Inferring average radiative efficiency of accretion in ULXs from their XLF

Marat Gilfanov
MPA, Garching

with Wenda Zhang and Rashid Sunyaev

Radiative efficiency of accretion

$$L(\dot{M}) = \eta(\dot{M}) \times \dot{M} c^2$$

radiative efficiency of accretion

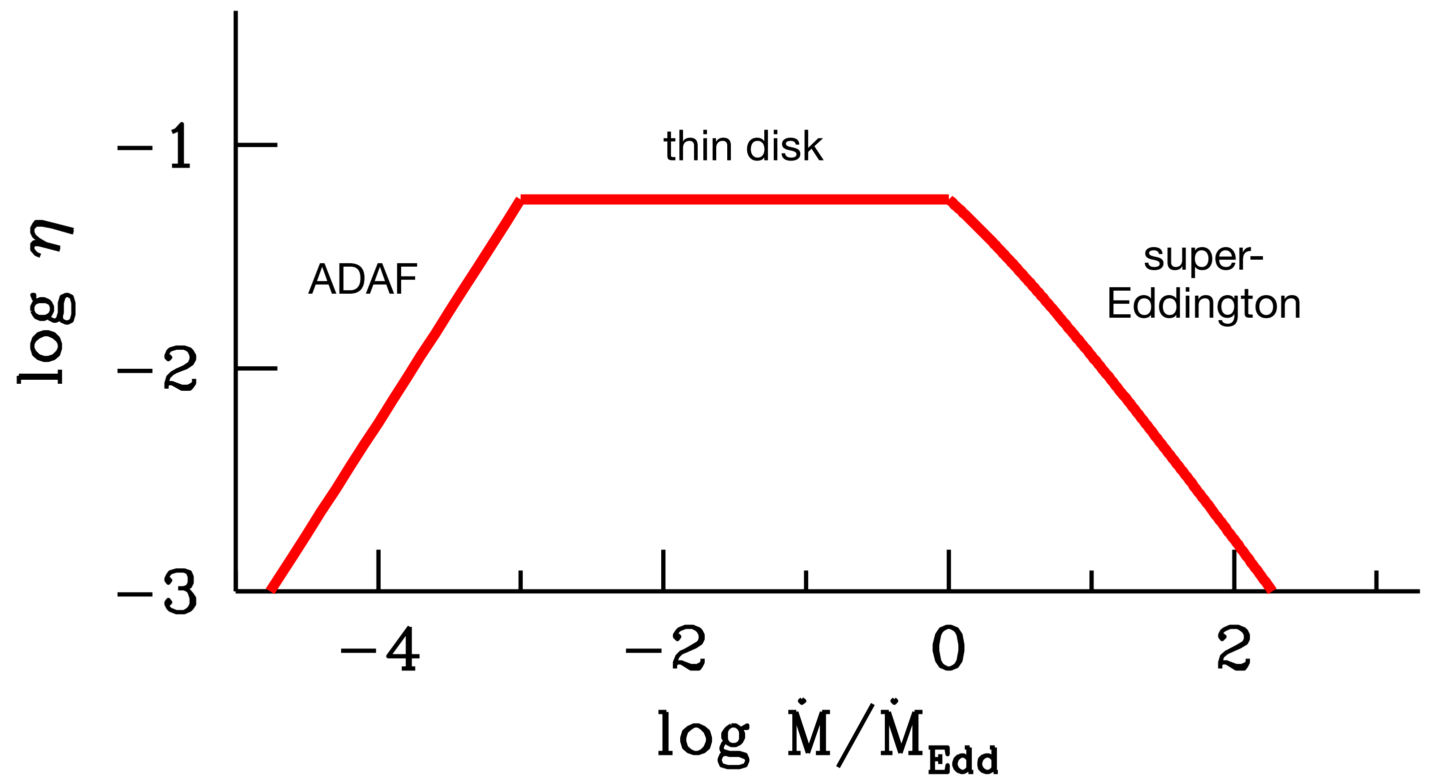
$$\eta(\dot{M}) = \frac{L(\dot{M})}{\dot{M}}$$

is difficult to measure (main difficulty is $\dot{M}$)

$\dot{M}$ - mass transfer rate (e.g. at the Roche lobe or Bondi radius)

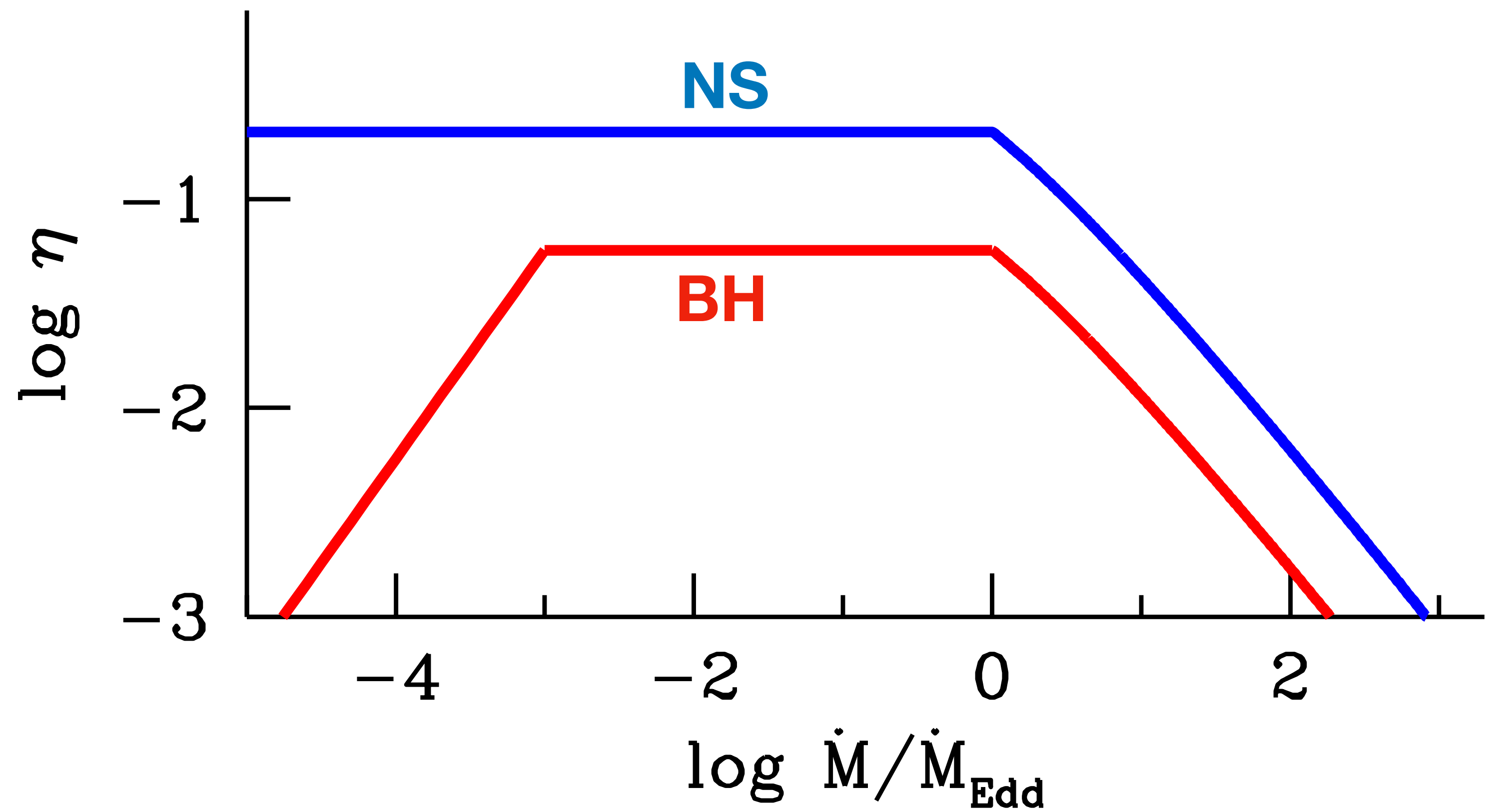
L - bolometric (mostly X-ray) luminoisty

Radiative efficiency of accretion (BH)



- thin Shakura-Sunyaev disk: $\eta \sim const$ (=0.057 for a nr BH)
- ADAF at small $\dot{M}$: $\eta \sim \dot{m}$
  (Naraya & Yi; Narayan+1998)
- super-Eddington regime: $\eta \sim \frac{\ln \dot{m}}{\dot{m}}, \quad L = L_{Edd} \times (1 + \ln \dot{m})$
  (Shakura & Sunyaev 1973;
  Abramowicz+ 1988)

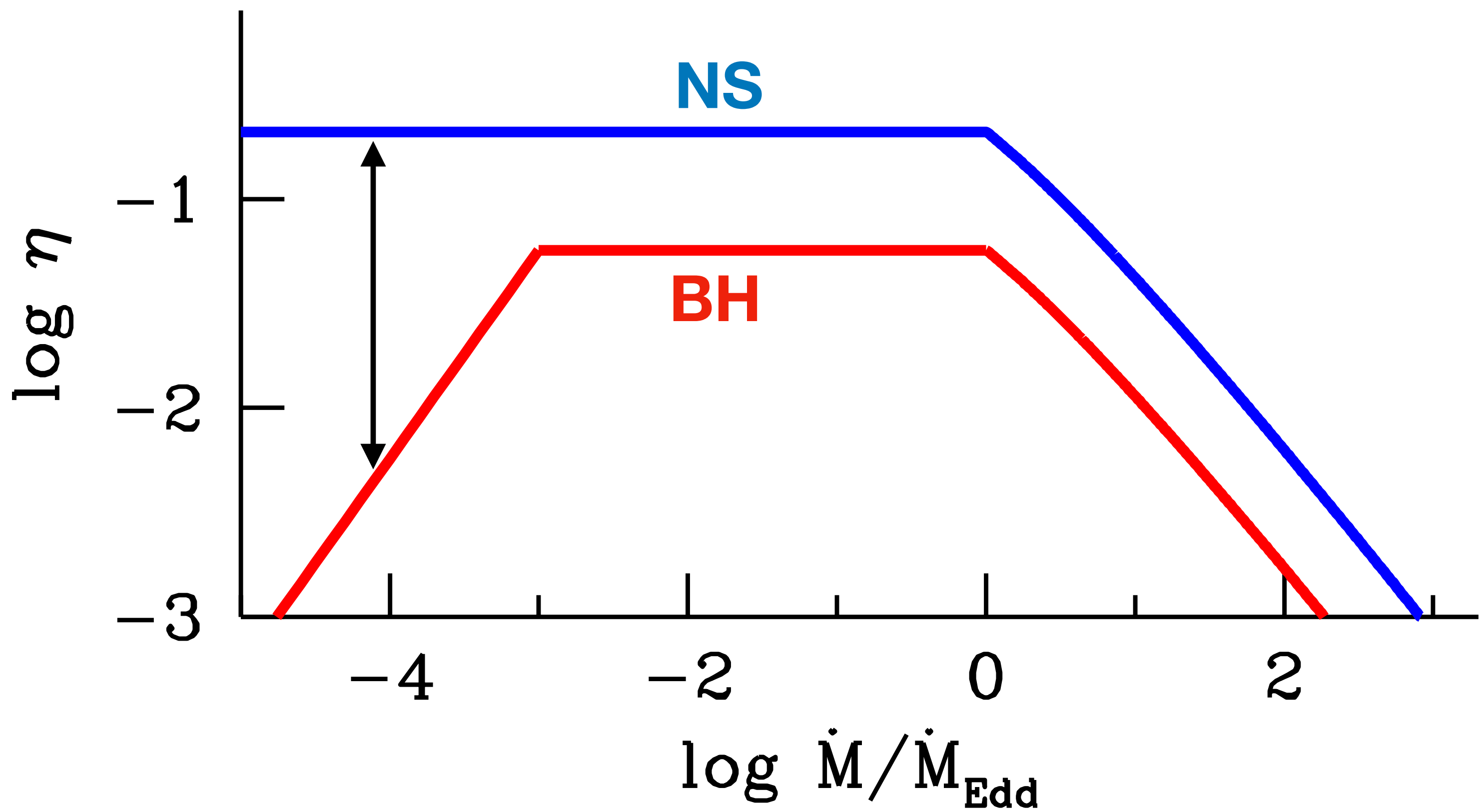
Radiative efficiency of accretion in BH and NS



- boundary layer near NS surface ~doubles the luminosity: non-rotating NS: $\eta = 0.21$ (EOS FPS, Sibgatullin & Sunyaev 2000)
- ADAF regime still exists, but no drop of the total accretion efficiency (Yi et al., 1996)

Radiative efficiency of accretion in BH and NS

Narayan, Garcia, McClintock 1997



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A method to measure the radiative efficiency of accretion in the population average sense

Relation between XLF and Mdot distribution

$$L = L(\dot{M})$$

$$\frac{dN}{dL} = \frac{dN}{d\dot{M}} \times \frac{d\dot{M}}{dL}$$

$$\int_L^{\infty} \frac{dN}{dL} dL = \int_L^{\infty} \frac{dN}{d\dot{M}} \times \frac{d\dot{M}}{dL} dL$$

$$\int_L^{\infty} \frac{dN}{dL} dL = \int_{\dot{M}(L)}^{\infty} \frac{dN}{d\dot{M}} \, d\dot{M}$$

$$N(>L) = N(>\dot{M}(L))$$

Population averaged accretion efficiency

$$N(>L) = N(>\dot{M}(L))$$

XLF of X-ray binaries **known!**

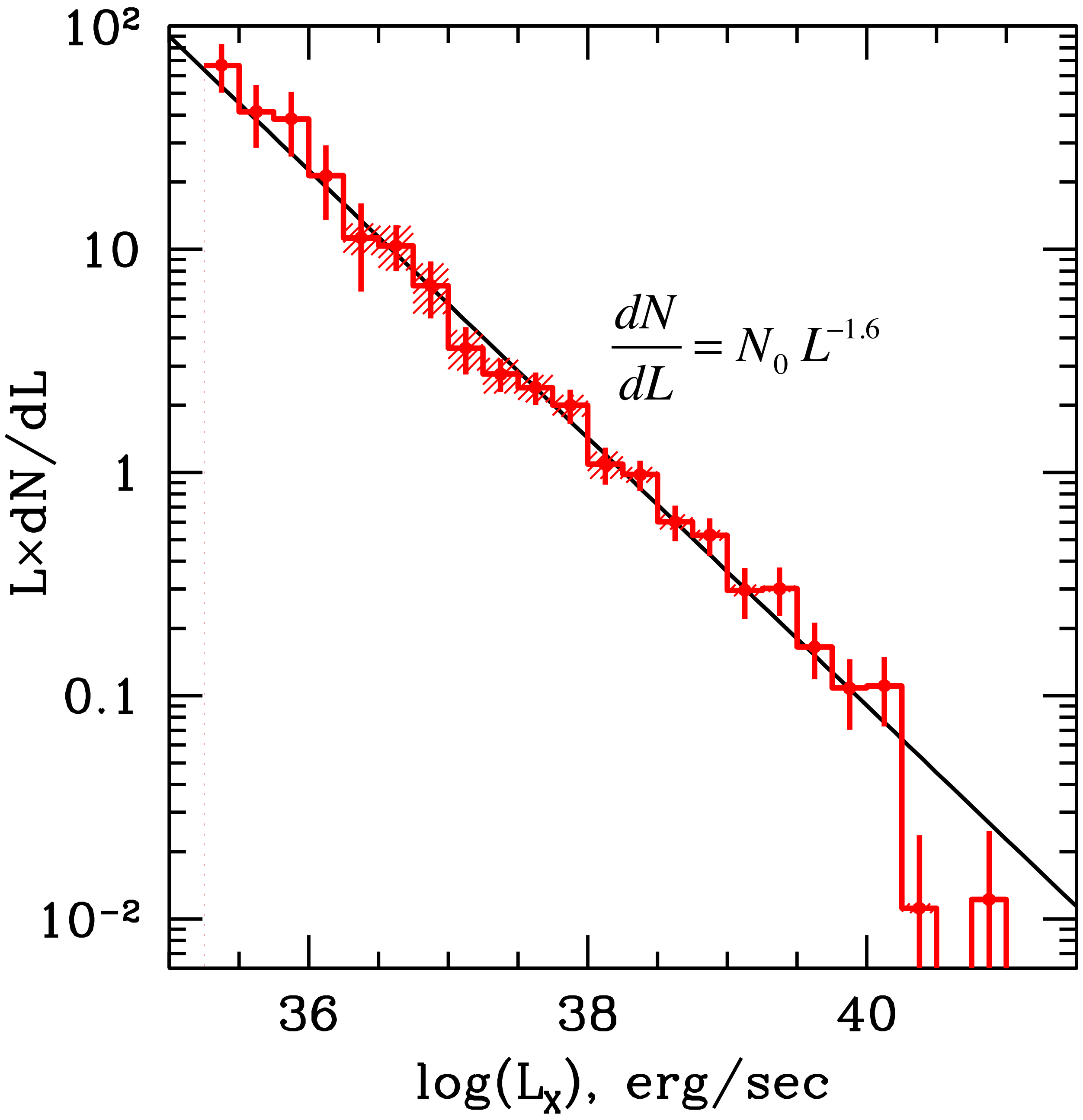
distribution of binaries over mass-transfer rate:

- from observations (difficult!)
- from binary population synthesis calculation
- inferred from some other considerations

X-ray luminosity function of HMXBs

a power law with a roll-over or a cut-off at $\log(L_X)\sim40$

Grimm, MG, Sunyaev, 2003
Swartz et al., 2004, 2011
Mineo, MG, Sunyaev, 2012



Mdot distribution

at $\log(L_X) \sim 35...38$ (thin disk case) one should expect

$$L = \eta_0 \dot{M} c^2$$

$$\frac{dN}{d\dot{M}} = \eta_0 c^2 \frac{dN}{dL} \quad \Rightarrow \quad \frac{dN}{d\dot{M}} = N_0 \left(\eta_0 c^2\right)^{-0.6} \dot{M}^{-1.6}$$

assuming that $\frac{dN}{d\dot{M}} = N_0 \left(\eta_0 c^2\right)^{-0.6} \dot{M}^{-1.6}$ in the entire $\dot{M}$ range of interest

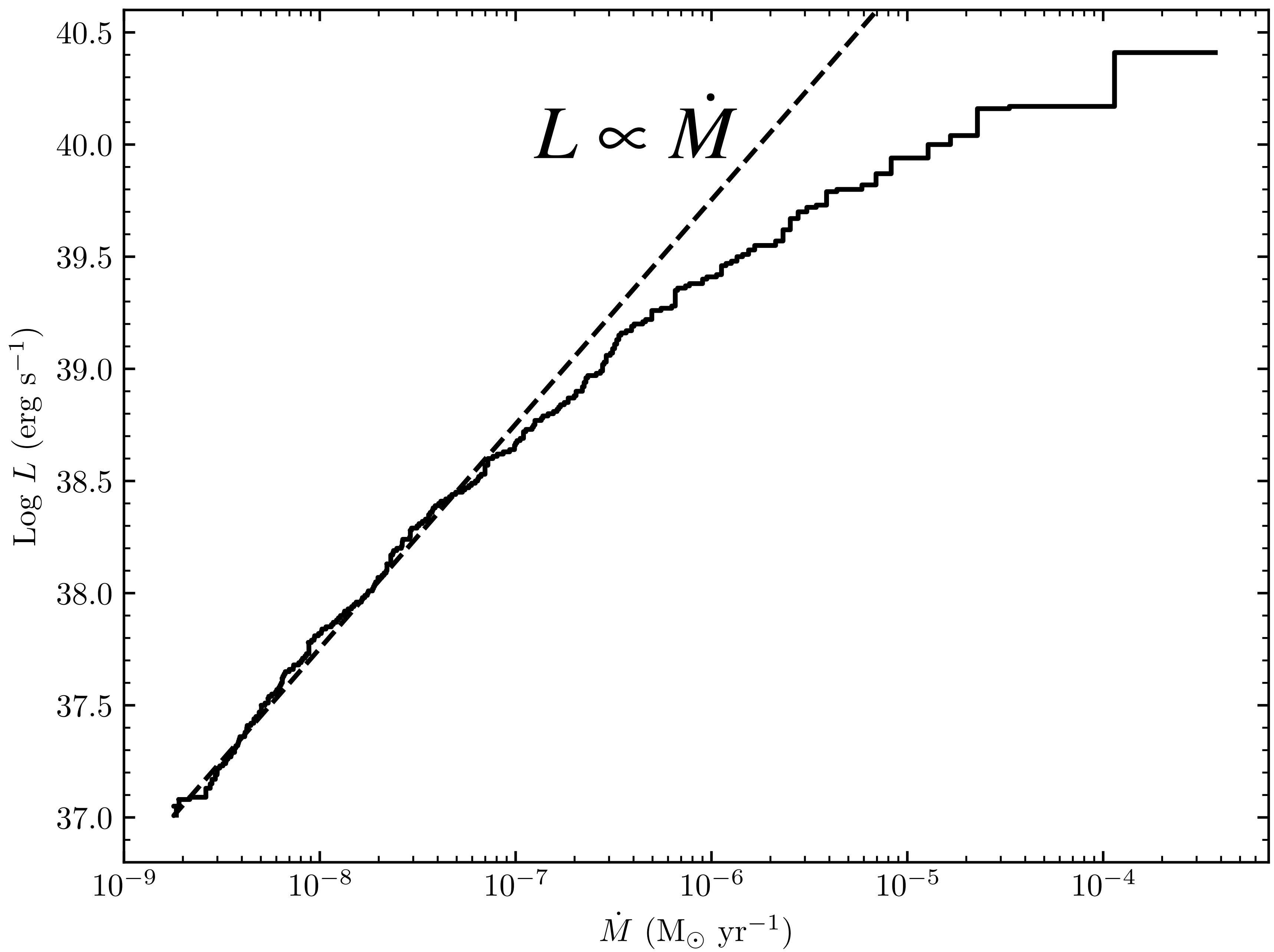
we obtain:

$$\dot{M}(L) = \frac{1}{\eta_0 c^2} \left[\frac{0.6\, N(>L)}{N_0}\right]^{-\frac{1}{0.6}} \quad \text{and} \quad \eta = \eta_0 \frac{L N_0^{-\frac{1}{0.6}}}{\left[0.6\, N(>L)\right]^{-\frac{1}{0.6}}}$$

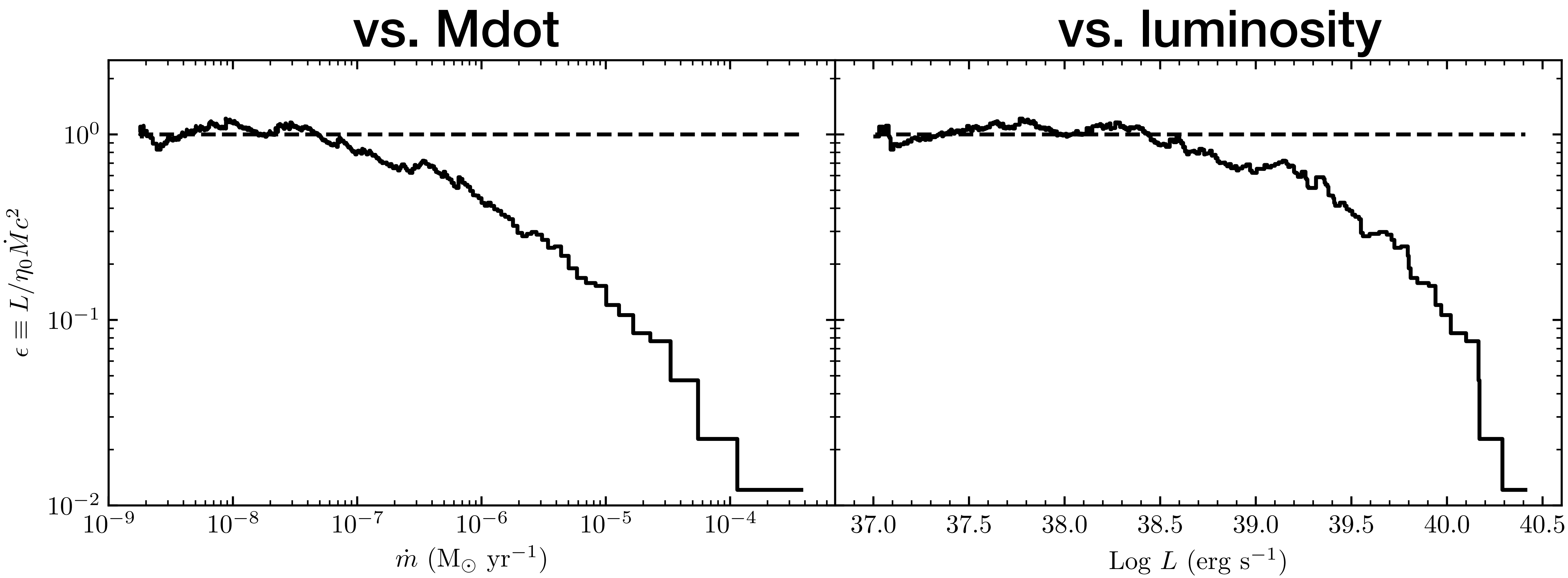
where $N(>L)$ is the observed XLF of HMXBs

This formula is valid as long as $\frac{dN}{d\dot{M}} \propto \dot{M}^{-1.6}$ extends to sufficiently high $\dot{M}$

Average Mdot-L_X relation for HMXBs



Average radiative efficiency of HMXBs



- nearly constant at $\log(L_X) \leq 38.5$
- starts to decline near L_{Edd} for a neutron star
- drops down by a factor of ~10 in the ULX regime
  brightest ULXs must be fed at ~10^{-5} Msun/yr

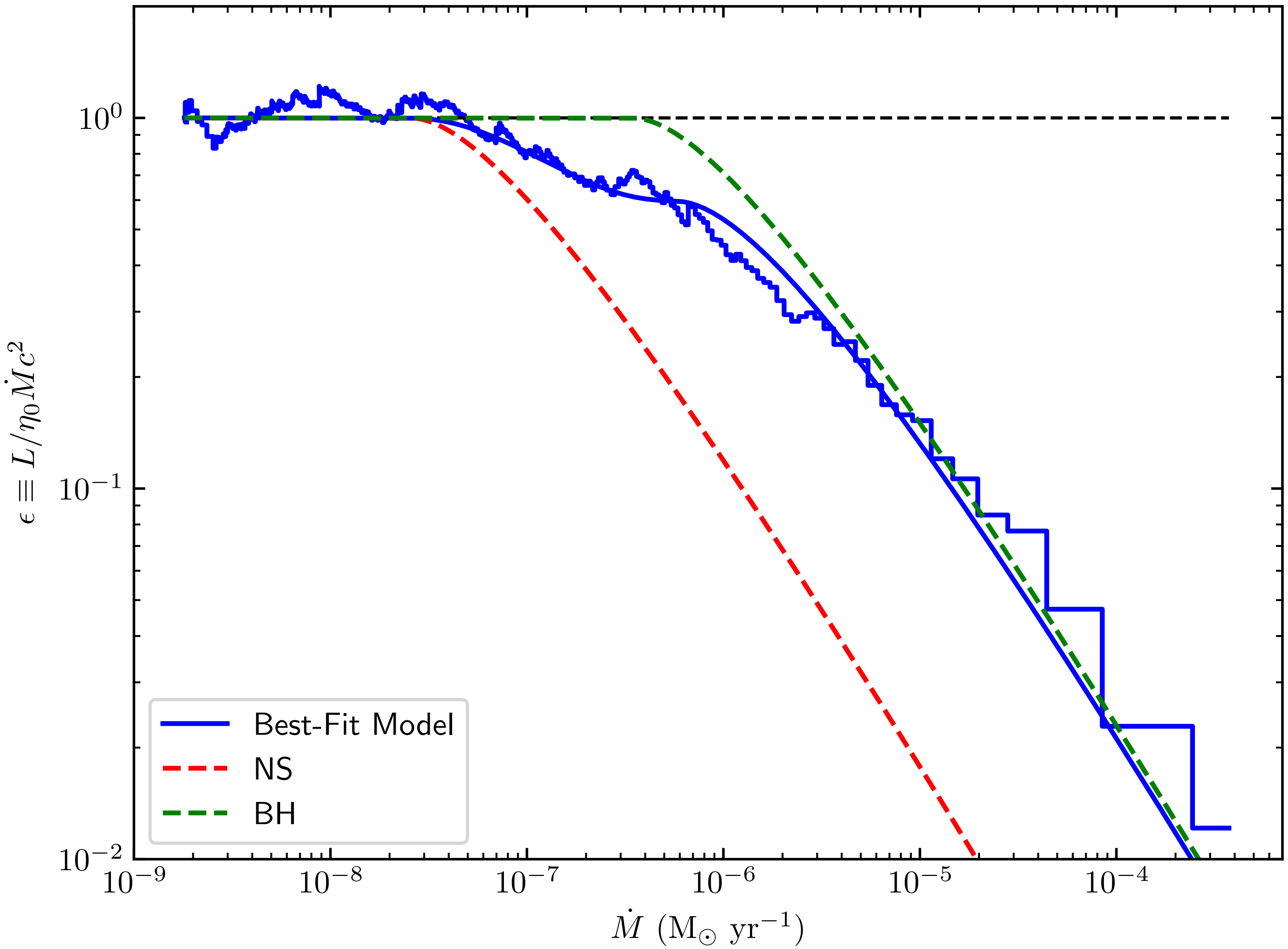
Fit with a $L_X = L_{Edd}(1 + \ln \dot{m})$ model

- one population model does not work
- a model of two populations with different L_{Edd} good fit
- parameters of the two populations:

population	mass	fraction
light (=NS)	$1.0^{+0.62}_{-0.36}\ M_\odot$	0.26 ± 0.10
heavy (=BH)	$13.5^{+3.5}_{-2.3}\ M_\odot$	0.74 ± 0.10

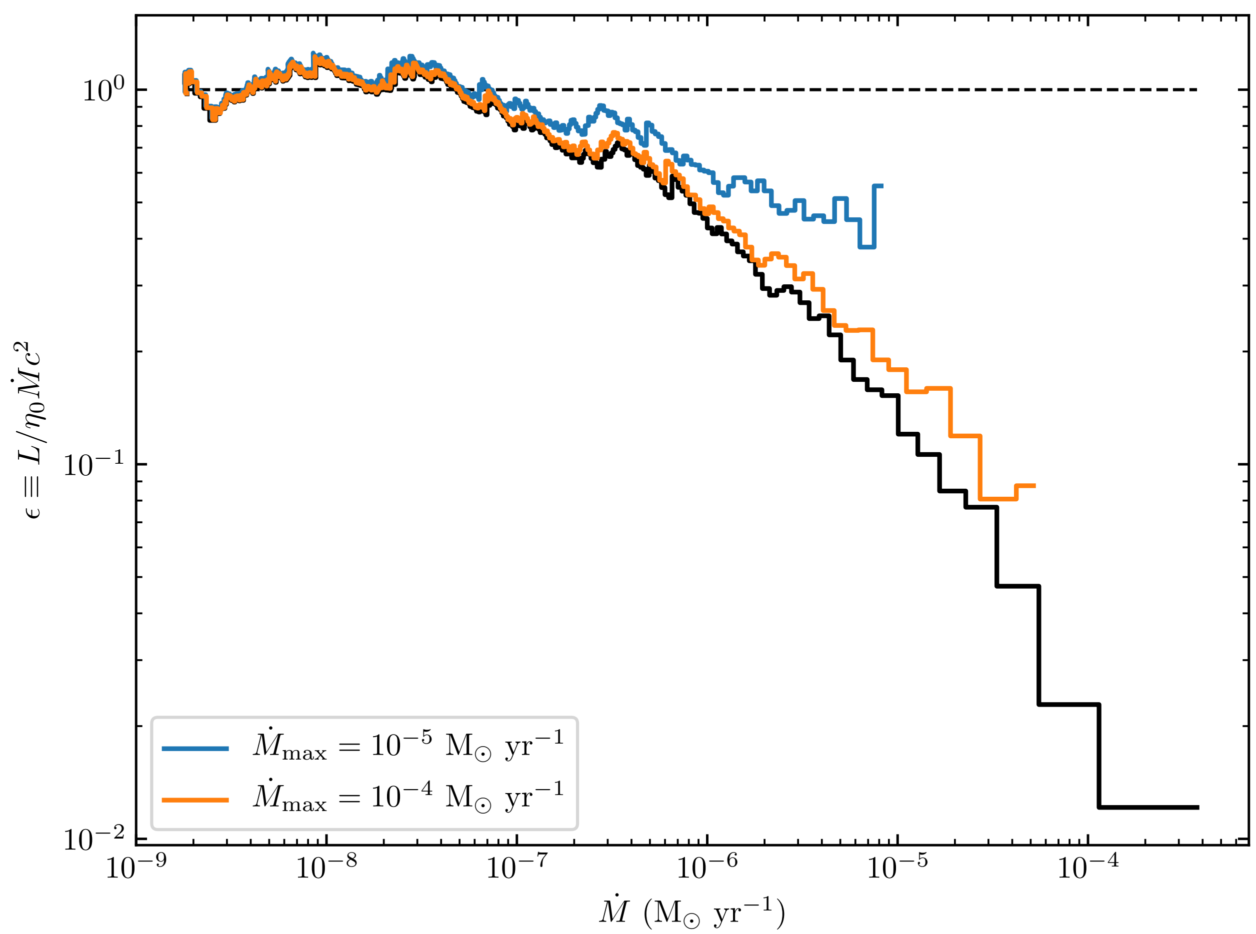
- model require large fraction of the BH population

Best-fit two population model



Impact of a cut-off in the $\dot{M}$ distribution

- it was assumed that $\frac{dN}{d\dot{M}} \propto \dot{M}^{-1.6}$ continues to $\dot{M} > 10^{-4}\ M_{\odot}/yr$
- if the $\dot{M}$ - distribution significantly steepens at $\dot{M} \sim 10^{-5}\ M_{\odot}/yr$ average radiative efficiency in ULXs must be high
- conversely, $\dot{M}$-distribution can not be significantly steeper than the $\dot{M}^{-1.6}$ law much below $\dot{M} \sim 10^{-6}\ M_{\odot}/yr$



Summary

- population average radiative efficiency of ULXs:
  - nearly constant at $\log(L_X) \leq 38.5$
  - starts to decline near L_{Edd} for a neutron star
  - drops down by a factor of ~10 in the ULX regime
    brightest ULXs must be fed at ~10^{-5} Msun/yr and
    lose about ~90% of the material in outflows
  - shape is well described by the $\propto (1+\ln \dot{m})$ law
- can be well approximated with a two population model with masses of populations close to NS and BH masses

- the model does not anticipate existence of ULX pulsars which may not have much impact due to their relatively small numbers

Thank you!