AGN Winds, Black Holes, and Galaxies

Andrew King

Charleston, October 2011

three points

1. brightest AGN should have *X-ray or UV outflows* with

$$\dot{M}v \simeq \frac{L_{\rm Edd}}{c}, \; v \sim \eta c \sim 0.1c$$

2. outflow shock against host ISM *cools* if close to BH; host ISM feels $P_{\rm ram} \simeq L_{\rm Edd}/c$, =>

$$M_{\rm BH} = M_\sigma \simeq \frac{f_g \kappa}{2\pi G^2}\sigma^4$$

3. shock does *not* cool if far from BH (i.e. if $M > M_\sigma$) host ISM feels $L_{\rm mech} \simeq \frac{\eta}{2} L_{\rm Edd} \simeq 0.05 L_{\rm Edd}$

=> *large-scale fast molecular outflows*

=> *galaxy becomes red and dead*

super—Eddington outflows: SMBH—bulge connection?

how super—Eddington are AGN?

galaxy bulge ~ isothermal sphere, with mass distribution

$$M(R) = \frac{f_g \sigma^2 R}{G}$$

maximum possible accretion rate: this mass falls in dynamical time

$$t_{\rm dyn} \sim \frac{R}{\sigma}$$

so

$$\dot{M}_{\rm max} \sim \frac{f_g \sigma^3}{G} \sim 100 \sigma_{200}^3 \ M_\odot \ {\rm yr}^{-1}$$

Eddington rate at $M - \sigma$ mass is

$$\dot{M}_{\rm Edd} = 3\sigma_{200}^4 \eta_{0.1}^{-1} M_{\odot}\ {\rm yr}^{-1}$$

so Eddington ratio $\dot{m}$ of outflow is modest

$$\dot{m} = \frac{\dot{M}_{\rm out}}{\dot{M}_{\rm Edd}} << 30 \frac{\eta_{0.1}}{\sigma_{200}}$$

i.e. we expect $\dot{m} \sim 1$

AGN are never *very* super--Eddington

nature of outflows

outflow has optical depth ~ 1, ➔ outflow momentum is of order photon momentum, i.e.

$$\dot{M}v \simeq \frac{L_{\rm Edd}}{c}$$

implying

$$v \simeq \frac{\eta}{\dot{m}} c \sim 0.1c$$

momentum conservation, modest optical depth ➔ $v \sim 0.1c$

cf talk by Ken Osuga

outflow has low a.m., so quasi--spherical:

mass conservation equation

$$\dot{M}_{\rm out} = 4\pi b N R^2 m_p v$$

implies ionization parameter

$$\xi = \frac{L_i}{NR^2} = 3 \times 10^4 \eta_{0.1}^2 \left(\frac{l_i}{10^{-2}} \right) \dot{m}^{-2}$$

where L_i = ionizing luminosity, and $l_i = L_i/L$

for a given quasar spectrum, ionizing component l_i must correspond to photon energy implied by ξ

mass conservation ➔ *X—rays ,UV*

so Eddington outflows <=> X--ray, UV lines with $v \sim 0.1c$

effect on host galaxy must be significant

SMBH binding energy $\eta c^2 M$ exceeds bulge binding energy $\sigma^2 M_b$

outflow shock

outflow must shock against bulge gas and shock -- what happens?

either

(a) shocked gas cools in flow time `momentum--driven flow': negligible thermal pressure

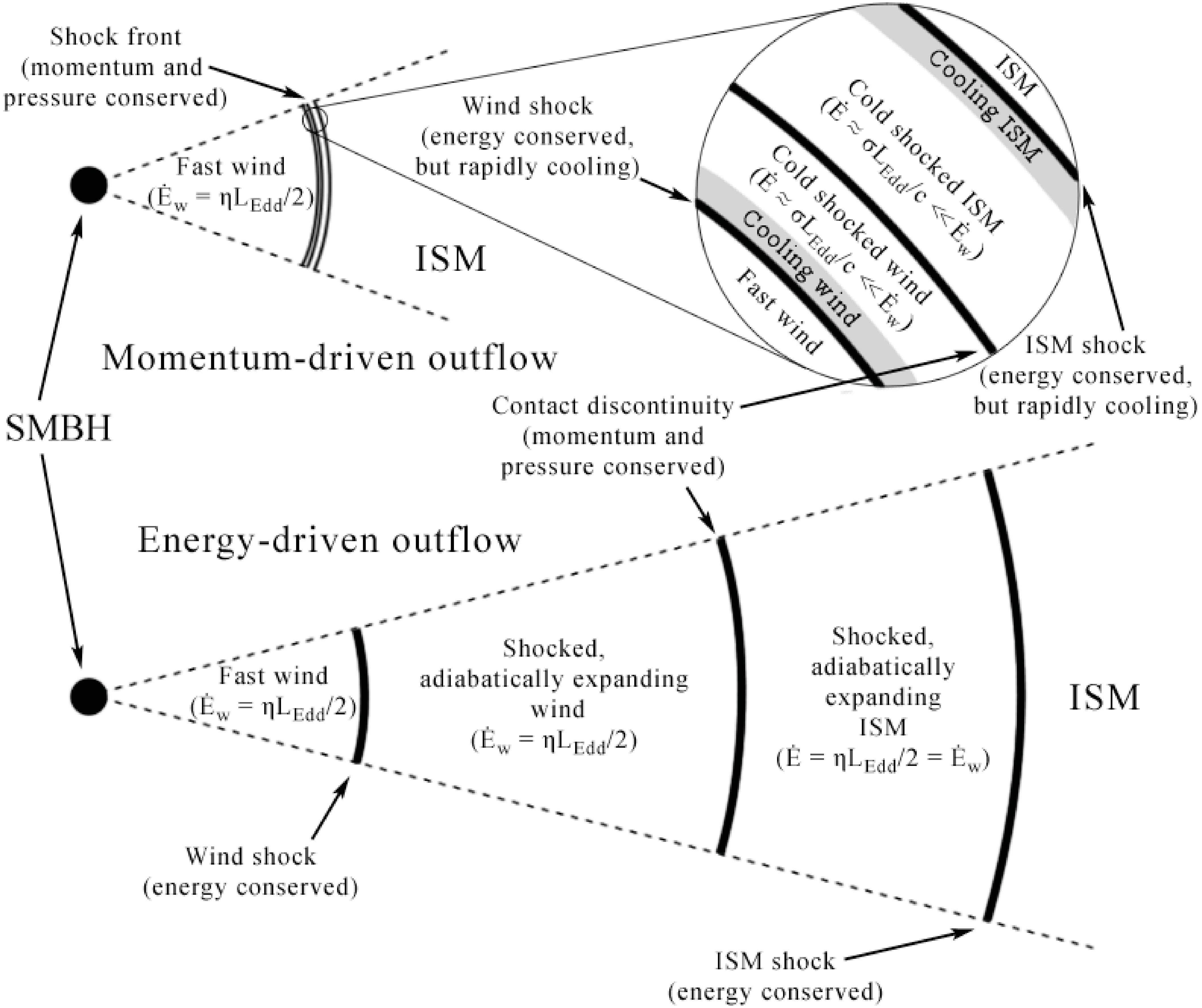
or

(b) shocked gas does not cool . . . . `energy--driven flow': adiabatic expansion of hot bubble

Compton cooling by quasar radiation field very effective out to bulge radii ~ 1 kpc (cf Ciotti & Ostriker, 1997, 2001), other cooling ineffective

so

flows are momentum--driven at small radii, energy--driven at large



Shock front
(momentum and
pressure conserved)

Fast wind
($\dot{E}_w = \eta L_{Edd}/2$)

Wind shock
(energy conserved,
but rapidly cooling)

ISM

ISM

Cooling ISM

Cold shocked ISM
($\dot{E} \approx \sigma L_{Edd}/c \ll \dot{E}_w$)

Cold shocked wind
($\dot{E} \approx \sigma L_{Edd}/c \ll \dot{E}_w$)

Cooling wind

Fast wind

Momentum-driven outflow

ISM shock
(energy conserved,
but rapidly cooling)

Contact discontinuity
(momentum and
pressure conserved)

SMBH

Energy-driven outflow

Fast wind
($\dot{E}_w = \eta L_{Edd}/2$)

Shocked,
adiabatically expanding
wind
($\dot{E}_w = \eta L_{Edd}/2$)

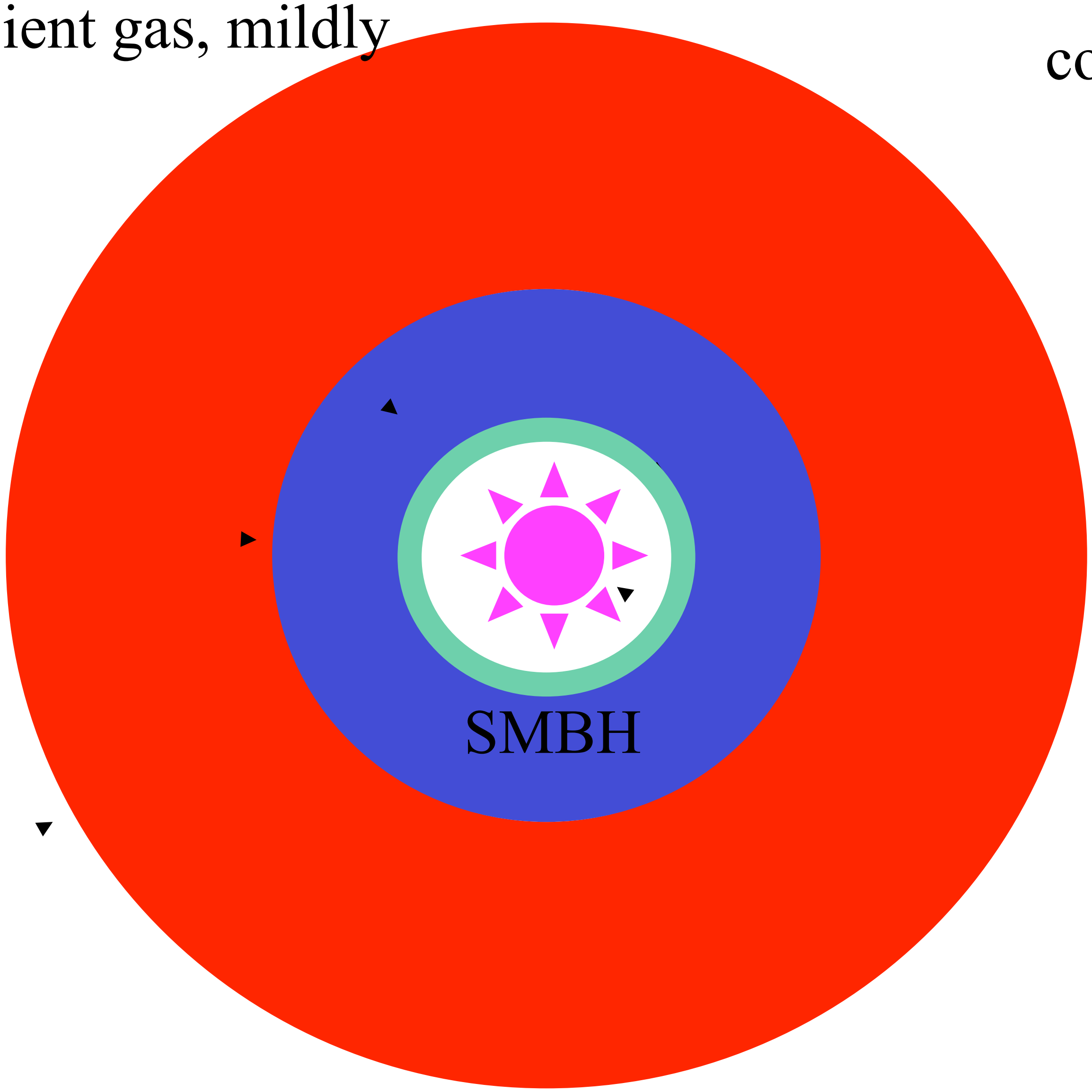
Shocked,
adiabatically
expanding
ISM
($\dot{E} = \eta L_{Edd}/2 = \dot{E}_w$)

ISM

Wind shock
(energy conserved)

ISM shock
(energy conserved)

shock pattern near AGN



swept-up ambient gas, mildly
shocked

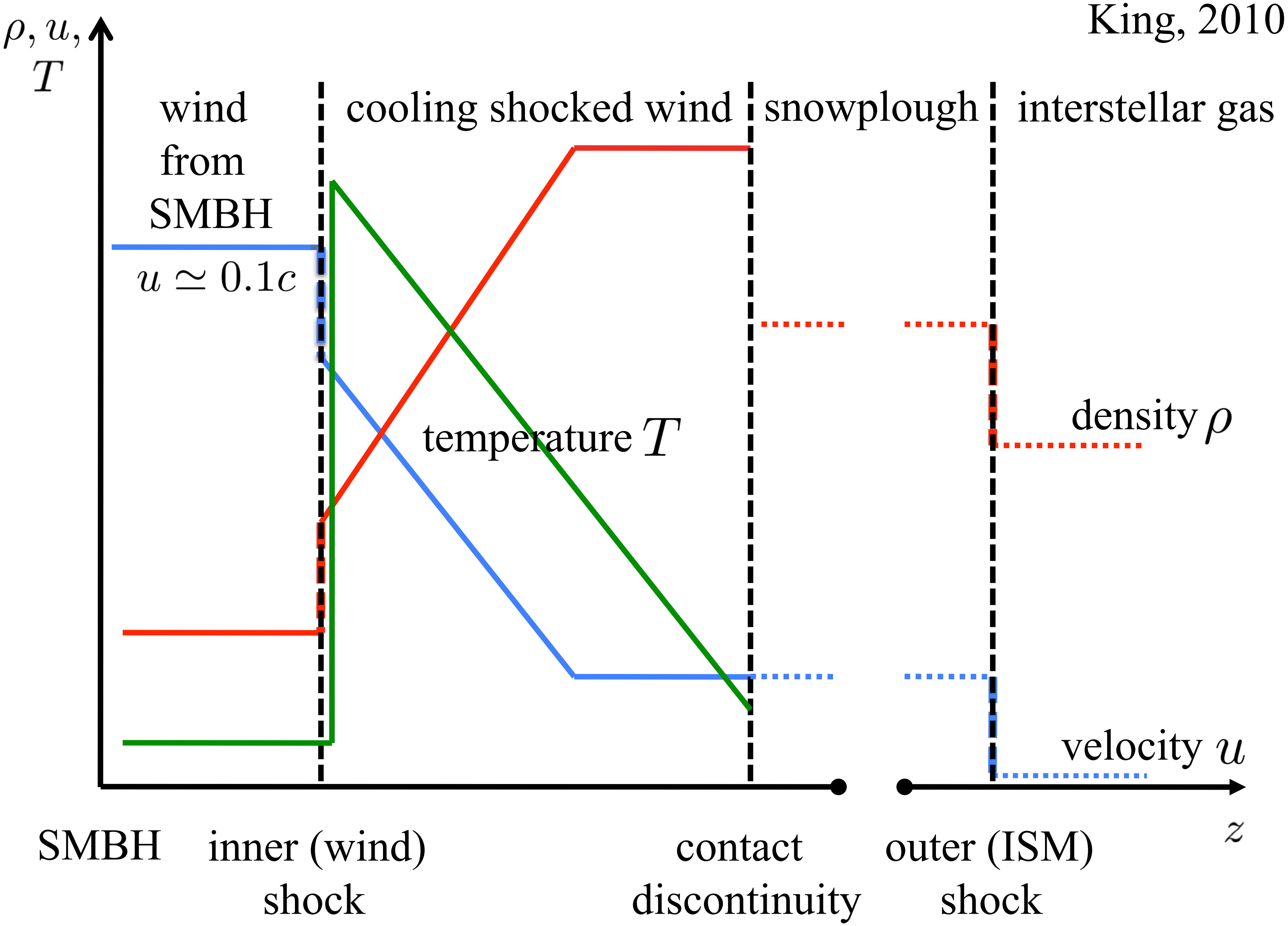
cooling shocked
wind
(`momentum –
driven’)

outer shock
driven into
ambient gas

ambient gas

Eddington
wind,
v ~ *0.1c*

(single scattering limit)


$\rho, u,$
T
wind
from
SMBH
$u \simeq 0.1c$
cooling shocked wind
snowplough
interstellar gas
temperature T
density ρ
velocity u
z
SMBH
inner (wind)
shock
contact
discontinuity
outer (ISM)
shock

King, 2010

evidence for cooling shock

ionization parameter decreases with outflow velocity as required by mass conservation

$$\dot{M}_{\rm out} \propto \frac{L_i v}{\xi} = {\rm const}$$

NGC 4051, Pounds & Vaughan, 2011

effect on galaxy: M – sigma relation

(simple derivation)

matter originally distributed so that

$$\frac{GM_{tot}(R)}{R} = 2\sigma^2$$

with

$$\frac{GM_{gas}(R)}{R} = 2f_g\sigma^2 \qquad (f_g \approx 0.16)$$

at radius R total *weight* of shell is

$$\frac{GM_{tot}M_{gas}}{R^2} = \frac{4f_g\sigma^4}{G}$$

BH mass grows until Eddington thrust $\frac{L_{\rm Edd}}{c}$ matches this weight, i.e.

$$\frac{4\pi GM_{BH}}{\kappa} = \frac{4f_g\sigma^4}{G}$$

or

$$\boxed{M_{BH} = \frac{f_g\kappa}{\pi G^2}\sigma^4}$$

(King, 2003; 2005)

NB: *no free parameter*

full derivation using equation of motion of swept-up shell gives factor 1/2; with $f_g = 0.16,$ get

$$M = 2 \times 10^8 M_\odot \sigma_{200}^4$$

so Eddington outflows <=> X--ray, UV lines with $v \sim 0.1c$

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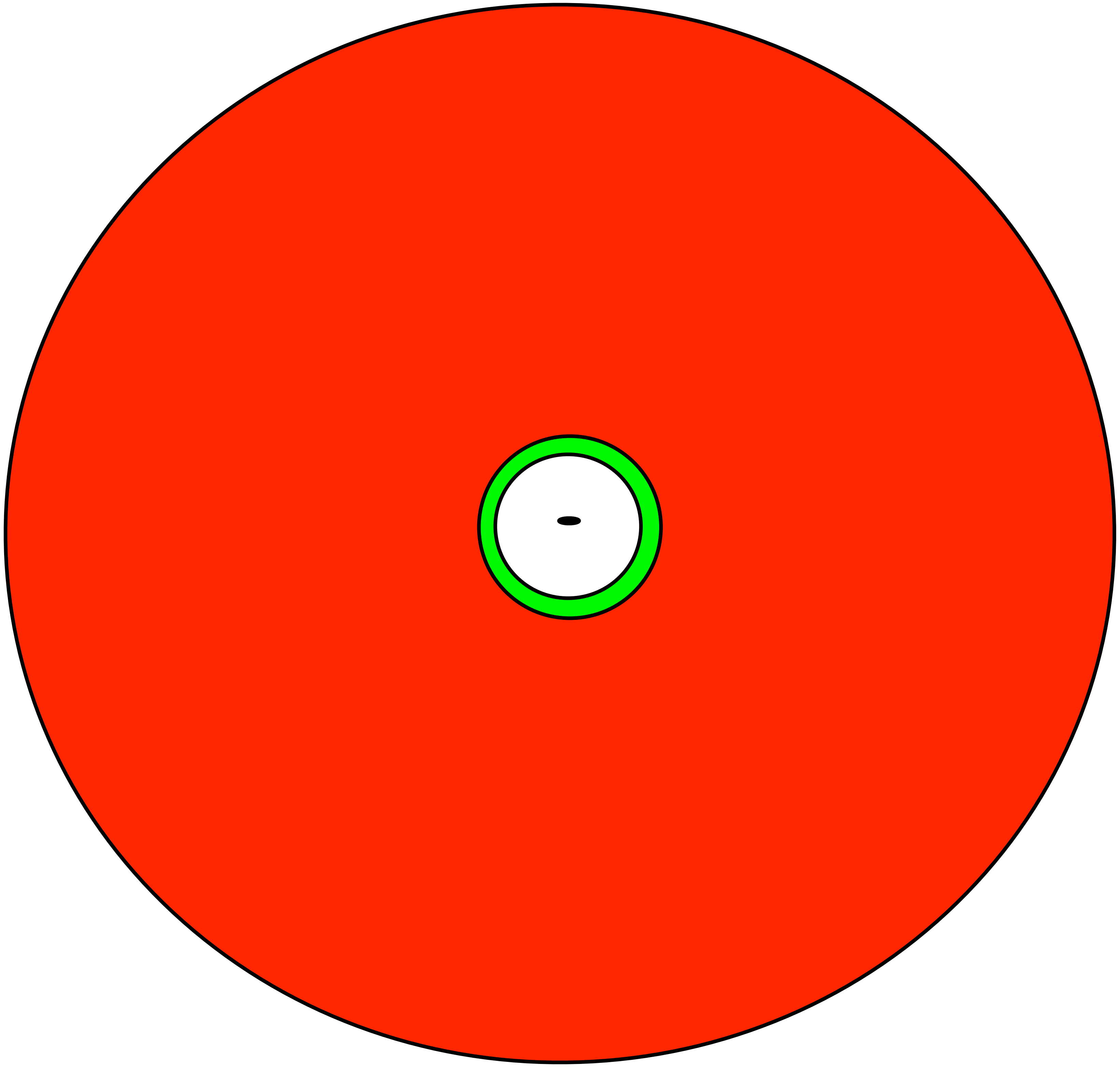
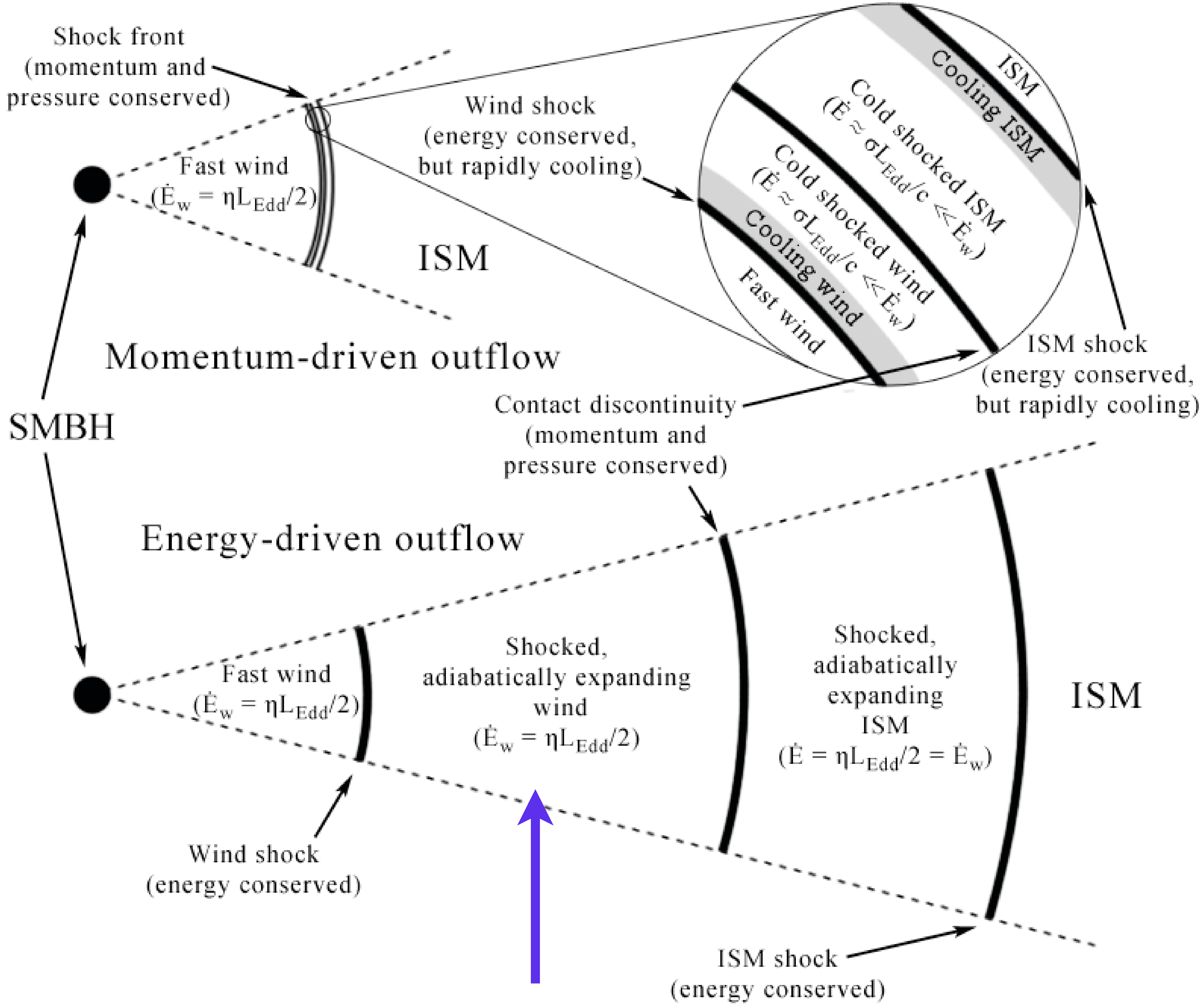
most of binding energy is radiated away:
if not, M would be smaller by a factor $\times (c/\sigma) \sim 1000$
cf Silk & Rees, 1998, which implies $M \sim 10^5 M_\odot$

shells confined to vicinity of BH until $M = M_\sigma$

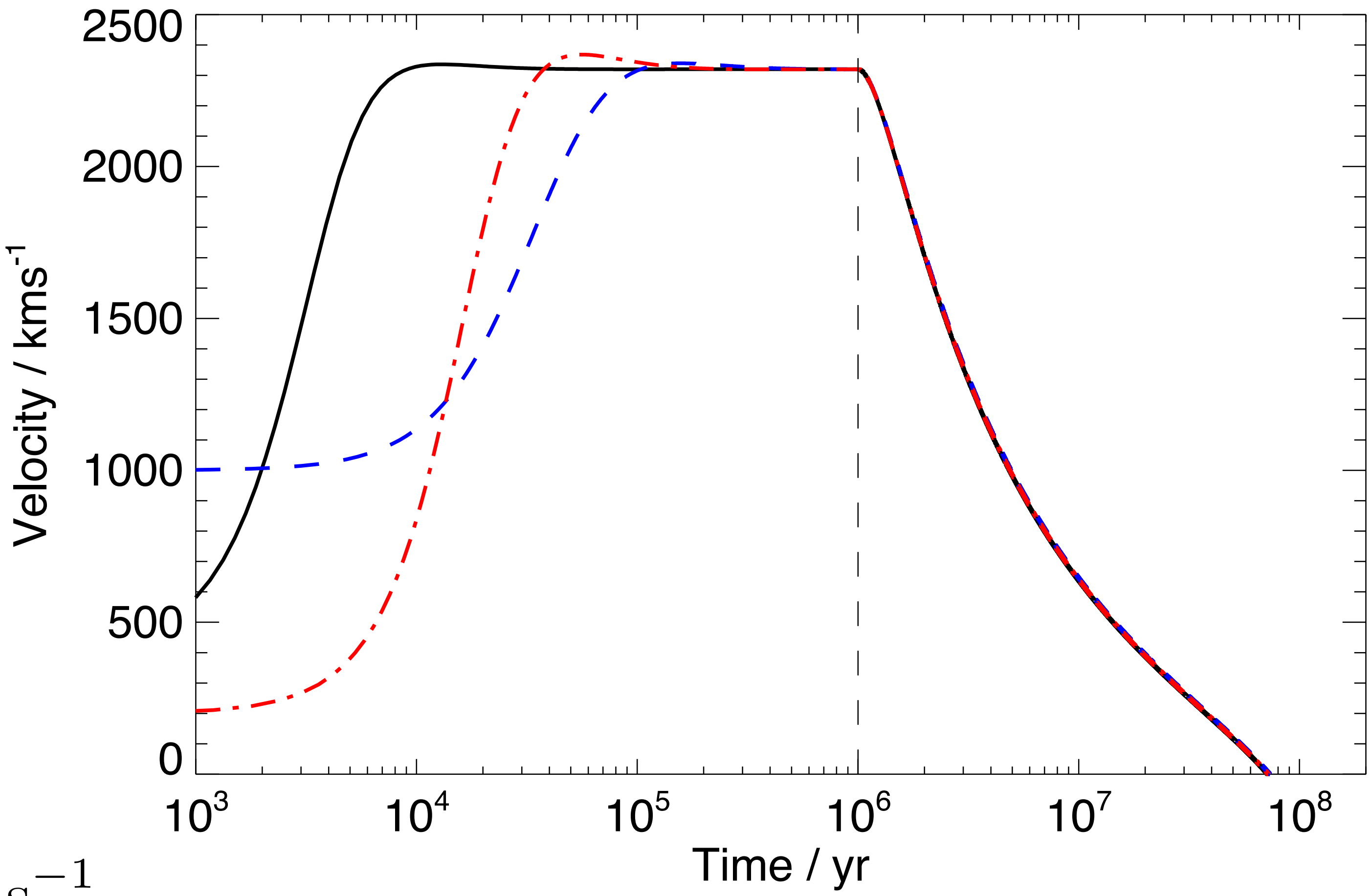
fallback may give redshifted absorptions





once BH grows to $M > M_\sigma$, shock passes cooling radius

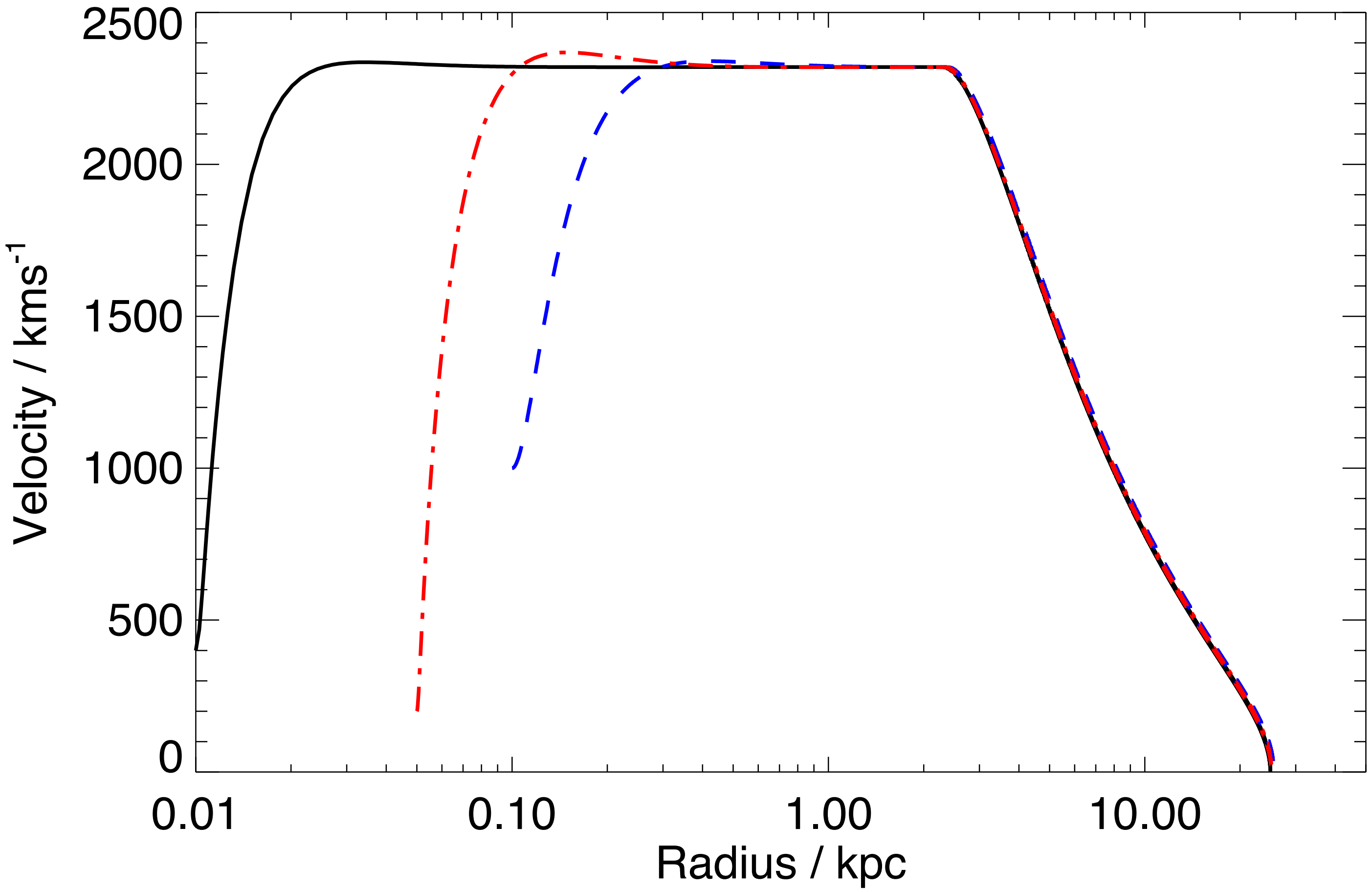
=> large-scale energy-driven flow



energy--driven outflows rapidly converge to

$$v_e \simeq \left[\frac{2\eta f_c}{3f_g}\sigma^2 c\right]^{1/3} \simeq 925\sigma_{200}^{2/3}(f_c/f_g)^{1/3}\ \mathrm{km\ s^{-1}}$$

and persist even after central quasar turns off



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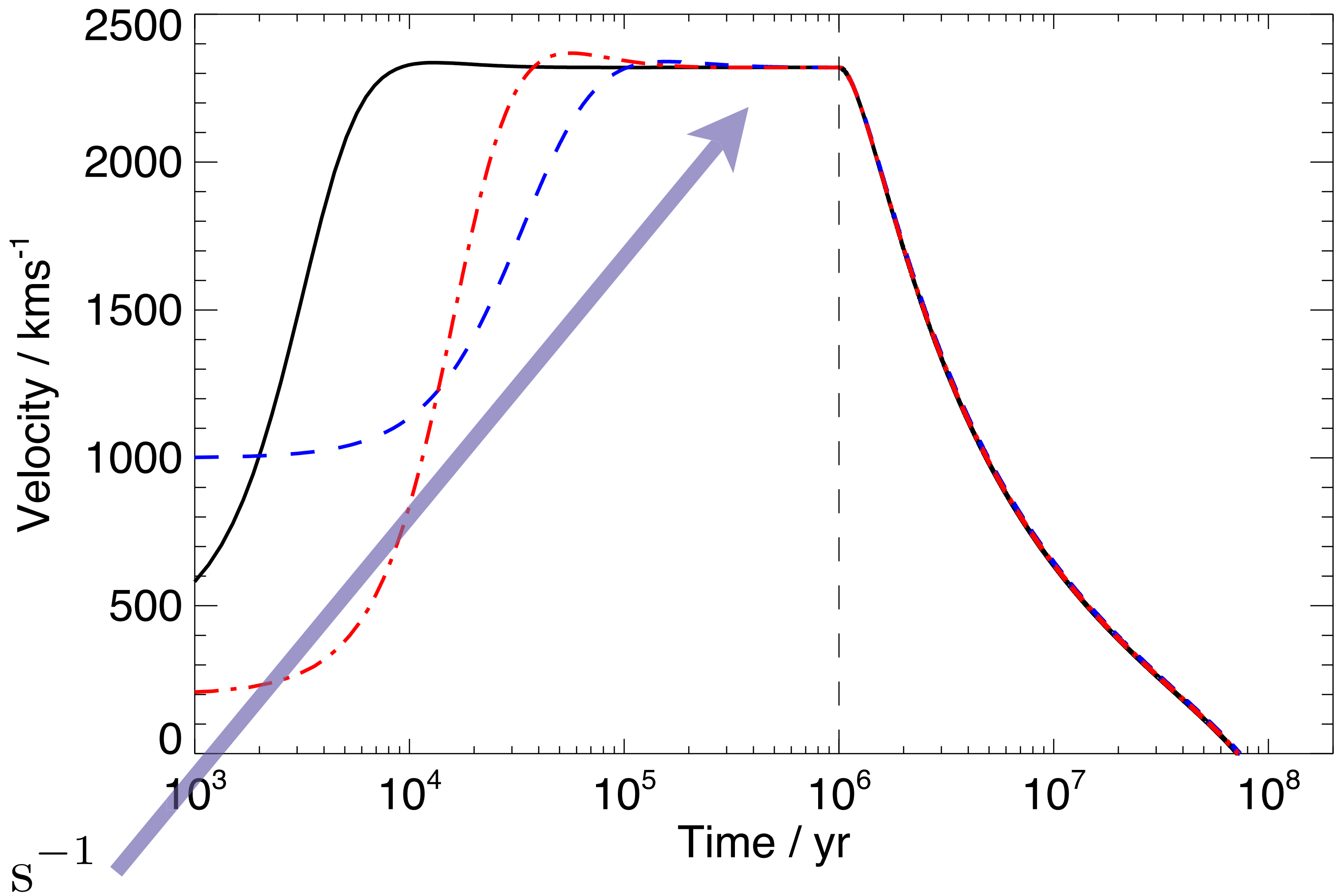

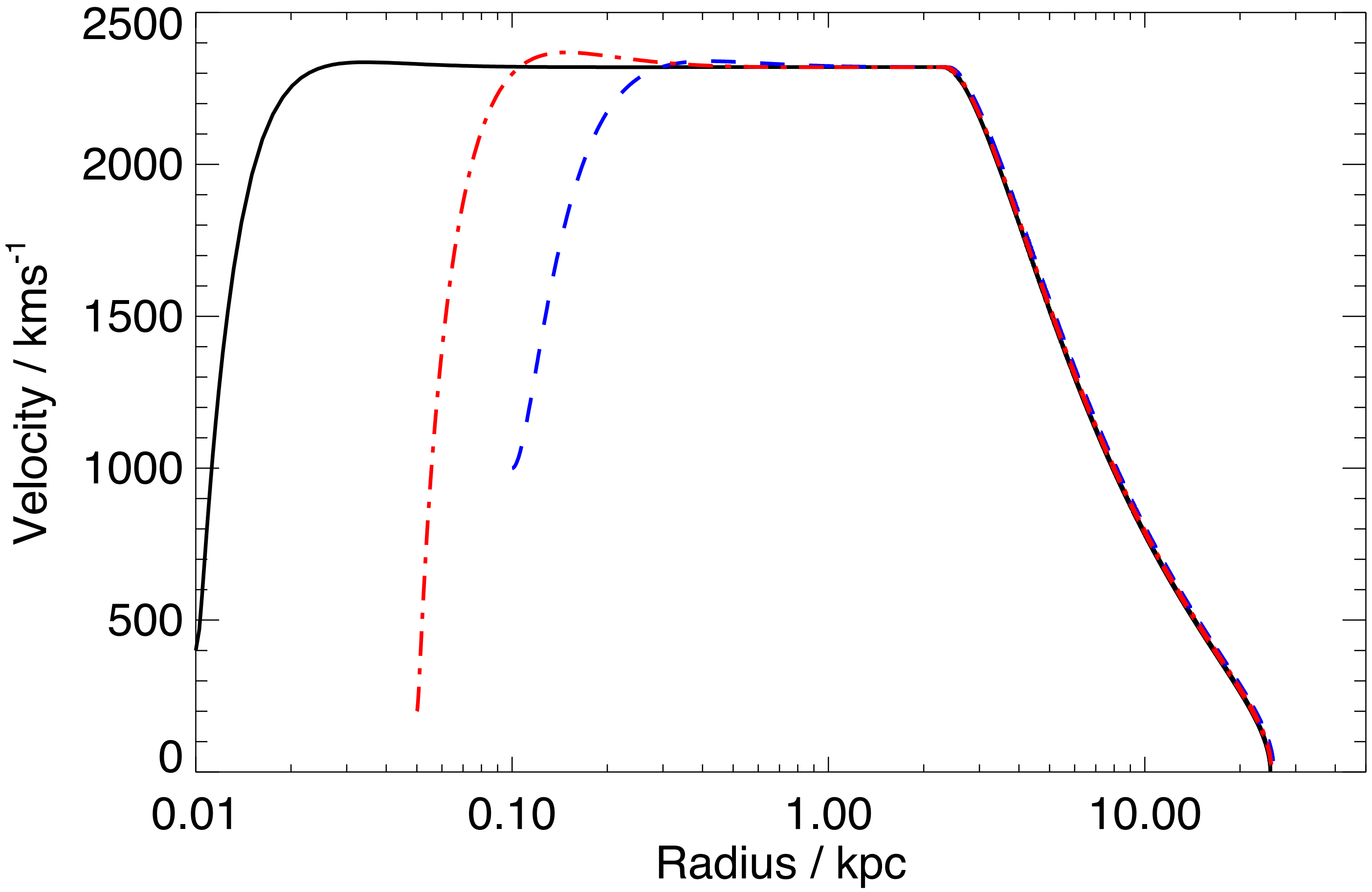

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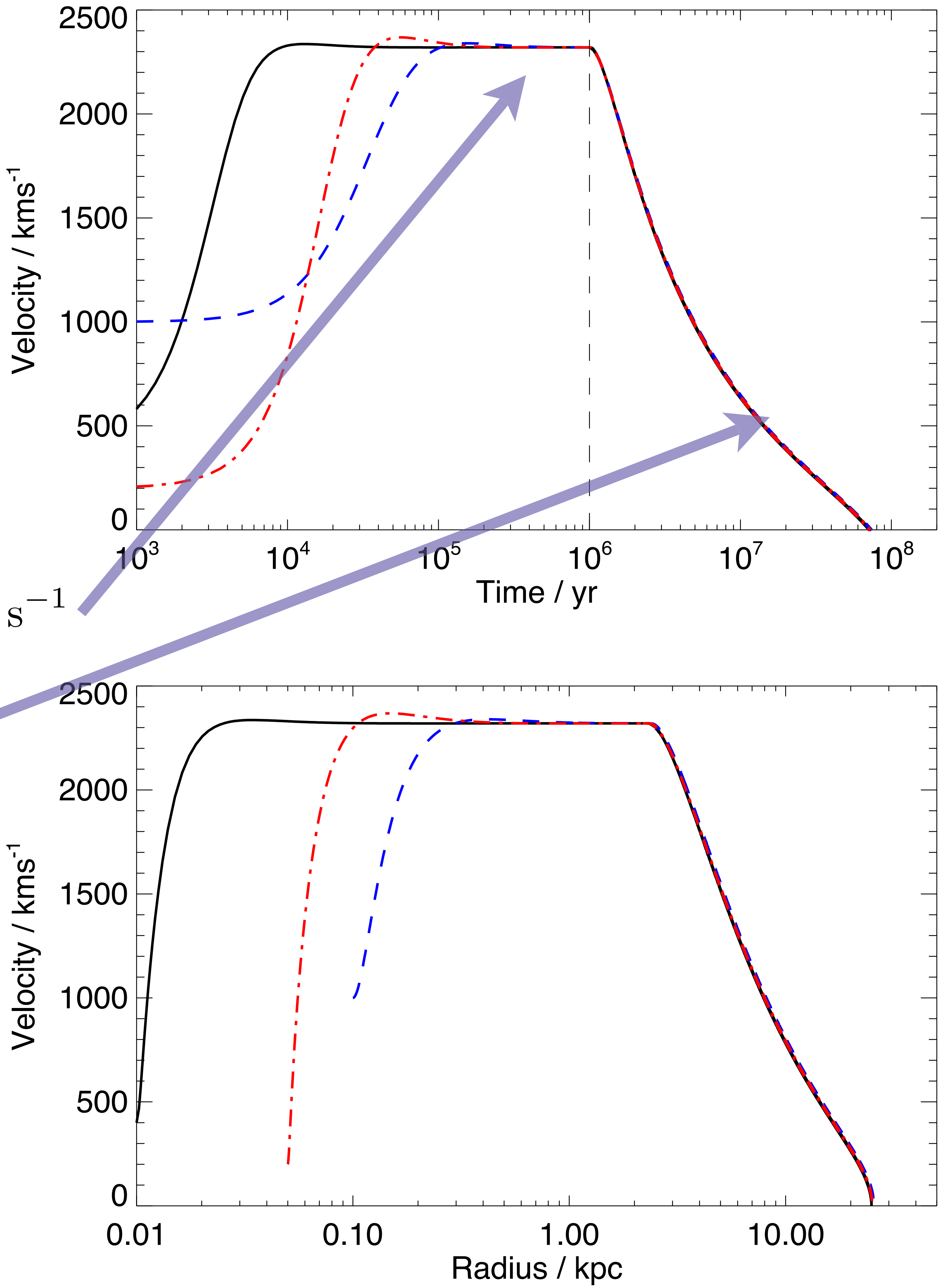

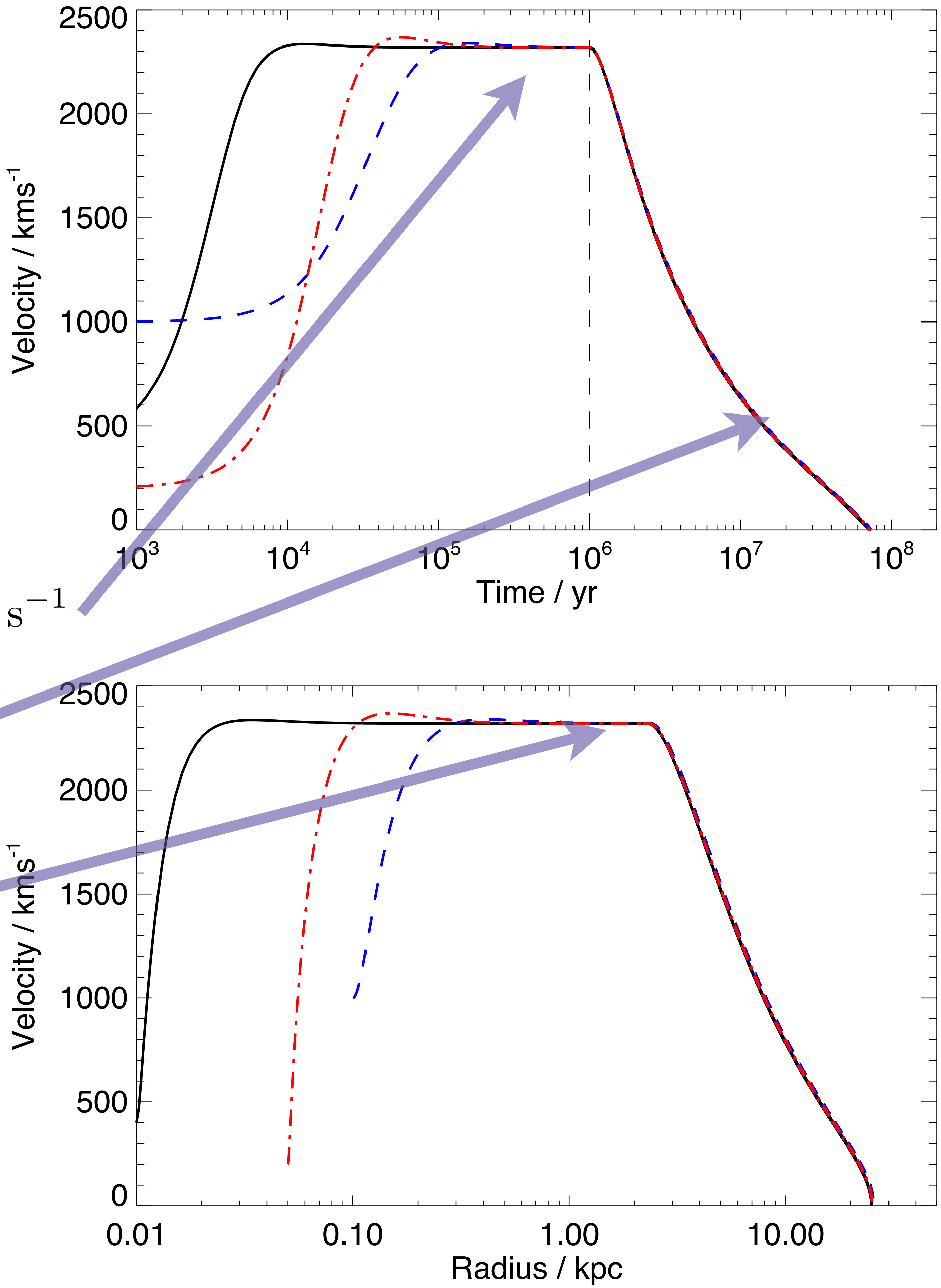

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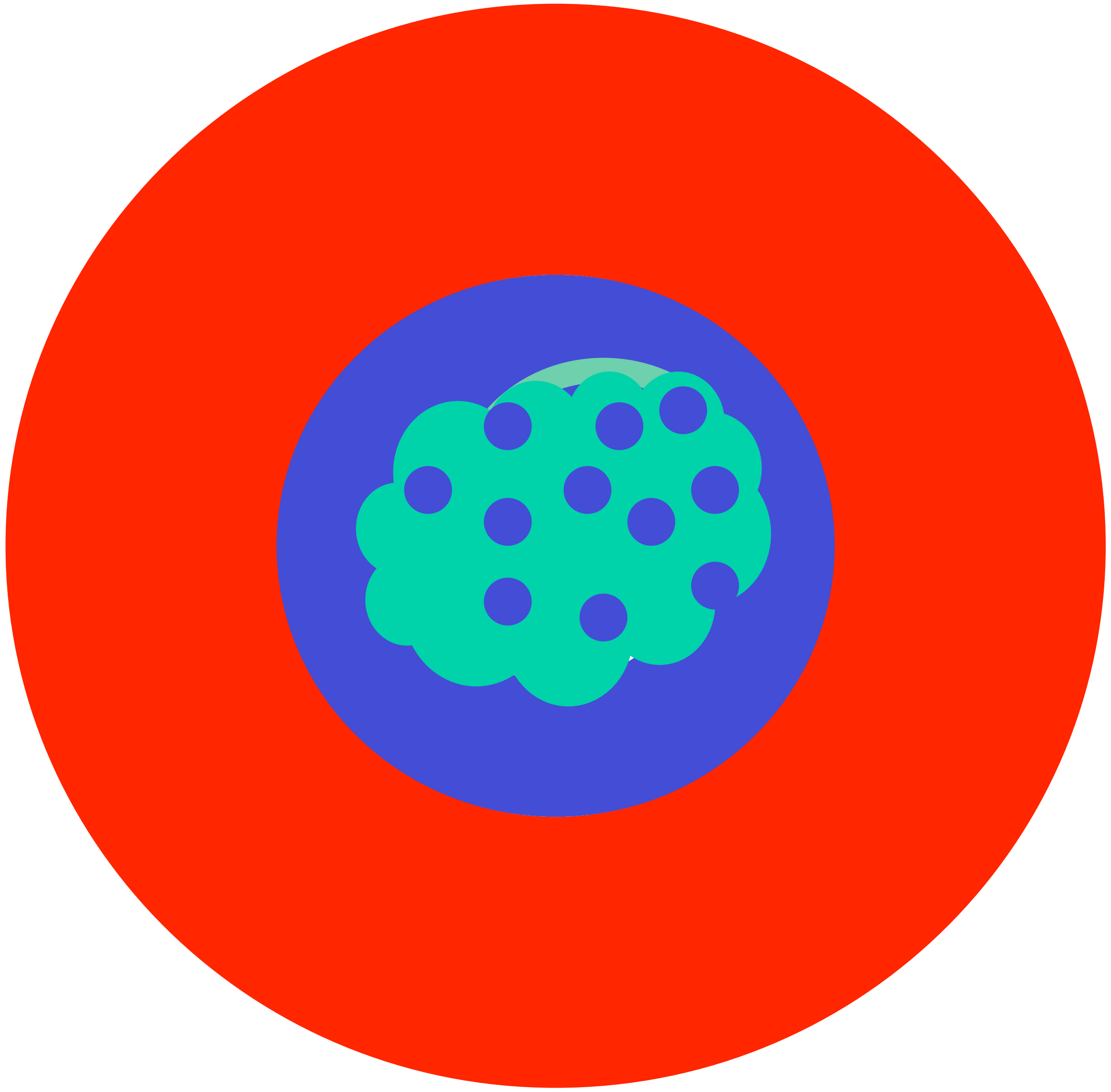
high velocity outflow at large radius

density contrast => energy-driven outflow

shock may be *Rayleigh-Taylor unstable*



two—phase medium: gamma—rays and molecular emission mixed

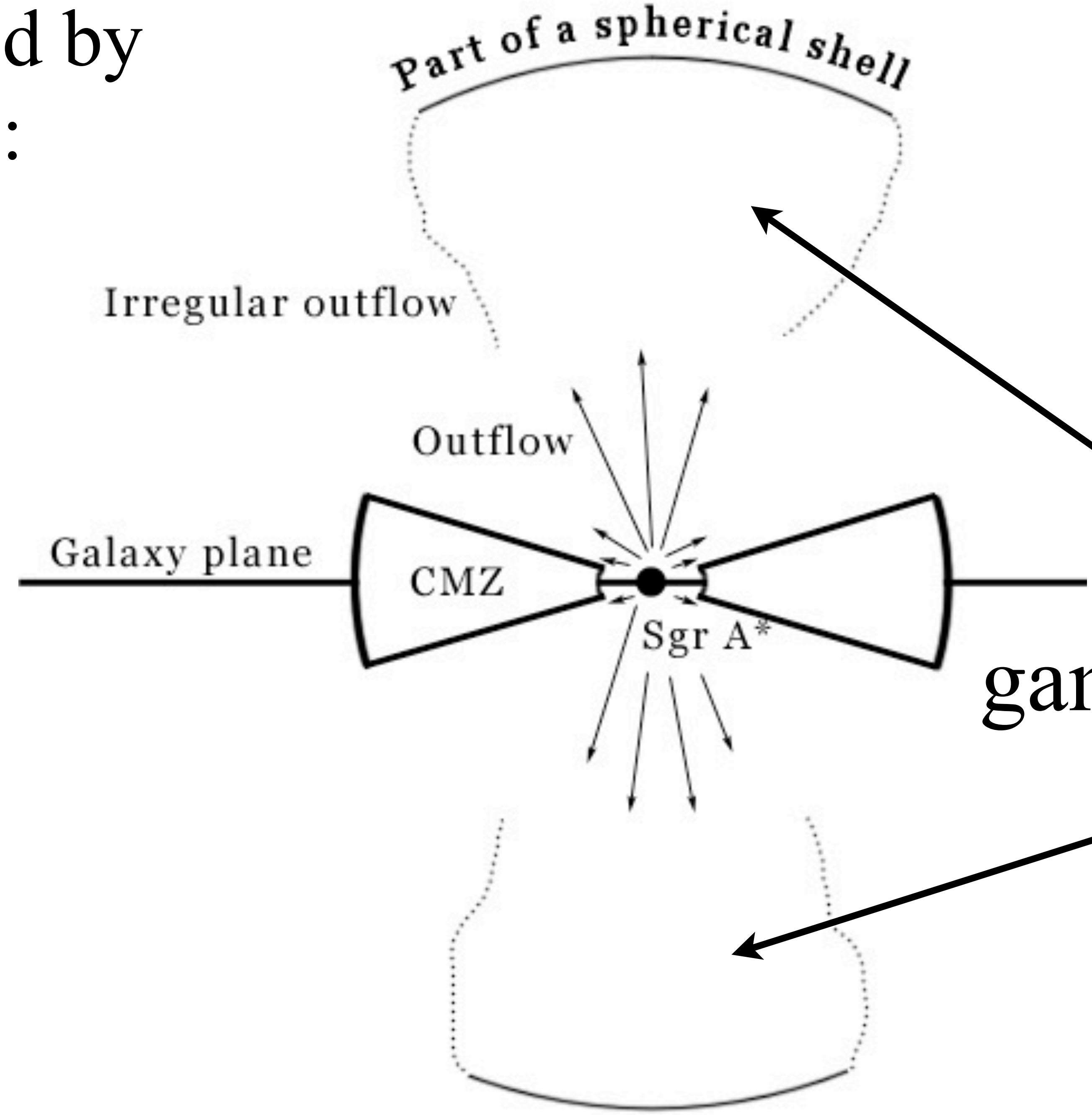
large--scale high speed molecular outflows, e.g. Mrk 231:

these have $L_{\rm mech} \simeq 0.05 L_{\rm Edd}$ as expected

galaxy cleared out in $\sim 10^7$ yr

galaxy bulge should produce gamma-ray emission

outflow blocked by
galaxy disc:



gamma-ray emission

gamma--rays generally too weak to detect: possible exception?

Fermi gamma--ray bubbles in Milky Way?

poster by Kastytis Zubovas

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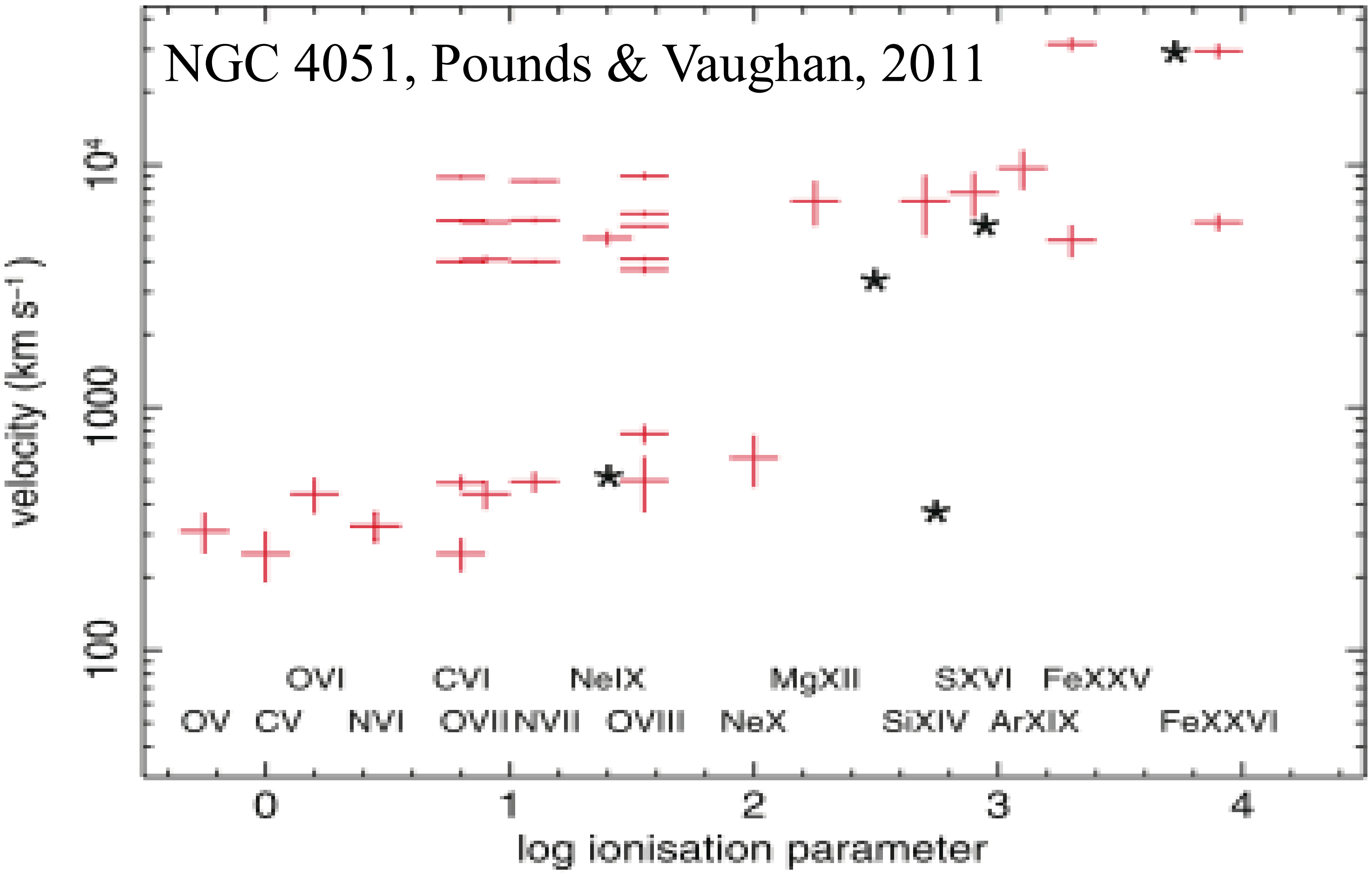


Figure 8. Outflow velocities derived from the Gaussian fitting plotted against the optimum ionization parameter for each parent ion stage. Also shown by asterisks are the parameters of the four photoionized absorbers derived from XSTAR modelling of the RGS absorption spectra, together with a velocity/ high-ionization point to represent the putative pre-shock wind.

frequency of Eddington outflows

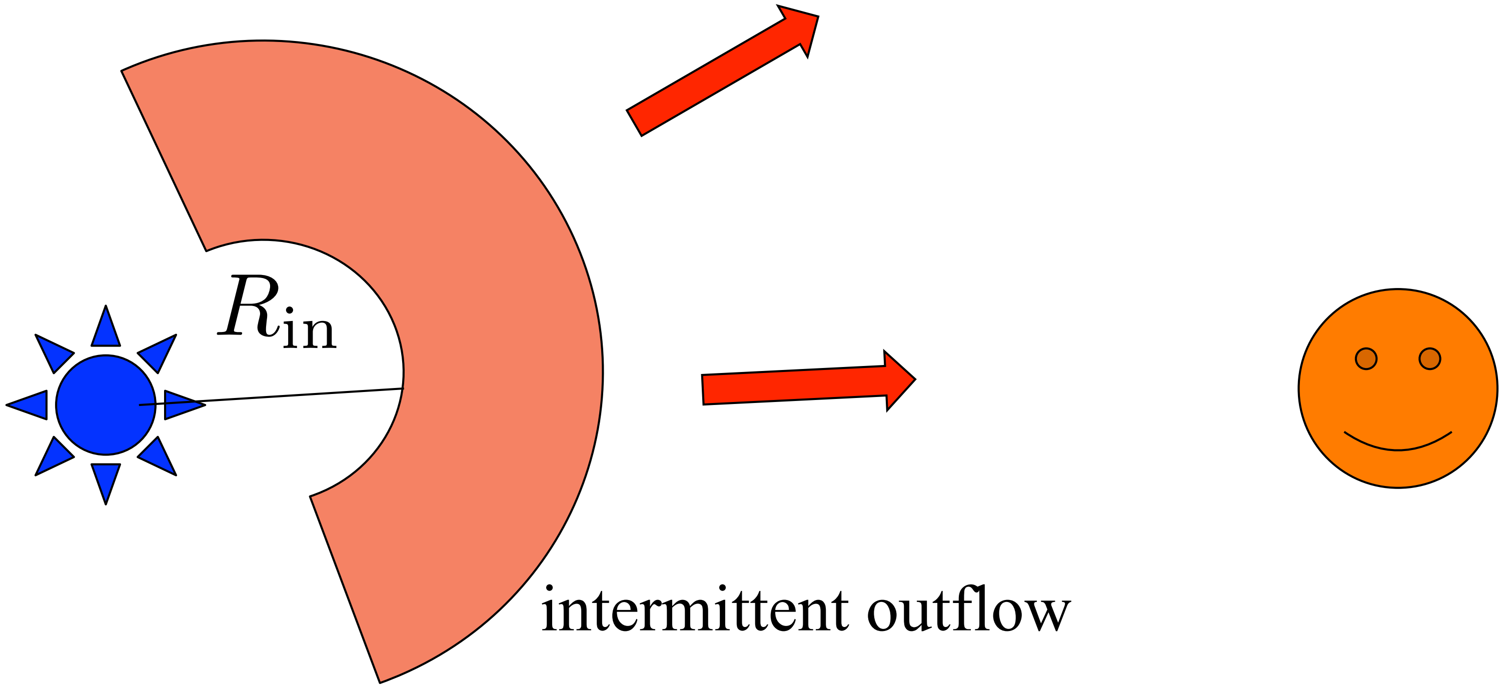
Tombesi et al 2010 a, b:

22/42 radio—quiet AGN, 3/5 BLRGs show outflows with

$$v \sim 0.1c - 0.3c, \quad \xi \sim 10^4$$

and hence $\dot{M}_{\rm out} \sim 1 - 10 M_{\odot}\,{\rm yr}^{-1}$, with very large momentum rates

high frequency ➔ solid angles large, $b \sim 0.5 - 1$: ~ 50% of sample
have super—Eddington episodes with significant duty cycles



observed X—ray column fixed by inner boundary of flow $R_{\rm in}$

$$N_{\rm H} \simeq \frac{10^{24}\dot m^3}{b\eta_{0.1}^2(R_{\rm in}/100R_s)}\ {\rm cm}^{-2}$$

so if outflow stopped a time $t_{\rm off}$ ago, we have

$$t_{\rm off} \simeq 0.2\frac{\dot m^3 M_8}{b\eta_{0.1}^2 N_{23}}\ {\rm yr}$$

recent!