Radiative jets / jets in thin disks

Cracow · Aleksander Sądowski, MIT · 4/20/2015

Radiation from accretion disks

Thin disks

Thick disks

KORAL

KORAL code

The power of radiative jets

Radiative jets in super-critical disks

Super-critical disks

The funnel

Energy fluxes in the funnel

Isotropic equivalent luminosities

Radiative jets in super-critical BH accretion disks

Applications

Radiative jets - applications

Magnetic vs radiative

Magnetic vs radiative jets

Magnetic vs radiative jets

Thin disks (preliminary)

Jets in thin disks

Simulations of strongly magnetized thin disks

Magnetic flux at BH horizon

Jet power in thin disks

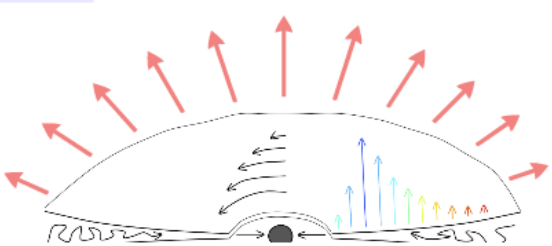
Radiative jets / jets in thin disks

Cracow Aleksander Sądowski, MIT 4/20/2015

Radiation from accretion disks

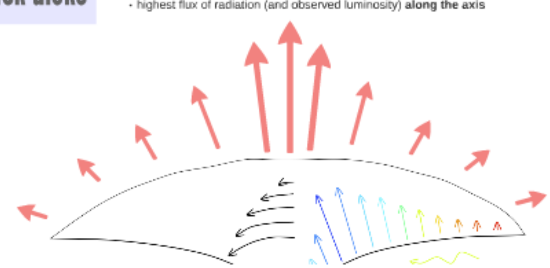
Thin disks

- accretion disks **thin for sub-Eddington** accretion rates
- integrated radiation roughly **isotropic**



Thick disks

- disks **thick** for super-Eddington accretion rates
- **radiation collimated** by the disk walls (Lynden-Bell 1978, Abramowicz & Piran 1980, Sikora 1981)
- highest flux of radiation (and observed luminosity) **along the axis**

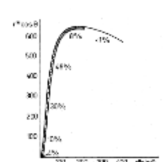


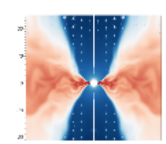
Superluminous disks - radiative flux in the funnel

Superluminous accretion discs

Marek Sikora *Institute of Astronomy*, Madingley Road, Cambridge CB3 0HA and N. Copernicus Astronomical Center, Polish Academy of Sciences, Bartycka 18, 00-716 Warszawa, Poland*

Received 1980 November 25; in original form 1980 July 4





Radiative jets /

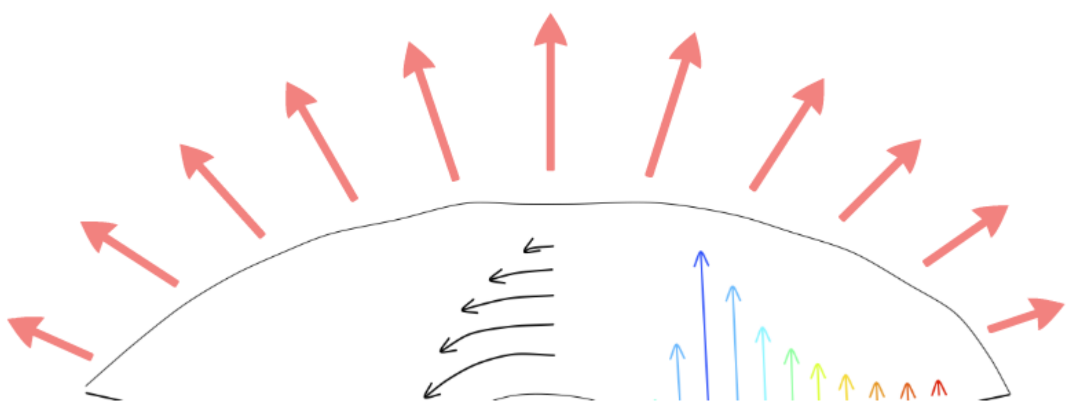
Cracow

Aleksander S

Radiation from accretion disks

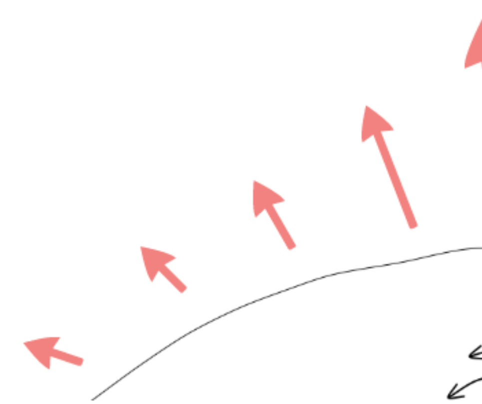
Thin disks

- accretion disks **thin for sub-Eddington** accretion rates
- integrated radiation roughly **isotropic**



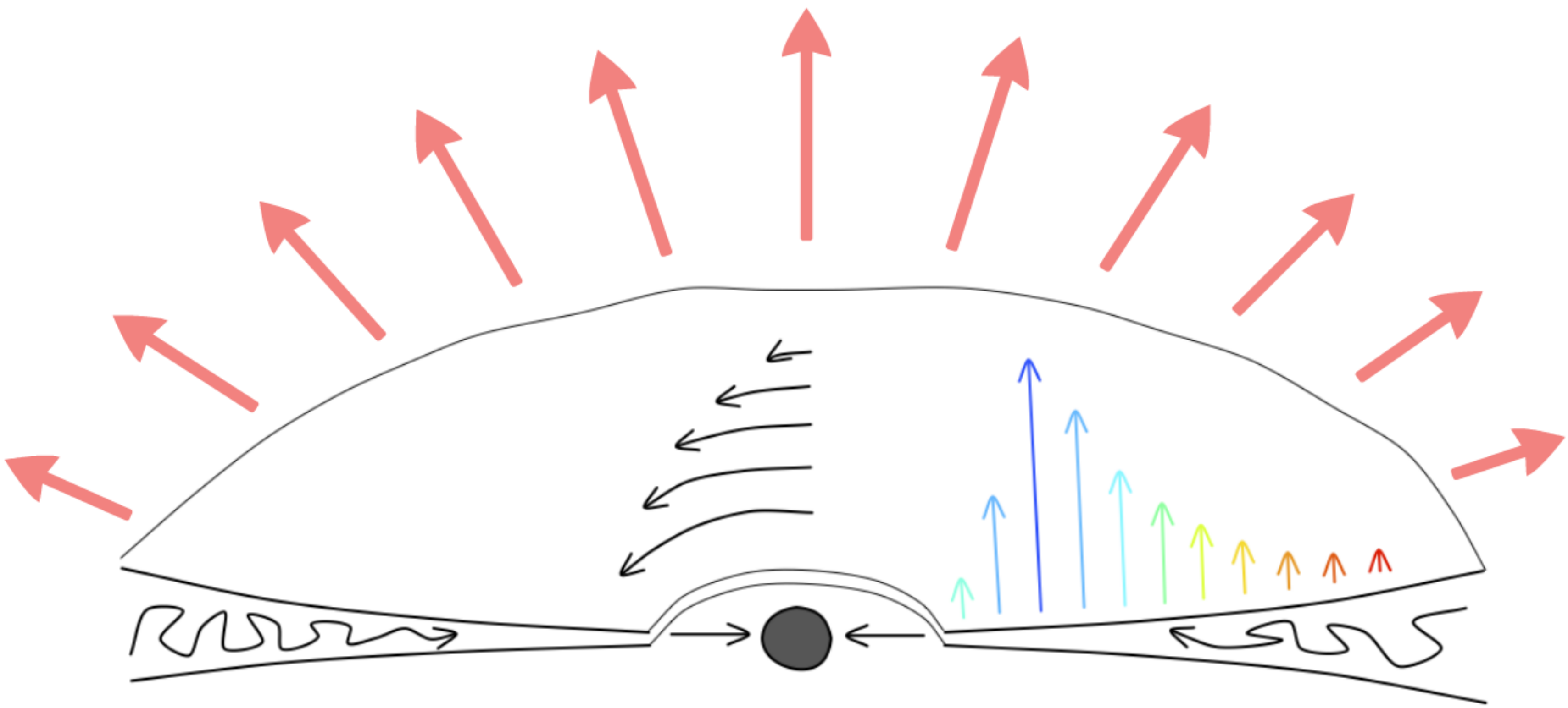
Thick disks

- disks **thick** for super-E
- **radiation collimated**
  (Lynden-Bell 1978, Ab
- highest flux of radiatio



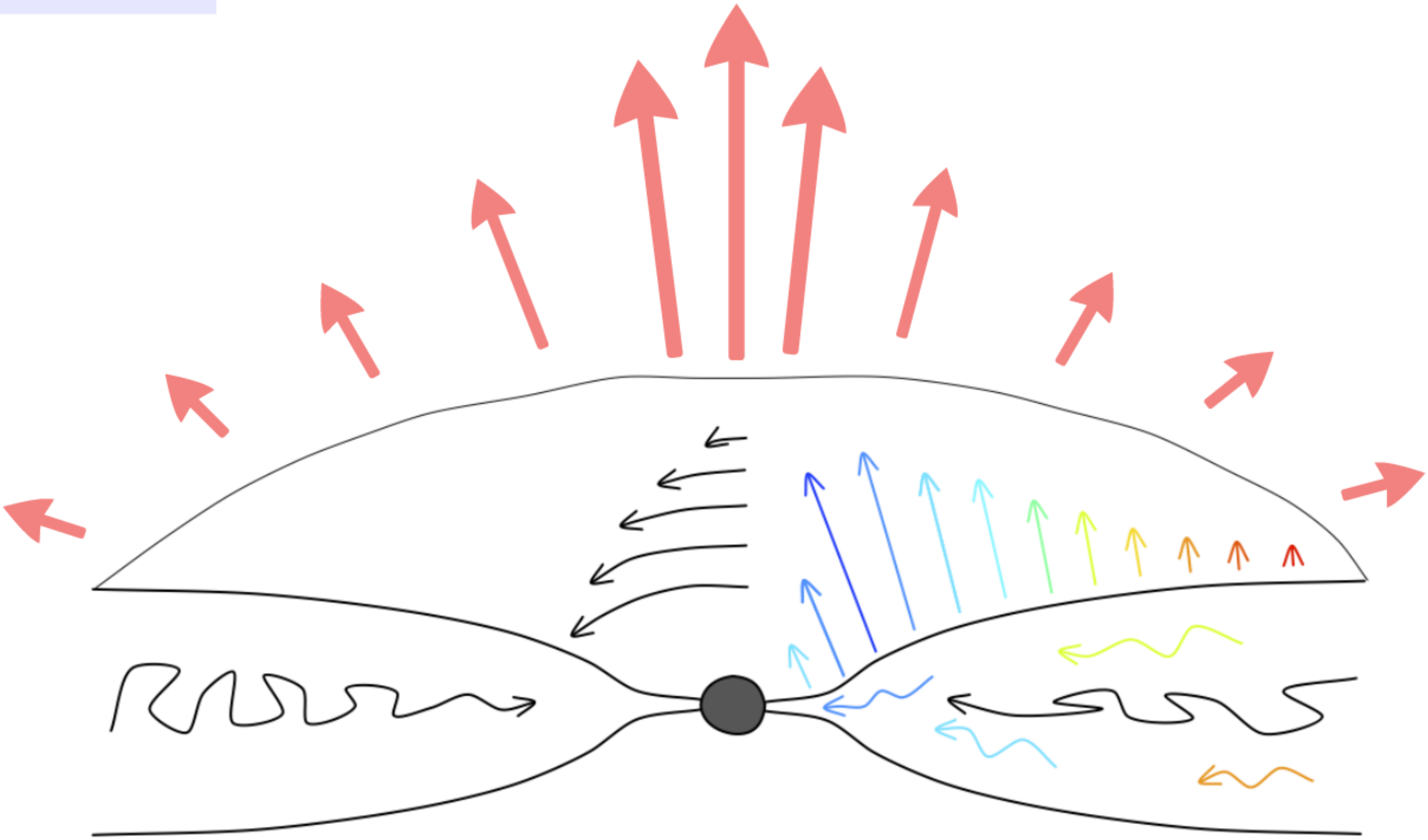
Thin disks

- accretion disks **thin for sub-Eddington** accretion rates
- integrated radiation roughly **isotropic**



Thick disks

- disks **thick** for super-Eddington accretion rates
- **radiation collimated** by the disk walls (Lynden-Bell 1978, Abramowicz & Piran 1980, Sikora 1981)
- highest flux of radiation (and observed luminosity) **along the axis**



Superluminous disks - radiative flux in the funnel

Superluminous accretion discs

Marek Sikora *Institute of Astronomy*, Madingley Road, Cambridge CB3 0HA and N. Copernicus Astronomical Center, Polish Academy of Sciences, Bartycka 18, 00-716 Warszawa, Poland*

Received 1980 November 25; in original form 1980 July 4

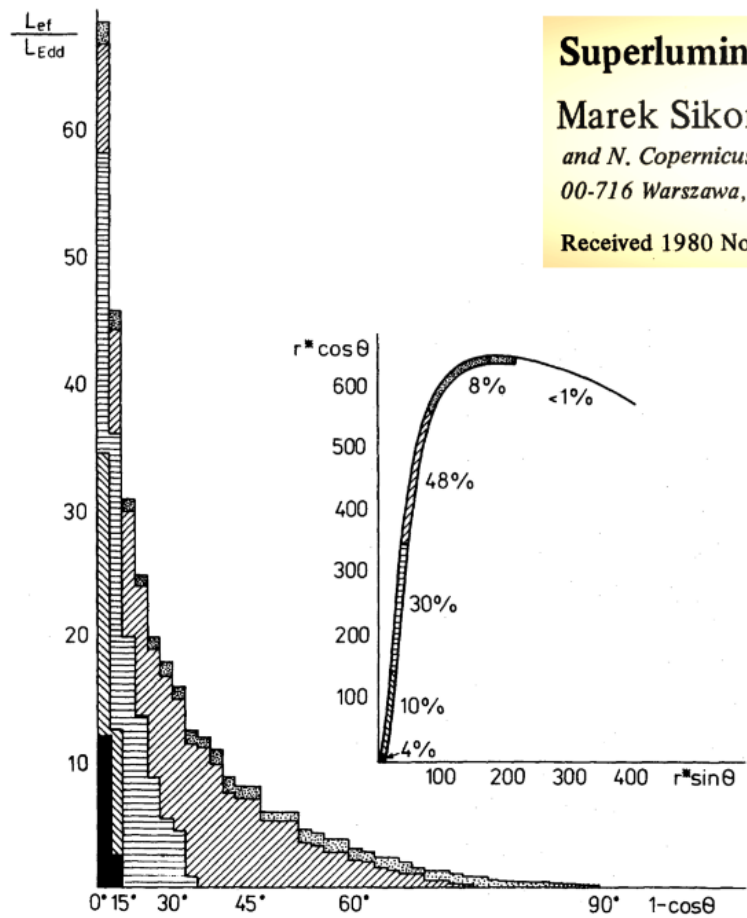
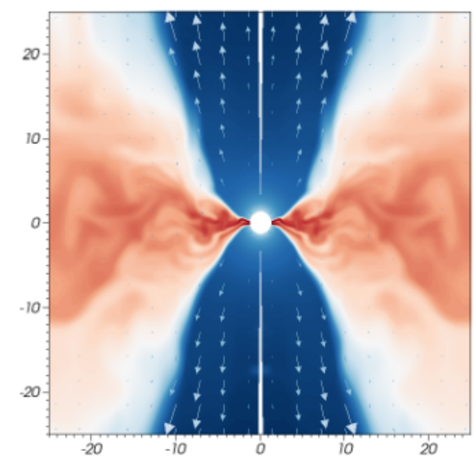
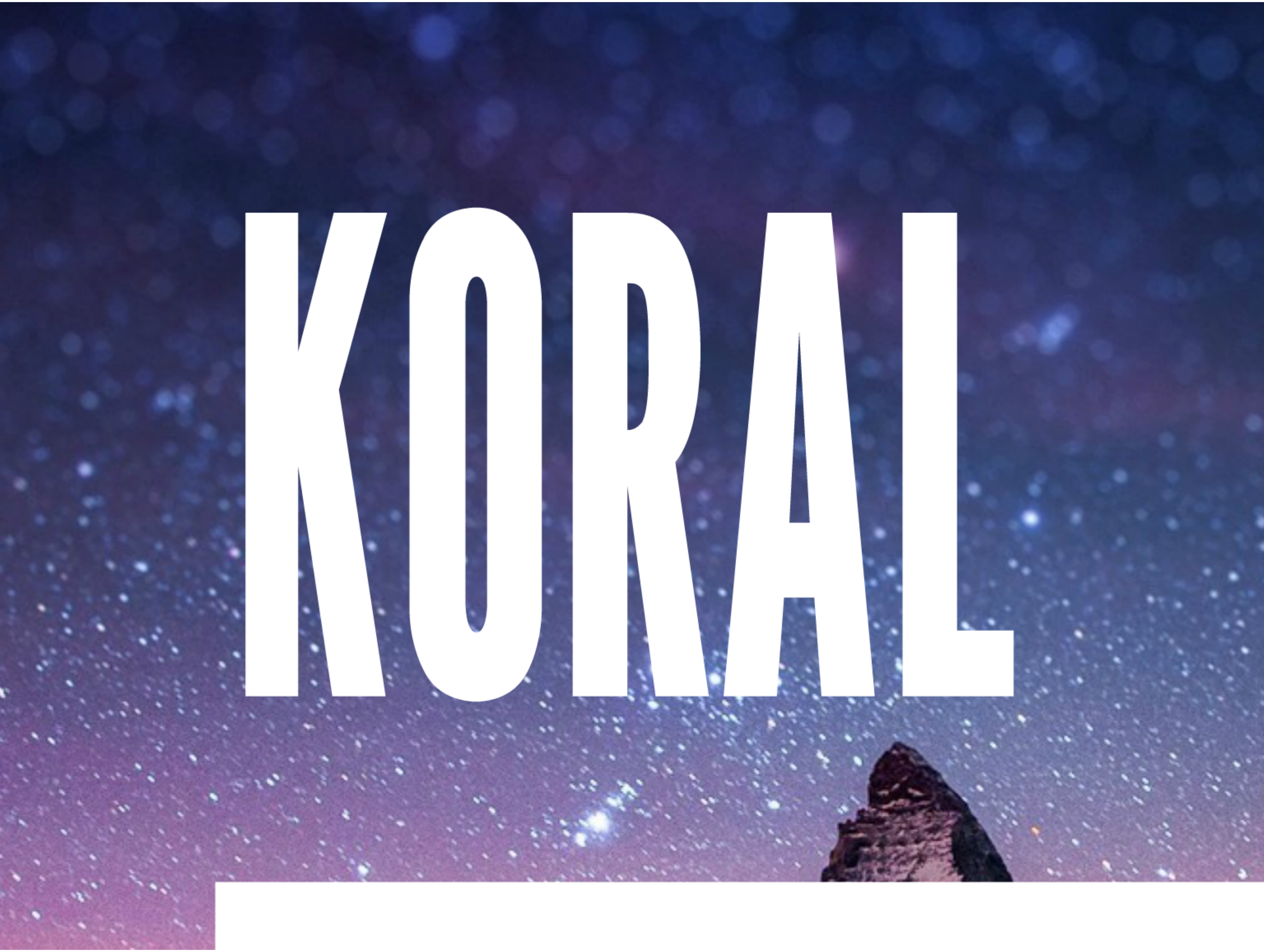
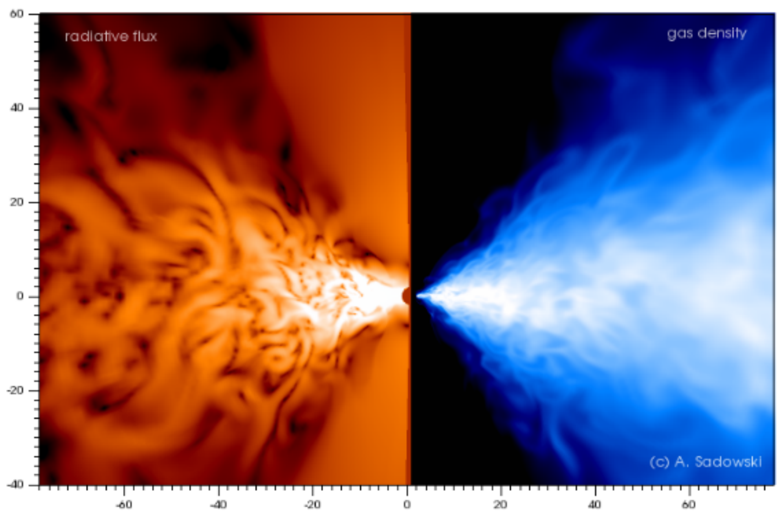


Figure 5. The distributions of the luminosity at infinity as a function of $\cos\theta_{B-L}$. Contributions of different parts of disc to this distribution are also marked.




KORAL

KORAL code (Sądowski+13,+14)



Sadowski+15

(jets, BH spin, any metric)

(full structure)

(superior to FLD)

Global + GR + M1 closure + ideal MHD + (dynamo)

(MRI)

(long duration axisymmetric simulations)

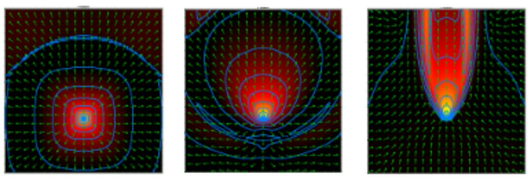
α, β

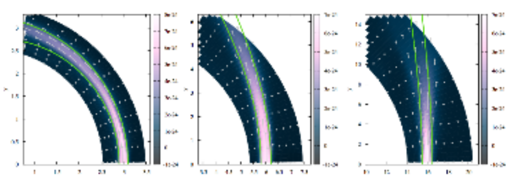
M1 a covariant radiative closure

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

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





- reasonable, local, simple in GR, cheap
- conserves energy and momentum
- far from perfect

Radiation - gas coupling

Conservation of mass, energy & momentum:

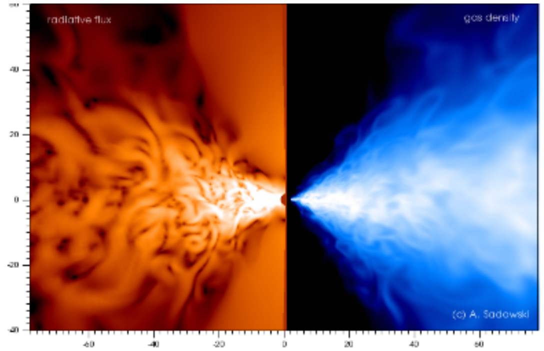
$$\begin{aligned} (\rho u^\mu)_{;\mu} &= 0 \\ (T^\mu_\nu)_{;\mu} &= G_\nu \\ (R^\mu_\nu)_{;\mu} &= -G_\nu \end{aligned}$$

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:

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



Sadowski+15

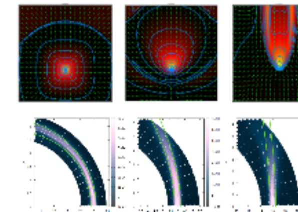
Global + GR + M1 closure + ideal MHD + (dynamo)

(MRI)

(long duration axisymmetric simulations)

α, β

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



reasonable, local, simple in GR
conserves energy and mome
far from perfect

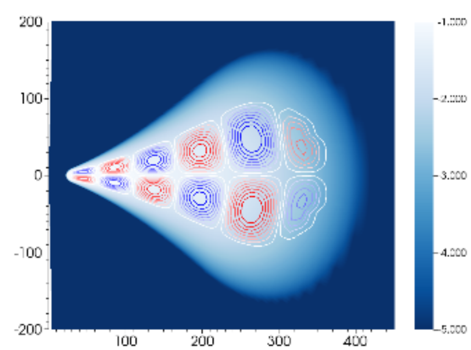
The power of radiative jets

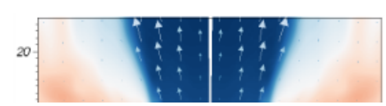
Radiative jets in super-critical disks

simulation setup

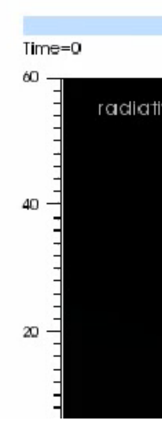
- initiated as equilibrium torus of gas and radiation
- mildly supermassive black hole
- wide rang of accretion rates
- multiple loops of initial magnetic field
  - **weak magnetic flux limit**
- zero BH spin
  - **no Blandford - Znajek**

- to study **how efficient the polar outflow can be without BZ**
- first study based on global GR simulations





Super-critical d



Radiative jets in super-critical disks

simulation setup

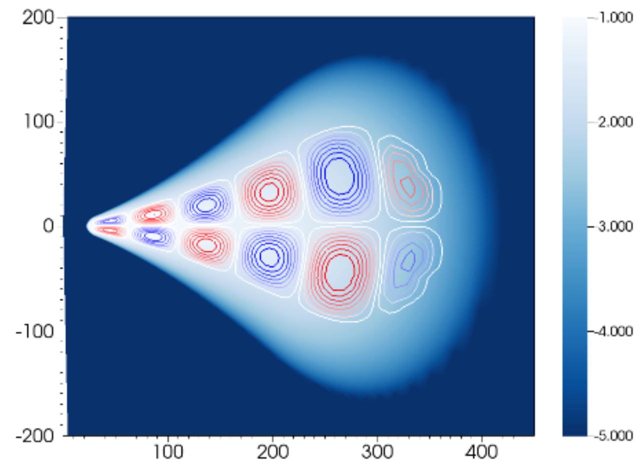
- initiated as equilibrium torus of gas and radiation
- mildly supermassive black hole
- wide rang of accretion rates
- multiple loops of initial magnetic field
  - **weak magnetic flux limit**
- zero BH spin
  - **no Blandford - Znajek**

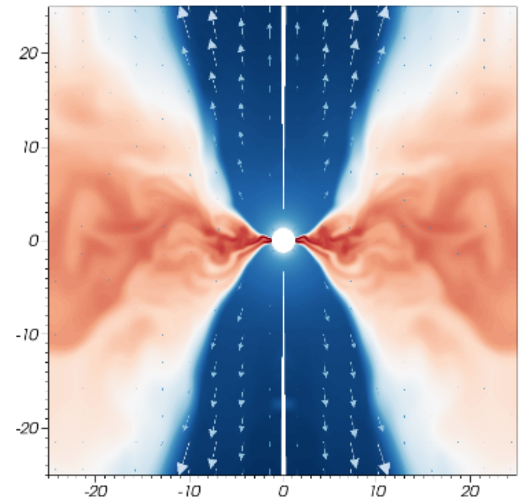
- to study **how efficient the polar outflow can be without BZ**
- first study based on global GR simulations

Table 1. Model parameters

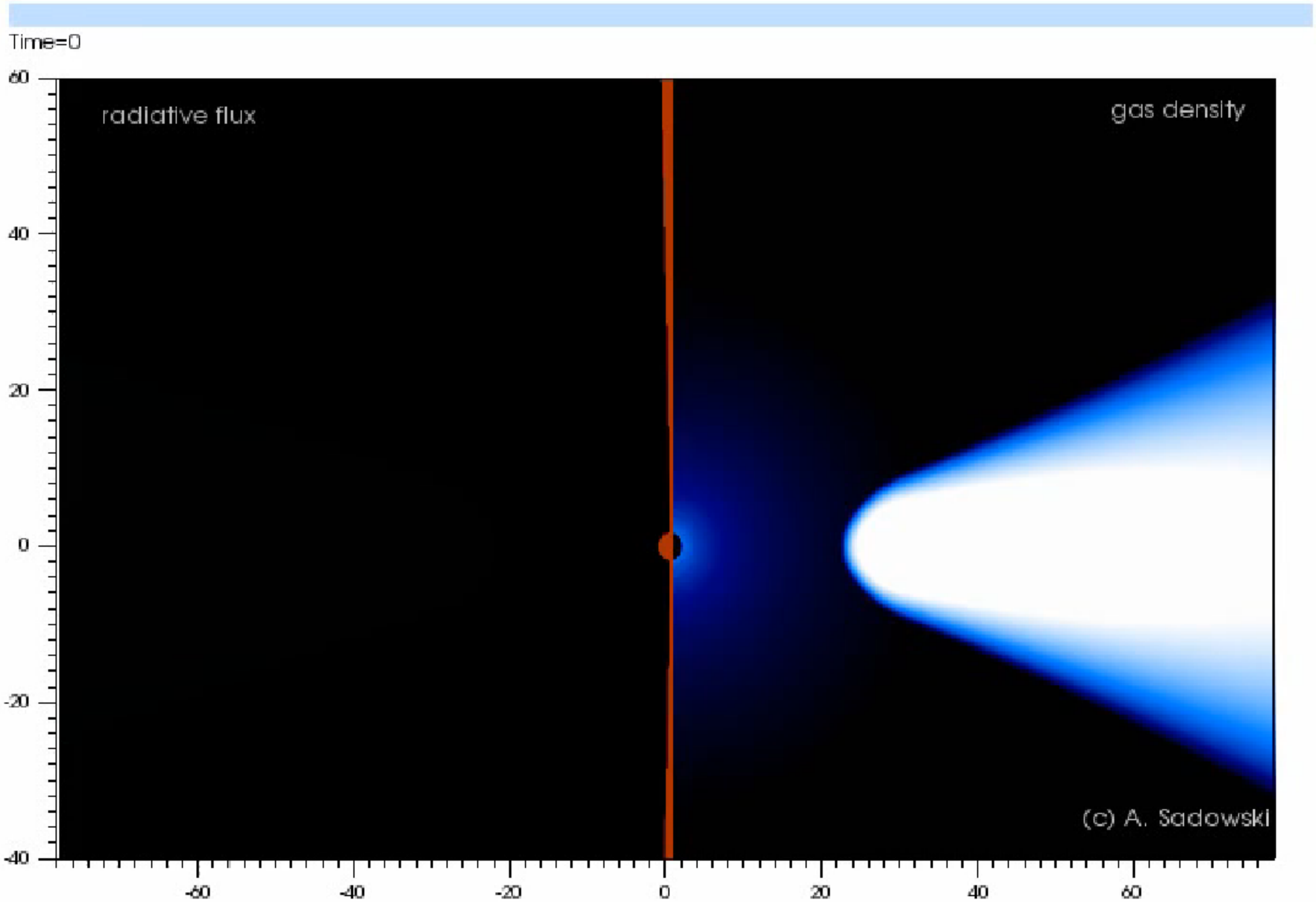
Name	$\mathcal{K}$	$t_{\rm max}/(GM/c^3)$	$\langle\dot{M}\rangle/\dot{M}_{\rm Edd}$	η
A	10.0	200,000	45	5.3%
B	5.0	170,000	310	4.0%
C	1.0	190,000	4800	4.6%

Other parameters: $M_{\rm BH} = 3{\times}10^5 M_\odot$, $a_* = 0.0$, 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).



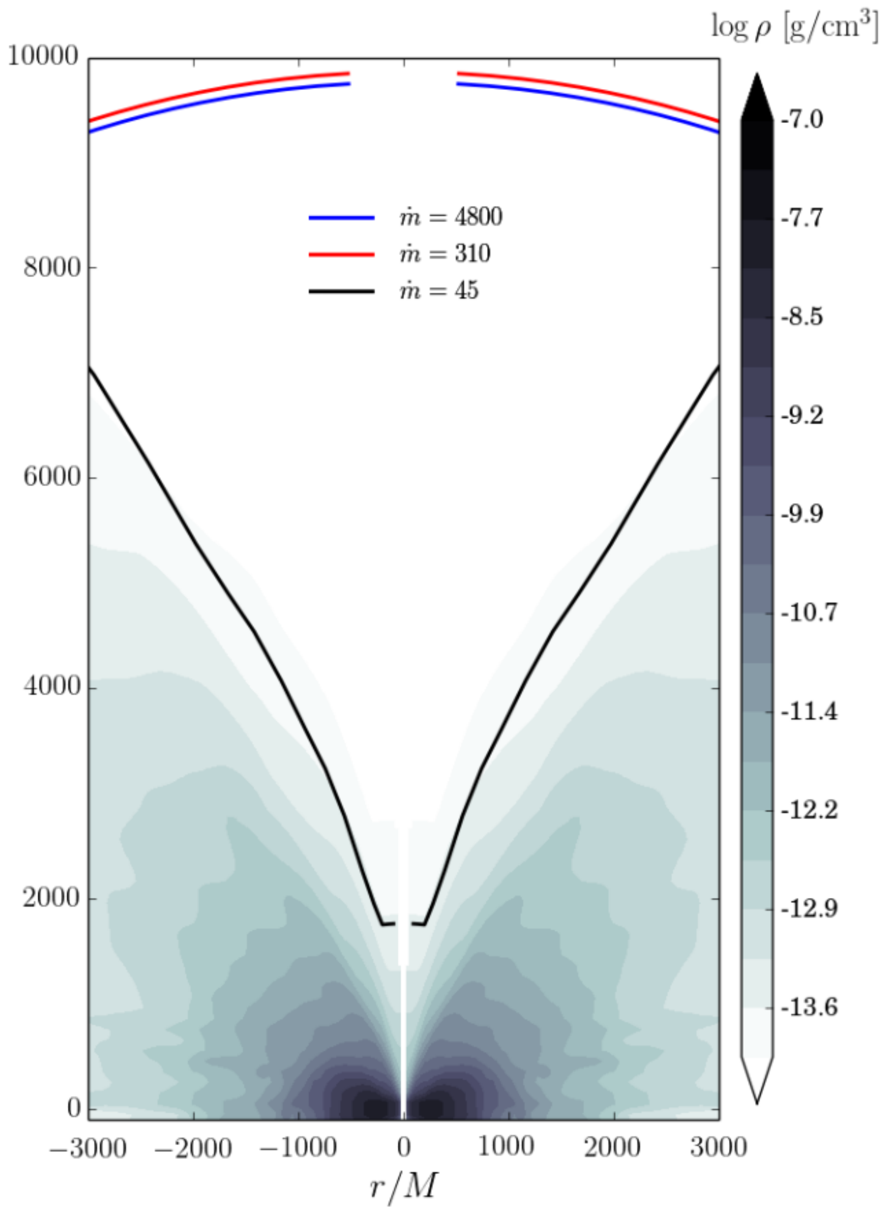


Super-critical disks



The funnel

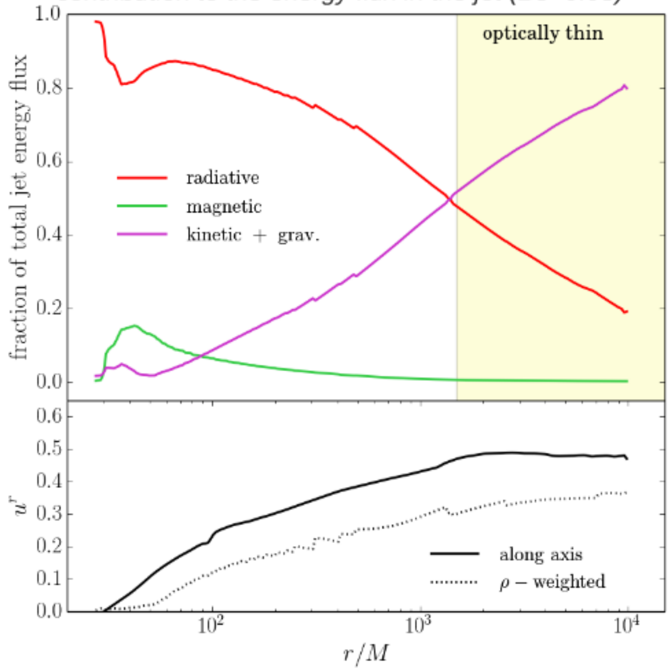
- disks geometrically very thick
- lowest density near the axis in the funnel region
- but the photosphere far from BH!
- radiation interacts with the gas below the photosphere

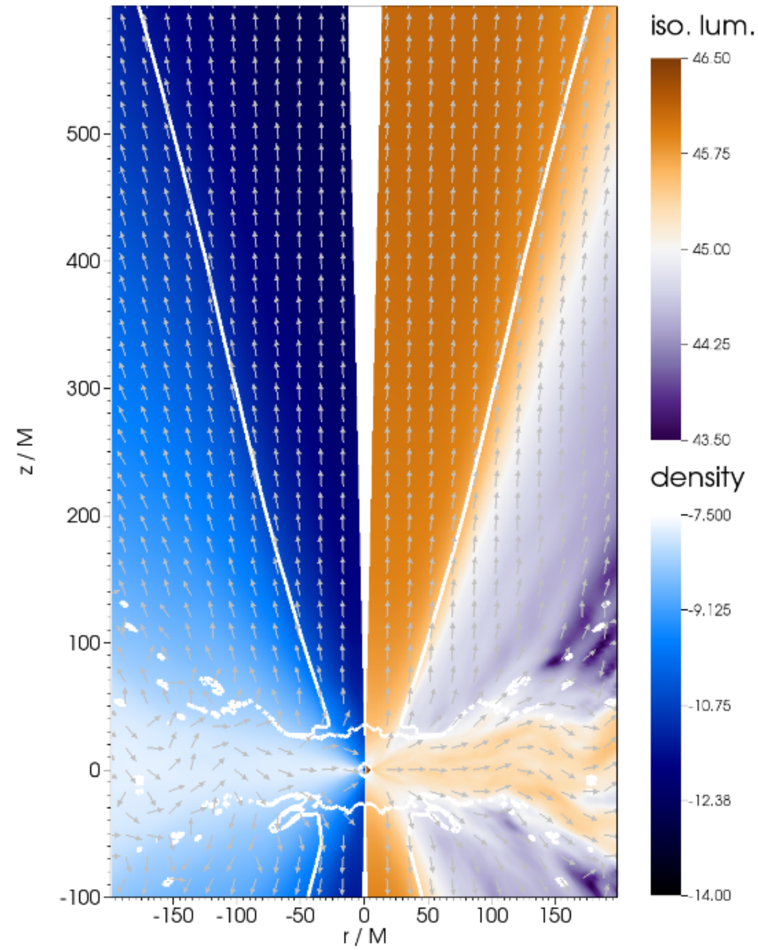


Energy fluxes in the funnel

- energy flux dominated initially by the radiative flux, converting gradually into kinetic energy of gas
- for $\dot{M} \gtrsim 10\dot{M}_{\rm Edd}$ most radiative energy converted into kinetic
- luminosity in the funnel ~1-2% of accreted rest mass energy
- gas reaches mildly-relativistic velocities ~0.3c

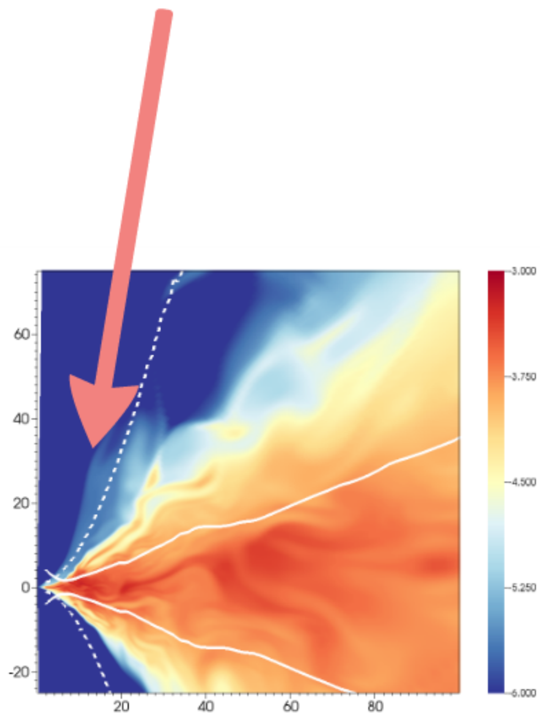
contribution to the energy flux in the jet (Be>0.05)

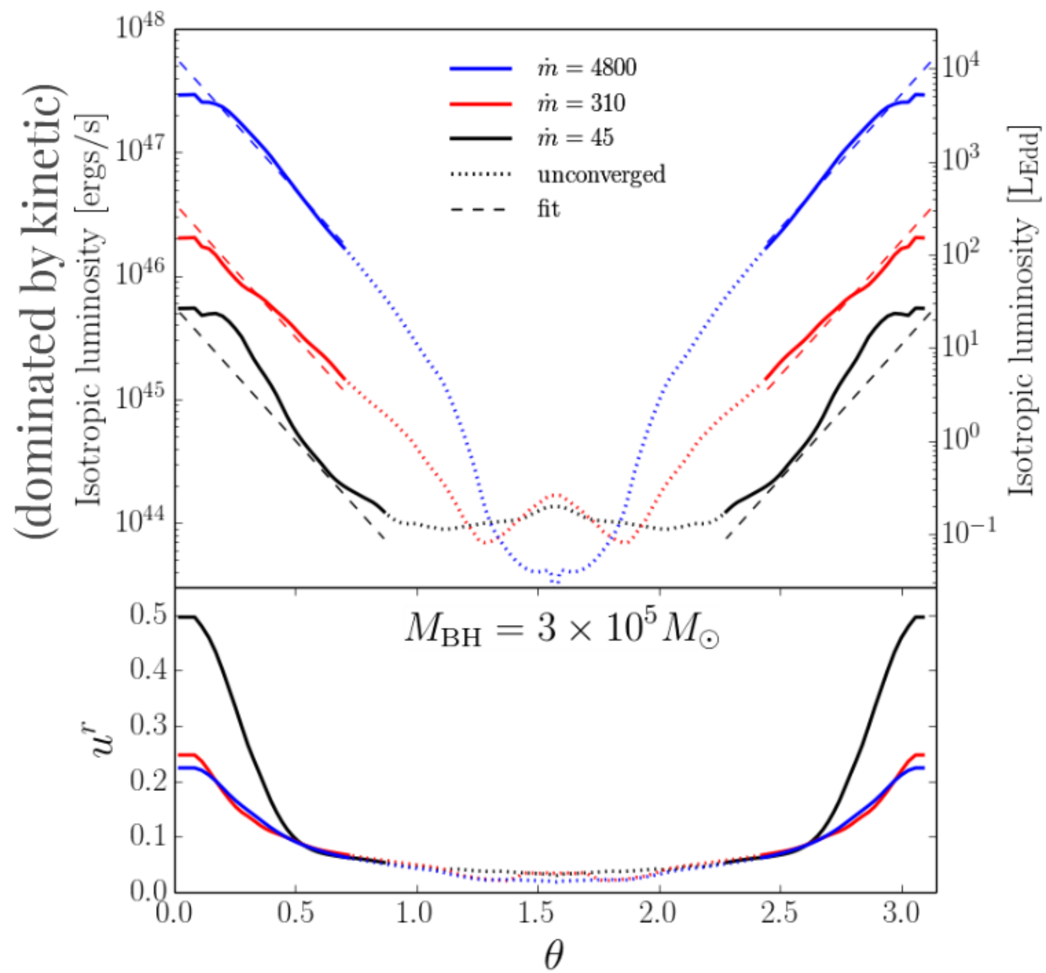




Isotropic equivalent luminosities

observer looking at
angle theta

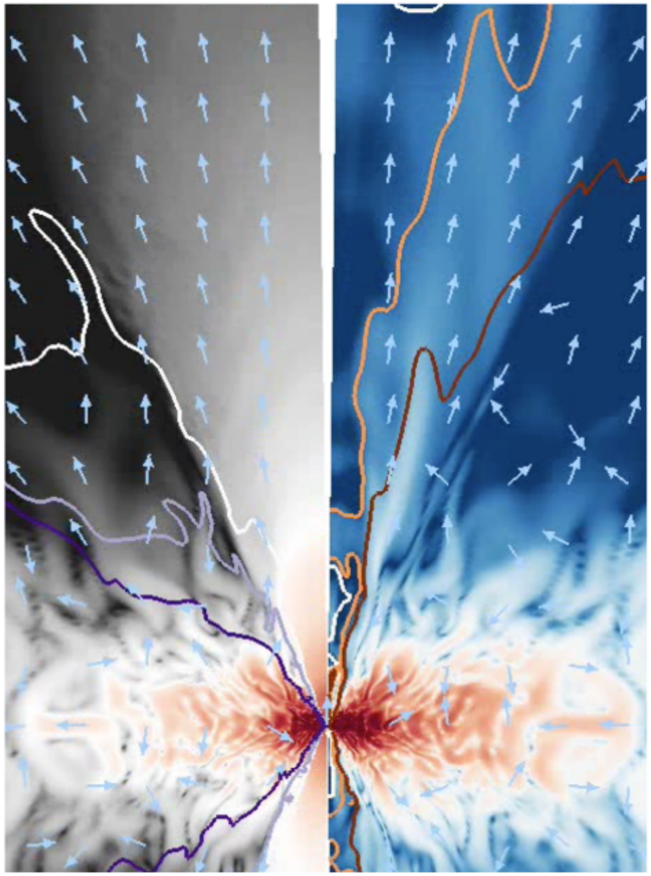


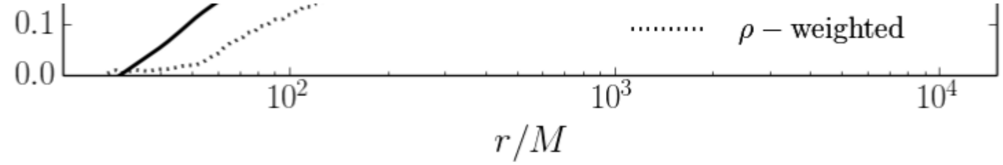


Radiative jets in super-critical BH accretion disks

- Super-critical accretion produces powerful jet-like outflows of energy
- Isotropic equivalent luminosity (in total energy) up to $L_{\rm iso} \lesssim 10^{48}$ erg/s for $10^6\, M_\odot$ and $1000\, \dot{M}_{\rm Edd}$
- No magnetic flux or BH spin required!
- Opening angle ~15 deg

- Radiative energy converted into kinetic flux for $\dot{M} \gtrsim 10\dot{M}_{\rm Edd}$
- Gas velocities saturates at ~0.3c because of radiative drag
- Kinetic energy may dissipate in internal shocks

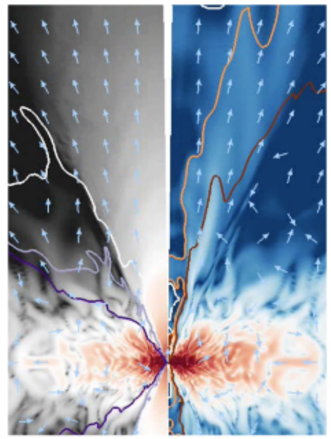




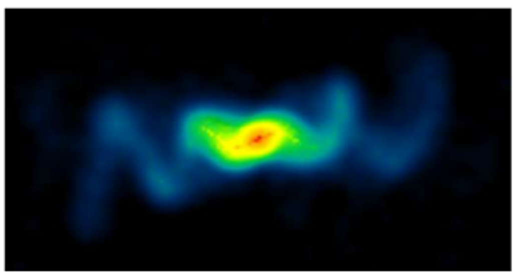
Applications

Radiative jets - applications

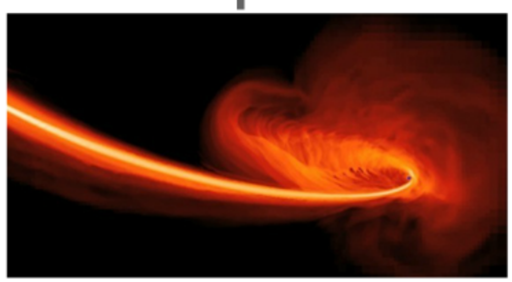
Radiative jets - applications



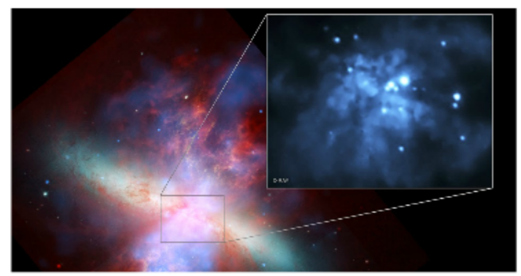
SS433



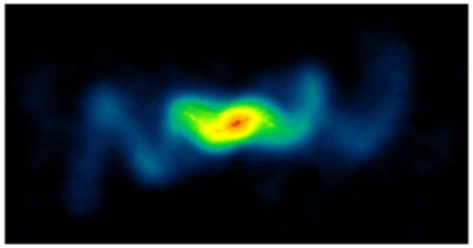
Tidal Disruption Events



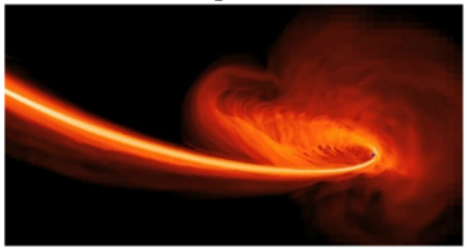
ULX / HLX



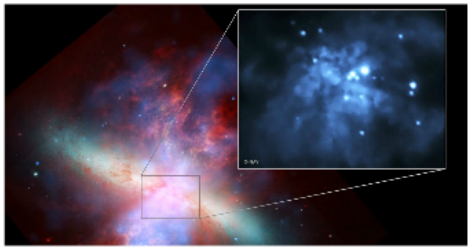
SS433



Tidal Disruption Events



ULX / HLX



Magnetic vs radiative

Magnetic vs radiative jets

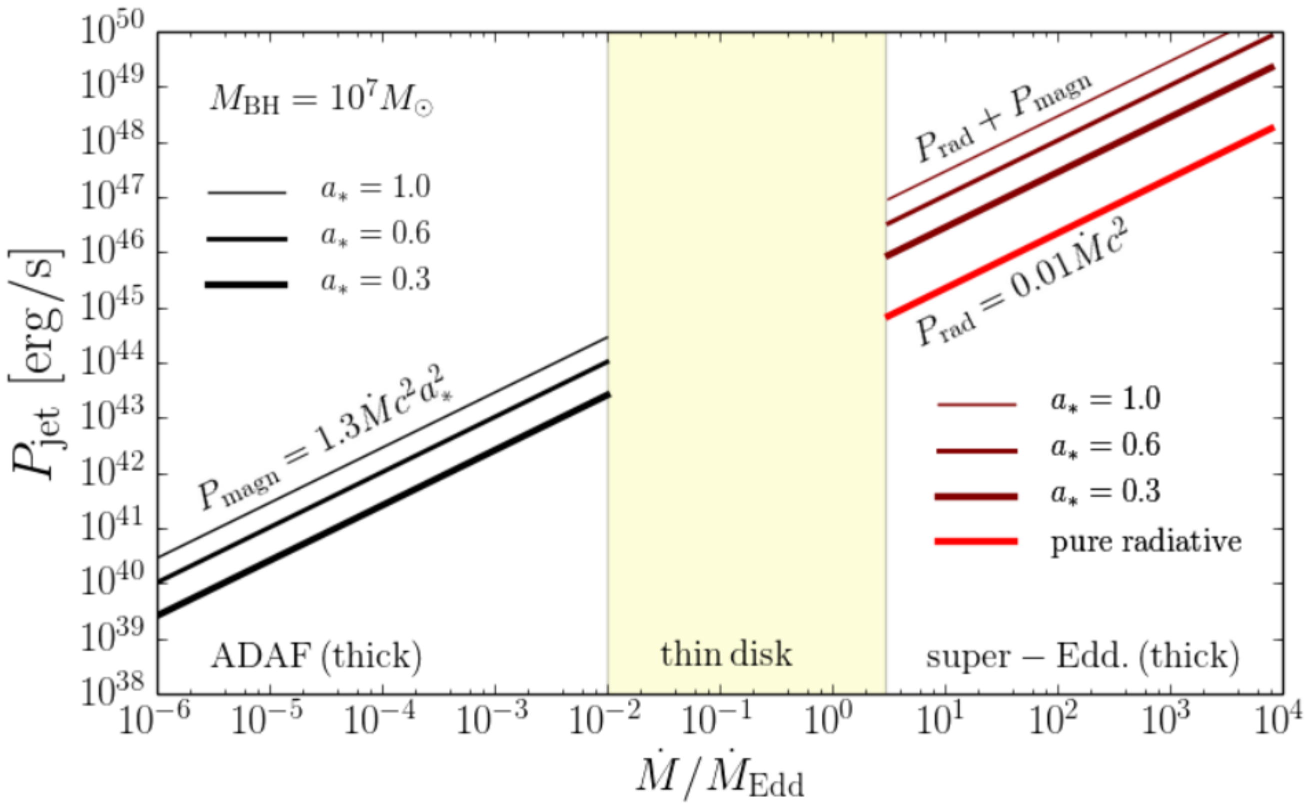
Jets:	magnetic	radiative
acceleration mechanism:	Blandford-Znajek	radiation pressure

Magnetic vs radiative jets

Jets:	magnetic	radiative
acceleration mechanism:	Blandford-Znajek	radiation pressure
energy source:	BH rotation	dissipation inside the disk
disk regime:	ADAF & super-Edd.	super-Edd.
accretion rates:	$\dot{M} \lesssim 10^{-2} \dot{M}_{\rm Edd}$	$\dot{M} \gtrsim 3\dot{M}_{\rm Edd}$
	$\dot{M} \gtrsim 3\dot{M}_{\rm Edd}$	
velocities:	$\gamma \gtrsim 10$	$v = 0.3c$
collimation:	strong	weak ($\theta_0 = 0.2$)
energy flux:	magnetic	radiative / kinetic
total power in the jet:	$\sim 1.3\dot{M}c^2 a_*^2$	$\sim 0.01\dot{M}c^2$

Magnetic vs radiative jets

Jets:	magnetic	radiative
acceleration mechanism:	Blandford-Znajek	radiation pressure
energy source:	BH rotation	dissipation inside the disk
disk regime:	ADAF & super-Edd.	super-Edd.
accretion rates:	$\dot{M} \lesssim 10^{-2}\dot{M}_{\rm Edd}$ $\dot{M} \gtrsim 3\dot{M}_{\rm Edd}$	$\dot{M} \gtrsim 3\dot{M}_{\rm Edd}$
velocities:	$\gamma \gtrsim 10$	$v = 0.3c$
collimation:	strong	weak ($\theta_0 = 0.2$)
energy flux:	magnetic	radiative / kinetic
total power in the jet:	$\sim 1.3\dot{M}c^2a_*^2$	$\sim 0.01\dot{M}c^2$



[illegible]	[illegible] $\dot{M}_{\rm Edd}$ $\dot{M} \gtrsim 3\dot{M}_{\rm Edd}$	[illegible] $\dot{M}_{\rm Edd}$
velocities:	$\gamma \gtrsim 10$	$v = 0.3c$
collimation:	strong	weak ($\theta_0 = 0.2$)
energy flux:	magnetic	radiative / kinetic
total power in the jet:	$\sim 1.3\dot{M}c^2 a_*^2$	$\sim 0.01\dot{M}c^2$

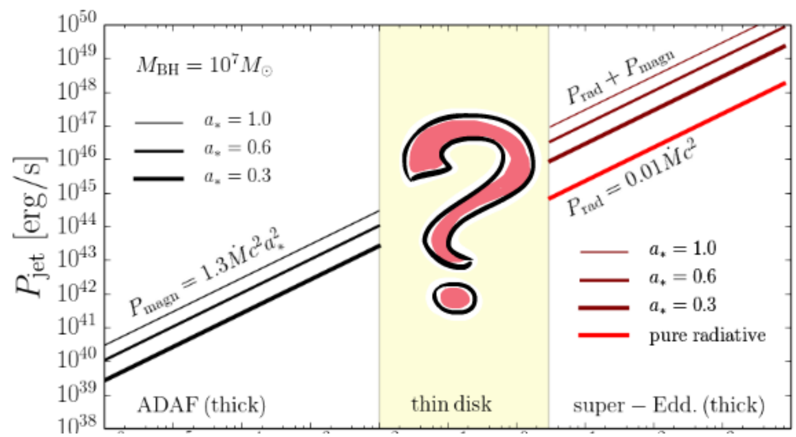
Thin disks (preliminary)

Jets in thin disks

- Sub-Eddington disks geometrically thin

Radiative jets:

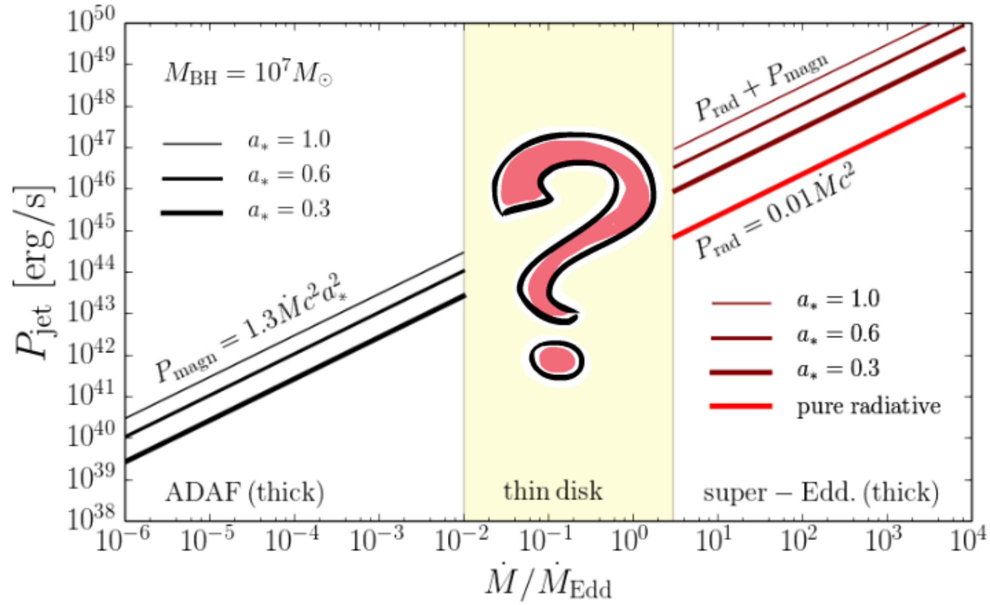
- Lack of collimation
- Photosphere at the disk surface



Simulatio[...] magnetiz[...]

- 3D simula[...] near- and [...]
- Self-consi[...]
- Magnetize[...] flux injecte[...]

Jets in thin disks



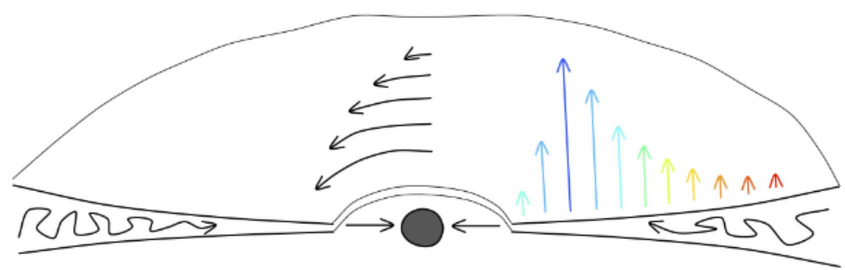
- Sub-Eddington disks geometrically thin

Radiative jets:

- Lack of collimation
- Photosphere at the disk surface
- Radiation almost isotropic

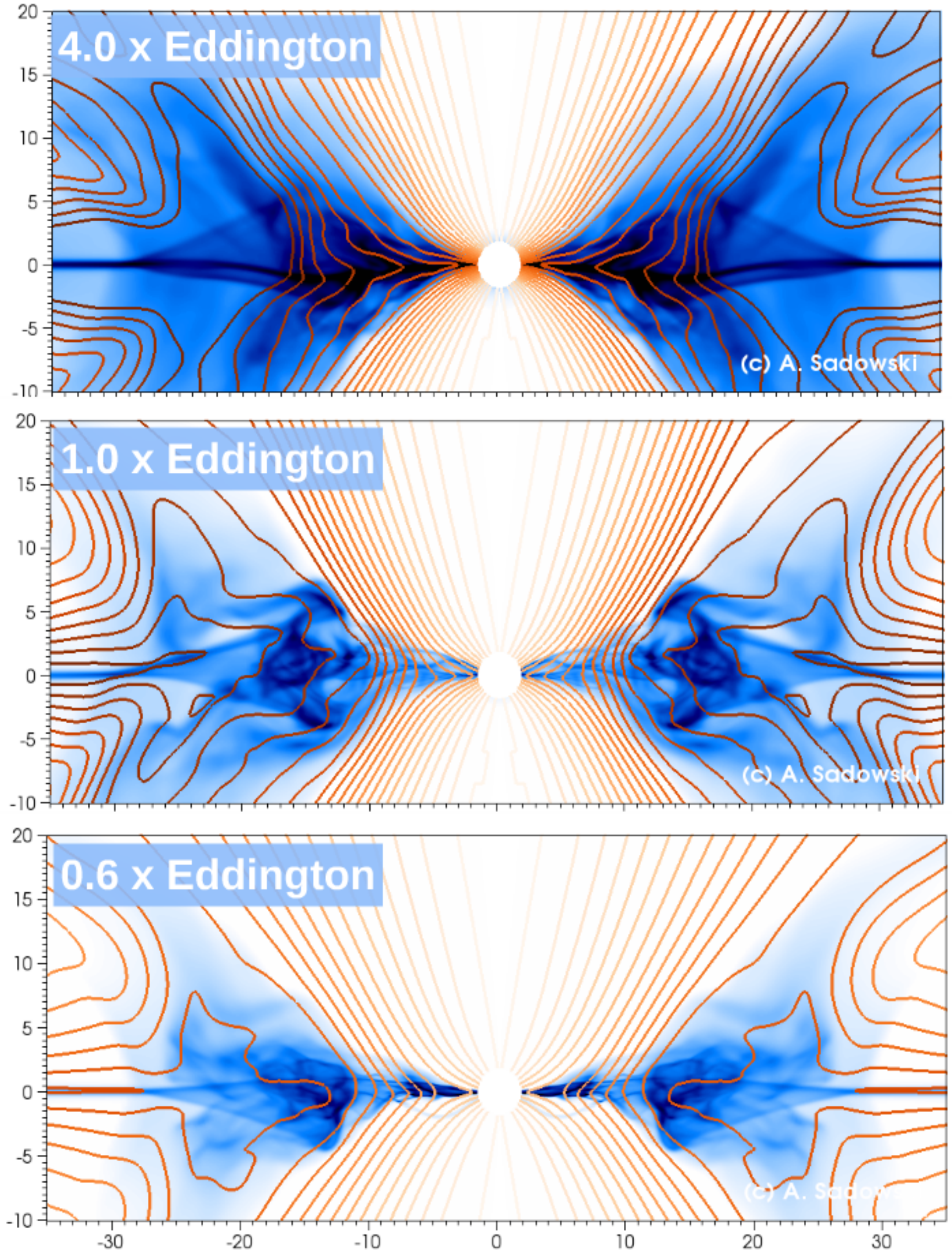
Magnetic jets:

- Slow inflow velocity
- Thin disks
- Dragging of the magnetic flux less efficient
- Outward diffusion may win and prevent MAD state or at least lower its efficiency



Simulations of strongly magnetized thin disks

- 3D simulations of optically thick disks at near- and sub-Eddington accretion rates
- Self-consistent radiative cooling
- Magnetized gas with significant magnetic flux injected through the outer boundary
- Gas circularizes at R = 15-20 M
- Magnetic flux brought on the BH
- Duration of simulations ~ 70 orbital periods at ISCO



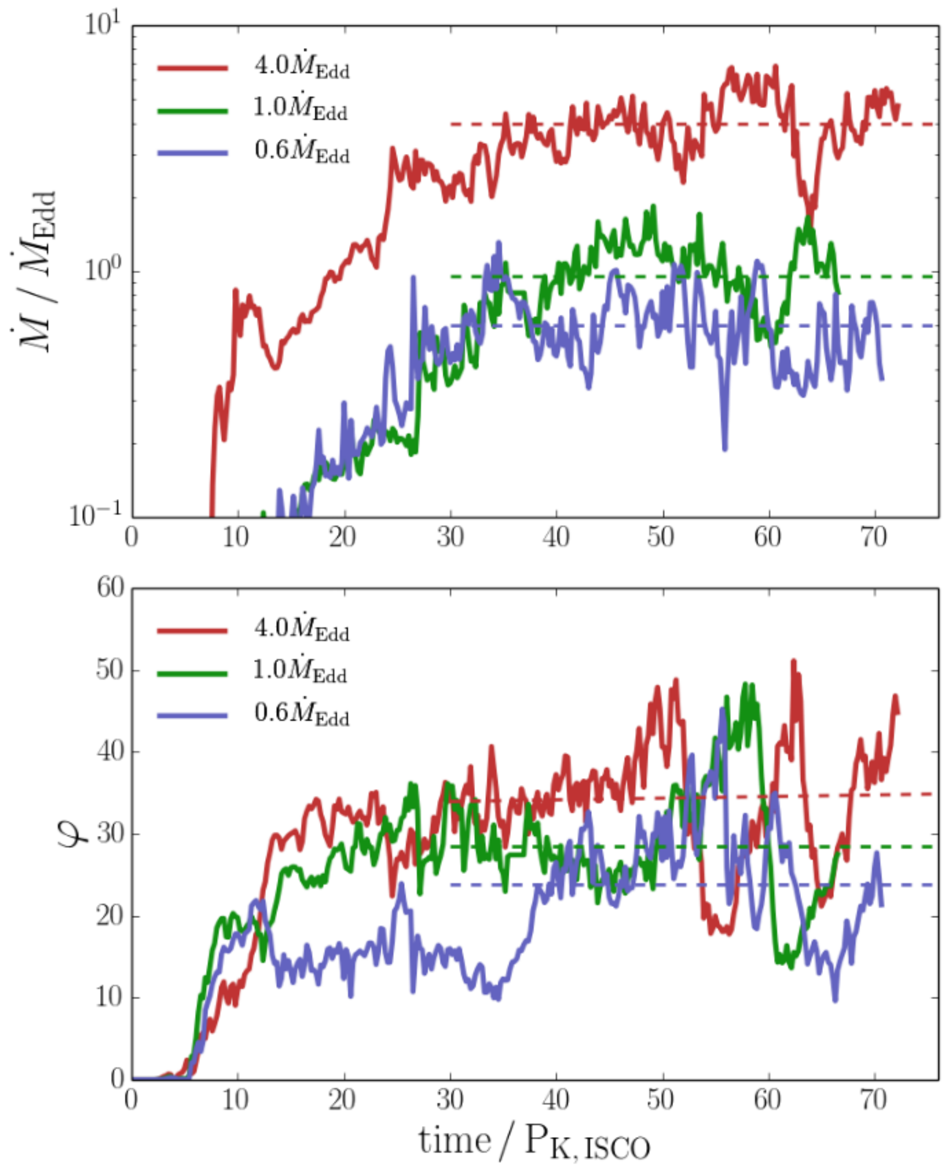
Magnetic flux at BH horizon

- Jet power depends on the magnetic flux accumulated at BH horizon
- The amount of flux at the BH parametrized through:

$$\varphi = \frac{1}{\sqrt{\langle \dot{M} \rangle}} \frac{4\pi}{2} \int_0^{\pi} \int_0^{2\pi} \sqrt{-g}\, |B^r|\, d\varphi d\theta$$

- Flux parameter value determined by the balance of inward dragging of magnetic field and outward diffusion
- Thick disks give ~50
- Our results:

Accretion rate	φ
$4.0\dot{M}_{\rm Edd}$	34 ± 7
$1.0\dot{M}_{\rm Edd}$	29 ± 7
$0.6\dot{M}_{\rm Edd}$	23 ± 7



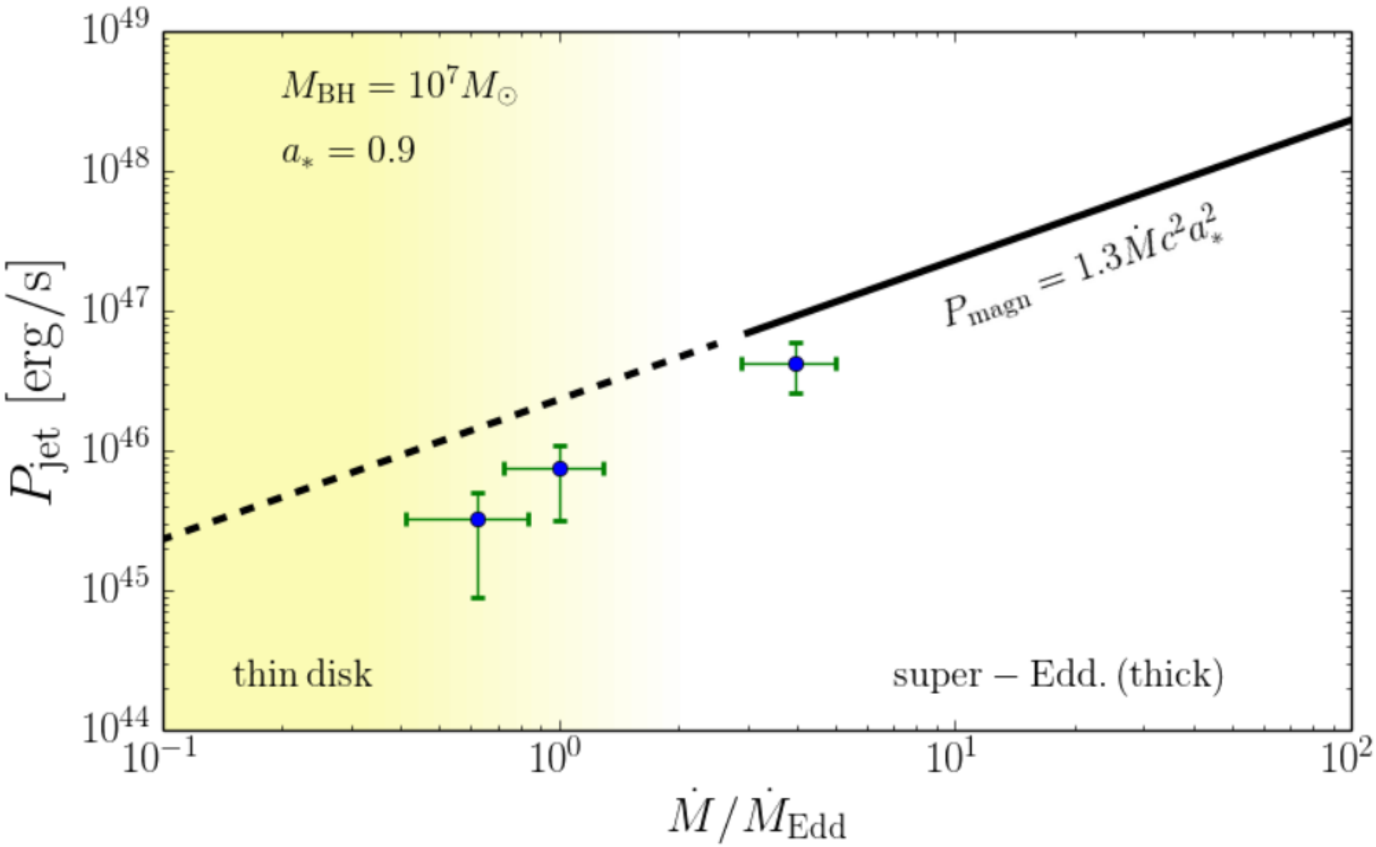
Jet power in thin disks

$$P_{\rm jet} = 1.3\dot{M}c^2\left(\frac{\varphi}{50}\right)^2 a_*^2$$

- Thin disks accumulate lower magnetic flux at the BH horizon
- Jet power goes down with decreasing accretion rate
- Jet shut off smooth

Caveats:

- small radial range of the equilibrium state
- applicable at least to tidal disruption events
- high magnetization of the flow



Radiative jets / jets in thin disks

Cracow

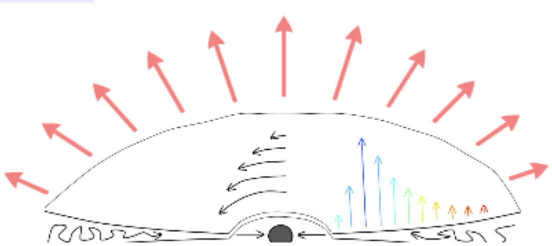
Aleksander Sądowski, MIT

4/20/2015

Radiation from accretion disks

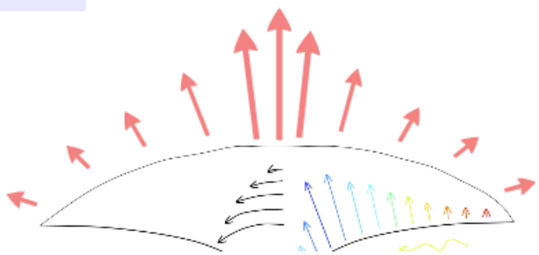
Thin disks

- accretion disks **thin for sub-Eddington** accretion rates
- integrated radiation roughly **isotropic**

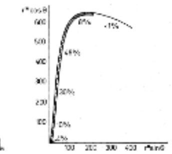


Thick disks

- disks **thick** for super-Eddington accretion rates
- **radiation collimated** by the disk walls (Lynden-Bell 1978, Abramowicz & Piran 1980, Sikora 1981)
- highest flux of radiation (and observed luminosity) **along the axis**



Superluminous disks - radiative flux in the funnel



Superluminous accretion discs

Marek Sikora *Institute of Astronomy*, Madingley Road, Cambridge CB3 0HA and N. Copernicus Astronomical Center, Polish Academy of Sciences, Bartycka 18, 00-716 Warszawa, Poland*

Received 1980 November 25; in original form 1980 July 4