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POPULATION III MICROQUASARS

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Population III are extremely metal-poor stars (EMP). They form a hypothetical population of massive and hot stars with virtually no metals, except possibly for intermixing ejecta from other nearby Pop III supernovae. Their existence is inferred from physical cosmology, but they have not yet been observed directly.

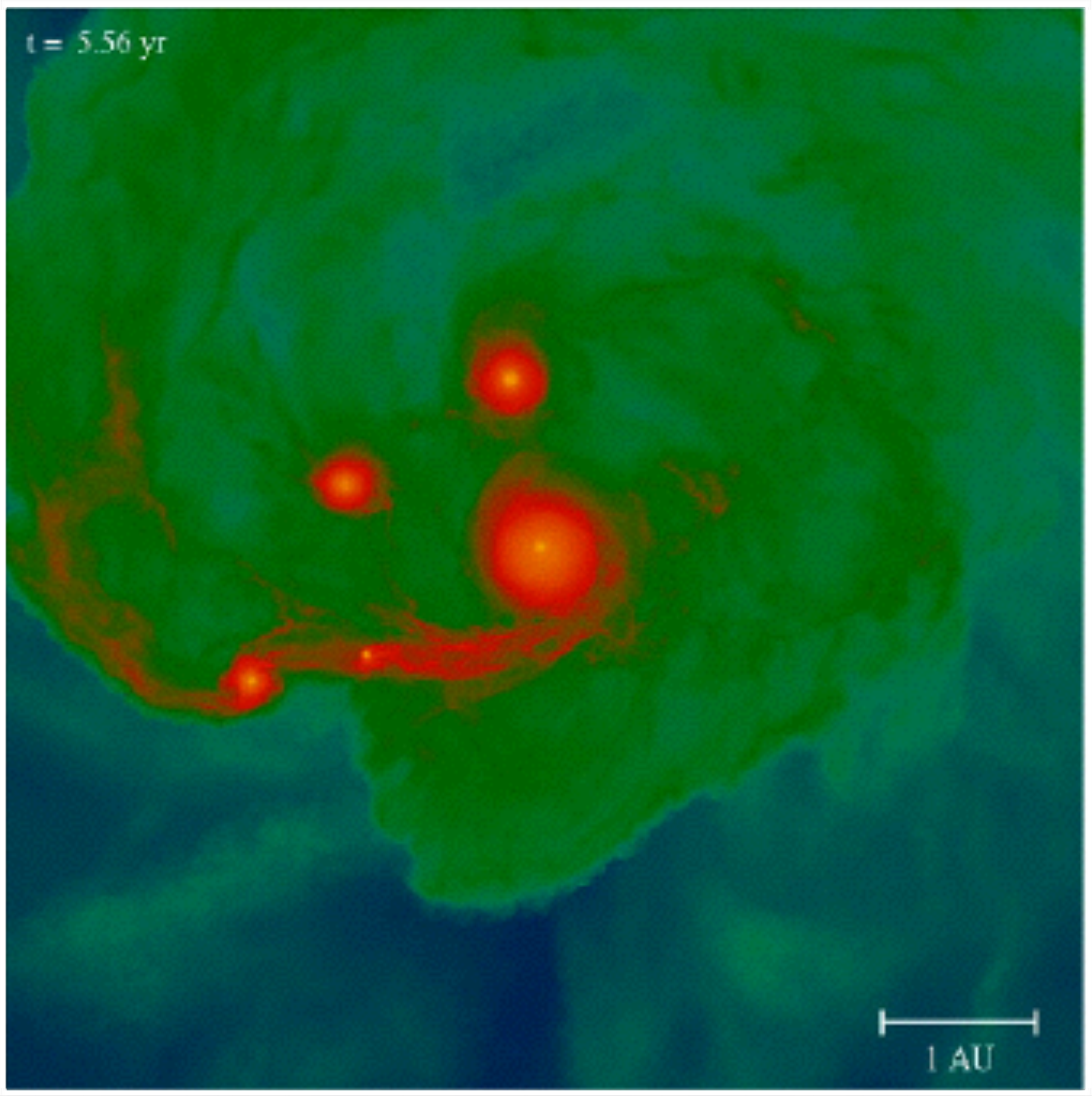
The formation of these first stars occurred at redshifts $z \sim 20 - 30$. These stars are predicted to form in dark matter minihalos, comprising total masses of $\sim 10^6\, M_\odot$. Current models suggest that Pop III stars were typically massive, or even very massive, with $M_* \sim 10 - 100\, M_\odot$; these models also predict that the first stars formed in small groups, including binaries or higher-order multiples.

Nomenclature

- Pop III.1
  - Gas of primordial composition
  - Initial conditions purely cosmological
- Pop III.2
  - Gas of primordial composition
  - Initial conditions modified by radiative or kinetic feedback of Pop III.1 stars, but not chemical feedback
- Pop II
  - Stars formed from metal enriched gas
  - $Z>Z_{crit}\sim10\text{-}3.5Z_{\odot}$ (Bromm& Loeb 2005; Smith et al. 2008, 2009)

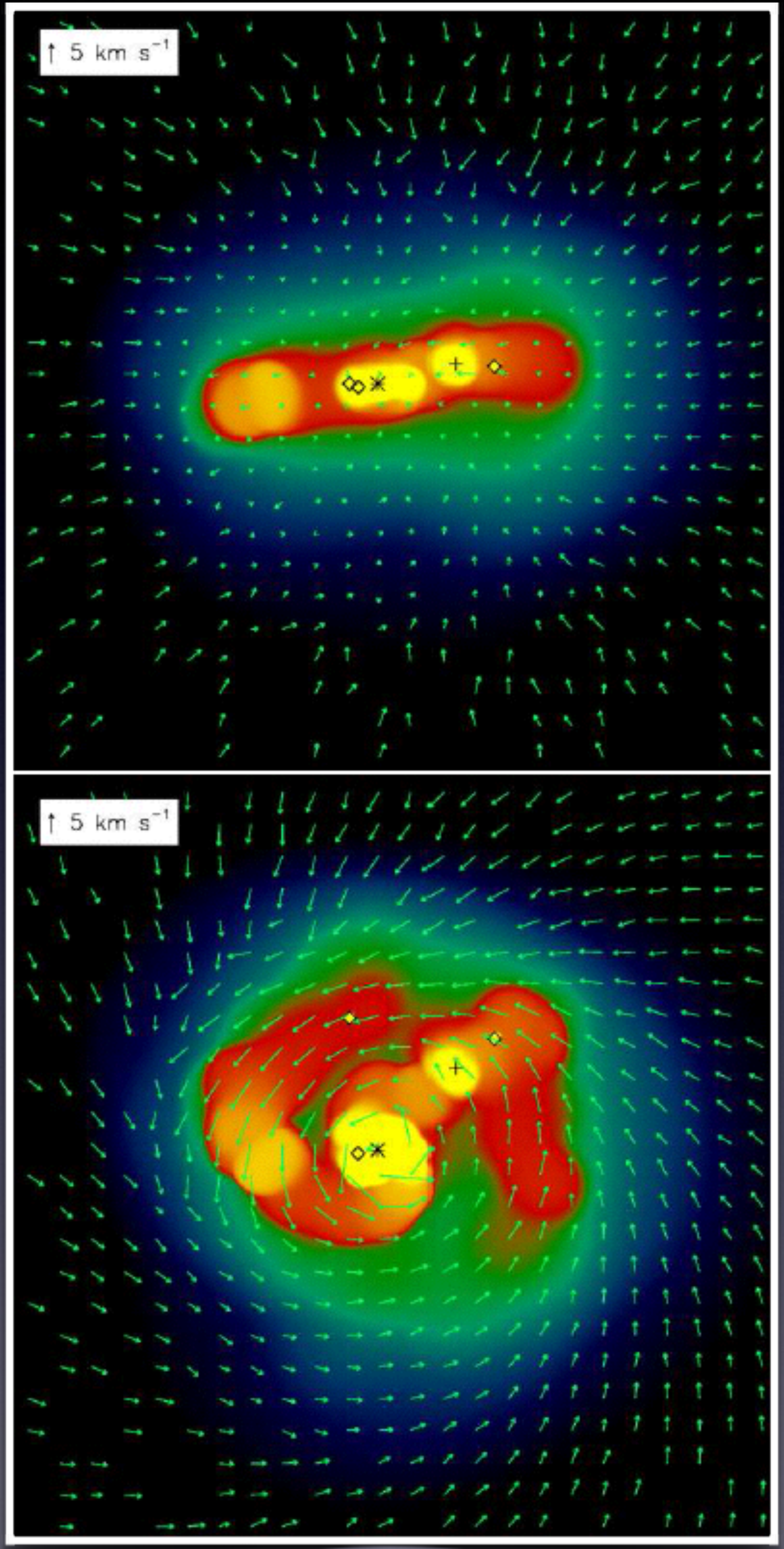
Using abundances of 53 extremely metal-poor stars, Fraser et al. (2017) inferred the masses of their Population III progenitors. They found that the mass distribution is well-represented by a power law IMF with exponent $2.35^{+0.29}_{-0.24}$ (close to Salpeter's). The inferred maximum progenitor mass for supernovae from massive Population III stars is $M_{max} = 87^{+13}_{-33}\ M_\odot$, with no evidence in for a contribution from stars with masses above $120\ M_\odot$.

$$\frac{dN}{dM} \propto M^{-x} ,$$



Simulation of the formation and fragmentation of a Pop III protostellar disk (Greif et al. 2012)

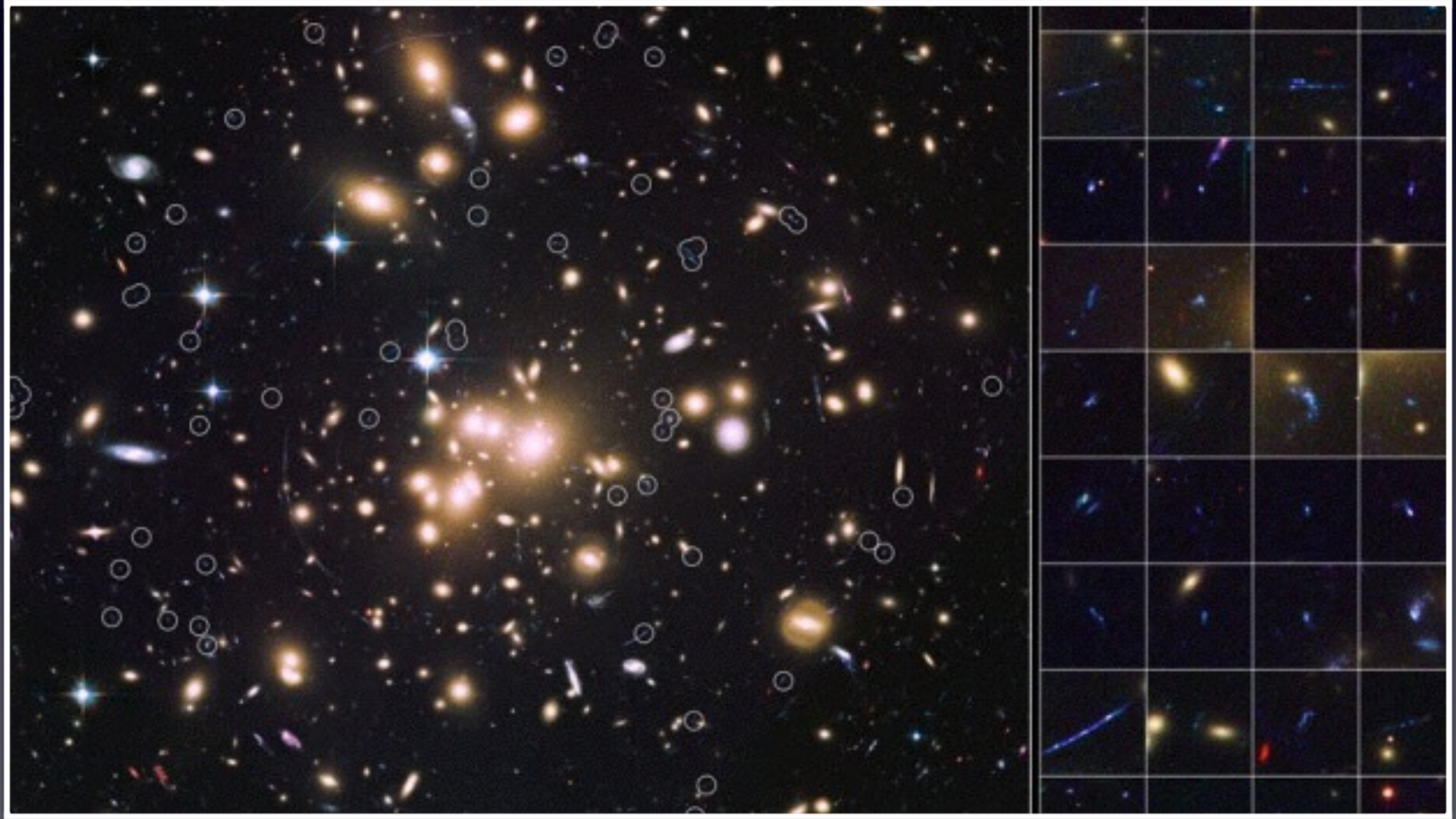
Binary and multiple systems formed (Stacy et al. 2009)



Most Pop III should be in binary systems

GW detections by LIGO from black hole mergers with holes of masses in the range 30-60 $M_\odot$ support the idea that Pop III stars had masses not beyond 100 $M_\odot$ and formed binaries.

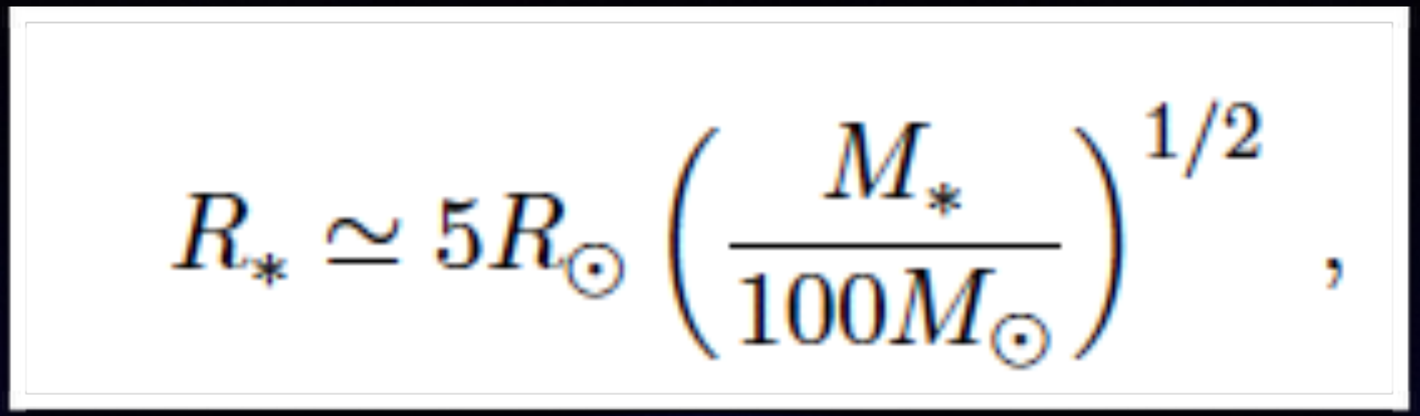
The first quasars, on the other hand, are predicted to have formed later on, at $z \sim 10$, in more massive dark matter halos, with total masses, $\sim 10^8\,M_\odot$, characteristic of dwarf galaxies.



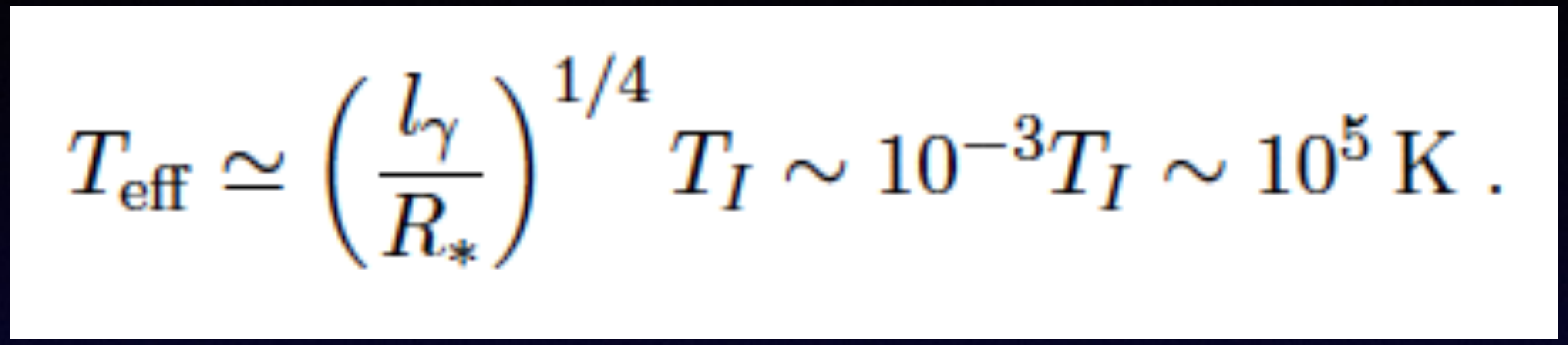
LIGHTING UP THE COSMOS

In the beginning of the Dark Ages, electrically neutral hydrogen gas filled the universe. As stars formed, they ionized the regions immediately around them, creating bubbles here and there. Eventually these bubbles merged together, and intergalactic gas became entirely ionized.

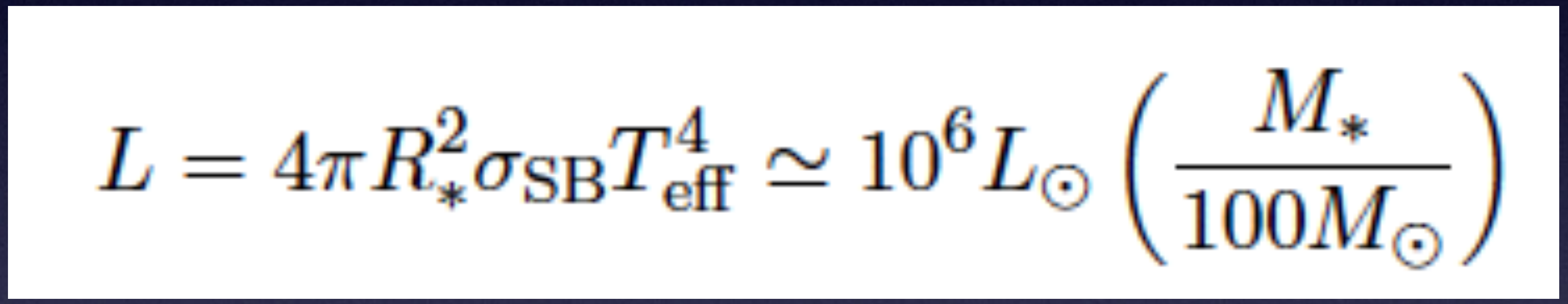
Typical properties of Pop III stars



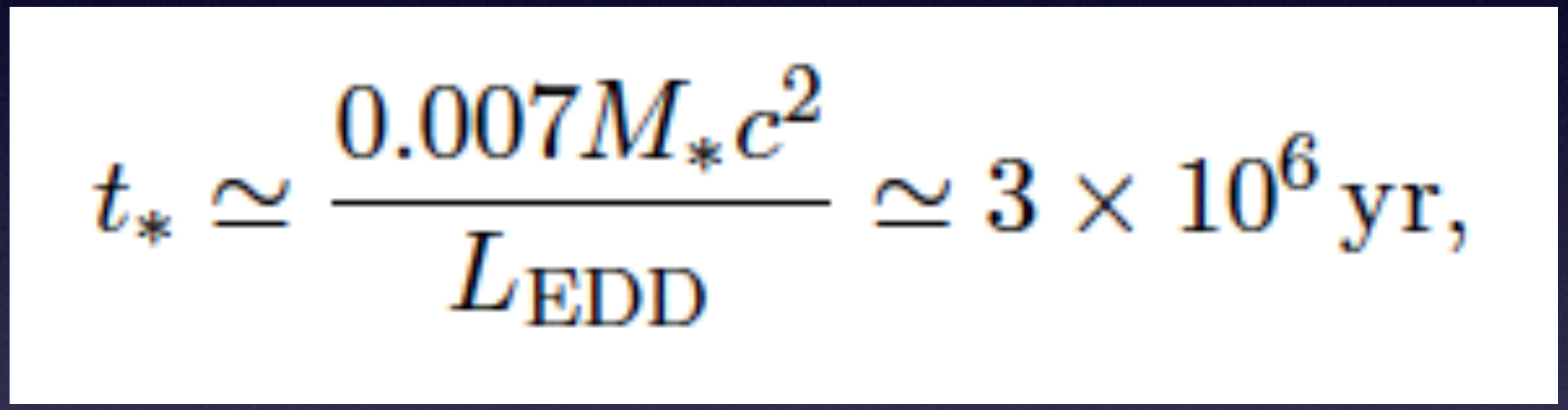
$$R_* \simeq 5R_\odot \left(\frac{M_*}{100M_\odot}\right)^{1/2} ,$$



$$T_{\rm eff} \simeq \left(\frac{l_\gamma}{R_*}\right)^{1/4} T_I \sim 10^{-3} T_I \sim 10^5\,{\rm K}\,.$$



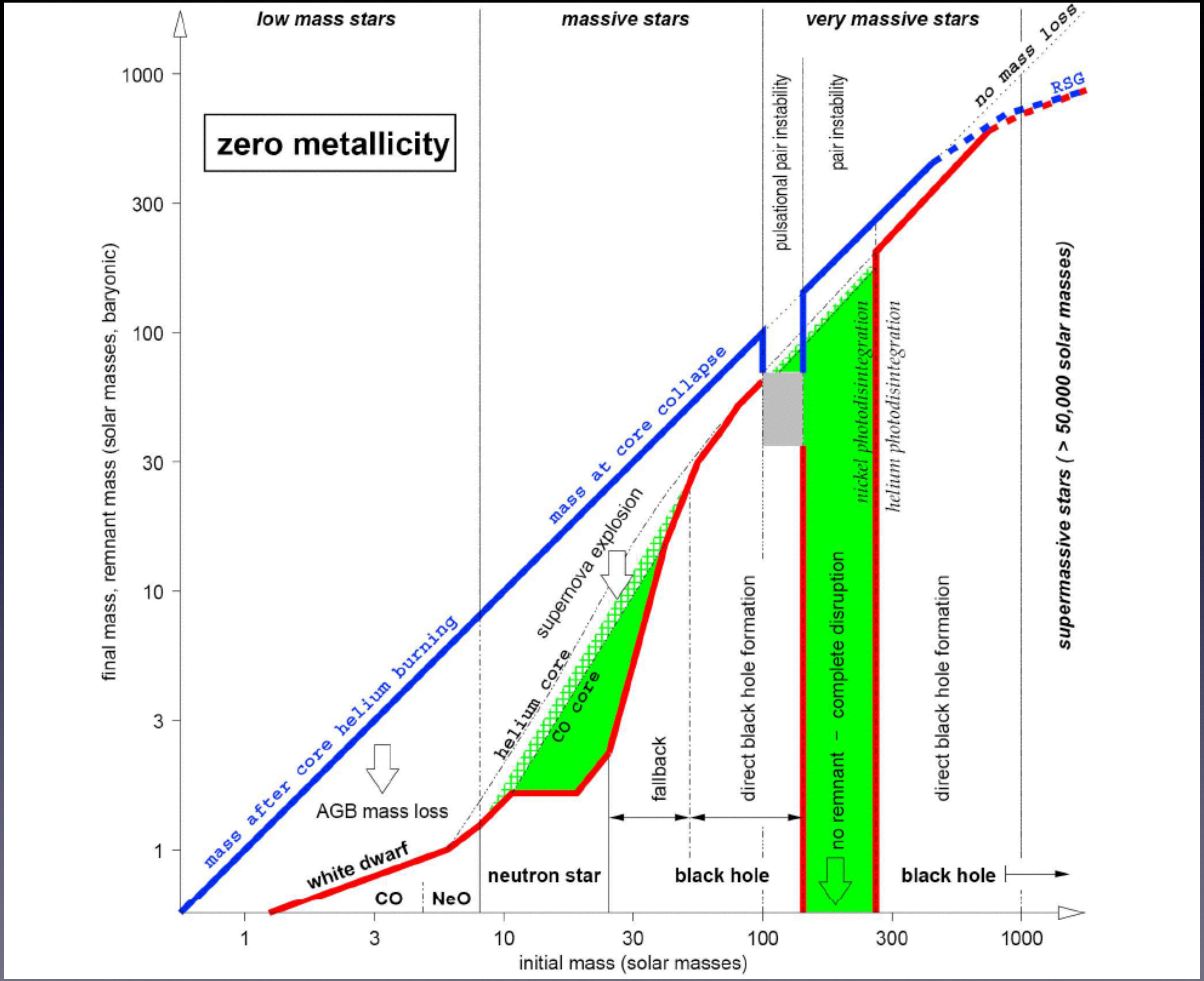
$$L = 4\pi R_*^2 \sigma_{\rm SB} T_{\rm eff}^4 \simeq 10^6 L_\odot \left(\frac{M_*}{100M_\odot}\right)$$



$$t_* \simeq \frac{0.007 M_* c^2}{L_{\rm EDD}} \simeq 3 \times 10^6\,{\rm yr},$$

No metals, no winds

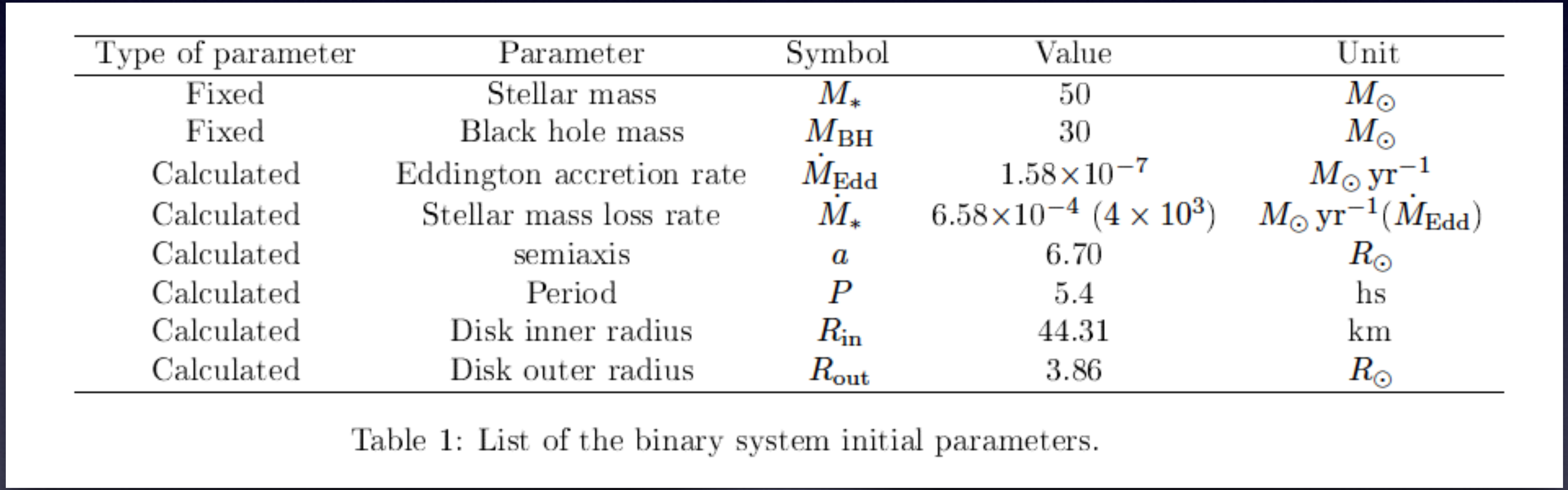
Fate of Pop III stars



Binary systems

Paczynski (1971)

$$\frac{R_*}{a} = 0.38 + 0.2 \log\left(\frac{M_*}{M_{\rm BH}}\right) \qquad \text{para } 0.3 < \frac{M_*}{M_{\rm BH}} < 20.$$



Type of parameter	Parameter	Symbol	Value	Unit
Fixed	Stellar mass	M_*	50	$M_\odot$
Fixed	Black hole mass	$M_{\rm BH}$	30	$M_\odot$
Calculated	Eddington accretion rate	$\dot{M}_{\rm Edd}$	1.58×10^{-7}	$M_\odot\,{\rm yr}^{-1}$
Calculated	Stellar mass loss rate	$\dot{M}_*$	6.58×10^{-4} (4×10^{3})	$M_\odot\,{\rm yr}^{-1}(\dot{M}_{\rm Edd})$
Calculated	semiaxis	a	6.70	$R_\odot$
Calculated	Period	P	5.4	hs
Calculated	Disk inner radius	$R_{\rm in}$	44.31	km
Calculated	Disk outer radius	$R_{\rm out}$	3.86	$R_\odot$

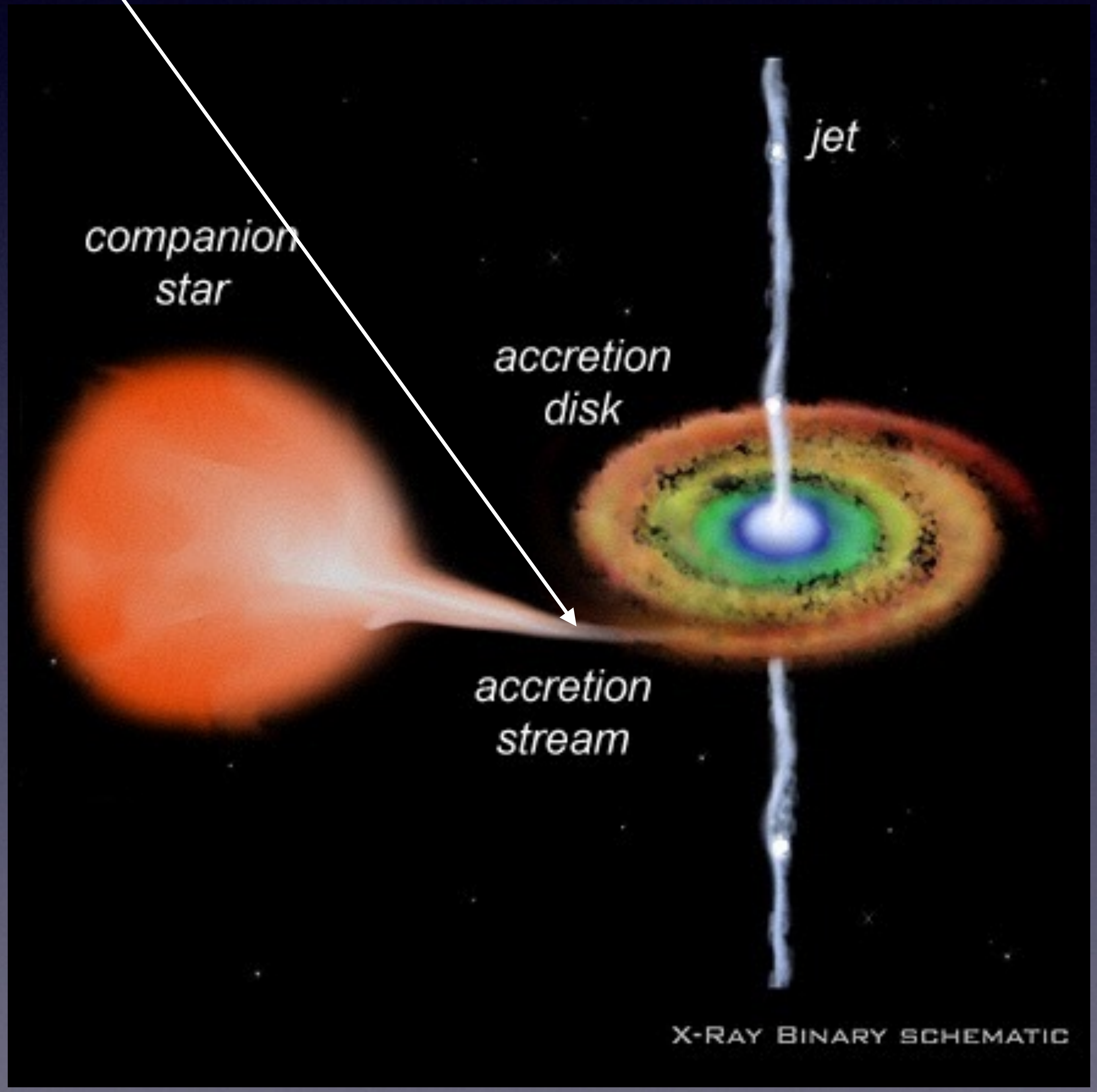
Table 1: List of the binary system initial parameters.

$$\dot{M}_* = 6.58\times10^{-4}\ (4\times10^{3}) \quad M_\odot\,{\rm yr}^{-1}(\dot{M}_{\rm Edd})$$

Pop III accreting binaries were extremely super-Eddington

Mass transfer in this binaries must occur through overflow of the Roche lobe

dM_{input}/dt

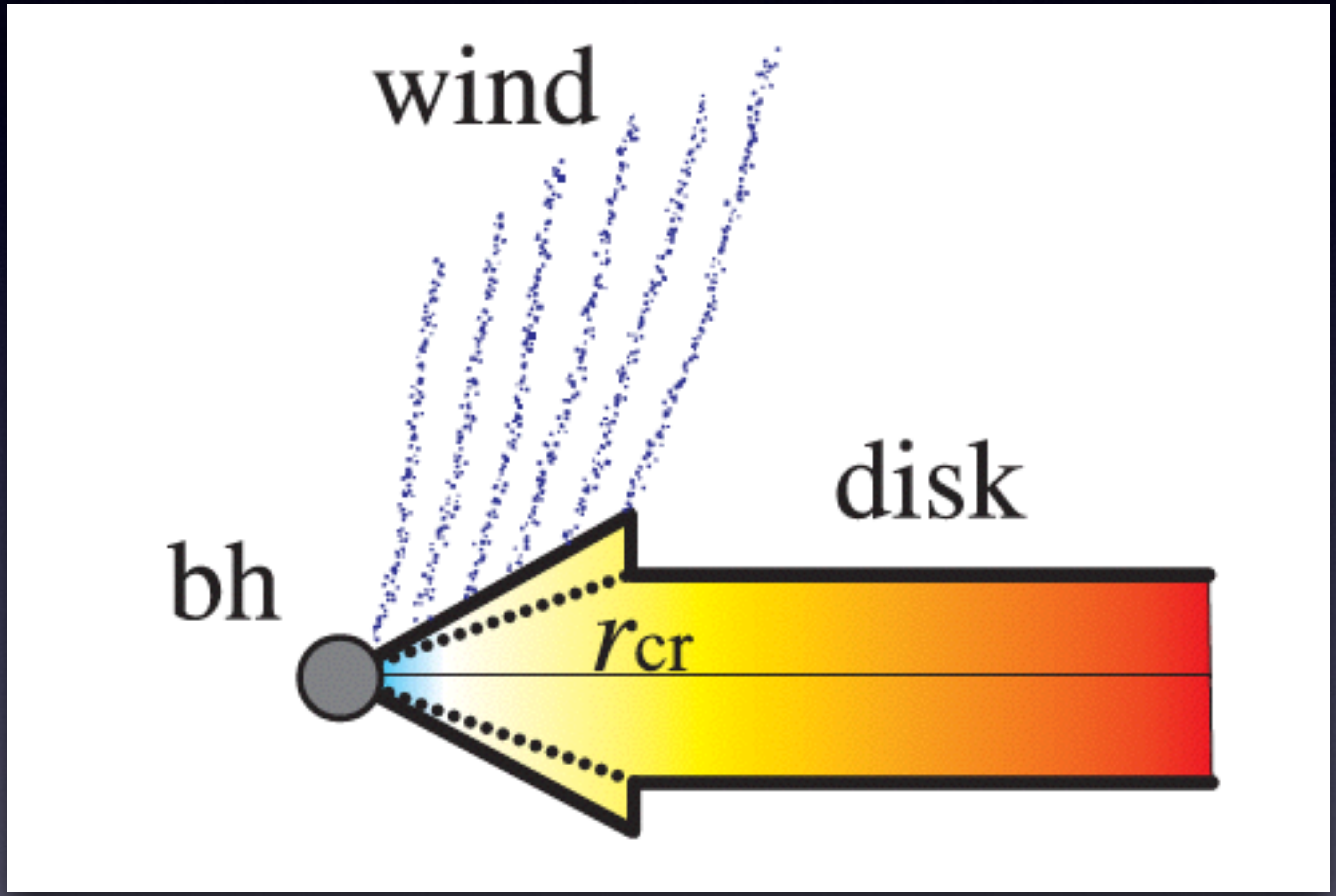


Hypercritical accretion

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

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

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



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

$$Q_{\rm adv} = Q_{\rm vis} - Q_{\rm rad} = f\, Q_{\rm vis}$$

$$v_r(r) = -c_1 \alpha v_{\rm K}(r),$$

$$v_\varphi(r) = c_2 v_{\rm K}(r),$$

$$c_s^2(r) = c_3 v_{\rm K}^2(r),$$

$$c_{\rm A}^2(r) = \frac{B_\varphi^2}{4\pi\rho} = 2\beta c_3 v_{\rm K}^2(r)$$

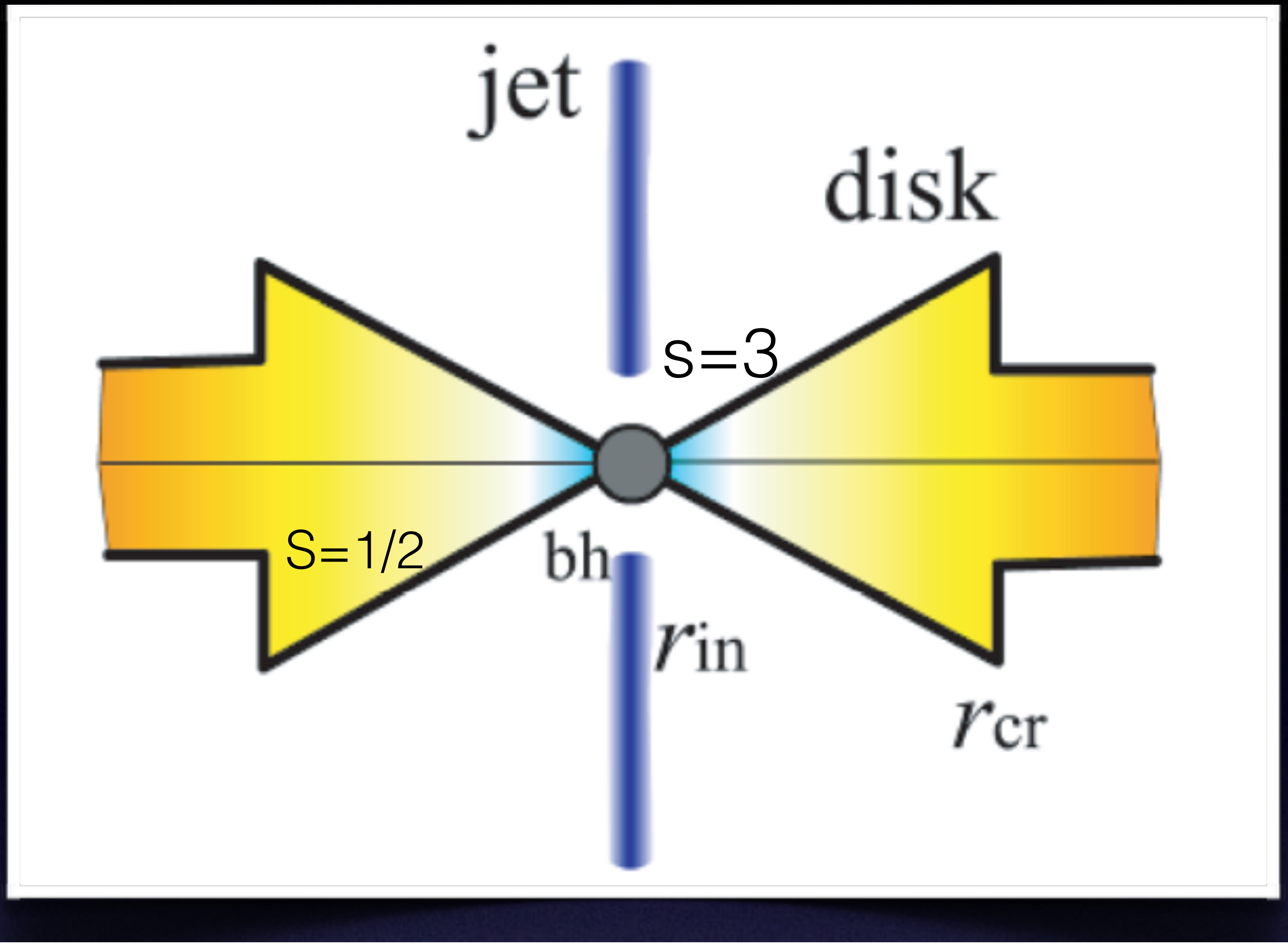
$$\Sigma(r) = \Sigma_0 r^s, \qquad \Sigma_0 = \frac{\dot{M}_{\rm input}}{2\pi\sqrt{GM}\, c_1 \alpha r_{\rm out}^{s+1/2}}.$$

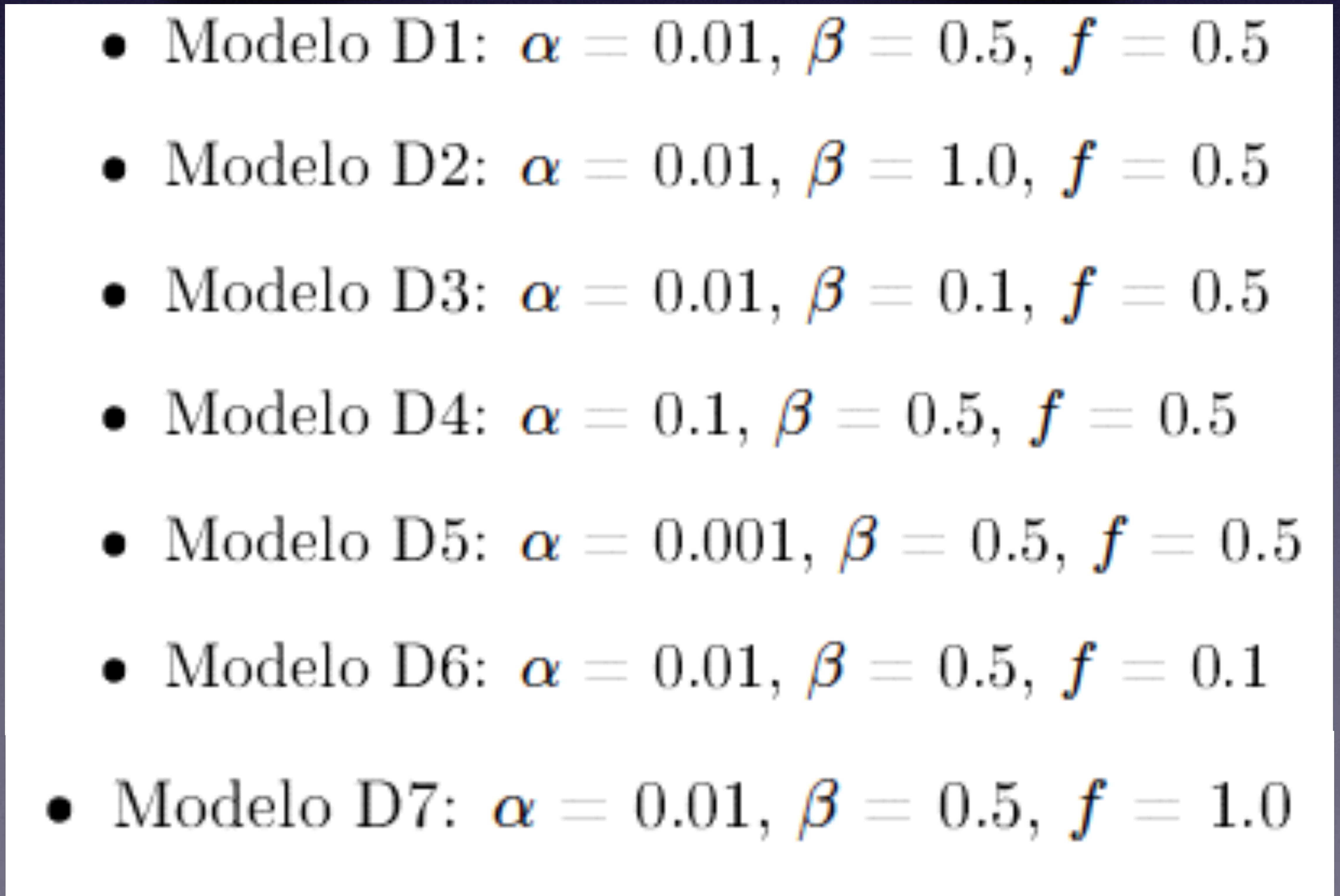
$$\dot{\rho}(r) = \dot{\rho}_0 r^{s-5/2}, \qquad \dot{\rho}_0 = -\left(s+\frac{1}{2}\right)\frac{c_1\alpha\Sigma_0}{2}\sqrt{\frac{GM}{(1+\beta)\, c_3}}$$

$$\dot{B}_\varphi(r) = \dot{B}_0 r^{(s-5)/2}, \qquad \dot{B}_0 = \frac{3-s}{2} c_1 \alpha GM \sqrt{4\pi\Sigma_0 \frac{\beta c_3}{(1+\beta)\, c_3}}$$

$$\dot{M} = -2\pi r \Sigma v_r = \dot{M}_{\rm input}\left(\frac{r}{r_{\rm out}}\right)^{s+1/2},$$

$$\beta = \frac{B^2/8\pi}{P_{\rm gas}}$$



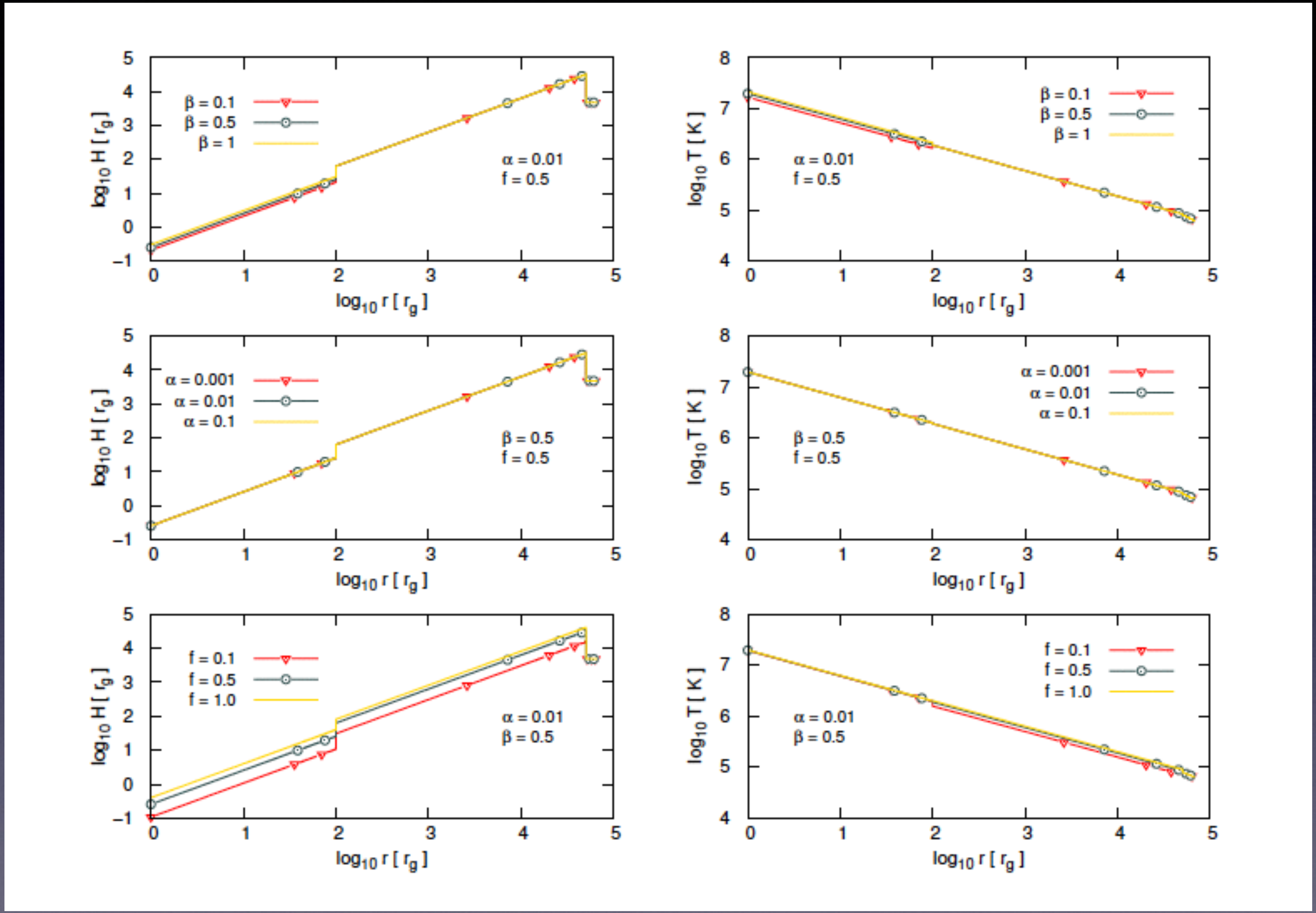


- Modelo D1: $\alpha = 0.01$, $\beta = 0.5$, $f = 0.5$
- Modelo D2: $\alpha = 0.01$, $\beta = 1.0$, $f = 0.5$
- Modelo D3: $\alpha = 0.01$, $\beta = 0.1$, $f = 0.5$
- Modelo D4: $\alpha = 0.1$, $\beta = 0.5$, $f = 0.5$
- Modelo D5: $\alpha = 0.001$, $\beta = 0.5$, $f = 0.5$
- Modelo D6: $\alpha = 0.01$, $\beta = 0.5$, $f = 0.1$
- Modelo D7: $\alpha = 0.01$, $\beta = 0.5$, $f = 1.0$

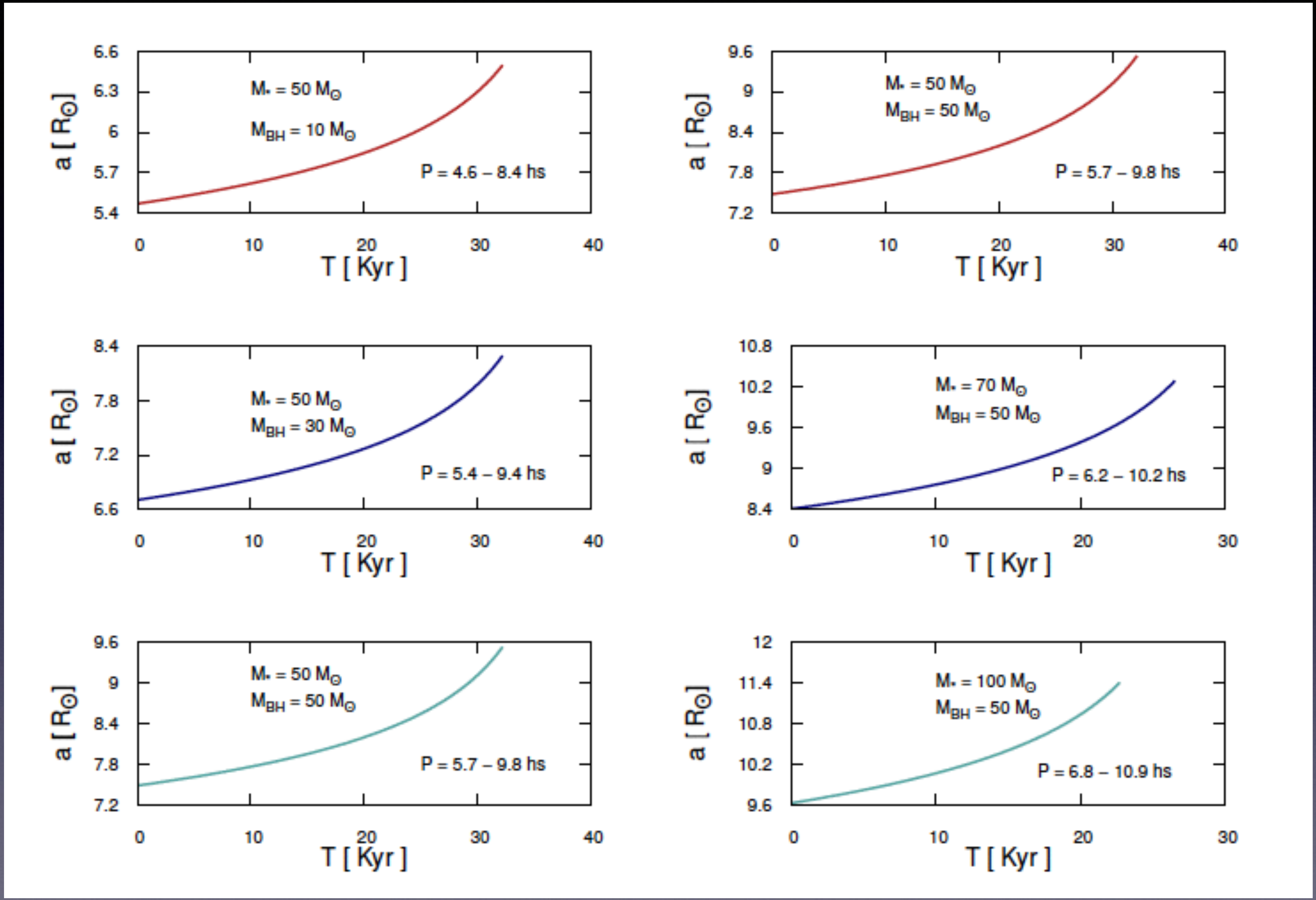
$$H = \begin{cases} \frac{3\kappa f_{\rm in}}{32\pi c}\dot{M}_{\rm out} & \text{for } r \geq r_{cr} \\ \sqrt{c_3}r & \text{for } 100\, r_{\rm g} \leq r \leq r_{cr} \\ \sqrt{(1+\beta)\, c_3'}r & \text{for } r \leq 100\, r_{\rm g} \end{cases}$$

$$\sigma T_{\rm eff}^4 = \begin{cases} \frac{3GM\dot{M}_{\rm input}}{8\pi r^3} f_{\rm in} & \text{for } r \geq r_{cr} \\ \frac{3}{4}\sqrt{c_3}\frac{L_{\rm Edd}}{4\pi r^2} & \text{for } 100\, r_{\rm g} \leq r \leq r_{cr} \\ \frac{3}{4}\sqrt{\frac{c_3'}{1+\beta}}\frac{L_{\rm Edd}}{4\pi r^2} & \text{for } r \leq 100\, r_{\rm g} \end{cases}$$

$$f_{\rm in} = 1 - \sqrt{r_{in}/r}.$$



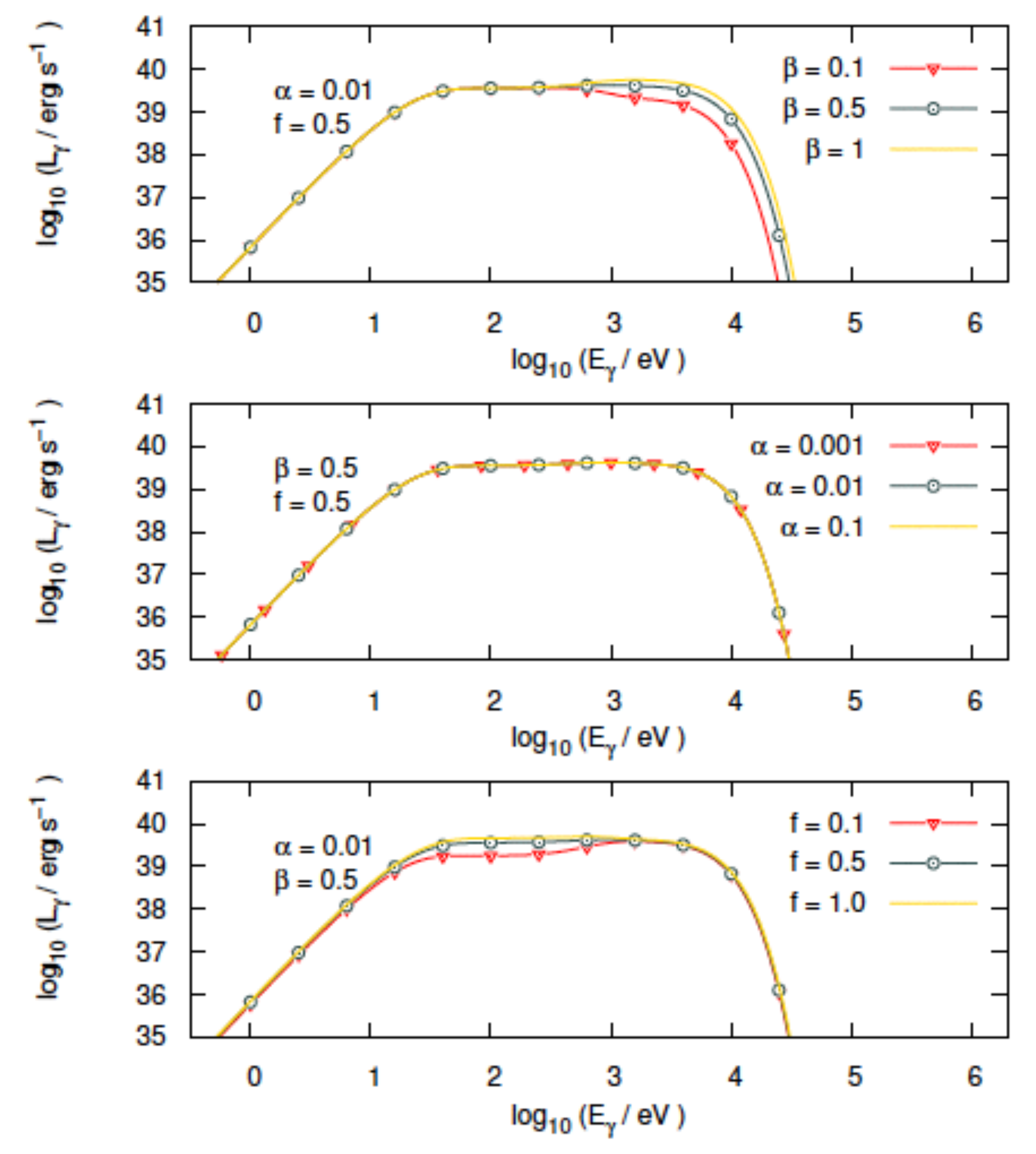
$$T_{eff} \propto r^{-1/2}$$



Evolution of the semi-major axis for several binary system models.
In each case we indicate the orbital period.

Spectral energy distribution of the accretion disk for differents accretion disk models.

t=16 kyr



A jet is magnetically launched from the innermost region (~100 r_g)

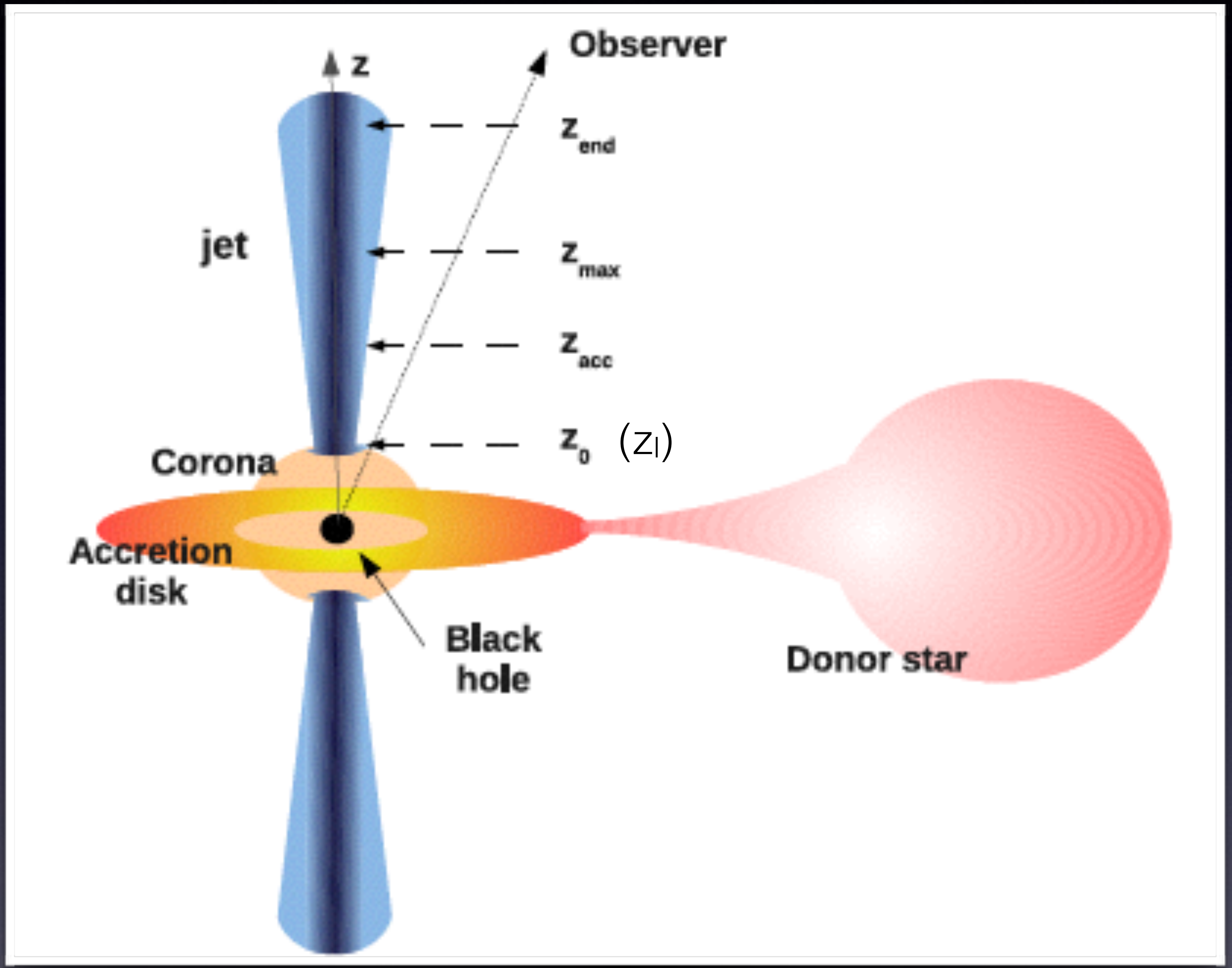
$$L_{\rm jet}(r_{\rm l}) = L_{\rm acc} - L_{\rm disk} - L_{\rm in} - L_{\rm wind},$$

$$L_{\rm jet} = \frac{G M_{\rm BH} 2\dot{m}_{\rm jet}}{r_{\rm l}} + (\Gamma_{\rm jet} - 1)\, 2\dot{m}_{\rm jet} c^2,$$

$$\frac{B^2(z_{\rm l})}{8\pi} = \frac{L_{\rm jet}}{2\pi r_{\rm l} v_{\rm jet}},$$

$$B(z) = B(z_{\rm l}) \left(\frac{z_{\rm l}}{z}\right),$$

$$e_{\rm p}(z) = \frac{\dot{m}_{\rm jet}}{2\pi z^2} v_{\rm jet}.$$



DSA works in a region from z_{acc} to z_{max}. Particles cool completely at z_{end}. From there on the jet is dark.

Radiative processes in the microquasar jet

(Romero et al. 2003; Aharonian et al. 2006; Romero & Vila, 2008, 2009; Vila & Romero 2010)

Interaction of relativistic *p* and e$^-$ with

magnetic field

matter

radiation fields

in the jet

- Synchrotron radiation $p,\ e^- + B \rightarrow p,\ e^- + \gamma$
- Relativistic Bremsstrahlung $e^- + p \rightarrow e^- + p + \gamma$
- Inverse Compton (IC) $e^- + \gamma \rightarrow e^- + \gamma$

- Proton-proton inelastic collisions $p + p \rightarrow p + p + a\,\pi^o + b(\pi^+ + \pi^-)$
- Photohadronic interactions ($p\gamma$)

$$p + \gamma \rightarrow p + e^+ + e^-$$

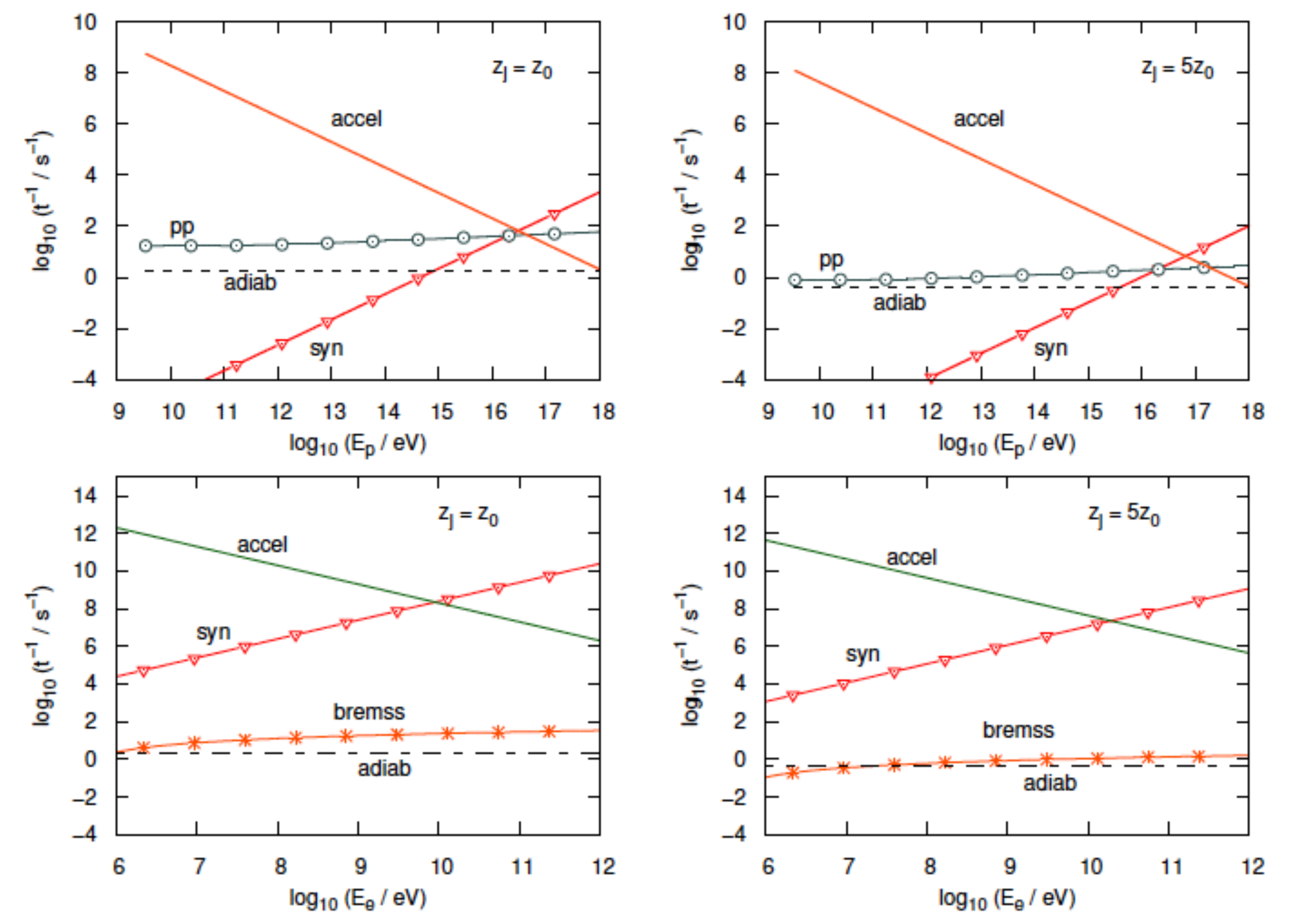
$$p + \gamma \rightarrow p + a\pi^o + b(\pi^+ + \pi^-)$$

$$\pi^o \rightarrow 2\gamma$$

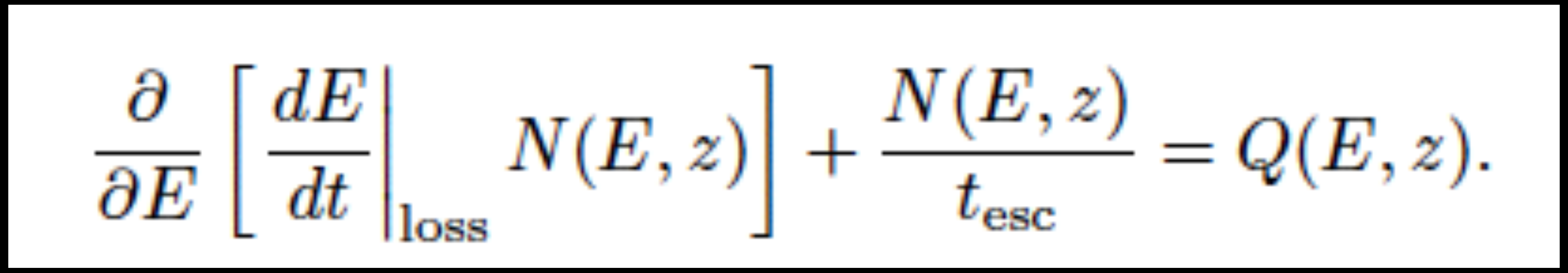
$$\pi^\pm \rightarrow \mu^\pm + \nu_\mu \left(\overline{\nu}_\mu\right) \qquad \mu^\pm \rightarrow e^\pm + \nu_e \left(\overline{\nu}_e\right) + \overline{\nu}_\mu \left(\nu_\mu\right)$$

$$e^\pm + B \rightarrow e^\pm + \gamma$$

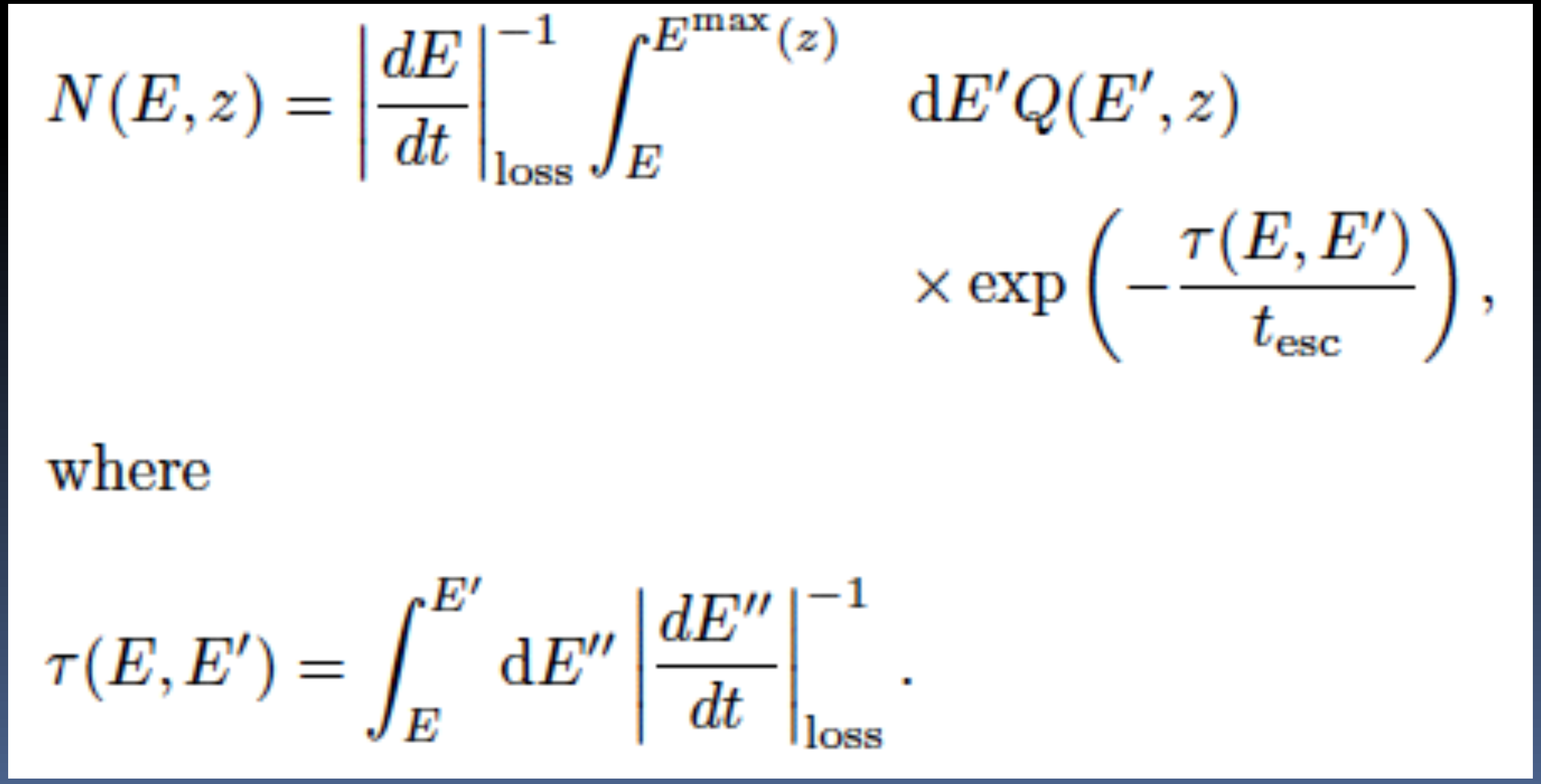
Losses (efficient acceleration of 0.1)



The steady state particle distributions N (E, z) are calculated in the “one-zone” approximation (Khangulyan et al. 2007). This approximation is valid if the losses are very strong in the acceleration region and diffusion can be neglected. Then the transport equation (Ginzburg & Syrovatskii 1964) can be written as



$$\frac{\partial}{\partial E}\left[\left.\frac{dE}{dt}\right|_{\rm loss} N(E,z)\right] + \frac{N(E,z)}{t_{\rm esc}} = Q(E,z).$$

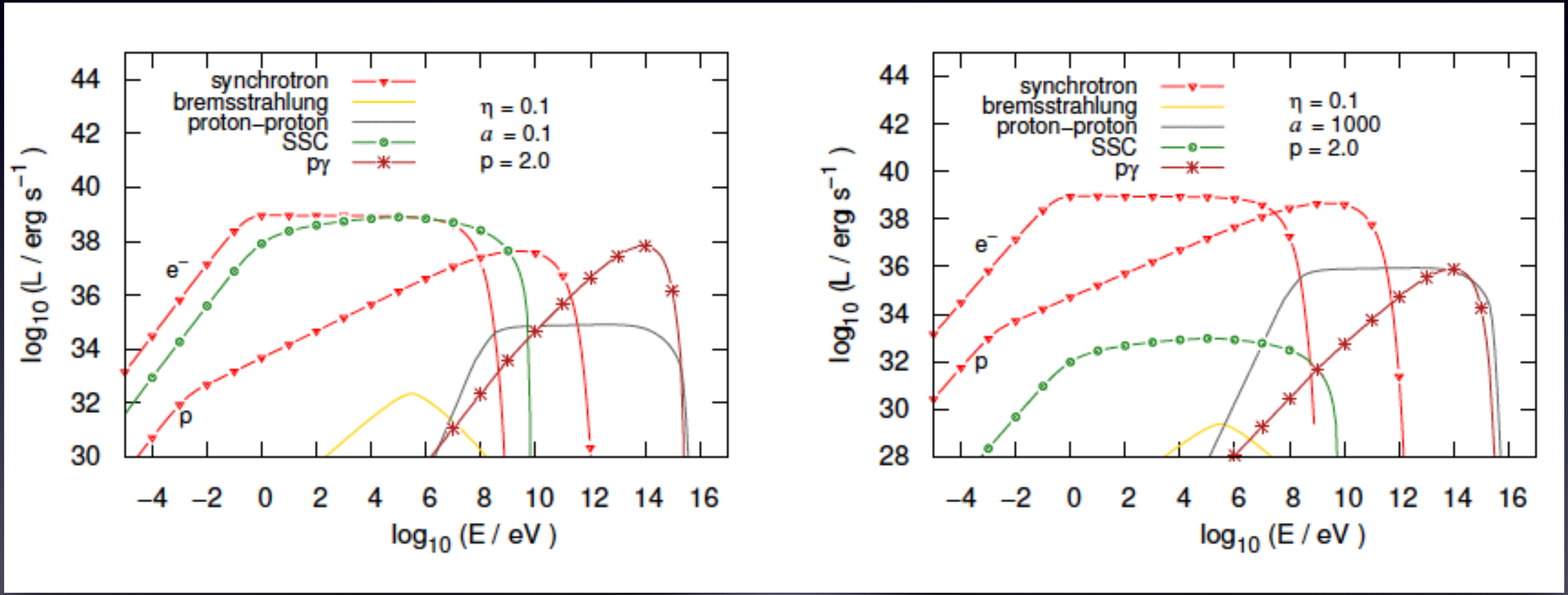


$$N(E,z) = \left|\frac{dE}{dt}\right|_{\rm loss}^{-1} \int_{E}^{E^{\rm max}(z)} \quad {\rm d}E' Q(E',z) \times \exp\left(-\frac{\tau(E,E')}{t_{\rm esc}}\right),$$

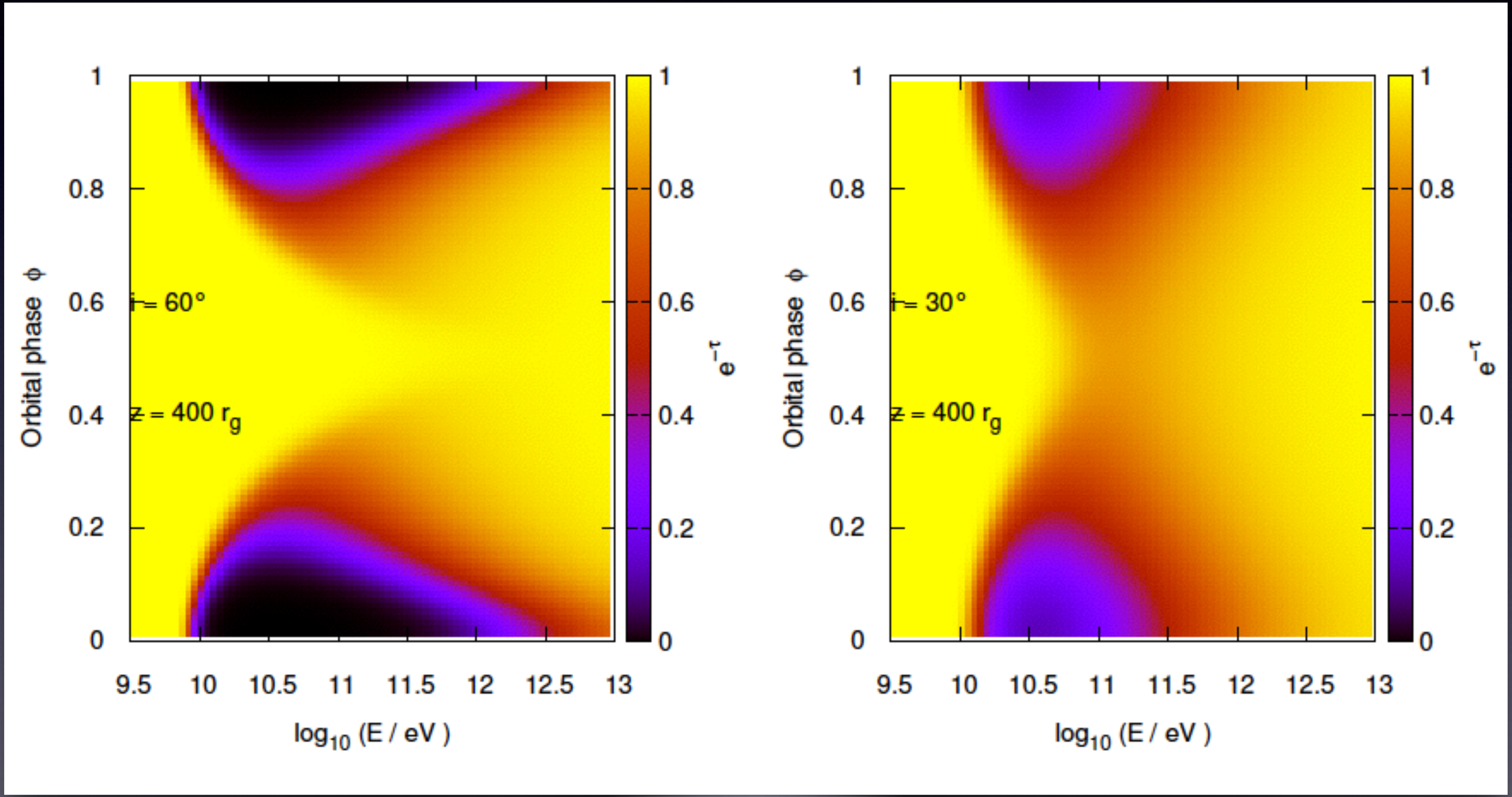
where

$$\tau(E,E') = \int_{E}^{E'} {\rm d}E'' \left|\frac{dE''}{dt}\right|_{\rm loss}^{-1}.$$

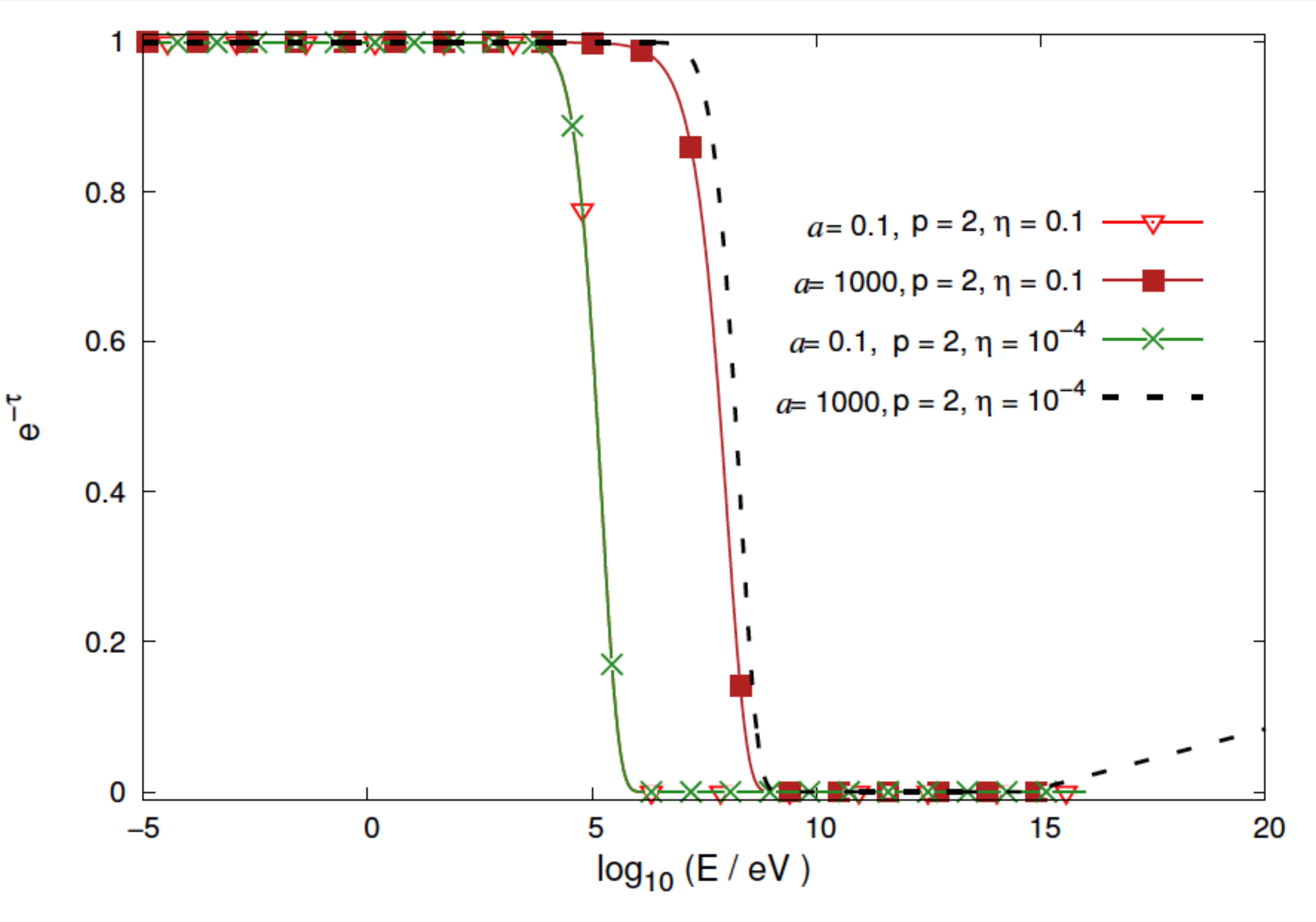
SEDs t=16 kyr a=L_p/L_e



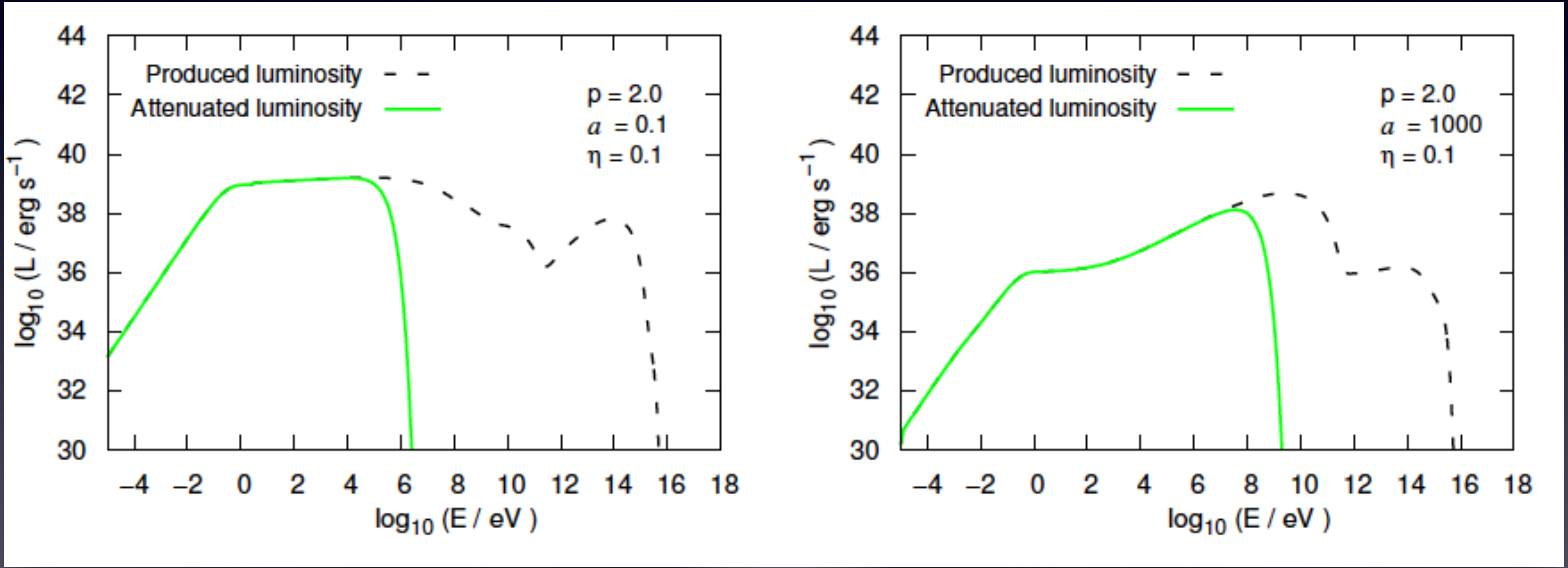
Opacity maps



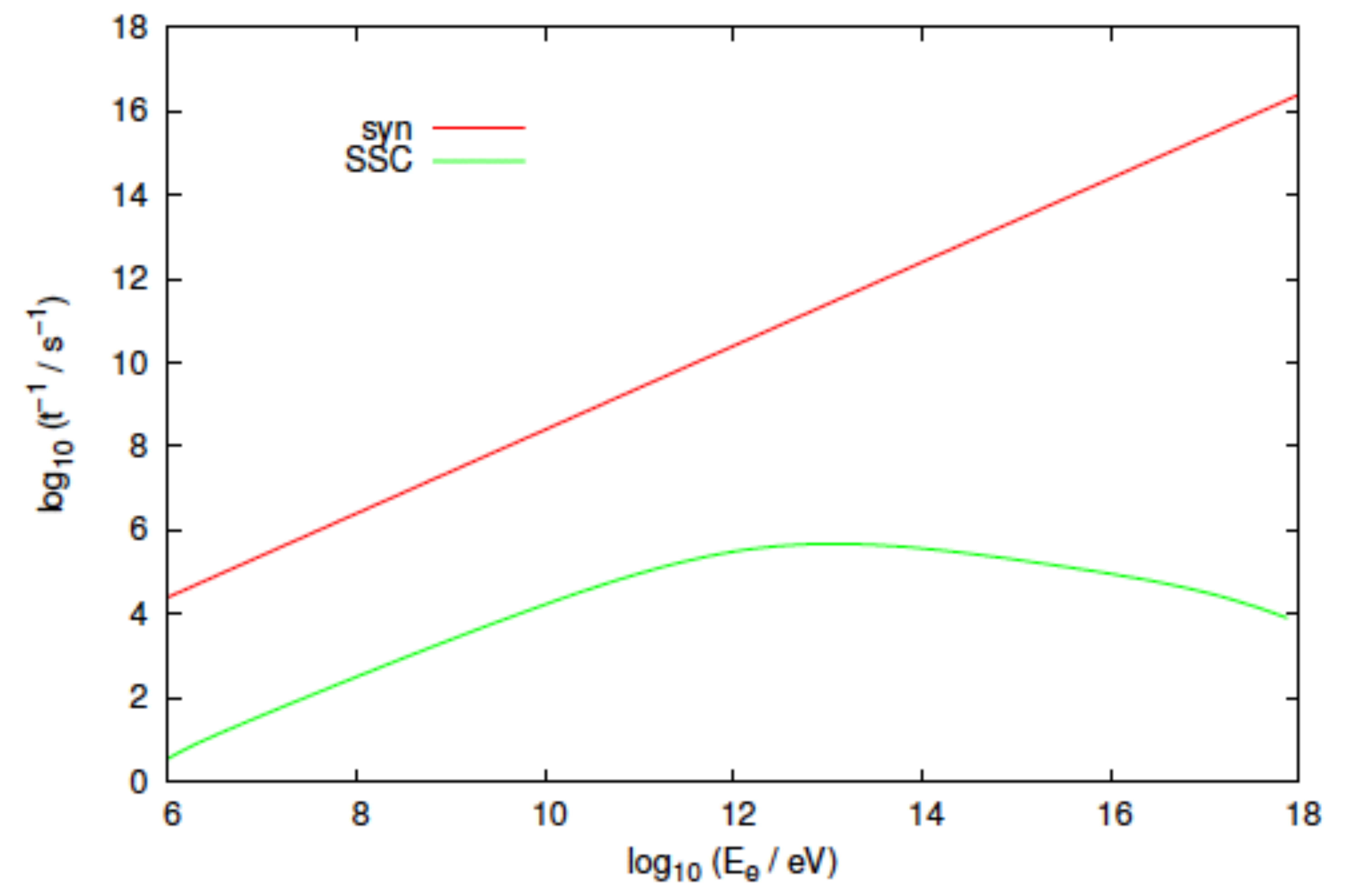
Internal absorption



SEDs, corrected by absorption



Cooling rates for secondary pairs

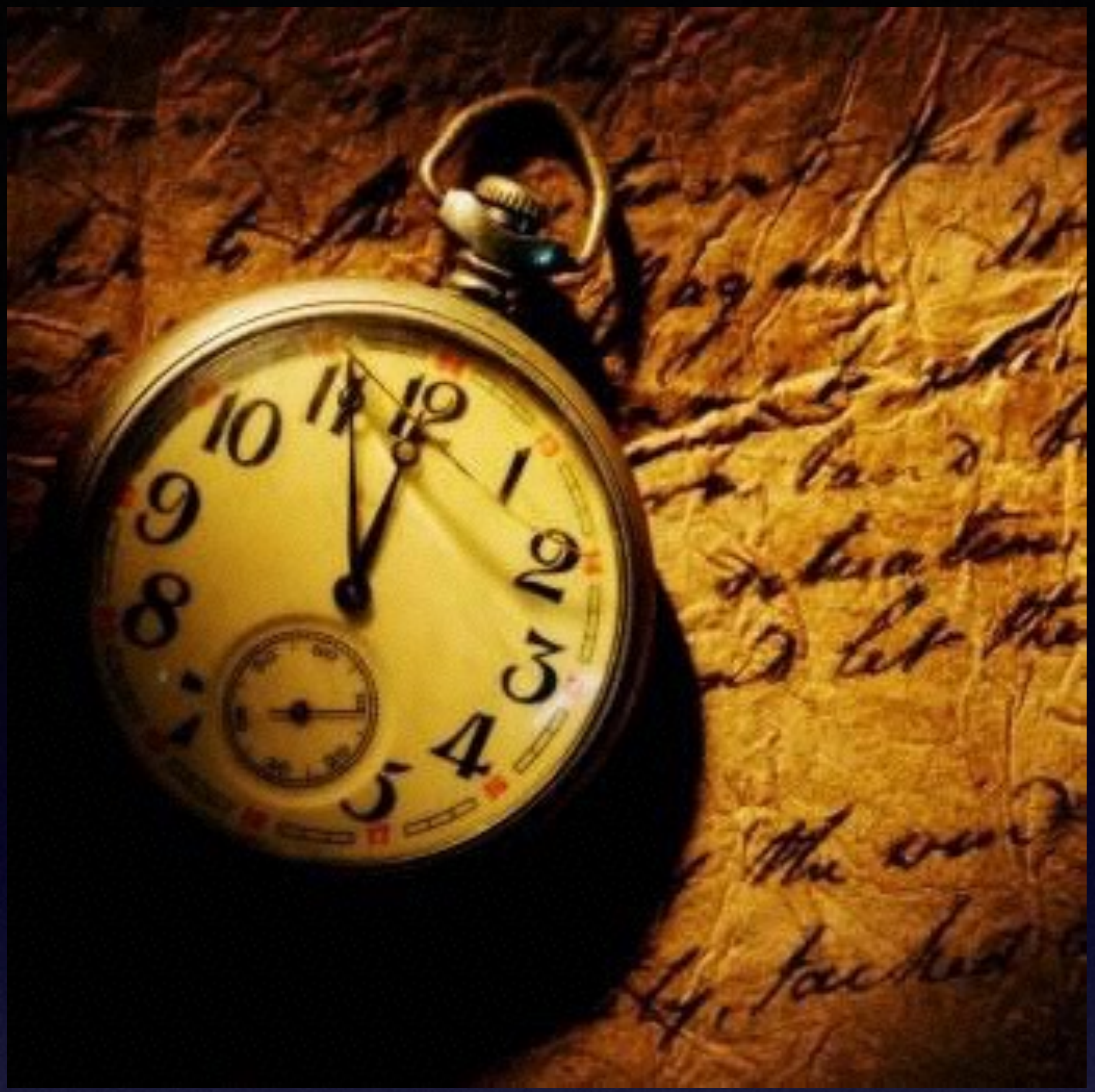


No cascades. Dark jets as in SS433

Conclusions

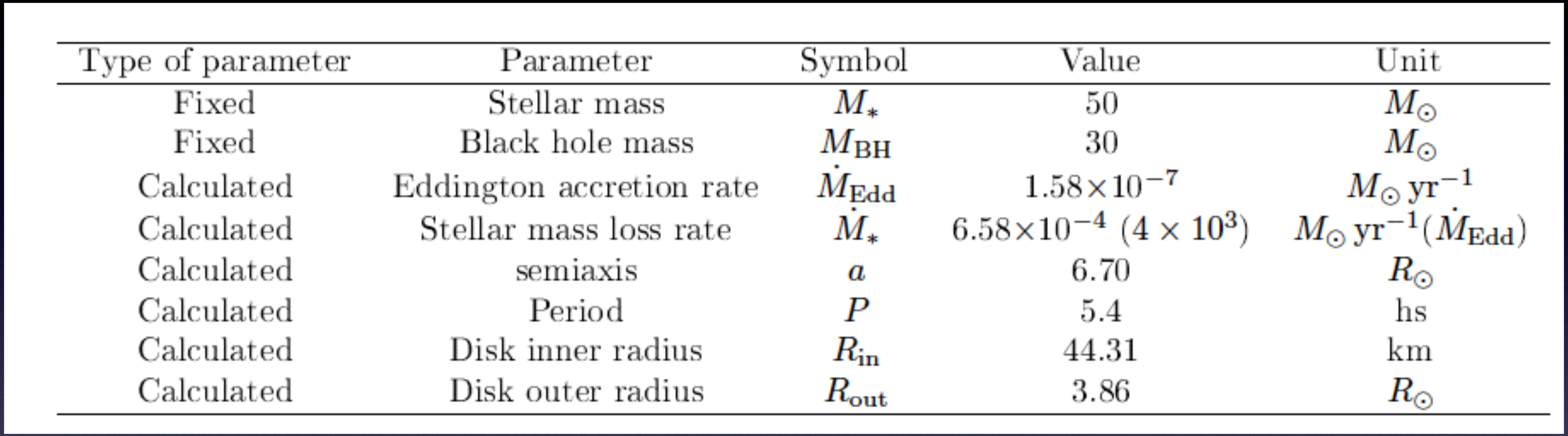
- Pop III MQs are hyper accreting sources with strong radiative winds ejected from the disks.
- The typical power of their jets is about ~ 10^{41} erg/s.
- Bulk velocities are jet. $\Gamma_{\mathrm{jet}} \sim 2$
- Electrons and protons in the jets can reach energies of about 10 GeV and 10 PeV, respectively.
- Absorption and pair production is important. The jets inject low energy pairs in the IGM, far away from the source.
- Total ionising power very significant: Pop III MQs might have been important in the re-ionisation of the universe, especially the inter bubble medium.

More on cosmological effects and reionization soon…



Thanks!

List of the binary system initial parameters.



Type of parameter	Parameter	Symbol	Value	Unit
Fixed	Stellar mass	M_*	50	$M_\odot$
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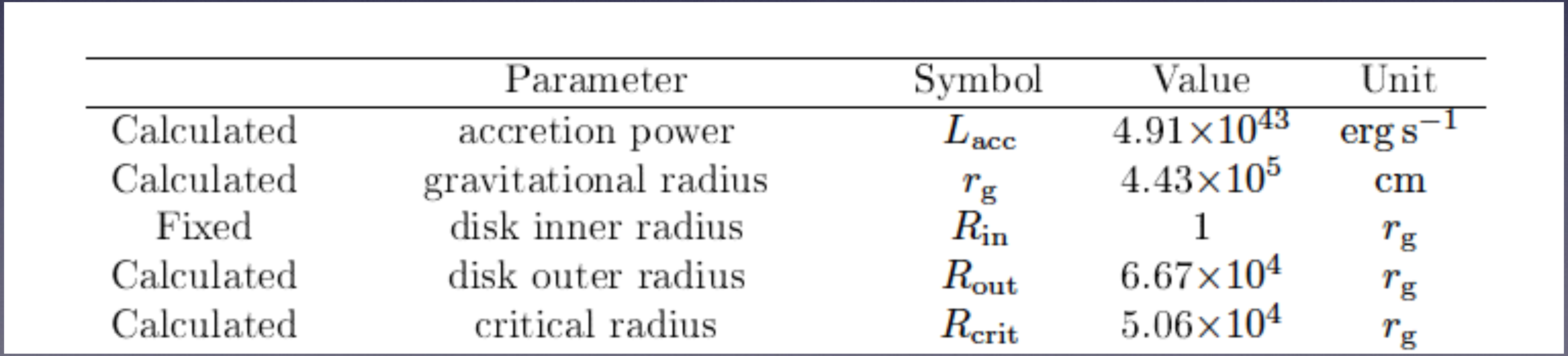
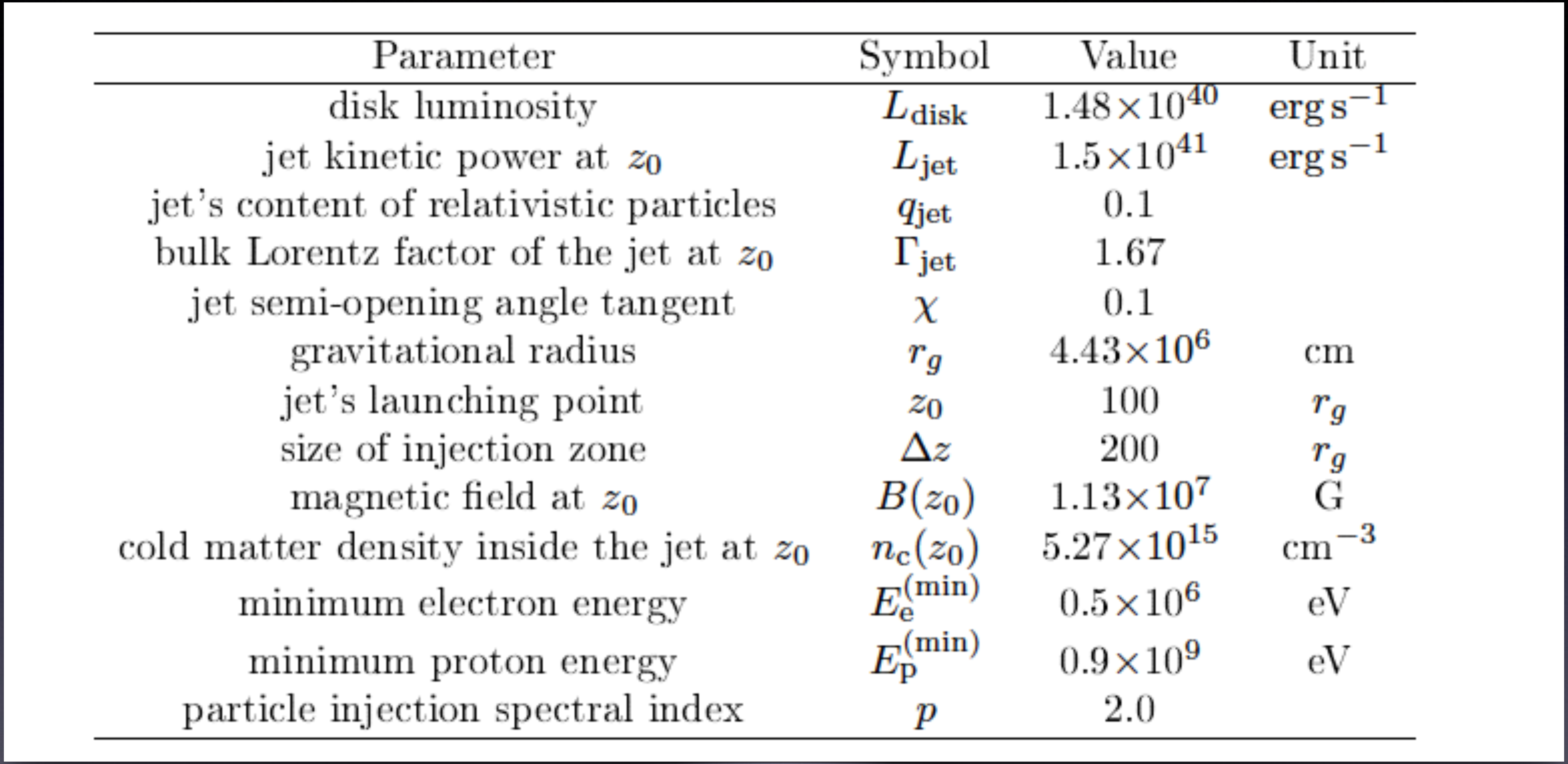
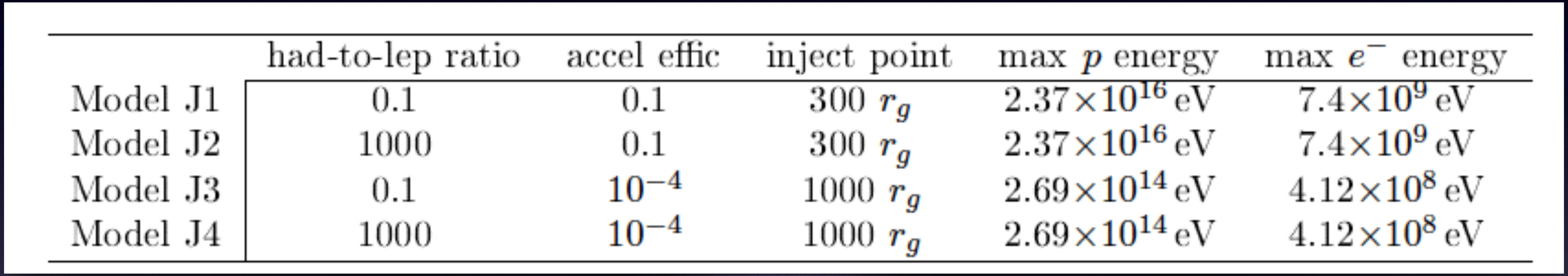


	Parameter	Symbol	Value	Unit
Calculated	accretion power	$L_{\rm acc}$	4.91×10^{43}	${\rm erg\,s^{-1}}$
Calculated	gravitational radius	$r_{\rm g}$	4.43×10^5	cm
Fixed	disk inner radius	$R_{\rm in}$	1	$r_{\rm g}$
Calculated	disk outer radius	$R_{\rm out}$	6.67×10^4	$r_{\rm g}$
Calculated	critical radius	$R_{\rm crit}$	5.06×10^4	$r_{\rm g}$



Parameter	Symbol	Value	Unit
disk luminosity	$L_{\rm disk}$	1.48×10^{40}	$\rm erg\,s^{-1}$
jet kinetic power at z_0	$L_{\rm jet}$	1.5×10^{41}	$\rm erg\,s^{-1}$
jet's content of relativistic particles	$q_{\rm jet}$	0.1	
bulk Lorentz factor of the jet at z_0	$\Gamma_{\rm jet}$	1.67	
jet semi-opening angle tangent	χ	0.1	
gravitational radius	r_g	4.43×10^{6}	cm
jet's launching point	z_0	100	r_g
size of injection zone	Δz	200	r_g
magnetic field at z_0	$B(z_0)$	1.13×10^{7}	G
cold matter density inside the jet at z_0	$n_{\rm c}(z_0)$	5.27×10^{15}	$\rm cm^{-3}$
minimum electron energy	$E_{\rm e}^{(\rm min)}$	0.5×10^{6}	eV
minimum proton energy	$E_{\rm p}^{(\rm min)}$	0.9×10^{9}	eV
particle injection spectral index	p	2.0	



	had-to-lep ratio	accel effic	inject point	max p energy	max e^- energy
Model J1	0.1	0.1	300 r_g	2.37×10^{16} eV	7.4×10^{9} eV
Model J2	1000	0.1	300 r_g	2.37×10^{16} eV	7.4×10^{9} eV
Model J3	0.1	10^{-4}	1000 r_g	2.69×10^{14} eV	4.12×10^{8} eV
Model J4	1000	10^{-4}	1000 r_g	2.69×10^{14} eV	4.12×10^{8} eV

$$c_1 = \frac{1}{3\alpha^2} h(\alpha, \epsilon),$$

$$c_2^2 = \frac{\epsilon}{3\alpha^2} h(\alpha, \epsilon),$$

$$c_3 = \frac{1}{9\,(1+s)\,\alpha^2} h(\alpha, \epsilon),$$

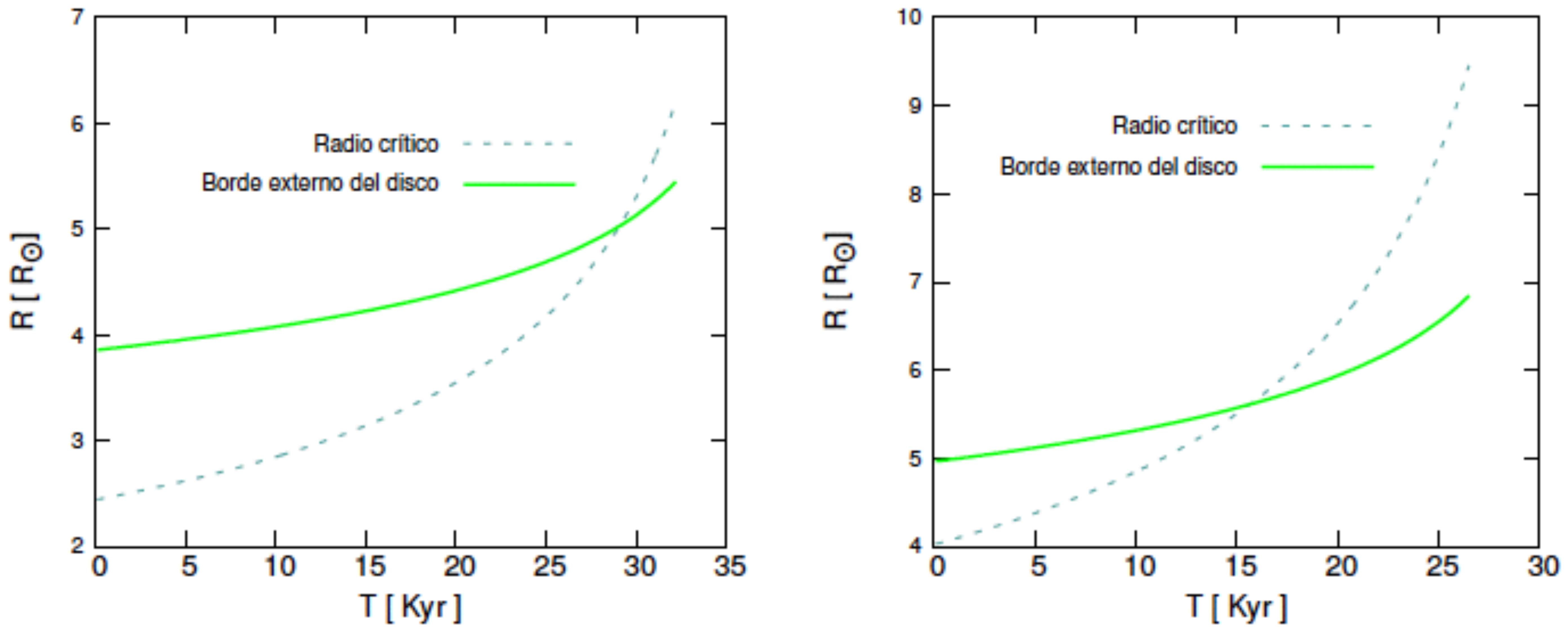
$$\epsilon = \frac{2}{9}\left(\frac{3-\gamma}{\gamma-1}\right)\frac{1}{f}$$

$$\gamma = 4/3$$

$$h(\alpha, \epsilon) \equiv \sqrt{\left(\frac{1-s}{1+s} - \beta + 3\epsilon\right)^2 + 18\alpha^2} - \left(\frac{1-s}{1+s} - \beta + 3\epsilon\right).$$

$$L_{\rm disk} = \int_{r_{\rm in}}^{100 r_{\rm g}} 2\sigma T_{\rm eff}^4 2\pi r dr \int_{100 r_{\rm g}}^{r_{\rm cr}} 2\sigma T_{\rm eff}^4 2\pi r dr + \int_{r_{\rm cr}}^{\infty} 2\sigma T_{\rm eff}^4 2\pi r dr$$

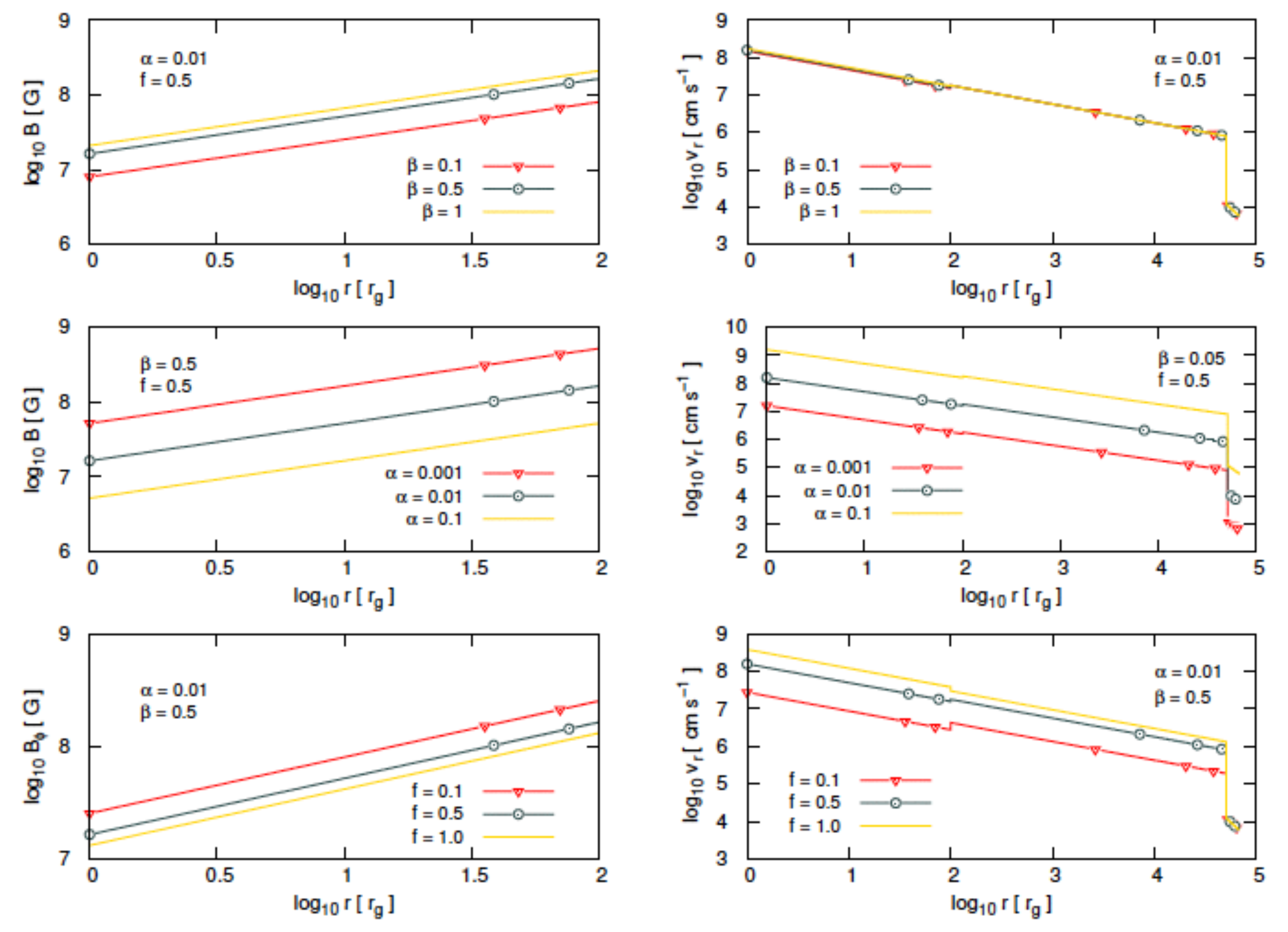
$$L_{\rm disk} \sim L_{\rm Edd}.$$

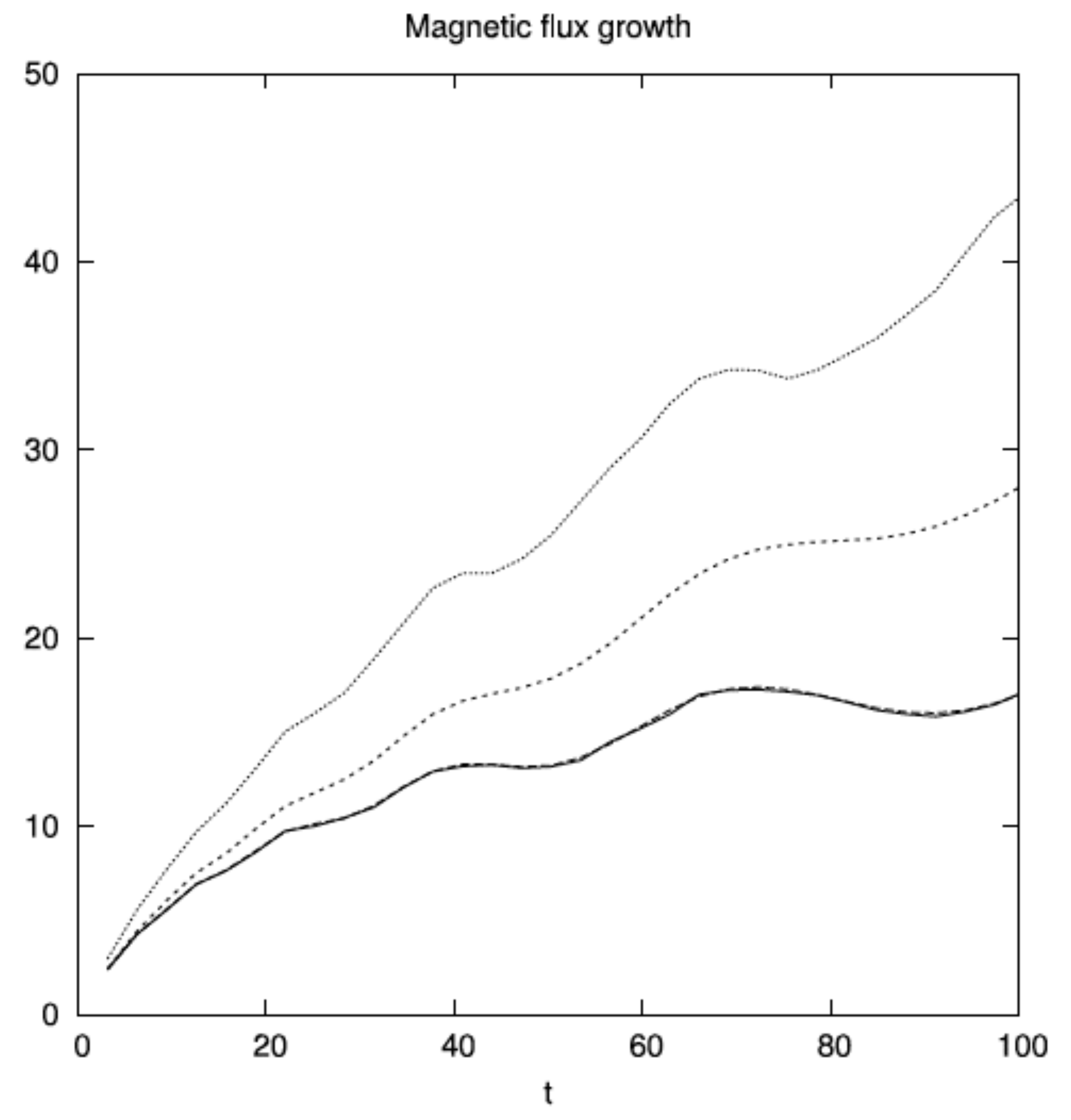


$$t \sim \frac{B(z_0)}{\partial B/\partial t} \sim 10^{11}\ \mathrm{s} \sim 4500\ \mathrm{yr}.$$

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

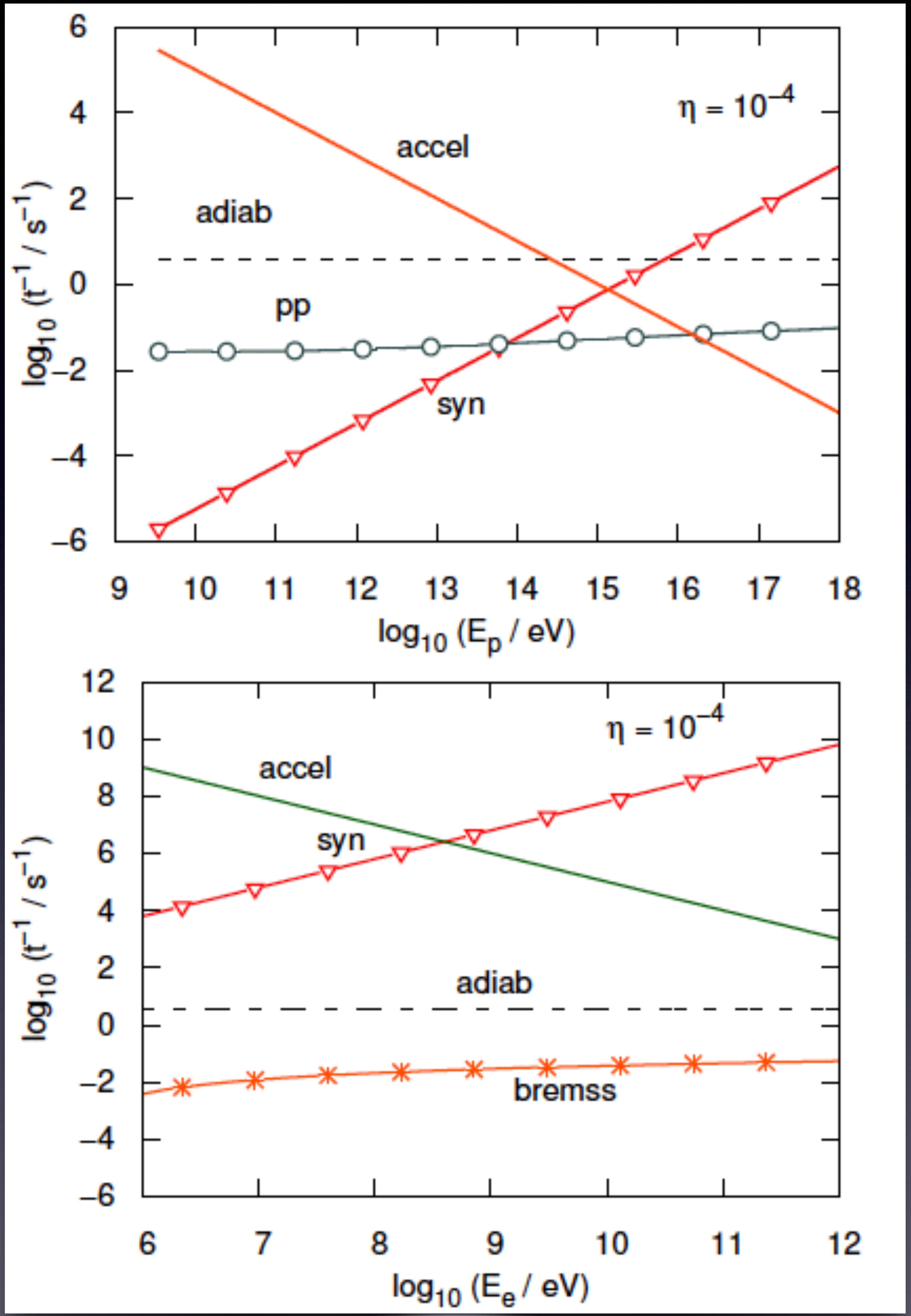
Contopoulos et al. 2006



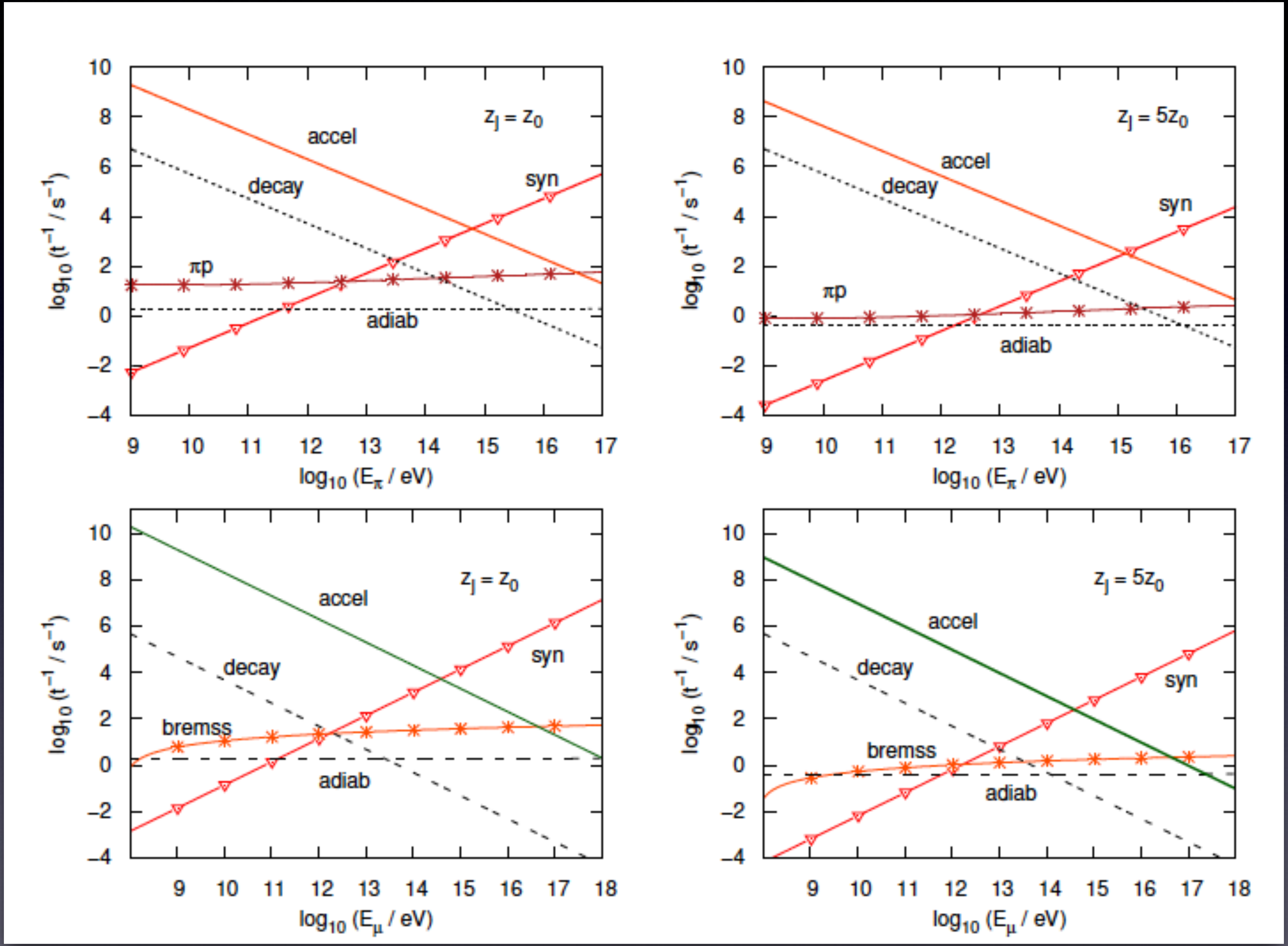


Contopoulos et al. 2006

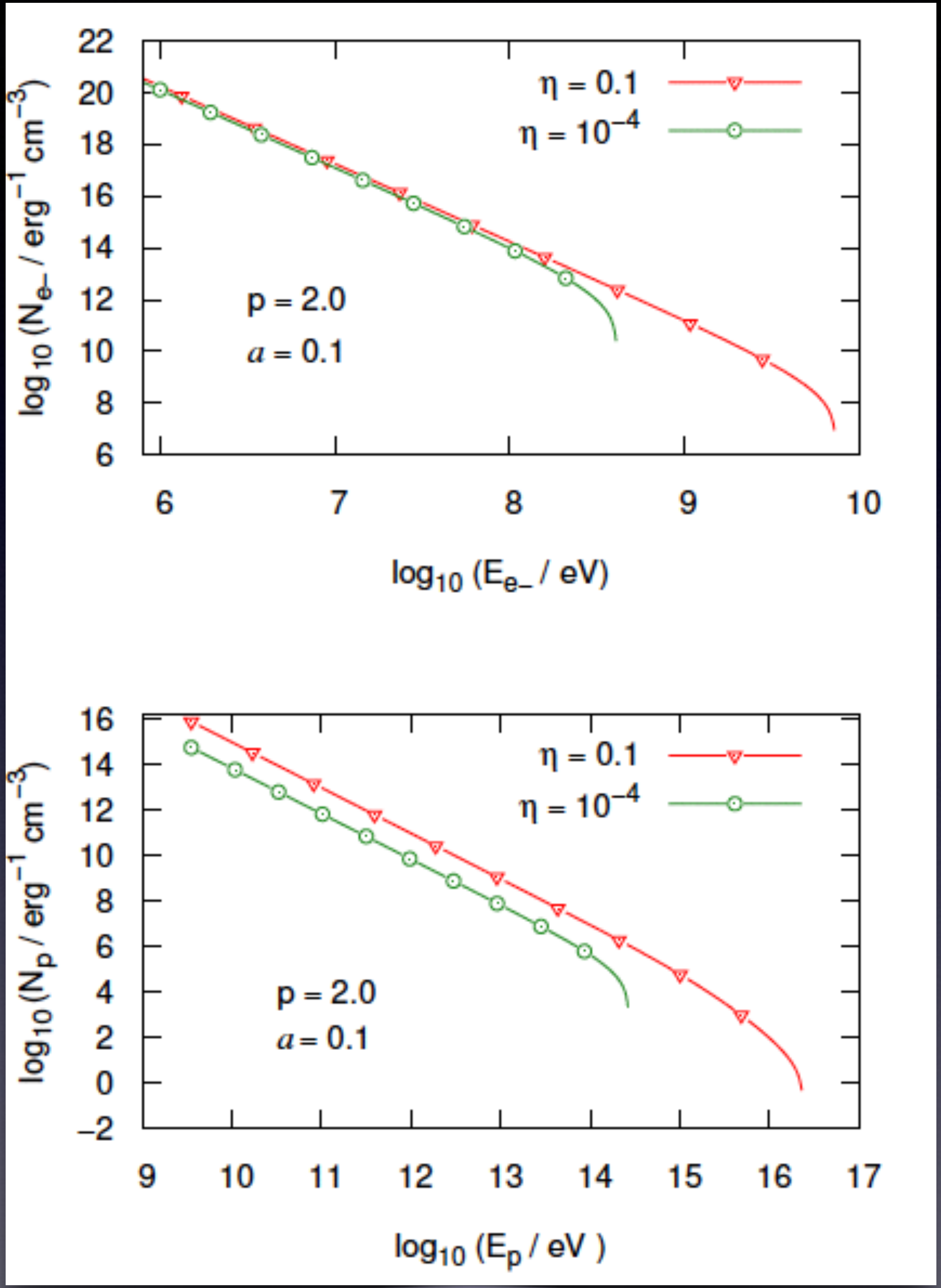
Losses
(low efficiency acceleration of 0.0001)



Losses for pions and muons



Particle distributions



Low efficiency