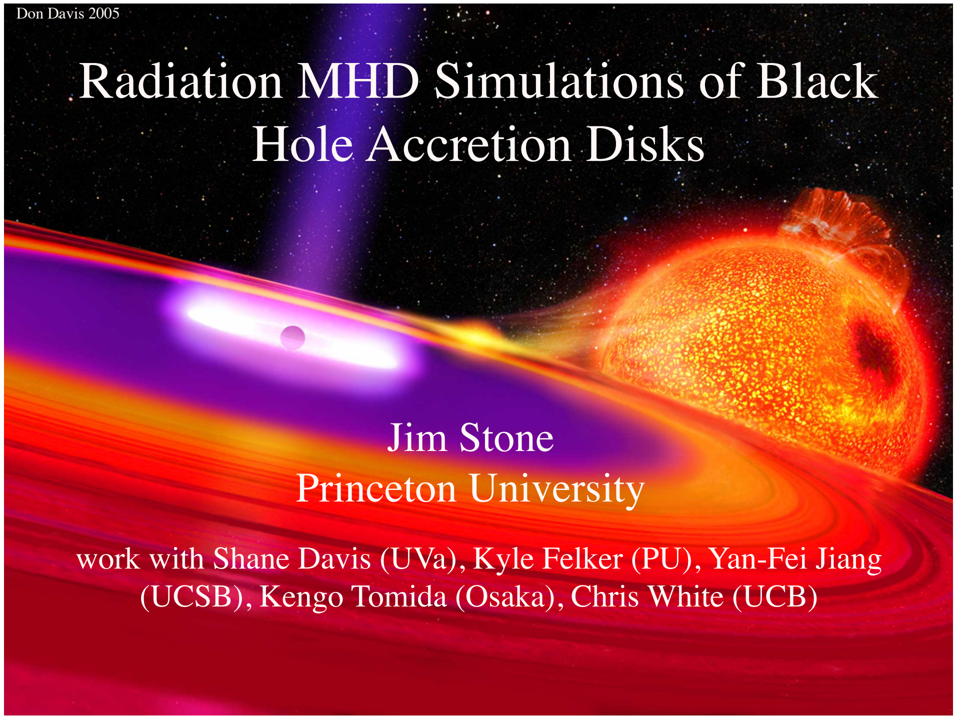


Don Davis 2005

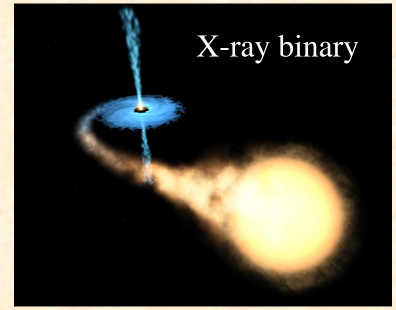
Radiation MHD Simulations of Black Hole Accretion Disks

Jim Stone
Princeton University

work with Shane Davis (UVa), Kyle Felker (PU), Yan-Fei Jiang (UCSB), Kengo Tomida (Osaka), Chris White (UCB)

Motivation:

- Compute structure and dynamics of **radiation-dominated accretion flows**, near Eddington limit.
- Study whether thermal and/or viscous instabilities exist in MRI-driven accretion.
- Compute emergent spectra and variability to compare to observations
- Calculate kinetic and radiative luminosity (feedback).



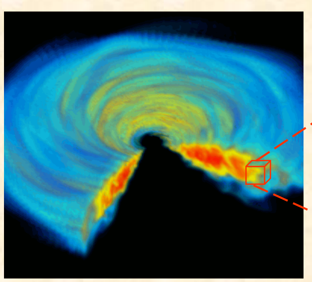
X-ray binary

AGN

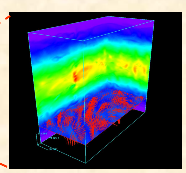
MHD is essential

Angular momentum transport is driven by MHD turbulence produced by the magneto-rotational instability (MRI): Balbus & Hawley (1991)

Nonlinear saturation of MRI widely studied with both *local* ("shearing-box") and *global* simulations.



Global simulation



Local simulation

Radiation is essential

In black hole accretion disks, radiation pressure exceeds gas pressure inside

$$r/R_G < 170(L/L_{\rm Edd})^{16/21}(M/M_\odot)^{2/21}$$

(Shakura & Sunyaev 1973). Radiation needs to be included in dynamical models.

If stress $\tau_{r\phi} = \alpha P$ then radiation dominated disks are subject to both

- Viscous instability (Lightman & Eardley 1974)
- Thermal instability (Shakura & Sunyaev 1976)

MRI-unstable disks are thermally unstable (Jiang et al 2014)

Still unclear if they are viscously unstable.

Numerical Methods: `Athena++`

- Complete rewrite of `Athena` MHD code to C++
- Adaptive and static mesh refinement
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- General relativistic MHD in stationary spacetimes
- Full-transport radiation MHD
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- Task-based execution model
- Improved performance and scaling

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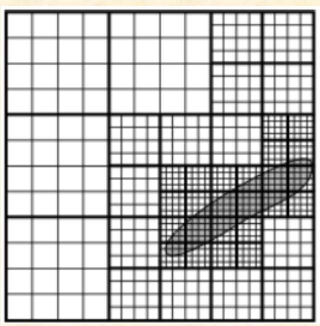
Athena++: AMR

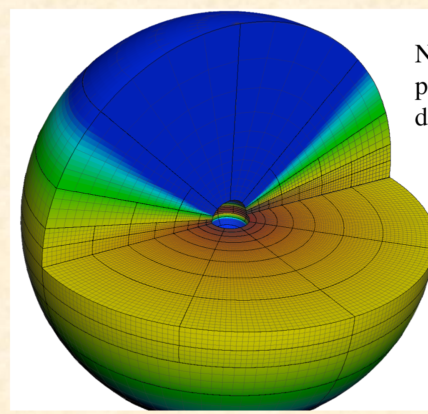


Based on "block-based" oct-tree refinement. Regions of mesh refinement restricted by block locations.

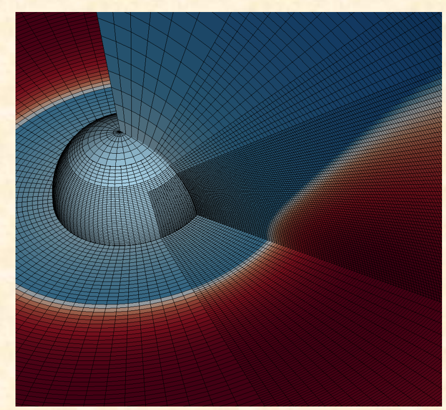
Implemented with staggered-mesh CT.

- Blocks communicate only through boundaries.
- No overlap between fine and coarse grids.
- Solution at each point represented on only one mesh – avoids inconsistencies between fine/coarse solutions.
- Very efficient on large core counts.
- Much easier to code

Athena++: non-uniform and curvilinear meshes



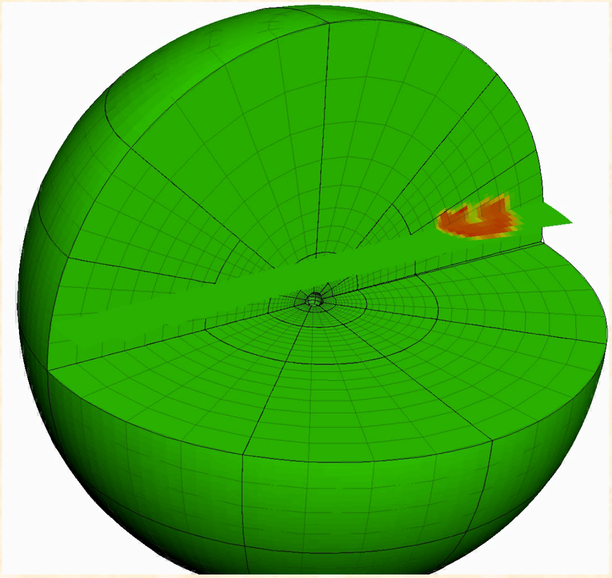
Non-uniform grid in spherical polar coordinates allows large dynamic range in radius.



Nested grid allows de-refinement towards pole, avoiding very small cells.

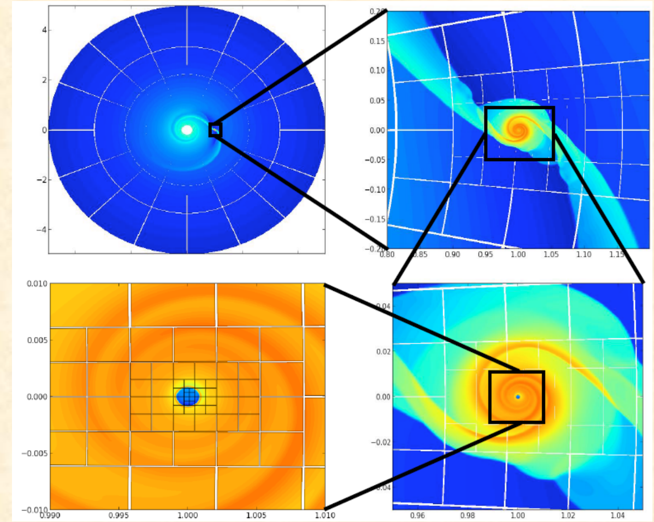
Polar boundary condition allows free-flow over poles.

Test: field loop advection over pole



AMR in spherical polar

Allows resolution of spiral density waves in circumplanetary disk due to planet-disk interaction (Zhu et al. 2016)



Athena++: Radiation transport algorithms

Two-moment methods closed using variable Eddington tensor (VET) (Davis et al. 2012, Jiang et al. 2012)

- VET computed from solution of time-independent transfer equation including scattering
- Implicit update of radiation moment equations
- Suitable for **non-relativistic** problems

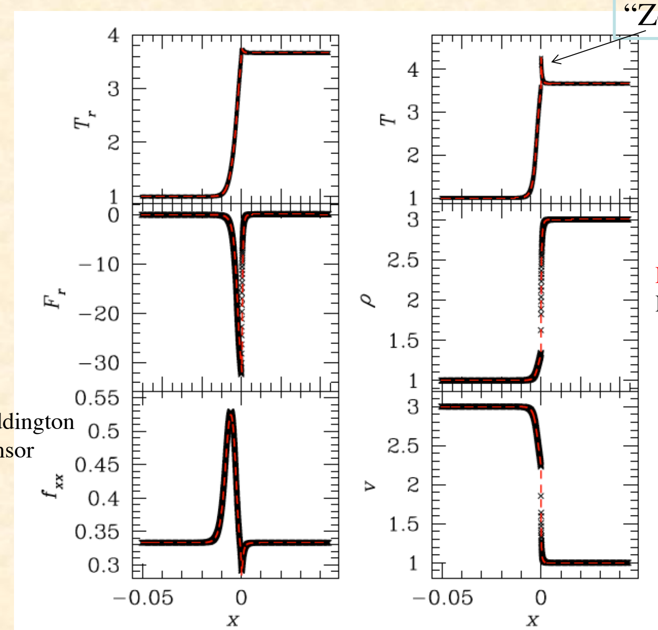
Evolve time-dependent transfer equation directly (Jiang et al. 2014)

- Discretize and evolve specific intensity $I_\nu(\mathbf{x},\mu,\phi,t)$ over ~100 angles at each grid point
- Compute net heating rate and force on fluid from angular quadrature of $I_\nu(\mathbf{x},\mu,\phi,t)$
- Feasible since cost to integrate TE per angle much less than cost of MHD per grid cell
- Suitable for **relativistic** problems

Structure of radiation-dominated shock

“Zeldovich spike”

Eddington tensor



Red line=reference sol’n
Points=numerical sol’n

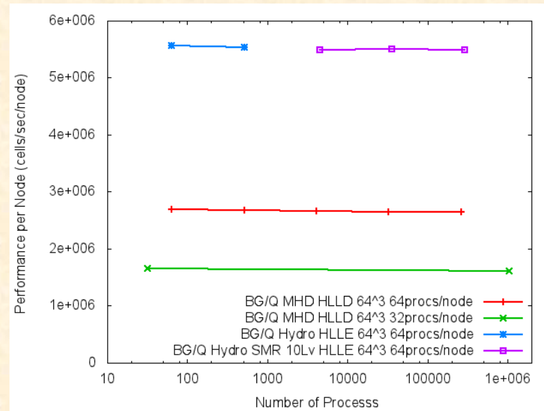
Athena++: Task-based execution

- AMR design results in many mesh blocks per core.
- Integration steps on each block are organized into a ***task list***, e.g.
  1. Calculate hydro fluxes
  2. Calculate electric fields for MHD
  3. Flux-correction (MPI communication)
  4. Update conserved variables
  5. Integrate magnetic fields using CT
  6. Swap ghost zones (MPI communication)
- Order of tasks is dynamic, based on which MPI calls have finished.
- Allows overlap of computation and communication.
- Makes adding more physics very easy.

Athena++: Performance and Scaling

Single core performance of `Athena++` is greatly improved (~4x) by very efficient vectorization.

- 99% of operations are vectorized, 80% use AVX instructions
- 0.8 μs per cell per core for 3D MHD on Intel Haswell with SMR
- About 1/20 performance of hand-tuned GPU versions of same algorithm
- Mixed (OpenMP and MPI) parallelization targeting KNL



Weak scaling up to $O(10^6)$ cores is near perfect (98.5% efficiency)

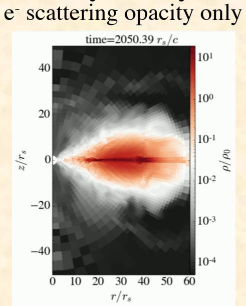
Radiation MHD simulations of super-Eddington Accretion

DOE INCITE allocation is allowing us to compute 3D global models over a range of parameters.

- Time-dependent RT with 80 angles
- Spherical polar nested mesh $1 < r < 1000$
- Effective resolution at finest level $\sim 1000^3$
- Typical job uses 256,000 cores

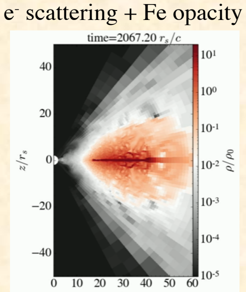
X-ray binary

e^- scattering opacity only



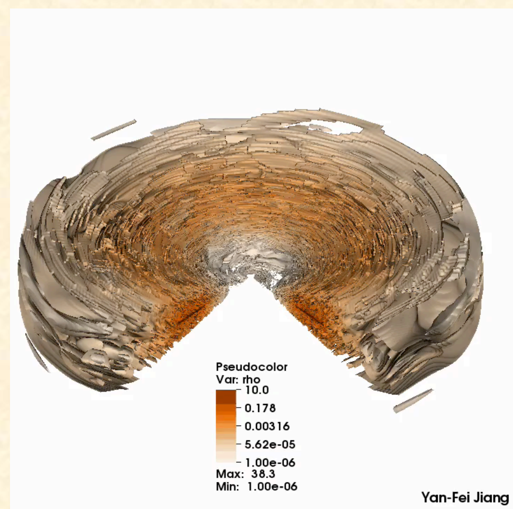
AGN

e^- scattering + Fe opacity

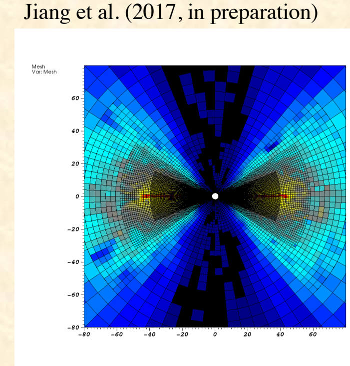


Models for both X-ray binaries and AGN (different opacities)

Radiation-dominated flows are very compressible



Jiang et al. (2017, in preparation)



Level 0

$N_r \times N_\theta \times N_\phi = 64 \times 32 \times 64$

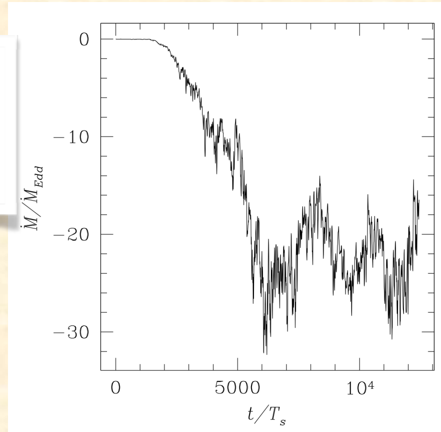
Level 4

$N_r \times N_\theta \times N_\phi = 1024 \times 512 \times 1024$

Super-Eddington accretion

$$L_{\rm edd} = \frac{4\pi G M_{\rm BH} c}{\kappa_{\rm es}},$$

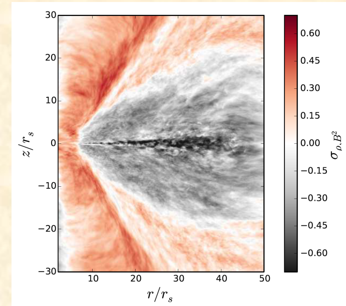
$$M_{\rm edd} = \frac{L_{\rm edd}}{0.1c^2} = \frac{40\pi G M_{\rm BH}}{\kappa_{\rm es} c}.$$



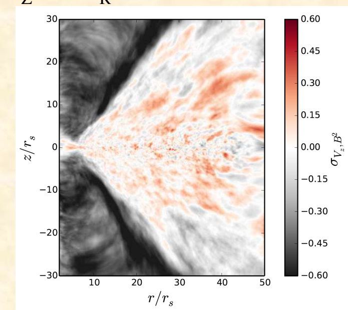
Advection dominates vertical transport

- Magnetic buoyancy produces vertical motions
- Vertical motions transport (advect) radiation energy to photosphere

ρ and B^2 fluctuations *anti-correlated*



V_Z and E_R fluctuations *correlated*



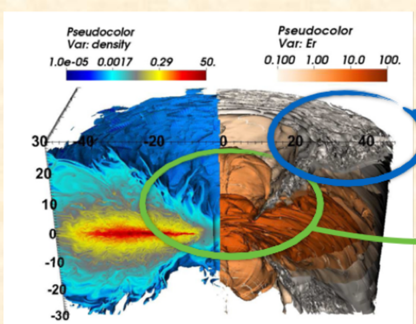
Results in important changes compared to the standard steady-state solutions

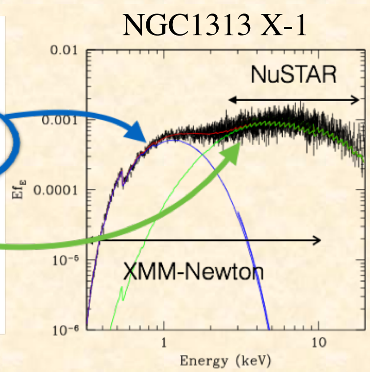
- Scale height is reduced
- Luminosity is increased
- Photon "trapping-radius" is decreased

These results differ from results computed using M1 – further studies needed!

Spectral fit to ULXs

Monte Carlo + XSPEC used to compute synthetic spectra from global simulations (preliminary work by S. Davis & M. Middleton)





- Model fits hard X-ray spectra remarkably well
- Only free parameter is normalization (since M and Mdot not known)
- Additional soft component from material at large distances (not included in the model) is required

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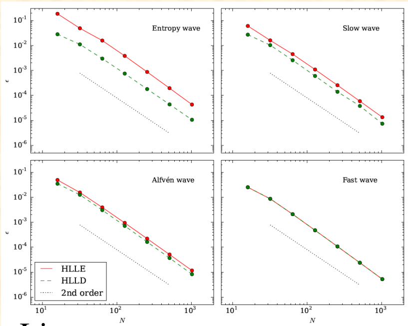
Athena++: GR-MHD

White, Stone, & Gammie 2016

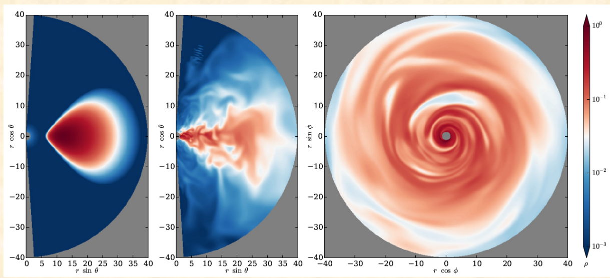


Linear wave convergence test

Athena++ has been extended to GR-MHD.

More accurate Riemann solvers compares to other GR-MHD codes (e.g. HARM) based on LLF fluxes

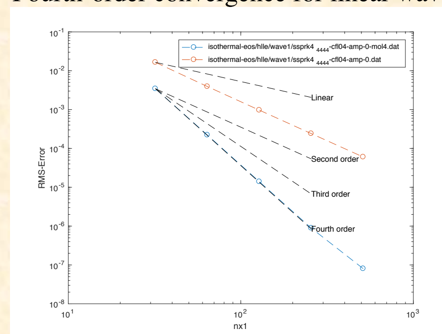
Dynamical evolution of MRI-unstable torus around a spinning BH



Athena++: higher-order FV methods

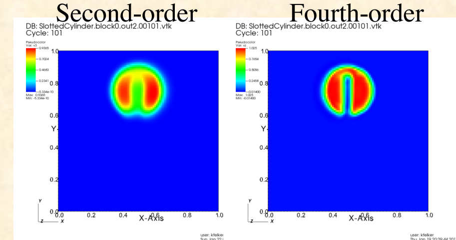
- Fourth order spatial reconstruction and SSP RK4 timestepping
- Compact stencil finite-volume approach of Colella et al (2011)
- Extremum-preserving limiter of McCorquodale et al (2013)
- Better behaved at shocks than DG methods

Fourth-order convergence for linear waves



Slotted cylinder advection test: lower advection errors

Second-order Fourth-order



Summary and Outlook

- We can now study *ab initio* models of radiation-dominated accretion flows onto compact objects, including spectra and variability.
- Code features under development:
  - Self-gravity on AMR grid using finite-element discretization
  - Non-ideal MHD
  - Particles (dust and kinetic ions)
- Future applications:
  - Global models of disks in ULXs
  - Star-formation and cosmic-ray feedback
  - Proto-stellar collapse
  - Proto-planetary disks