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GARRA Group

Outflows in super-critical binaries

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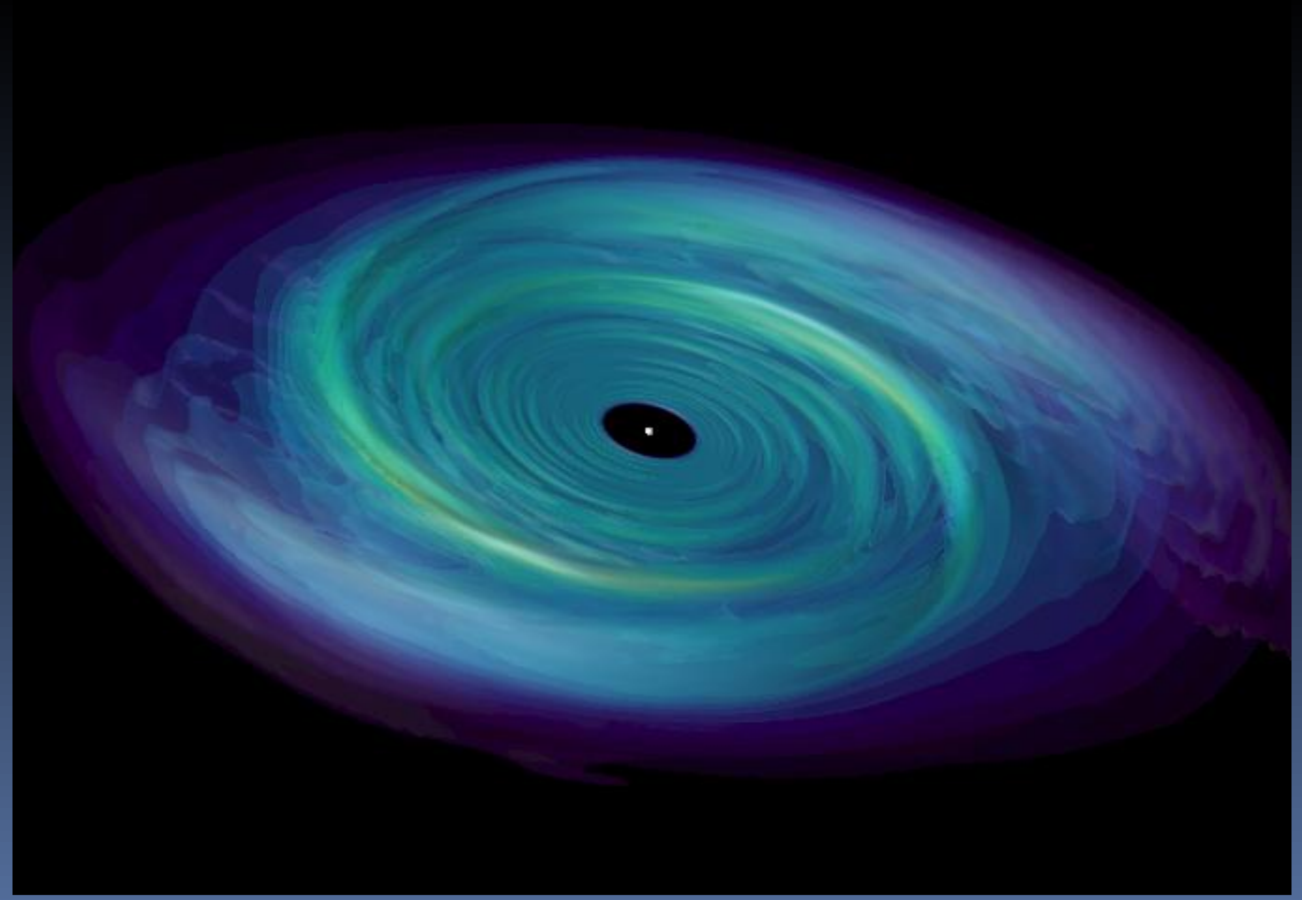
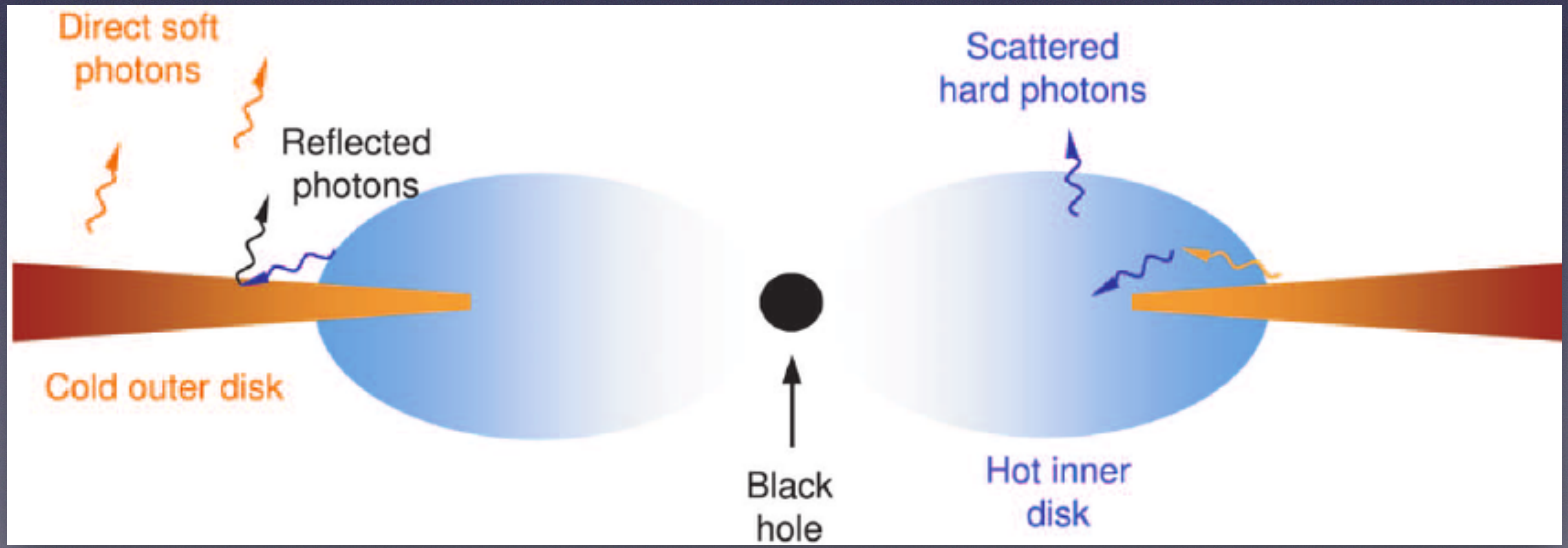
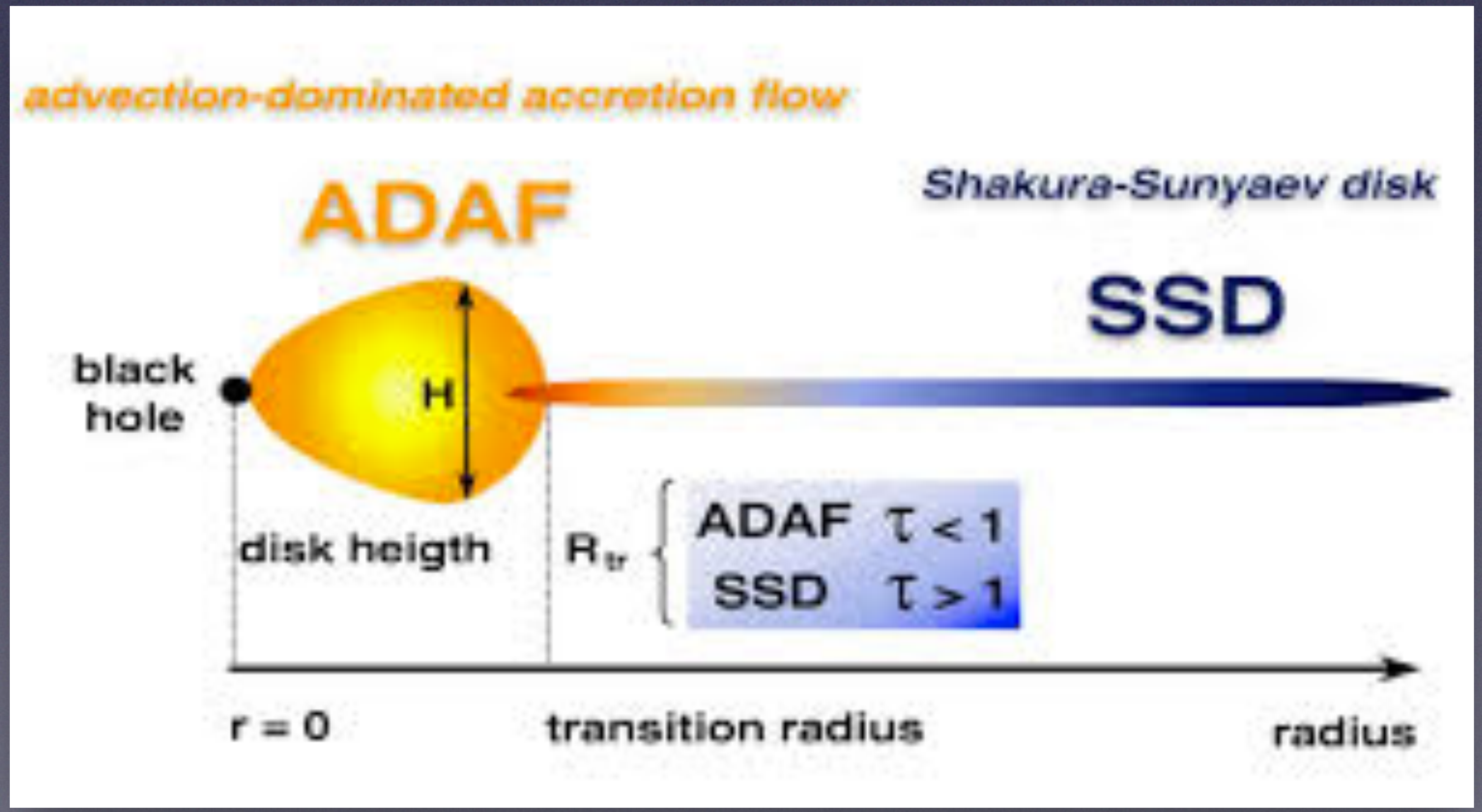
The heat generated by viscosity in accretion processes is NOT radiated away for all accretion rates. Under some conditions the radial velocity of the accretion flow becomes large and the heat cannot be transformed into radiation and emitted fast enough. A significant fraction of the heat is stored as kinetic energy in the flow and advected onto the accretor. This regime is known as "Advected Dominated Accretion Flow" (ADAF).



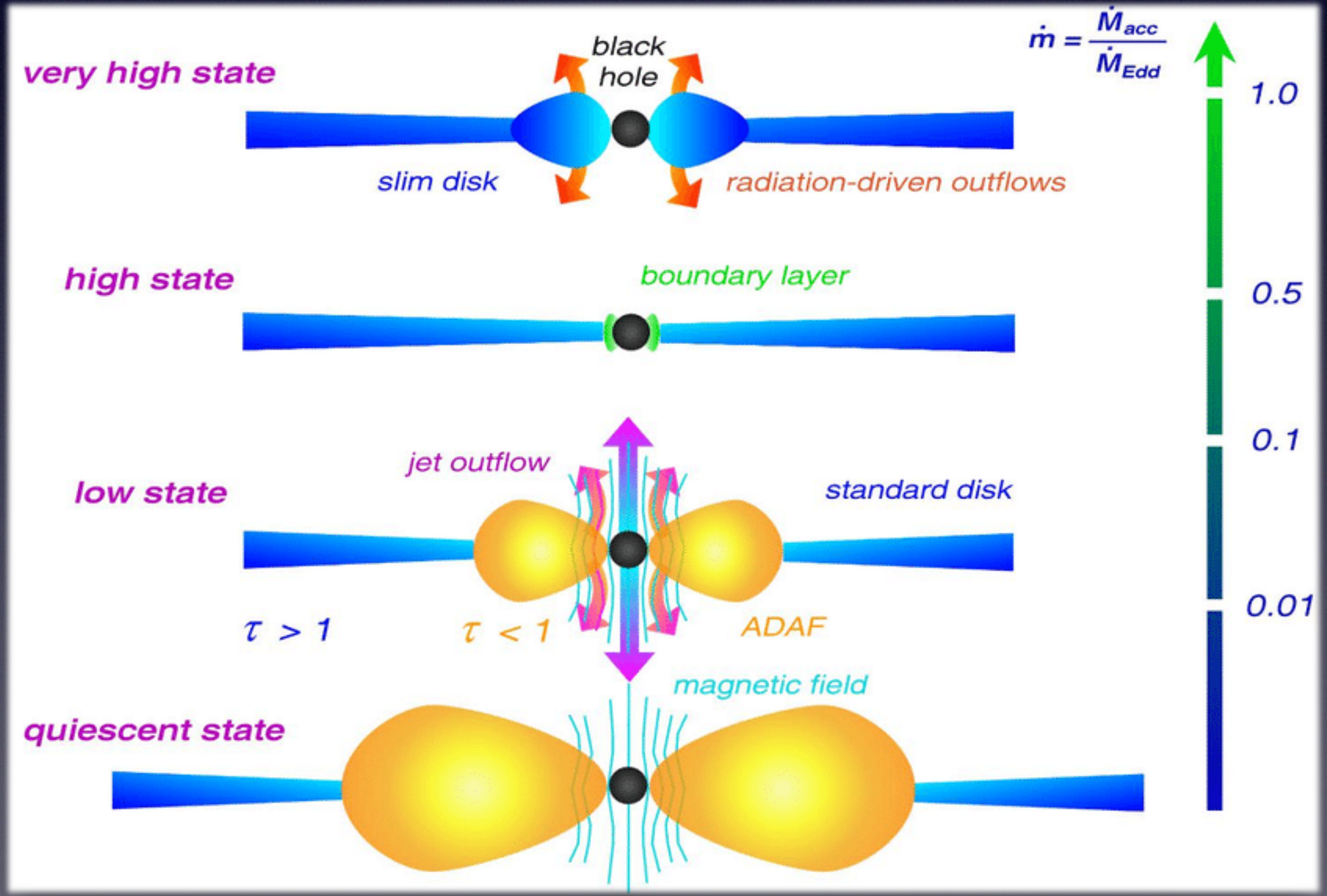
Advection-dominated accretion flows exist between two extremes.

Optically thin ADAFs occur in the limit of sufficiently low accretion rates. In this regime the cooling timescale of the flow is longer than the accretion timescale, resulting in a significant fraction of the energy being advected. The inner disk inflates and has two temperatures. These models are similar to the disk + corona models (e.g. Bisnovatyi-Kogan, & Blinnikov 1977; Romero et al. 2010).



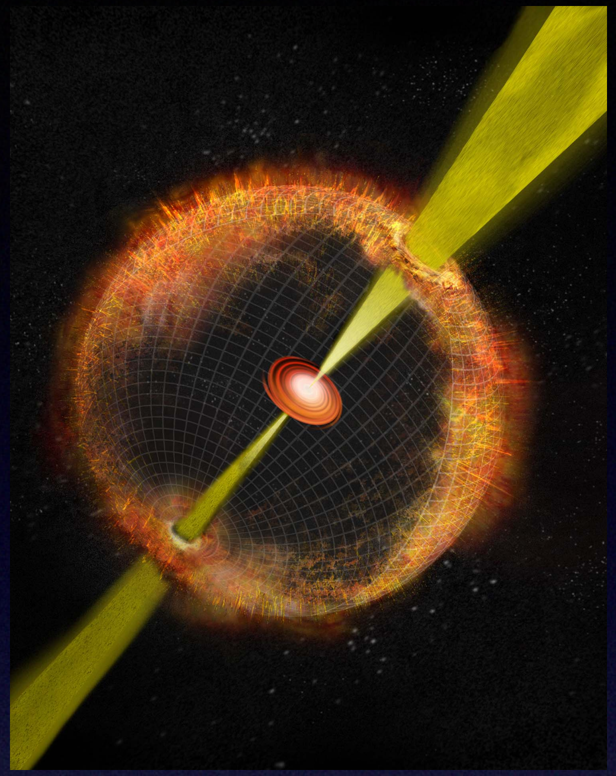


Optically thick ADAFs develop at very high accretion rates, typically larger than the Eddington value. In this limit the radiation gets trapped in the accretion flow and is advected because the optical depth is very large. The luminosity of these flows is ~ L_{Edd} and they are expected to power strong (super-Eddington) winds.

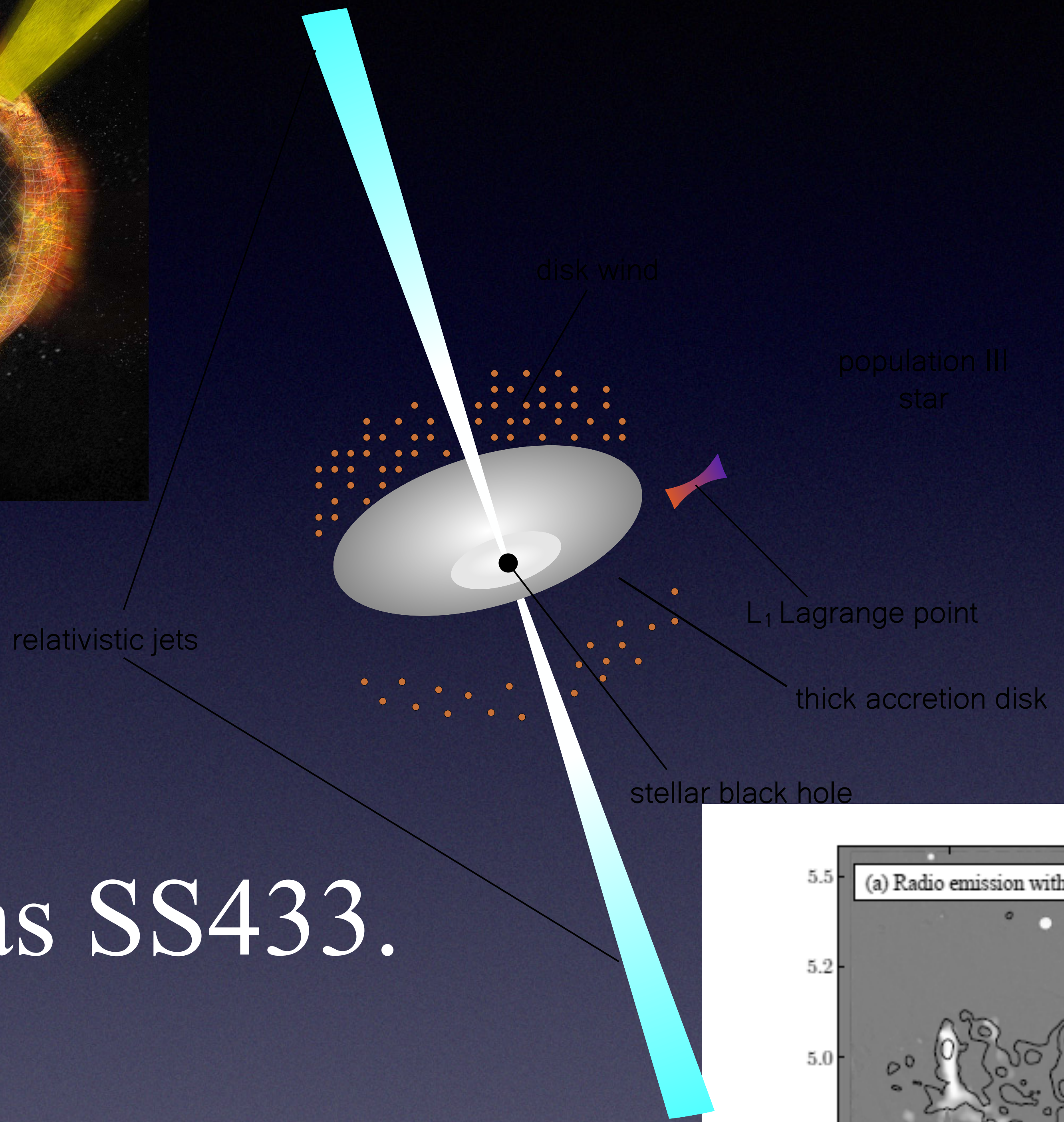


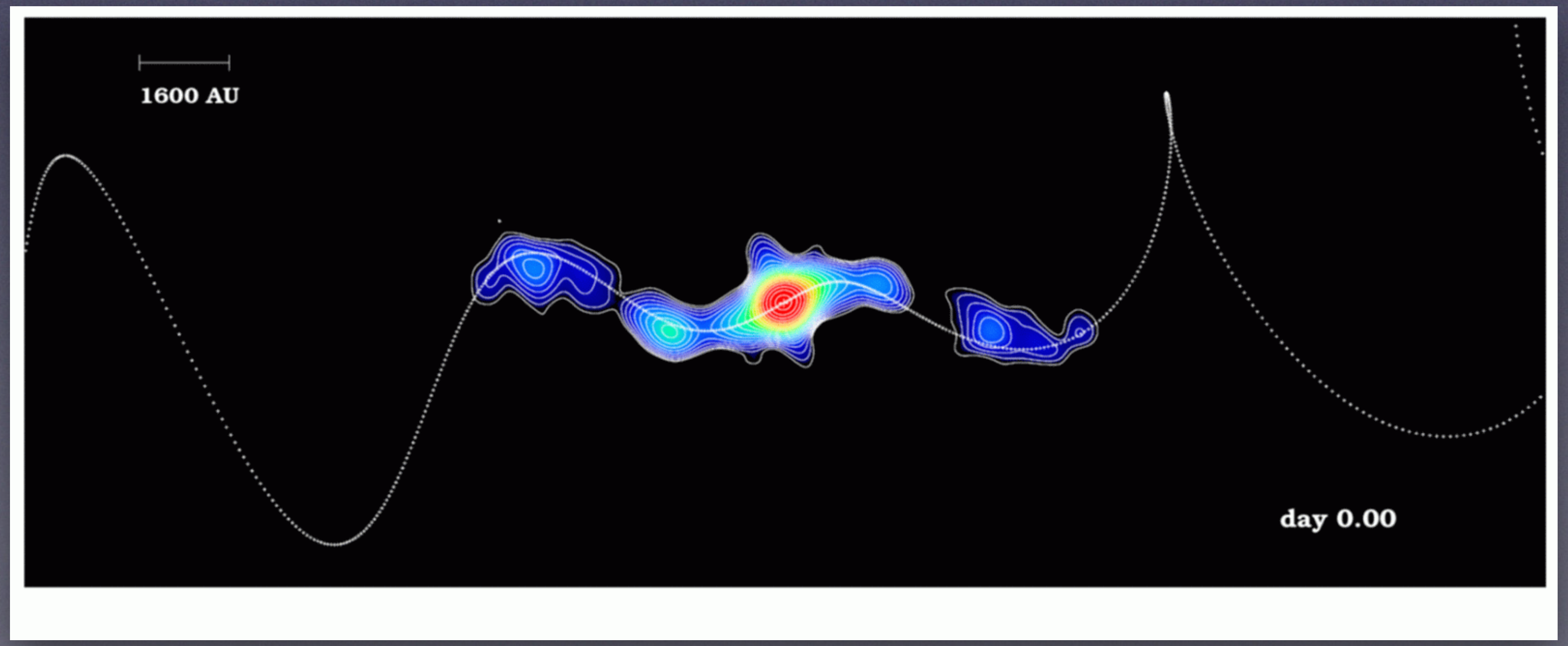
In some cases the accretion rate can be super-critical, to the level of 100s or even 1000s of L_{Edd}.

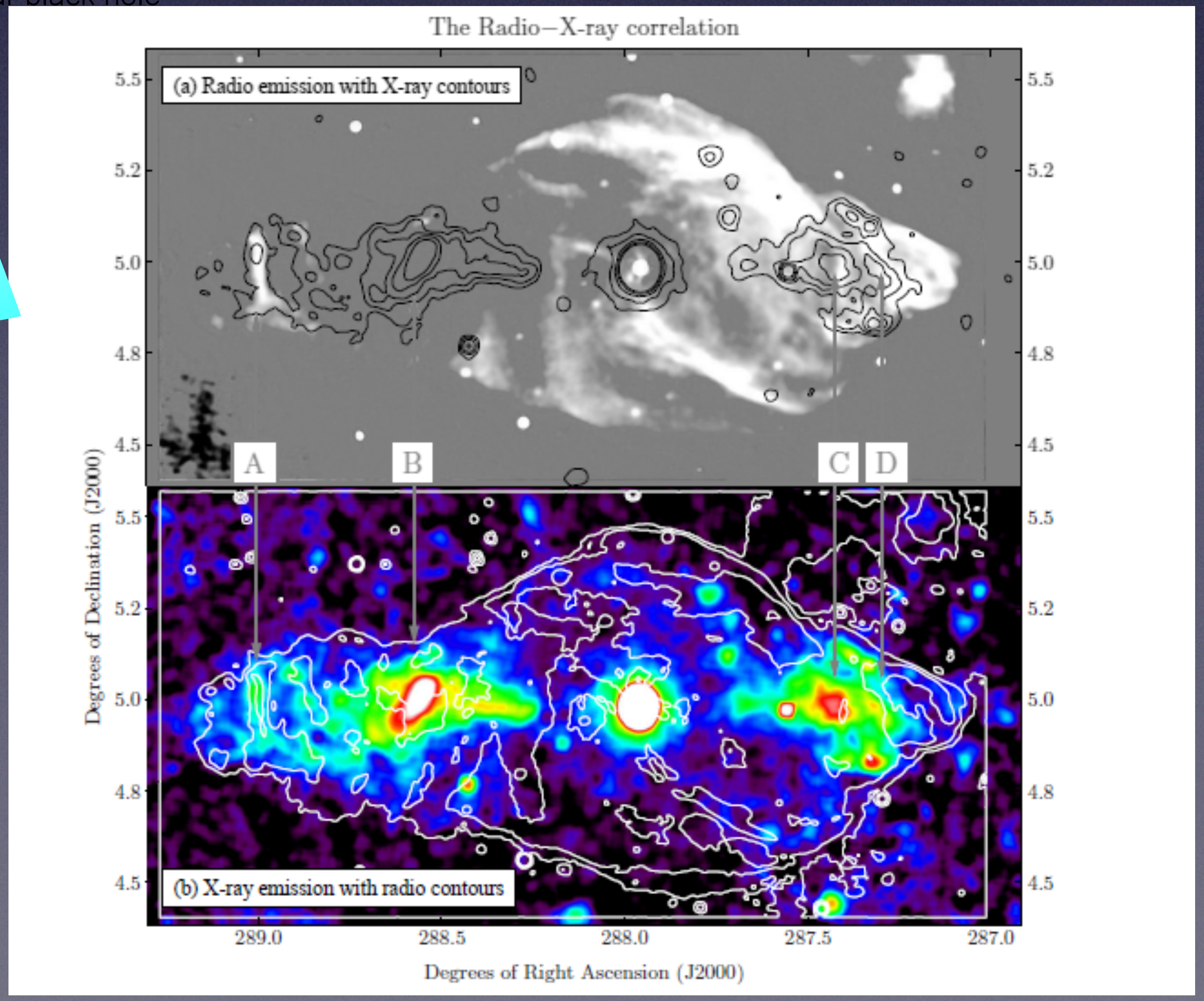
Examples:



- Collapsars, GRBs
- Pop III microquasars
- Some extreme objects such as SS433.





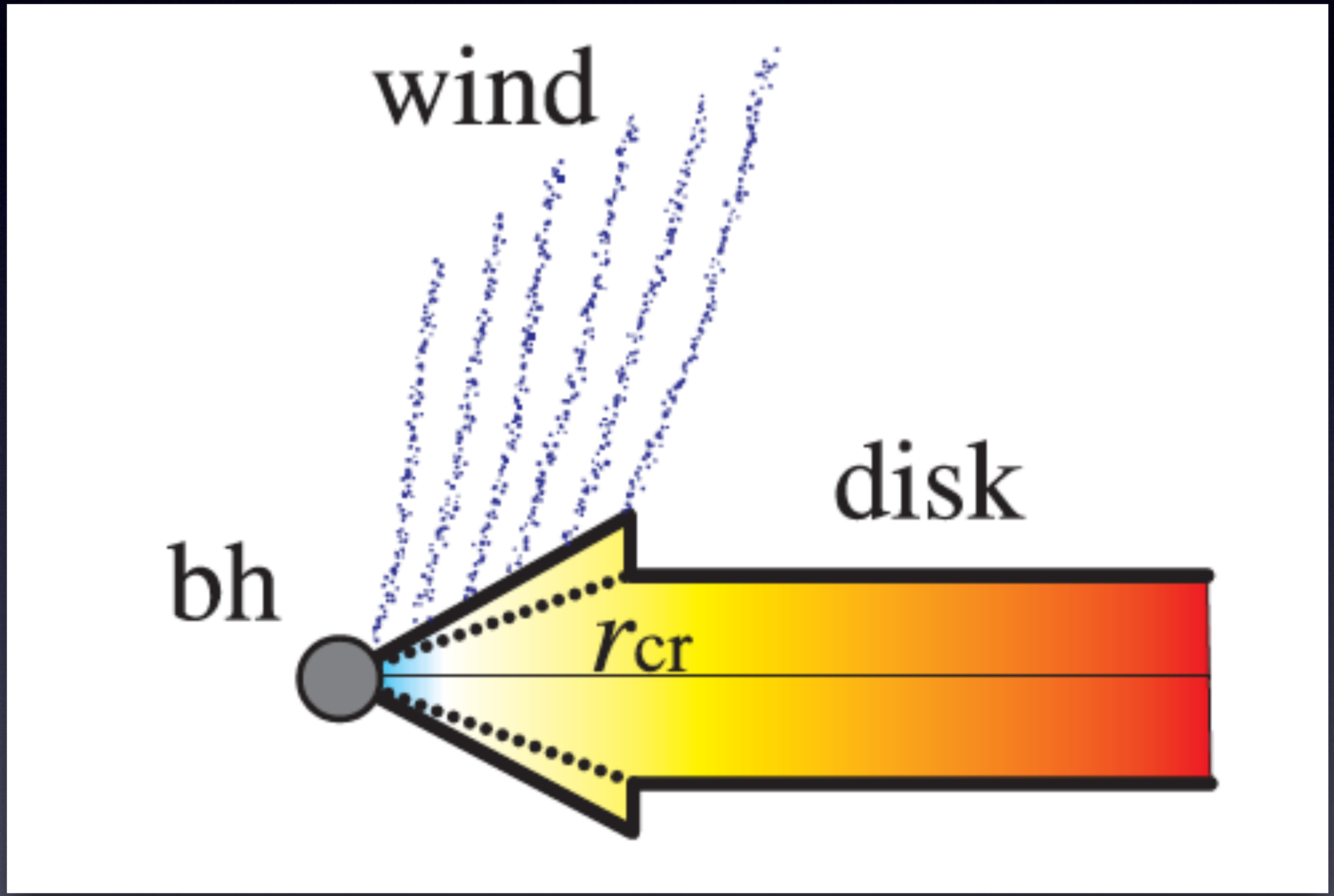


Hypercritical accretion

$$\text{Vertical Force} = -\frac{GMz}{R^3} + \frac{\sigma_T}{m_p c} F,$$

$$R = \sqrt{r^2 + z^2}$$

$$F = \sigma T^4 = 3GM\dot{M}/(8\pi r^3)$$



Outside r_{cr}, the accretion rate is constant and the disk is a radiation-pressure dominated standard disk. Inside r_{cr}, the accretion rate decreases with the radius so as to maintain the critical rate, expelling any excess mass by the radiation-driven wind.

$$r_{cr} = \frac{9\sqrt{3}\sigma_T}{16\pi m_p c} \dot{M}_{input},$$

$$\dot{M}(r) = \frac{16\pi c m_p}{9\sqrt{3}\sigma_T} r,$$

$$\dot{M}_{wind}(r) = \dot{M}_{input} - \dot{M}(r).$$

Fukue 2004

Disk structure

We assume a steady and axisymmetric disk and all physical quantities depend only on the radius r. The basic equations are:

$$\frac{1}{r}\frac{\mathrm{d}}{\mathrm{d}r}\left(r\Sigma v_{\mathrm{r}}\right) = 2\dot{\rho}H, \tag{1}$$

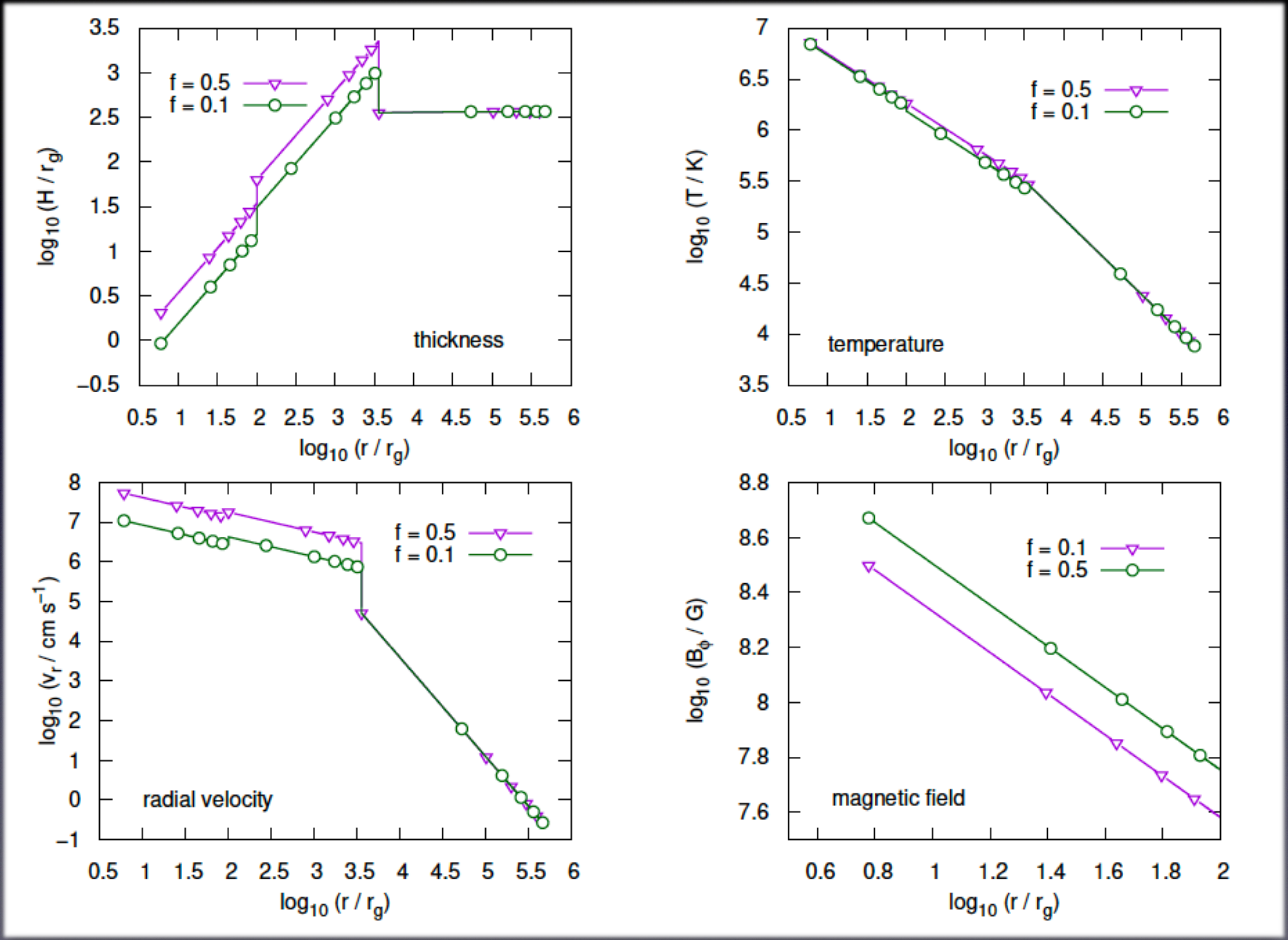
$$v_{\mathrm{r}}\frac{\mathrm{d}v_{\mathrm{r}}}{\mathrm{d}r} - \Omega^2 r = -\Omega_{\mathrm{K}}^2 - \frac{1}{\rho}\frac{\mathrm{d}}{\mathrm{d}r}\left(\rho c_{\mathrm{s}}^2\right), \tag{2}$$

$$v_{\mathrm{r}}\frac{\mathrm{d}}{\mathrm{d}r}\left(\Omega r^2\right) = \frac{1}{\rho r H}\frac{\mathrm{d}}{\mathrm{d}r}\left(\frac{\alpha\rho c_{\mathrm{s}}^2 r^3 H}{\Omega_{\mathrm{K}}}\frac{\mathrm{d}\Omega}{\mathrm{d}r}\right), \tag{3}$$

$$\Omega_{\mathrm{K}}^2 H^2 = c_{\mathrm{s}}^2. \tag{4}$$

$$\frac{\Sigma v_{\mathrm{r}}}{\gamma - 1}\frac{\mathrm{d}c_{\mathrm{s}}^2}{\mathrm{d}r} + 2Hc_{\mathrm{s}}^2\left(\dot{\rho} - v_{\mathrm{r}}\frac{\mathrm{d}\rho}{\mathrm{d}r}\right) = f\frac{\alpha\Sigma c_{\mathrm{s}}^2 r^2}{\Omega_{\mathrm{K}}}\left(\frac{\mathrm{d}\Omega}{\mathrm{d}r}\right)^2, \tag{5}$$

We solve the equations of the dynamics of the accreted fluid using self-similar treatment (e.g. Narayan and Yi 1994). $Q_{\mathrm{adv}} = Q_{\mathrm{vis}} - Q_{\mathrm{rad}} = fQ_{\mathrm{vis}}$



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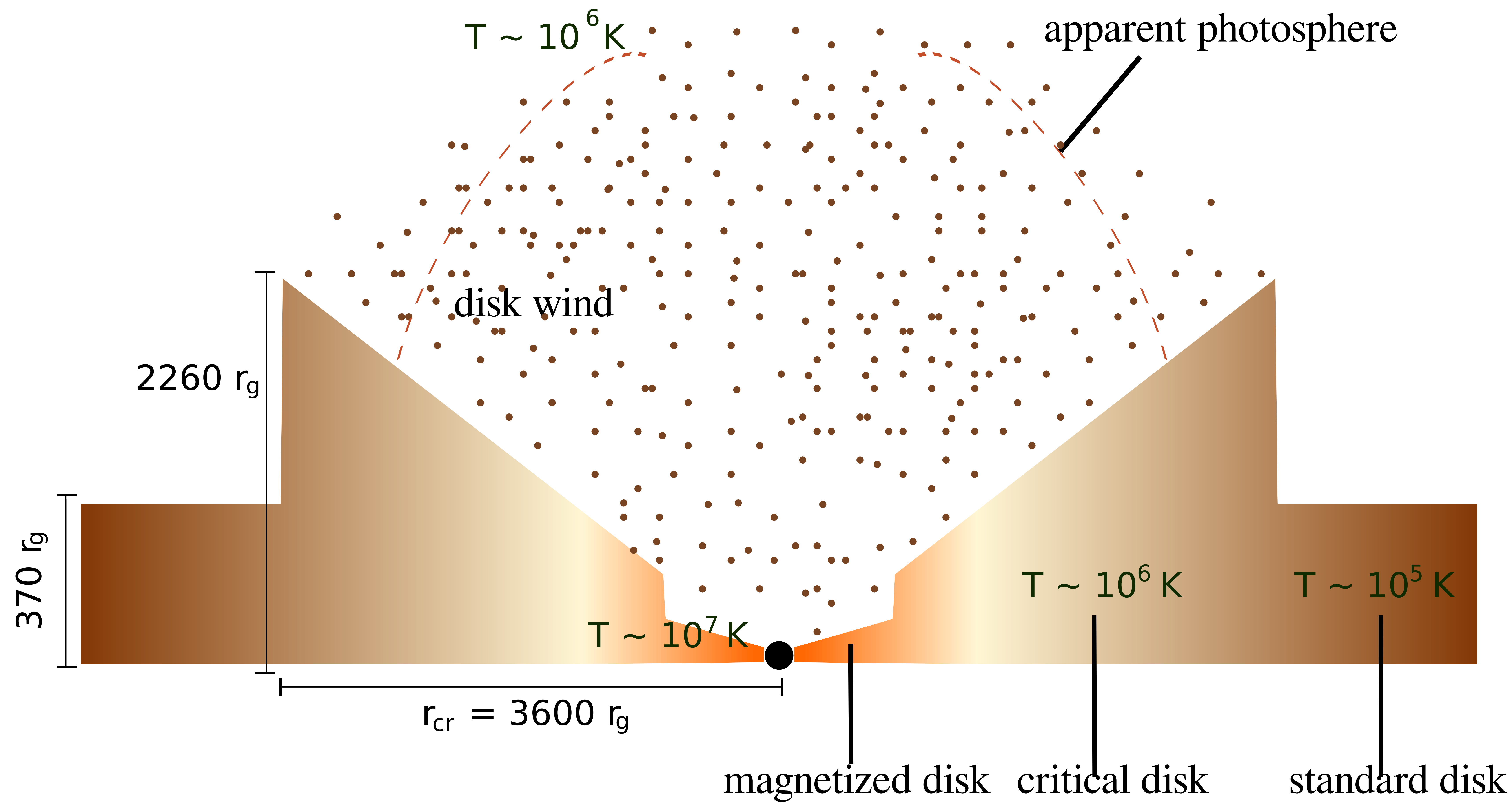
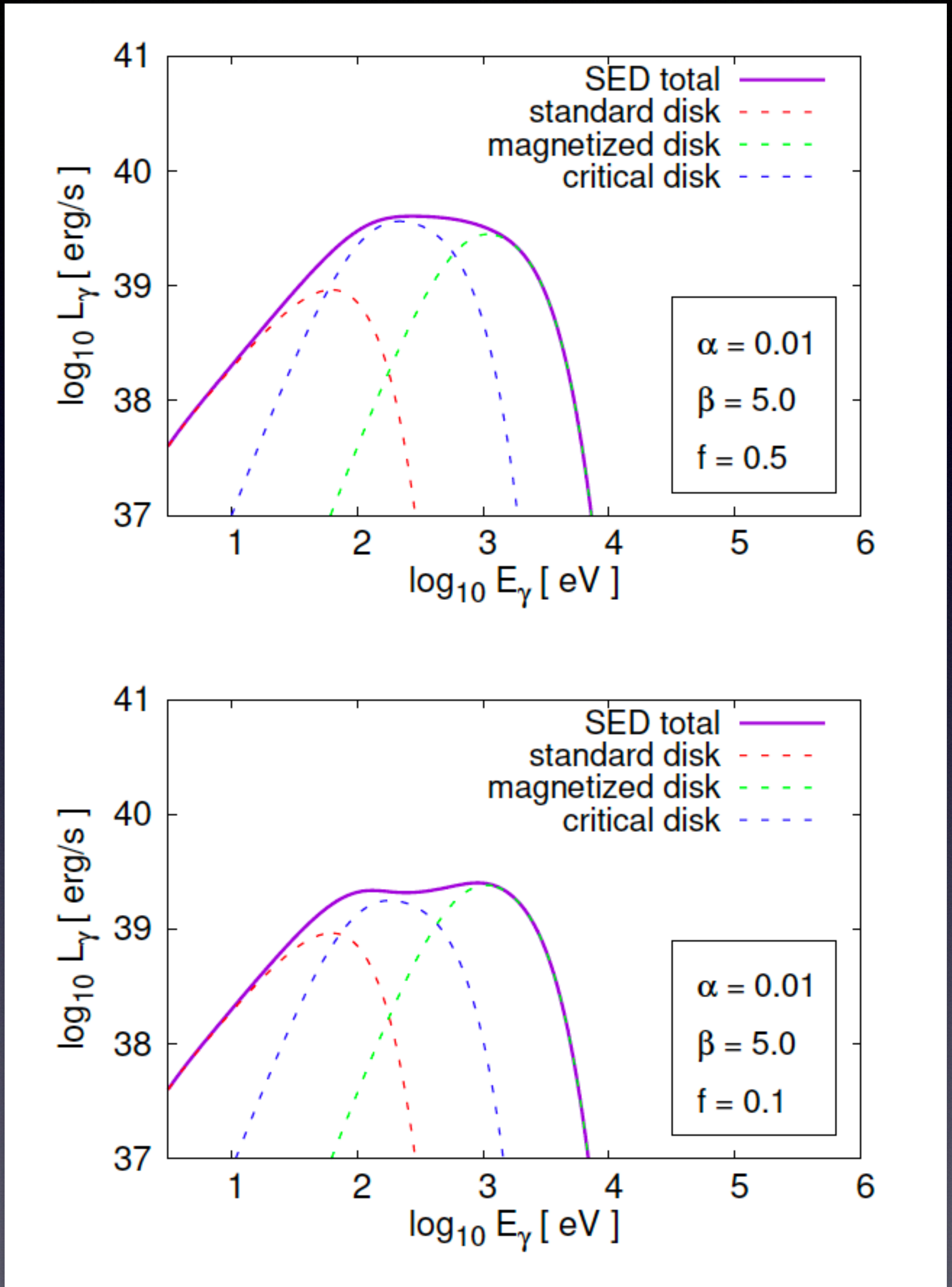
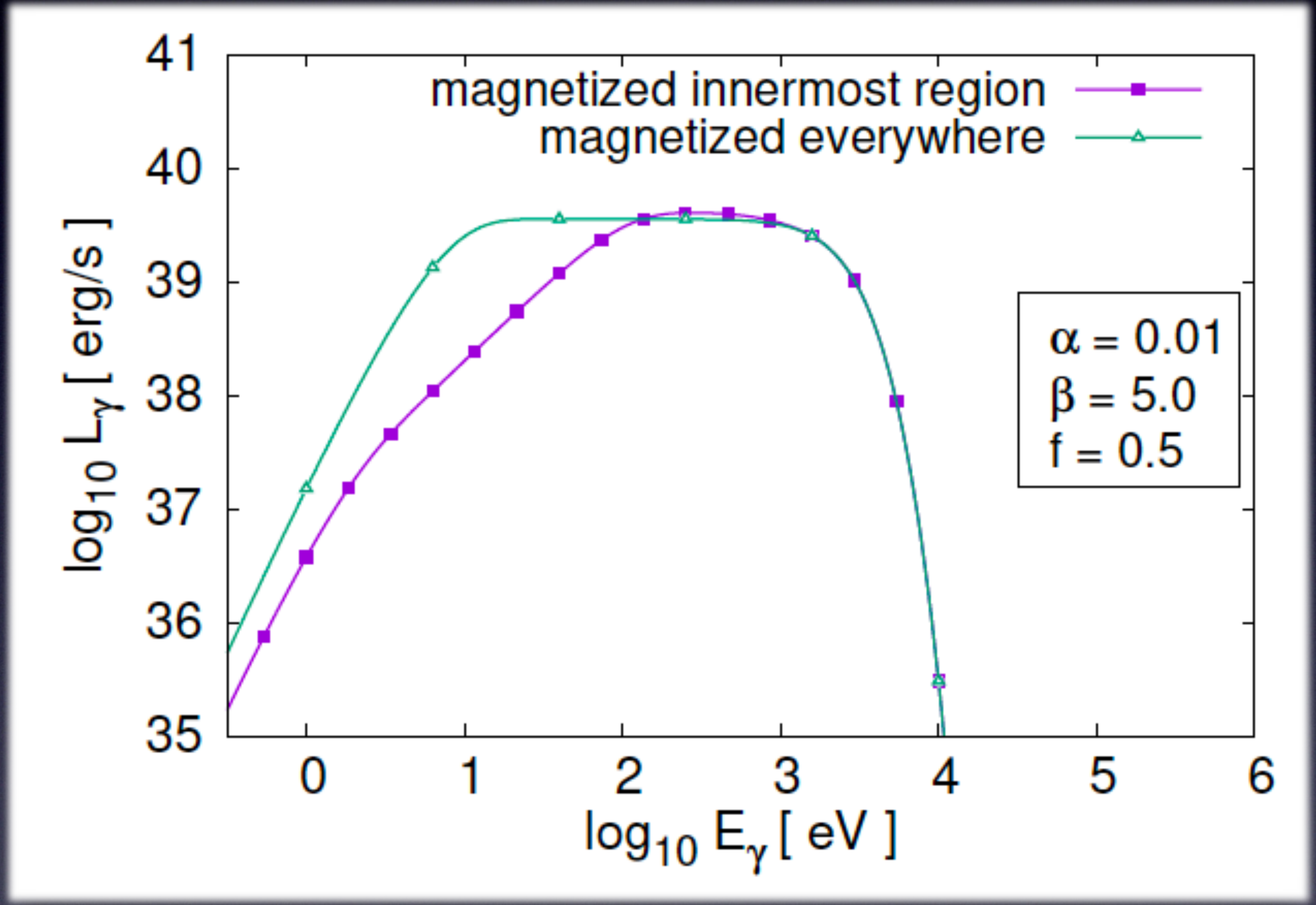


T ~ 10^6 K
apparent photosphere
disk wind
2260 r_g
370 r_g
T ~ 10^7 K
T ~ 10^6 K
T ~ 10^5 K
r_cr = 3600 r_g
magnetized disk
critical disk
standard disk

Disks (SEDs)





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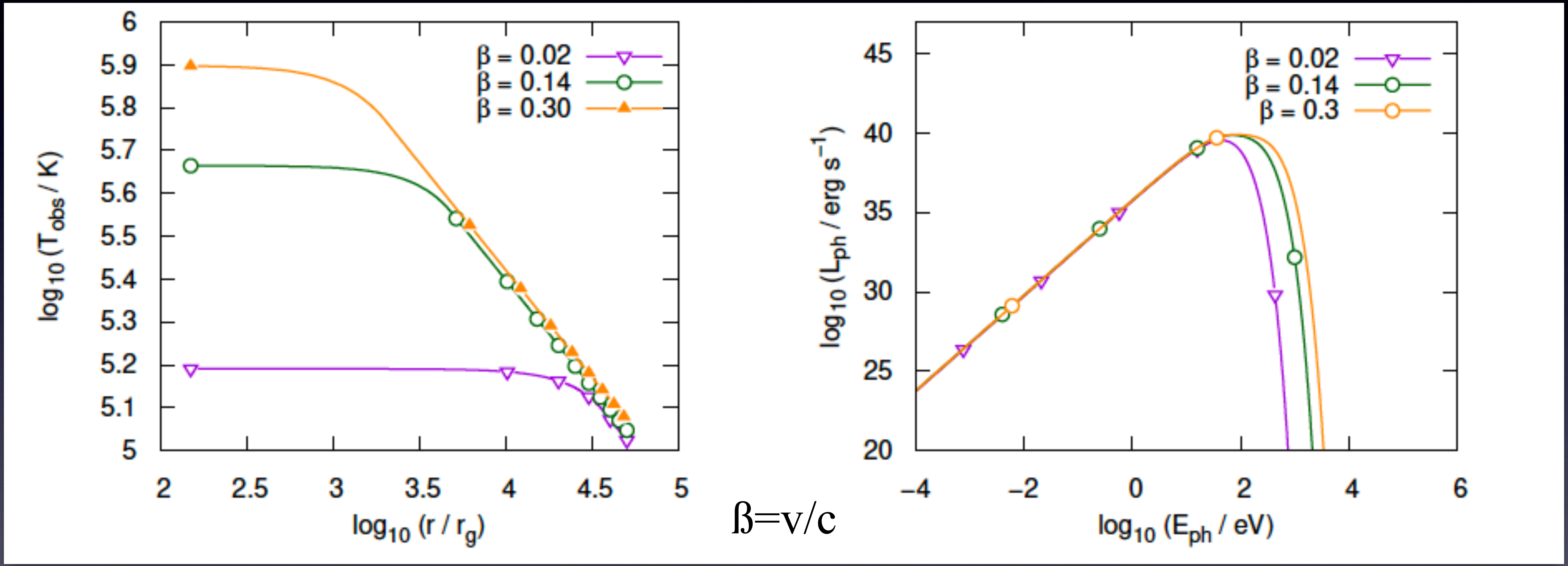
Wind



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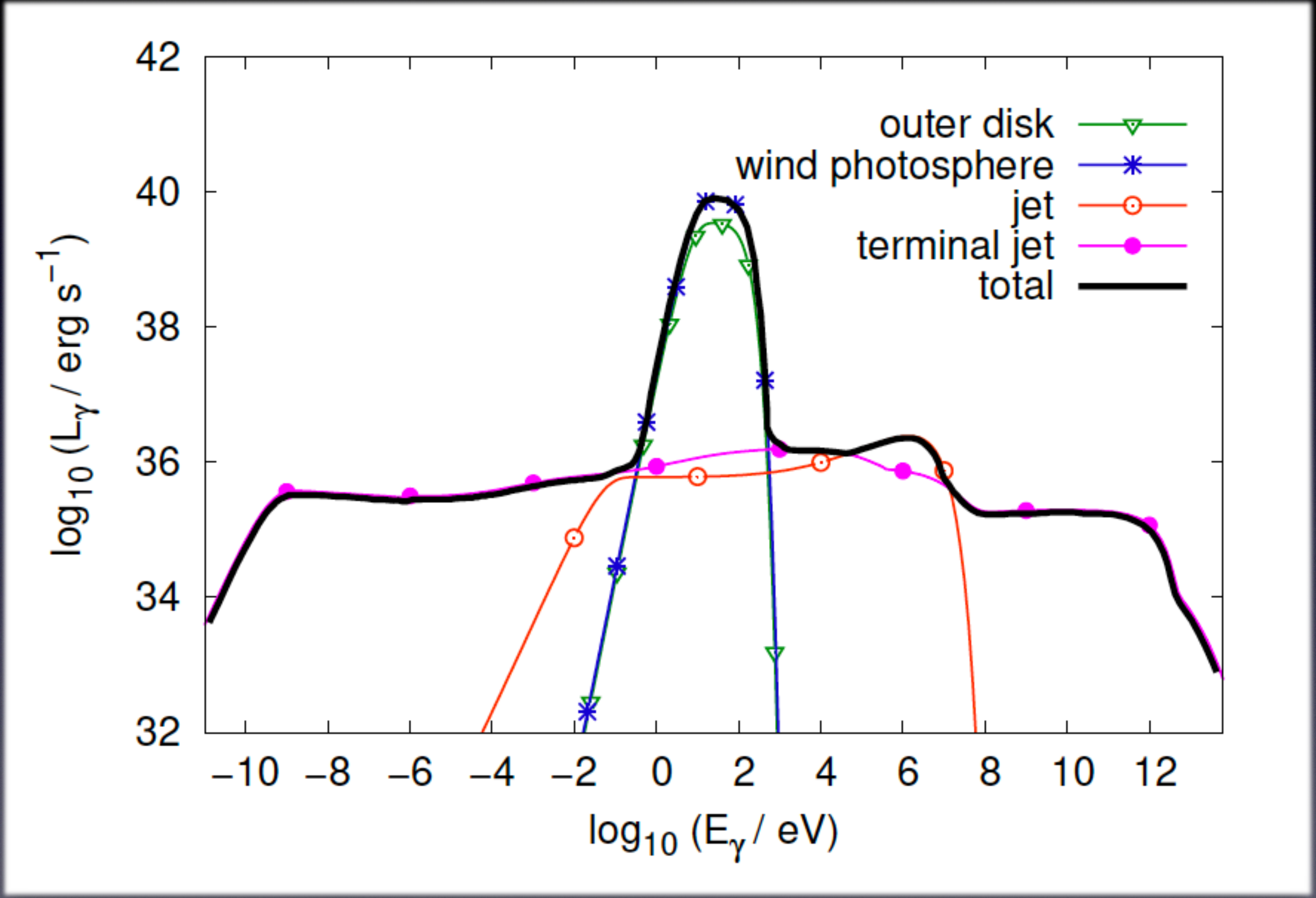
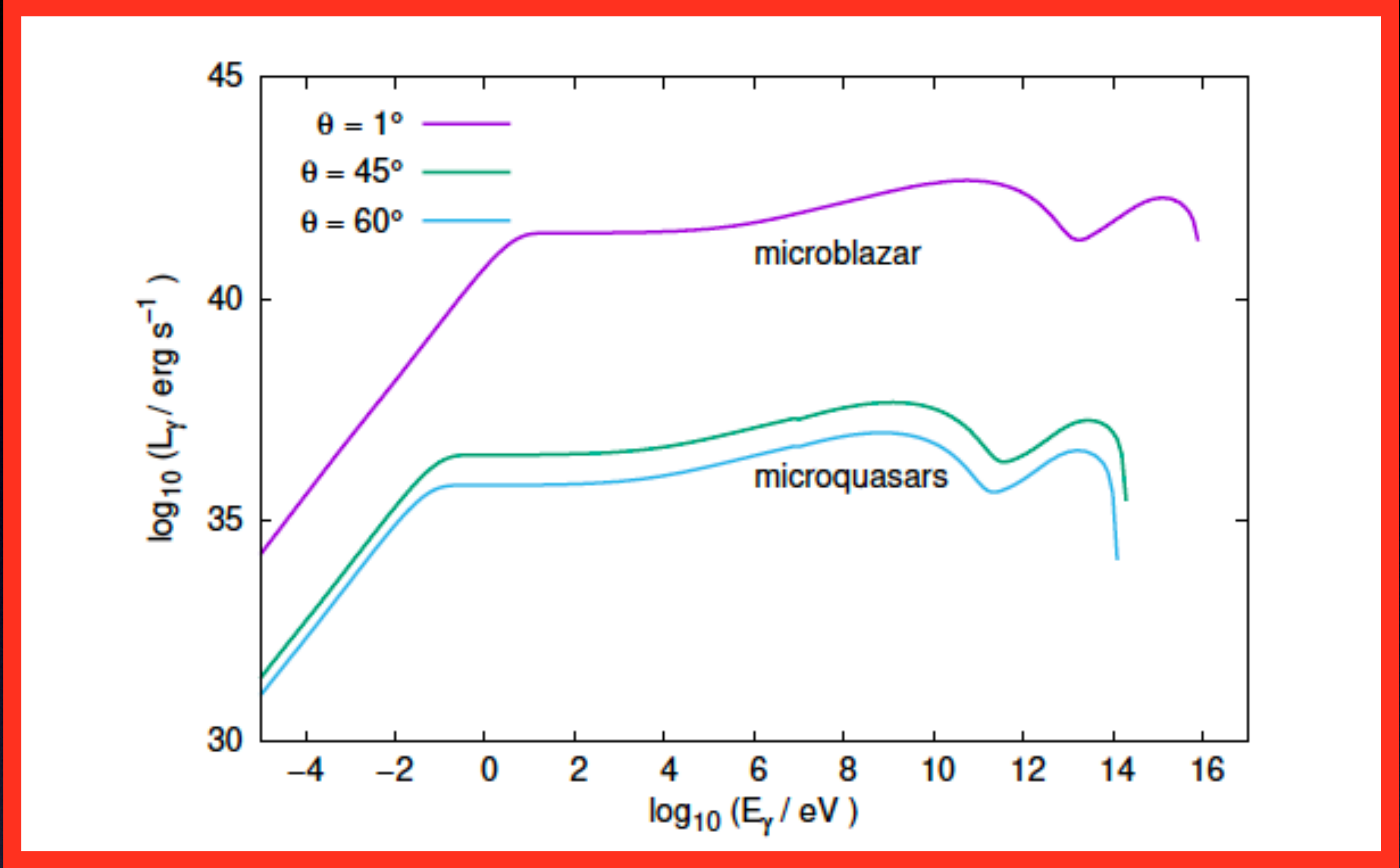
Disk + jet





Jet model: Romero & Vila 2008, Pepe et al. 2015.

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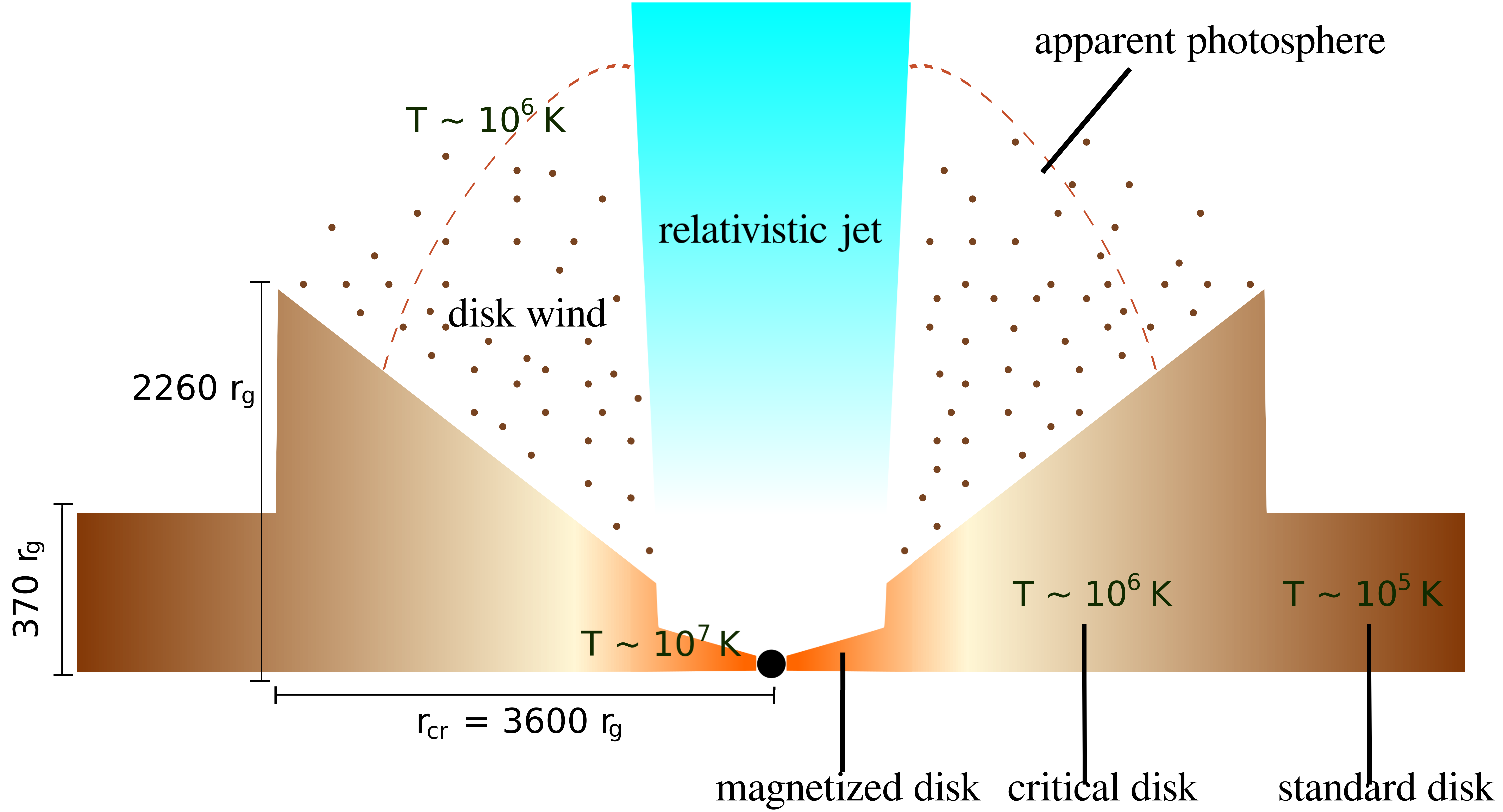

apparent photosphere
T ~ 10^6 K
relativistic jet
disk wind
2260 r_g
370 r_g
T ~ 10^7 K
T ~ 10^6 K
T ~ 10^5 K
r_{cr} = 3600 r_g
magnetized disk
critical disk
standard disk

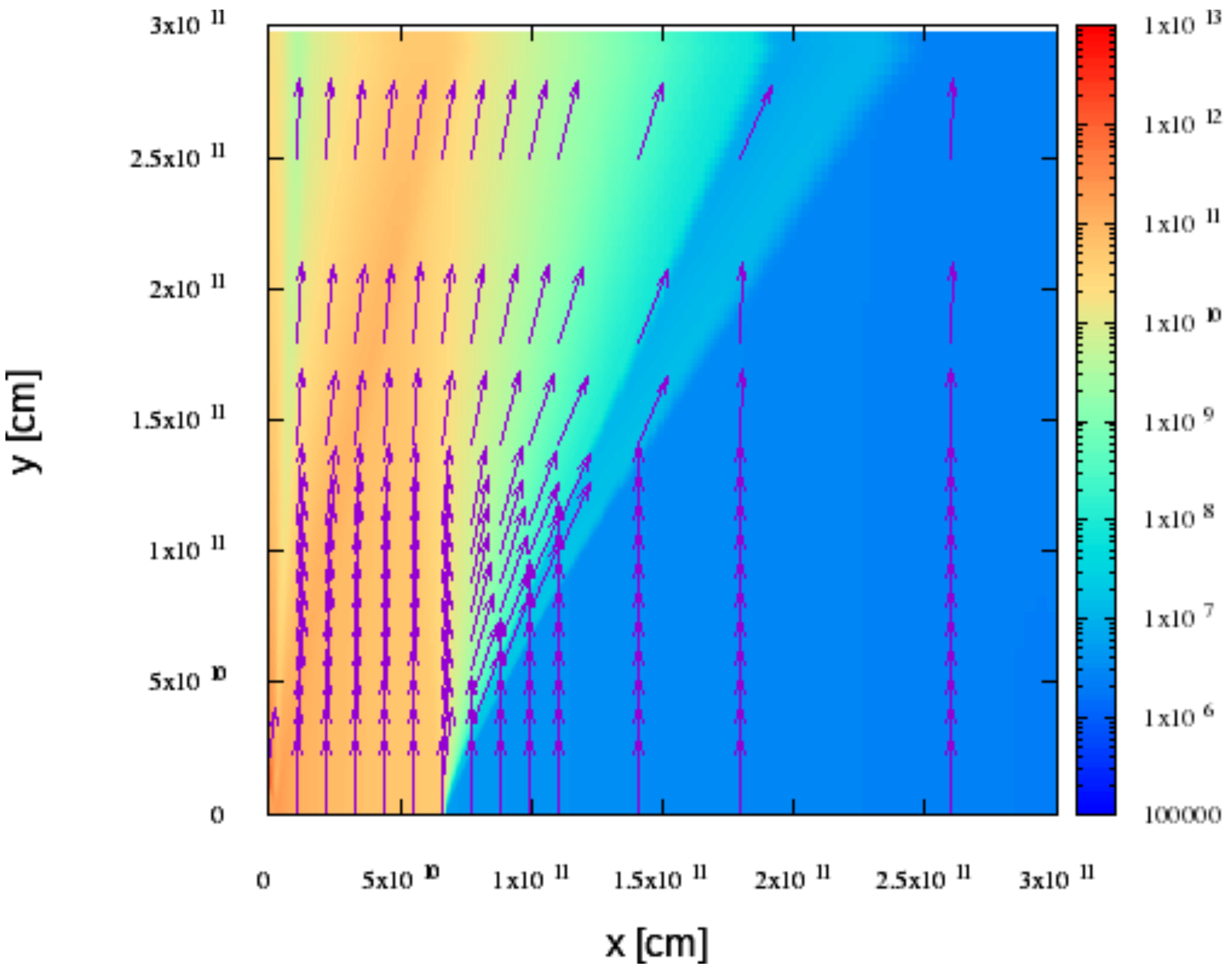
Simulations

We performed axisymmetric, relativistic hydrodynamical (RHD) simulations in 2 dimensions of the interaction between the jet and the super-Eddington wind. The jet is considered cold. Details: de la Cita et al. (2016).

Case 1	
Wind velocity [$v_{\rm wind}$]	$\sqrt{2GM/r}$
Wind kinetic power [$L_{\rm wind}$]	10^{39} erg s^{-1}
Jet bulk Lorentz factor [$\Gamma_{\rm jet}$]	9
Jet kinetic power [$L_{\rm jet}$]	10^{41} erg s^{-1}
Case 2	
Wind velocity [$v_{\rm wind}$]	$\sqrt{18GM/r}$
Wind kinetic power [$L_{\rm wind}$]	10^{40} erg s^{-1}
Jet bulk Lorentz factor [$\Gamma_{\rm jet}$]	1.35
Jet kinetic power [$L_{\rm jet}$]	10^{40} erg s^{-1}
Case 3	
Wind velocity [$v_{\rm wind}$]	$9\times\sqrt{2GM/r}$
Wind kinetic power [$L_{\rm wind}$]	10^{41} erg s^{-1}
Jet bulk Lorentz factor [$\Gamma_{\rm jet}$]	1.035
Jet kinetic power [$L_{\rm jet}$]	10^{39} erg s^{-1}

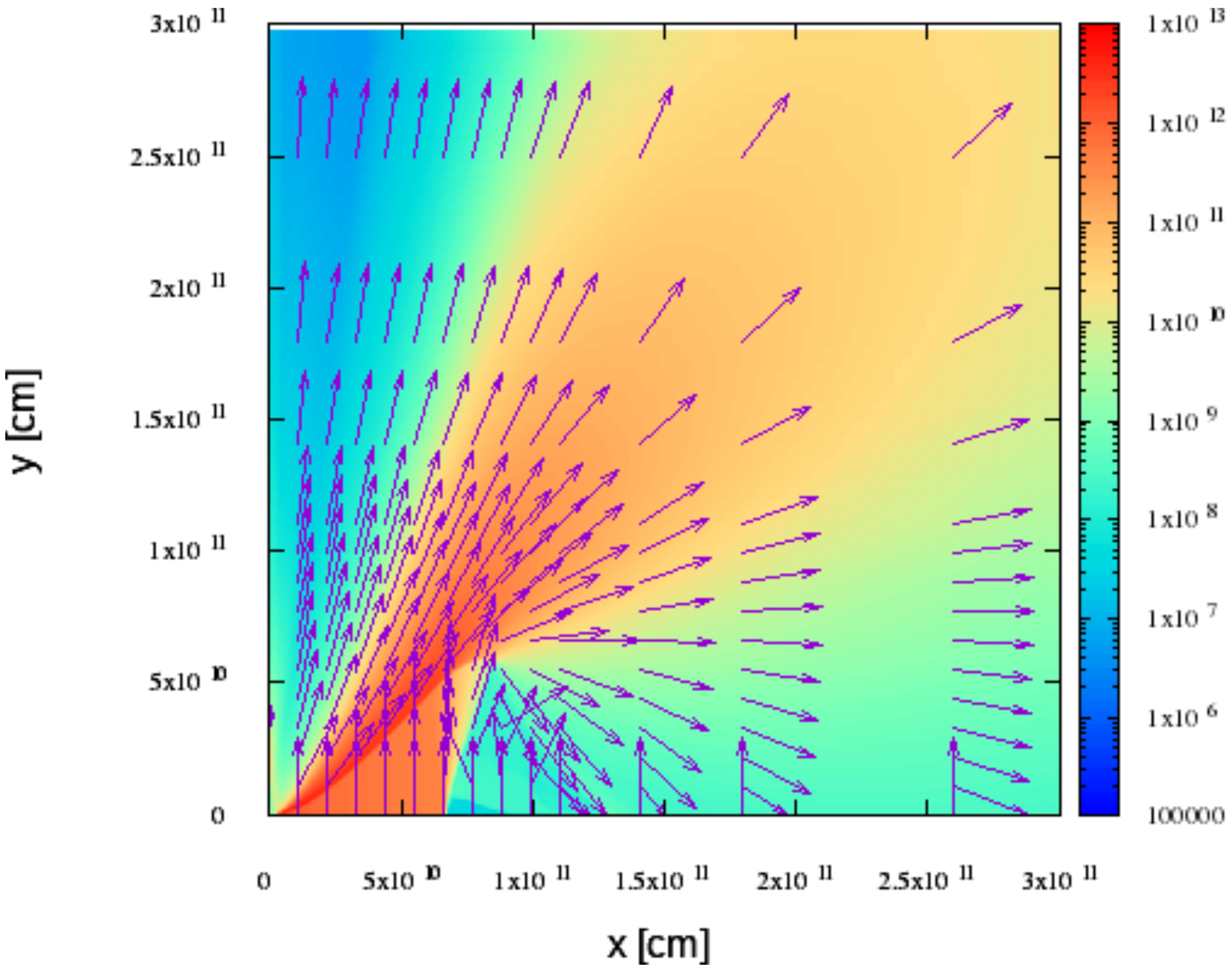
Cases 2-3

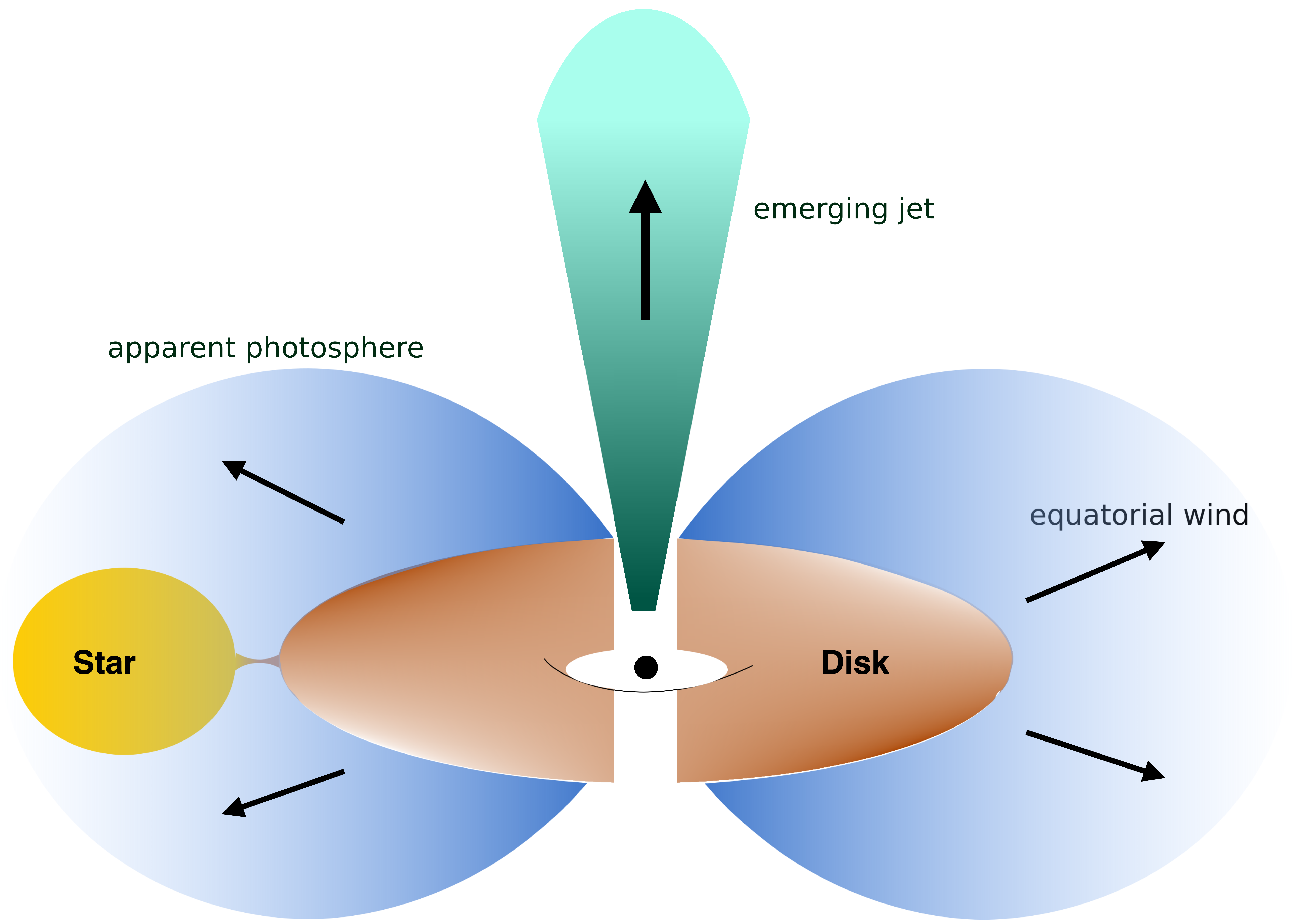
$L_{wind} \sim L_{jet}$



Case 1

$L_{jet} >> L_{wind}$



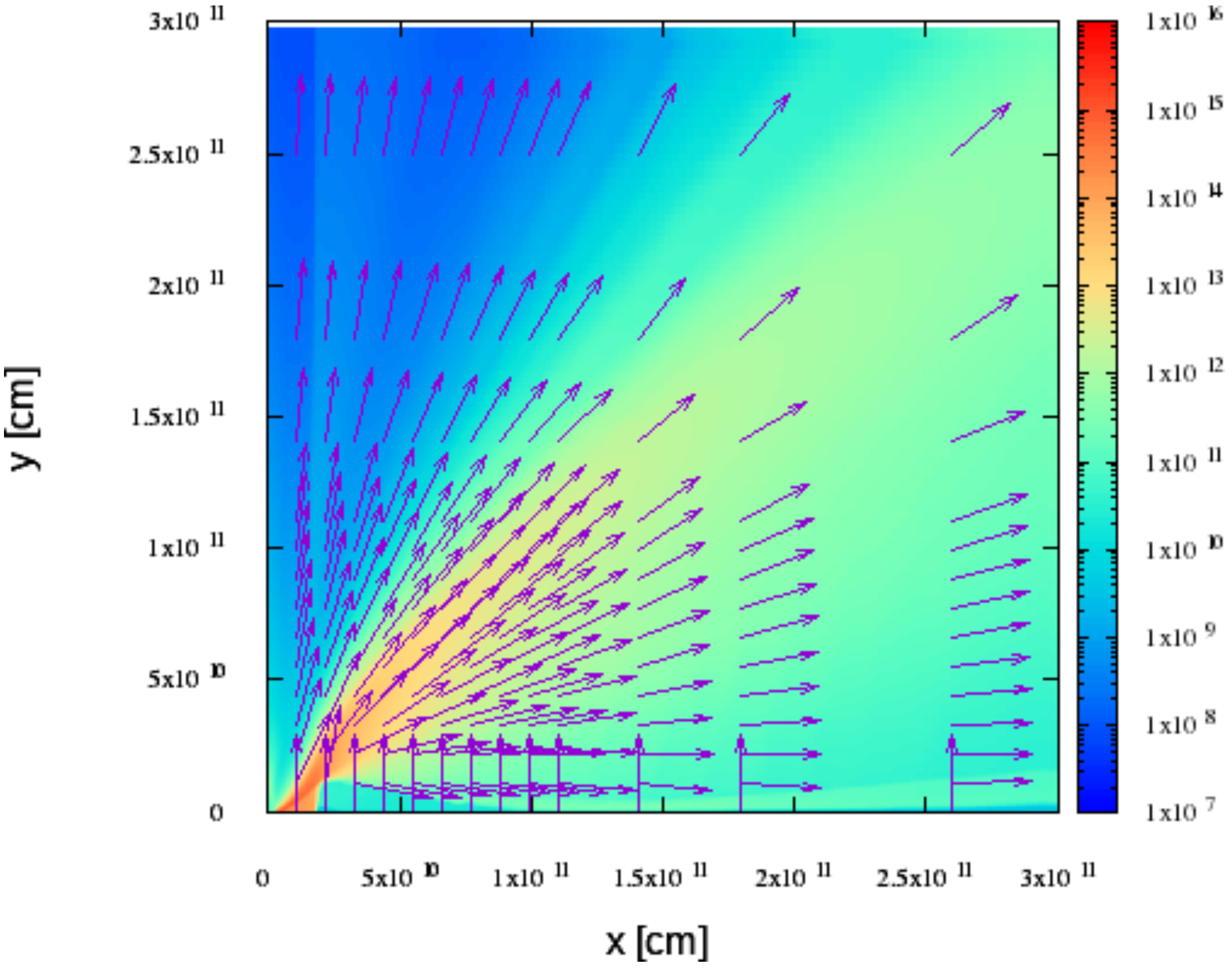

emerging jet
apparent photosphere
equatorial wind
Star
Disk

SS 433

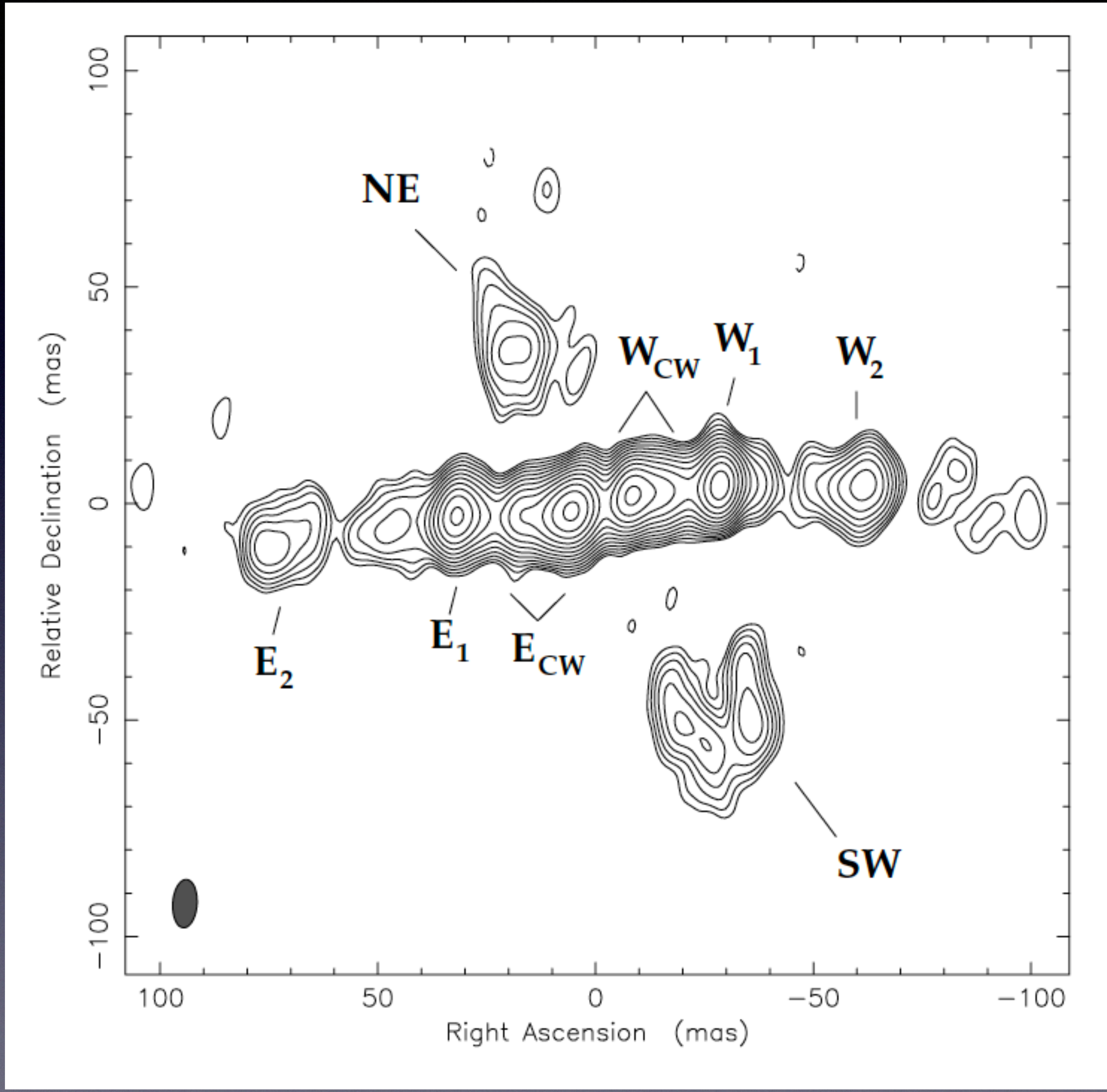
Case 4: SS433-like model

Donor star mass [M_*]	$30\,M_\odot$
Black hole mass [M_{BH}]	$9\,M_\odot$
Orbital semiaxis [a]	$38\,R_\odot$
Mass loss rate [$\dot{M}_*$]	$10^{-4}\,M_\odot\,yr^{-1}$
Gravitational radius [r_g]	13.5 km
Jet velocity [v_{jet}]	0.26c
Jet initial radius [r_0]	$1900\,r_g$
Line of sight angle [i]	57°
Jet launching point [z_0]	$50\,r_g$
Wind velocity [v_{wind}]	$350\,km\,s^{-1}$
Height of the wind photosphere [z_{ph}]	10^{12} cm
Wind kinetic power [L_{wind}]	$10^{37}\,erg\,s^{-1}$
Jet kinetic power [L_{jet}]	$10^{39}\,erg\,s^{-1}$

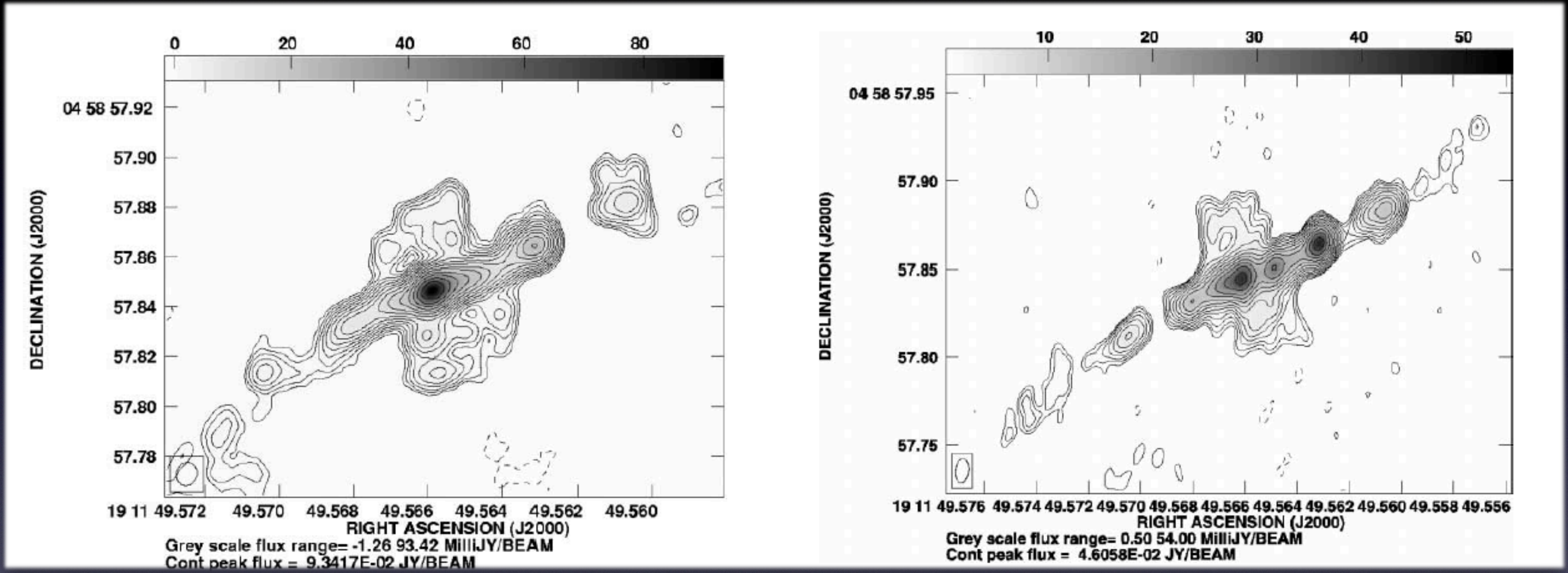
SS433



y [cm]
x [cm]
3x10 11
2.5x10 11
2x10 11
1.5x10 11
1x10 11
5x10 10
0
5x10 10
1x10 11
1.5x10 11
2x10 11
2.5x10 11
3x10 11
1x10 16
1x10 15
1x10 14
1x10 13
1x10 12
1x10 11
1x10 10
1x10 9
1x10 8
1x10 7



VLBA+VLA image of SS433 at1.6 GHz. Paragi et al. (1999).



4.99 GHz and 1.6 GHZ images of SS 433, combining VLBA, MERLIN, and VLA data. Blundell et al. (2001). The emission is thermal.

Conclusions

- Pop III MQs and some binaries such as SS433 are hyper-accreting sources with strong radiative winds ejected from the disks.

- The typical power of their jets is in the range $\sim 10^{39}$ - 10^{41} erg/s.

- Winds can reach $\sim 10^{42}$ erg/s.

- The jet-wind interaction can result, under some conditions (powerful jet), in the ejection of equatorial winds.

- SS433 seems to be one of these sources.

- jet.

Thanks!

General parameters for Pop III MQs used in the sims

Parameter [Symbol]	Value
Cases 1 - 3: PopIII MQs	
Donor star mass [M_*]	$41\, M_\odot$
Black hole mass [$M_{\rm BH}$]	$34\, M_\odot$
Orbital semiaxis [a]	$36\, R_\odot$
Mass-loss rate [$\dot{M}_*$]	$7.5 \times 10^{-5}\, M_\odot\, {\rm yr}^{-1}$
Gravitational radius [$r_{\rm g}$]	50 km
Disk viscosity parameter [α]	0.01
Advection parameter [f]	0.5
Beta factor of the plasma [β]	5
Critical radius [$r_{\rm cr}$]	$1.3 \times 10^4\, r_{\rm g}$
Disk luminosity [$L_{\rm disk}$]	$10^{40}\, {\rm erg\, s}^{-1}$
Jet semi-opening angle tangent [χ]	0.1
Jet initial radius [r_0]	$500\, r_{\rm g}$
Total wind mass-loss rate [$\dot{M}_{\rm wind}$]	$7.3 \times 10^{-5}\, M_\odot\, {\rm yr}^{-1}$

Parameters of the outflows (Pop III MQs)

Parameter	Symbol	Value	Unit
Total wind mass-loss rate	$\dot{M}_{\rm wind}$	7.3×10^{-5}	$M_\odot\,{\rm yr}^{-1}$
Total power of the wind	$L_{\rm wind}$	4.1×10^{42}	${\rm erg\,s}^{-1}$
Total jet mass-loss rate	$\dot{M}_{\rm jet}$	3.5×10^{-7}	$M_\odot\,{\rm yr}^{-1}$
Mass-accretion rate in the inner edge	$\dot{M}_{\rm in}$	2.1×10^{-8}	$M_\odot\,{\rm yr}^{-1}$
Wind velocity at $r_{\rm cr}$	$v_{\rm wind}(r_{\rm cr})$	6×10^{3}	${\rm km\,s}^{-1}$
Wind velocity at r_0	$v_{\rm wind}(r_0)$	4.2×10^{4}	${\rm km\,s}^{-1}$

$$t \sim \frac{B(z_0)}{\partial B/\partial t} \sim 10^{11}\ \mathrm{s} \sim 4500\ \mathrm{yr.}$$

$$\frac{\partial \mathrm{B}}{\partial t} = -\frac{ck_{\mathrm{B}}}{e}\frac{\nabla p \times \nabla T_e}{\rho}$$

Contopoulos et al. 2006