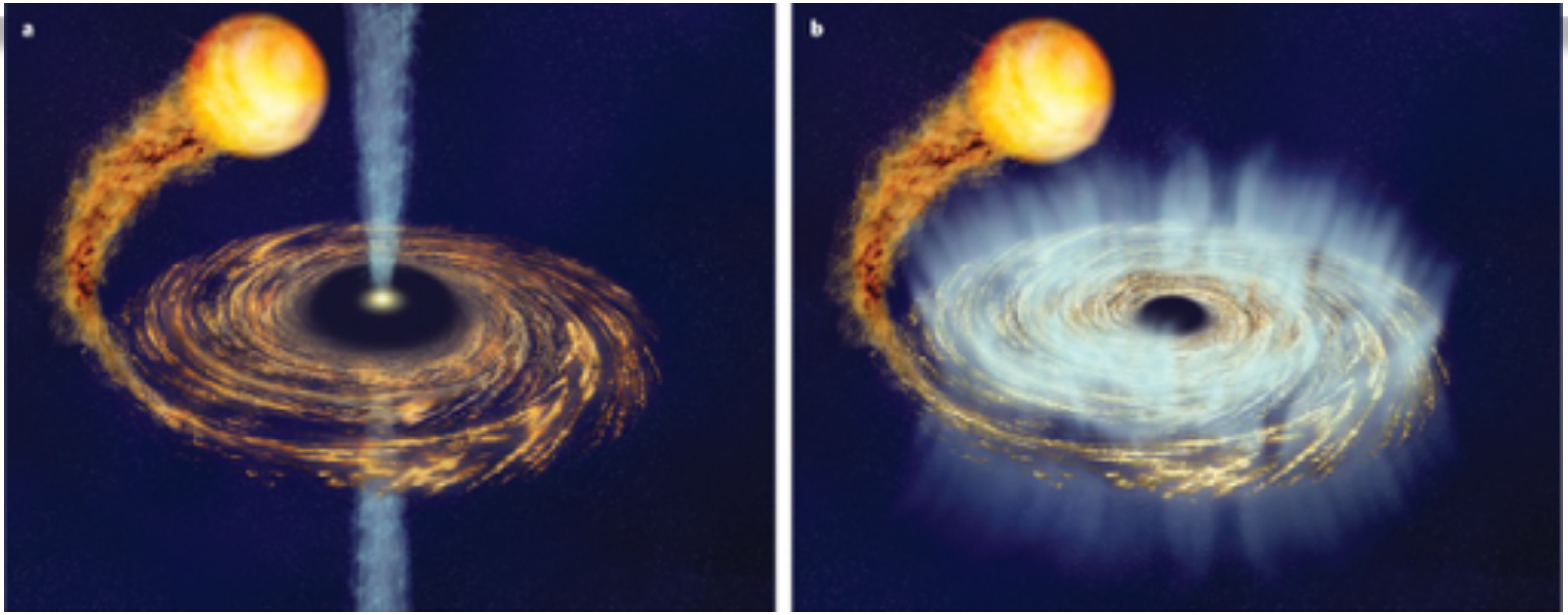
Theory of Outflows from Accretion Flows



Daniel Proga

University of Nevada, Las Vegas

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

OUTLINE

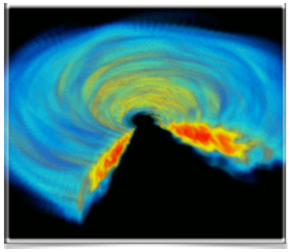
1) Introduction

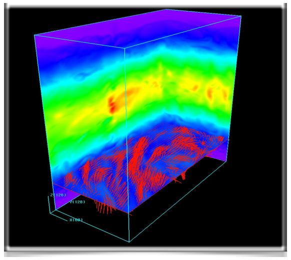
2) Toward a More Fundamental Model of Disk Winds

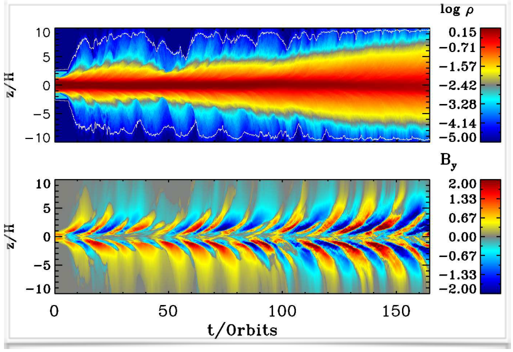
  a) thermally driven winds and effects of different SEDs

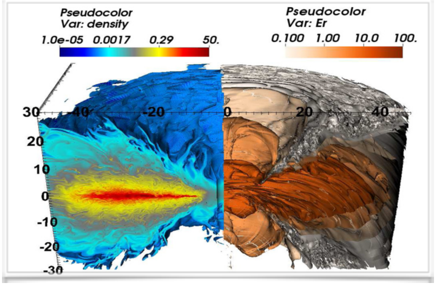
  b) inefficient line driving in X-ray binaries

Disks: Radiation and MHD are essential









mean motion (rotation)

↓

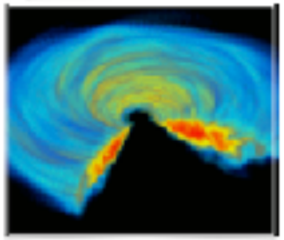
internal energy

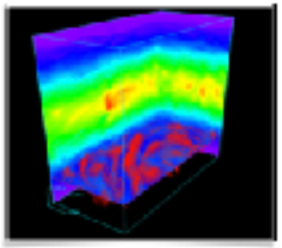
↓

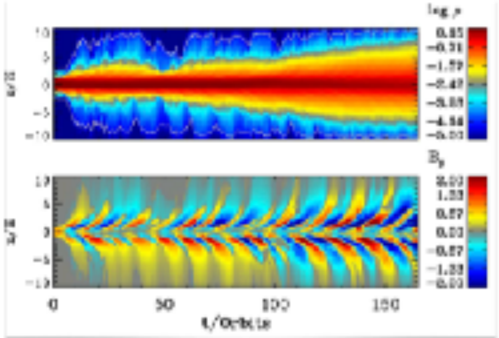
emission of EM radiation, magnetic fields, and gas

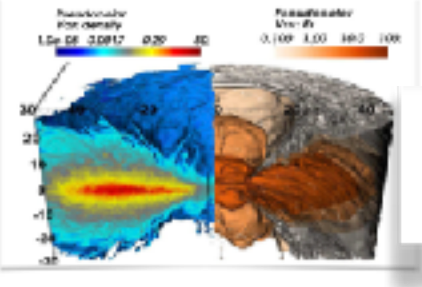
The energy flow.

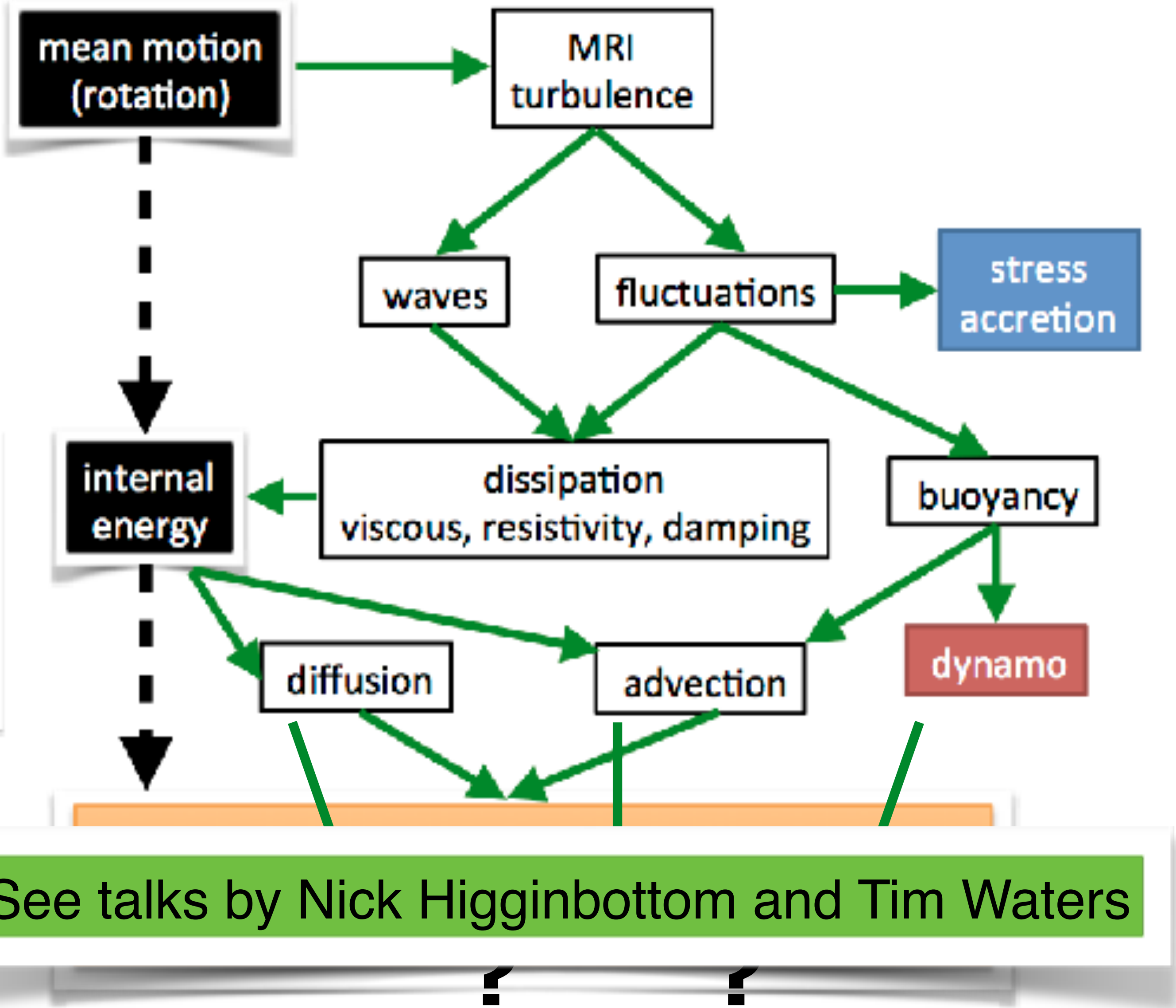
S. Balbus, J. Hawley, J. Stone,
C. Gammie, J. Krolik, S. Hirose
R. Narayan, O. Blaes, S. Davis,
Y.-F. Jiang, A. Sadawski











mean motion (rotation)

MRI turbulence

waves

fluctuations

stress accretion

internal energy

dissipation viscous, resistivity, damping

buoyancy

diffusion

advection

dynamo

?

?

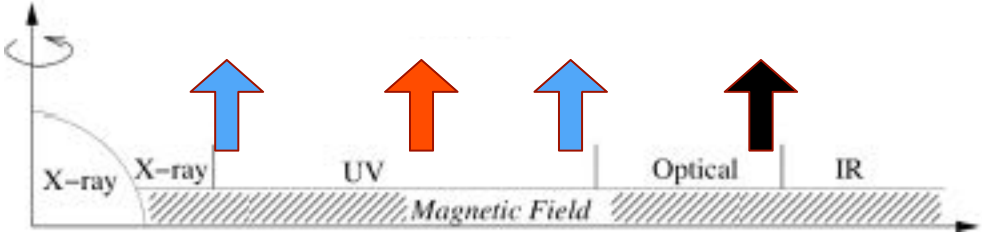
See talks by Nick Higginbottom and Tim Waters

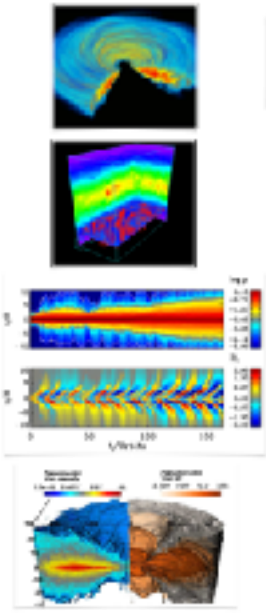
What can drive an outflow or regulate accretion?

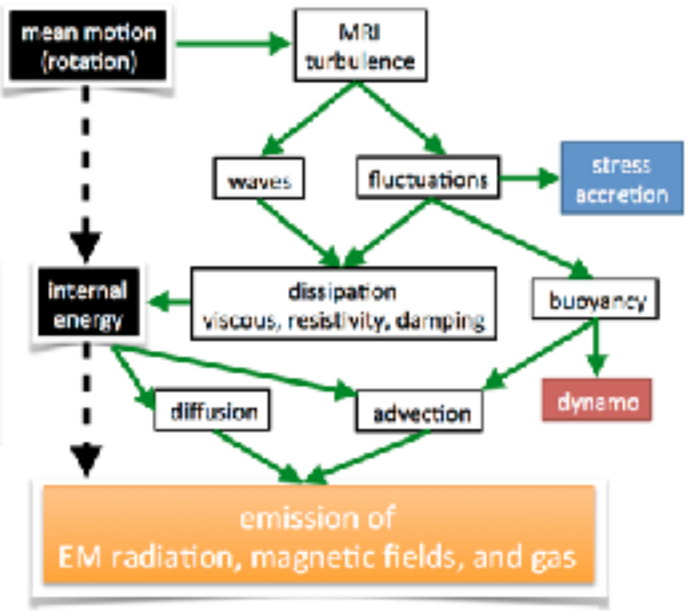
- Thermal expansion (evaporation, hydrodynamical escape)
- Radiation pressure (due to lines and continuum)
- Magnetic fields.

In most cases, rotation plays a key role (directly

Radiation momentum and en







mean motion (rotation)

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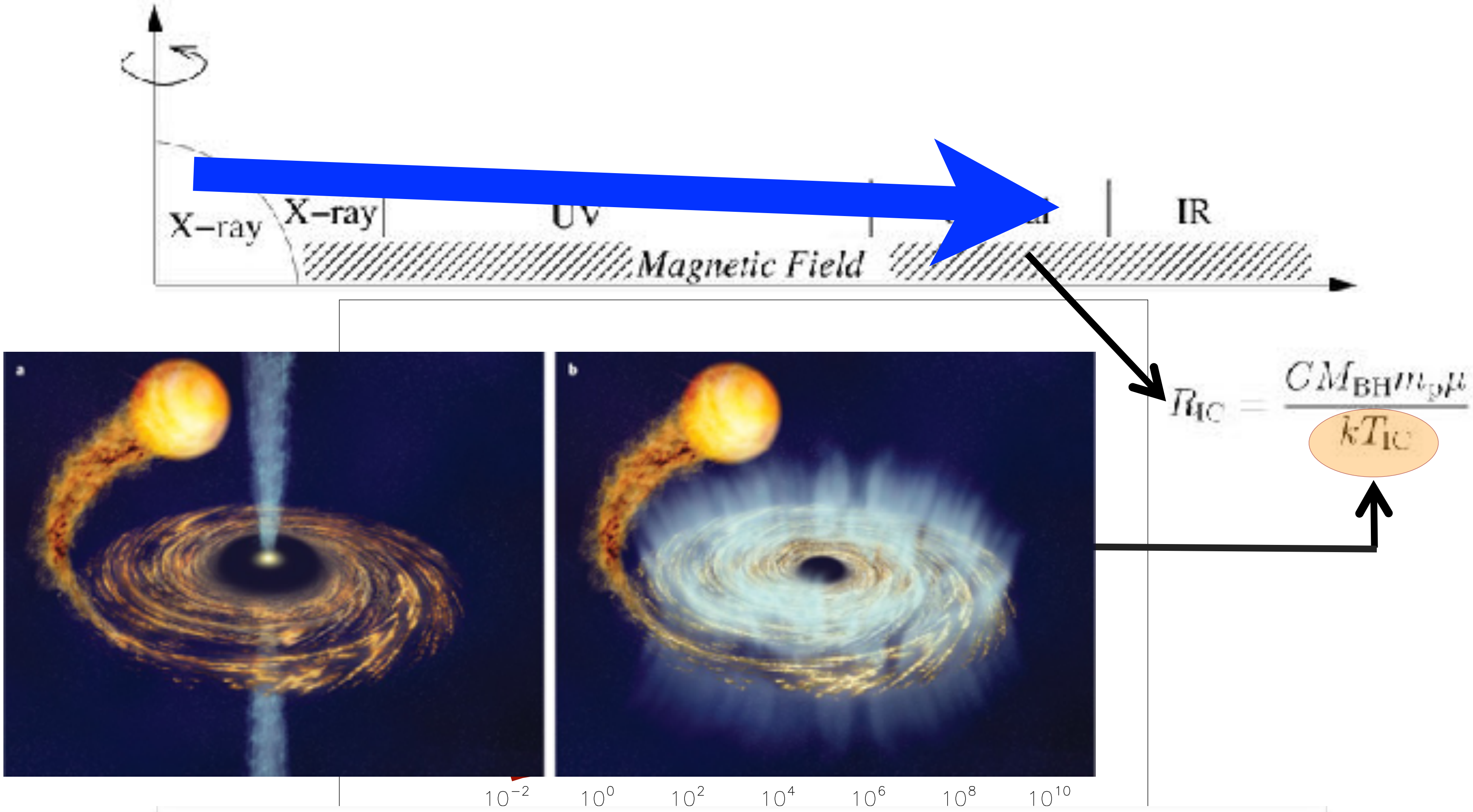
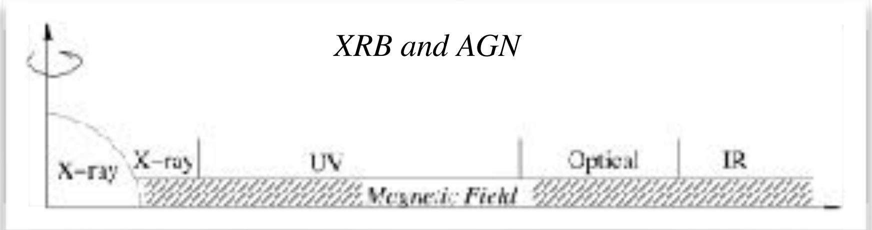
Irradiation of a Disk

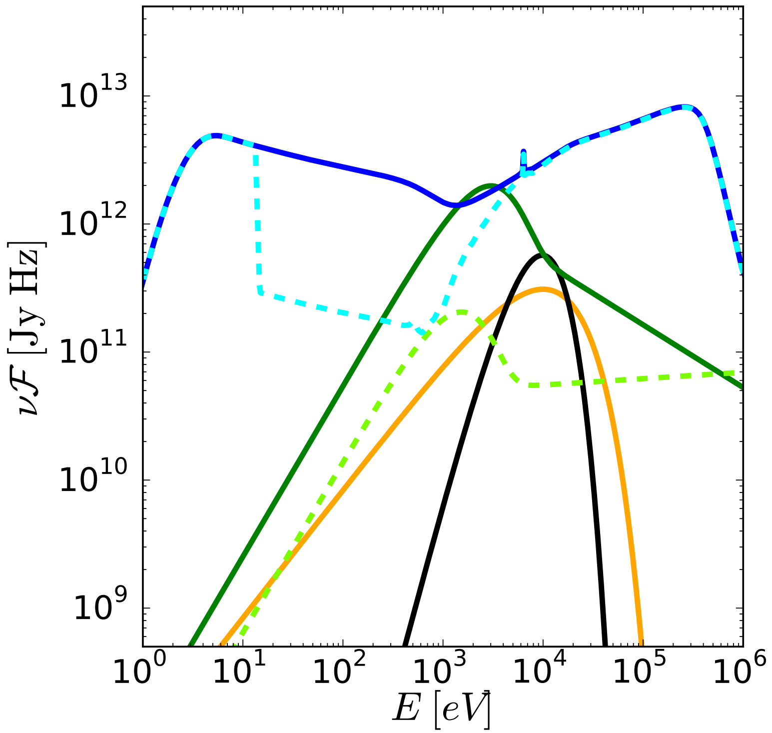


$$R_{\mathrm{IC}} = \frac{C M_{\mathrm{BH}} m_{\mathrm{p}} \mu}{k T_{\mathrm{IC}}}$$

Luketic et al. (2010), see also Proga & Kallman (2002), Waters & Proga (2012), Higginbottom & Proga (2015), and Higginbottom et al. (2017)

Accretion Disks in Various Objects

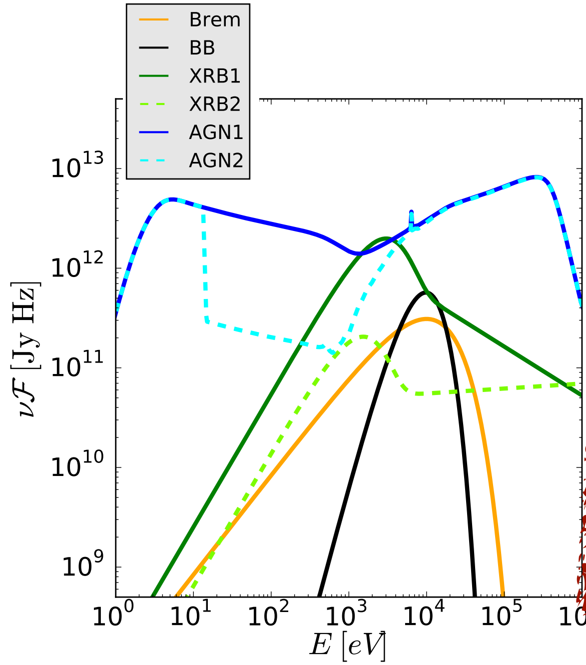


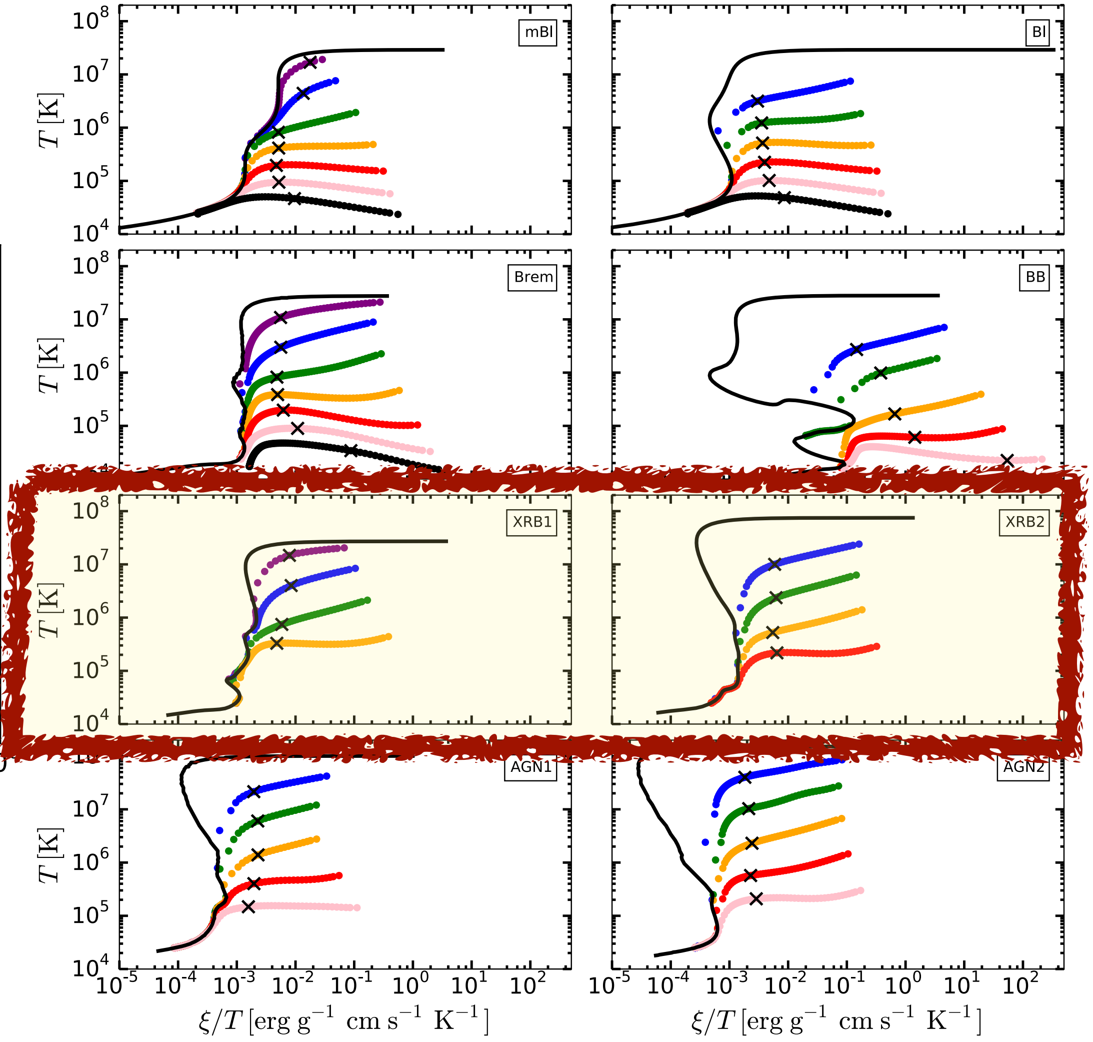


Dyda, Dannen, Waters, DP (2017)

photoionization calculations using XSTAR

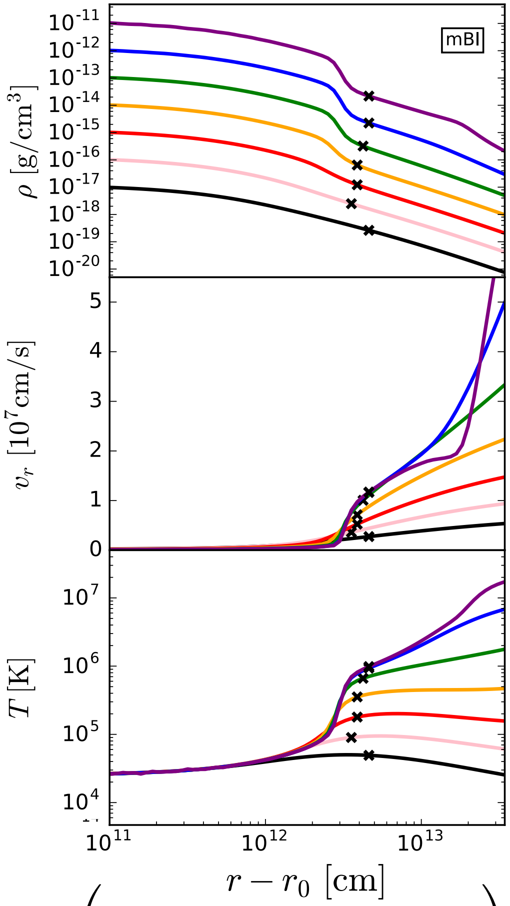
Thermal winds: effects of SED, flux and adiabatic cooling.

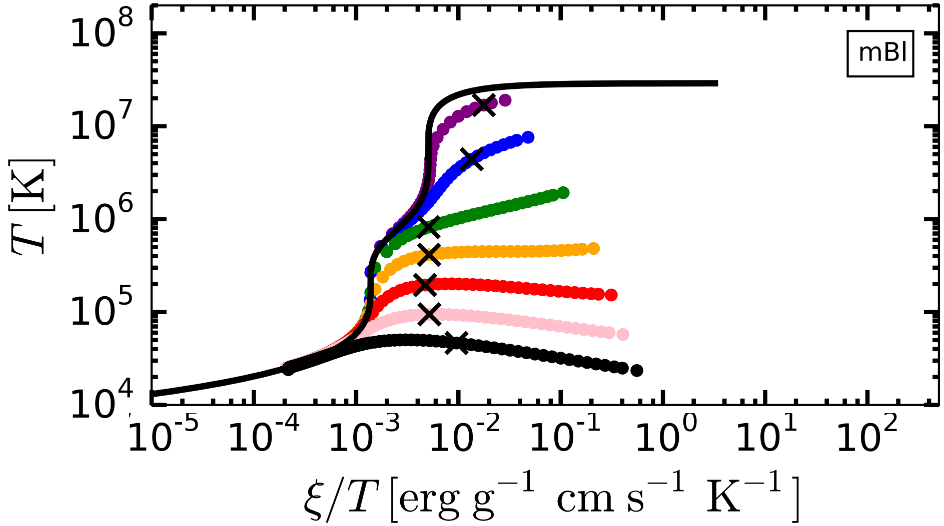




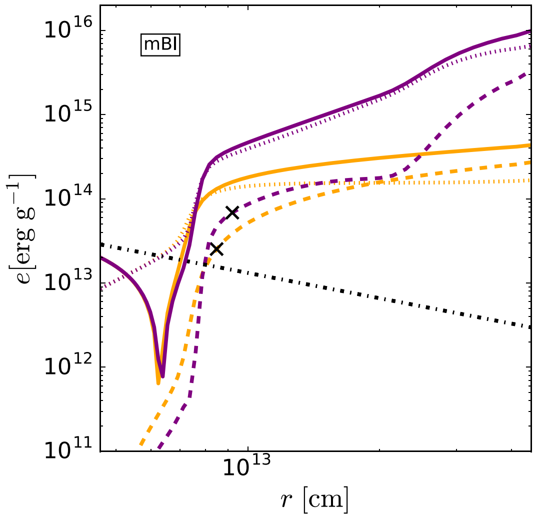
Dyda, Dannen, Waters, DP (2017)

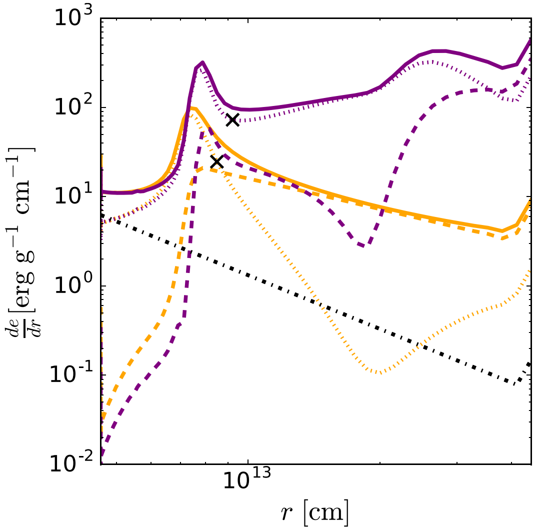
Thermal winds: effects of SED, flux and adiabatic cooling.



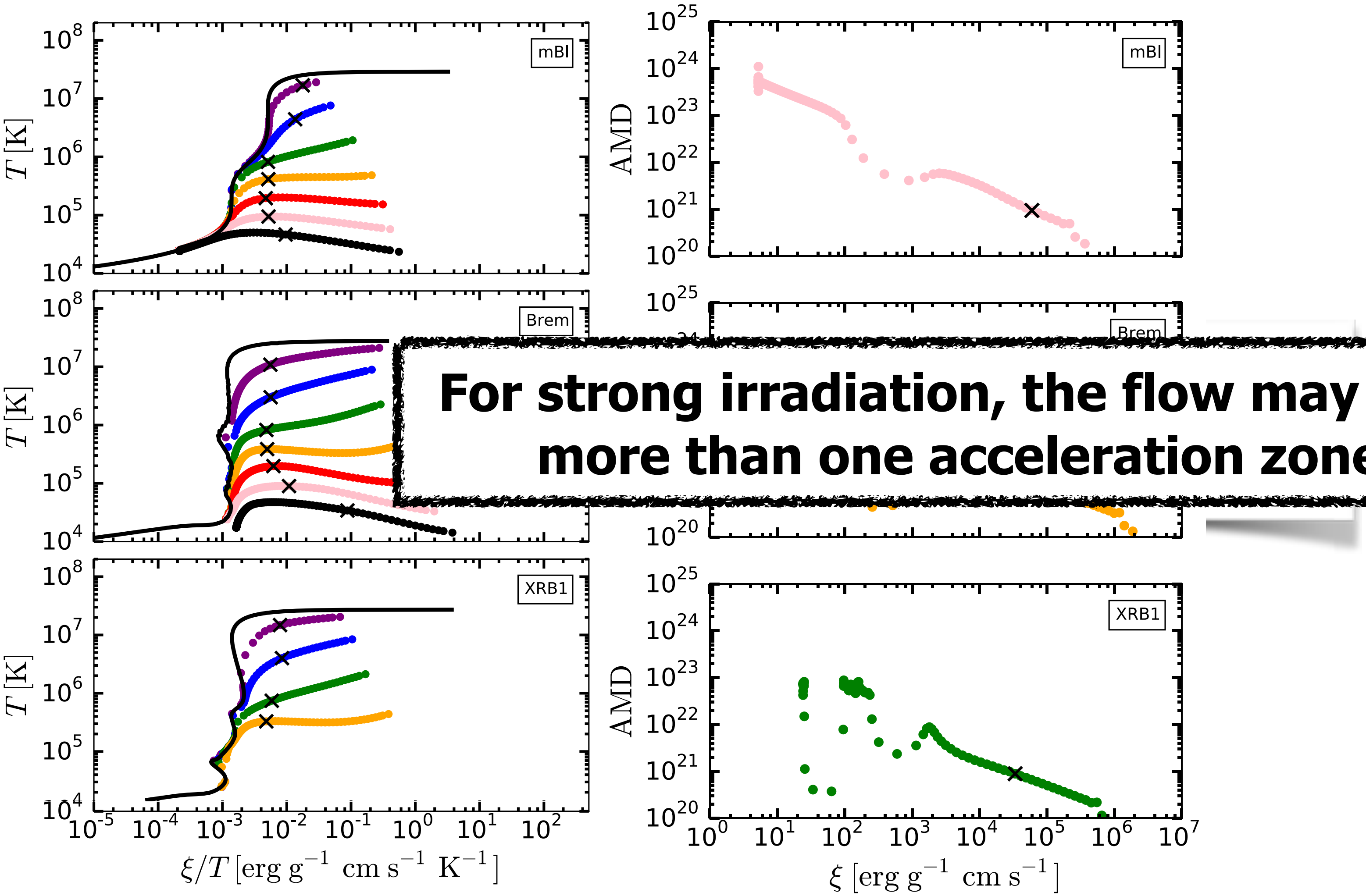


$$\frac{\mathrm{d}}{\mathrm{d}r}\left(\underbrace{\frac{v_r^2}{2}}_{e_{\rm kin}}+\underbrace{\frac{\gamma}{\gamma-1}\frac{k_{\rm b}T}{\mu m_{\rm p}}}_{e_{\rm th}}-\underbrace{\frac{GM}{r}}_{e_{\rm grav}}\right)=-\underbrace{\frac{\mathcal{L}}{v_r}}_{\frac{\mathrm{d}Q}{\mathrm{d}r}}.$$





Thermal winds: effects of TI on observability



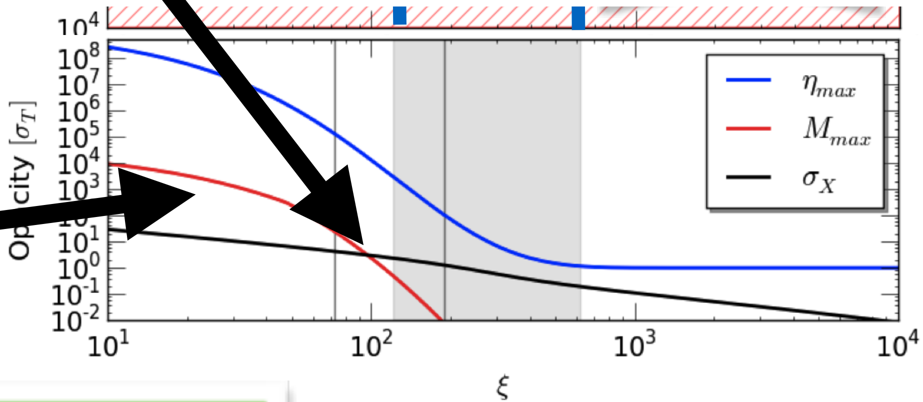
For strong irradiation, the flow may have more than one acceleration zone!

Dyda, Dannen, Waters, DP (2017)

The main question is:

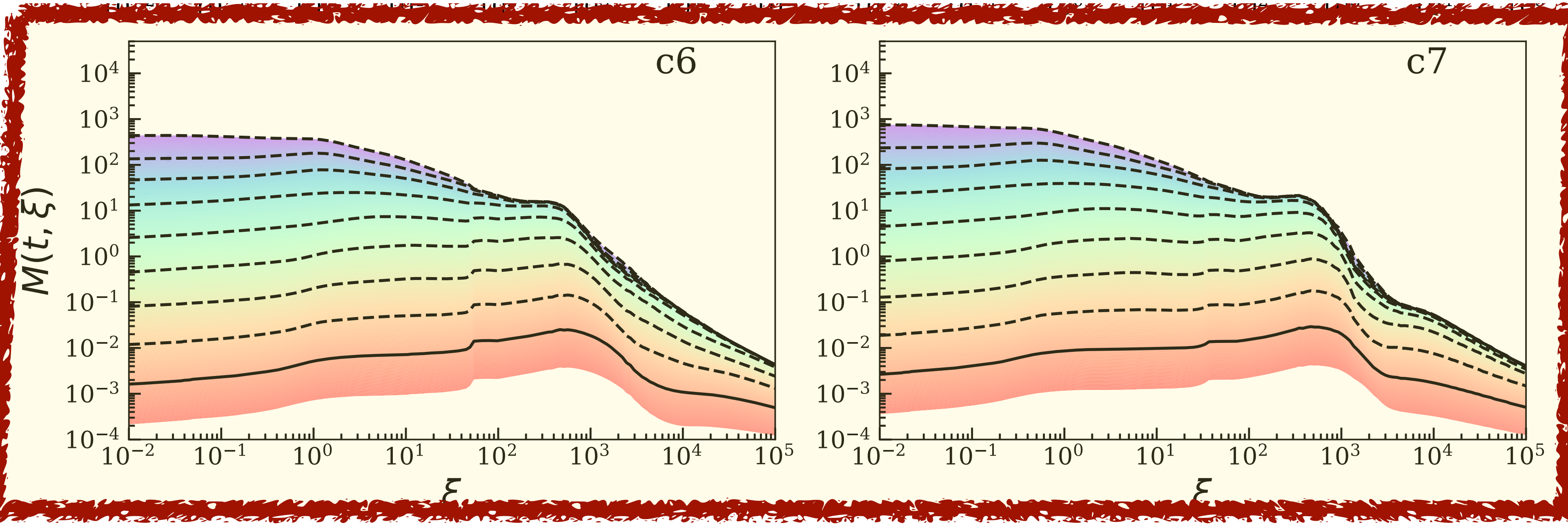
$$L_D M_{max} \quad ? \quad L_{Edd}$$

Opacities decrease with increasing irradiation



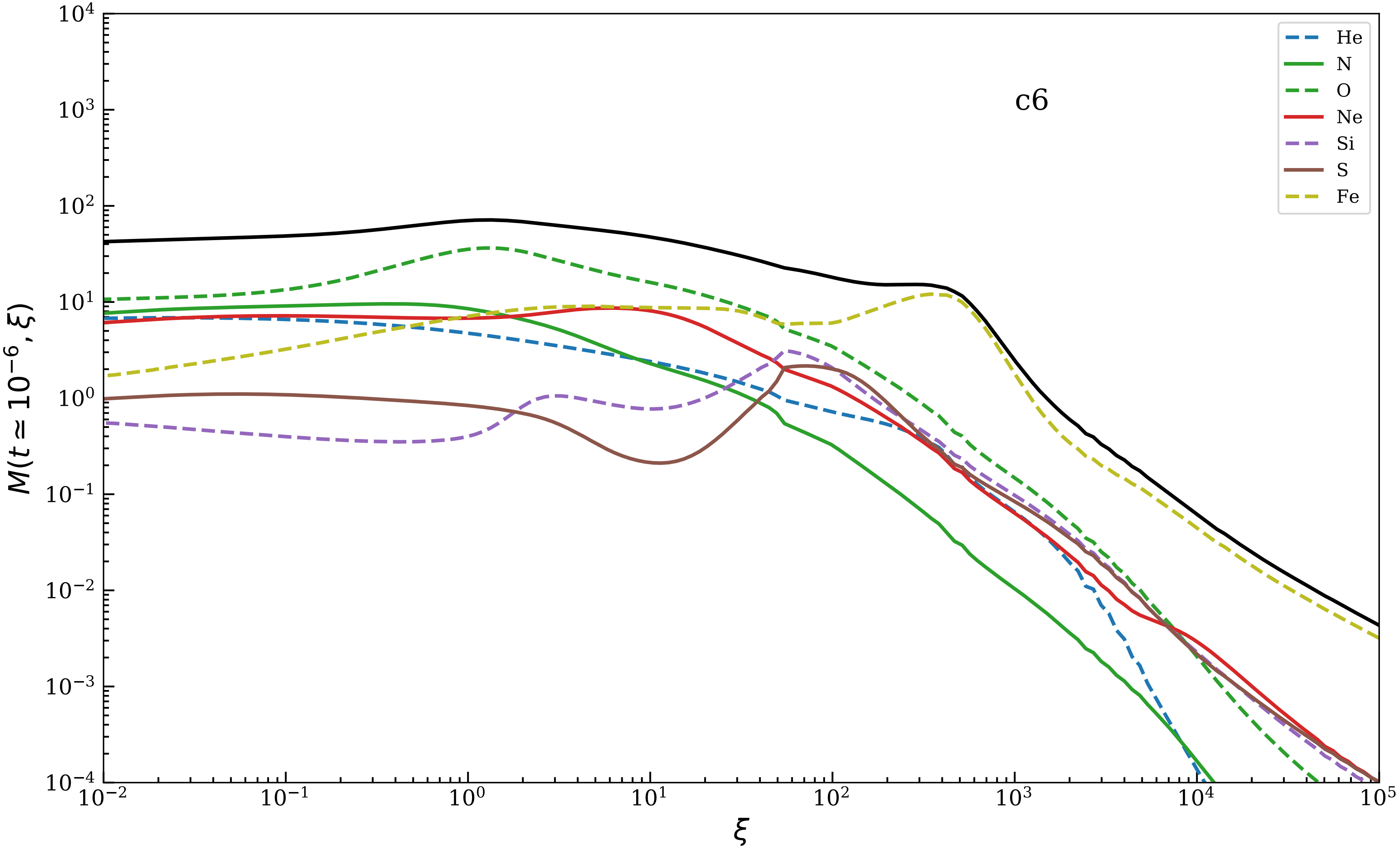
DP & Waters (2015, see also DP & Kallman 2002)

Line driving: effects of SED



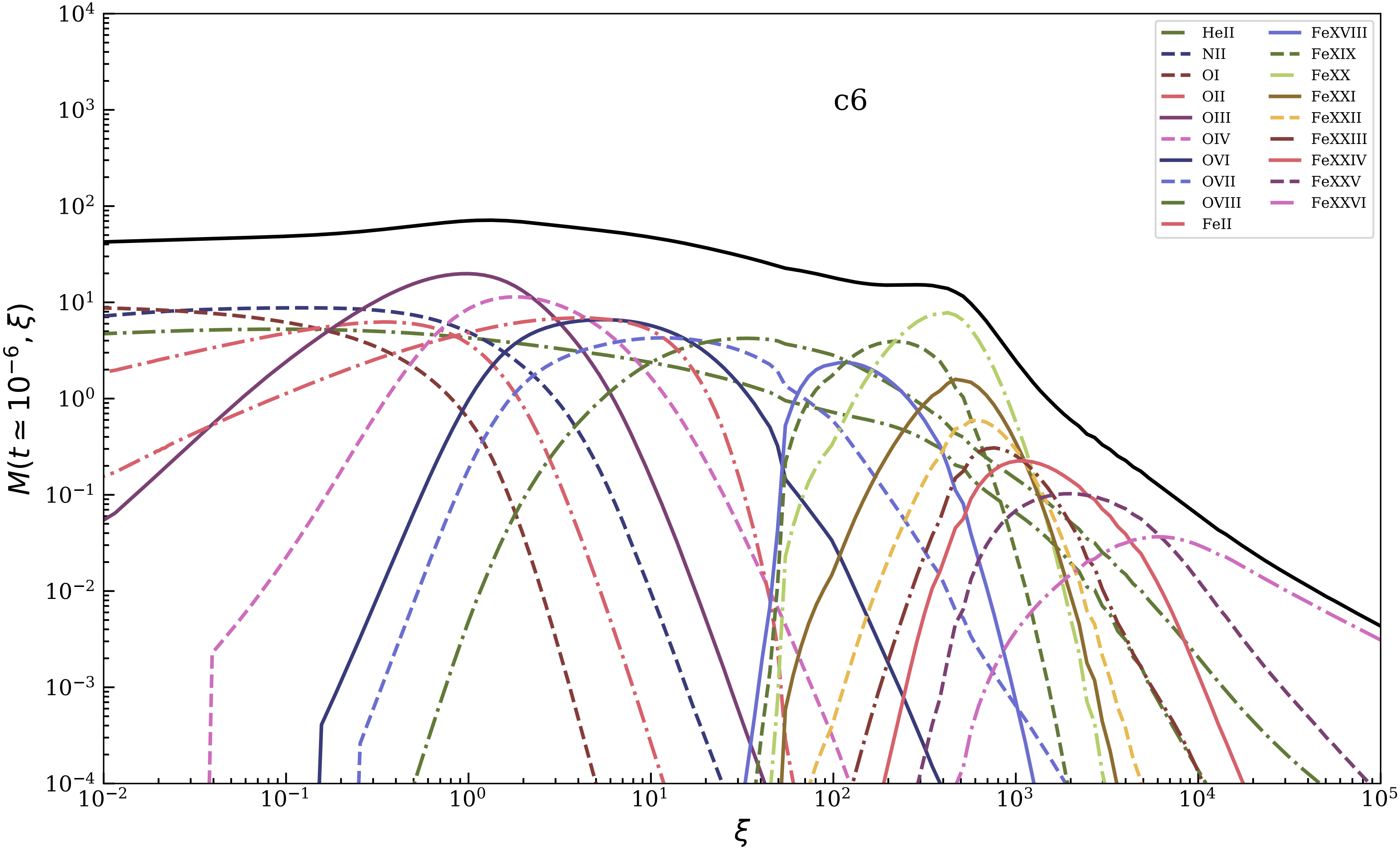
Randall Dannen (MS thesis 2018)

Line driving: element contribution



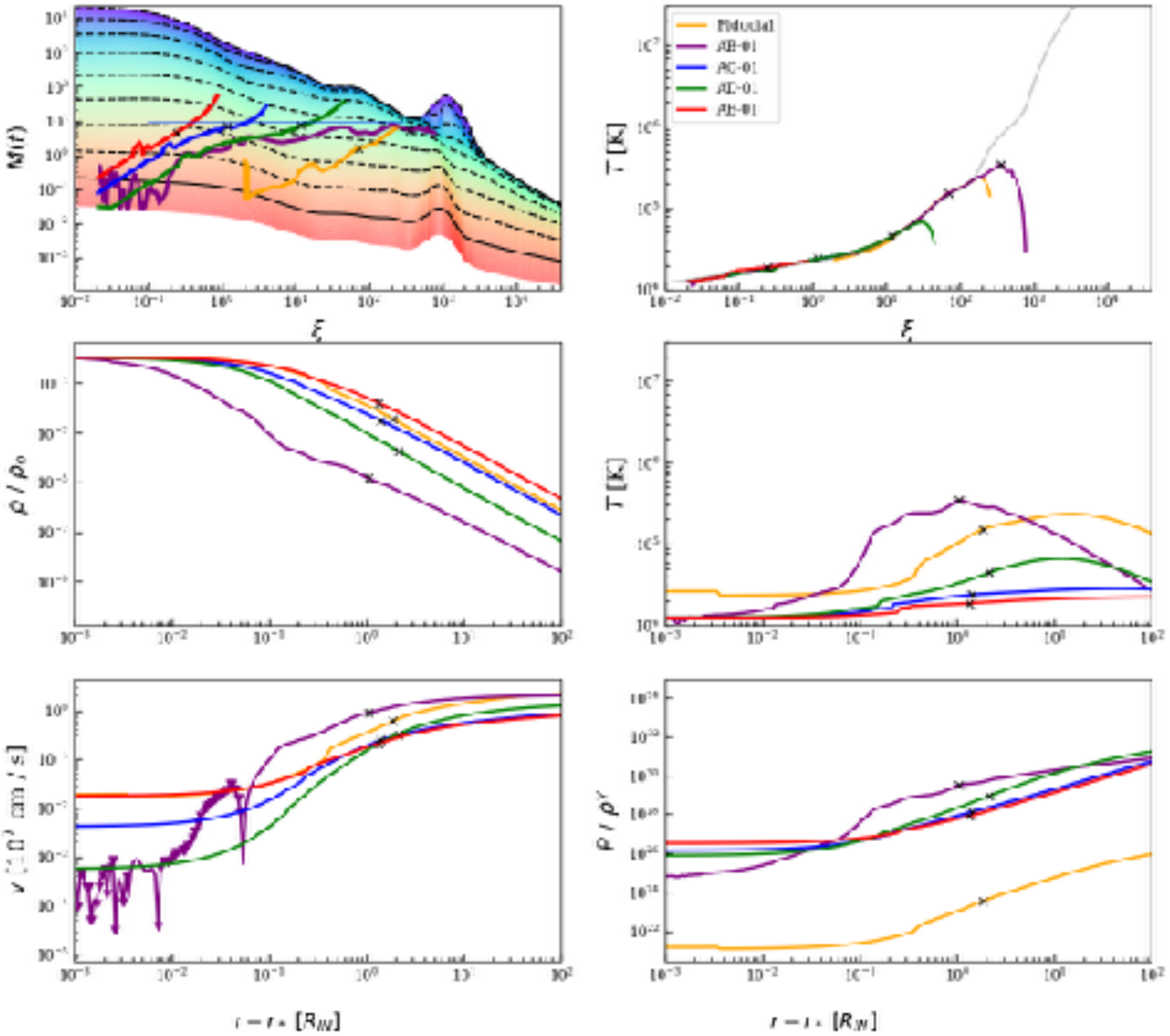
Randall Dannen (MS thesis 2018)

Line driving: ion contribution



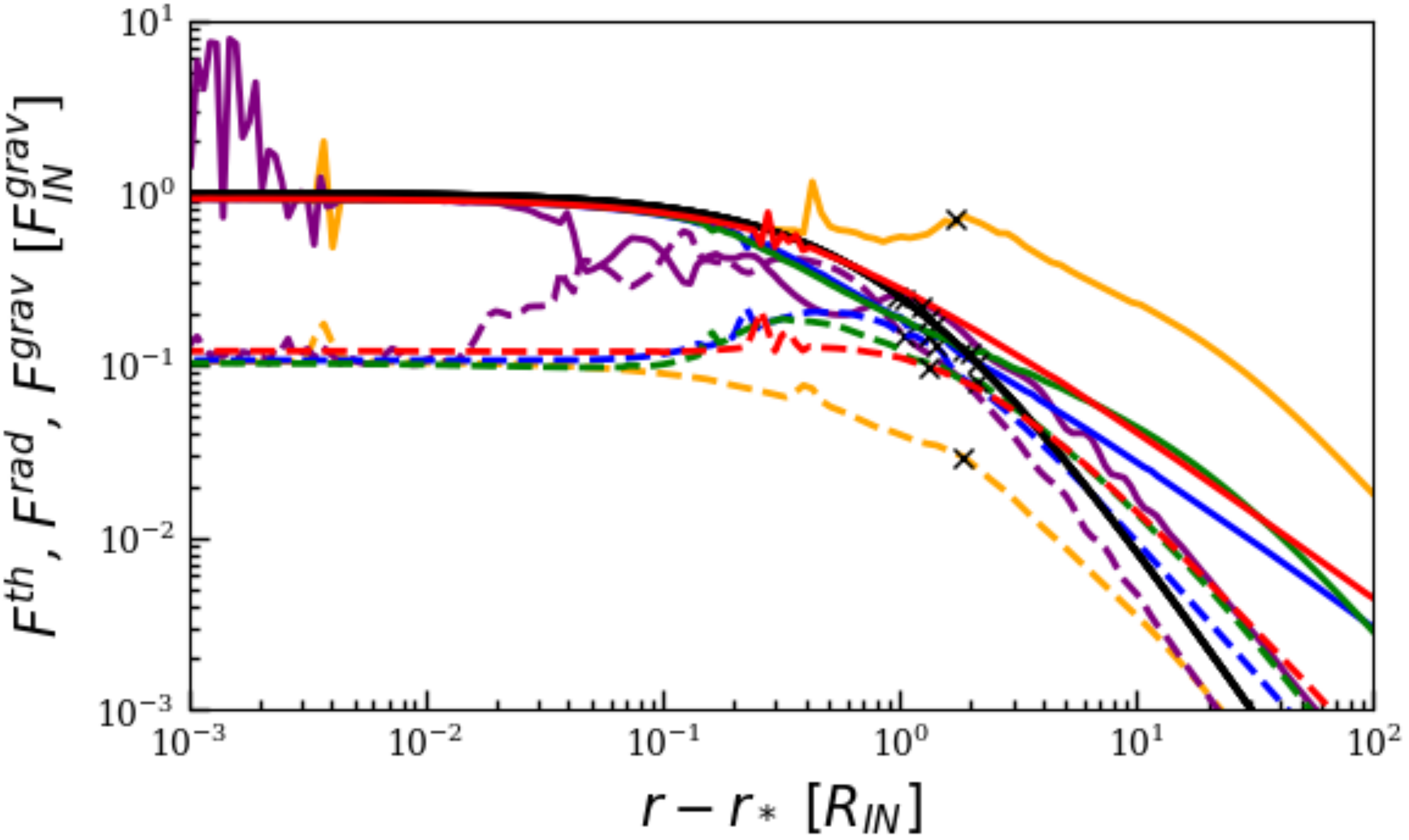
Randall Dannen (MS thesis 2018)

Line and thermal driving



Randall Dannen (MS thesis 2018)

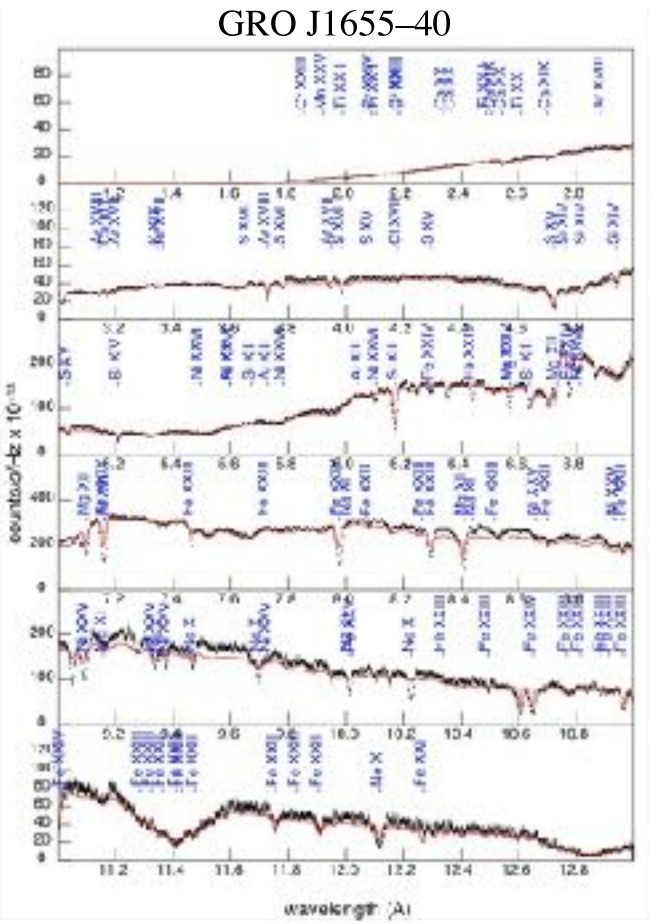
Line and thermal driving



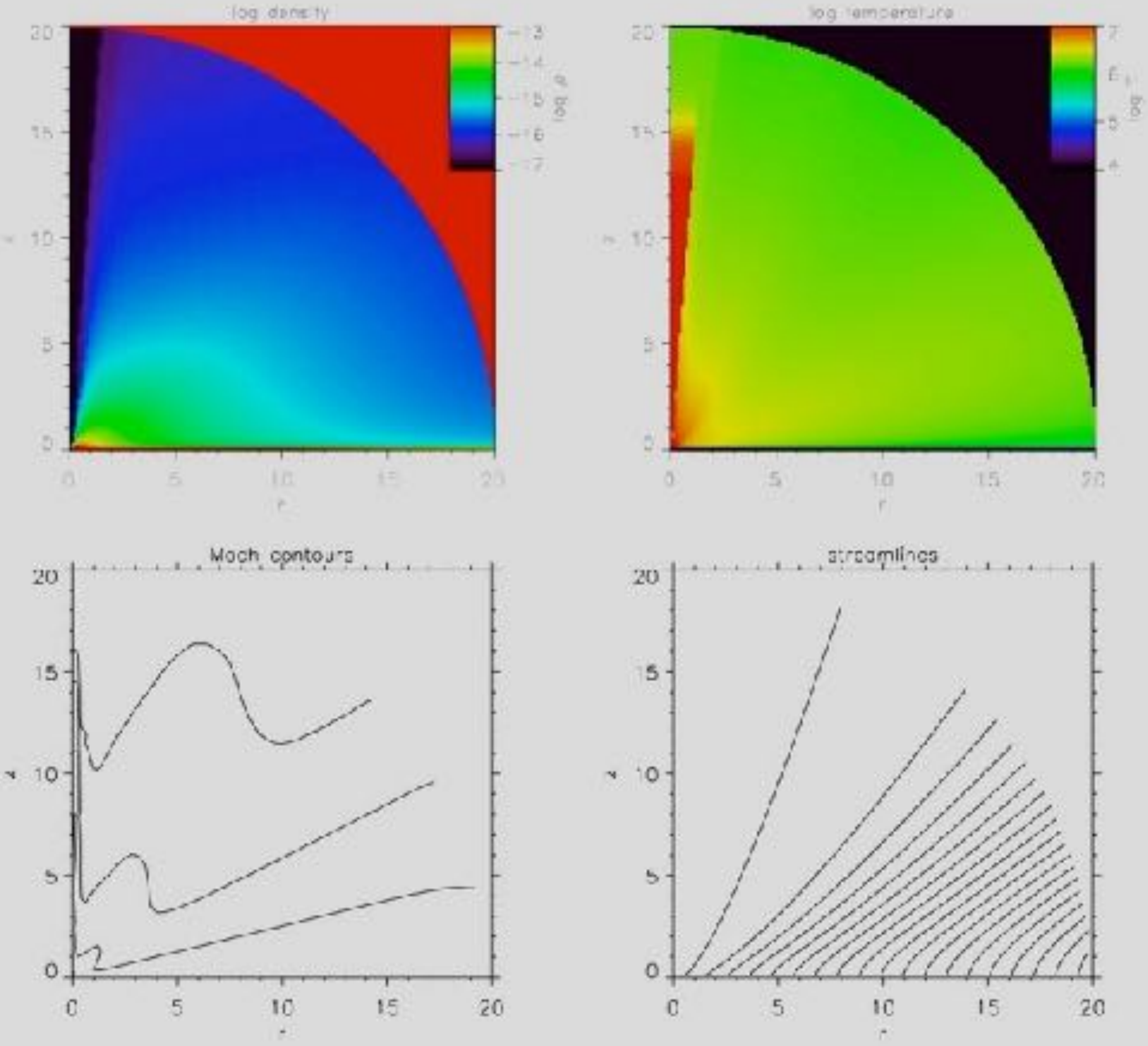
Randall Dannen (MS thesis 2018)

X-ray Transient Sources

- Most of the accretion energy is emitted in X-rays.
- The radiation energy is still too low to drive an outflow from the inner disk.
- But the radiation from the inner disk can heat up the outer disk.
- However, spectral features of disk winds have not been seen from these systems until high res. X-ray spectra (Schulz & Brandt 2002; Miller et al. 2006, 2008, 2014, 2015; Kubota et al. 2007; Neilsen & Lee 2009; Ueda et al. 2009; Diaz Trigo et al. 2007;

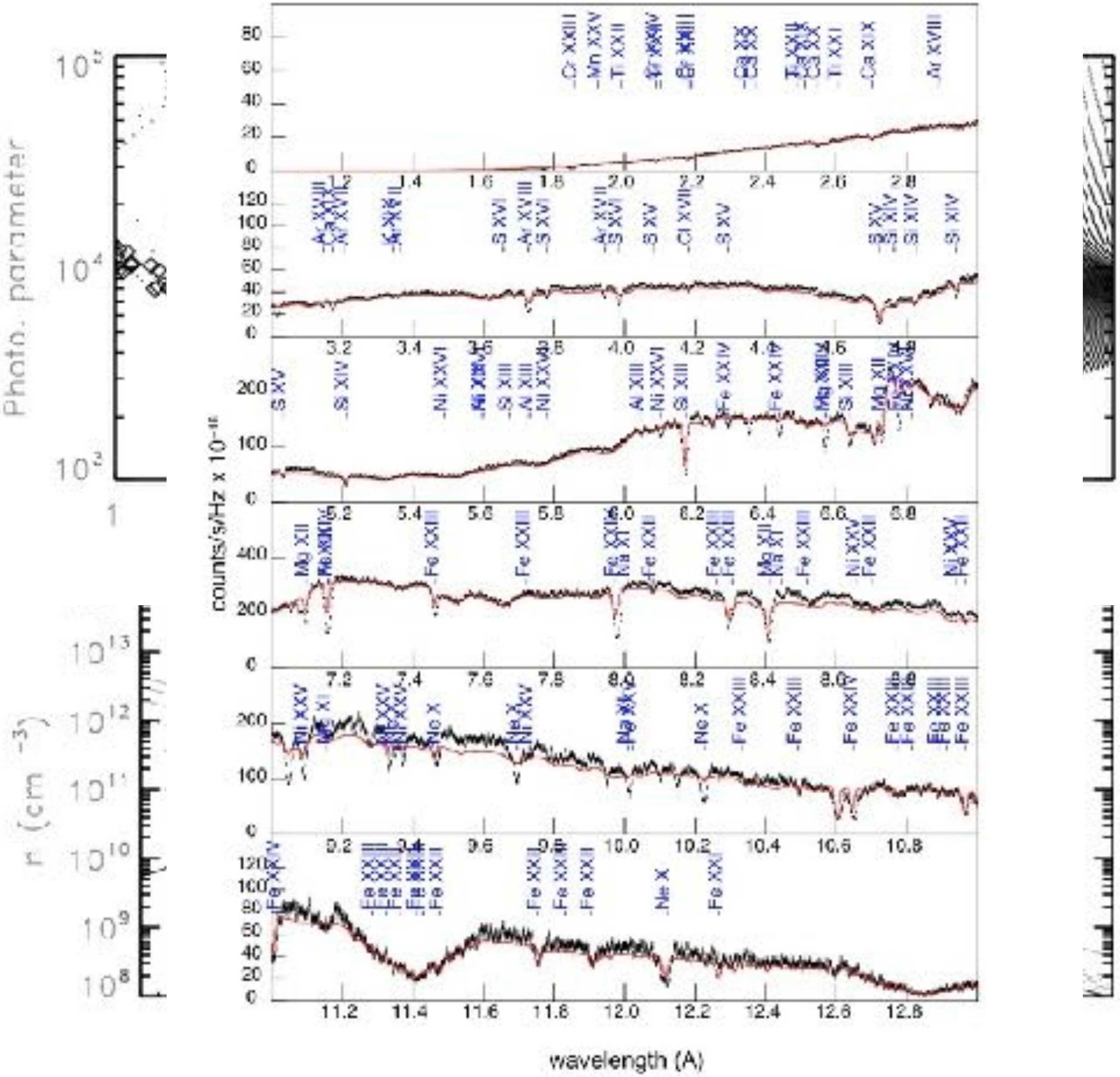


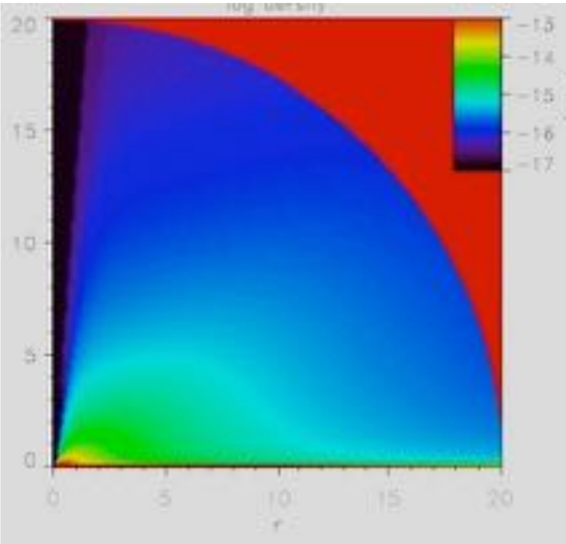
Observations: Miller et al. (2006)



$$R_{\rm IC} = \frac{G M_{\rm BH} m_{\rm p} \mu}{k T_{\rm IC}}$$

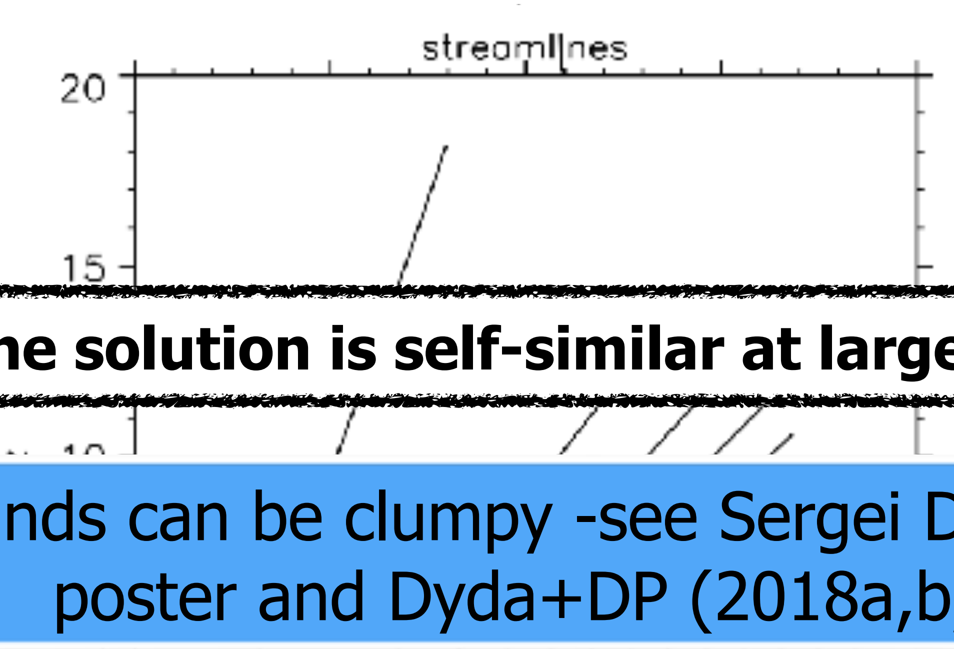
Luketic et al. (2010), see also Proga & Kallman (2002), Waters & Proga (2012), Higginbottom & Proga (2015), and Higginbottom et al. (2017)





$\theta = 48.3°$ (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).

The wind geometry and self-similarity



The solution is self-similar at large radii

Disk winds can be clumpy -see Sergei Dyda and his poster and Dyda+DP (2018a,b, c)


3D Line Driven Winds - Clumpy Outflows

Sergei Dyda & Daniel Proga

University of Nevada Las Vegas

Launching Radius

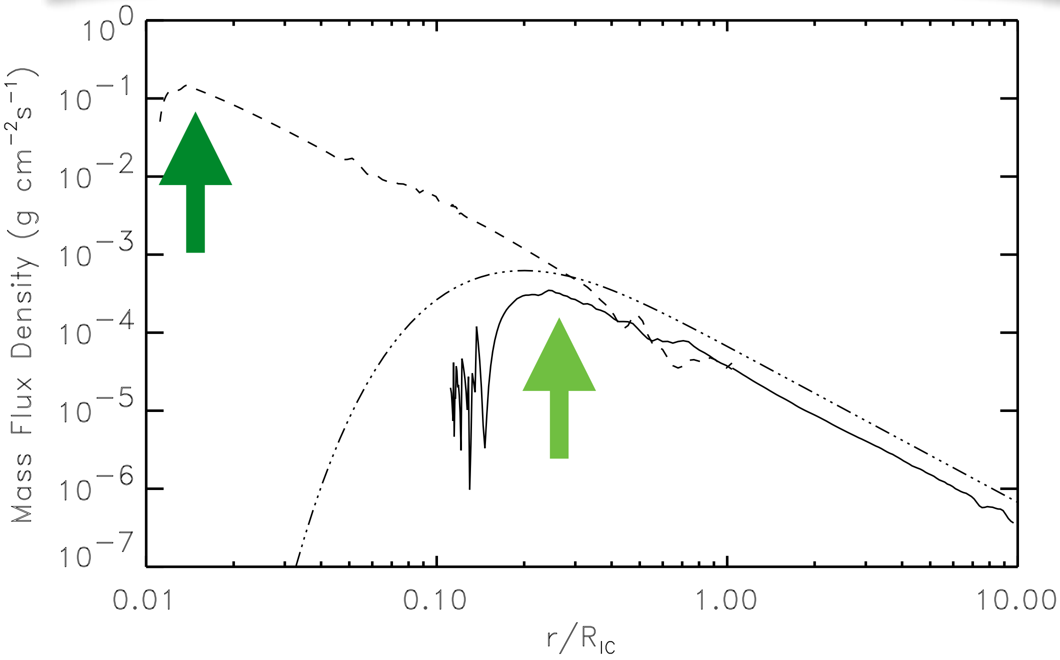


FIG. 5.—Mass flux density as a function of radius for the test models. The solid line represents our results for $\Gamma_D = 0.667$ with radiation force and X-ray attenuation switched off, whereas the dashed line represents our results with radiation force switched on (in both cases $\kappa_X = \kappa_{UV} = 0$). The mass flux density is measured along a fiducial surface at a fixed θ of 87°. For comparison, the figure also shows the analytic fit (*triple-dot–dashed line*) by Woods at al. (1996) to their numerical results (their eq. [5.2]). For the constant C_0 in the expression of Woods et al., we adopted value of 10^{-4}.

Proga & Kallman (2002, see also Luketic et al. 2010)

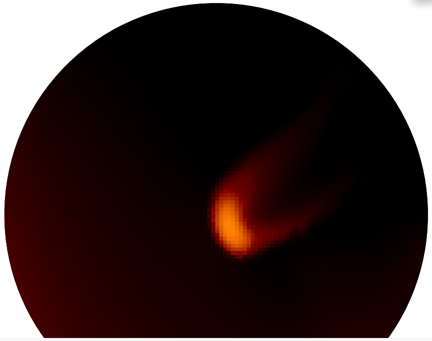
Summary

- Line driving is unlikely to be significant in winds driven from X-ray binaries (PK 2002).
- However, thermal disk winds might be enhanced by radiation pressure due to electron scattering (radiation pressure reduces the effective Compton radius, PK 2002).
- The thermal disk winds are different from spherical thermal winds in many respects mainly due to the geometrical effects.
- Unless the radiation field is very strong, thermal winds are not in thermal equilibrium regardless of the geometry (in other words, adiabatic cooling is significant, L. etal 2010, HP 2015, H. et al.2017, D. et al. 2017).
- For some SEDs and relatively strong radiation fields, a wind can have more than one zone of rapid acceleration due to efficient radiative heating (a run-away heating/TI, D et a. 2017).
- Thermal winds are not very fast but they carry a lot of mass (the wind

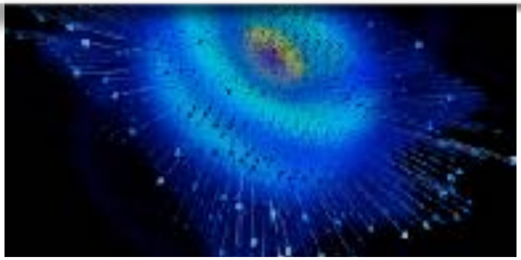
Summary

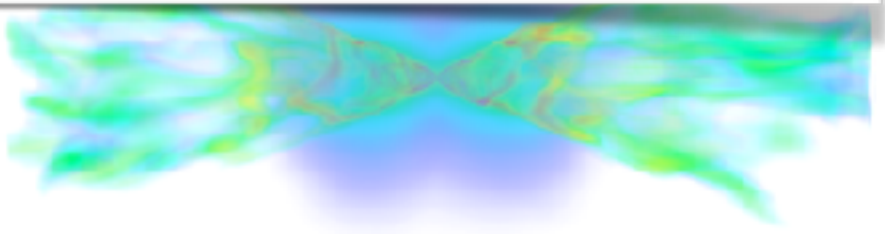
- We have atomic and molecular data, computers and numerical methods that allow us to develop and observationally test direct ab initio models of mass outflows (i.e., that will include the object where the outflows originate from).
- Combined with present and future high-quality observations, numerical 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).

Future



Multi-frequency Radiation-Magnetohydrodynamics.

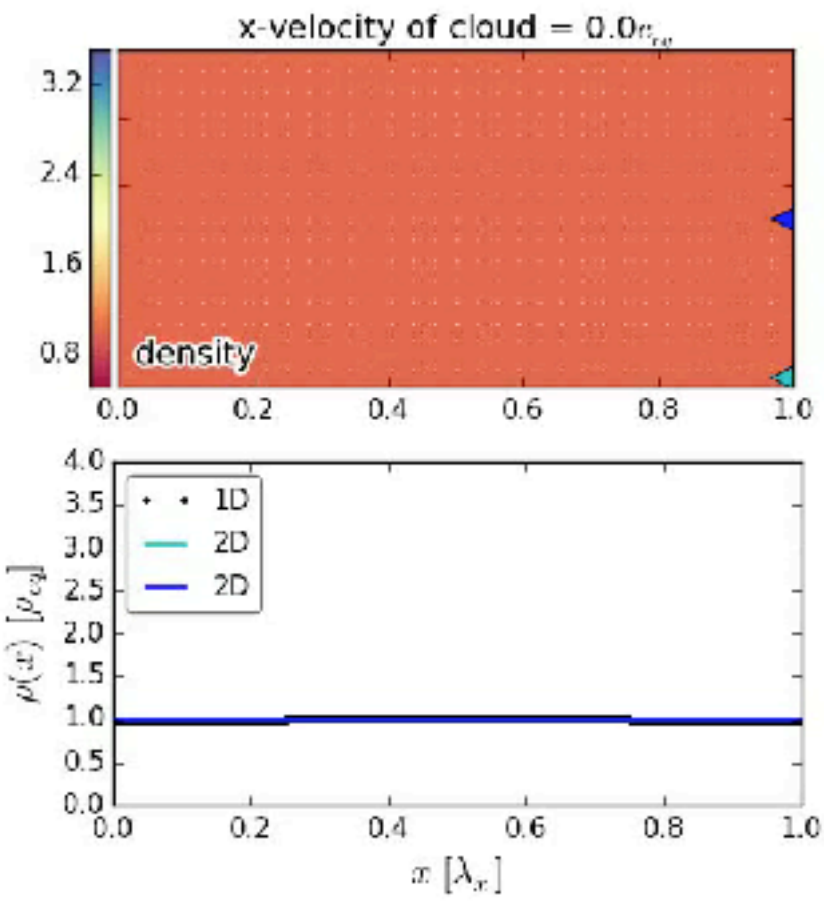


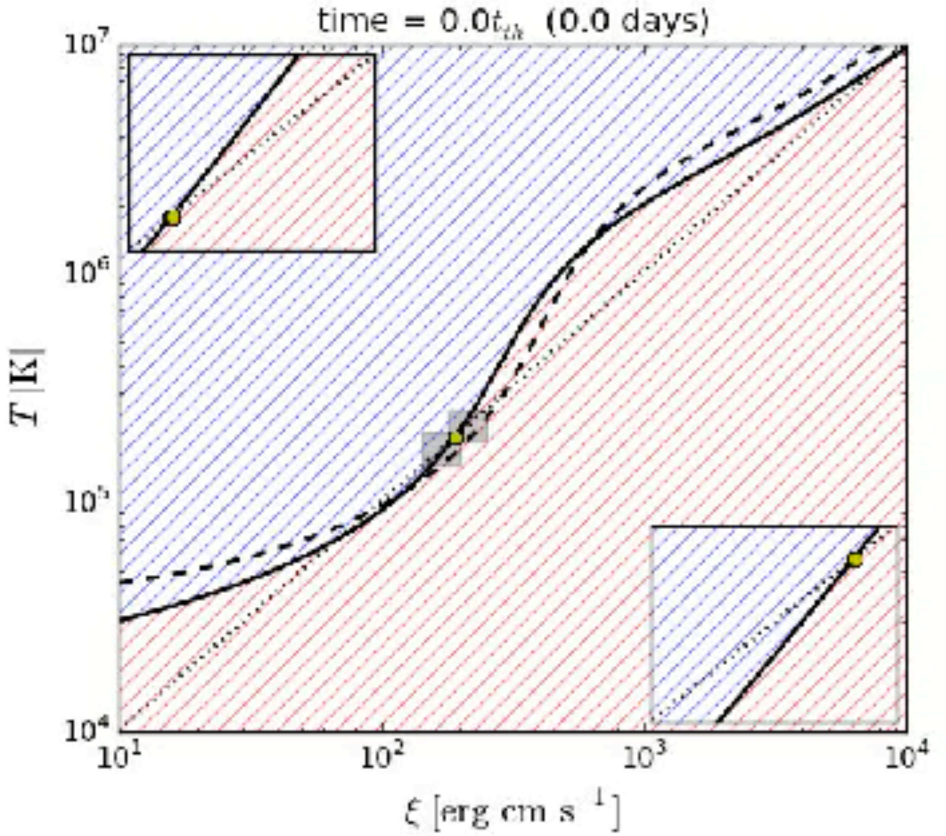


Winds in AGNs and PPDs

Inflows and Outflows in GRBs and AGNs

TI and condensations

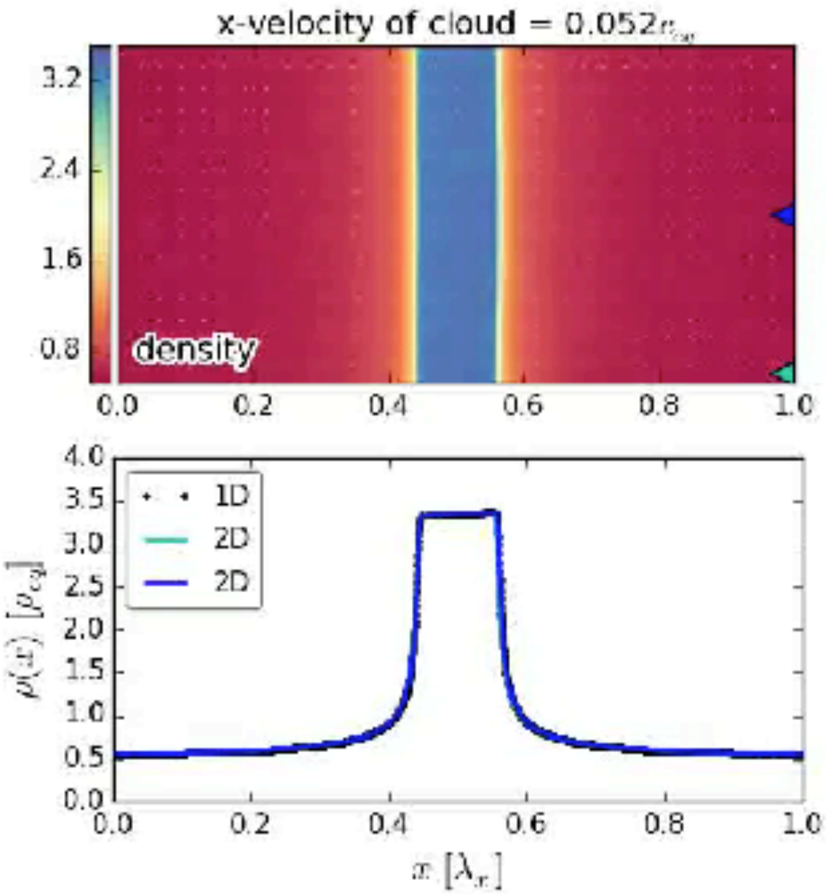


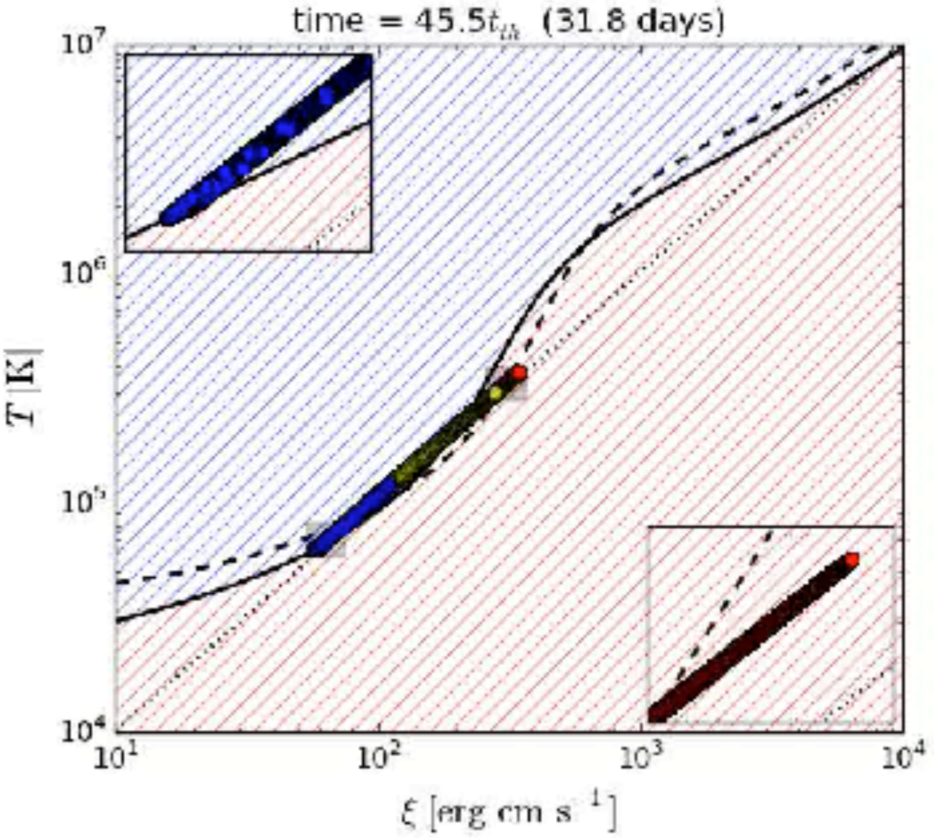


Simulation by Tim Waters and Daniel Proga, UNLV

DP & Waters (2015, see also Waters & DP 2016)

TI and condensations

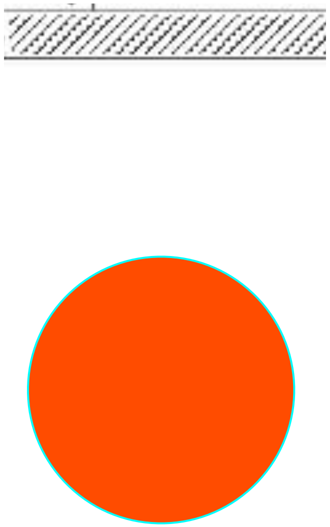




Simulation by Tim Waters and Daniel Proga, UNLV

DP & Waters (2015, see also Waters & DP 2016)

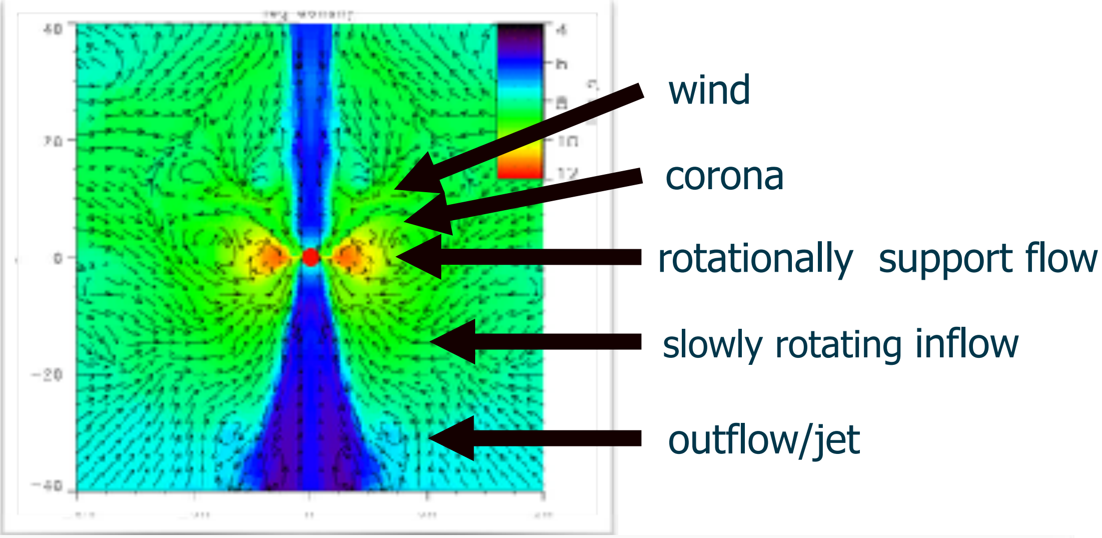
Disks vs Stars



MHD is essential

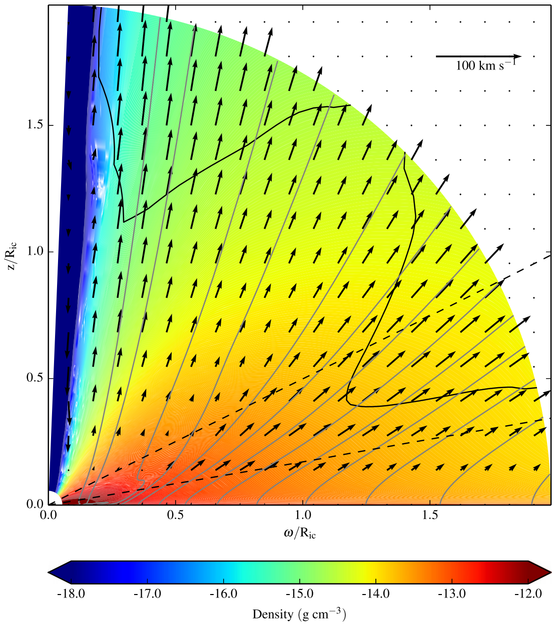
For a wide range of outer boundary conditions (spherical/aspherical, slow/fast rotation etc) and gas microphysics (photon/neutrino or efficient/inefficient cooling)

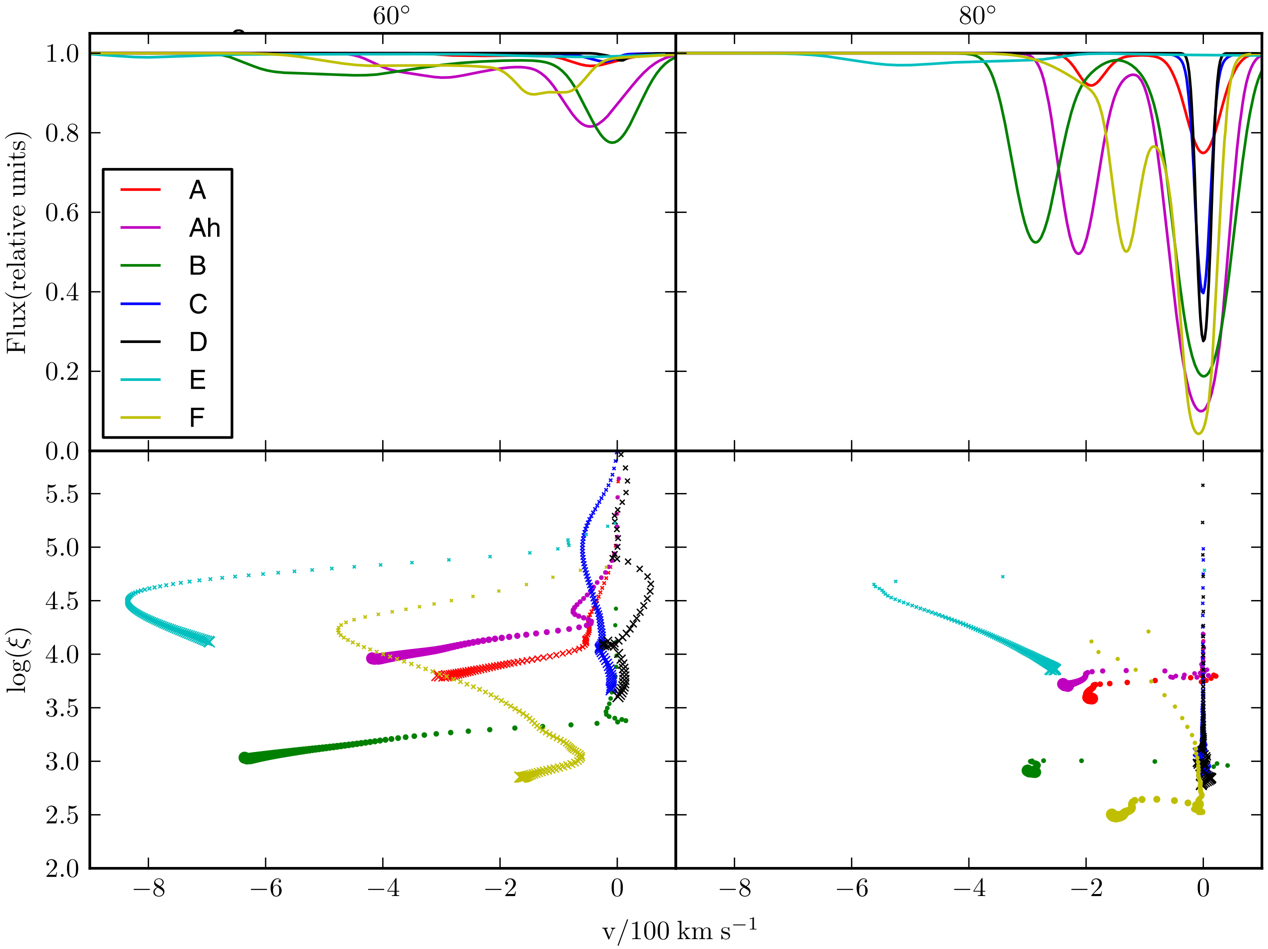
Balbus & Hawley (1991). Stress arises from correlated magnetic and velocity fluctuations with the turbulence itself. Nonlinear saturation of MRI has been widely studied with both local ("shearing-box") and global simulations.



e.g., DP et al. (2003a/b), Moscibrodzka & DP (2008, 2009)

Thermal winds: effects of SED, flux and adiabatic cooling.





Higginbottom & Proga (2015)