired by numerical relativity simulations of black hole-neutron star mergers that include detailed microphysics and find complicated magnetic field structure in the post-merger disk. With the high resolution enabled by the GPU-accelerated AthenaK, we can probe whether dynamo action occurs in such cases and study its properties.

Tejas Prasanna (Ohio State University)

The early evolution of magnetars

In the seconds following their formation in core-collapse supernovae, proto-magnetars drive neutrino-heated magneto-centrifugal winds. Using a suite of two-dimensional axisymmetric MHD simulations in Athena++, we show that relatively slowly rotating magnetars with initial spin periods of 50-500 ms and polar magnetic field strength of about 10^15 G spin down rapidly to periods greater than 1 s during the neutrino Kelvin-Helmholtz cooling epoch. Since the flow is non-relativistic at early times, and because the Alfven radius is much larger than the proto-magnetar radius, spindown is millions of times more efficient than the typically-used dipole formula. Quasi-periodic plasmoid ejections from the closed zone enhance spindown. We discuss the implications for observed magnetars, including the discrepancy between their characteristic ages and supernova remnant ages. We also speculate on the origin of 1E 161348-5055 in the remnant RCW 103, and the potential for other ultra-slowly rotating magnetars.

On the other hand, we show that rapidly rotating magnetars with initial spin period of less than 5 milliseconds and strong magnetic fields greater than 10^15 G are viable central engines for producing gamma-ray bursts. Millisecond magnetars with moderate magnetic field strengths of about 10^14 G can power super-luminous supernovae.

William Cook (Friedrich Schiller University Jena)

Neutron Star Evolutions with Athena++ in Dynamical Spacetimes

Accurate parameter estimation in future generations of gravitational wave (GW) detectors, for GWs emitted from the merger of binary neutron stars (BNSs), will require more accurate waveform models than are currently available. In order to construct such models, it will be necessary to produce highly accurate numerical relativity waveforms for BNS mergers, beyond those currently available. In this talk we demonstrate the performance of GR-Athena++, a code built on top of Athena++ with the additional capability of the full evolution of the Einstein equations, in evolving general relativistic magnetohydrodynamics problems in a dynamically evolving spacetime. We demonstrate the evolution of neutron stars, with and without magnetic fields, in a dynamical spacetime; and demonstrate scaling properties which will allow highly accurate BNS waveforms to be produced with this code in an efficient fashion.

Coffee:

Morgan MacLeod(Center for Astrophysics)

A heartbreak star: Using Athena to model tidal wave breaking in an extreme heartbeat star system

Heartbeat stars are eccentric binary systems that show photometric variations driven by tides. The characteristic "heartbeat" shape of their light curves gives them their name. I'll discuss using Athena to model the most extreme of this class of objects, which suffers tidal distortions so large that they lose phase coherence and break following each periapse passage.

Jared Goldberg (Flatiron Institute, Center for Computational Astrophysics)

3D Envelopes of Evolved Massive Stars and their Explosions

Motivated in part by the desire to understand the outermost 0.1Msun of Red and Yellow Supergiants responsible for early-time Supernova (SN) emission, we have completed semi-global 3D radiation-hydrodynamics (RHD) simulations of RSG envelopes with Athena++. These envelopes exhibit an extended density structure with large-scale convective plumes spanning large fractions of the stellar surface. Driving a strong shock through these simulations, we show how the 3D structure impacts the duration and brightness of the SN shock breakout signal

Ian Rabago (University of Nevada, Las Vegas)

Warps and Breaks in Protoplanetary Disks

Disks are common features in astrophysical systems at all scales, from planets to stars to galaxies. Though usually planar, external forces can disturb the disk and cause it to become warped. Warped disks are able to explain a variety of observations, such as bending waves in Saturn's rings and periodicity of X-ray binaries, and the study and evolution of these disks is an area of active research. We present Athena++ simulations of accretion disks warped by a central binary star system. Our simulations reproduce the expected theoretical behavior at the high and low viscosity limits. At low viscosities, disk breaking is observed. We provide predictions to the location of the breaking radius, and examine the conditions where repeated breaks can occur.

Haiyang Wang (University of Cambridge)

Hydrodynamical Simulations of Circumbinary Accretion: Balance between Heating and Cooling

Hydrodynamical interaction in circumbinary discs (CBDs) plays a crucial role in various astrophysical systems, ranging from young stellar binaries to supermassive black hole binaries in galactic centers. Most previous simulations of binary-disc systems have adopted locally isothermal equation of state. We use the grid-based code `Athena++` to conduct a suite of two-dimensional viscous hydrodynamical simulations of circumbinary accretion on both a cylindrical grid and a cartesian grid (resolving the central cavity of the binary). The gas thermodynamics is treated by thermal relaxation towards an equilibrium temperature (based on the constant−β cooling ansatz, where β is the cooling time in units of the local Keplerian time). Focusing on equal mass, circular binaries in CBDs with (equilibrium) disc aspect ratio $H/R=0.1$, we find that the cooling of the disc gas significantly influences the binary orbital evolution, accretion variability, and CBD morphology, and the effect depends sensitively on the disc viscosity prescriptions. When adopting a constant kinematic viscosity, a finite cooling time ($\beta \gtrsim 0.1$) leads to binary inspiral as opposed to outspiral and the CBD cavity becomes more symmetric. When adopting a dynamically varying α−viscosity, binary inspiral only occurs within a narrow range of cooling time (corresponding to β around 0.5). The linear theory of eccentric mode in CBD explaining the morphology transition due to cooling effect is also included. The CBD eccentricity is damped most efficiently when cooling time is comparable to the Keplerian period.

Damien Gagnier (Institute of Theoretical Physics, Charles University, Prague)

Post-dynamical inspiral phase of common envelope evolution: Binary orbit evolution and angular momentum transport

Despite its importance, common envelope evolution is far from being fully understood. Great efforts have been made to confront numerical simulations outcomes to observational constraints over the last few decades. 3D hydrodynamical simulations have provided insight into the physical processes important in the dynamical inspiral, the common envelope evolution ejecta dynamics and thermodynamics, or radiation hydrodynamics of the ejecta and the associated transients. However, many ab initio simulations fail to eject the common envelope during dynamical plunge-in when only orbital energy injection by the secondary star is considered, and the obtained post-dynamical inspiral orbital separations are often larger than that observed in post-common envelope systems.

After the companion dynamically plunges through the primary's envelope, the two cores remain surrounded by a common envelope and the decrease of the orbital period stalls. Because of the wide range of temporal and spatial scales that need to be resolved and the associated high numerical cost, the subsequent evolution has never been systematically explored with multi-dimensional simulations.

I will present results from the first 3D hydrodynamical simulations dedicated to the post-dynamical phase by means of an original setup mimicking the preceding dynamical inspiral, making use of the Athena++ code to solve the hydrodynamics equations using an adaptively refined spherical grid. I will show that local advective torques from the mean flow and Reynolds stresses associated with the turbulent flow dominate the angular momentum transport, which occurs outward in a disk-like structure about the orbital plane and inward along the polar axis. I will show that short-term variability in the envelope is remarkably similar to circumbinary disks, including the formation and destruction of lump-like overdensities, which enhance mass accretion and contribute to the outward transport of eccentricity generated in the vicinity of the binary. If accretion onto the binary is allowed, the orbital decay timescale settles to a nearly constant value of the order 1000-10 000 orbital periods, while preventing accretion leads to a slowly increasing orbital decay timescale which reaches 100 000 orbital periods at the end of our simulations. Our results suggest that the post-dynamical orbital contraction and envelope ejection will slowly continue while the binary is surrounded by gas and that the orbital contraction timescale is often much shorter than the thermal timescale of the envelope. Finally, I will briefly present my ongoing work on the role of magnetic fields on binary orbit evolution and on the shared envelope dynamics.

Day 3

Lachlan Lanca (Columbia University)

Feedback from Massive Stars in Turbulent, Ionized, and Magnetized Environments

I will discuss the expansion of feedback bubbles from massive O and B type stars which play a key role in regulating star formation on the scales of giant molecular clouds. In particular I will show how simulating the expansion of such bubble's in realistic, three-dimensional environments can provide a basis upon which to build physical models to explain this expansion and the dependence of different "feedback channels," namely stellar winds and photo-ionizing radiation, on the environment's properties.

Drummond Fielding (CCA)

Push it to the limit: Plasmoids in the Multiphase ISM

The interstellar medium (ISM) is a dynamic environment that lies at the nexus of numerous phenomena that combine to regulate the formation of stars, the growth of supermassive black holes, and the evolution of galaxies. Despite the central importance of the ISM to many astrophysical systems a robust theory of the interplay of thermal instabilities, turbulence, and magnetic fields remains elusive. I will present a new suite of high resolution 3D MHD simulations of thermally unstable turbulent systems representative of the ISM. Throughout these simulations large current sheets unstable to rapid plasmoid-mediated magnetic reconnection form regularly. The resulting plasmoids form in three distinct environments: (i) within cold clumps, (ii) at the asymmetric interface of the cold and warm phases, and (iii) within the warm, volume-filling phase. I will discuss the role of the plasmoid instability in setting the magneto-thermal phase structure of the ISM and the scattering of cosmic rays, as well as how we can use plasmoids as observational probes of uncertain plasma processes.

Ka Wai HO (University of Wisconsin Madison)

Multi phase media and the HI filaments

The ubiquity of very thin and lengthy cold neutral medium (CNM) has been reported by multiple authors in the H I community. Yet, the reason of how the CNM can be so long and lengthy is still in debate. In this paper, we recognize a new type of instability due to the attractive nature of the pressure force in the unstable phase. We provide a new estimation of the average CNM filament aspect ratio with the consideration of force balances at the phase boundary, which is roughly 5–20 in common CNM environment. We show that most of the cold filaments are less filamentary than what usually predicted via MHD turbulence theory or inferred from observations: The average length of CNM filament is roughly 1/2 of that in isothermal MHD turbulence with similar turbulence conditions. This suggests that the ‘cold filaments’ that are identified in observations might not be in pressure equilibrium or generated via other mechanisms.

Lucia Armillota (Princeton University)

Cosmic-ray transport in simulations of star-forming galactic disks

In recent years, there has been an increasing interest in the role of cosmic rays (CRs) in galaxy evolution. Most galaxy simulations including CR physics have shown that CRs can contribute to the dynamics of the interstellar medium (ISM), aiding in the internal support against gravity and in the launching of galactic outflows. However, the extent to which CRs affect these phenomena in simulations is strongly sensitive to the treatment of CR propagation. Recently, we developed a detailed, physically motivated prescription for CR transport, where the CR scattering coefficient varies with the local gas properties. We implemented this prescription in ATHENA++, and used it to compute the transport of CRs within the TIGRESS MHD simulations modeling kpc-sized portions of star-forming galactic disks. In my talk, I will review the main results of this analysis and discuss the potential impact of CRs on the dynamical state of the ISM.

Xiaoshan Huang (University of Virginia)

A First Bright Day for TDEs

The disruption of a star by the tidal force from a supermassive blackhole can power a bright transient flare in multiple wavebands that lasts a few weeks to months. However, the origin of detected electromagnetic emission from tidal disruption events is an unresolved puzzle, especially the optical-ultraviolet emission. In this work, we study an important pre-peak emission mechanism: stream-stream collision by series of 3D radiation hydrodynamical simulations. We show that for a range of fallback rates, the collision efficiently converts debris' kinetic energy to radiation. We found that the strong radiation pressure can drive aspherical optical-thick outflow that extends to larger radius, creating photosphere roughly consistent with pre-peak optical-ultraviolet observations. We'll also discuss the follow-up of this work to simulate the TDE fallback system in more global calculation domain, and the implications of early emissions in different wavebands.

Coffee

Can Cui (University of Cambridge)

Gas Dynamics in Protoplanetary and Debris Disks

Gas dynamics is key to understanding many aspects of planetary systems. In its early stage, the planetary formation processes are largely governed by the gas dynamics in protoplanetary disks. In its later stage, debris disk gas can affect the dust dynamics in the planetesimal belts and potentially lead to the formation of secondary atmospheres of planets. In this talk, I will focus on the gas dynamics in both protoplanetary and debris disks, with a particular emphasis on the physical mechanisms that can drive angular momentum transport and turbulence.

Yisheng Tu (University of Virginia)

Disk formation and evolution in magnetized molecular cloud core with turbulance and ambipolar diffusion using Adaptive Mesh Refinement in ATHENA++

Protostellar disks are formed in magnetized, turbulent molecular clouds. Despite intensive investigation over the last decade, many crucial questions remain regarding the formation of both stars and planets. Three of these questions are: 1) what is the physical structure of the inner envelope; 2) how strongly magnetized is the disk and 3) how important is the magnetic field in the evolution of a formed disk compared with gravity? To address these questions, we use ATHENA++ to conduct a series of 3D non-ideal MHD numerical simulations of protostellar disk formation with turbulence, self-gravity, ambipolar diffusion (AD), and Adaptive Mesh Refinement (AMR). In our models, a protostellar core (a pseudo-Bonner-Ebert sphere) collapses under self-gravity to form a protostar and a protostellar disk. The ambipolar diffusion coefficient and strength of initial turbulence are varied across models. We find that without initial turbulence in the molecular cloud core, a magnetically flattened, rotationally-unsupported disk-like structure (the pseudo-disk) forms in the inner envelope. With initial turbulence, the disk-like structure is disrupted into dense filaments that are compressed by the magnetic field. These filaments carry most of the mass to the protostar but are infalling slower than free-fall due to retardation by the magnetic field. Ambipolar diffusivity determines how much magnetic field is carried by these filaments into the disk, which controls how magnetized the disk is. If ambipolar diffusivity is too weak, only a small (~10au), highly disrupted disk can form. The material in the small disk is kept accreated by the protostar. With more effective ambipolar diffusivity, a larger, more persistent disk can form. The material in the disk would stay in the disk for a sustained period of time and all models with such a persistent disk share a similar degree of magnetization (poloidal plasma beta about 2000). In a persistent, formed disk, the magnetic field is the dominant agent transporting angular momentum out of the disk.

Shinsuke Takasao (Osaka University)

A closer look at star-disk interaction of young stars

Protostars and pre-main-sequence (pre-MS) stars grow while receiving mass, angular momentum, etc. The growth history of the accreting stars depends on the final state of the accreting matter, which is controlled by star-disk interaction at the stellar scale. Pioneering studies such as Miller and Stone (1997) demonstrated the importance of MHD dynamics at this scale. To reveal star-disk interaction, we have been performing 3D MHD simulations of accreting young stars. In this talk we will present the results of accreting stars with and without stellar magnetospheres. We will discuss the accretion-ejection connection and the time variability related to magnetic activities, with a particular focus on 3D effects.

Zhaohuan Zhu (University of Nevada, Las Vegas)

Global Ideal MHD simulations: from net vertical field simulations to magnetospheric accretion

Large scale magnetic fields are thought to be present in astronomical disks. They can be remnant fields from large scale environment or supplied from the central object. We have carried out global ideal MHD simulations threaded by either net vertical fields or stellar dipole fields. These two types of disks share a lot of similarities but also bear significant differences. I will discuss the accretion mechanisms and flow structure in these disks and how they shed light on protoplanetary disk observations and planet formation.

Shangjia Zhang (University of Nevada, Las Vegas)

Vertical Shear Instability in Protoplanetary Disks with Stellar Irradiation

Turbulence plays a crucial part in the gas and dust dynamics in protoplanetary disks. Vertical Shear Instability (VSI) is a promising source of turbulence. We use Athena++ radiation module to study the VSI in full and transition disks, considering radiation transport and stellar irradiation. The location of the inner rim and the radial optical depth are crucial to the disk thermal structure. The thermal structure has a strong impact on all velocity components and turbulence levels in radial and vertical directions. With a temperature gradient in the vertical direction, the typical n=1 corrugation mode disappears in realistic disk setups. The shear can be the strongest near the tau=1 surface for the star, which leads to a strong accretion. Depending on the location of the inner rim, the radial-azimuthal turbulence stress at several gas scale heights can be stronger than that in the vertical isothermal simulations, closer to the vertical-azimuthal stress (~1e-2). In the midplane, both stress terms can be weak (~1e-4-1e-3). The observed strong dust vertical settling in dust continuum observations can be explained by the weak turbulence in the midplane and the closer-to-isotropic turbulence levels between radial and vertical directions near or above the midplane.

Lunch

Konstantin Gerbig (Yale University)

On the Prospects of Hurricane-like Vortices in Protoplanetary Disks

Protoplanetary disks are the birthplaces of planets, and as such, the physical processes operating within are of great interest. I will present our recent results that point at the possibility of hurricane-like storms being active in protoplanetary disks. When water ice on the surface of dust grains sublimates, it adds its latent heat of sublimation to the enthalpy of the surrounding flow. Drawing on the analogy provided by tropical cyclones on Earth, we investigate if, and under which conditions, this energy source is sufficient to sustain or magnify anticyclonic disk vortices that would otherwise fall victim to viscous dissipation. Our analytical treatment, supported by exploratory two-dimensional simulations in Athena++, suggests that even modestly under-saturated flows can significantly extend the lifetime of vortices found near the disk's water ice line, which ultimately affects particle trapping and planet formation.

Ruobing Dong (University of Victoria)
Using Athena++ to study planet formation and disk-planet interactions

Planets form in gaseous protoplanetary disks surrounding newborn stars. As they do, they gravitationally interact with the disk, and produce structures. I will introduce a few projects in which we use Athena++ to study planet formation and disk-planet interactions.

Xiaoyi Ma (University of Victoria)

Simulating rings and gaps induced by vortices using Athena++

The co-existence of crescents and rings has been observed in protoplanetary disks in dust continuum emission, such as the HD143006 disk. The crescents in continuum emission have been proposed to be the dust-trapping vortices produced by Rossby Wave Instability. We hypothesize that the RWI vortices could induce rings and gaps by driving density waves, analogous to planets. We study the properties of density waves and substructures induced by vortex in 2D hydrodynamic simulations in both global disks and shearing sheet performed via Athena++. We aim to find ring and gaps induced by vortices in disks similar to those found in observations.

Yuhiko Aoyama (Peking University)

Type II planet-disk interaction in windy protoplanetary disks

Recent studies have established magnetized disk winds as the primary mechanism driving accretion and evolution in protoplanetary disks, which can co-exist with turbulence from the magneto-rotational instability (MRI) in the outer disk. We conduct 3D global non-ideal magnetohydrodynamic (MHD) simulations of type-II planet-disk interaction that properly resolves the MRI turbulence and accommodates the MHD disk wind. We found that the planet triggers the poloidal magnetic flux concentration around its orbit, likely associated with spiral density shocks. The concentrated magnetic flux strongly enhances angular momentum removal in the gap region and alters the torque balance, making the planet-induced gap shape more similar to an inviscid disk, while being much deeper. The gap region is characterized by a fast trans-sonic accretion flow that is asymmetric in azimuth about the planet and lacks the horseshoe turns. The formation of a magnetized circumplanetary disk will also be discussed.

Sabina Sagynbayeva (Stony Brook University)

Feeding giant planets: accretion onto circumplanetary disks

Circumplanetary disks, of which the disk in the PDS 70 system is the first directly observed example, play a crucial role in the accretion of material onto planets, as well as in the formation of their satellite systems. By studying the properties of circumplanetary disks, we can gain insight into the role they play in shaping the Solar System and other planetary systems. In our work, we developed high-resolution 3D hydrodynamical simulations with Athena++ to study angular momentum transport onto CPDs. Angular momentum accretion onto CPDs determines the overall long-term disk evolution, and helps us understand the accretion of dust that creates planetary satellites. We present results from nested mesh simulations that will help us understand the early stages of the formation of Solar System and extrasolar gas giants and potentially their satellites.

Jordan (JT) Laune (Cornell University)

The effects of gas accretion on giant planet migration

One major formation channel for giant planets is core accretion: rocky planet cores of a few Earth masses form in the outer disk and accumulate a gas envelope. The migration timescale for Jupiter-mass planets is comparable to the mass-doubling timescale (~10^5 years), which is short compared to the lifetime of the disk (~a few ×10^6 years). Accretion affects migration by altering the angular momentum budget and, for a gap-opening planet, disrupting the gap-crossing flow. Because accretion occurs on a much smaller length scale than migration, it is computationally challenging to simulate both processes simultaneously, and so most previous planet migration studies treat the planet as a gravitationally-softened point mass instead (see, e.g., Durmann & Kley 2017 for an exception). How accretion affects migration therefore remains unclear in the literature. In this work, we utilize Athena++'s adaptive mesh refinement (AMR) framework with an absorbing sphere accretion model to simulate both the small accretion flow and the global disk simultaneously. For simplicity, we keep the planet on a fixed orbit; this is a first step towards our goal of a self-consistent treatment for giant planet accretion and migration. We compare our results to the non-accreting gravitationally-smoothed point mass approach.

Coffee

Avery Bailey (UNLV)

Short Characteristics Radiative Transfer for Models of Planetary Envelopes

In the core accretion model of planet formation, envelope cooling regulates the accretion of material and ultimately sets the timescale to form a giant planet. Given the diversity of planet-forming environments, opacity uncertainties, and the advective transport of energy by 3-dimensional recycling flows, it is unclear whether 1D models can adequately describe envelope structure and accretion in all regimes. Even in 3D models, it is unclear whether approximate radiative transfer methods sufficiently model envelope cooling particularly at the planetary photosphere. To address these uncertainties, we implement a formal solver of the radiative transfer equation by the method of short characteristics into the Athena++ framework. We present details of the implementation along with general results from our radiation-hydrodynamic models of planet envelopes. Additionally, we evaluate the fidelity of approximate radiative transfer methods and find that in general, more approximate methods are sufficiently accurate while being computationally efficient.

Huazhi Ge (University of California, Santa Cruz)

A stable and superadiabatic weather layer in Jupiter induced by moist convection --- An application to the planetary atmosphere study by Athena++

Jupiter is the most massive planet in the solar system. Its weather layer possesses iconic banded circulations and is covered by thick clouds with various colors. Jupiter still undergoes Kelvin-Helmholtz contraction and slowly releases its internal energy into space through emission. Traditional theory suggests that Jupiter's weather layer is part of a fully-convective zone and thermal convection connects Jupiter's interior and radiative zone. Combining the recent observations and nonhydrostatic cloud-resolving simulations with SNAP, an extension code of Athena++, I will show this picture is oversimplified, and Jupiter's weather layer is only partially-convective. Cloud-forming species are heavier than the background hydrogen-helium mixtures in giant planets. The condensation of water, the most abundant cloud-forming species, causes a molecular weight gradient and disconnects the deep atmosphere and upper weather layer. Thus, thermal convection is turned off. Instead, latent heat flux relates the heat flow in the deep atmosphere to the upper weather layer. The condensation of water also leads to a persistent stable layer and a superadiabatic temperature structure. I will show the implications for giant planets' evolution, interior structure, and atmospheric dynamics. The result from this work will help us understand the current observations from the ongoing Juno mission and look ahead to the future Uranus mission.

Logan Prust (Kavli Institute for Theoretical Physics, UCSB)

Planetary Engulfment in Athena++

As a star ascends the giant branch, its envelope can expand to engulf one or more of its inner planets. Many of these planets spiral into the giant and are ultimately destroyed, while more massive planets may eject a portion of the envelope. In any case, the energy deposited into the envelope leads to a temporary increase in luminosity which could be observable as a transient. To study this phenomenon, it is important to determine the drag forces experienced by the planet and to understand the flow morphology near its surface. In this talk, I present wind-tunnel simulations of the immediate vicinity of an engulfed planet using Athena++. I show the dependence of drag coefficients and shock stand-off distance on the accretion radius and discuss the formation of a quasi-hydrostatic halo around the planet.

Chi-Ho Chan (Georgia Institute of Technology)

Magnetorotational instability in eccentric disks

The magnetorotational instability (MRI) has been extensively studied in circular magnetized disks, and its ability to drive accretion has been demonstrated in a multitude of scenarios. There are reasons to expect eccentric magnetized disks to also exist, but the behavior of the MRI in these disks remains largely uncharted territory. Here we present the first simulations performed with Athena++ that follow the nonlinear development of the MRI in eccentric disks. We find that the MRI in eccentric disks resembles circular disks in two ways, in the overall level of saturation and in the dependence of the detailed saturated state on magnetic topology. However, in contrast with circular disks, the Maxwell stress in eccentric disks can be negative in some disk sectors, even though the integrated stress is always positive. The angular momentum flux raises the eccentricity of the inner parts of the disk and diminishes the same of the outer parts. Because material accreting onto a black hole from an eccentric orbit possesses more energy than material tracing the innermost stable circular orbit, the radiative efficiency of eccentric disks may be significantly lower than circular disks. This may resolve the "inverse energy problem" seen in many tidal disruption events.

Yue Hu (University of Wisconsin-Madison)

Diagnose Turbulence in Partially Ionized Medium with Athenak

The interstellar medium is turbulent, magnetized, and also partially ionized. The coupling and decoupling of ions and neutrals play a key role in the dynamics of magnetohydrodynamic (MHD) turbulence, but are difficult to study. This talk will focus on the damping of MHD turbulence in a ionized medium, using 3D two-fluid turbulence simulations generated from the Athenak code. We examine the statistics of the ion and neutral's density, velocity, and magnetic field. I will show that when the ion and neutral are well-coupled, the velocity statistics resemble that of single-fluid MHD turbulence. Conversely, when the neutral decouples from the ion, both the turbulence in the neutral and ion are damped, with steep velocity spectra compared to the Kolmogorov-type spectrum with a slope of −5/3. The ion's density structures are filamentary and the neutral's density structures are clumpy when the ion and neutral are well-coupled, and this difference is less apparent in the presence of damping.

Poster:

Kris Beckwith (Sandia National Laboratories)

TBD

Harrison Cook (New Mexico State University)

Black Hole Merger or Type II Supernova?

An unusual AGN flare observed by ZTF has been proposed as an electromagnetic counterpart to the most massive gravitational wave detection to date, GW190521. Though binary black hole mergers do not intrinsically radiate light, interactions with a dense gaseous environment may provide a mechanism to explain this observation. However, the flare's total energy also matches that of a core-collapse supernova explosion. While the ZTF flare exhibited no color evolution as is typical for supernovae, observations of one embedded in an AGN disk may differ from 'naked' supernovae. Distinguishing black hole merger electromagnetic counterparts from embedded supernovae will be vitally important as transient observations increase in the coming decade. I will present and discuss local shearing box models and resulting lightcurves of supernova explosions in AGN disks using Athena++ with an eye towards ruling out a major source of contamination for electromagnetic counterpart searches.

Yoram Kozak (Tel Aviv University)

Coupling the Athena++ Numerical Framework with the Ghost Fluid Method – A New Flow Solver for Engineering Applications

Athena++ is a massively parallel compressible flow solver with state-of-the-art computational capabilities. This advanced numerical framework is specially designated for treating multi-physics astrophysical flows by using a structured grid with either static or adaptive mesh refinement. However, structured-grid-based solvers cannot naturally handle flow interactions with complex geometric structures. This capability is essential for modeling fluid dynamics phenomena relevant to various engineering applications of interest. To resolve this issue, we extend the Athena++ framework for treating practical engineering problems by implementing in the code a Ghost Fluid Method (GFM). We demonstrate that the new GFM can model flow interactions with arbitrary shaped surfaces while retaining the original numerical framework excellent scalability and performance. Moreover, we show that the newly implemented GFM offers flexibility to handle various physical problems that involve stationary or moving interfaces. In particular, we validate and verify the new code against classical benchmarks from the literature that involve flow interactions with rigid bodies. Then, we show that new framework can fully resolve conjugate heat and mass transfer processes relevant to realistic multi-phase flows. Finally, we present a variety of numerical simulations that tackle practical engineering problems, such as a sudden hydrogen jet release from a pressurized tank, and fully resolved ignition and combustion processes of iron particles in air.

Rixin Li (Cornell University)

Hydrodynamical Evolution of Binary Black Holes Embedded in AGN Disks

Stellar-mass binary black holes (BBHs) embedded in active galactic nucleus (AGN) disks offer a distinct dynamical channel to produce black hole mergers detected in gravitational waves by LIGO/Virgo. However, the hydrodynamical evolution of stellar-mass BBHs interacting with the disk gas is poorly understood and lacks sufficient numerical studies. In this talk, I will present our high-resolution simulations of binaries in 2D local disk models, with an extensive coverage of parameter space. We find that prograde comparable-mass circular binaries contract in some setups, with an orbital decay rate of a few times the mass doubling rate, but much faster than their migration rate in AGN disks. More generally, less massive and wider binaries embedded in disks with a non-isothermal equation of state and a low viscosity are easier to be hardened. Furthermore, retrograde binaries always experience rapid orbital decay and eccentric binaries experience eccentricity damping. Our survey demonstrates that their orbital evolution in AGN disks is a complex, multifaceted problem.

Shengtai Li (Los Alamos National Lab)

Using Athena++ for proto-planetary disk simulation

Athena++ has adaptive mesh refinement (AMR) capability. In this talk, I will describe experience and results using Athena++ with AMR for proto-planetary disk simulation, and compare them with our LA-COMPASS using uniform grid.

Jake Simon (Iowa State University)

Planetesimal Formation (or Lack Thereof) in Pressure Bumps and Implications for Early Planet Formation

A crucial step in the planet formation process is the formation of smaller bodies known as planetesimals. However, how these small bodies formed is one of the largest outstanding issues in planetary science and astronomy. One promising route is a process known as the streaming instability, the end product of which is enhanced concentration of dust grains in the gaseous planet-forming disk. However, even this instability requires an initial enhancement in grain concentration to get started. This initial enhancement can occur in axisymmetric regions of relatively high gas pressure known as pressure bumps; inwardly drifting dust grains slow down as they enter the bump, leading to a localized enhancement.

Here, I present a series of very high-resolution simulations of grain concentration + streaming instability in axisymmetric pressure bumps at stellar distances equivalent to the Cold Classical Kuiper Belt. We find that planetesimal formation via this process is extremely robust for cm-sized grains, but completely fails for mm-sized grains unless the pressure bump is sufficiently large in amplitude to completely trap the inwardly drifting grains. However, such large pressure bumps may themselves be unstable and break down into vortices. Furthermore, models suggest that grains cannot grow beyond mm sizes at these distances.

Our main conclusion is that either planet-forming disks form grains larger than ~1 mm , or planetesimals do not form by the streaming instability in pressure bumps. This result has a number of important implications for early planet formation, including alternative routes towards planetesimal formation. I will conclude with a brief discussion of these implications.

Joseph Weller(University of Illinois Urbana-Champaign)

Investigation of Mixing and Magnetic Fields in the Moon Forming Giant Impact using an Adaptive Mesh Refinement Scheme

The canonical giant impact theory for the formation of the Moon involves a collision between the proto-Earth and a Mars sized impactor. The collision ejects material into a disk around the proto-Earth that either accretes, is ejected from the system, or remains in orbit to later form the Moon. Similar planetary-scale collisions are likely to be common in young planetary systems. Using the Adaptive Mesh Refinement framework provided by Athena++, we simulate the canonical giant impact at up to 64 km resolution using a Tillotson equation of state. We measure mixing of material between the impactor and target to determine the origin of matter in the post impact disk. We also track the growth of magnetic fields during and after the collision. These simulations quantify the effect of resolution on magnetic field amplification and mixing, and demonstrate the difficulty of mixing between the Earth and protolunar disk.

Ziyan Xu (CRAL ENS de Lyon)

Numerical Implementation of Local Spherical Collapsing/Expanding Box in Athena++

Spherical collapsing/expanding flows are a classic problem in astrophysics, including protostellar collapse, star and disk formation, and stellar winds. We develope a local model for a spherical collapsing/expanding gas cloud, in the spirit of the shearing box approach. This local model consists of a Cartesian periodic box with time-dependant geometry. By modifying the Riemann solver to incorporate a time-dependent anisotropic effective sound speed, we integrate the local model into the Athena++ code.

We present a series of test problems, including non-linear solutions and linear perturbations of the local model, which confirm the code's desired performance. During a collapse, a horizontal shear flow, corresponding to zonal flows in the global problem, is amplified due to the conservation of angular momentum; a diagonally propagating sound wave may generate a shear flow perpendicular to the wave propagation direction, corresponding to the advection of the background flow by the velocity perturbations in the diagonal waves in the global picture.

This numerical implementation of the local model holds potential for application beyond the early stages of star or protoplanetary disk formation. A straightforward extension to include a dust fluid may prove valuable for examining dust-related local instabilities and phenomena, which may potentially lead to dust concentration and initial stages of planet formation.

Francesco Zappa (FSU Jena)

GR-AthenaK: the first performance portable dynamical spacetime solver

High-resolution numerical relativity (NR) simulations are required for the construction of gravitational-wave (GW) models for compact binary mergers, accurate beyond current standards. Such simulations can be computationally very expensive and thus they require highly performant scalable codes. The recent technological advances in terms of hetereogeneous high performance computing platforms push towards the production of performance portable NR codes, capable of efficiently making use of the new architectures which include GPU accelerators. In this talk we present GR-AthenaK, the first performance portable spacetime solver obtained by implementing the Z4c formulation of the Einstein equations in the Kokkos-based code AthenaK. GR-AthenaK incorporates the main features of the Athena++-based NR code GR-Athena++, such as computations performed in a tensorial fashion. We demonstrate the convergence properties of GR-AthenaK and its correctness with cross-code comparisons against GR-Athena++. Moreover, we compare performances between the two codes with full 3D black hole runs, obtaining a speedup ∼50 of GR-AthenaK on one GPU against GR-Athena++ on one CPU core. Finally, we discuss the feasibility of binary black hole (BBH) merger simulations with GR-AthenaK, arguing that it is possible to run medium/high resolution simulations using $O(1-10)$ GPUs. These results demonstrate that GR-AthenaK can be used in principle to perform BBH evolutions with a significant gain in speed with respect to GR-Athena++, providing an excellent option of an NR code for pre-exascale heterogeneous architectures.