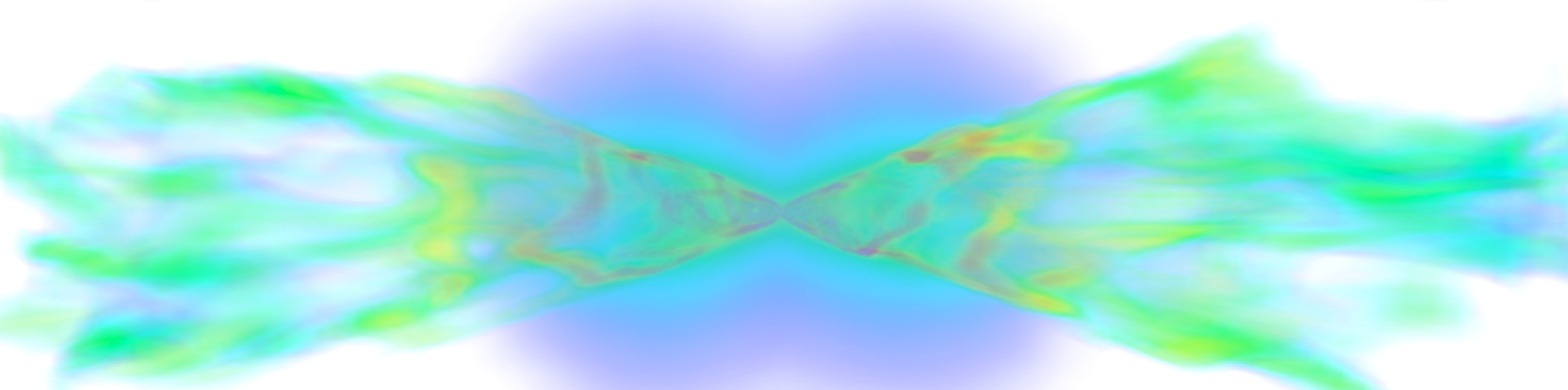
The Physical Models and Observational Consequences of AGN Winds



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Collaborators: J. Stone, T. Kallman, M. Begelman, J. Ostriker, S. Sim, Y-F. Jiang, S. Davis, **A. Janiuk, R. Kurosawa, M. Moscibrodzka**, **P. Barai, A. Kashi, N. Higginbottom, S. Dyda, and T. Waters,** and many more

OUTLINE

1) Introduction

2) Toward a More Fundamental Model of Quasars/AGNs

 a) radiation driven disk winds

  - AGN: Are they the BLRs?

  - AGN FB: What is the physics of a 'subgrid'?

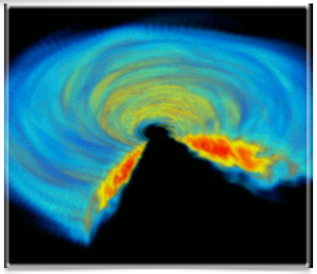
 b) large scale inflows and outflows

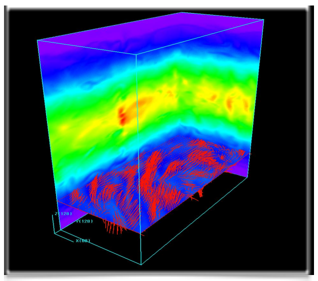
  - AGN: Are they the NLRs?

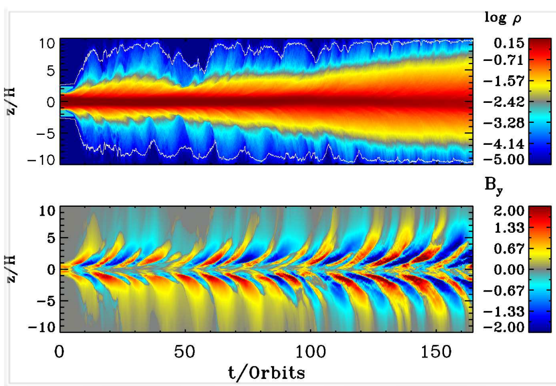
  - AGN FB: Can we model the AGN FB directly?

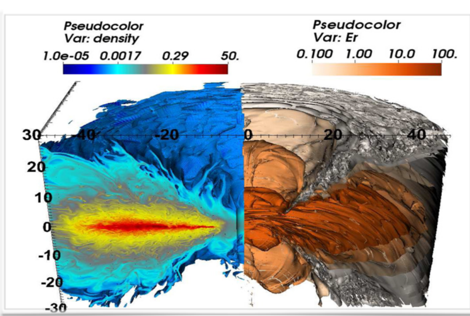
3) Future Work

Radiation and MHD are essential









mean motion (rotation)

↓

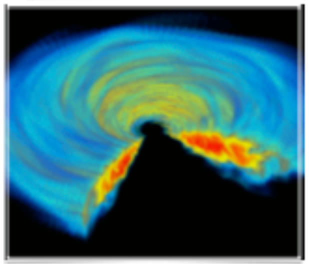
internal energy

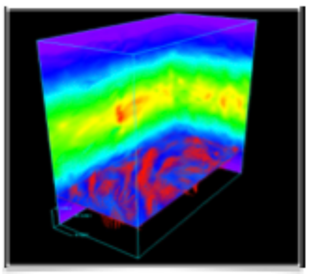
↓

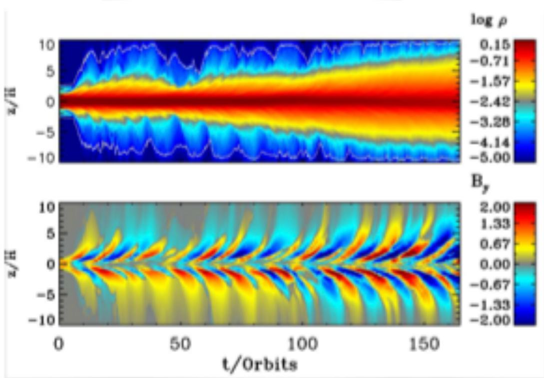
emission of EM radiation, magnetic fields, and gas

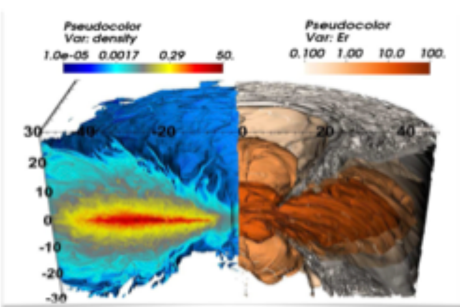
The energy flow.

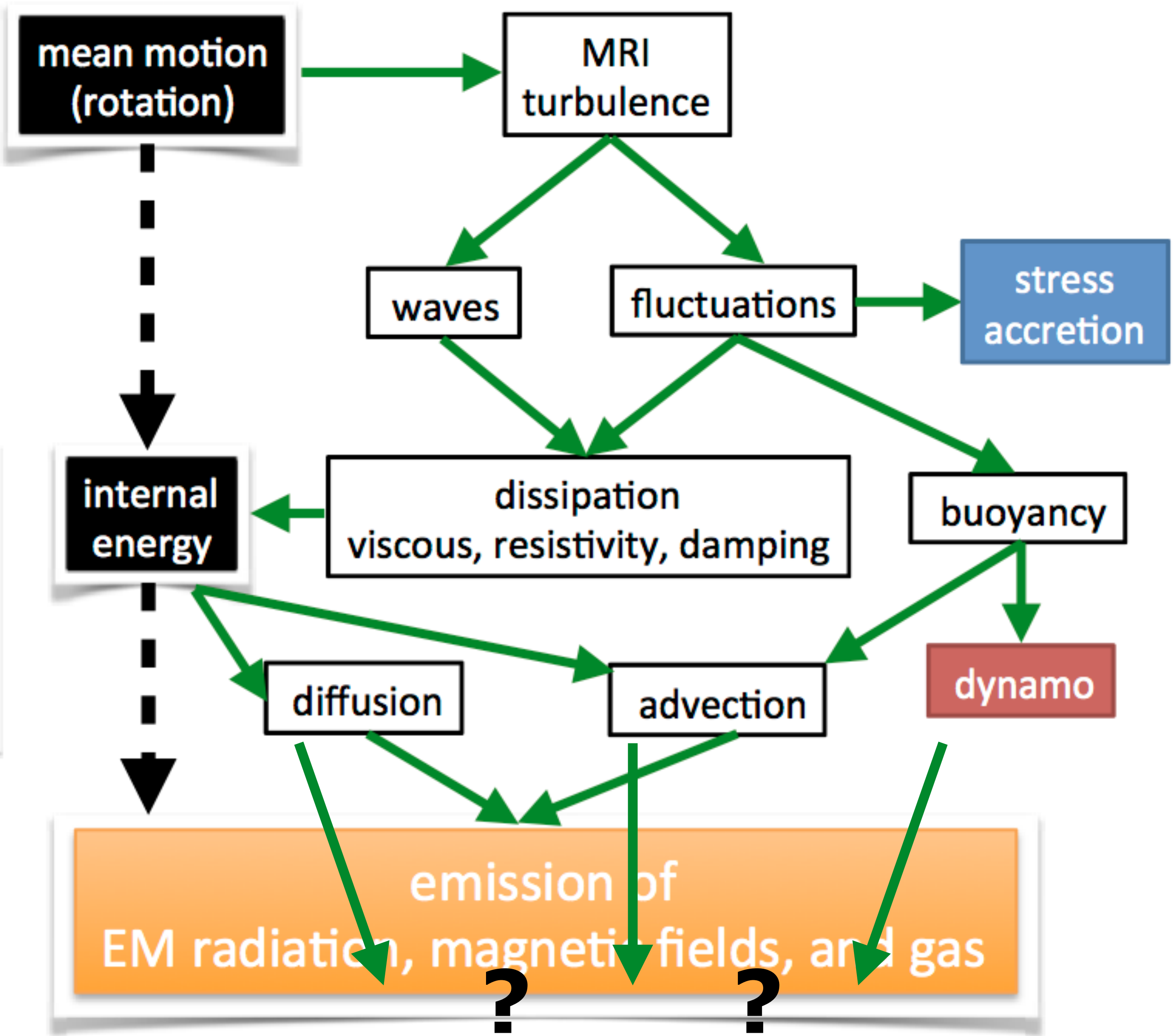
S. Balbus, J. Hawley, J. Stone, C. Gammie, J. Krolik, S. Hirose R. Narayan, O. Blaes, S. Davis, Y.-F. Jiang, A. Sadawski






log ρ
B_y
z/H
t/Orbits

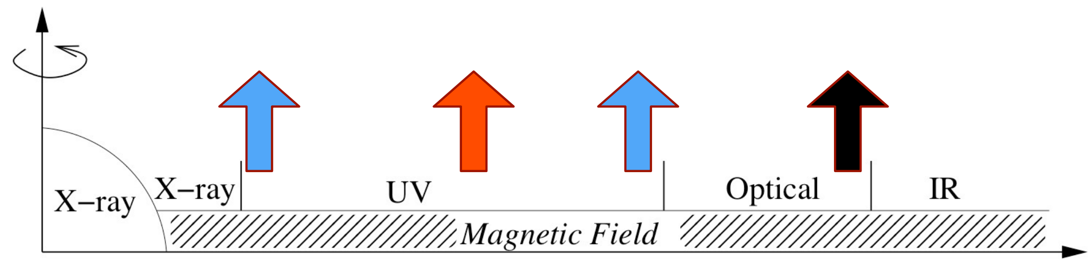

Pseudocolor
Var: density
Pseudocolor
Var: Er


mean motion
(rotation)
MRI
turbulence
waves
fluctuations
stress
accretion
internal
energy
dissipation
viscous, resistivity, damping
buoyancy
diffusion
advection
dynamo
emission of
EM radiation, magnetic fields, and gas
?
?

What can drive an outflow or regulate accretion?

- Thermal expansion (evaporation, hydrodynamical escape)
- Radiation pressure (due to gas and dust opacities)
- Magnetic fields.

In most cases, rotation plays a key role (directly or indirectly).



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

$$\frac{\partial (\rho \mathbf{v})}{\partial t} + \nabla \cdot (\rho \mathbf{v}\mathbf{v} + P + B^2/2 - \mathbf{B}\mathbf{B}) = -\mathbb{P}\mathbf{S}_{\mathbf{M}}$$

$$\frac{\partial E}{\partial t} + \nabla \cdot [(E+P)\mathbf{v} + (B^2/2)\mathbf{v} - \mathbf{B}(\mathbf{B}\cdot\mathbf{v})] = -\mathbb{P}\mathbb{C}S_E$$

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

$$\frac{\partial E_r}{\partial t} + \mathbb{C}\nabla \cdot \mathbf{F}_r = \mathbb{C}S_E$$

$$\frac{\partial \mathbf{F}_r}{\partial t} + \mathbb{C}\nabla \cdot \mathsf{P}_r = \mathbb{C}\mathbf{S}_{\mathbf{M}}$$

Radiation momentum and energy source terms:

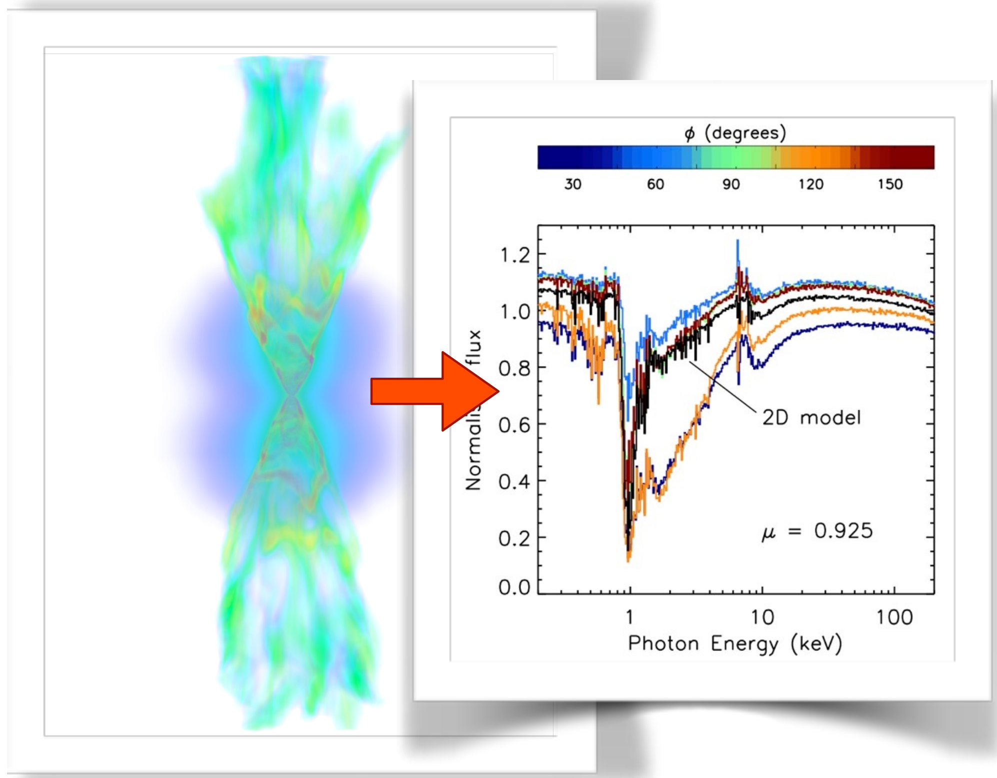
$$\mathbf{S}_{\mathbf{M}} \approx -(\sigma_a + \sigma_s)\boldsymbol{F}_r$$

$$S_E \approx \sigma_a (T^4 - E_r)$$

Essentials:

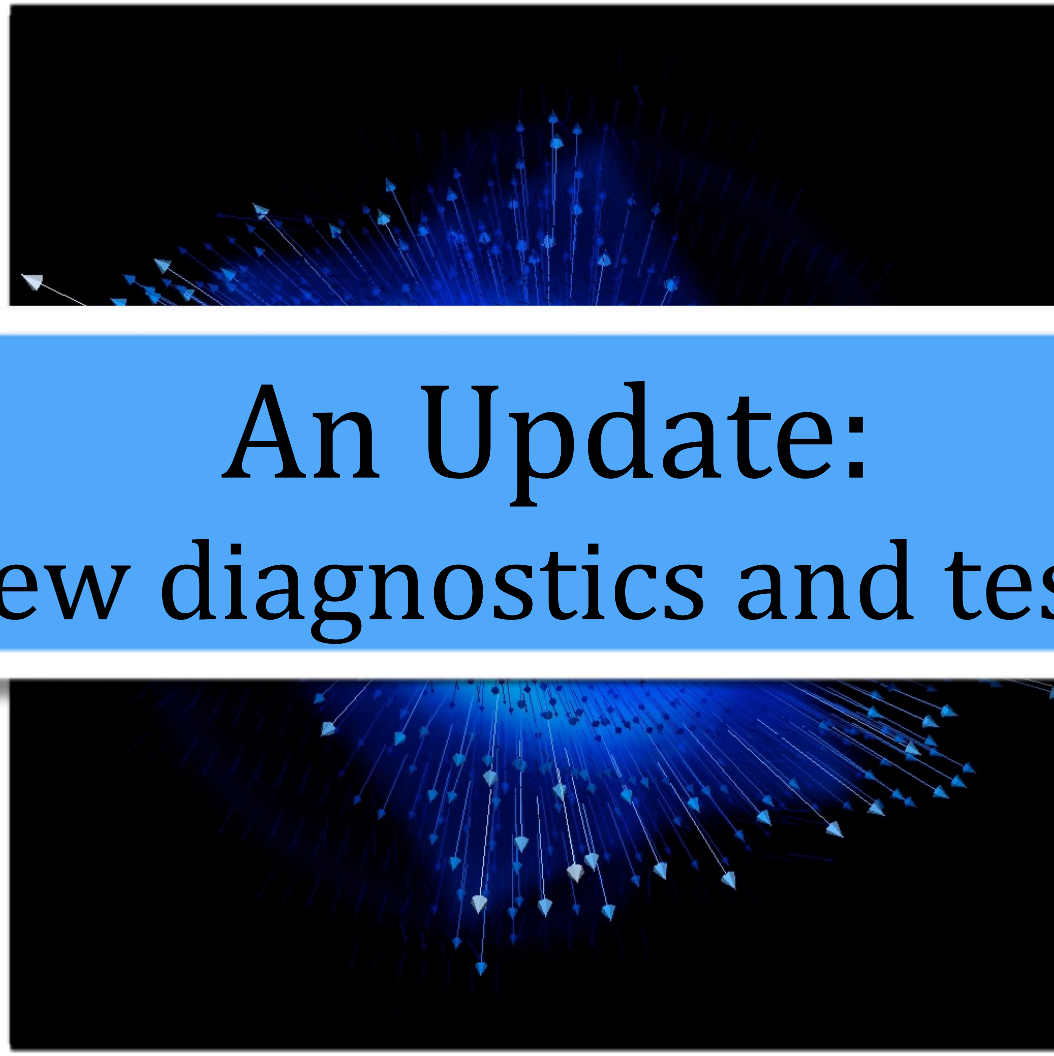
1) Calculations of the physical conditions and emission/ transmitted spectra of photo-ionized gases.
2) Simulations of fluid dynamics.

- Compute structure and dynamics of accretion flows and related outflows.
- Study thermal, MRI and other instabilities.
- Determine strength of outflows/ feedback (e.g., mass accretion & supply rates), growth rate of BHs.
- Compute emergent spectra and variability to compare to observations.



Radiation Driven Disk Winds

(Are they the BLRs? What is the physics of a 'subgrid'?)



An Update:

new diagnostics and tests

Line-Driven Disk Winds

Radiation pressure on UV lines can drive a powerful wind from a disk even when the wind is irradiated by a strong central source of X-rays.

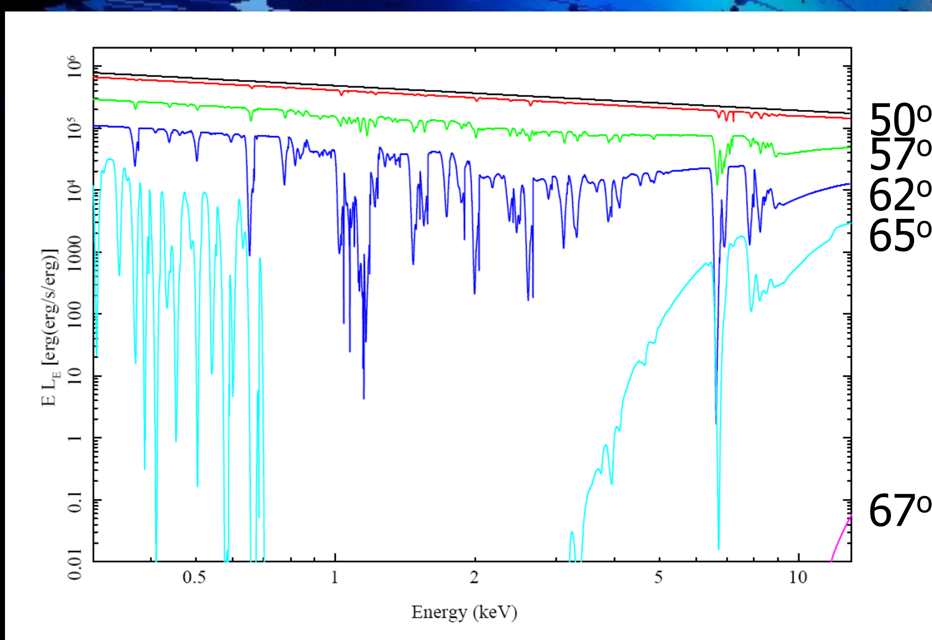
The wind can be very fast (~20,000 km/s) and its mass loss rate is high (~1 solar mass per year)

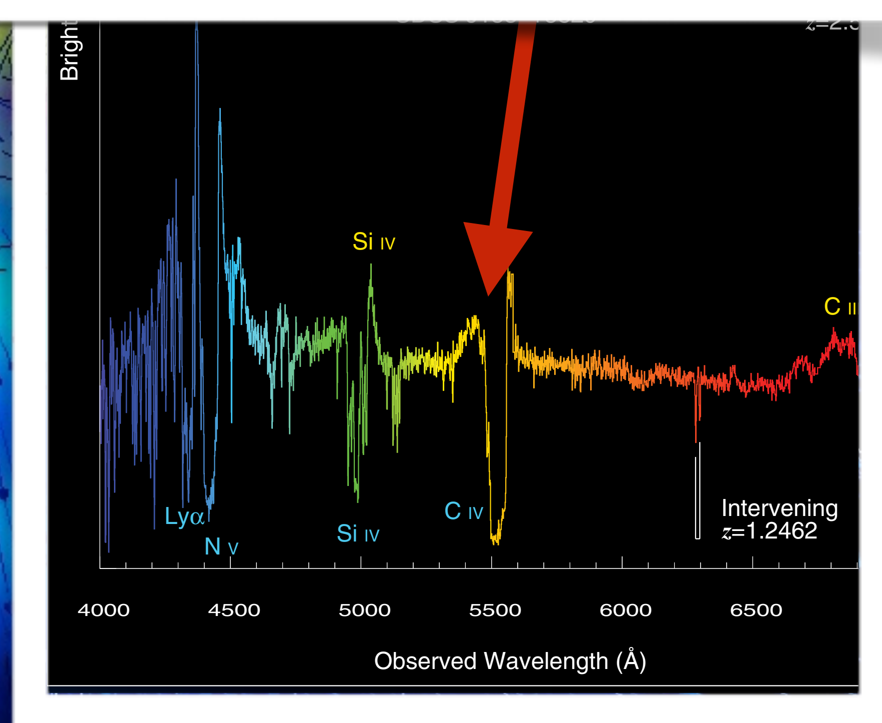
Results from the line-driven disk wind simulations have been applied in models of AGN momentum-driven feedback, e.g., Ostriker et al. (2010), Choi et al. (2012), Ciotti et al. (2016)

Proga, Stone & Kallman (2000), Proga & Kallman (2004)

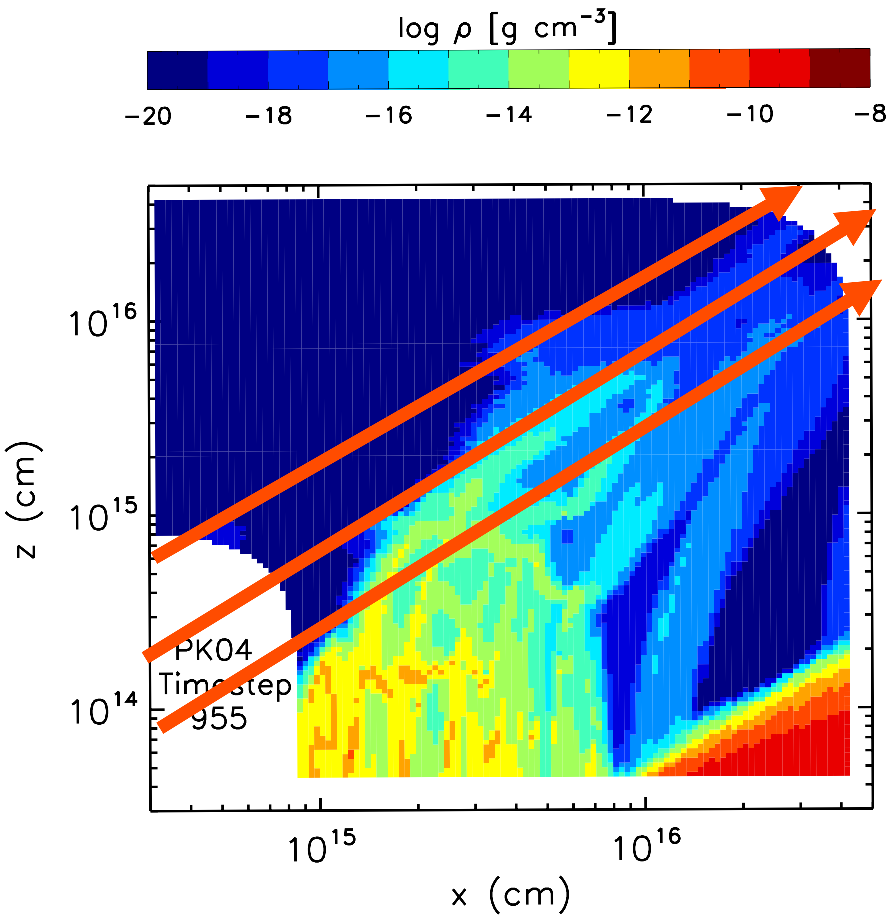
$\Gamma = 0.6$

Computed profiles of UV resonant lines resemble the observed profiles (strong single-peaked emission lines for low and intermediate inclinations; P-Cygni like lines for high inclinations). BAL quasars should be X-ray weak because of the shielding.



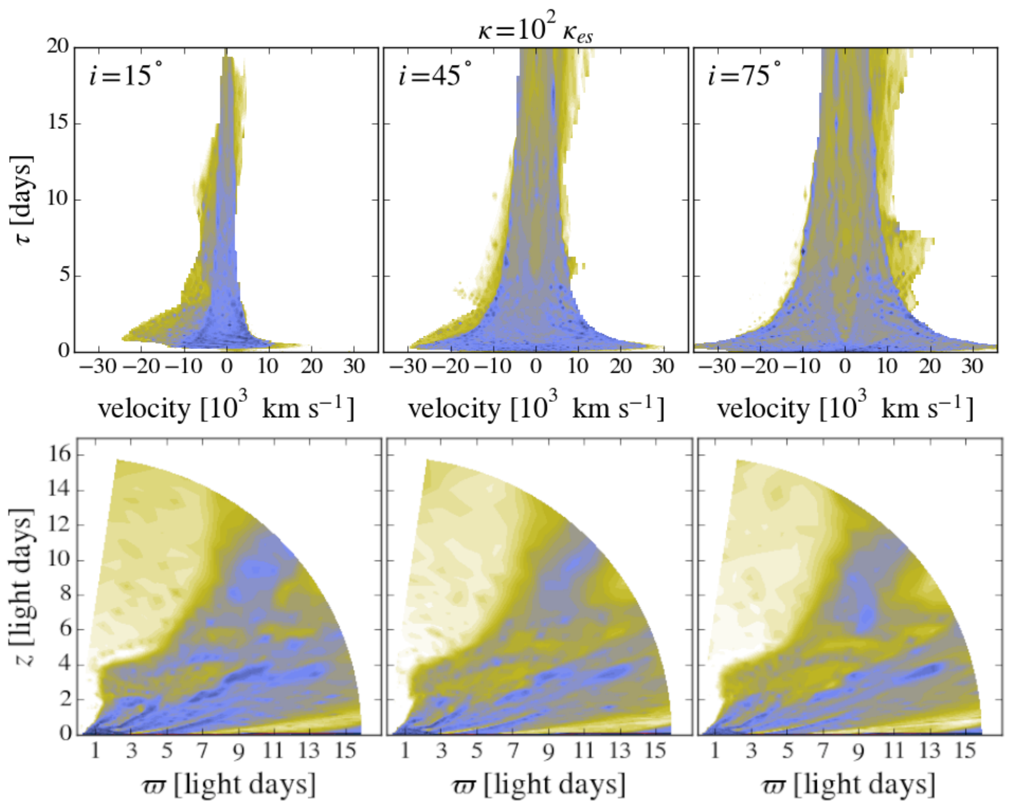


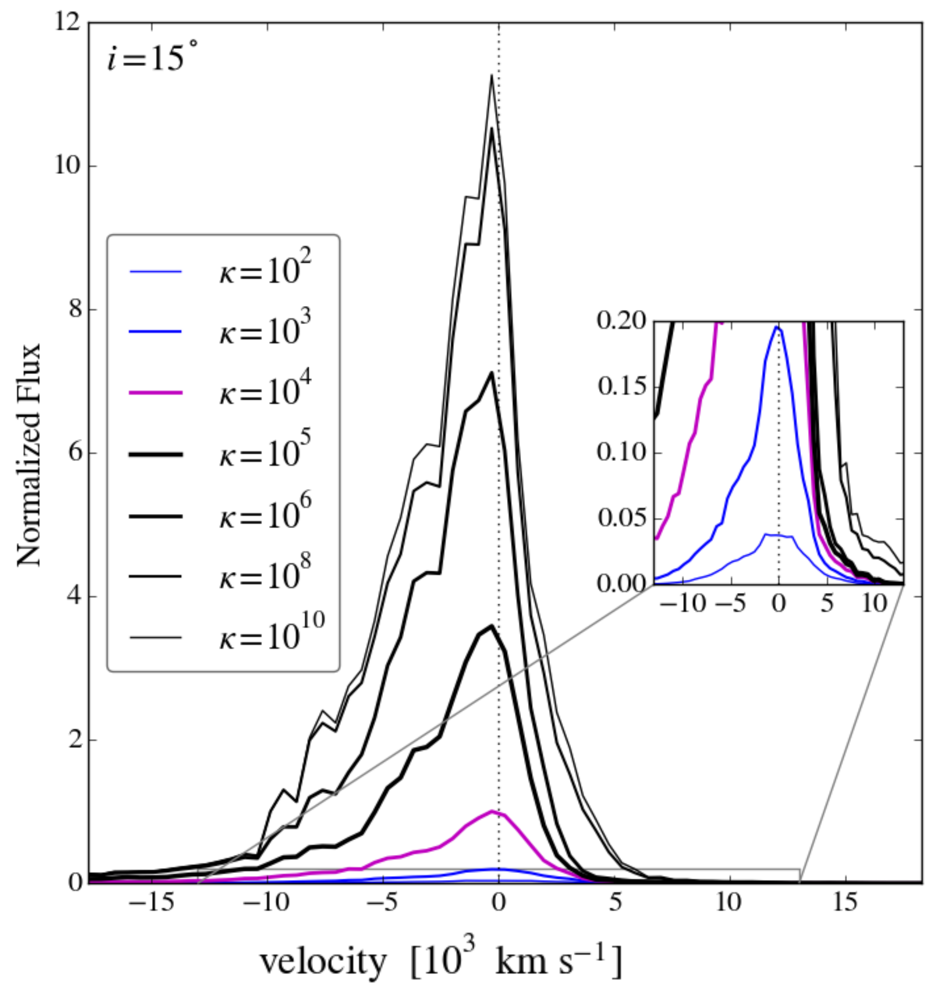
Monte Carlo photoionization and radiative transfer calculations.



Sim, DP et al. (2010) and Higginbottom, DP et al. (2014)

Reverberation Mapping

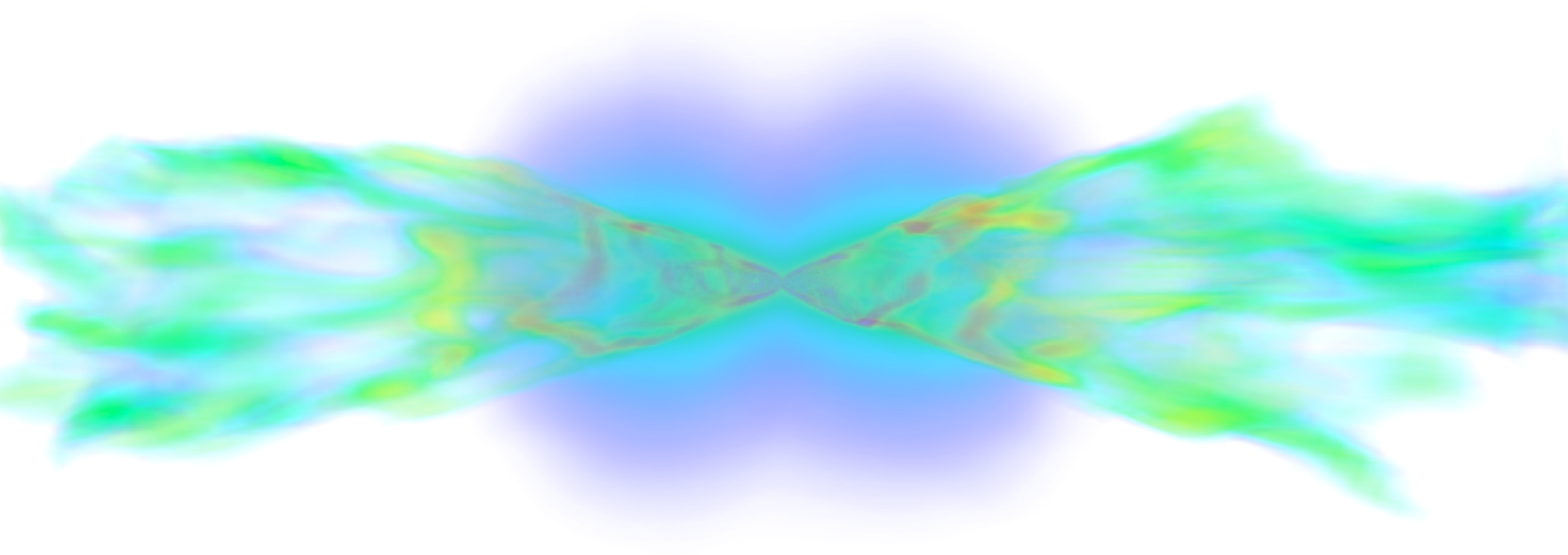




Waters, Kashi, DP et al. (2016)

Large Scale Inflows and Outflows

(Are they the NLRs? Can we model the AGN FB directly?)



Irradiation of an Inflow

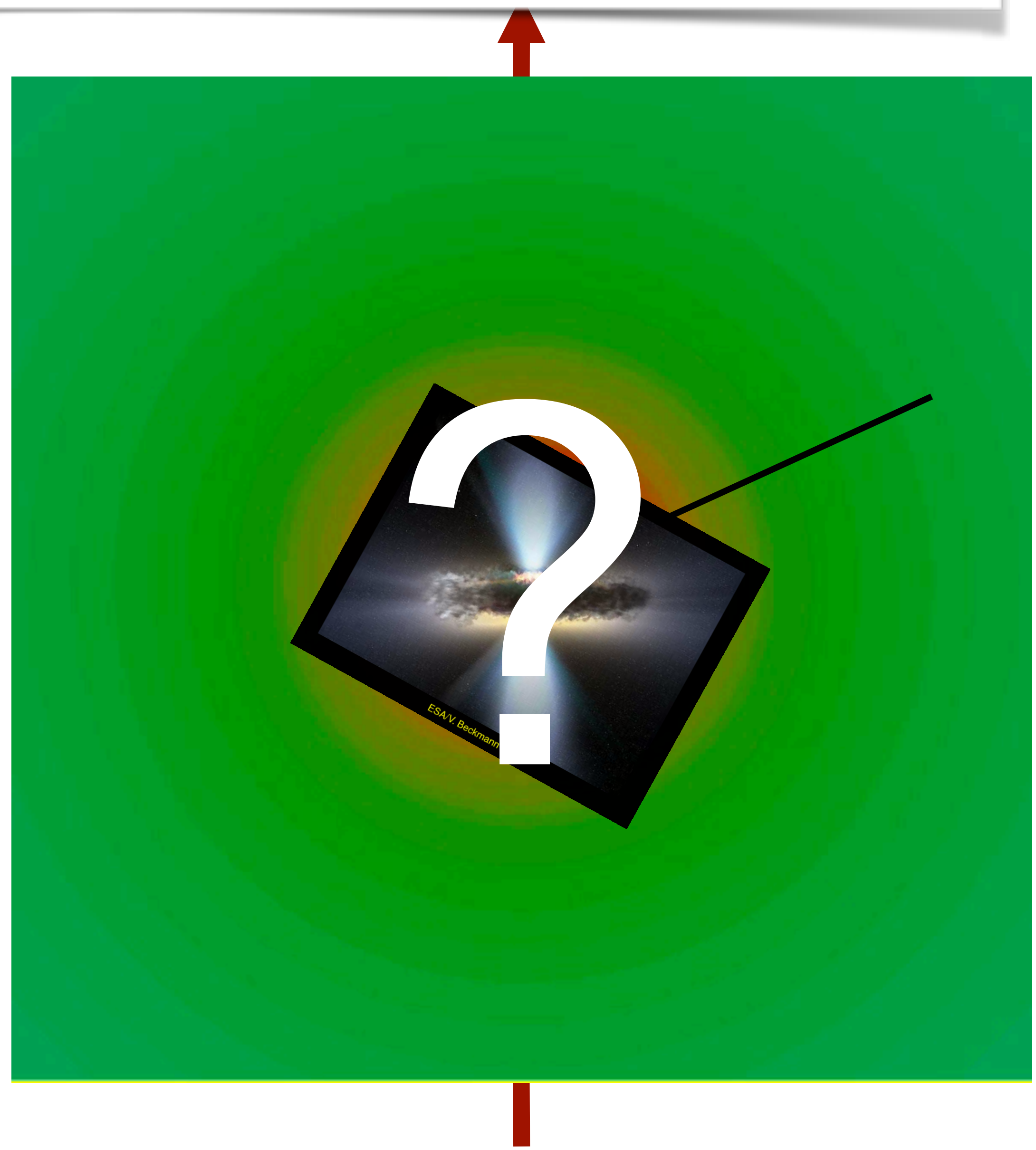
(effects of radiative heating/cooling and radiation pressure)

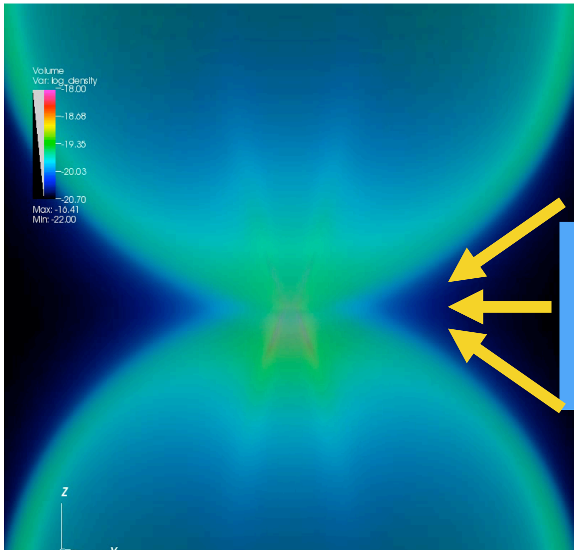
$$\frac{D\rho}{Dt} + \rho\nabla \cdot v = 0$$

$$\rho\frac{Dv}{Dt} = -\nabla P + \rho g + \rho f^{rad}$$

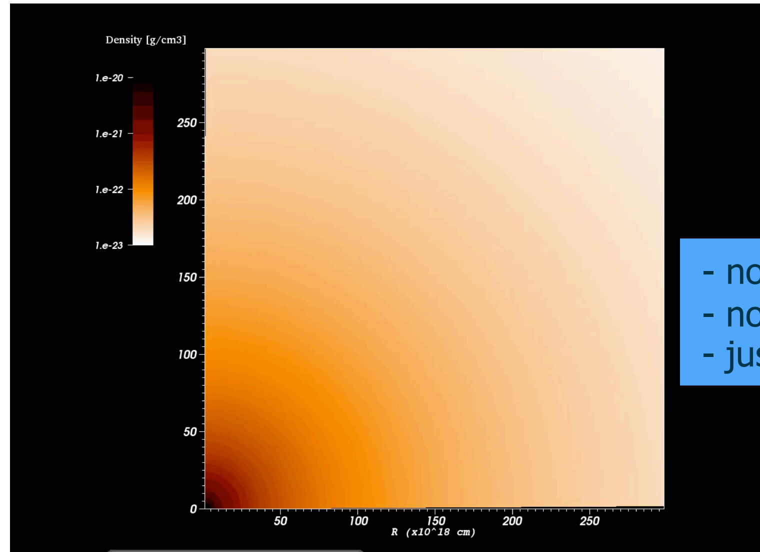
$$\rho\frac{D}{Dt}\left(\frac{e}{\rho}\right) = -P\nabla \cdot v + \rho L$$

$$P = (\gamma - 1)e$$





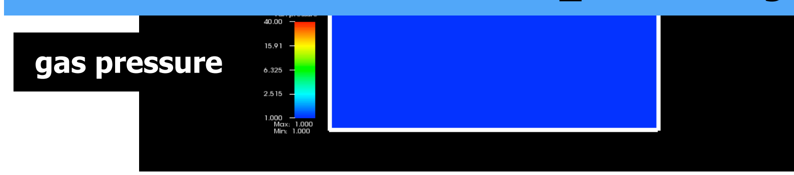
- slowly rotating inflow
- rad. force
- rad. H&C

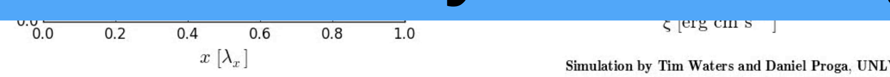


- no rotation
- no rad. force
- just rad. H&C

Dos and Don'ts: Take gas and radiation and let clouds to be accelerated while they form (TI+ line driving+lifting by a hot gas; gas rotation and variable radiation help).

Do not try to accelerate pre-existing clouds unless the opacity is dominated by scattering!





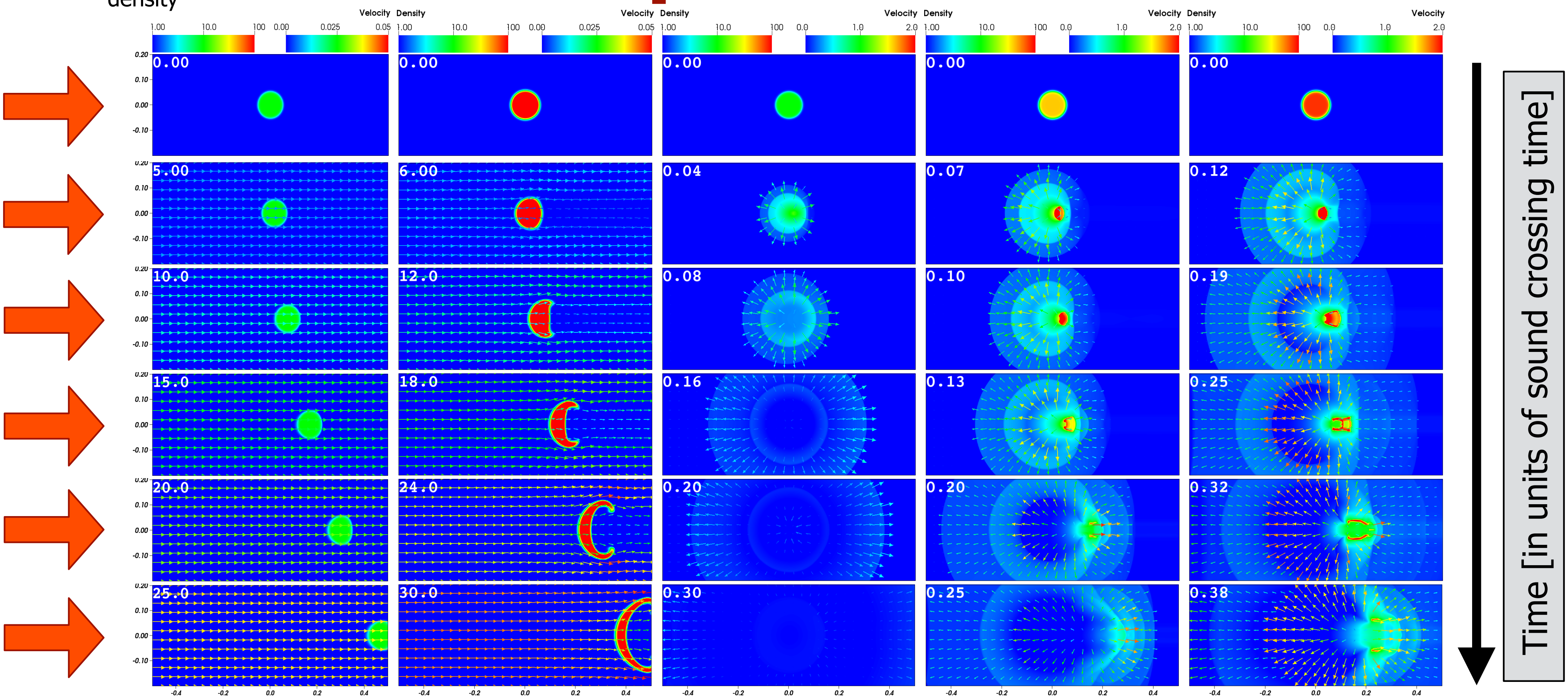
Proga, Jiang, Davis, Stone, & Smith (2014)

Proga & Waters (2015)
Waters & Proga (2016)

Five cases:

Pure scattering | Absorption dominated

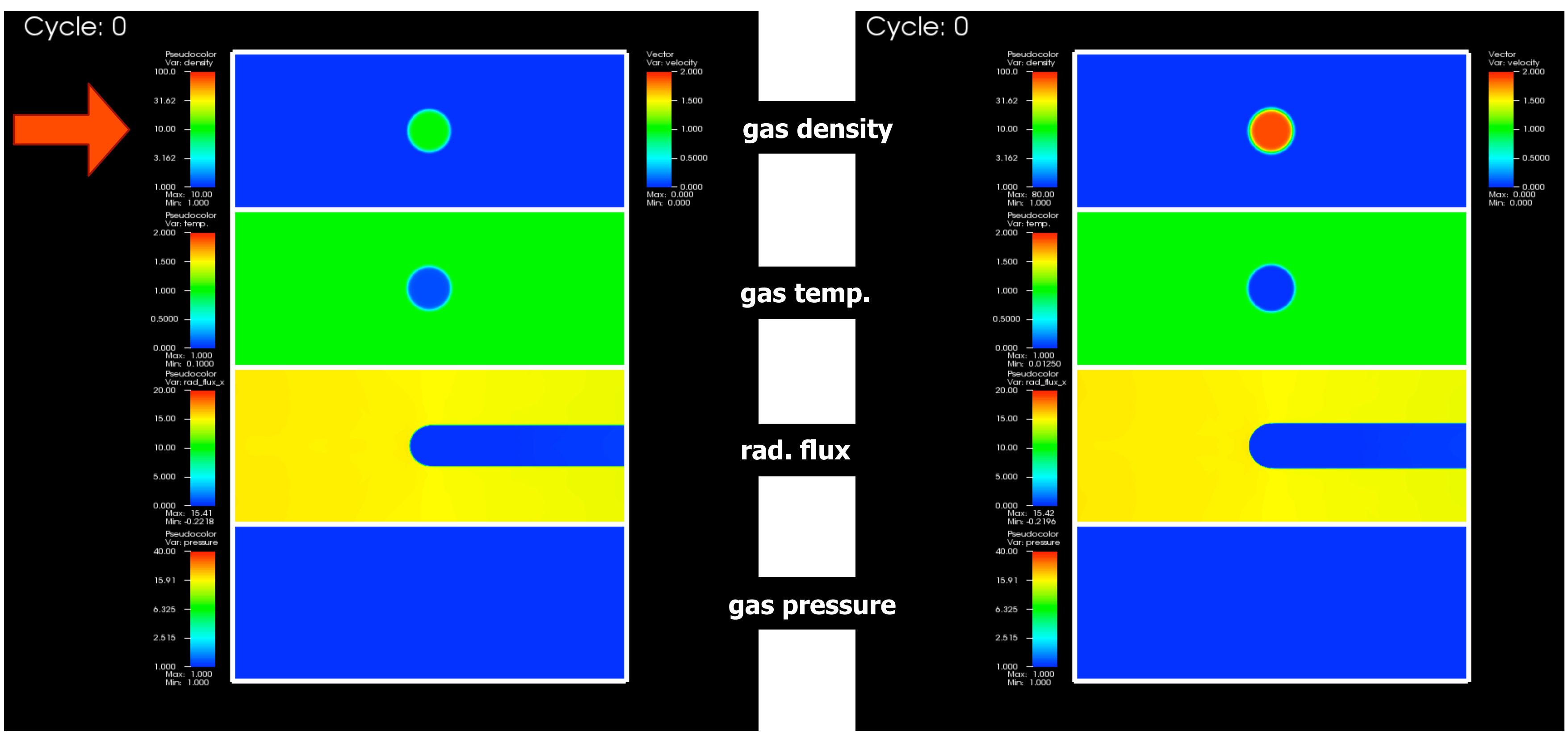
density $\tau_s = 0.2$ $\tau_s = 4.0$ $\tau_{tot} = 2\times10^3$ $\tau_{tot} = 4\times10^6$ $\tau_{tot} = 1.8\times10^8$



DP et al. (2014)

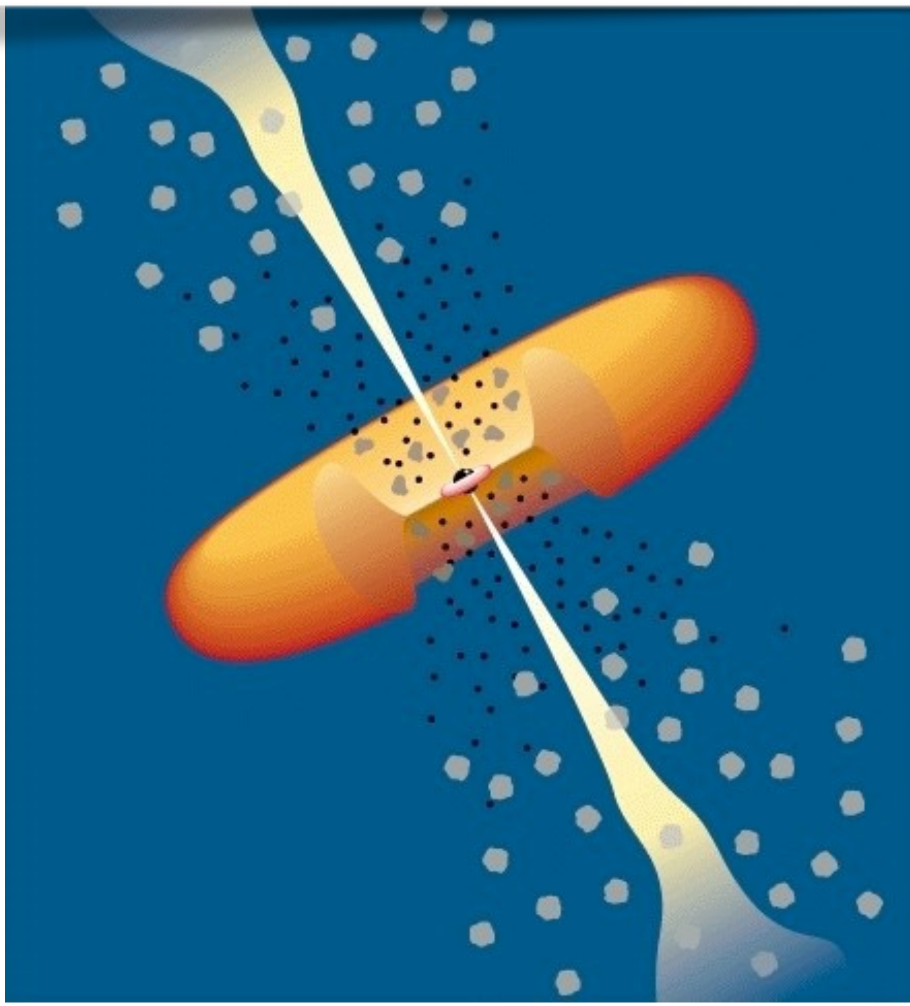
Absorption dominated cases

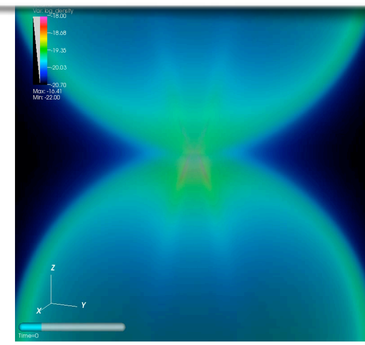
$\tau_{tot} = 2\times10^{3}$ $\tau_{tot} = 1.8\times10^{8}$

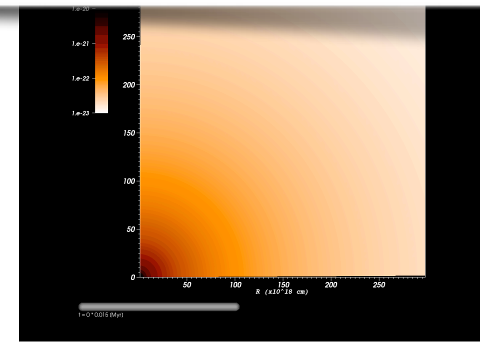


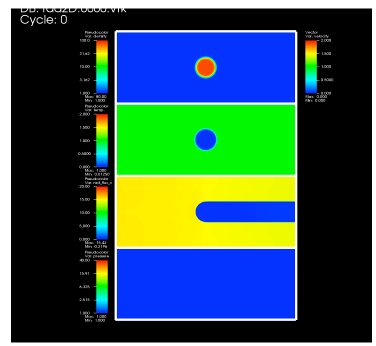
DP et al. (2014)

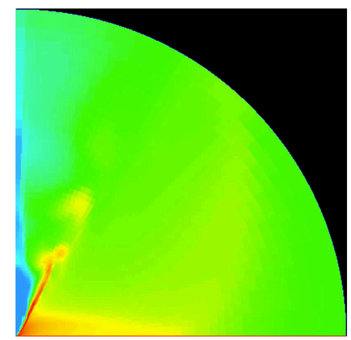
We have been building a physical model of NLRs: clouds are formed and accelerated (result of TI and radiation force). Although they are destroyed, they can be formed again.

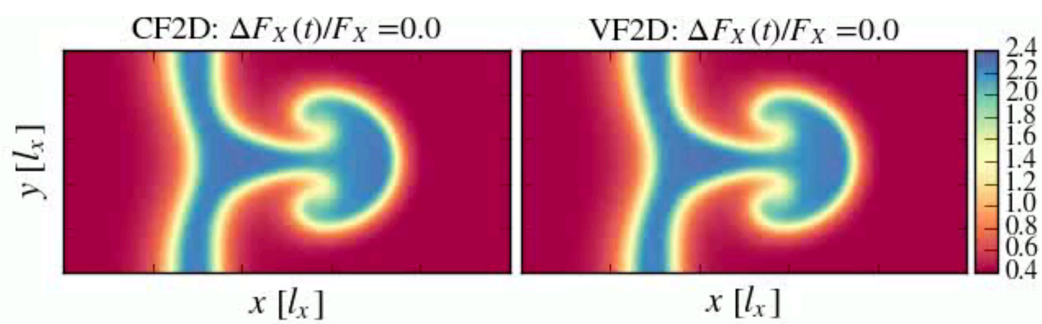




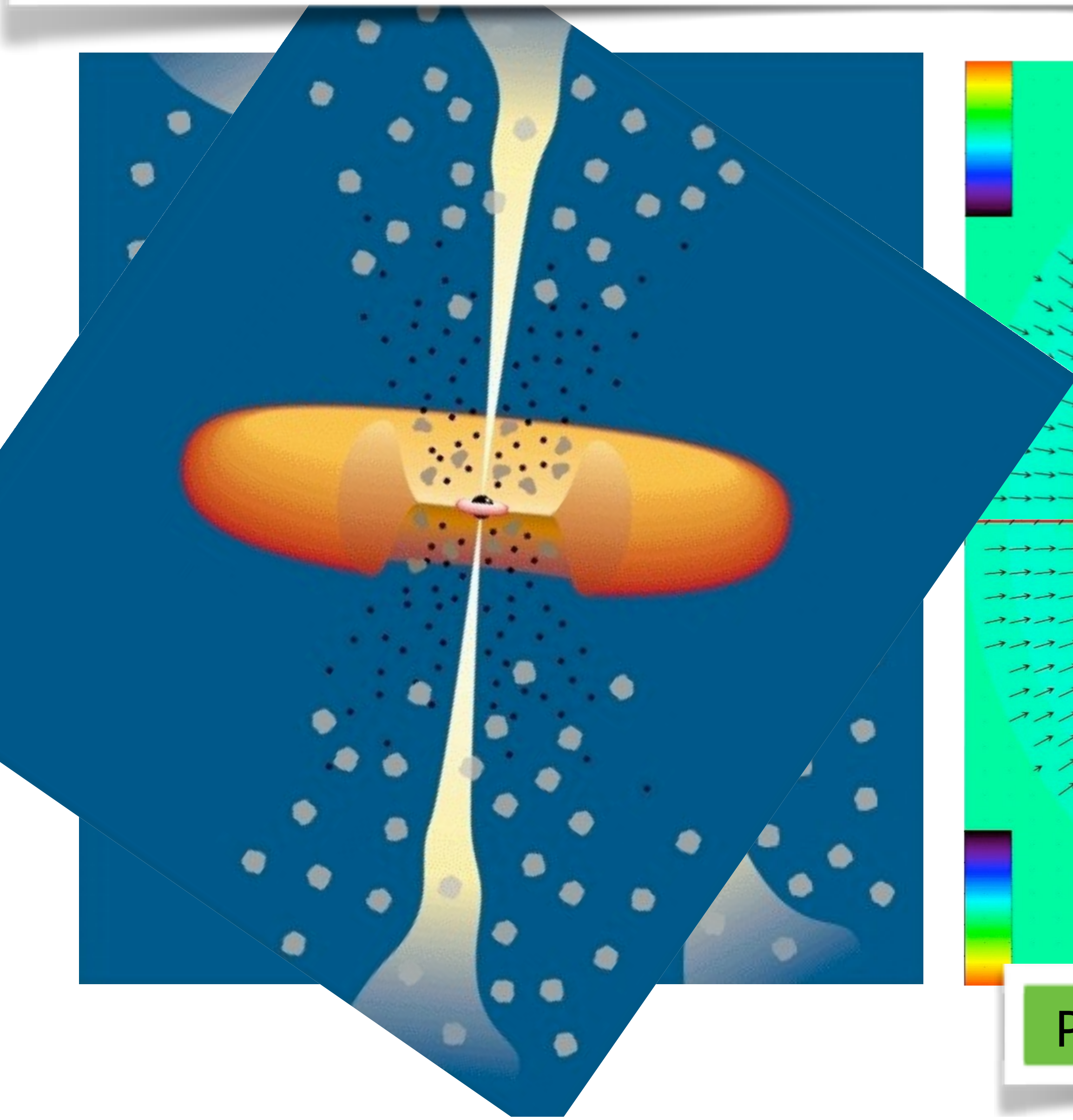


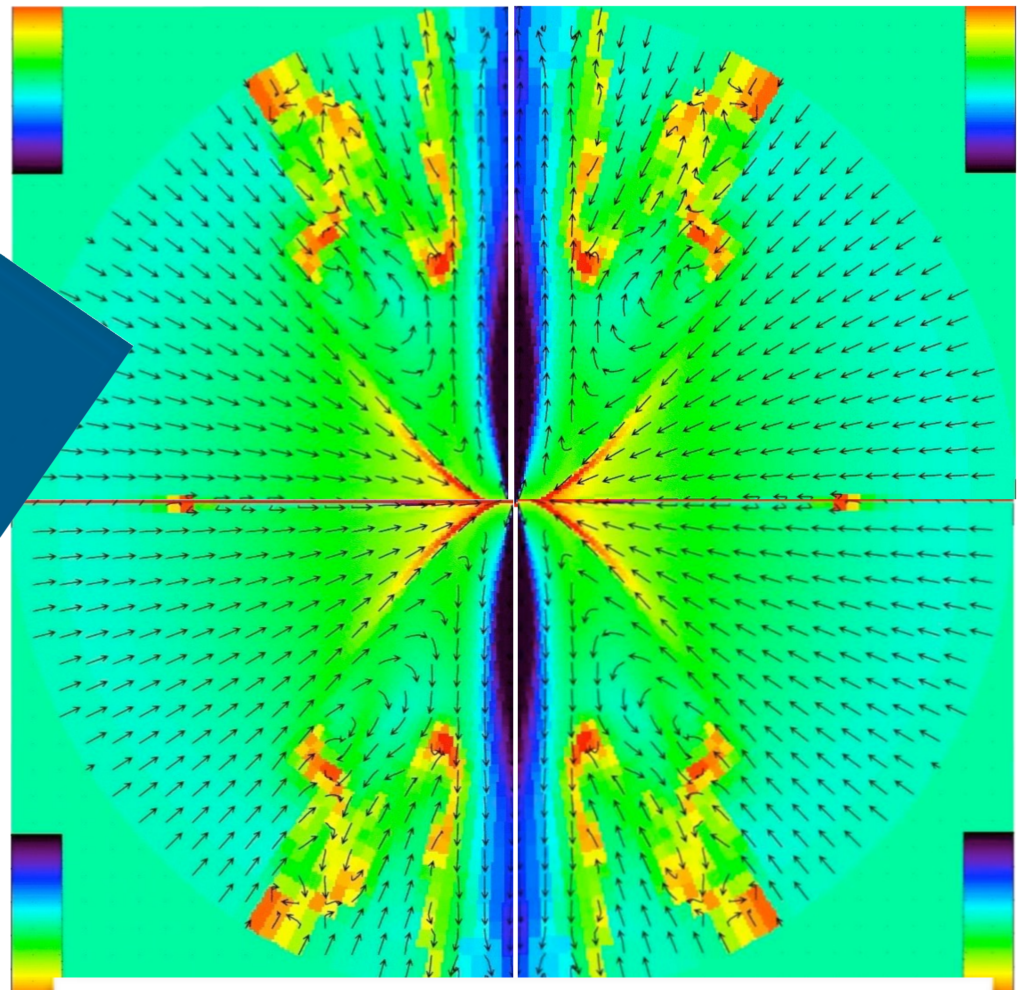






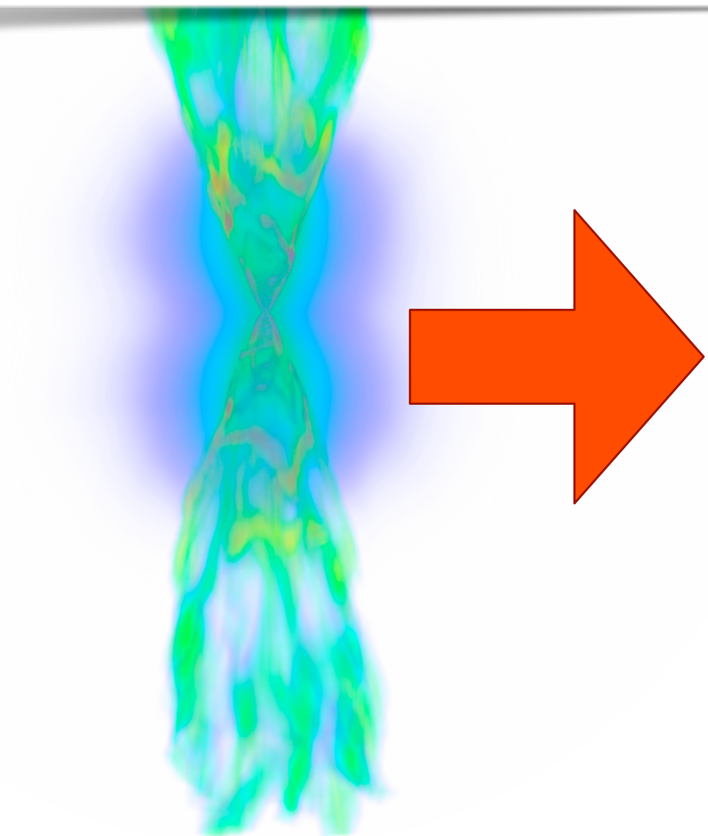
The model is promising not only because it predicts the dynamics and morphology that resemble our old picture but it also makes several more specific predictions.





Proga, Ostriker, & Kurosawa (2010)

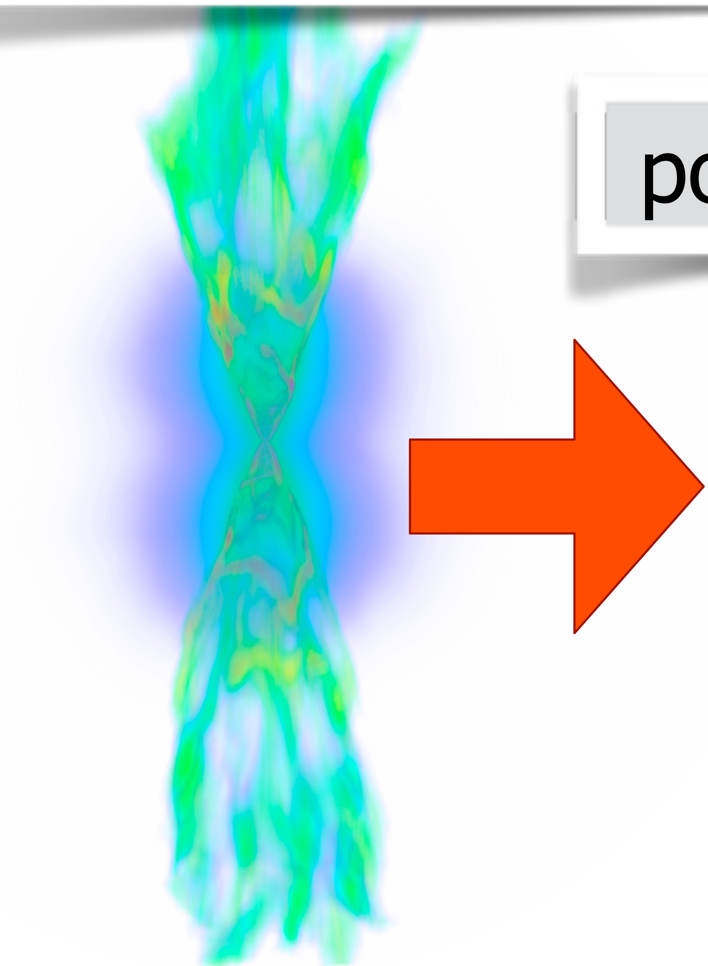
Broad band spectra for various lines of sight (Monte Carlo calculations).



Kurosawa & Proga (2009a)

Connecting simulations with observations has been done mostly through

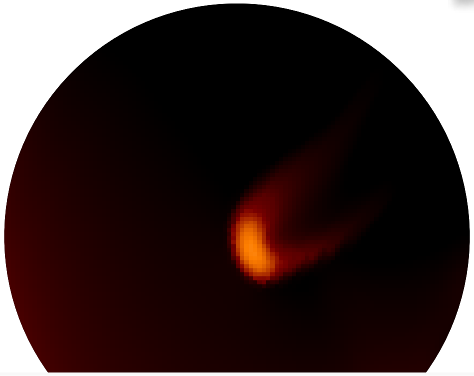
post-processing

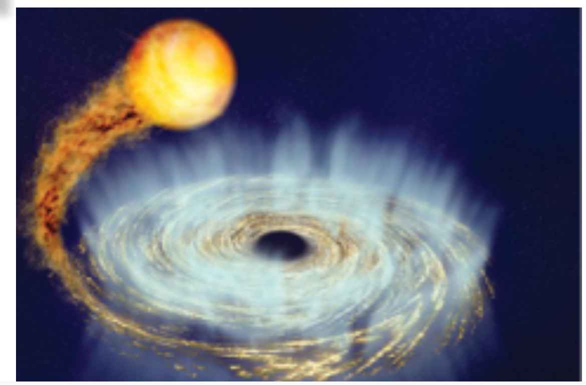


Kurosawa & Proga (2009a)

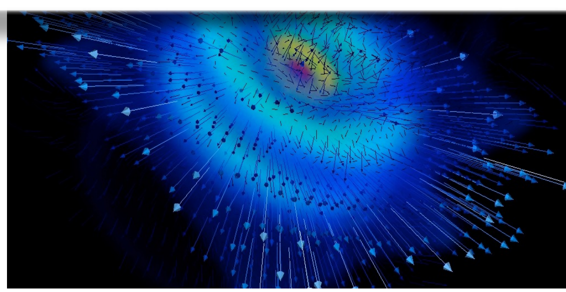
Sim, DP et al. (2012)
MC photoionization/RT calculations

Future

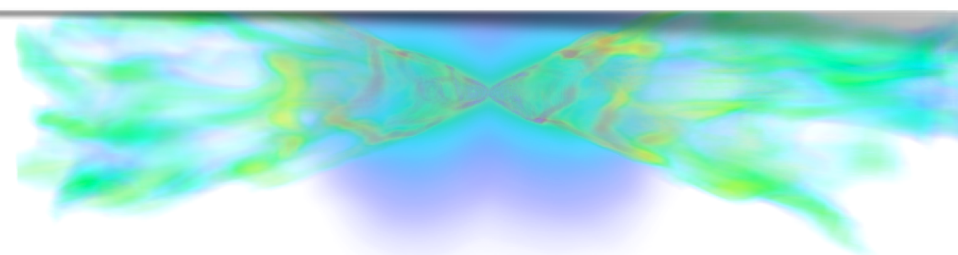




Multi-frequency Radiation-Magnetohydrodynamics.



Winds in AGNs and PPDs



Inflows and Outflows in GRBs and AGNs

Summary

- The inner and outer workings of quasars involve very many processes that are important in other objects (e.g., inflows and outflows, atomic/molecular/dust processes, irradiation, reprocessing, radiative transfer, magnetic field effects, energy generation, its release, transport and dissipation).
- We have atomic and molecular data, computers and numerical methods that allow us to develop and observationally test direct ab initio models of mass outflows (i.e., that will include the object where the outflows originate from).
- Combed with present and future high-quality observations, numerical R-MHD simulations will not only continue to provide us with important insights about complex objects (test long-held assumptions and assertions) but also allow to quantify various processes and effects so that we can determine what is really most important (from the theoretical as well as observational point of view).