LECTURE 2: OUTLINE

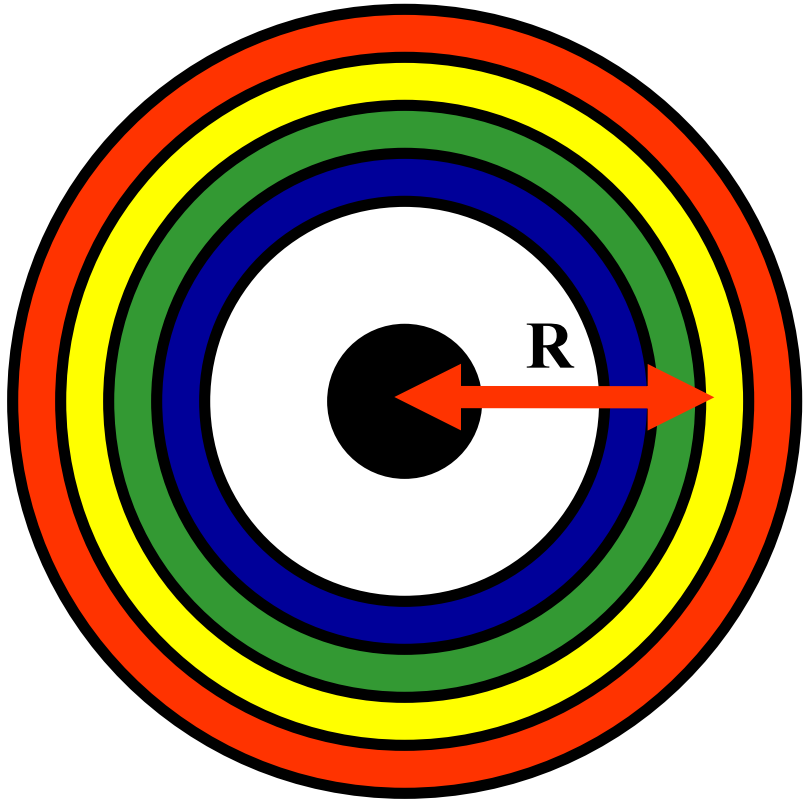
1. Wrapping up thin disks
2. Sketching out Super-Eddington accretion
3. Modeling BH feedback
4. Outflows, Winds – observational evidence
5. Scaling laws derived from above for SAMs: BH mass growth cap, variability, accretion models (Lecture 3)

References: Accretion power in Astrophysics (Frank, King & Raine)

ARA&A Accretion Disks (Pringle); Reviews by King, Di Matteo, PN, Krolik, Gaspari & Sadowski, Pounds

Accretion Disk Structure & Emergent Spectrum

The accretion disk can be considered as rings or annuli of blackbody emission as we saw yesterday



Dissipation rate, D(R) is

$$= \frac{3GM\dot{M}}{8\pi R^3}\left[1-\left(\frac{R_*}{R}\right)^{0.5}\right]$$

$$= \text{blackbody flux}$$

$$= \sigma T^4(R)$$

Disk Temperature

Thus temperature as a function of radius T(R):

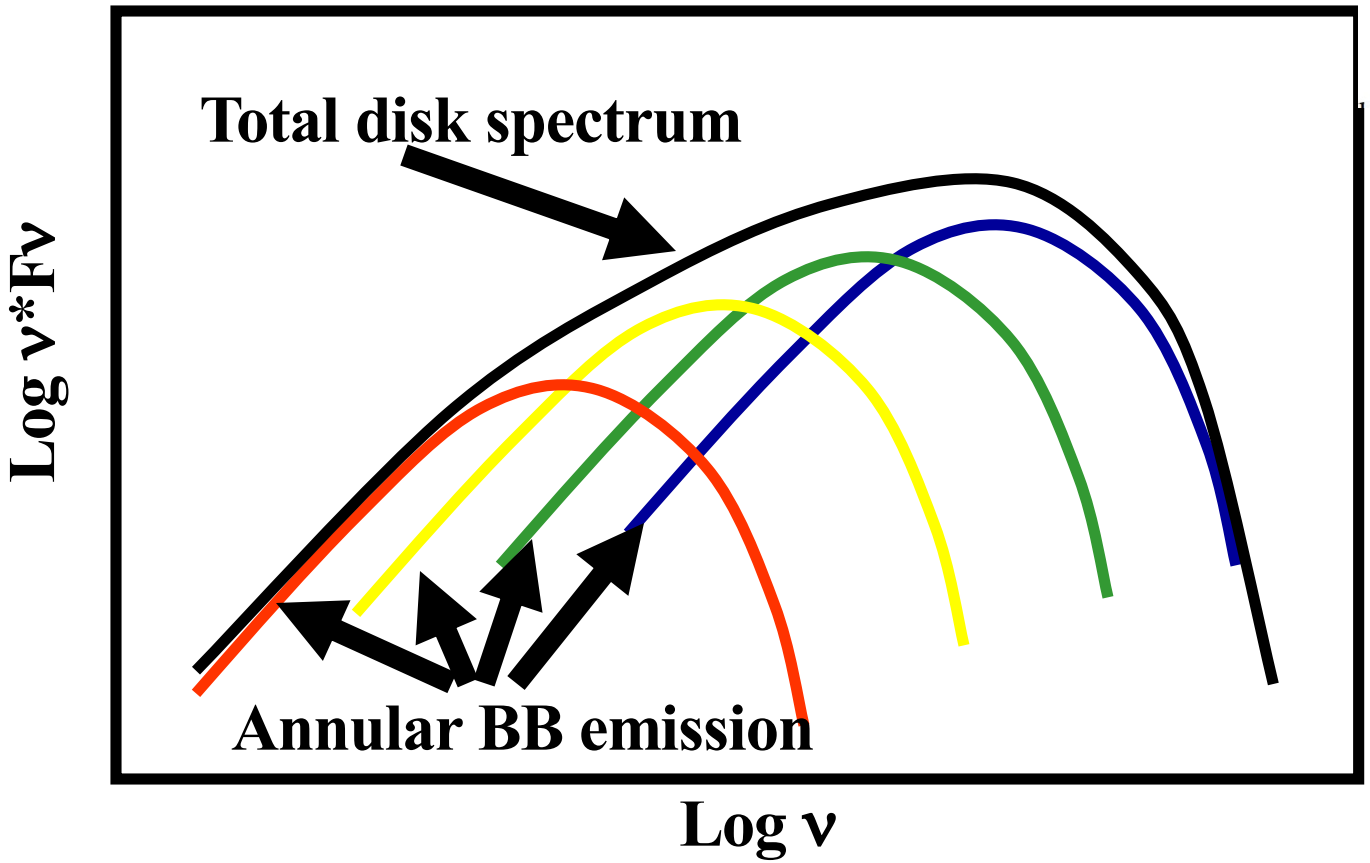
$$T(R) = \left\{ \frac{3GM\dot{M}}{8\pi R^3 \sigma} \left[1 - \left(\frac{R_*}{R} \right)^{0.5} \right] \right\}^{1/4}$$

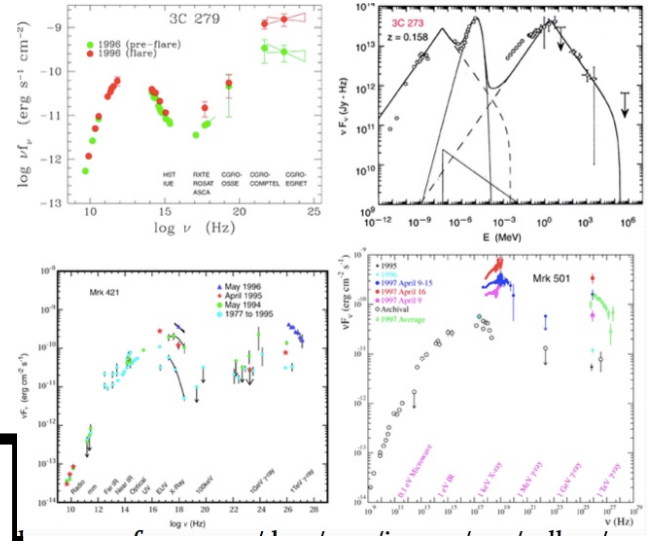
and if $T_* = \left(\frac{3GM\dot{M}}{8\pi R_*^3 \sigma} \right)^{1/4}$

then for $R >> R_*$ $\qquad T = T_* \left(R / R_* \right)^{-3/4}$

Disk Spectrum

Flux as a function of frequency

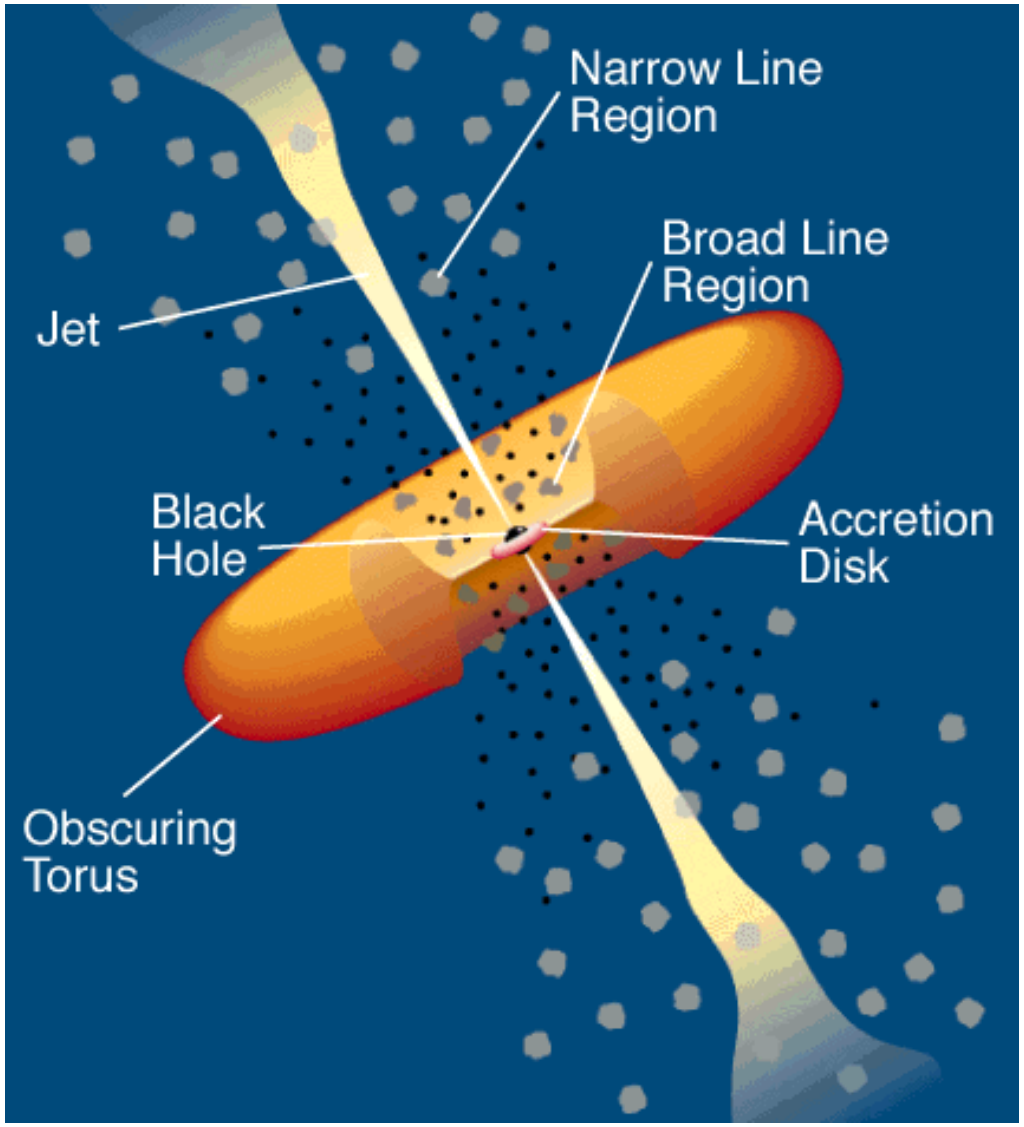




Emission from AGN

- Very large luminosities (up to 10,000 times a typical galaxy)
- The emission spans a huge range of photon energy (radio to gamma-rays)
- The source of energy generation is very compact (< size of the solar system)
- In some cases, there is significant energy transported in relativistic jets

Active Galactic Nuclei (AGN)



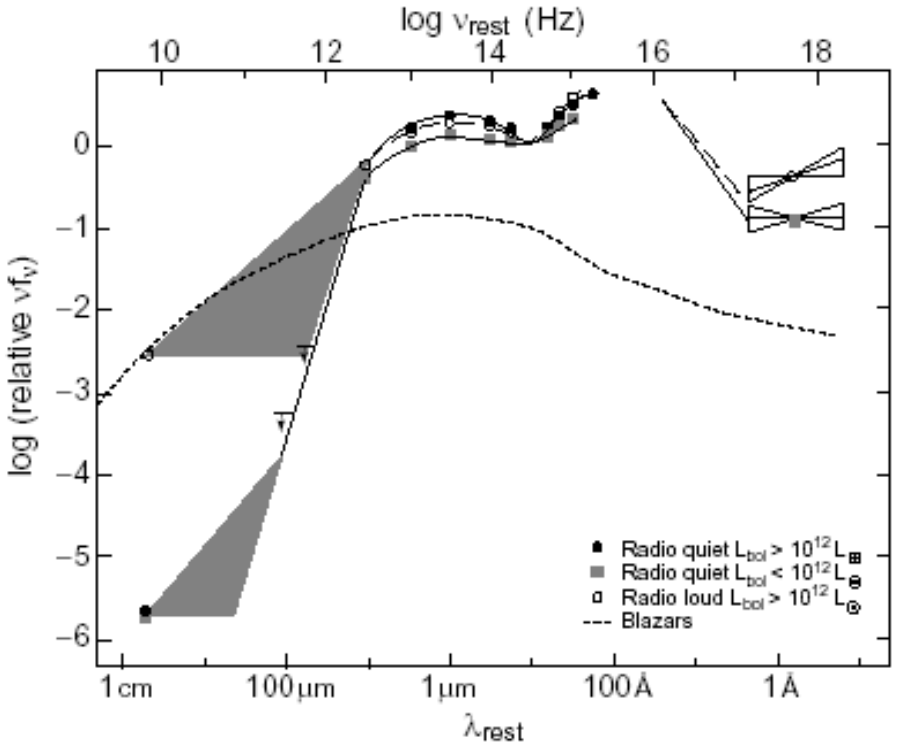
The Lay of the Land

($M\bullet = 10^8\ M_\odot, L \sim 0.1\ L_{Edd}$; everything scales with accretion luminosity)

10^{-3} pc	~ 1000 R_S **broad-line region** (base of outflow?)	UNRESOLVED probed by emission- and absorption-line spectroscopy and variability
10^{-2} pc		
0.1 pc	**onset of dust** (inner edge of torus?)	
1 pc	**dust torus, M-maser disk** (R_h in bulge of spiral)	resolvable by radio and IR interferometry in nearby Seyferts ($z \sim 0.05$)
10 pc	**narrow-line region** (R_h in giant elliptical)	
10^2 pc	**disk of neutral gas** outflowing ionized gas	resolvable by the HST in nearby Seyferts ($z \sim 0.05$)
10^3 pc	**large-scale, ionized gas outflows**	resolvable by the Gemini IFU in nearby quasars ($z \sim 0.1$)

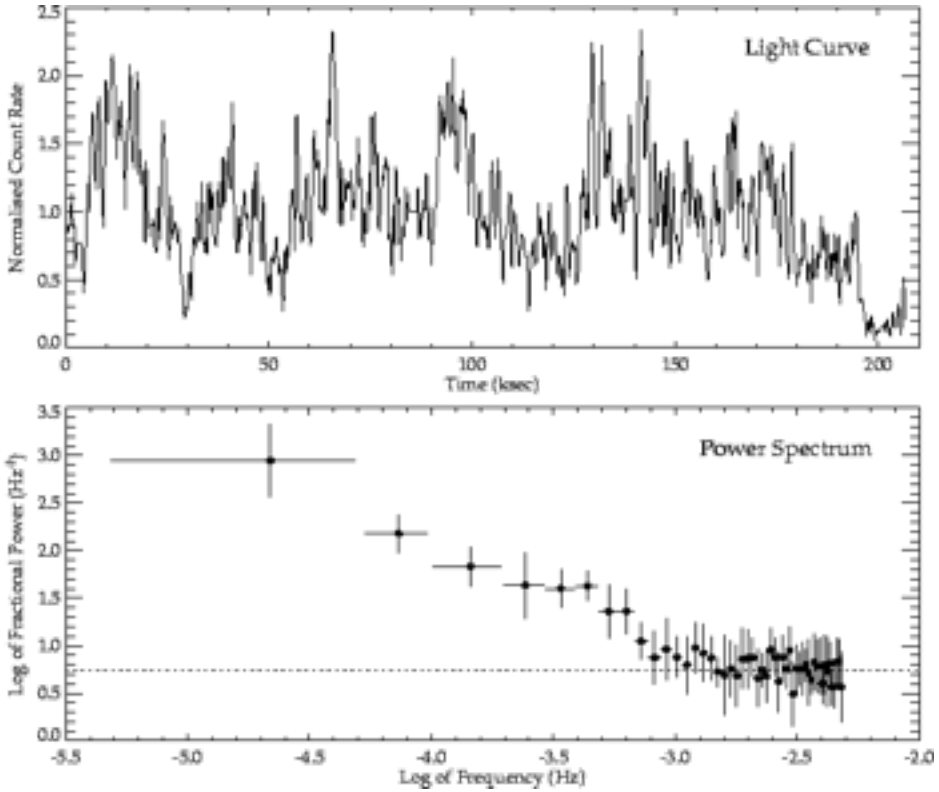
Slide courtesy of M. Eracleous

AGN spectrum: broad-band + variability



Comparable power emitted across ~ 7 orders of magnitude in photon energy; given the size (few to ten Schwarzchild radii) of the accretion disk and its luminosity, we expect thermal emission peaking in the far-ultraviolet – Big Blue Bump

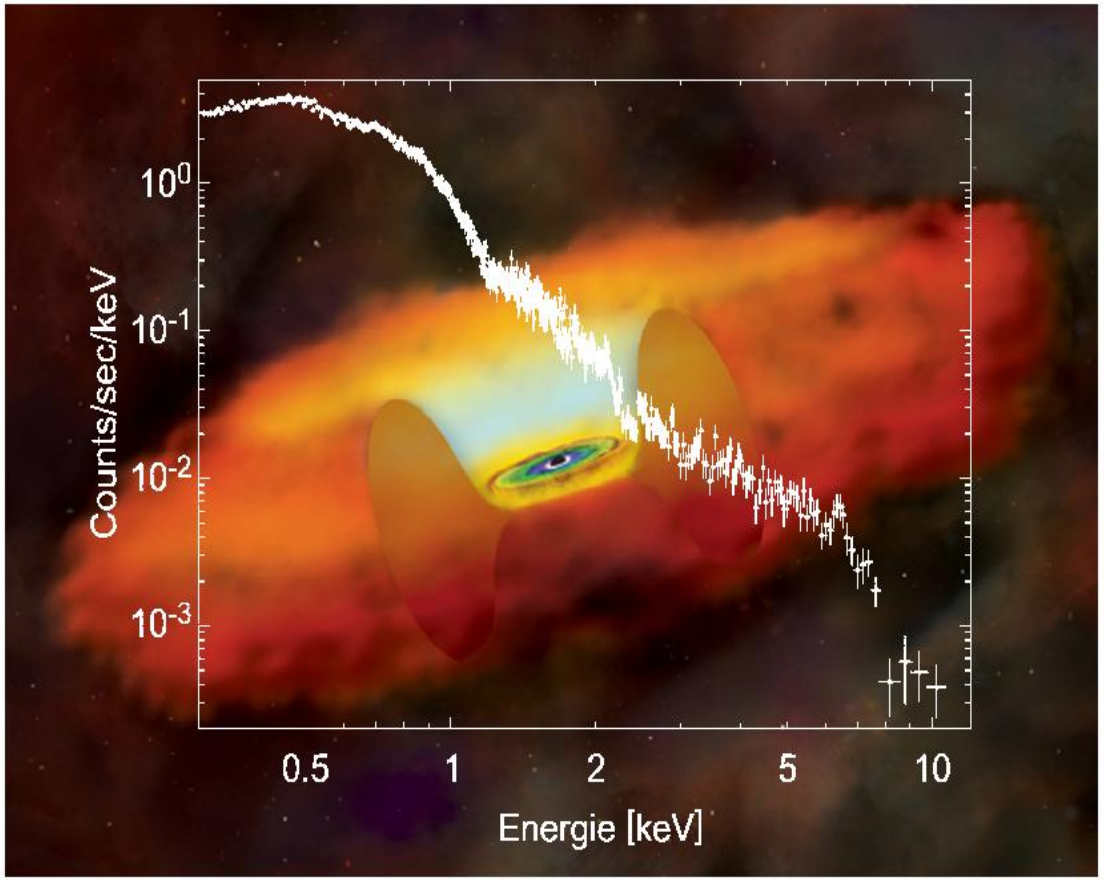
FLICKERING



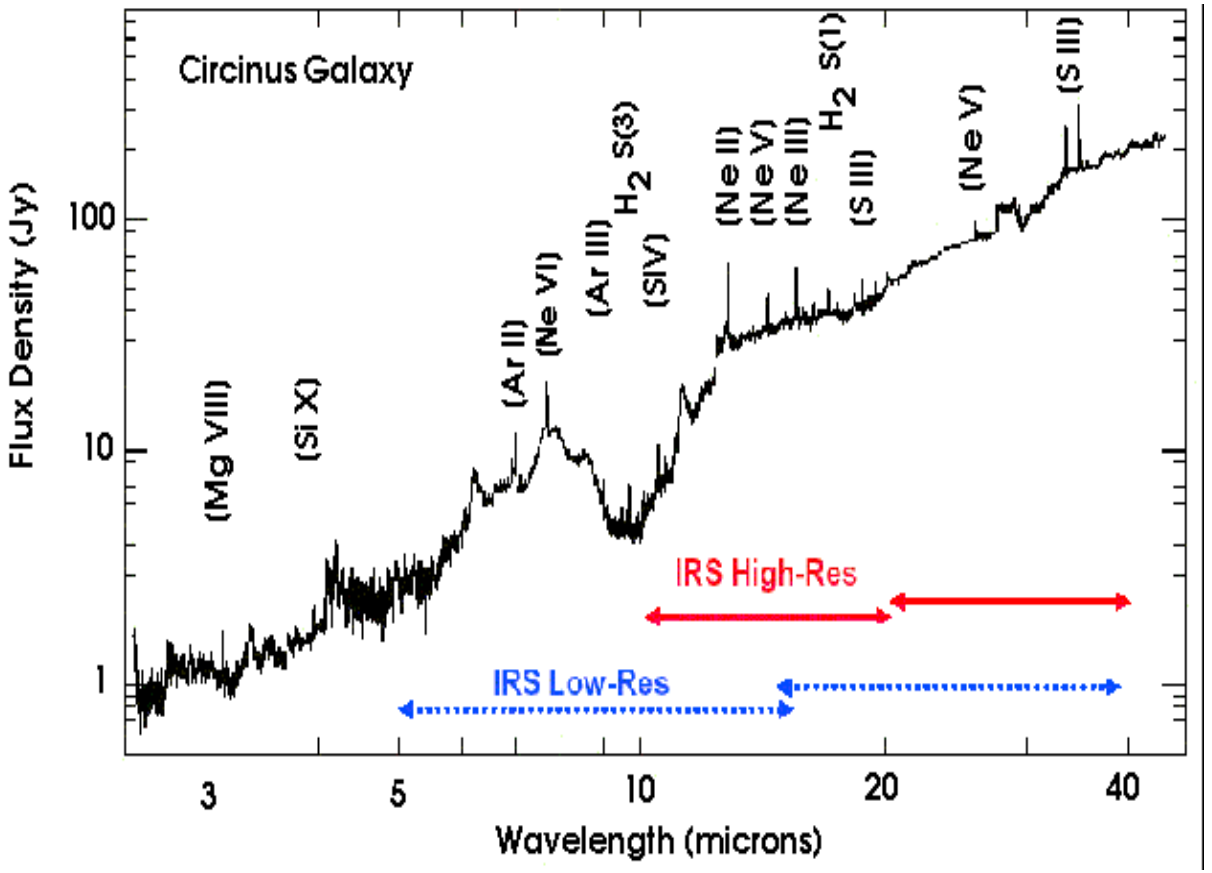
Light travel time argument: a source that varies in time t must have size

$R < ct$

Accretion Disk Corona & Torus

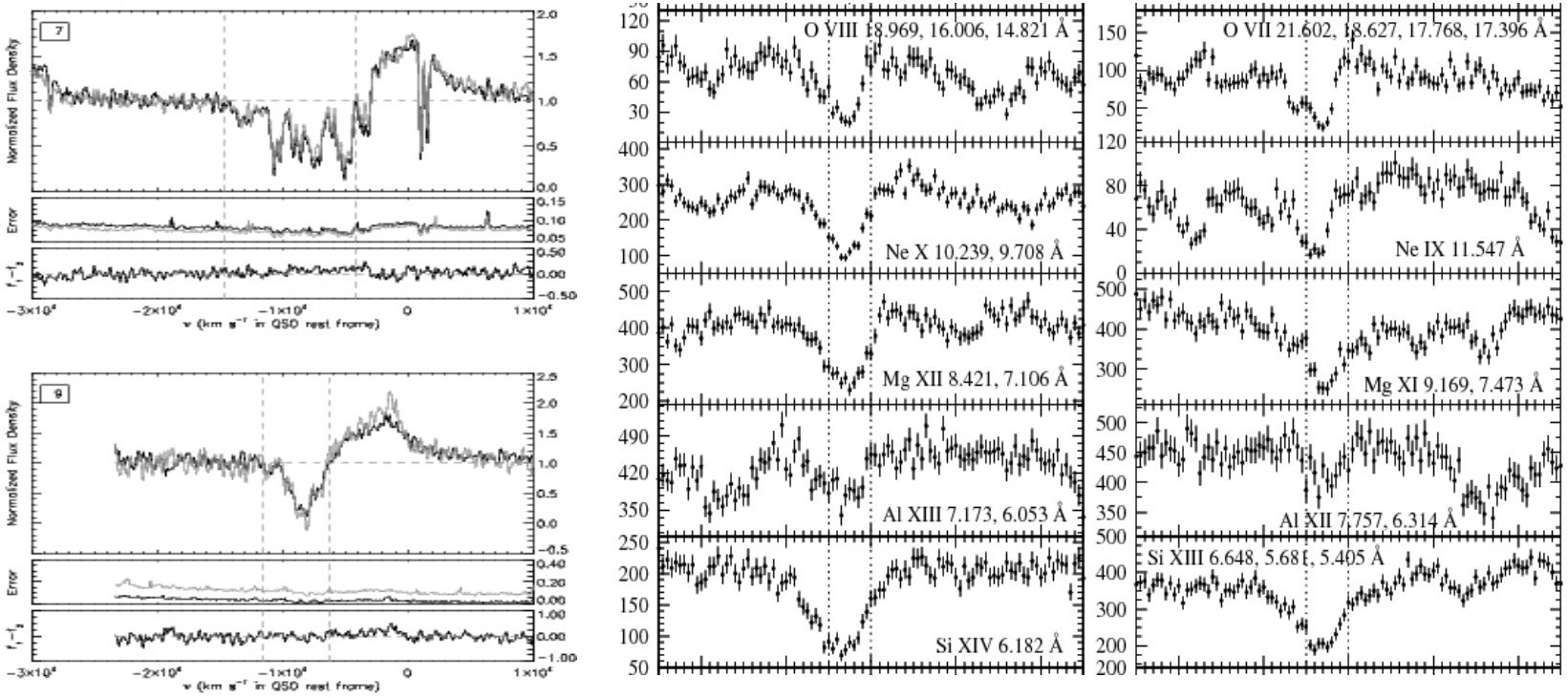


- Very hot gas responsible for the X-ray emission
- X-rays irradiate the disk, which alters the X-ray spectrum



Dust in the molecular torus absorbs optical/UV radiation from the accretion disk
Dust heated to ~100 to 1000K. Emit in the IR
L_IR ~ L_UV: torus intercepts ~half the light

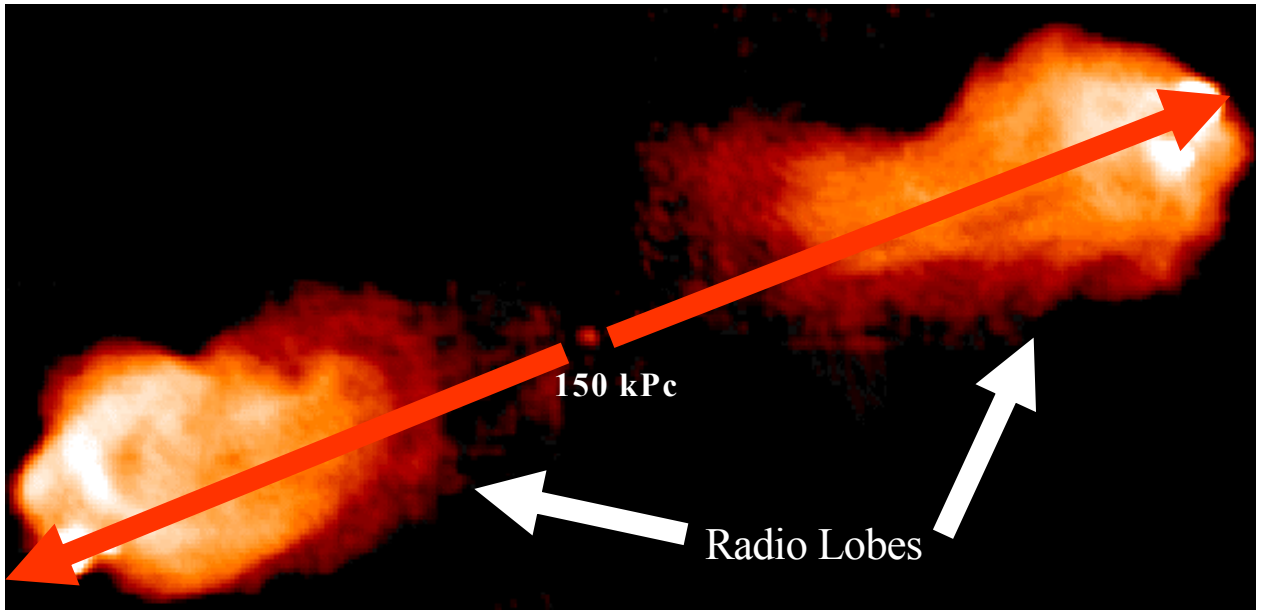
Broad & Narrow Absorption-Lines

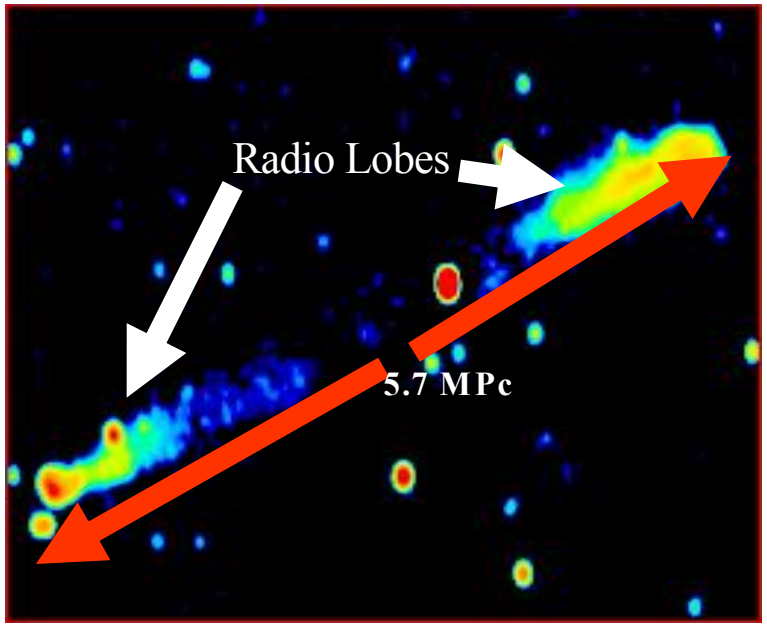


- High velocity outflows (up to ~0.1c)
- Sizes are uncertain: similar to BLR? (<torus)
- Small sizes imply modest kinetic energy

Radio Galaxies and Jets

Cygnus-A →
VLA radio image at
$\nu = 1.4.10^9$ Hz
- the closest powerful radio galaxy
(d = 190 Mpc)

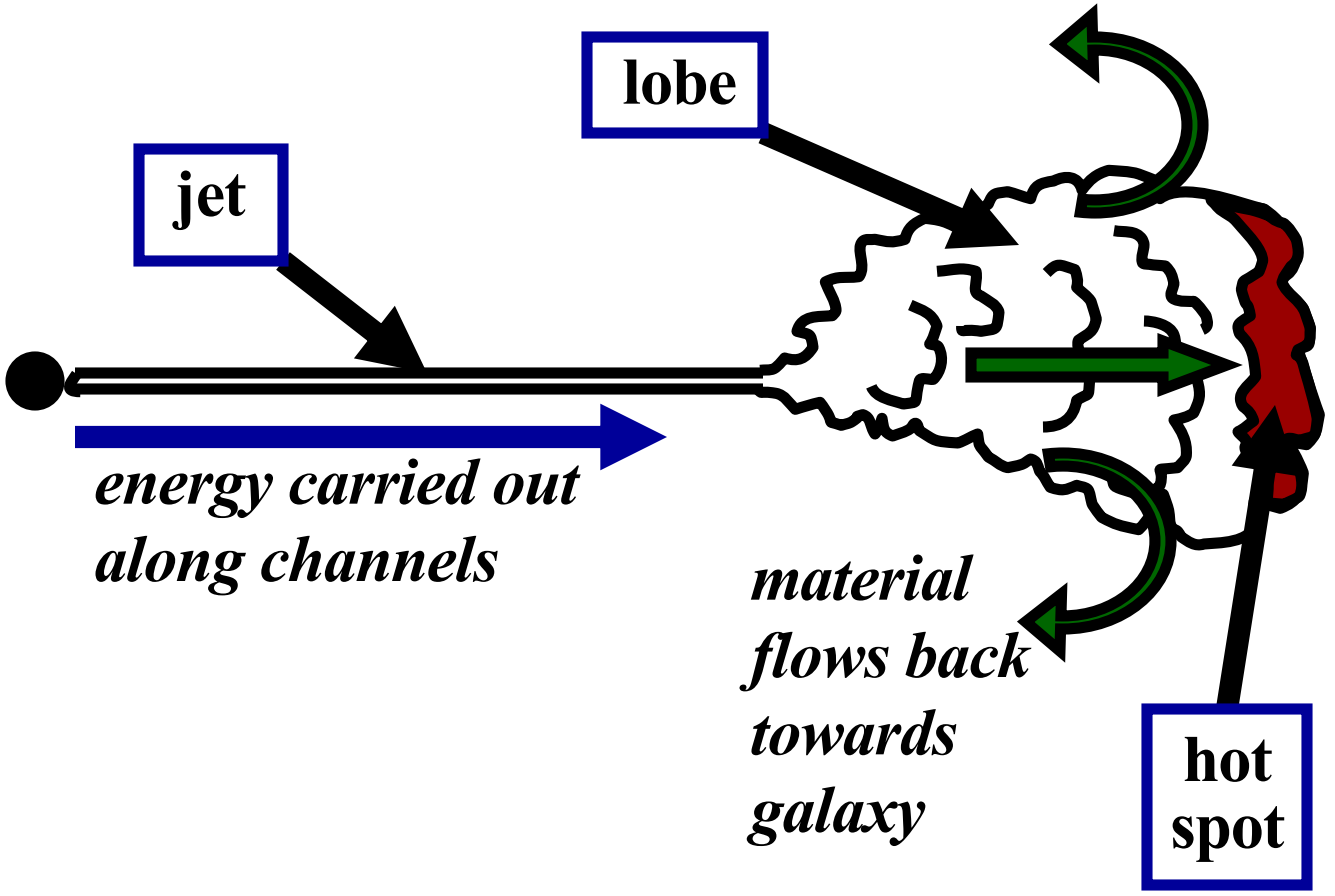




← 3C 236 Westerbork radio image at $\nu = 6.08.10^8$ Hz – a radio galaxy of very large extent
(d = 490 Mpc)

Jets, emanating from a central highly active galaxy, are due to relativistic electrons that fill the lobes

Jets: Focussed Streams of Ionized Gas



Thin discs?

Thin disc conditions hold in many observed cases.

If not, disc is *thick, non—Keplerian, and does not cool efficiently*.
Pressure is important: disc ~ rapidly rotating `star'.

Progress in calculating structure slow: e.g. flow timescales far shorter at inner edge than further out.

One possibility: matter flows inwards without radiating, and can accrete to a black hole `invisibly' (ADAF = advection dominated accretion flow). Most rotation laws → dynamical instability (PP).

Numerical calculations suggest indeed that most of matter flows out (ADIOS = adiabatic inflow—outflow solution)

Viscosity

Early parametrization: $\nu \sim \lambda u$ with typical length and velocity scales λ, u . Now argue that

$$\lambda < H, u < c_s$$

First relation obvious, second because supersonic random motions would shock. Thus set

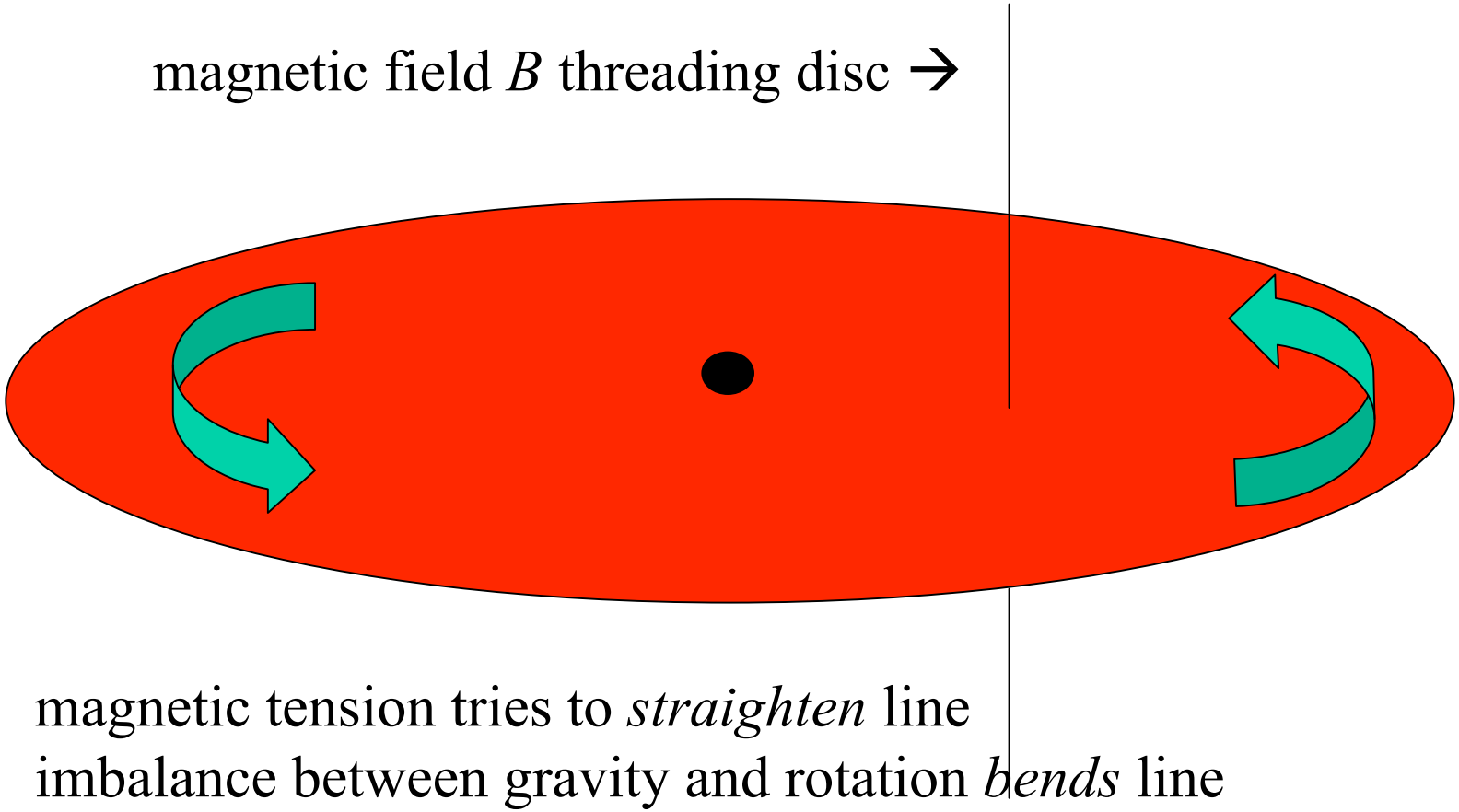
$$\nu = \alpha c_s H$$

and argue that $\alpha < 1$. *But* no reason to suppose $\alpha = const$

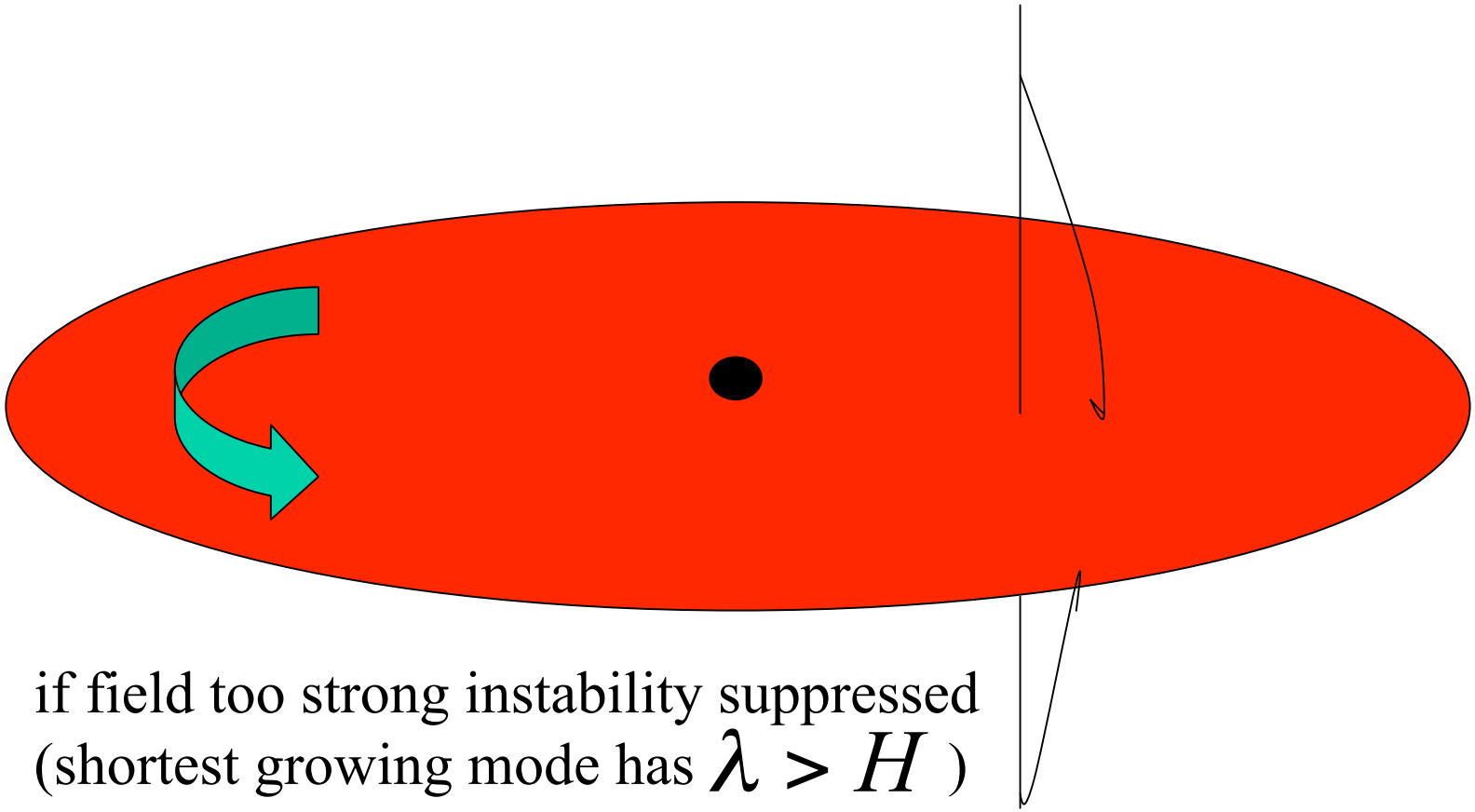
`Alpha—prescription' useful because disc structure only depends on low powers of α . But *no predictive power*

need a mechanism sensitive to Ω or v_K

Balbus—Hawley (magnetorotational, MRI) instability

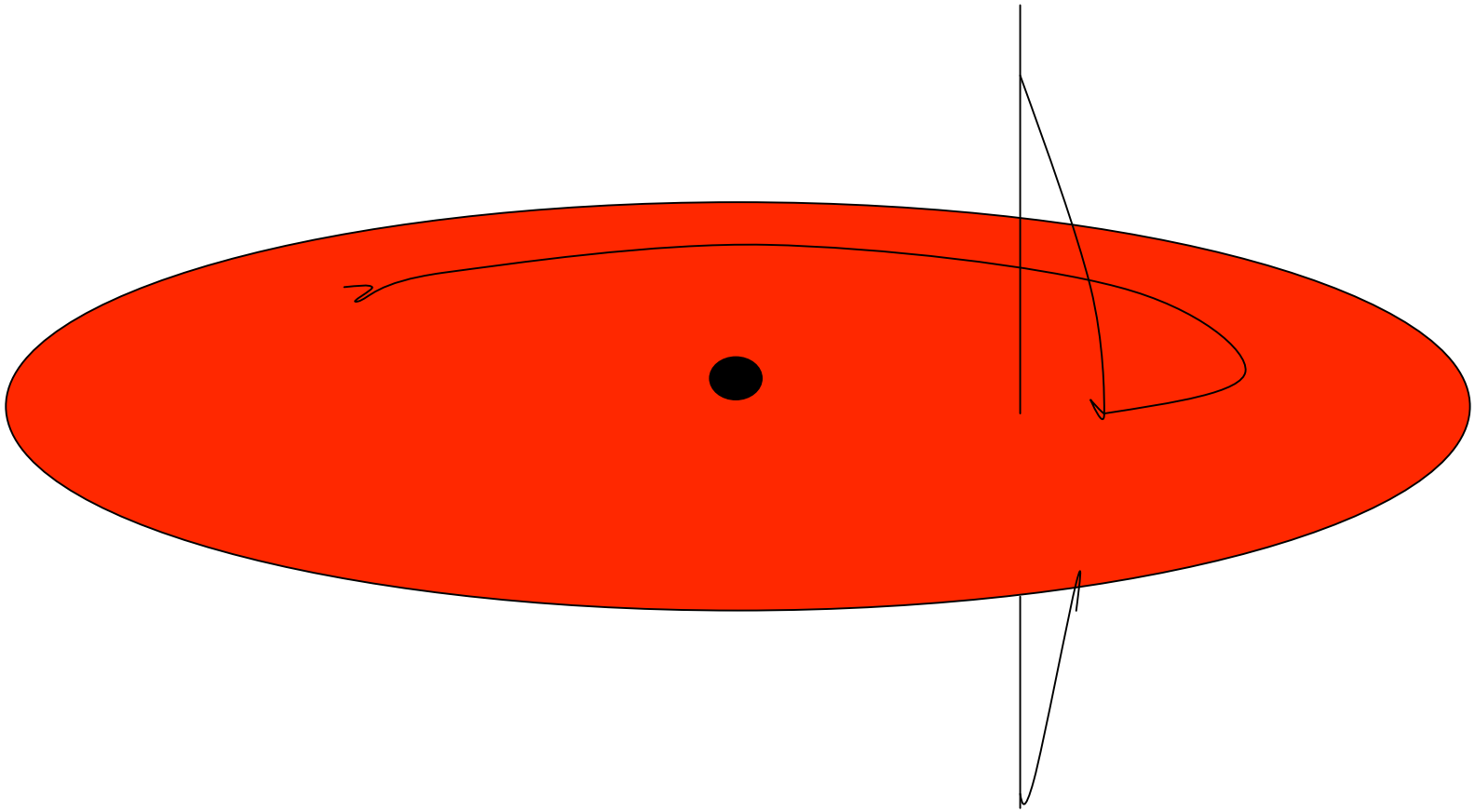


Vertical fieldline perturbed outwards, rotates faster than surroundings, so centrifugal force > gravity → *kink increases.* Line connects fast-moving (inner) matter with slower (outer) matter, and speeds latter up: ***outward a.m. transport***



if field too strong instability suppressed (shortest growing mode has $\lambda > H$)

distorted fieldline stretched azimuthally by differential rotation, *strength grows*

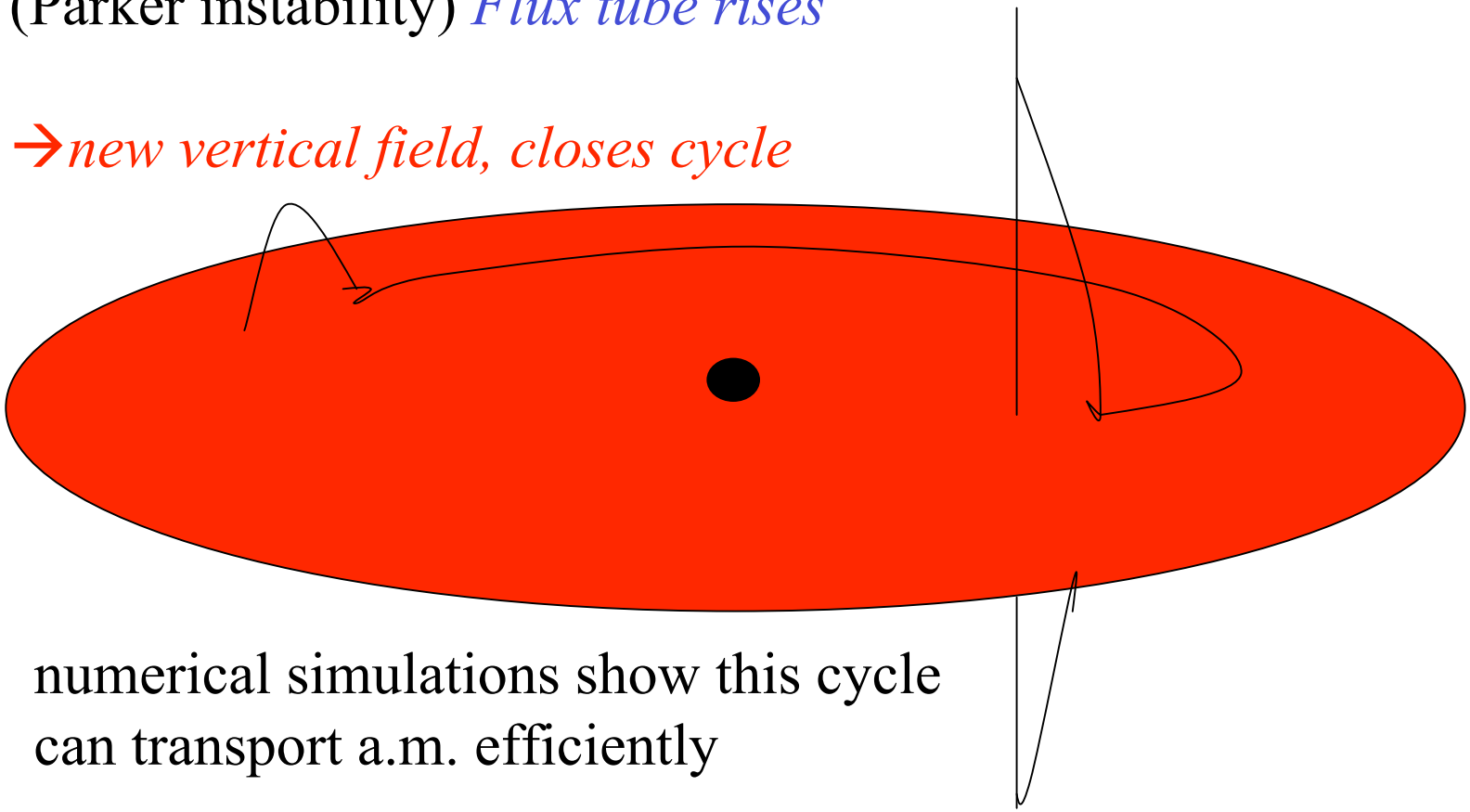


pressure balance between flux tube and surroundings requires

$$\frac{B^2}{8\pi} + P_{gas,in} = P_{gas,out}$$

so gas pressure and hence density lower inside tube → *buoyant* (Parker instability) *Flux tube rises*

→*new vertical field, closes cycle*

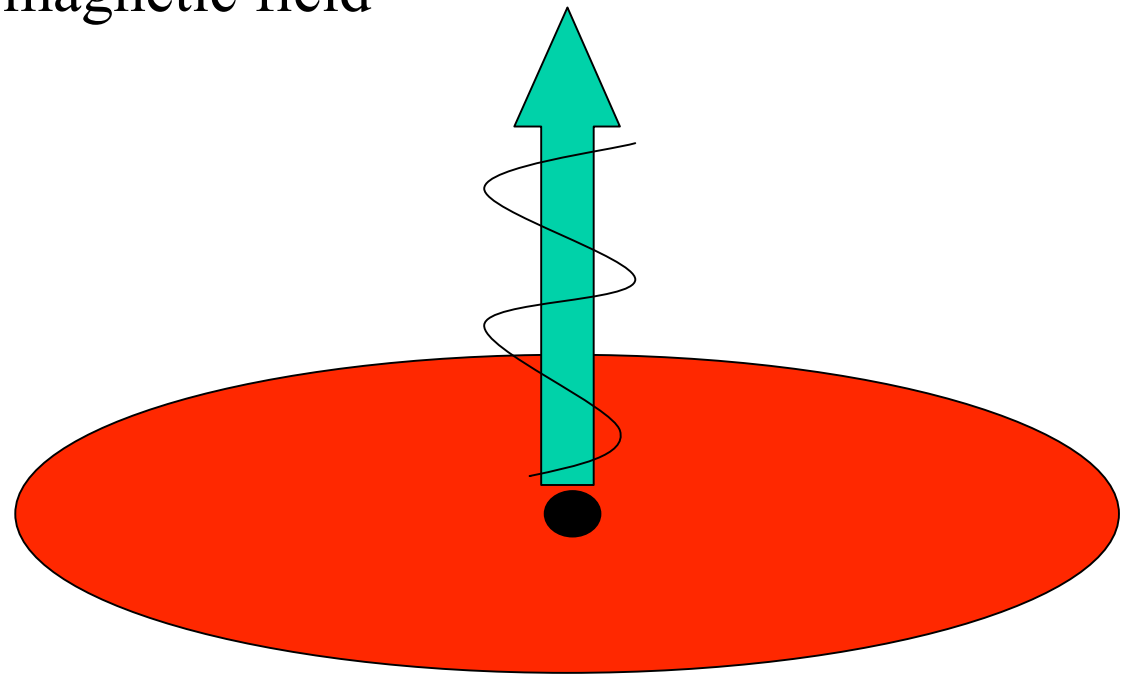


numerical simulations show this cycle can transport a.m. efficiently

Jets

One observed form of outflow: jets with ~ escape velocity from point of ejection, ~ c for black holes

Launching and collimation not understood – probably requires toroidal magnetic field



Eddington limit

accretion is inhibited once $F_{\rm rad} \geq F_{\rm grav}$, i.e. once

$$L \geq L_{\rm Edd} = \frac{4\pi GMc}{\kappa} = 1.3 \times 10^{46} M_8 \ {\rm erg \ s^{-1}}$$

Eddington limit: luminosity requires minimum mass

$(\kappa = \sigma_T/m_p = \textit{electron scattering opacity} \simeq 0.34 \ {\rm cm^2 \ g^{-1}})$

Can a black hole *ignore* the Eddington limit?

accretion would *not* be limited by the Eddington rate

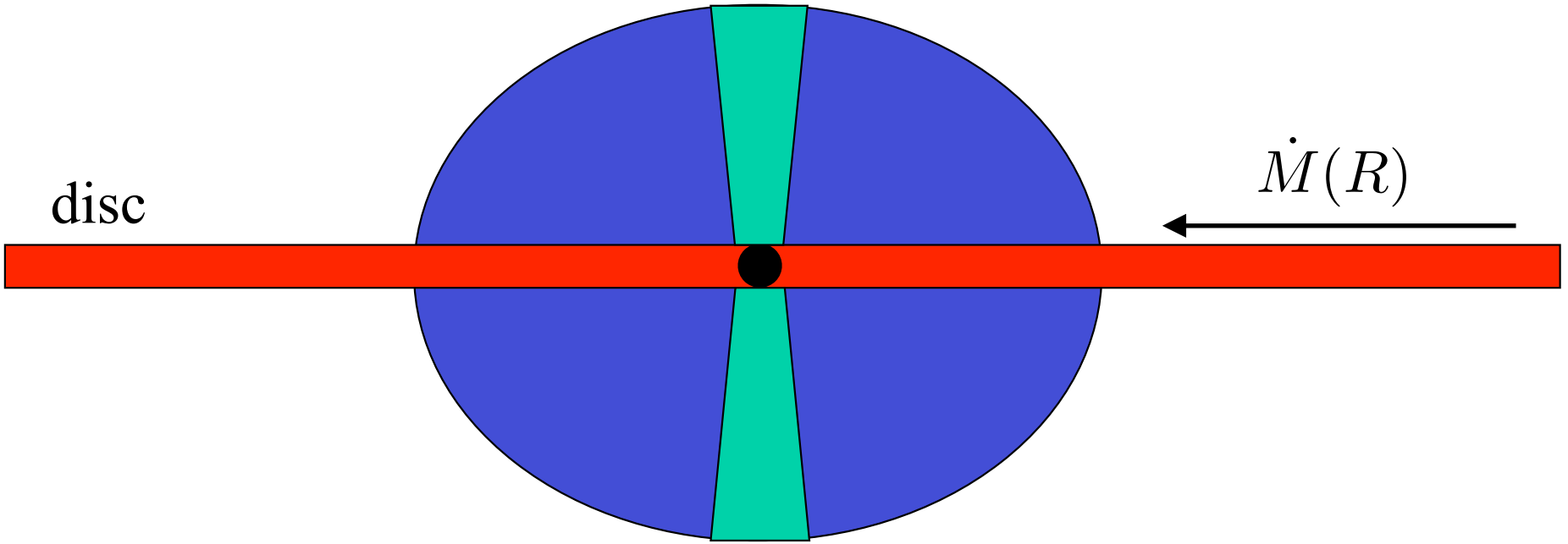
$$\dot{M}_{\rm Edd} = \frac{L_{\rm Edd}}{\eta c^2}$$

if radiation could somehow escape without pushing matter away.

radiative transfer calculations sometimes suggest this

Super-Eddington Accretion

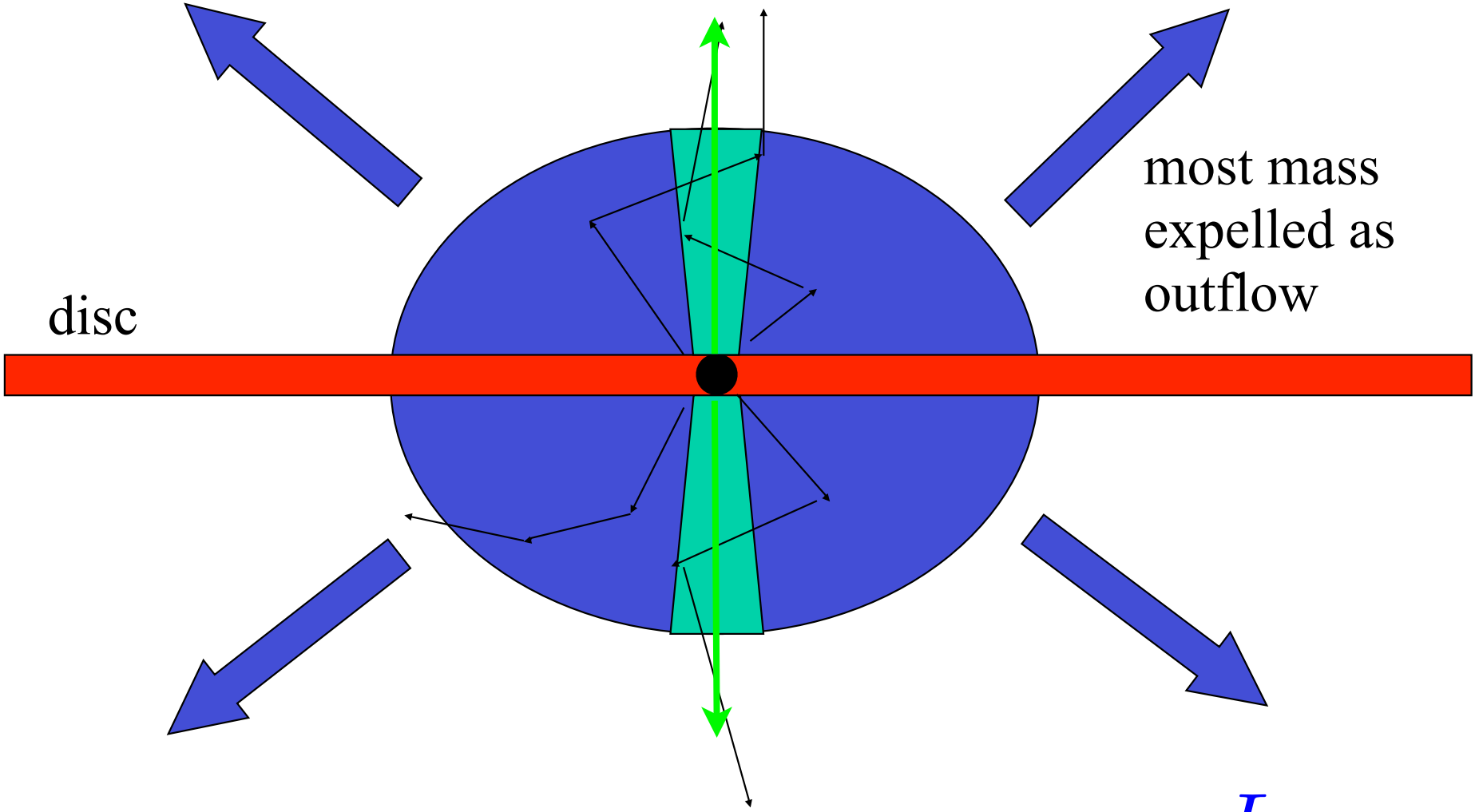
$\dot{M}(R)$ adjusts to keep $GM\dot{M}(R)/R = L_{\rm Edd}$



so $\dot{M}(R) \propto R$

Super-Eddington Accretion

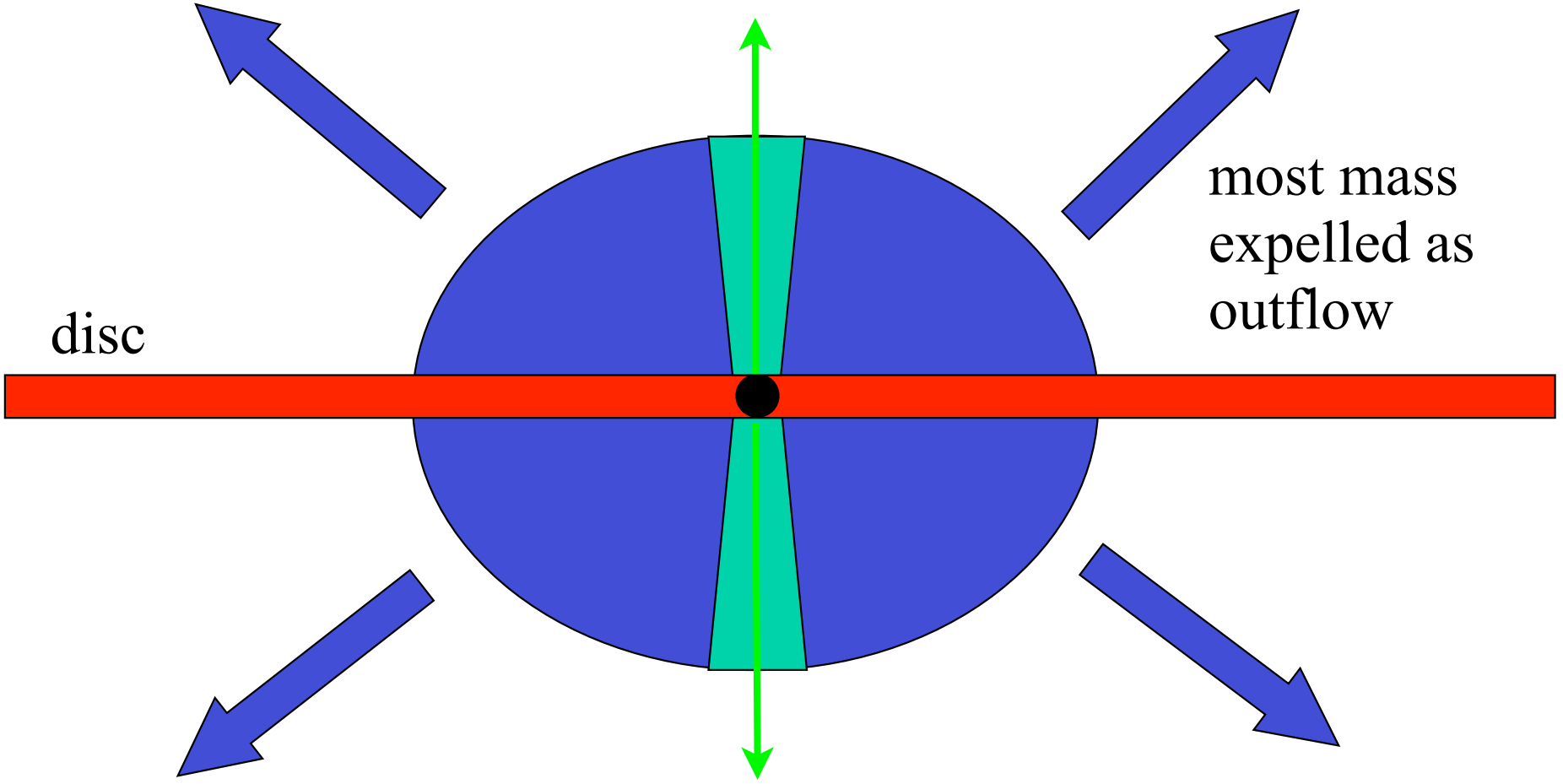
most photons eventually escape along cones near axis



on average photons give up all
momentum to outflow after ~ 1 scattering

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

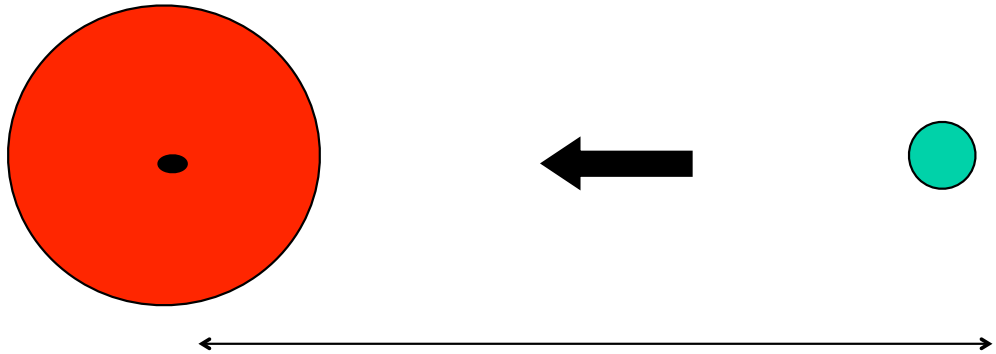
Super-Eddington Accretion



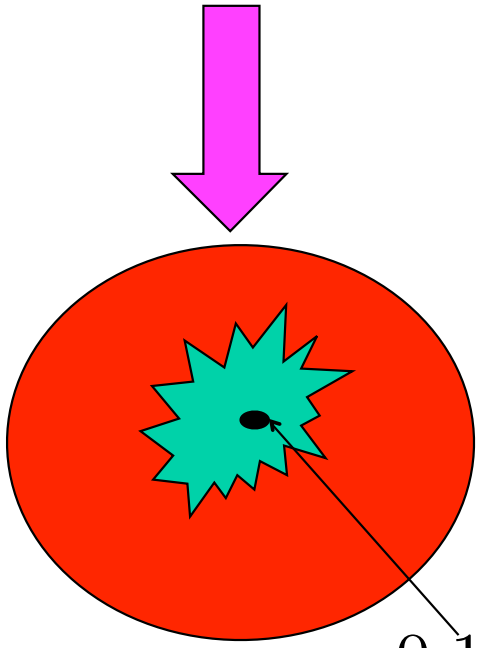
$$L = L_{\rm Edd}[1 + \ln(\dot{M}/\dot{M}_{\rm Edd})] \quad \text{(beamed)}$$

compare with SS433

cosmological picture of growth: big galaxy swallows small



megaparsecs, gas/star mass $10^{11} - 10^{12} M_\odot$



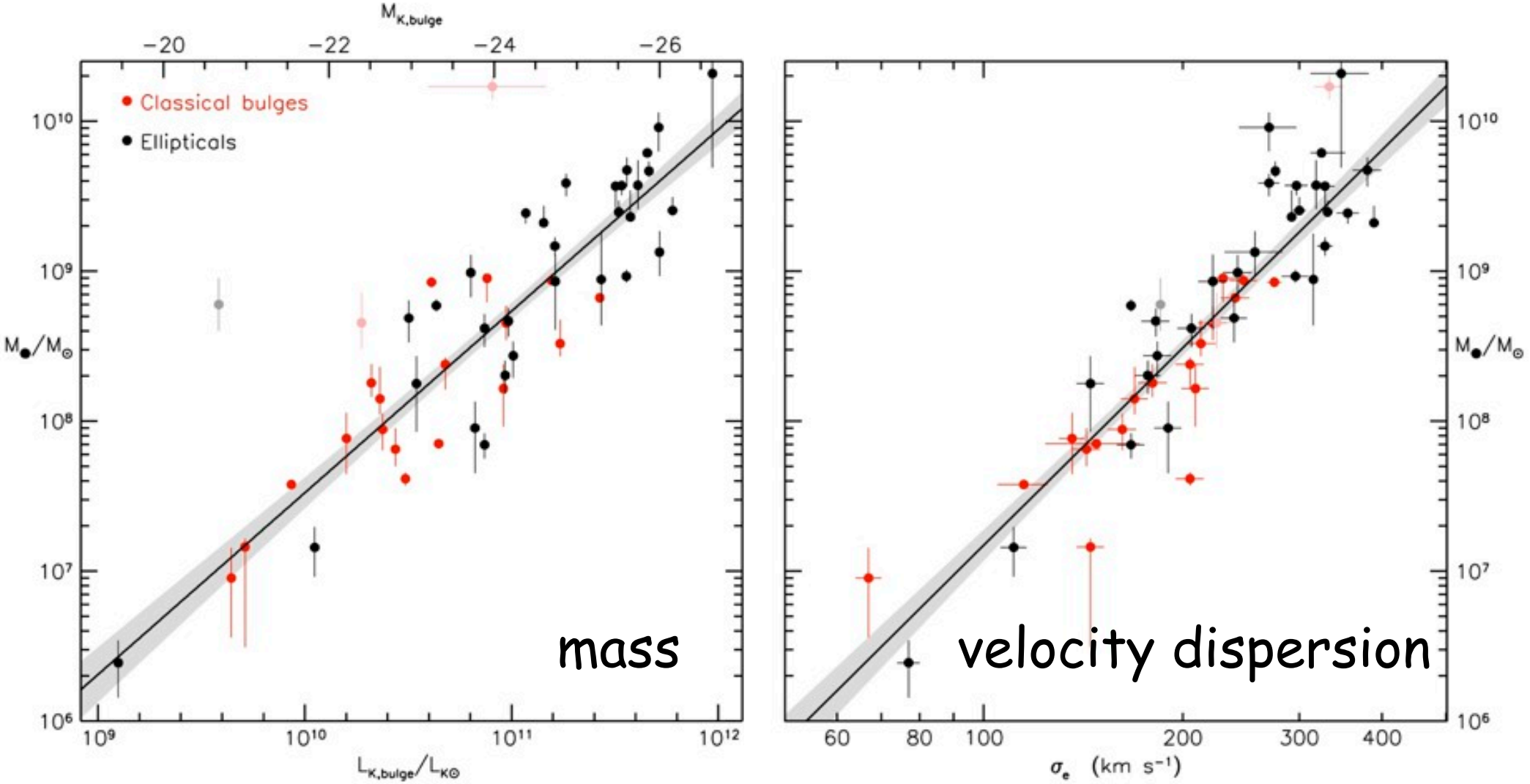
dynamical friction =>
BHs coalesce!

merger

0.1 parsec, gas masses $< 10^5 M_\odot$

huge range of mass and length scales: numerical treatment impossible

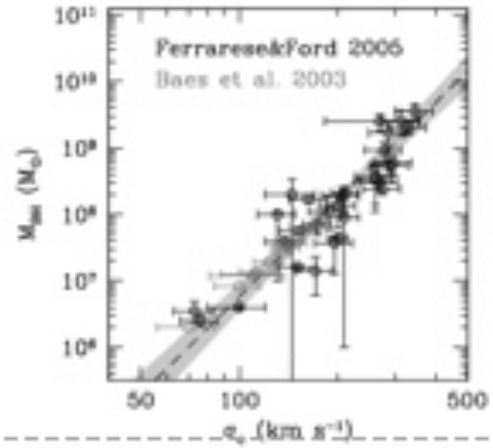
galaxy knows about central SMBH

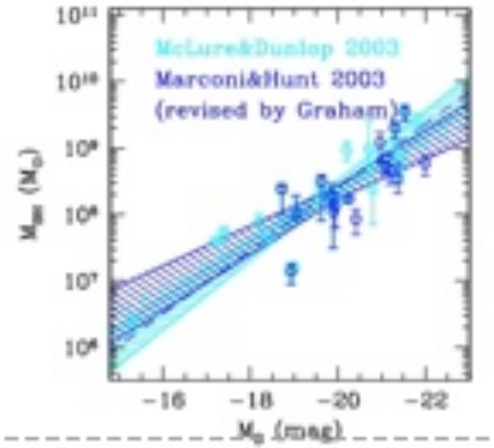


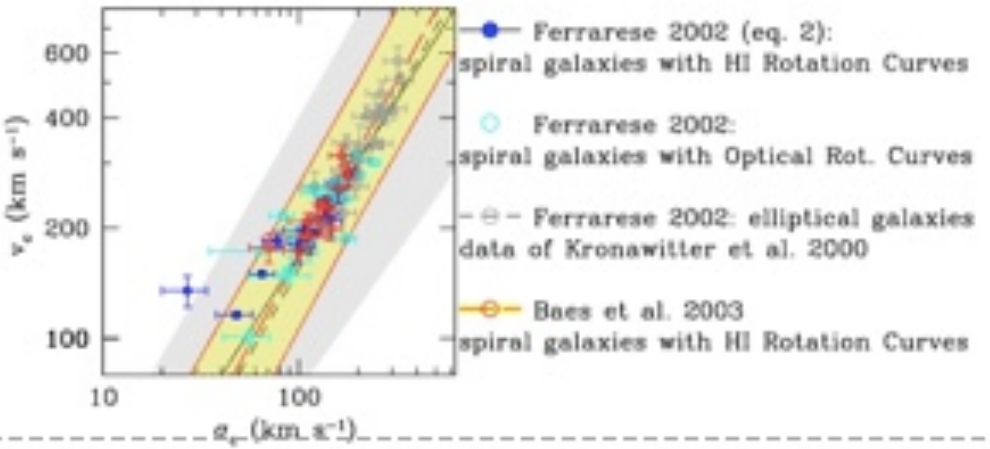
galaxy bulge ⟶

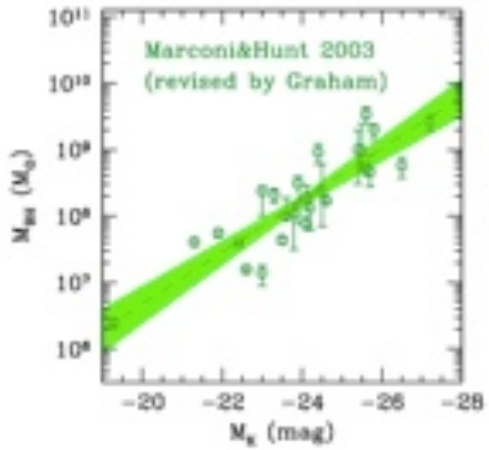
Kormendy & Ho, 2013

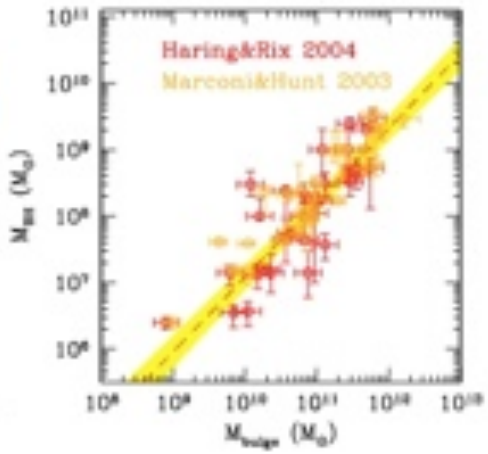
BLACK HOLE SCALING RELATIONS

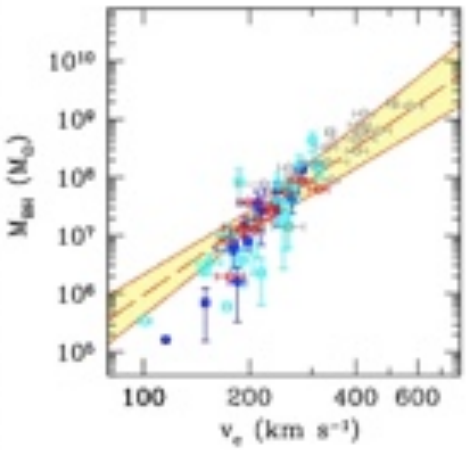


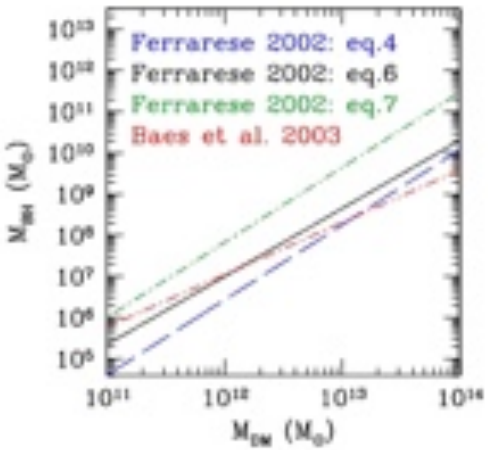












how?

SMBH mass is completely insignificant: $M \sim 10^{-3} M_{\rm bulge}$,

so its gravity affects only a region

$$R_{\rm inf} = \frac{GM}{\sigma^2} \sim 10 \frac{M_8}{\sigma_{200}^2} \ {\rm parsec}$$

$$\left(M_8 = M/10^8 M_\odot \ , \ \sigma_{200} = \sigma/200 \ {\rm km\,s^{-1}} \right)$$

- far smaller than bulge

why does the galaxy notice the hole?

well....

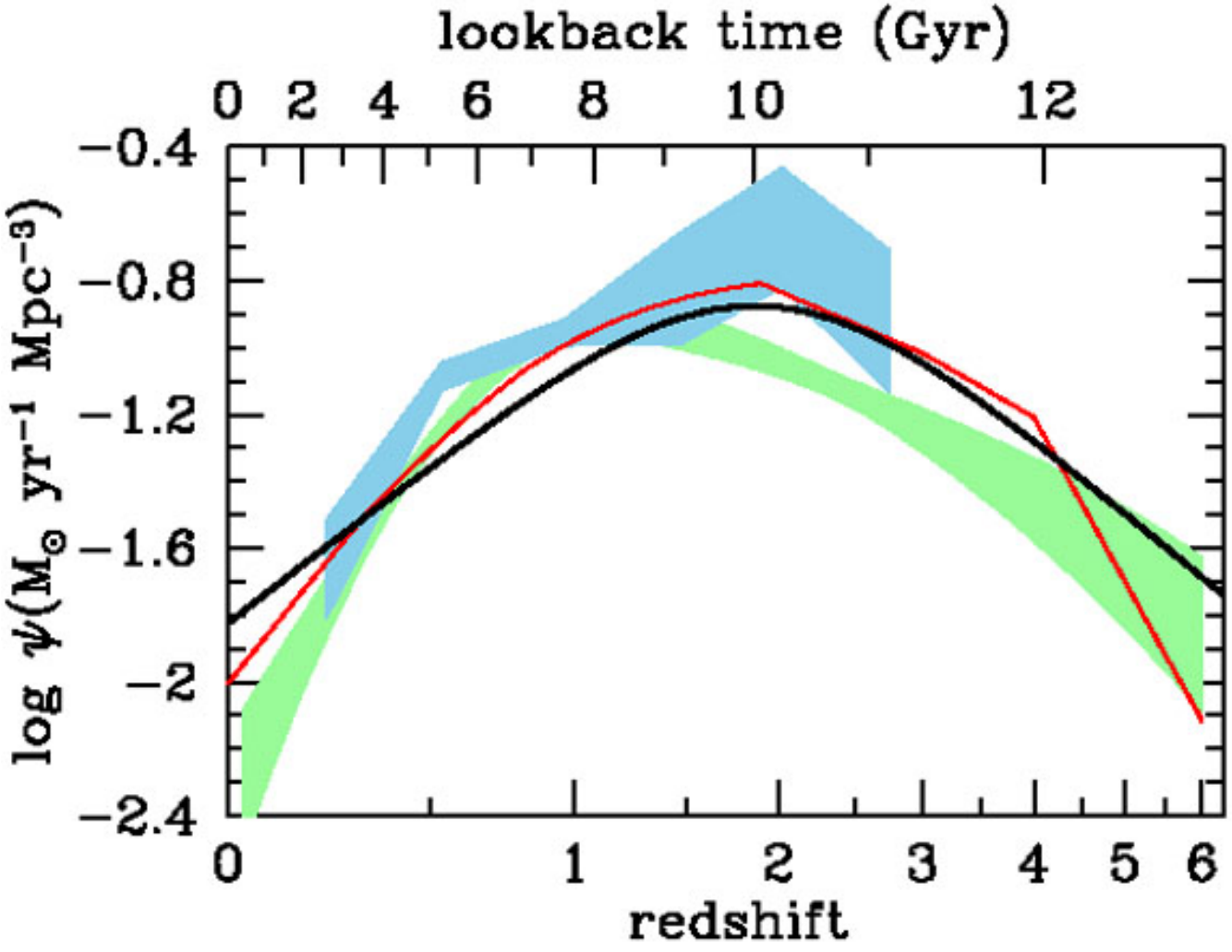
SMBH releases accretion energy $\sim 0.1 M_{BH} c^2 \sim 10^{61}$ erg
galaxy bulge binding energy $M_b \sigma^2 \sim 10^{58}$ erg

galaxy notices hole through energy release:

`feedback'

Globally averaged BHAR traces over cosmic time

feedback models need to couple BH to host galaxy



Understanding M_{bh} – sigma

Back reaction of the accretion flow with the energy emitted (radiation) from the growing BH. Luminosity exceeds energy deposition rate required to unbind the disc on a dynamical time-scale (this scales v^5) Haehnelt, PN & Rees 1998; PN & Treister 2009

$$M_{\rm bh} \sim 10^8\,(f_{\rm kin}/0.001)^{-1}\,j_{\rm d}^{-5} \times \left(\frac{\lambda}{0.05}\right)^{-5}\left(\frac{m_{\rm d}}{0.1}\right)^{5}\left(\frac{v_{\rm halo}}{400\,{\rm km\,s^{-1}}}\right)^{5}{\rm M}_\odot,$$

Another view: Feedback from momentum driven winds limits stellar luminosity which in turn regulates BH mass (Murray, Quataert & Thompson 2004) Eddington limited star formation. Momentum driven outflows that couple star formation & BH growth (King 2005; 2009; King & Pounds 2015; King & PN in prep)

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

outflow 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

Eddington outflows: summary

momentum outflow rate

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

speed

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

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

energy outflow rate

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

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

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 $\frac{L_{\rm Edd}}{c}$

COUPLING BH GROWTH TO STAR FORMATION

Driving BH driving winds into the galaxy

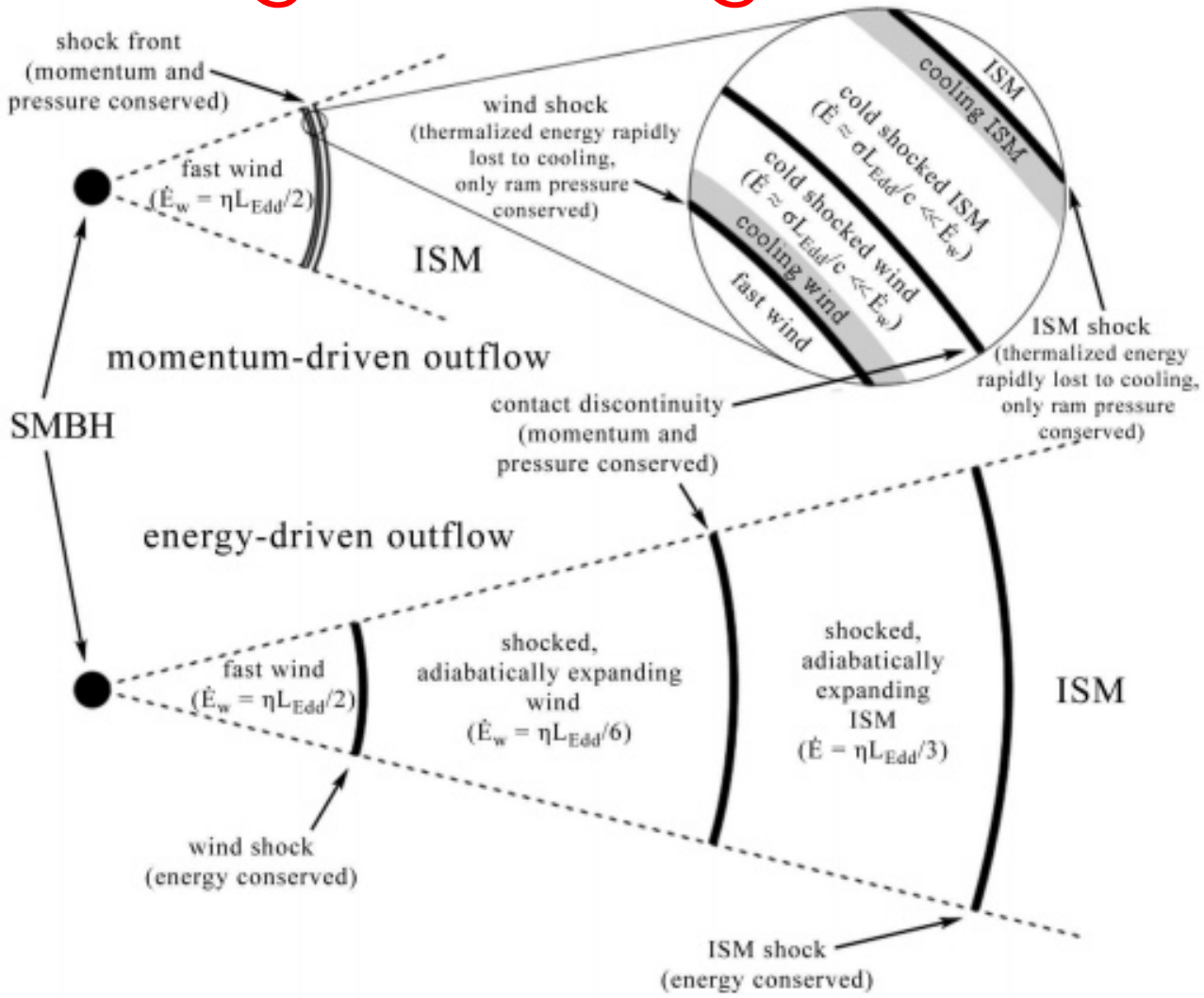
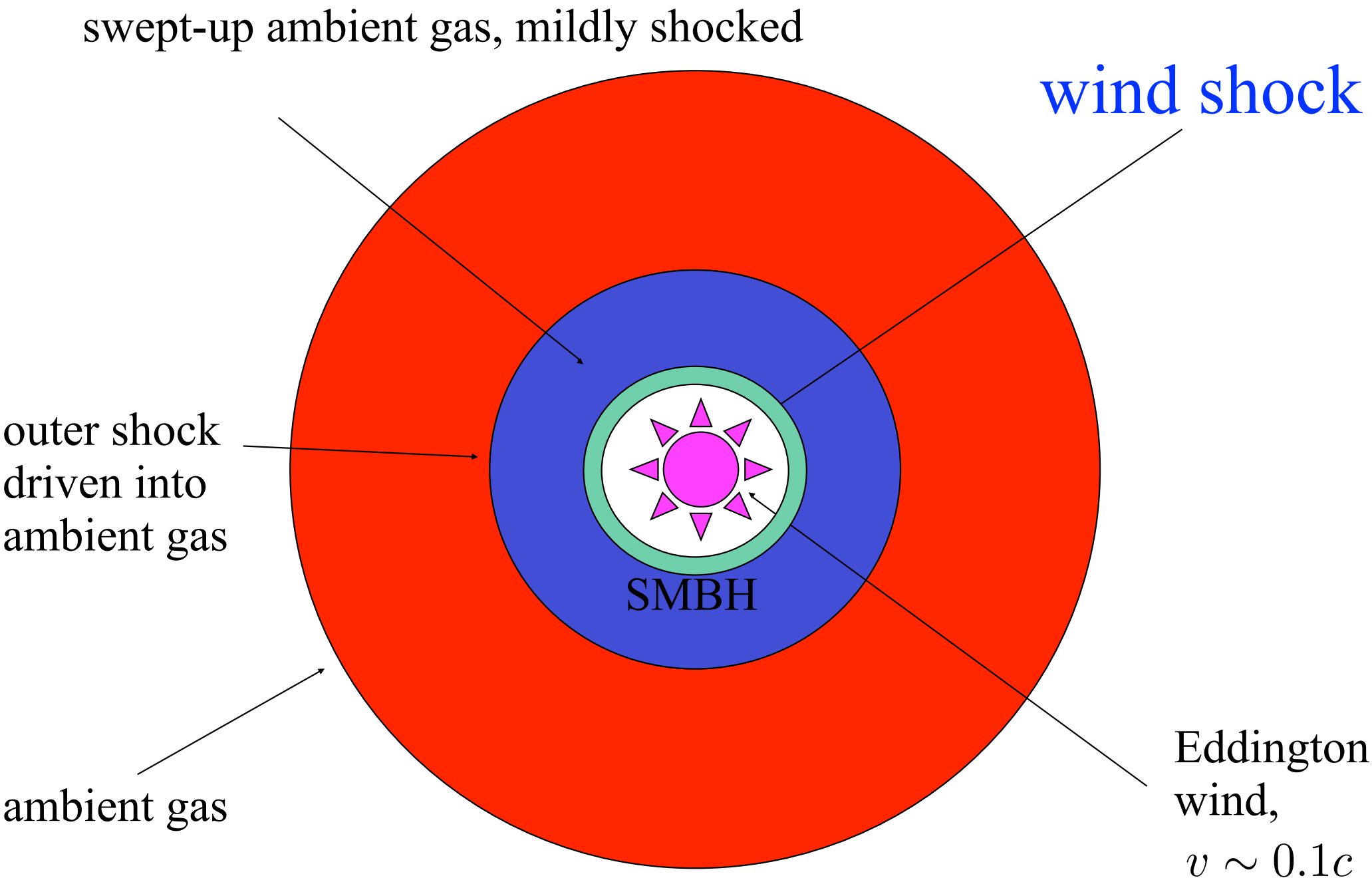


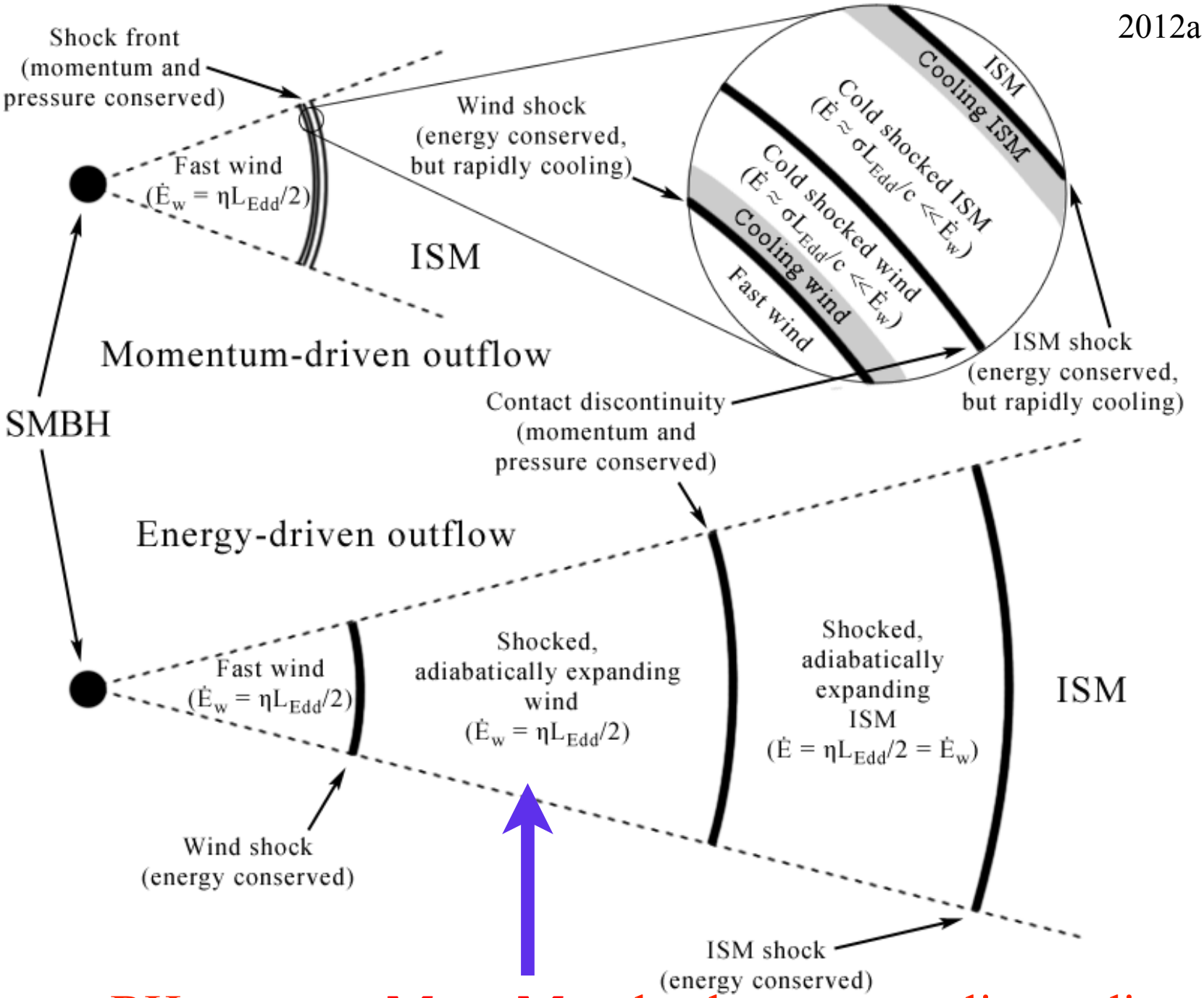
Fig. 8 Schematic picture of momentum–driven (top) and energy–driven (bottom) outflows. In both cases a fast wind (velocity $\sim 0.1c$) impacts the interstellar gas of the host galaxy

COOLING
Momentum Driven
$M_{bh} < M_{limit}$

NO COOLING
Energy Driven
$M_{bh} > M_{limit}$


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

Zubovas & King, 2012a



once BH grows to $M > M_\sigma$, shock passes cooling radius
=> large-scale energy-driven flow

wind shock

electrons (and ions) reach energies $E \simeq 9 m_p v^2/16$ in the wind shock

hotter $(T \sim 10^{11}\ \mathrm{K})$ than the quasar radiation field $(T \sim 10^{7}\ \mathrm{K})$

Compton cooling time is

$$t_C = \frac{3 m_e c}{8\pi \sigma_{\mathrm{T}} U_{\mathrm{rad}}} \frac{m_e c^2}{E}$$

where

$$U_{\mathrm{rad}} = \frac{L_{\mathrm{Edd}}}{4\pi R^2 c b}$$

is the radiation intensity of the quasar

thus $t_C = \frac{2}{3}\frac{cR^2}{GM}\left(\frac{m_e}{m_p}\right)^2\left(\frac{c}{v}\right)^2 b \simeq 10^5 R_{\rm kpc}^2\left(\frac{c}{v}\right)^2 b M_8^{-1}$ yr :

this is shorter than the shock travel time $t_{\rm shock} \sim R/\dot{R}_s \sim R/\sigma$

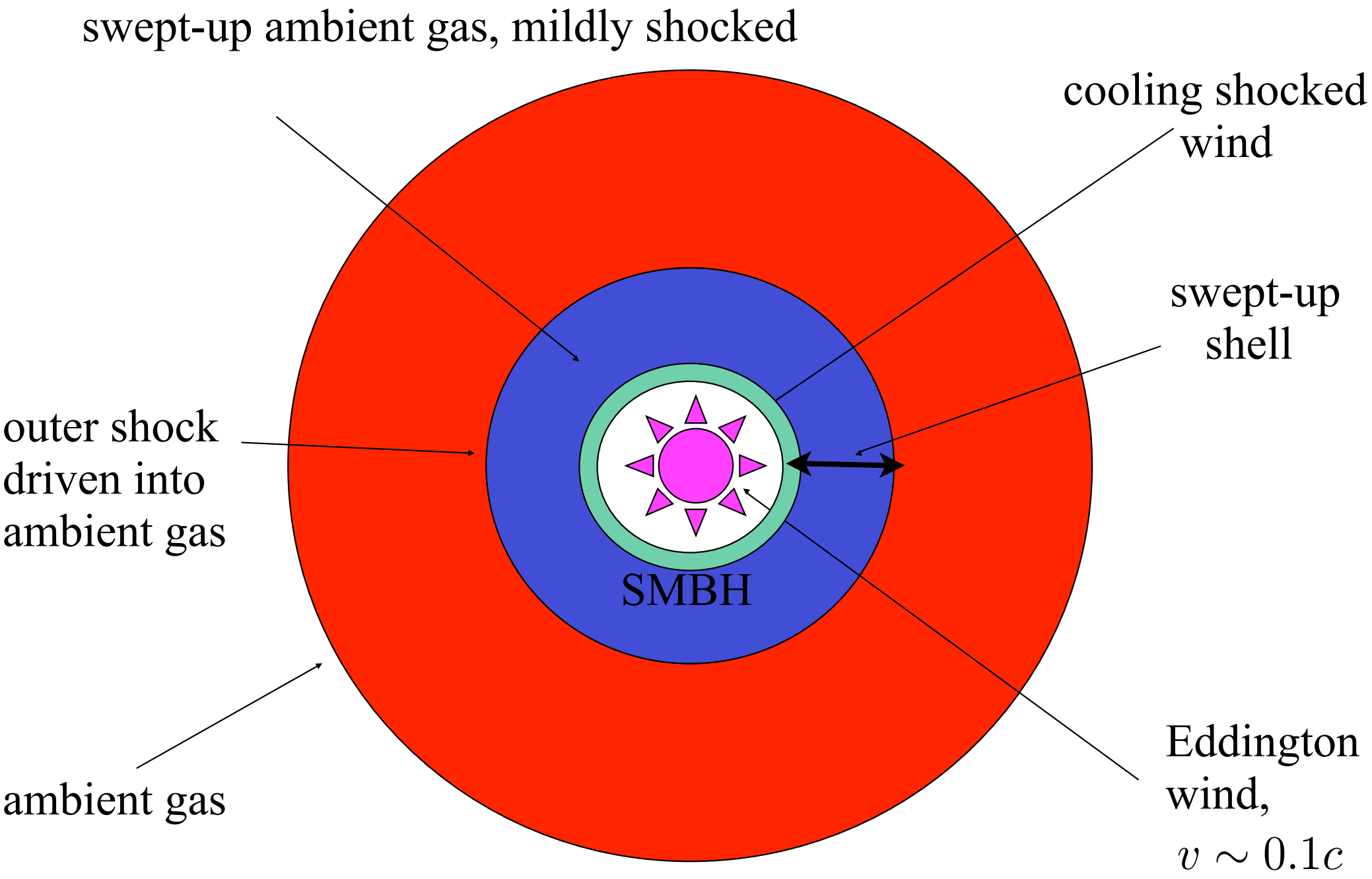
for shock radii

$$R < R_C \sim 0.5\frac{M_8}{\sigma_{200}}\ {\rm kpc}$$

two-fluid effects (electrons cooler than ions) can decrease R_C to as little as 20 pc - but still larger than SMBH influence radius $R_{\rm inf}$

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

strong cooling makes shocked region very narrow (`isothermal')


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

bulge mass distribution

- typical bulge (formed by mergers) has

$$\rho(r) = \frac{\sigma^2}{2\pi G r^2}$$

$\sigma = \text{constant}$ is velocity dispersion: `isothermal distribution'

- cumulative mass inside radius R is

$$M(R) = 4\pi \int_0^R \rho(r) r^2 \mathrm{d}r = \frac{2\sigma^2 R}{G}$$

- most of this mass is stars: with *gas fraction* $f_g (\sim 0.1)$ the gas has

$$\rho_g(r) = \frac{f_g \sigma^2}{2\pi G r^2} \qquad \text{and} \qquad M_g(R) = \frac{2 f_g \sigma^2 R}{G}$$

motion of swept-up shell

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

forces on shell are gravity of mass within R , and wind ram pressure:
since gas fraction f_g is small, gravitating mass inside R
is $\simeq M_{\rm tot}(R)$: equation of motion of shell is

$$\frac{\rm d}{{\rm d}t}[M(R)\dot{R}] + \frac{GM(R)[M + M_{\rm tot}(R)]}{R^2} = 4\pi R^2 \rho v^2 = \dot{M}_{\rm out} v = \frac{L_{\rm Edd}}{c}$$

where M is the black hole mass

using $M(R), M_{\rm tot}(R)$ this reduces to

$$\frac{\mathrm{d}}{\mathrm{d}t}(R\dot{R}) + \frac{GM}{R} = -2\sigma^2\left[1 - \frac{M}{M_\sigma}\right]$$

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

integrate equation of motion by multiplying through by $R\dot{R}$: then

$$R^2\dot{R}^2 = -2GMR - 2\sigma^2\left[1 - \frac{M}{M_\sigma}\right]R^2 + \text{constant}$$

using $M(R), M_{\rm tot}(R)$ this reduces to

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if $M < M_\sigma$, no solution at large R (rhs < 0)

Eddington thrust too small to lift swept-up shell

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if $M < M_\sigma$, no solution at large R (rhs < 0)

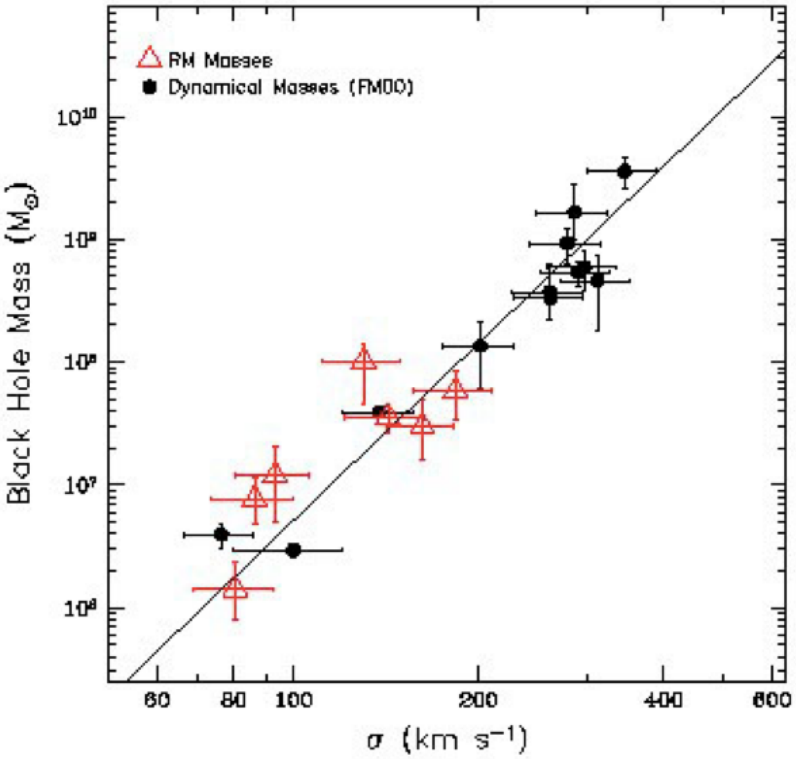
Eddington thrust too small to lift swept-up shell

but if $M > M_\sigma$, $\dot{R}^2 \to 2\sigma^2$, and shell can be expelled completely

critical value

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

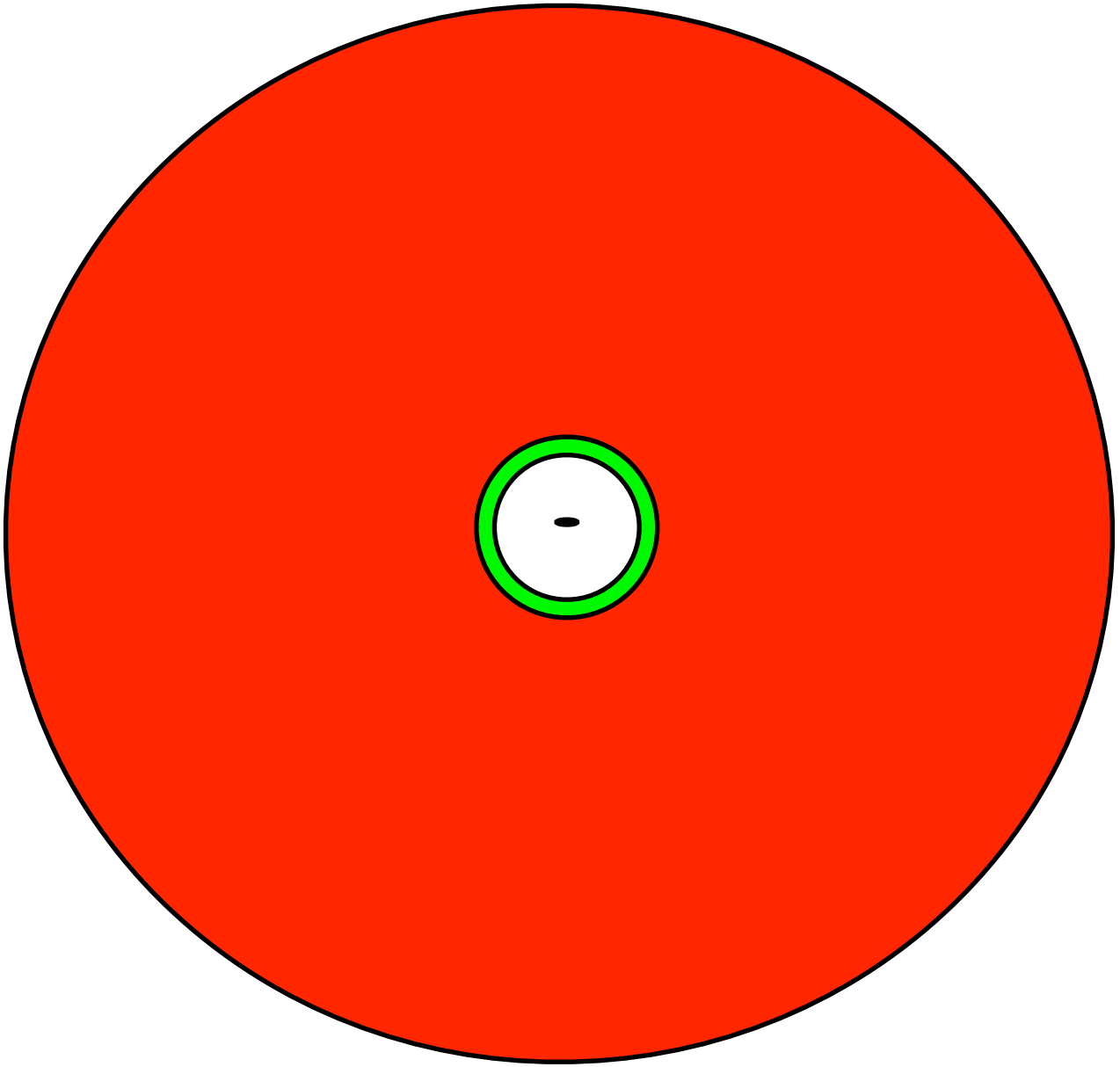
remarkably close to observed $M - \sigma$ relation despite effectively no free parameter $(f_g \sim 0.1)$ (King, 2003; 2005)



SMBH mass grows until
Eddington thrust expels gas feeding it

**

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



transition to energy-driven flow once M_σ reached

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

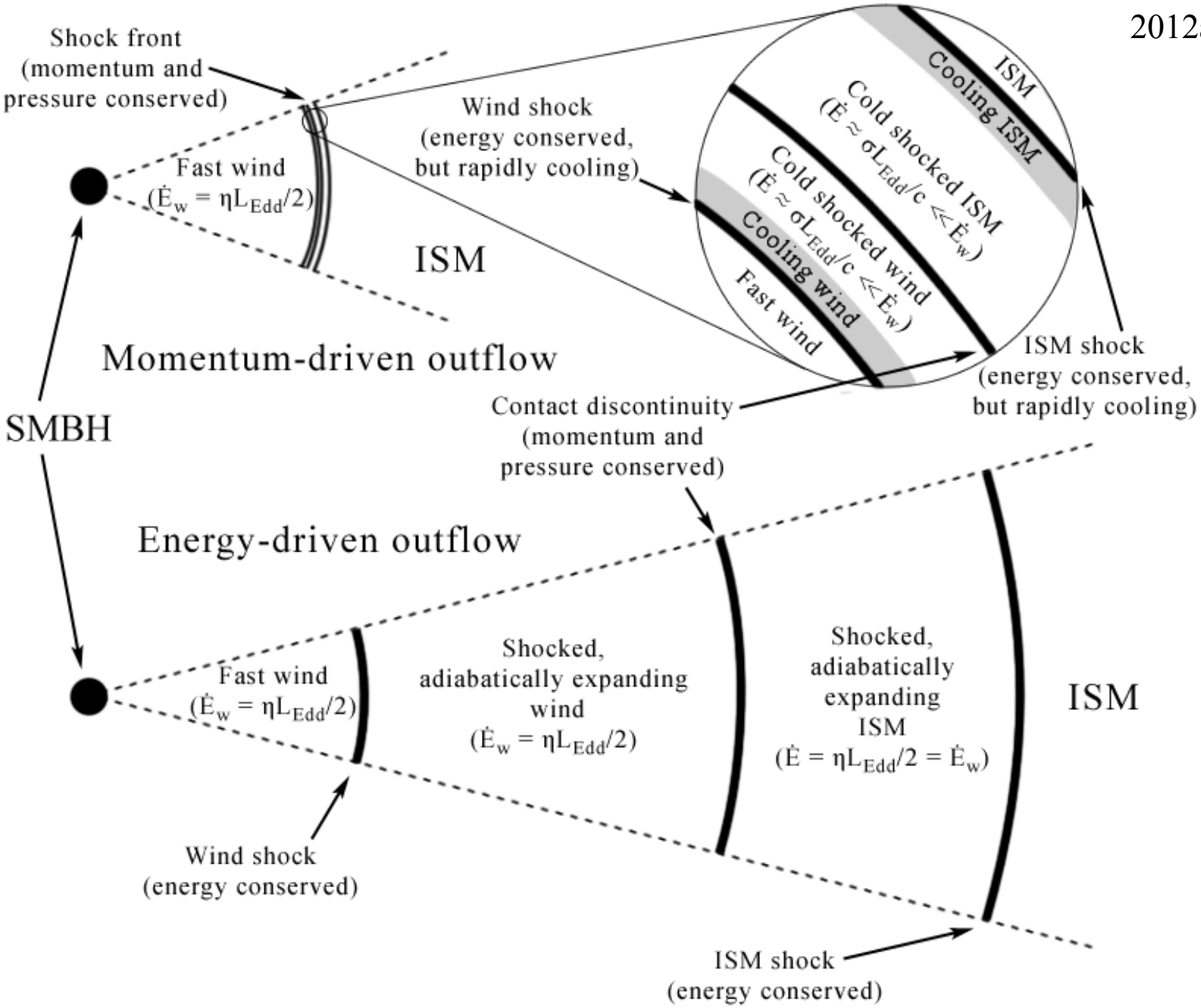
but once $M > M_\sigma$, R can exceed R_C: wind shock no longer cools

wind shock is adiabatic: hot postshock gas does $P\mathrm{d}V$ work on surroundings

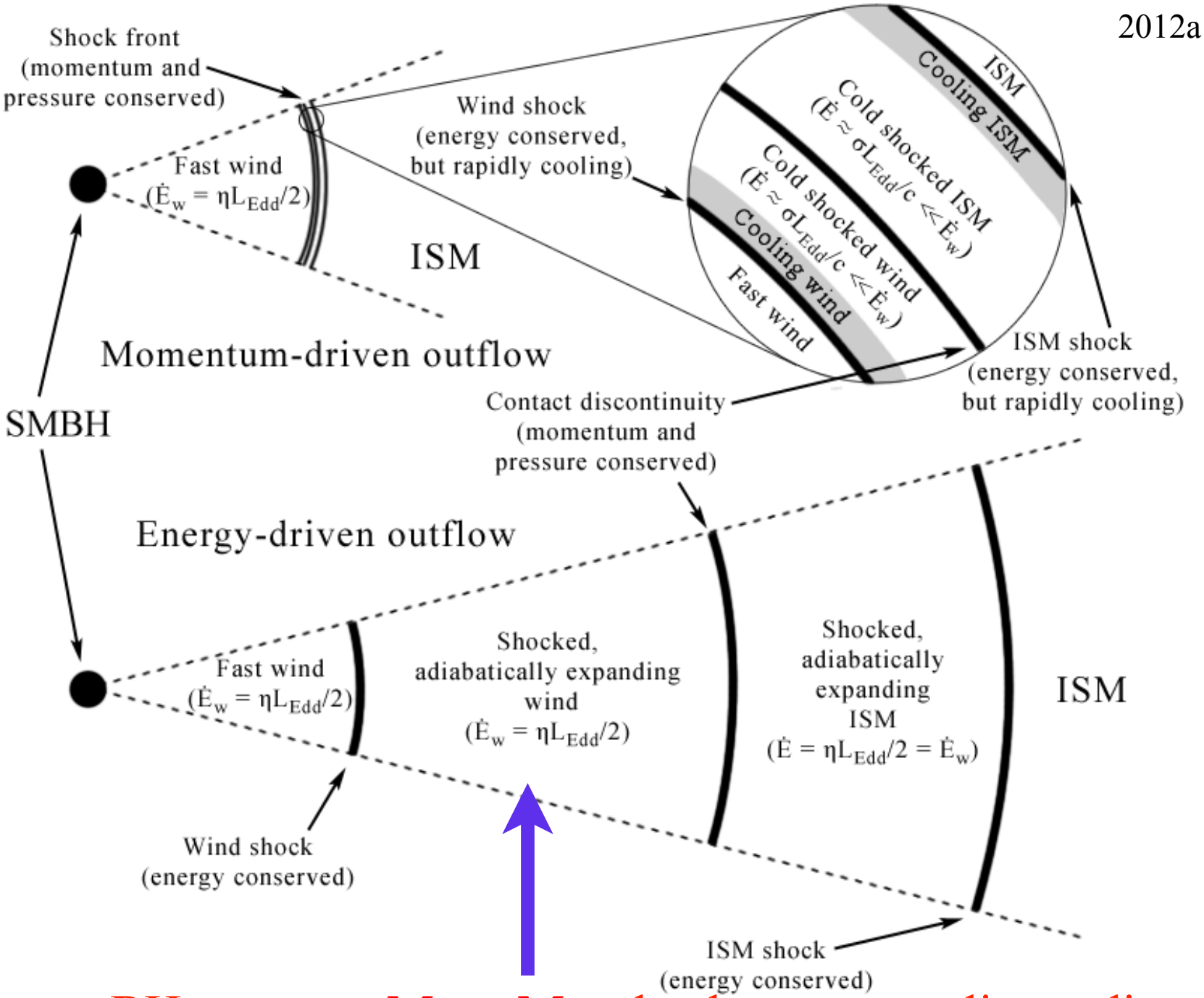
eqn of motion now contains *total* postshock pressure P (gas plus ram)

wind shock always stays near cooling radius: high sound speed ensures near-constant pressure in extended region from here to contact discontinuity (radius R) with swept-up host gas

Zubovas & King, 2012a



Zubovas & King, 2012a



once BH grows to $M > M_\sigma$, shock passes cooling radius
=> large-scale energy-driven flow

equation of motion of swept-up shell (contact discontinuity) is

$$\frac{\mathrm{d}}{\mathrm{d}t}\left[M(R)\dot{R}\right] + \frac{GM(R)[M + M_{\rm tot}(R)]}{R^2} = 4\pi R^2 P$$

energy equation is

$$\frac{\mathrm{d}}{\mathrm{d}t}[VU] = \frac{1}{2}\dot{M}_{\rm out}v^2 - P\frac{\mathrm{d}V}{\mathrm{d}t} - \frac{GM(R)M_{\rm tot}(R)}{R^2}\dot{R}$$

where

$$V = \frac{4\pi}{3}R^3, \quad U = \frac{3}{2}P, \quad \dot{M}_{\rm out}v = \frac{L_{\rm Edd}}{c},$$

$$M(R) = \frac{2f_g\sigma^2 R}{G}, \quad M_{\rm tot}(R) = \frac{2\sigma^2 R}{G}, \quad v = \eta c$$

using equation of motion to eliminate P from energy equation finally determines motion of shell at R

$$\frac{\eta}{2} L_{\rm Edd} = \frac{2 f_g \sigma^2}{G} \left\{ \frac{1}{2} R^2 \dddot{R} + 3 R \dot{R} \ddot{R} + \frac{3}{2} \dot{R}^3 \right\} + 10 f_g \frac{\sigma^4}{G} \dot{R}$$

coasting solution $\dot{R} = v_e = \text{constant}$ has

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

(where SMBH mass M appearing in $L_{\rm Edd}$ is set to M_σ)

(King, 2005)

once quasar driving switches off (i.e. $L_{\rm Edd} = 0$) at $R = R_0$ the velocity decays as

$$\dot{R}^2 = 3\left(v_e^2 + \frac{10}{3}\sigma^2\right)\left(\frac{1}{r^2} - \frac{2}{3r^3}\right) - \frac{10}{3}\sigma^2$$

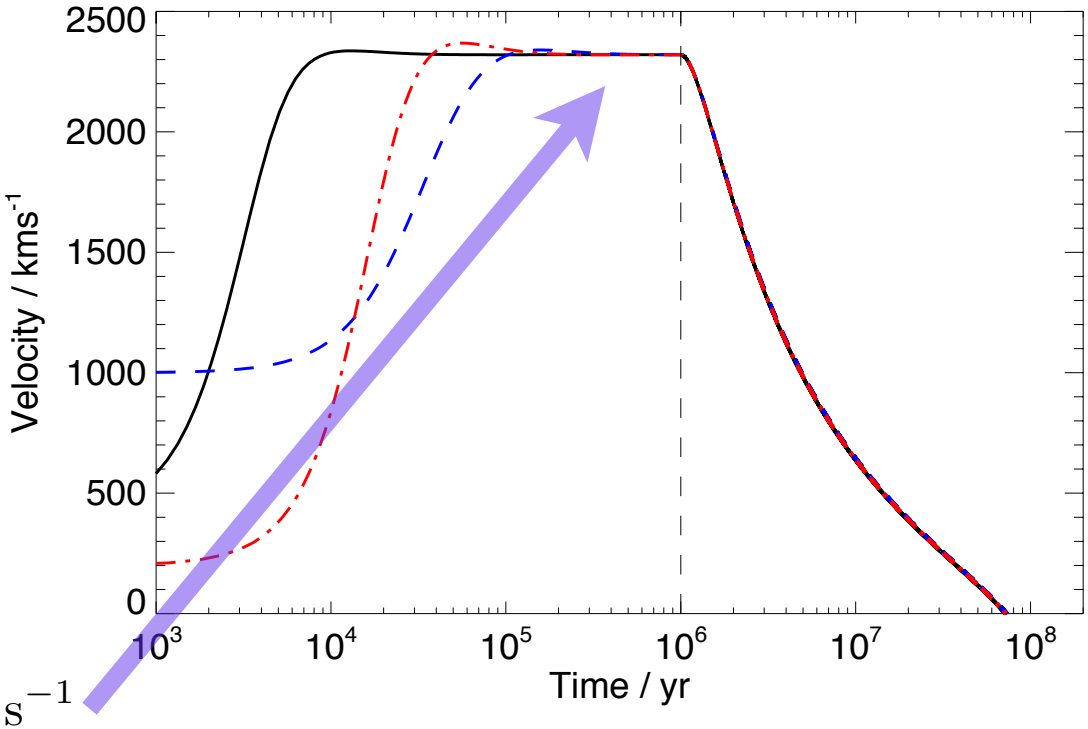
where $r = R/R_0 \geq 1$

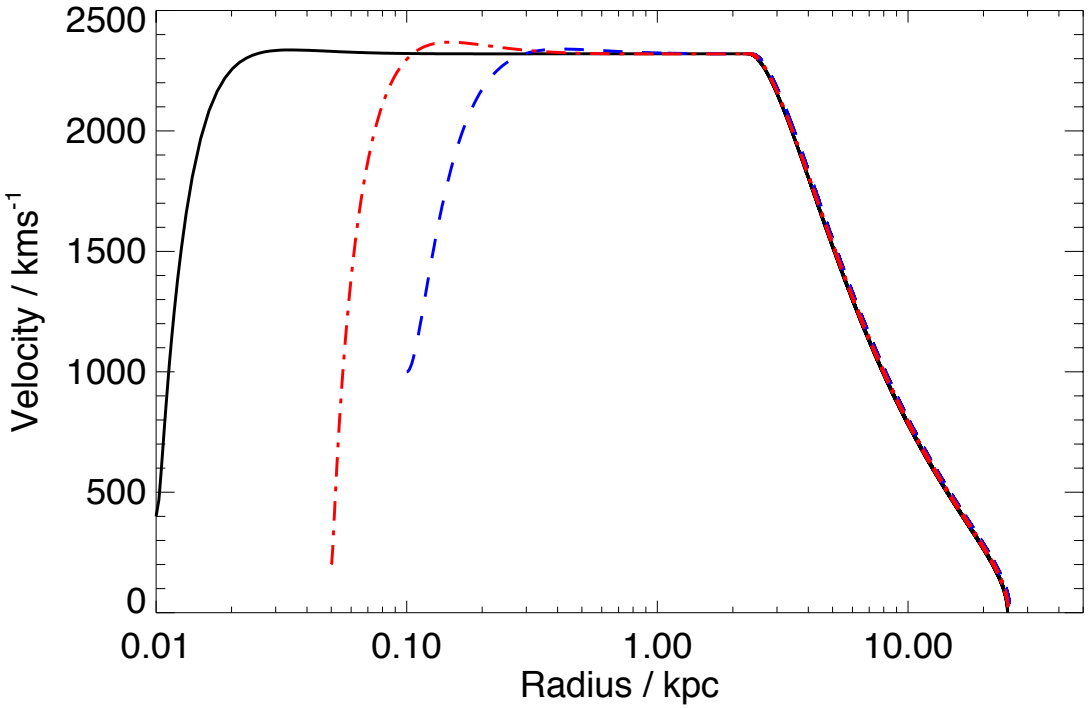
numerical solutions show that coasting + decay are attractors -- all outflows do this

(King, Zubovas & Power, 2011)

energy--driven outflows rapidly converge to

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





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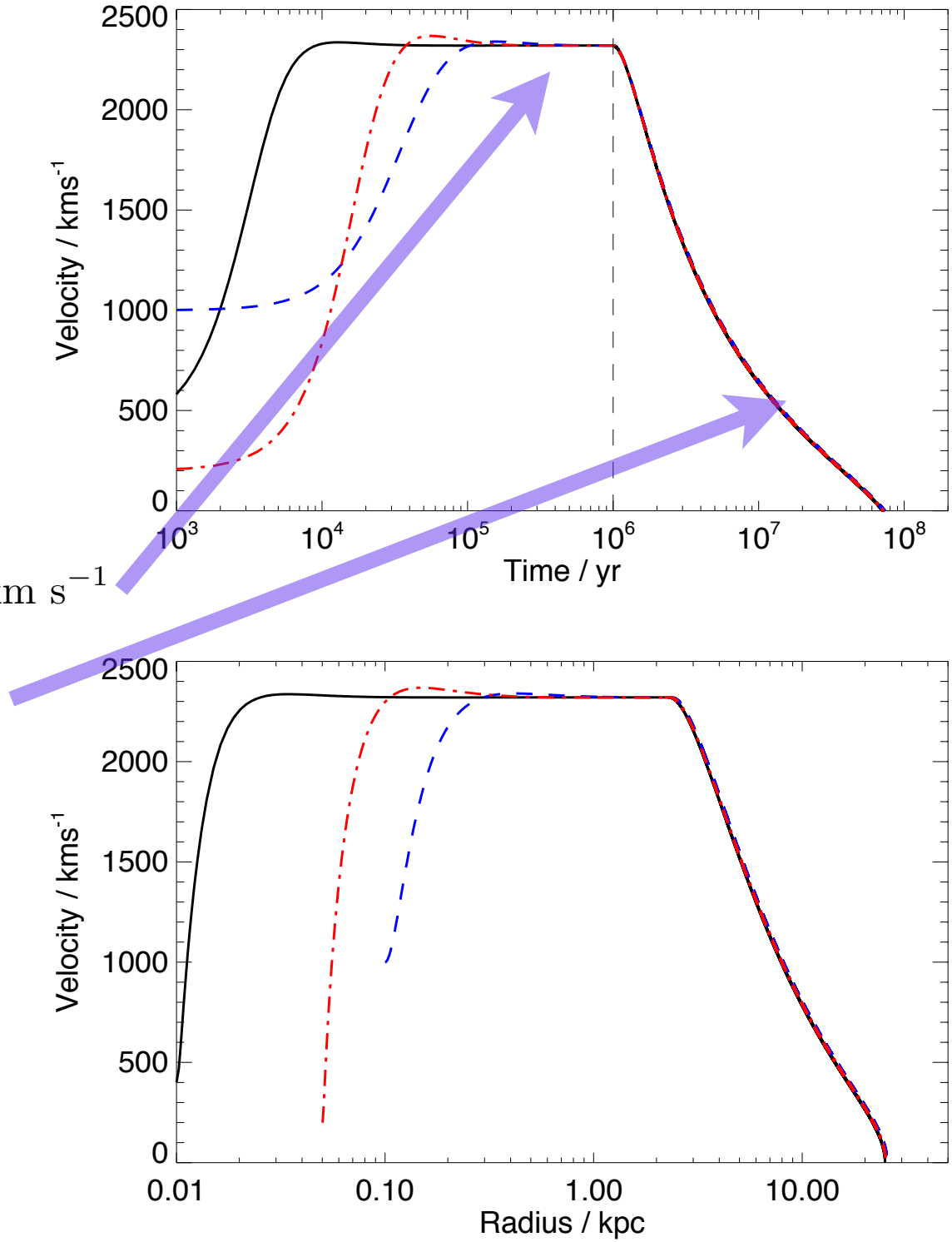
and persist even after central quasar turns off



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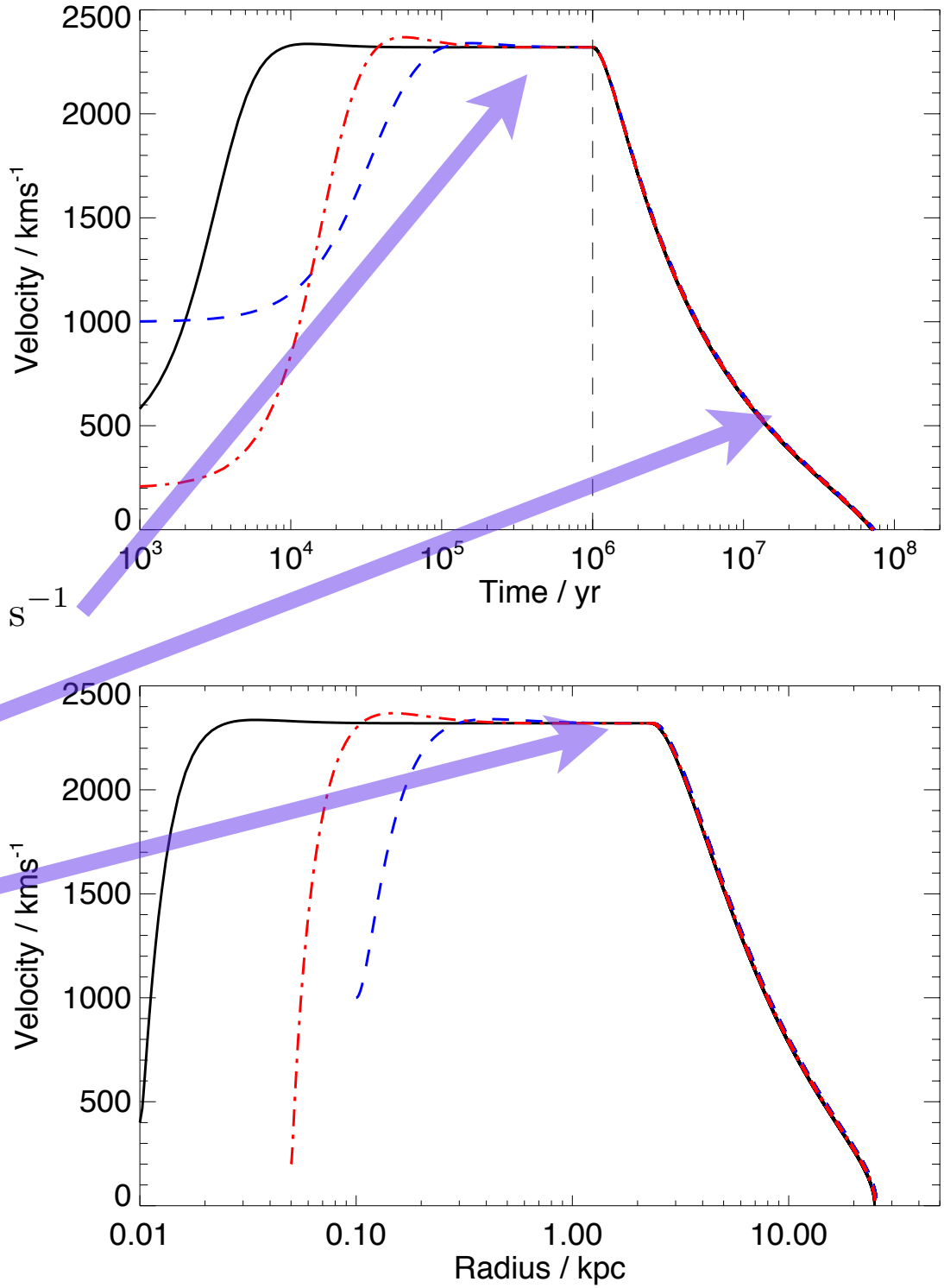
high velocity outflow at large radius



energy--driven outflows rapidly converge to

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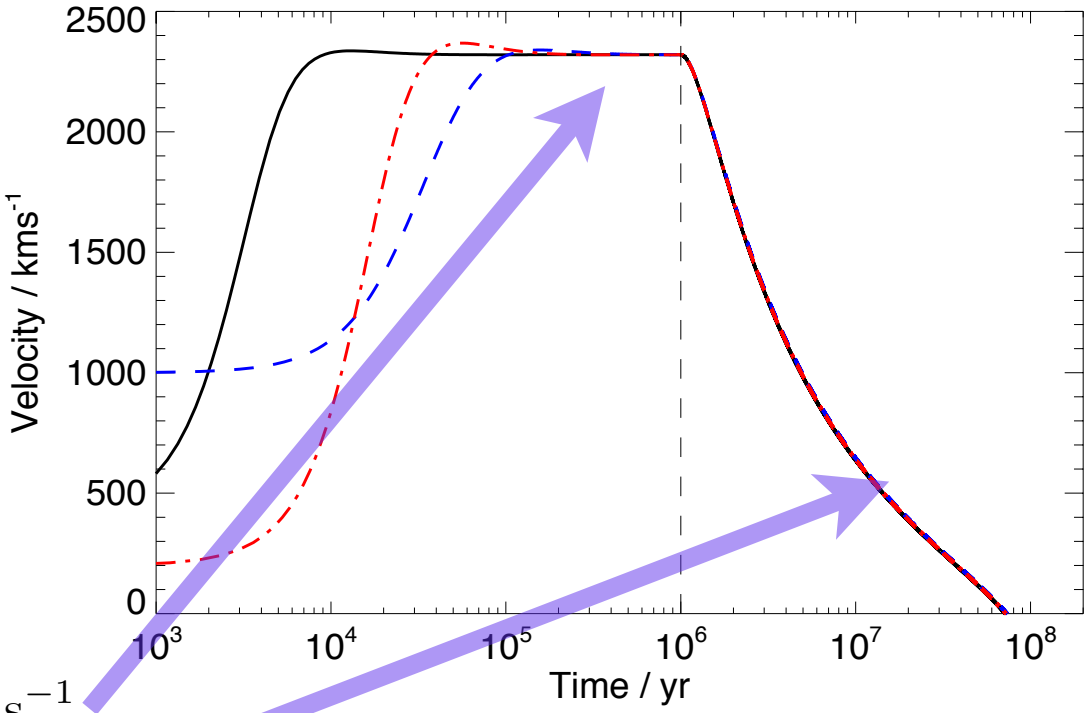
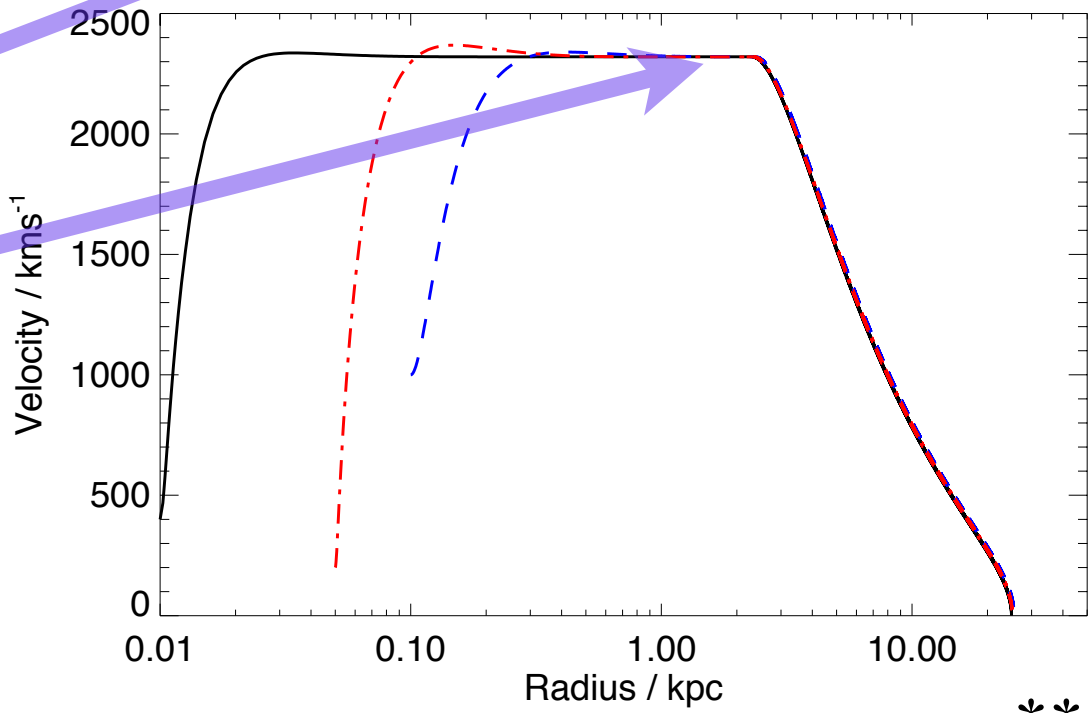
and persist even after central quasar turns off

high velocity outflow at large radius

also for other potentials: Zubovas & King, 2012b





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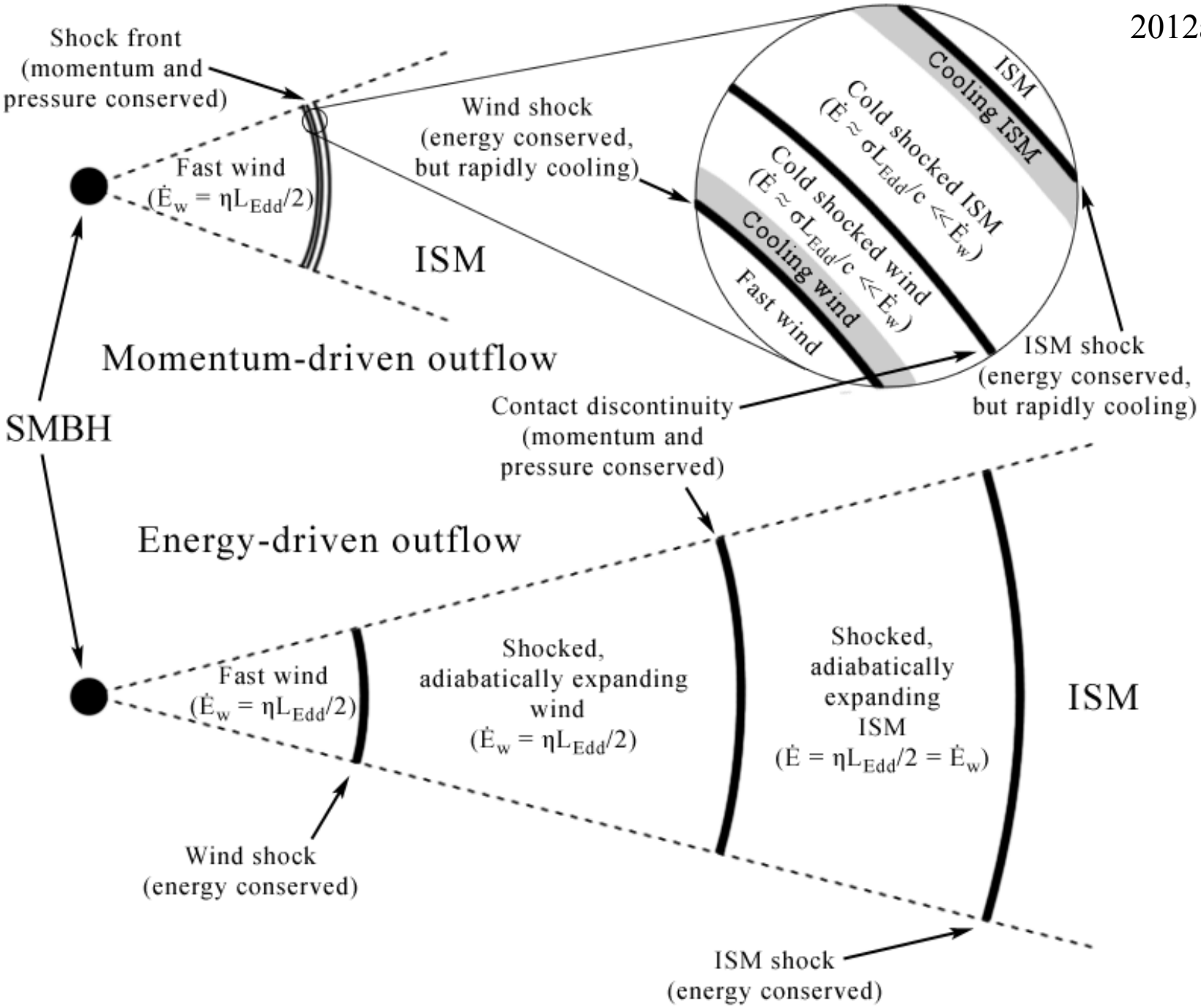
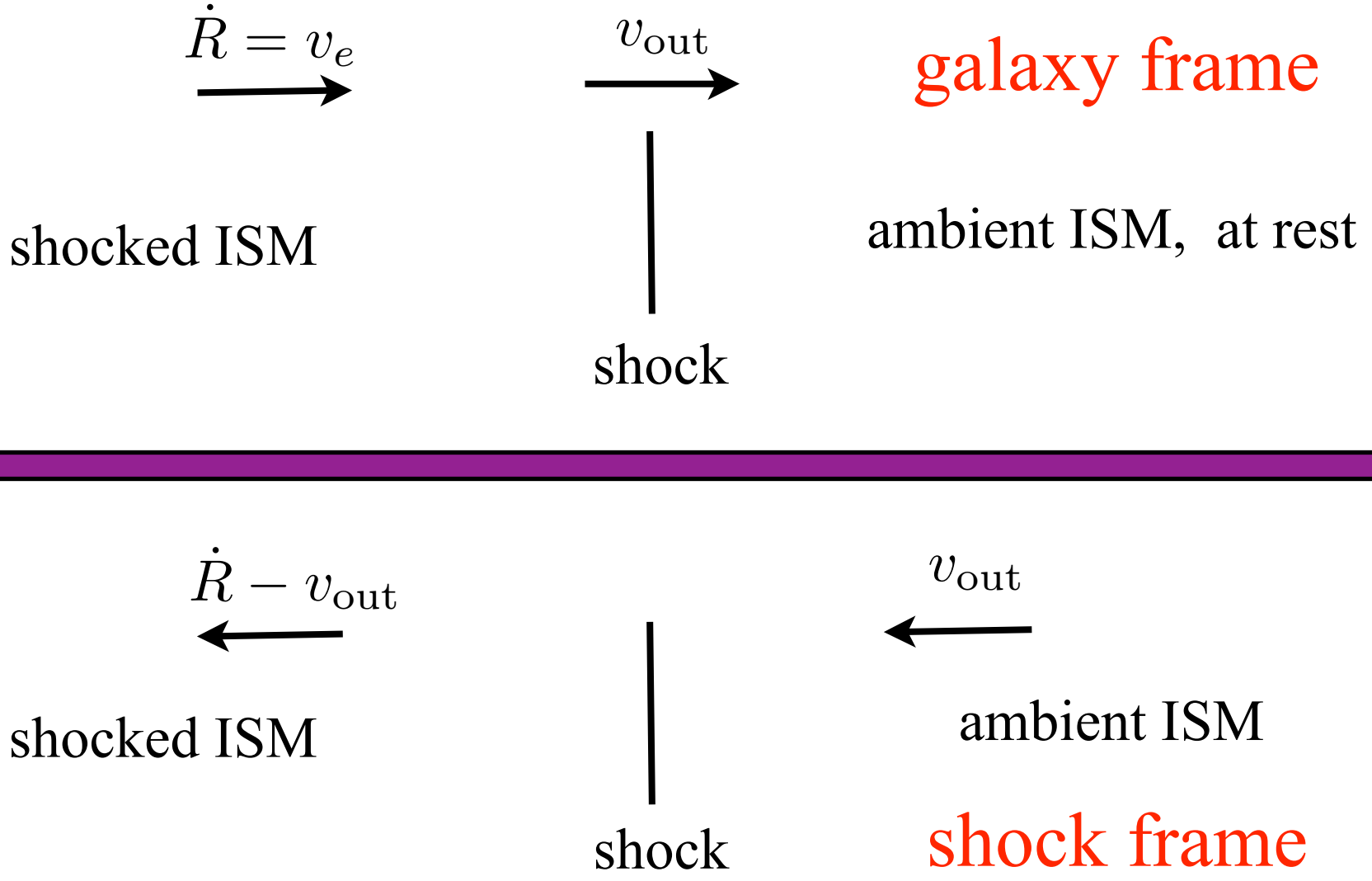
Zubovas & King, 2012a



forward shock speed



$$\frac{v_{\rm out}}{\dot{R} - v_{\rm out}} = \frac{\gamma + 1}{\gamma - 1} \Rightarrow v_{\rm out} = \frac{\gamma + 1}{2}\dot{R}$$

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

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

and radius as

$$R_{\rm out} = \frac{\gamma+1}{2}R$$

outflow rate of shocked interstellar gas is

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

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

approximate equality

$$\frac{1}{2}\dot{M}_{\rm w}v_{\rm w}^2 \simeq \frac{1}{2}\dot{M}_{\rm out}v_{\rm out}^2$$

means swept-up gas must have momentum rate $> L_{\rm Edd}/c$, since can rewrite it as

$$\frac{\dot{P}_{\rm w}^2}{2\dot{M}_{\rm w}} \simeq \frac{\dot{P}_{\rm out}^2}{2\dot{M}_{\rm out}}$$

$$\dot{P}_{\rm out} = \dot{P}_{\rm w}\left(\frac{\dot{M}_{\rm out}}{\dot{M}_{\rm w}}\right)^{1/2} \sim 20\sigma_{200}^{-1/3}l^{1/6}\frac{L_{\rm Edd}}{c}$$

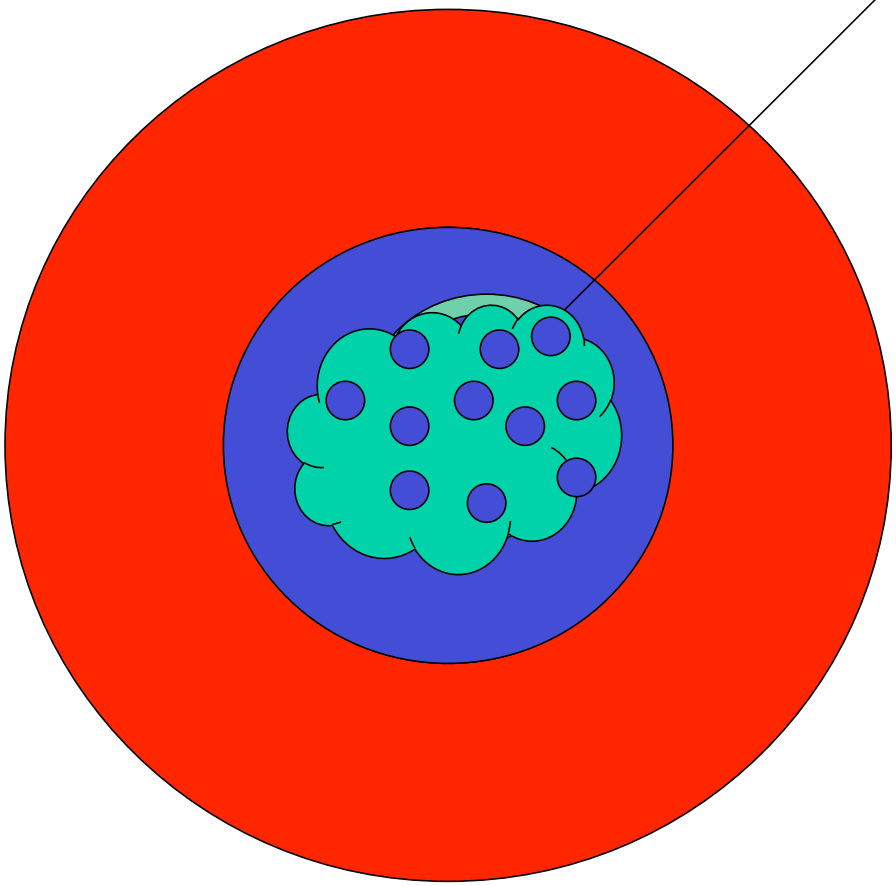
all molecular outflows have super-Eddington thrust!

(Zubovas & King, 2012a)

galaxy becomes red and dead

density contrast => energy-driven outflow

shock may be *Rayleigh-Taylor unstable*

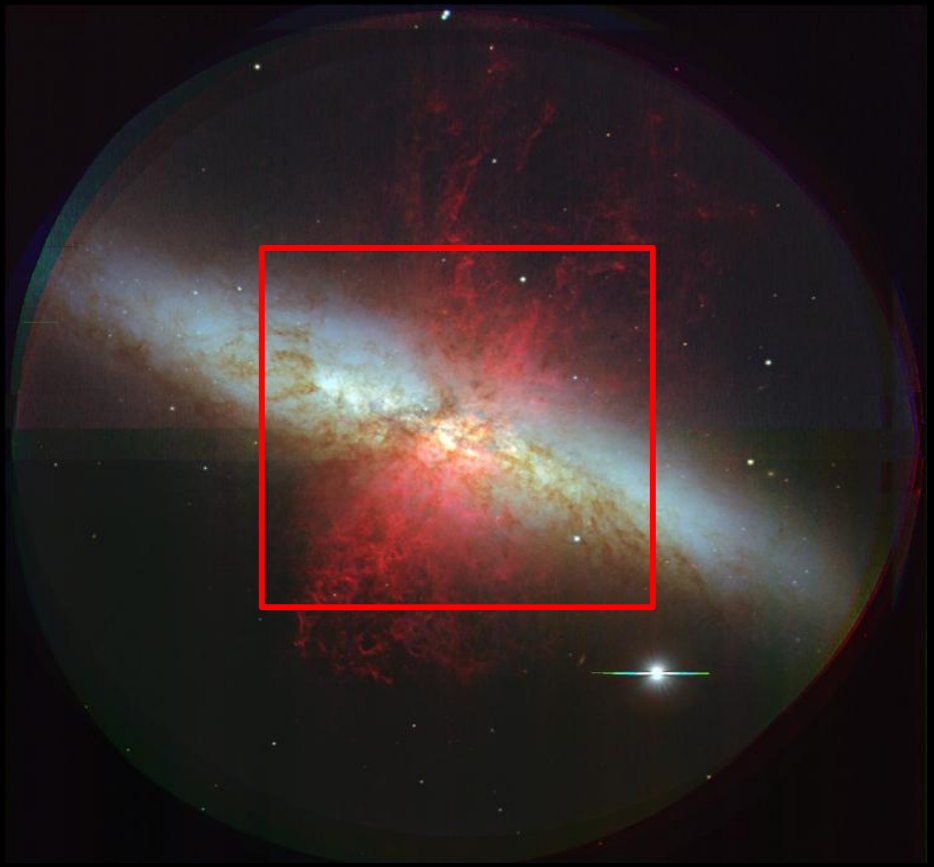


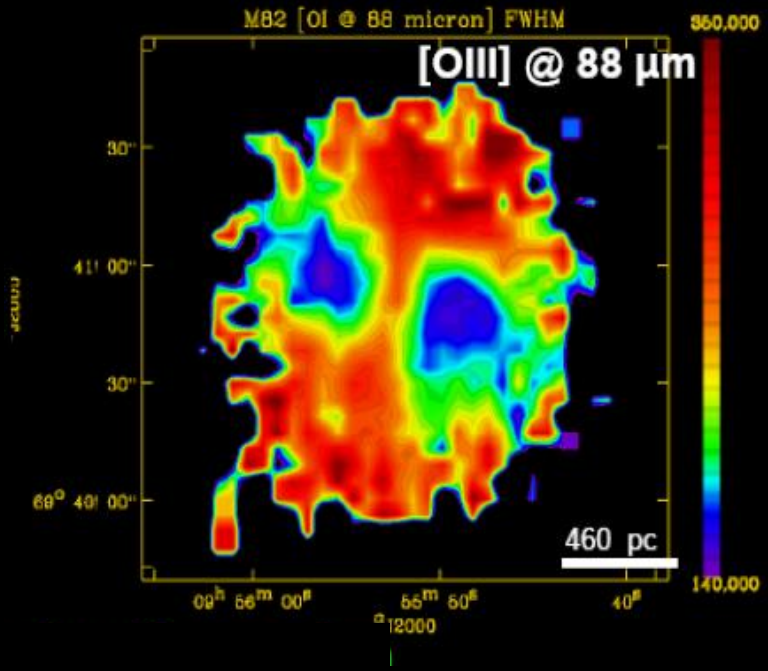
two—phase medium: gamma—rays and molecular emission mixed

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

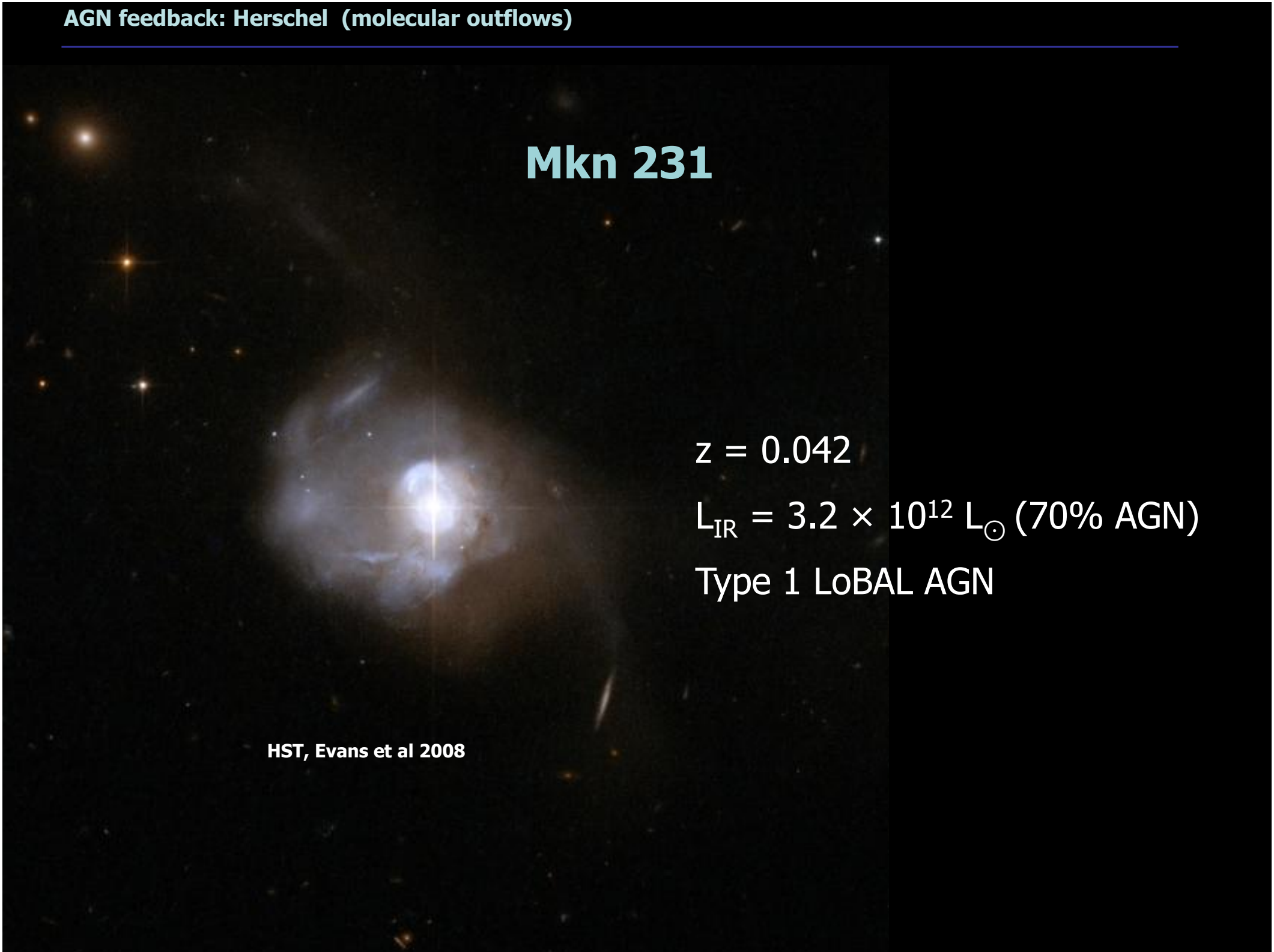
galaxy bulge should produce gamma-ray emission

M82





Contursi+ 2012



Mkn 231

$z = 0.042$

$L_{IR} = 3.2 \times 10^{12} L_{\odot}$ (70% AGN)

Type 1 LoBAL AGN

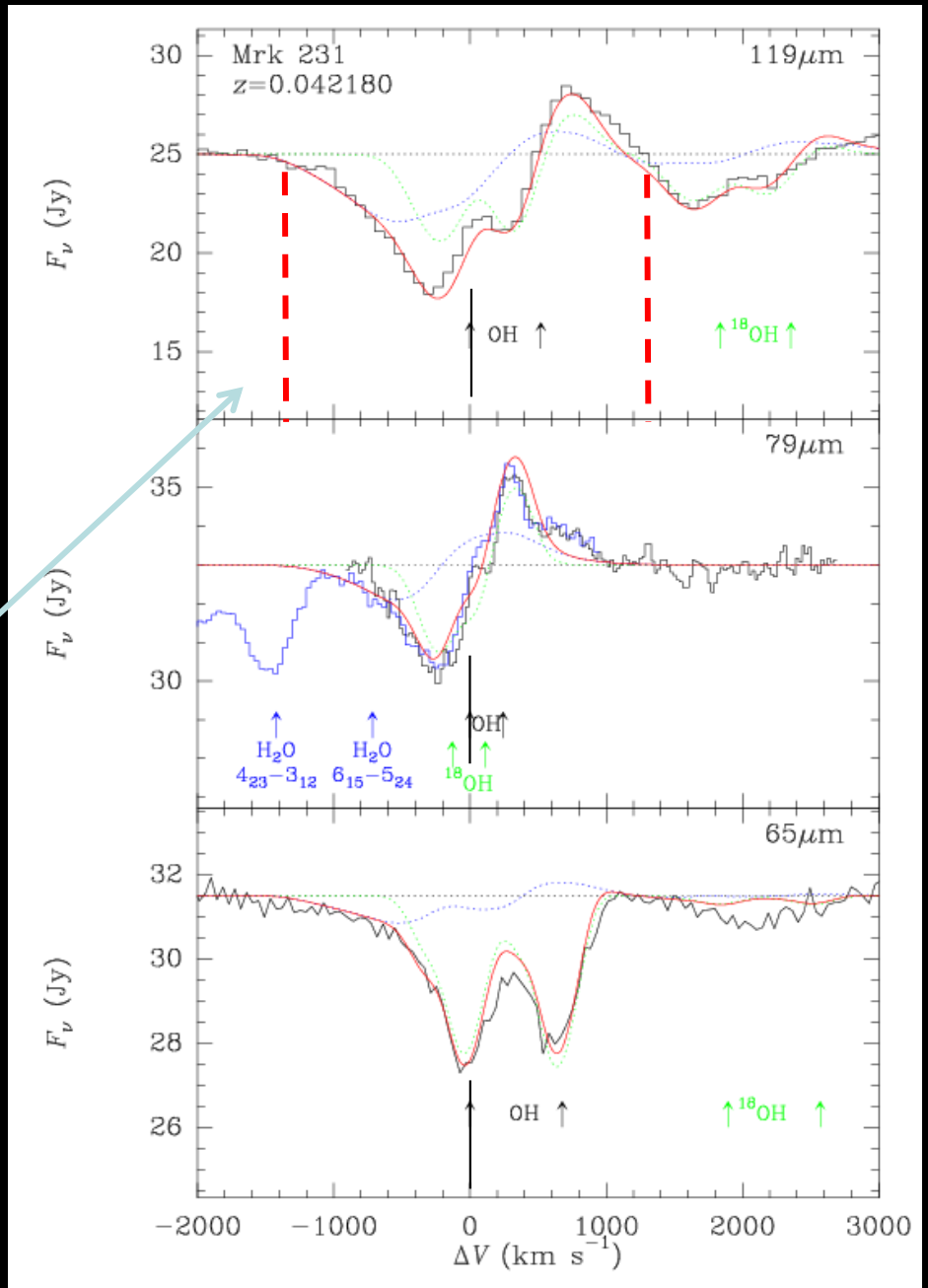
HST, Evans et al 2008

Mrk 231

P-Cygni profile with
blue-shifted absorption
and red-shifted emission

Δv ~ 1,170 km/s

Fischer + 2010



Mrk 231 – OH Outflow

terminal velocity (obs): ~1.100 km/s

R_{out} (model) ~1.0 kpc

outflow rate (dM/dt): ~1.200 $M_\odot$/yr

SFR: ~100 $M_\odot$/yr

gas mass (from CO): 4.2 x 10^9 $M_\odot$

depletion time scale ($M_{gas}/\dot{M}$): ~4 x 10^6 yr

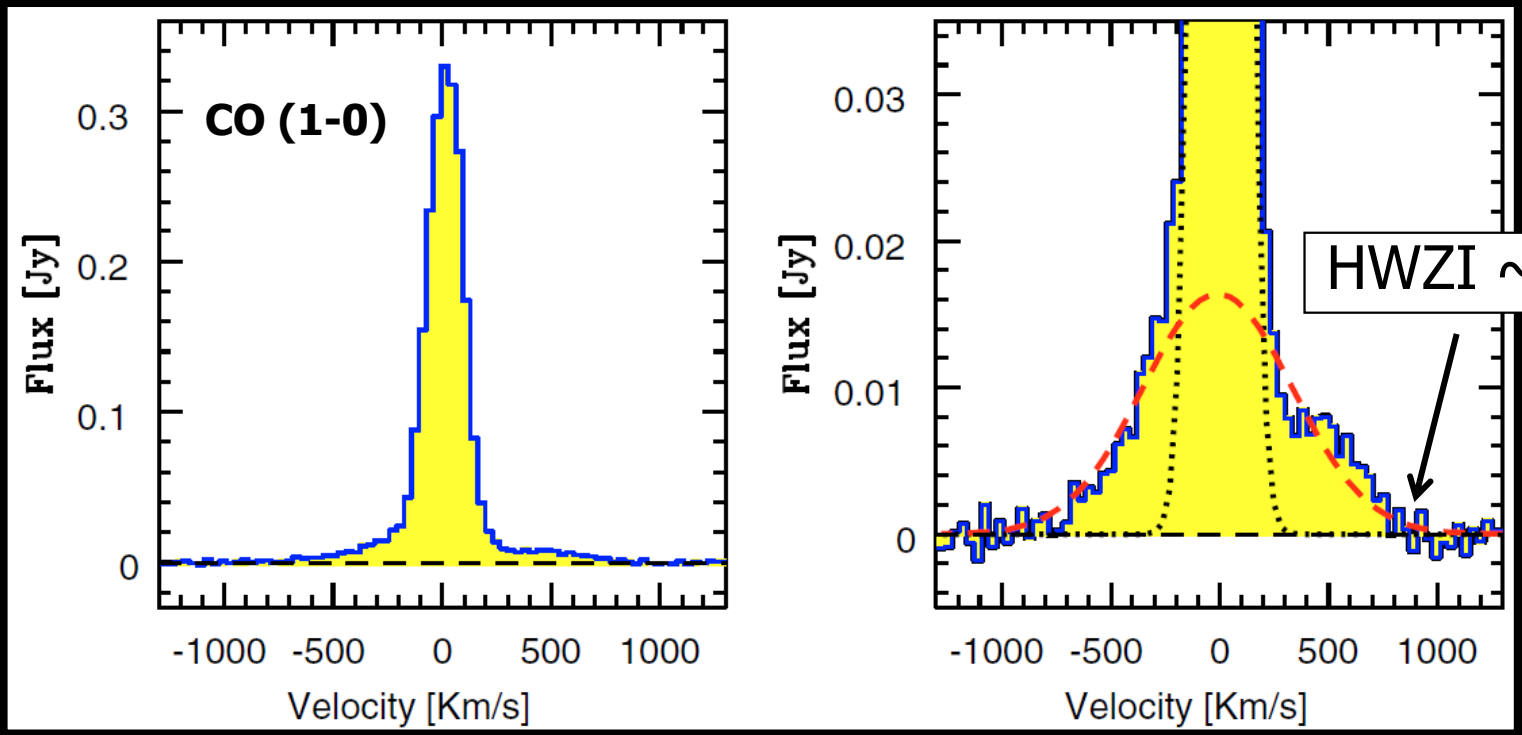
mechanical energy: ≥ 10^{56} ergs

$$T = \frac{1}{2} M_{\rm gas} v^2$$

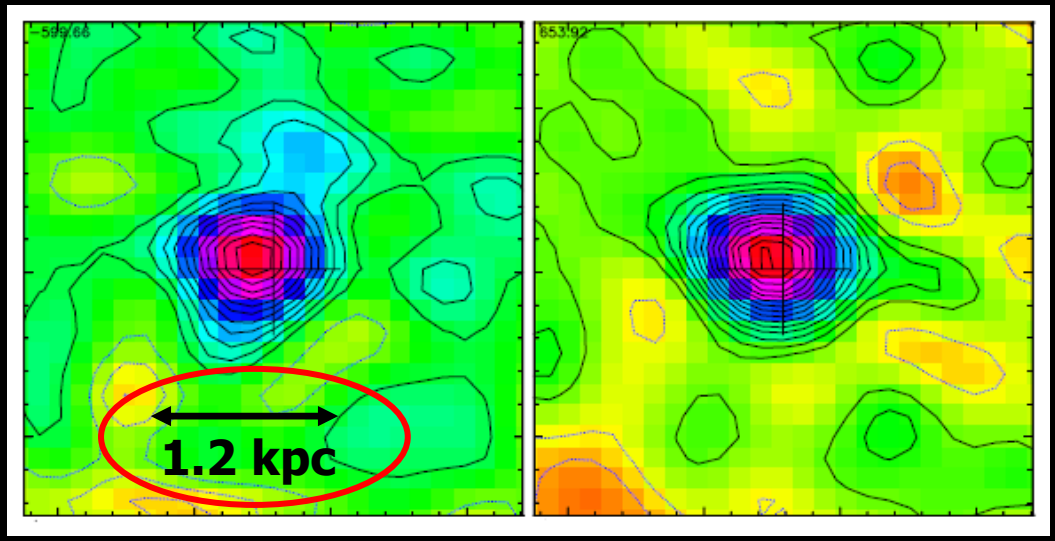
mechanical luminosity: ≥ 1% L_{IR}

$$P = \frac{T}{t_{\rm dyn}}$$

Mrk 231 – CO Outflow



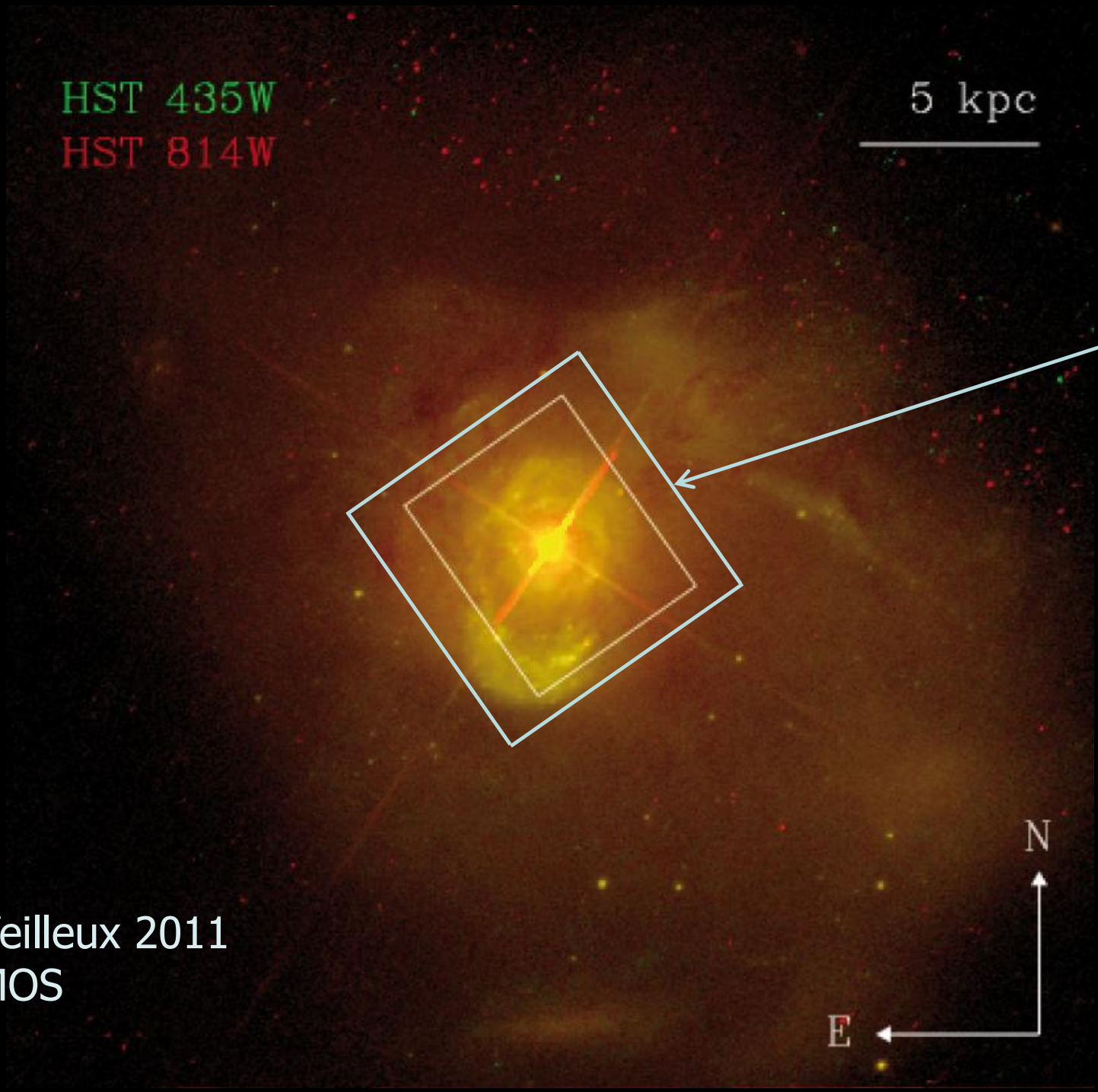
Feruglio+2010



outflow mass of $5.8 \times 10^8\ M_\odot$

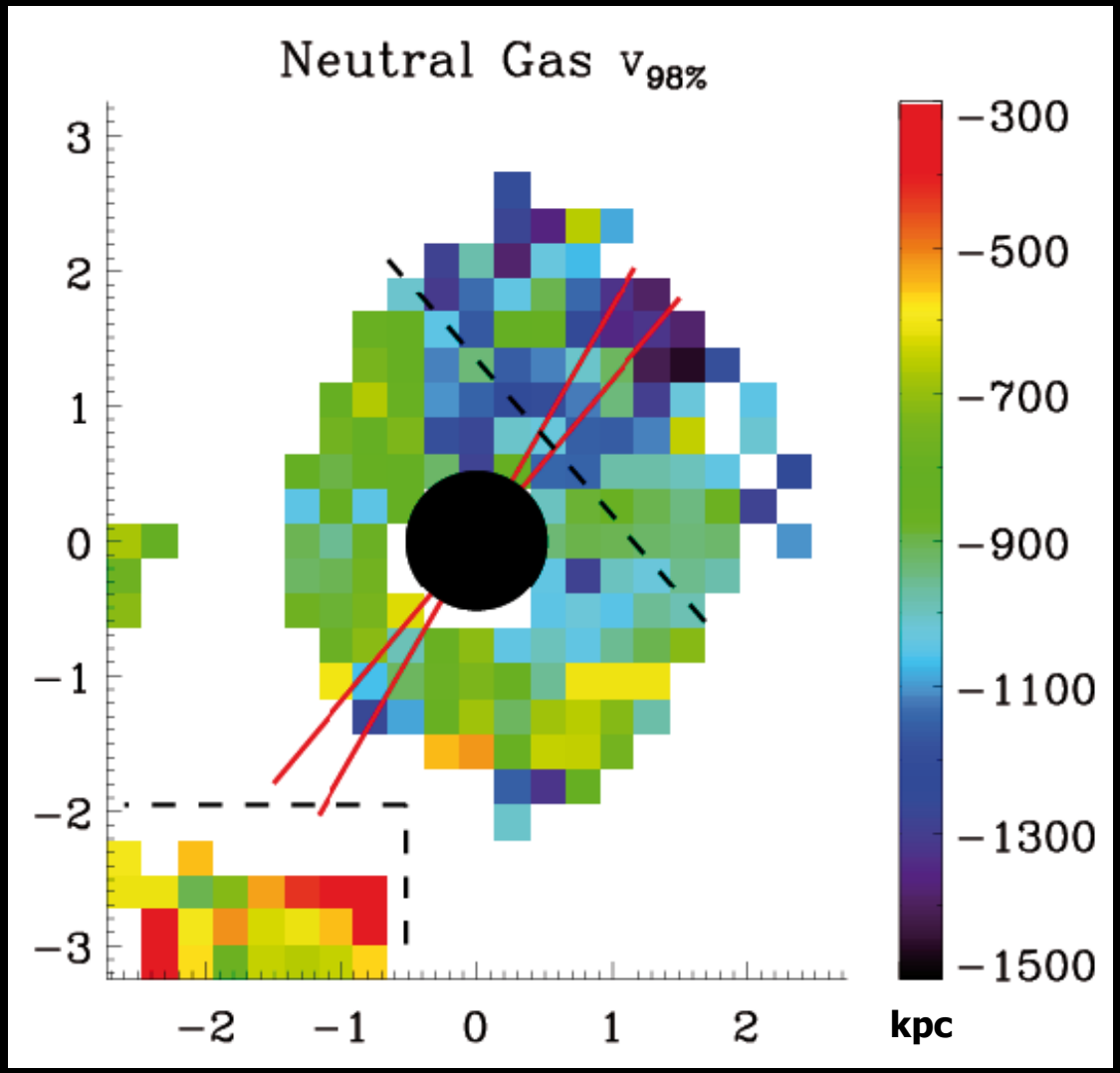
outflow rate of $\gtrsim 700\ M_\odot/yr$

Mrk 231 – Na I D Outflow

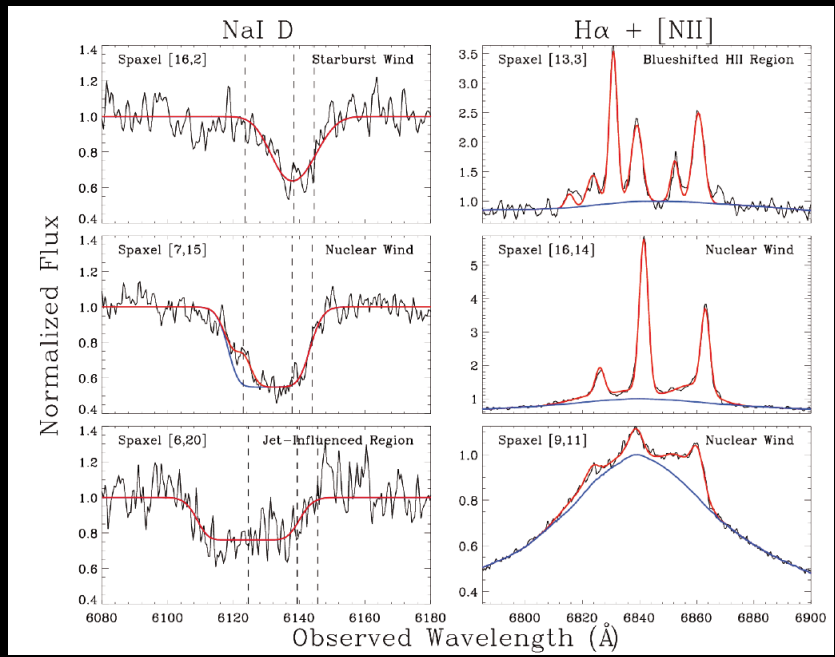


Rupke & Veilleux 2011
Gemini GMOS

Mrk 231 – Na I D Outflow



- Wide angle outflow (i.e. only minor contribution from jet)
- Outflow velocity up to ~1100 km/s
- 2-3 kpc extension



Rupke & Veilleux 2011
Gemini GMOS

Eddington outflows: summary

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

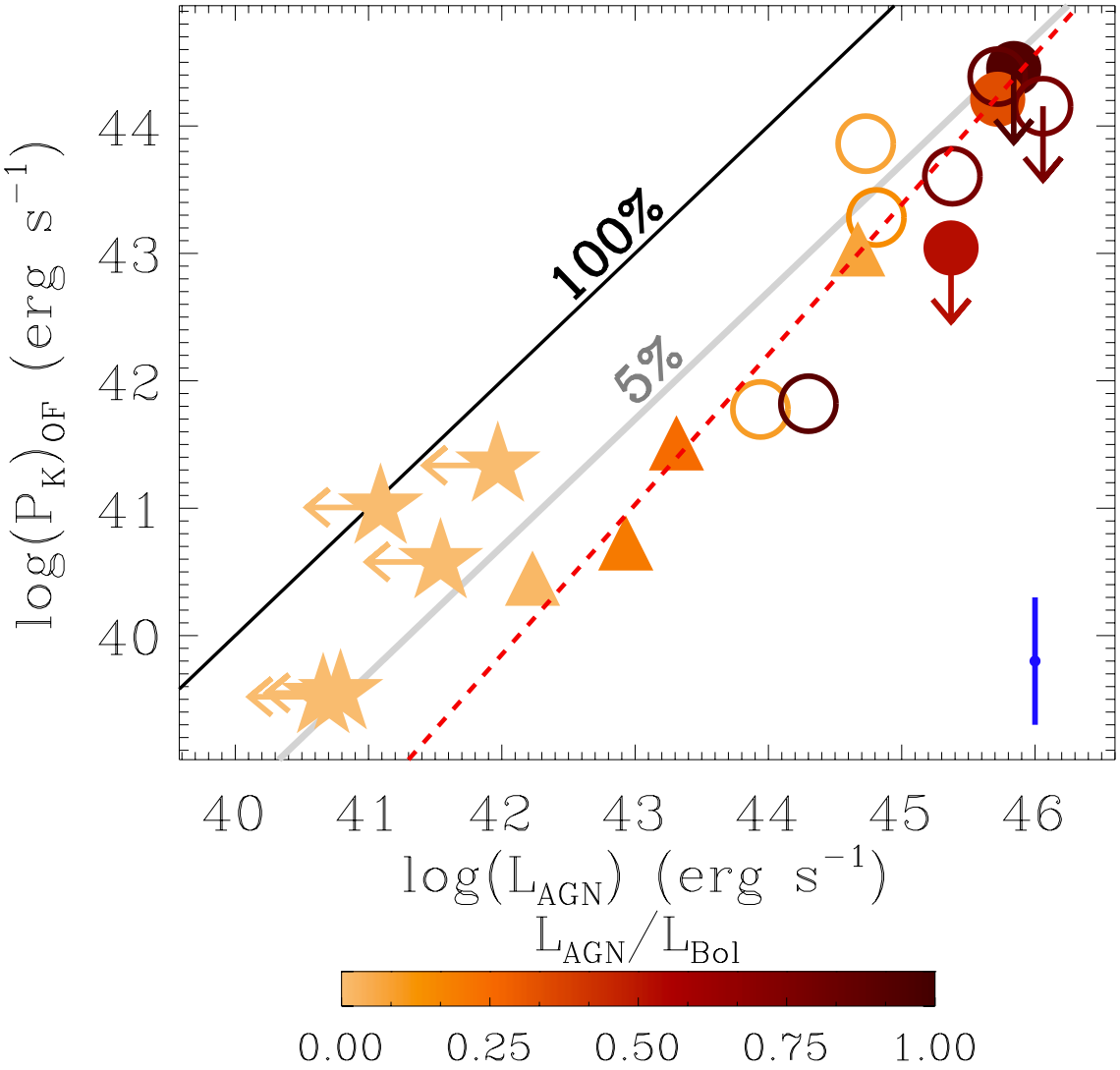


Fig. 12. Correlation between the kinetic power of the outflow and the AGN bolometric luminosity. Symbols and colour-coding as in Fig. 8. The grey line represents the theoretical expectation of models of AGN feedback, for which $P_{\rm K,OF} = 5\% L_{\rm AGN}$. The red dashed line represents the linear 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.

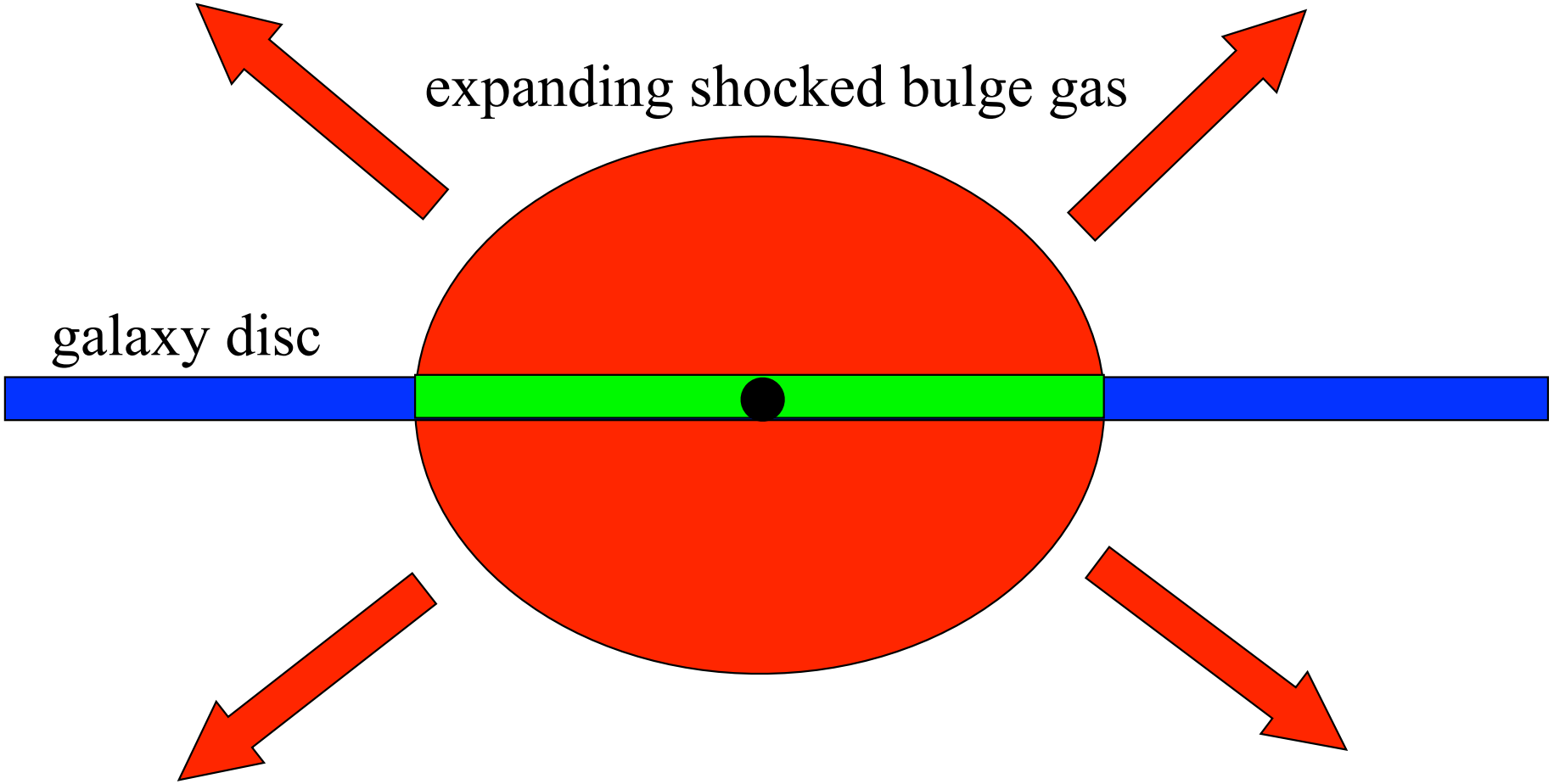
Tombesi et al., Nature, 2015

Here we show the clear detection of a powerful AGN accretion disk wind with a mildly relativistic velocity of 0.25c in the X-ray spectrum of IRAS F11119+3257, a nearby (z = 0.189) optically classified type 1 ULIRG hosting a powerful molecular outflow. The AGN is responsible for ~80% of the emission, with a quasar-like luminosity of L_(AGN} = 1.5 Å~ 1046 erg s–1.

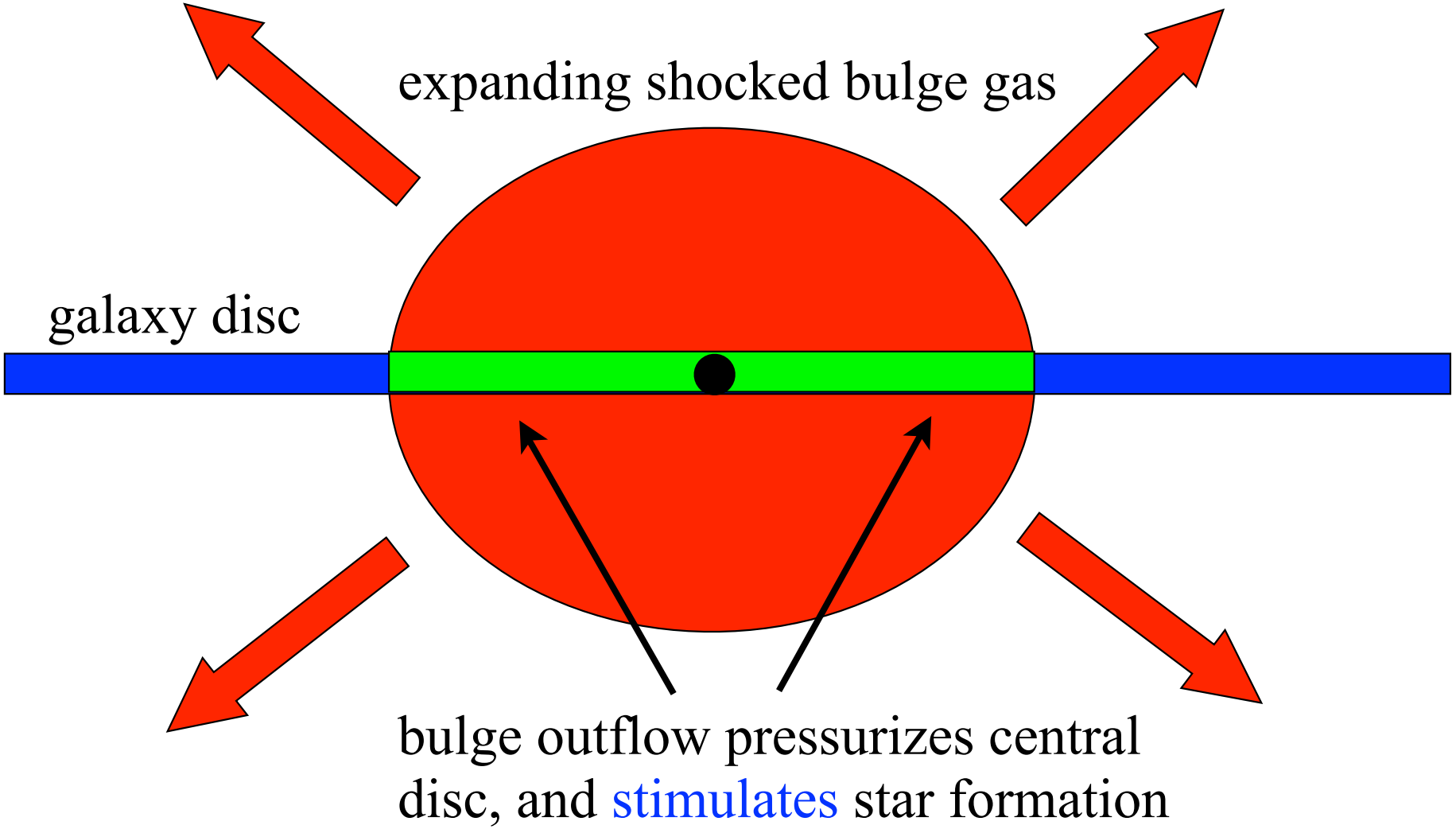
The energetics of these winds are consistent with the energy-conserving mechanism.

**

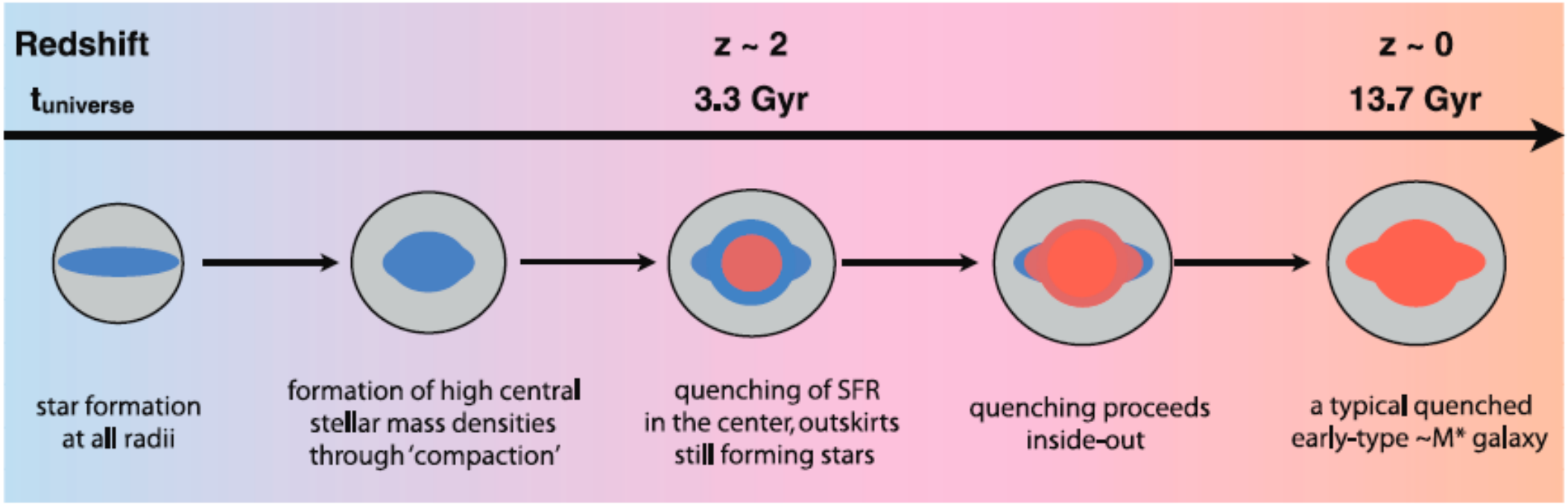
spirals: outflow pressure => star formation in disc



spirals: outflow pressure => star formation in disc



observational picture



(Tachella et al., 2015)

outflows may be episodic, as AGN driving is variable

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

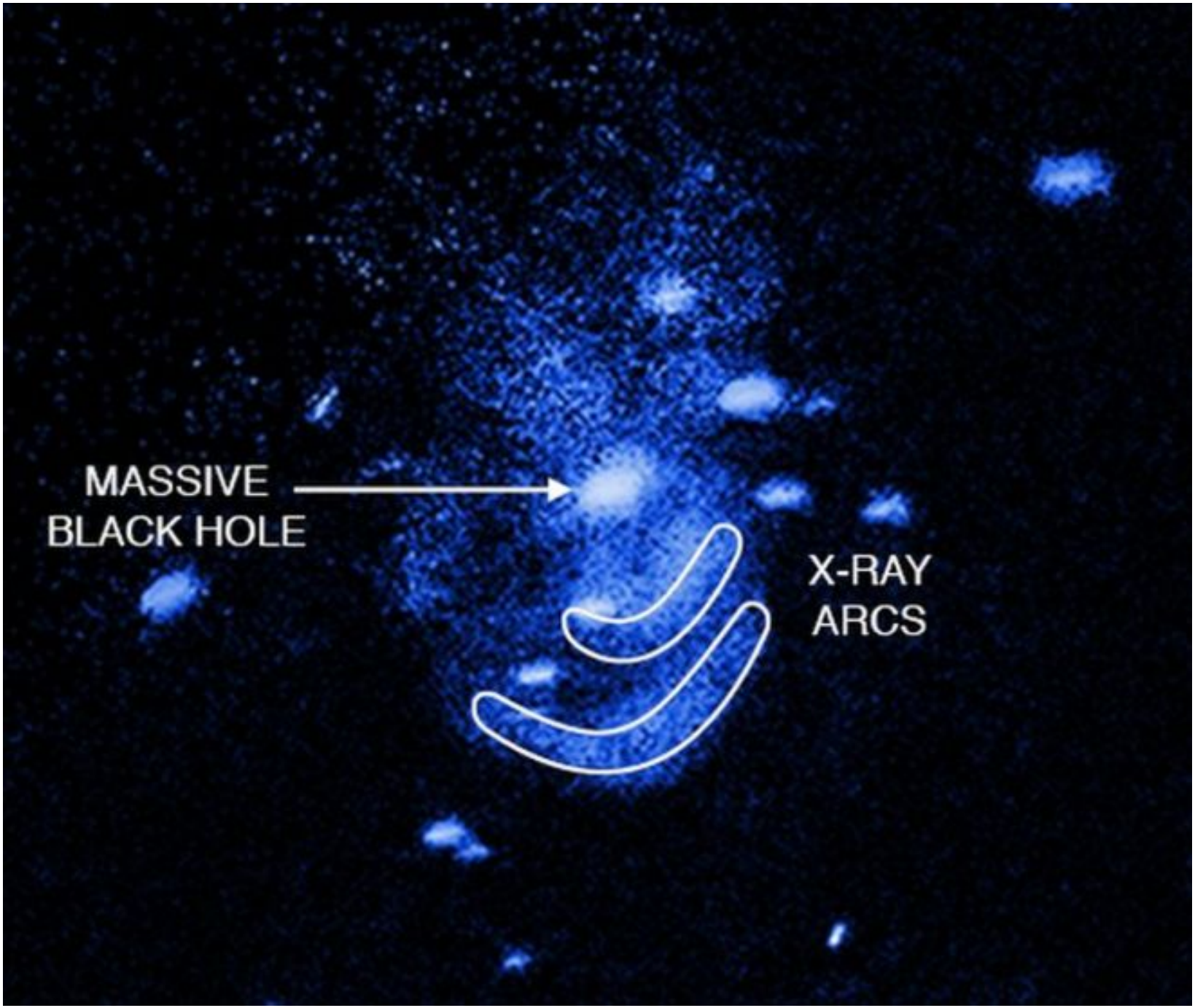
$$M_d \lesssim \frac{H}{R} M_{\rm BH} \simeq 10^{-3} M_{\rm BH}$$

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



(Schlegel et al., 2016)

bulge stellar mass

stars produce luminosity $L_* \sim \epsilon_* \dot{M}_* c^2$,
and so momentum p_* at rate $\dot{p}_* \sim \epsilon_* c \dot{M}_*$

star formation is inhibited if total momentum p_* reaches $\sim M_g \sigma$,
where M_g is original gas mass, so maximum bulge stellar mass is

$$M_b \sim \frac{\sigma}{\epsilon_* c} M_g$$

now $M_g \sim f_g M_V$, where

$$M_V \sim \frac{1}{H} \times \frac{\sigma^3}{G}$$

is virial mass
so combining, we get

$$M_b \sim \frac{f_g \sigma^4}{\epsilon_* c H G} \sim 10^{11} M_\odot \sigma_{200}^4$$

black-hole -- bulge-mass relation

now using

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

we find

$$\frac{M_{\rm BH}}{M_b} \sim \frac{\epsilon_* \kappa c H}{\pi G} \simeq 10^{-3}$$

but note the nature of this relation:

SMBH mass limited to $M \propto \sigma^4$ by *black hole* momentum feedback (K 2003, 2005) - *tiny* scales ~ pc

bulge stellar mass limited to $M_b \propto \sigma^4$ by *stellar* momentum feedback and cosmological mass growth

ratio is

$$\frac{M}{M_b} \simeq 10^{-3} h(z) \left[1 + \frac{0.41 \sigma_{200}}{h(z)} \right] \quad \text{(Power + 2011)}$$

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the dark ages?

in all this work, we have assumed that the radiation of the accreting SMBH escapes freely - is this true?

if not, the entire accretion luminosity must be trying to drive the ISM away, so L, not just $(\eta/2)L \simeq 0.05L$

we need to work out the optical depth of the ISM

with

$$\rho(r) = \frac{f_g \sigma^2}{2\pi G r^2}$$

the optical depth from radius R to infinity is

$$\tau(R) = \int_R^\infty \kappa \rho(r) \mathrm{d}r = \frac{\kappa f_g \sigma^2}{2\pi G R}$$

this gets large for small R

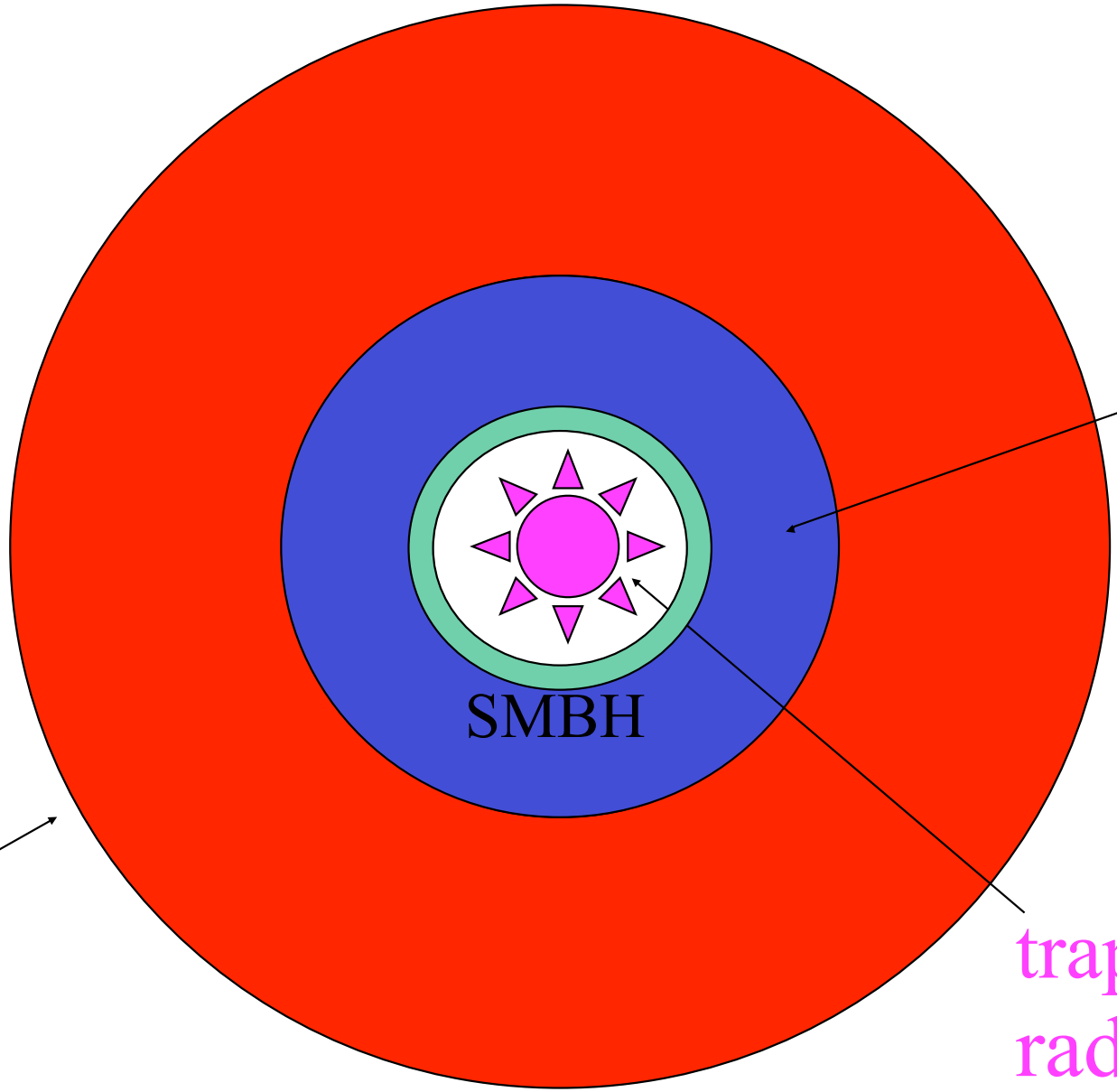
so the luminosity is trapped at small R

=> radiation pushes the ISM into a shell of mass

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

(just as the wind does [later])

radiation driving



expect expansion of bubble faster than wind case since L not $\frac{\eta}{2}L$

the optical depth across this shell is $\kappa\times$ (column density), i.e.

$$\tau_{\rm sh}(R) = \frac{\kappa M_g(R)}{4\pi R^2} = \frac{\kappa f_g \sigma^2}{2\pi G R} = \tau(R)$$

so the trapped radiation sees *total* optical depth (shell + ambient ISM)

$$\tau_{\rm tot}(R) = \tau(R) + \tau_{\rm sh}(R) \simeq \frac{\kappa f_g \sigma^2}{\pi G R}$$

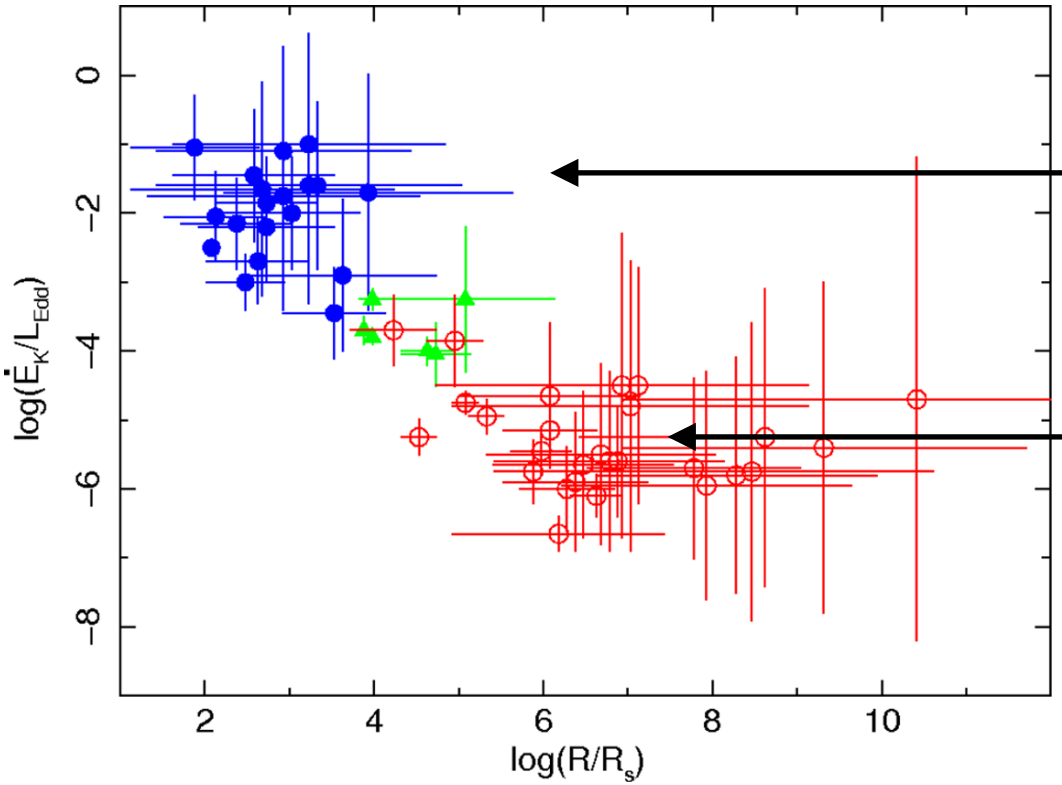
this becomes optically thin (=> radiation can escape) once R reaches

`transparency radius'

$$R_{\rm tr} \sim \frac{\kappa f_g \sigma^2}{\pi G} \simeq 50 \left(\frac{f_g}{0.16}\right) \sigma_{200}^2 \ {\rm pc} \sim 10^7 R_g$$

so now the shell gradually slows down and the radiation escapes -

end of the `dark ages'



UFOs

`warm absorbers'

dust?

while shell is optically thick, radiation is trapped and must build up a black body distribution,

temperature given by $L_{\rm Edd} = 4\pi R^2 \sigma T_b^4$

i.e.

$$T_b = \frac{100}{r^{1/2}} \left(\frac{\kappa}{\kappa_{es}} \right)^{1/2} \ {\rm K}, (r = R/R_{\rm tr} < 1)$$

ISM opacity cannot be dust ($\kappa >> \kappa_{es}$), as T_b gets large and exceeds dissociation temperature

transparency radius determined by electron scattering

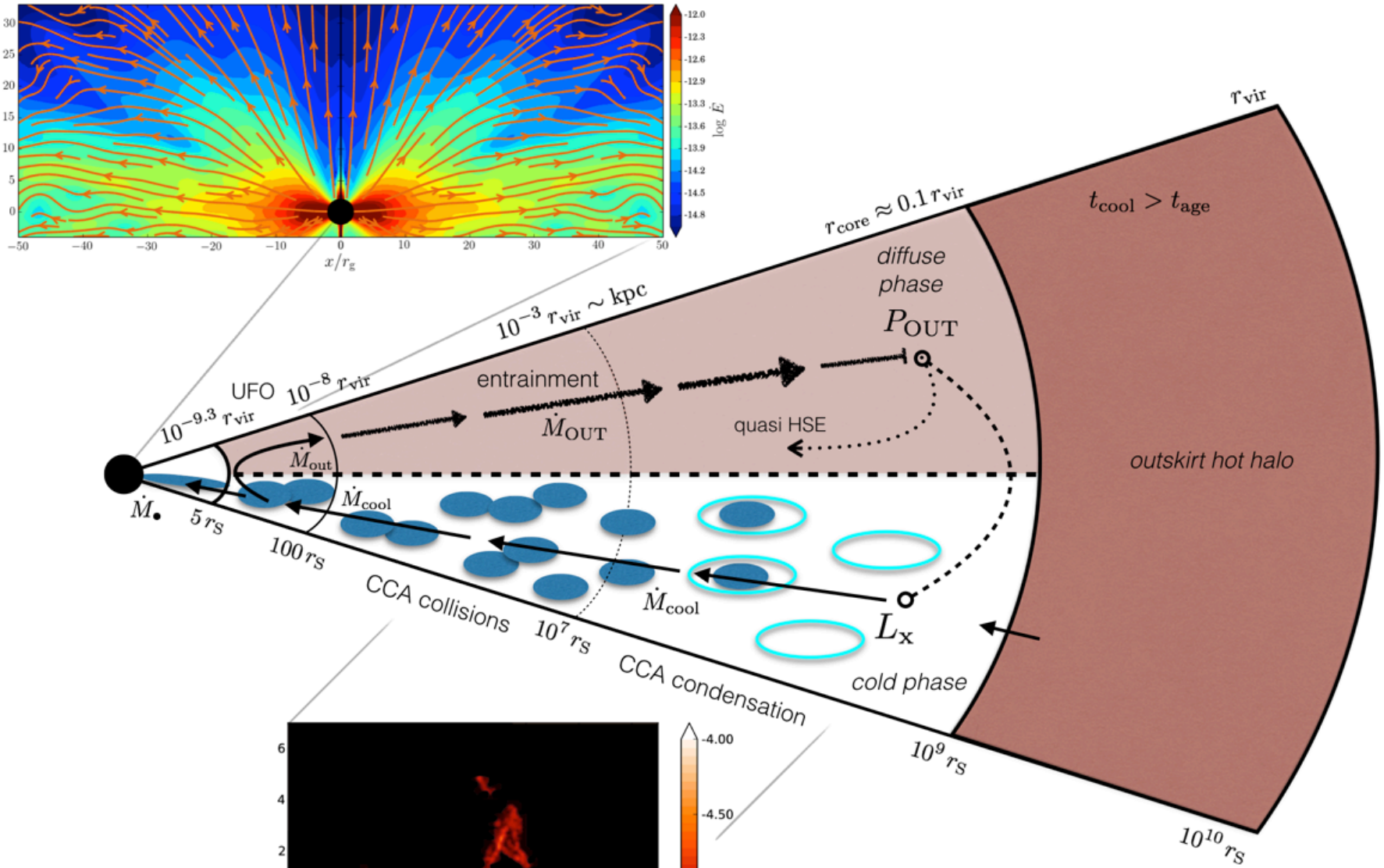
some other consequences of SMBH outflows

super-solar abundances in AGN spectra: momentum—driven outflows ($M < M_\sigma$) repeatedly sweep up and compress the same gas: generations of massive stars forming out of same gas enrich metals

dark matter cusp removal by same mechanism: large masses move

little SF in AGN hosts

metals spread to IGM by subsequent energy-driven outflows



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UNIFYING THE MICRO AND MACRO PROPERTIES OF AGN FEEDING AND FEEDBACK

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ABSTRACT

We unify the feeding and feedback of supermassive black holes with the global properties of galaxies, groups, and clusters, by linking for the first time the physical mechanical efficiency at the horizon and Mpc scale. The macro hot halo is tightly constrained by the absence of overheating and overcooling as probed by X-ray data and hydrodynamic simulations ($\varepsilon_{\rm BH} \approx 10^{-3}\, T_{\rm x,7.4}$). The micro flow is shaped by general relativistic effects tracked by state-of-the-art GR-RMHD simulations ($\varepsilon_\bullet \approx 0.03$). The SMBH properties are tied to the X-ray halo temperature $T_{\rm x}$, or related cosmic scaling relation (as $L_{\rm x}$). The model is minimally based on first principles, as conservation of energy and mass recycling. The inflow occurs via chaotic cold accretion (CCA), the rain of cold clouds condensing out of the quenched cooling flow and recurrently funneled via inelastic collisions. Within 100s gravitational radii, the accretion energy is transformed into ultrafast $10^4\,{\rm km\,s^{-1}}$ outflows (UFOs) ejecting most of the inflowing mass. At larger radii the energy-driven outflow entrains progressively more mass: at roughly kpc scale, the velocities of the hot/warm/cold outflows are a few 10^3, 1000, 500 $\rm km\,s^{-1}$, with median mass rates $\sim$10, 100, several $100\,M_\odot\,{\rm yr}^{-1}$, respectively. The unified CCA model is consistent with the observations of nuclear UFOs, and ionized, neutral, and molecular macro outflows. We provide step-by-step implementation for subgrid simulations, (semi)analytic works, or observational interpretations which require self-regulated AGN feedback at coarse scales, avoiding the a-posteriori fine-tuning of efficiencies.

Keywords: black hole accretion – ISM, IGM, ICM – methods: 3D GR-RMHD simulations, analytics

COUPLING BH GROWTH TO STAR FORMATION

Driving BH driving winds into the galaxy

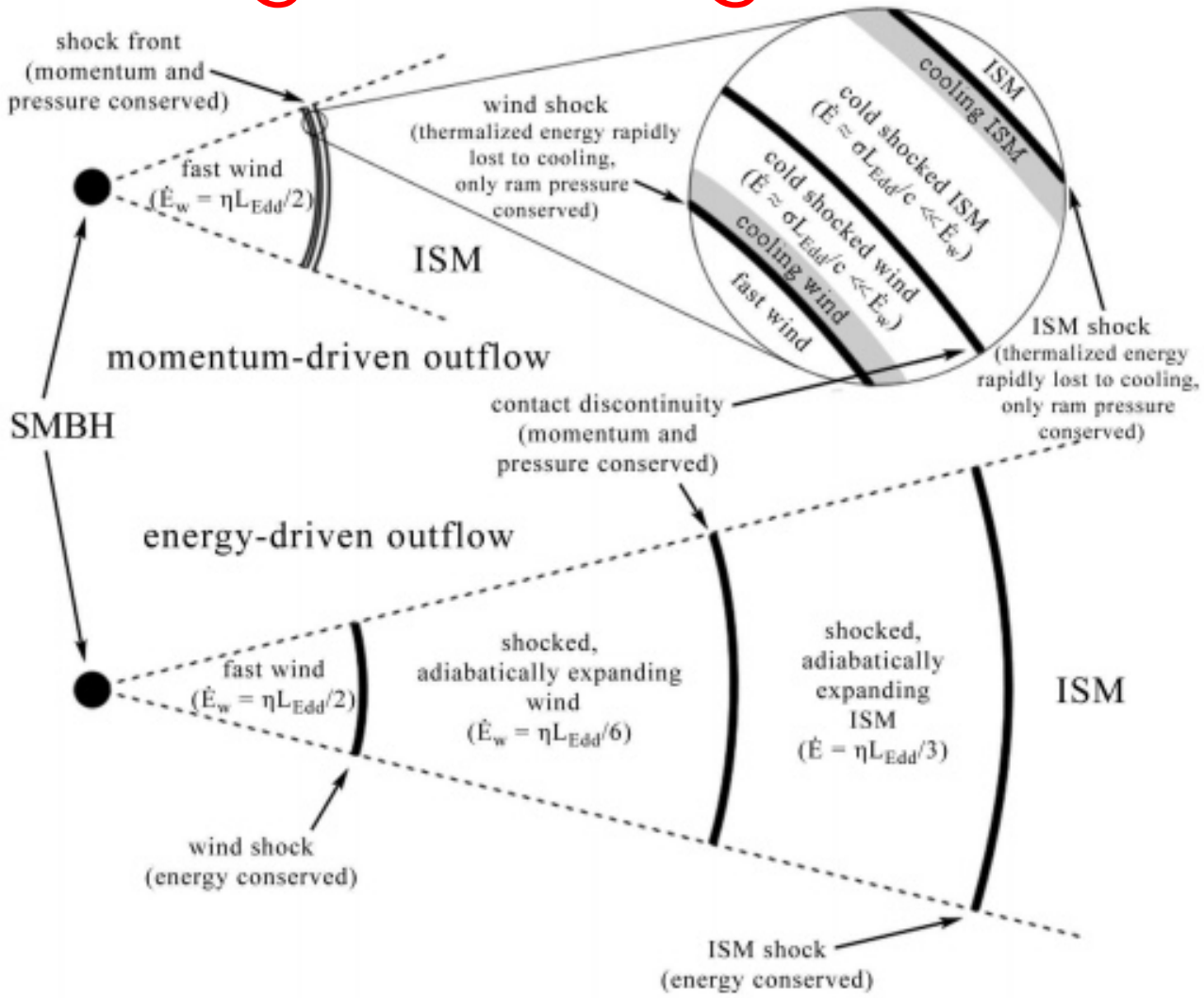

Fig. 8 Schematic picture of momentum–driven (top) and energy–driven (bottom) outflows. In both cases a fast wind (velocity $\sim 0.1c$) impacts the interstellar gas of the host galaxy

COOLING

Momentum Driven

NO COOLING

Energy Driven

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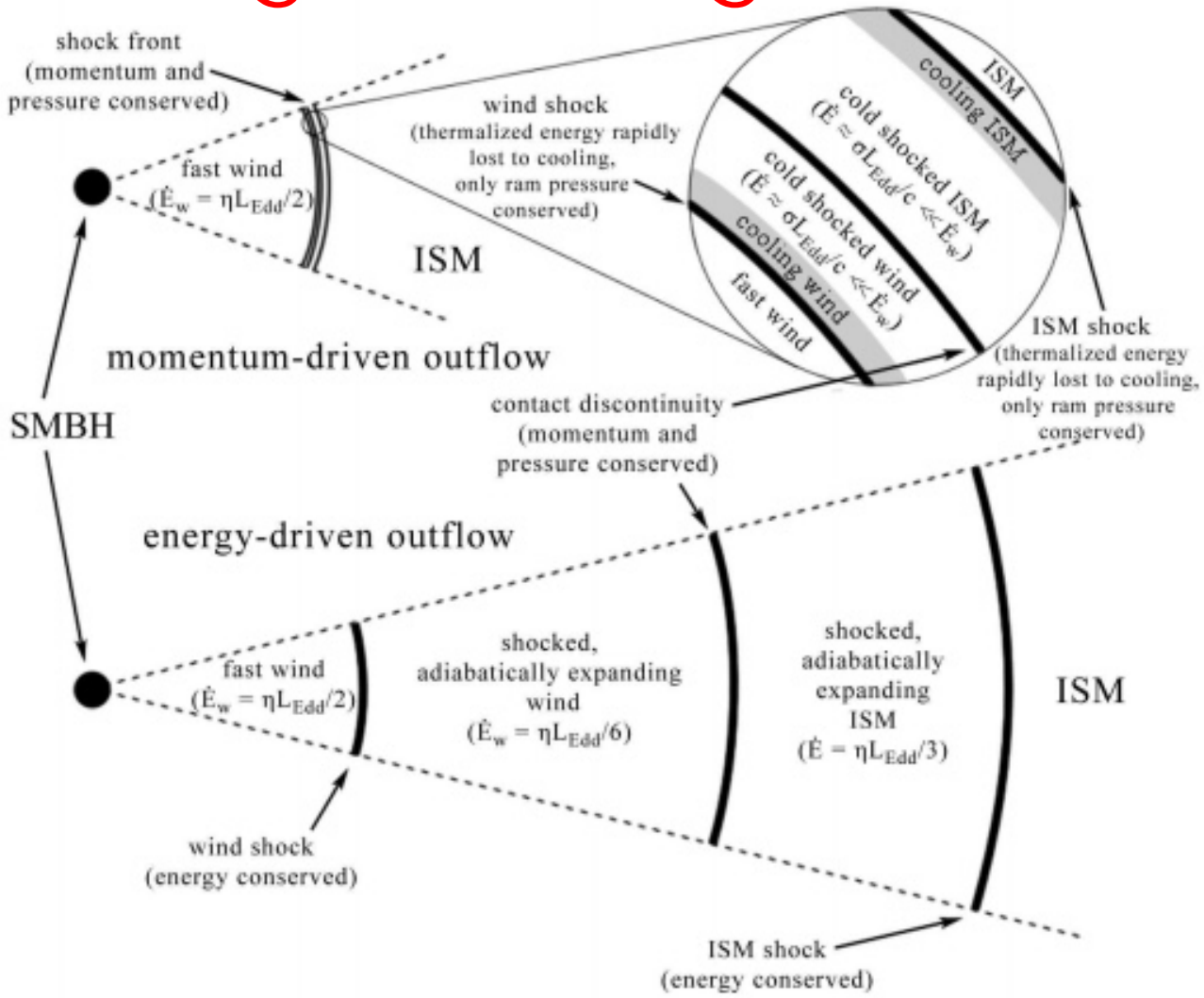

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COOLING
Momentum Driven
$M_{bh} < M_{limit}$

NO COOLING
Energy Driven
$M_{bh} > M_{limit}$