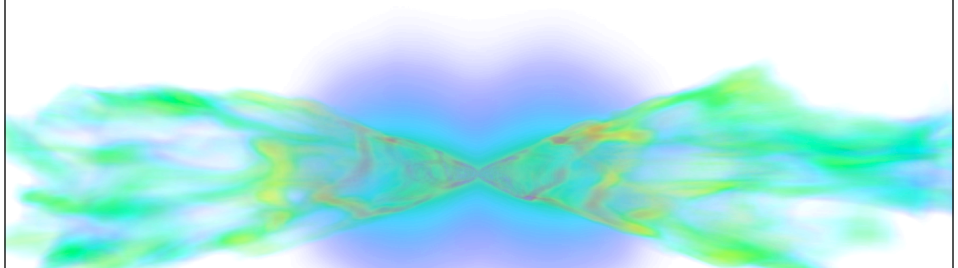
Theory and Simulations of Radiation-Driven Disk Winds

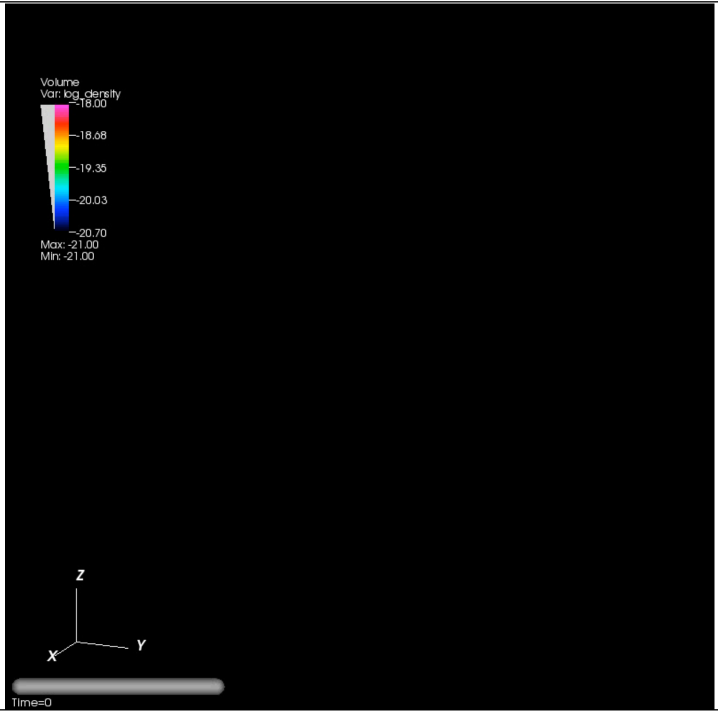


Daniel Proga

UNLV & Princeton University

Collaborators

- J. Stone, T. Kallman, J. Raymond, M. Begelman, J. Ostriker, **R. Kurosawa,** J. Drew, A. Janiuk, **M. Moscibrodzka**, B. Czerny, A. Siemiginowska, A. Dorodnityn, S. Sim, S. Luketic, T. Waters, K. Nagamine, P. Barai, and many more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-18.68
-19.35
-20.03
-20.70
Max: -21.00
Min: -21.00
Z
X
Y
Time=0

OUTLINE

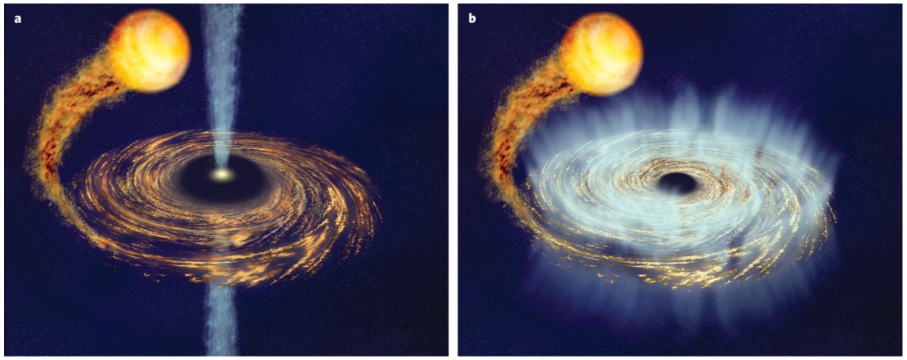
1. Introduction
2. Multidimensional, time-dependent simulations of disk winds driven by:
 - radiation pressure
 and
 - radiation pressure with thermal expansion
3. Conclusions

What can drive an outflow?

- Thermal expansion (e.g., evaporation and hydrodynamical escape)
- Radiation pressure (gas, dust)
- Magnetic fields

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

BHBs



Miller et al. (2006, 2008), Neilsen & Lee (2009) and others

(fig. from DP's 2009)

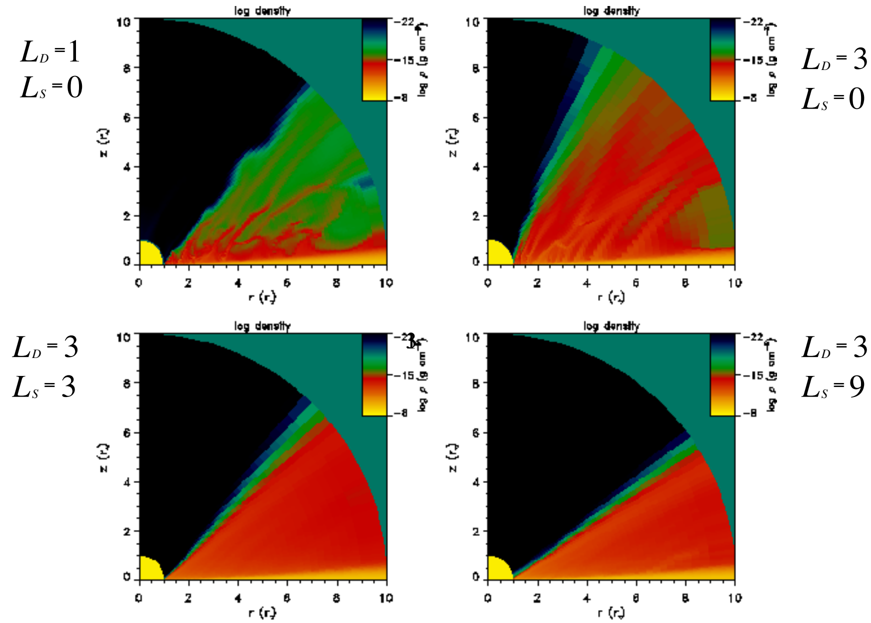
Radiation-Driven Winds

The equations of hydrodynamics

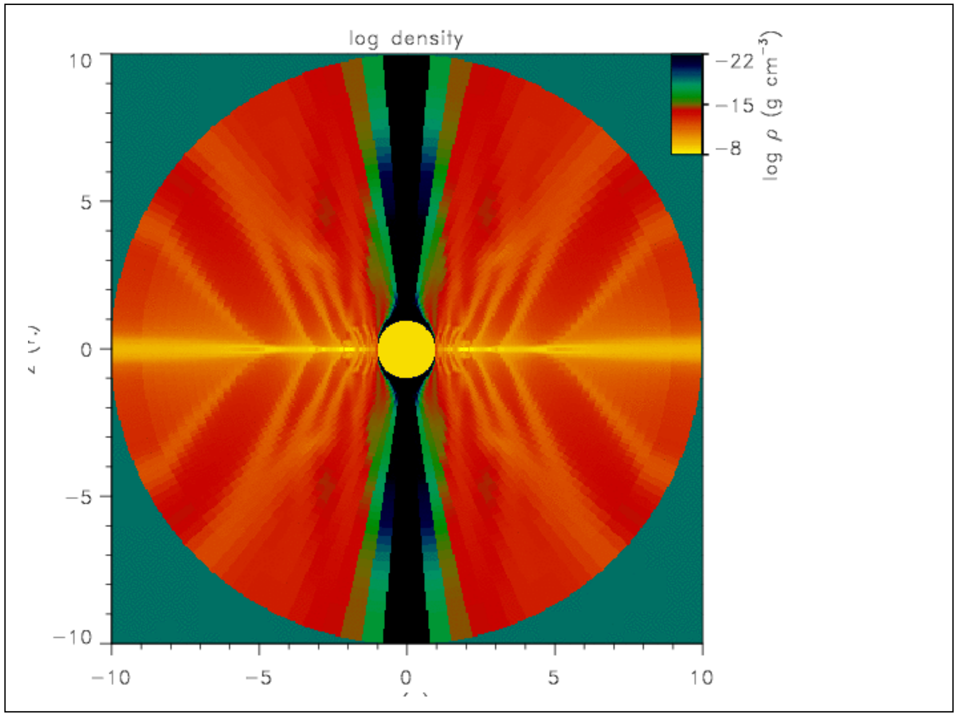
$$\frac{D\rho}{Dt} + \rho\nabla \cdot v = 0$$

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

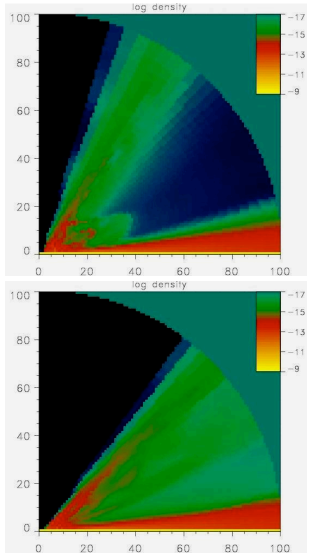
$$\rho\frac{D}{Dt}\left(\frac{e}{\rho}\right) = -P\nabla \cdot v$$

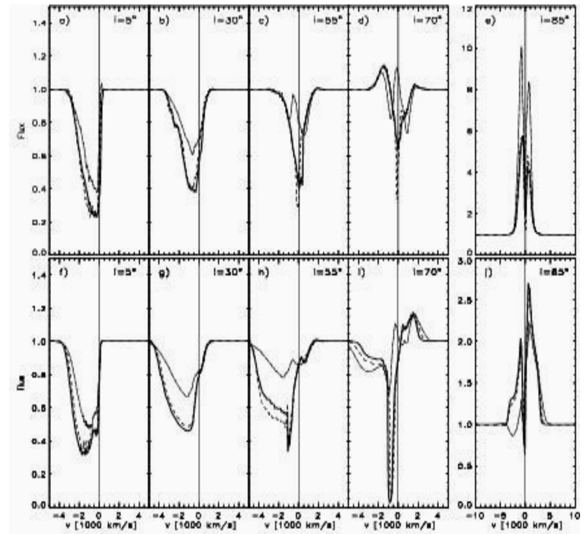


Proga, Stone & Drew (1998)

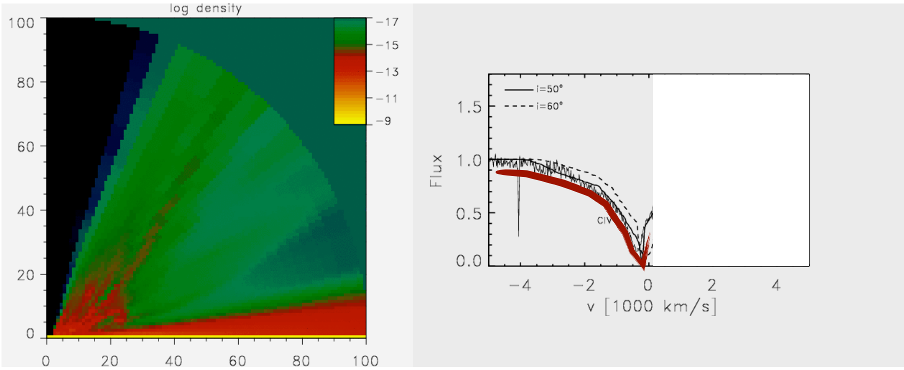

log density
10
5
0
−5
−10
−10
−5
0
5
10
−22
−15
−8
log ρ (g cm^-3)

HD simulations and their line profiles



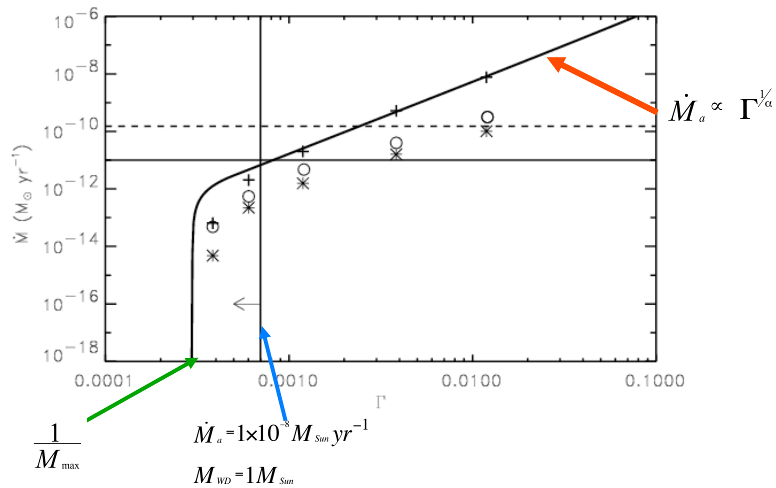


HD simulations and observations



$L_D = 23.4 L_{SUN},\ L_{WD} = 0.25 L_D,\ \dot{M}_a = 3\times10^{-8} M_{SUN}\, yr^{-1}$ $\dot{M}_W = 3\times10^{-12} M_{SUN}\, yr^{-1}$

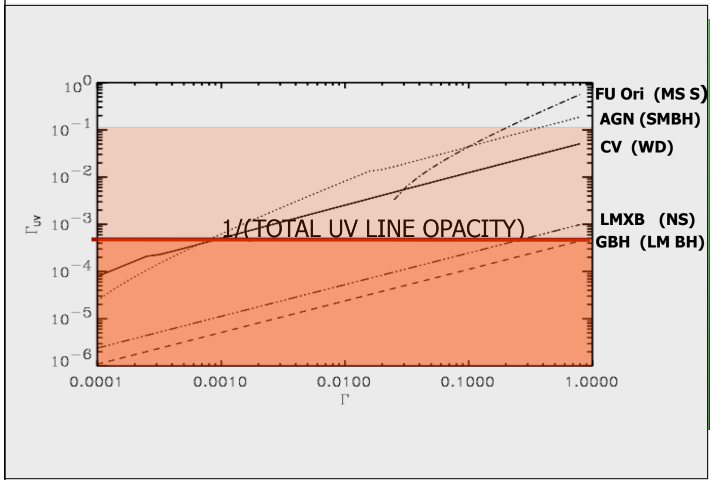
CIV 1549 for IX Vel (Hartley et al. 2001); models Proga (2003b)



Drew & Proga (1999)

$M_{\max} = 4400,\ \ k = 0.2,\ \ \alpha = 0.6$

A big picture



$$L_{Edd} = \frac{4\pi c G M_a}{\sigma}$$

$$L = \frac{M \dot{M}_a G}{2 r_a}$$

$$\Gamma = \frac{L}{L_{Edd}} = \frac{\dot{M}_a \sigma}{8\pi c r_a}$$

$$\Gamma_{UV} = \frac{L_{UV}}{L_{Edd}}$$

DP (2002)

Thermal and Radiation-Driven Winds

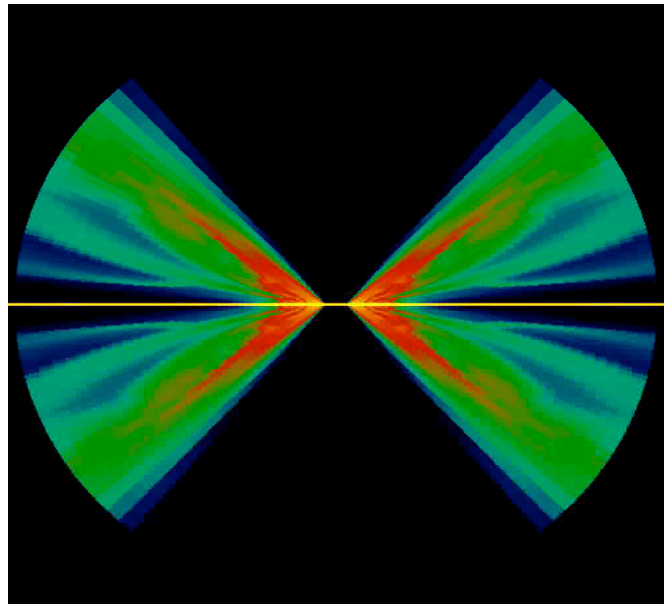
The equations of hydrodynamics

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

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

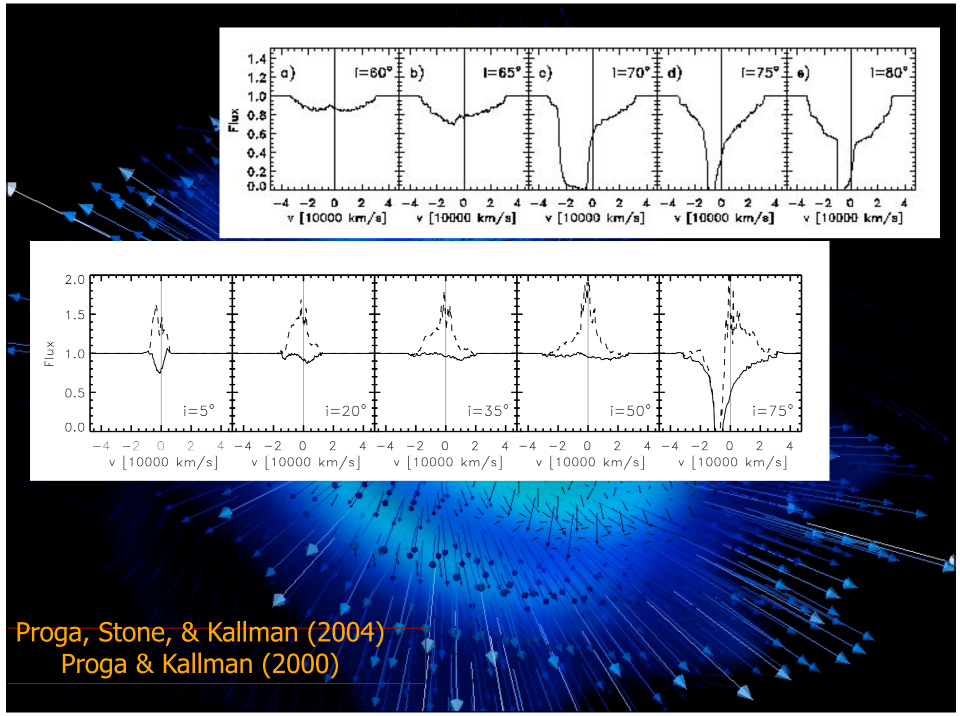
$$\rho\frac{D}{Dt}\left(\frac{e}{\rho}\right) = -P\nabla \cdot v$$

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

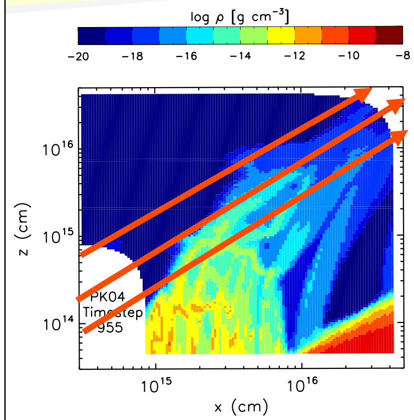


$M_{BH} = 10^8 Msun$

$\Gamma = 0.6$

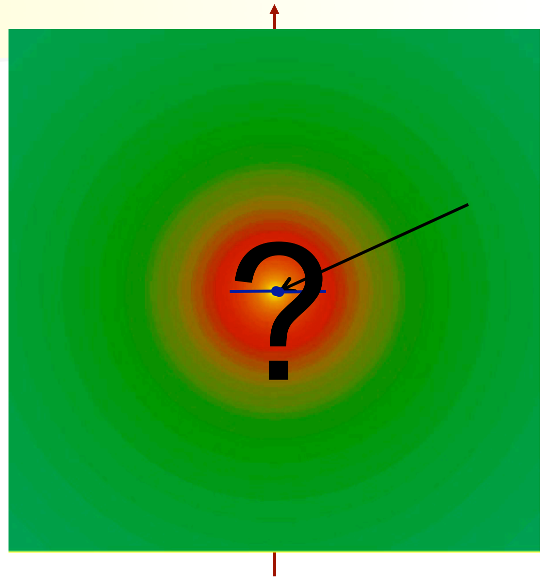

a) i=60°
b) i=65°
c) i=70°
d) i=75°
e) i=80°
Flux
v [10000 km/s]
i=5°
i=20°
i=35°
i=50°
i=75°
Flux
v [10000 km/s]
Proga, Stone, & Kallman (2004)
Proga & Kallman (2000)

Broad band spectra for various l.o.s.

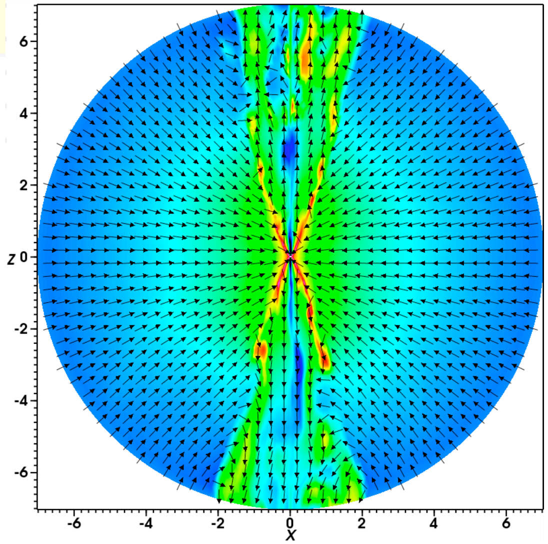


Sim et al. (2010)

Quasar Irradiation



An outflow from an inflow



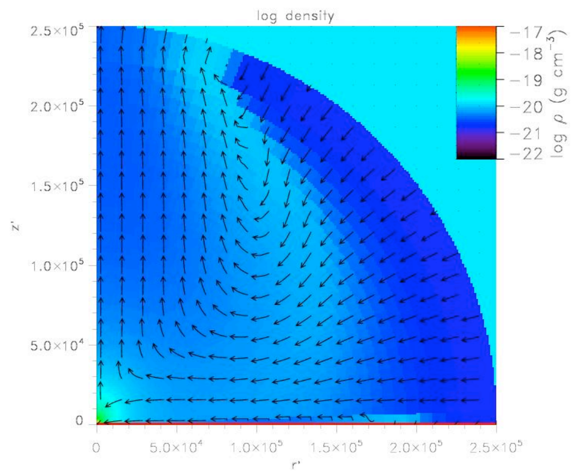
$M_{BH} = 10^8 M_{SUN}$

$\dot{M}_D = 10^{26} g/s = 1.6 M_{SUN}/yr$

$T_X = 8 \times 10^7 K$

$\rho(r_o) = 10^{-21} g/cm^3$

$f_{UV} = f_X = 0.5$



DP (2007)

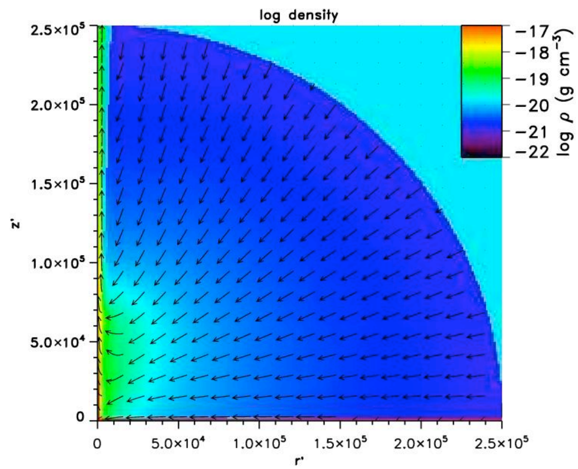
$M_{BH} = 10^8 M_{SUN}$

$\dot{M}_D = 10^{26} g/s = 1.6 M_{SUN}/yr$

$T_X = 8 \times 10^7 K$

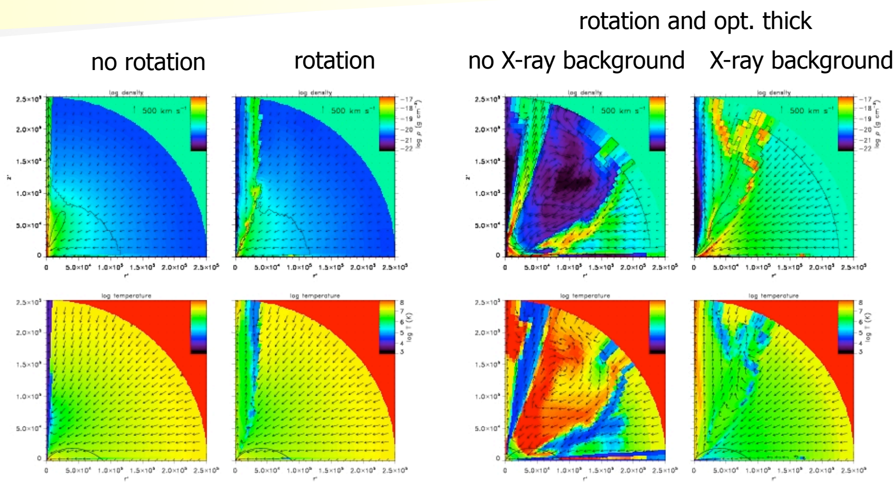
$\rho(r_o) = 10^{-21} g/cm^3$

$f_{UV} = 0.95 \quad f_X = 0.05$



DP (2007)

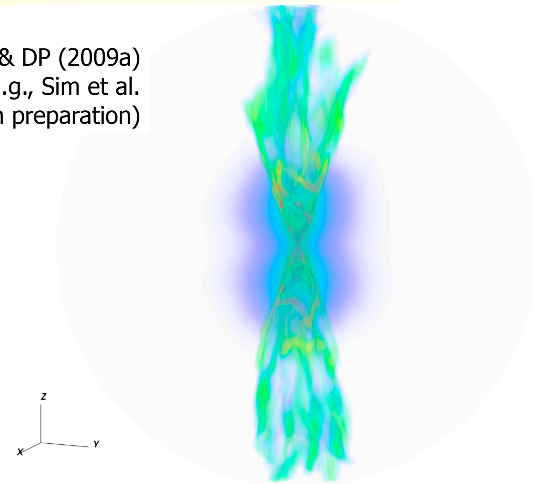
Effects of gas rotation, optical depth and X-ray background radiation

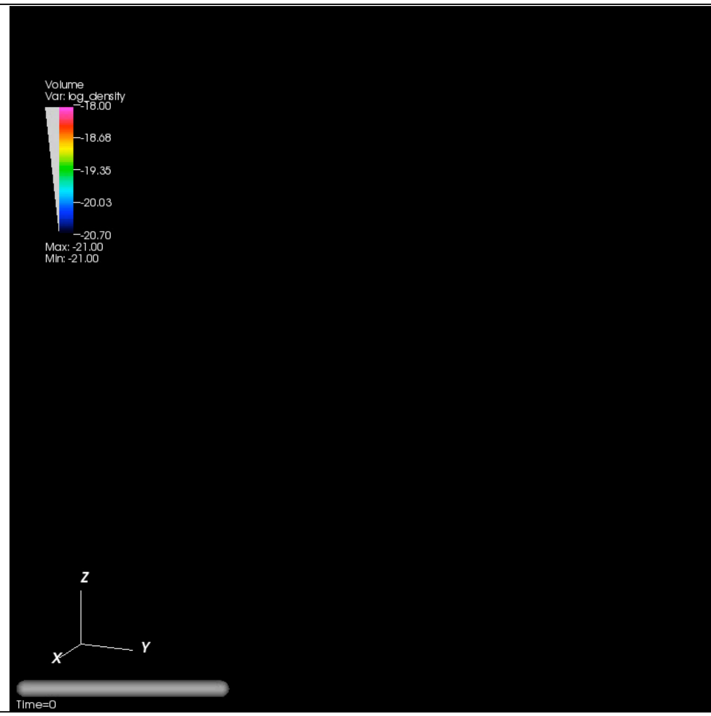


DP, Ostriker, Kurosawa (2007)

3-diminesional simulations

Kurosawa & DP (2009a)
stay tuned ... e..g., Sim et al.
(in preparation)

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-18.68
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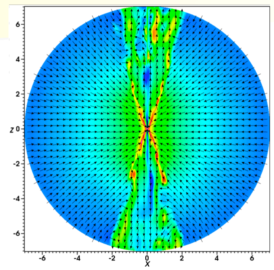
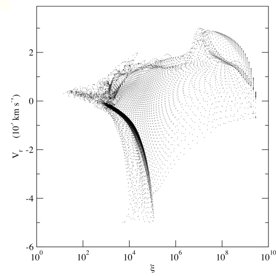
Z
Y
X
Time=0

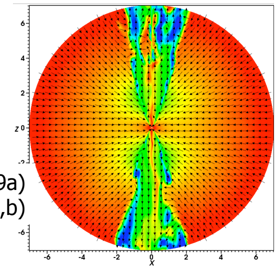
Clouds properties

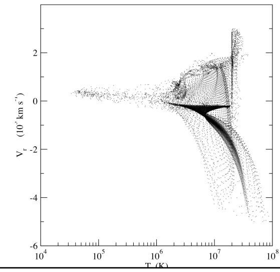
density map





temperature map



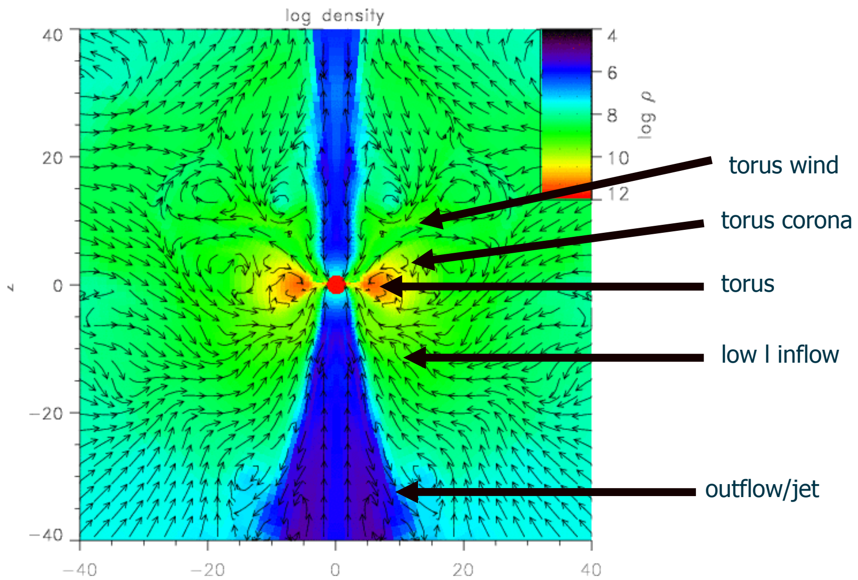


Kurosawa & DP (2009a)
see also Barai et al. 2011a,b)

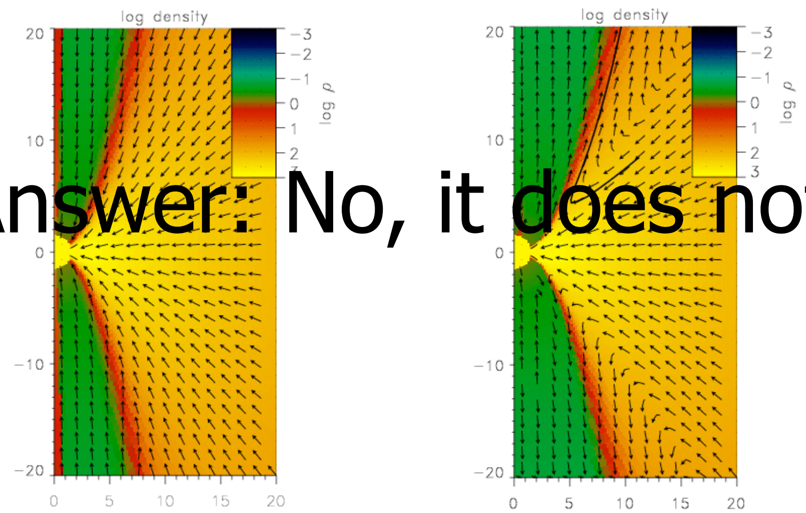
Conclusions

- Simulations of accretion flows and their outflows provide important insights into the dynamics and geometry of the material that produces radiation. In particular, we can use the simulations to assess the effects of radiation on the flow properties. We can also explore coupling between accretion flows and they outflows as well as mass supply (e.g., various forms of feedback).
- The simulations can be and are used to compute synthetic spectra for direct comparison with the observations. As such, the simulations are useful in explaining specific spectral features as well as overall shape of the SED.

Multi-component flow



Does it have to be so complex?



Answer: No, it does not.

Proga (2005)