Simulations of accretion disks and outflows

Shane Davis (U. of Virginia), Technion, May 24, 2017

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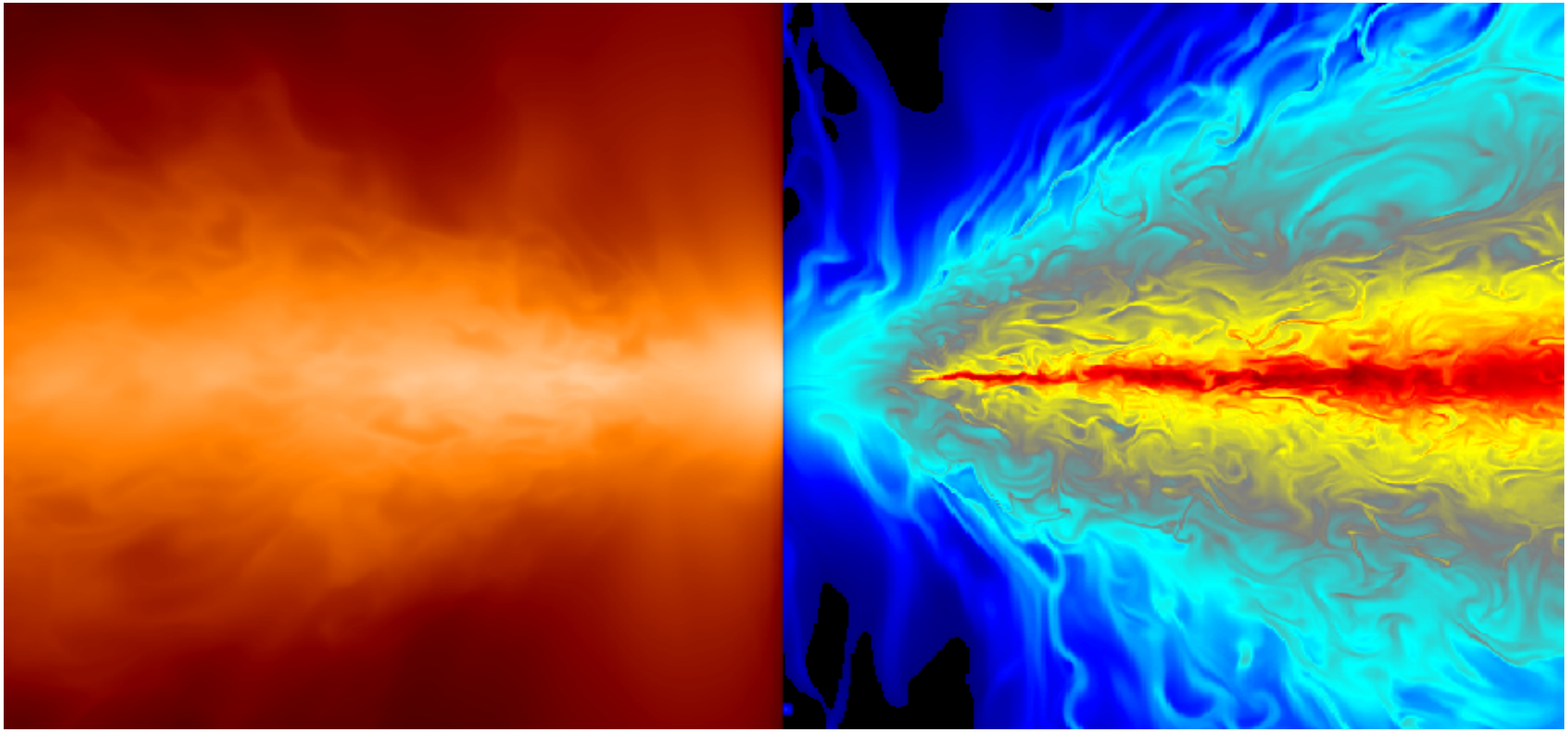


Questions

- What role does UV opacity play in the structure and evolution of accretion disks?
- What can simulations tell us about how winds are launched by radiation and, in particular, how that launching feeds back on the disk structure?
- Given the limits of numerical simulations, how can we best design the simulations that address these issues?
- Do the outflows being launched at relatively small radii in accretion disk simulations connect with either the broad absorption line quasars or ultrafast outflows?

Accretion Disk Scale Invariance

The standard accretion disk mode is approximately "scale invariant" with respect to mass and accretion rate. The effective temperature follows a relation:

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

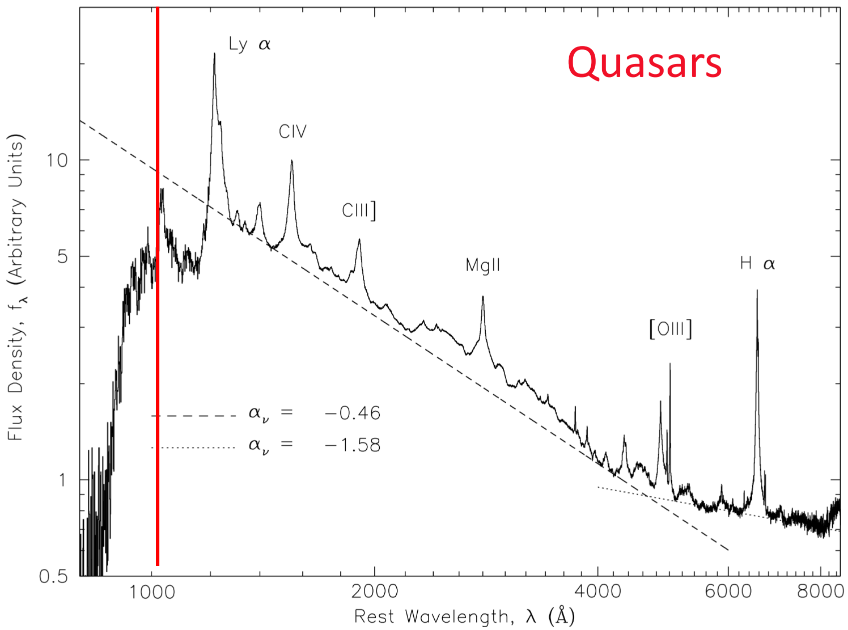
where I have glossed over the dependence of torques (etc.), and location of the inner edge (spin?).

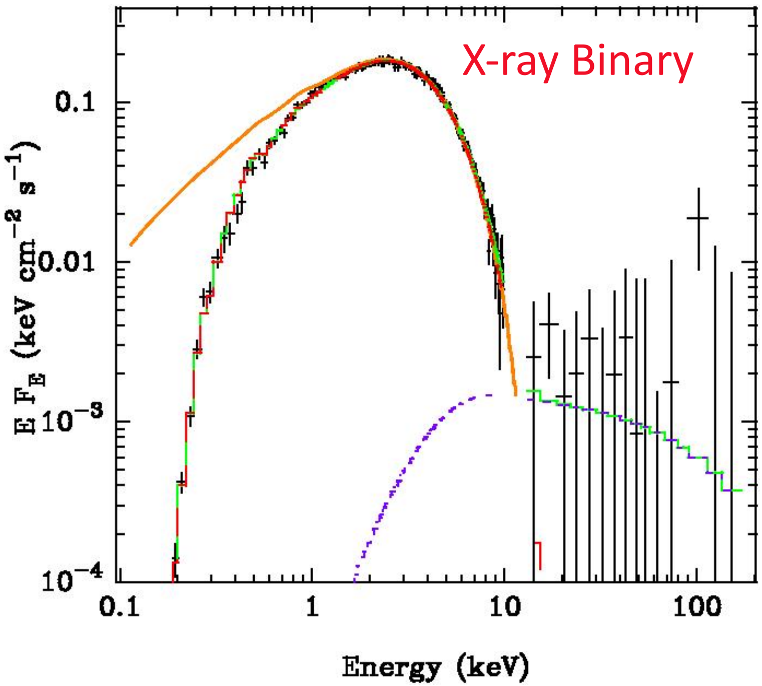
If this is all there was to accretion, we would expect supermassive black holes to simply be colder version of stellar mass black holes – easy to test with 9 orders of magnitude in mass.

Black Holes: Small are Hot, Big are Cold

And it basically works – supermassive black holes peak in the UV while stellar mass black holes peak in the X-rays.

Vanden Berk+ (2001)



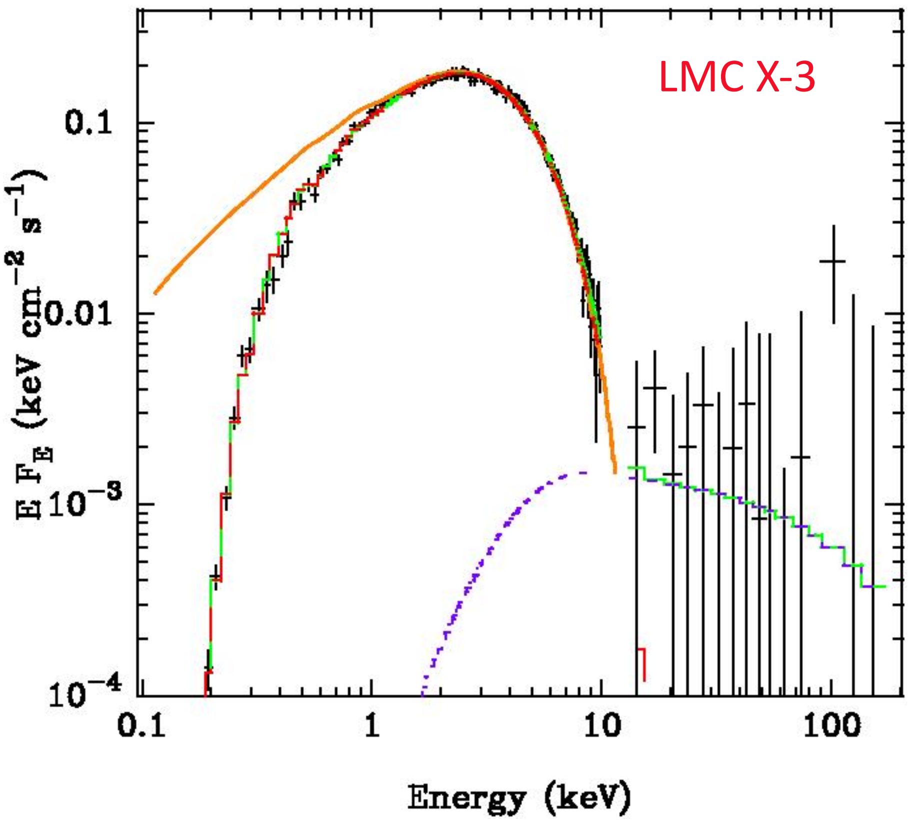


Davis+ (2006)

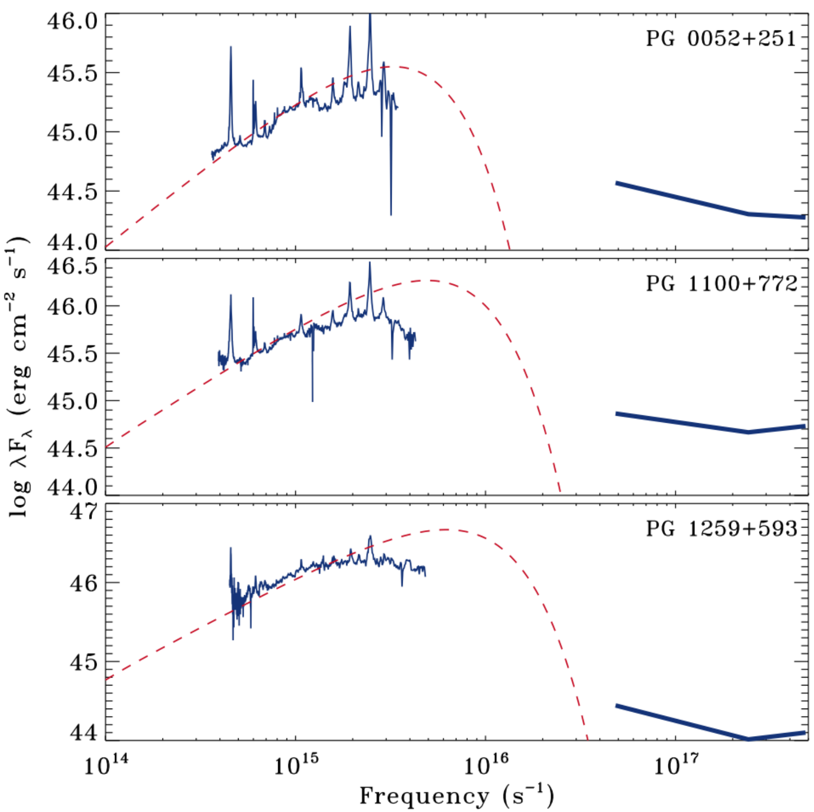
Also works ok for accreting white dwarfs and neutron stars.

If you look close there is an issue

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.



~10 M_{sun} BH



10^8 M_{sun} BHs

What is different about AGNs?

Radiation pressure Since SS73, we have known 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 includes Lyman and He edges, combined contribution of strong resonance lines and large number of weaker lines.

What is different about AGNs?

Dust reddening? Almost certainly present but hard to assess given uncertainties in reddening curve. (see e.g. Hopkins+ 2004, Davis+ 2007, Capellupo+ 2015, Baron+ 2016)

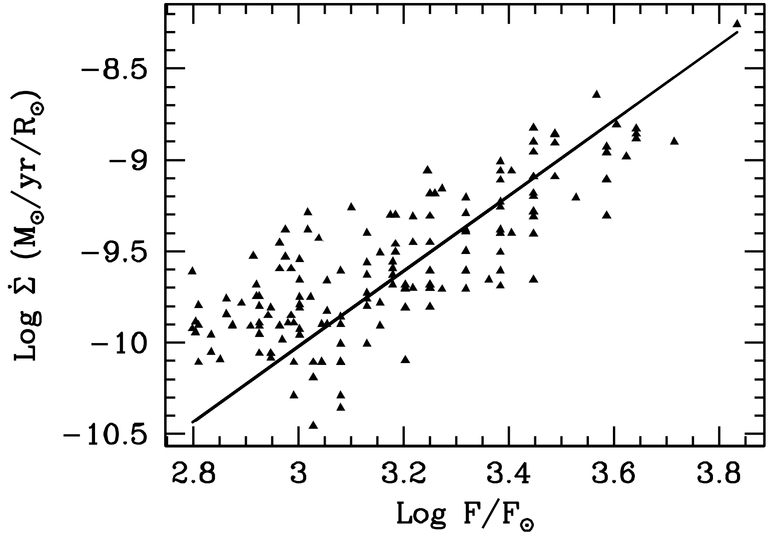
Outflow from accretion disk? Maybe, but needs to be launched close in (~10-100 r_g) and needs to carry away mass at a rate comparable to the accretion rate (see e.g. Sloan & Netzer 2012, Laor & Davis 2014, Capellupo+ 2015)

Line Driven O star winds

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

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

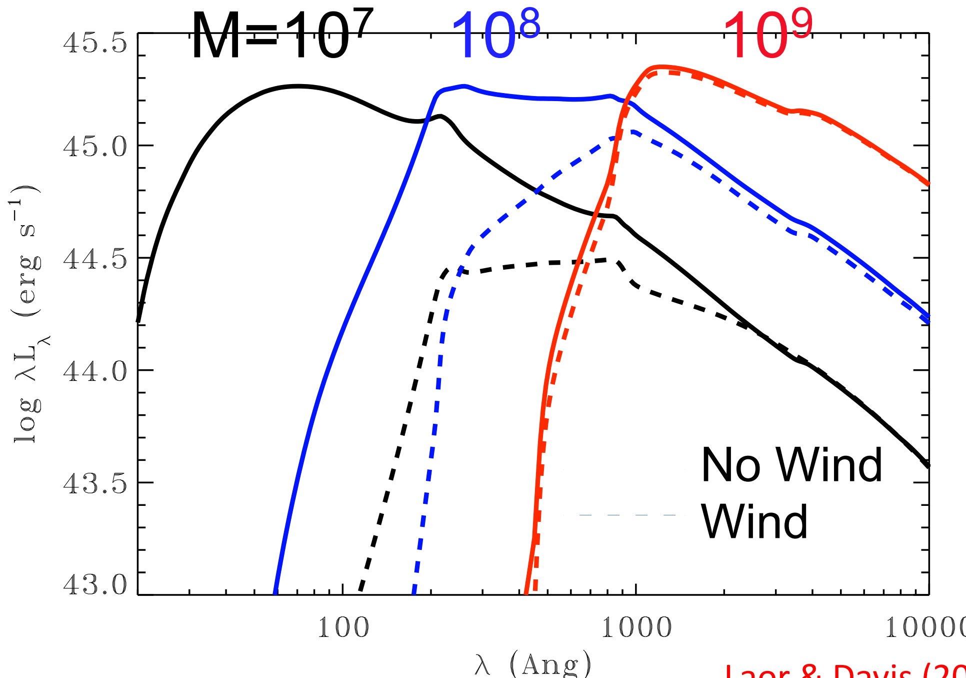
Mass loss rates from O star seem to correlate well with the flux (and surface gravity).



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 M



Laor & Davis (2014)

This model is not without issues – e.g. 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. But, note that some Proga+ simulations did show outflow rates a large fraction of the assumed accretion rate.

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

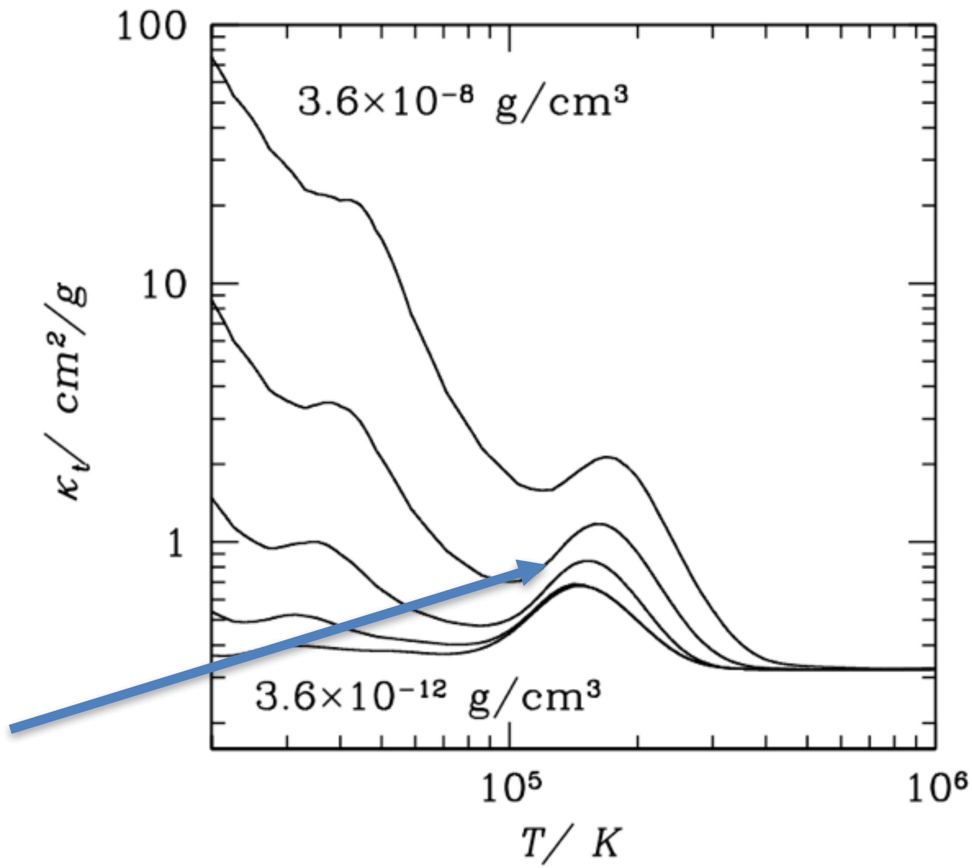
Net heating/cooling

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

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

Grey UV Opacity

AGNs are in the same temperature and density ranges as stars so we use the OPAL opacity tables (adapted by Paxton+2013 for MESA)



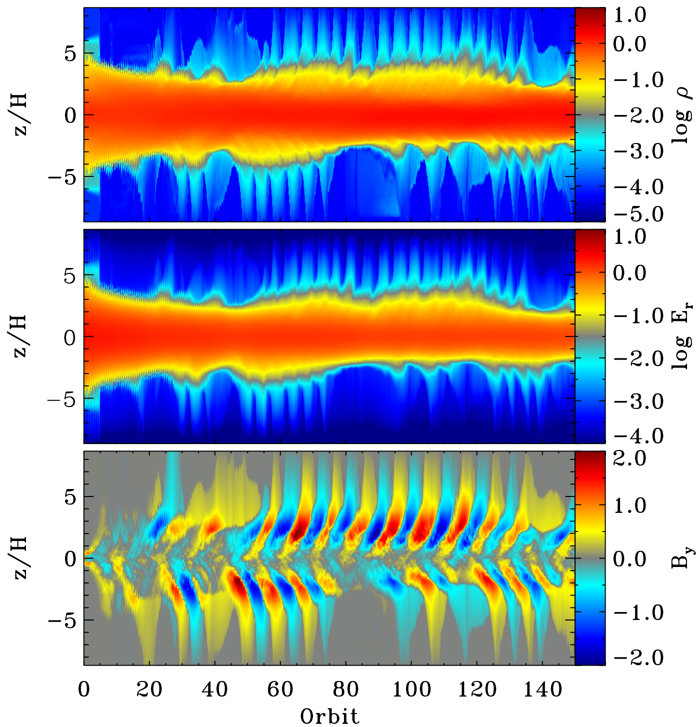
Fe opacity bump: This can't really be a big deal, can it? Maybe…

Further Questions for Discussion

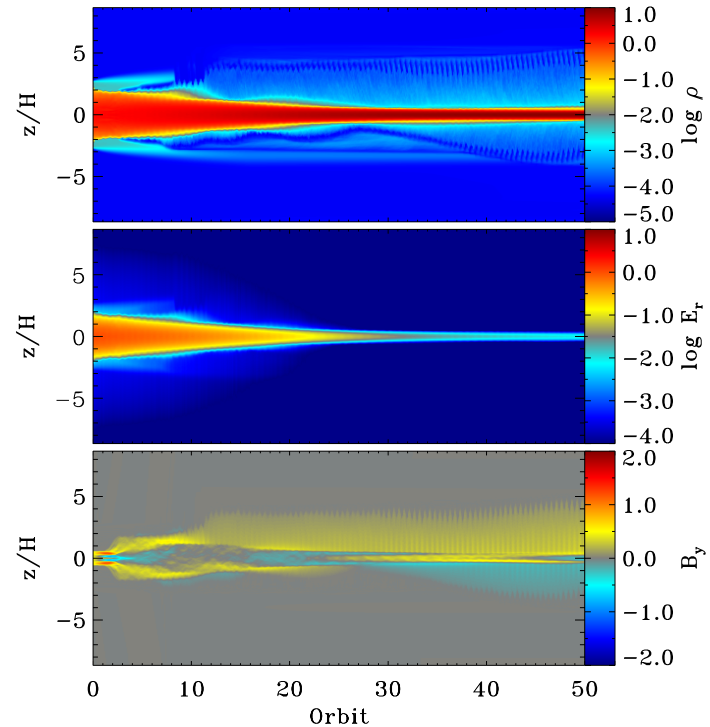
- Is grey opacity sufficient? (Not really, but how bad?)
- How does MHD macroturbulence and shear affect opacity near disk surface?
- Are claims of super-solar abundances in AGN correct? (If true, radiative driving will be enhanced.)
- Can we combine grey opacity with force multiplier formalism?

Local (Shearing Box) Simulations in AGN regime (Jiang+ 2016)

+ OPAL



Electron Scattering and free-free

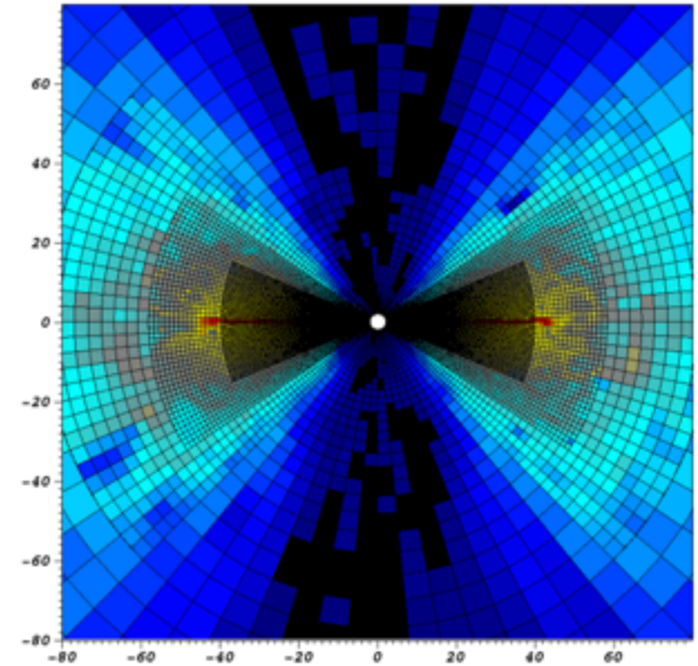


- Scattering only simulations rapidly collapse, but those with OPAL opacity persist for 10+ thermal times. More stable?!
- Models are thicker: 3-4 times SS73! and position of the photosphere varies due to dynamo cycles.

Global Simulations with Athena++

Algorithms now running in Athena++ code:

- General relativisitic magnetohydrodynamics
- Fast with efficient scaling to large numbers of cpus.
- Allows for larger simulations with non-uniform, refined mesh
- Radiation transfer still not fully general relativistic in production runs, but we've begun implementation.
- MHD in current runs is non-relativistic with pseudo-Newtonian potential



Level 0

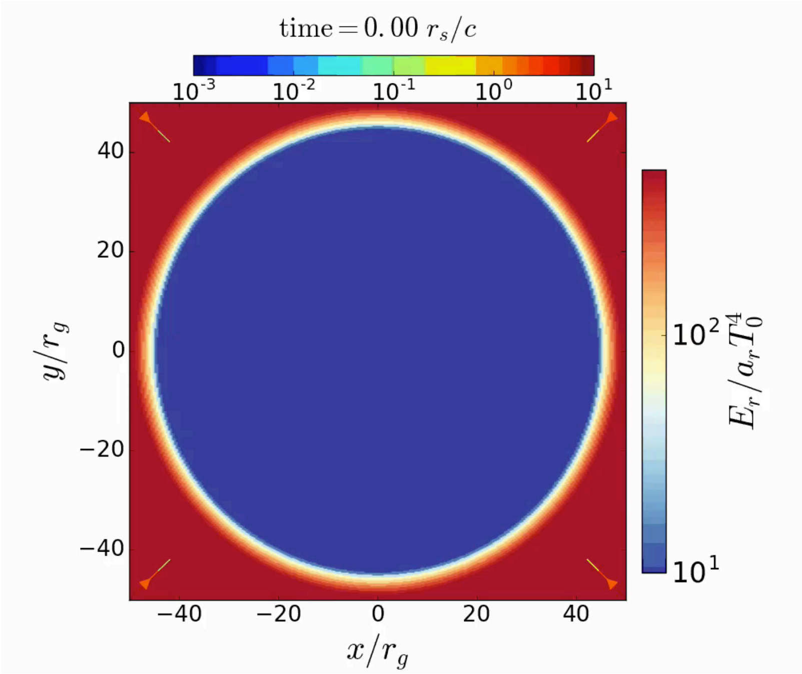
$$N_r \times N_\theta \times N_\phi = 64 \times 32 \times 64$$

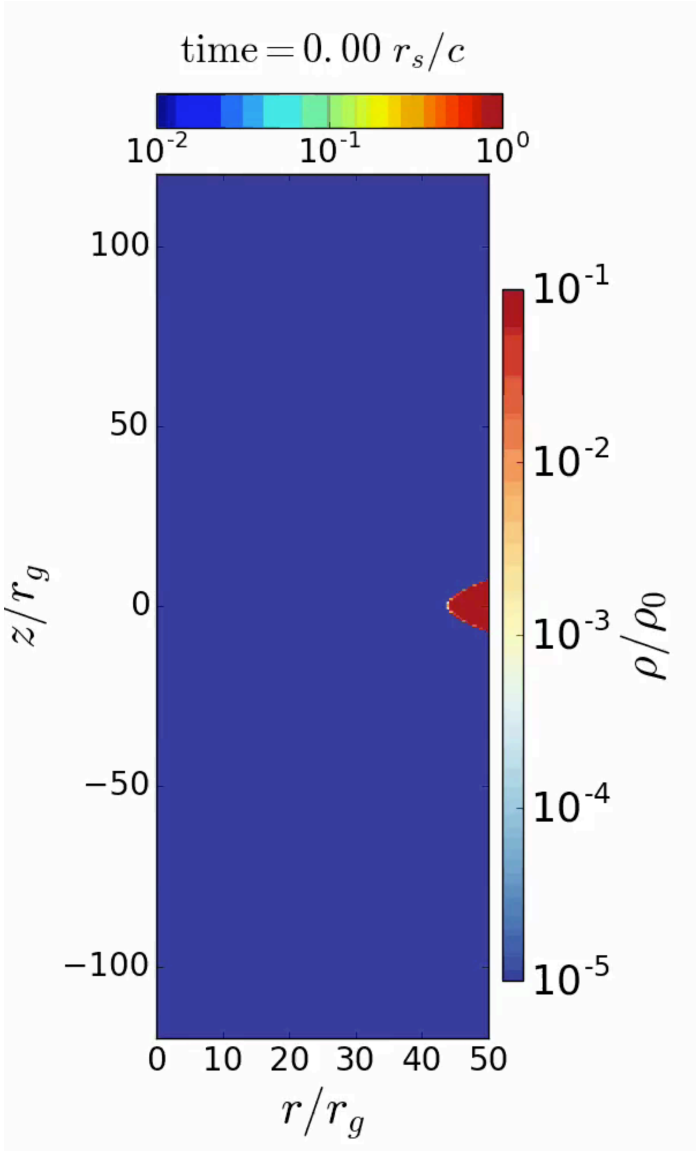
Level 4

$$N_r \times N_\theta \times N_\phi = 1024 \times 512 \times 1024$$

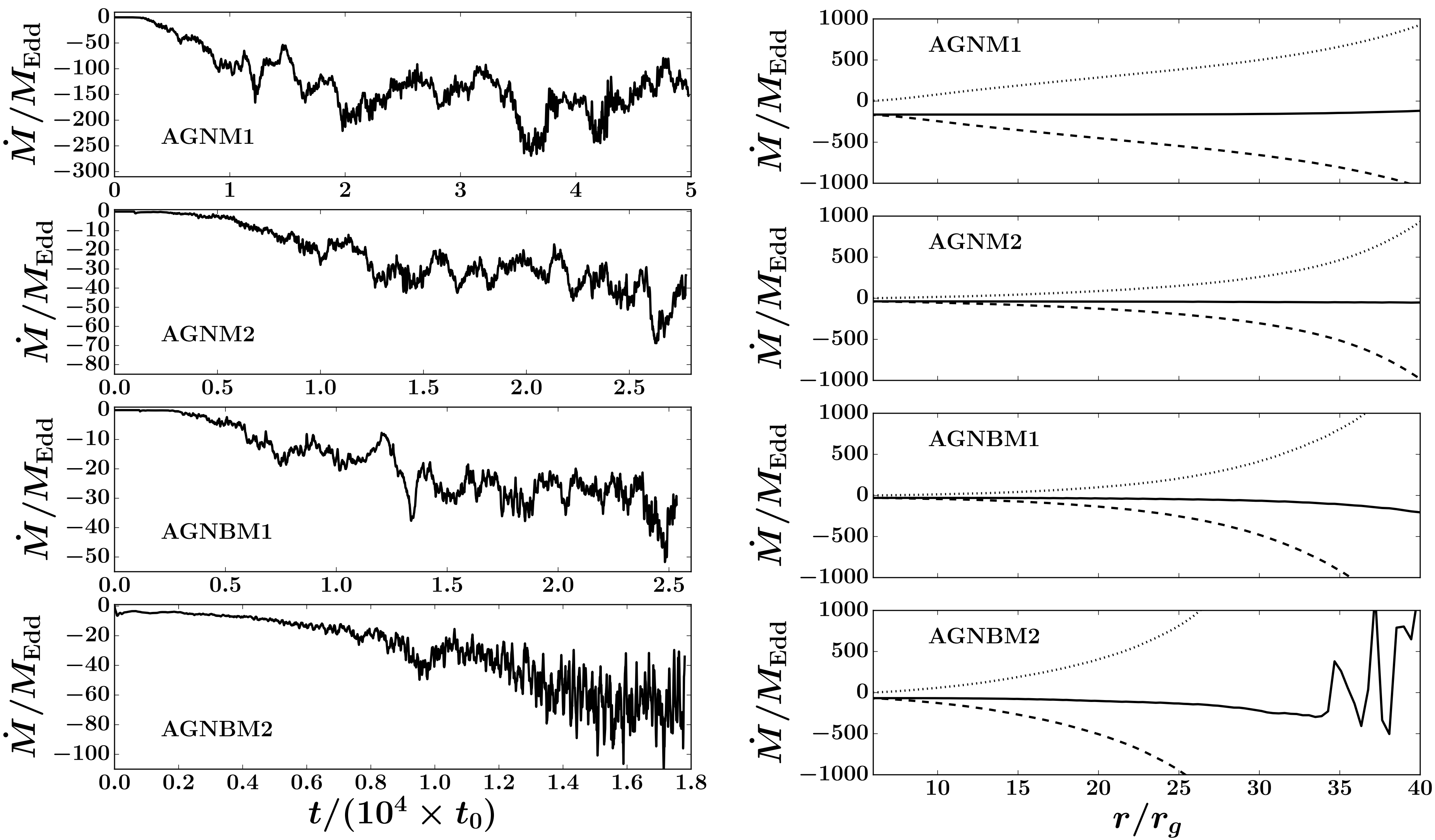
Super Eddington Simulations

Thus far, we have done significant analysis of only four runs with black hole mass of 5 x 10^8 M_{sun}. All initialized by torus centered at 80 r_g. All reach super-Eddington accretion rates

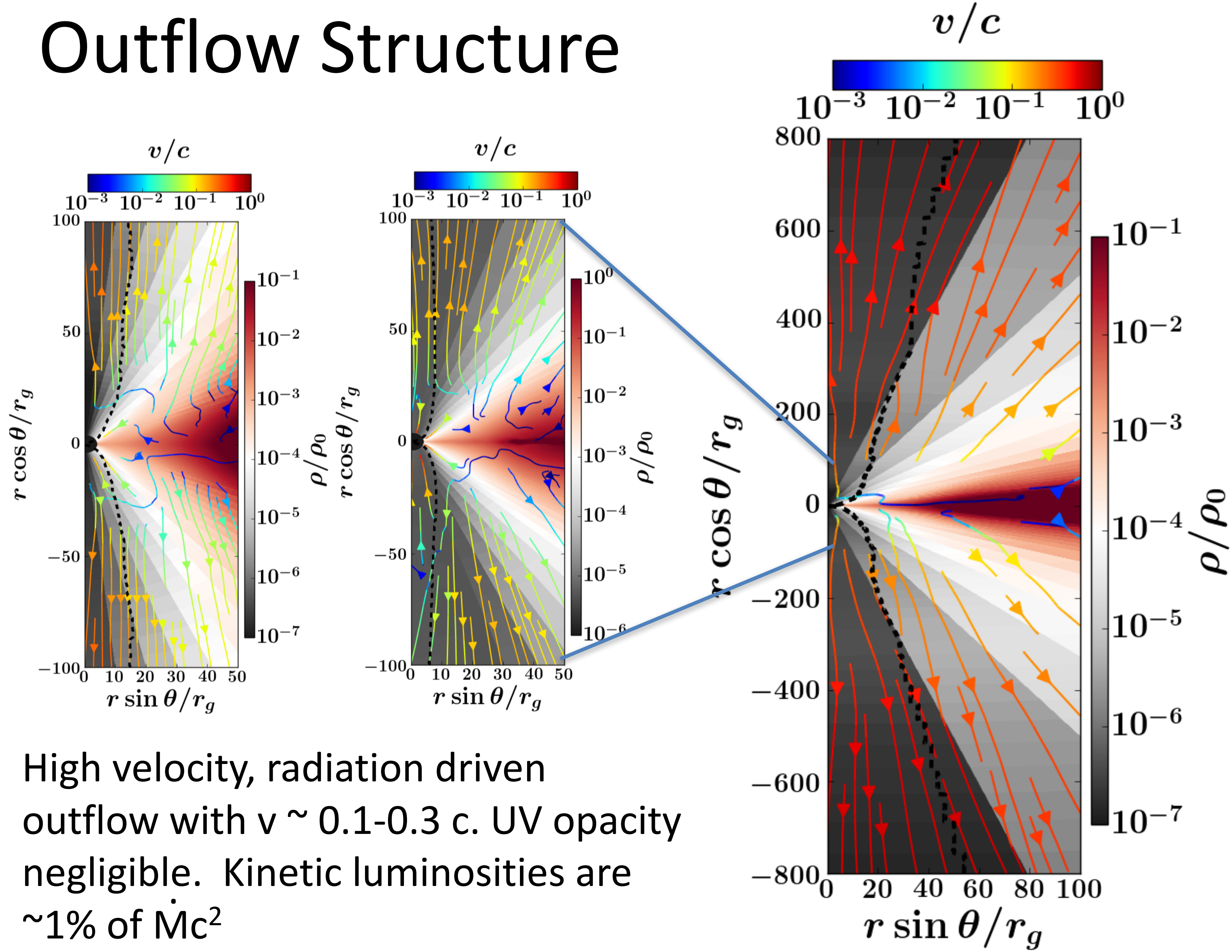




Accretion Rates



Outflow Structure



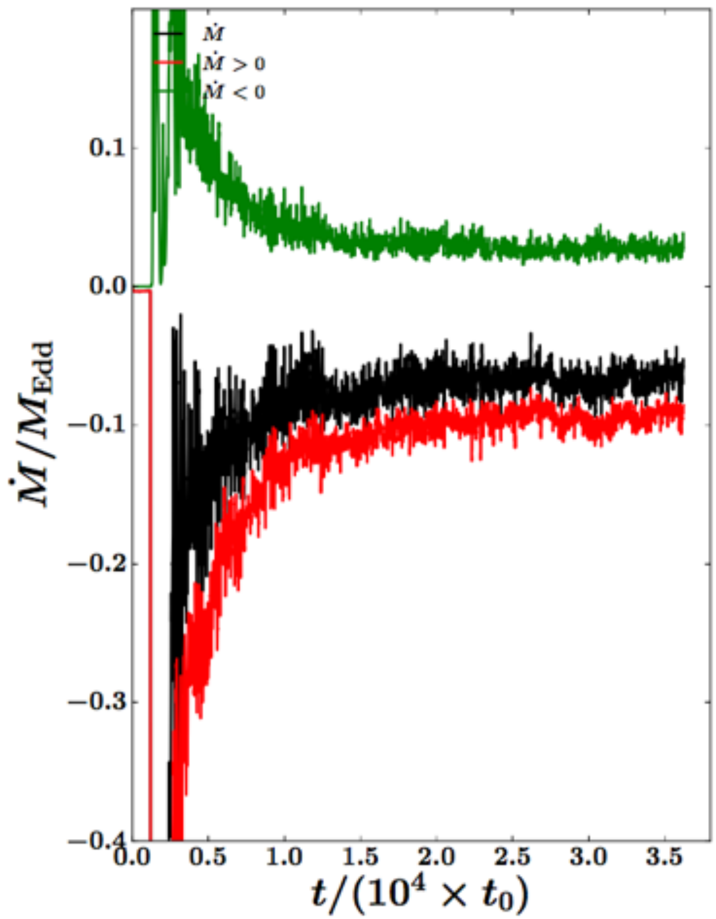
High velocity, radiation driven outflow with v ~ 0.1-0.3 c. UV opacity negligible. Kinetic luminosities are ~1% of $\dot{M}c^2$

THE FOLLOWING IS PRELIMINARY!

Sub-Eddington Simulation

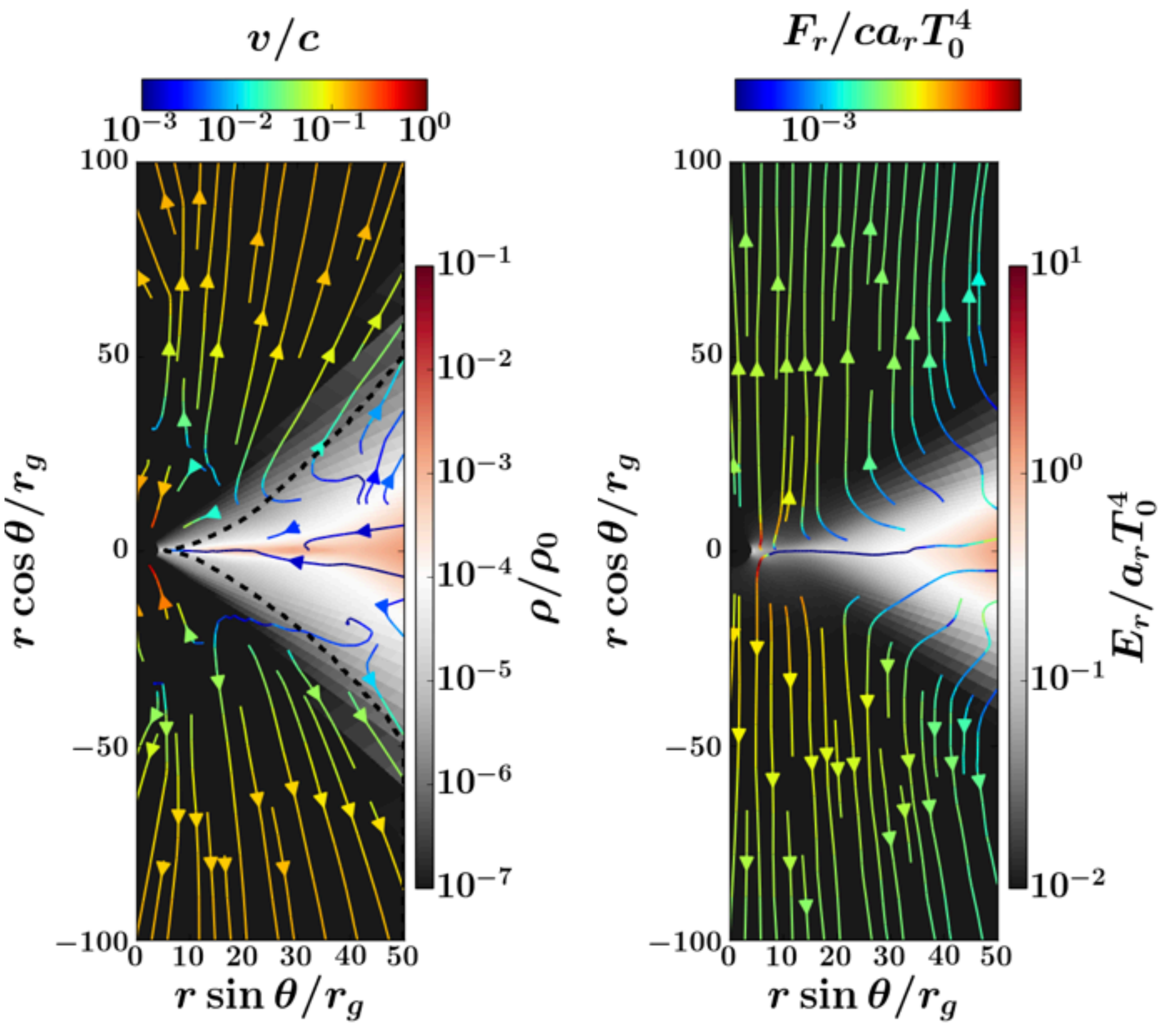
We have one well behaved sub-Eddington accretion rate simulation.

Net inward accretion rate at 10 r_g is about 0.07 M_{edd}, with outflow of ~0.03 M_{Edd}



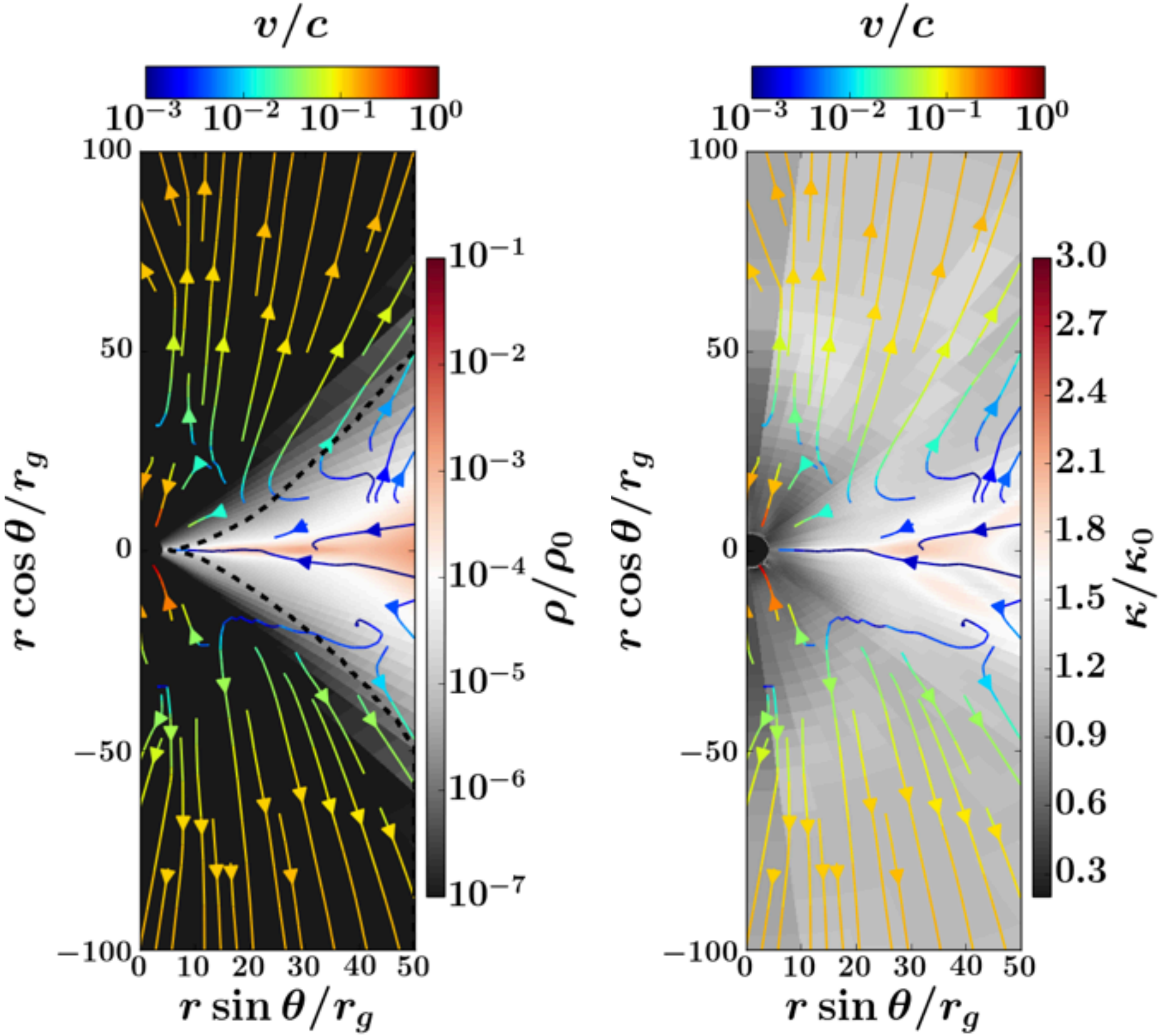
Flow Structure

Outflow velocities are about ~0.1 c and radiation driven even though accretion rate is sub-Eddington.

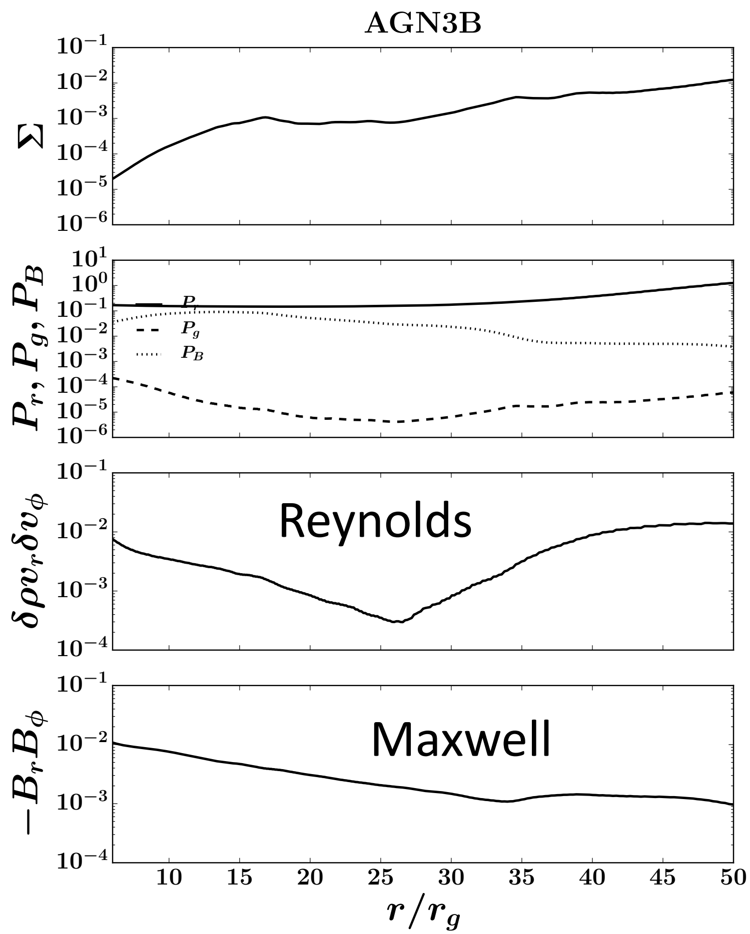


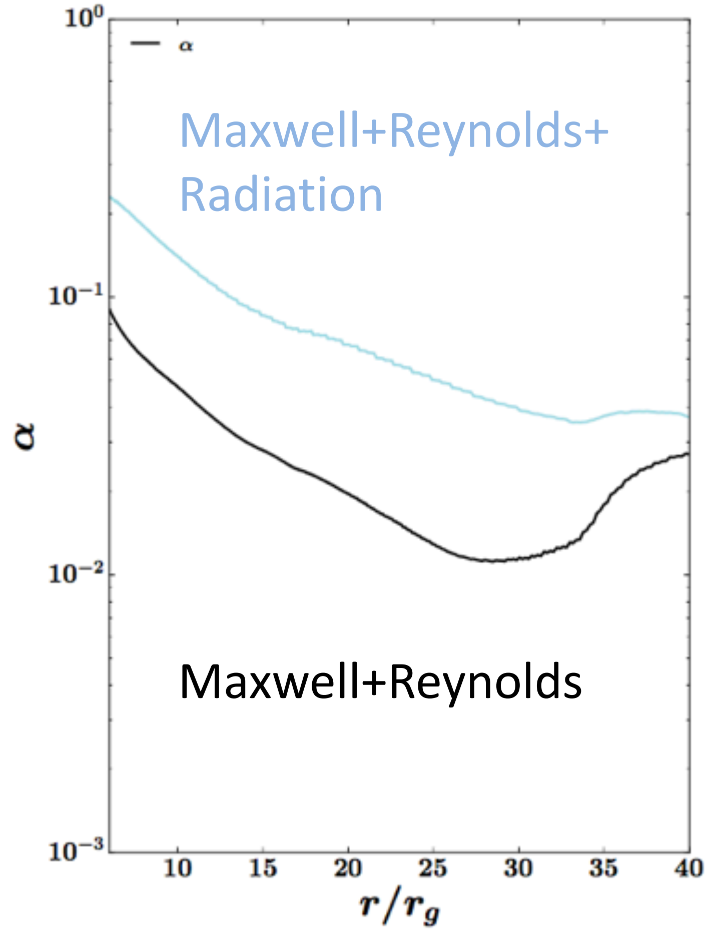
Flow Structure with Opacity

Outflow velocities are about ~0.1 c and radiation driven even though accretion rate is sub-Eddington.



Angular Momentum Transport





Radiation viscosity is comparable to turbulent stress! (Laor & Loeb 1992)

Summary

- Very strong outflows from the inner regions of accretion disks might be necessary to reconcile accretion theory with observations of AGN.
- 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
- Global simulations with super-Eddington accretion rates show strong winds. (Duh)
- Global simulations with sub-Eddington (~10) accretion rates also show substantial outflows.