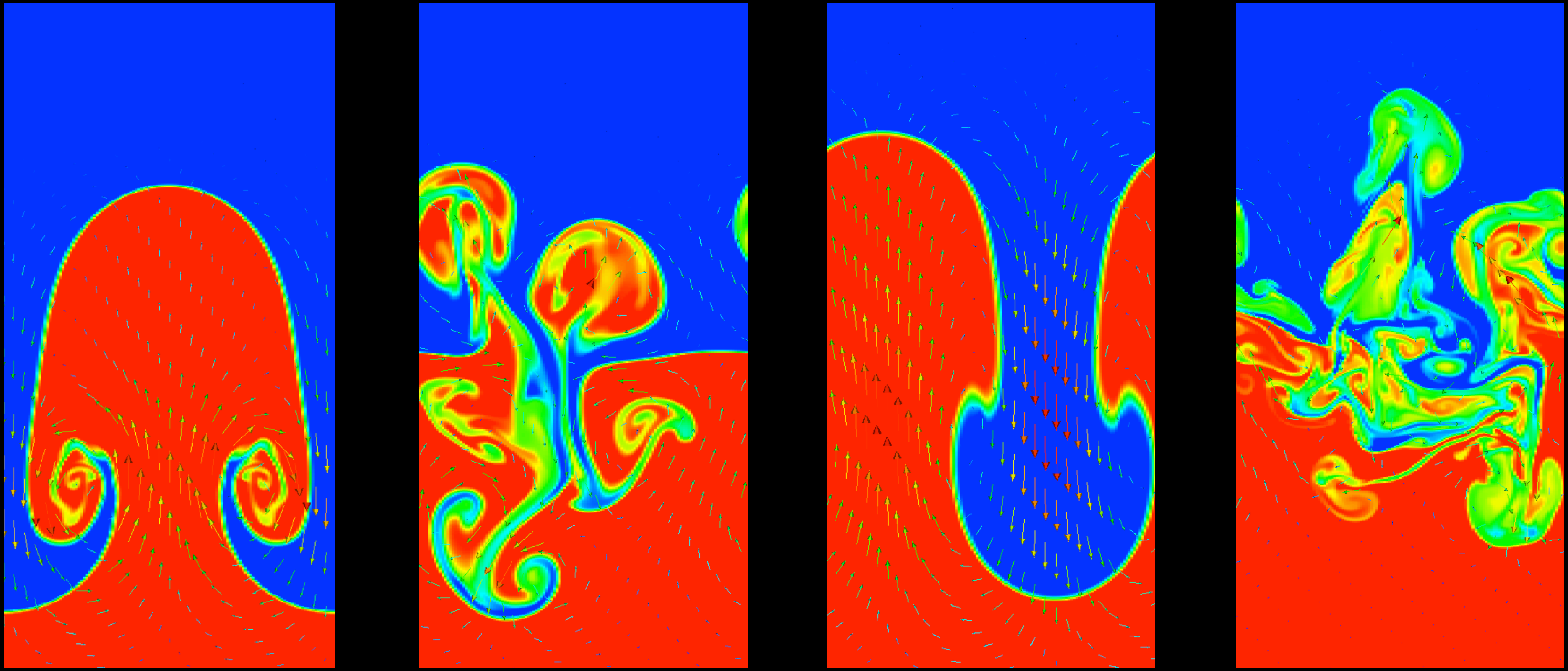
Radiation Feedback in ULIRGS: Are Photons Movers and Shakers?

Shane Davis (CITA)

Yan-Fei Jiang (CfA) Jim Stone (Princeton) Norm Murray (CITA)



Turbulence and Outflows in Star Forming Galaxies

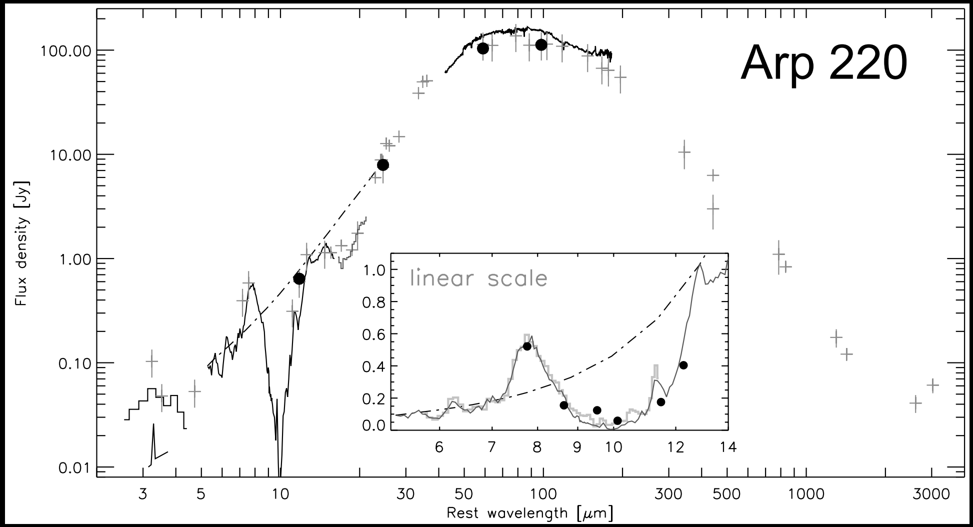
- What drives the high mach number turbulence?
- What drives the outflows (neutral and molecular gas)?

Radiation pressure from UV and IR on dust grains?

Credit: NOAO/AURA/NSF/WIYN

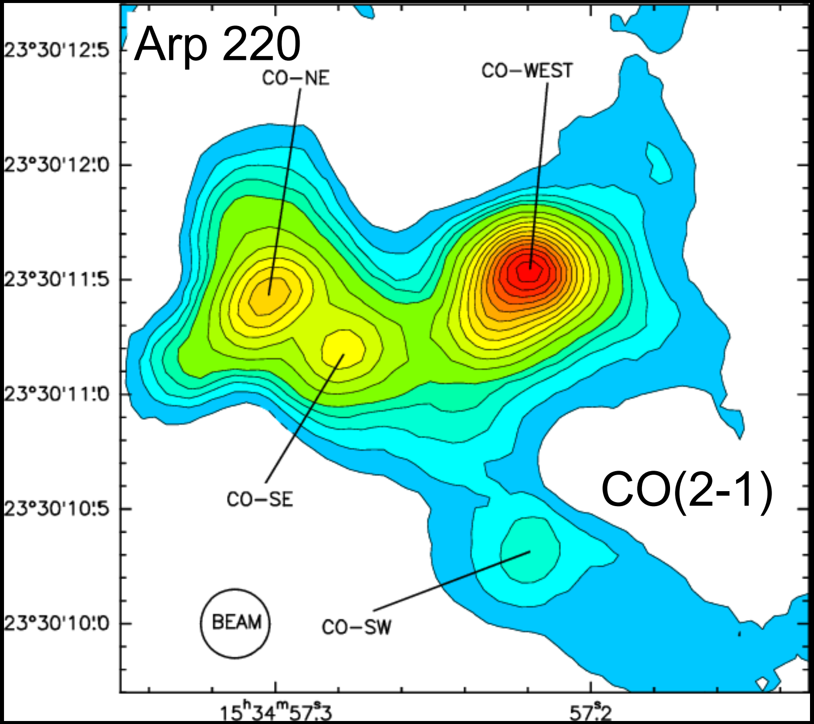
Ultraluminous Infrared Galaxies (ULIRGS)

From SEDs and molecular lines, there is evidence that some (most?) ULIRGs are optically thick to their own infrared emission



Spoon et al. 2004

Downes & Eckart



Arp 220: Rangwala et al. (2011) estimate that τ ~ 5 @ 100 μm

The Role of Radiation Forces

Murray, Quataert & Thompson (2005) and others have argued that momentum injection from radiation pressure on dust is the primary driver of turbulence and winds in ULIRGS; starbursts, and may also drive disruption of GMCs

momentum injection:

$$\dot{p} \simeq (1 + \tau_{ir})\frac{L}{c}$$

ultraviolet

infrared

Numerical Simulations and Rayleigh Taylor Instability

Galaxy scale simulations can reproduce wind velocities and mass loss rates, but radiative feedback is important (Hopkins, Agertz, Keres)

$$\dot{p} = (1 + \eta\tau_{ir})\frac{L}{c}$$

$$\eta \lesssim 1$$

Krumholz & Thompson (2012, 2013) argued based on radiation hydro simulations that the Rayleigh-Taylor instability inhibits radiation feedback

$$\dot{p} \lesssim \frac{L}{c}$$

$$\eta \ll 1$$

$$\tau_{\rm ir} < 1$$

Can we reproduce these results in our Athena radiation hydrodynamics sims?

Radiation Transfer and Radiation Hydrodynamics

Radiation transfer equation (grey):

$$\frac{1}{c}\frac{\partial I}{\partial t} + \hat{n}\cdot\nabla I = \eta - \chi_{\mathrm{t}} I + \chi_s J - \chi_{\mathrm{s}}\frac{\mathbf{v}\cdot\mathbf{H}}{c} + \left(\frac{\hat{n}\cdot\mathbf{v}}{c}\right)(2\eta + \chi_{\mathrm{t}} I + 2\chi_{\mathrm{s}} J)$$

Radiation energy equation:

$$\frac{1}{c}\frac{\partial E_{\mathrm{r}}}{\partial t} + \nabla\cdot\mathbf{F}_{\mathrm{r}} = \chi_{\mathrm{a}}\left(aT^4 - E_{\mathrm{r}}\right) + (\chi_{\mathrm{a}} - \chi_{\mathrm{s}})\frac{\mathbf{v}}{c^2}\cdot(\mathbf{F}_{\mathrm{r}} - \mathbf{v}E_{\mathrm{r}} - \mathbf{v}\cdot\mathsf{P}_r)$$

Radiation momentum equation:

$$\frac{1}{c^2}\frac{\partial \mathbf{F}_{\mathrm{r}}}{\partial t} + \nabla\cdot\boxed{\mathsf{P}_{\mathrm{r}}} = -\frac{\chi_{\mathrm{t}}}{c}(\mathbf{F}_{\mathrm{r}} - \mathbf{v}E_{\mathrm{r}} - \mathbf{v}\cdot\mathsf{P}_r) + \chi_{\mathrm{a}}\frac{\mathbf{v}}{c}\left(aT^4 - E_{\mathrm{r}}\right)$$

How do we handle the radiation pressure?

$$\mathsf{f} = \frac{\mathsf{P}_{\mathrm{r}}}{E_{\mathrm{r}}}$$

Equation of Radiation Hydrodynamics

Standard hydro equations:
sound crossing time

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

$$\frac{\partial (\rho \mathbf{v})}{\partial t} + \nabla \cdot (\rho \mathbf{v}\mathbf{v}) + \nabla P = -\mathbf{S}_{\mathrm{r}}(\mathbf{P})$$

stiff source terms:
radiation relaxation time

$$\frac{\partial E}{\partial t} + \nabla \cdot (E\mathbf{v} + P\mathbf{v}) = -cS_{\mathrm{r}}(E)$$

Radiation subsystem:
light crossing time

$$\frac{1}{c^2}\frac{\partial \mathbf{F}_{\mathrm{r}}}{\partial t} + \nabla \cdot (\boxed{\mathsf{f}}\, E_{\mathrm{r}}) = \mathbf{S}_{\mathrm{r}}(\mathbf{P})$$

$$\frac{1}{c}\frac{\partial E_{\mathrm{r}}}{\partial t} + \nabla \cdot \mathbf{F}_{\mathrm{r}} = S_{\mathrm{r}}(E)$$

What do you do for f?

Sekora & Stone (2010)
Jiang, Stone & Davis (2012)

Common Solution: Flux-limited Diffusion (FLD)

Replace momentum eq. with diffusion approximation:

$$\mathbf{F}_\mathrm{r} = -\lambda(E_\mathrm{r}, \chi)\frac{c}{3\chi}\nabla E_\mathrm{r}$$

optically thin $|F_\mathrm{r}| \rightarrow cE_\mathrm{r}$

optically thick $\lambda(E_\mathrm{r}, \chi) \rightarrow 1$

Flux comes directly from energy density solve one PDE instead of four

But several issues: e.g. limiter is a simple function of local variables; flux always points along gradient of energy density

Our Method: Variable Eddington Tensor (VET)

On each timestep we compute f_{ij} by solving the time-independent transfer equation:

$$\hat{n}\cdot\nabla I = \chi_{\rm t}\left(S - I\right)$$

Davis, Stone & Jiang (2012)

Short Characteristics: Solve radiative transfer equation at each grid zone along a set of rays using intensities, emissivities, and opacities interpolated from neighboring zones

$$\hat{n}\cdot\nabla I = \eta - \chi_{\rm t} I + \chi_s J - \chi_{\rm s}\frac{\mathbf{v}\cdot\mathbf{H}}{c} + \left(\frac{\hat{n}\cdot\mathbf{v}}{c}\right)\left(2\eta + \chi_{\rm t} I + 2\chi_{\rm s} J\right)$$

Radiation Hydrodynamics with VET in Athena

On each timestep we:

1) Solve the equations of (magneto)hydrodynamics using standard Athena algorithms

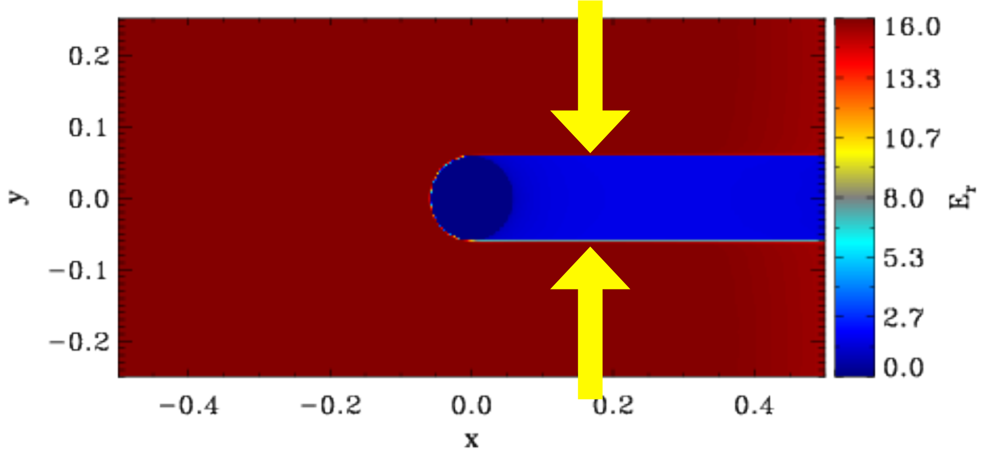
2) Solve time-independent radiative transfer to compute the Eddington tensor with densities and temperatures from step 1

3) Solve the time-dependent radiation energy and momentum equations using the Eddington tensor from step 2

4) Update hydro variables with radiation source terms from step 3

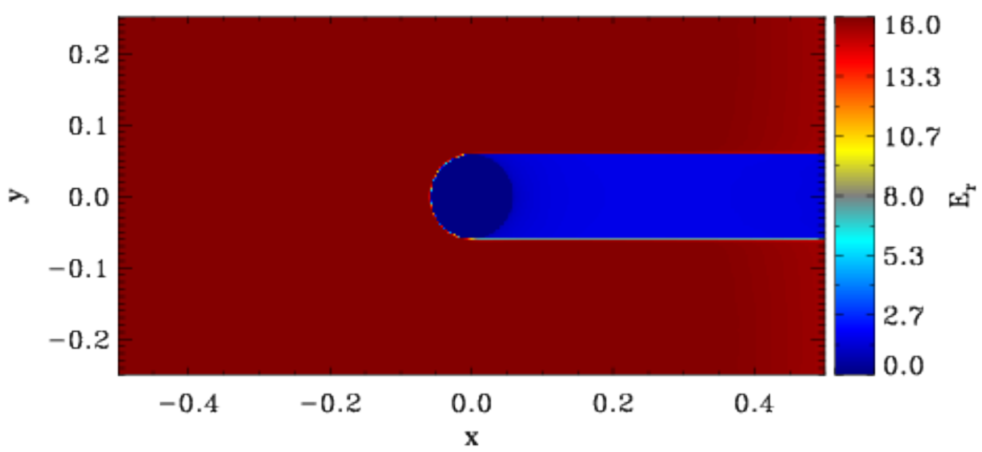
Example: Cloud Irradiation (Proga et al. 2014)

VET

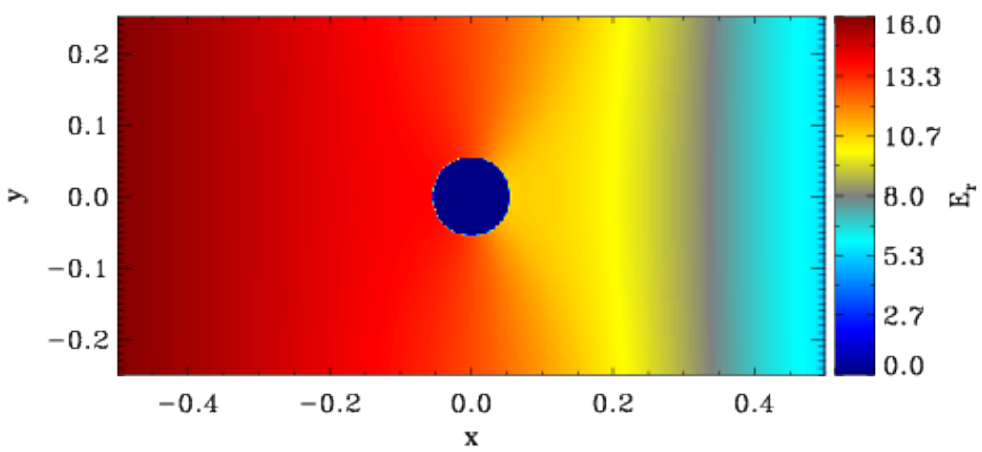


Example: Cloud Irradiation (Proga et al. 2014)

VET



FLD



Hydrostatic Equiliibrium in a ULIRG Disk

Assume IR radiation dominates and dust opacities is proportional to T^2

$$F \sim F_{\mathrm{ir}} \sim \mathrm{const}$$

$$\kappa \sim \kappa_{\mathrm{ir}} \propto T^2$$

Radiative equilibrium tells us temperature must increase if disk is optically thick

$$T^4 = \frac{3F}{4\sigma}\left(\frac{2}{3} + \tau\right)$$

If g ~ const and radiation pressure dominates then hydrostatic equilibrium is impossible

$$-\xcancel{\frac{1}{\rho}\frac{dP}{dz}} + \frac{\kappa F}{c} = g$$

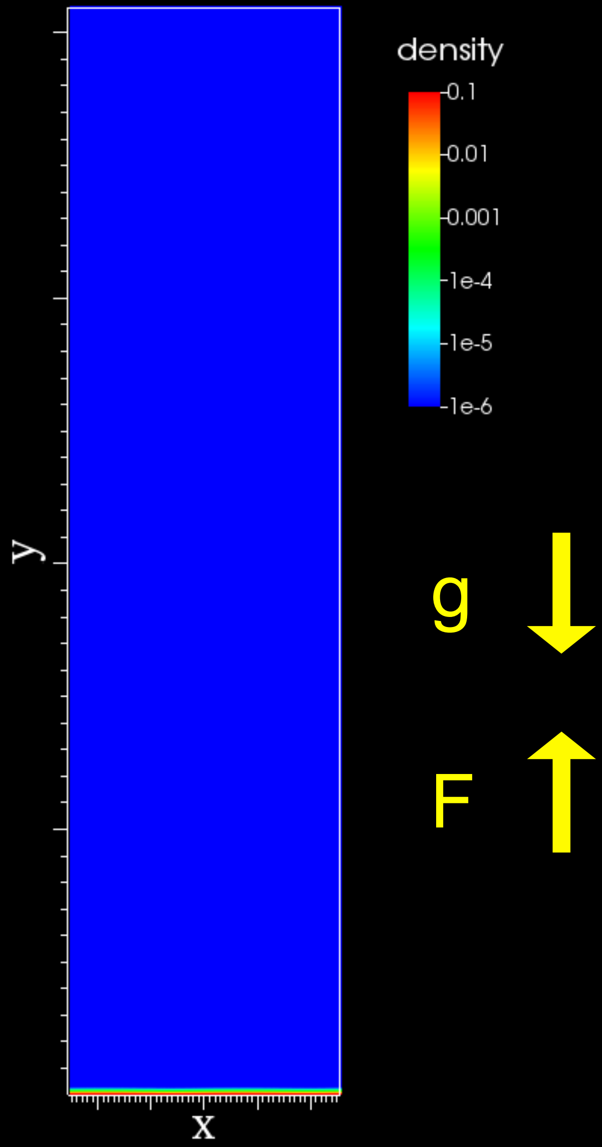
2D simulations of Dusty Gas with IR Radiation Field

Krumholz & Thompson (2012)

- Constant gravity and IR flux incident at lower boundary
- 2D Atmosphere is initially isothermal
- Sinusoidal density perturbation
- Radiation field is assumed to be blackbody with T ~ 80 K
- Initial optical depth and Eddington ratio:

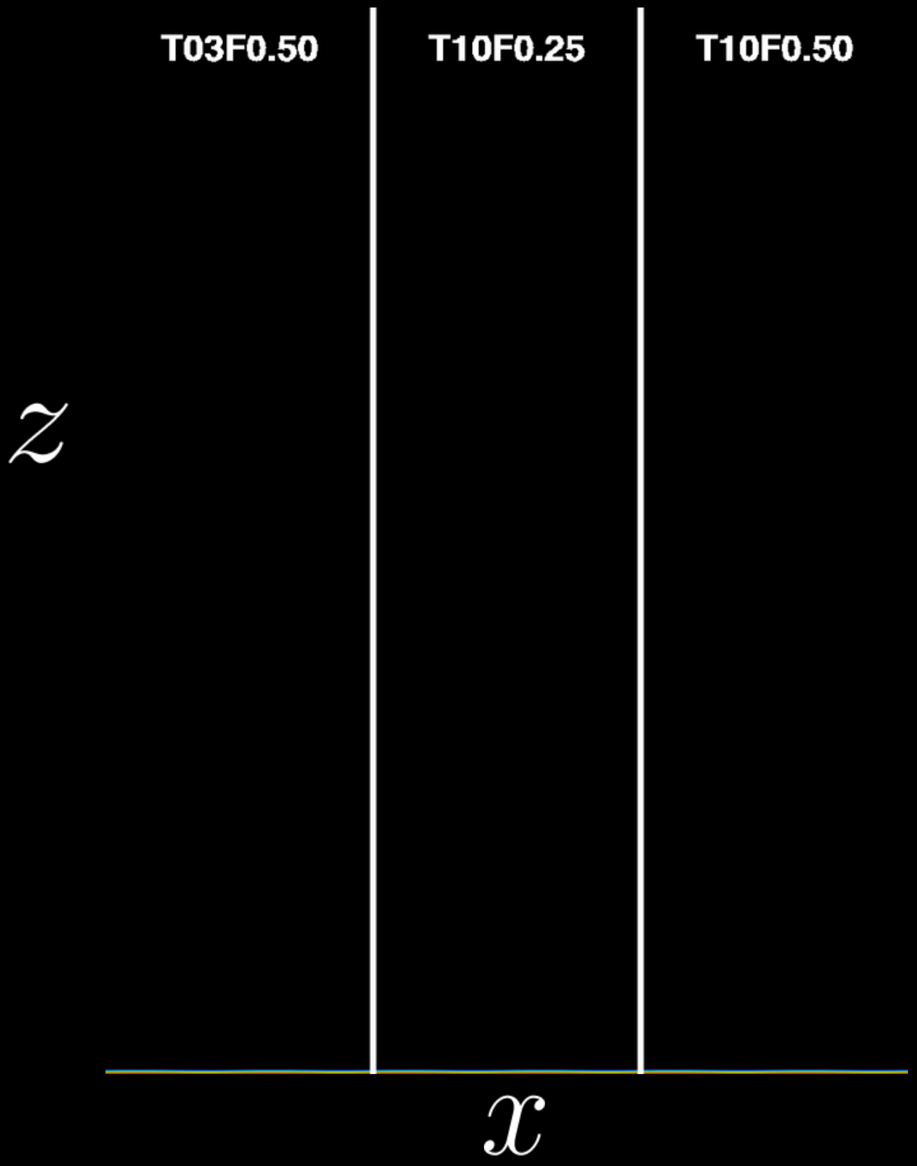
$$\frac{\kappa F}{cg} = (0.25, 0.5)\left(\frac{T}{80\mathrm{K}}\right)^2$$

$$\tau = 3, 10$$



Radiation Hydrodynamics Simulations with ORION FLD

Krumholz & Thompson (2012)
Movies show (log) density from three different atmospheres with varying initial optical depth and Eddington ratio

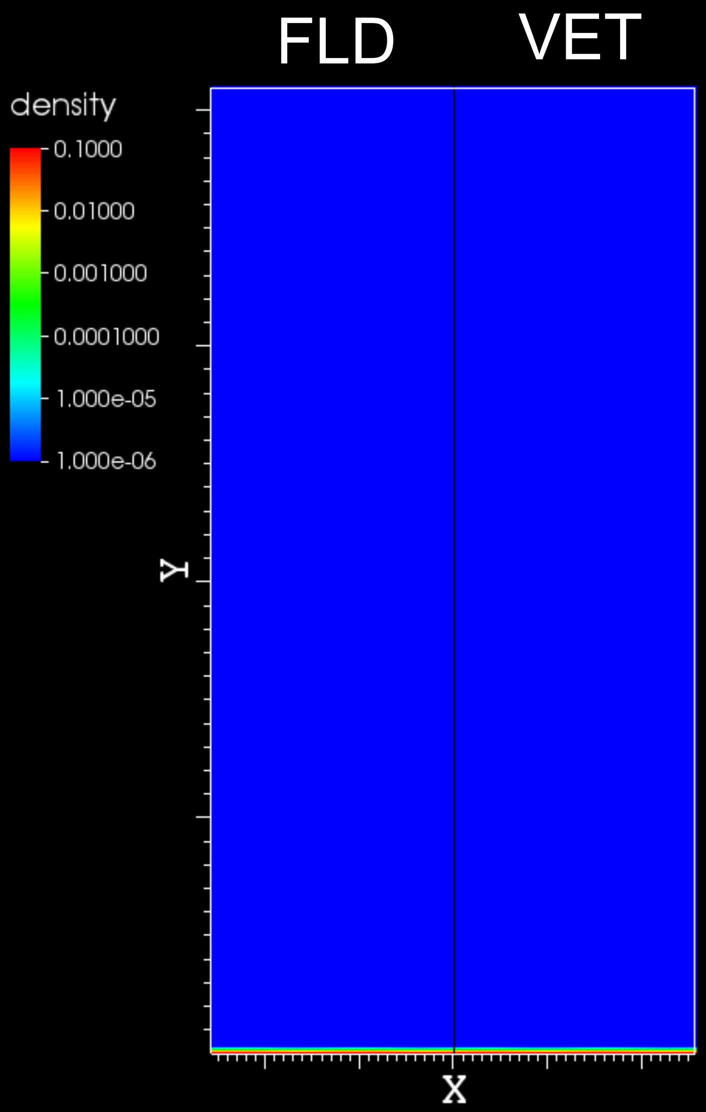


Radiation Hydrodynamics Simulations with Athena

Same setup as Krumholz & Thompson (2012), except with random perturbation in addition to sinusoidal perturbations

$$\frac{\kappa F}{cg} = 0.5 \left(\frac{T}{80\mathrm{K}} \right)^2$$

$$\tau = 3$$

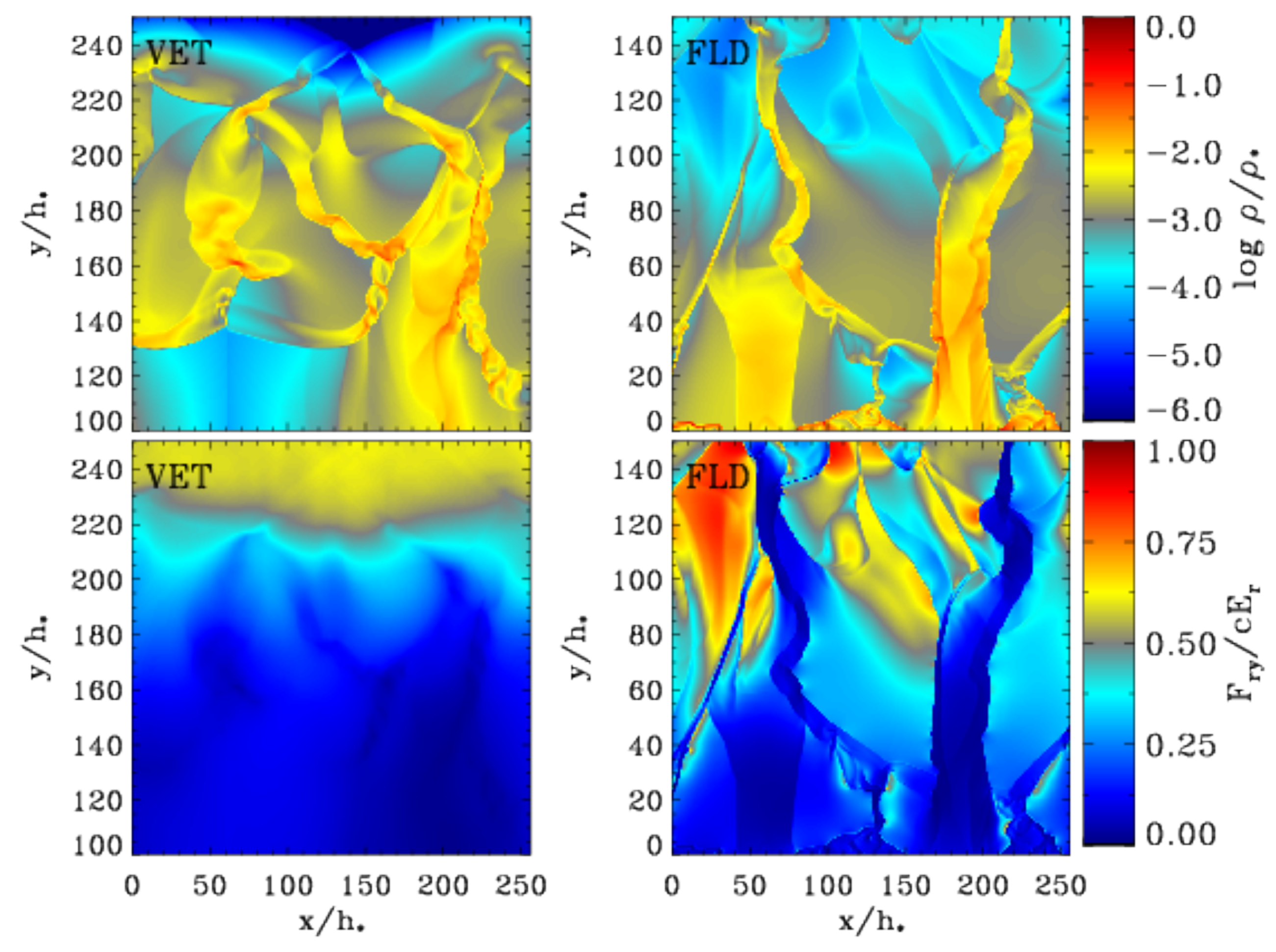


Difference Between FLD and VET

VET FLD

log density

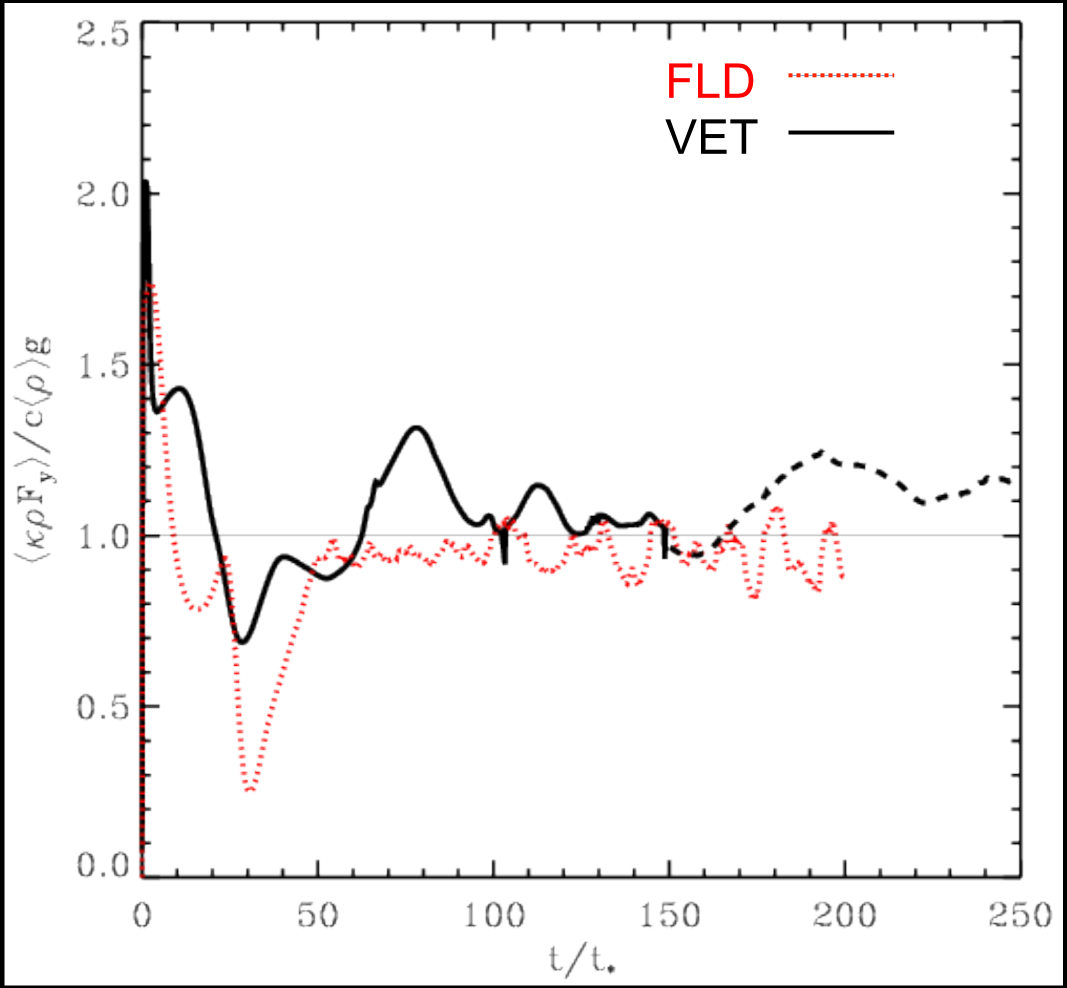
$$\frac{\text{vertical flux}}{\text{energy density}}$$



Force Balance

Radiation force matches or exceeds gravity:

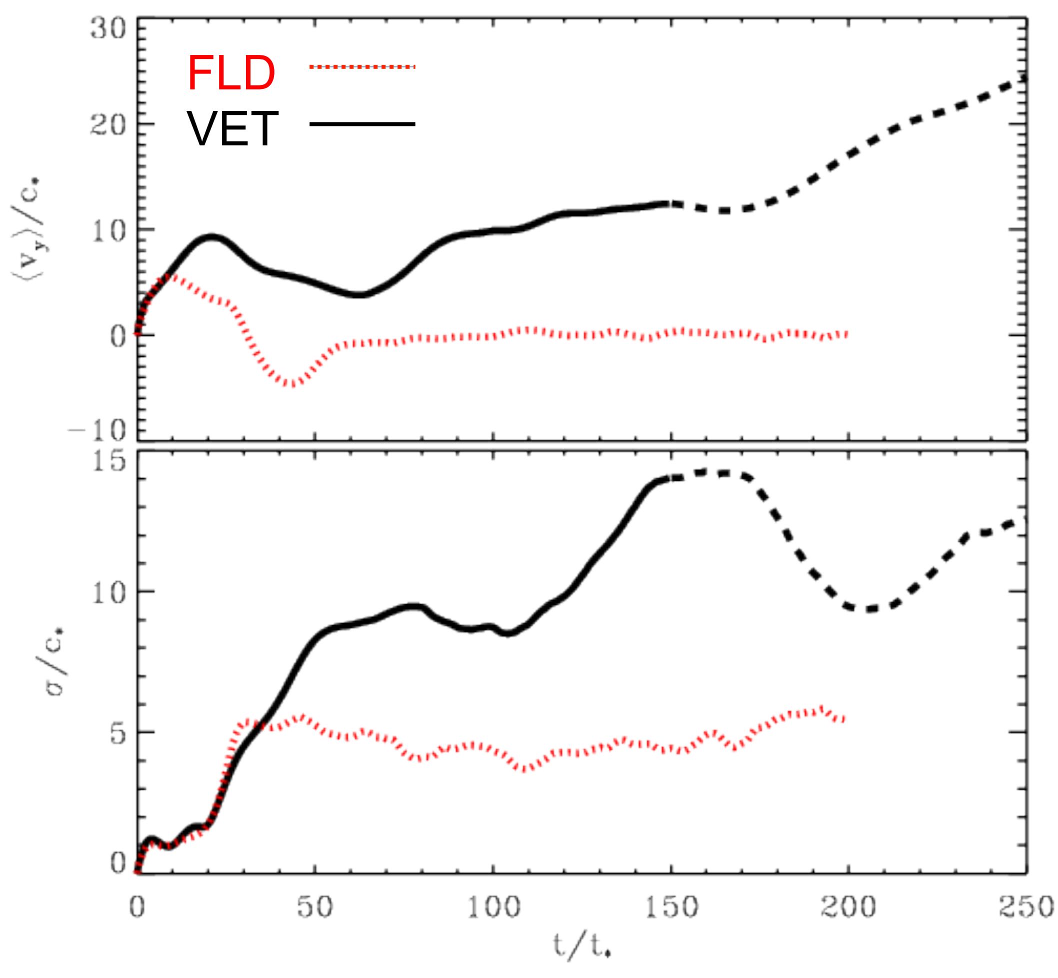
$$\frac{\langle \kappa \rho F \rangle}{c \langle \rho \rangle g} \gtrsim 1$$



Mass Weighted Velocity and Velocity Dispersion

Velocity dispersion Mach number is too low: $\mathcal{M} \sim 15$ (8 km/s). But mean velocity continues increasing:

gas is unbound!



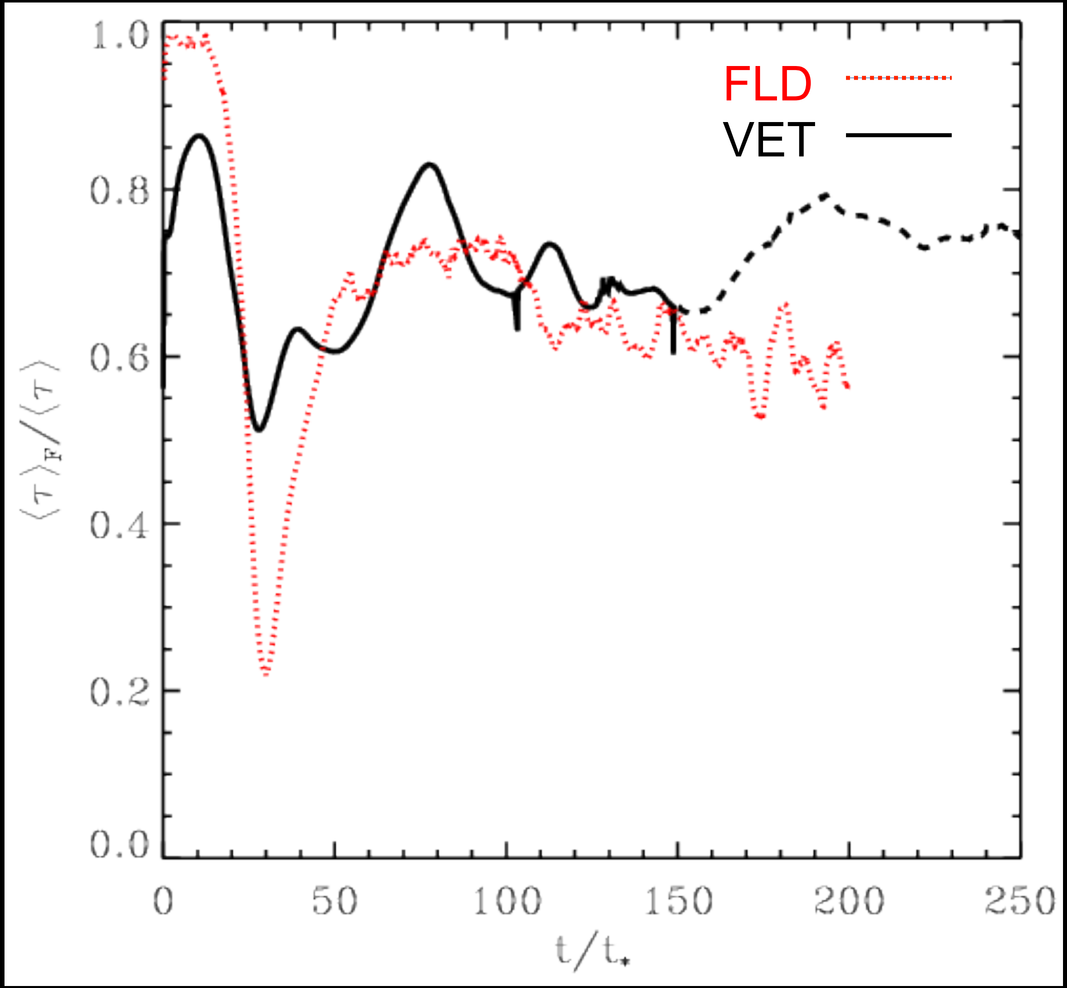
Implications for Momentum Feedback

RTI may or may not significantly inhibit momentum injection:

$$\dot{p} \simeq \langle \tau \rangle_F \frac{L}{c}$$

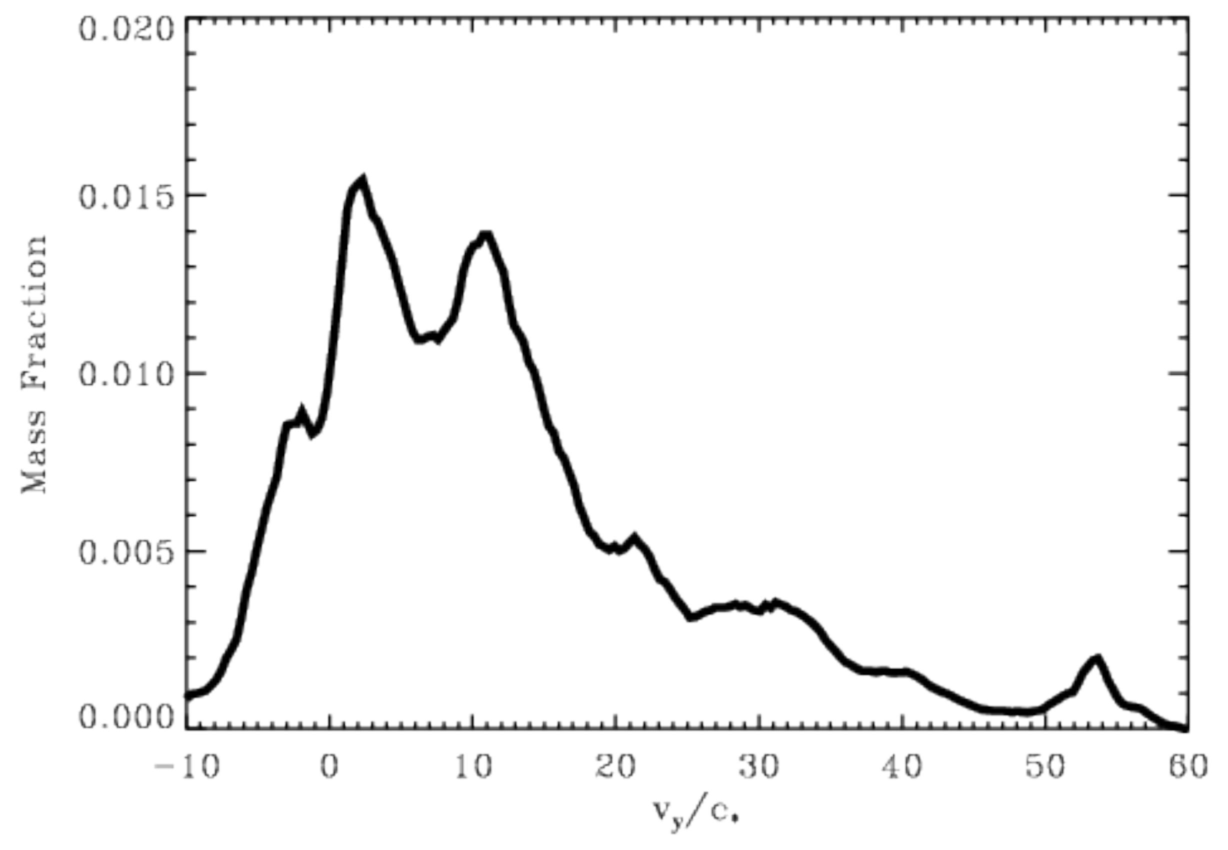
$$\langle \tau \rangle_F \simeq \kappa_{\mathrm{E}} \Sigma$$

$$\kappa_{\mathrm{E}} \equiv \frac{cg}{F}$$



$$\langle \tau \rangle_F \simeq 6 \qquad \eta \simeq \langle \tau \rangle_F / \langle \tau \rangle \simeq 0.7$$

Mass Weighted Velocity Distribution and Outflows

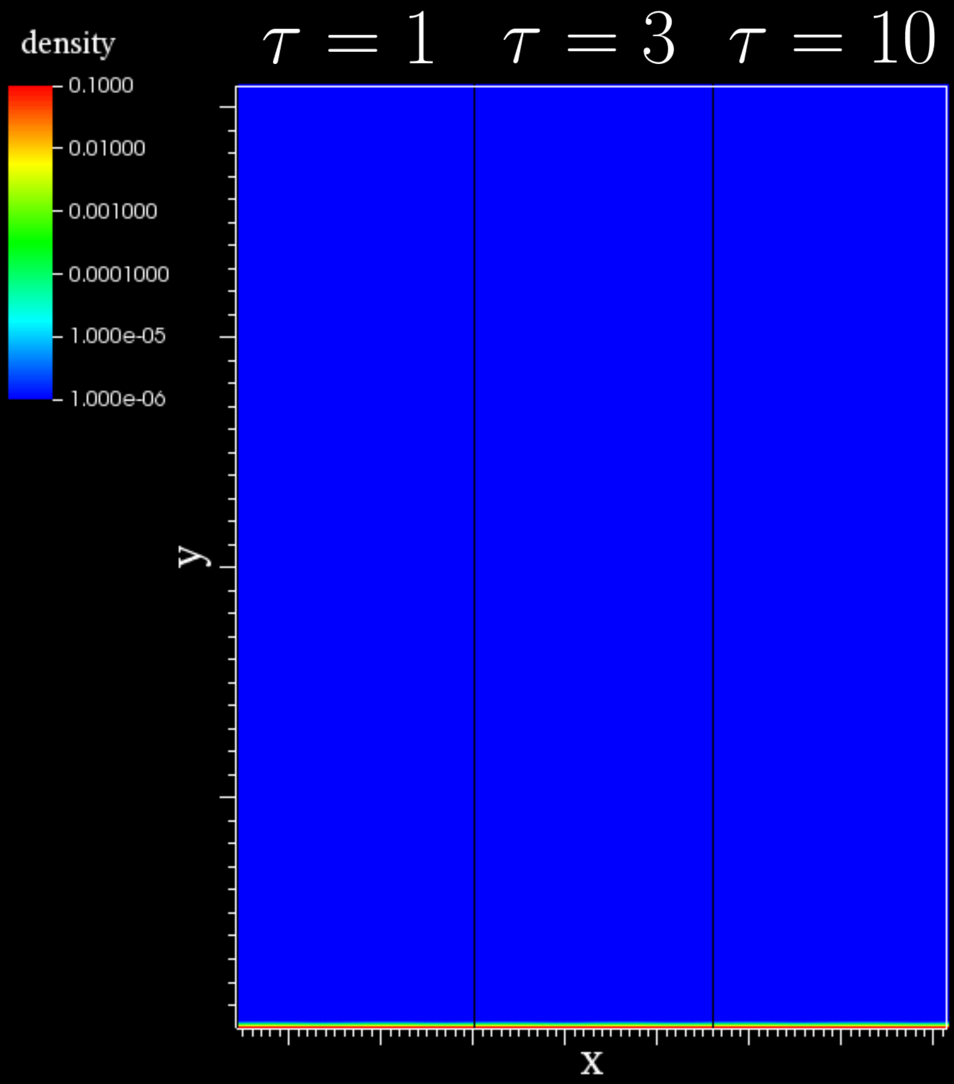


A few % of mass has velocity greater than ~ 4 times velocity dispersion

Varying the (Initial) Optical Depth

Same setup as above, but with varying optical depth

$$\frac{\kappa F}{cg} = 0.5\left(\frac{T}{80\mathrm{K}}\right)^2$$



Summary

- VET *is better than* FLD
- We confirm the importance of the Rayleigh-Taylor instability in limiting the Eddington ratio to be near unity.
- The precise Eddington ratio depends on transfer method. In VET radiation provides a modest acceleration above gravity and gas appears to be unbound.
- A small fraction of mass is accelerated to high velocities – mechanism for launching of outflows?
- Our results depend on optical depth: runs with $\tau \sim 1$ show little net acceleration and low velocity dispersion.
- More realistic setups are needed.