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Among the first collapsars: gamma-ray binaries in the early Universe

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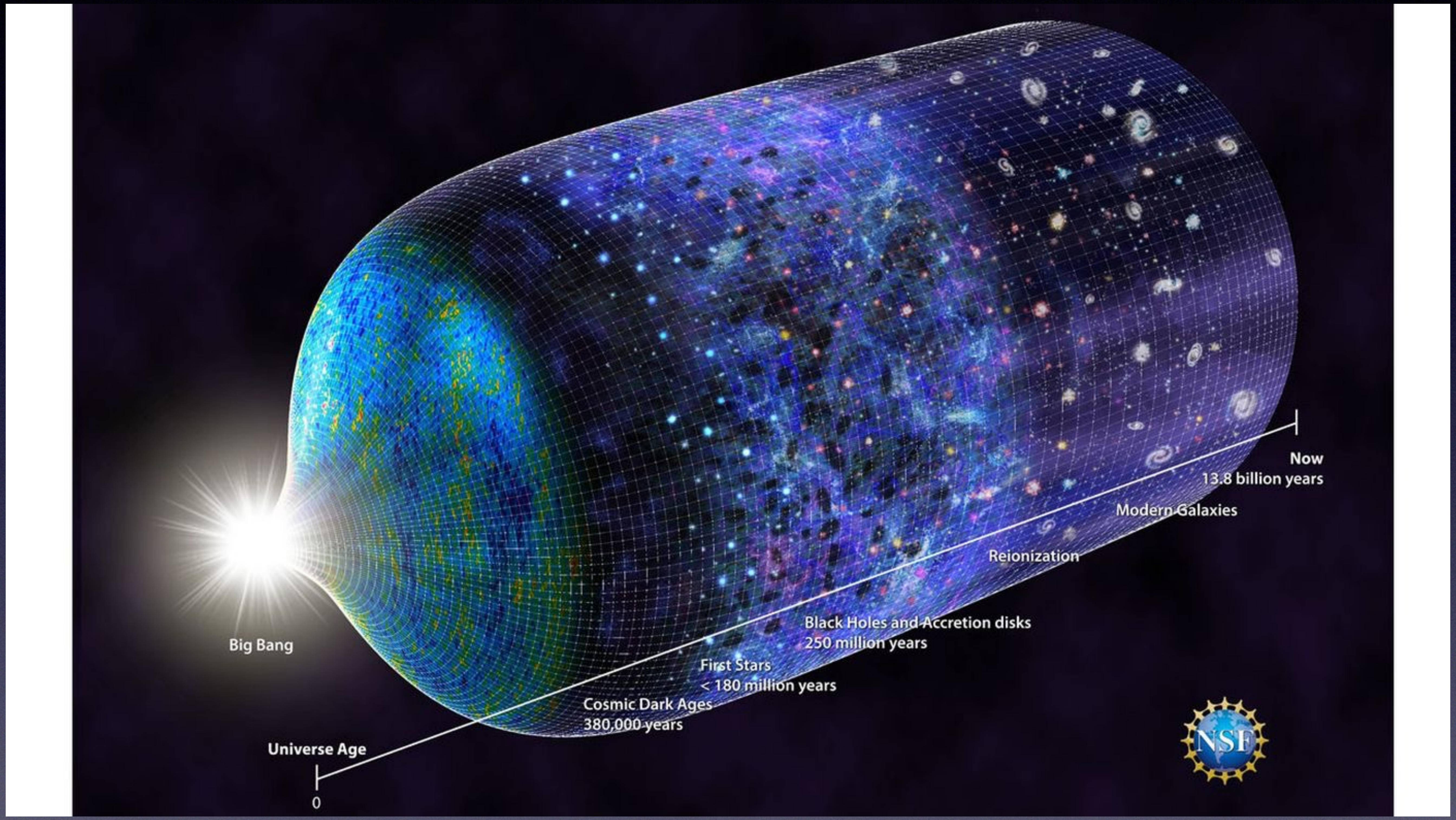
Reionization: initiated by the first stars - ended by the first quasars

The formation of the first stars occurred at redshifts $z \sim 20 - 30$, after the recombination, in the so-called dark era. These stars are predicted to form in dark matter minihalos, comprising total masses of $\sim 10^6 M_\odot$.



These first stars are called Population III stars

Population III are extremely metal-poor stars (EMP). They form from primeval gas and constitute 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.

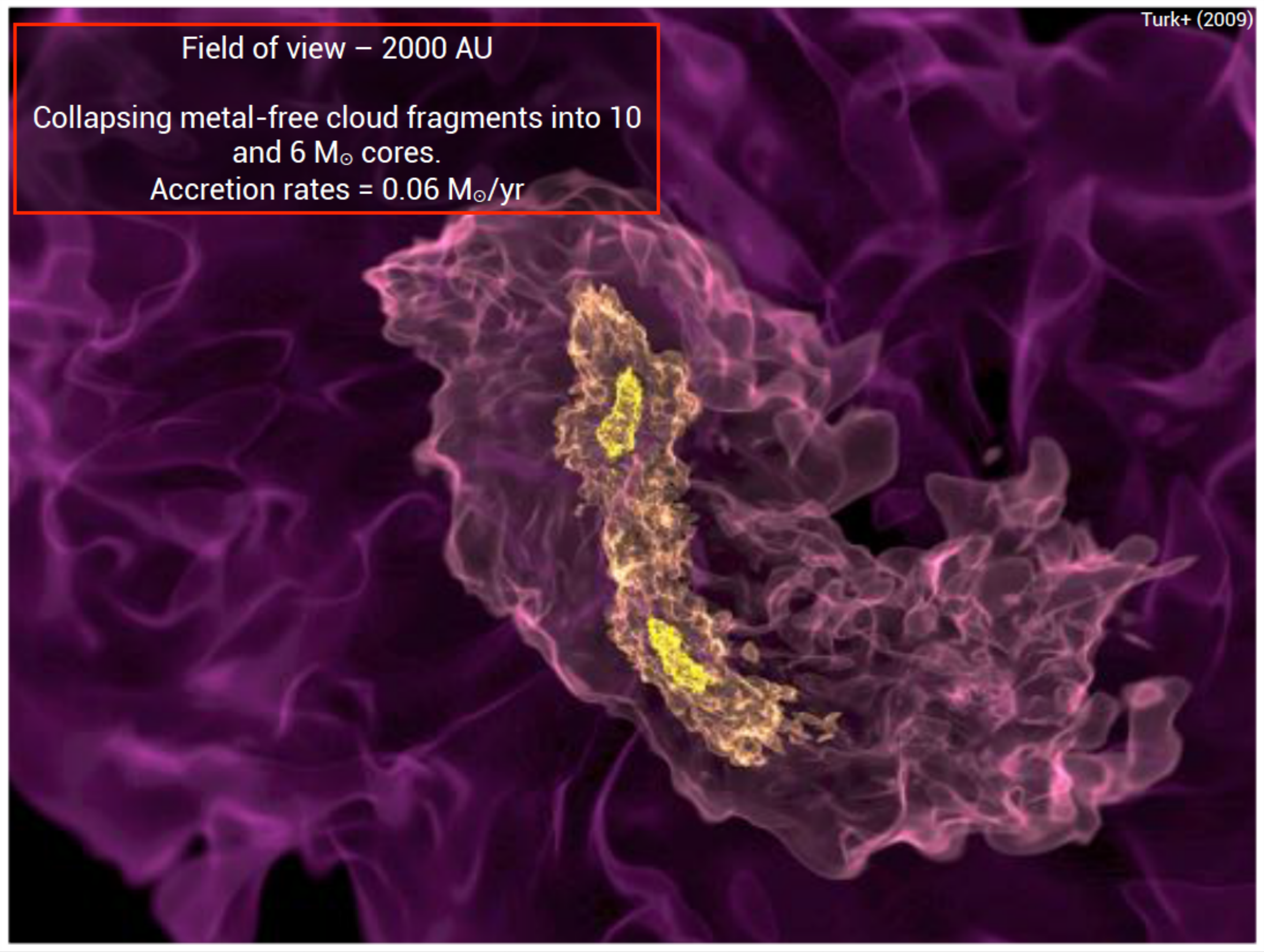
Current models suggest that Pop III stars were typically massive, or even very massive, with $M_* \sim 10 - 100\ M_\odot$; these models also predict that the first stars formed in small groups, including binaries or higher-order multiples.

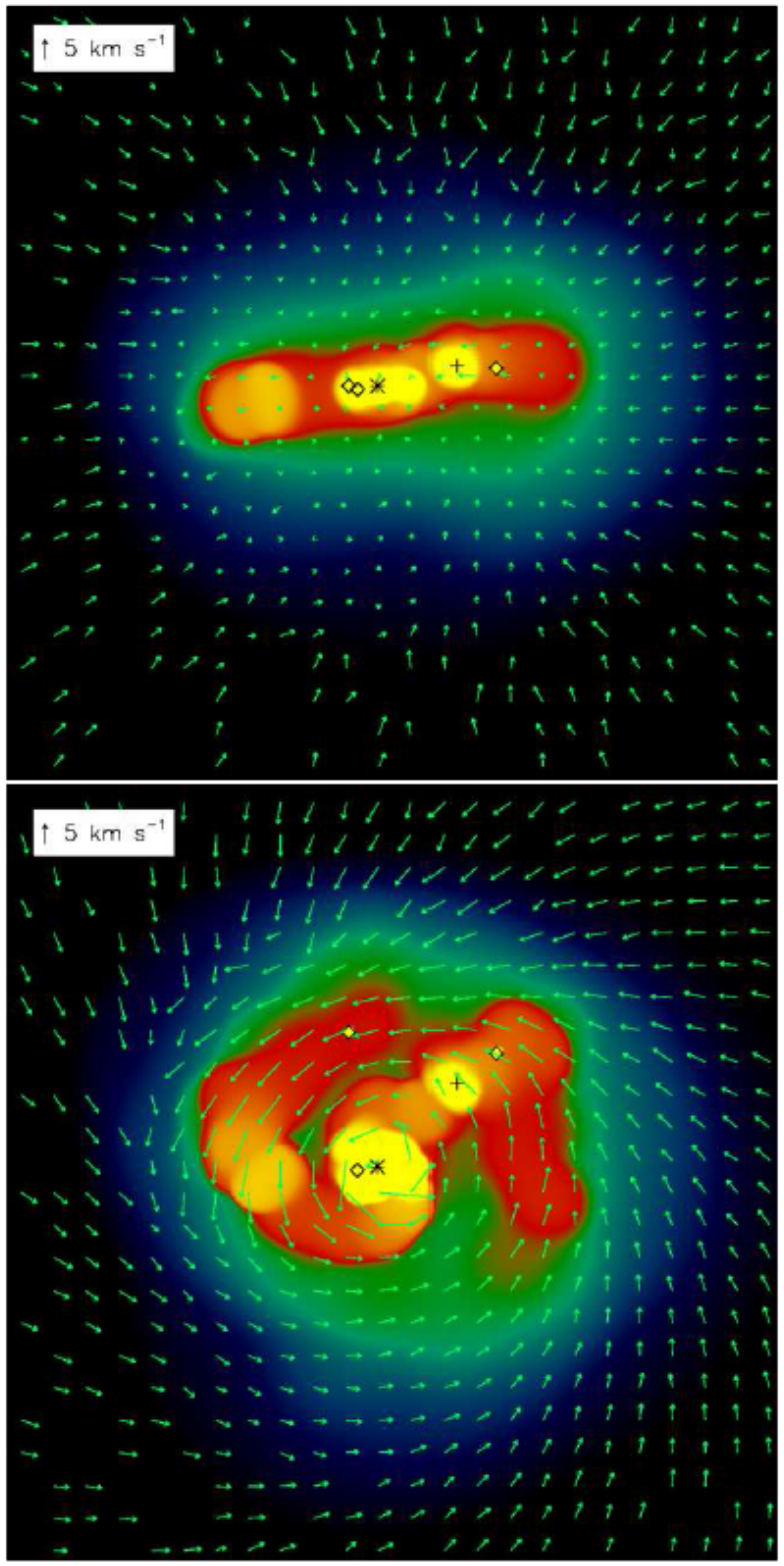
Using abundances of 53 extremely metal-poor stars, Fraser et al. (2017) inferred the masses of their Population III progenitors. They found that the mass distribution is well-represented by a power law IMF with exponent $2.35^{+0.29}_{-0.24}$ (close to Salpeter's). The inferred maximum progenitor mass 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 $M_{\odot}$.

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

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

Most Pop III should be in binary systems

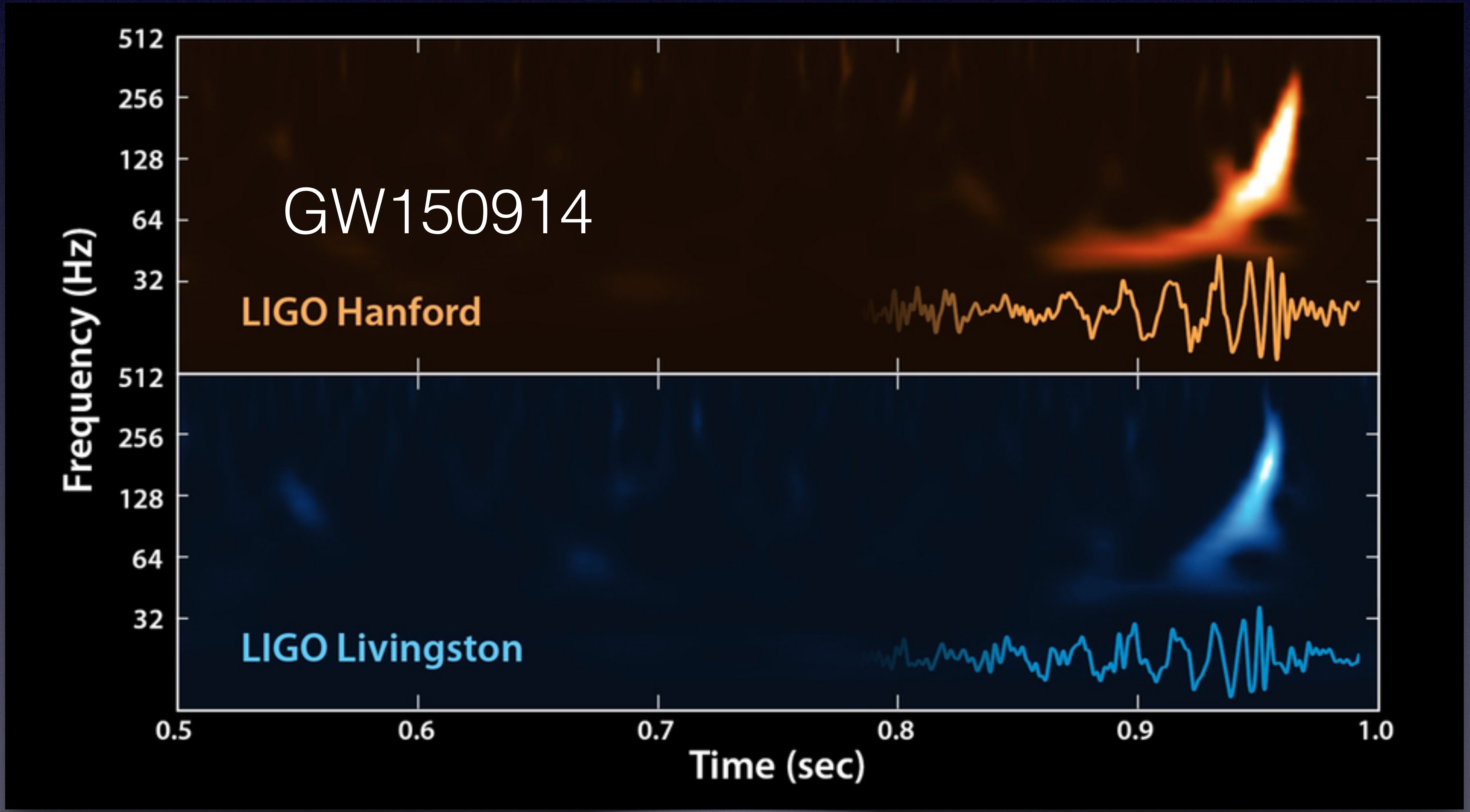


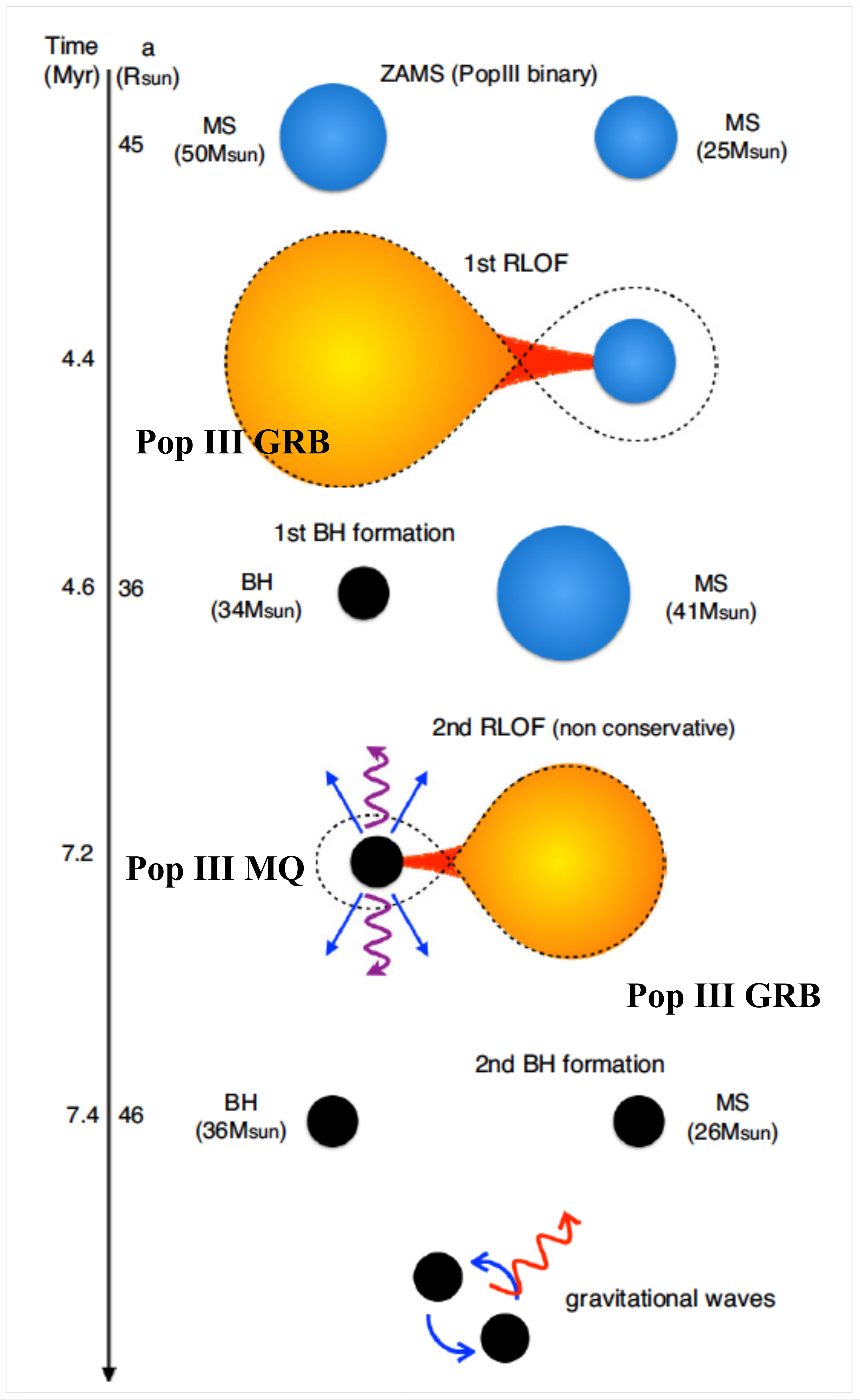


GW detections by LIGO from black hole mergers with holes of masses in the range 30-60 $M_\odot$ support the idea that Pop III stars had masses not beyond 100 $M_\odot$ and formed binaries.

Evolution of a Pop III binary (Inayoshi et al. 2017)

Such systems are thought to be progenitors of some black hole binaries whose final mergers were detected as gravitational wave events by LIGO.





For Pop III GRBs see Toma et al. (2016) review

Typical properties of Pop III stars

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

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

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

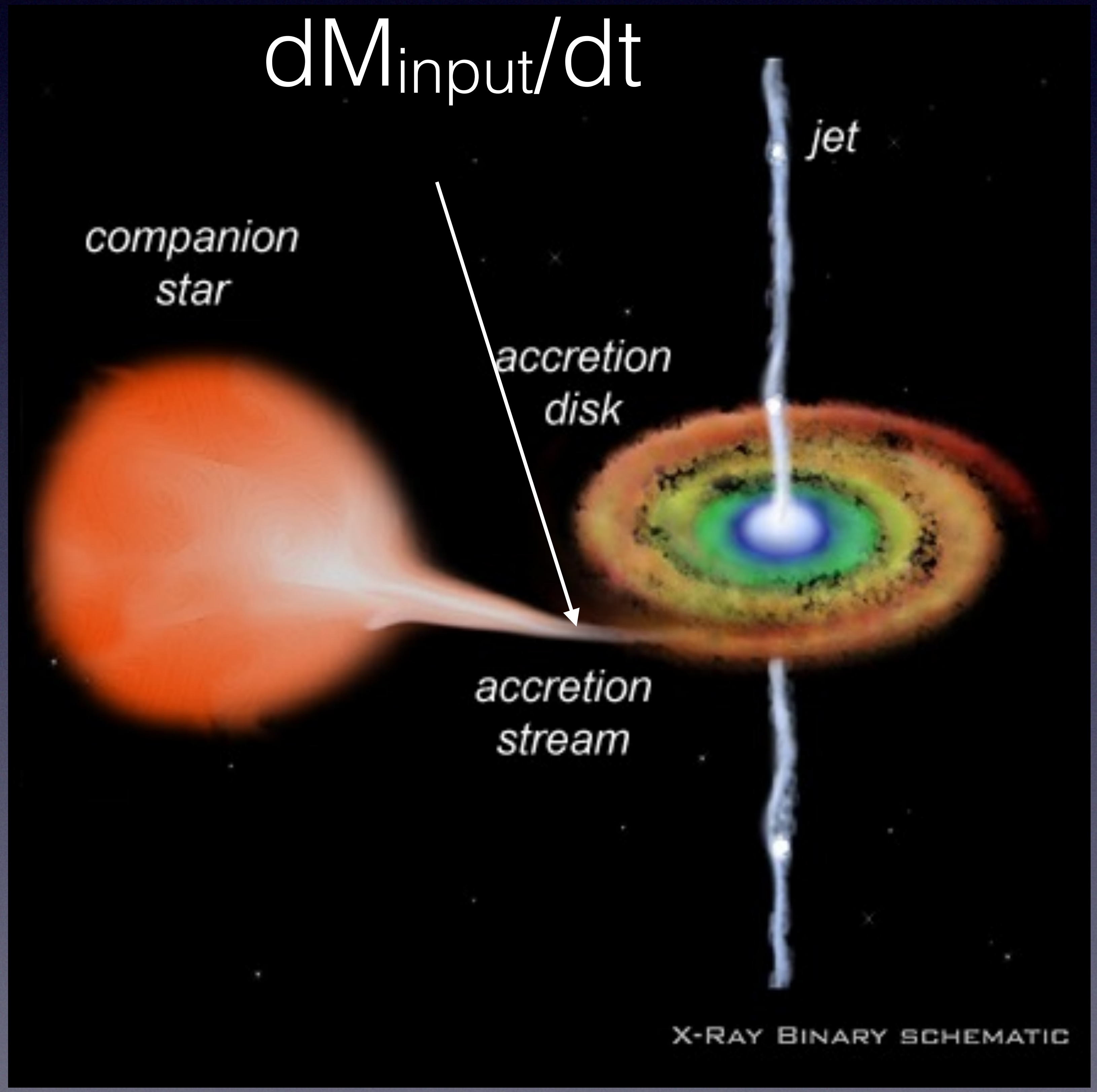
$$t_* \simeq \frac{0.007 M_* c^2}{L_{\rm EDD}} \simeq 3 \times 10^6\,{\rm yr},$$

No metals, no winds

Pop III binary systems

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

The differences between these systems and the current types of MQs lie in the peculiar features of Pop III stars.



In the MQ phase the radius of the star is approximated by the average radius of its Roche lobe.

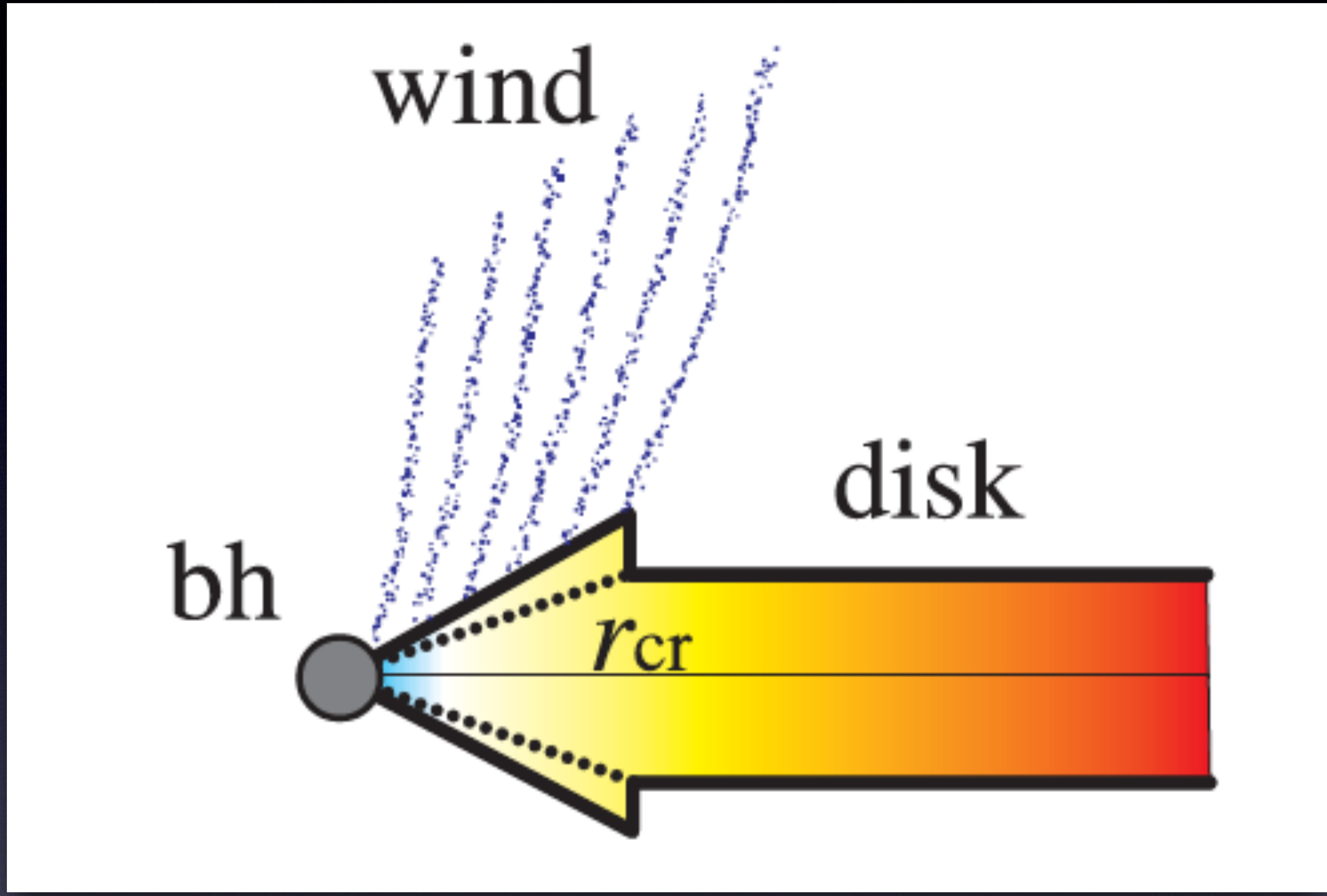
→ Pop III accreting binaries were extremely super-Eddington

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.

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

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

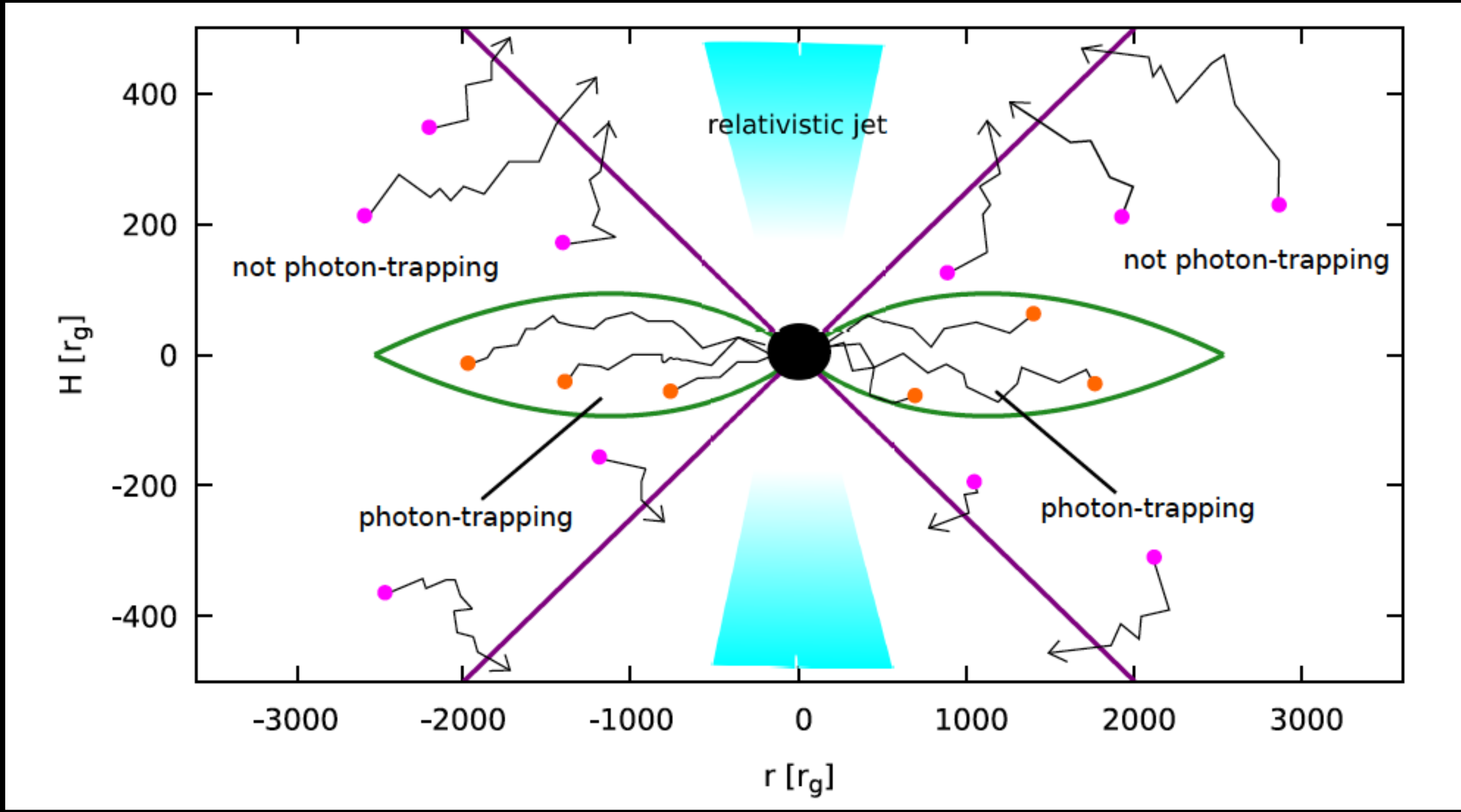
$$\dot{M}_{wind}(r) = \dot{M}_{input} - \dot{M}(r).$$

Fukue 2004

dM_{input}/dt is the accretion rate at the outer edge of the disk (and at the critical radius).

Disk structure

The main characteristic of supercritical accretion discs is the presence of photon trapping (see e.g. Begelman 1978; Ohsuga et al. 2003, 2005). Photon trapping occurs when the photon diffusion timescale exceeds the accretion timescale



Under such circumstances, photons generated via the viscous process are advected inward with the accreted flow without being able to go out from the surface. Advection of photons decreases the luminosity and energy conversion efficiency of the accretion disk.

Disk structure

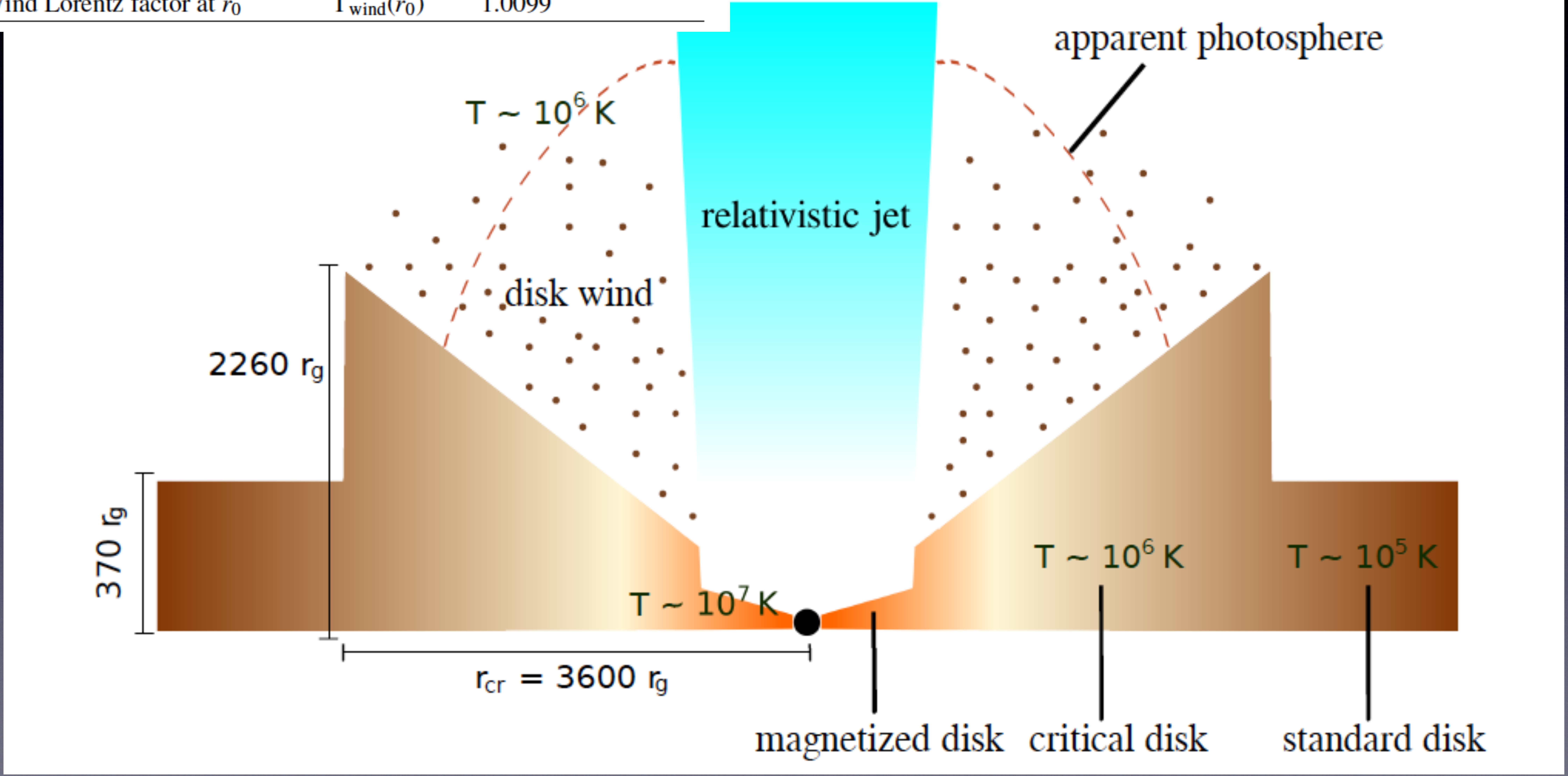
- For $r > r_{crit}$ the disk is well described by standard radiation-dominated accretion disk model.
- For $r_0 < r < r_{crit}$ the disk is well described by critical accretion disk model with a strong wind.
- For $r < r_0$ the disk is well described by an optically thick ADAF with a toroidal magnetic field model.

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

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

$$\Sigma = \Sigma_0 r^s,$$

Parameter	Symbol	Value	Unit
Total wind mass-loss rate	$\dot{M}_{\rm wind}$	7.3×10^{-5}	$M_\odot\,{\rm yr}^{-1}$
Total jet mass-loss rate	$\dot{M}_{\rm jet}$	2.1×10^{-6}	$M_\odot\,{\rm yr}^{-1}$
Mass-accretion rate in the inner edge	$\dot{M}_{\rm in}$	2.9×10^{-13}	$M_\odot\,{\rm yr}^{-1}$
Wind Lorentz factor at $r_{\rm cr}$	$\Gamma_{\rm wind}(r_{\rm cr})$	1.0002	
Wind Lorentz factor at r_0	$\Gamma_{\rm wind}(r_0)$	1.0099	
Accretion power	$L_{\rm accr}$	1×10^{43}	${\rm erg\,s}^{-1}$
Jet luminosity	$L_{\rm jet}$	1×10^{41}	${\rm erg\,s}^{-1}$
Jet's bulk Lorentz factor	$\Gamma_{\rm jet}$	1.47	
Jet semi-opening angle tangent	χ	0.1	

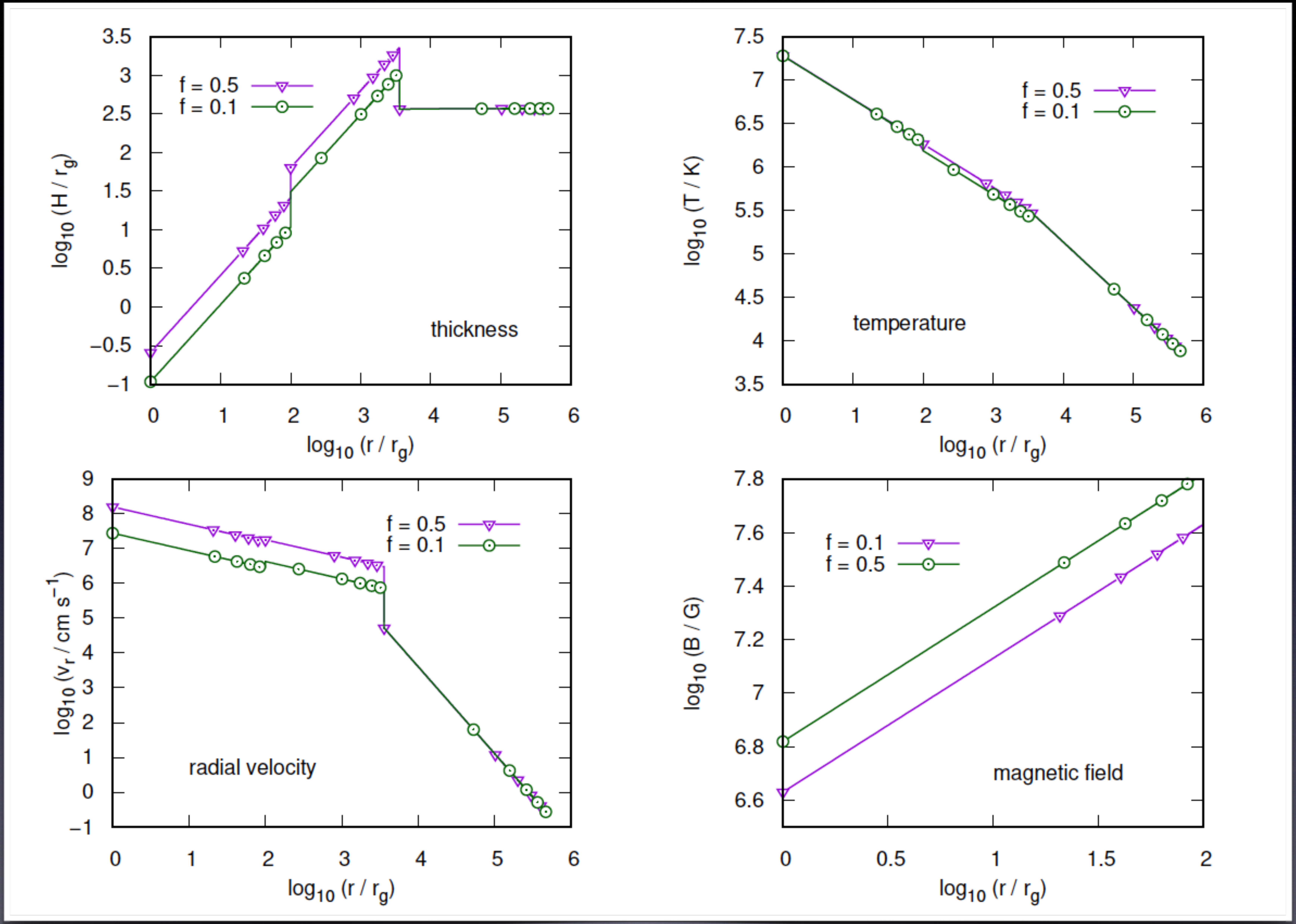


Based on Inayoshi et al. (2017) we adopt a binary system whose components are a Population III star of $M_* = 41\ M_{sun}$ and a black hole of $M_{BH} = 34\ M_{sun}$ in order to make some quantitative estimates.

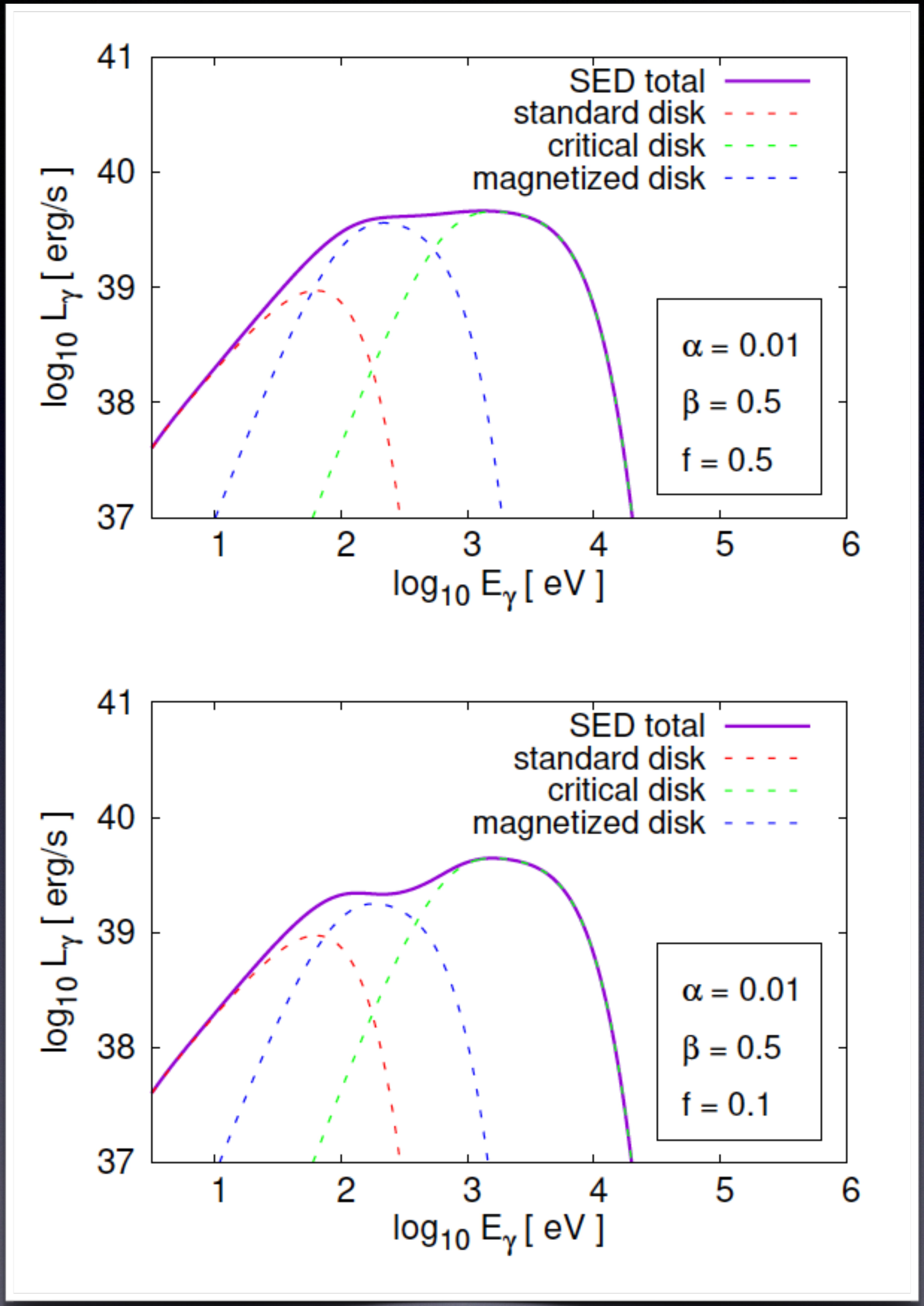
(this evolves to the binary BH system GW150914).

Parameter	Symbol	Value	Unit
Donor star mass	M_*	41	$M_\odot$
Black hole mass	$M_{\rm BH}$	34	$M_\odot$
Star radius	R_*	14.2	$R_\odot$
Star luminosity	L_*	1×10^6	$L_\odot$
Star temperature	T_*	5×10^4	K
Orbital semiaxis	a	36	$R_\odot$
Orbital period	P	2.9	days
Mass loss rate	$\dot{M}_*$	7.5×10^{-5}	$M_\odot\,{\rm yr}^{-1}$
Eddington accretion rate	$\dot{M}_{\rm Edd}$	2.2×10^{-8}	$M_\odot\,{\rm yr}^{-1}$
Black hole Eddington luminosity	$L_{\rm Edd}$	4.3×10^{39}	${\rm erg\,s}^{-1}$
Gravitational radius	$r_{\rm g}$	50	km

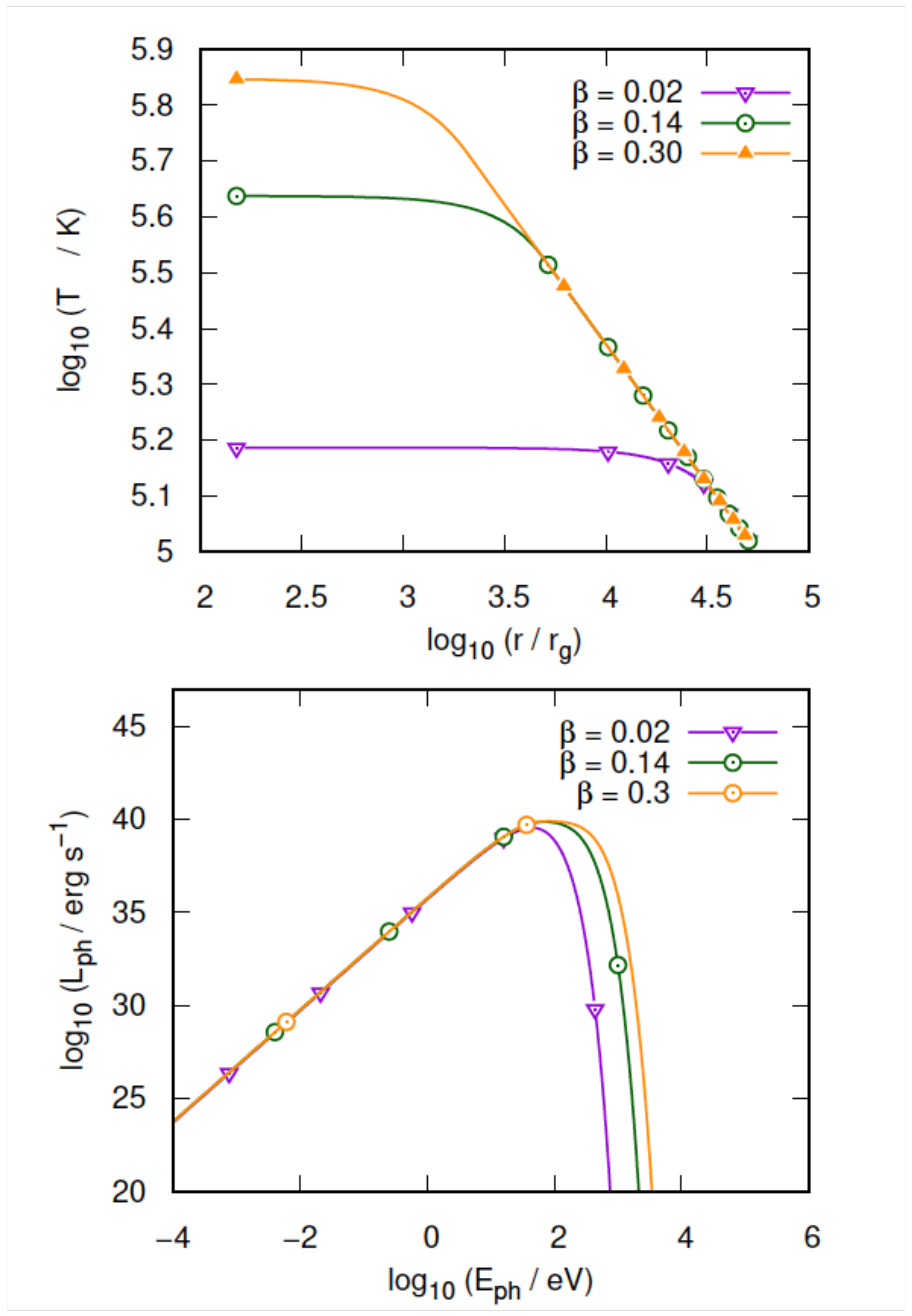
Disk structure



SED - total disk



Wind



The wind masks the disk emission

$\beta = v/c$

Jet

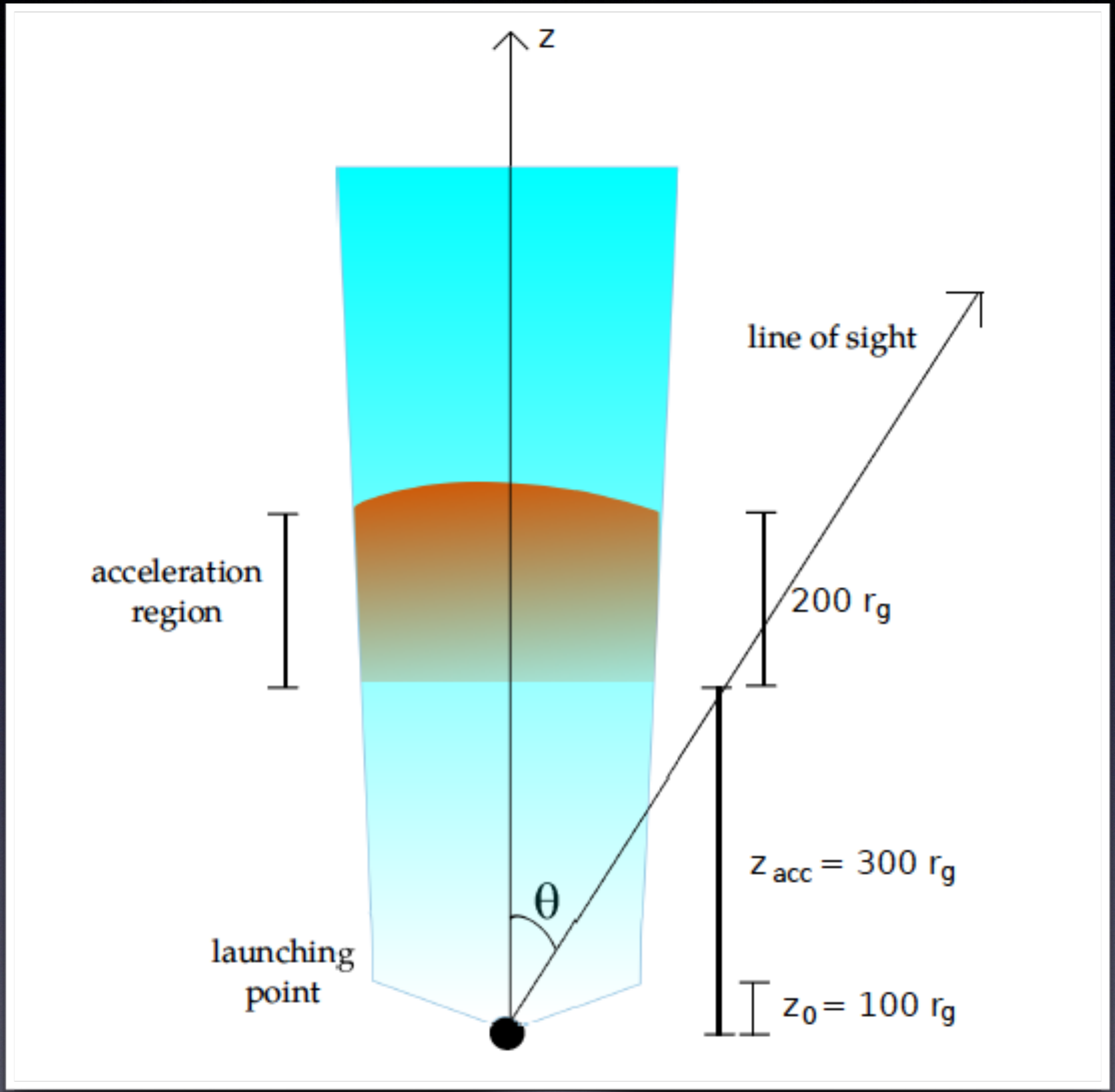
A jet is magnetically launched from the innermost region (~100 r_g)

$$L_{\rm jet} = L_{\rm acc} - L_{\rm disk} - L_{\rm in} - L_{\rm wind},$$

$$L_{\rm jet} = \frac{GM_{\rm BH} 2\dot{m}_{\rm jet}}{r_0} + \left(\Gamma_{\rm jet} - 1\right) 2\dot{m}_{\rm jet} c^2.$$

$$\frac{B^2(z_0)}{8\pi} = \frac{L_{\rm jet}}{2\pi r_0 v_{\rm jet}},$$

$$B(z) = B(z_0)\left(\frac{z_0}{z}\right),$$



$$L_{\rm rel} = q_{\rm rel} L_{\rm jet},$$

$$L_{\rm rel} = L_p + L_e.$$

$$L_p = a L_e$$

$$a = 100.$$

See Romero & Vila 2008 and Vila, Romero & Casco A&A 2012 for details

Radiative losses

- Electron/positron pairs

$$b(E) = -\left.\frac{dE}{dt}\right|_{Synchr} - \left.\frac{dE}{dt}\right|_{IC} - \left.\frac{dE}{dt}\right|_{Bremsstr} - \left.\frac{dE}{dt}\right|_{e^{\pm}\to\gamma\gamma}$$

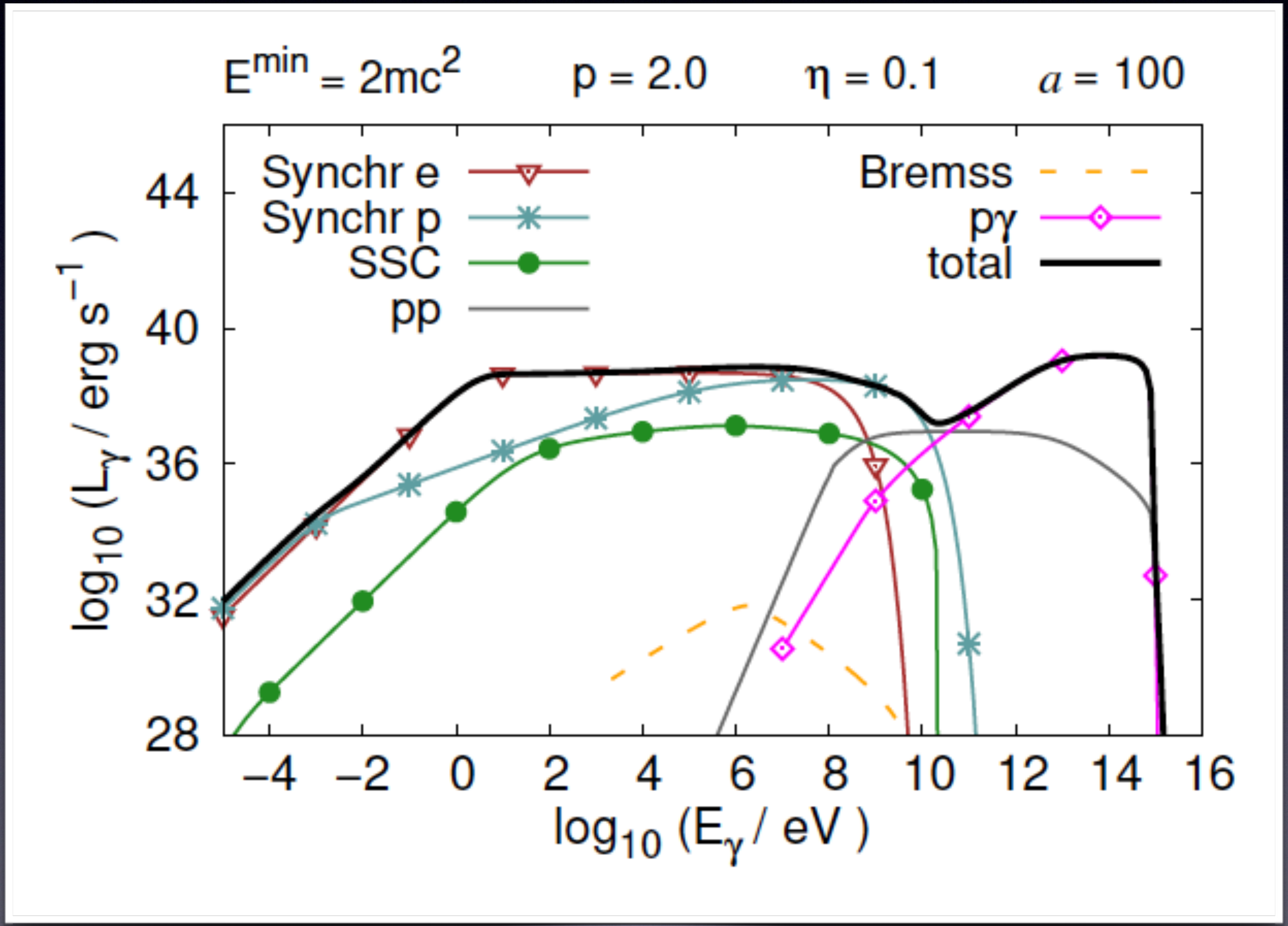
- Protons and charged pions

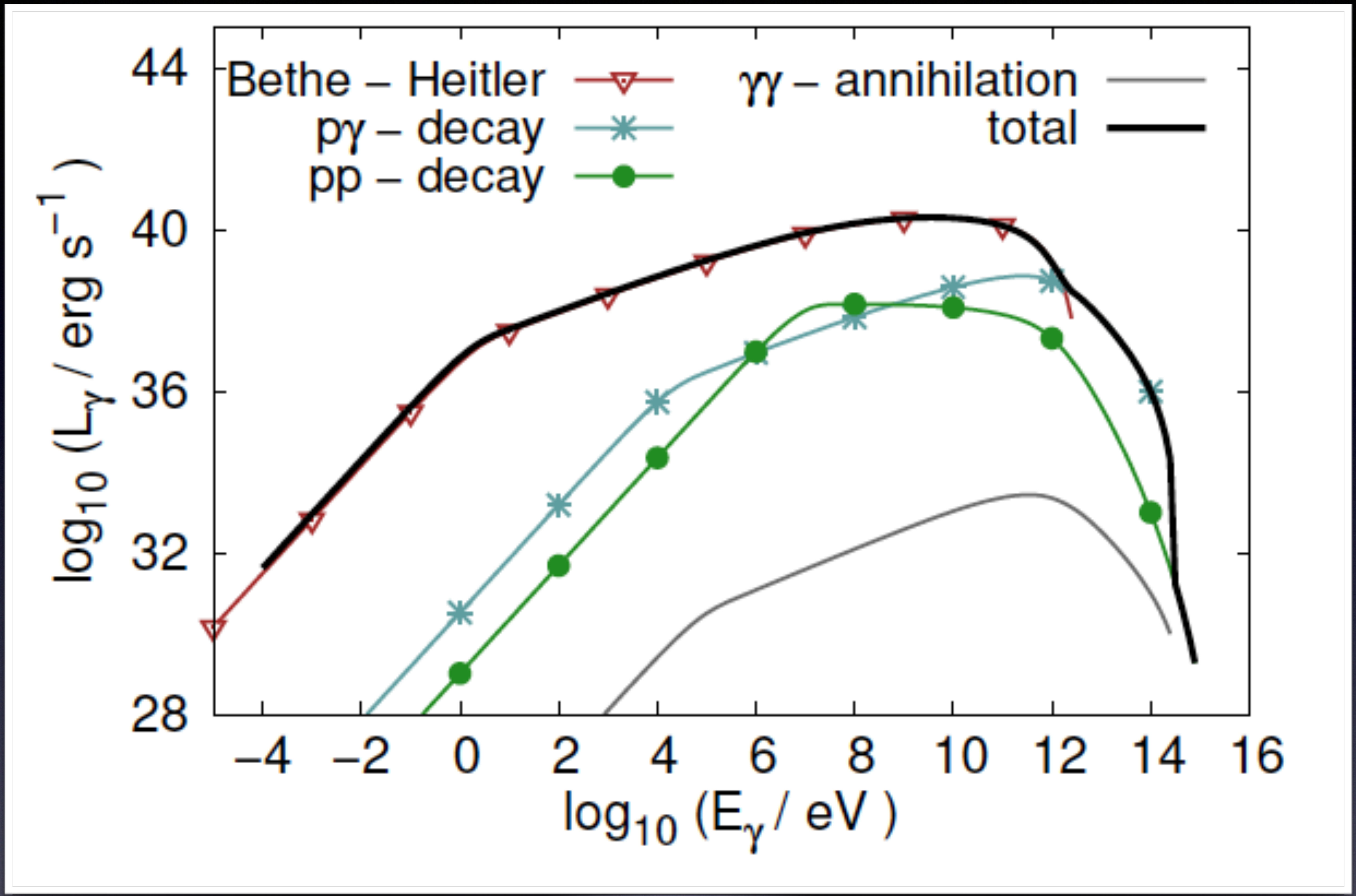
$$b(E) = -\left.\frac{dE}{dt}\right|_{Synchr} - \left.\frac{dE}{dt}\right|_{p\gamma} - \left.\frac{dE}{dt}\right|_{pp}$$

- Muons

$$b(E) = -\left.\frac{dE}{dt}\right|_{Synchr} - \left.\frac{dE}{dt}\right|_{IC} - \left.\frac{dE}{dt}\right|_{Bremsstr}$$

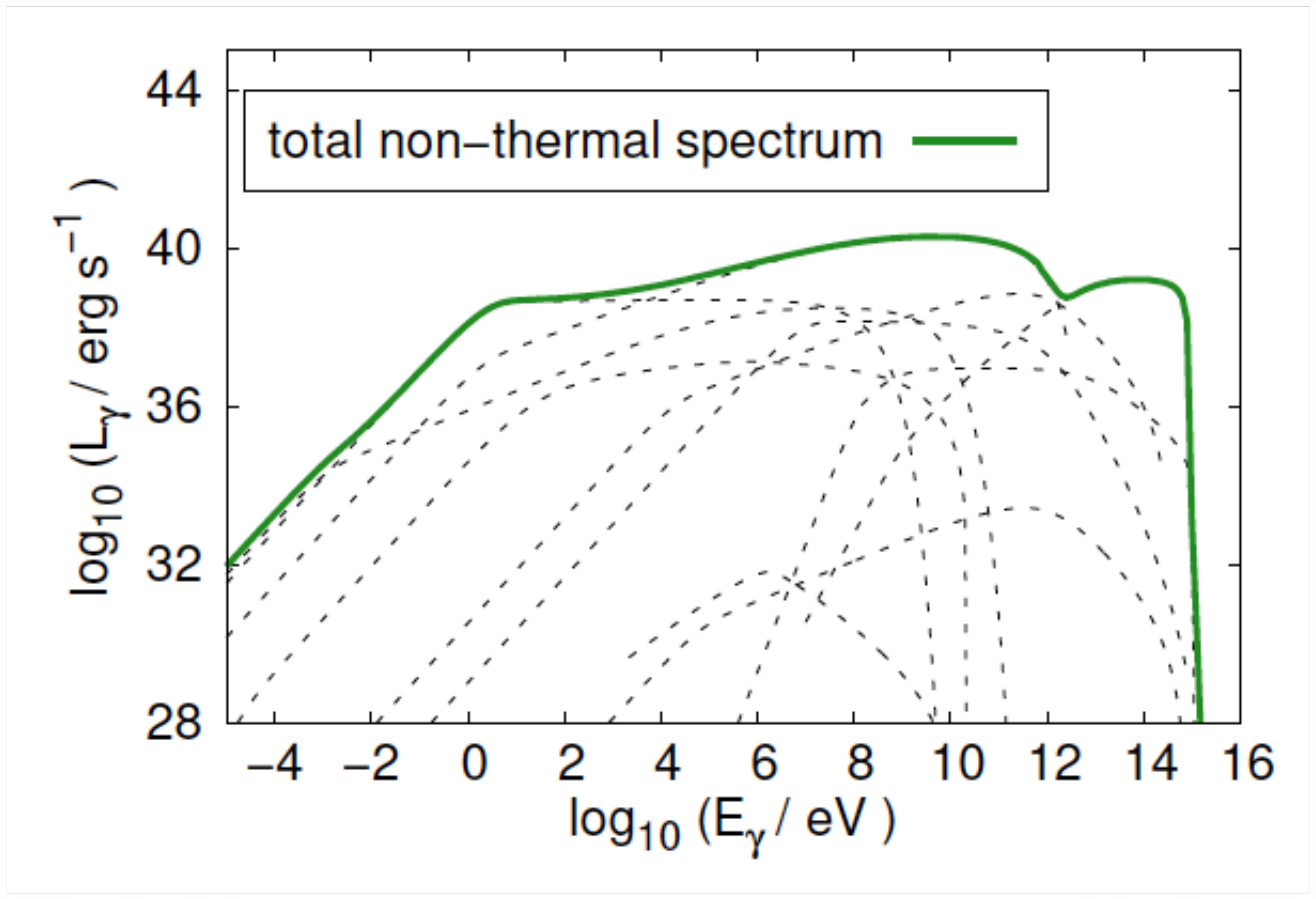
Non-thermal spectral energy distribution of the radiation produced in the jet by the population of primary particles. The adopted viewing angle is 60 deg.



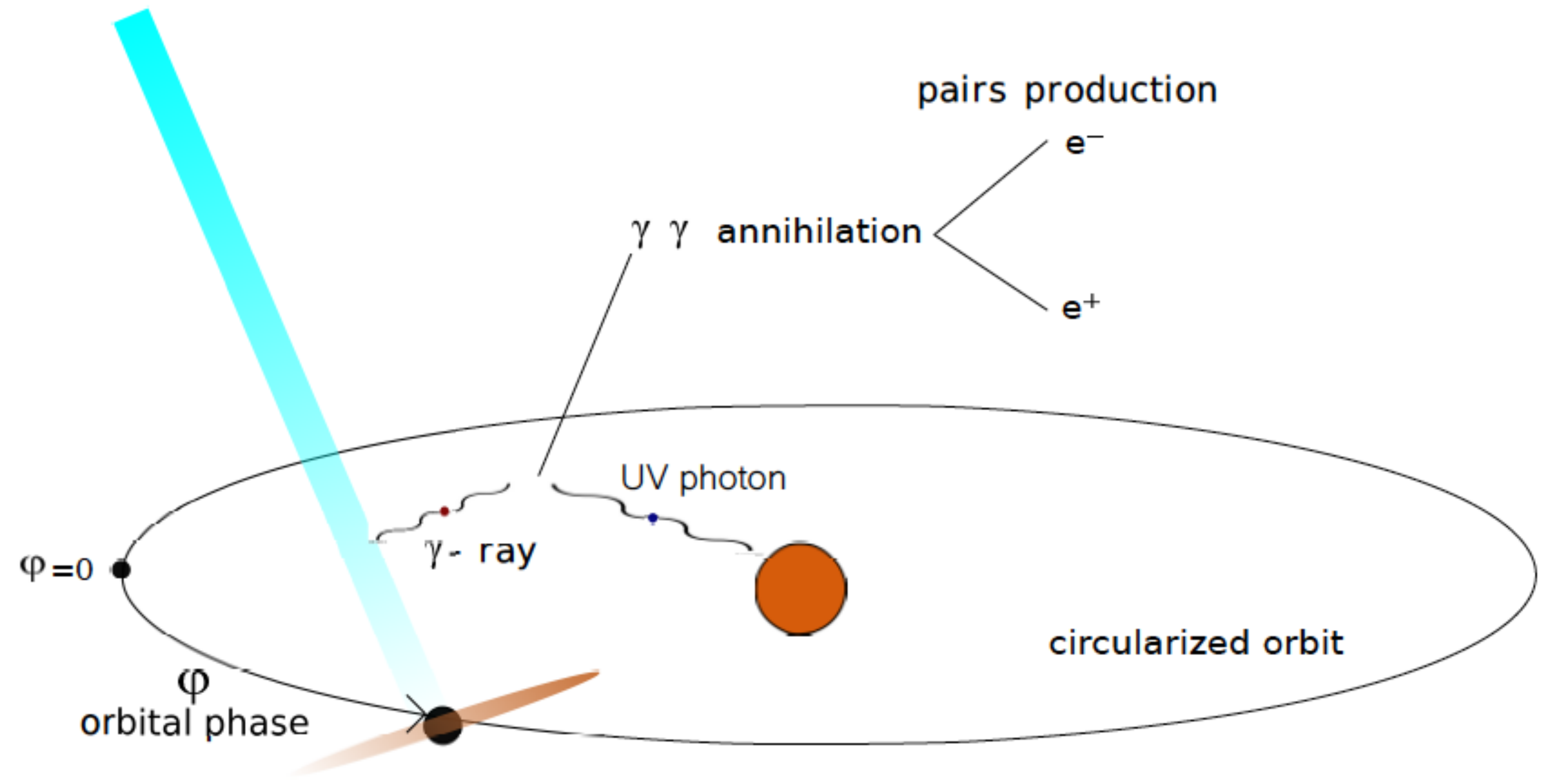


Spectral energy distribution of the synchrotron radiation for electron-positron pairs. The adopted viewing angle is 60 deg.

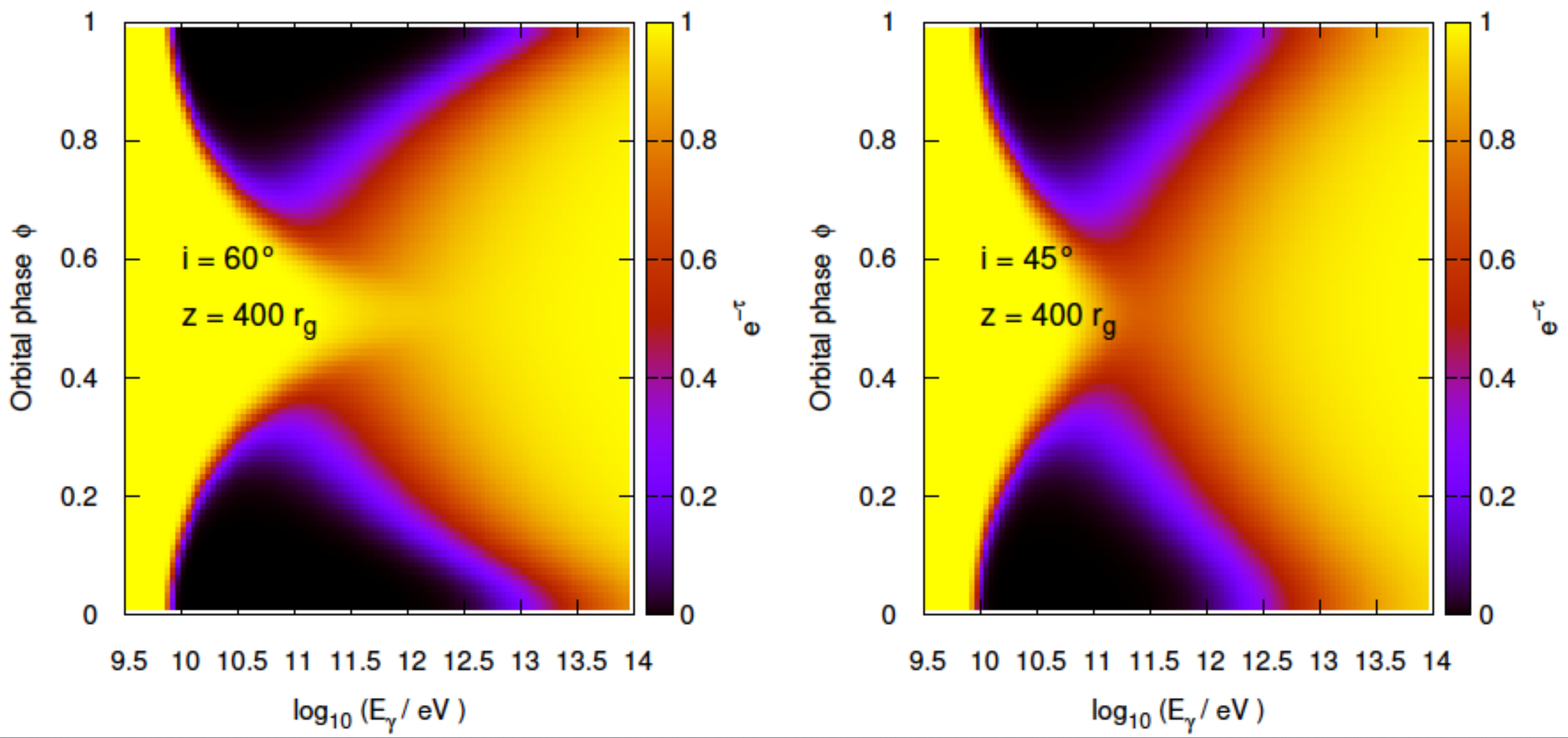
Total SED (primary plus secondary)

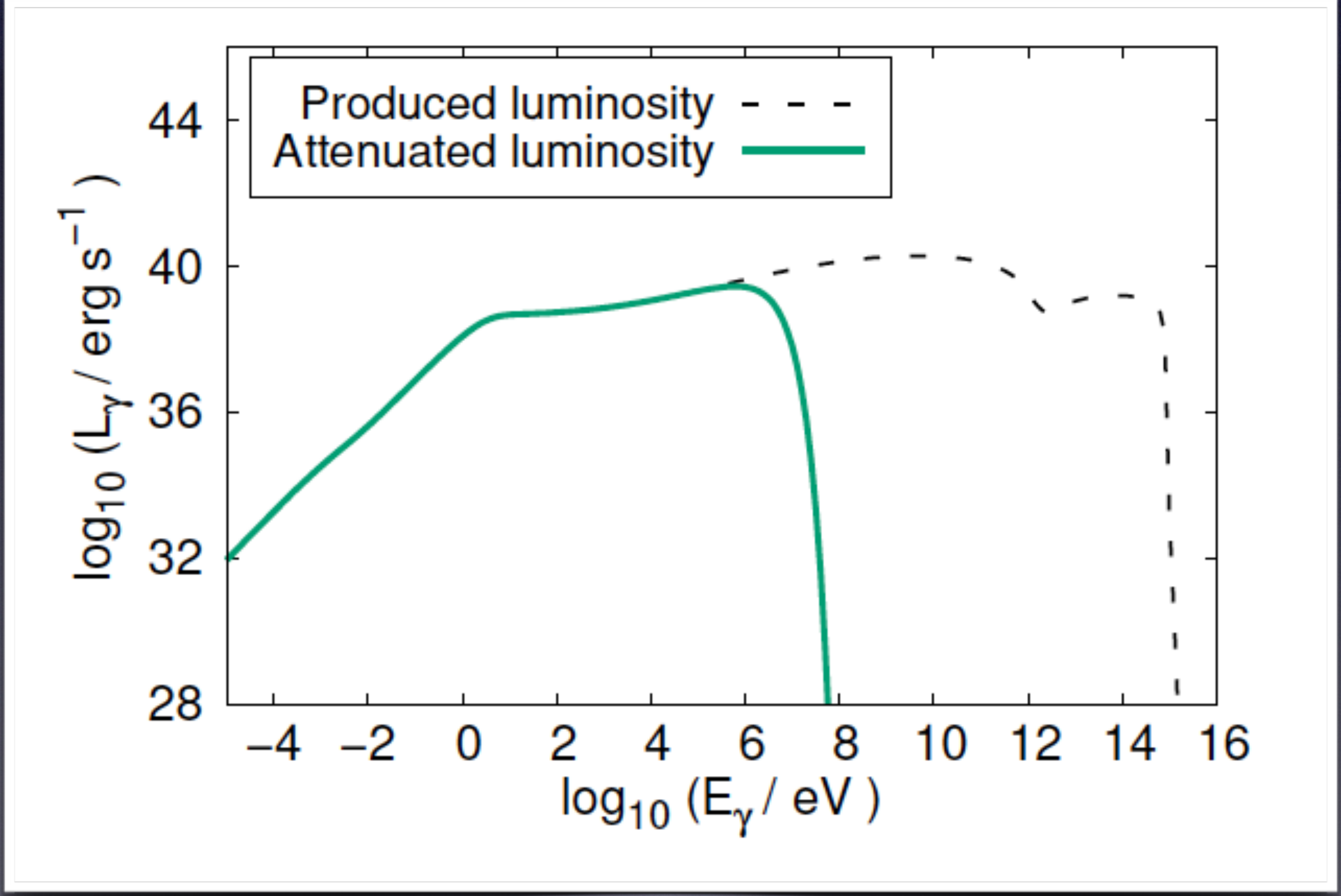


Attenuation by photon absorption (inner source)



Sketch of the orbital dependence of the annihilation between γ-rays from jets and ultraviolet photons from the donor star. Orbital phase $\phi = 0$ and $\phi = 1$ corresponds to the source of γ-rays in opposition. Orbital phase ϕ=0.5 corresponds to inferior conjunction.

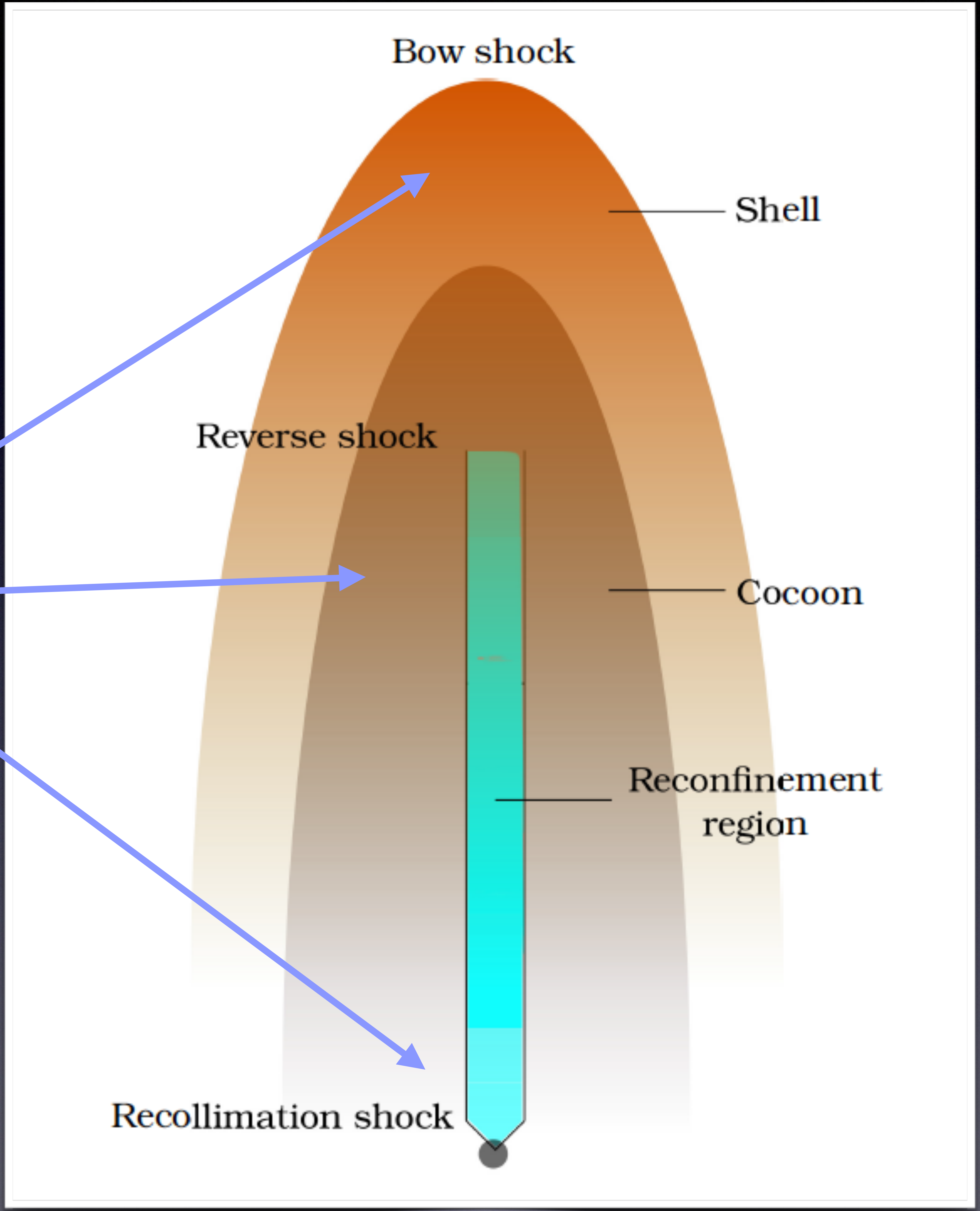




Terminal region of the jets

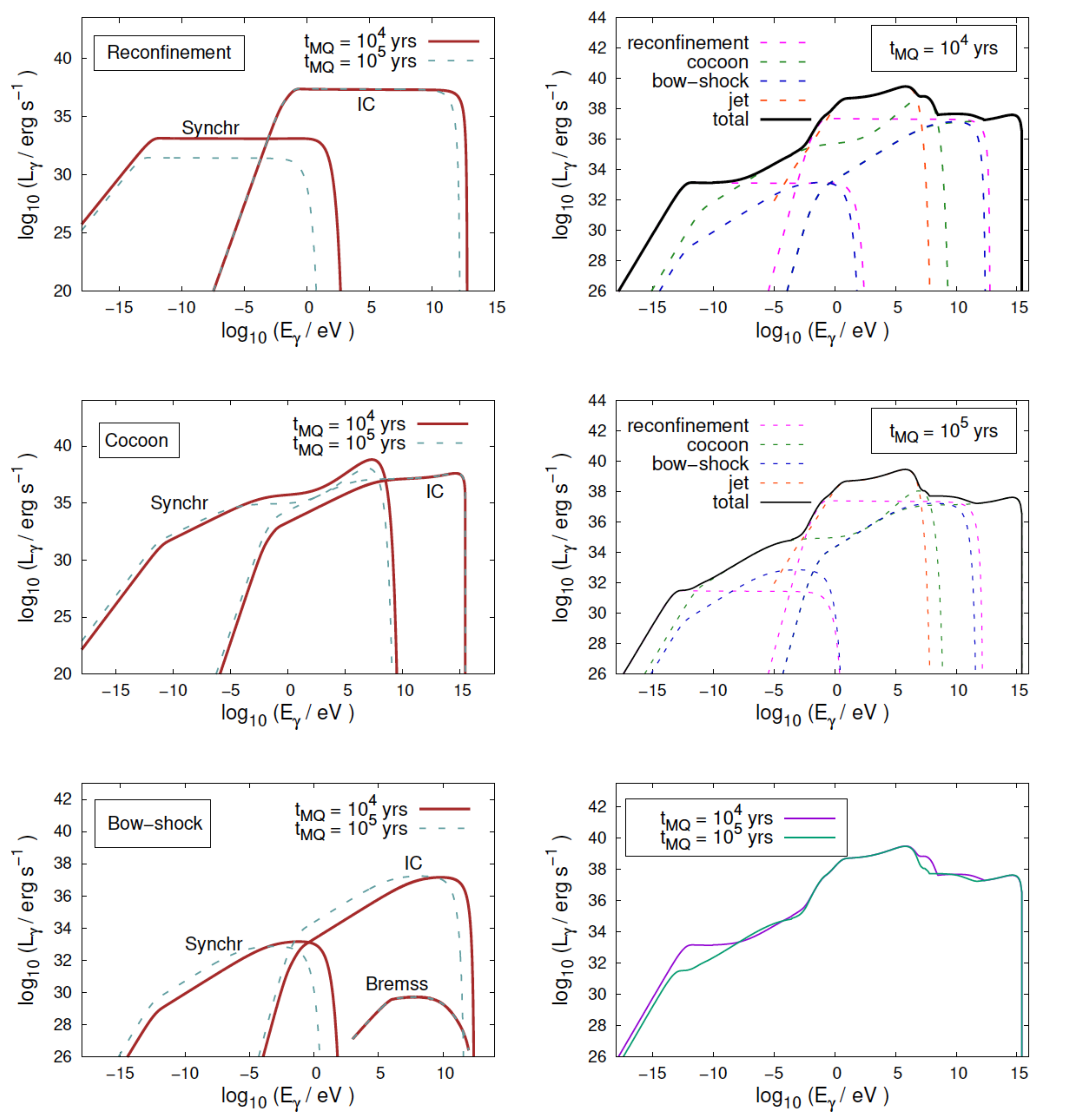
Distance from source to terminal region r~10^{21} cm

Additional sites of particle acceleration



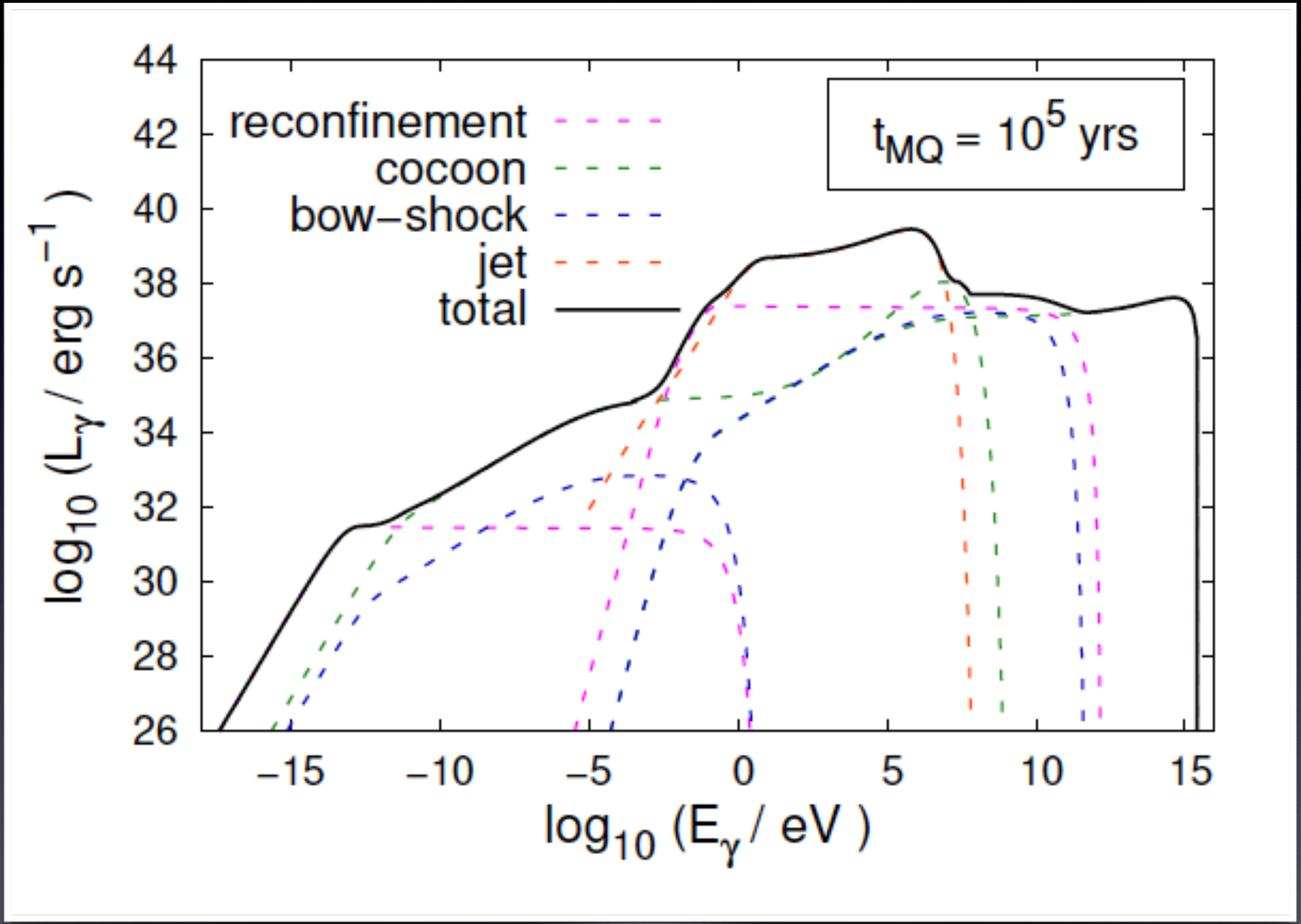
$$z_{\rm recoll} \approx \sqrt{\frac{2\,L_{\rm jet} v_{\rm jet}}{(\gamma + 1)(\Gamma_{\rm jet} - 1)\,\pi c^2 P_{\rm c}}},$$

SEDs outer jet



Sotomayor Checa & Romero, A&A 2019

Total SED



reconfinement
cocoon
bow–shock
jet
total
$t_{MQ} = 10^5$ yrs
$\log_{10} (L_\gamma / \text{erg s}^{-1})$
$\log_{10} (E_\gamma / \text{eV})$
44
42
40
38
36
34
32
30
28
26
–15
–10
–5
0
5
10
15

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.
- This power is deposited at distances of ~10^{21} cm, allowing for de∫ionization well beyond the stelar ionization bubble.
- Bulk velocities are jet. $\Gamma_{\rm jet} \sim 2$.
- 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 Inter proto-GM, far away from the source.
- Total ionizing power very significant: Pop III MQs might have been important in the re-ionisation of the universe, especially the inter bubble medium, if cascades resulted in high multiplicities. E_{ion}~13.6 eV

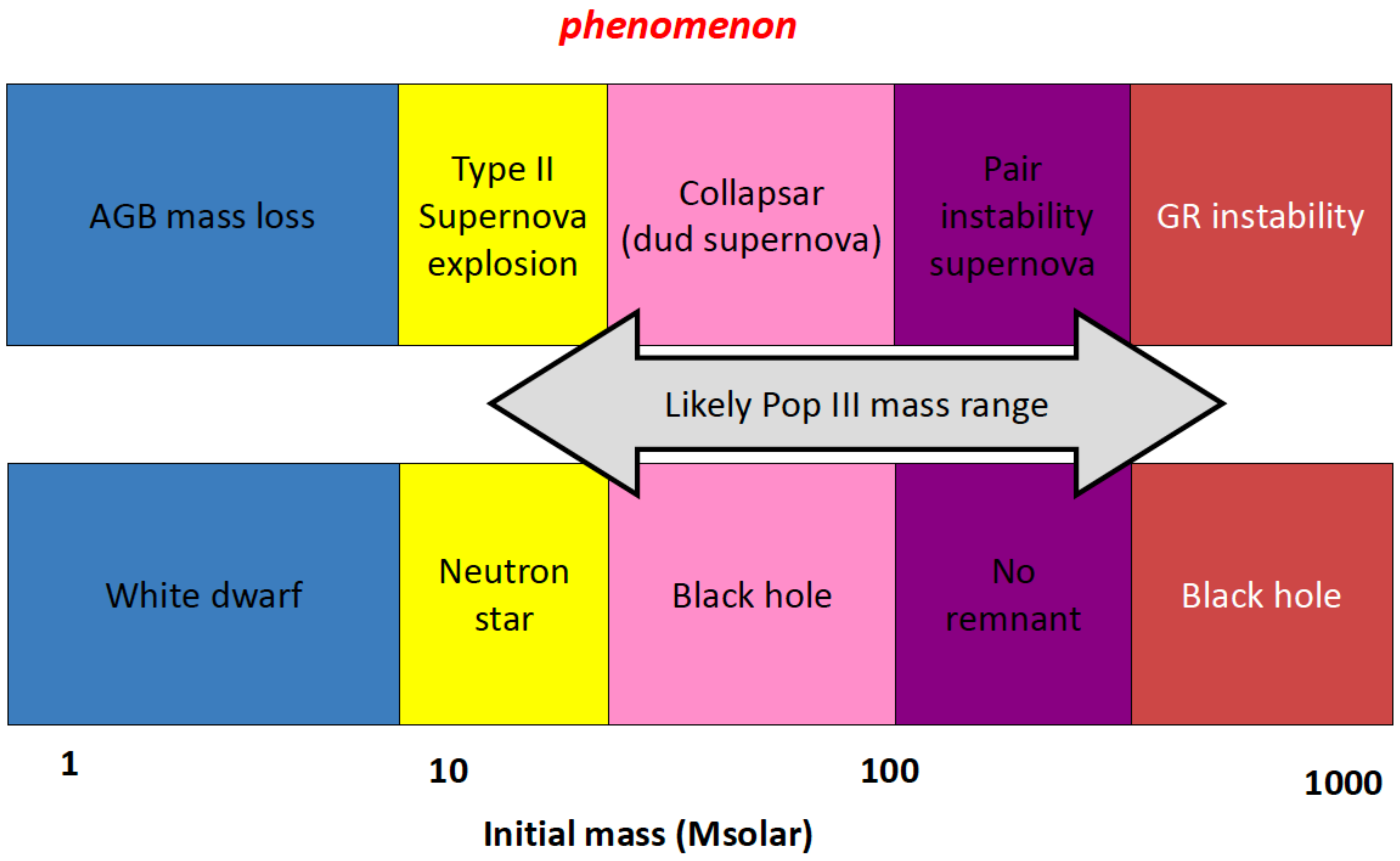
Thanks!

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

Fate and Remnants of Pop III Stars

non-rotating models (Heger & Woosley 2002)



Disk structure

We assume a steady and axisymmetric disk and all physical quantities de-
pend 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). $Q_{\mathrm{adv}} = Q_{\mathrm{vis}} - Q_{\mathrm{rad}} = fQ_{\mathrm{vis}}$

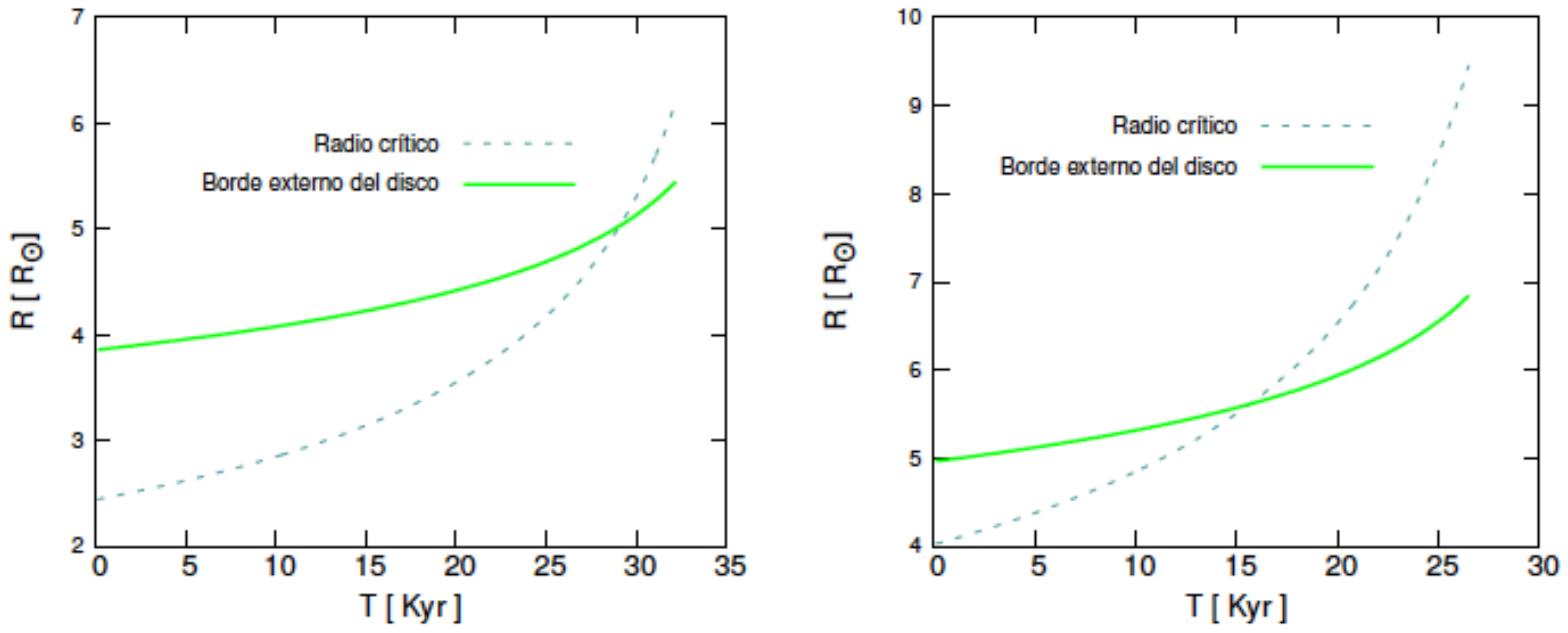
Typical Pop III MQ's parameters.

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	$R_\odot$

	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	$r_{\rm g}$

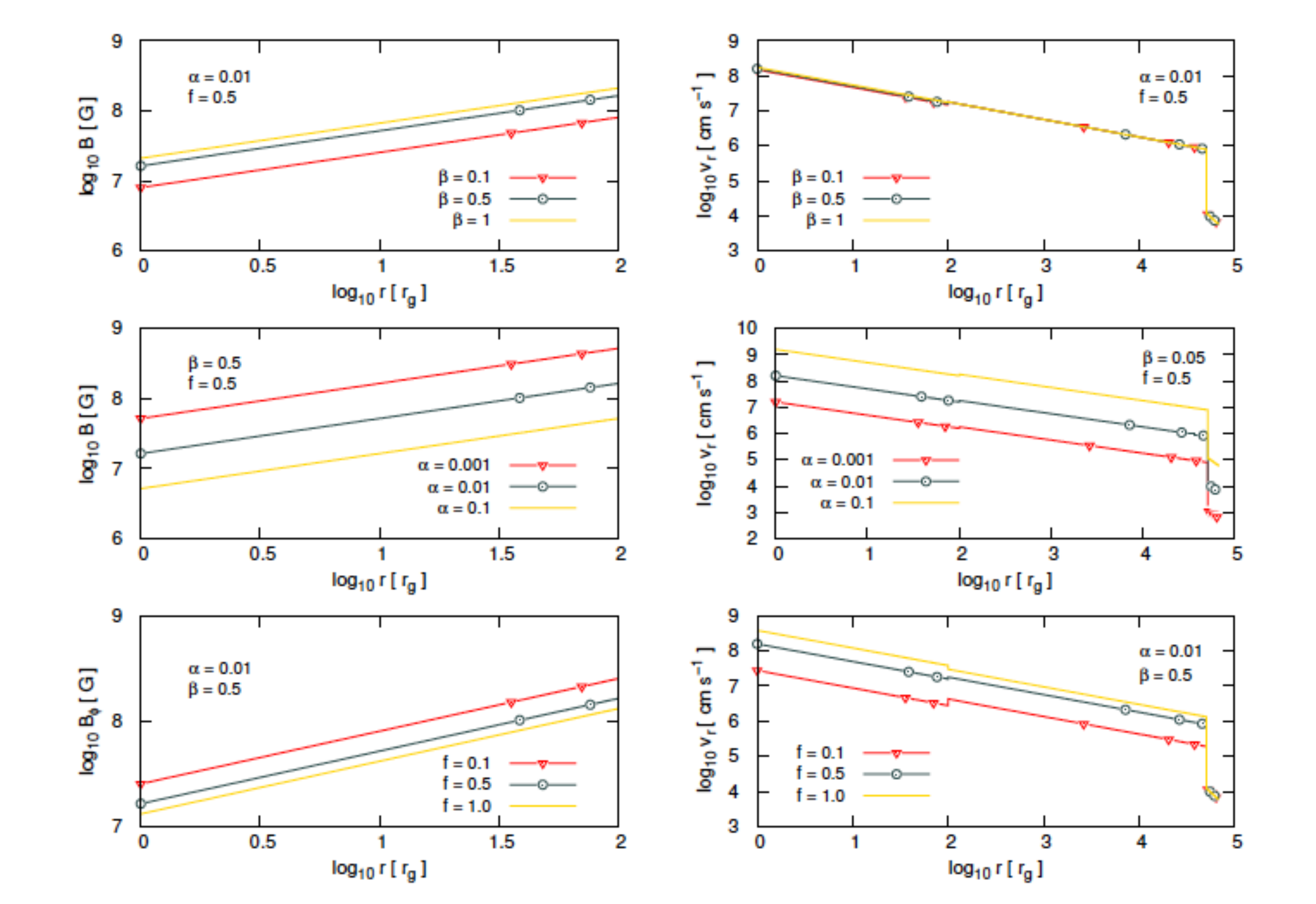
$$L_{\rm disk} = \int_{r_{\rm in}}^{100r_{\rm g}} 2\sigma T_{\rm eff}^4 2\pi r dr \int_{100r_{\rm g}}^{r_{\rm cr}} 2\sigma T_{\rm eff}^4 2\pi r dr + \int_{r_{\rm cr}}^{\infty} 2\sigma T_{\rm eff}^4 2\pi r dr$$

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



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

$$\frac{\partial \vec{B}}{\partial t} = \frac{1}{e n_e} \nabla T_e \times \nabla n_e$$



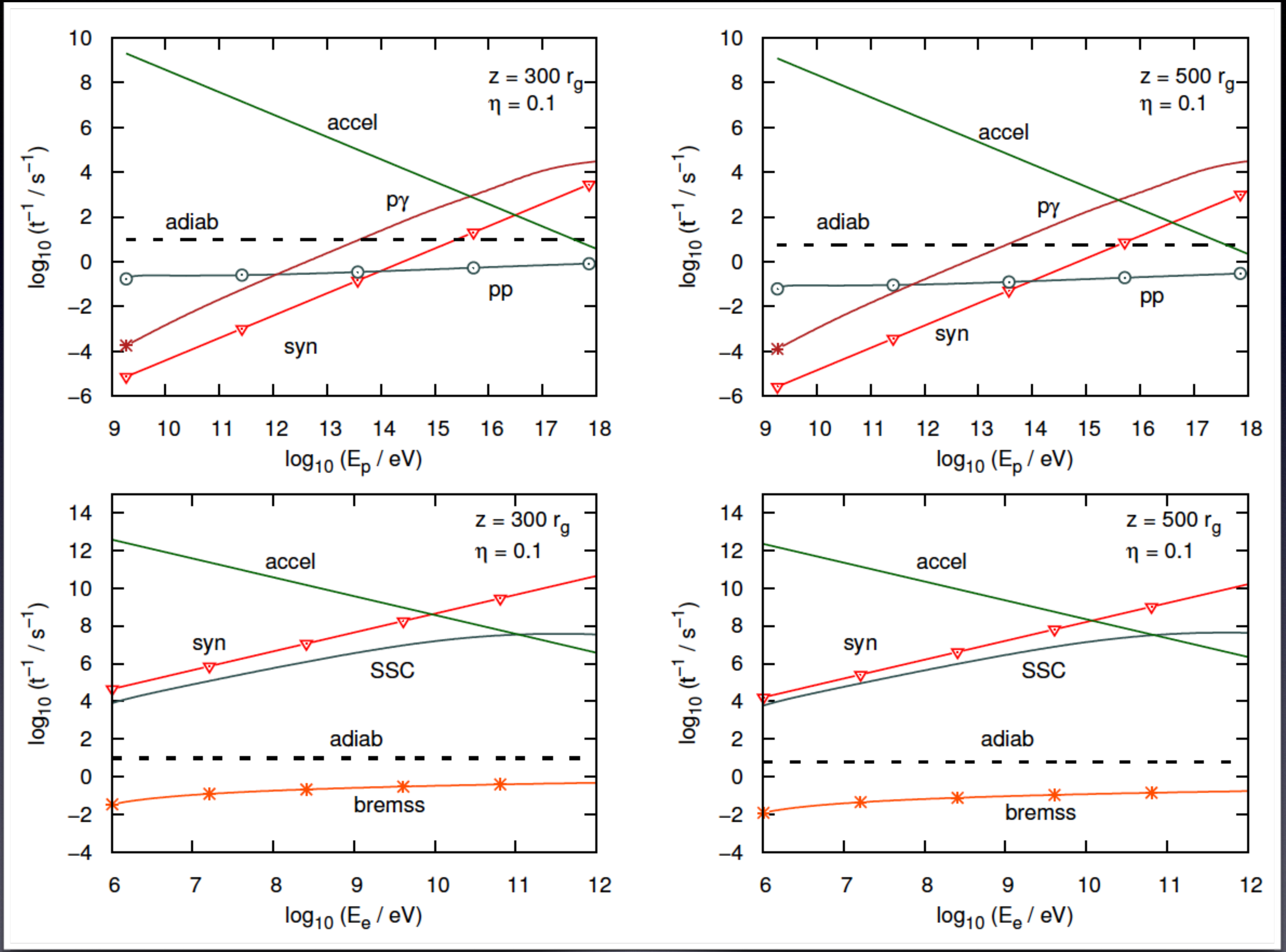
$$\frac{\partial B}{\partial t} \sim 3.6 \times 10^{6} \left(\frac{r}{2r_g}\right)^{-3} \left(\frac{M}{M_\odot}\right)^{-2} \frac{\gamma - 1}{9\gamma - 5} \text{ G/sec,}$$

where γ is the ratio of specific heats.

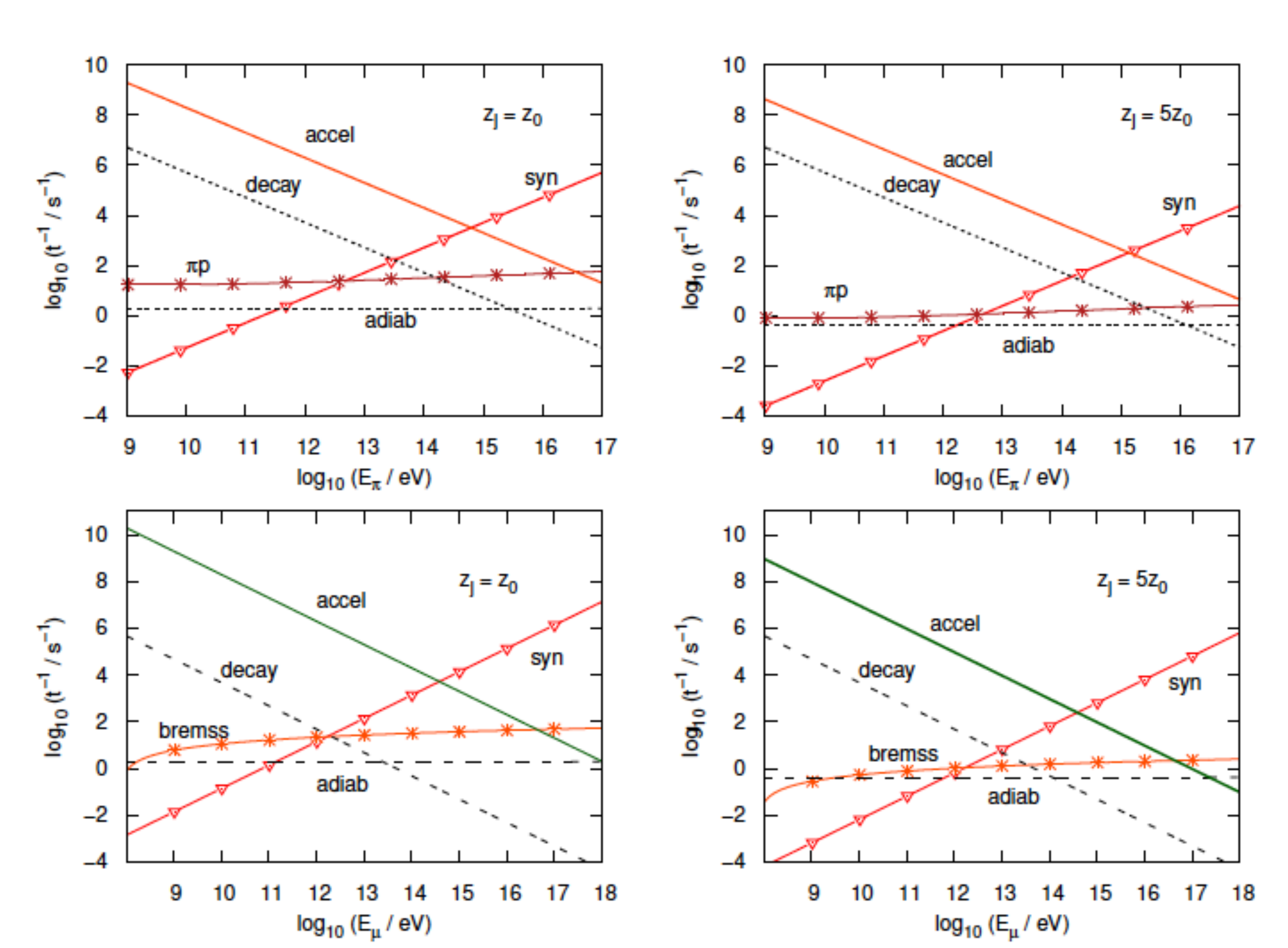
Losses of relativistic particles

p

e



Losses for pions and muons



The first quasars, on the other hand, are predicted to have formed later on, at z ~ 10-15, in more massive dark matter halos, with total masses, ~ 10^8 $M_\odot$, characteristic of dwarf galaxies.