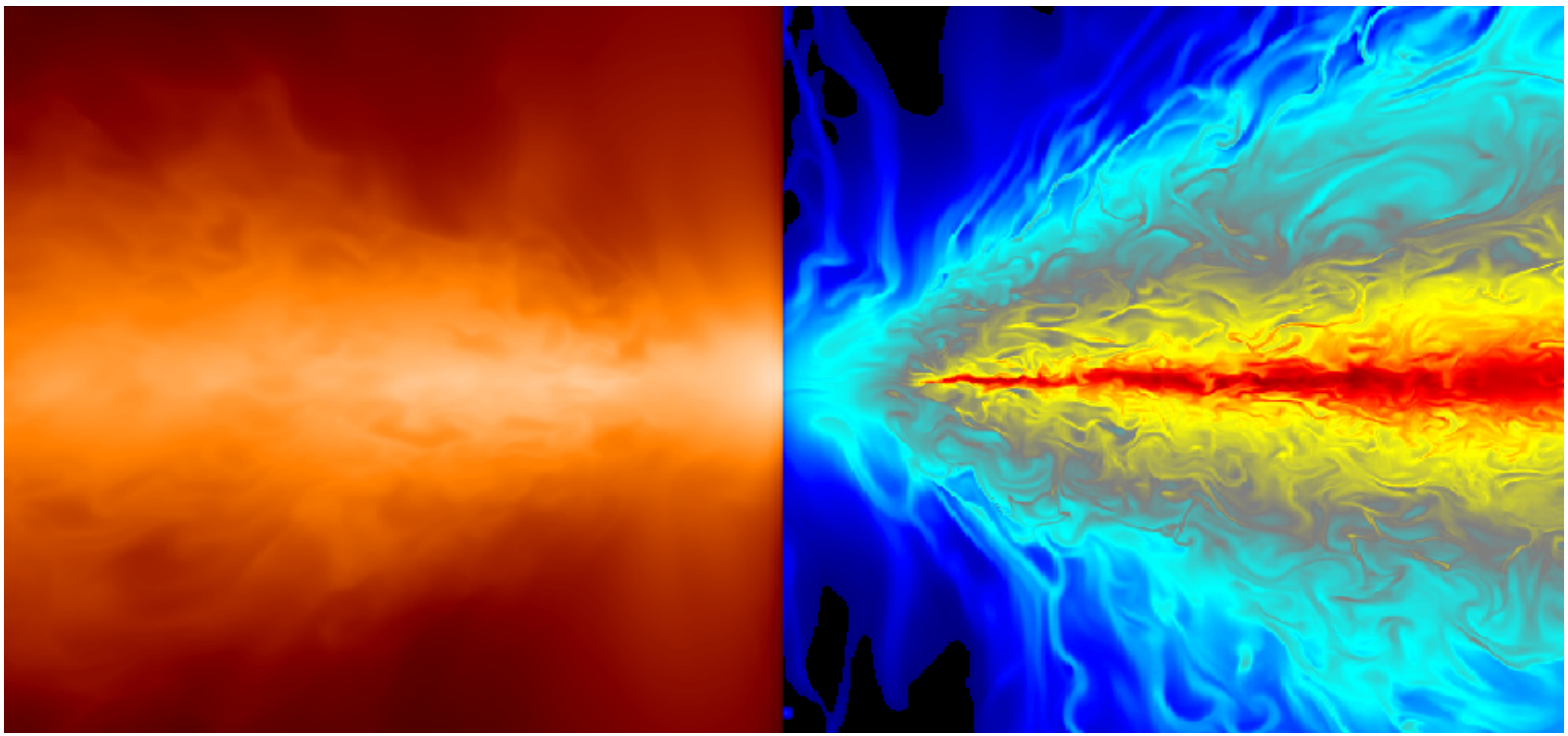
Impact of Opacity in Quasar Accretion Flows

Shane Davis (U. of Virginia), Aug. 7, 2019

with Yan-Fei Jiang (KITP/CCA), Yara Yousef (UVa), Jim Stone (IAS), Omer Blaes (UCSB) and Ari Laor (Technion)



Standard Accretion Disks

The standard accretion disk model (SS73) depends rather simply on mass and accretion rate. The effective temperature follows a relation:

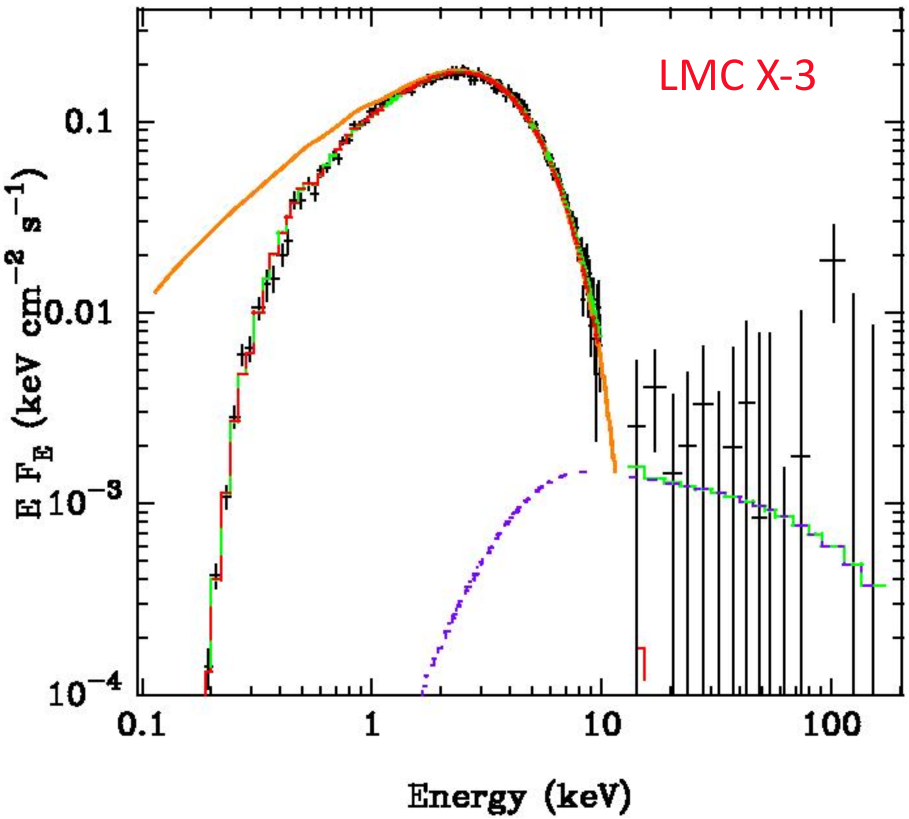
$$T \approx 50\mathrm{eV}\left(\frac{M}{10^8 M_\odot}\right)^{-1/4}\left(\frac{\dot{M}}{\dot{M}_{\mathrm{Edd}}}\right)^{1/4}\left(\frac{r}{r_g}\right)^{-3/4}$$

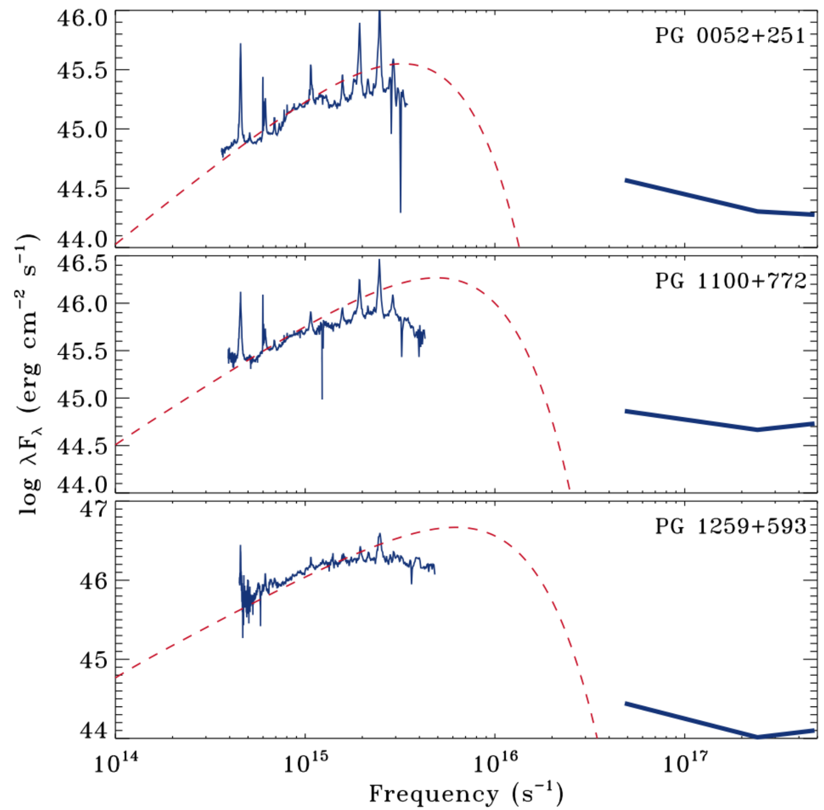
where I have glossed over the dependence of torques (etc.), and location of the inner edge (spin?).

If this is all there was to accretion, we would expect supermassive black holes to simply be colder version of stellar mass black holes – works to first order: AGN peak in UV, X-ray binaries peak in X-ray

Spectral Differences

Black hole X-ray binaries peak almost exactly where they should, but supermassive black hole do not. Typical quasar spectrum should peak in the extreme UV but typical peak is closer to 1000 ang. Just dust?



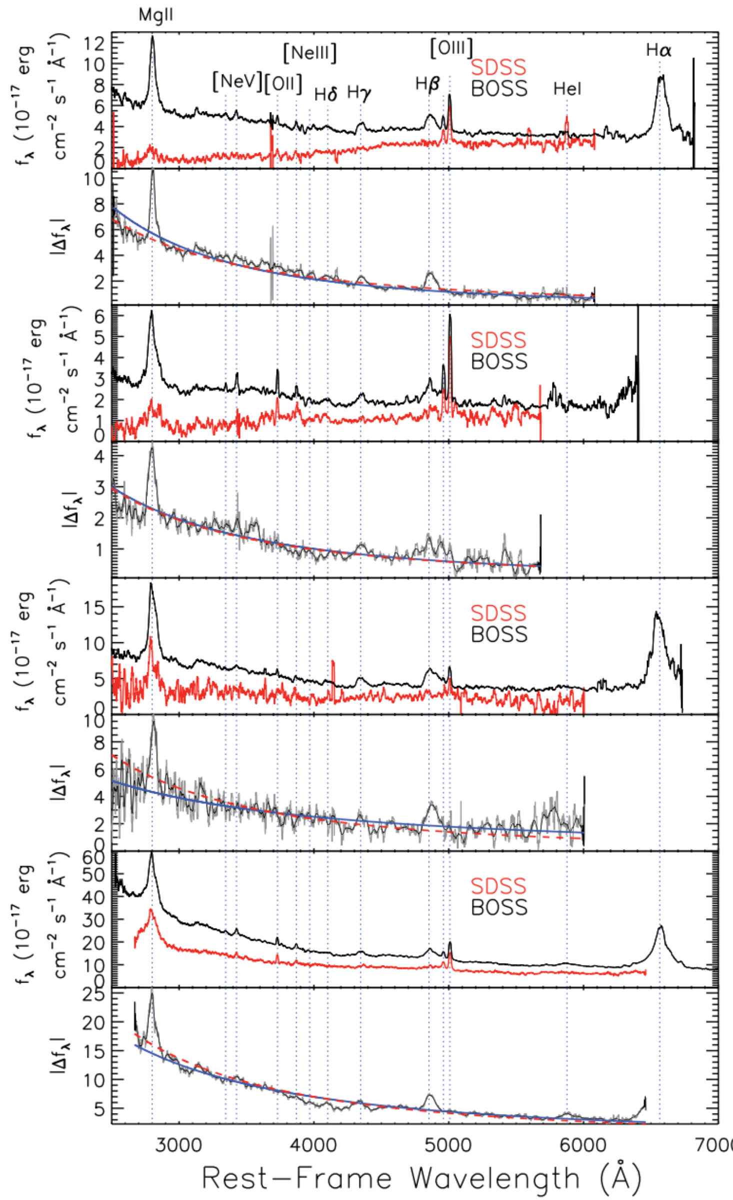


See also: Bonning+ 2007, Davis, Woo & Blaes 2007, Davis & Laor 2011, Stern & Laor 2012, Jin, Ward & Done 2012, Capellupo+ 2015, …

Other Differences/Issues with AGN

Microlensing and continuum reverberation sizes indicate that the emission/reprocessing regions in AGN are larger than standard model prediction (e.g. Morgan+ 2010; Edelson+ 2015)

A fraction of AGN show extreme variability on short time scales (changing look AGN) while the disk dominated part of X-ray binary spectra are low variability (e.g. Done & Gierlinski 2014)



MacLeod+ 2016

And more…

Theoretical Differences

Radiation pressure SS73 tells us that radiation pressure is much larger relative to gas pressure in AGN than X-ray binaries. Thermal and inflow instability? Radiation damping/viscosity?

Opacities Electron scattering plays dominant role in X-ray binaries but less important in AGN, where the UV opacity is dominated by atomic transitions

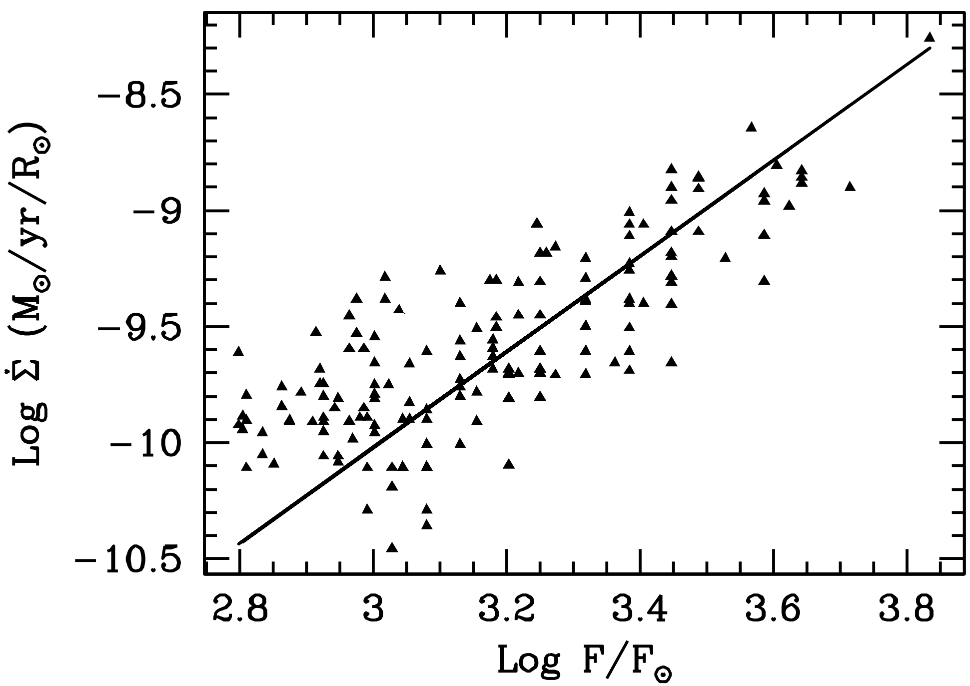
Environment Feeding may be more complicated and more heterogeneous in AGN. Accretion of magnetic flux? Disk self gravity? Obscuration? Interactions with stars?

Line Driven O star winds

Simulating disk with feedback from the mass loss is very difficult!

Can we do something really simple like parameterizing the mass loss and seeing how that would affect the disk?

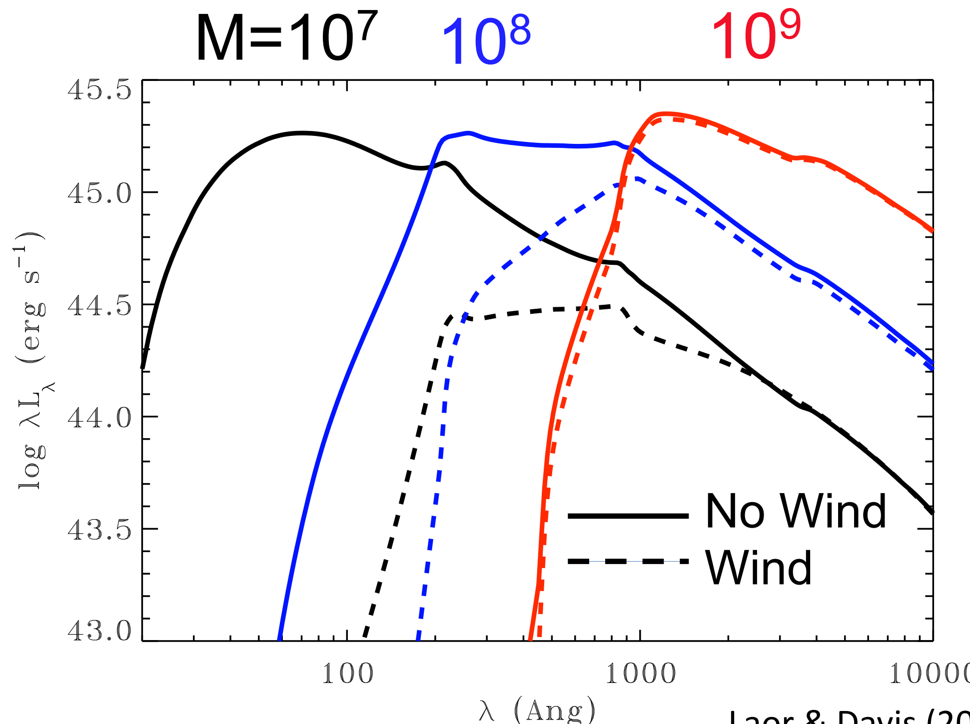
Mass loss rates from O star seem to correlate well with the flux (and surface gravity).



Laor & Davis (2014)

Effect of Mass Loss on SED

Strong dependence of mass loss on flux effectively caps T_{eff}, leading to SED peak always near 1000 ang but requires huge outflows launched from r < 200 R_g



Laor & Davis (2014)

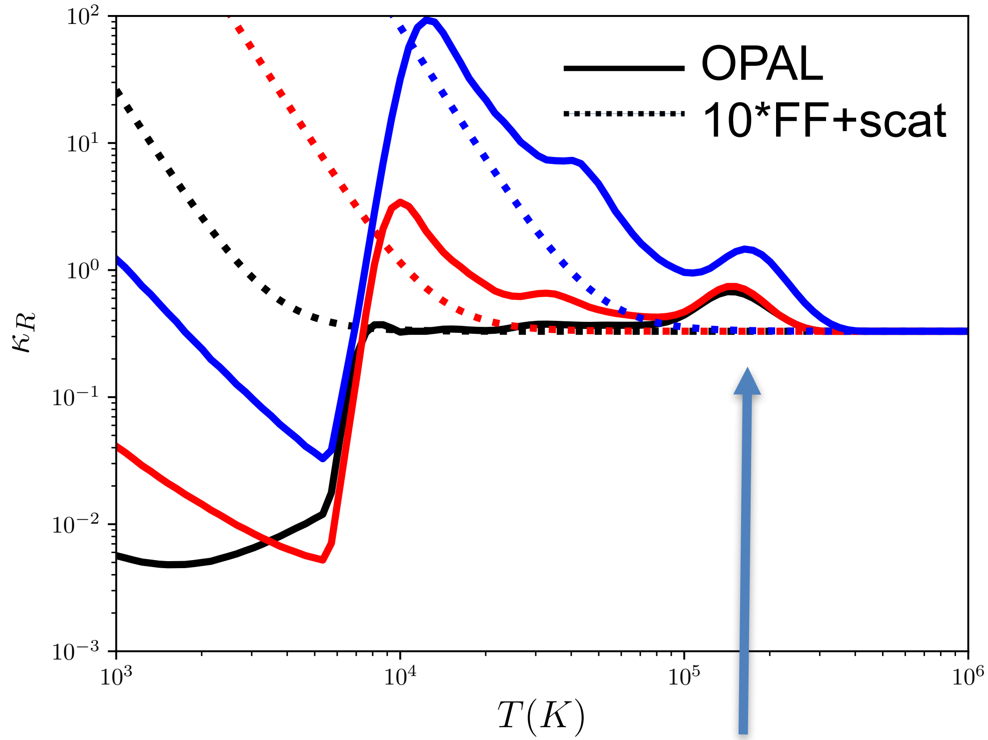
This model is not without issues – unclear if such high mass outflow rates are possible close to the BH due to X-ray ionization,   Doesn't include reprocessing of disk continuum by wind.

Quasar Opacity Regime

X-ray binary opacity is dominated by electron scattering but AGNs are in the same temperature and density ranges as stars so contributions from atomic transitions are very important!

This is likely the *minimum* opacity since it only assumes thermal broadening and ignores the effect of Doppler shifting for moving gas that leads to line driven winds in stars.

$\rho = 10^{-12}$, 10^{-10}, 10^{-8} g/cm^3



Fe opacity bump: This can't really be a big deal, can it?

1D Models of Vertical Structure

Can solve coupled equations of hydrostatic and radiative equilibrium, and radiative transfer for mean (opal) opacities in accretion disk annuli, making same assumptions as SS73. Compare with free-free + Thomson opacity

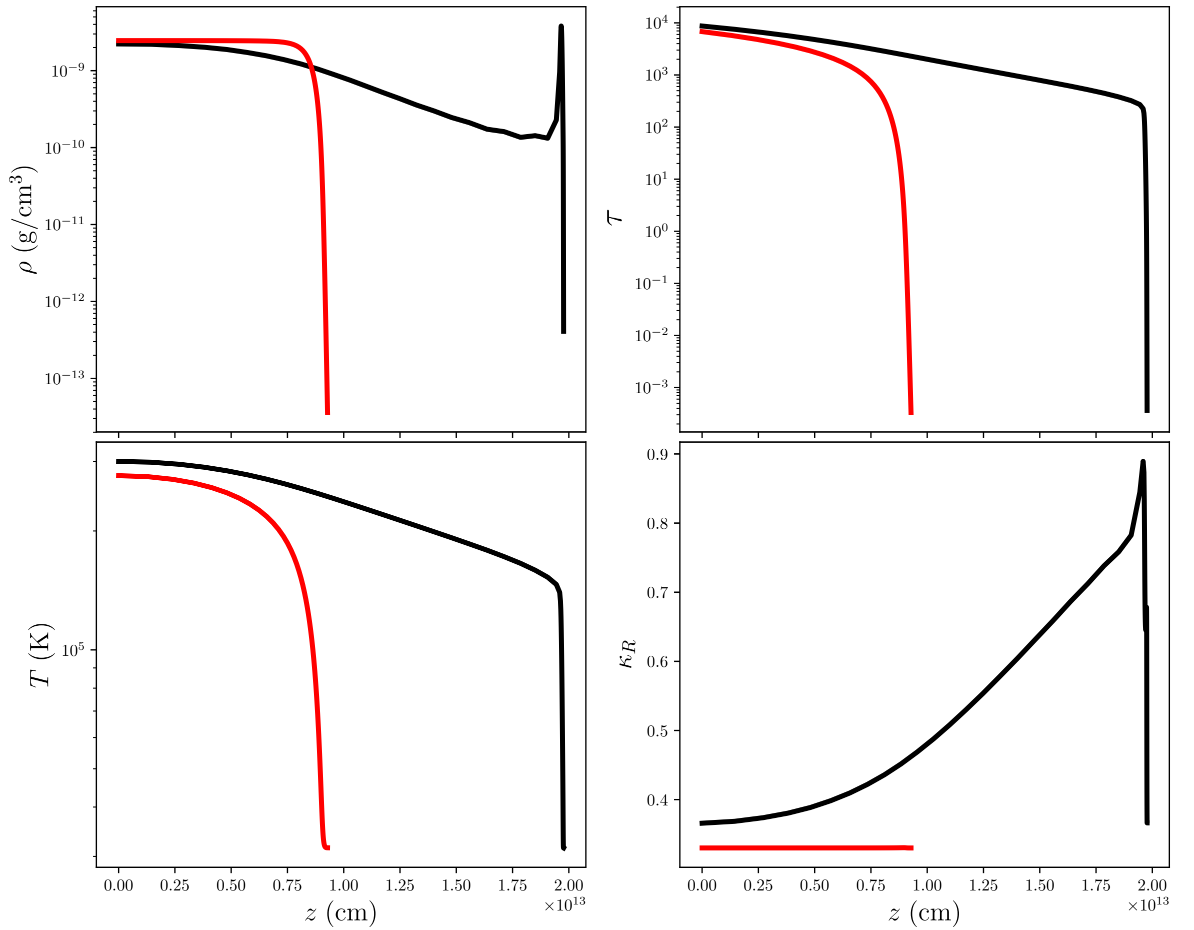
Free-free + Thomson

Opal

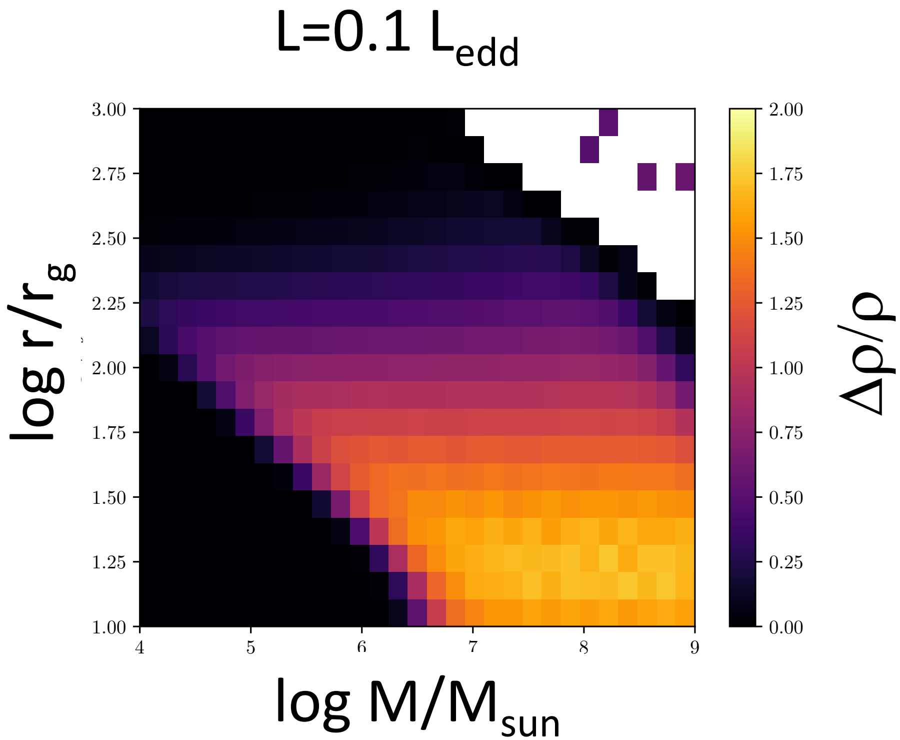
10^8 M_{sun}, 0.1 L_{edd},

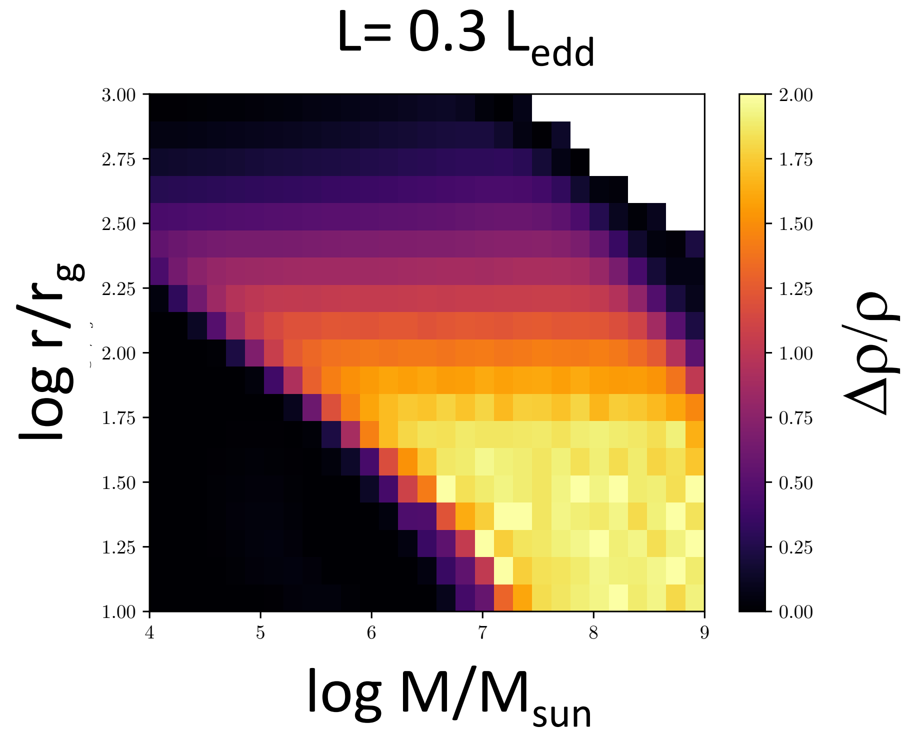
α=0.1, a=0, 30 r_g

Outcome: extended atmospheres and density inversions in surface regions



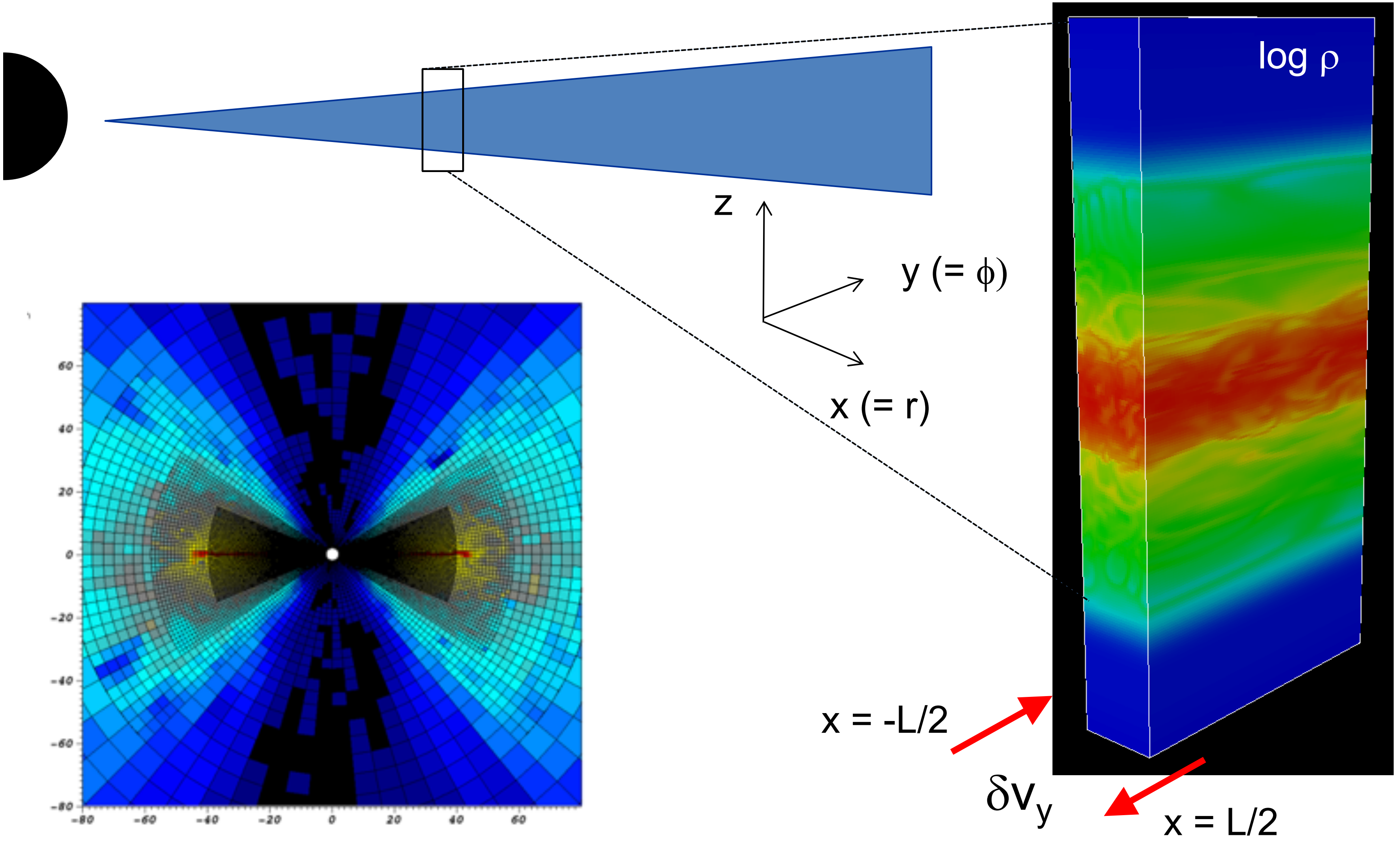
Variations with Mass and Radius





With more realistic opacity, density inversions are generic and can be quite large. Standard disk model doesn't really hold at all radii in the range of masses and accretion rates of interest!

Accretion Simulations



Radiation Hydrodynamics in Athena++

Jiang+ 2014

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

$$\frac{\partial (\rho \boldsymbol{v})}{\partial t} + \boldsymbol{\nabla} \cdot (\rho \boldsymbol{v}\boldsymbol{v} - \boldsymbol{B}\boldsymbol{B} + \mathsf{P}^*) = -\boldsymbol{S_r}(\boldsymbol{P}) - \rho \boldsymbol{\nabla} \phi,$$

$$\frac{\partial E}{\partial t} + \boldsymbol{\nabla} \cdot [(E + P^*)\boldsymbol{v} - \boldsymbol{B}(\boldsymbol{B} \cdot \boldsymbol{v})] = -cS_r(E) - \rho \boldsymbol{v} \cdot \boldsymbol{\nabla} \phi,$$

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

Radiation force

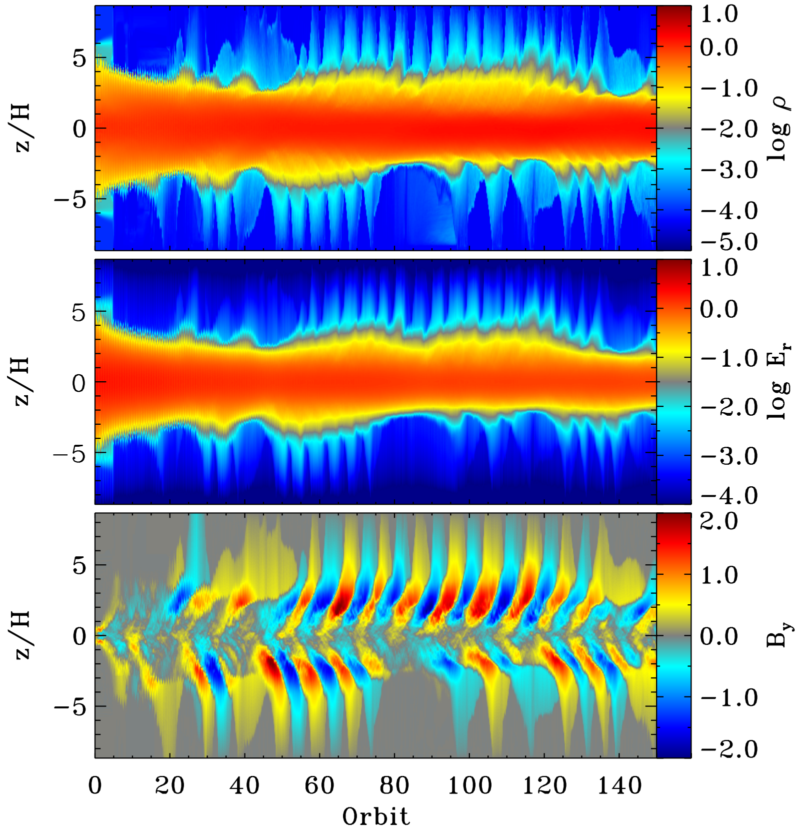
Net heating/cooling

Radiation transfer: $$\frac{\partial I}{\partial t} + c\mathbf{n} \cdot \nabla I = S$$

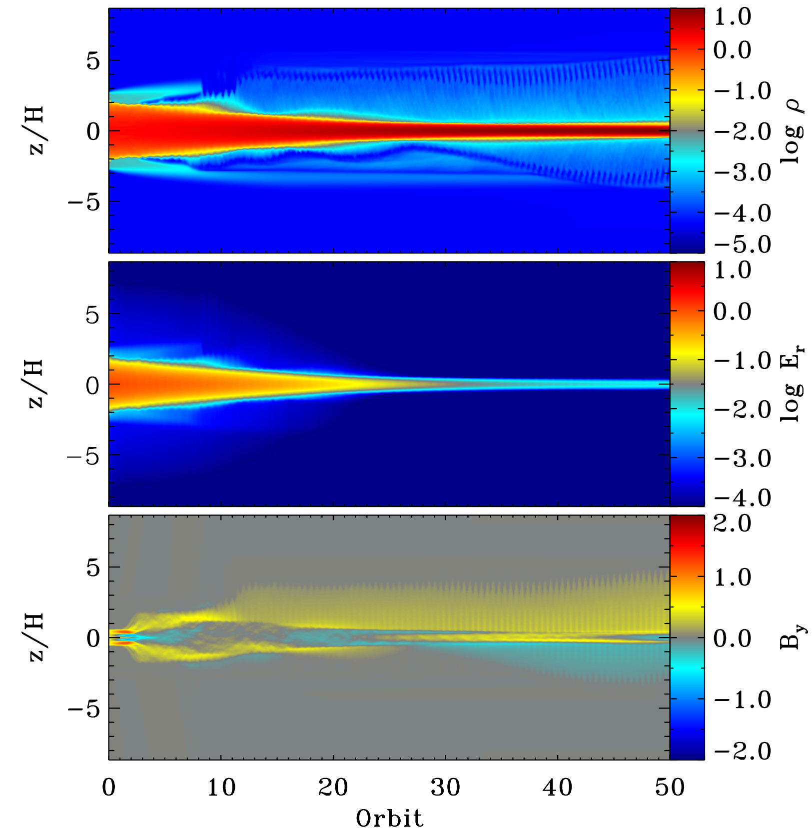
$$S_0 = c\rho \left(\kappa_P \frac{aT^4}{4\pi} - \kappa_E I_0 \right) + c\rho\kappa_s (J_0 - I_0)$$

Shearing Box Simulations of AGN

+ OPAL



Electron Scattering and free-free



- Jiang, Davis & Stone (2016): Scattering only simulations rapidly collapse, but those with OPAL opacity persist for 10+ thermal times!
- Compare with Grzędzielski+ 2017

Shearing Box Simulations of AGN

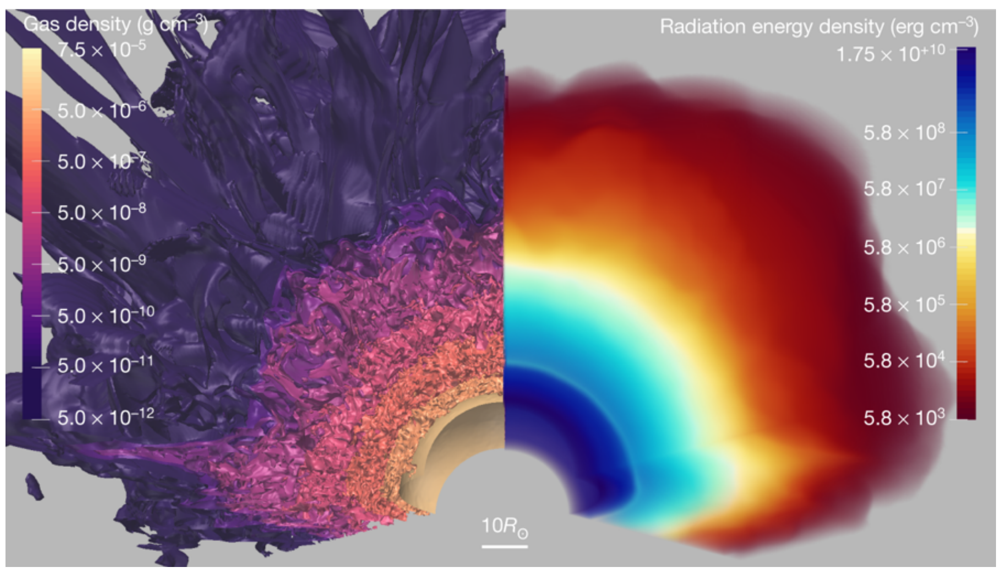
Results with OPAL models:

- Models are thicker: 3-4 times than standard disks
- Unstable entropy gradient and evidence for convection – very different from most previous shearing box simulations where MRI turbulence sets up stable entropy gradients
- Convection is clearly important for disk thermodynamics. Stability is not just a matter of changing opacity – enhanced convection matters!
- No sign of density inversions that are present in 1D models – wiped out by convection!

Implications

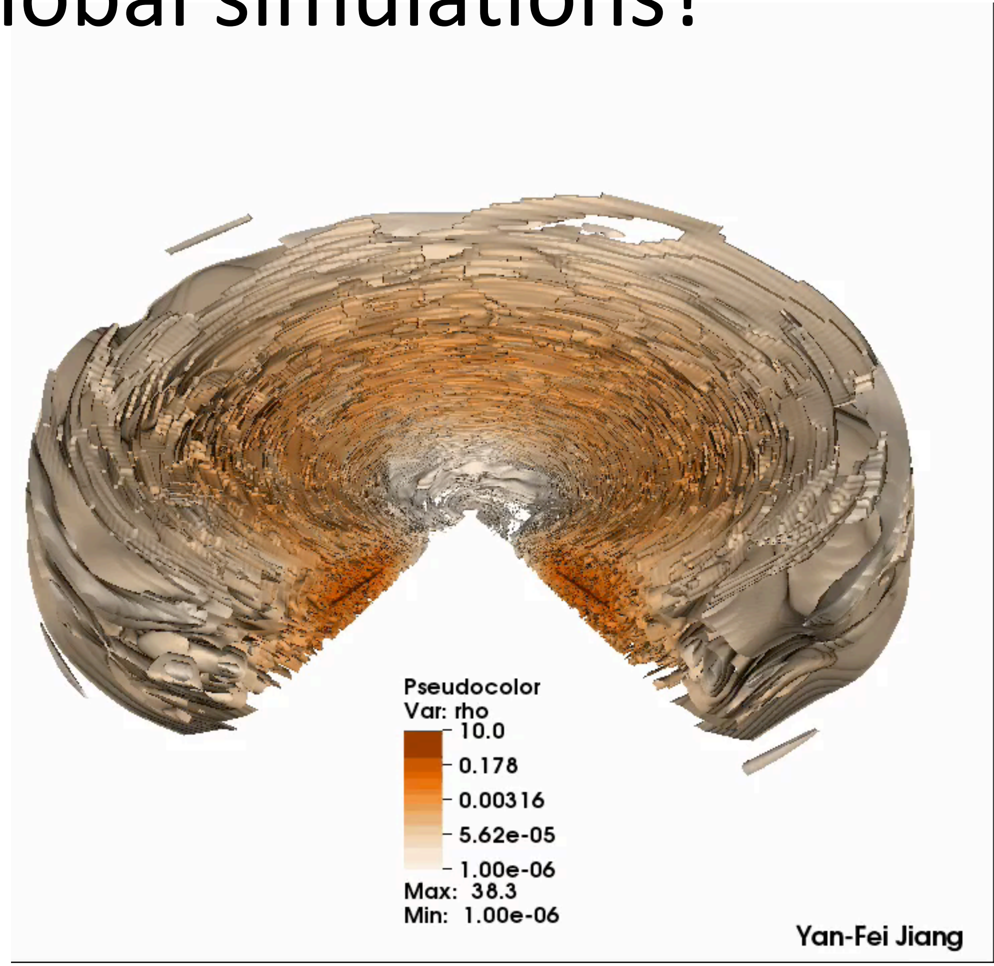
So what? Maybe this only causes modest differences in the scale height and reprocessing. Maybe disks are still globally unstable (e.g. Grzędzielski+ 2017)?

BUT, reminiscent of very massive stars, where same opacities lead to similar inversions in 1D stellar evolution models. 3D simulations show opacity and convection can drive significant mass loss (Jiang+ 2018)



So what about global simulations?

- Algorithms now running in Athena++ code: Jiang+ 2019a,b
- Transfer still not fully general relativistic in production runs, but partially working
- Simulations of 5×10^8 M_{sun} BH with OPAL opacity
- Simulate black hole accretion with pseudo-Newtonian potential, non-relativistic MHD and transfer



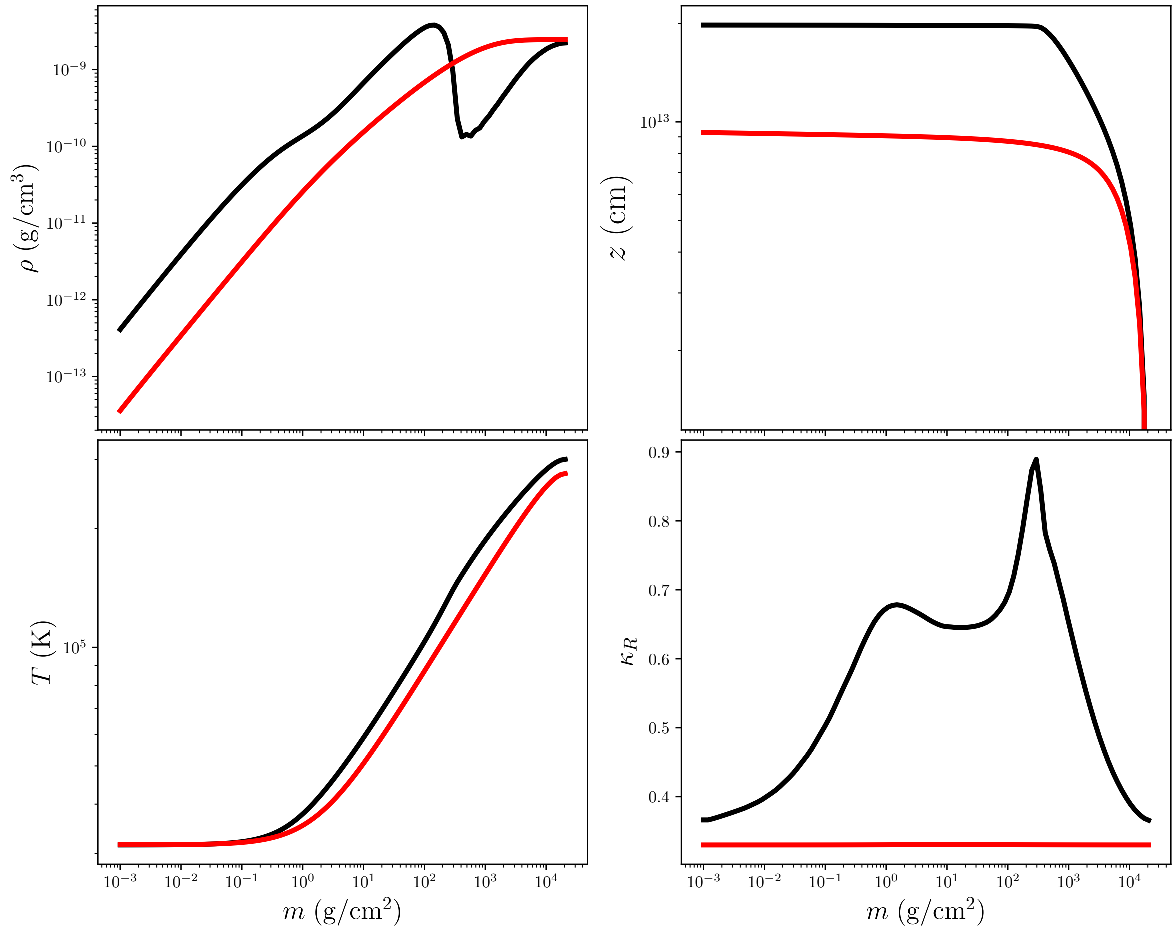
Unfortunately, only get inflow equilibrium out to ~20 R_g where flow is too hot for Fe bump.

Need new simulations in relevant regime → Omer's talk!

1D Models of Vertical Structure

Can solve coupled equations of hydrostatic and radiative equilibrium, and radiative transfer for mean (opal) opacities in accretion disk annuli, making same assumptions as SS73. Compare with free-free + Thomson opacity

Free-free + Thomson
Opal
10^8 M_{sun}, 0.1 L_{edd},
α=0.1, a=0, 30 r_g



Outcome: extended atmospheres and density inversions in surface regions

$dm = -\rho\, dz$

Summary

- Accretion disk theory seems to work ok for disk dominated X-ray binaries but not AGN. Why?

- UV Opacity is a good candidate for why AGN would deviate more from a standard disk model. Seems to affect both stability and structure of disk in local simulations.

- May drive winds but could also impact the disk structure and thermodyanimcs

- Impact of opacity likely depends on accretion rate, mass, spin and radius within the disk. Also on metallicity?

- Need global simulations that probe the correct regime…