AGN Feedback

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SMBH affects galaxy bulge

outflow energy $\sim 0.1 M_{BH} c^2$ is $\sim 10^{61}$ erg
for $10^8 M_\odot$ black hole
binding energy of bulge of mass $10^{11} M_\odot$
and $\sigma = 200$ km s^{-1} is 10^{58} erg

more than enough energy to unbind bulge – only a fraction used

galaxy must notice presence of hole

1. how do SMBH grow?

Soltan => gas accretion (low z)

disc formation is unavoidable

all accreting gas has enough angular momentum to orbit
the hole, so a disc always forms

large disc mass => fragmentation, star formation, mass loss....

disc probably never in steady state: Bondi is not a good estimate

2. disc accretion is slow

Σ spreads on *viscous timescale*

$$t_{\rm visc} = \frac{R^2}{\nu} = \frac{1}{\alpha}\left(\frac{R}{H}\right)^2 t_{\rm dyn}$$

where $t_{\rm dyn}$ is the *dynamical timescale* $R/v_K = (R^3/GM)^{1/2}$

this is *long*: $t_{\rm visc} \simeq 10^{10}$ yr for $R \sim 1$ pc

can we get gas closer in - cancel angular momentum?

either borrow some a.m. from SMBH (via Lense-Thirring) to cancel gas a.m. (`disc tearing'),

or use radial SMBH feedback to give energy but not a.m. => eccentric => collisions….

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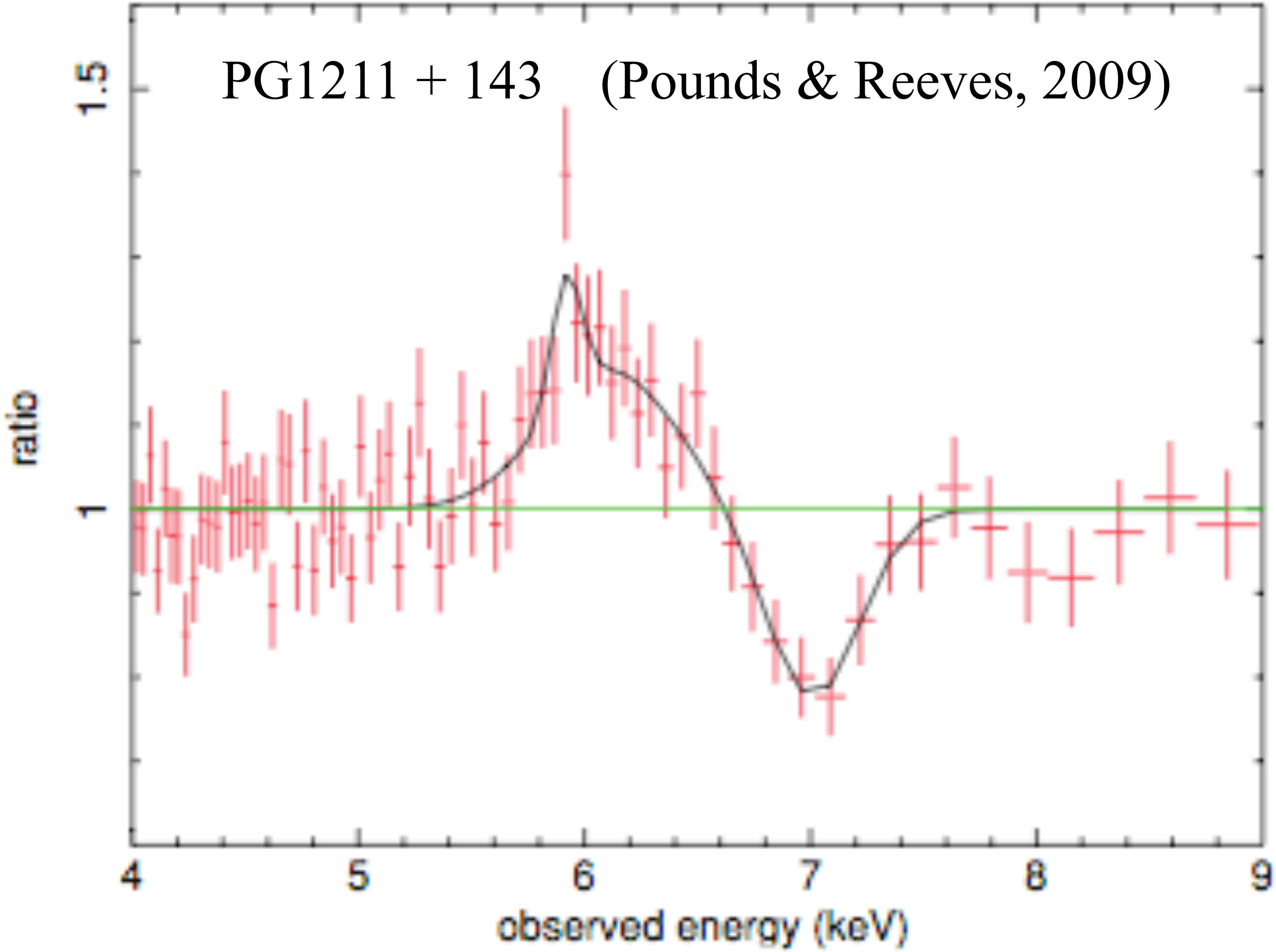
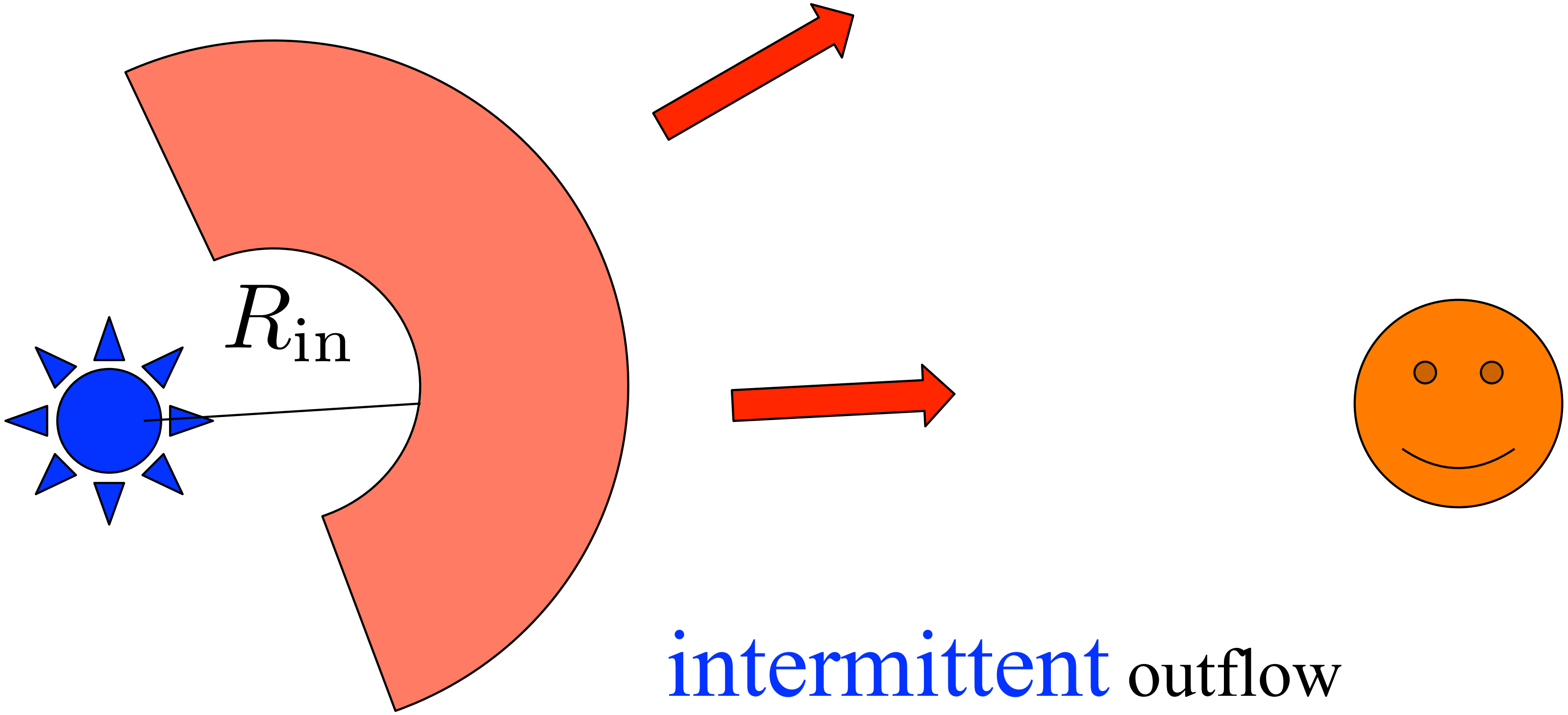
how?



P Cygni profile of iron K- alpha: *outflow* with $v \simeq 0.1c$

`ultrafast outflow' -- `UFO': measured ionization parameter =>

$$\dot{M}_{\rm out} = 4\pi b m_p N R^2 v \sim 1 {\rm M_\odot\, yr^{-1}} \sim \dot{M}_{\rm Edd}$$



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!

a *continuous* Eddington wind would be

Compton thick

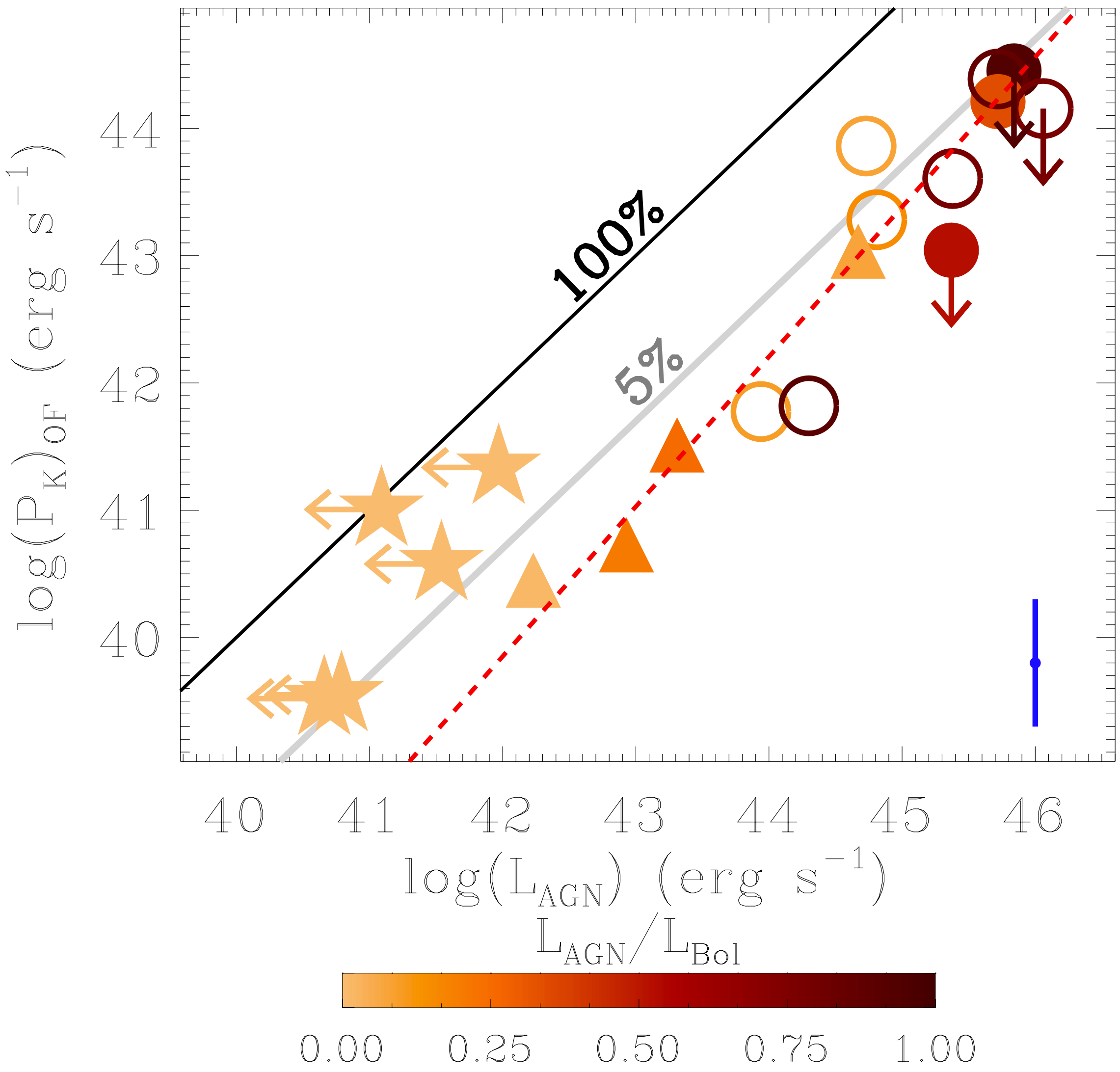
outflows are variable on timescales of weeks or less!

- UFOs establish $M - \sigma$ relation by momentum driving
- at $M = M_\sigma$ outflows become energy-driven
- huge increase in lengthscales: pc to kpc
- most powerful feedback is *Compton-thick* : invisible?
- AGN driving is highly variable - correlations tricky!

do shocks cool? - rarity of NGC 4051?

UFO - molecular outflow correlations….?

what determines the SMBH feeding rate?



Cicone + 2014

Fig. 12. Correlation between the kinetic power of the outflow and the AGN bolometric luminosity. Symbols and colour-coding as in Fig. 8. The grey line represents the theoretical expectation of models of AGN feedback, for which $P_{K,OF} = 5\% L_{AGN}$. The red dashed line represents the linear fit to our data, excluding the upper limits. The error bar shown at the bottom-right of the plot corresponds to an average error of ±0.5 dex.

outflow shock

outflow must collide with bulge gas, and shock – what happens?

either

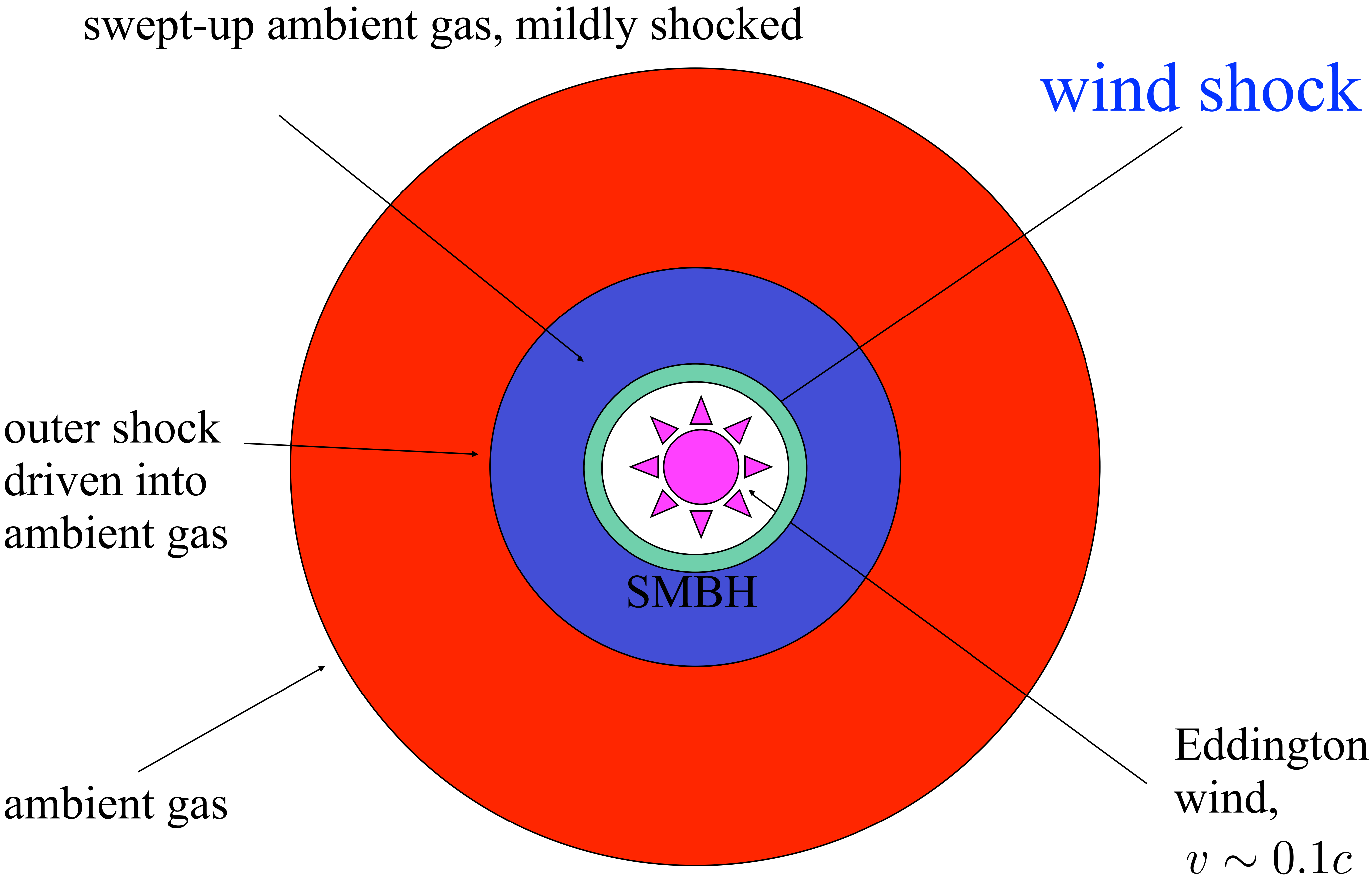
(a) shocked gas cools: `momentum–driven flow'
negligible thermal pressure

or

(b) shocked gas does not cool: `energy–driven flow'
thermal pressure > ram pressure

Compton cooling by quasar radiation field very effective out to large bulge radii (cf Ciotti & Ostriker, 1997, 2001)

expansion into bulge gas is driven by momentum $\frac{L_{\rm Edd}}{c}$


swept-up ambient gas, mildly shocked
wind shock
outer shock
driven into
ambient gas
SMBH
ambient gas
Eddington
wind,
$v \sim 0.1c$

outflow dynamics fixed by cooling

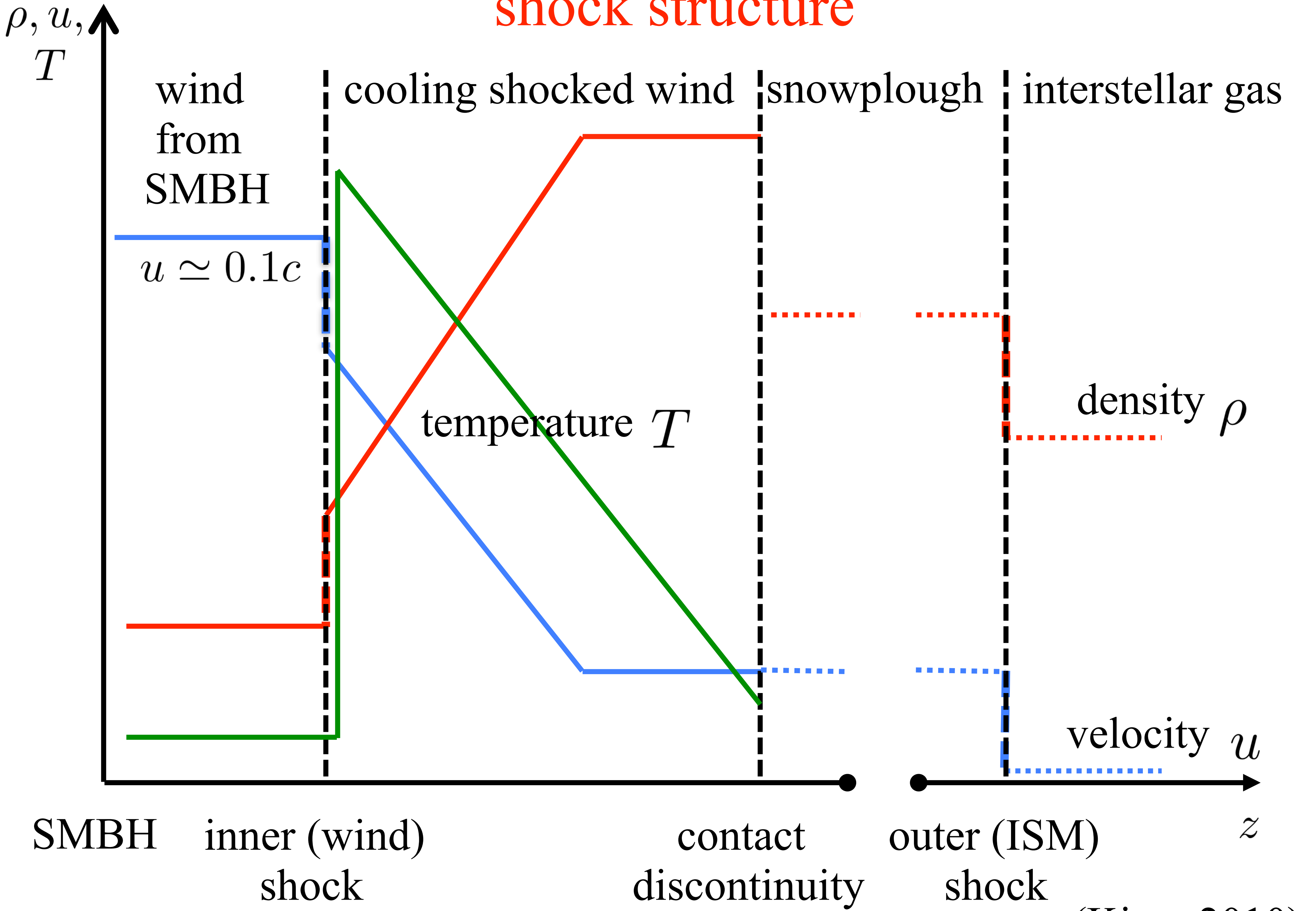
close to quasar shocked wind gas cooled by inverse Compton effect (`momentum—driven flow')

strong evidence for cooling shock: ionization parameter decreases with outflow velocity, conserving mass flow rate

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

NGC4051: 10x decrease in *v*, seen in 14 species (Pounds et al.), correlates with ionization

shock structure



(King, 2010)

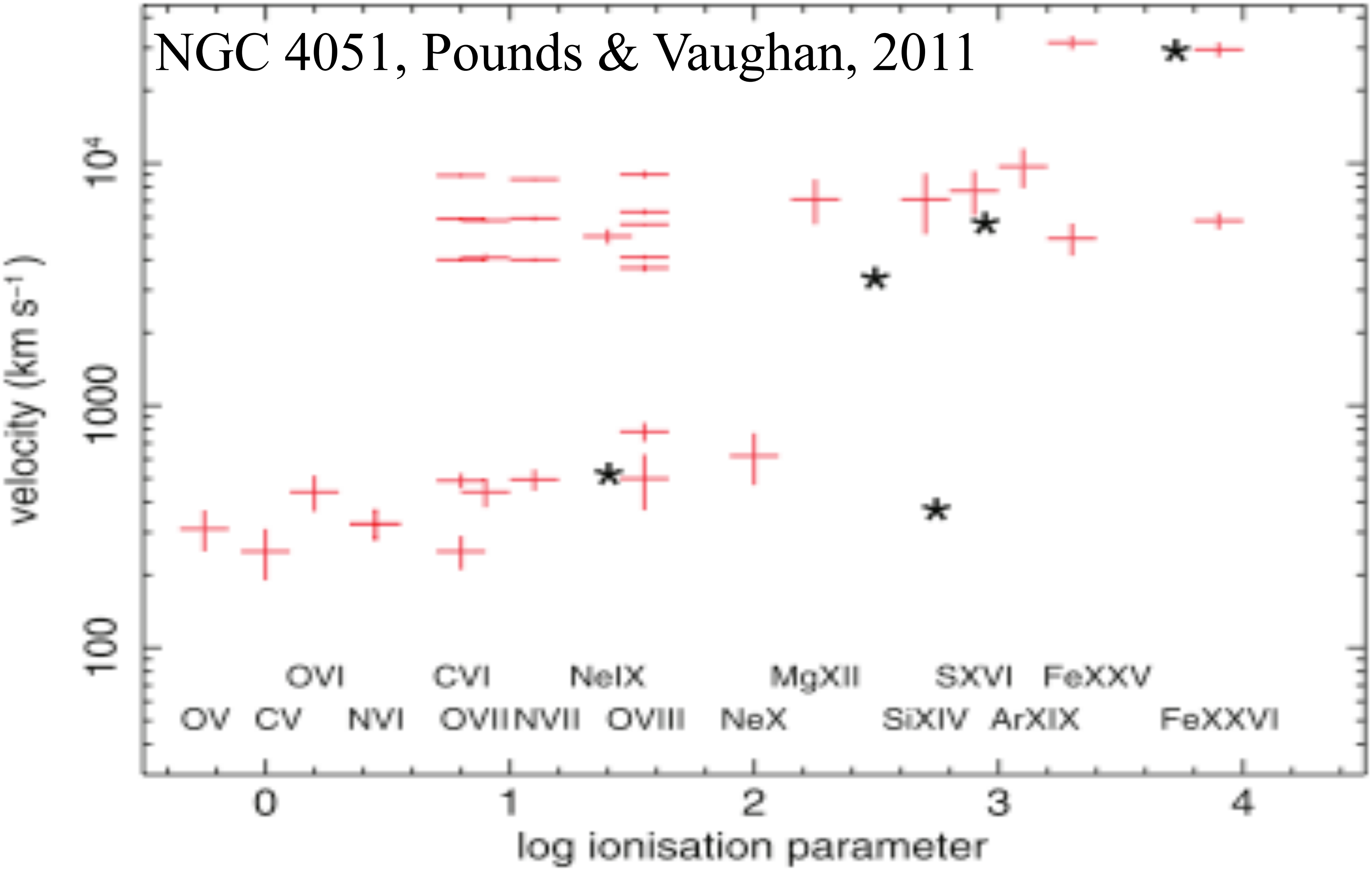


Figure 8. Outflow velocities derived from the Gaussian fitting plotted against the optimum ionization parameter for each parent ion stage. Also shown by asterisks are the parameters of the four photoionized absorbers derived from XSTAR modelling of the RGS absorption spectra, together with a velocity/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

NGC 4051, Pounds & Vaughan, 2011

X-ray spectrum of NGC 4051

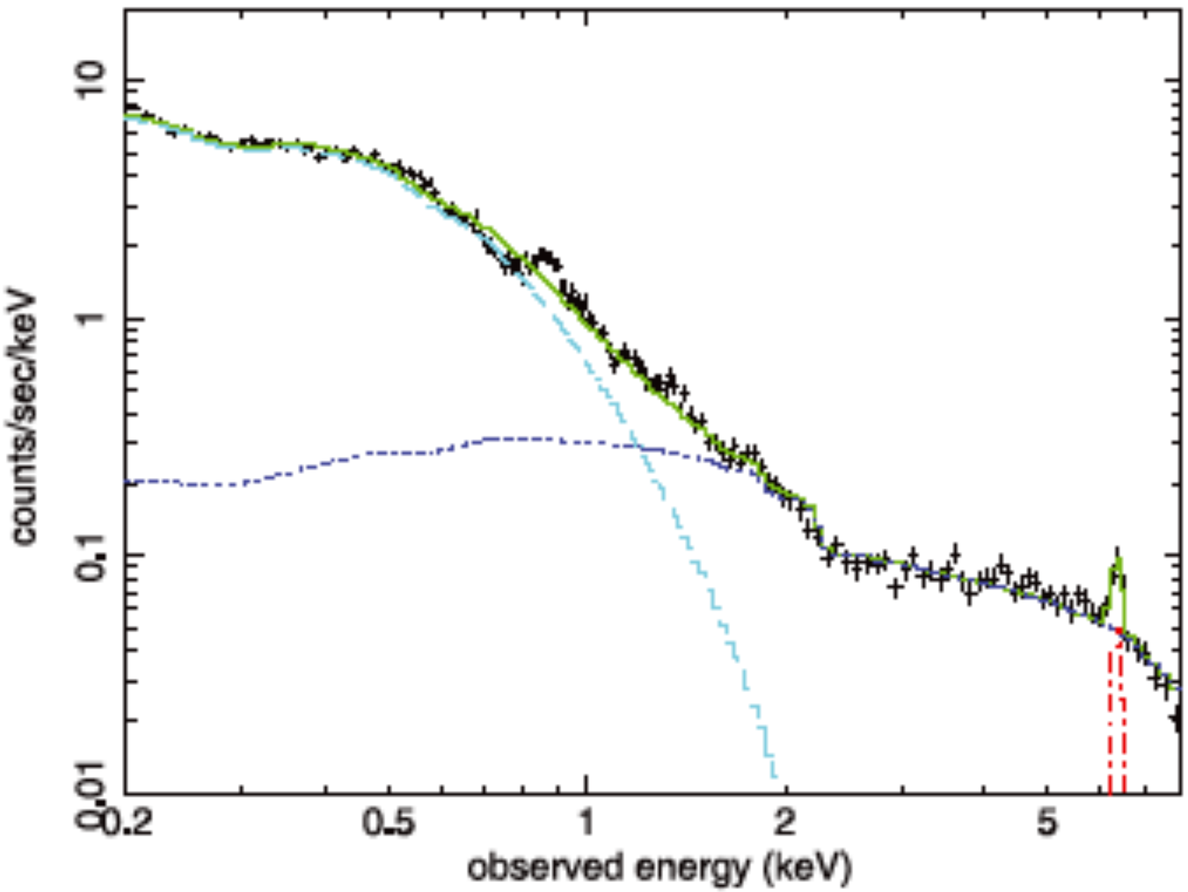


Figure 11. Parametric model fit to the low-flux rev1739 pn data. The hard power law and soft Comptonized continuum components are shown as dotted and dashed lines.

Eddington outflows

momentum outflow rate

$$\dot{M}_{\rm out} v = \frac{L_{\rm Edd}}{c}$$

speed

$$v = \frac{L_{\rm Edd}}{\dot{M}_{\rm out} c} = \frac{\eta c}{\dot{m}} \sim 0.1c$$

where $\dot{m} = \dot{M}_{\rm out}/\dot{M}_{\rm Edd} \sim 1$

energy outflow rate

$$\frac{1}{2}\dot{M}_{\rm out} v^2 = \frac{\eta}{2}.\eta c^2 \dot{M}_{\rm out} = \frac{\eta}{2} L_{\rm Edd} \simeq 0.05 L_{\rm Edd}$$

where $\dot{m} = \dot{M}_{\rm out}/\dot{M}_{\rm Edd} \sim 1$

force balance

total mass (dark, stars, gas) inside radius R of unperturbed bulge is

$$M_{\rm tot}(R) = \frac{2\sigma^2 R}{G}$$

but swept-up gas mass $M(R) = \dfrac{2f_g\sigma^2 R}{G}$

forces on shell are wind ram pressure: $F = \dfrac{L_{\rm Edd}}{c} = \dfrac{4\pi GM}{\kappa}$

and weight of gas within R, $\quad W = \dfrac{GM(R)M_{\rm tot}(R)}{R^2} = \dfrac{4f_g\sigma^4}{G}$

ram pressure balances weight $(F = W)$ when

$$M = M_\sigma = \frac{f_g\kappa}{\pi G^2}\sigma^4 \simeq 3\times 10^8 {\rm M}_\odot \sigma_{200}^4$$

${\rm M}_8 = M/10^8{\rm M}_\odot$, $\sigma_{200} = \sigma/200\,{\rm km\,s^{-1}}$ (K, 2003, 2005)

transition to energy-driven flow once M_σ reached

close to quasar shocked gas cooled by inverse Compton effect (momentum-driven flow)

but once $M > M_\sigma$, R can exceed R_C: wind shock no longer cools

wind shock is adiabatic: hot postshock gas does PdV work on surroundings: energy-driven outflow

dramatic change of lengthscales:

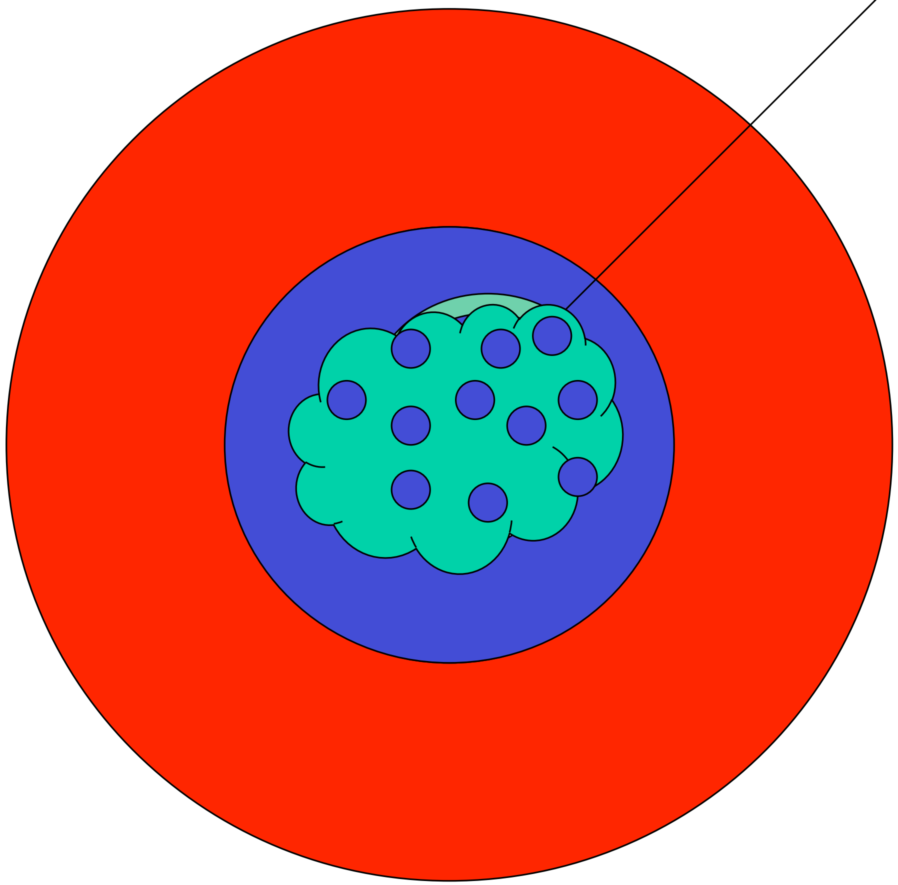
momentum-driven flows are confined to ~ few pc (micro)

energy-driven flows can be ~ kpc (meso)

cf K & Pounds, ARAA, 2015

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:

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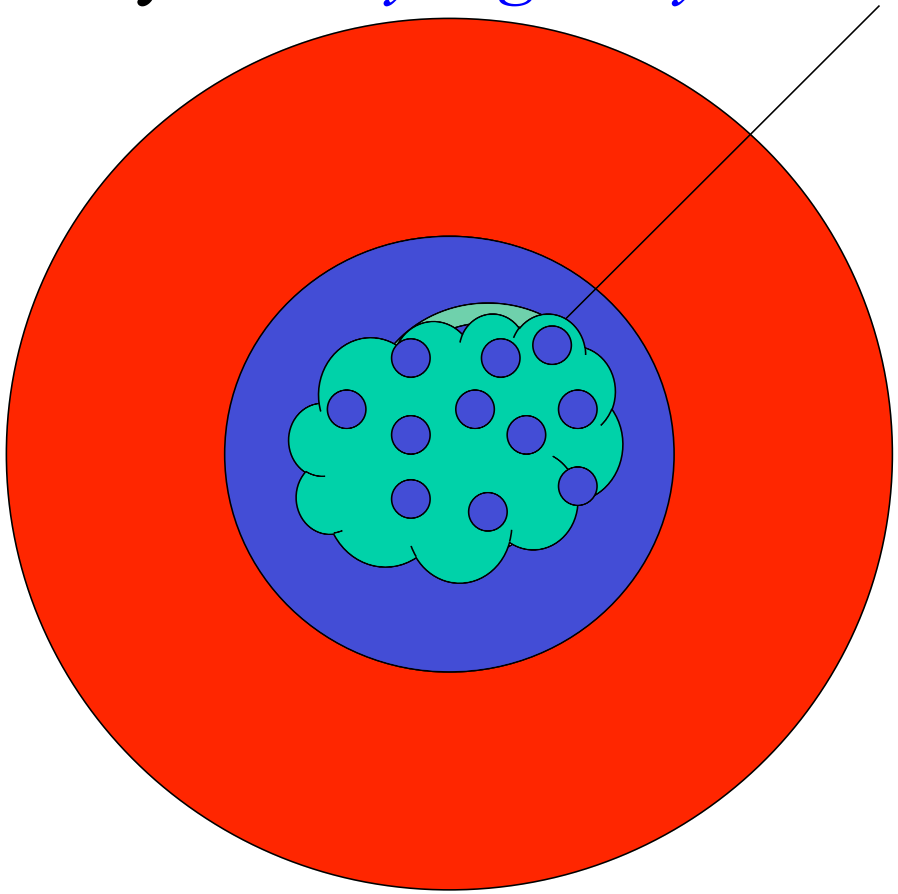

two—phase medium: gamma—rays and molecular emission mixed

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

very cool gas at high speeds

outer shock runs ahead of contact discontinuity into ambient ISM: velocity jump across it is a factor $(\gamma+1)/(\gamma-1)$: fixes velocity as

$$v_{\rm out} = \frac{\gamma+1}{2}\dot{R} \simeq 1230\sigma_{200}^{2/3}\left(\frac{lf_c}{f_g}\right)^{1/3}\ {\rm km\ s^{-1}}$$

outflow rate of shocked interstellar gas is

$$\dot{M}_{\rm out} = \frac{{\rm d}M(R_{\rm out})}{{\rm d}t} = \frac{(\gamma+1)f_{\rm g}\sigma^2}{G}\dot{R}$$

$$\dot{M}_{\rm out} \simeq 3700\sigma_{200}^{8/3}l^{1/3}\ M_{\odot}\,{\rm yr}^{-1}$$

(Zubovas & K, 2012

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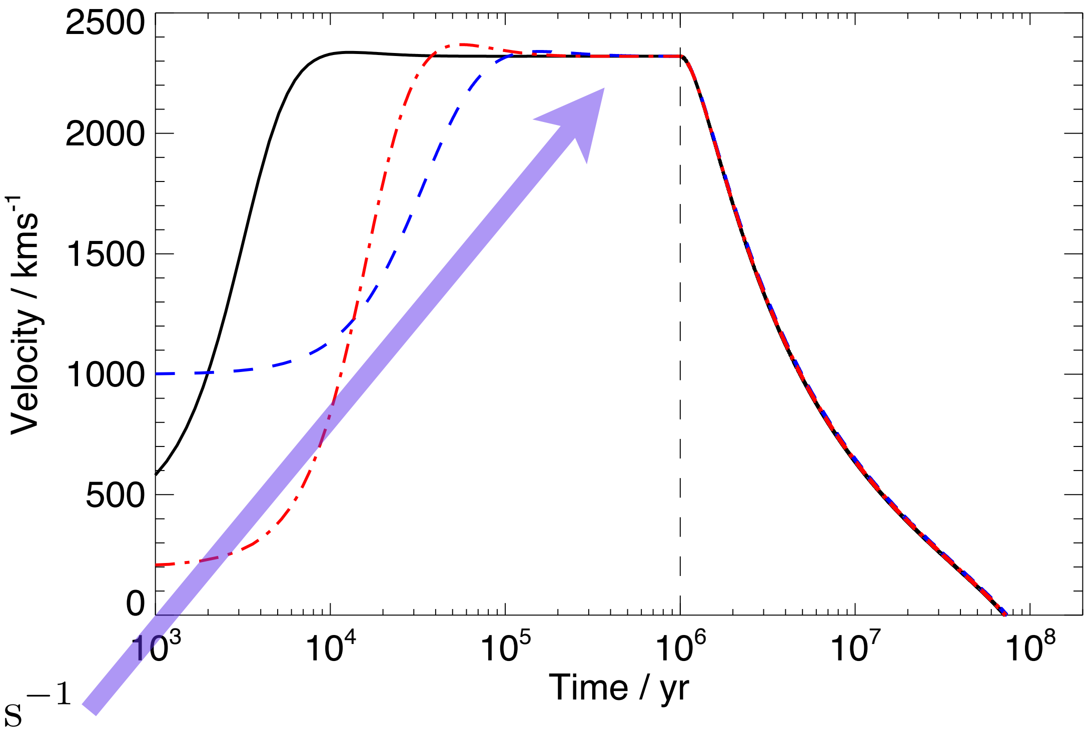
energy outflow rate

$$\frac{1}{2}\dot{M}_{\rm out} v^2 = \frac{\eta}{2}.\eta c^2 \dot{M}_{\rm out} = \frac{\eta}{2} L_{\rm Edd} \simeq 0.05 L_{\rm Edd}$$

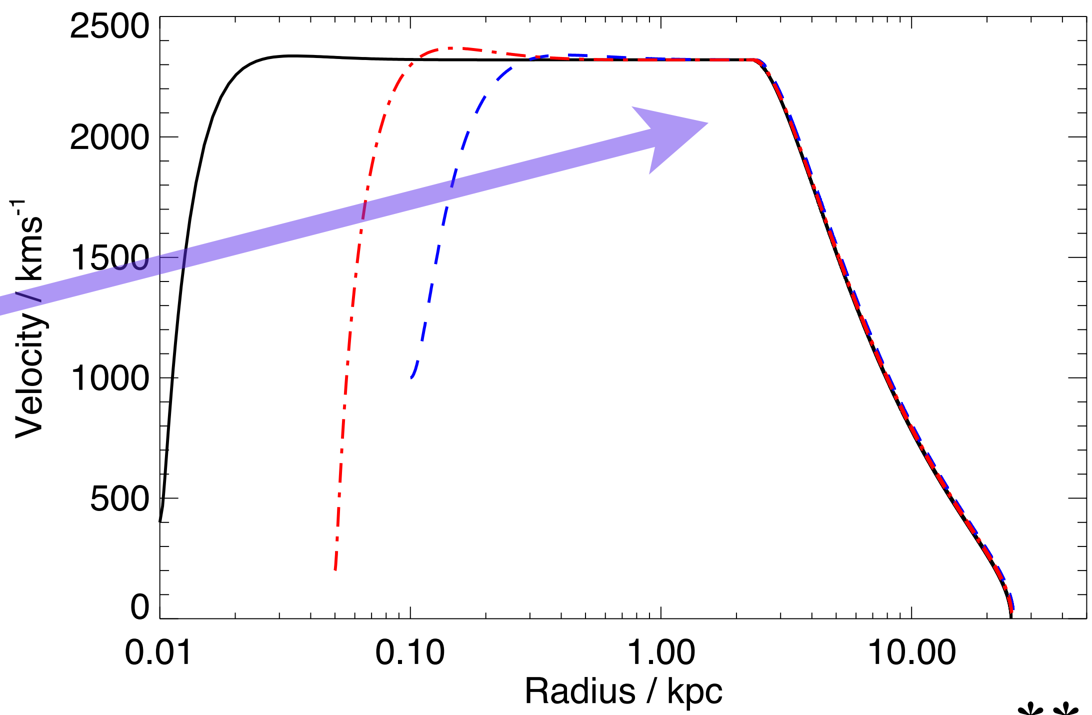
where $\dot{m} = \dot{M}_{\rm out}/\dot{M}_{\rm Edd} \sim 1$

energy--driven outflows rapidly converge to

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



high velocity outflow at large radius



also for other potentials: Zubovas & King, 2012b

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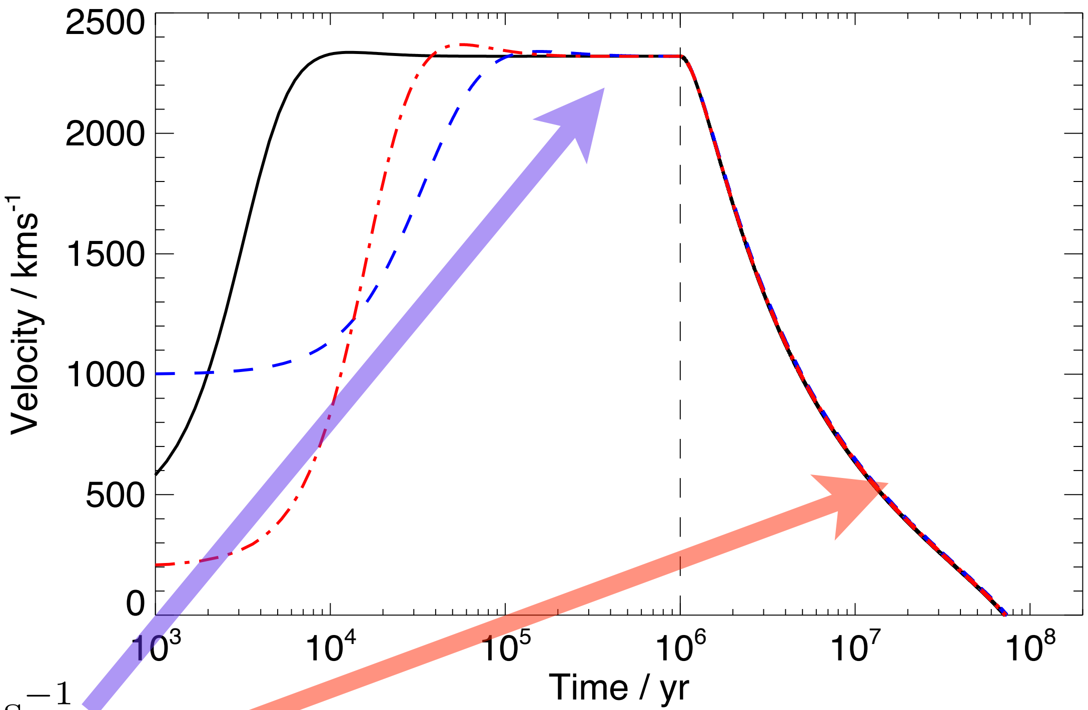
observed ratios > 1 are possible!



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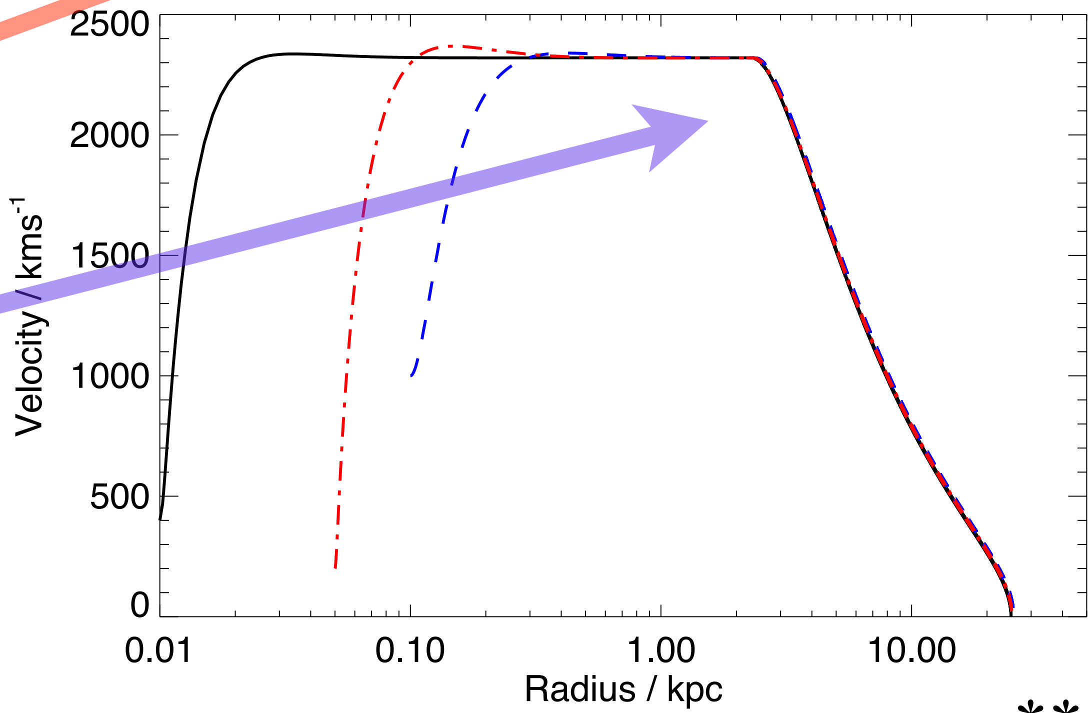
and persist even after central quasar turns off!



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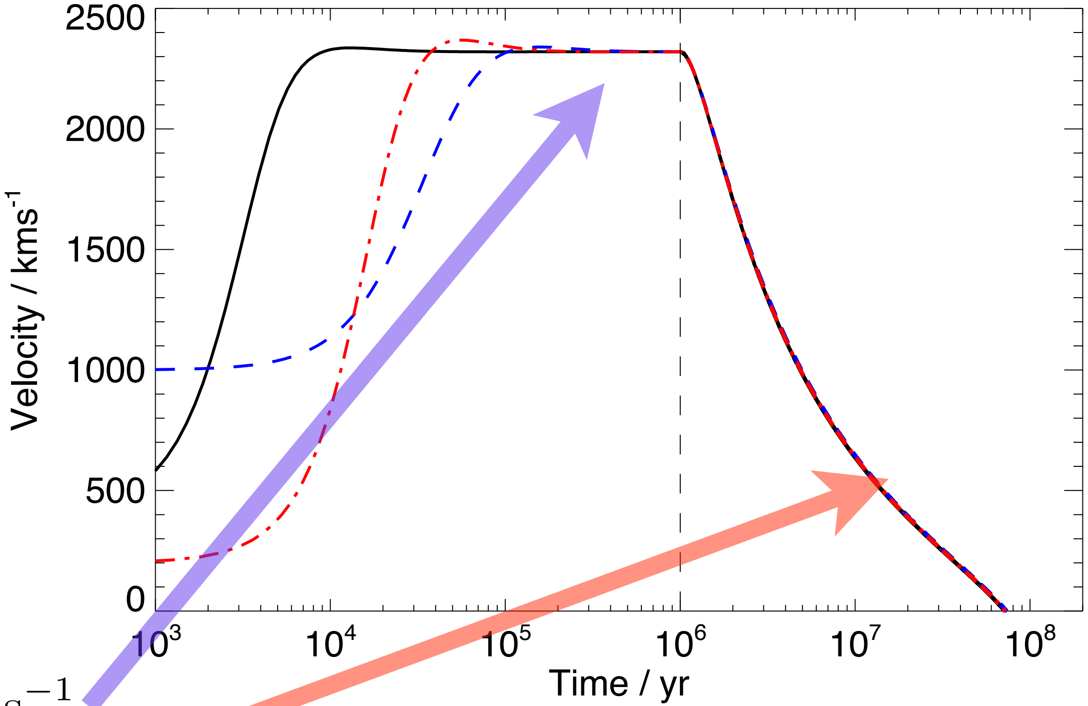

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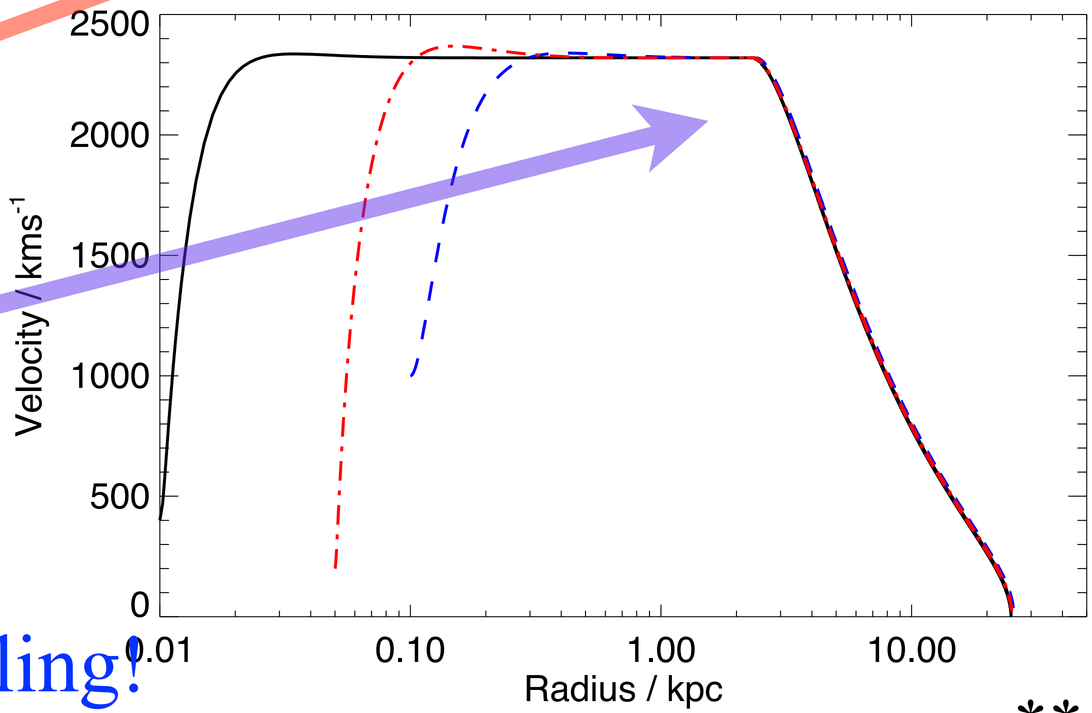

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AGN variability changes scaling!

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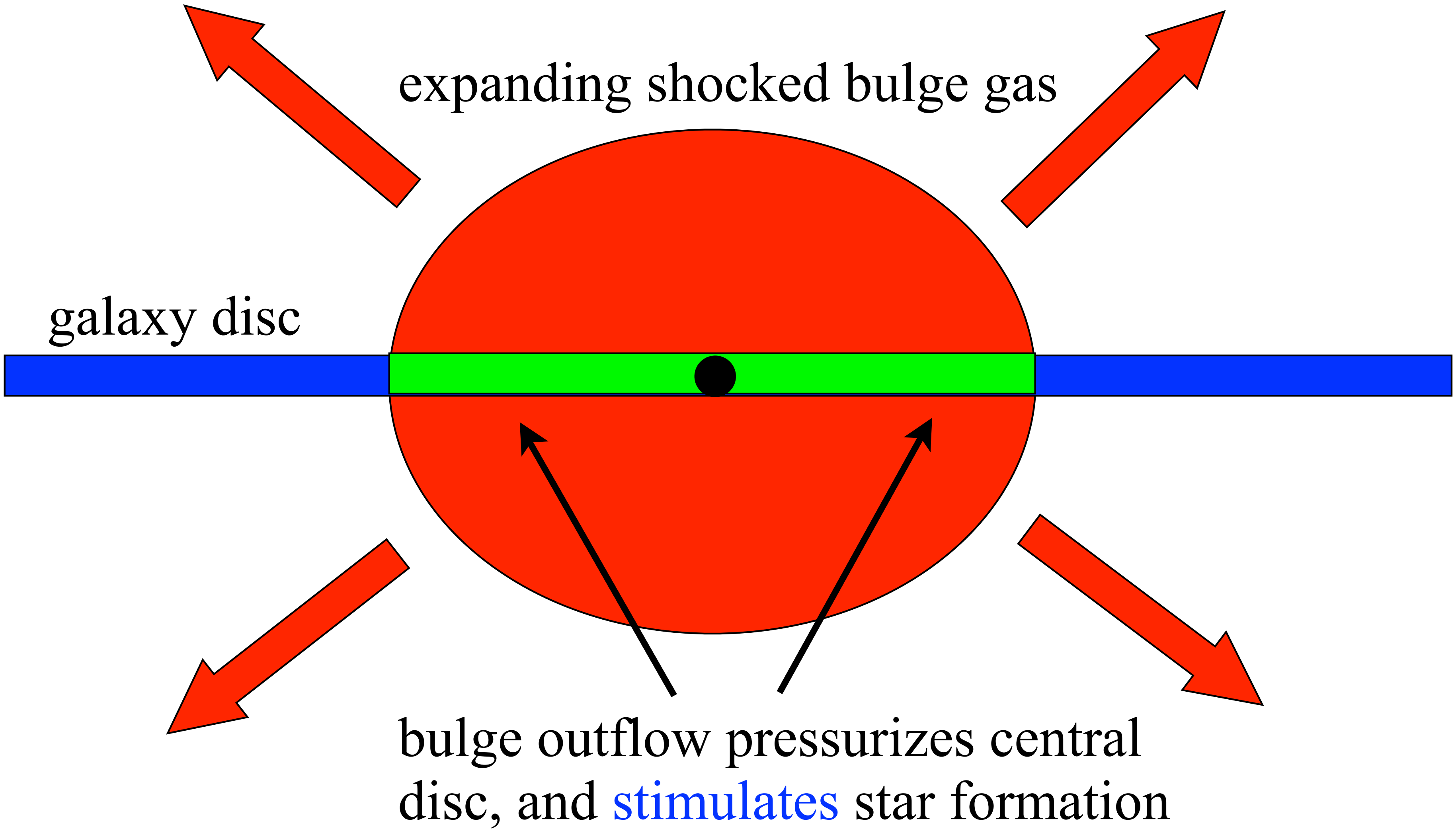
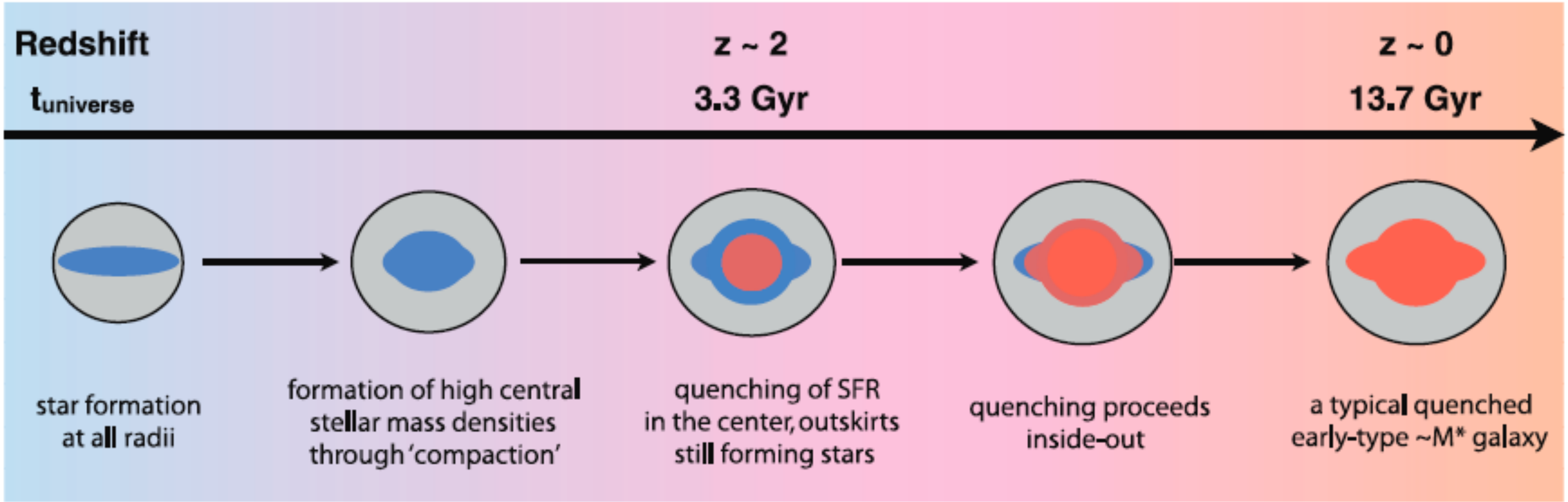
spirals: outflow pressure => star formation in disc



observational picture



(Tachella + 2015)

outflows must be episodic, as AGN driving is variable

K & Pringle 2007 `chaotic accretion':
each accretion disc event limited by self-gravity to a mass

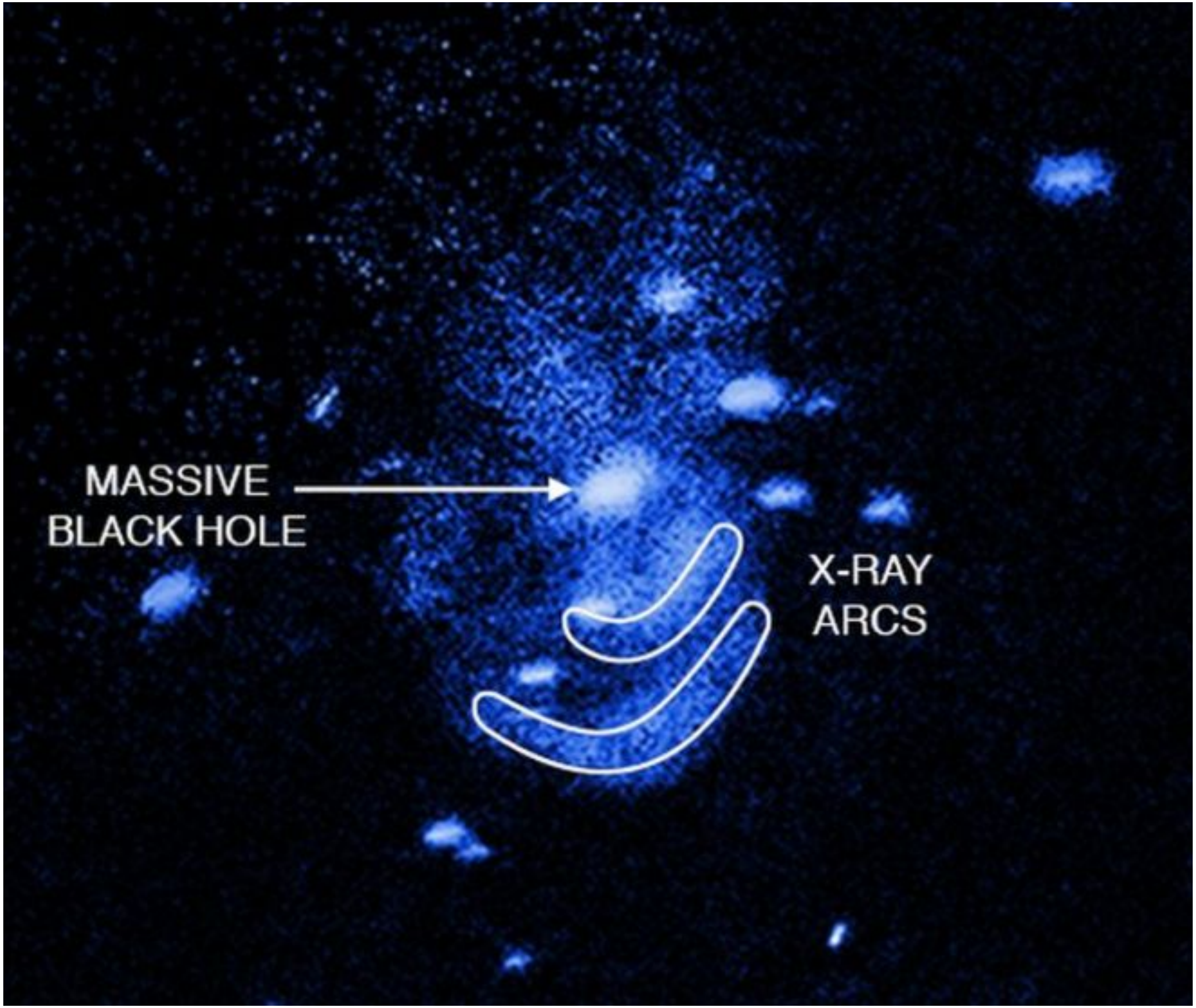
$$M_d \lesssim \frac{H}{R} M_{\rm BH} \simeq 10^{-3} M_{\rm BH}$$

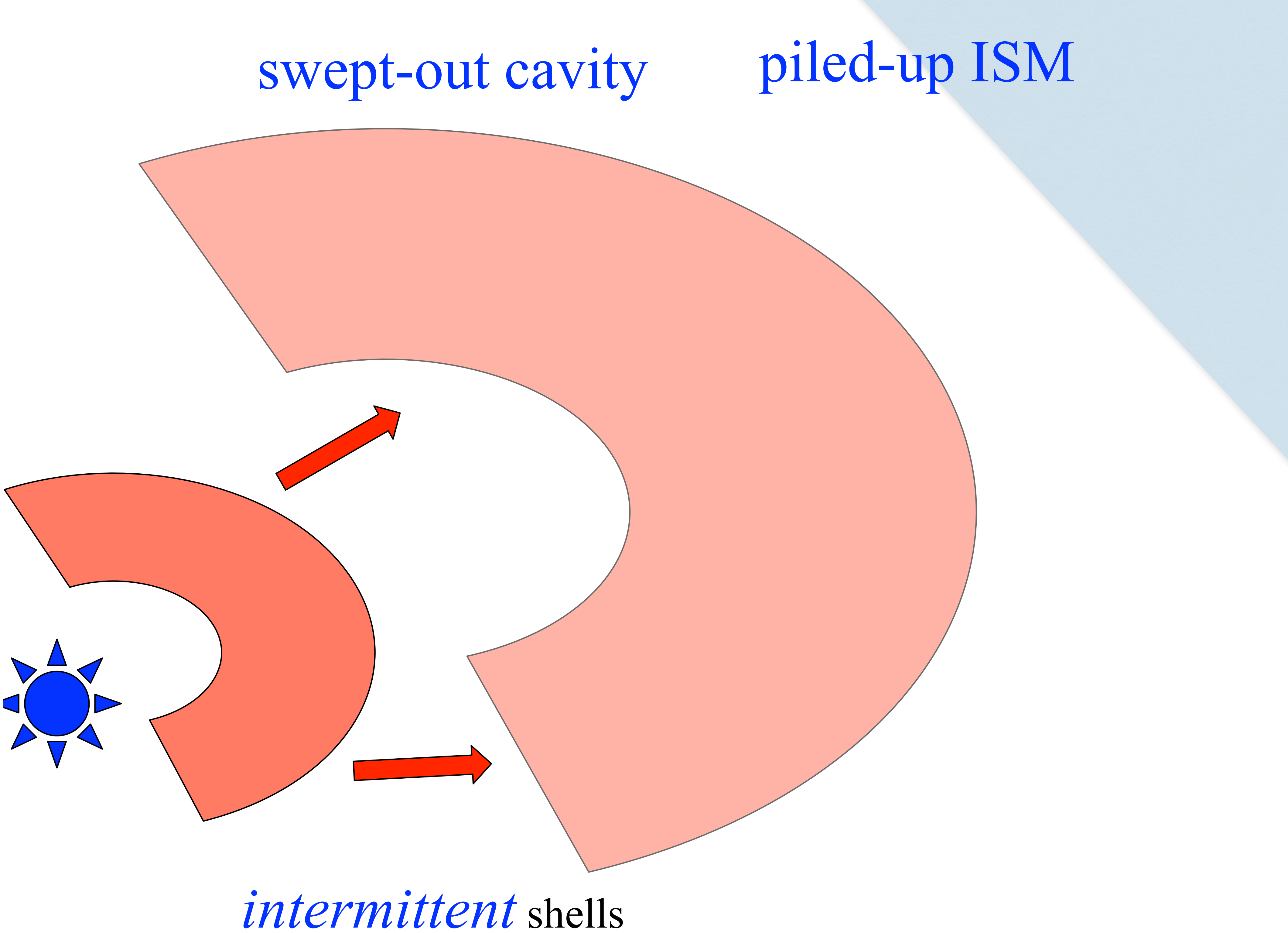
so characteristic variation (`flicker') timescale is

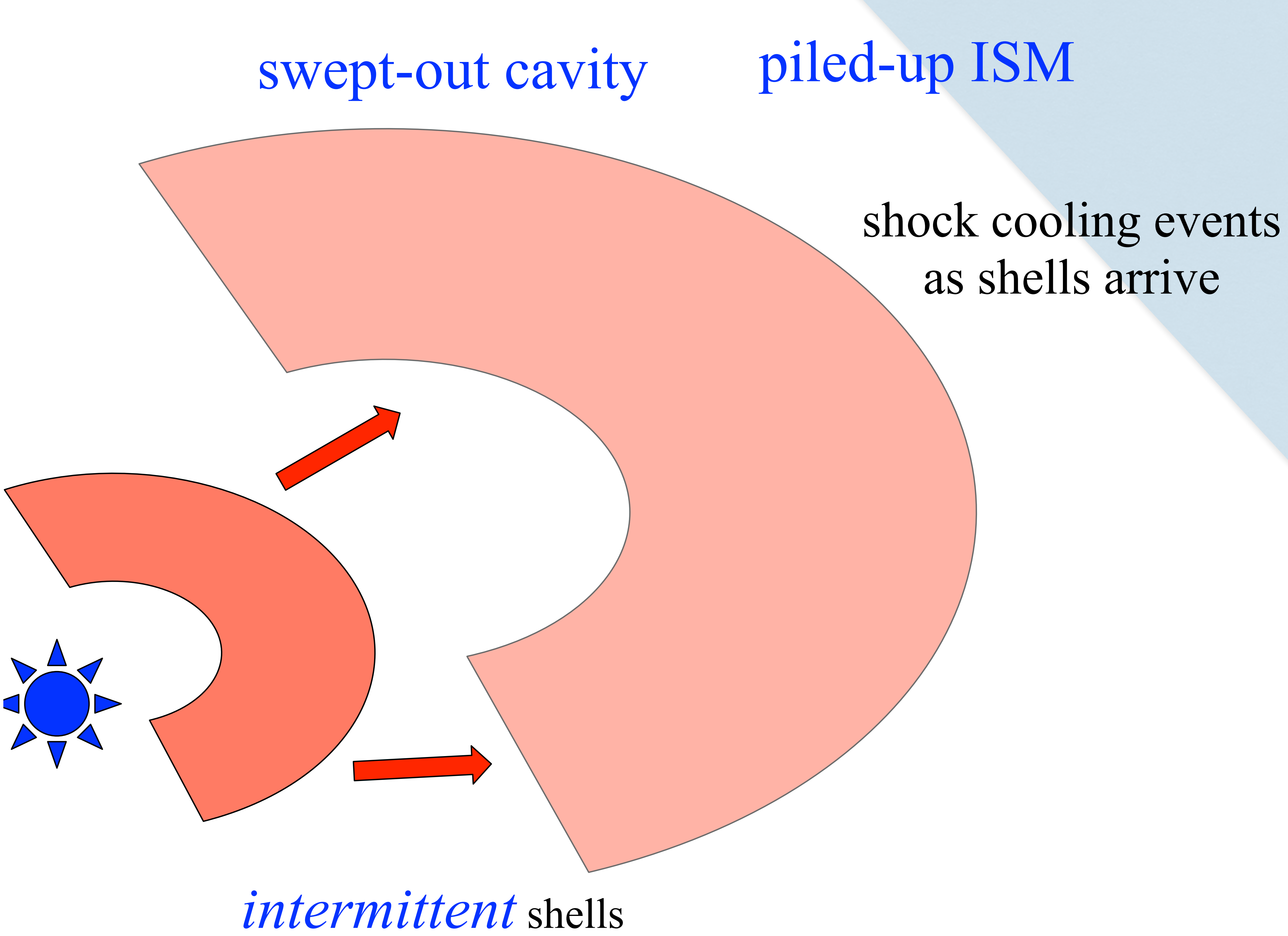
$$t_{\rm var} \sim \frac{M_d}{\dot M} \sim \frac{H M_{\rm BH}}{R \dot M} \sim 10^5 \,{\rm yr}$$

duty cycle $\lesssim 10^8$ yr (most galaxies are not AGN, but all have SMBH)
(K & Pringle, 2006; K & Nixon 2015; Schawinski + 15)

progress of outflow may be slower than measured velocity outflows must be episodic, as AGN driving is variable




swept-out cavity
piled-up ISM
intermittent shells



swept-out cavity
piled-up ISM
shock cooling events
as shells arrive
intermittent shells

outflows collide with swept-up ISM gas, and shock

but shell time of flight

$$\sim R/v \sim 5\,\mathrm{pc}/0.1c \sim 150\,\mathrm{yr}$$

so incidence of shocks reflects activity of AGN *in the past*

duration of shocks reflects duty cycle of AGN *in the past*

similarly UFO — molecular outflow connection:
AGN can vary, but not outflow