Study Radiation Feedback with Rad-(M)HD Simulations: Stars to AGNs

Yan-Fei Jiang（姜燕飞）
Einstein Fellow
Harvard-Smithsonian Center for Astrophysics

Collaborators: James Stone (Princeton), Shane Davis (CITA), Norm Murray (CITA), Daniel Proga (UNLV)

Outline

- Numerical Techniques of Radiation (Magneto-) Hydrodynamic Simulations
- Understanding Radiation Feedback from Stars - Radiation Rayleigh-Taylor Instability
- Global Radiation MHD Simulations of Black Hole Accretion Disks to Study the central engin of AGNs

Radiation Feedback At different Scales

- AGN: Radiation from central black hole can trigger or quench star formations
- Galaxy Scale: Radiation force on the dusty gas can drive galaxy scale outflow and turbulence
- Sub-galactic Scale: Radiation from massive young star clusters limits star formation

Netzer (2009)
Reines et al. (2010)
Karouzos et al. (2014)
Greene et al. (2014)

Thompson et al. (2005)
Murray et al. (2005)

But,

- Coupling between radiation and gas depends on opacity, ratio between radiation pressure and gas pressure, angular distribution of photons
- Understanding these processes requires detailed radiatio-(Magneto) hydrodynamic simulations

Fall et al. (2010)
Murray et al. (2010)

Radiation MHD Equations

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) = 0,$$

$$\frac{\partial (\rho \boldsymbol{v})}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}\boldsymbol{v} - \boldsymbol{B}\boldsymbol{B} + \mathsf{P}^*) = -\boldsymbol{S_r}(\boldsymbol{P})$$

$$\frac{\partial E}{\partial t} + \nabla \cdot [(E + P^*)\boldsymbol{v} - \boldsymbol{B}(\boldsymbol{B} \cdot \boldsymbol{v})] = -cS_r(E)$$

$$\frac{\partial \boldsymbol{B}}{\partial t} - \nabla \times (\boldsymbol{v} \times \boldsymbol{B}) = 0,$$

$$\frac{\partial E_r}{\partial t} + \nabla \cdot \boldsymbol{F}_r = cS_r(E)$$

$$\frac{1}{c^2}\frac{\partial \boldsymbol{F}_r}{\partial t} + \nabla \cdot \mathsf{P}_r = \boldsymbol{S_r}(\boldsymbol{P}),$$

$$\frac{\partial I}{\partial t} + c\boldsymbol{n} \cdot \nabla I = c\sigma_a \left(\frac{a_r T^4}{4\pi} - I\right) + c\sigma_s (J - I)$$
$$+ 3\boldsymbol{n} \cdot \boldsymbol{v}\sigma_a \left(\frac{a_r T^4}{4\pi} - J\right)$$
$$+ \boldsymbol{n} \cdot \boldsymbol{v}(\sigma_a + \sigma_s)(I + 3J) - 2\sigma_s \boldsymbol{v} \cdot \boldsymbol{H}$$
$$- (\sigma_a - \sigma_s)\frac{\boldsymbol{v} \cdot \boldsymbol{v}}{c} J - (\sigma_a - \sigma_s)\frac{\boldsymbol{v} \cdot (\boldsymbol{v} \cdot \mathsf{K})}{c}.$$

Jiang et al. (2012)

Davis et al. (2012)

- ideal MHD equations plus radiation momentum and energy source terms
- Moment equations of the radiation field

- Directly solve the time-dependent transfer equation
- Reduced speed of light

Jiang et al. (2014)

Skinner & Ostriker (2013)

Numerical Algorithms for RT

Specific Intensity:

$$\frac{\partial I}{\partial t} + c\boldsymbol{n} \cdot \boldsymbol{\nabla} I = \eta - \chi I$$

Mihalas & Mihalas (1984)

Moment Equations:

$$\begin{aligned} \frac{\partial E_r}{\partial t} + \boldsymbol{\nabla} \cdot \boldsymbol{F}_r &= S(E) \\ \frac{1}{c^2}\frac{\partial \boldsymbol{F}_r}{\partial t} + \boldsymbol{\nabla} \cdot \mathsf{P}_r &= \boldsymbol{S_r}(\boldsymbol{P}) \end{aligned}$$

Flux-limited Diffusion:
(FLD)

$$\boldsymbol{F}_r = -D\boldsymbol{\nabla} E_r, \quad D = \frac{c\lambda}{\chi}$$

Turner & Stone (2001)

Gonzalez et al. (2007)

M1 Closure:

$$\mathsf{P}_r = \mathsf{f} E_r, \quad \mathsf{f} = \frac{1-\xi}{2}\mathsf{I} + \frac{3\xi - 1}{2}\left(\frac{\boldsymbol{F}_r}{cE_r}\right) \otimes \left(\frac{\boldsymbol{F}_r}{cE_r}\right)$$

Variable Eddington Tensor:
(VET)

$$\frac{\partial I}{\partial s} = \frac{\eta - \chi I}{c}$$

$$\mathsf{f} = \frac{\mathsf{P}_r}{E_r} = \frac{\oint I\boldsymbol{n}\boldsymbol{n}d\omega}{\oint I d\omega}$$

Stone et al. (1992)
Hayes & Norman (2003)
Jiang et al. (2012)
Davis et al. (2012)

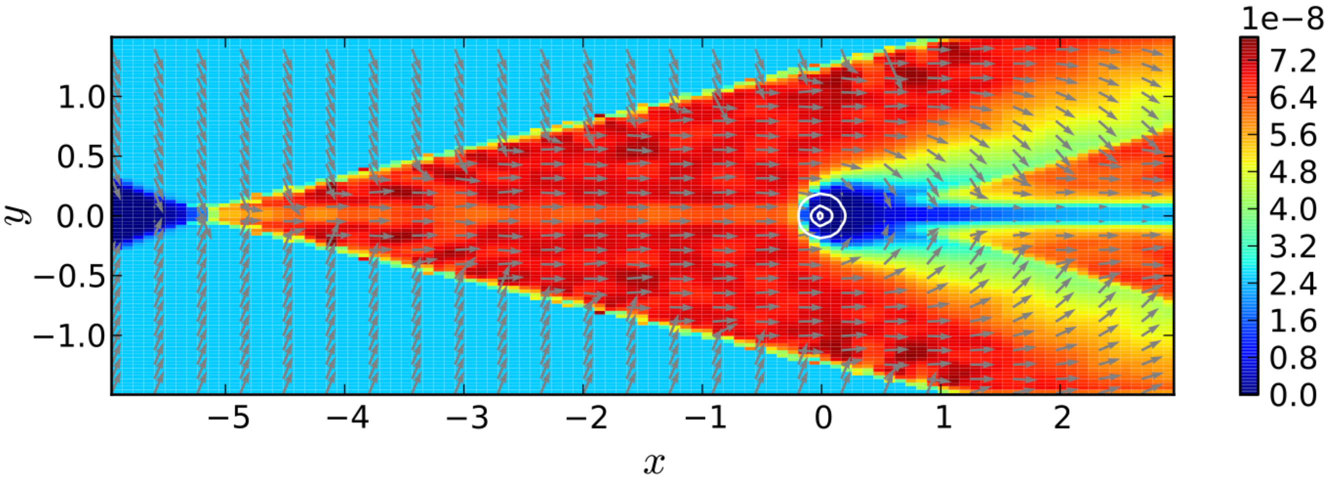
Shadow Test

FLD

Gonzalez et al. (2007)

Skinner & Ostriker (2013)

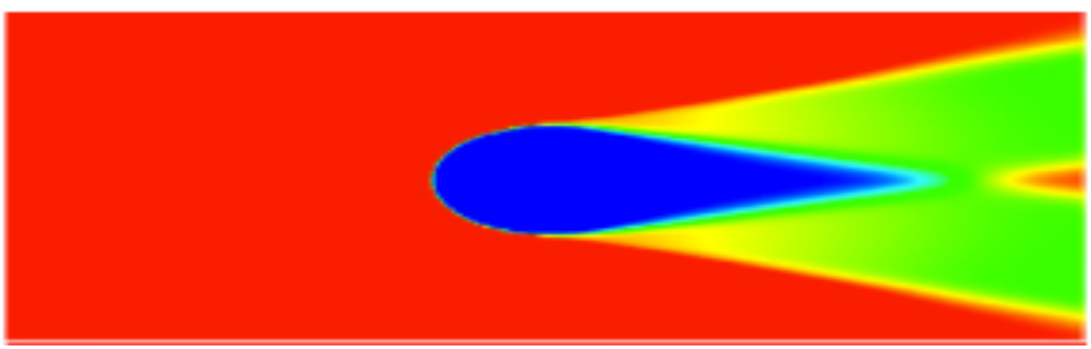
M1 u



Sądowski et al. (2013)

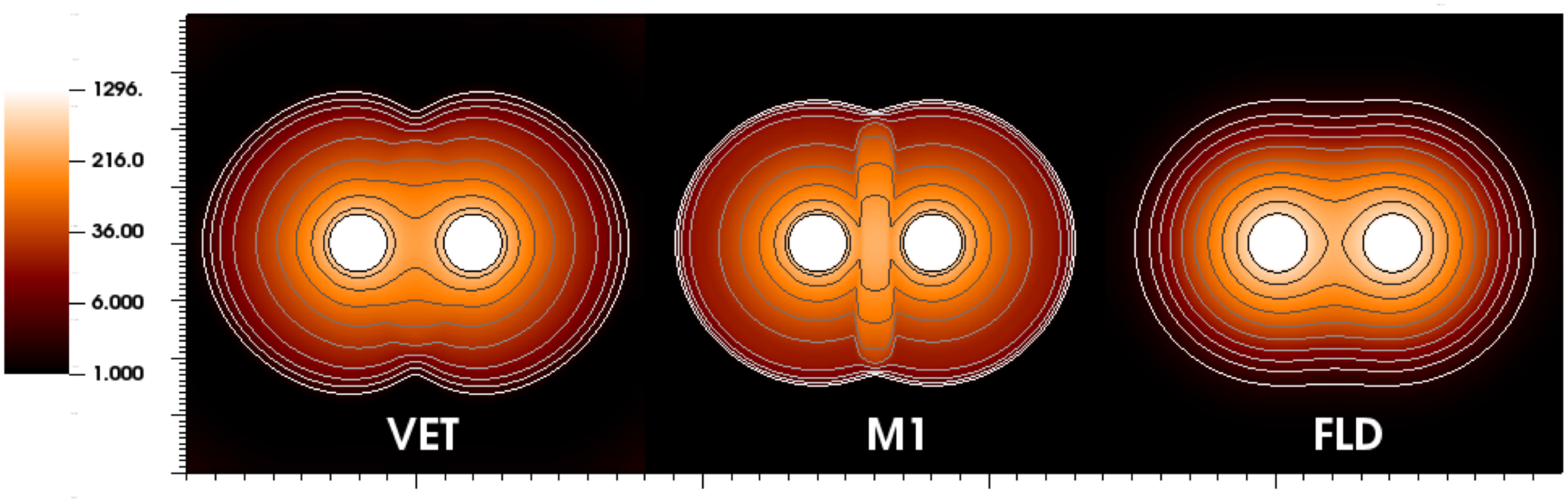
McKinney et al. (2014)

VET



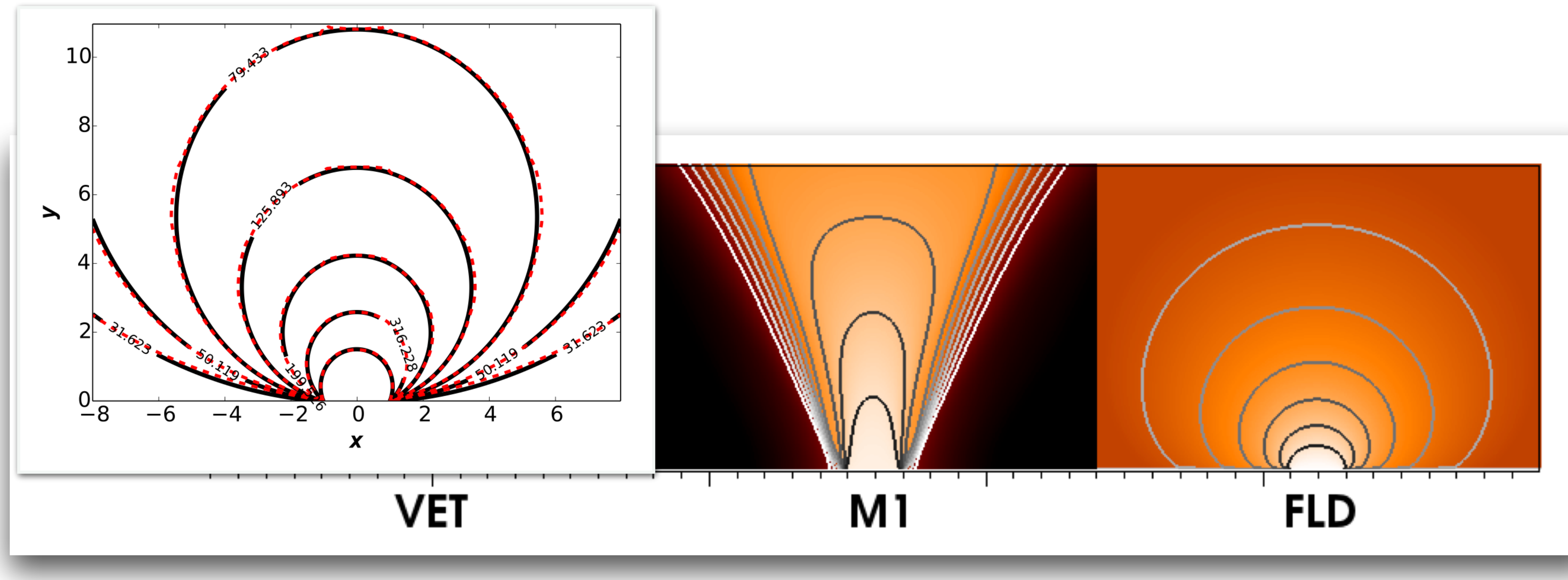
Jiang et al. (2012)

"Binary" Test



- The two clouds are optically thick
- Background medium is optically thin

Emission from a Disk

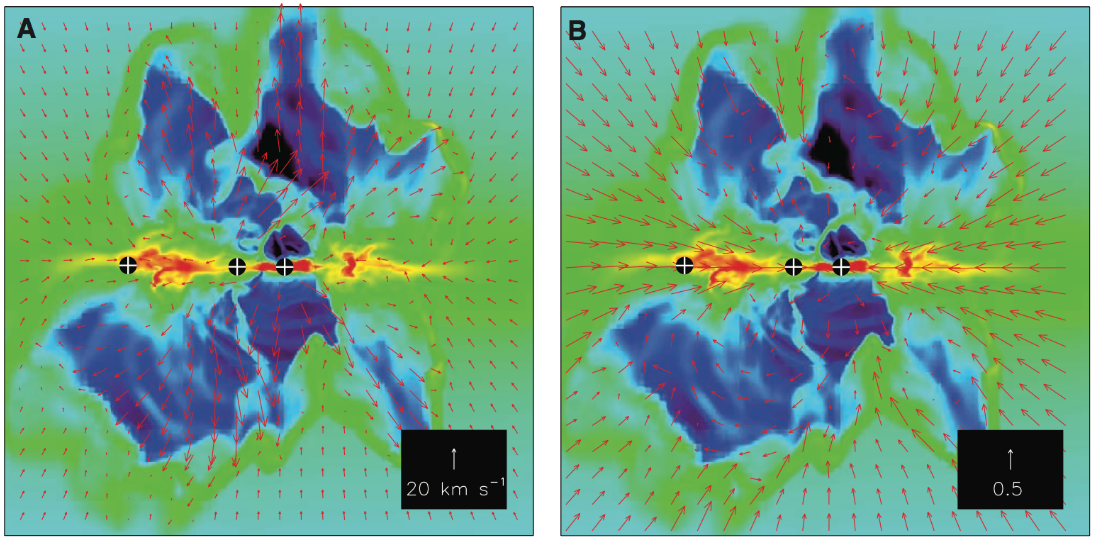


- Uniform and isotropic radiation source is located at the bottom boundary between (-1,1).
- Exactly the same radiation energy density and flux are used at the boundary
- Background medium is optically thin

Radiation Rayleigh-Taylor Instability

Krumholz et al. (2009)

- Massive Star formation

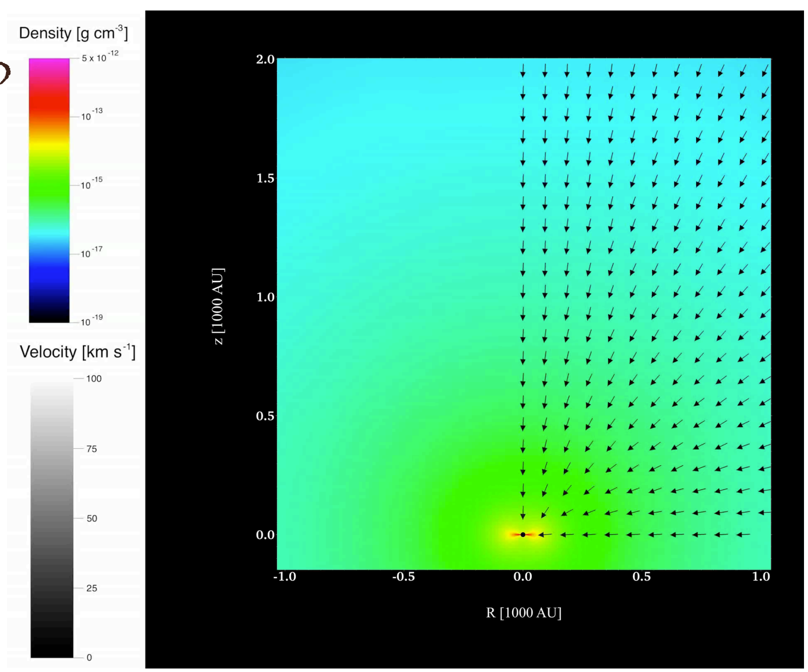


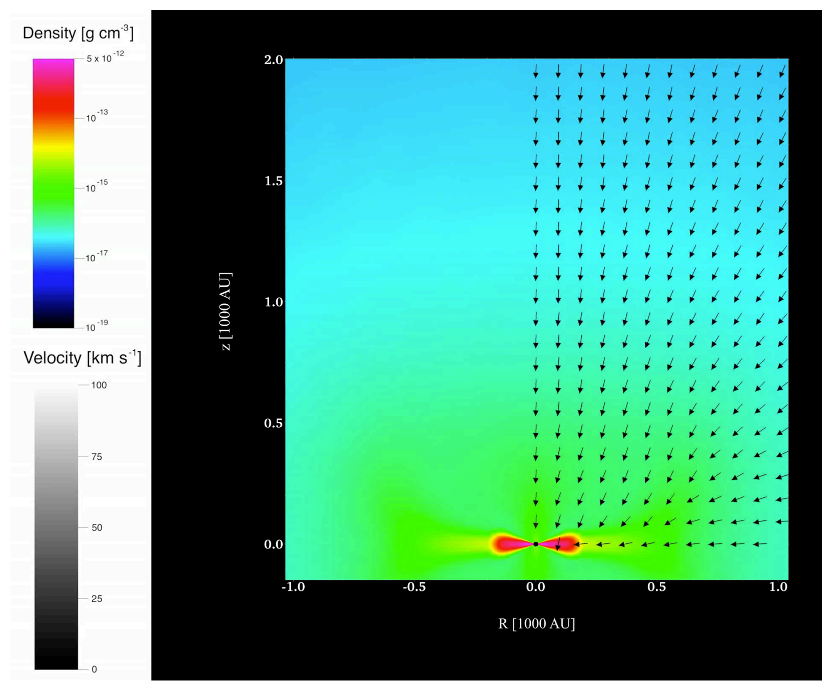
- Rayleigh-Taylor instability helps gas fall back

Kuiper et al. (2012)

- But, if direct UV phones from the star are included

FLD





Ray-Tracing

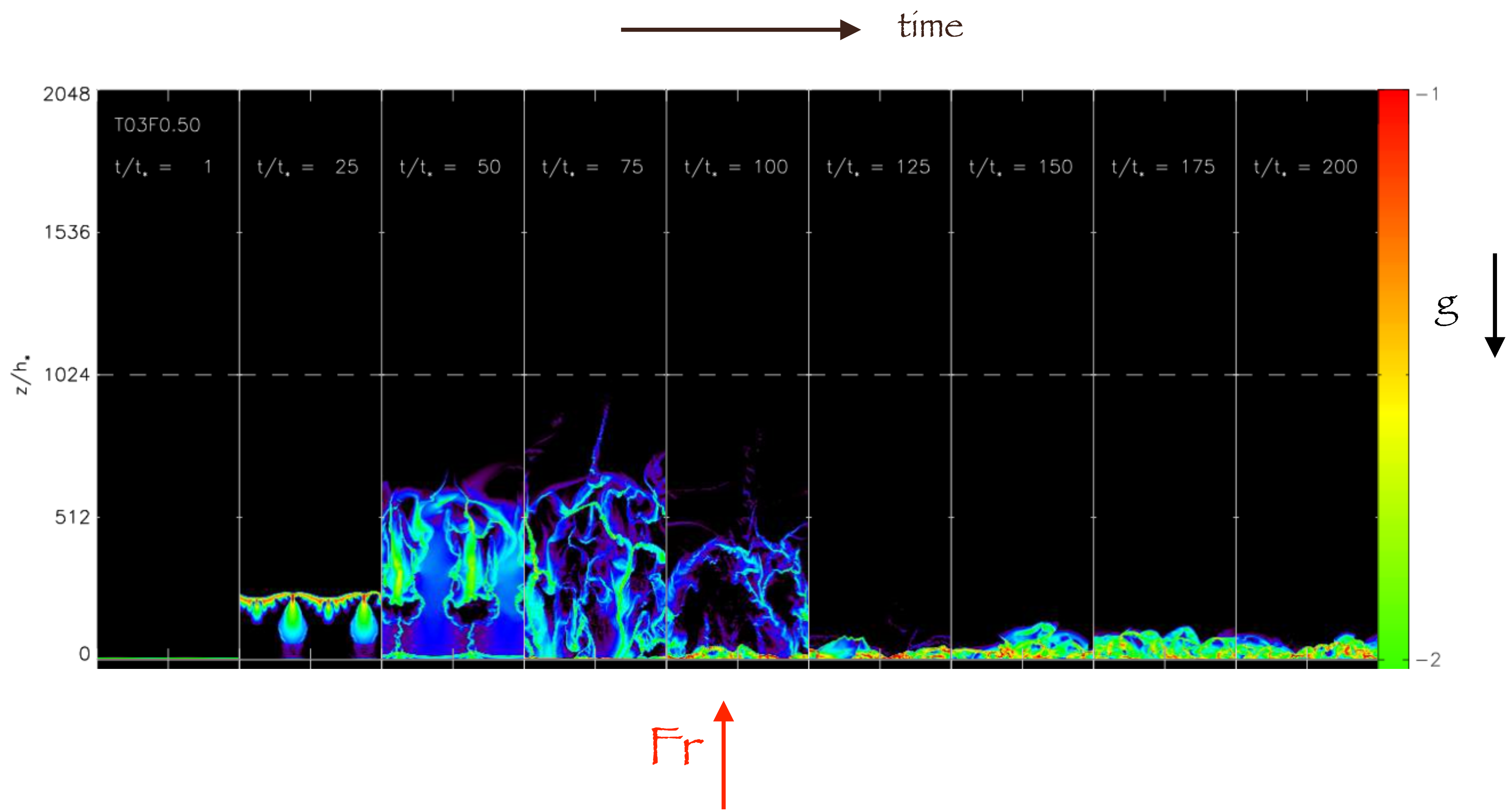
+

FLD

Radiation Rayleigh-Taylor Instability

Krumholz & Thompson (2012,2013)

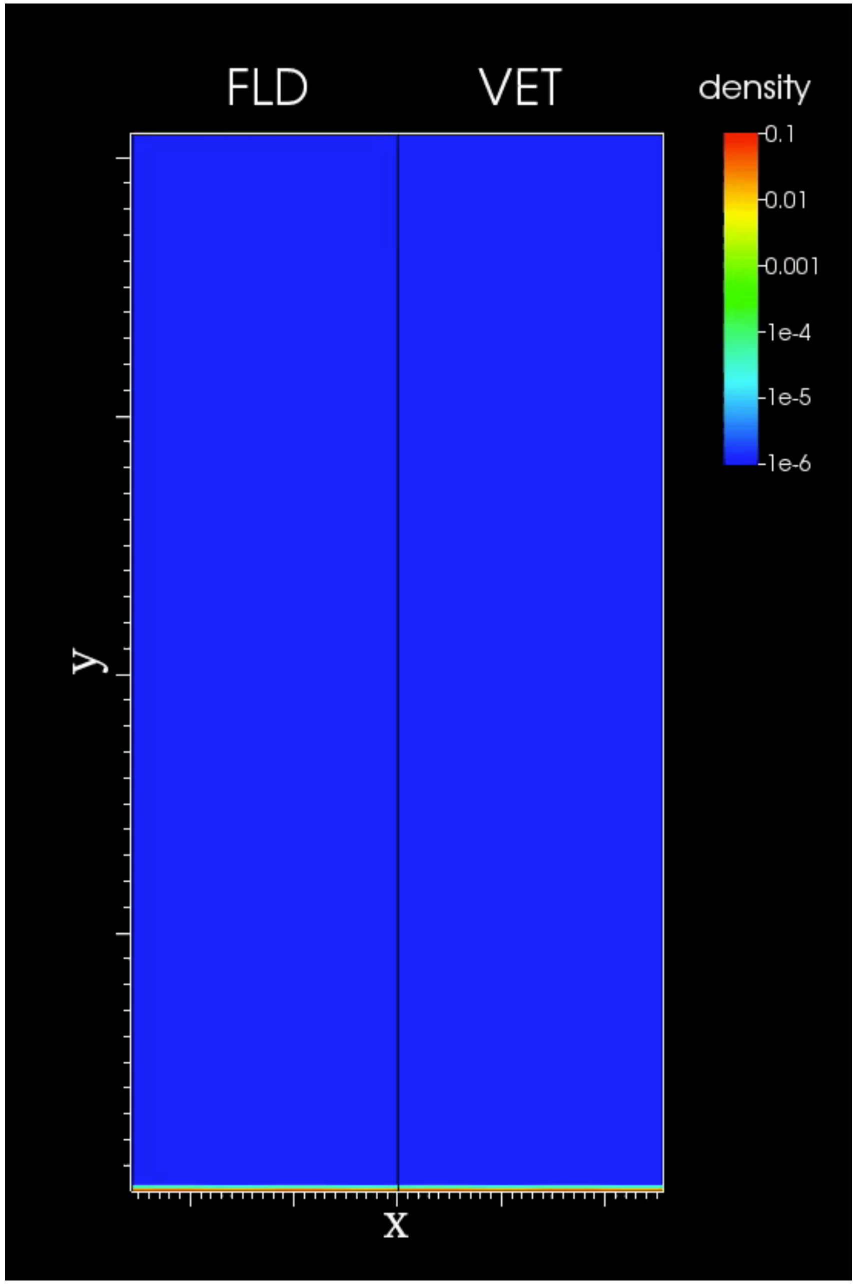
- Radiation driven outflow and turbulence from ULIRS
- IR photons on the dusty gas
- Total optical is 3



Radiation Rayleigh-Taylor Instability

- But, FLD can be misleading again — Davis, Jiang, Stone & Murray (2014)

  - Athena FLD calculations reproduce previous calculations.
  - Athena VET calculations produces continuous outflow

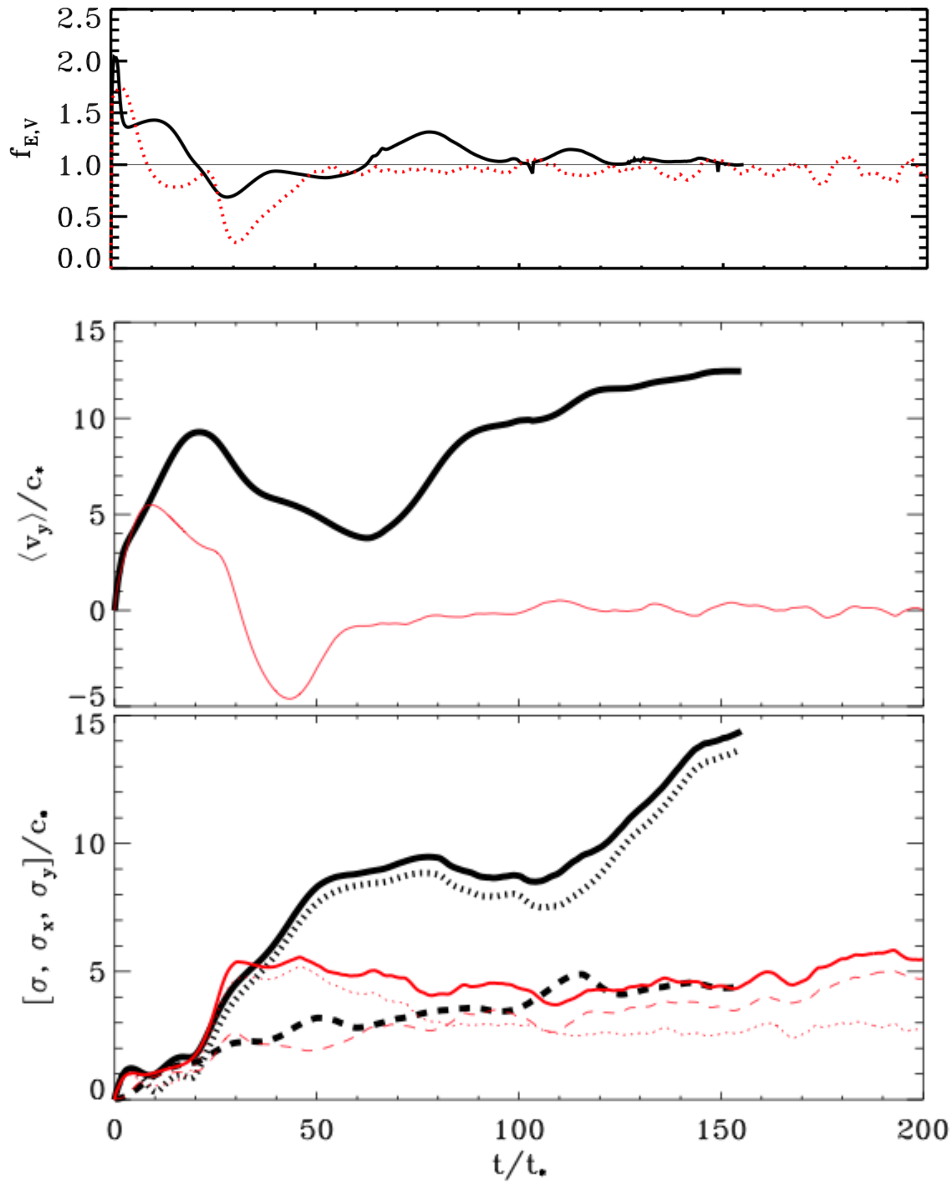


Radiation Rayleigh-Taylor Instability

Davis, Jiang, Stone & Murray (2014)

- History of outflow velocity and velocity dispersion.

- Red lines: FLD run
- Black lines: VET run



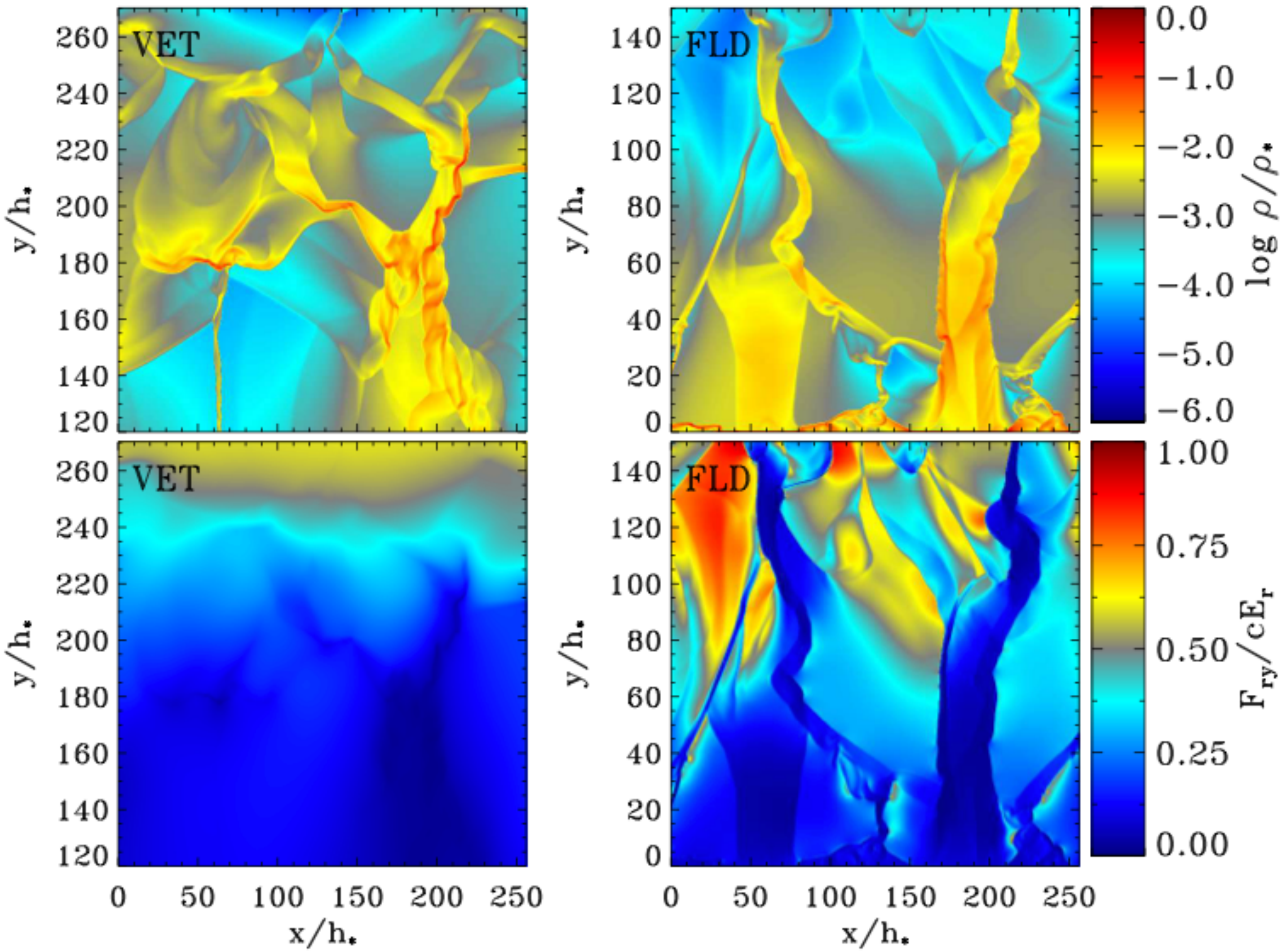
Eddington Ratio

Vertical Velocity

Velocity Dispersion

Radiation Rayleigh-Taylor Instability

Davis, Jiang, Stone & Murray (2014)



FLD gets a much stronger density-flux anti-correlation than it should be.

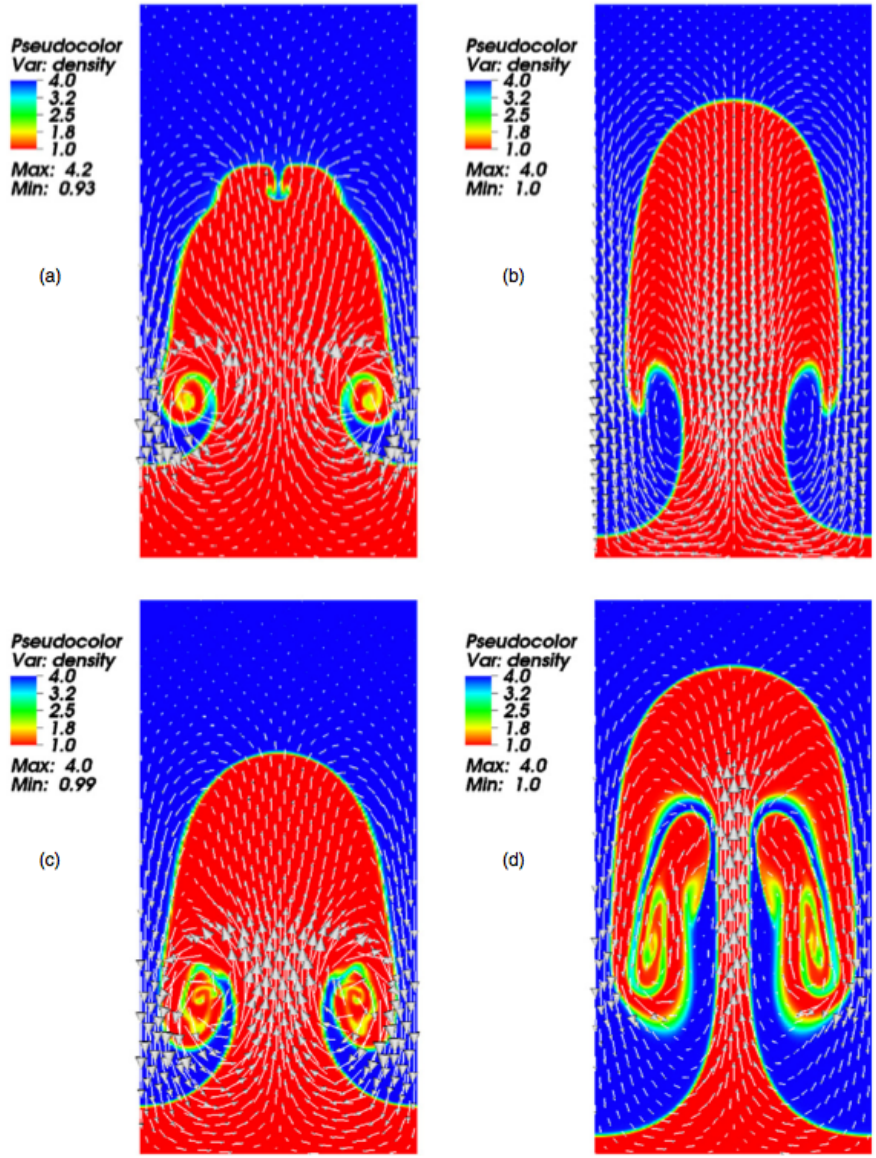
Radiation Rayleigh-Taylor Instability

- Effects of radiation pressure and opacity on the growth rate of Rayleigh-Taylor Instability

Jacquet & Krumholz (2011)
Jiang et al. (2013)

Hydro

$P_r / P_g \sim 10^4$
$\tau = 1$



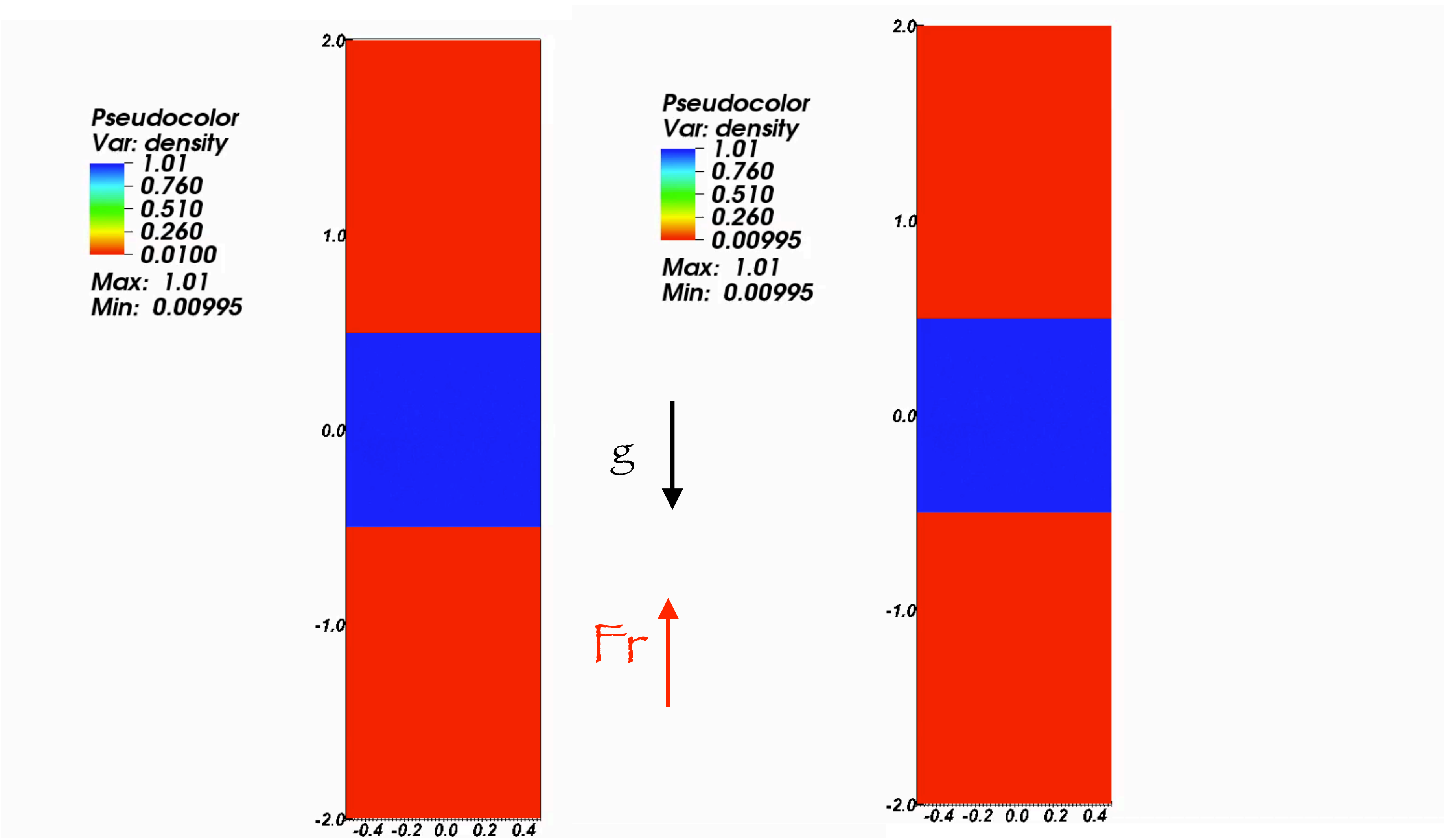
$P_r / P_g \sim 1$
$\tau = 1$

$P_r / P_g \sim 10^4$
$\tau = 10^3$

Radiation Rayleigh-Taylor Instability

- Efficiency of RTI depends on the relative time scale of RTI and acceleration time scale

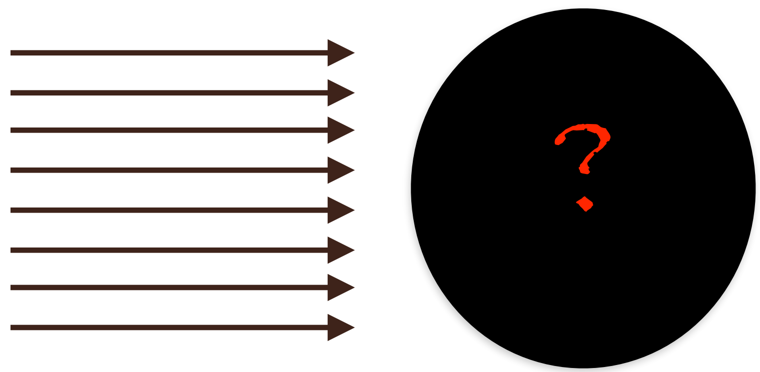
Jiang et al. (2013)



Evolution of Gas Clouds Under Radiation Field

Proga, Jiang, Davis, Stone & Smith (2014)

- External radiation field on the molecular cloud
- Irradiation of AGN

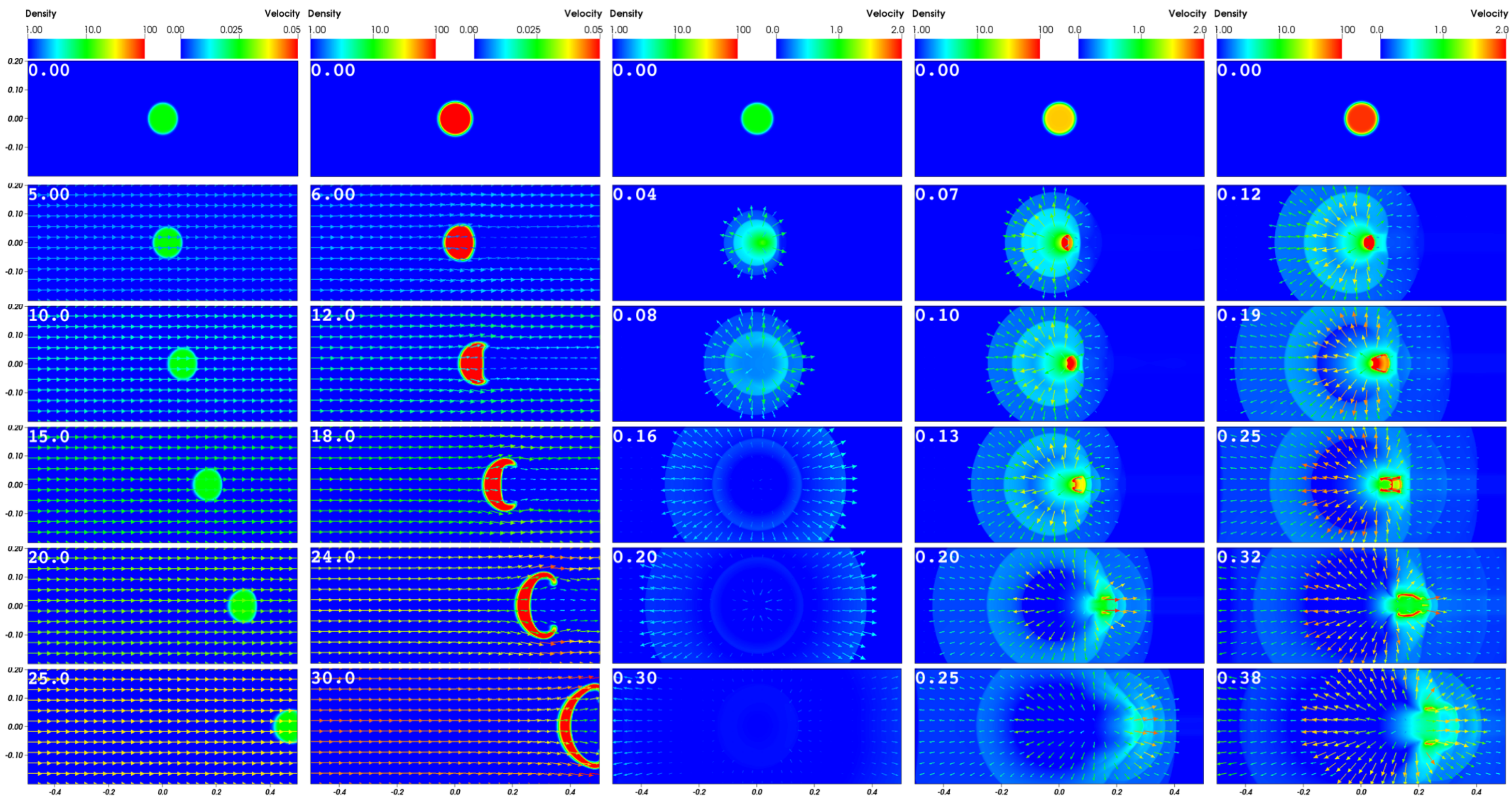


Evolution of Gas Clouds Under Radiation Field

Proga, Jiang, Davis, Stone & Smith (2014)

- External radiation field on the molecular cloud
- Irradiation of AGN

Pure scattering **Absorption dominated**



The Central Engine of AGN

Jiang et al. (2014, in preparation)

- Big Questions we want to know
  - For a given accretion rate, what is the radiation efficiency
  - Radiative feedback and mechanical feedback
  - Angular distribution of photons

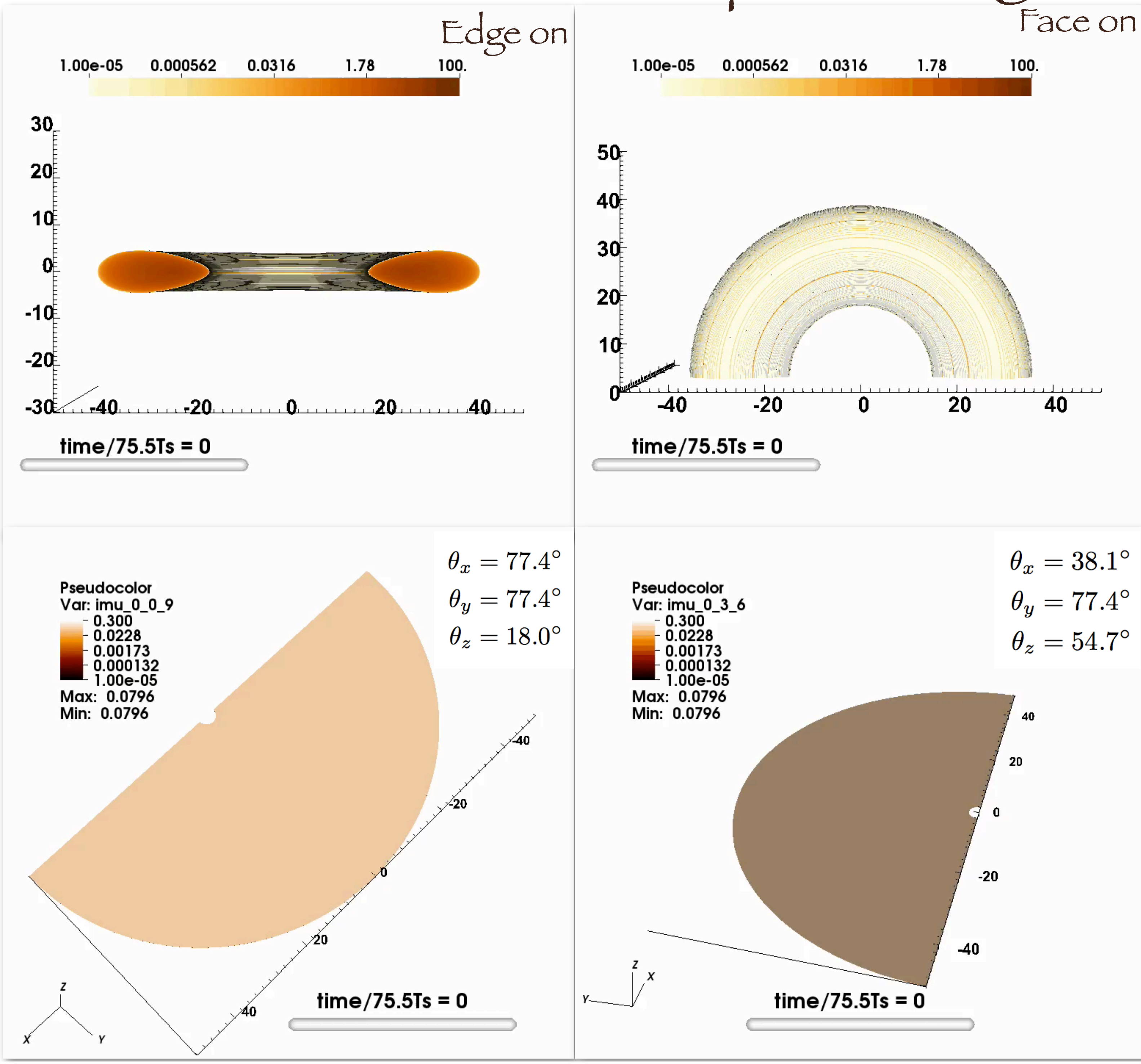
- Photon Trapping: inflow velocity is larger than vertical photon diffusive speed

$$r_{\rm trap} = \frac{3}{2}\dot{m} r_g h \ ,$$

$$L/L_{\rm Edd} \approx 2\left(1+\log\left(\frac{\dot{M}}{50\dot{M}_{\rm Edd}}\right)\right)$$

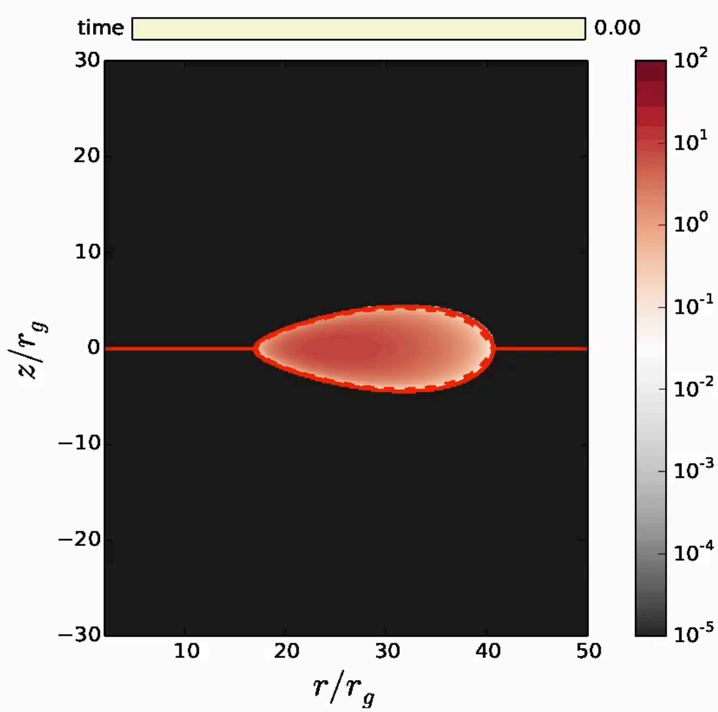
- The physics we include
  - Turbulence from magneto-rotational instabilities provides angular momentum transfer
  - Solve specific intensities from time-dependent radiative transfer equation
  - Pseudo-newtonian potential

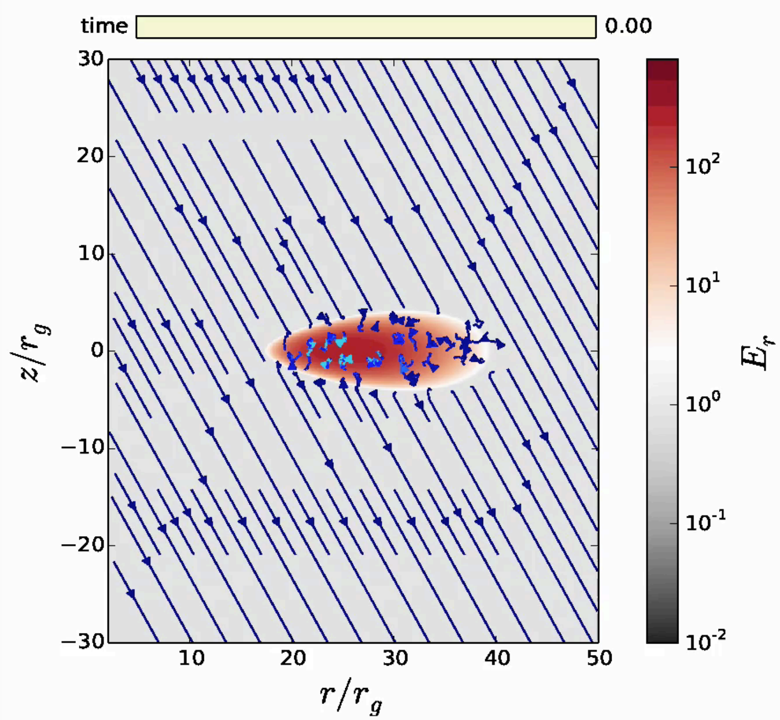
Global Simulations of Super-Eddington Flow



$$r \in (2, 50)r_g$$
$$\phi \in (0, \pi)$$
$$z \in (-30, 30)r_g$$
$$N_r = 512$$
$$N_\phi = 128$$
$$N_z = 1024$$
$$N_n = 80$$

Azimuthally Averaged Structures





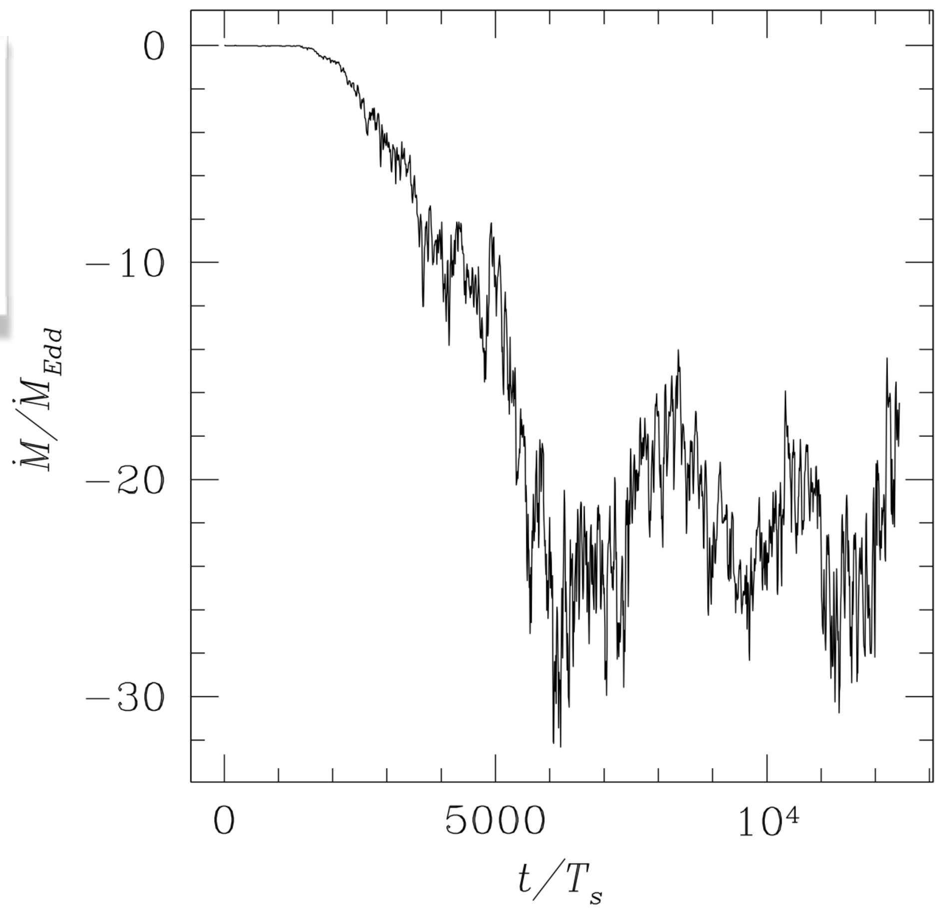
Density and velocity

Radiation energy density and co-moving radiation flux.

Simulation History

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

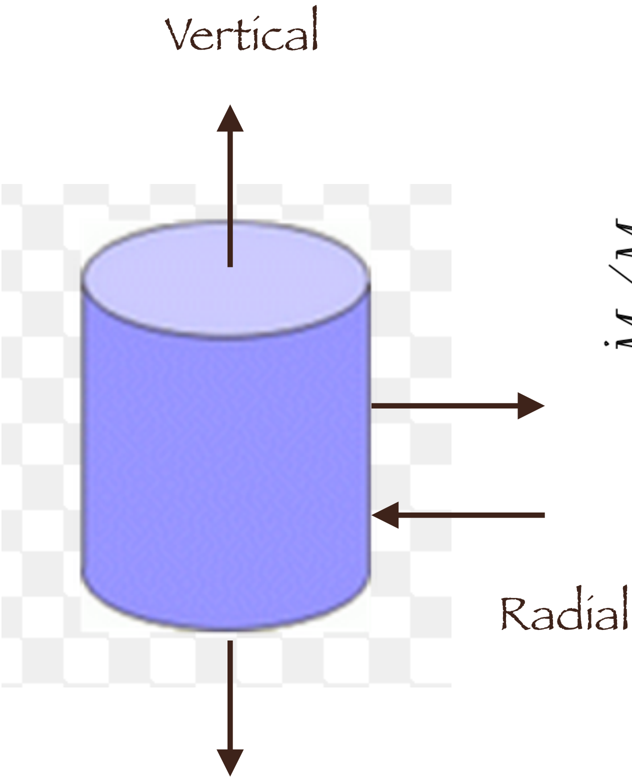
$$M_{\rm edd} = \frac{L_{\rm edd}}{0.1c^2} = \frac{40\pi G M_{\rm BH}}{\kappa_{\rm es} c}.$$

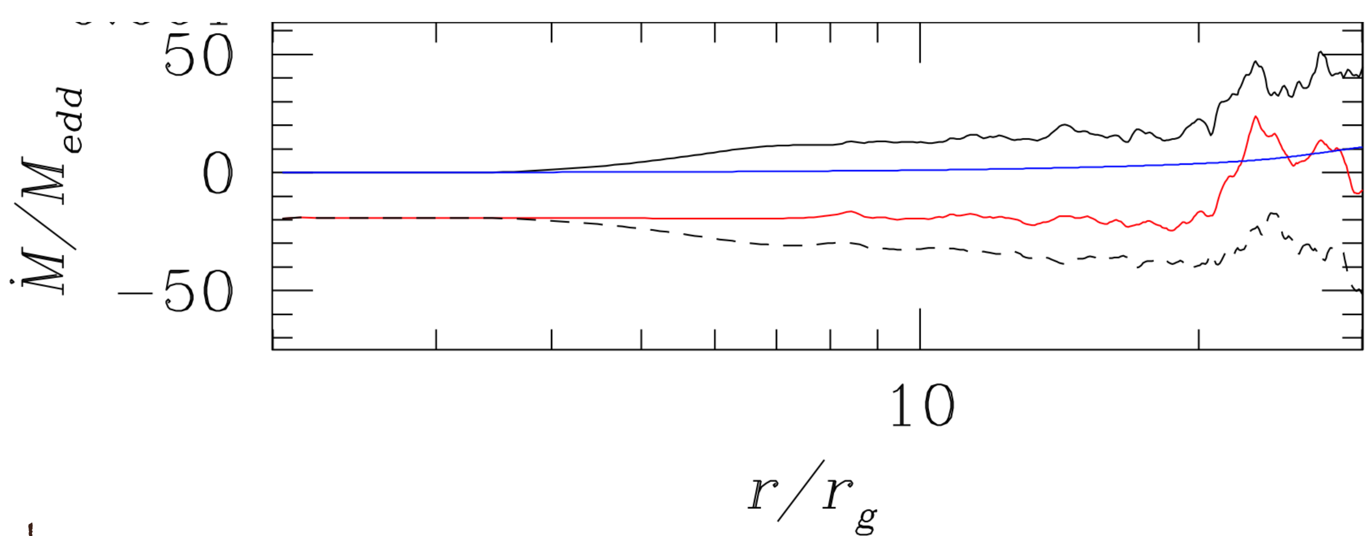


Accretion Rate at 5 r_g

Inflow Equilibrium

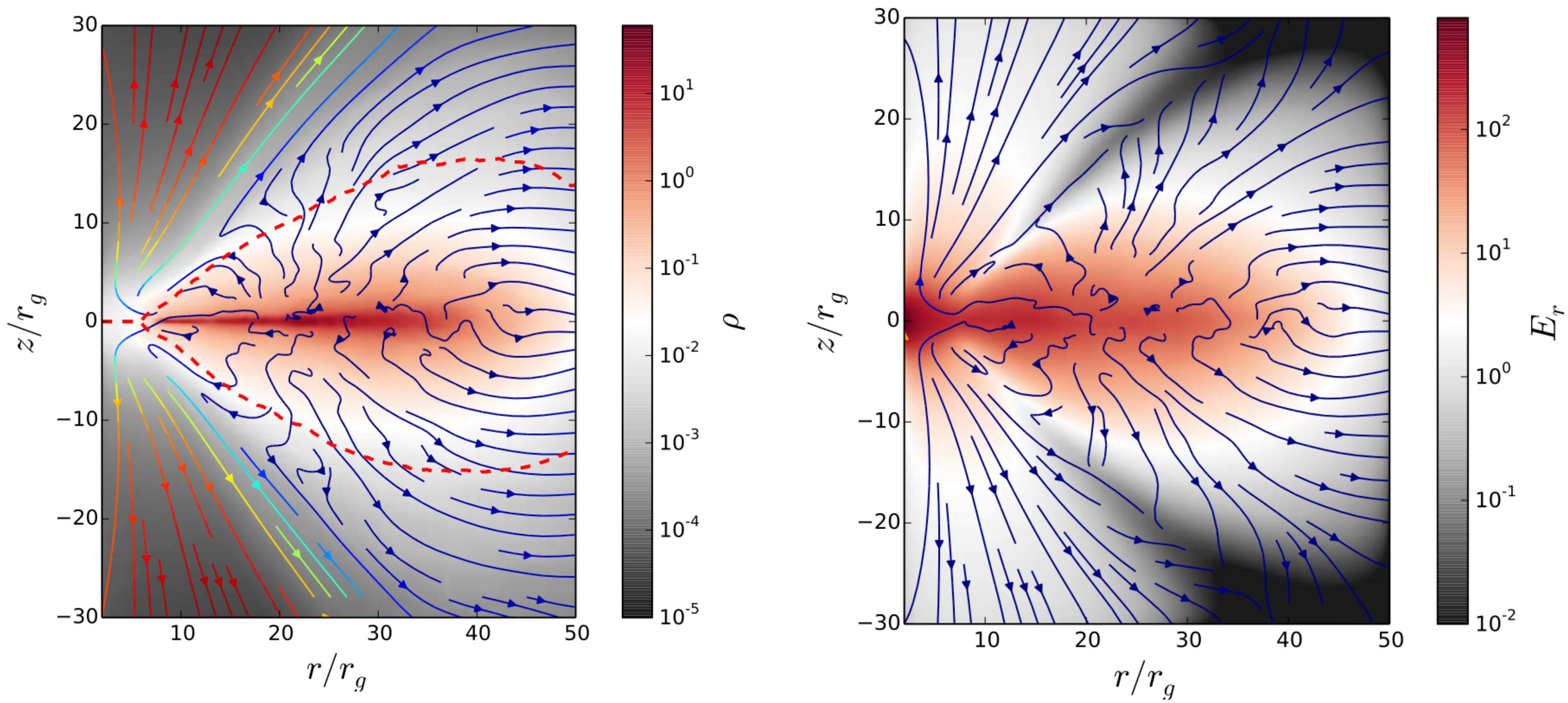
- Inflow equilibrium reached up to ~20 r_g





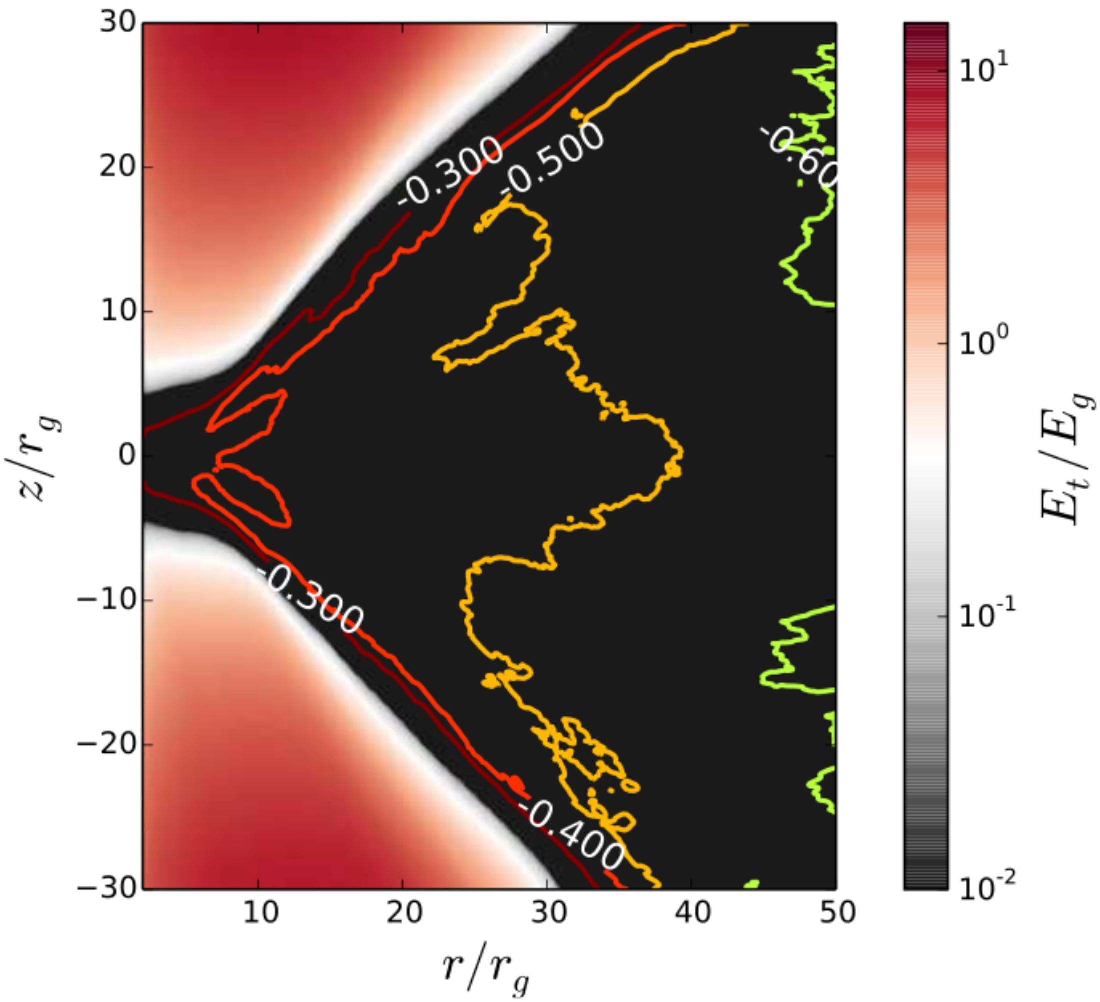
- Solid Black: radial outward
- dashed black: radial inward
- blue: vertical outflow
- red: net inflow

Azimuthally Averaged Structures



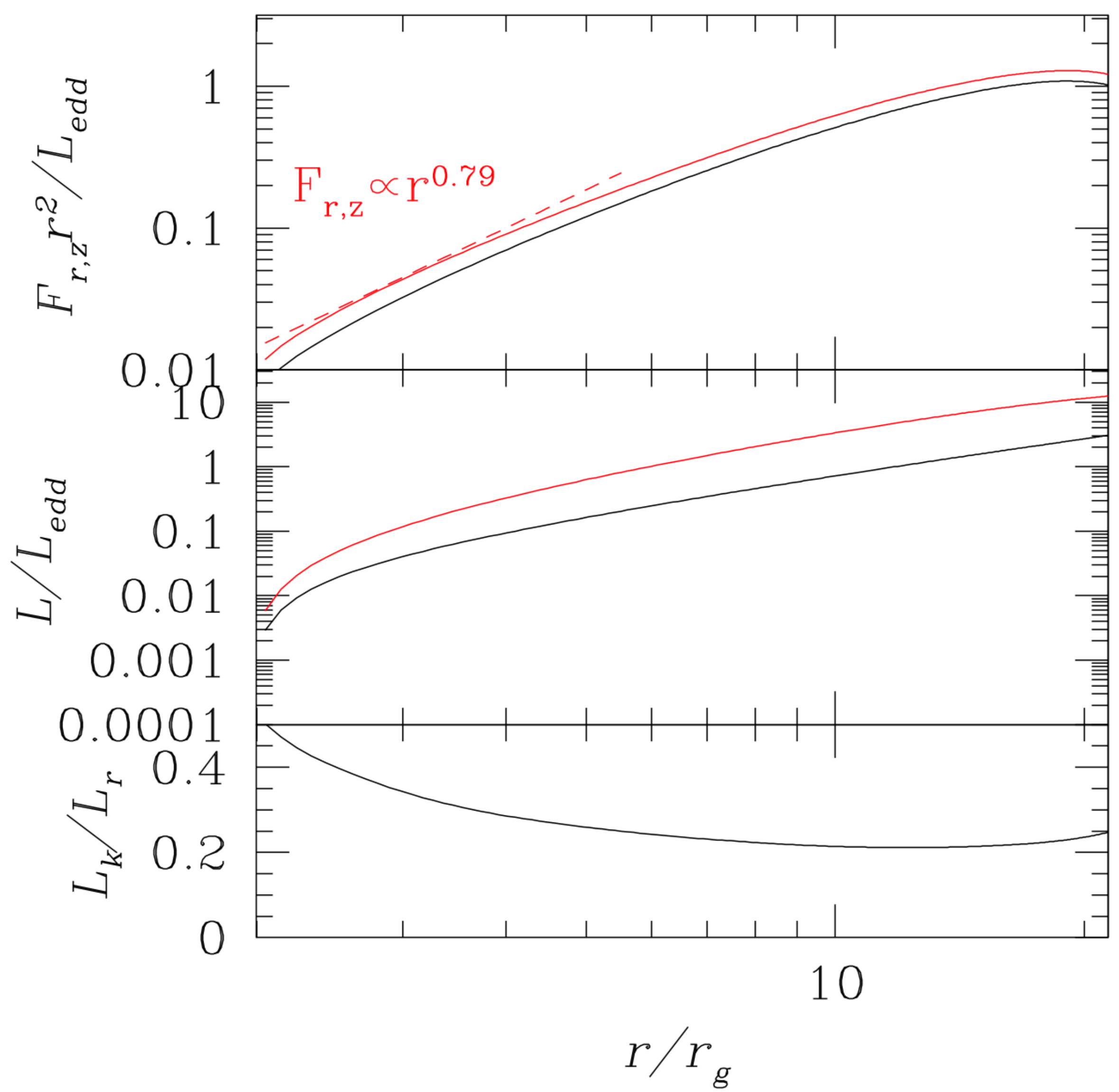
- Strong outflow with a large open angle

Radiation Driven Outflow



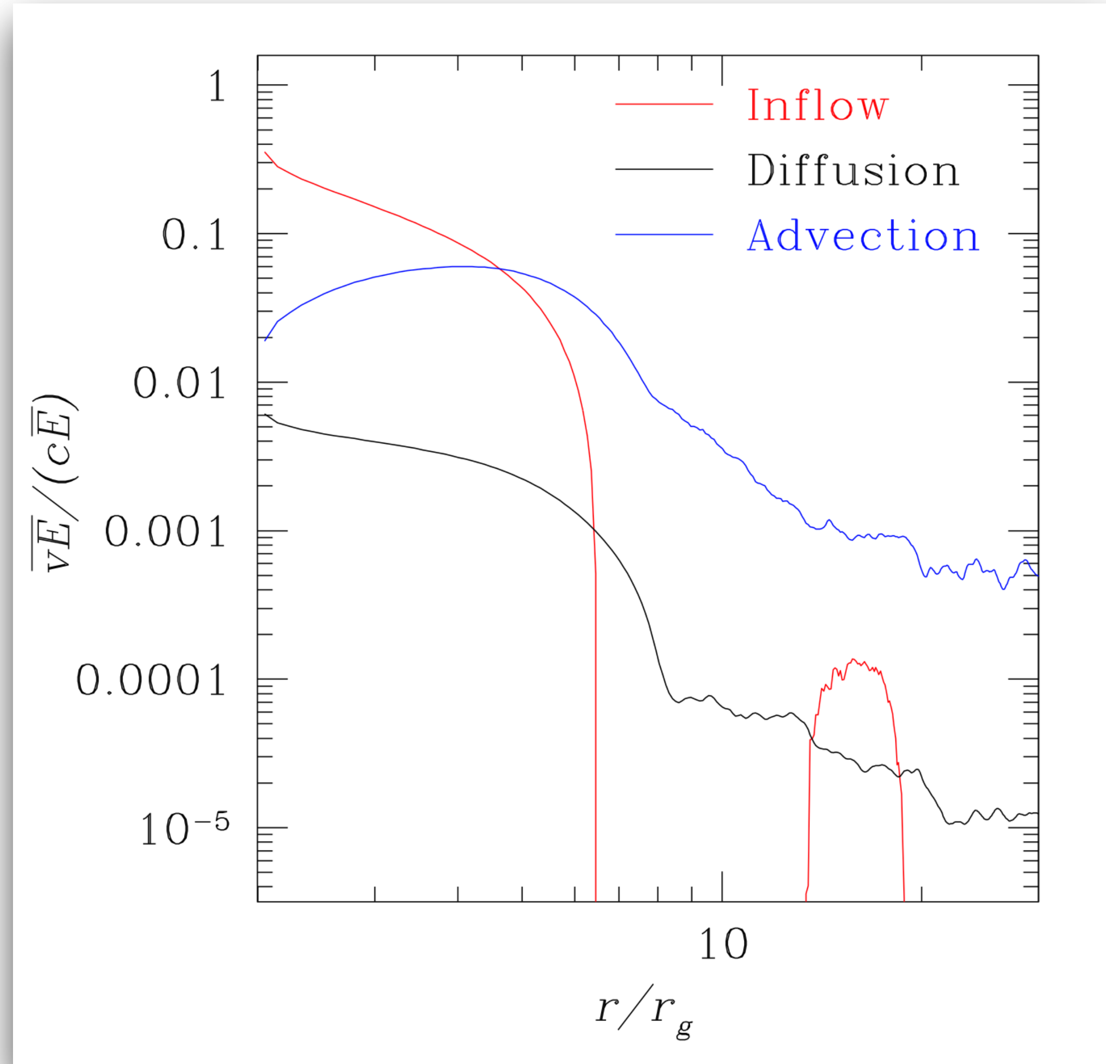
- total energy is positive in the outflow

Radiative and Kinetic Energy Flux



Vertical Energy Transport

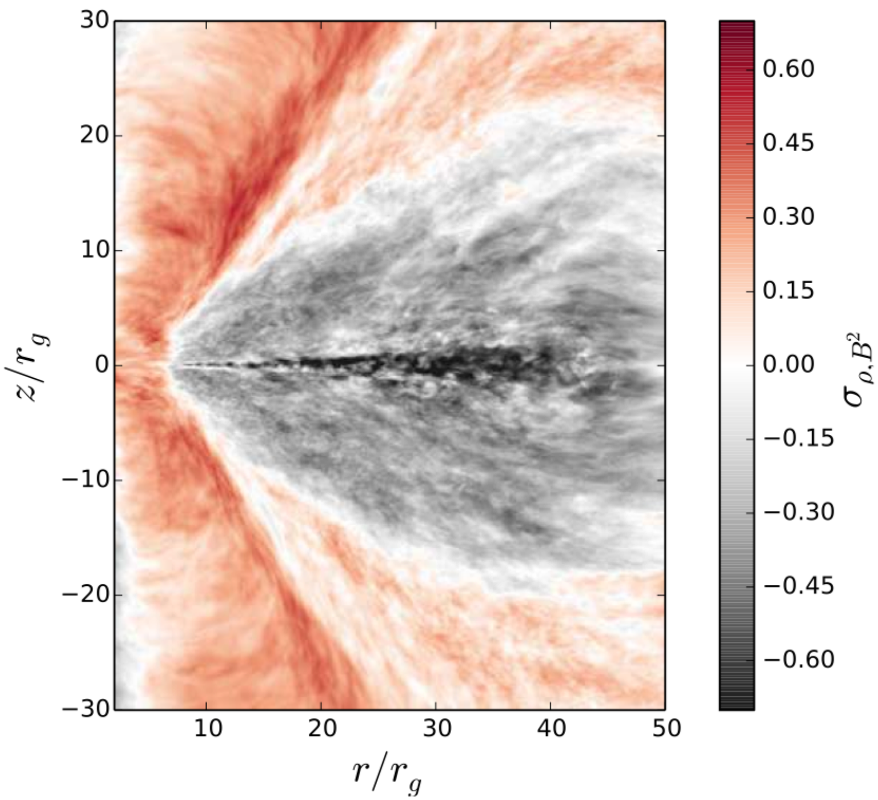
- Compare diffusive, vertical and radial advective speed (energy weighted)



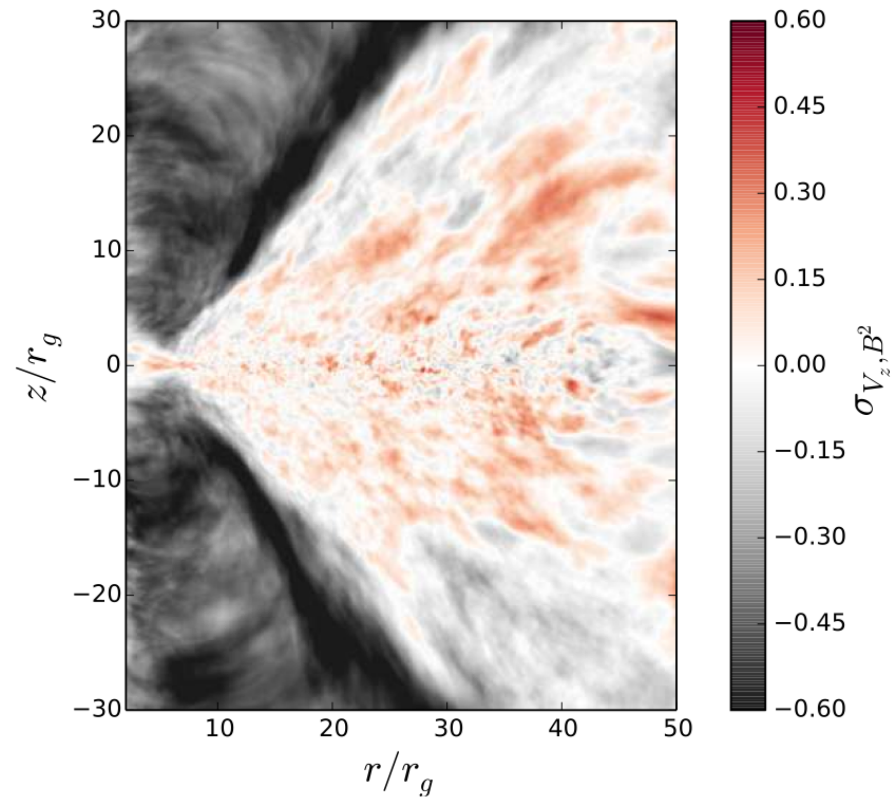
- Advective photons are released near the photosphere
- Scale height is reduced
- Dissipation is moved away from the disk mid-plane
- Luminosity is increased

Vertical Energy Transport

- Magnetic buoyancy causes energy transport
- Density, magnetic pressure, vertical velocity correlations for the global simulations along the azimuthal direction (3D)



Density - Magnetic pressure



Magnetic Pressure - Vertical Motion

Implications

- Radiation MHD simulations teach us something that not included in the classical accretion disk models
- Radiation efficiency can still reach 5% for super-Eddington flow
- kinetic energy of the outflow is more than 20% of the radiation luminosity
- The opening angle of the radiation driven outflow is large