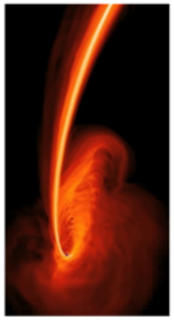
Radiative jets in global simulations
of super-critical accretion disks in general relativity

Einstein Symposium

Aleksander Sądowski, MIT Kavli

10/29/2014

Super-critical accretion


(c) James Guillochon & Suvi Gezari

- Spherical accretion limited by the critical (Eddington) luminosity

$$L_{\rm Edd} = \frac{4\pi c G M m_p}{\kappa_{\rm es}} = 1.25\times 10^{38}\frac{M}{M_\odot}\,{\rm erg/s}$$

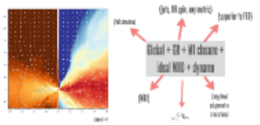
- Breaking the spherical symmetry allows for luminosities exceeding the Eddington limit
- For a thin disk (efficiency for spin zero $\eta = 0.057$), this luminosity corresponds to

$$\dot M_{\rm Edd} = \frac{L_{\rm Edd}}{\eta c^2} = 2.4\times 10^{18}\frac{M}{M_\odot}\,{\rm g/s}$$

- Radiatively inefficient accretion allows for super-critical accretion rates with moderate luminosities
- Whenever there is enough gas close to the BH - super-critical accretion

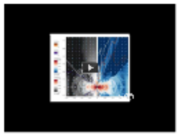
mergers of galaxies | tidal disruption events | GRBs | ULXs (?)

KORAL code

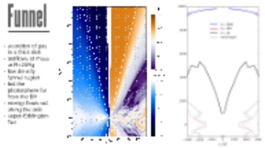


M1 a covariant radiative closure

Super-critical disk

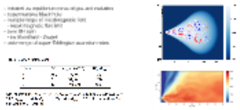


Funnel

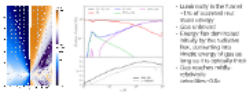


jets in super-critical disks

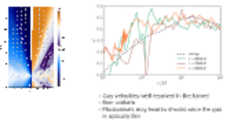
simulation setup



Energy fluxes in the funnel



Gas velocity in the jet



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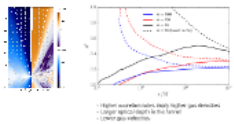

Radiative jets in GR simulations of super-critical BH accretion disks

- Super-critical accretion produces powerful jet-like outflows even without BZ!
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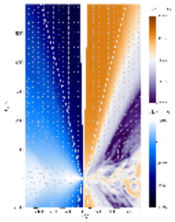
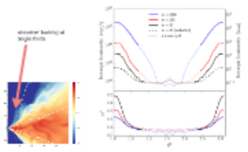
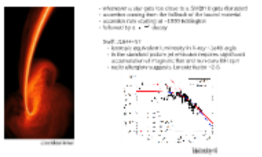


Isotropic equivalent luminosities



Tidal Disruption Events



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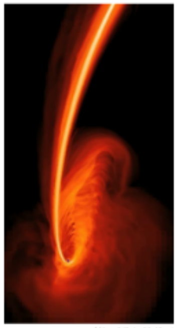

(c) James Guillochon & Suvi Gezari

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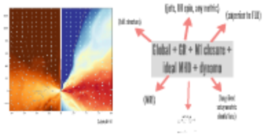

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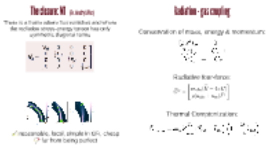

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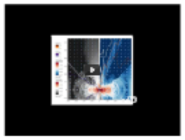

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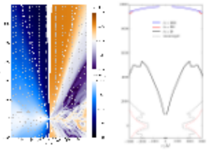
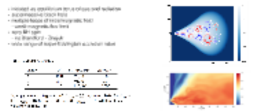


jets in super-critical disks simulation setup



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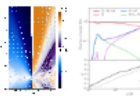

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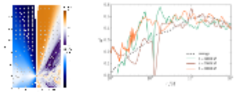

- Gas velocities well resolved in the funnel

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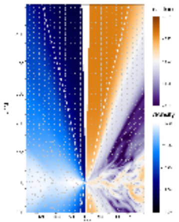

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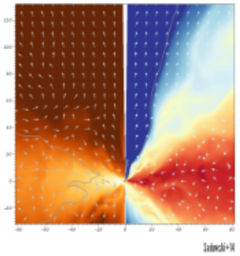
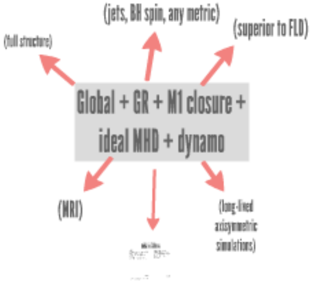
KORAL code (Sadowski+13,+14)


Sadowski+14


Global + GR + M1 closure + ideal MHD + dynamo

(full structure)

(jets, BH spin, any metric)

(superior to FLD)

(MRI)

(long-lived axisymmetric simulations)

Super-critical accretion

(c) James Guillochon & Suvi Gezari

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mergers of galaxies

tidal disruption events

GRBs

ULXs (?)

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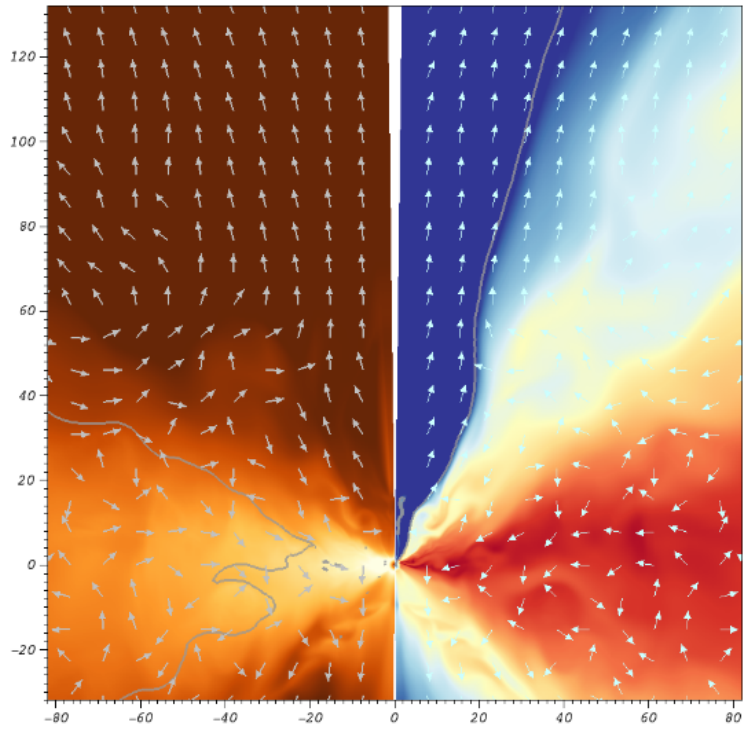

Sadowski+14

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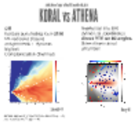
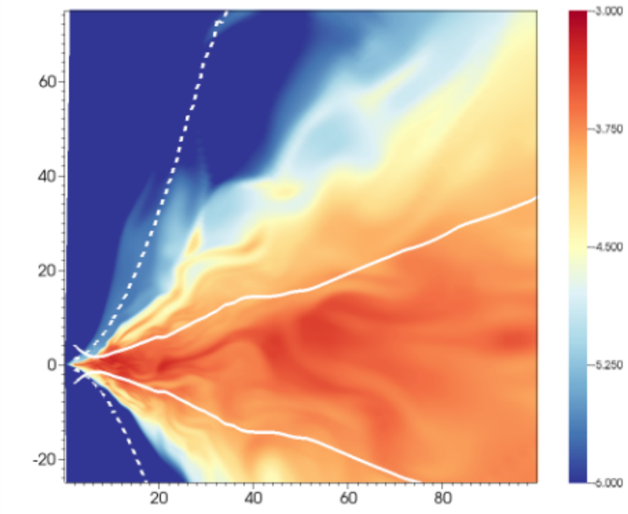


KORAL vs ATHENA

simulations of super-critical BH accretion disks in

KORAL vs ATHENA

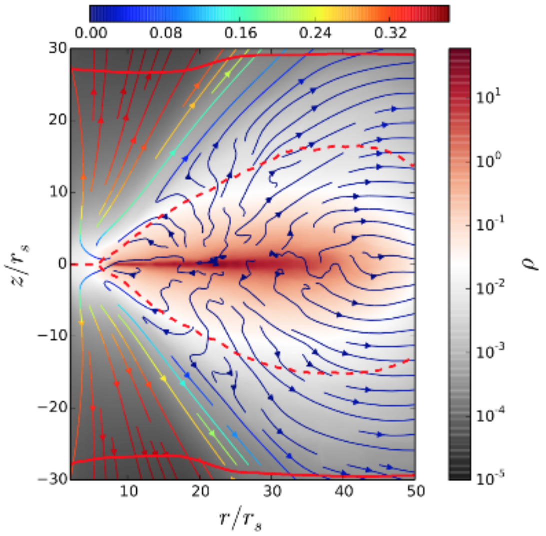
GR
horizon penetrating Kerr-Shild
M1 radiative closure
axisymmetric + dynamo
big box
Comptonization (thermal)



Sadowski+14

Similar approach in HARMRAD (McKinney+14)
and Cosmos++ (Fragile+14)

Newtonian (no BH)
cylindrical coordinates
direct RTE on 80 angles
three dimensional
small box



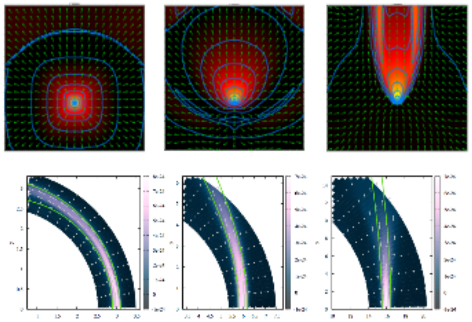
Jiang+14

M1 a covariant radiative closure

The closure: M1 (En. density & Flux)

There is a frame where flux vanishes and where the radiation stress-energy tensor has only symmetric diagonal terms

$$R_{\rm rf}^{ij} = \begin{bmatrix} E_{\rm rf} & 0 & 0 & 0 \\ 0 & \frac{1}{3}E_{\rm rf} & 0 & 0 \\ 0 & 0 & \frac{1}{3}E_{\rm rf} & 0 \\ 0 & 0 & 0 & \frac{1}{3}E_{\rm rf} \end{bmatrix}$$



👍 reasonable, local, simple in GR, cheap

👎 far from being perfect

Radiation - gas coupling

Conservation of mass, energy & momentum:

$$\begin{aligned} (\rho u^\mu)_{;\mu} &= 0 \\ (T^\mu_\nu)_{;\mu} &= G_\nu \\ (R^\mu_\nu)_{;\mu} &= -G_\nu \end{aligned}$$

Radiative four-force:

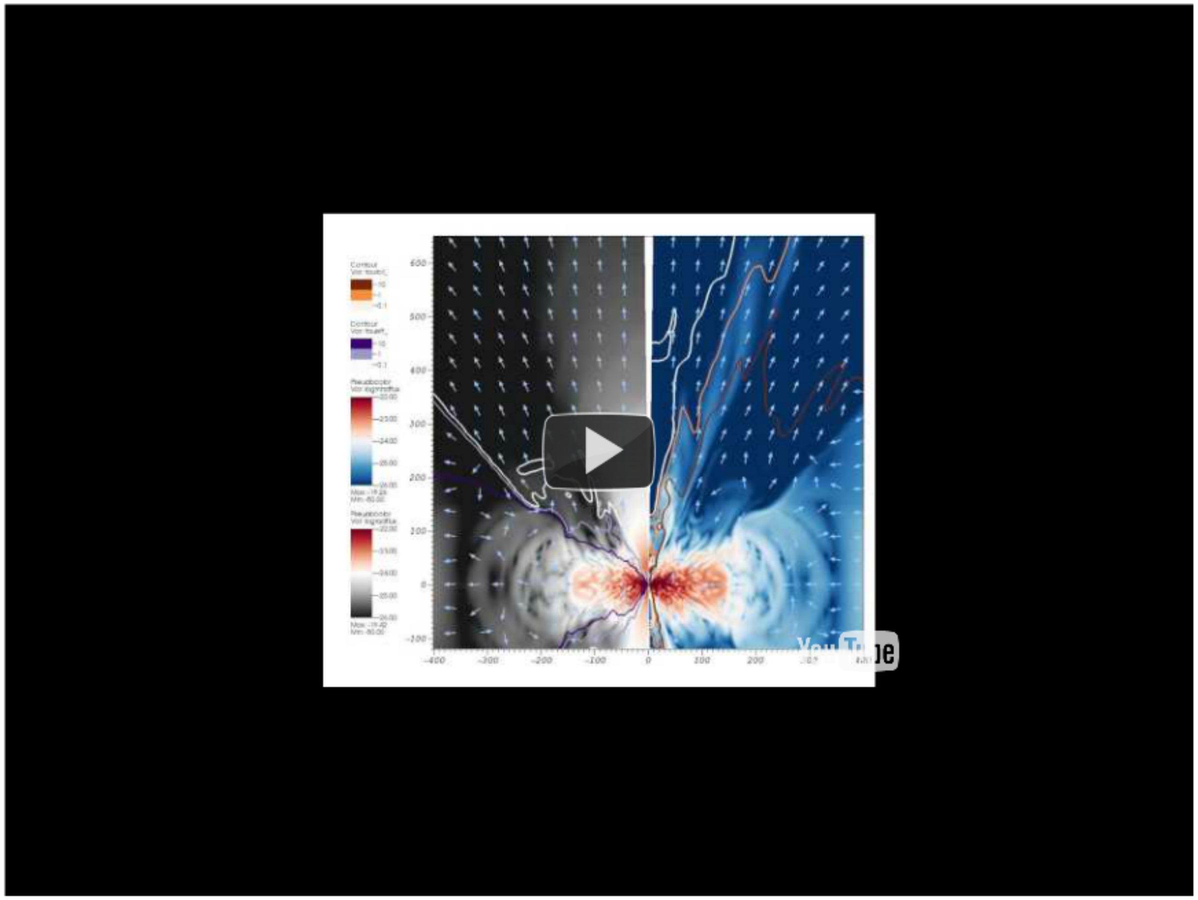
$$\widehat{G}^\mu = \begin{bmatrix} \rho\kappa_{\rm abs}(\widehat{E} - 4\pi B) \\ \rho(\kappa_{\rm abs} + \kappa_{\rm es})\widehat{F}^i \end{bmatrix}$$

Thermal Comptonization:

$$\widehat{G}^t_{\rm Compt} = \rho\kappa_{\rm es}\widehat{E}\frac{4k}{m_{\rm e}}\left(\widehat{T}_{\rm rad} - \widehat{T}_{\rm gas}\right)\left(1 + \frac{4k}{m_{\rm e}}\widehat{T}_{\rm gas}\right)$$

Super-critical disk

spin zero, accretion rate 30 times Eddington



jets in super-critical disks simulation setup

- initiated as equilibrium torus of gas and radiation
- supermassive black hole
- multiple loops of initialmagnetic field
  - weak magnetic flux limit
- zero BH spin
  - no Blandford - Znajek
- wide range of super-Eddington accretion rates

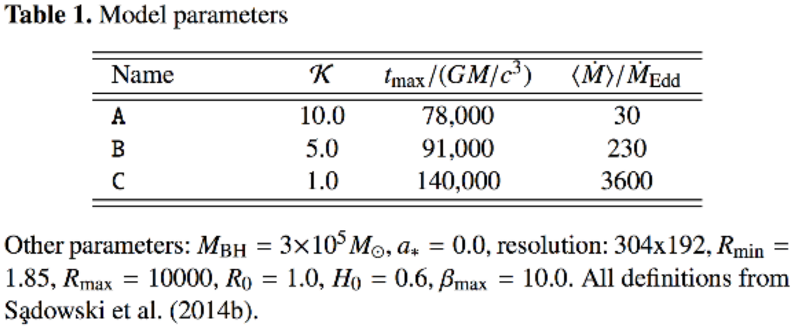
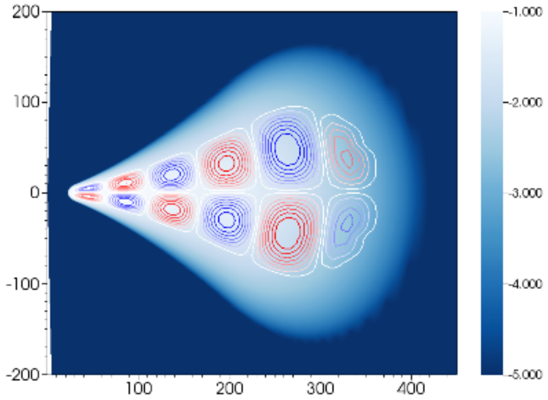
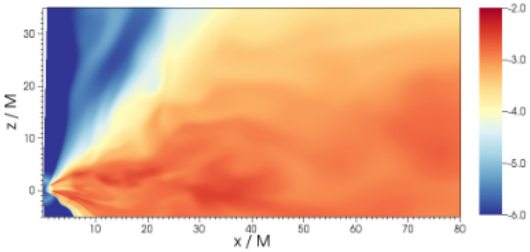


Table 1. Model parameters

Name	$\mathcal{K}$	$t_{\rm max}/(GM/c^3)$	$\langle \dot{M} \rangle / \dot{M}_{\rm Edd}$
A	10.0	78,000	30
B	5.0	91,000	230
C	1.0	140,000	3600

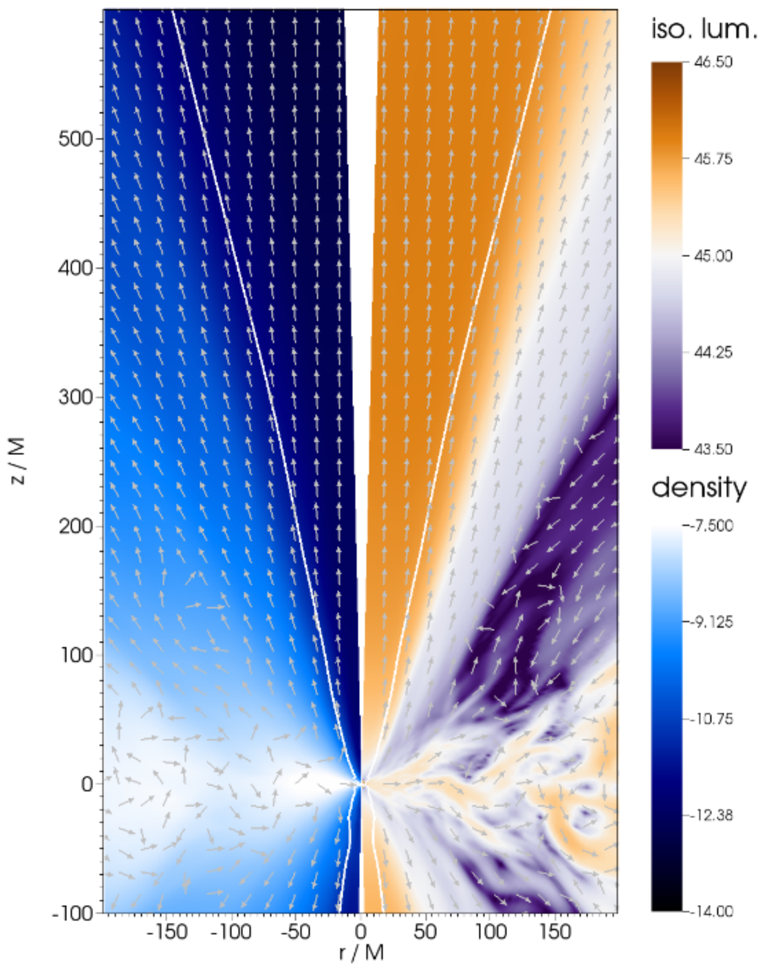
Other parameters: $M_{\rm BH} = 3\times10^5 M_\odot$, $a_* = 0.0$, resolution: 304x192, $R_{\rm min} = 1.85$, $R_{\rm max} = 10000$, $R_0 = 1.0$, $H_0 = 0.6$, $\beta_{\rm max} = 10.0$. All definitions from Sądowski et al. (2014b).

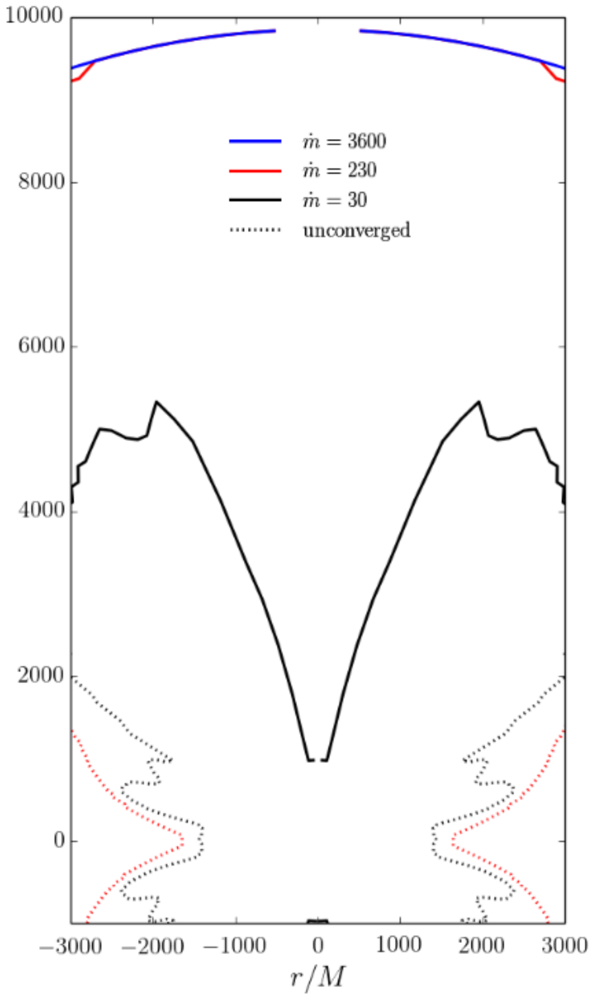




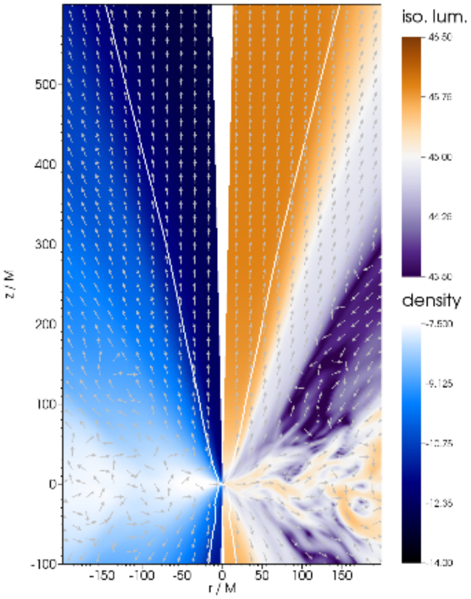
Funnel

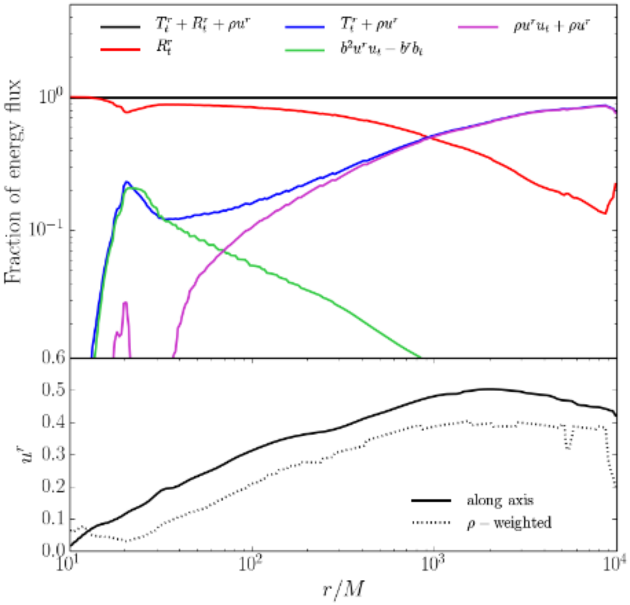
- accretion of gas in a thick disk
- outflows of mass at R>20Rg
- low density funnel region
- but the photosphere far from the BH
- energy flows out along the axis
- super-Eddington flux





Energy fluxes in the funnel





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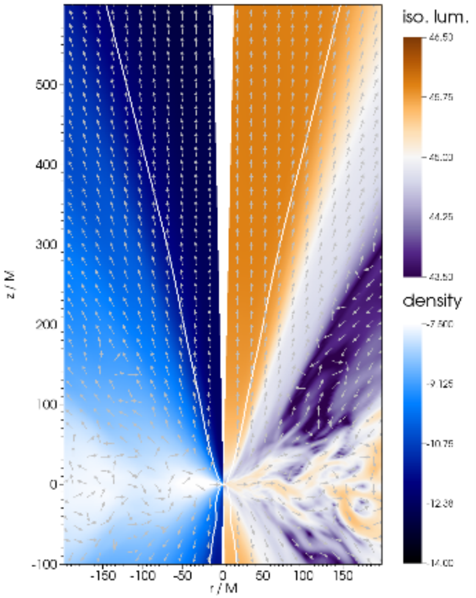
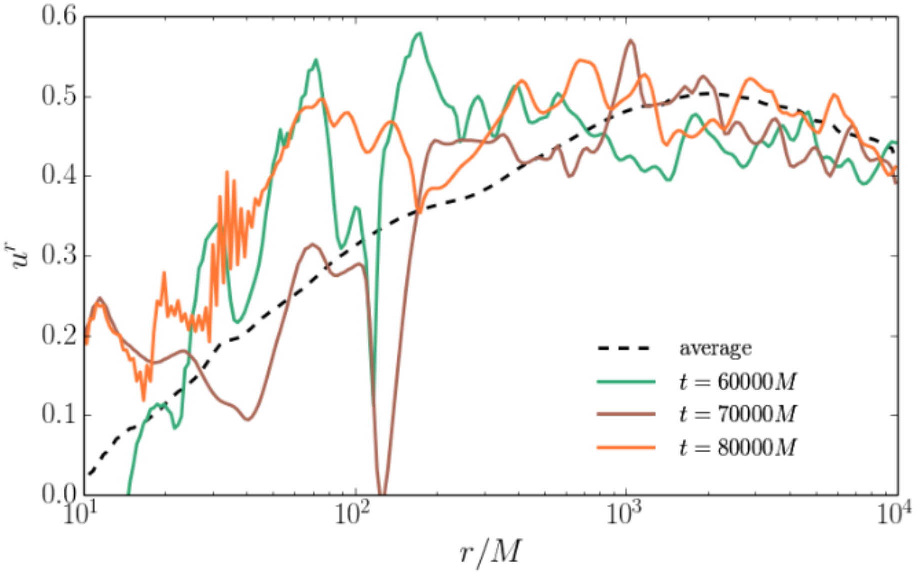
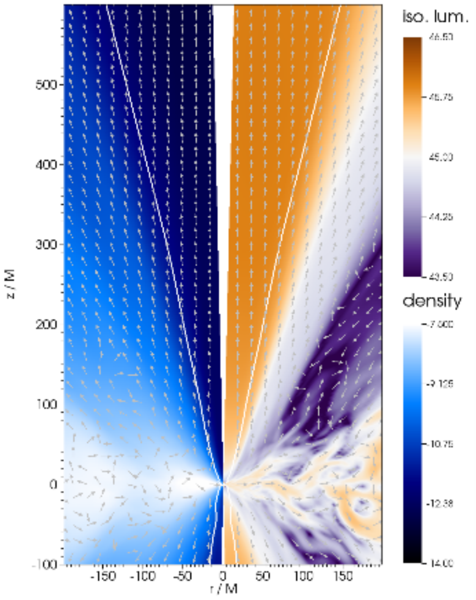
Gas velocity in the jet

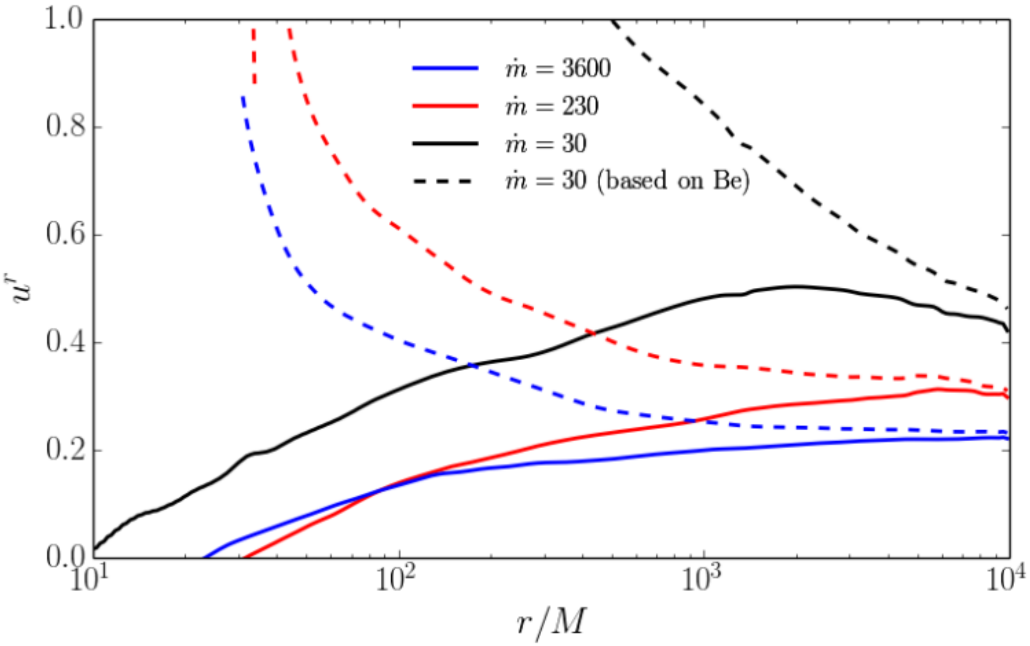




- Gas velocities well resolved in the funnel
- Non-uniform
- Fluctuations may lead to shocks once the gas is optically thin

Gas velocity in the jet

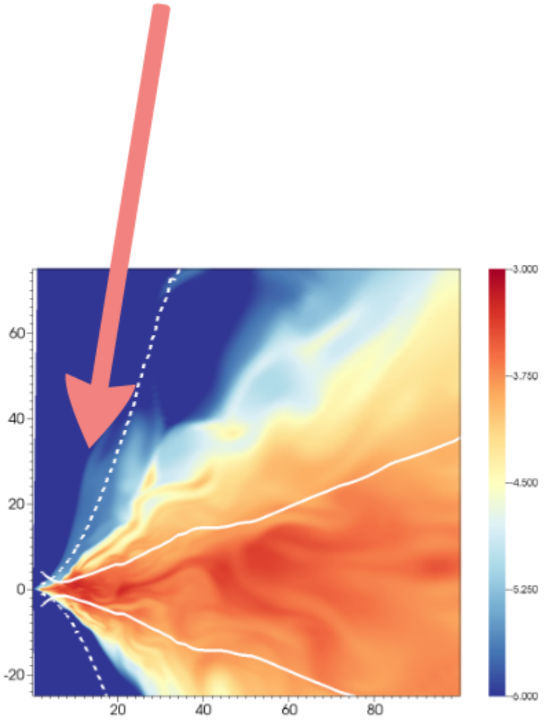


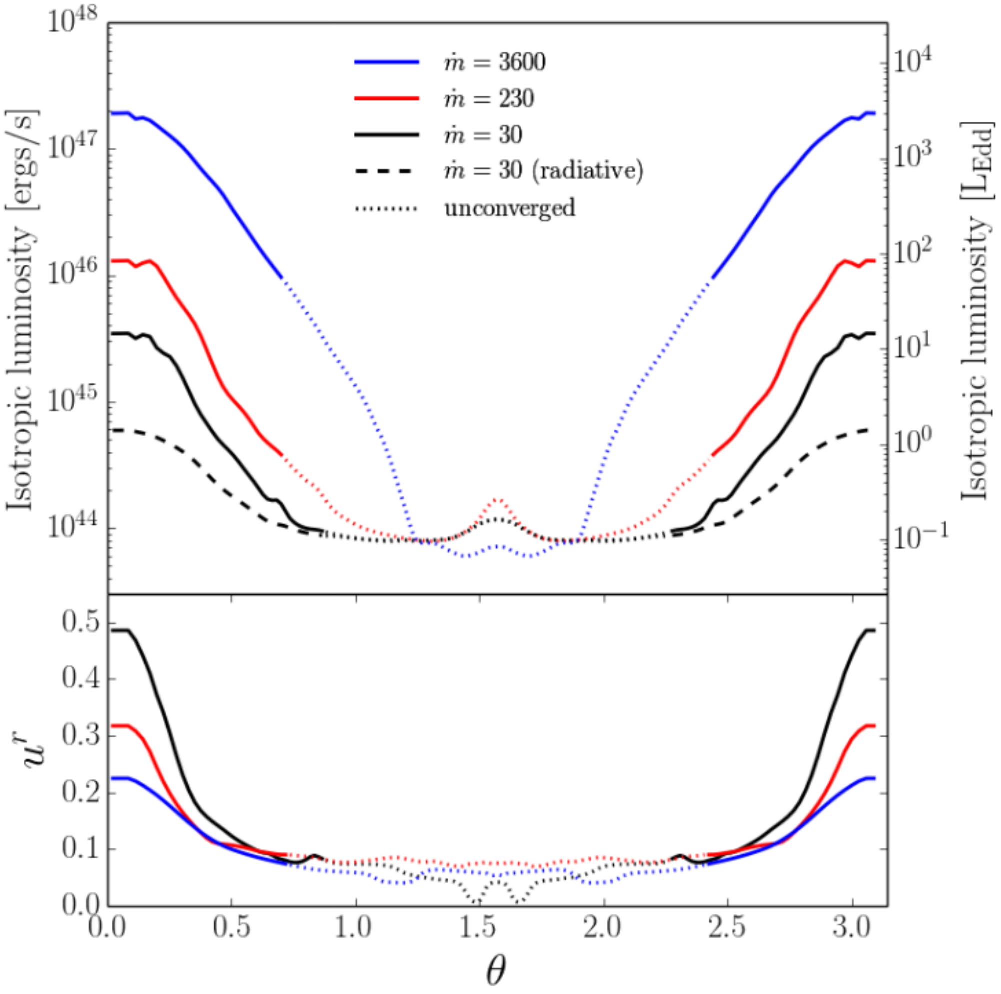


- Higher accretion rates imply higher gas densities
- Larger optical depth in the funnel
- Lower gas velocities

Isotropic equivalent luminosities

observer looking at angle theta



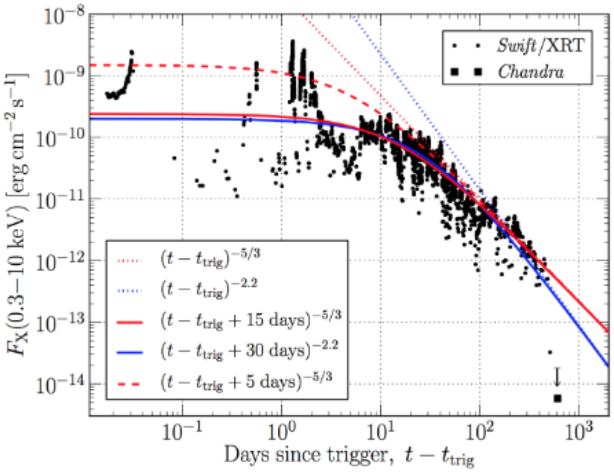


Tidal Disruption Events

(c) James Guillochon & Suvi Gezari

- whenever a star gets too close to a SMBH it gets disrupted
- accretion coming from the fallback of the bound material
- accretion rate starting at ~1000 Eddington
- followed by a $t^{-5/3}$ decay

Swift J1644+57
  - isotropic equivalent luminosity in X-ray ~1e48 erg/s
  - in the standard picture jet emission requires significant accumulation of magnetic flux and non-zero BH spin
  - radio afterglow suggests Lorentz factor ~2-5



Tchekhovskoy+14

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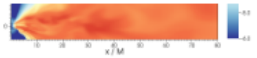

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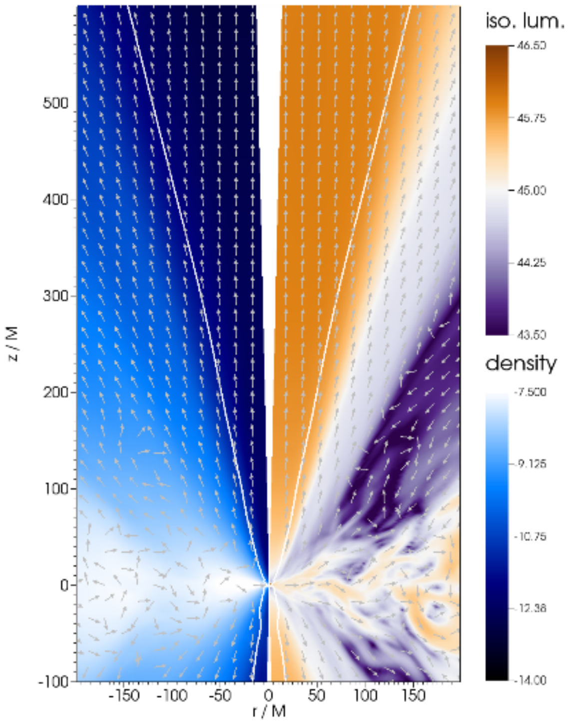

Isotropic equivalent luminosities

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