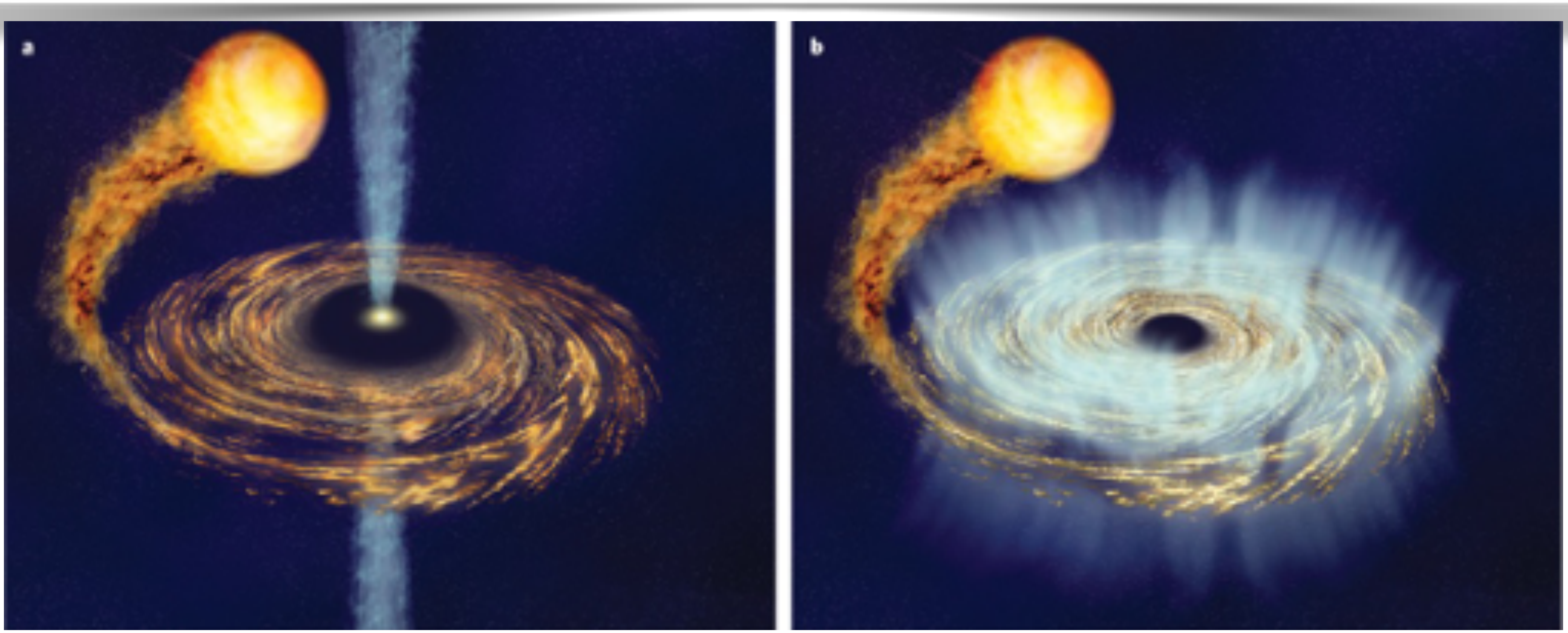
Radiation Driven Winds from MHD Accretion Disks



Daniel Proga

University of Nevada, Las Vegas

Collaborators: J. Stone, T. Kallman, M. Begelman, J. Drew, **A. Janiuk, R. Kurosawa, M. Moscibrodzka**, **P. Barai, A. Kashi, N. Higginbottom, T. Waters, S. Dyda, and R. Dannen** and many more

OUTLINE

1) Introduction

2) Toward a More Fundamental Model of Disk Winds

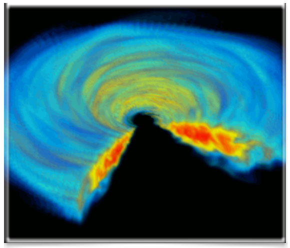
  a) thermally driven winds and effects of different SEDs

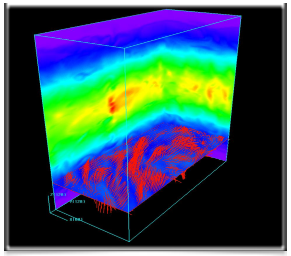
  b) line driven winds and MHD effects

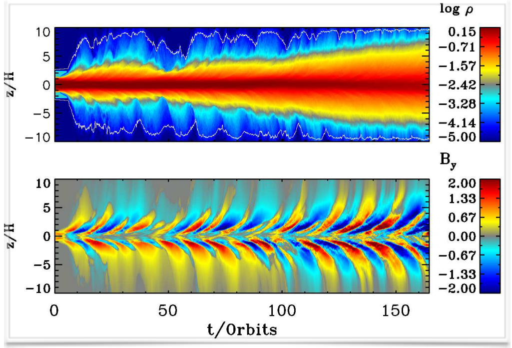
  d) from disk winds in binary stars to disk winds in AGN

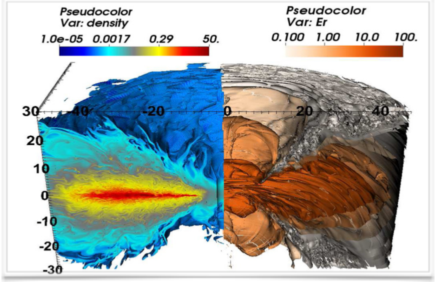
3) Future Work

Disks: Radiation and MHD are essential









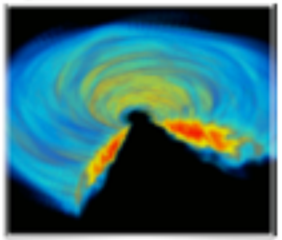
mean motion
(rotation)

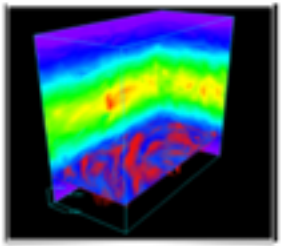
The energy flow.

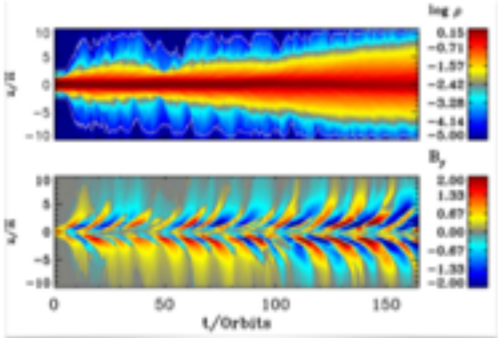
internal
energy

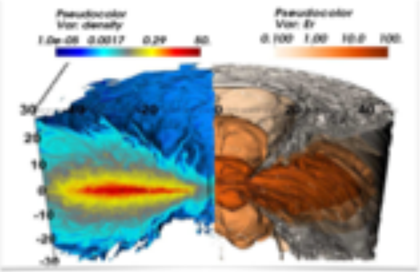
S. Balbus, J. Hawley, J. Stone,
C. Gammie, J. Krolik, S. Hirose
R. Narayan, O. Blaes, S. Davis,
Y.-F. Jiang, A. Sadawski

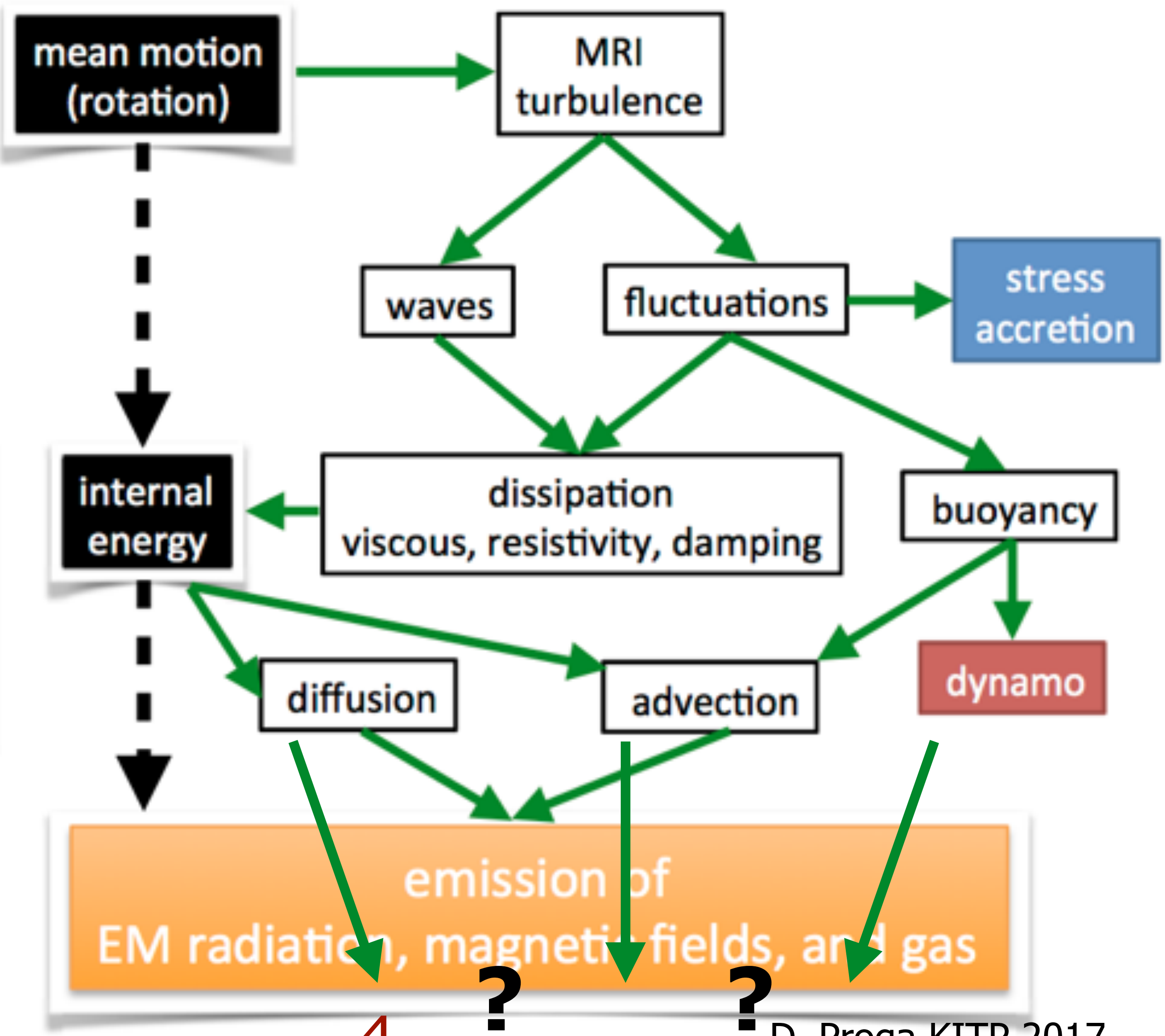
emission of
EM radiation, magnetic fields, and gas











mean motion (rotation)

MRI turbulence

waves

fluctuations

stress accretion

internal energy

dissipation
viscous, resistivity, damping

buoyancy

diffusion

advection

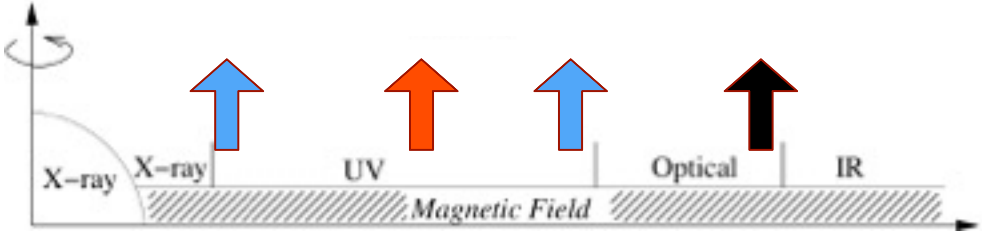
dynamo

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).



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

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

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

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

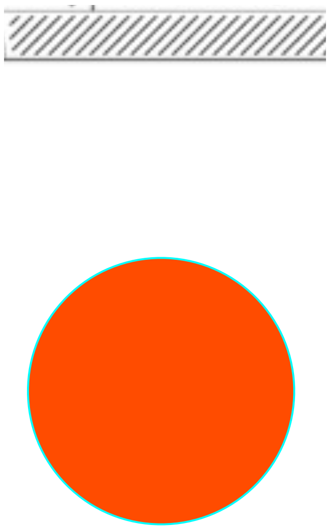
$$\frac{\partial E_r}{\partial t} + \mathbb{C}\nabla \cdot \mathbf{F}_r = \mathbb{C}S_E$$

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

Radiation momentum and energy source terms:

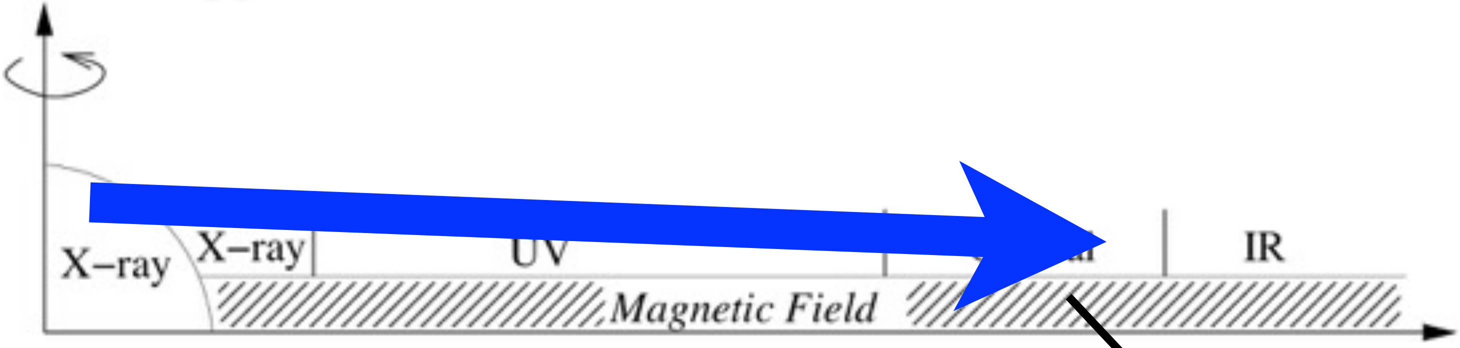
$$\boxed{\begin{gathered} \mathbf{S}_{\mathrm{M}} \approx -\underline{(\sigma_a + \sigma_s)}\boldsymbol{F}_r \\ S_E \approx \underline{\sigma_a}(T^4 - E_r) \end{gathered}}$$

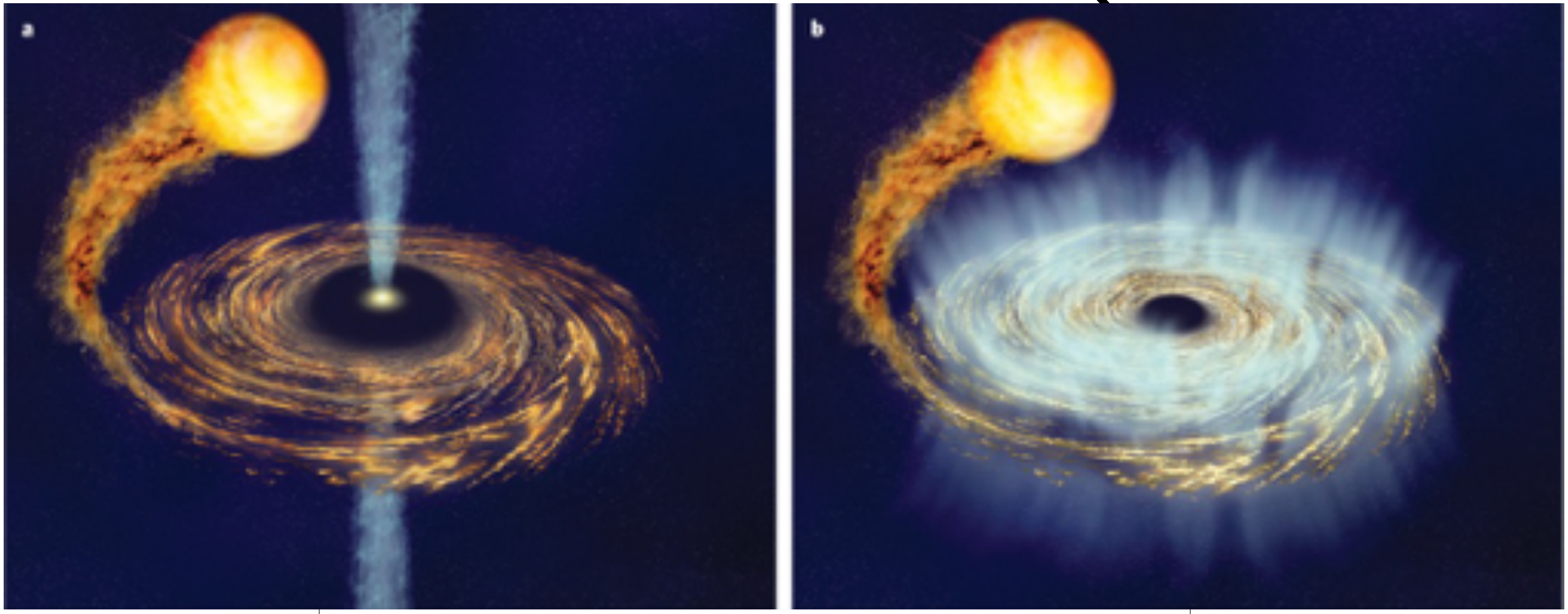
Accretion Disks vs Stars

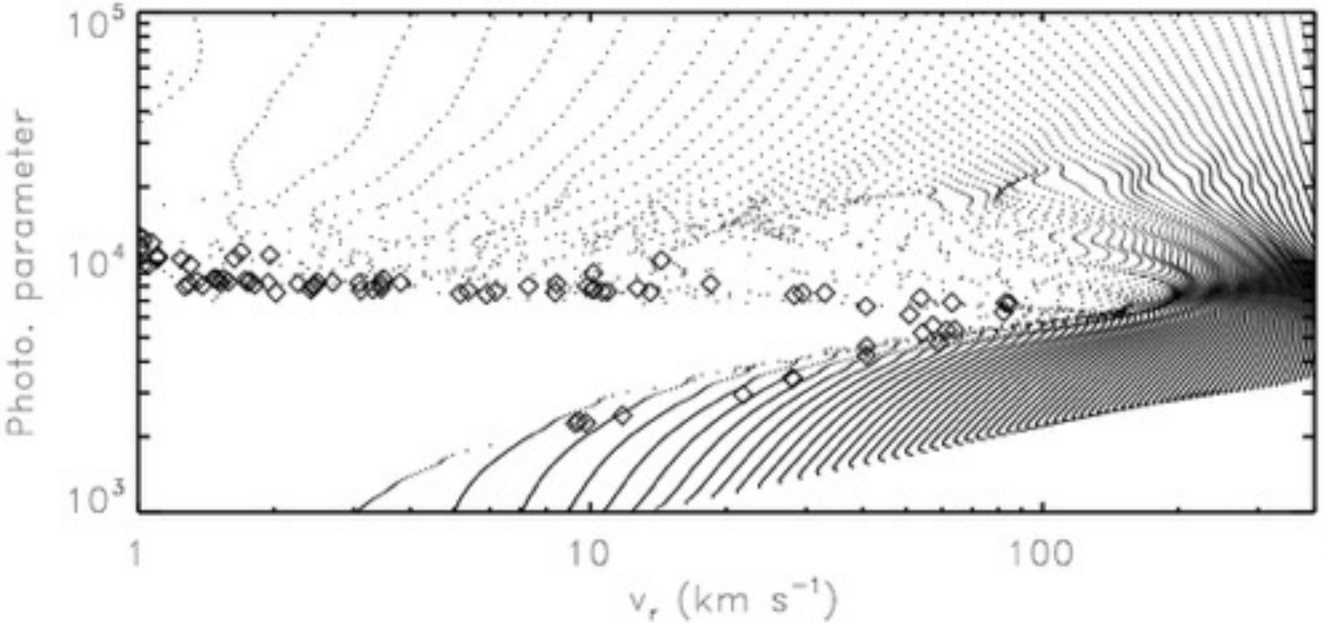


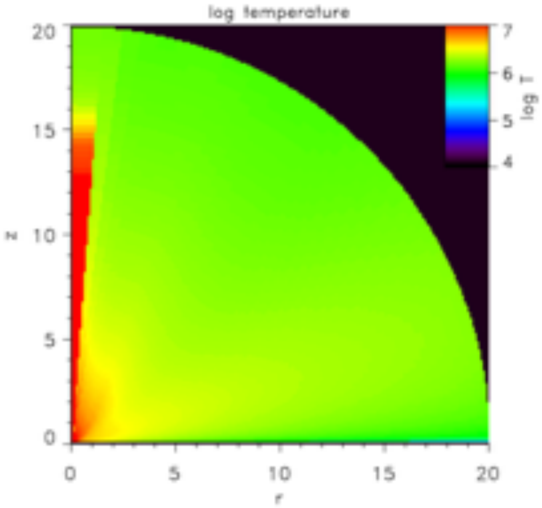
Irradiation of a Disk

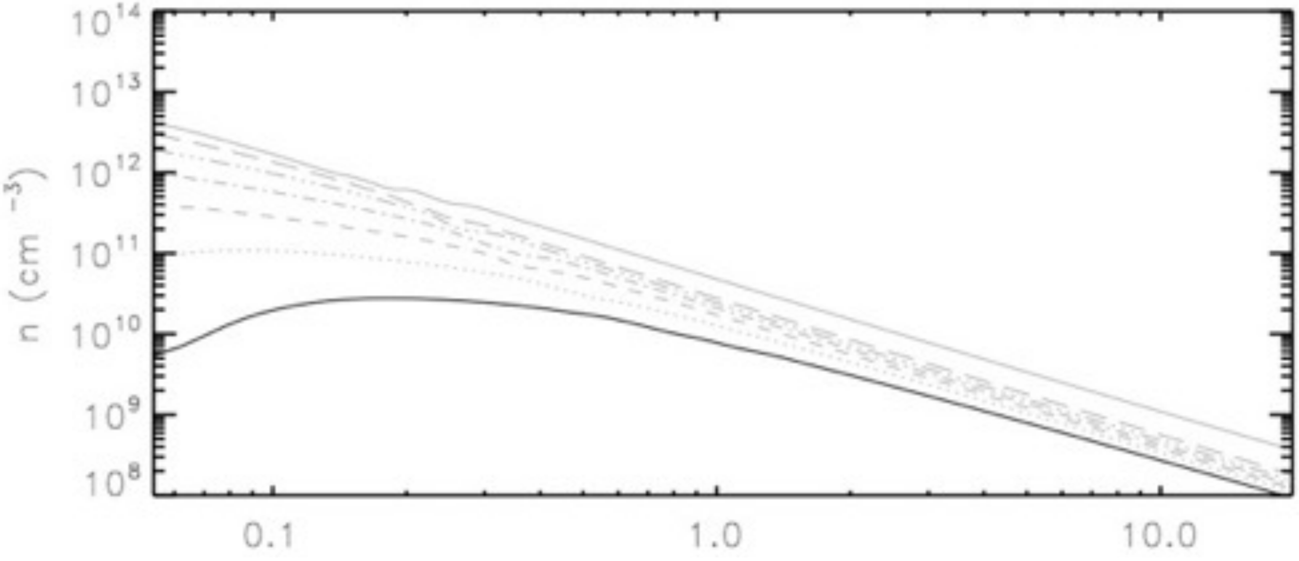
See Nick Higginbottom's talk

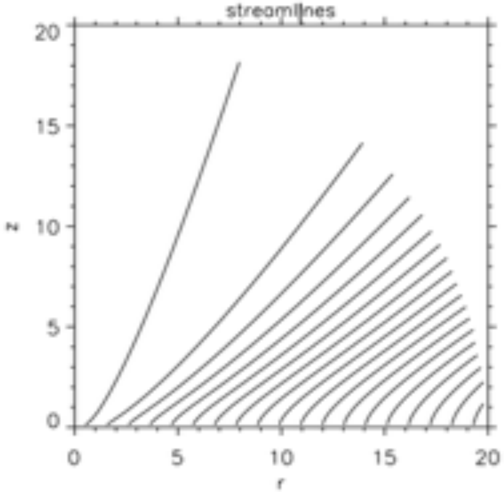








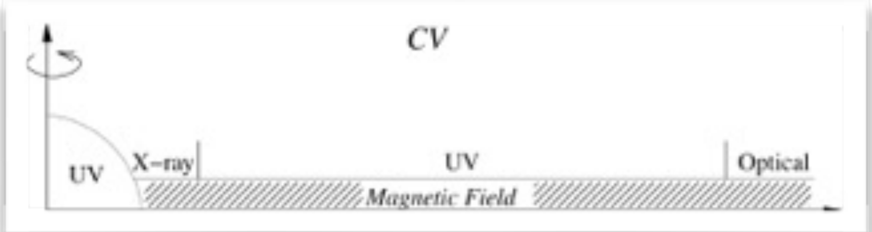


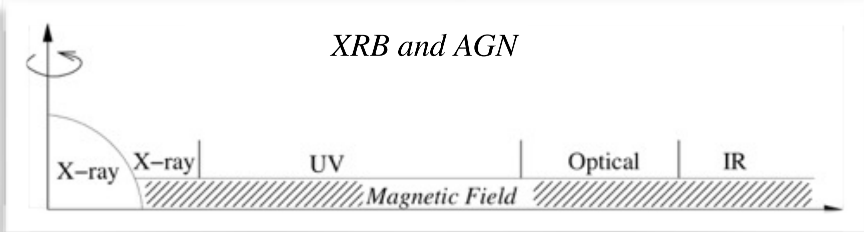


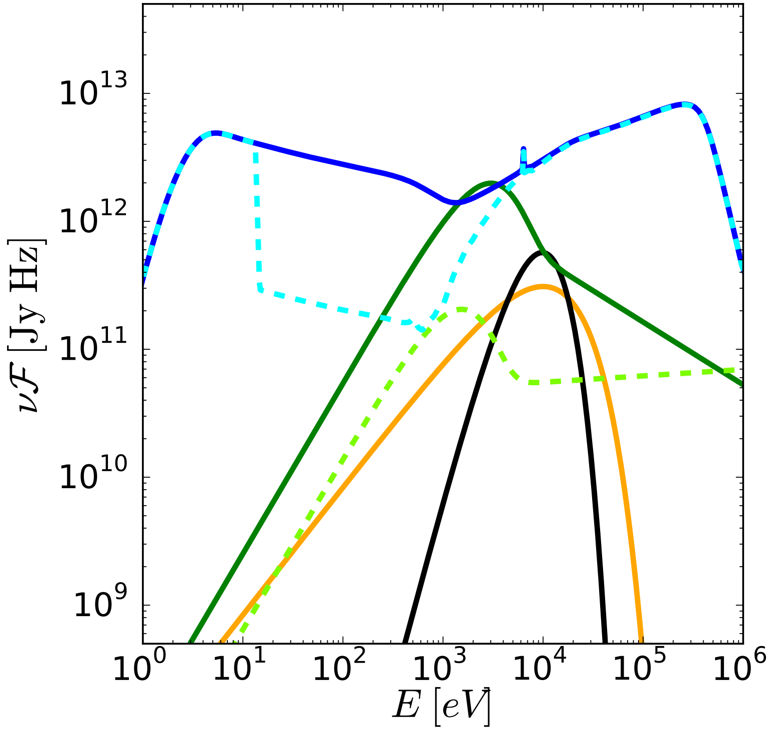
Luketic et al. (2010)

$\theta = 48.3°$ (thick solid), $\theta = 60.5°$ (dotted), $\theta = 69.4°$ (dashed), $\theta = 76.0°$ (dot-dashed), $\theta = 80.9°$ (triple dot-dashed), $\theta = 84.5°$ (long dashed) and $\theta = 89.1°$ (thin solid). Note that

Accretion Disks in Various Objects



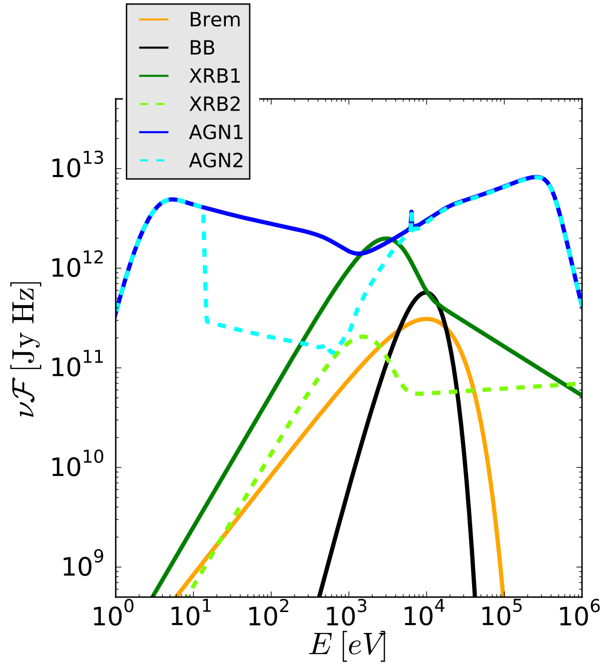


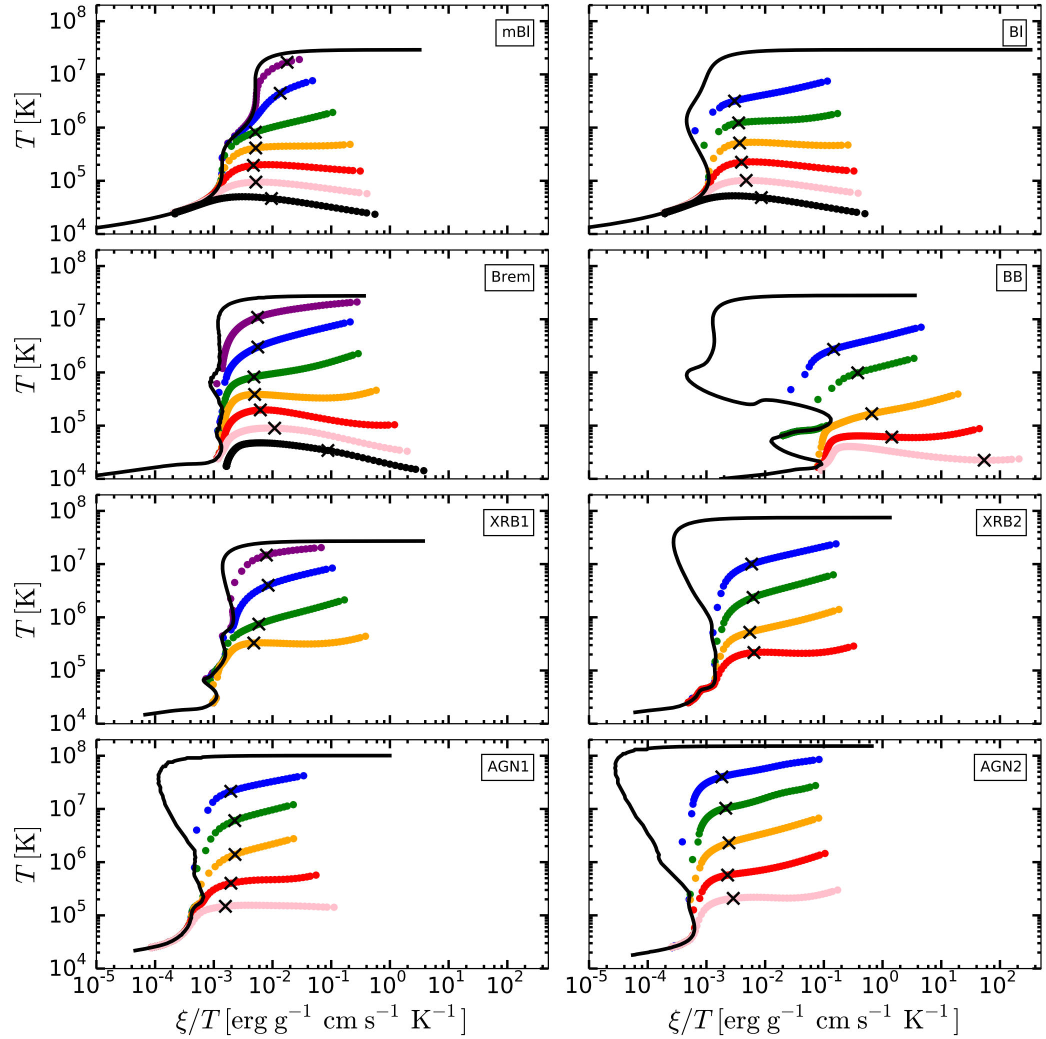


Dyda, Dannen, Waters, DP (2017, submitted)

photoionization calculations using XSTAR

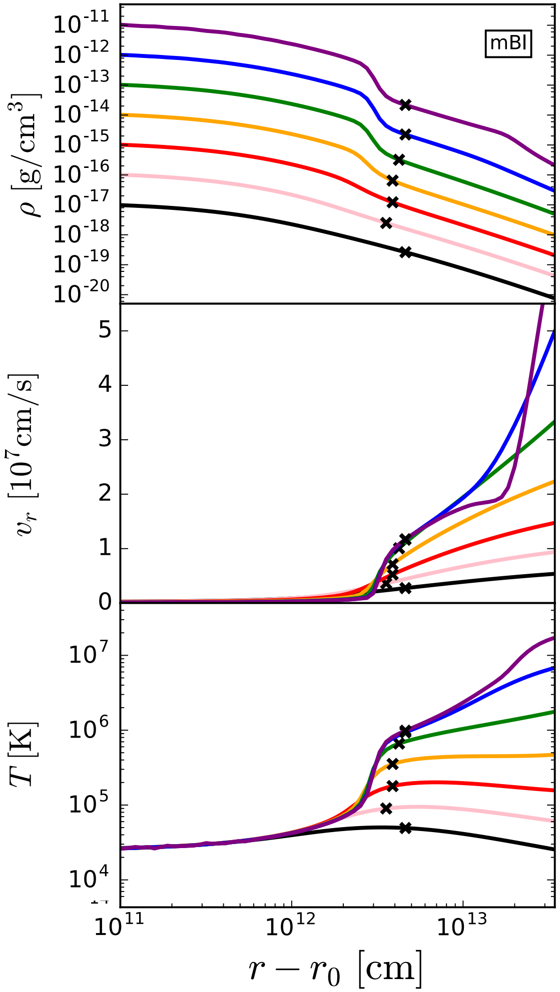
Thermal winds: effects of SED and flux

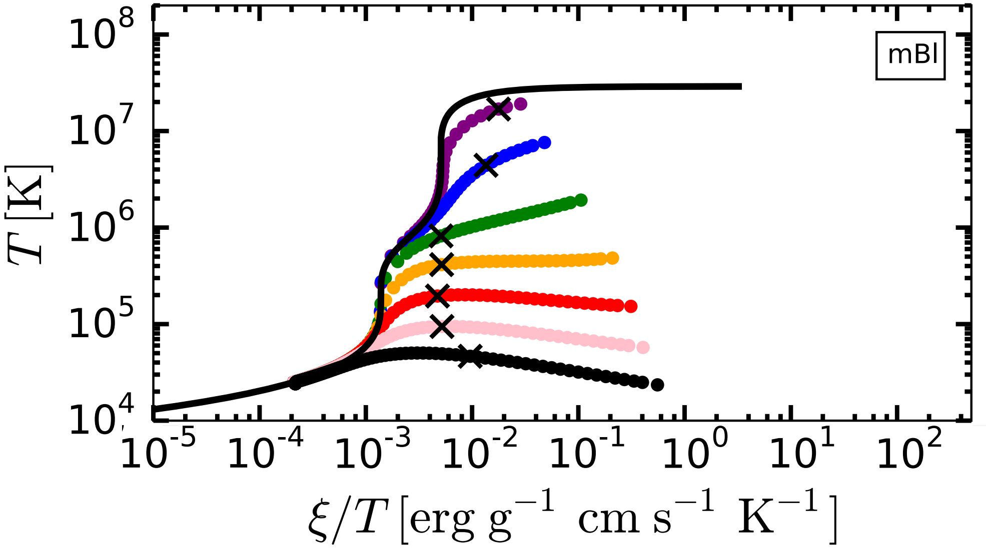




Dyda, Dannen, Waters, DP (2017, submitted)

Thermal winds: effects of flux



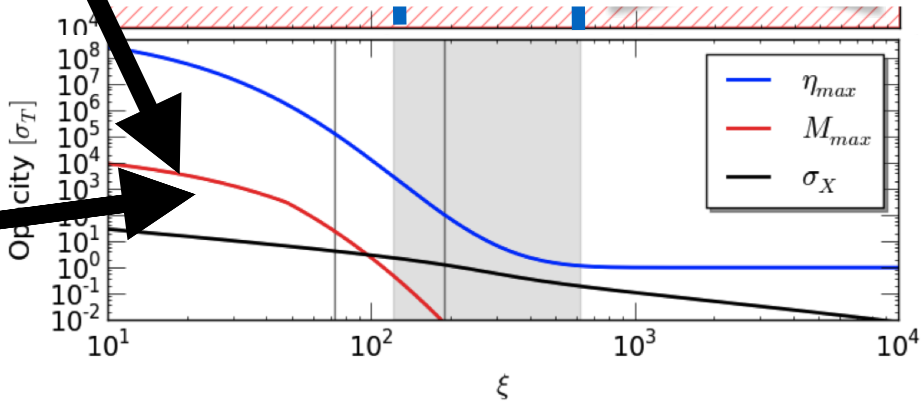


Dyda, Dannen, Waters, DP (2017, submitted)

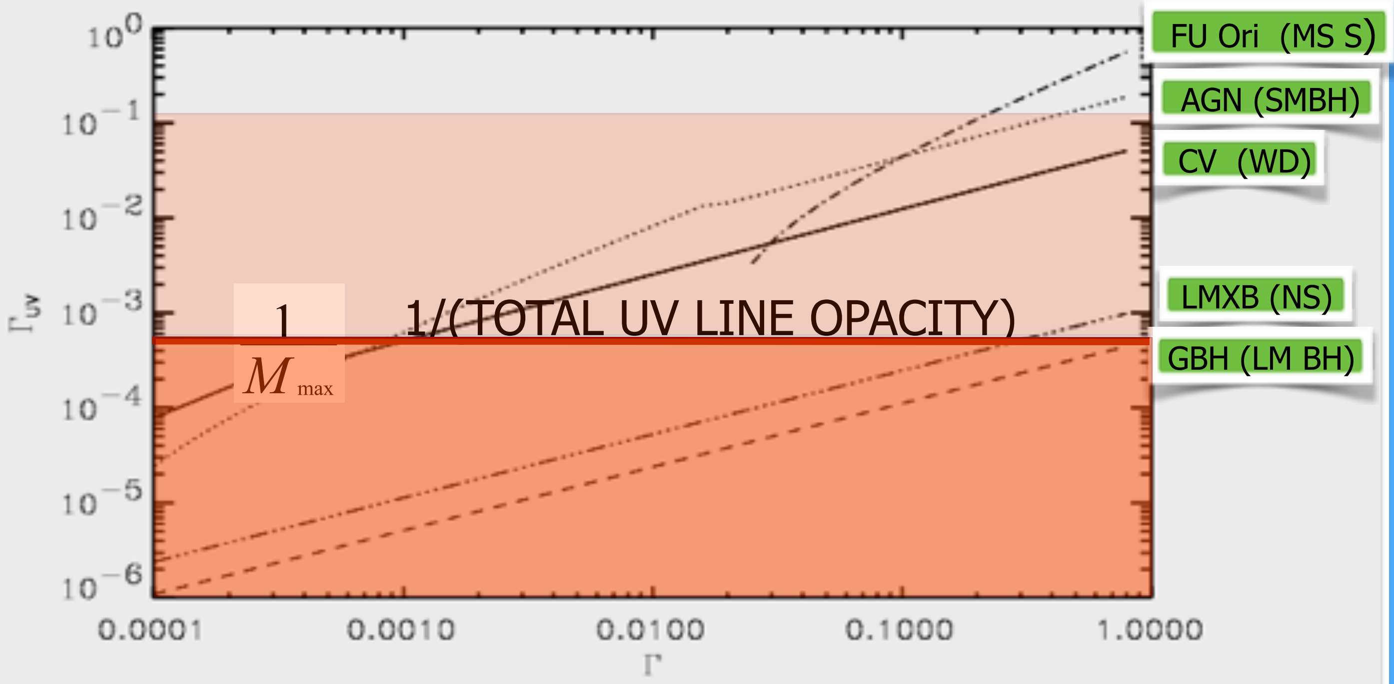
The main question is:

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

Radiation force increases with decreasing irradiation.



Line Driven Disk Winds: across various scales



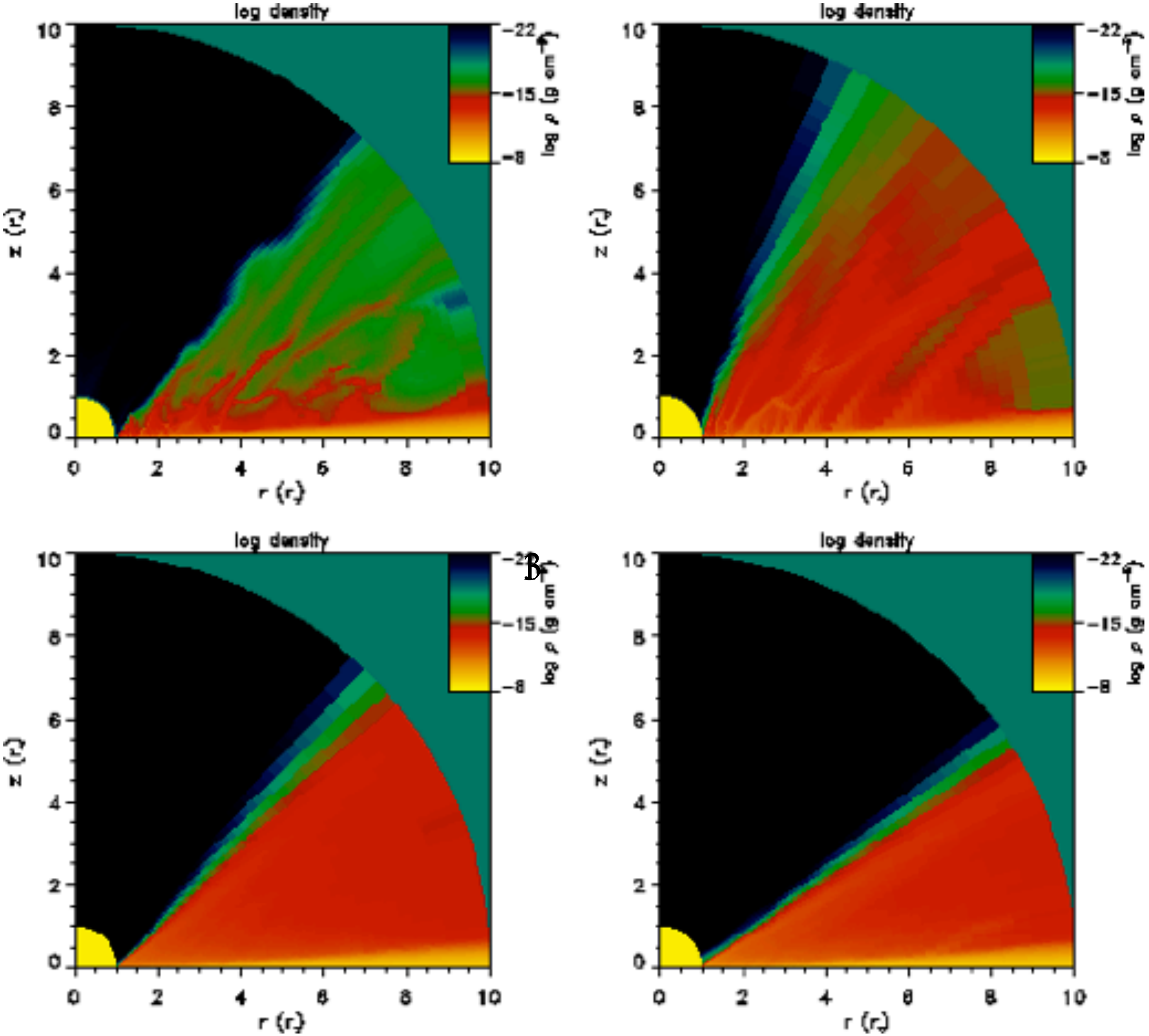
$$L_{Edd} = \frac{4\pi c G M_a}{\sigma}$$

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

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

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

Proga (2002)



$L_D = 1$
$L_S = 0$

$L_D = 3$
$L_S = 0$

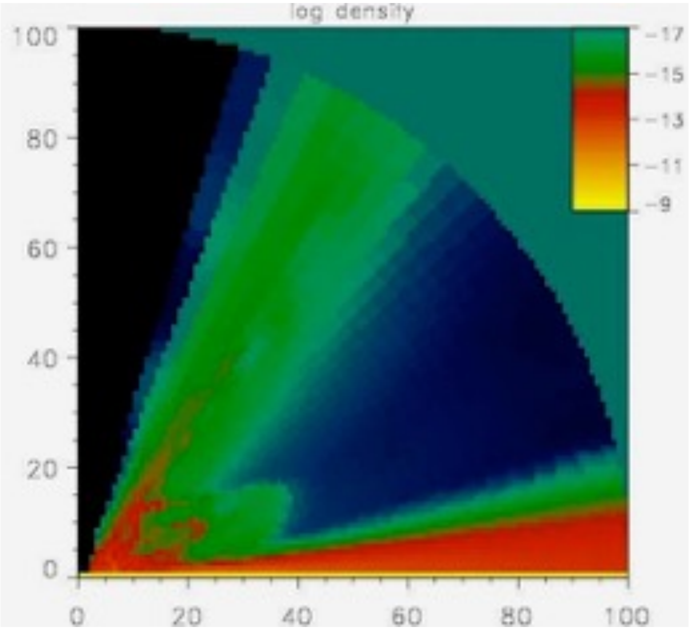
$L_D = 3$
$L_S = 3$

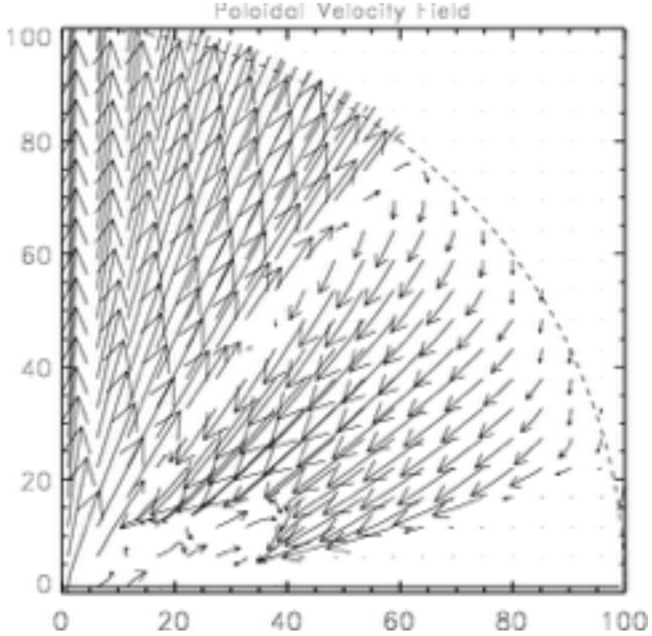
$L_D = 3$
$L_S = 9$

Proga, Stone & Drew (1998)

L(disk)=3

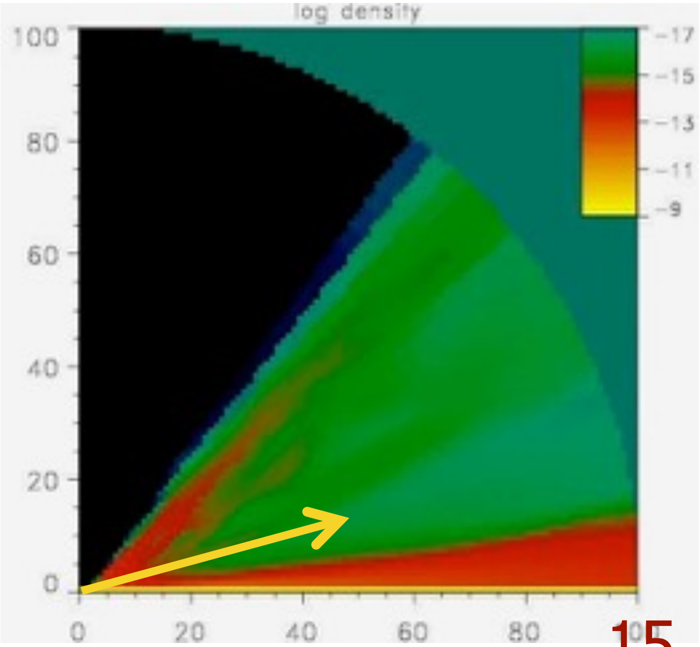
L(star)=0

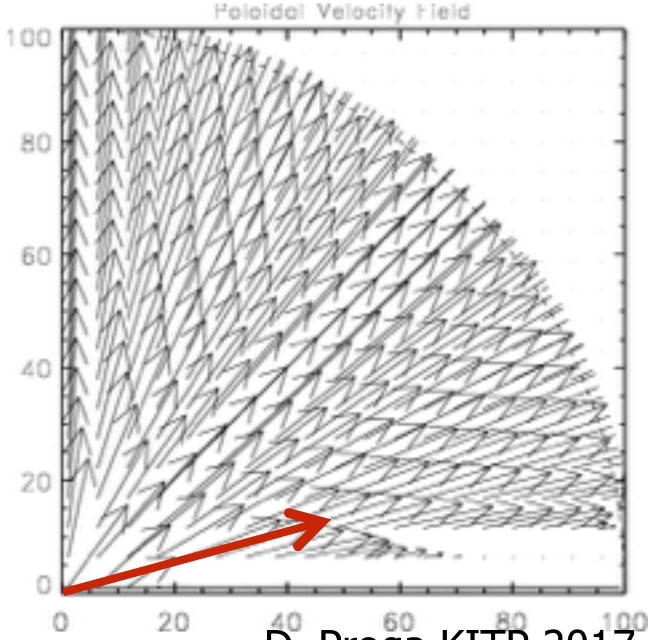




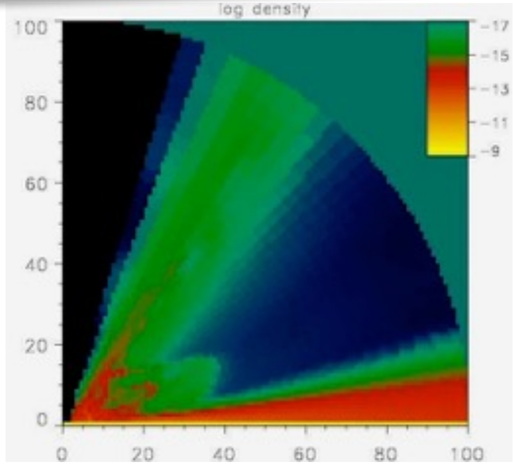
L(disk)=3

L(star)=3



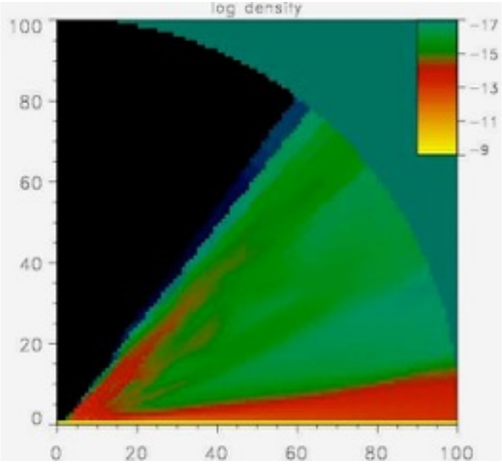


Line driven disk winds and their line profiles (application to CVs)



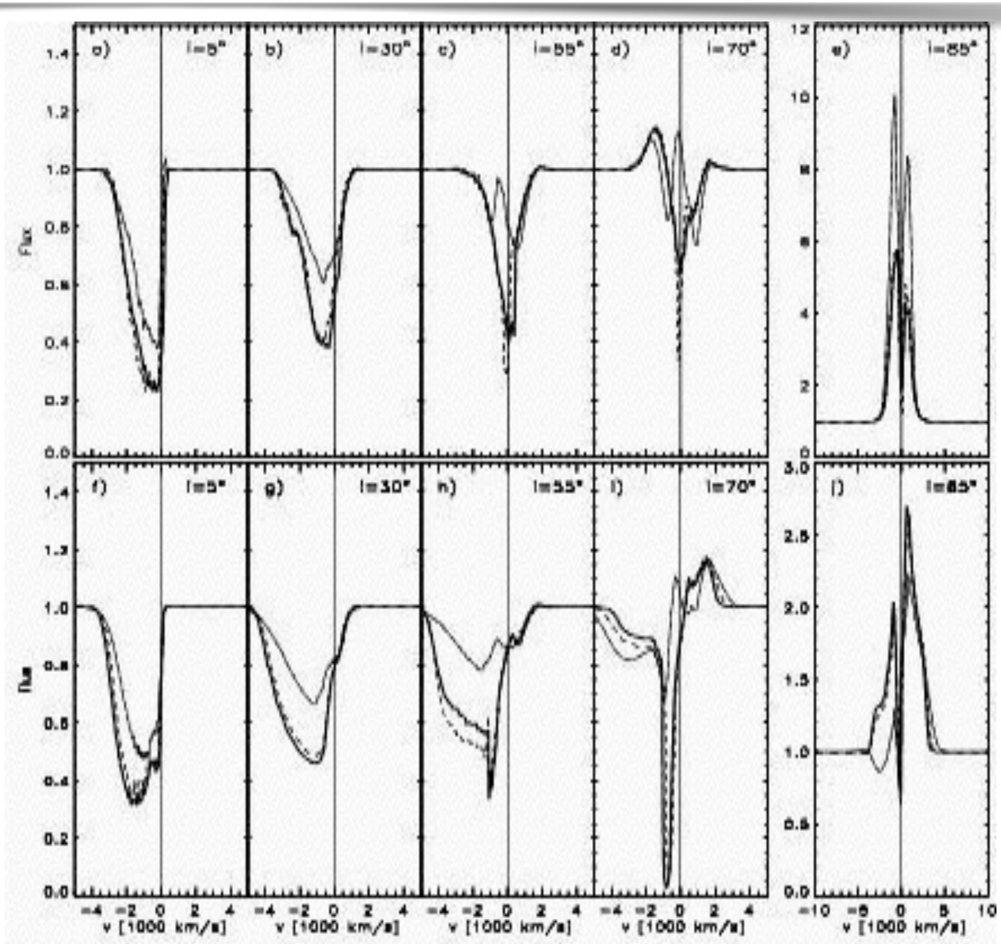
L(disk)=3

L(star)=0



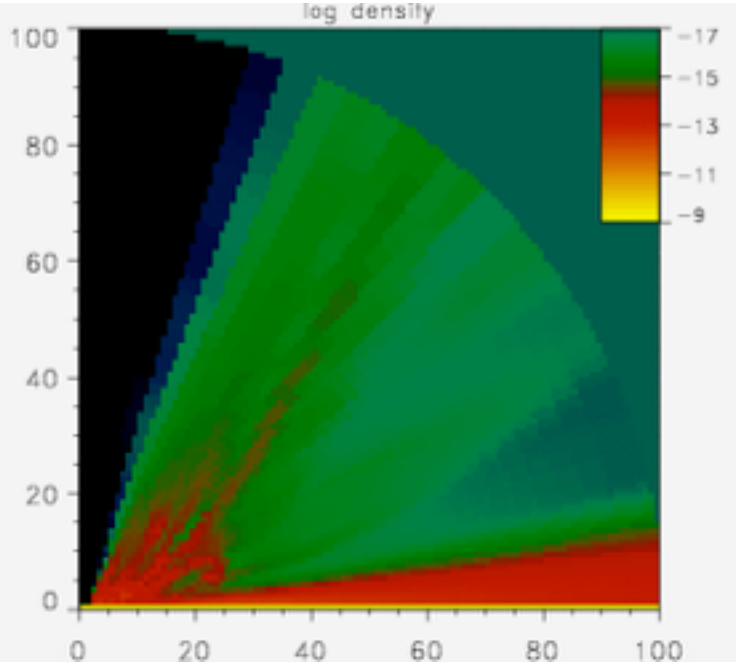
L(disk)=3

L(star)=3



D. Proga KITP 2017

Line driven disk winds and their line profiles (application to CVs)

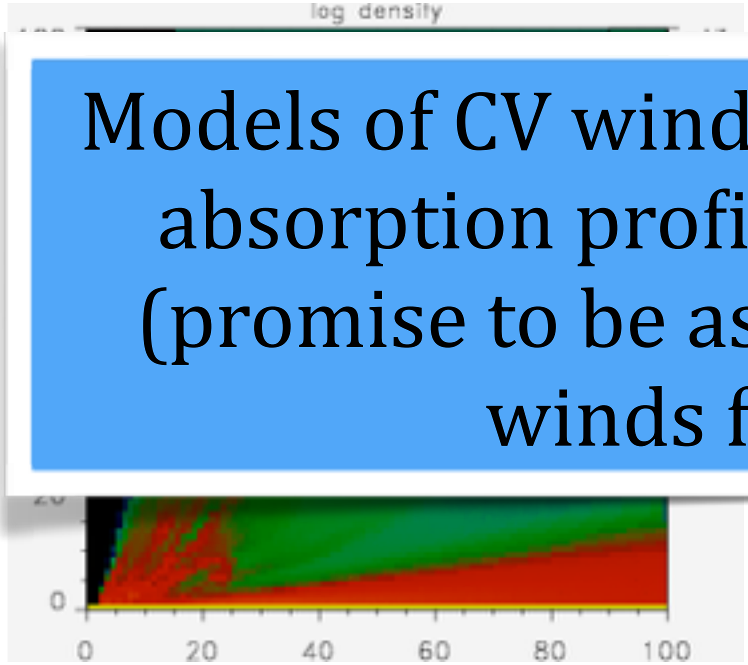


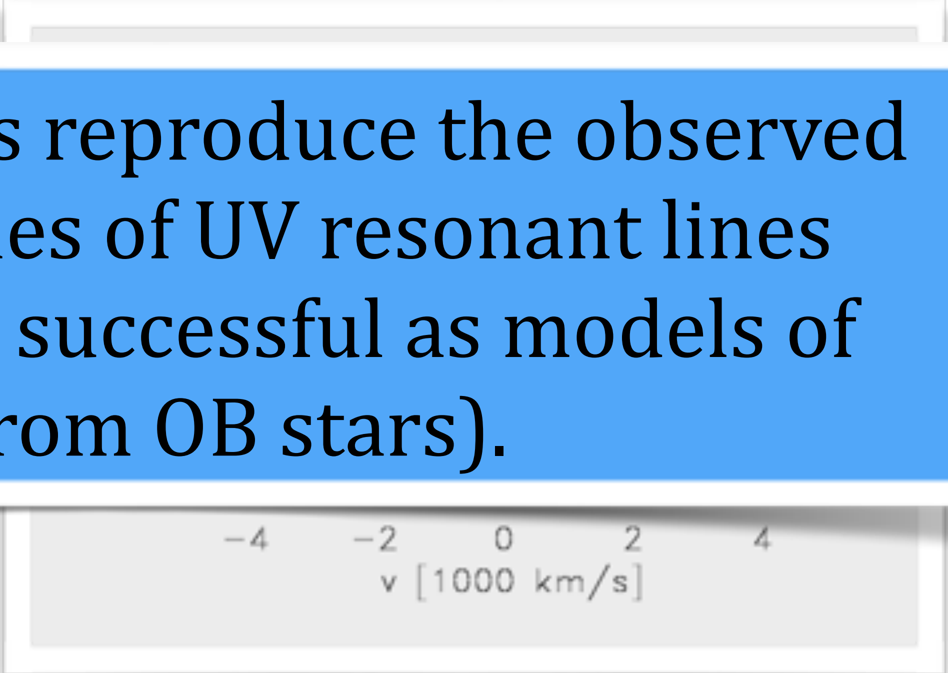
$L_D = 23.4 L_{SUN}$, $L_{WD} = 0.25 L_D$, $\dot{M}_a = 3\times10^{-8} M_{SUN}\, yr^{-1}$

$\dot{M}_W = 3\times10^{-12} M_{SUN}\, yr^{-1}$

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

Line driven disk winds and their line profiles (application to CVs)





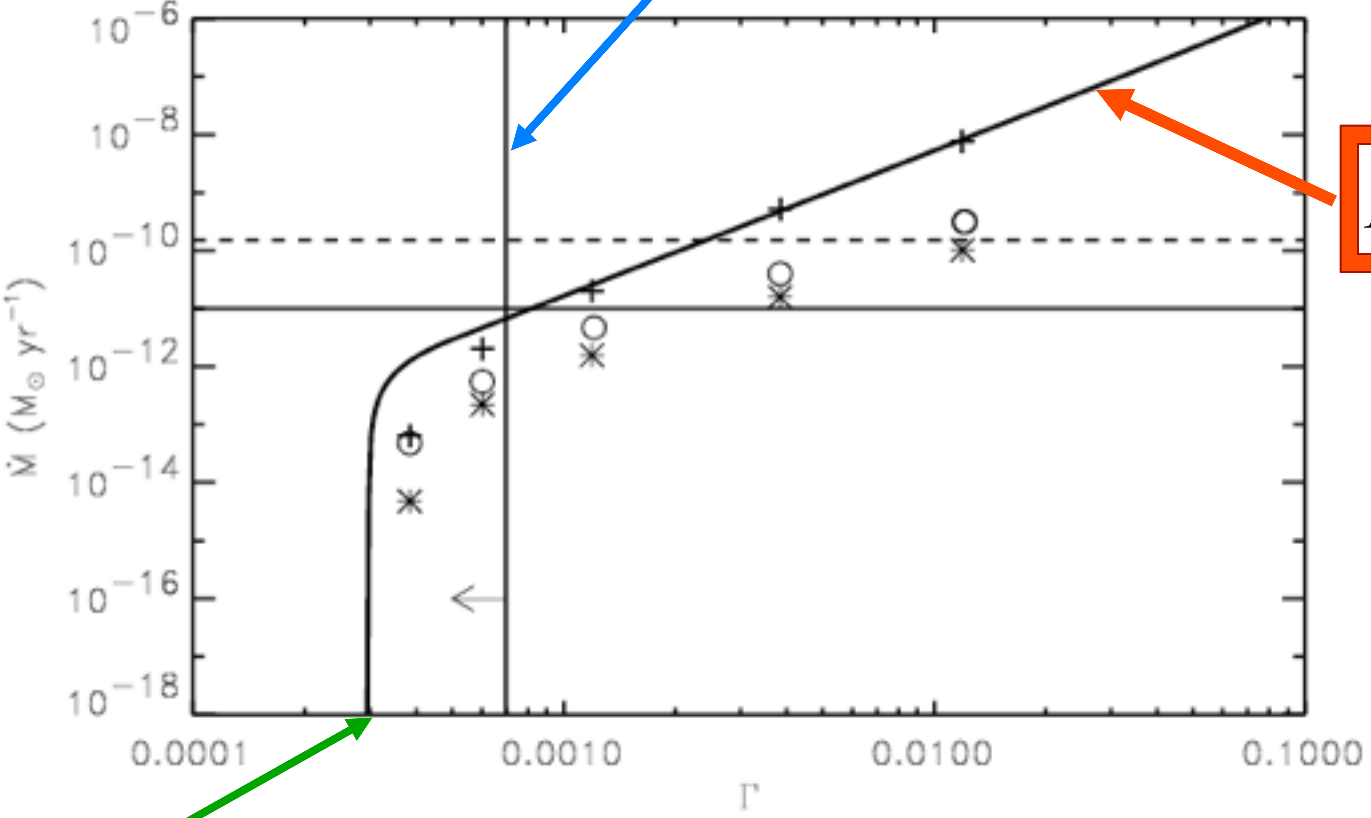
Models of CV winds reproduce the observed absorption profiles of UV resonant lines (promise to be as successful as models of winds from OB stars).

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

$\dot{M}_W = 3\times10^{-12}\,M_{SUN}\,yr^{-1}$

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

Lower limit for the mass accretion rate



$\dot{M} \propto \Gamma^{1/\alpha}$

$\frac{1}{M_{\max}}$

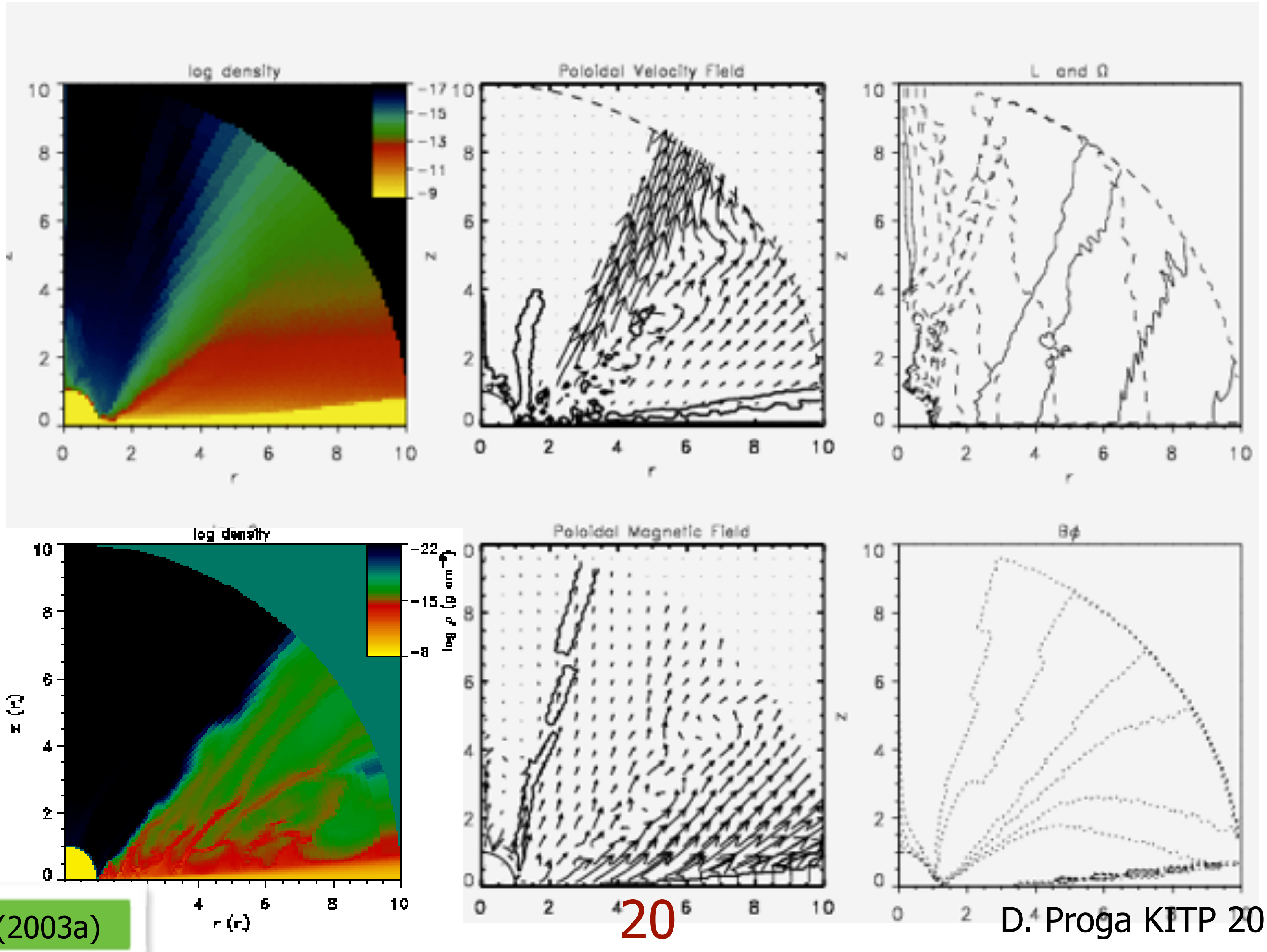
Drew & Proga (1999)

$\dot{M}_a = 1\times10^{-8} M_{Sun}\, yr^{-1}$

$M_{WD} = 1 M_{Sun}$

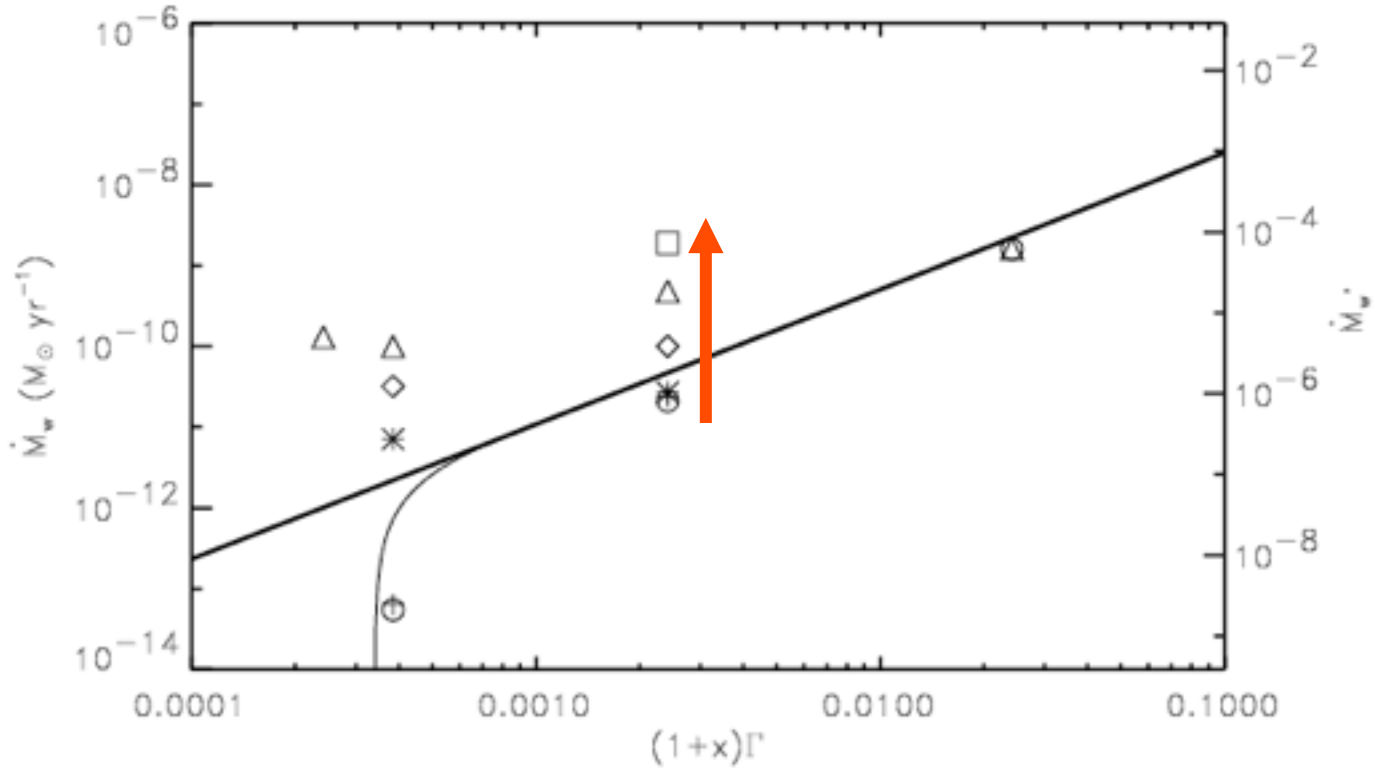
$M_{\max} = 4400, \;\; k = 0.2, \;\; \alpha = 0.6$

MHD-Line Driven disk winds



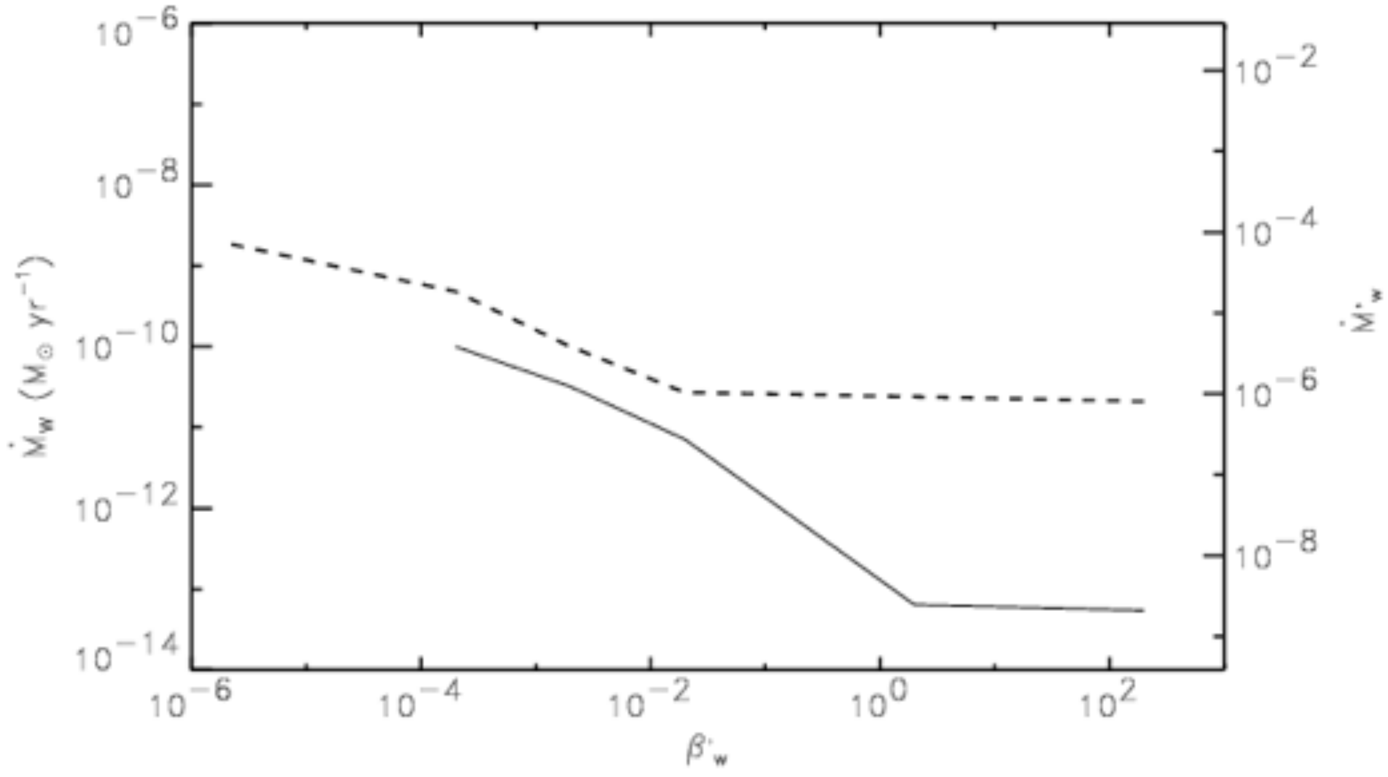
Proga (2003a)

The mass loss rate in MHD-LD winds



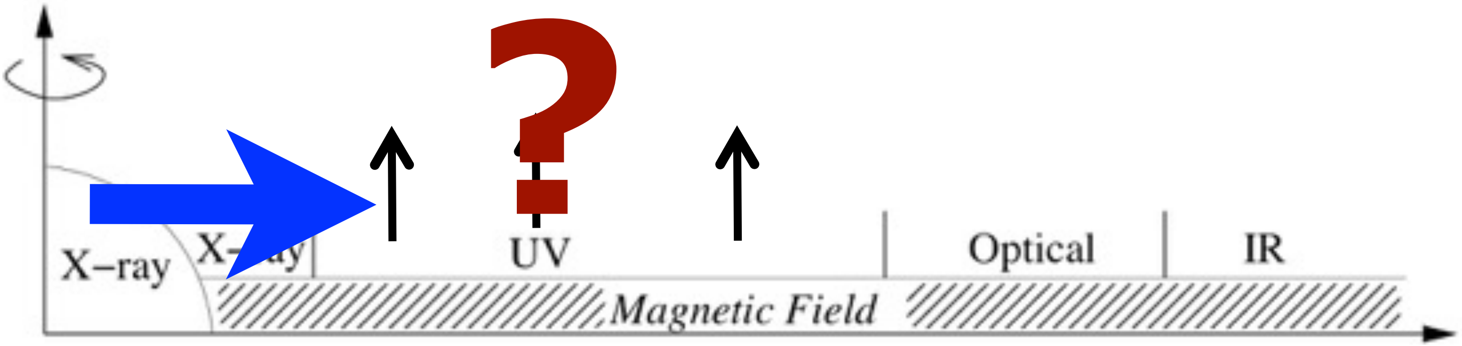
Proga (2003a)

The mass loss rate in MHD-LD winds



Proga (2003a)

Irradiation of a Disk Wind



A wind driven by UV photons, similar to winds from OB stars or CVs

(main differences: the geometry and energy distribution of radiation field).

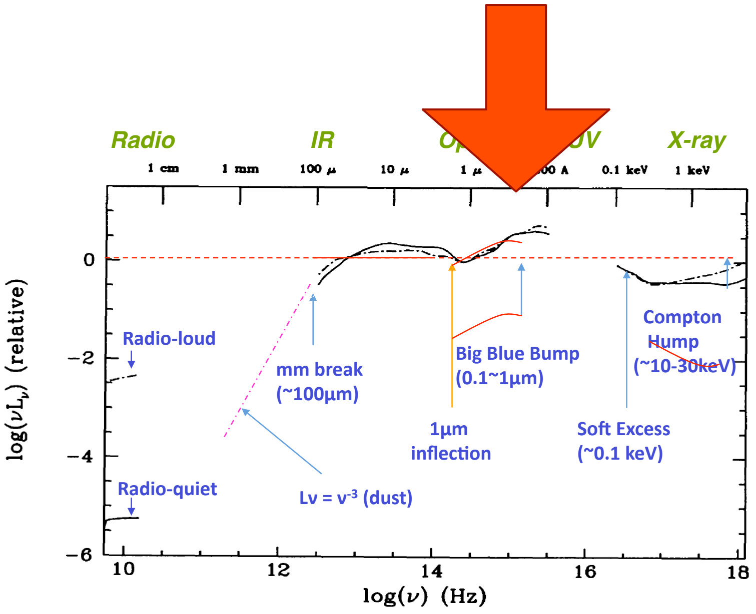
Radiation Driven Disk Winds

(Are they the BLRs?)

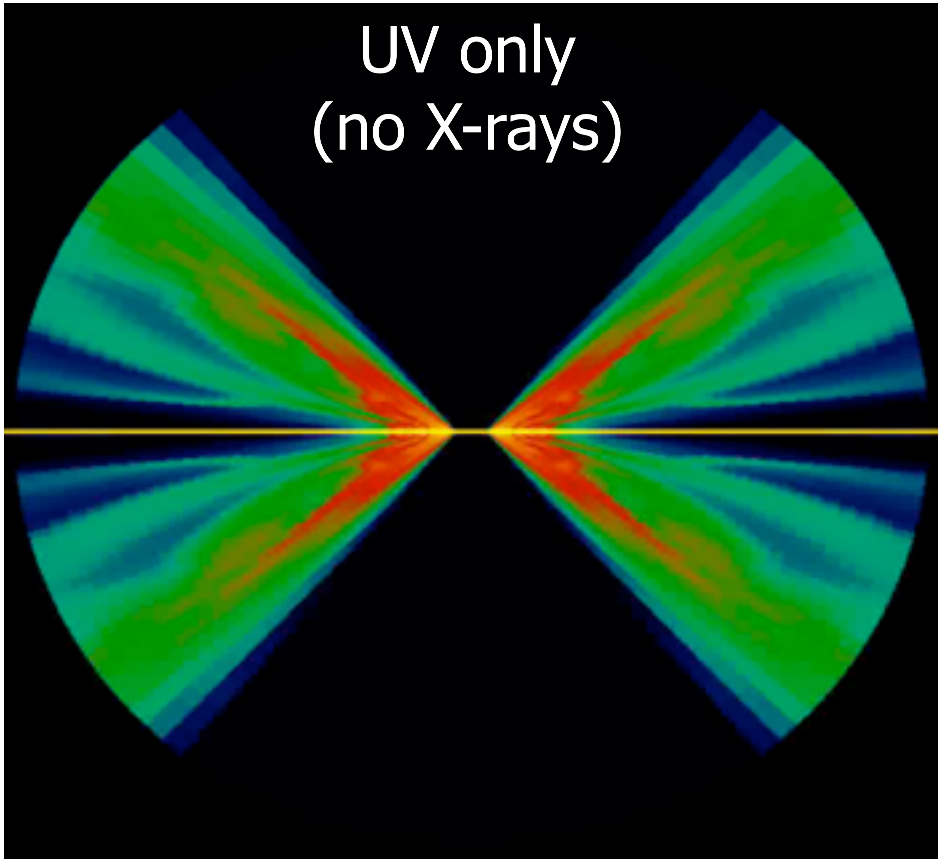
An Update:

new diagnostics and tests

Line-Driven Disk winds (application to quasars)



Elvis et al., 1994, ApJS, 95, 1



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

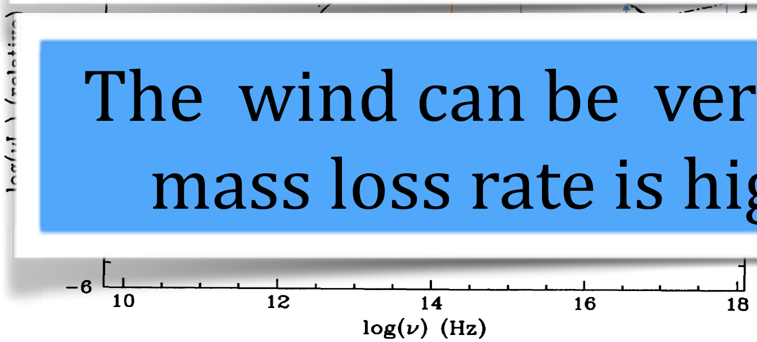
$\Gamma = 0.6$

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

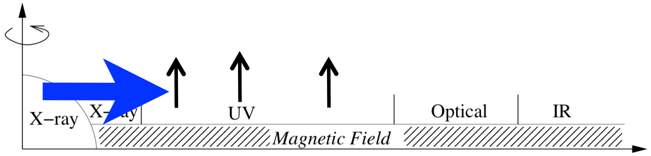
Line-Driven Disk winds (application to quasars)

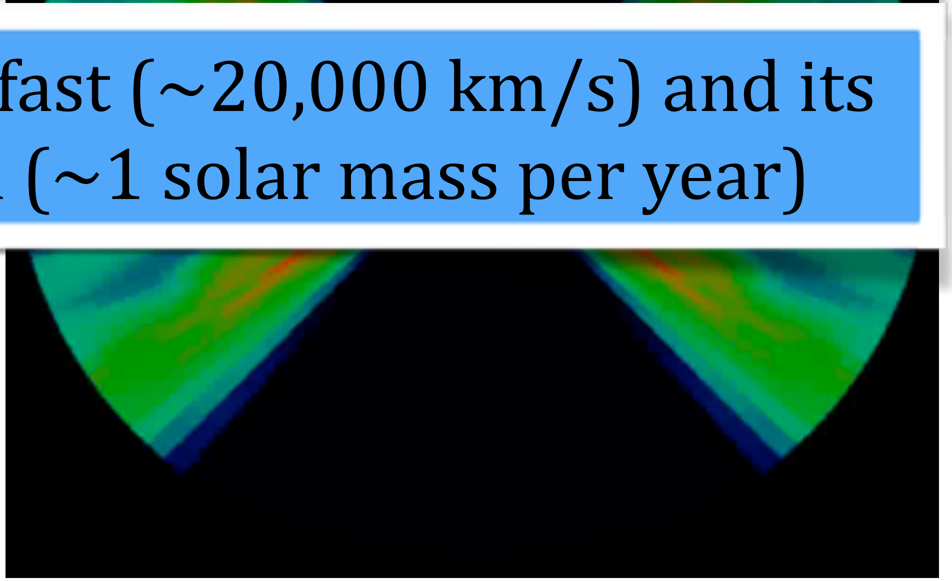
Radiation pressure on UV lines can drive a powerful wind from a disk even when the wind is irradiated by a strong central source of X-rays.

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



Elvis et al., 1994, ApJS, 95, 1





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

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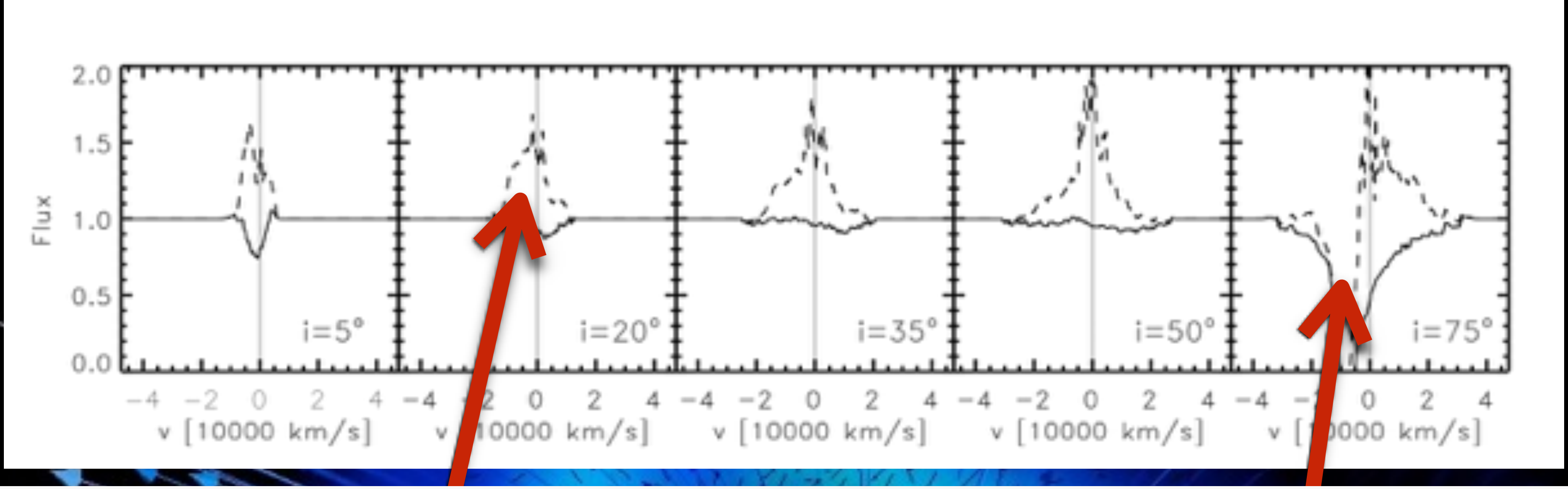
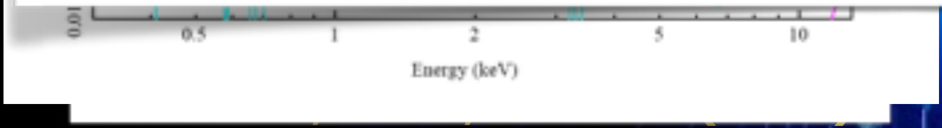
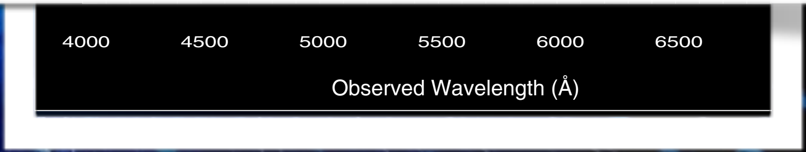
Proga, Stone & Kallman (2000), Proga & Kallman (2004)

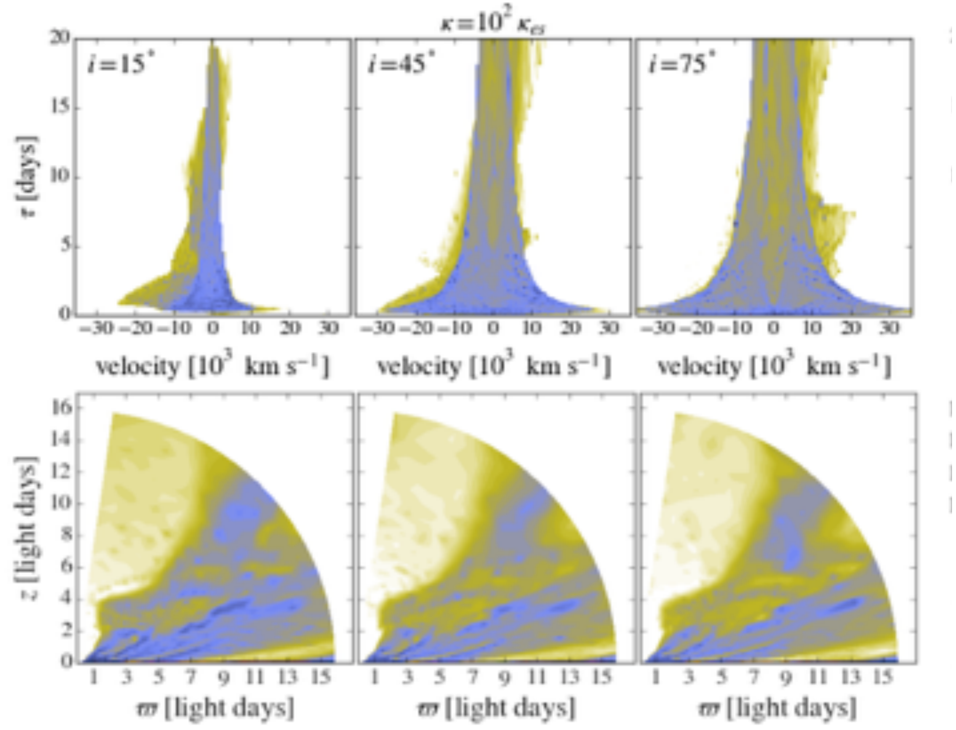


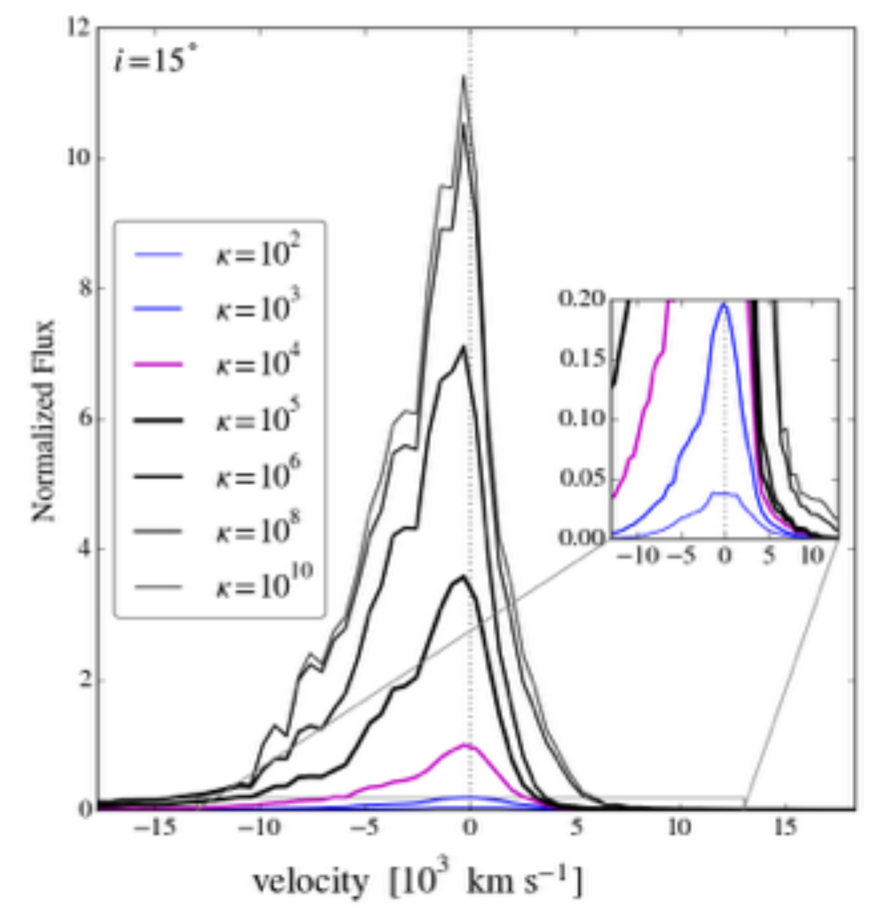
Computed profiles of UV resonant lines resemble the observed profiles (strong single-peaked emission lines for low and intermediate inclinations; P-Cygni like lines for high inclinations). BAL quasars should be X-ray weak because of the shielding.





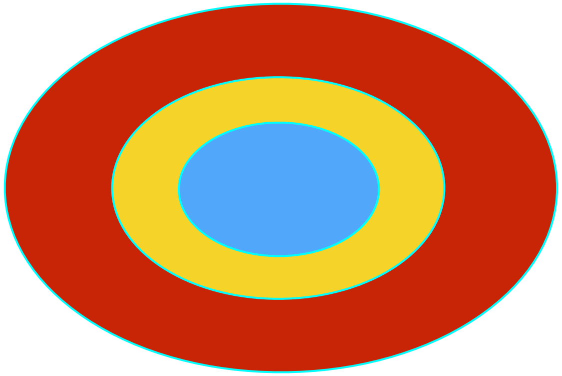
Reverberation Mapping



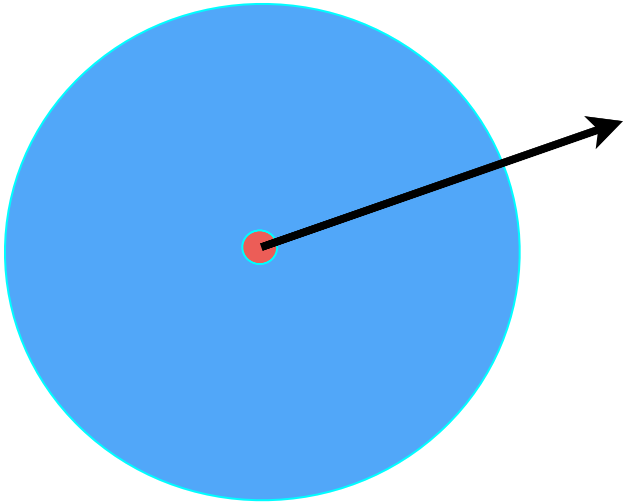


Waters, Kashi, DP et al. (2016)

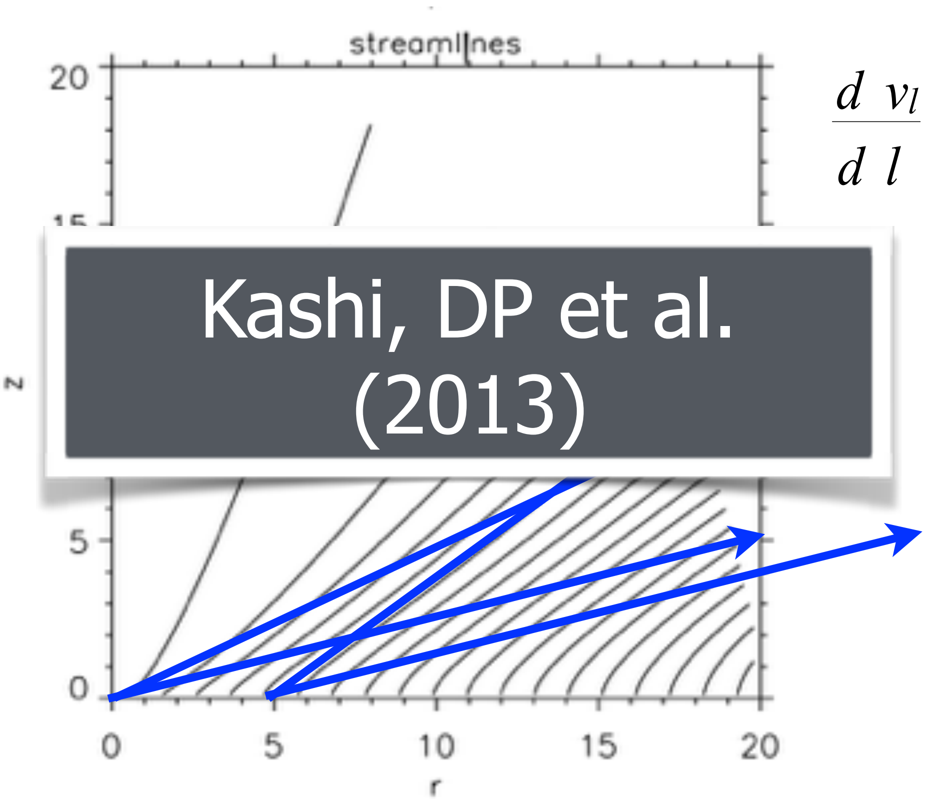
Disk Winds



geometrically thin Keplerian disk (virialized)



spherical supersonic wind (not virtualized)

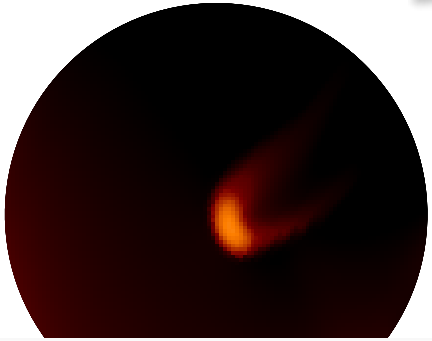


$$\frac{d\ v_l}{d\ l}$$

Kashi, DP et al. (2013)

aspherical, non-radial rotating wind
(launched from a virialized disk)

Future



Multi-frequency Radiation-Magnetohydrodynamics (with photoionization)

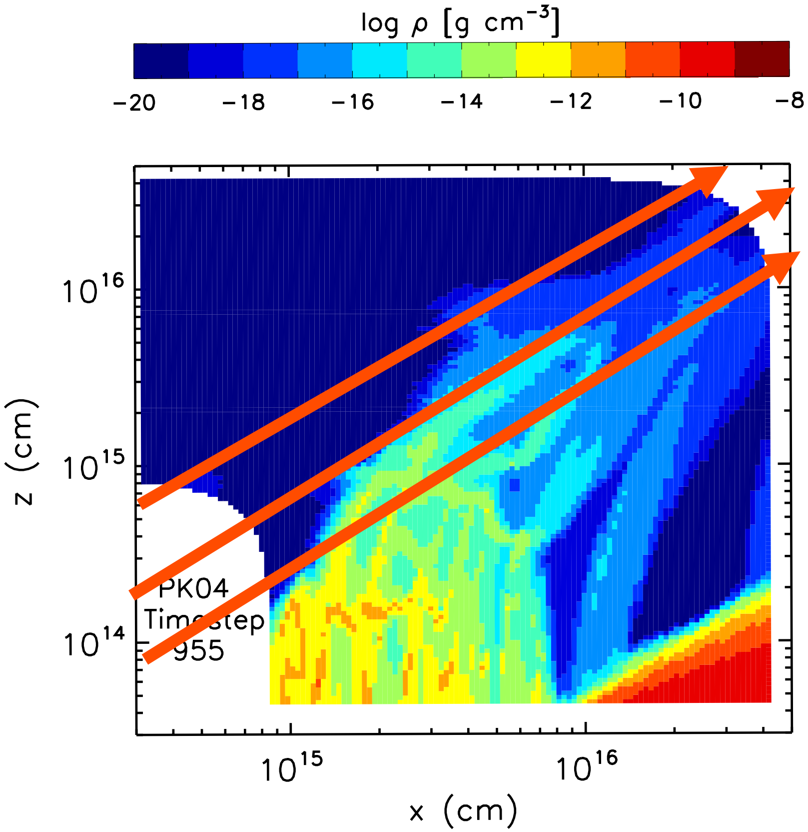
Winds in AGNs and PPDs

Inflows and Outflows in GRBs and AGNs

Summary

- The inner and outer workings of accreting systems involve very many processes (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).

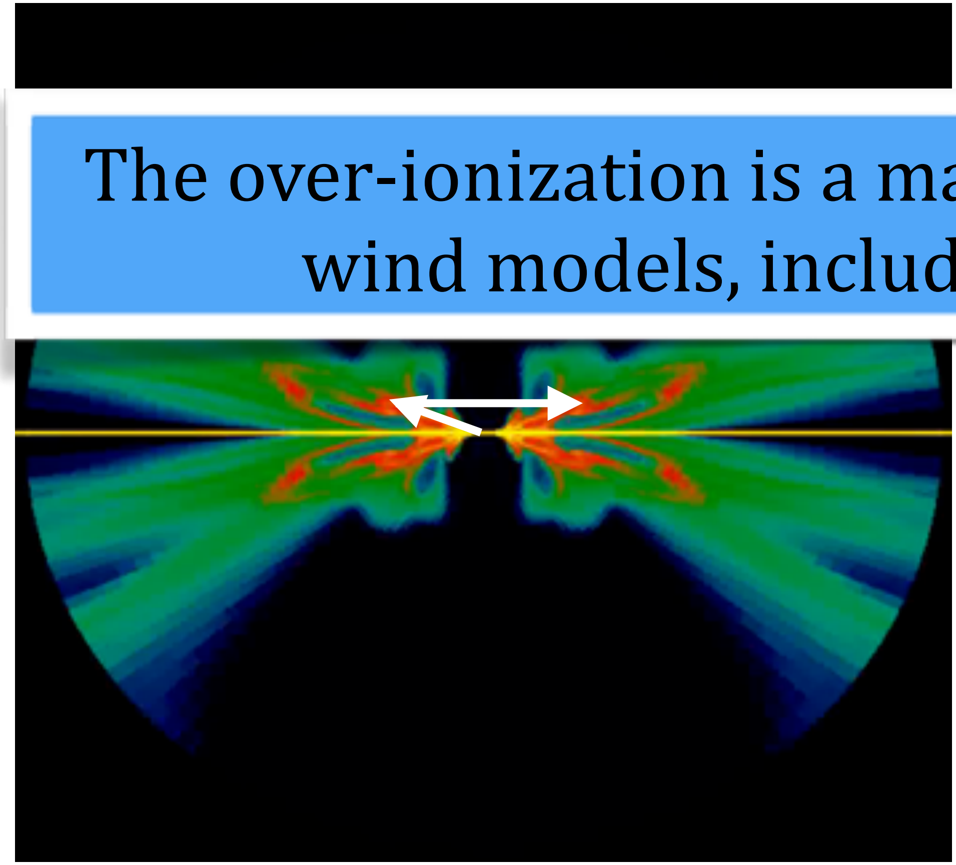
Monte Carlo photoionization and radiative transfer calculations.



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

Monte Carlo photoionization and radiative transfer calculations.

The over-ionization is a major problem for all AGN wind models, including MHD models.

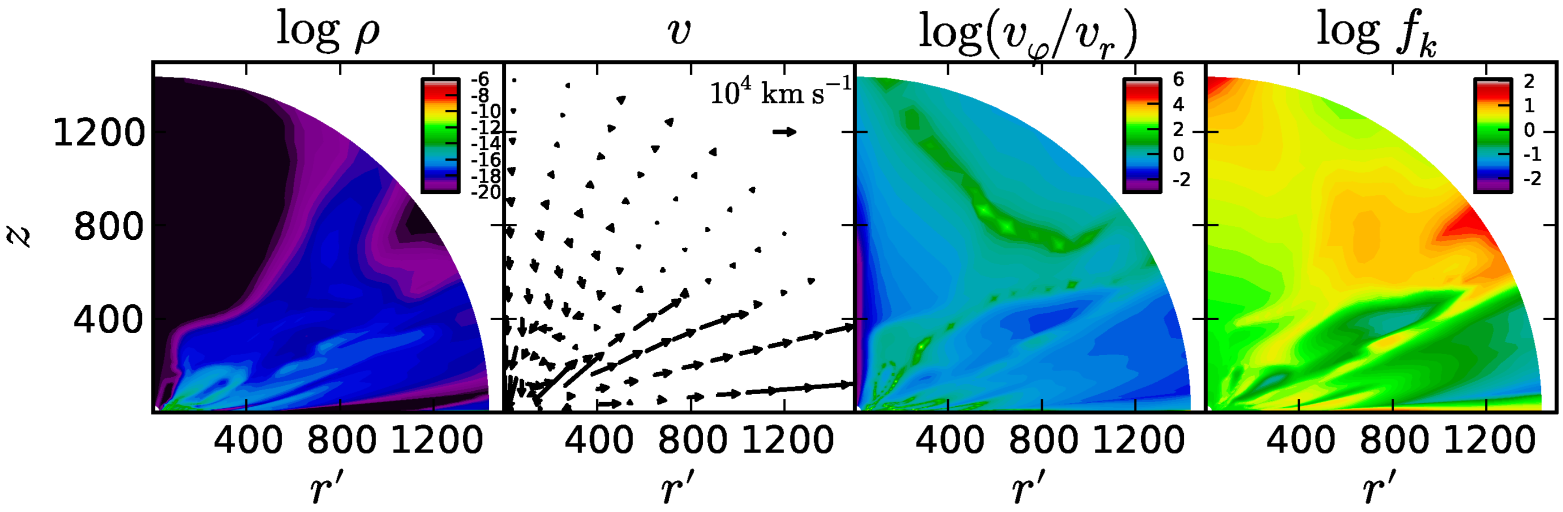


can affect the dynamics of a line driven disk wind, e.g., multiple scattering as well as the EUV photons from the inner most disk can significantly increase the wind ionization. So the problem is not just the direct irradiation.

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

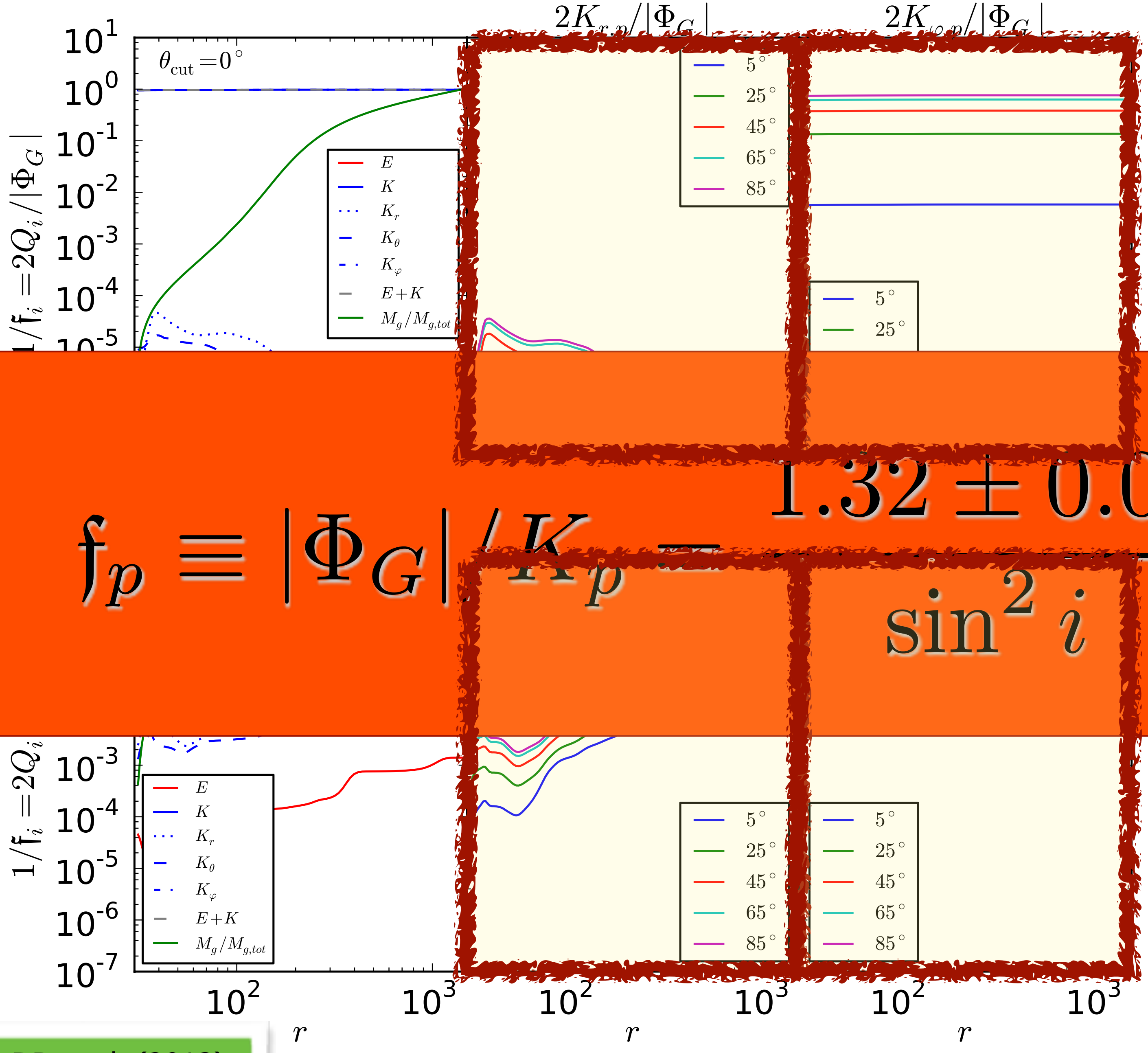
Are disk winds virialized?

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



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

Kashi, DP et al. (2013)



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

Kashi, DP et al. (2013)