Title: How Black Holes Dine above the Eddington "Limit" without Overeating or Excessive Belching

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Abstract: <p>The study of super-Eddington accretion is essential to our understanding of the growth of super-massive black holes in the early universe, the accretion of tidally disrupted stars, and the nature of ultraluminous X-ray sources. Unfortunately, this mode of accretion is particularly difficult to model because of the multidimensionality of the flow, the importance magnetohydrodynamic turbulence, and the dominant dynamical role played by radiation forces. However, recent increases in computing power and advances in algorithms are facilitating major improvements in our ability to model radiation in numerical simulations of astrophysical plasmas. I will briefly describe our new radiation transfer modules and discuss our efforts to model super-Eddington accretion flows around stellar mass and supermassive black holes. I will focus on applications to ultraluminous X-ray sources, which must be radiating well above their Eddington luminosity unless they harbour intermediate mass black holes. I will argue that most of these sources can be (and likely are) "normal" ~10 solar mass black holes accreting and radiating with luminosities well above their Eddington "limitâ€•.</p>

Ultraluminous X-ray Sources (ULXs)

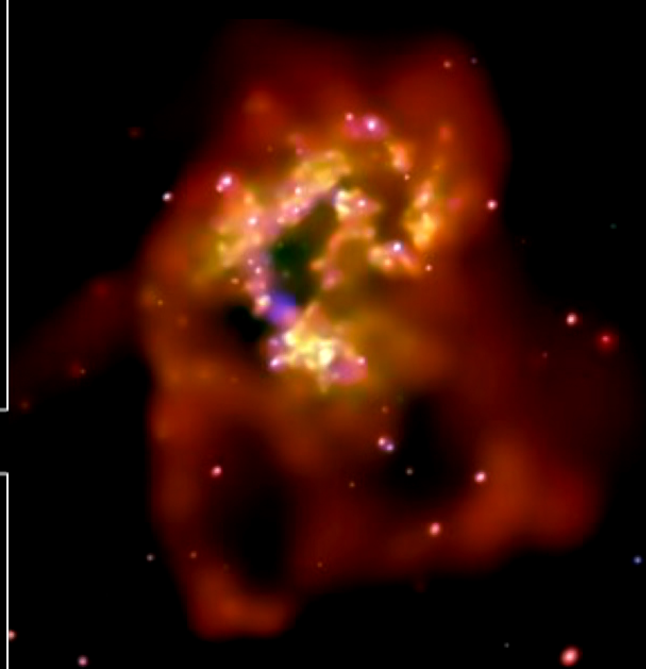
$L \sim 10^{39}$-10^{42} erg/s ($L_{Edd} \sim 10^{39}$ erg/s for $\sim 10\ M_{sun}$ BH).

Standard stellar evolution does not predict BHs with $M > 20$-$30\ M_{sun}$.

Abundant in nearby star-forming galaxies.

Possible explanations include:

- Super-Eddington accretion
- Beamed emission
- Intermediate mass black holes (IMBH)
- Black holes or neutron stars?!



Antennae Galaxy *Chandra*

An intermediate mass black hole (IMBH)?

- Radiates at ~ 10^{42} erg/s near maximum (L_{edd} for 10^4 M_{sun} BH)
- Not AGN: off nuclear; optical flux << X-ray flux
- Undergoes outbursts with ~1 yr period and X-ray binary like state transitions

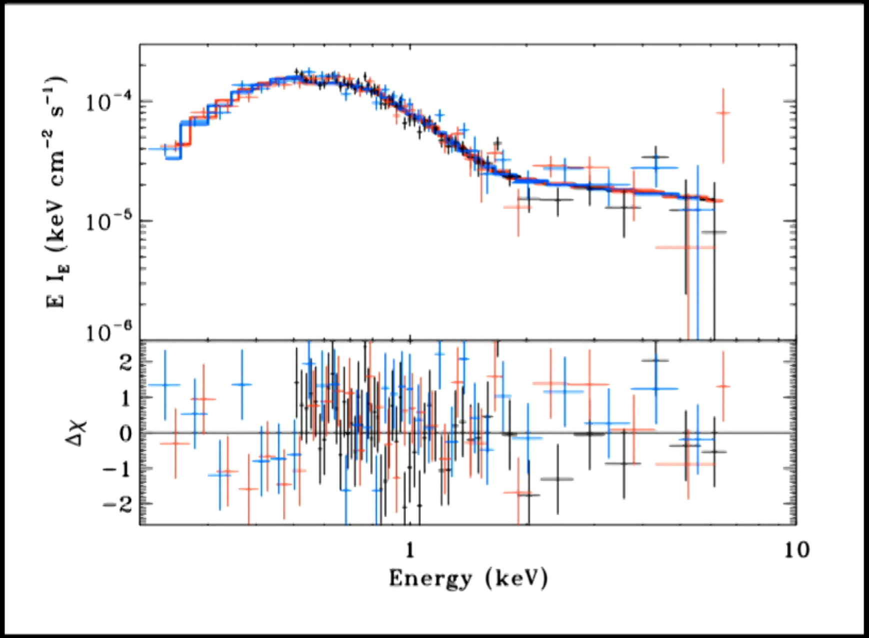
HLX-1 Spectrum Matches an IMBH

If IMBHs we expect cool disk with peak at low energies:

$$T \propto \frac{1}{M^{1/4}} \left(\frac{\dot{M}}{\dot{M}_{\rm Edd}} \right)^{1/4}$$

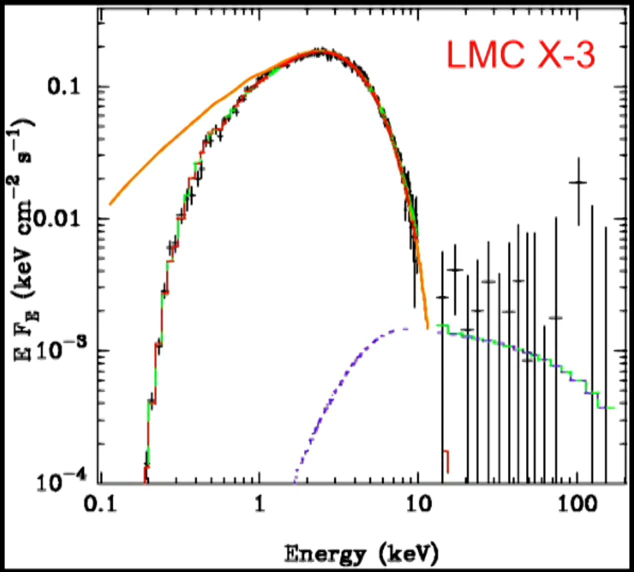
Peak E_{ph} ~ 0.5 keV

M > 10^4 M_{sun} when fit with relativistic disk model

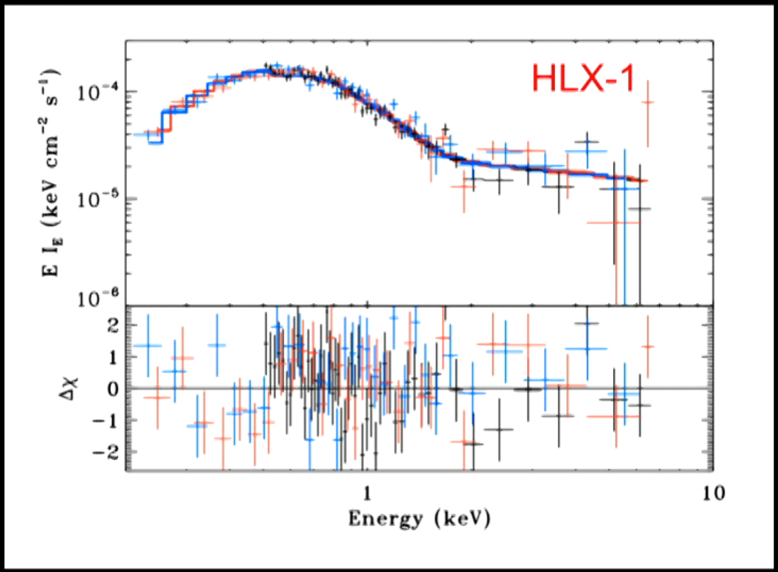


Davis+ 2011

Is HLX-1 an IMBH?



Davis, Done & Blaes 2006



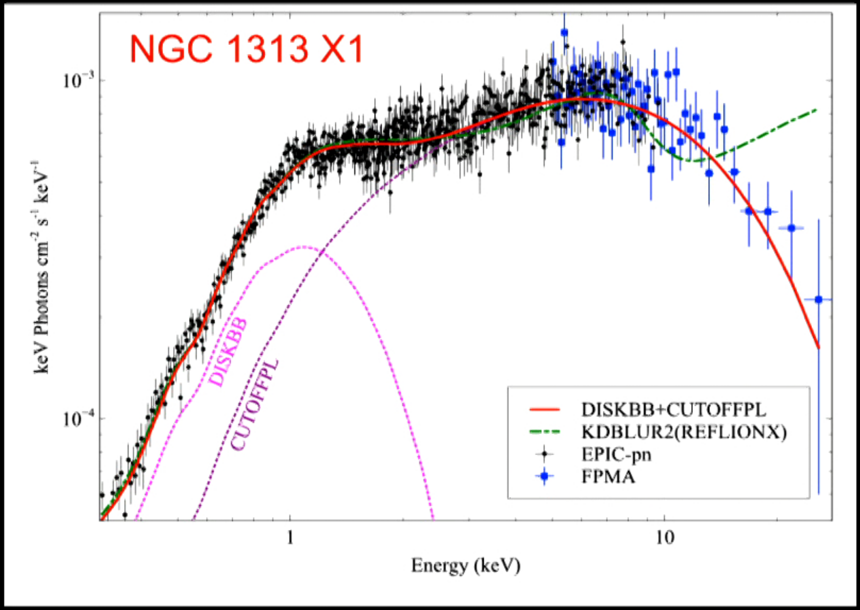
Davis+ 2011

But many ULXs do not look like IMBHs

Many (most?) luminous ULXs are dominated by hard X-ray emission and the curvature of this hard X-ray component suggests thermal emission rather than power law emission (Gladstone+ 2006).

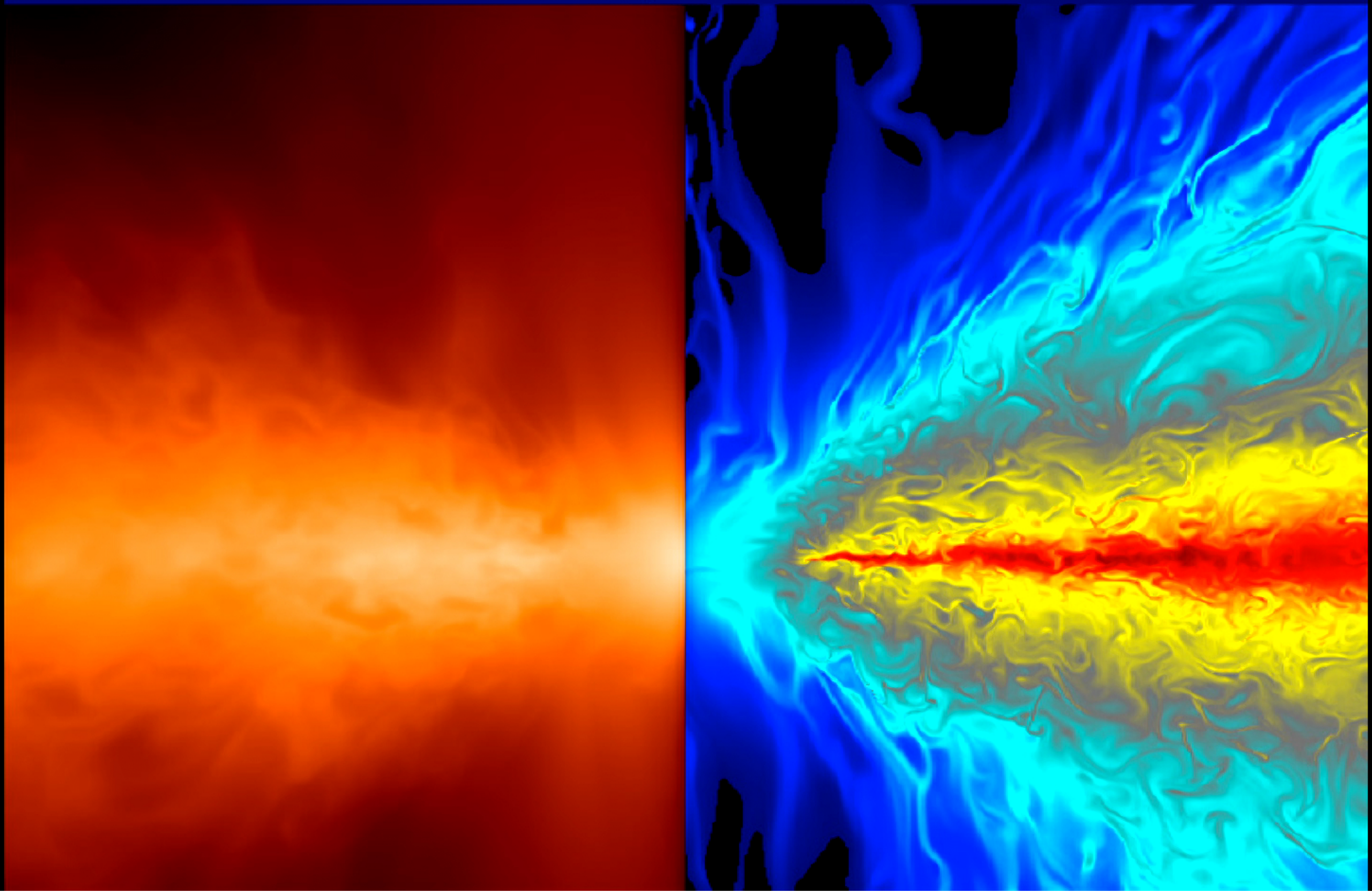
The curvature of the hard X-ray component has been confirmed by NuSTAR. Peak energy is ~4-10 keV.

$$T \propto \frac{1}{M^{1/4}} \left(\frac{\dot{M}}{\dot{M}_{\mathrm{Edd}}} \right)^{1/4}$$



Bachetti+ 2013

3. Simulations of Super-Eddington Accretion



Equation of Radiation (magneto-)Hydrodynamics

Standard hydro equations
stiff source terms
Radiation transfer

Jiang, Stone & Davis (2014)

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

radiation force

$$\frac{\partial (\rho \mathbf{v})}{\partial t} + \nabla \cdot (\rho \mathbf{v}\mathbf{v}) + \nabla P = -\mathbf{S}_{\rm r}(\mathbf{P})$$

$$\frac{\partial E}{\partial t} + \nabla \cdot (E\mathbf{v} + P\mathbf{v}) = -cS_{\rm r}(E)$$

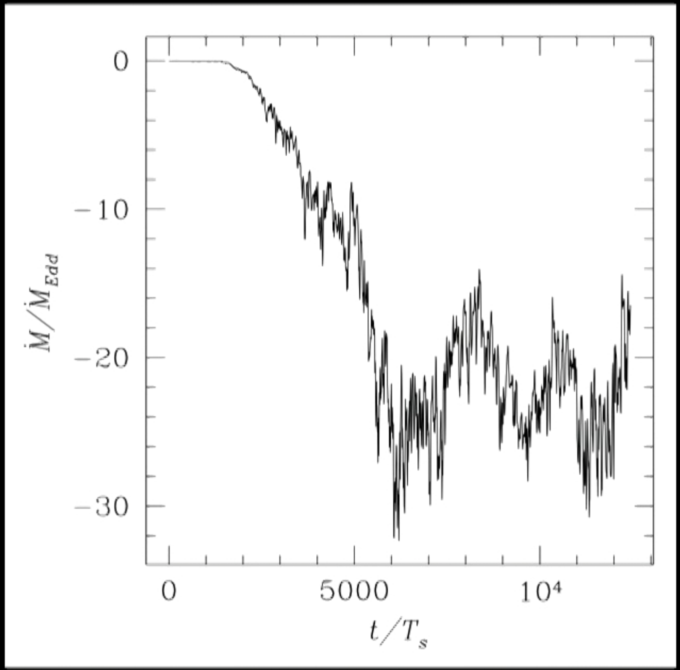
net heating/cooling

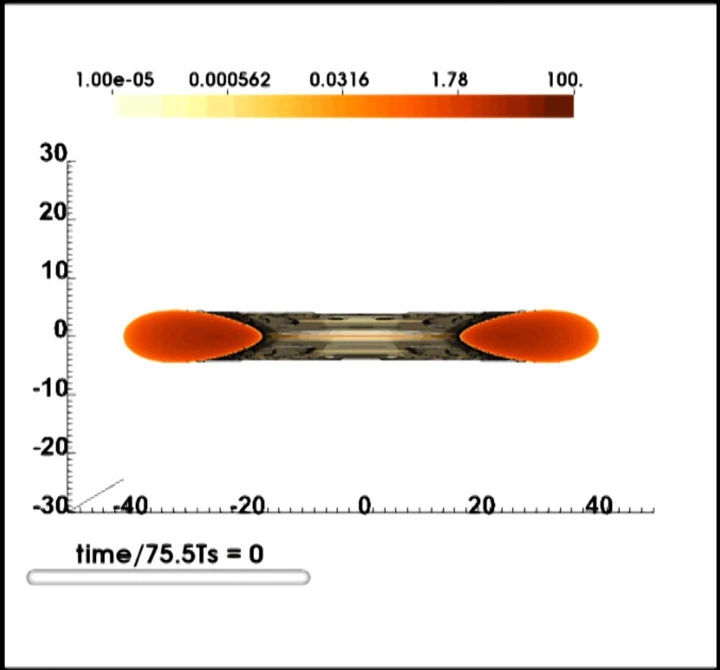
$$\frac{1}{c}\frac{\partial I}{\partial t} + \hat{n} \cdot \nabla I = \eta - \chi_{\rm t} I + \chi_s J$$

Simulation Summary (Jiang+ 2014)

- BH mass: ~7 M_{sun}
- Accretion rate : ~20 $\dot{M}_{Edd}$
- Cylindrical coordinates: 512 x 1024 x 128 ($r \times z \times \phi$)
- Uniformly spaced gridzones
- $r_{out} = 50\ r_s$; $L_z = 60\ r_s$; $\Delta\phi = \pi$
- Non-relativistic hydro; Paczynski-Wiita potential
- Angular grid: 80 rays
- Initial condition: torus centered at 25 r_s w/ B-field loops
- T ~ 15,000 r_s/c
- Expense: 230 cpu-years

Super Eddington Accretion onto 7 M_{sun} BH





Jiang+ 2014

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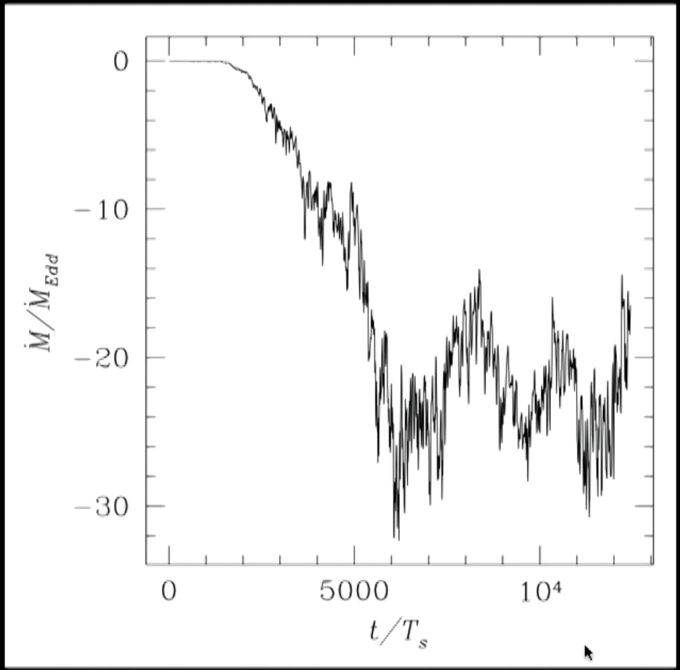
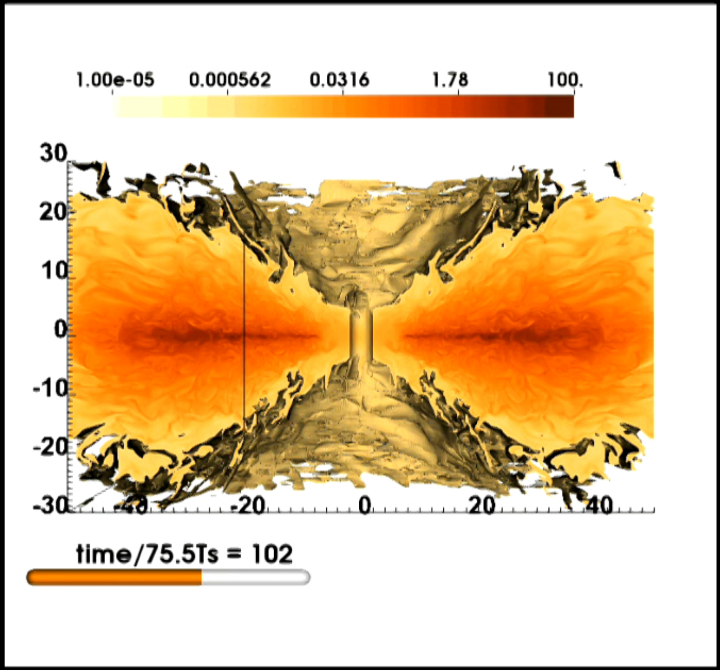




Jiang+ 2014

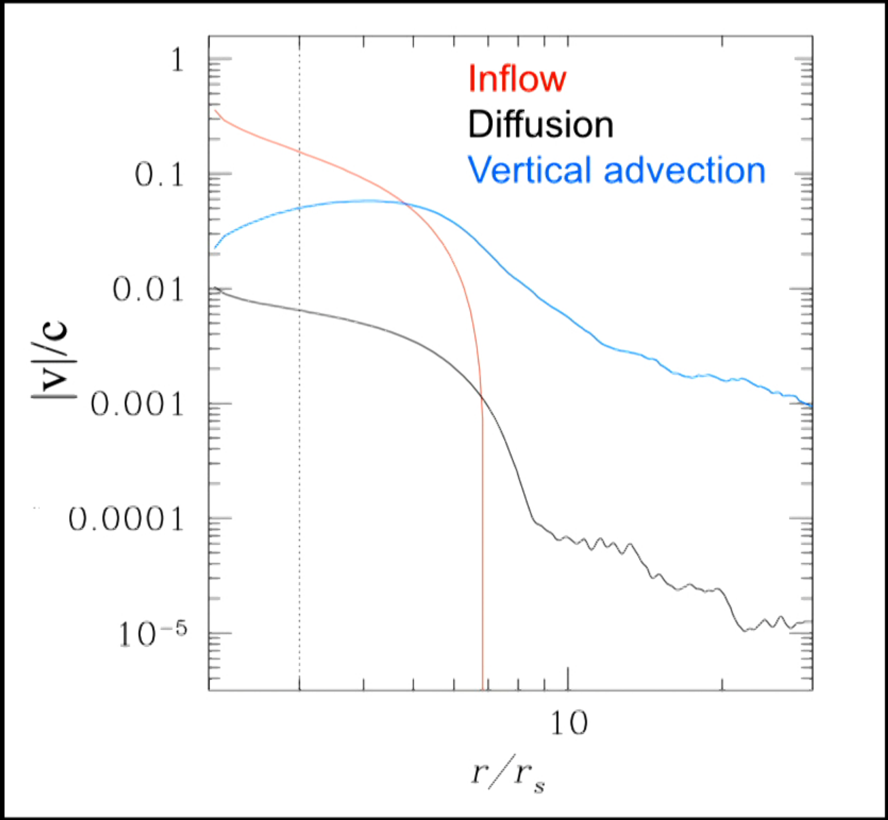
Vertical Radiation Advection

Cooling of the disk is dominated by the vertical advection of radiation even though there is relatively little net vertical flow of matter

Vertical advection is associated with buoyant magnetic field

$$\text{force} = \frac{\kappa\rho}{c}\left(F_{\rm rad} - \frac{4}{3}vE_{\rm rad}\right)$$

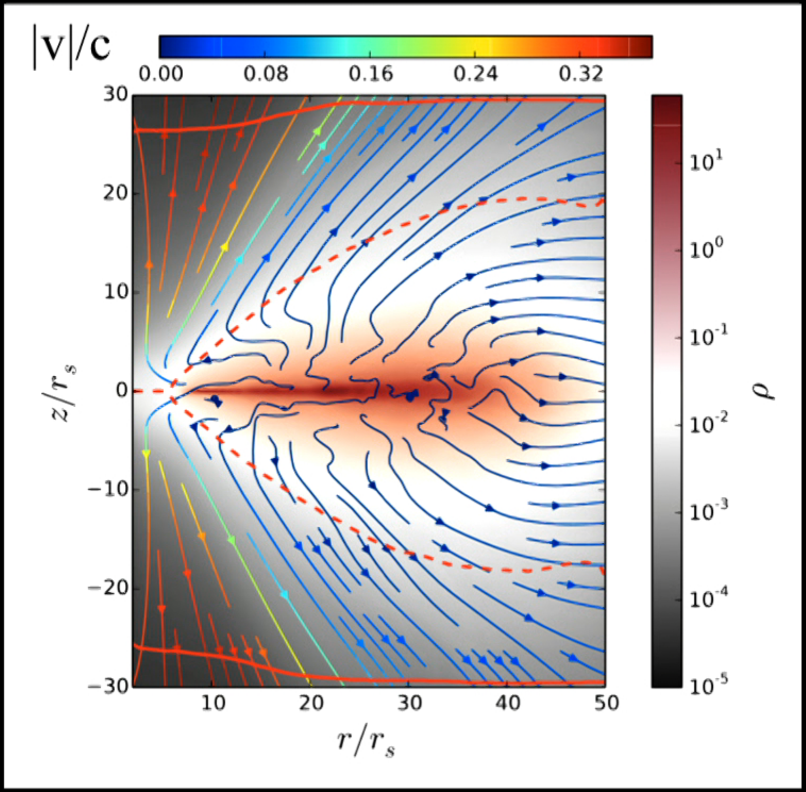
$$F_{\rm rad} \approx \frac{4}{3}vE_{\rm rad}$$



Flow Geometry

3 components to density distribution: evacuated funnel, extented optically thick wind and thin disk

Strong polar outflow driven by radiation pressure – not magnetic stresses



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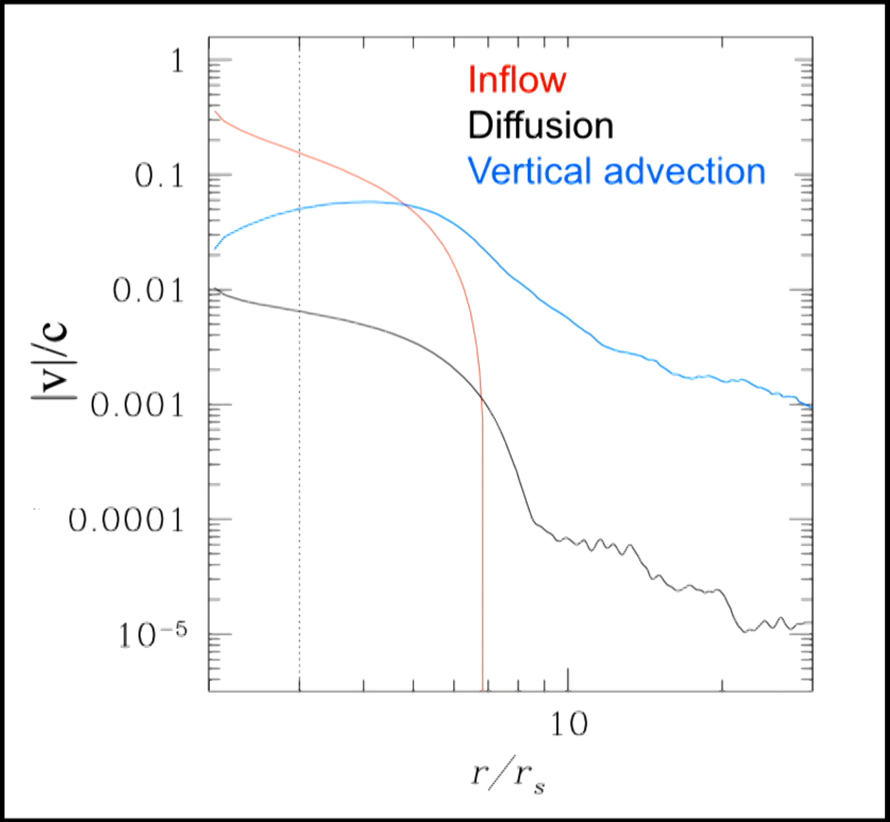
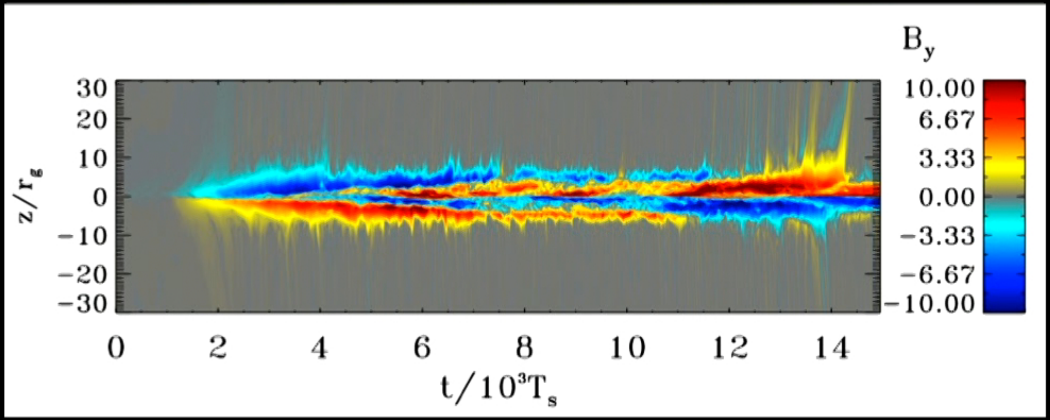


Magnetic Buoyancy



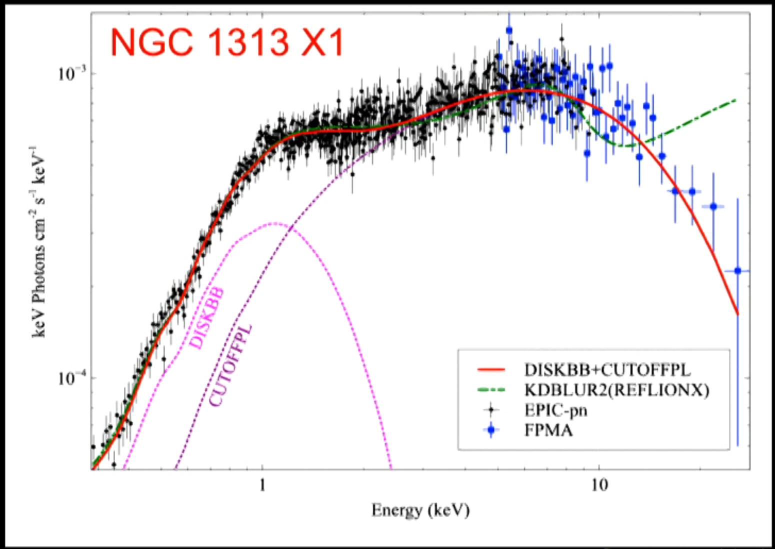
Magnetic field dynamics driven by a dynamo process ubiquitously observed in high resolution local simulations (but not clearly in previous global simulations)

Strongly magnetized regions near midplane have lower density than weakly magnetized regions and rise upward. Carry photons along with them. Little mass flux because sinking regions offset rising regions, but sinking regions carry less photon energy!

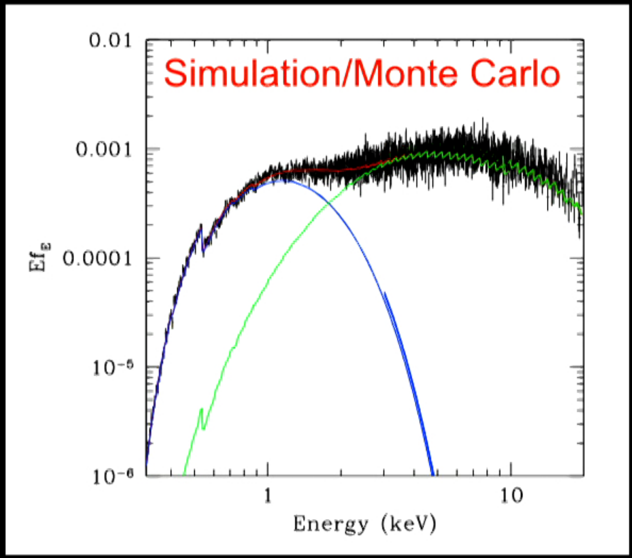
Emergent Luminosity and Mass Outflow

- Flux is rather constant in the inner 20 r_s – notably different from the thin or slim disk solutions
- Radiative luminosity is ~10 times Eddington luminosity
- Kinetic luminosity of outflow is about ~1/5 of the radiative luminosity – opposite of what has been found previously (e.g. Sadowski+ 2014)

Emergent Spectrum

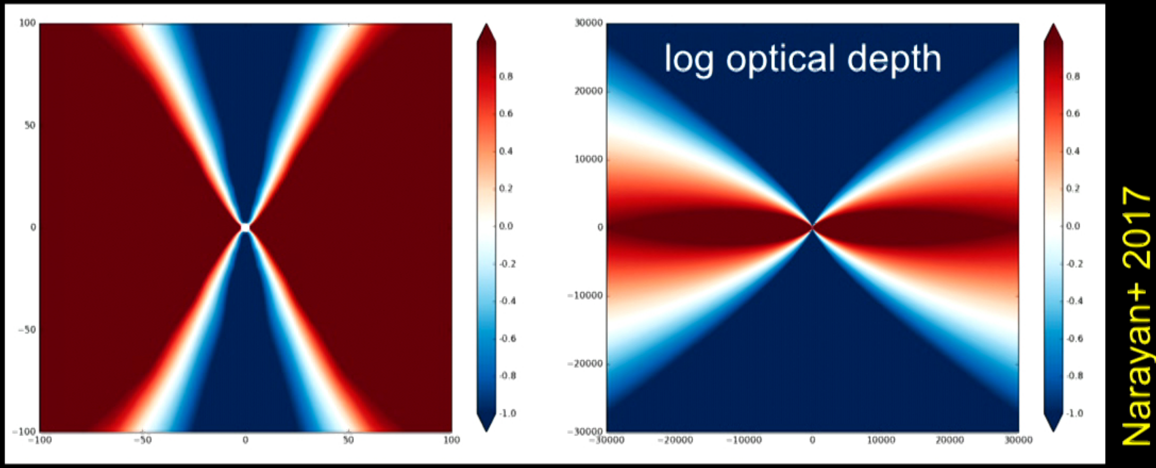


Bachetti+ 2013



The spectra we compute from these simulations agrees very well with data from ultraluminous X-ray sources that peak in the hard X-rays.

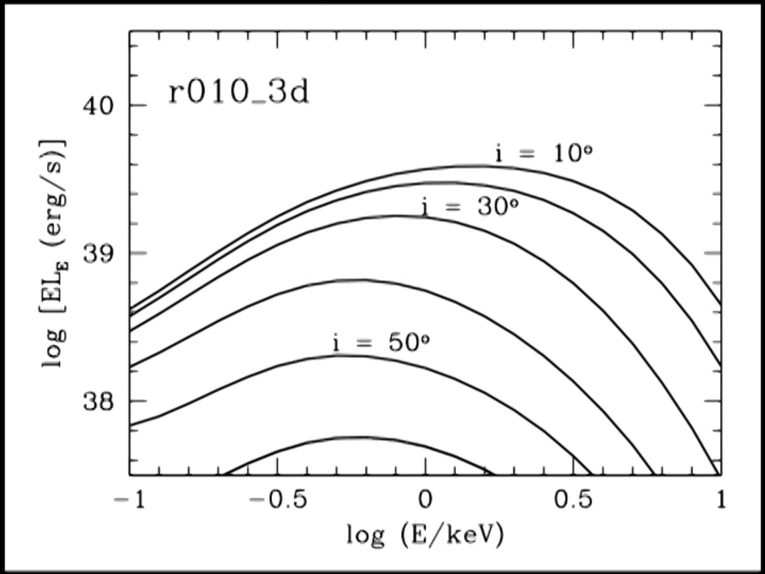
Comparison with other recent work



- Narayan+ 2017 generate spectra based on extension of Sadowski+ simulations. These are fully general relativistic but use the M1 scheme for transport
- Find lower radiative efficient (radial advection dominates over vertical advection) but the escaping radiation flux in the funnel is locally super-Eddington

Comparison with other recent work

- Spectra produced by Narayan+ look super-Eddington at nearly face on angles (down the funnel) but sub-Eddington at typical angles.
- Overall radiative efficiency is lower so more mass accretion is needed.

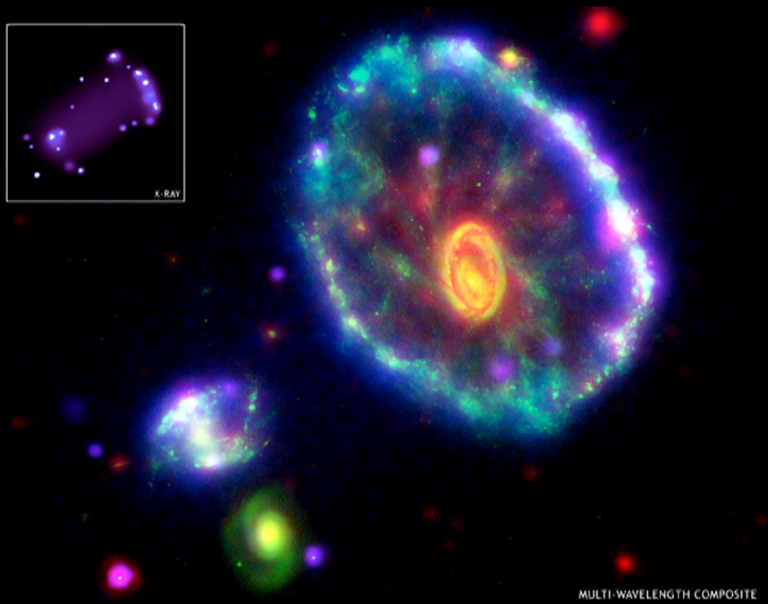


Narayan+ 2017

Kawashima+ 2012 and Kitaki+ 2017 find broadly similar results in Newtonian models

Why does radiative efficiency/beaming matter?

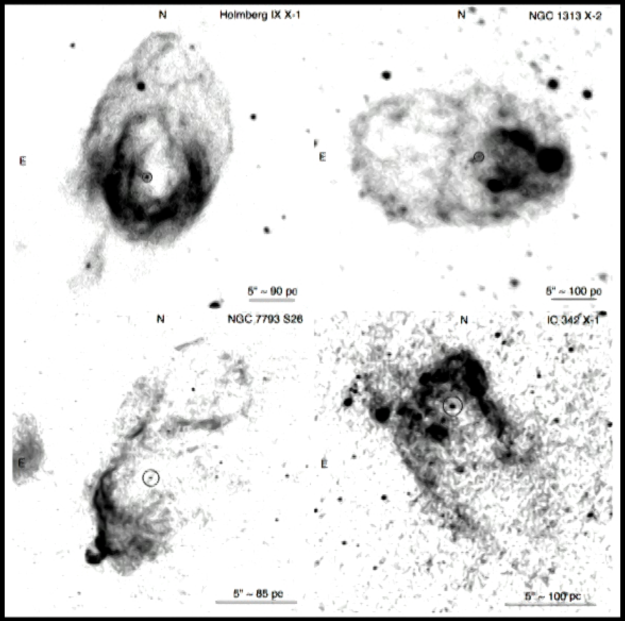
- Some galaxies have lots of luminous ULXs and instances of very high mass transfer rates are thought to be rare.
- Beaming makes this worse because there are more sources we don't see!



Cartwheel Galaxy (from *Chandra*)

Why does radiative efficiency/beaming matter?

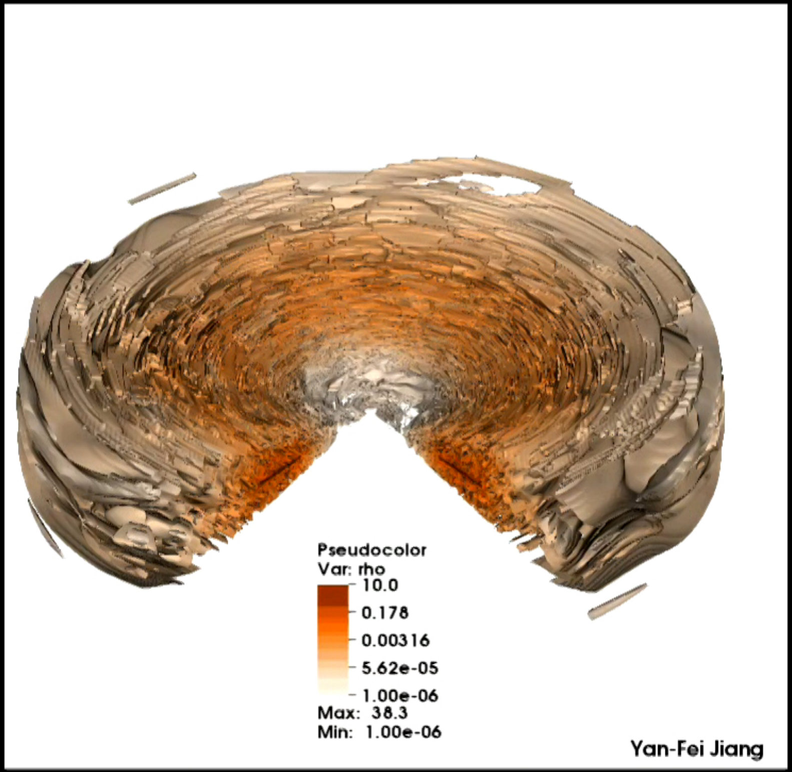
- Several ULX sources are surrounded by emission line nebula (Pakull & Mirioni 2002, Moon+ 2011).
- Models of this emission require luminosities comparable to the inferred isotropic luminosities.
- Beamed models would not seem to produce enough ionizing photons?



Feng & Soria 2014

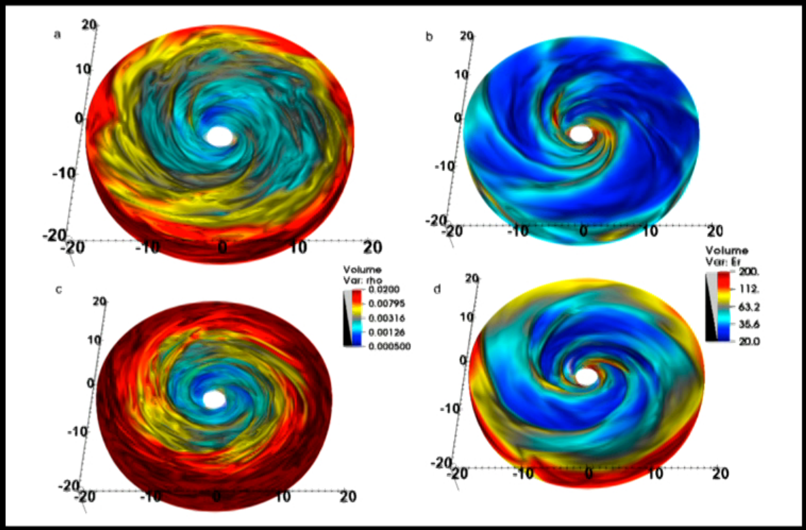
Current Efforts

- Algorithms now running in Athena++ code: AMR, general relativistic MHD
- Allows for significantly larger dynamic range
- Transfer still not fully general relativistic in production runs, but we've begun implementation.
- Simulations of ~10 M_{sun} BHs and supermassive black holes.



Super Eddington Accretion onto 10^8 M_{sun} BH

- Radiation pressure >> gas pressure
- Radiation damps (analogous to Silk damping) MRI turbulence!
- Angular momentum transport dominated by spiral waves!
- Excitations of spiral waves still not fully understood -- possibly excited by the MRI (which is still present, just not dominant)



Jiang+ 2017

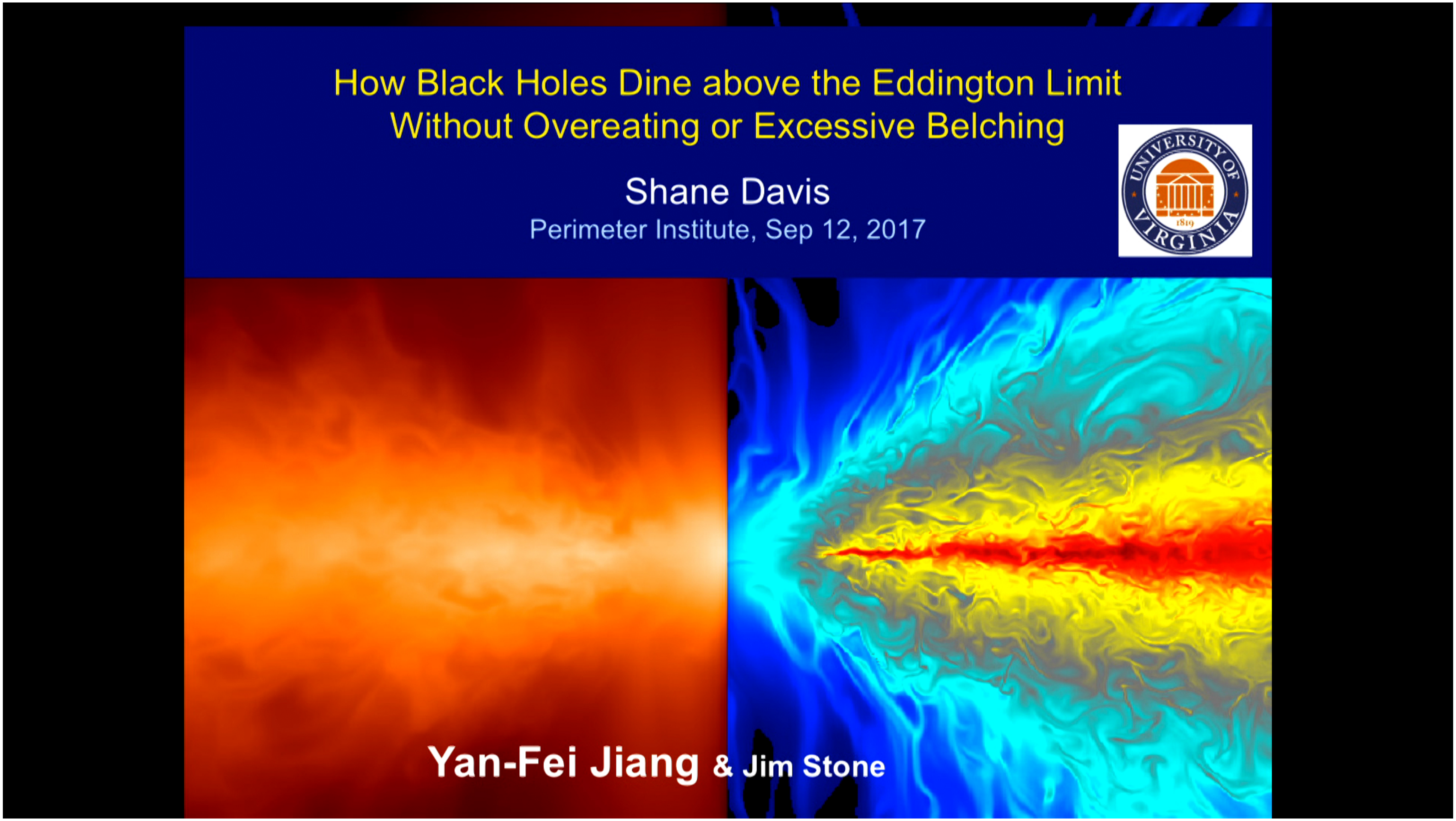
Time Dependent Relativistic Transfer

We have (re-)derived a flux conservative form for the transfer equation in full GR. Should be amenable to finite volume approach in both spatial and momentum coordinates, but there are a few issues with implementation that we have not yet worked out.

$$
\frac{1}{c}\frac{\partial I_\nu}{\partial t}+\frac{1}{r^2}\frac{\partial}{\partial r}\left[r^2\left(1-\frac{2r_g}{r}\right)n^{\hat{r}}I_\nu\right]+\frac{\left(1-\frac{2r_g}{r}\right)^{1/2}}{r\sin\theta}\left[\frac{\partial(\sin\theta\, n^{\hat{\theta}}I_\nu)}{\partial\theta}+\frac{\partial(n^{\hat{\phi}}I_\nu)}{\partial\phi}\right]
$$
$$
-\frac{\cos\zeta\, r_g}{r^2}\frac{\partial(\nu I_\nu)}{\partial\nu}-\left(1-\frac{3r_g}{r}\right)\frac{1}{r\sin\zeta}\frac{\partial(\sin^2\zeta\, I_\nu)}{\partial\zeta}
$$
$$
-\left(1-\frac{2r_g}{r}\right)^{1/2}\frac{\sin\zeta\cos\theta}{r\sin\theta}\frac{\partial(\sin\psi\, I_\nu)}{\partial\psi}=\left(1-\frac{2r_g}{r}\right)^{1/2}(j_\nu+\alpha_\nu I_\nu)
$$

Summary

- Vertical radiation advection dominates energy transport, leading to a much higher radiative efficiency than photon diffusion
- Luminosity exceeds the Eddington “limit” by a factor of ~10
- Radiative efficiency ~ 5%, outflow efficiency ~ 1% – *radiative efficiency is larger than other simulations*
- Spectrum is broadly consistent with hard X-ray dominated ultraluminous X-ray sources
- No evidence for geometric beaming in our simulations but other simulations differ with us
- New simulations (mostly in supermassive BH regime) covering larger radius and w/ spherical polar grid consistent with our earlier work


How Black Holes Dine above the Eddington Limit
Without Overeating or Excessive Belching
Shane Davis
Perimeter Institute, Sep 12, 2017
UNIVERSITY OF VIRGINIA
1819
Yan-Fei Jiang & Jim Stone

Outline

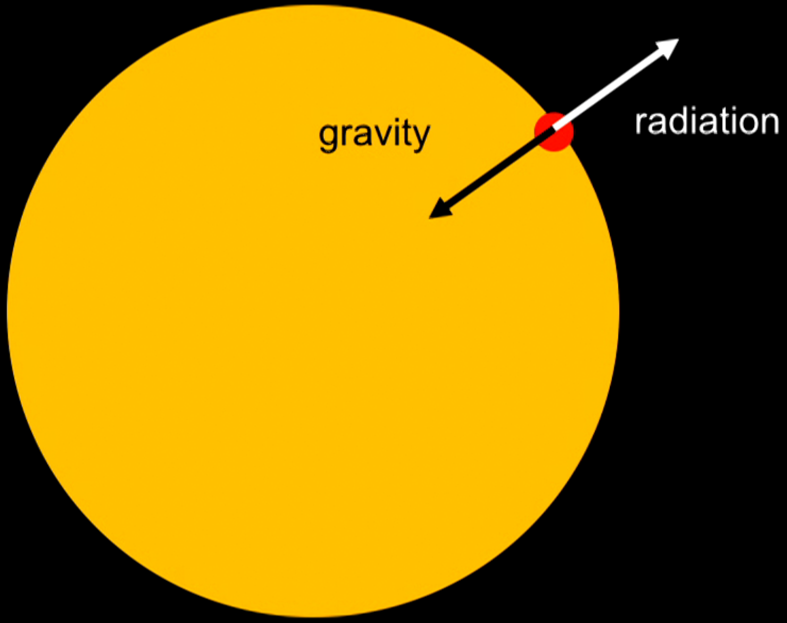
1. The Eddingon limit for black hole accretion
2. Ultraluminous X-ray Sources
3. Simulations of Super-Eddington accretion flows onto black holes

1. The Eddington Limit

www.facebook.com/TheEddingtonLimit

The Eddington Limit

The Eddington luminosity is the luminosity where the outward radiation force balances the inward gravitational force. For larger luminosities, we expect the radiation force to accelerate the surface layers away from the center of the object.



Sir Arthur Eddington

The Eddington Accretion Rate

Eddington Luminosity:

$$L_{\mathrm{Edd}} \approx 10^{38} \frac{M}{M_\odot} \,\mathrm{erg/s}$$

mass

Sun's mass

Radiative efficiency:

$$\eta = \frac{L}{\dot{M} c^2}$$

luminosity

Accretion rate

Eddington accretion rate:

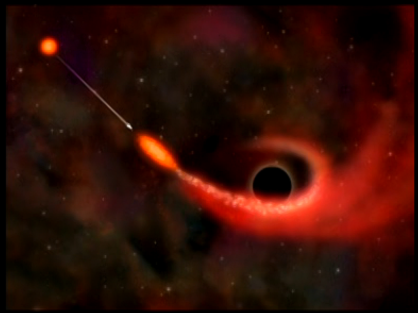
$$\dot{M}_{\mathrm{Edd}} = \frac{L_{\mathrm{Edd}}}{\eta c^2} \approx 2\times10^{-8} \left(\frac{0.1}{\eta}\right) \left(\frac{M}{M_\odot}\right) \; M_\odot/\mathrm{yr}$$

Accretion in excess of this rate is called super-Eddington accretion

Super-Eddington Accretion onto Black Holes

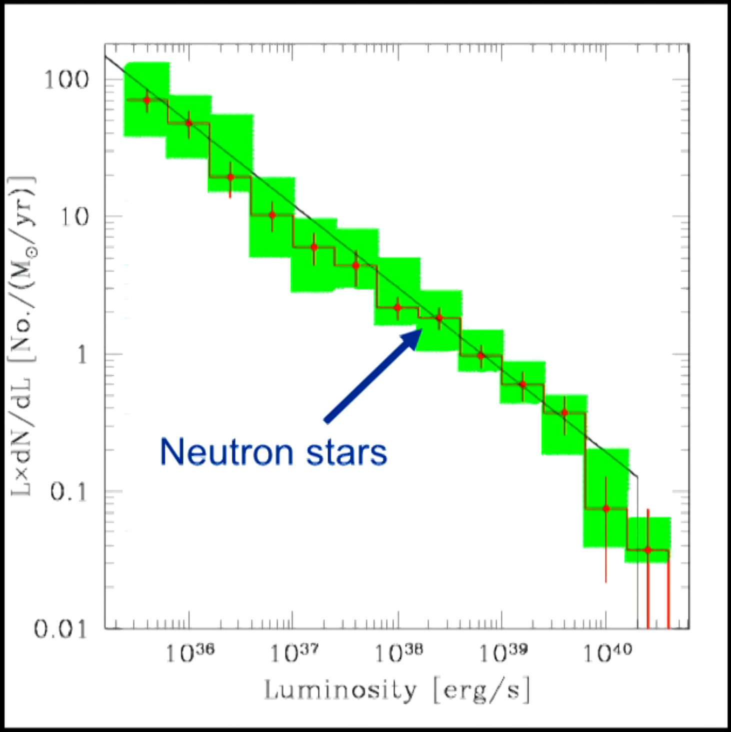
We have strong reasons to believe that many sources are supplied mass at rates that exceed the Eddington rate:

- Core collapse and compact binary mergers
- Fallback in stellar tidal disruptions
- Mass transfer in X-ray binary systems can exceed the Eddington rate for NSs and even ~10 M_{sun} BHs
- Galaxies seem to be capable of providing gas to their nuclei at rates exceeding Eddington rates – particularly for moderately massive BHs



Observational Evidence for Super-Eddington Accretion

- The existence of ultraluminous X-ray sources with $L \sim 10^{40}$-10^{42} erg/s.
- Observed luminosities and inferred masses of quasars
- Quasars at z ~ 6-7 with $M > 10^9\ M_{sun}$ (Mortlock+ 2011)
- No evidence for a break in the X-ray binary luminosity function (Grimm+ 2003, Gilfanov+ 2004)
- M82 X-2 is pulsar accreting higher than 10x Eddington



Grimm, Gilfanov & Sunyaev 2003

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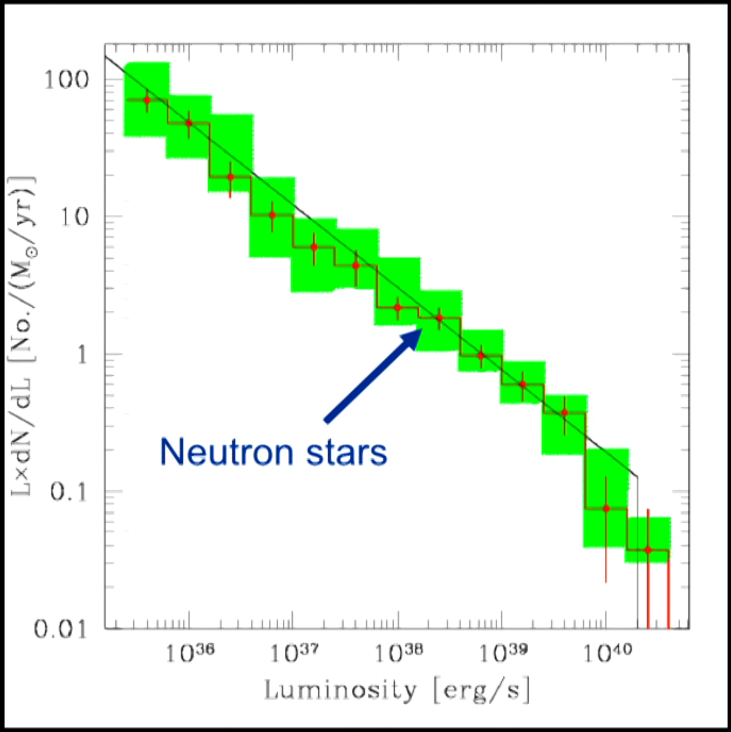
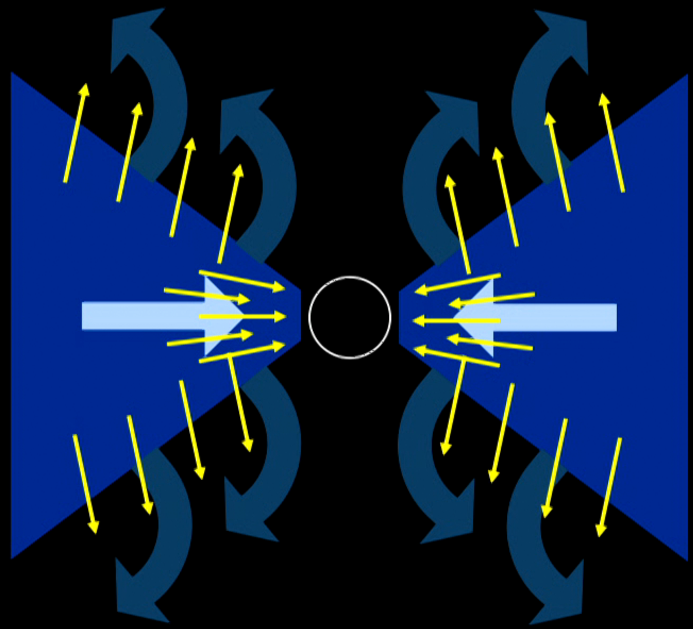


Grimm, Gilfanov & Sunyaev 2003

Super-Eddington Accretion



Shakura & Sunyaev (1973): Disk accretion allows $\dot{M} > \dot{M}_{edd}$ through disk, but flow becomes quasi-spherical in inner regions (H~R). Photons and outflow escape vertically while mass and fraction of radiation may be advected into the black hole.

2. Ultraluminous X-ray Sources

Credit: Heidi Sagerud