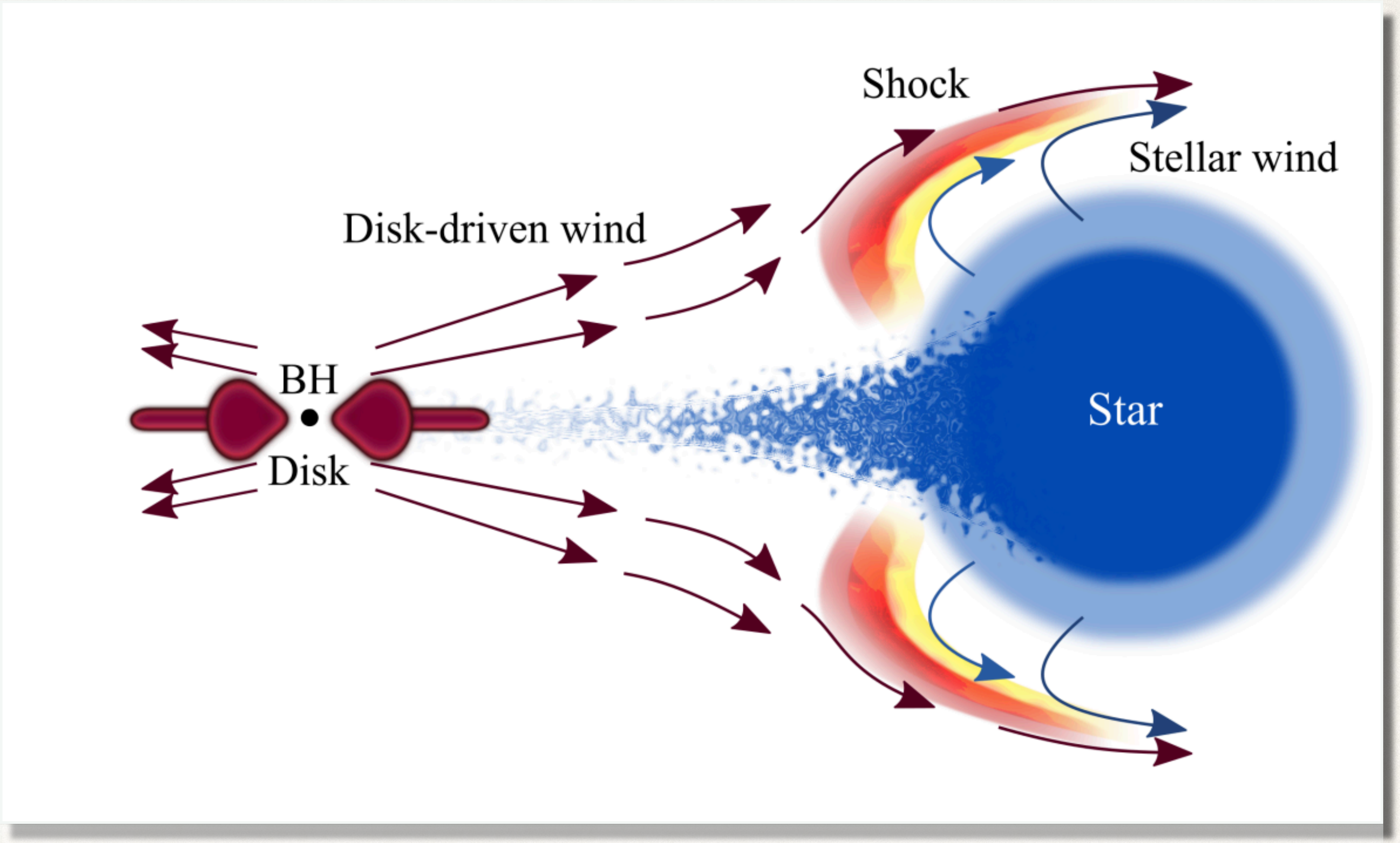

Super-Eddington Colliding Wind Binaries

Gustavo E. Romero & Leandro Abaroa

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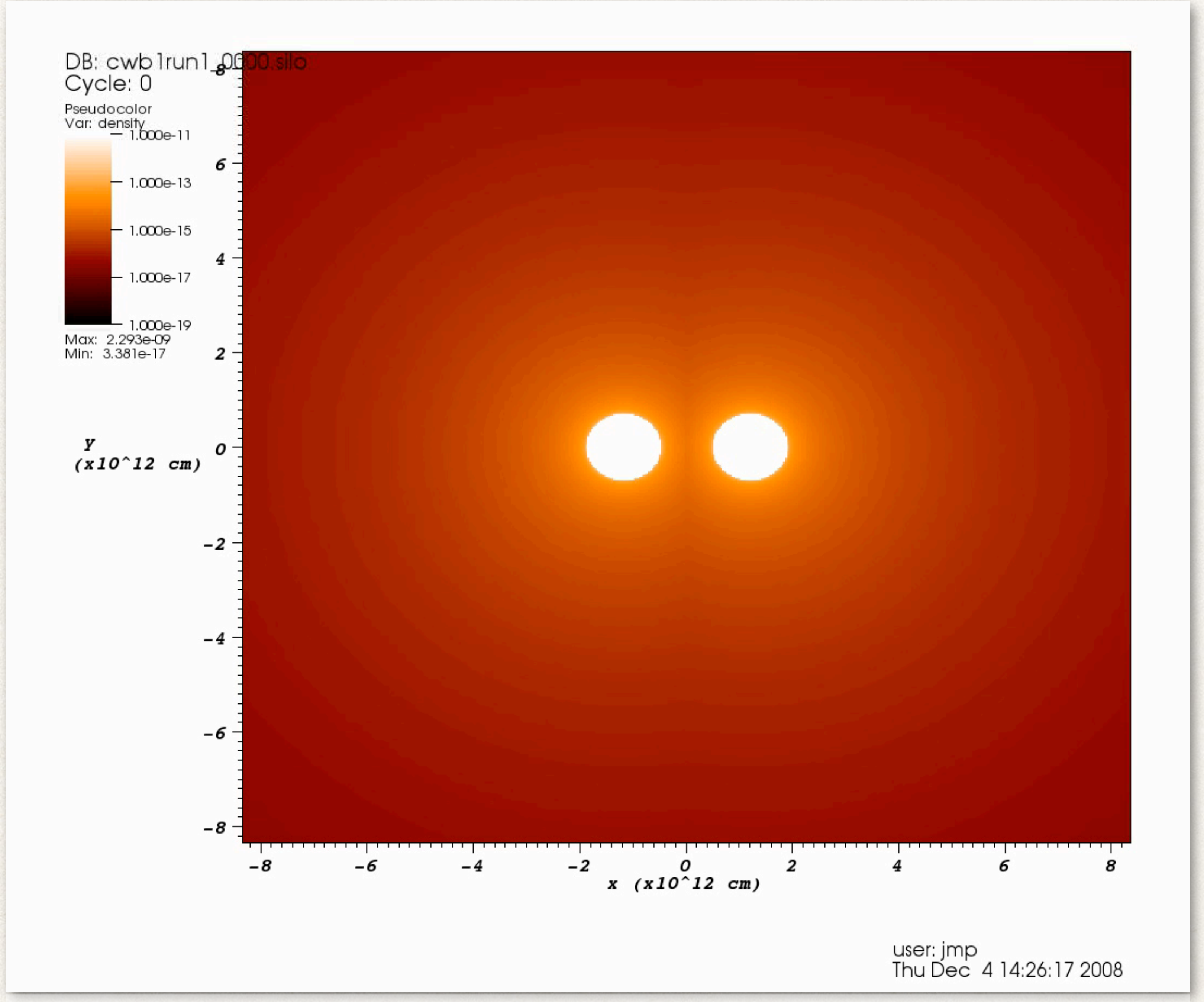
VGGRS, Innsbruck, April 13th, 2003

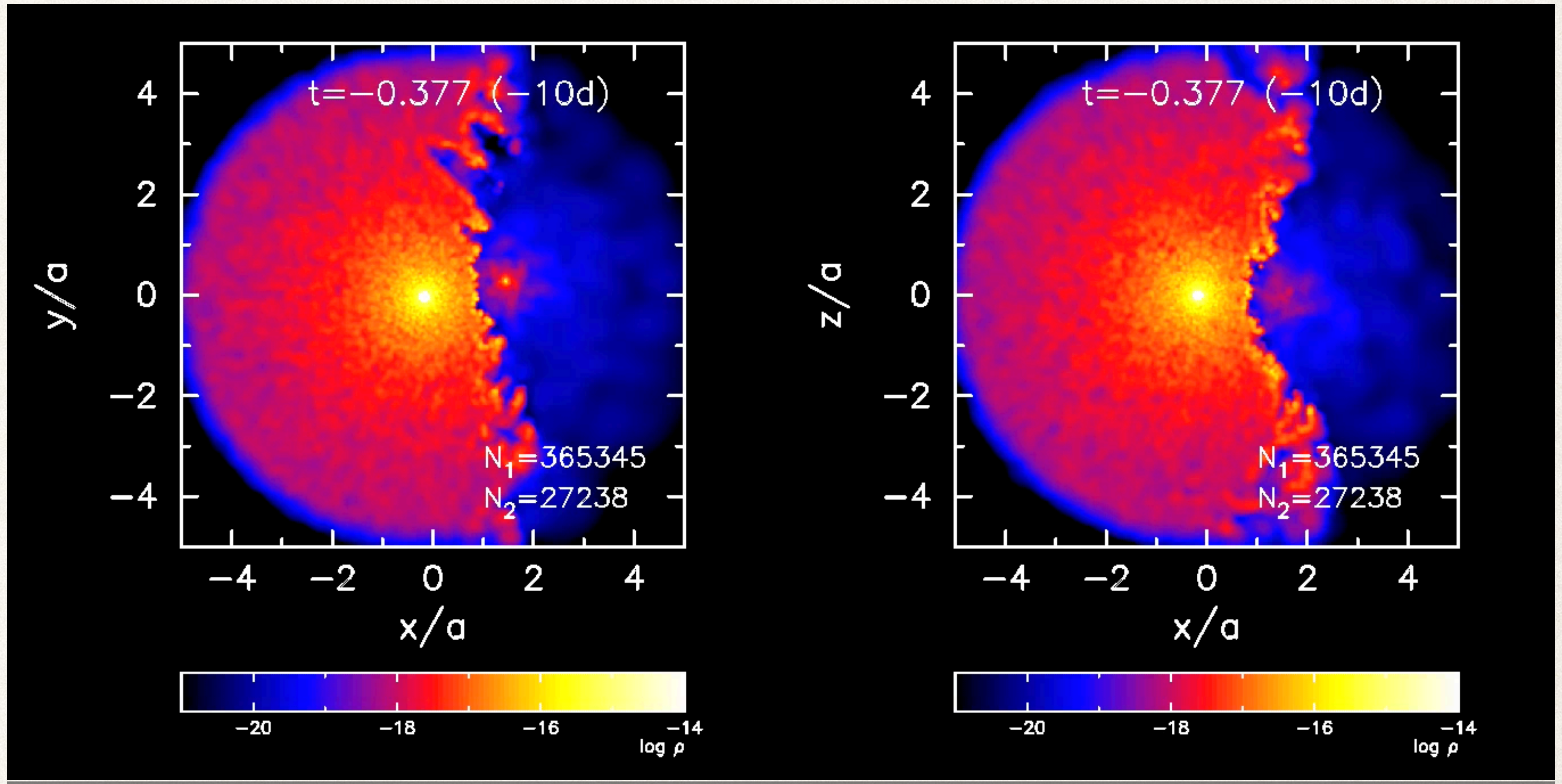
Two main types of colliding wind binaries (CWB) with non-thermal radiation

CWB with two massive stars



Pittard 2009

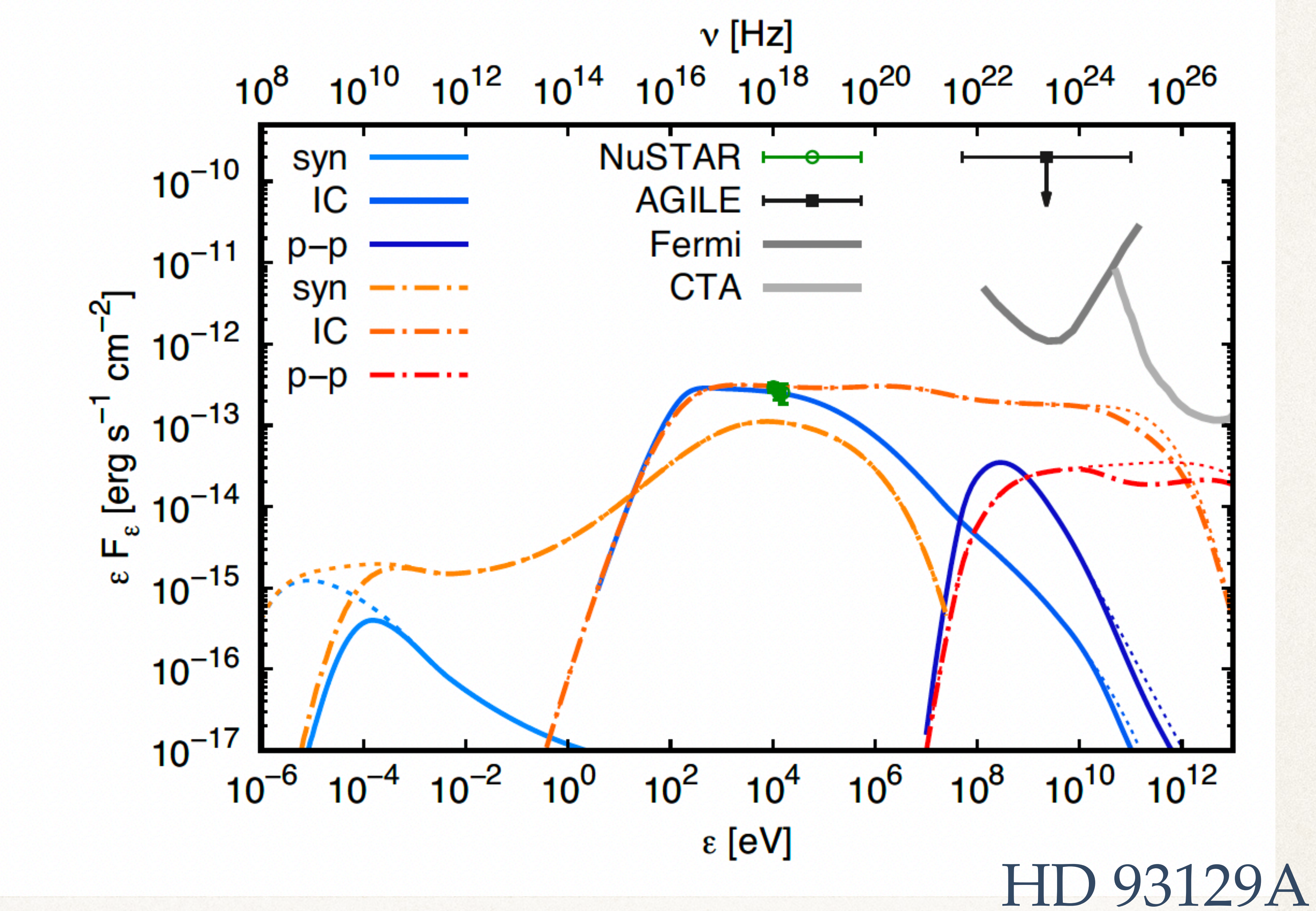
CWB with massive star and a pulsar



Romero, Okazaki, Orellana & Owocki (2007)

Two main types of colliding wind binaries (CWB) with non-thermal radiation

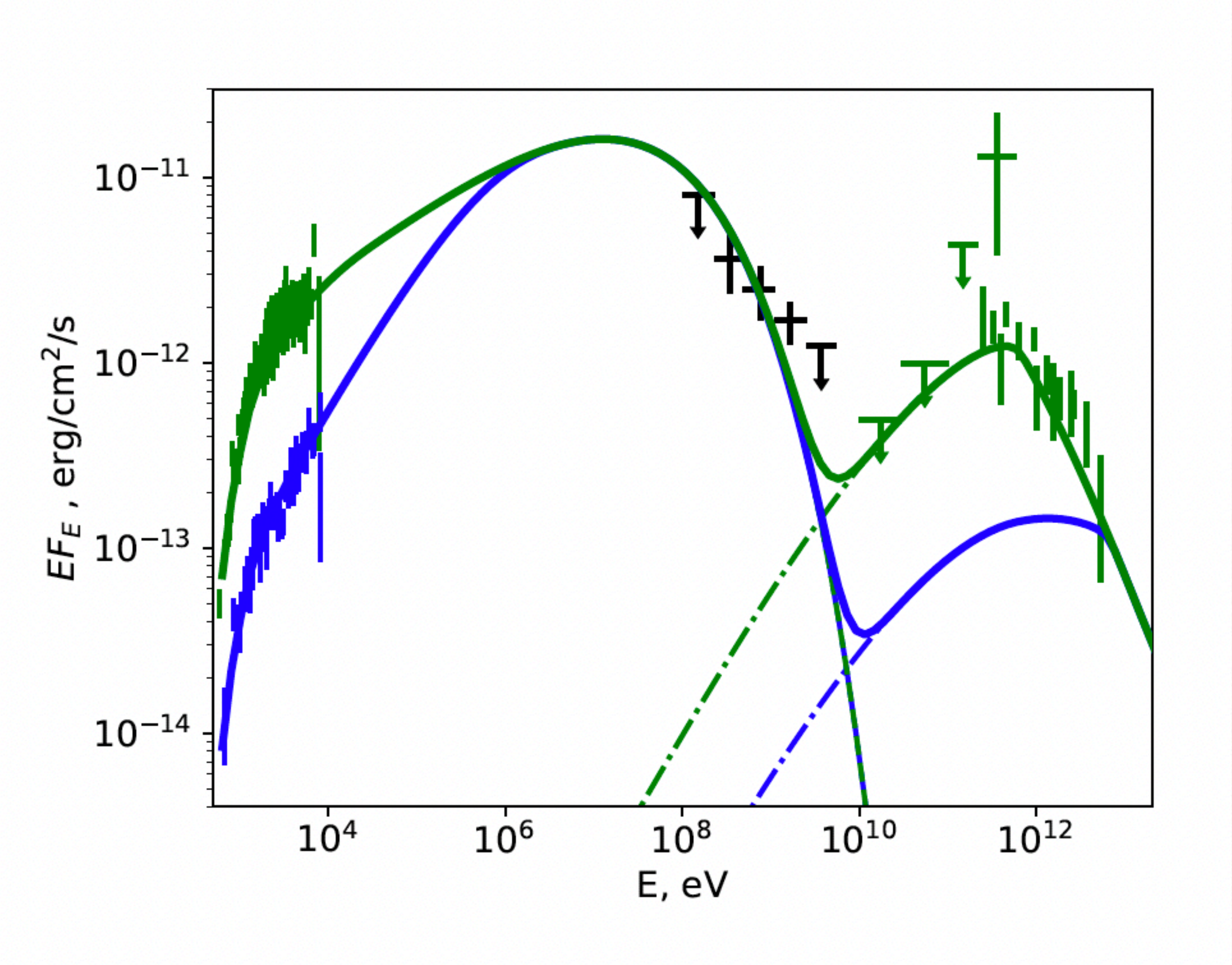
CWB with two massive stars



HD 93129A

del Palacio et al. 2020

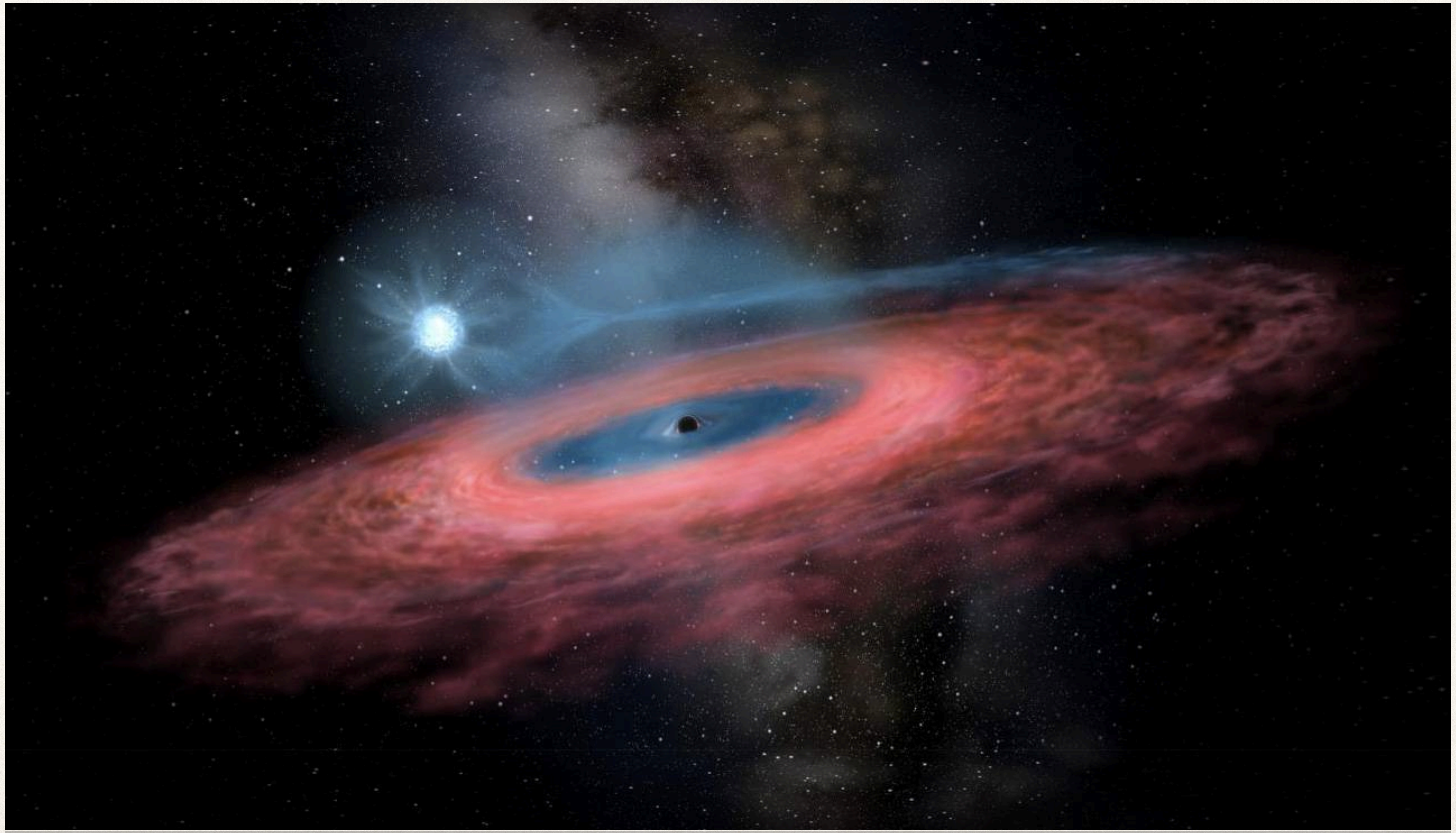
CWB with massive star and a pulsar



HESS J0632+057

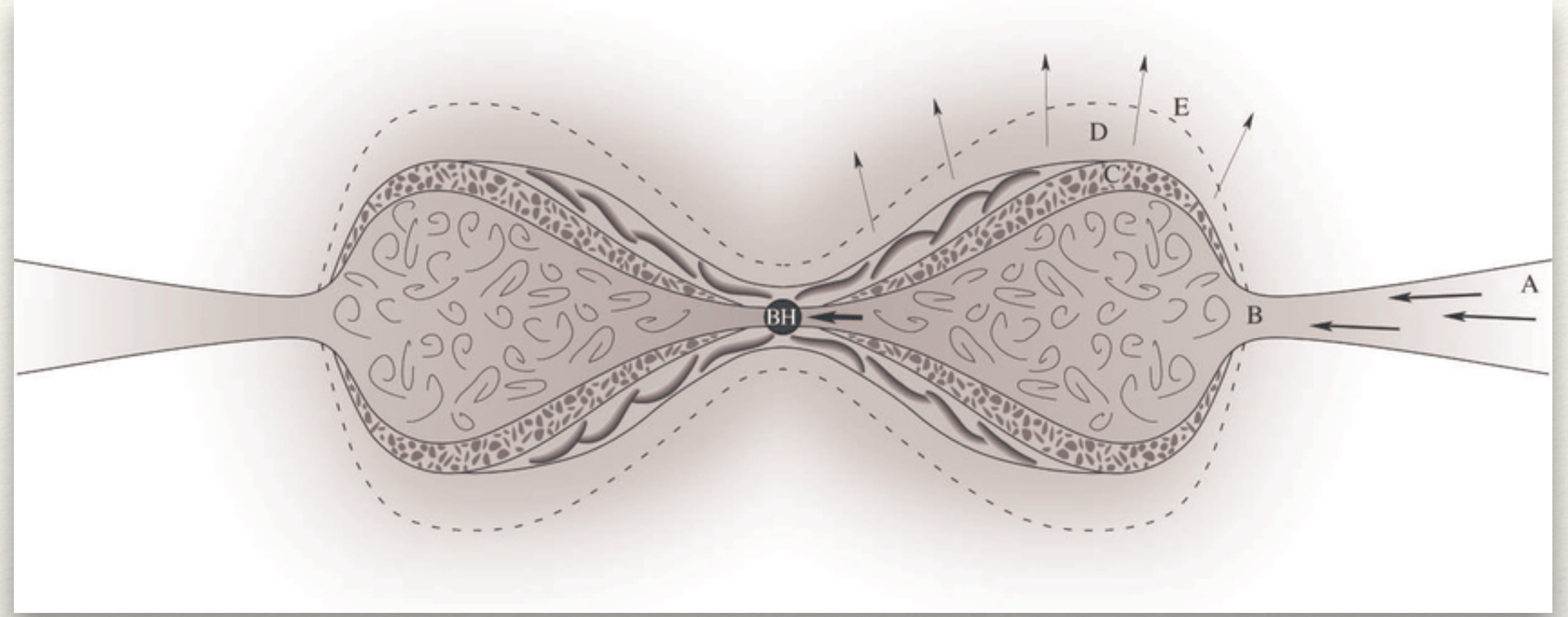
Chenyakova et al. (2019)

Colliding wind systems are not usually associated with the presence of a black hole (BH). However, when the accretion rate is sufficiently high, the disk itself can produce a powerful radiation-driven wind. If the donor star also produces a wind, a colliding wind region must be formed.



Super-critical disks

When the accretion regime is super-critical, the disk is divided into two regions: an outer standard disk without winds, and an inner, radiation-dominated disk that accretes matter at the Eddington rate and ejects the excess of gas in the form of a radiation-driven wind.

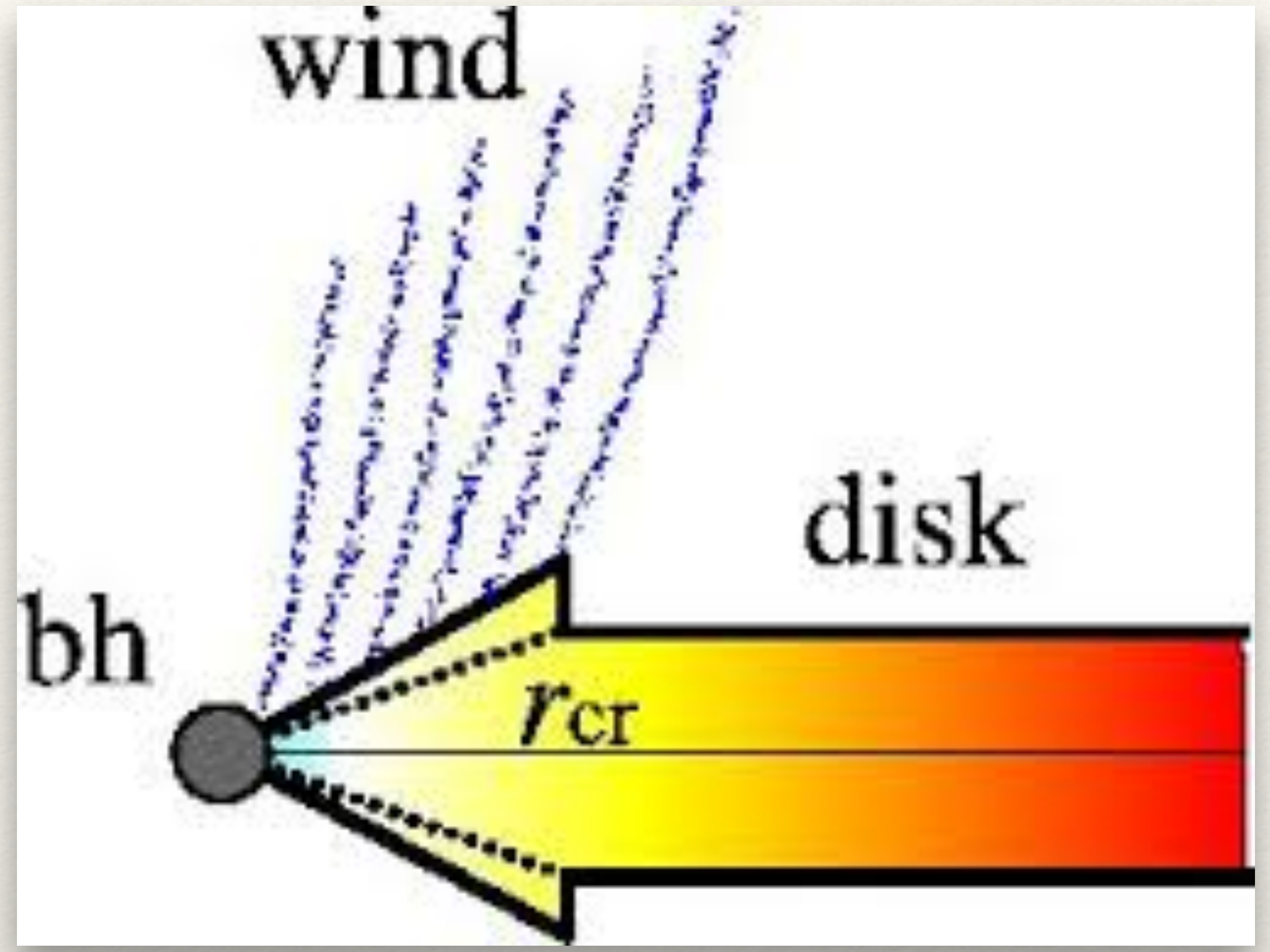


$r_{\rm cr} = \dfrac{9\sqrt{3}\sigma_{\rm T}}{16\pi m_{\rm p} c}\dot{M} \approx 4\dot{m} r_{\rm g}$ is the critical radius where the transition occurs.

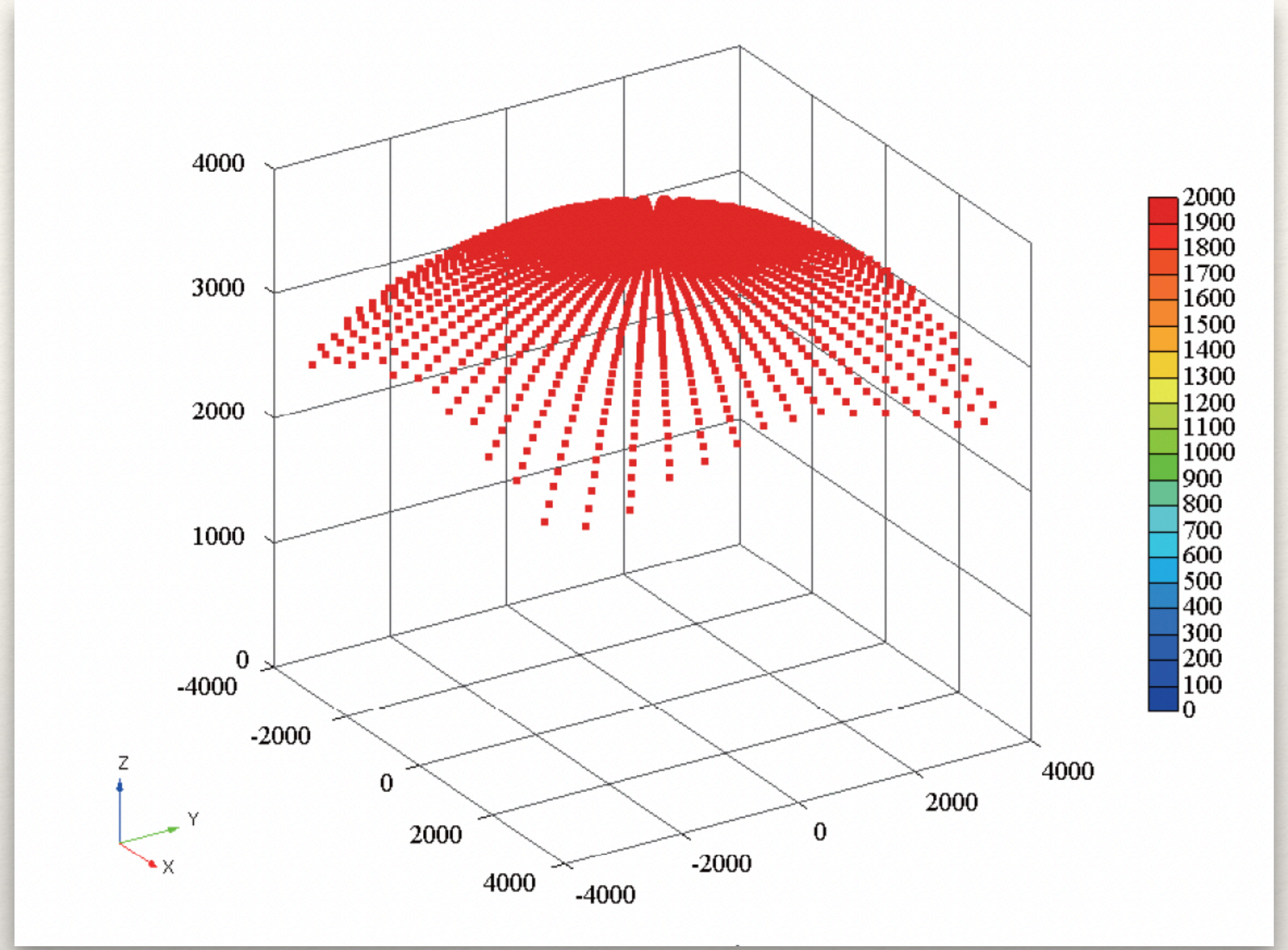
$L_{\rm bol} = L_{\rm Edd}\dfrac{2}{3\sqrt{3}}\left(1 + \ln\left(4\dot{m}\dfrac{r_{\rm g}}{r_{\rm in}}\right)\right)$ is the disk luminosity.

$v_{\rm w} \sim \sqrt{\dfrac{GM_{\rm BH}}{r_{\rm cr}}} = \dfrac{c}{2\sqrt{\dot{m}}}$ is the wind velocity.

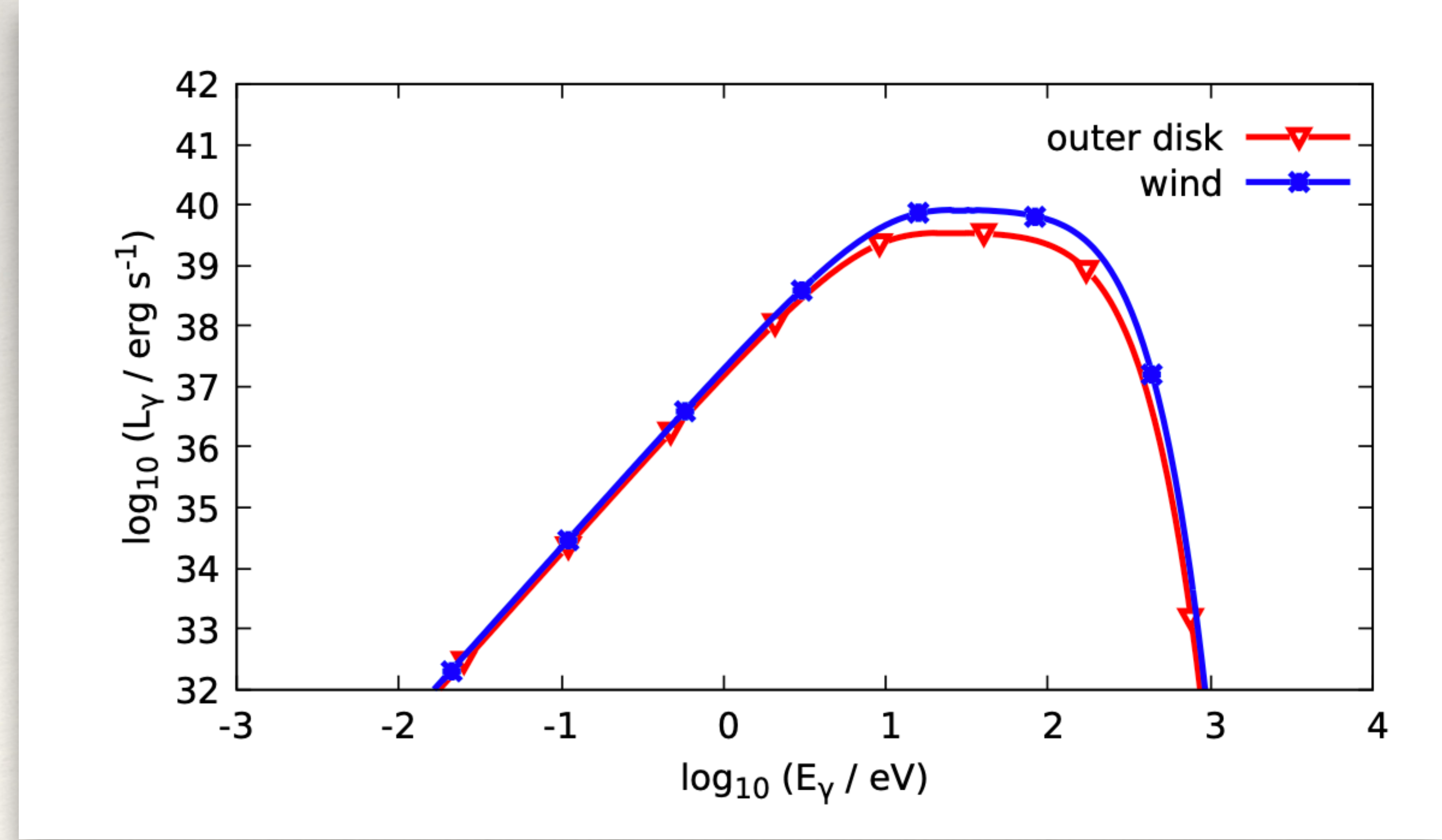
$\tau_{\rm ph} = -\int_{\infty}^{z_{\rm ph}} \Gamma_{\rm w}\left(1 - \beta\cos\theta\right)\kappa_{\rm co}\rho_{\rm co}{\rm d}z = 1$ determines the photosphere of the wind.



Since the wind is opaque the photosphere hides the disk emission

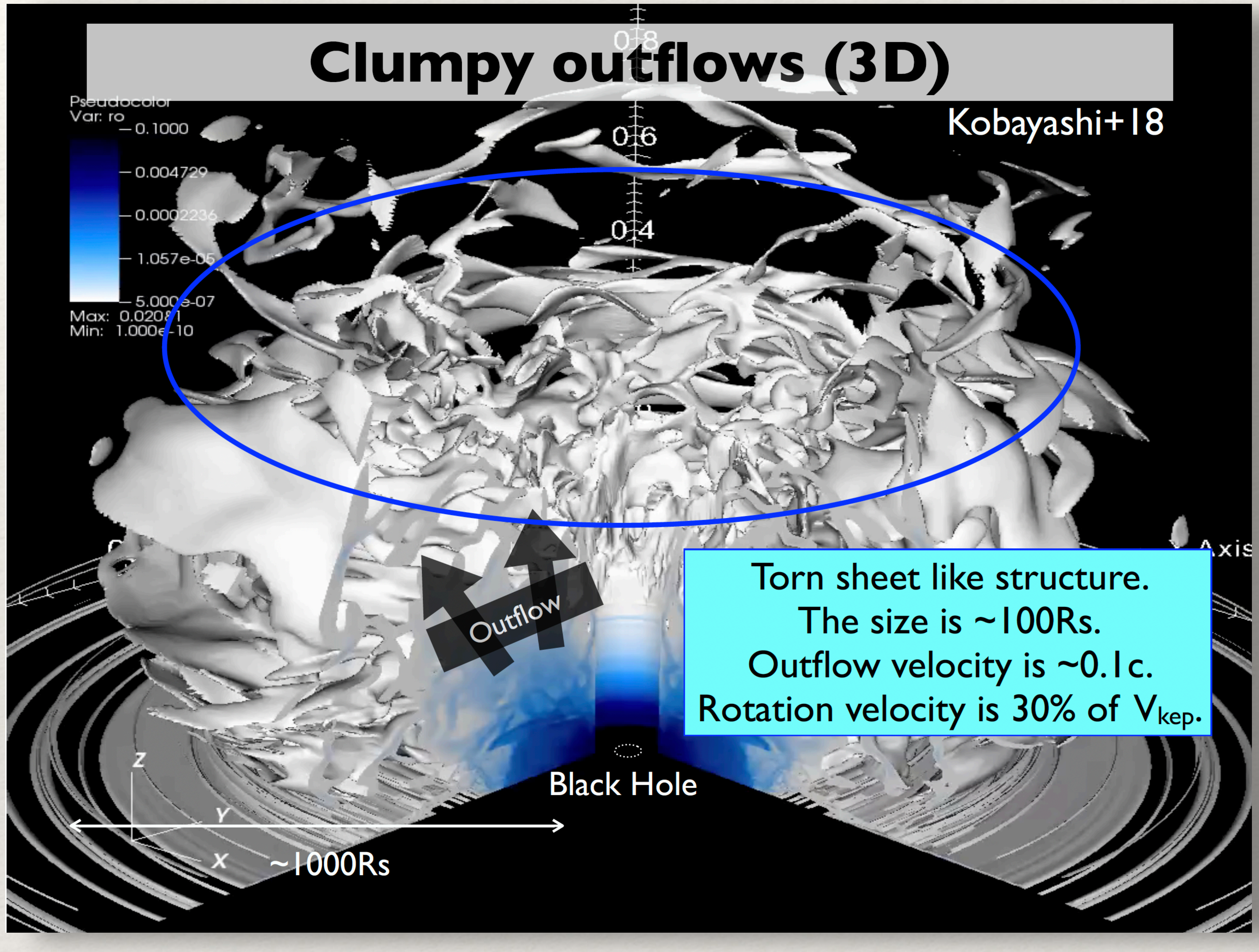


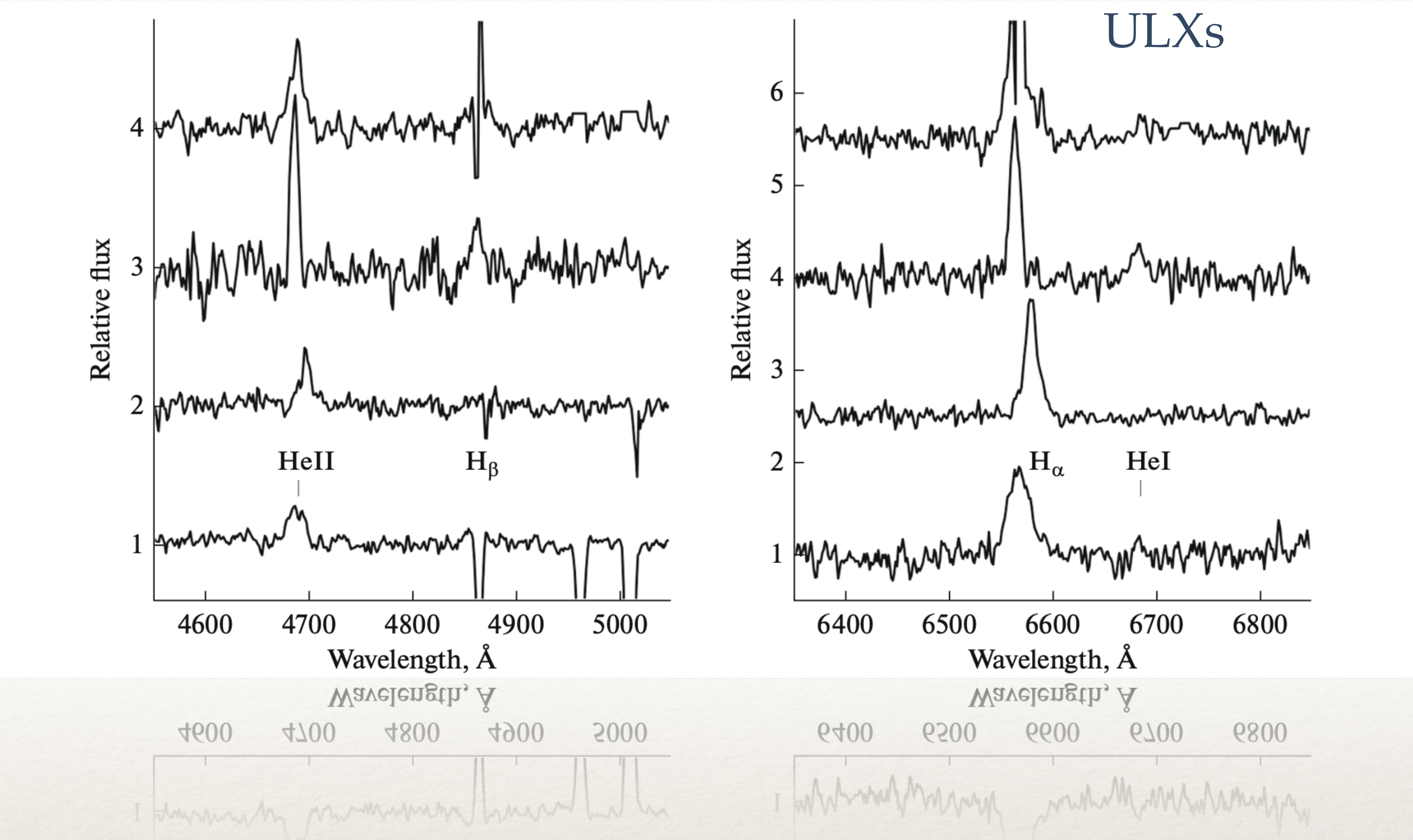
Shape of the wind photosphere for $v_w \sim 0.1c$, Fukue (2009)



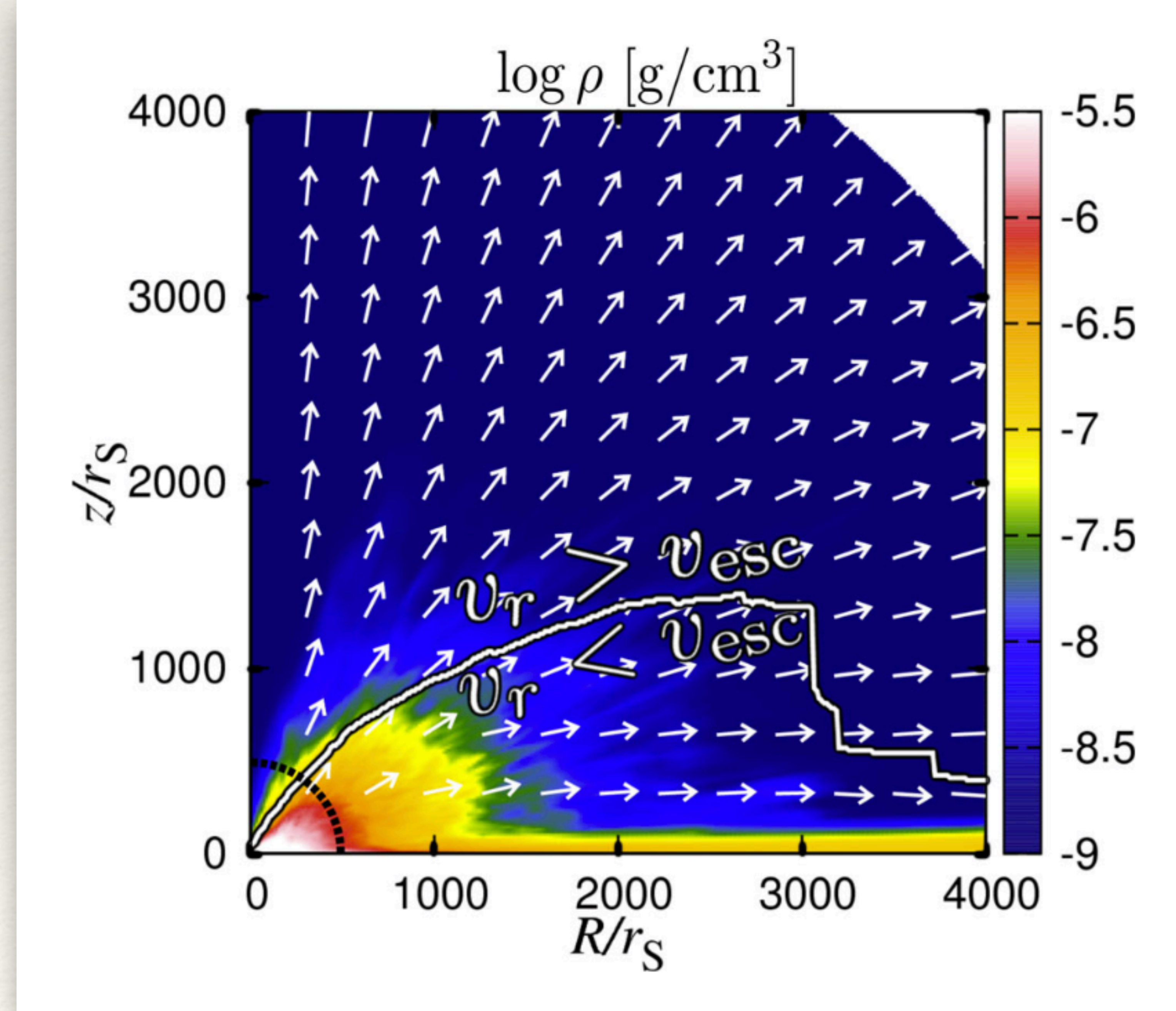
The radiation that escapes is that of the surface of the photosphere and that from the out disk (Sotomayor Checa & Romero 2019).

The existence of massive outflows or winds launched by super-accreting disk is corroborated by both observations and simulations.





Fabrika+ 2015



Hashizume + 2014

Radiation fields of the disk

$$Q_{\rm adv} = f Q_{\rm vis}$$

$$R^{\mu\nu} = \begin{pmatrix} E & \frac{1}{c}F^{\alpha} \\ \frac{1}{c}F^{\alpha} & P^{\alpha\beta} \end{pmatrix} = \frac{1}{c}\int I_{\nu} j^{i} j^{j} d\nu d\Omega$$

Radiation tensor

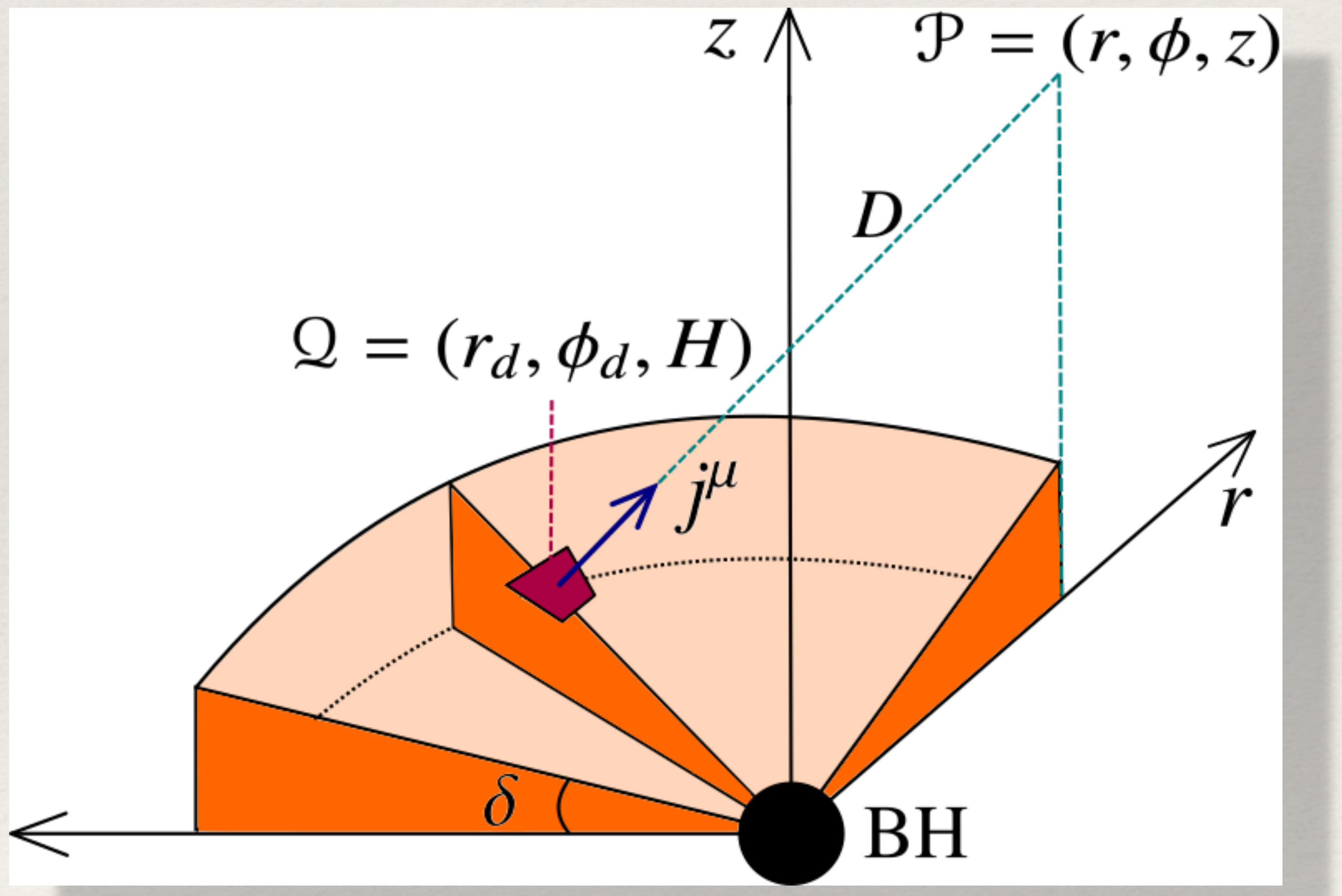
$$E = \frac{1}{4}\frac{m_{\rm p}}{\sigma_{\rm T}}\frac{GM_{\rm BH}}{r_{\rm g}^2}\epsilon, \quad F^{\alpha} = \frac{1}{4}\frac{m_{\rm p}c}{\sigma_{\rm T}}\frac{GM_{\rm BH}}{r_{\rm g}^2}f^{\alpha}, \quad P^{\alpha\beta} = \frac{1}{4}\frac{m_{\rm p}}{\sigma_{\rm T}}\frac{GM_{\rm BH}}{r_{\rm g}^2}p^{\alpha\beta}$$

Spatial distribution of the photon energy density

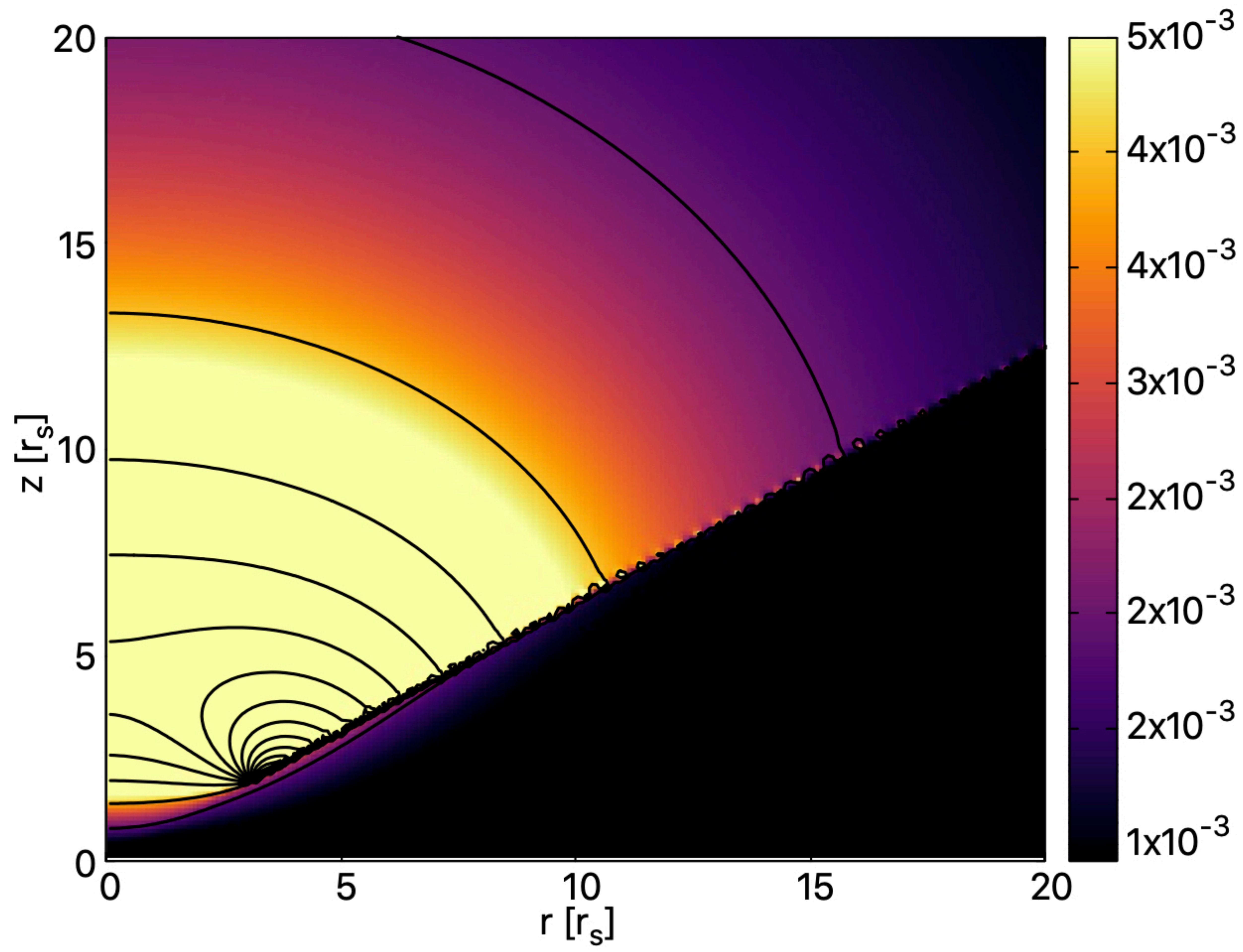
$$R^{00} = \frac{1}{c}\int I j^0 j^0 d\Omega$$

$$I = \mathscr{D}^4 I_0 = \frac{I_0}{(1+z_{\rm red})^4},$$

$$I_0 = \frac{1}{\pi}\sigma T_{\rm eff}^4 = \begin{cases} \frac{1}{\pi}\frac{3GM_{\rm BH}\dot{M}_{\rm input}}{8\pi r_{\rm d}^3} f_{\rm in}, & r_{\rm d} > r_{\rm crit} \\ \frac{1}{\pi}\frac{3}{4}\sqrt{c_3}\frac{L_{\rm Edd}}{4\pi r_{\rm d}^2}, & r_{\rm d} \le r_{\rm crit}, \end{cases}$$



$$(\boldsymbol{n}\cdot\boldsymbol{l}) = \frac{1}{D}[-(r\cos\varphi_{\rm d} - r_{\rm d})\sin\delta + (z-H)\cos\delta]$$



Effect of the radiation fields of the disk on the fluid

$$f_\mu = -\frac{\partial \Phi_e}{\partial x^\nu} + R^\nu_{\mu;\nu},$$

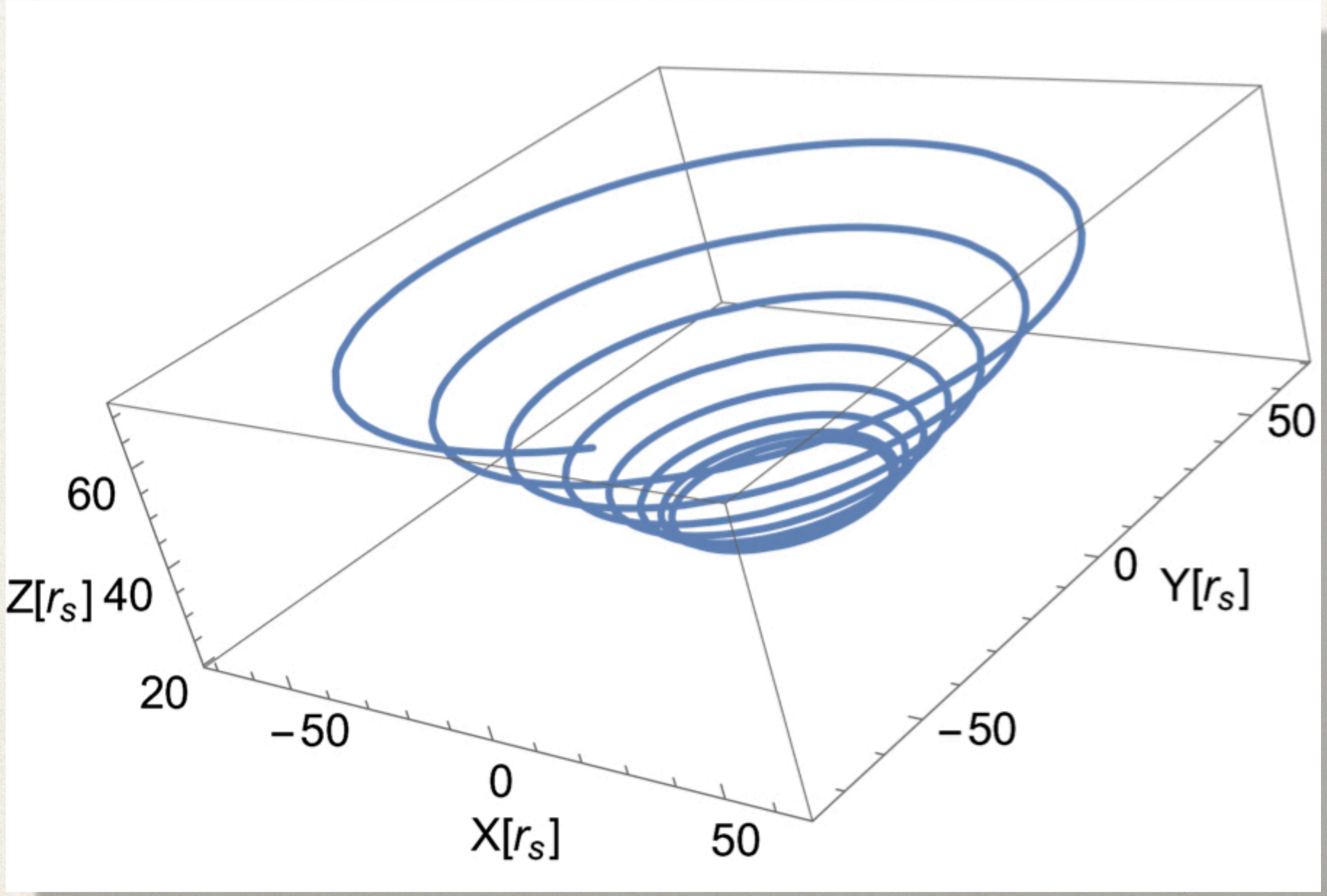
Equations of motion

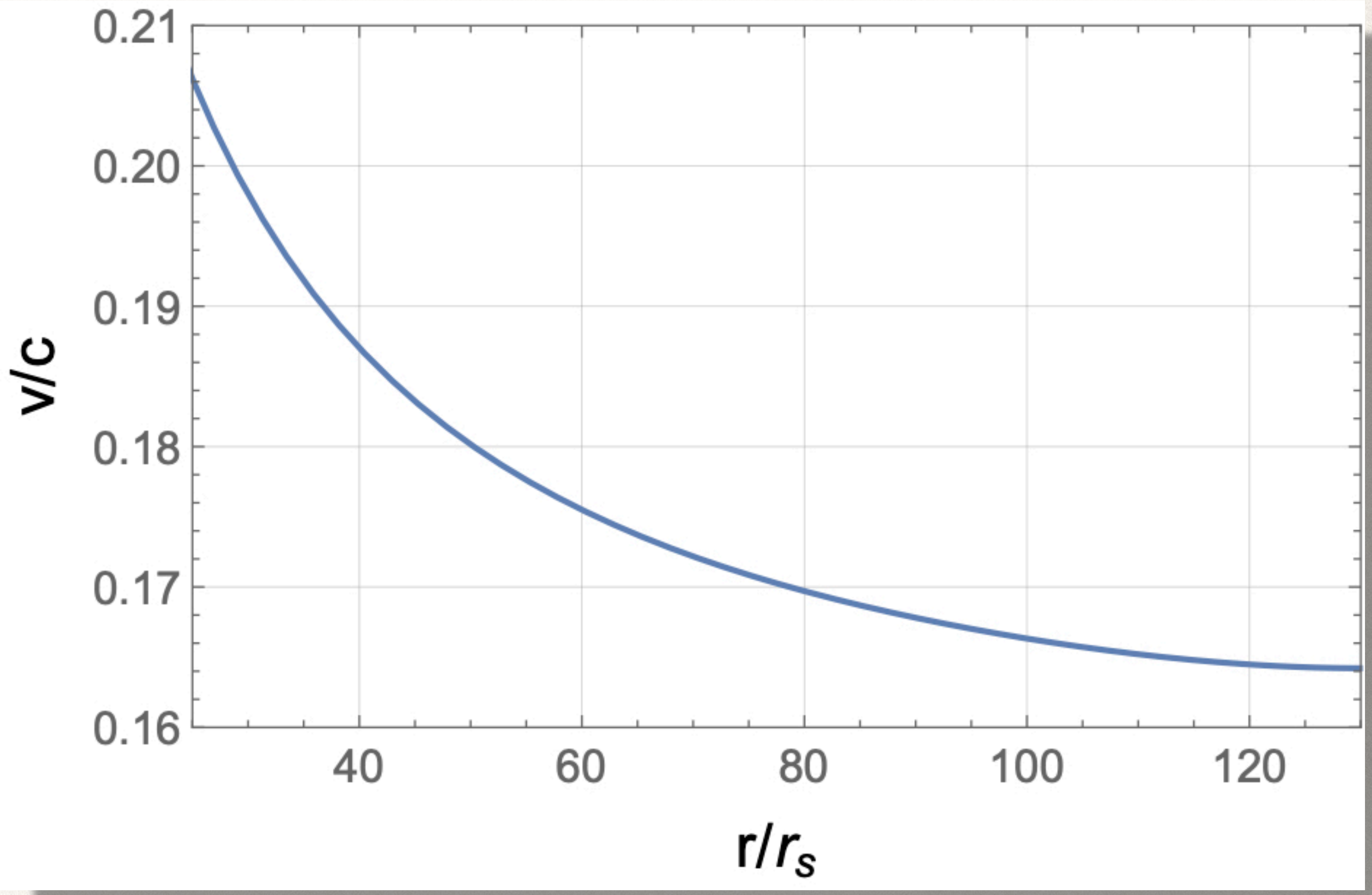
$$\frac{du^r}{d\tau} = -\frac{\partial \Phi_g}{\partial r} + \frac{l^2}{r^3} + \frac{1}{2}\left[\gamma f^r - p^{r\beta}u_\beta - \gamma^2 \epsilon u^r + u^r(2\gamma f^\beta u_\beta - p^{\beta\gamma}u_\beta u_\gamma)\right]$$

$$\frac{1}{r}\frac{dl}{d\tau} = \frac{1}{2}\left[\gamma f^\phi - p^{\phi\beta}u_\beta - \gamma^2 \epsilon (l/r) + (l/r)(2\gamma f^\beta u_\beta - p^{\beta\gamma}u_\beta u_\gamma)\right]$$

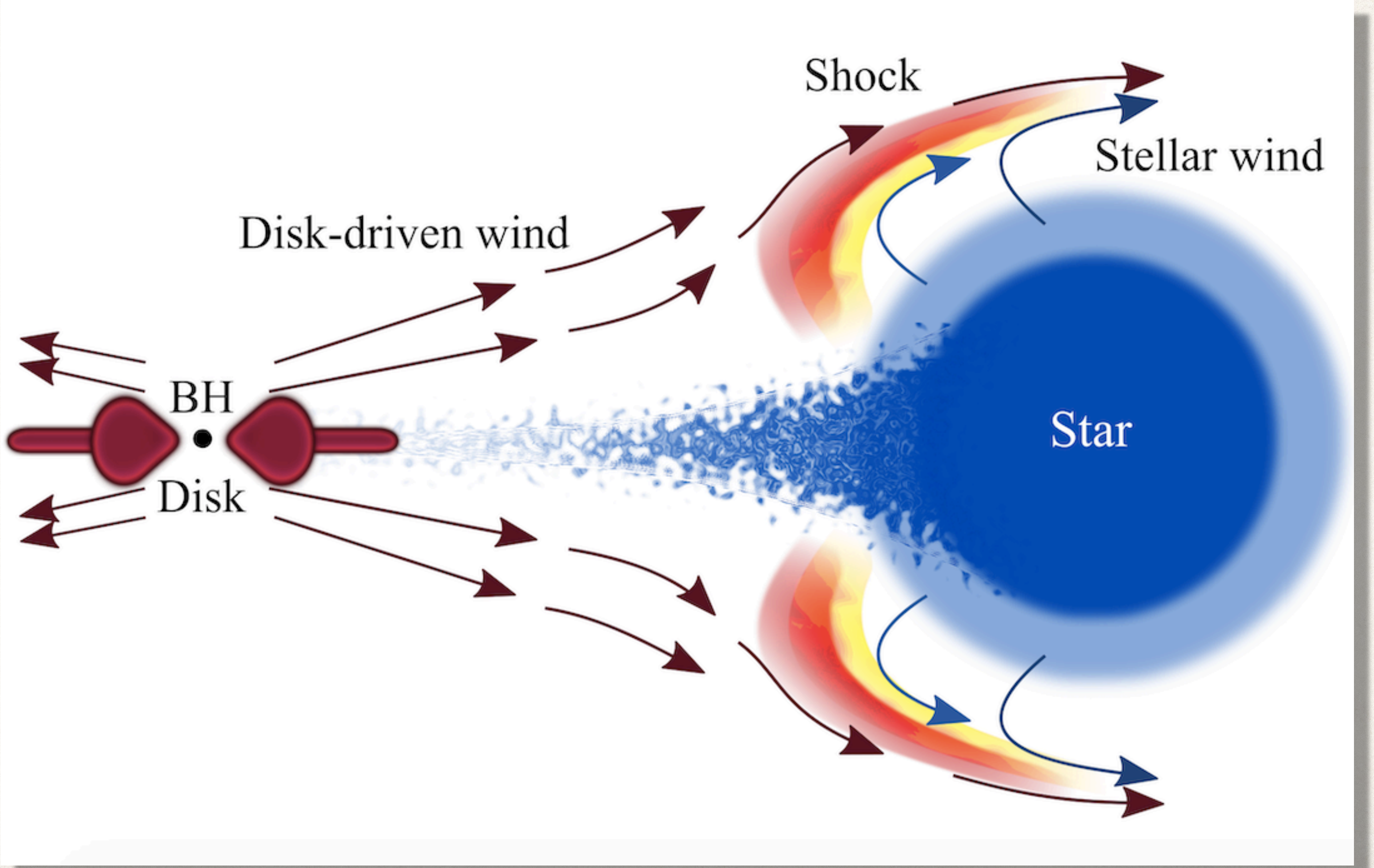
$$\frac{du^z}{d\tau} = -\frac{\partial \Phi_g}{\partial z} + \frac{1}{2}\left[\gamma f^z - p^{z\beta}u_\beta - \gamma^2 \epsilon u^z + u^z(2\gamma f^\beta u_\beta - p^{\beta\gamma}u_\beta u_\gamma)\right]$$

Outflow motion





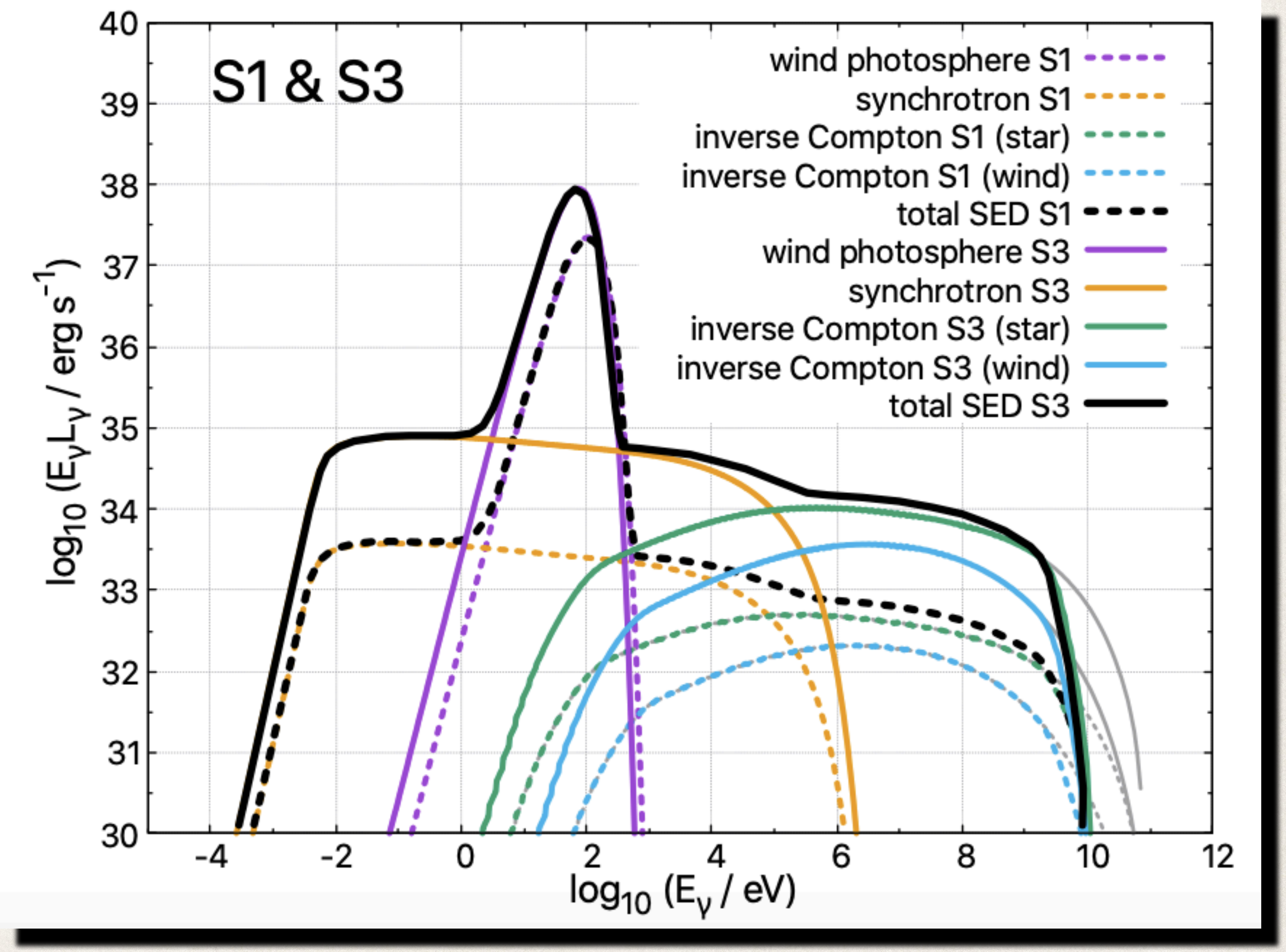
Colliding winds and non-thermal radiation



We solve the transport equation and computed the relevant radiative processes

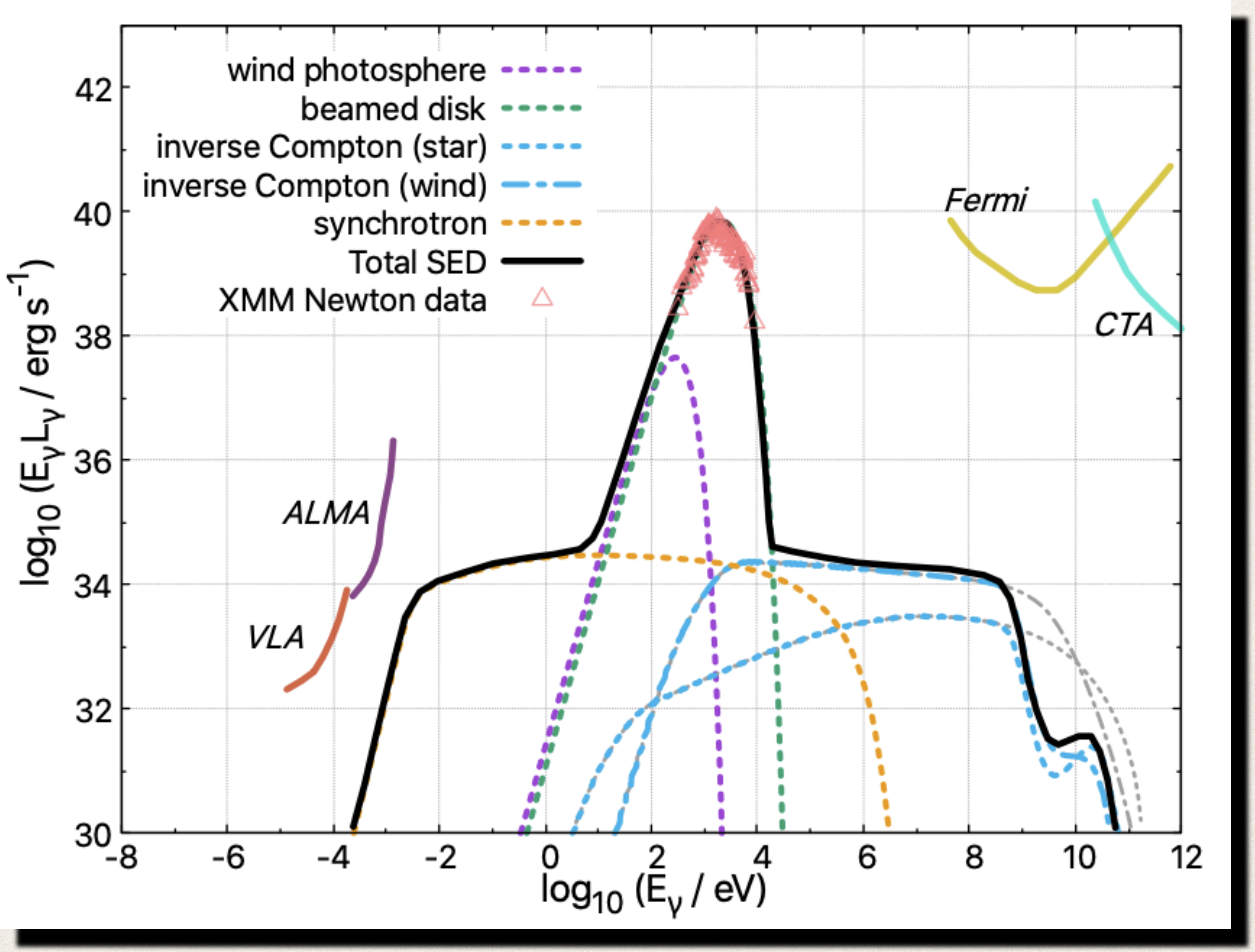
S1 & S3: generic scenarios

- Accretion: $\dot{M} = 10^2\ \dot{M}_{\rm Edd}$ & $\dot{M} = 10^3\ \dot{M}_{\rm Edd}$
- Star: O5V
- $v_*^{\rm wind} = 2900$ km s^{-1}
- $L_{\rm K}^* = 3.2 \times 10^{37}$ erg s^{-1}
- $v_{\rm disk}^{\rm wind} = 0.16\ c$
- $L_{\rm K}^{\rm wind} \sim 10^{39}$ erg s^{-1}
- $E_{\rm e}^{\rm max} \approx 100$ GeV
- $E_{\rm p}^{\rm max} \approx 1$ PeV
- $\eta_{\rm acc} = 10^{-2}$

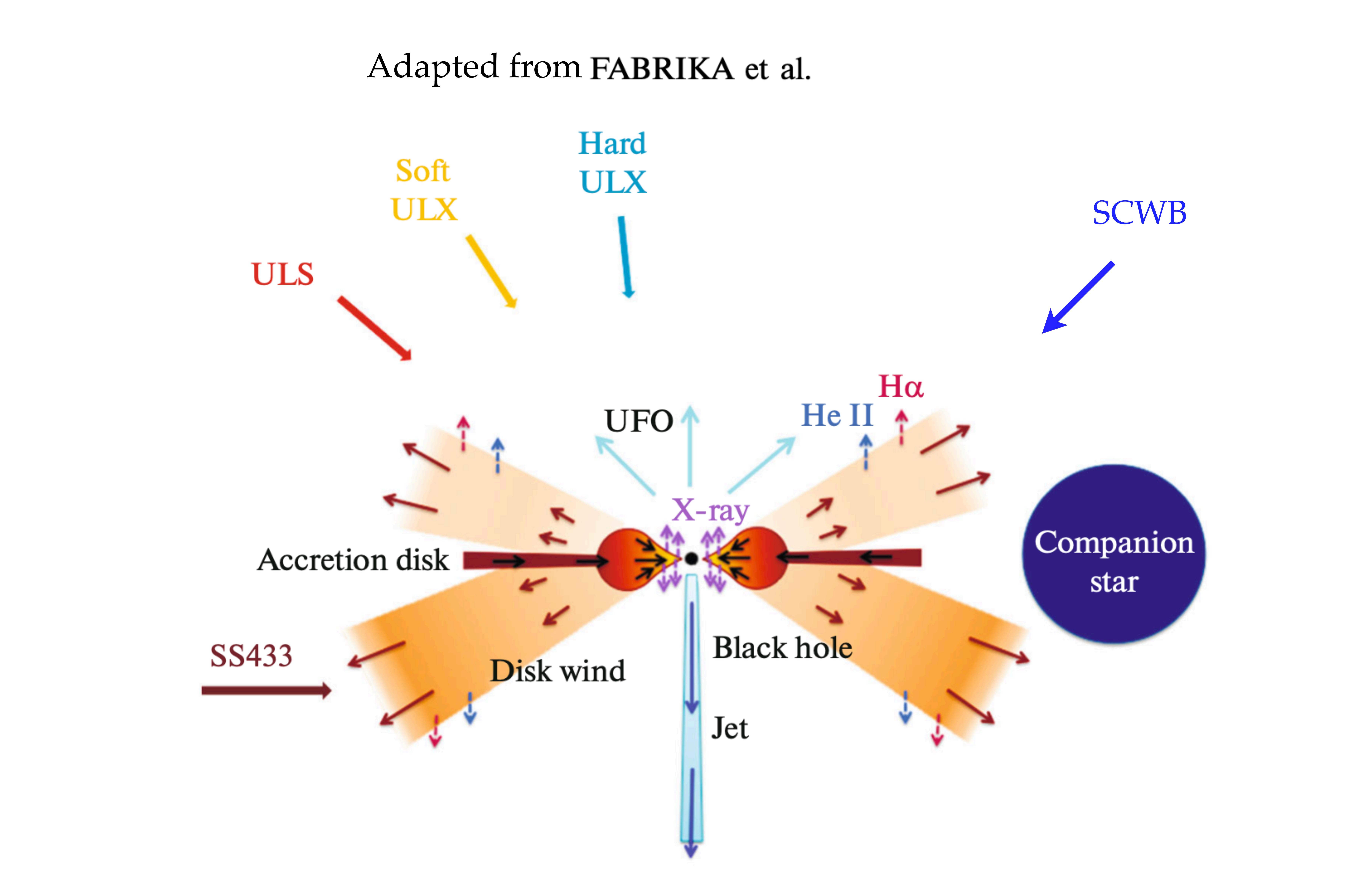


NGC 4190 X1

- $M_{\rm BH} = 10\, M_\odot$
- $\dot{M} = 10\, M_{\rm Edd}$
- Star: B2V
- $v_*^{\rm wind} = 700$ km s^{-1}
- $L_{\rm K}^* = 2.2 \times 10^{34}$ erg s^{-1}
- $v_{\rm disk}^{\rm wind} = 49500$ km s^{-1}
- $L_{\rm K}^{\rm wind} = 1.5 \times 10^{39}$ erg s^{-1}
- $E_{\rm e}^{\rm max} \approx 0.3$ TeV
- $E_{\rm p}^{\rm max} \approx 1$ PeV
- $\eta_{\rm acc} = 10^{-2}$
- Absorption almost total above 1GeV



Unification of supercritical sources



Conclusions

- CWs in ULXs (SCWBs) are potential sources of relativistic particles and, hence, of radio and gamma-ray emission, with luminosities in the range of ~10^{32}–10^{35} erg s^{-1}, which for the most part are produced by electron synchrotron and inverse Compton mechanisms.

- This emission could be detectable in some sources. R—ULXs in Magellanic Clouds could be detectable with SKA.

- Even if a fraction of just ~1% of the wind kinetic power goes to relativistic protons, the cosmic-ray output of a SCWB would be in the range 10^{37}-10^{38} erg s^{-1}.

- R—ULXs bubbles? Gamma-ray nebulae?

- The disk-wind could interact with dense regions far away from the source producing shocks and realeccerating particles with the consequent HE emission.

- Since the phenomenon is highly anisotropic, a hidden population might exist in our Galaxy.

- For details see L. Abaroa, G.E. Romero & P. Sotomayor, A&A 671, A9 (2023). https://doi.org/10.1051/0004-6361/202245285

Thanks!

Accretion and Eddington limit

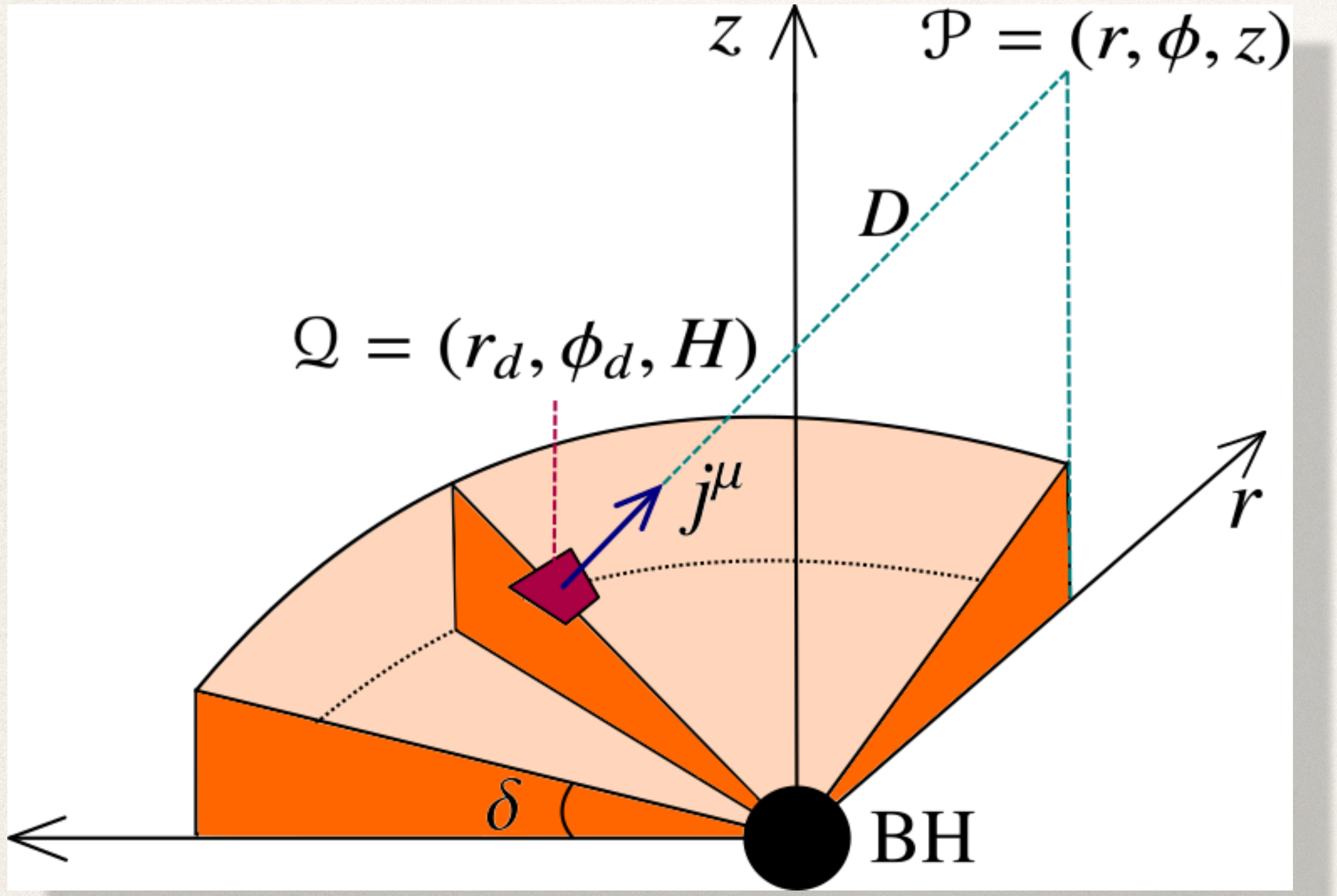
Accretion is the process that take place when matter falls into the potential well of a gravitating object. Conservation of angular momentum leads to the formation of a disk around the object (a BH in our case). Energy is dissipated through radiation created by viscosity. Then angular momentum is removed and there is an inflow. The Eddington luminosity is the maximum luminosity that can be achieved when there is a balance between the force of radiation acting outward and the gravitational force acting inward.

$$L_{\rm Edd} = \frac{4\pi G M m_{\rm p} c}{\sigma_{\rm T}}$$
$$\cong 1.26 \times 10^{31} \left(\frac{M}{M_\odot}\right) {\rm W} = 1.26 \times 10^{38} \left(\frac{M}{M_\odot}\right) {\rm erg/s} = 3.2 \times 10^{4} \left(\frac{M}{M_\odot}\right) L_\odot$$

$$\dot{M}_{\rm Edd} = \frac{L_{\rm Edd}}{c^2} \approx 0.2 \times 10^{-8} \left(\frac{M}{M_\odot}\right)\ M_\odot\ {\rm yr}^{-1}.$$

$$T_{\rm Edd} = \left(\frac{L_{\rm Edd}}{4\pi\sigma_{\rm SB} R^2_{\rm Schw}}\right) \approx 6.6 \times 10^{7} \left(\frac{M}{M_\odot}\right)^{-1/4}\ {\rm K}.$$

Radiation fields of the disk



$$\varepsilon = \frac{3}{4\pi}\sqrt{c_3}\int_{r_{\rm in}}^{\infty}\int_0^{2\pi}\frac{1}{r_{\rm d}}\frac{(\boldsymbol{n}\cdot\boldsymbol{l})}{(1+z_{\rm red})^4} \times \frac{\sqrt{1+c_3}}{D^2}dr_{\rm d}d\varphi_{\rm d},$$

$$f^\alpha = \frac{3}{4\pi}\sqrt{c_3}\int_{r_{\rm in}}^{\infty}\int_0^{2\pi}\frac{1}{r_{\rm d}}\frac{(\boldsymbol{n}\cdot\boldsymbol{l})}{(1+z_{\rm red})^4} \times \frac{\sqrt{1+c_3}}{D^2}l^\alpha dr_{\rm d}d\varphi_{\rm d},$$

$$p^{\alpha\beta} = \frac{3}{4\pi}\sqrt{c_3}\int_{r_{\rm in}}^{\infty}\int_0^{2\pi}\frac{1}{r_{\rm d}}\frac{(\boldsymbol{n}\cdot\boldsymbol{l})}{(1+z_{\rm red})^4} \times \frac{\sqrt{1+c_3}}{D^2}l^\alpha l^\beta dr_{\rm d}d\varphi_{\rm d},$$

$$(\boldsymbol{n}\cdot\boldsymbol{l}) = \frac{1}{D}[-(r\cos\varphi_{\rm d} - r_{\rm d})\sin\delta + (z-H)\cos\delta]$$

Donor star

Type O.5V Star		
Parameter	Value	Units
M_*	37	$M_\odot$
R_*	11	$R_\odot$
$T_{\rm eff}$	41500	K
$\dot{M}_*$	1.2×10^{-5}	$M_\odot$ yr^{-1}
$v_{*{\rm w}}$	2.9×10^{8}	cm s^{-1}
$v_*^{\rm rot}$	2.9×10^{7}	cm s^{-1}
L_K^*	3.2×10^{37}	erg s^{-1}
B_*	750	G

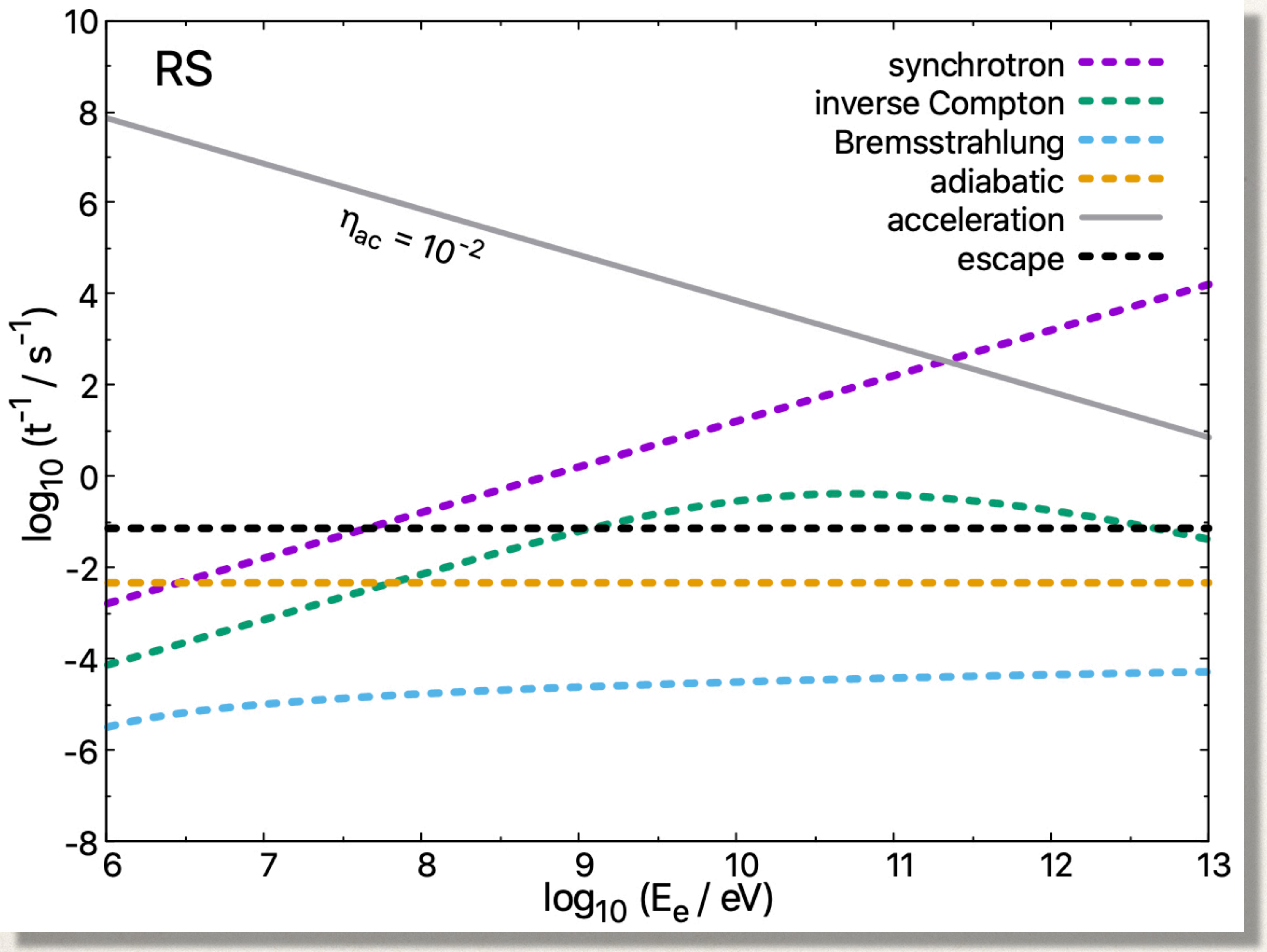
Parameter	Symbol [units]	Scenario			
		S1	S2	S3	S4
Black hole mass[(1)]	$M_{\rm BH}$ [$M_\odot$]	5	5	20	20
Mass accretion rate[(1)]	$\dot{M}_{\rm input}$ [$M_\odot$ yr^{-1}]	1.1×10^{-5}	1.1×10^{-4}	4.4×10^{-5}	4.4×10^{-4}
Orbital semi-axis[(1)]	a [$R_\odot$]	15	15	22	22
Gravitational radius[(2)]	$r_{\rm g}$ [cm]	7.4×10^{5}	7.4×10^{5}	2.9×10^{6}	2.9×10^{6}
Critical radius[(2)]	$r_{\rm crit}$ [$r_{\rm g}$]	4000	40000	4000	40000
Mass loss in disk winds[(1)]	$\dot{M}_{\rm dw}$ [$M_\odot$ yr^{-1}]	10^{-5}	10^{-4}	4.3×10^{-5}	4.3×10^{-4}
Kinetic power of the disk-driven wind[(2)]	$L_{\rm K}^{\rm dw}$ [erg s^{-1}]	7.8×10^{39}	7.8×10^{40}	3.4×10^{40}	3.4×10^{41}
Cold matter density at SP[(2)]	$n_{\rm dw}$ [cm^{-3}]	5.1×10^{12}	5.1×10^{13}	2.9×10^{12}	2.9×10^{13}
Distance to SP from BH[(2)]	$r_{\rm BH}$ [cm]	2.7×10^{11}	2.7×10^{11}	7.6×10^{11}	7.6×10^{11}
Size of acceleration region[(1)]	$\Delta x_{\rm ac}$ [cm]	2.7×10^{10}	2.7×10^{10}	7.6×10^{10}	7.6×10^{10}
Shock cold matter density[(2)]	$n_{\rm RS}$ [cm^{-3}]	2×10^{13}	2×10^{14}	1.2×10^{13}	1.2×10^{14}
Shock cooling length[(2)]	R_Λ [cm]	7.6×10^{11}	7.6×10^{10}	1.3×10^{12}	1.3×10^{11}
Maximum energy of electrons[(2)]	$E_{\rm e}^{\rm max}$ [eV]	10^{11}	1.6×10^{11}	10^{11}	10^{11}
Maximum energy of protons[(2)]	$E_{\rm p}^{\rm max}$ [eV]	10^{15}	10^{15}	3×10^{15}	3.1×10^{15}
Emission peak (low energy)[(2)]	$L_{\rm 0.01mm}$ [erg s^{-1}]	3.2×10^{33}	3.2×10^{33}	8×10^{34}	8×10^{34}
Emission peak (high energy)[(2)]	$L_{\rm 10MeV}$ [erg s^{-1}]	4×10^{32}	4×10^{32}	10^{34}	10^{34}

Table 3. Parameters of NGC 4190 ULX 1.

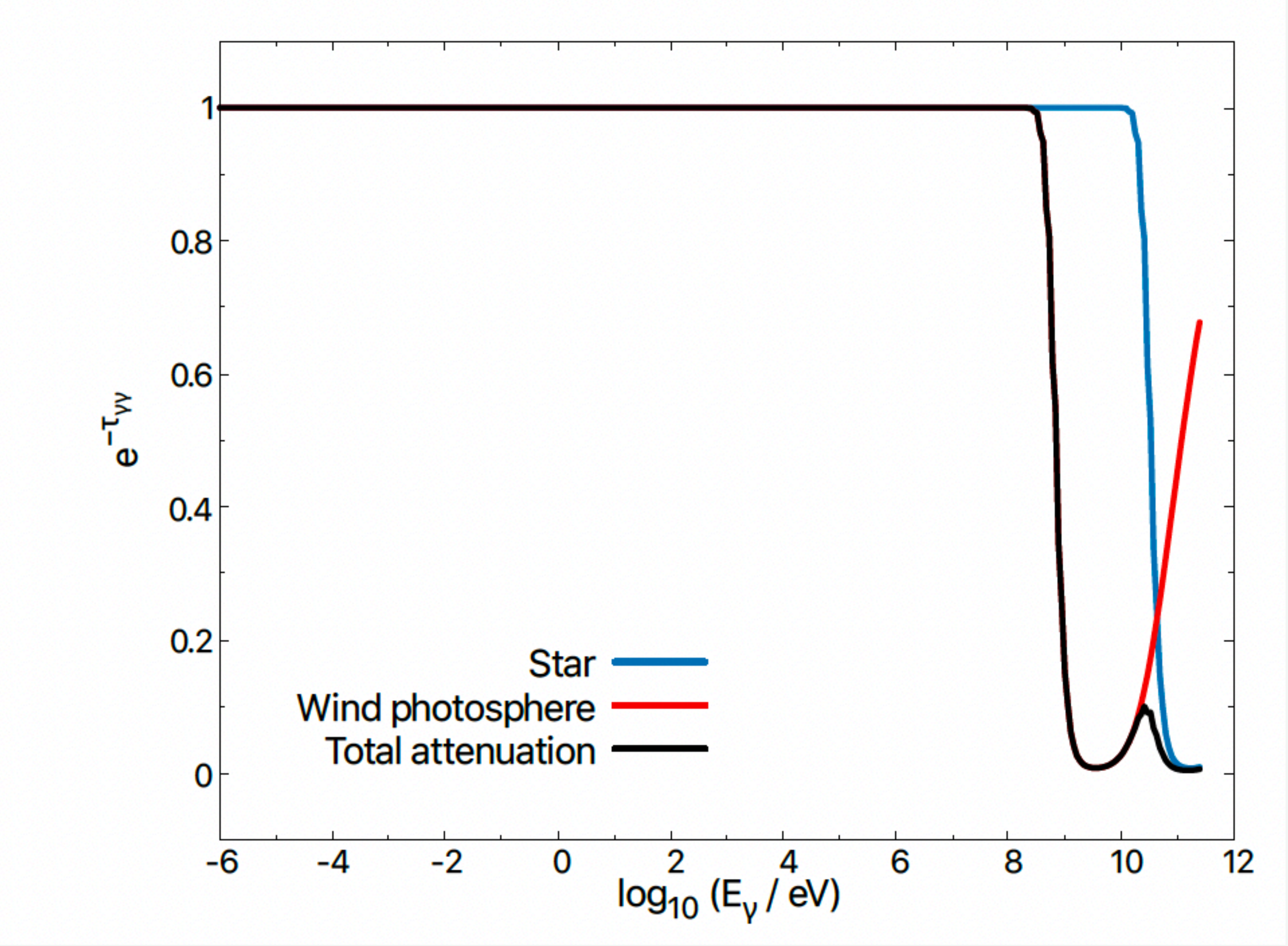
Parameter	Symbol	Value	Units
System			
Inclination [(1)]	i	0	$^\circ$
Orbital semi-axis [(2)]	a	15	$R_\odot$
Distance to the source [(3)]	d	3	Mpc
Black hole			
Mass [(1)]	$M_{\rm BH}$	10	$M_\odot$
Gravitational radius [(2)]	$r_{\rm g}$	1.48×10^6	cm
Accretion disk			
Disk semi opening angle [(1)]	δ	30	$^\circ$
Critical radius [(2)]	$r_{\rm crit}$	3.5×10^9	cm
Eddington accretion rate	$\dot{M}_{\rm Edd}$	2.2×10^{-7}	$M_\odot$ yr^{-1}
Mass accretion rate [(1)]	$\dot{M}_{\rm input}$	2.2×10^{-6}	$M_\odot$ yr^{-1}
Mass loss in winds [(1)]	$\dot{M}_{\rm dw}$	1.98×10^{-6}	$M_\odot$ yr^{-1}
Wind velocity [(2)]	$v_{\rm dw}$	4.95×10^9	cm s^{-1}
Wind semi opening angle [(2)]	θ	14.5	$^\circ$
Beaming factor [(2)]	b	0.07	–
B2V Star			
Mass [(4)]	M_*	8	$M_\odot$
Radius [(4)]	R_*	5.4	$R_\odot$
Temperature [(4)]	$T_{\rm eff}$	20600	K
Mass loss in winds [(4)]	$\dot{M}_*$	1.4×10^{-7}	$M_\odot$ yr^{-1}
Wind velocity [(4)]	$v_{*\rm w}$	7×10^7	cm s^{-1}
Rotation velocity [(1)]	$v_*^{\rm rot}$	7×10^6	cm s^{-1}
Magnetic field [(5)]	B_*	200	G
Colliding winds			
Kinetic power of disk-driven wind [(2)]	$L_{\rm K}^{\rm dw}$	1.5×10^{39}	erg s^{-1}
Kinetic power of stellar wind [(2)]	$L_{\rm K}^*$	2.17×10^{34}	erg s^{-1}
Distance from BH to SP [(2)]	$r_{\rm BH}$	6.68×10^{11}	cm
Size of acceleration region [(1)]	$\Delta x_{\rm ac}$	6.68×10^{10}	cm
Magnetic field at SP [(2)]	$B_{\rm SP}$	200	G
Injection spectral index [(1)]	p	2.2	–
Acceleration efficiency [(2)]	$\eta_{\rm ac}$	10^{-2}	–
Molecular mean weight [(1)]	μ	0.6	–
Reverse shock			
Velocity[(2)]	$v_{\rm RS}$	4.4×10^9	cm s^{-1}
Temperature[(2)]	$T_{\rm RS}$	10^{10}	K
Cold matter density[(2)]	$n_{\rm RS}$	6.9×10^{11}	cm^{-3}
Cooling length[(2)]	R_Λ	2.2×10^{13}	cm

Notes. We indicate the parameters we have assumed with superscript (1) and those we have derived with (2). Parameters with superscripts (3), (4), and (5) were taken from Tully et al. (2013), Kobulnicky et al. (2019), and Shultz et al. (2015), respectively.

Losses and gain: electrons



Attenuation factors due to photon annihilation between high-energy radiation and photon fields from the star and from the photosphere of the disk-driven wind.The total attenuation is plotted with a black line. Parameters for NGC 4190 ULX 1



Equations of motion

$$\frac{du^r}{d\tau} = -\frac{\partial \Phi_{\rm g}}{\partial r} + \frac{l^2}{r^3} + \frac{1}{2}\left[\gamma f^r - p^{r\beta}u_\beta - \gamma^2 \epsilon u^r + u^r(2\gamma f^\beta u_\beta - p^{\beta\gamma}u_\beta u_\gamma)\right]$$

$$\frac{1}{r}\frac{dl}{d\tau} = \frac{1}{2}\left[\gamma f^\phi - p^{\phi\beta}u_\beta - \gamma^2 \epsilon (l/r) + (l/r)(2\gamma f^\beta u_\beta - p^{\beta\gamma}u_\beta u_\gamma)\right]$$

$$\frac{du^z}{d\tau} = -\frac{\partial \Phi_{\rm g}}{\partial z} + \frac{1}{2}\left[\gamma f^z - p^{z\beta}u_\beta - \gamma^2 \epsilon u^z + u^z(2\gamma f^\beta u_\beta - p^{\beta\gamma}u_\beta u_\gamma)\right]$$