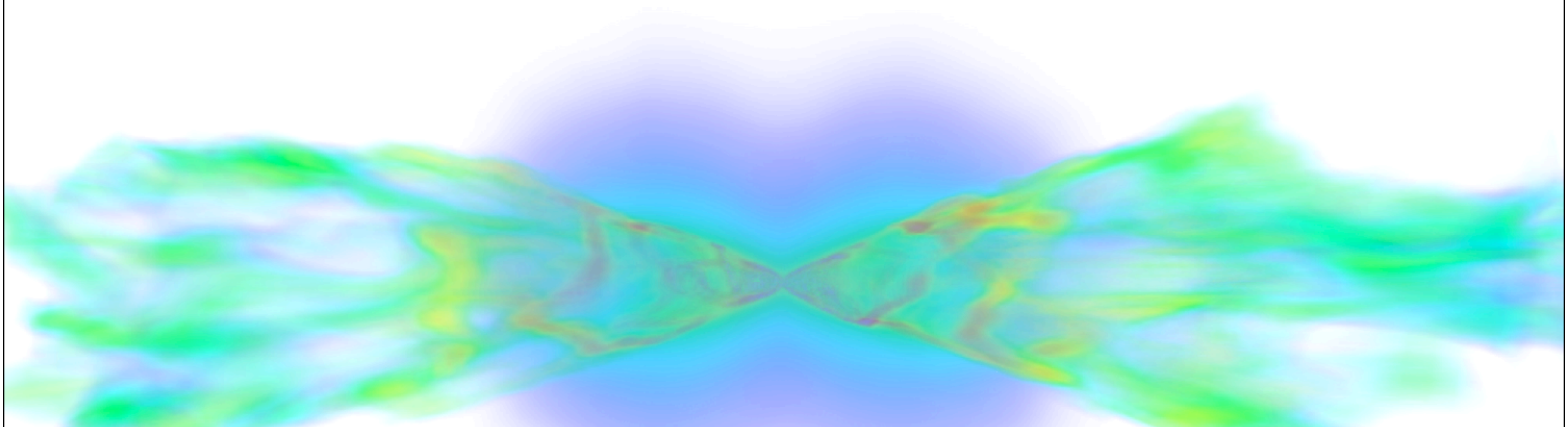
The physics of mass outflows driven by radiation from AGN



Daniel Proga

University of Nevada, Las Vegas

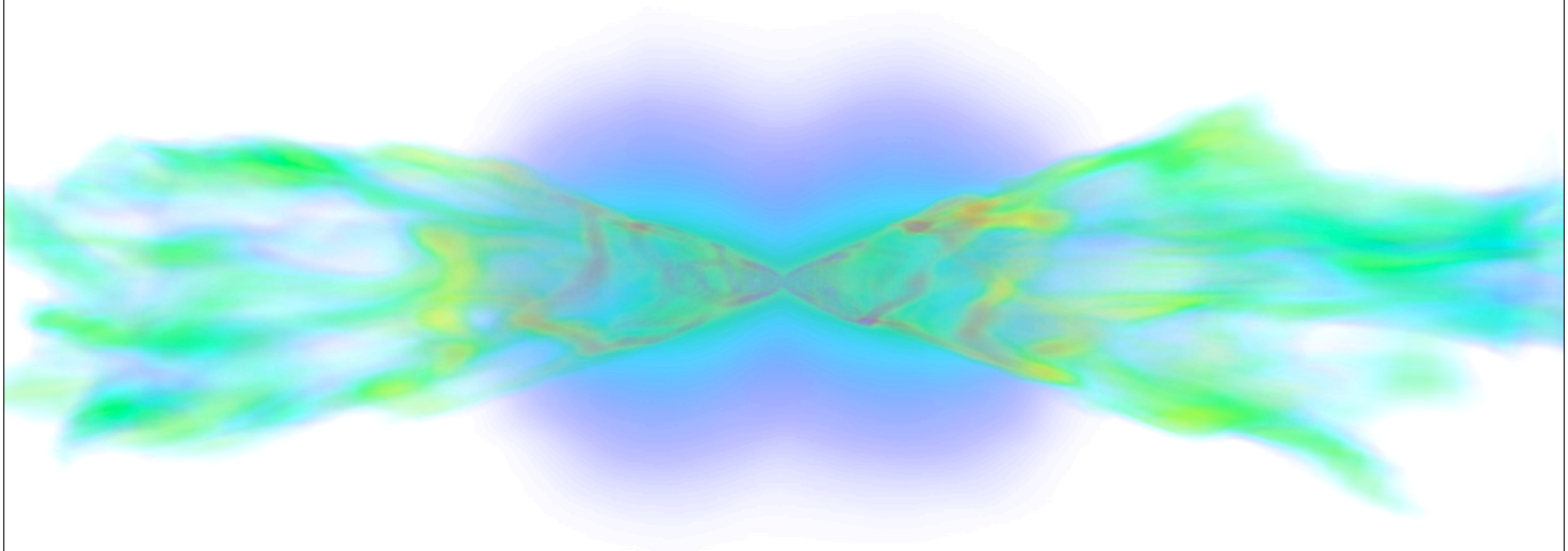
Collaborators: J. Stone, T. Kallman, M. Begelman, J. Drew, J. Ostriker, A. Dorodnitsyn, C. Done, K. Nagamine, J. Miller, L. Miller, J. Turner, J. S. Sim, Raymond, **R.Kurosawa, M. Moscibrodzka**, **P. Barai**, **A. Kashi, Y-F. Jiang, S. Davis, D. Smith,** and many more

Motivation

Supermassive black hole astrophysics is concerned with many processes, e.g.,

- the formation and dynamics of Broad Line Regions and Narrow Line Regions in AGN,
- the mass supply to a black hole accretion flow, and
- the black hole growth/impact.

What is inside the grid?



OUTLINE

1. Introduction
2. Multidimensional, time-dependent simulations of
   - accretion disk winds
     (What is the physics of a "sub-grid"?)

and
   - large scale inflows and related outflows
     (Can we model the AGN feedback directly?).

   See also KEN NAGAMINE's talk

3. Conclusions

Why outflows driven by radiation?

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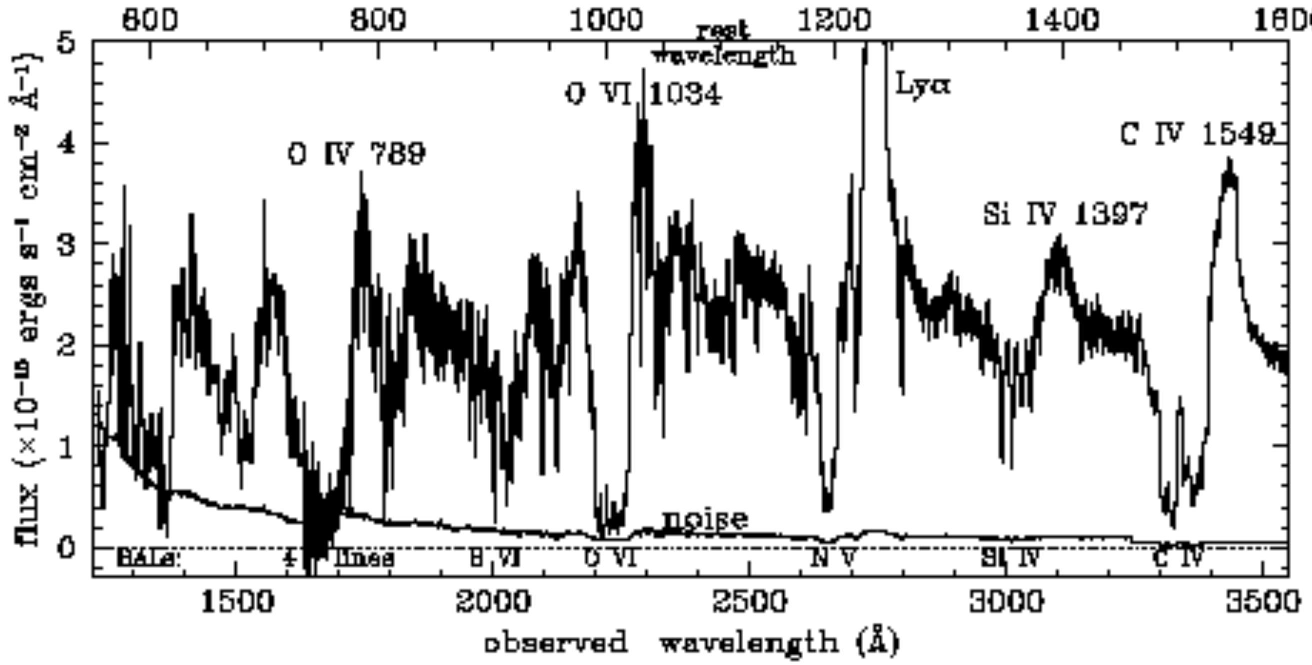
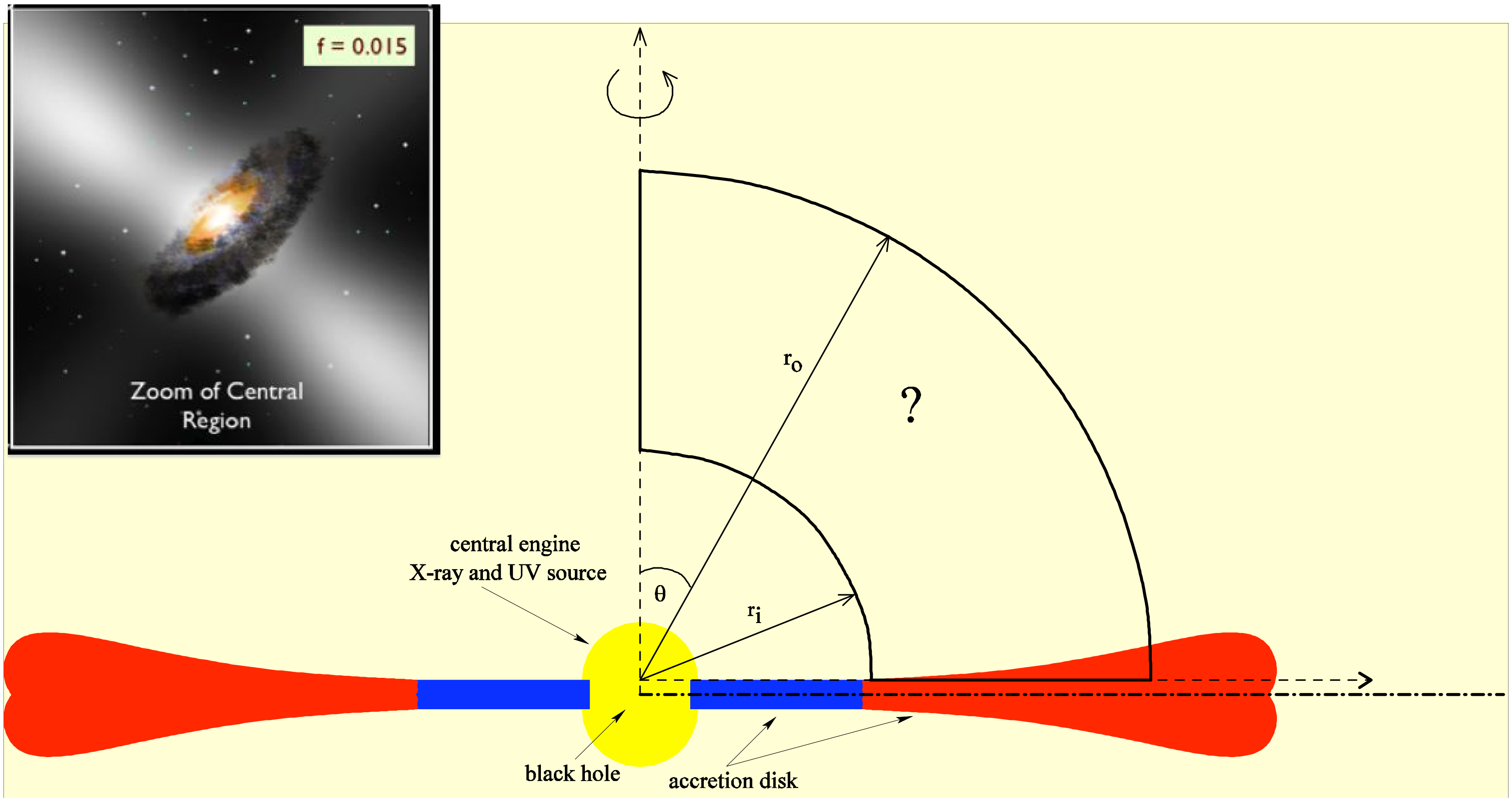


FIG. 1.—Composite spectrum of PG 0946+301; flux is measured in the observed frame

Arav et a. (1999) -- HST and ground-based observations of PG 0946+301

Radiation-Driven Disk Winds

The computational domain



X-ray and UV source

The equations of hydrodynamics

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

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

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

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

Line driving

$$f^{rad,e} = \frac{\sigma_e}{c}\frac{L}{4\pi r^2} = \frac{\sigma_e}{c}F$$

the radiation force due to electron scattering

$$f^{rad,l} = \sum_{lines}\frac{\kappa_L F_c \Delta\nu_D}{c}\min(1,\ 1/\tau_L)$$

the radiation force due to lines

$$f^{rad,total} = f^{rad,e} + f^{rad,l} = f^{rad,e}\left(1 + M\right)$$

the total radiation force

Lucy & Solomon (1970) and Castor, Abbott & Klein (1975)

CAK theory

$$t = t(\hat{n}, v) = \frac{\sigma_e \rho v_{th}}{|dv_l/dl|}$$

$$\tau_{max} = t\eta_{max}$$

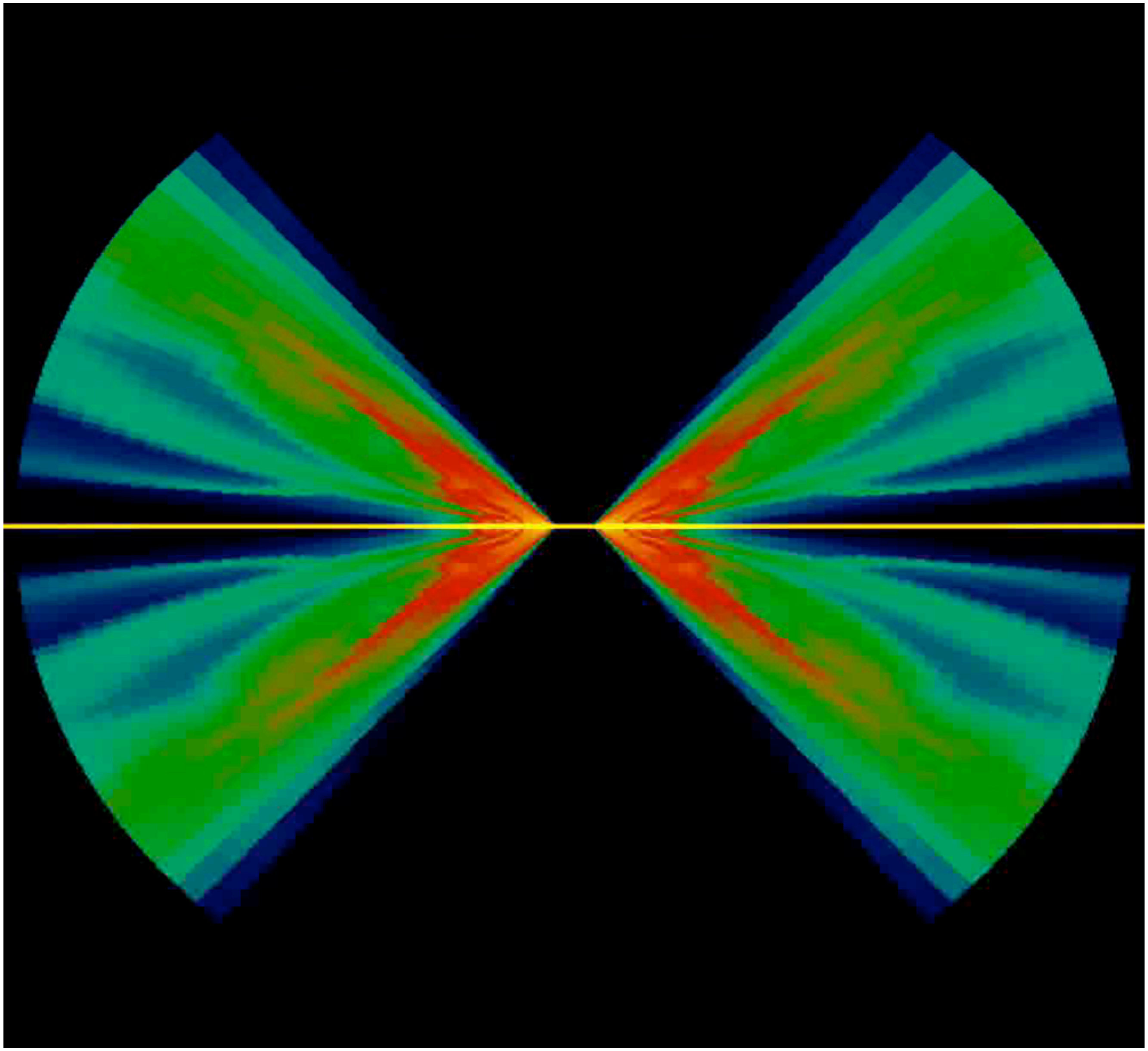
$$M(t) = kt^{-\alpha}\left[\frac{(1+\tau_{max})^{(1-\alpha)} - 1}{\tau_{max}^{(1-\alpha)}}\right]$$

$$\lim_{\tau_{max}\to\infty} M(t) = kt^{-\alpha}$$

$$\lim_{\tau_{max}\to 0} M(t) = M_{max} = k(1-\alpha)\eta_{max}^{\alpha}$$

What really matters is the following

$$L_D M_{max} \quad \textbf{?} \quad L_{Edd}$$



$M_{BH} = 10^8 Msun$

$\Gamma = 0.6$

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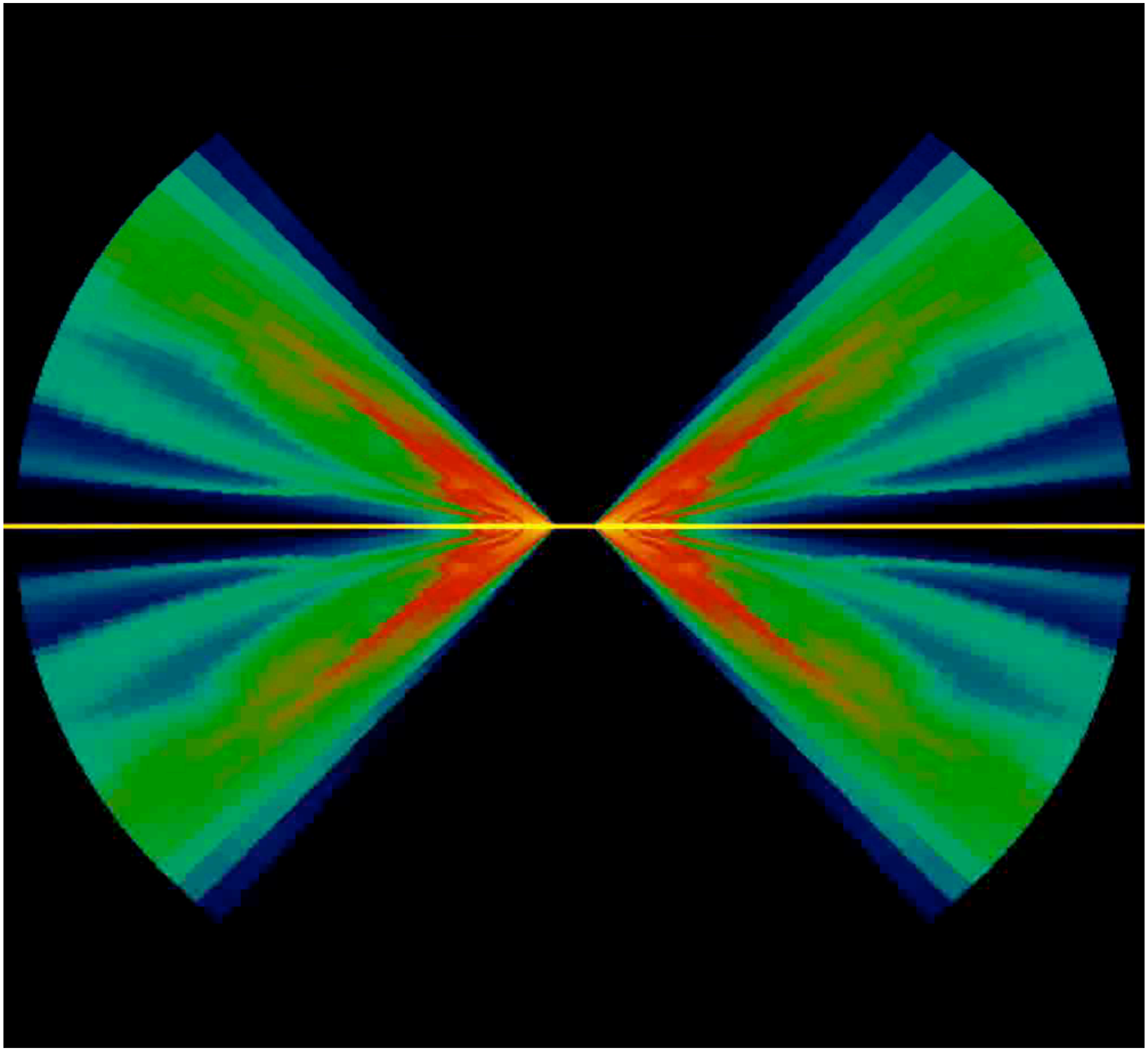

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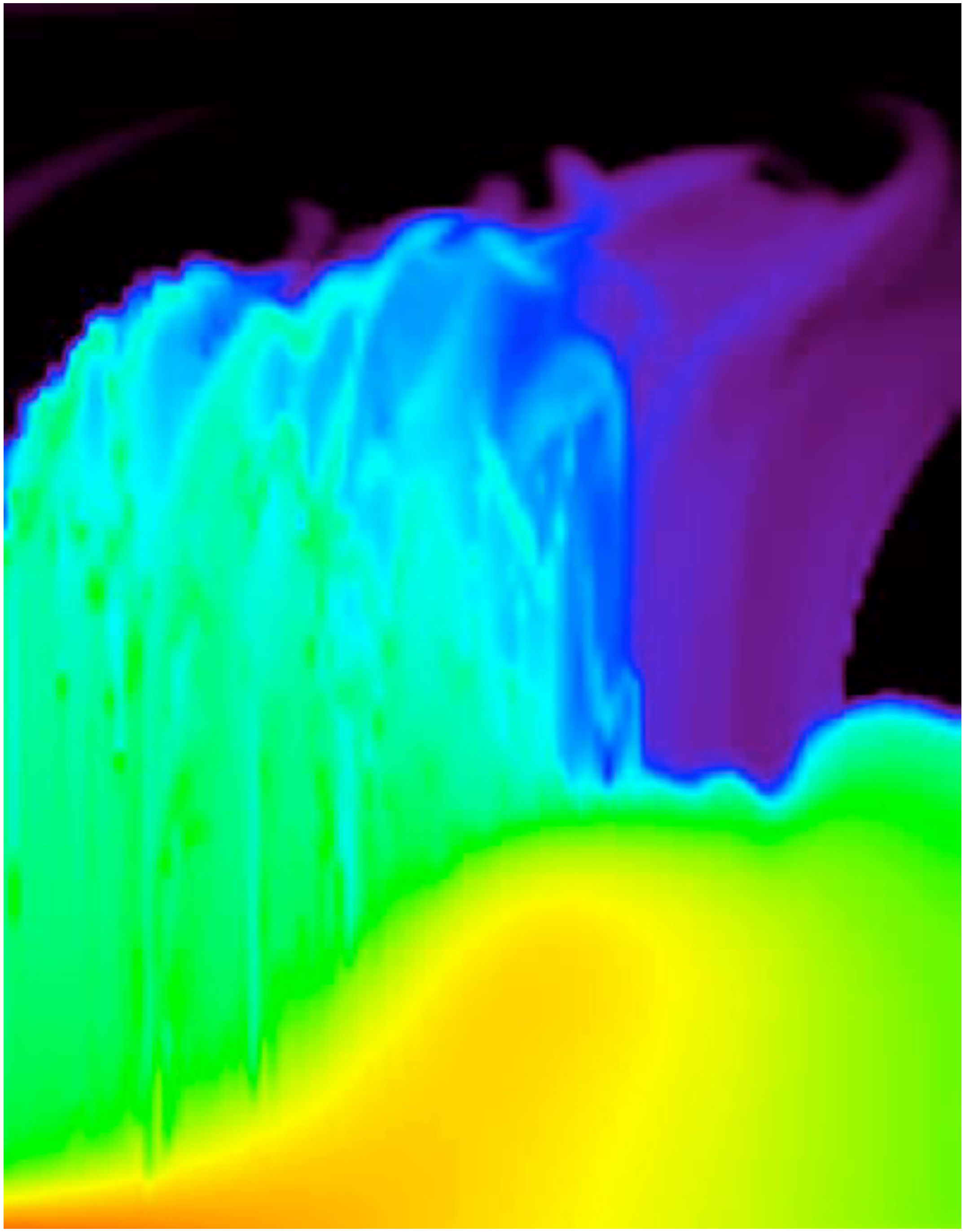
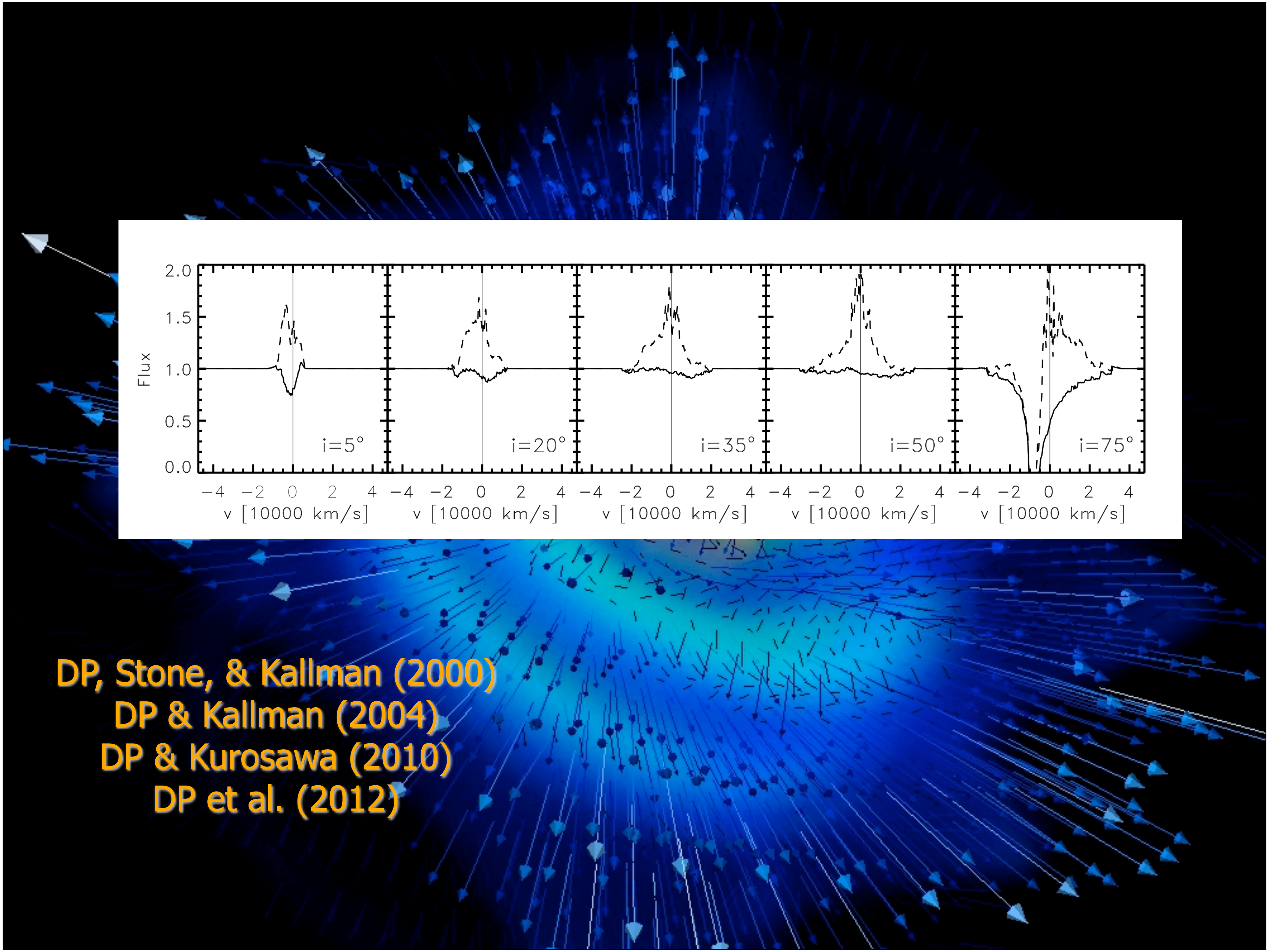
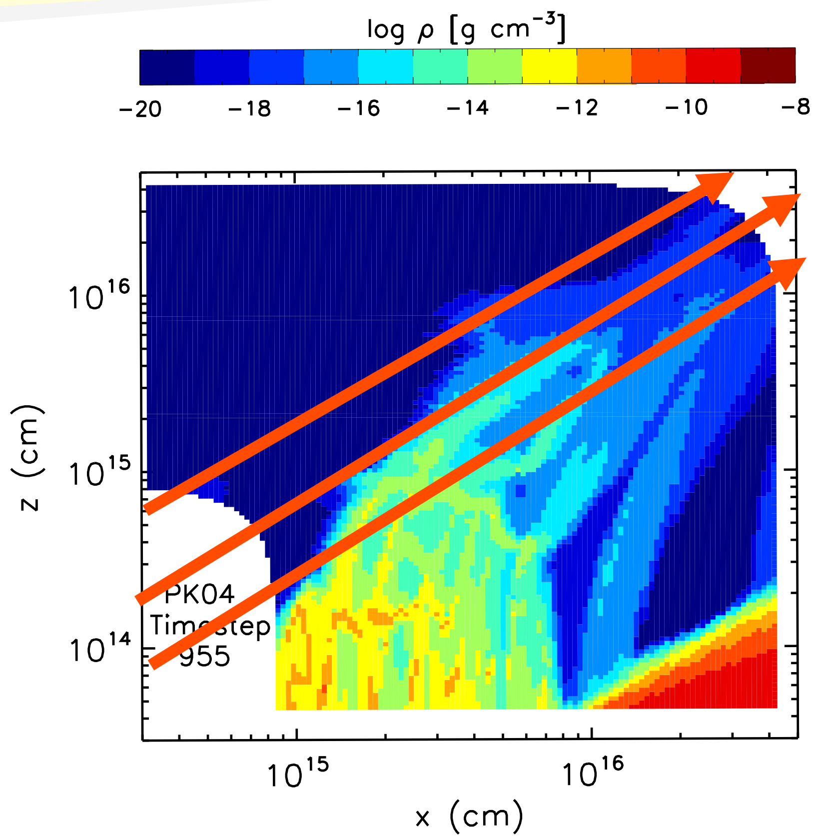




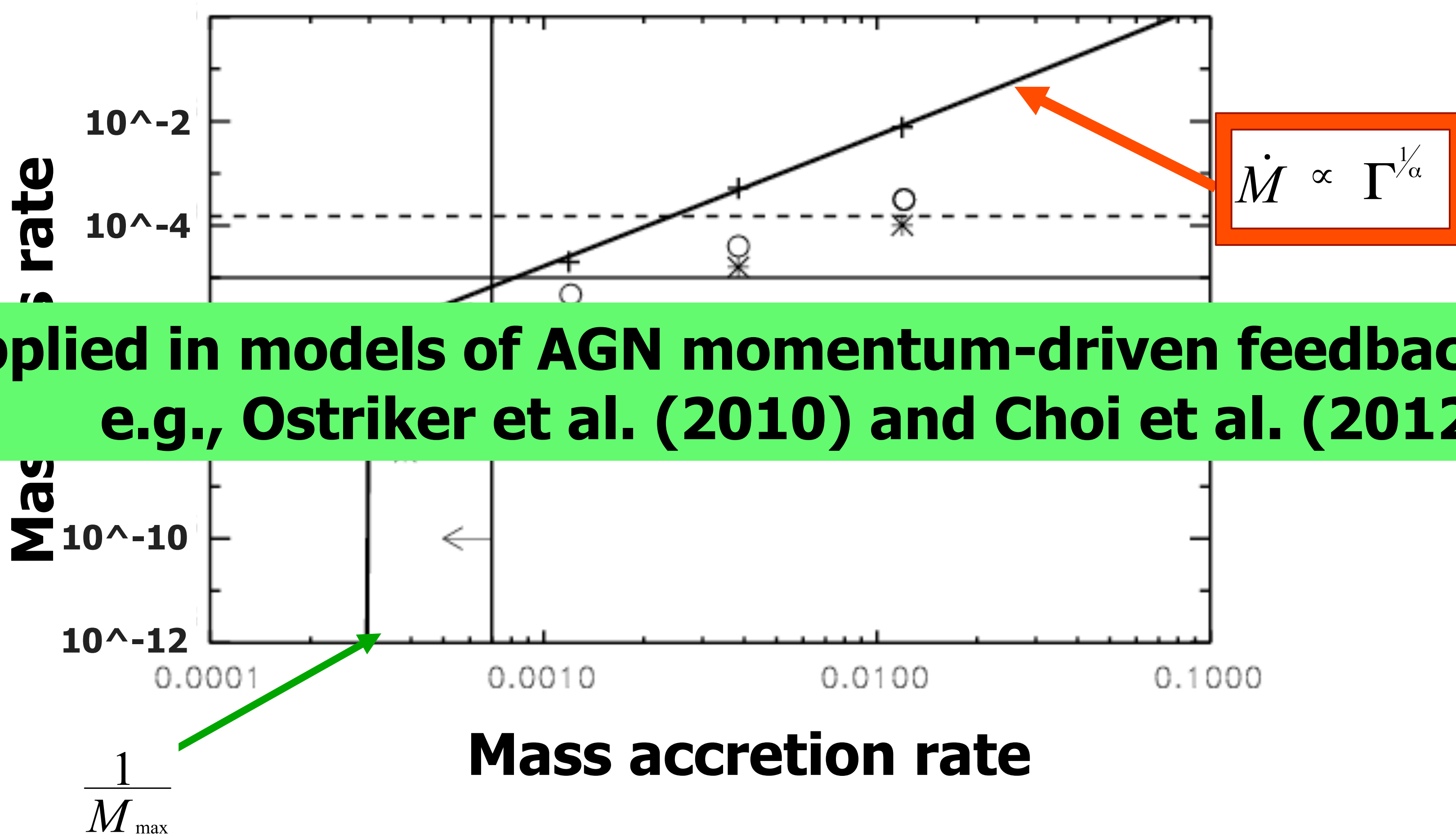
DP, Stone, & Kallman (2000)
DP & Kallman (2004)
DP & Kurosawa (2010)
DP et al. (2012)

Broad band spectra for various l.o.s.



Sim et al. (2010)

see also Schurch et al. (2009) and Giustini & DP (2012)



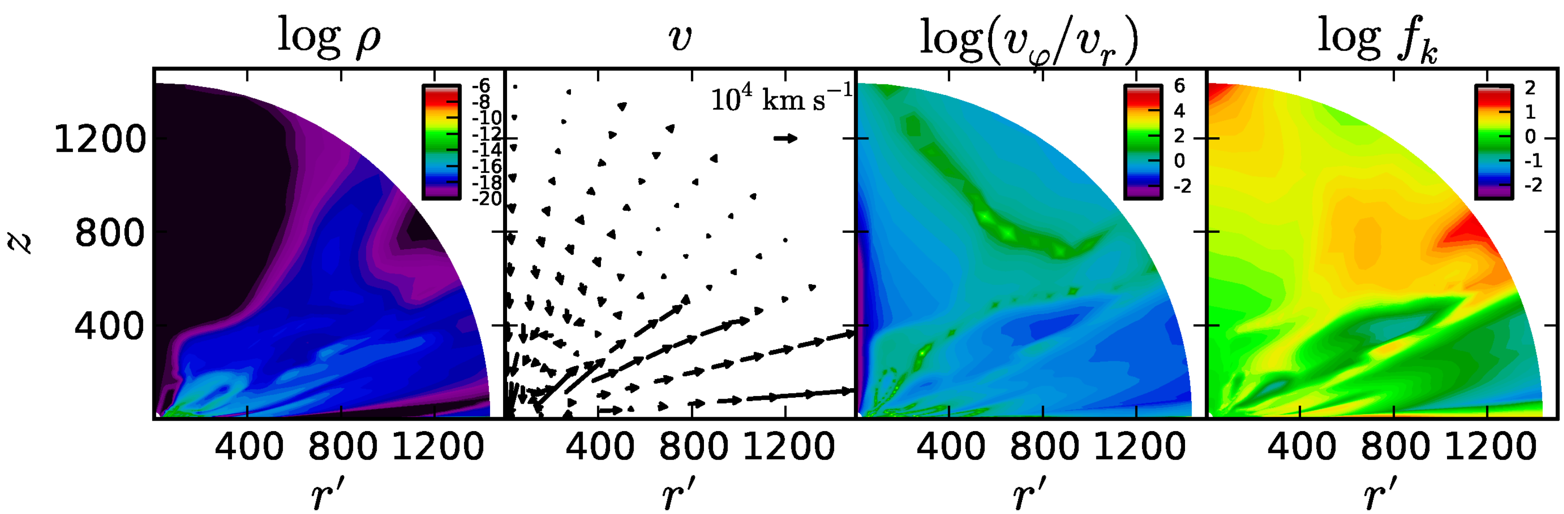
Applied in models of AGN momentum-driven feedback, e.g., Ostriker et al. (2010) and Choi et al. (2012).

Drew & Proga (1999)

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

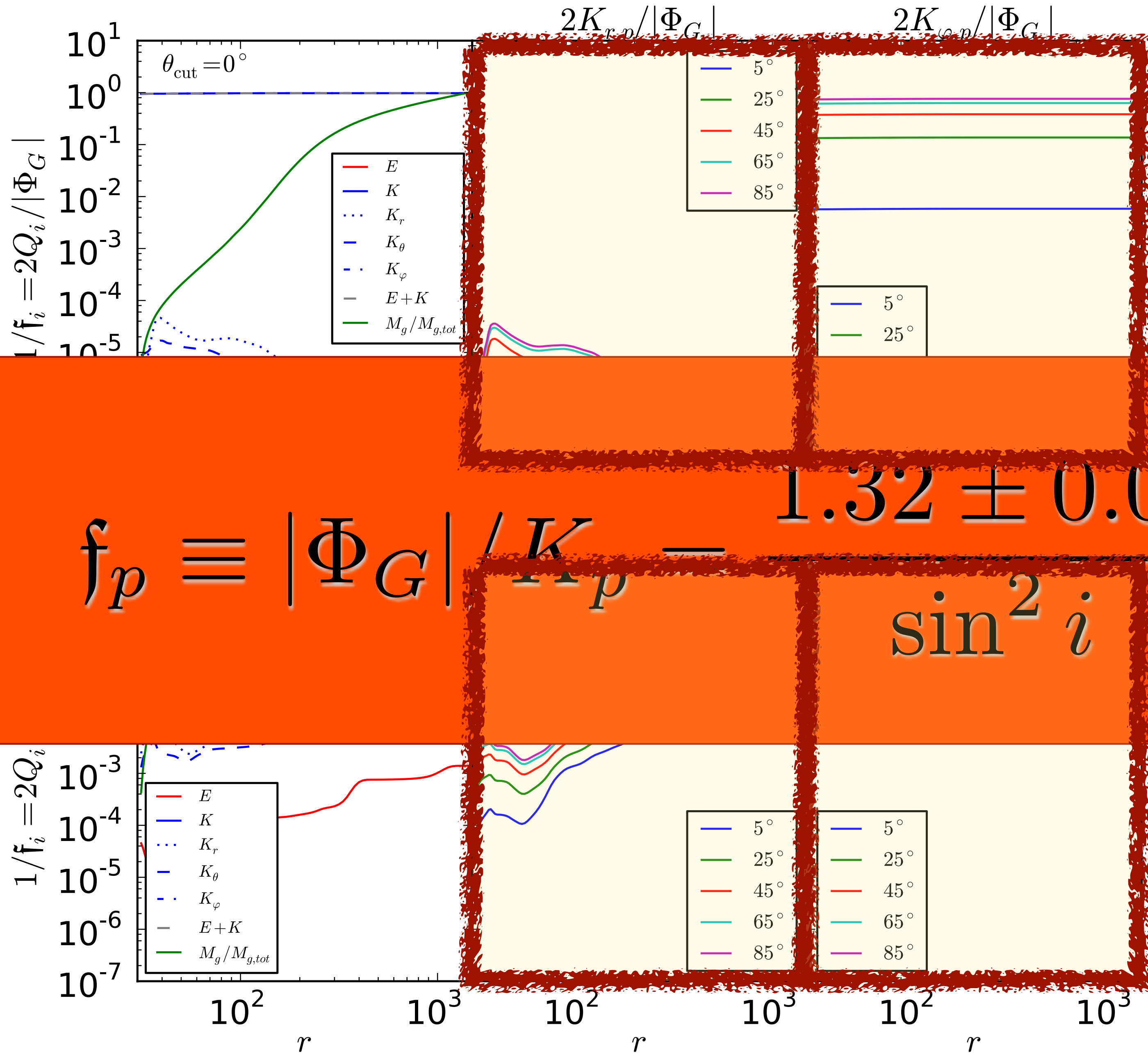
Are outflows virialized?

$$M(< r) = f\frac{rv^2}{G}$$



$$\mathfrak{f}_p \equiv |\Phi_G|/K_p$$

Kashi et al., submitted (aXriv:1310.1090)

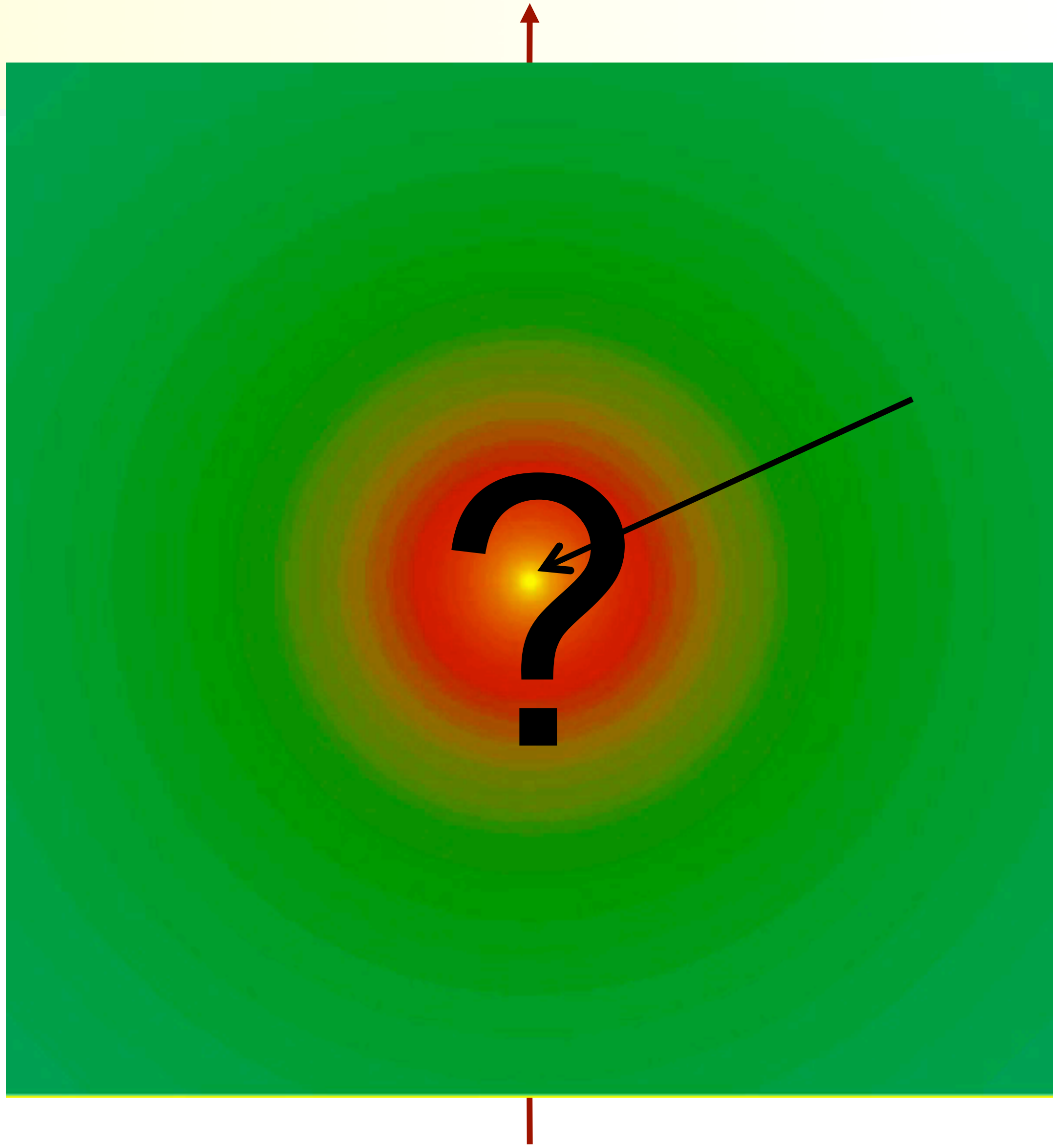


$$\mathfrak{f}_p \equiv |\Phi_G|/K_p = \frac{1.32 \pm 0.08}{\sin^2 i}$$

Radiation-Driven Winds from Inflows

Irradiation by Quasar.

Part I: effects of radiative heading and cooling.



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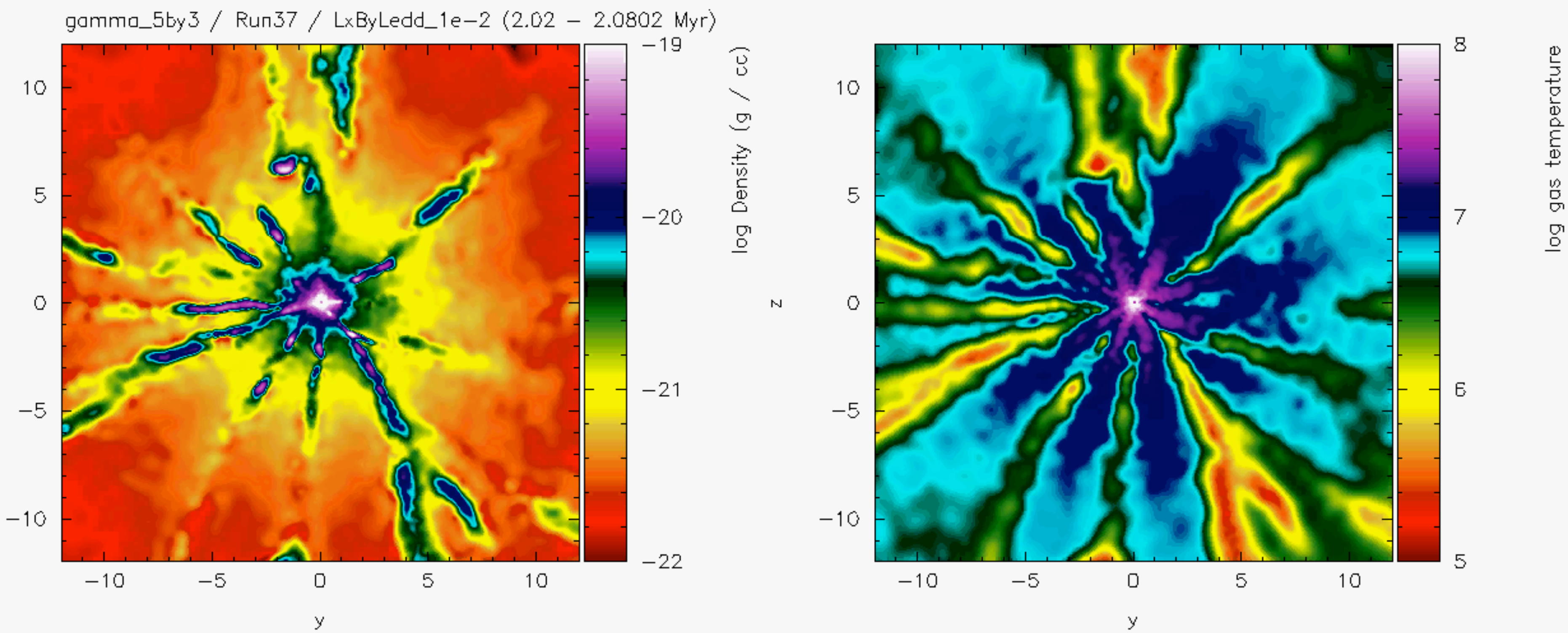
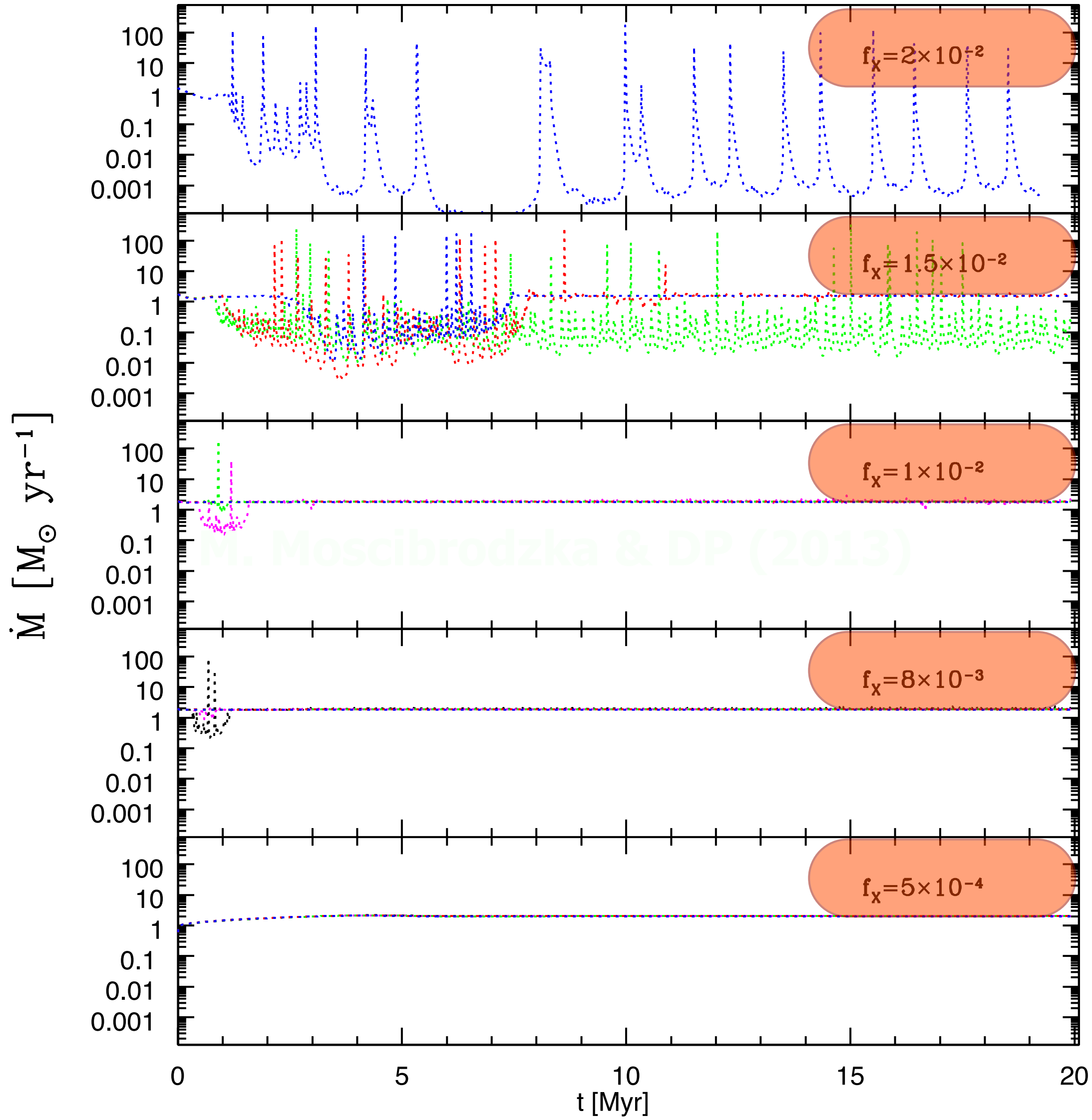
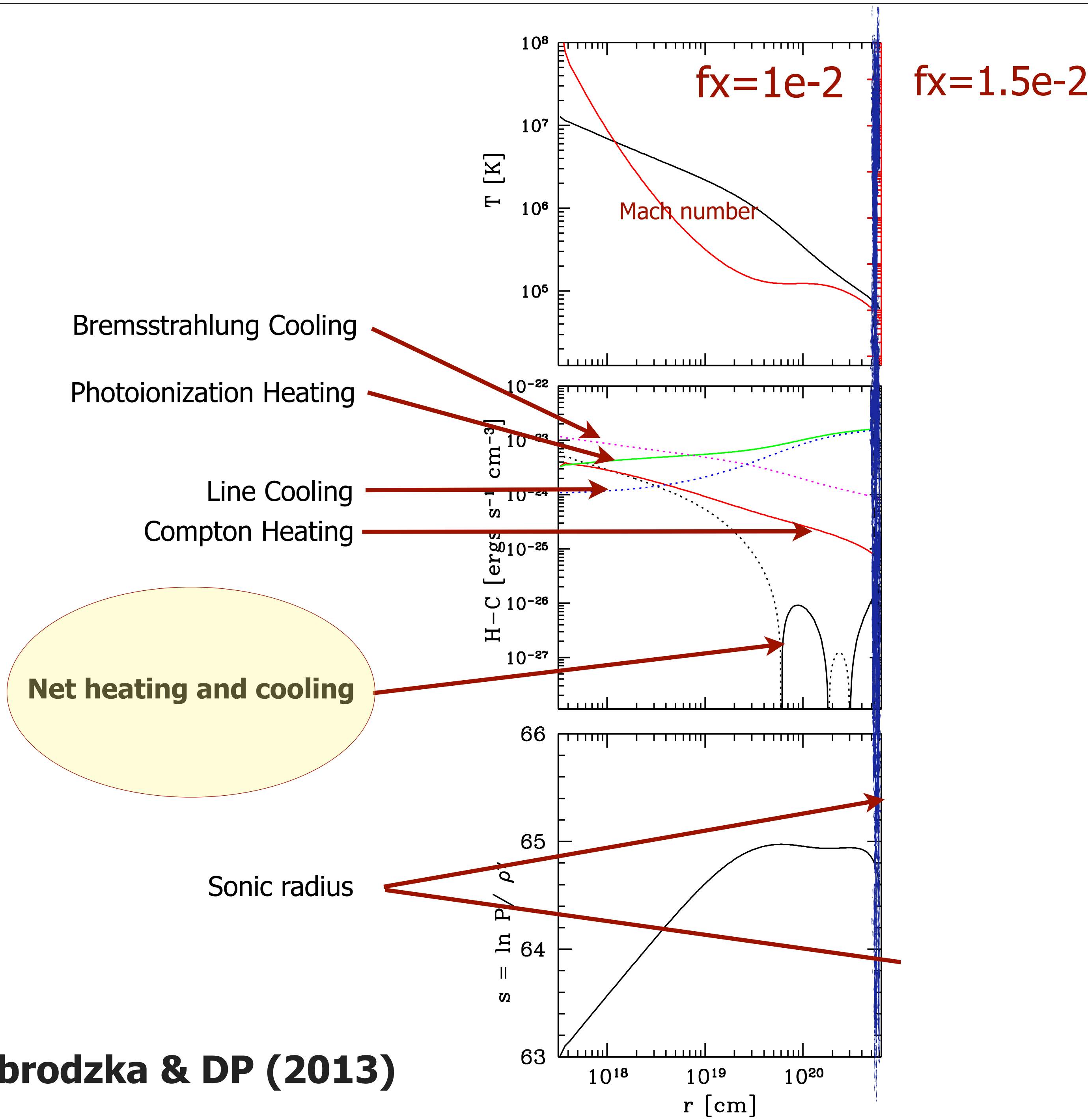


a 3-D SPH simulation (Barai, DP, & Nagamine 2012, see also BPN 2011)
see K. Nagamine's talk



M. Moscibrodzka & DP (2013)



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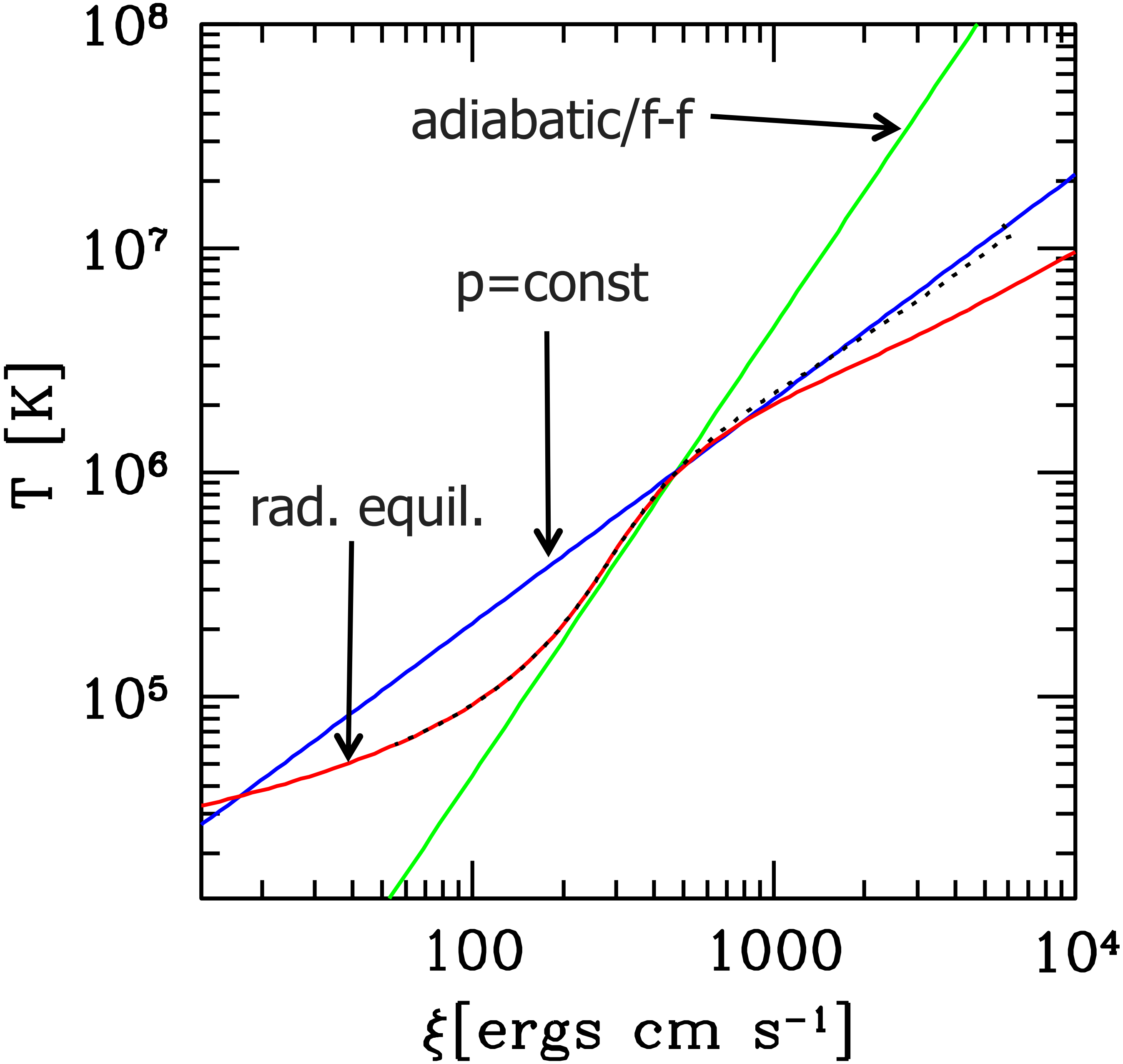
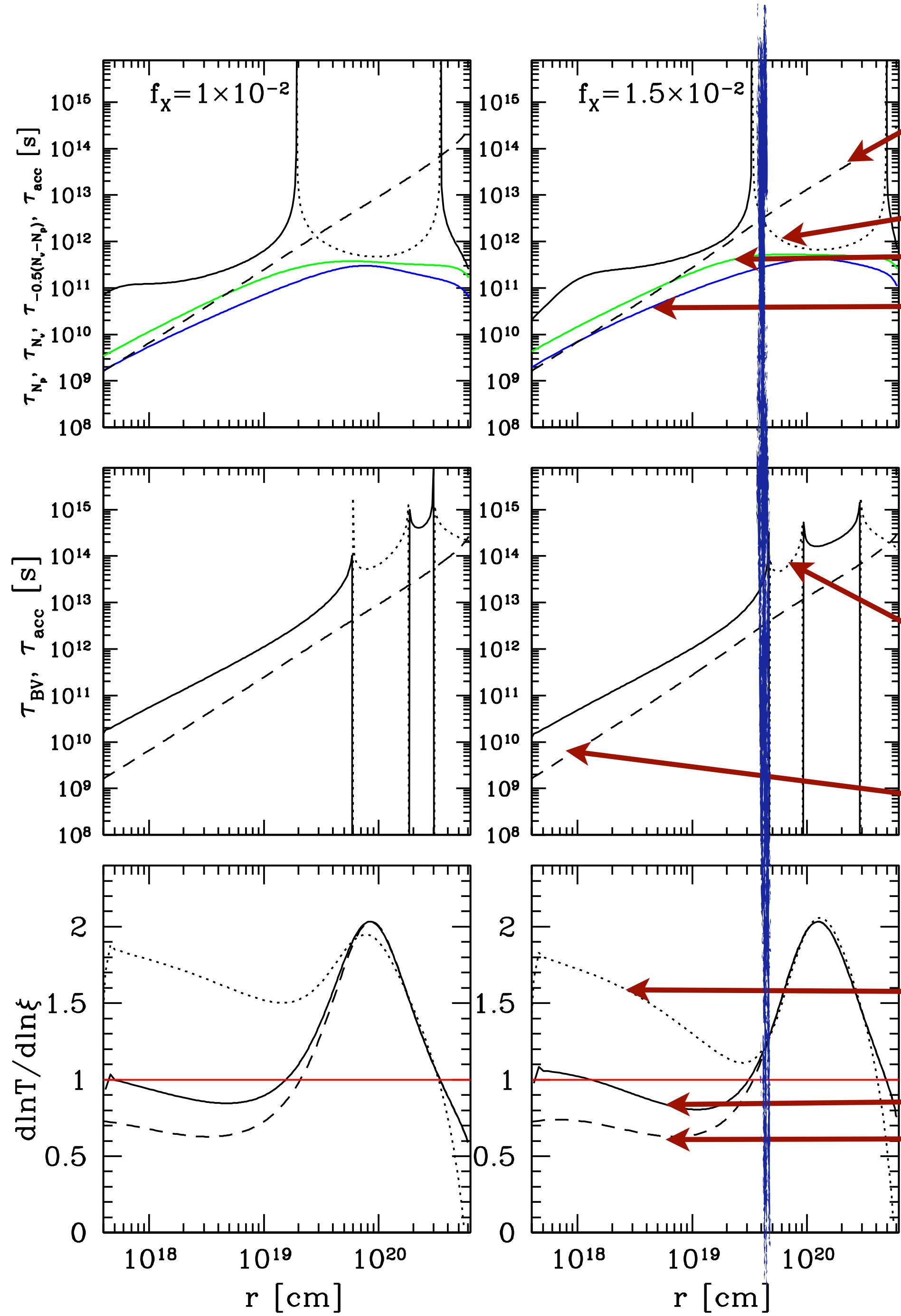


adiabatic/f-f
p=const
rad. equil.
T [K]
10^8
10^7
10^6
10^5
100
1000
10^4
ξ[ergs cm s^{-1}]



time scale for accretion

time scale for isobaric thermal mode

time scale for isochoric thermal mode

time scale for damping acoustic mode

$$n^3 + N_v n^2 + k^2 c_s^2 n + N_p k^2 c_s^2 = 0$$

$$N_p \equiv \frac{1}{c_p}\left(\frac{\partial \mathcal{L}}{\partial T}\right)\bigg|_P \qquad k = 2\pi/\lambda$$

$$N_v \equiv \frac{1}{c_v}\left(\frac{\partial \mathcal{L}}{\partial T}\right)\bigg|_\rho$$

time scale for the Brunt-Vaisala mode

$$\omega_{BV}^2 \equiv \left(-\frac{1}{\rho}\frac{\partial P}{\partial r}\right)\frac{\partial \ln S}{dr}$$

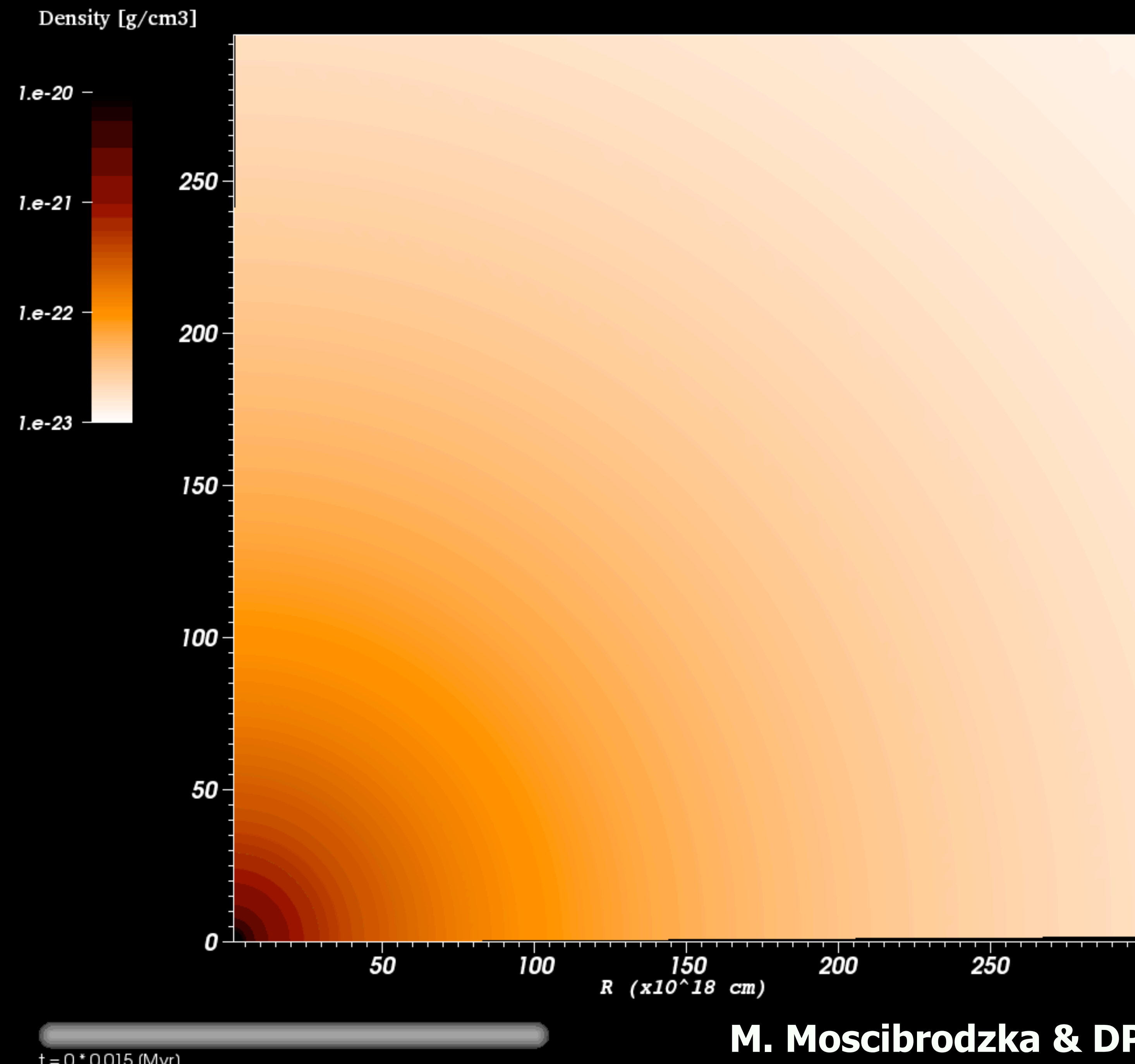
time scale for accretion

slope for adiabatic process (i.e., entropy=const)

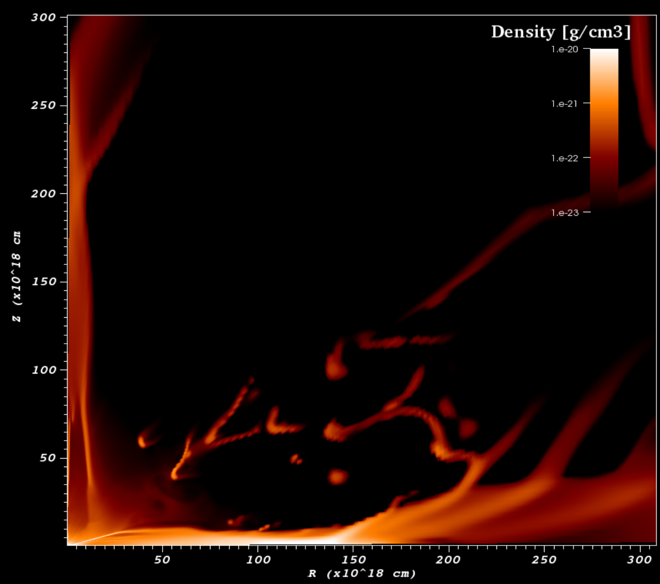
slope for the hydro results

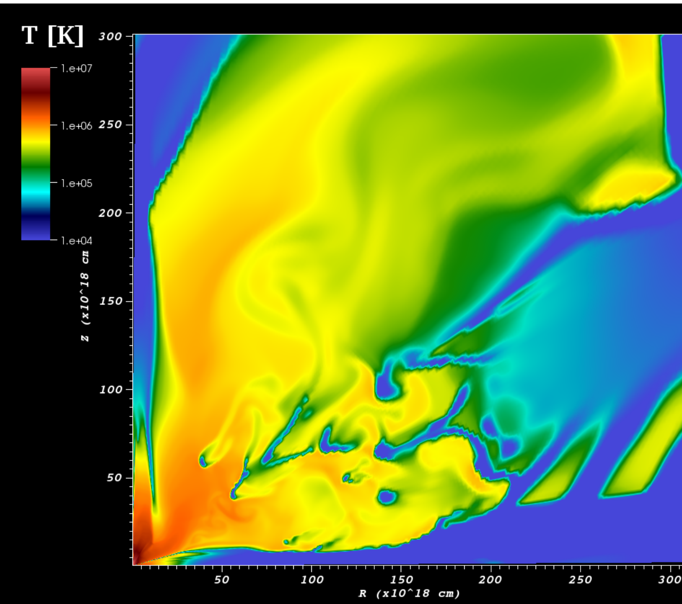
slope for radiative equilibrium

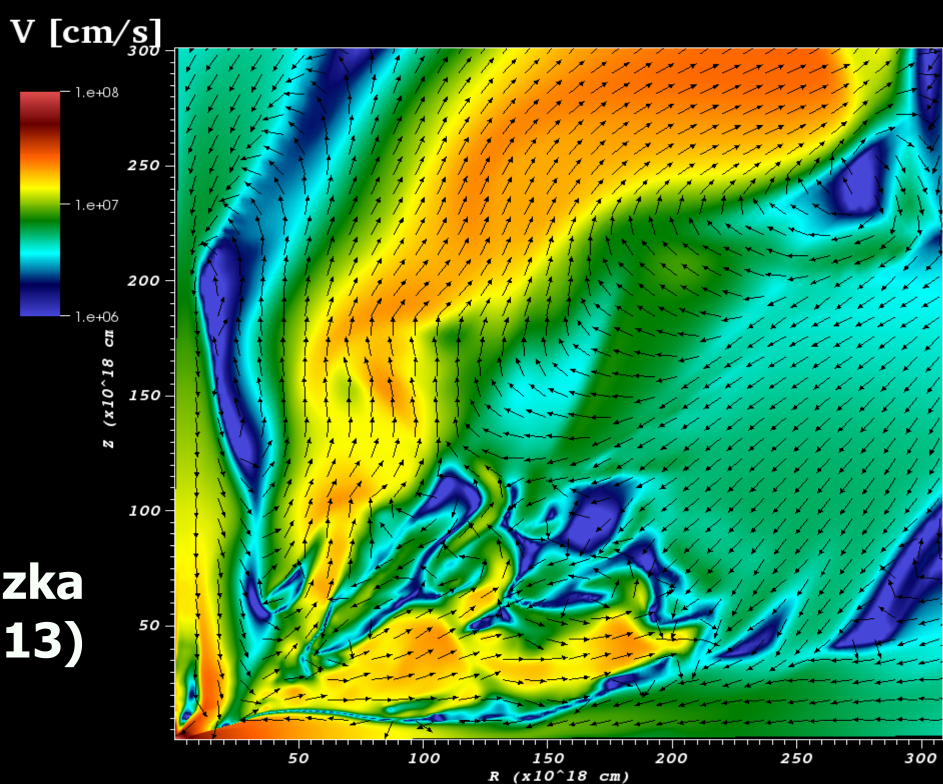
M. Moscibrodzka & DP (2013)



M. Moscibrodzka & DP (2013)







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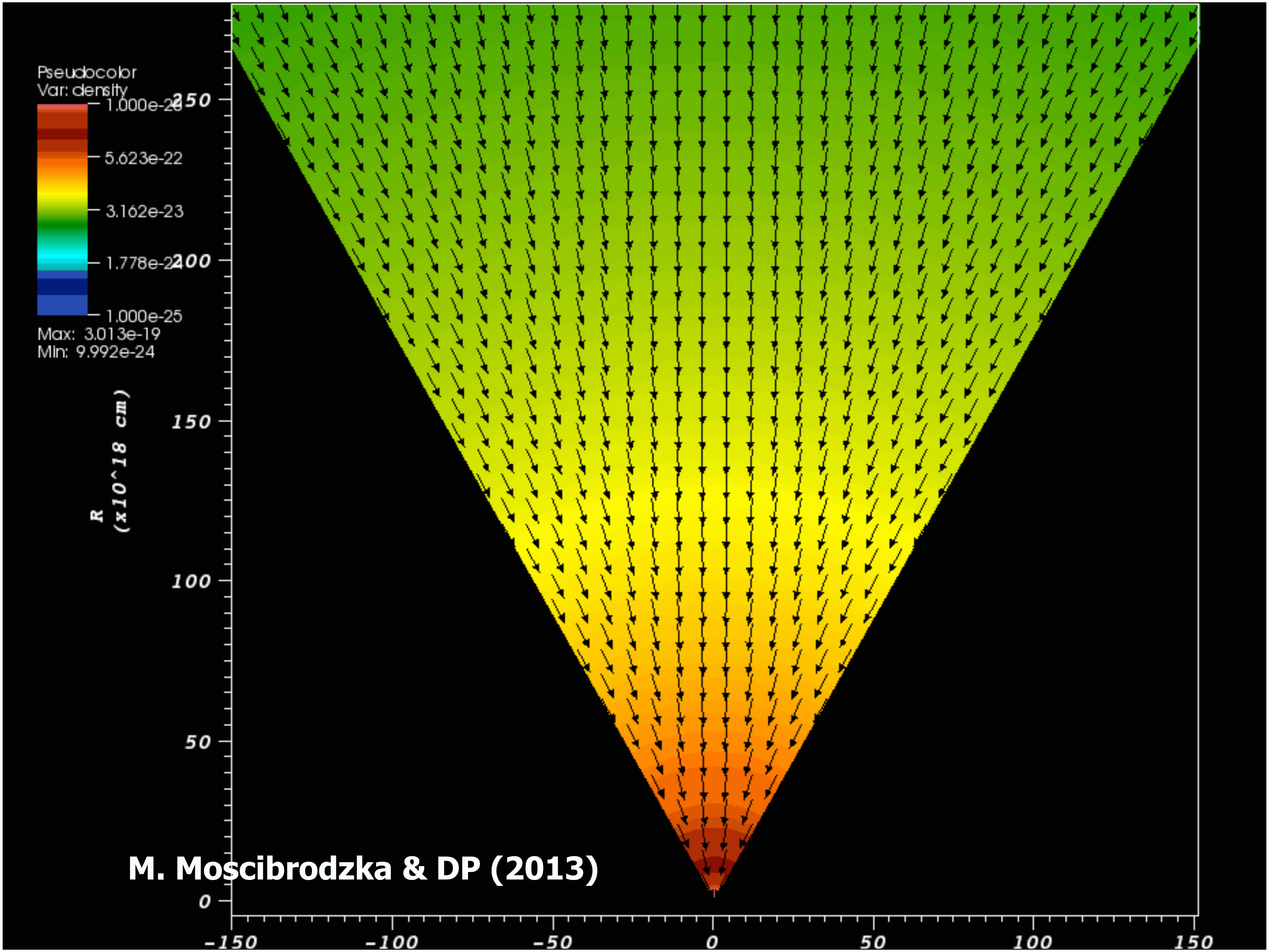
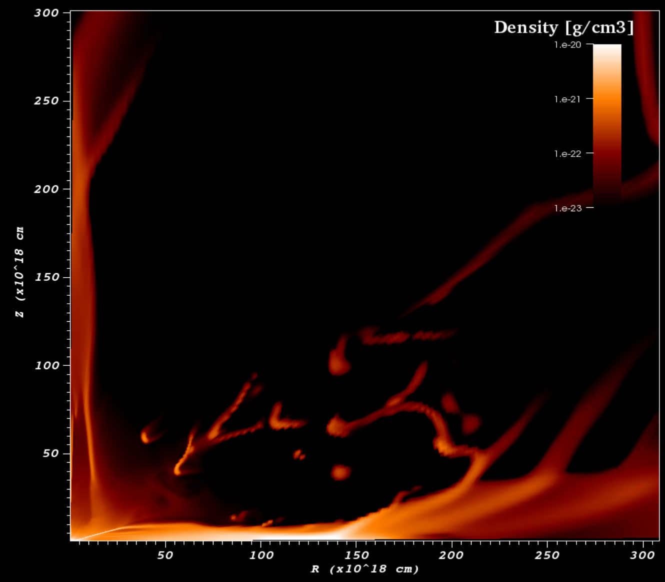
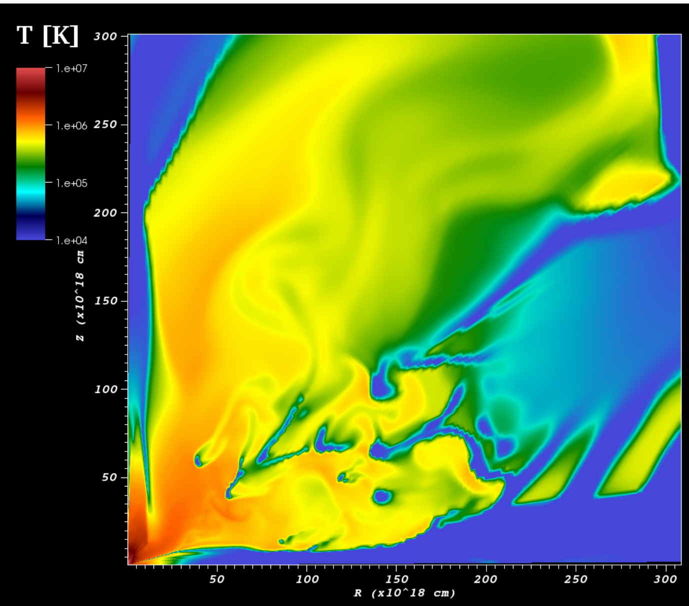
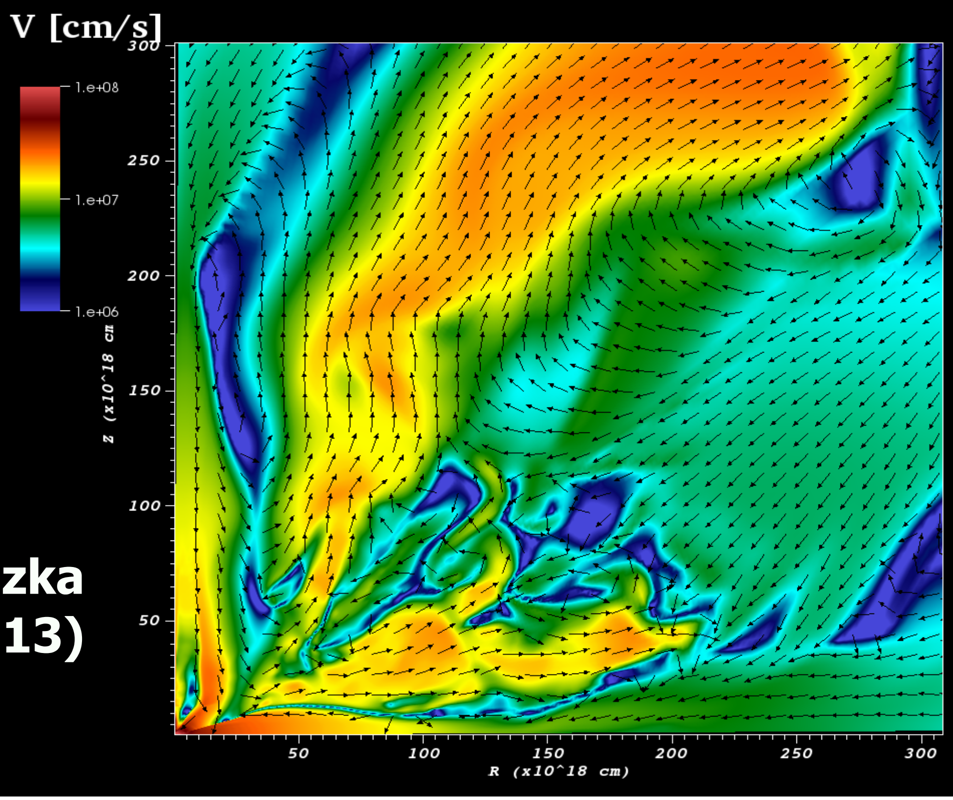


M. Moscibrodzka & DP (2013)







M. Moscibrodzka & DP (2013)

Cloud Irradiation

In collaboration with Yan-Fei Jiang (Princeton), Shane Davis (CITA), Jim Stone (Princeton), and Daniel Smith (UNLV).

The equations of R-HD

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

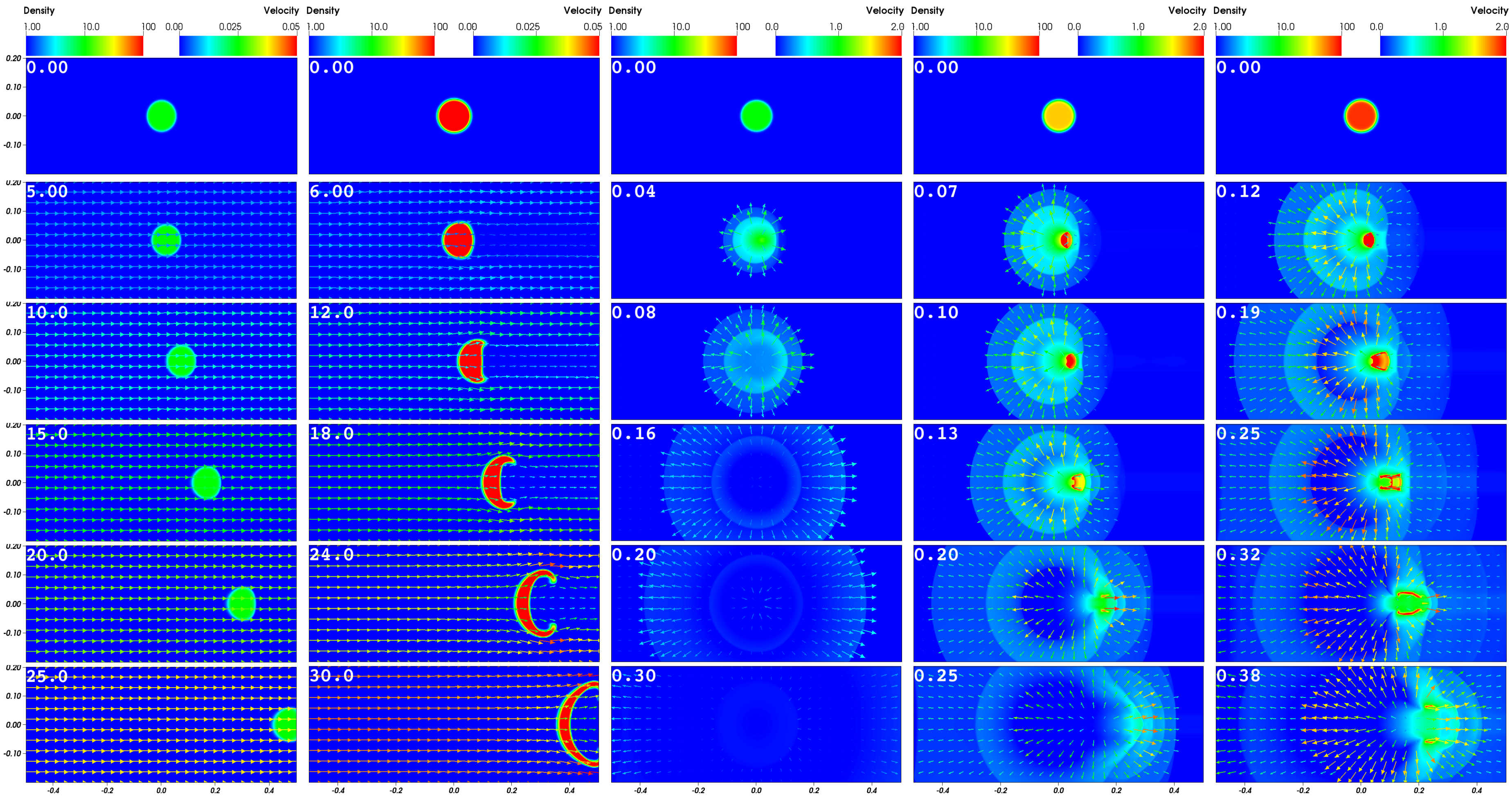
$$\frac{\partial (\rho \boldsymbol{v})}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}\boldsymbol{v} \qquad) = -\mathbb{P}\mathbf{S}_{\mathrm{r}}(\boldsymbol{P}),$$

$$\frac{\partial E}{\partial t} + \nabla \cdot [(E + P^*)\boldsymbol{v} \qquad)] = -\mathbb{P}\mathbb{C}S_r(E),$$

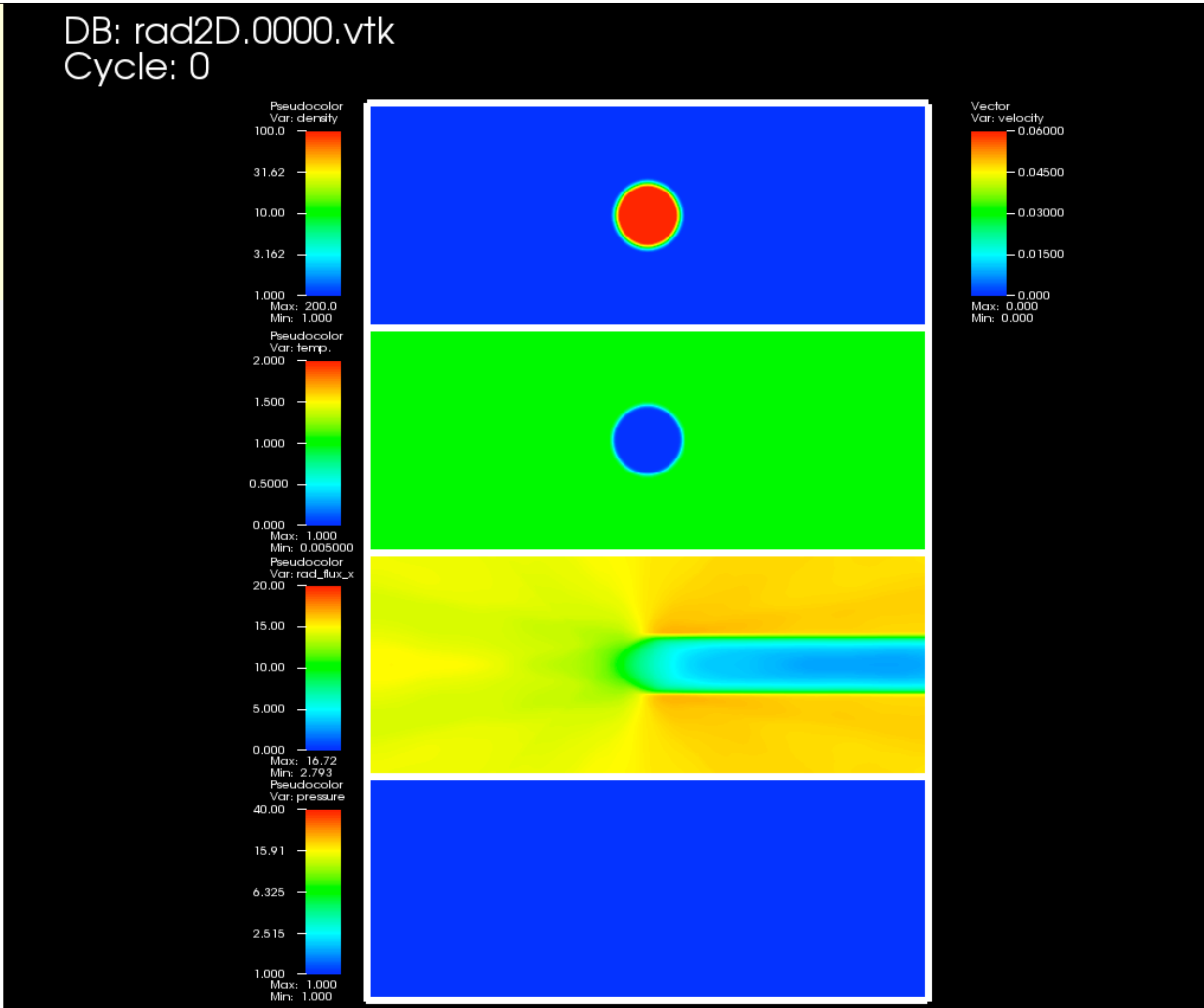
$$\frac{\partial E_r}{\partial t} + \mathbb{C}\nabla \cdot \boldsymbol{F}_r = \mathbb{C}S_r(E),$$

$$\frac{\partial \boldsymbol{F}_r}{\partial t} + \mathbb{C}\nabla \cdot \mathbf{P}_r = \mathbb{C}\mathbf{S}_{\mathrm{r}}(\boldsymbol{P}),$$

Pure scattering   Absorption dominated



Proga et al., in prep.



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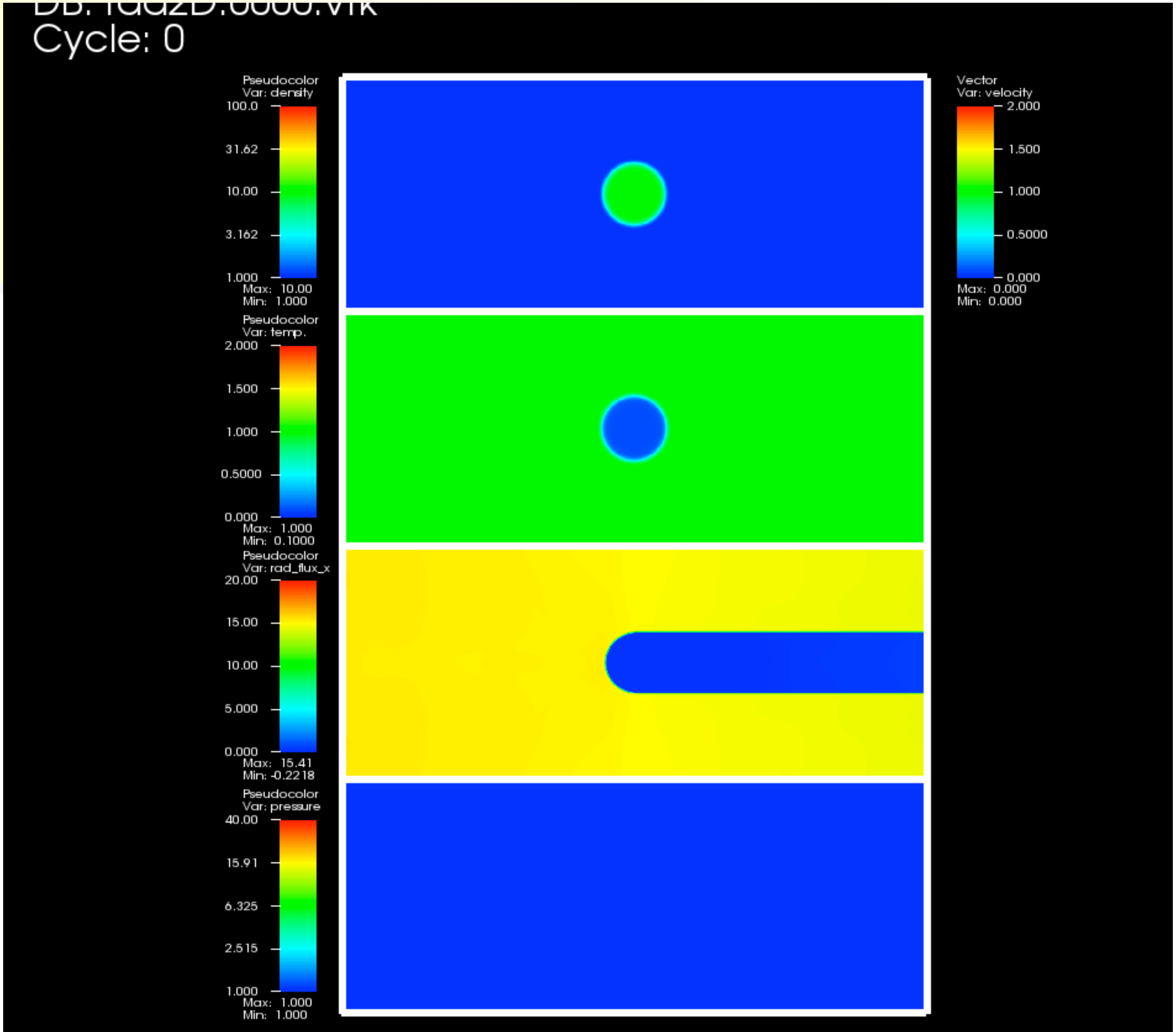

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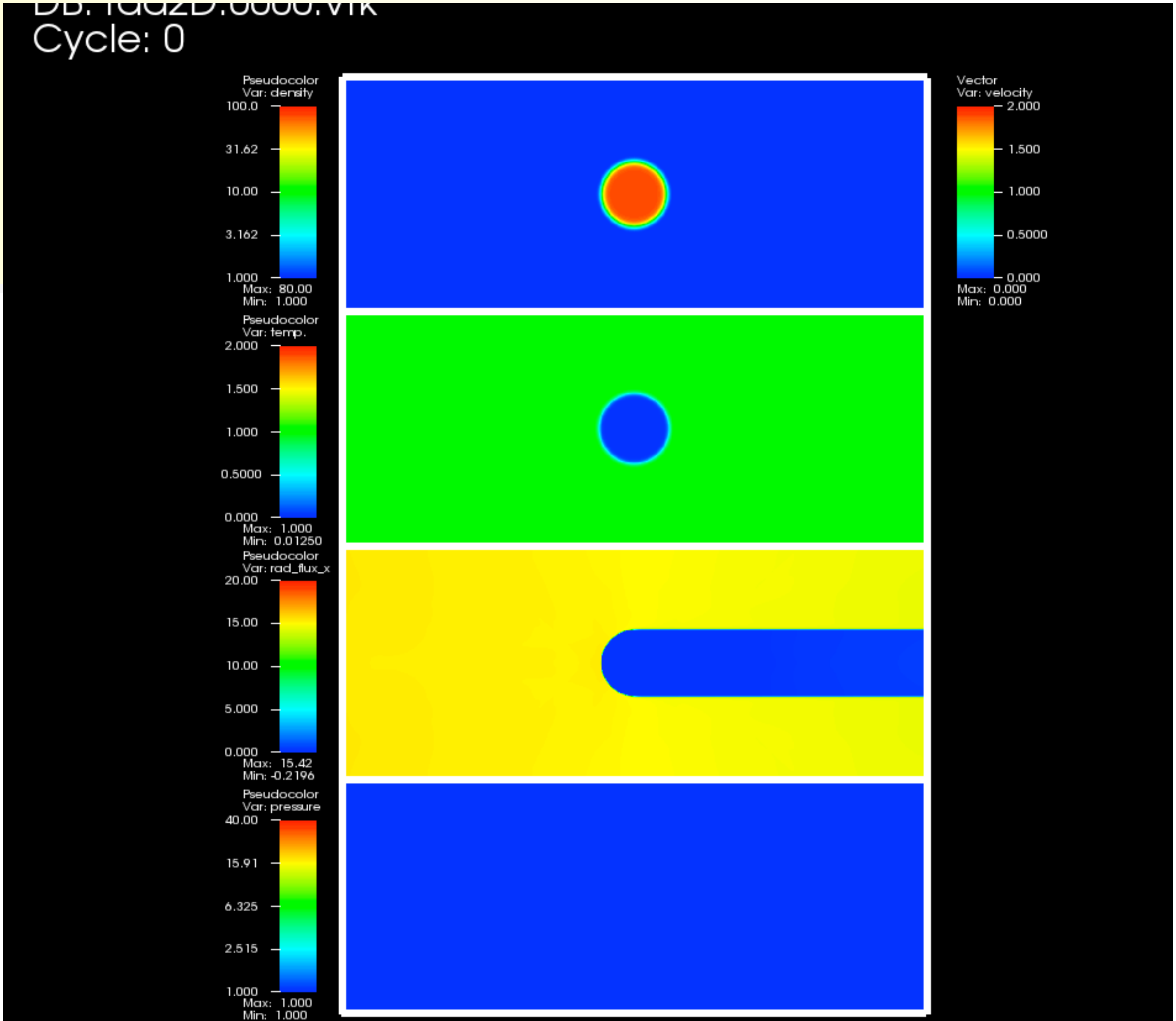

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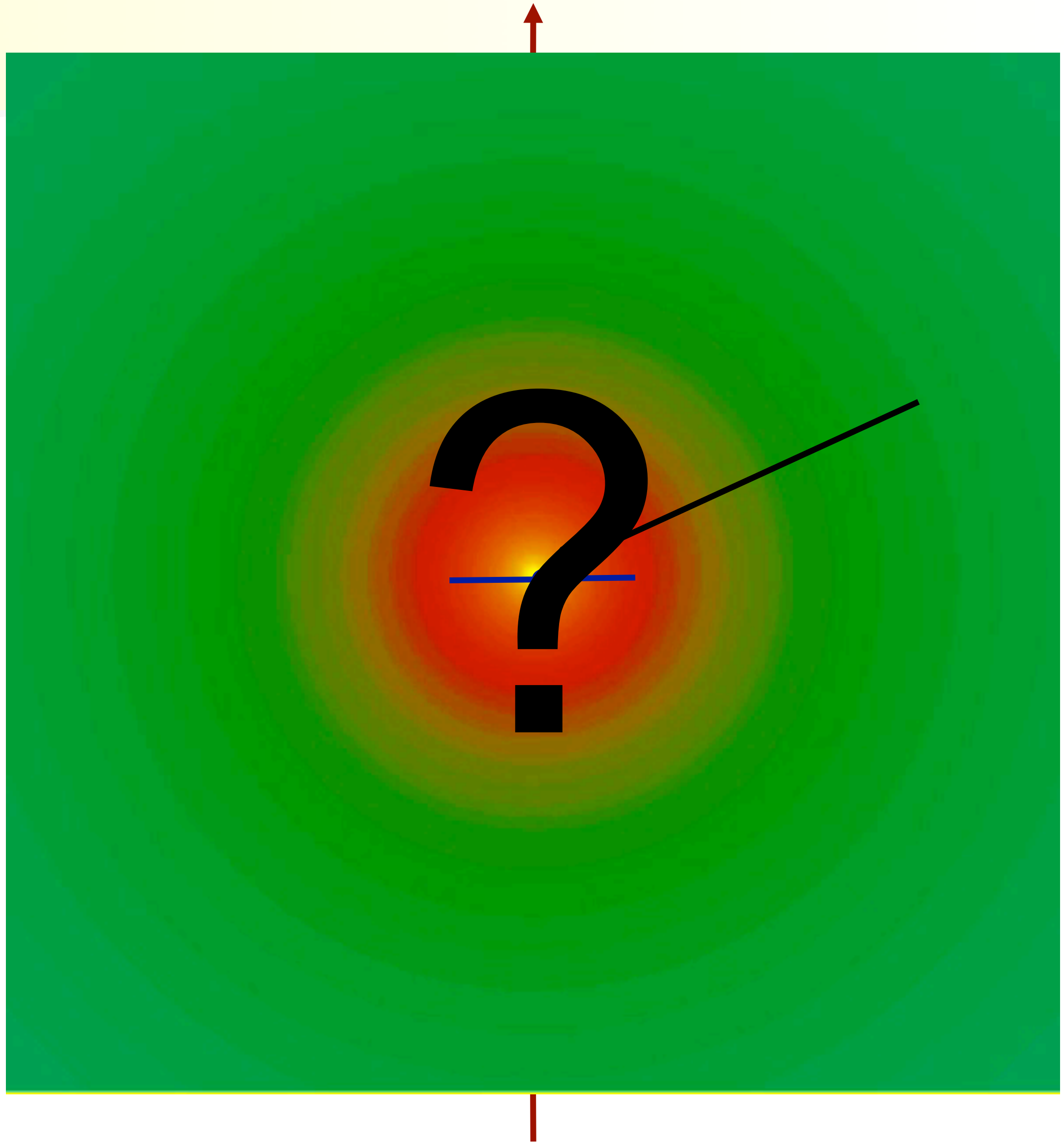
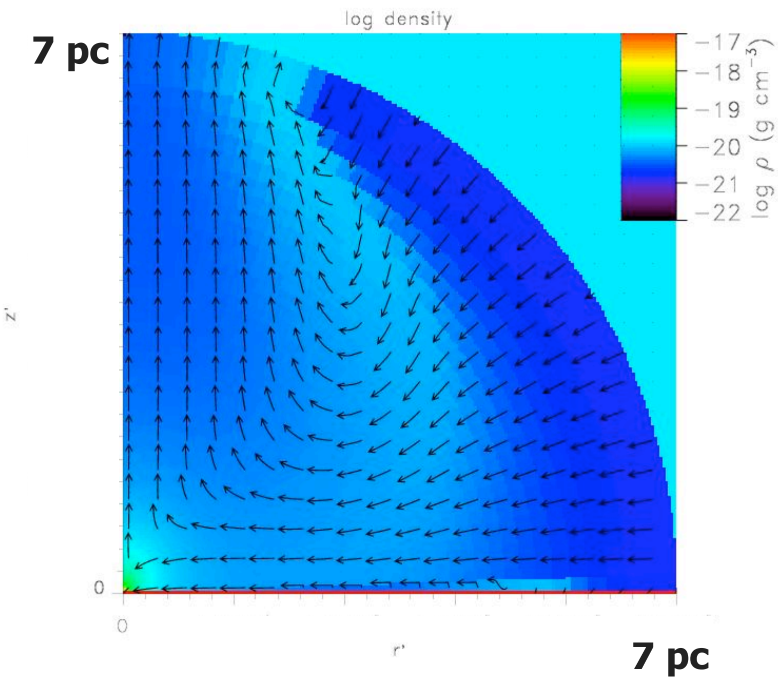




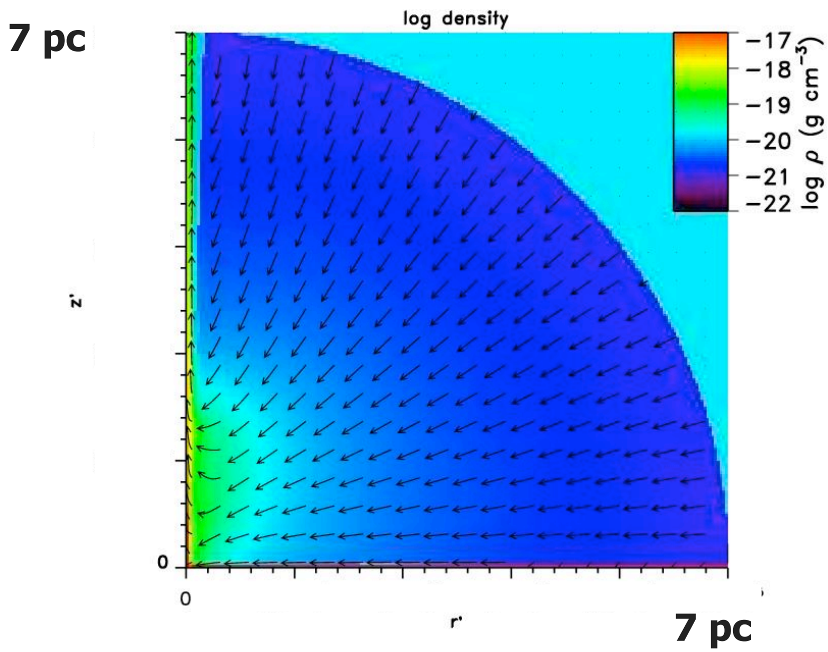
$M_{BH} = 10^8 M_{SUN}$

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

$T_X = 8 \times 10^7 K$

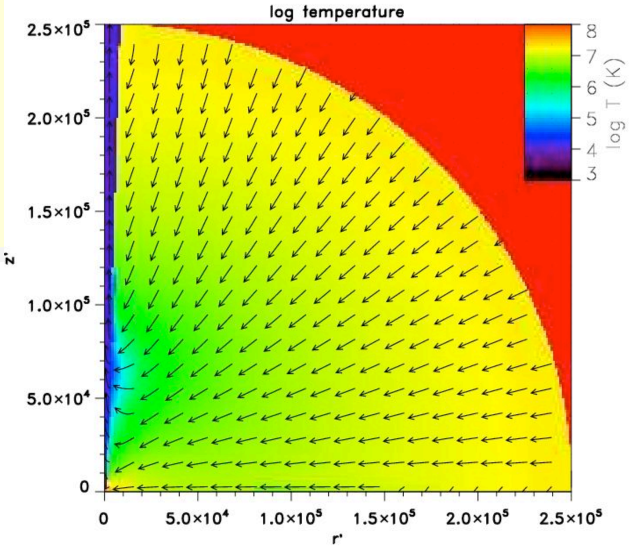
$\rho(r_o) = 10^{-21} g/cm^3$

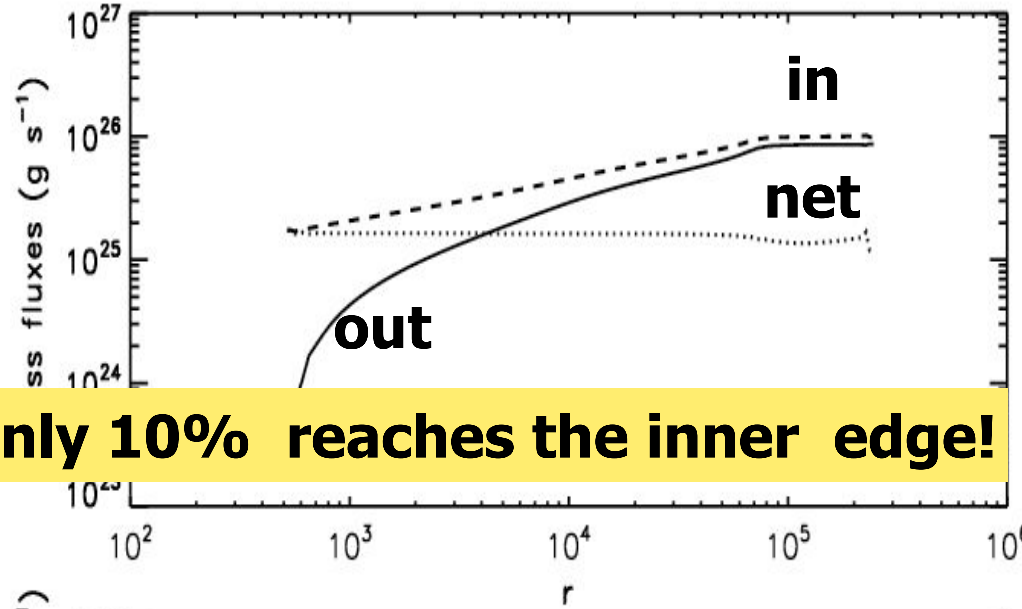
$f_{UV} = f_X = 0.5$



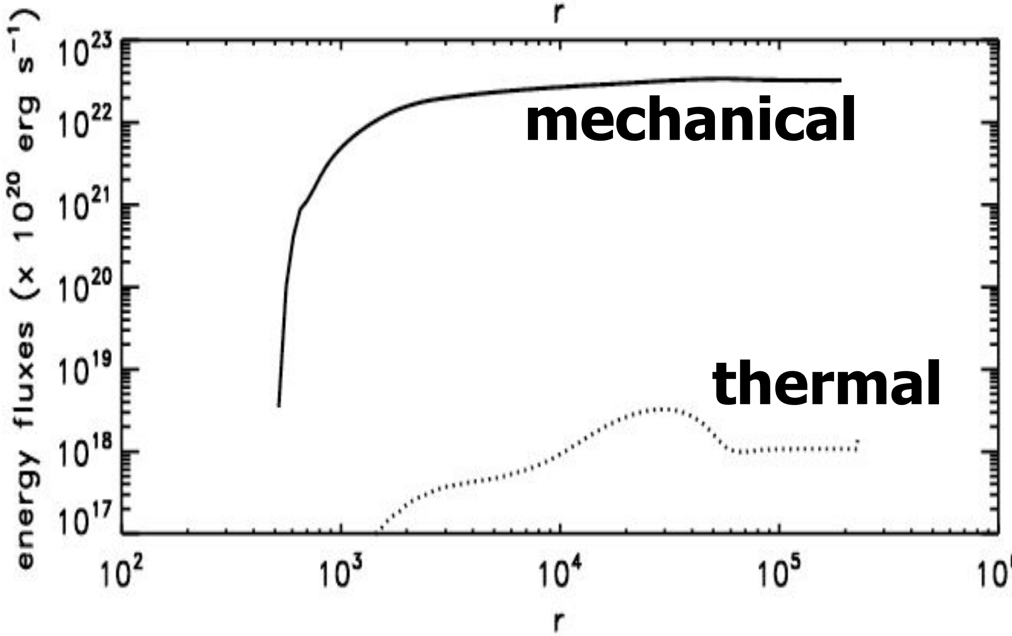
$f_{UV} = 0.95 \quad f_X = 0.05$

Proga (2007)





Only 10% reaches the inner edge!



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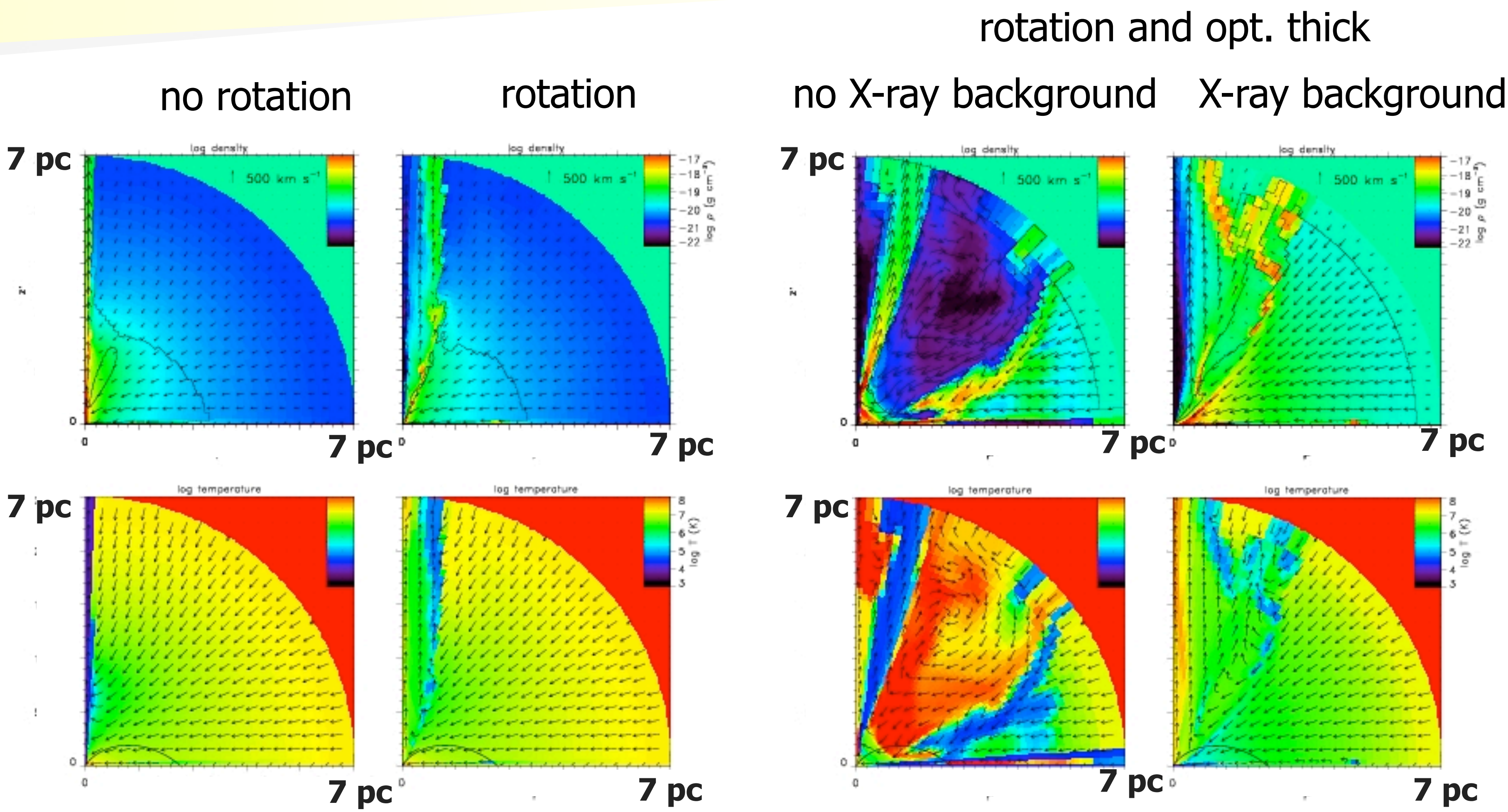
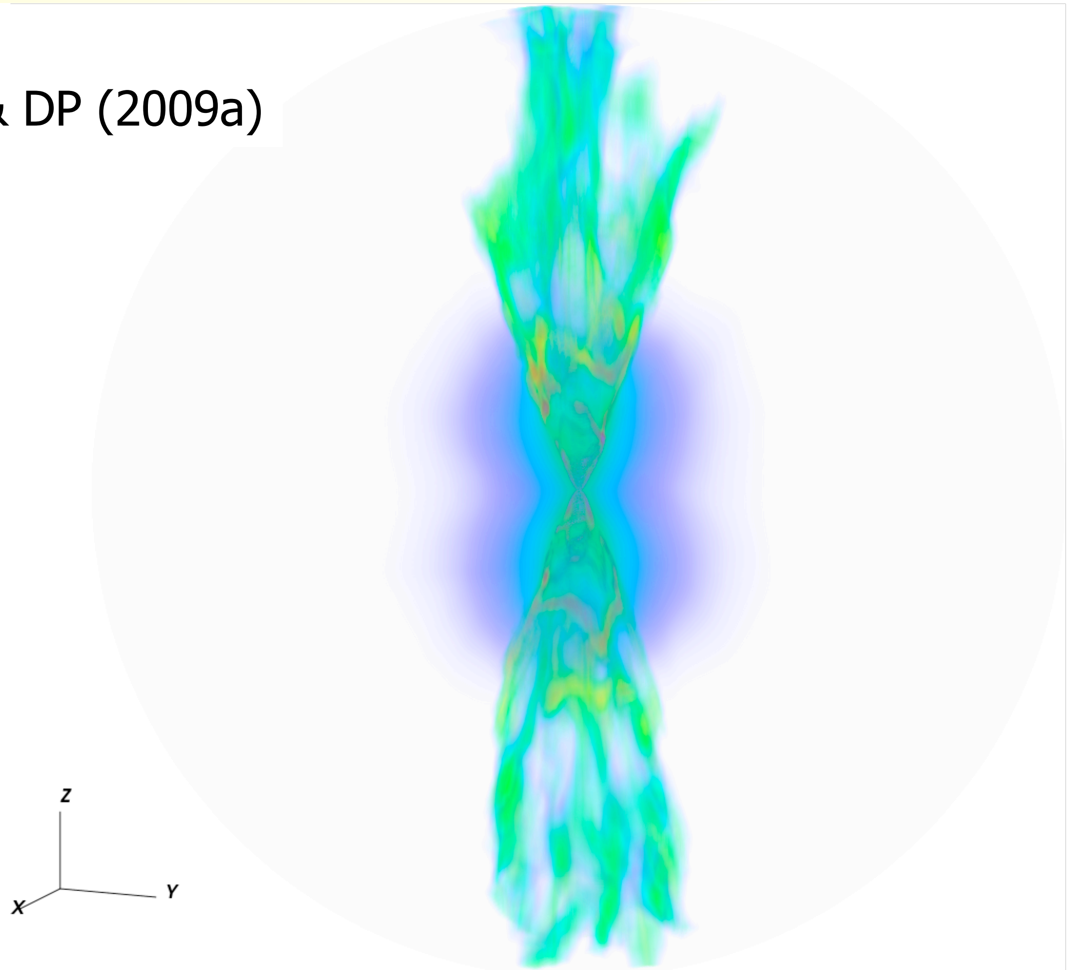
Effects of gas rotation, optical depth and X-ray background radiation

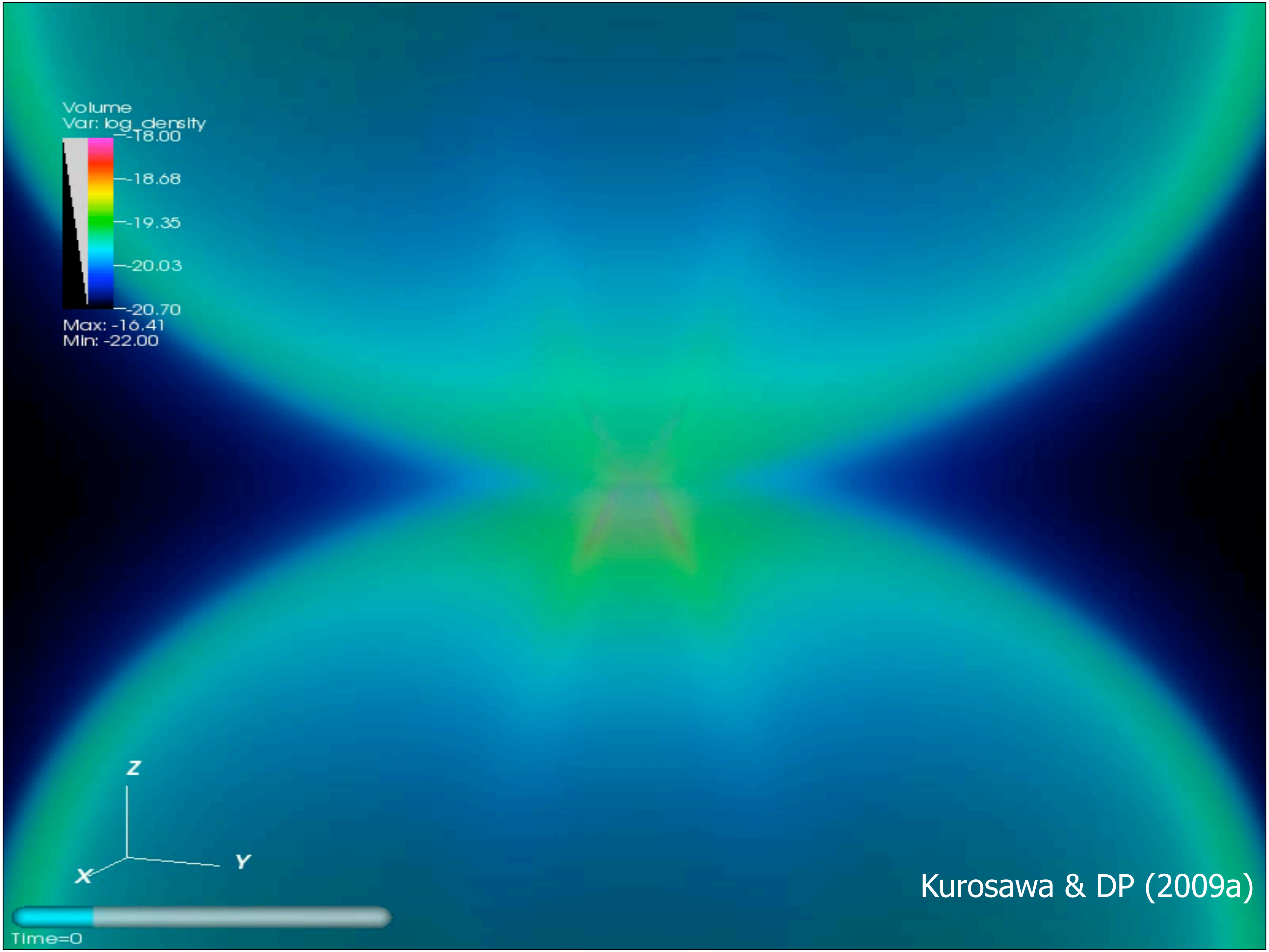


Proga, Ostriker, Kurosawa (2008)

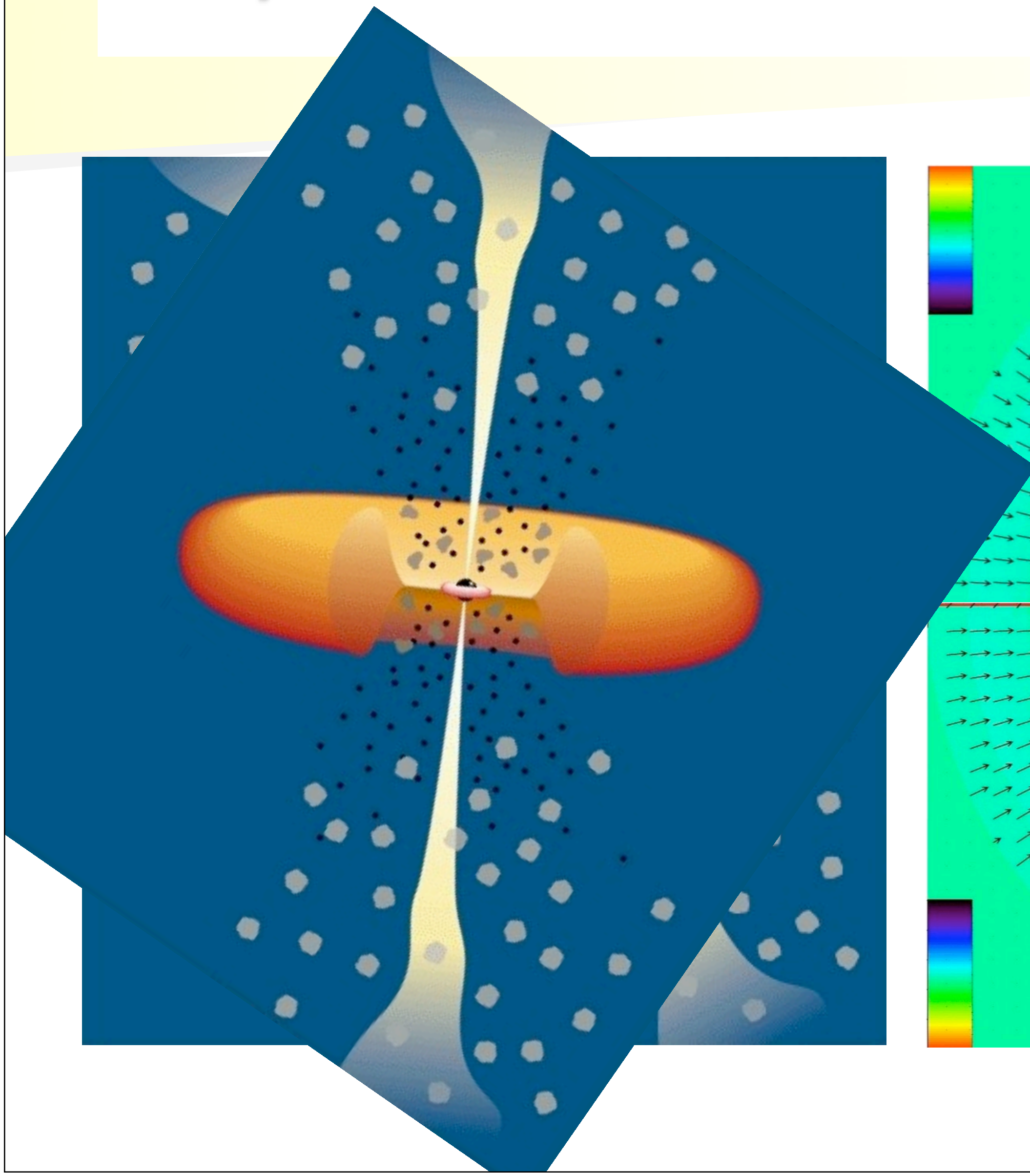
3-diminesional simulations

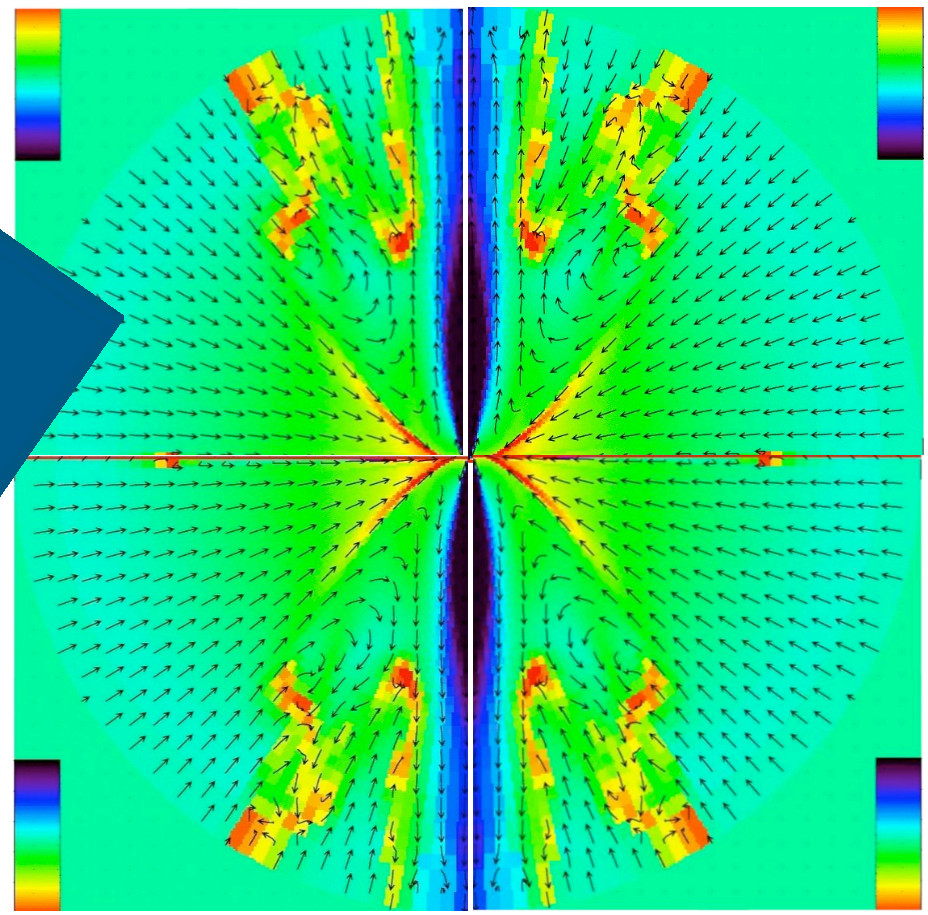
Kurosawa & DP (2009a)

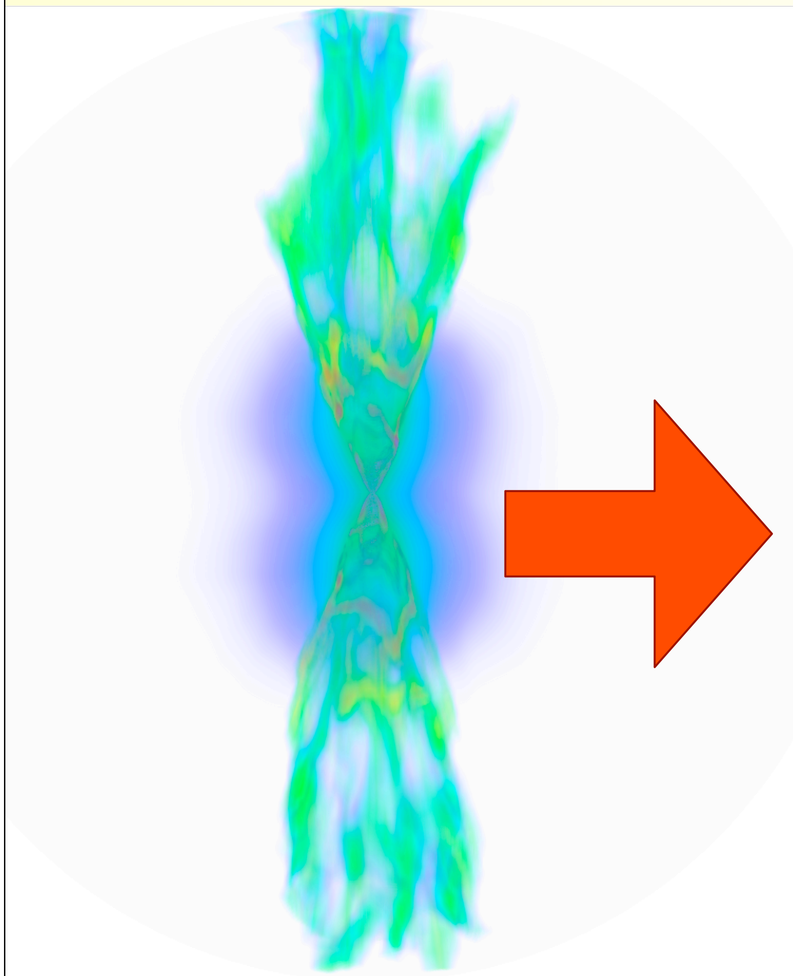



Volume
Var: log_density
-18.00
-18.68
-19.35
-20.03
-20.70
Max: -16.41
Min: -22.00
Z
Y
X
Time=0
Kurosawa & DP (2009a)

Dynamical model for clouds in NLR!?

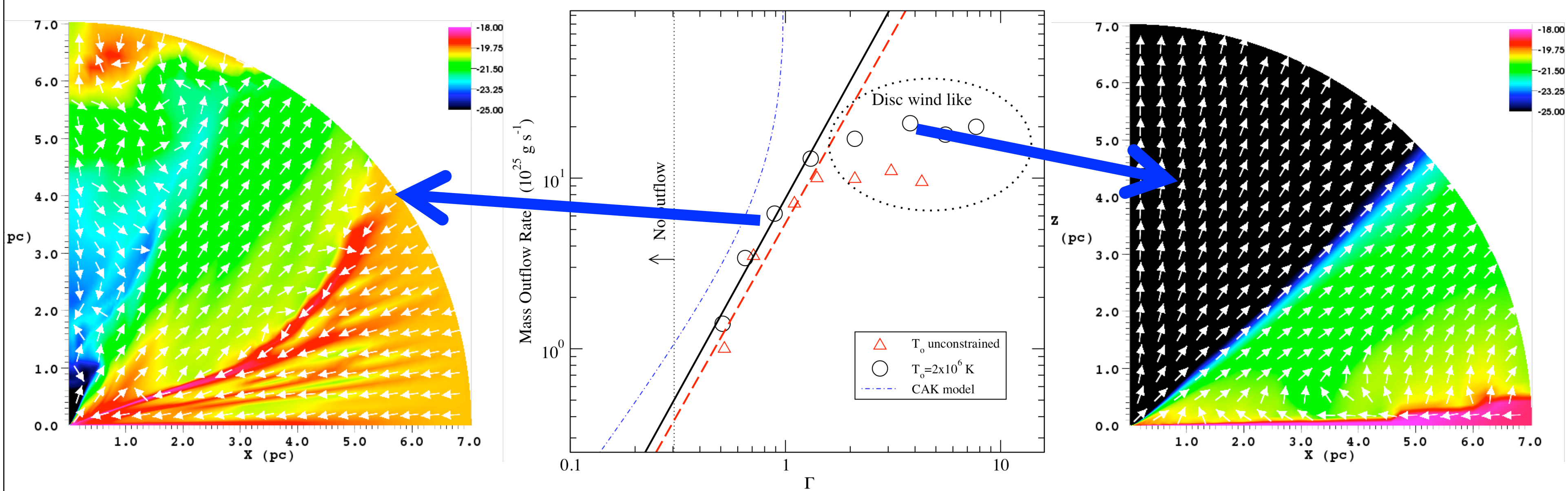






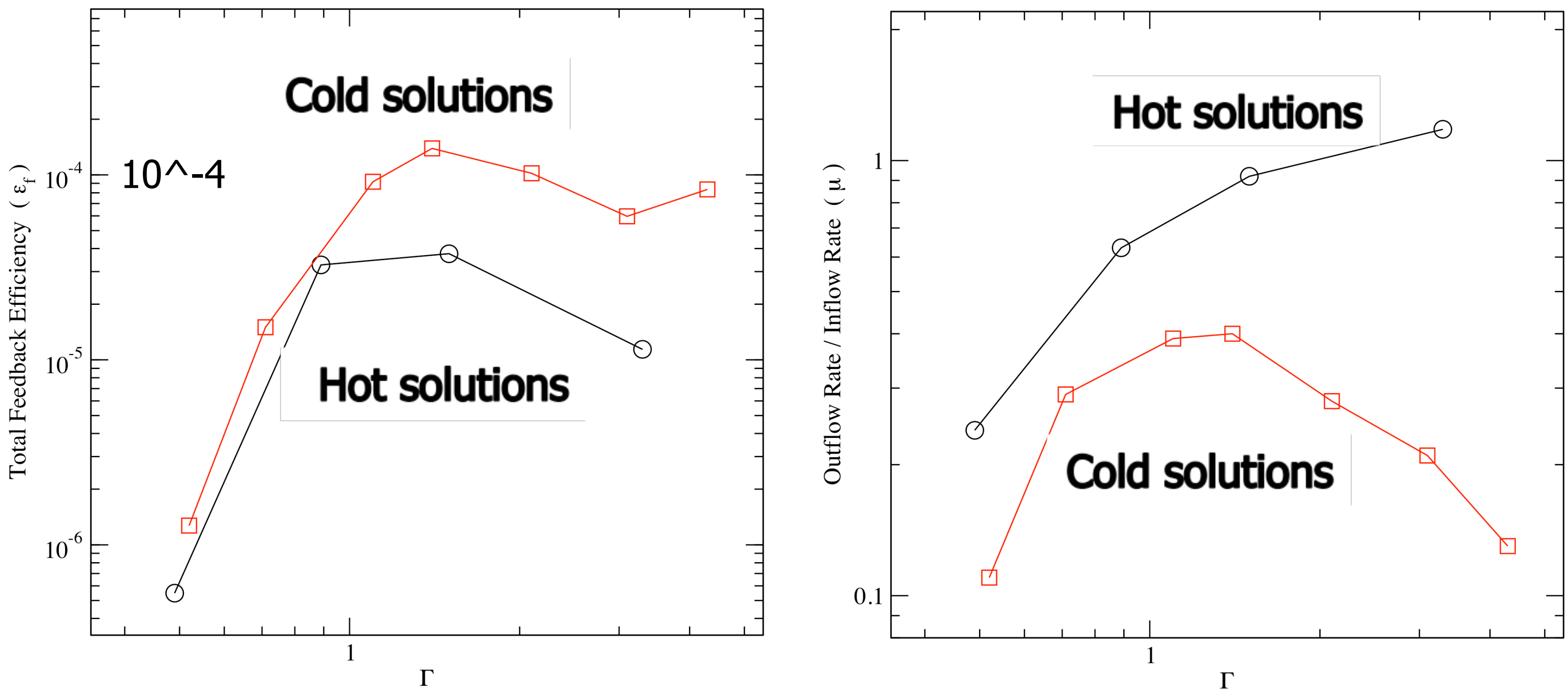
Kurosawa & DP (2009a)

What is the limit for the mass supply rate?



Kurosawa & DP (2009b) see also Liu et al. (2013)

How efficient are the large scale outflows?



Kurosawa et al. (2009)
See K. Nagamine's talk

Conclusions

- **Radiation-driven disk wind simulations predict line profiles and broad band spectra that are consistent with observations of BLRs.**
- **The disk winds are virialized up to a relatively large distance**.
- **The disk winds are much more energetically efficient than the large scale outflows.**
- A significant fraction of the inflowing matter can be expelled by radiation pressure and heating.
- The non-rotating flow settles into a steady inflow/outflow solution. Gas rotation and large optical depth can lead to time variability.
- In time variable flows, dense clouds form (as in NRL of AGN?). The cloud time evolution is very complex (no 'bullets').
- Inflows and outflows can be multi-temperature/phase media in part because of thermal instability (as in WA?).
- The I/O solution is quite robust but its characteristics are sensitive to the geometry and SED of the central object radiation.
- The mass supply rate does not appear to be limited by the luminosity of AGN.