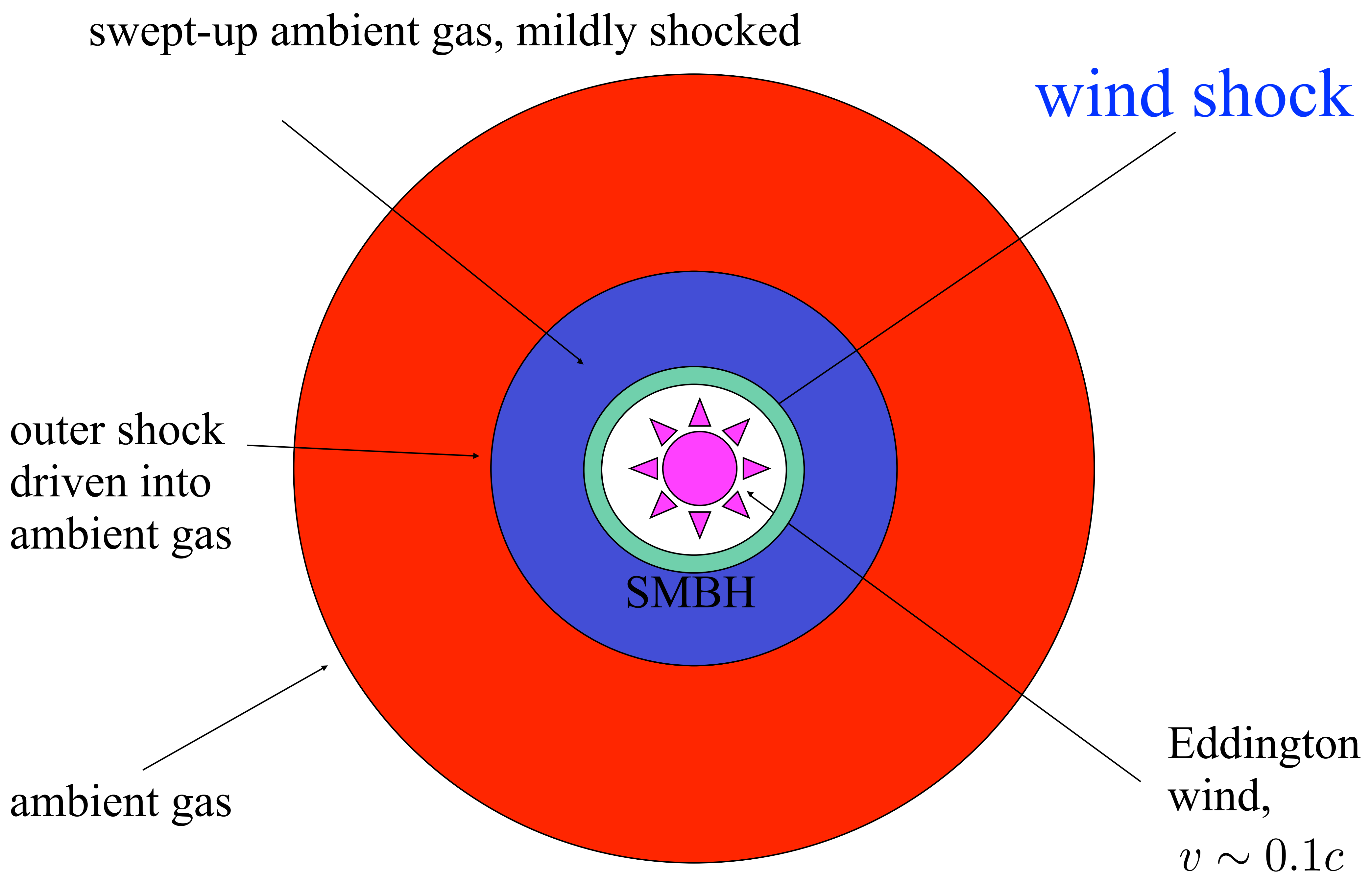

swept-up ambient gas, mildly shocked
wind shock
outer shock driven into ambient gas
SMBH
ambient gas
Eddington wind,
$v \sim 0.1c$

wind shock

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

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

where

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

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

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')

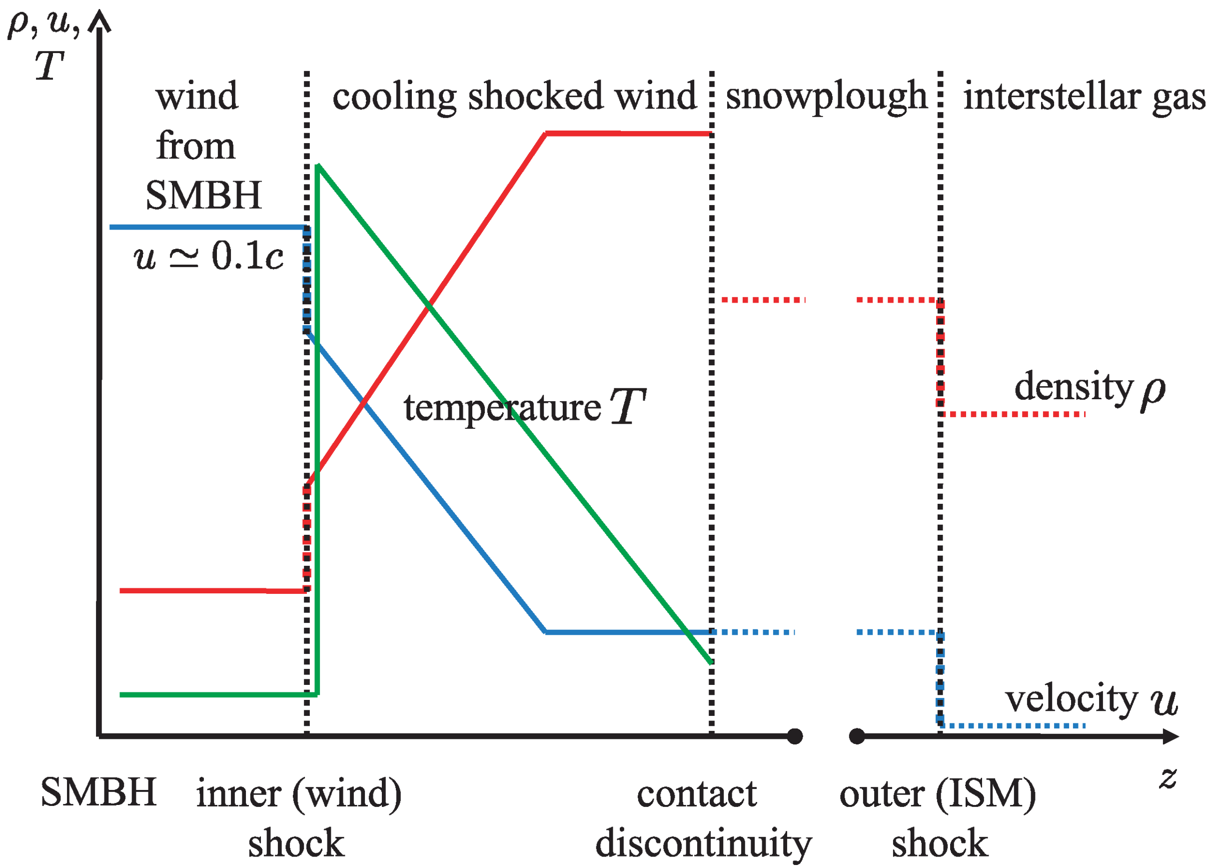
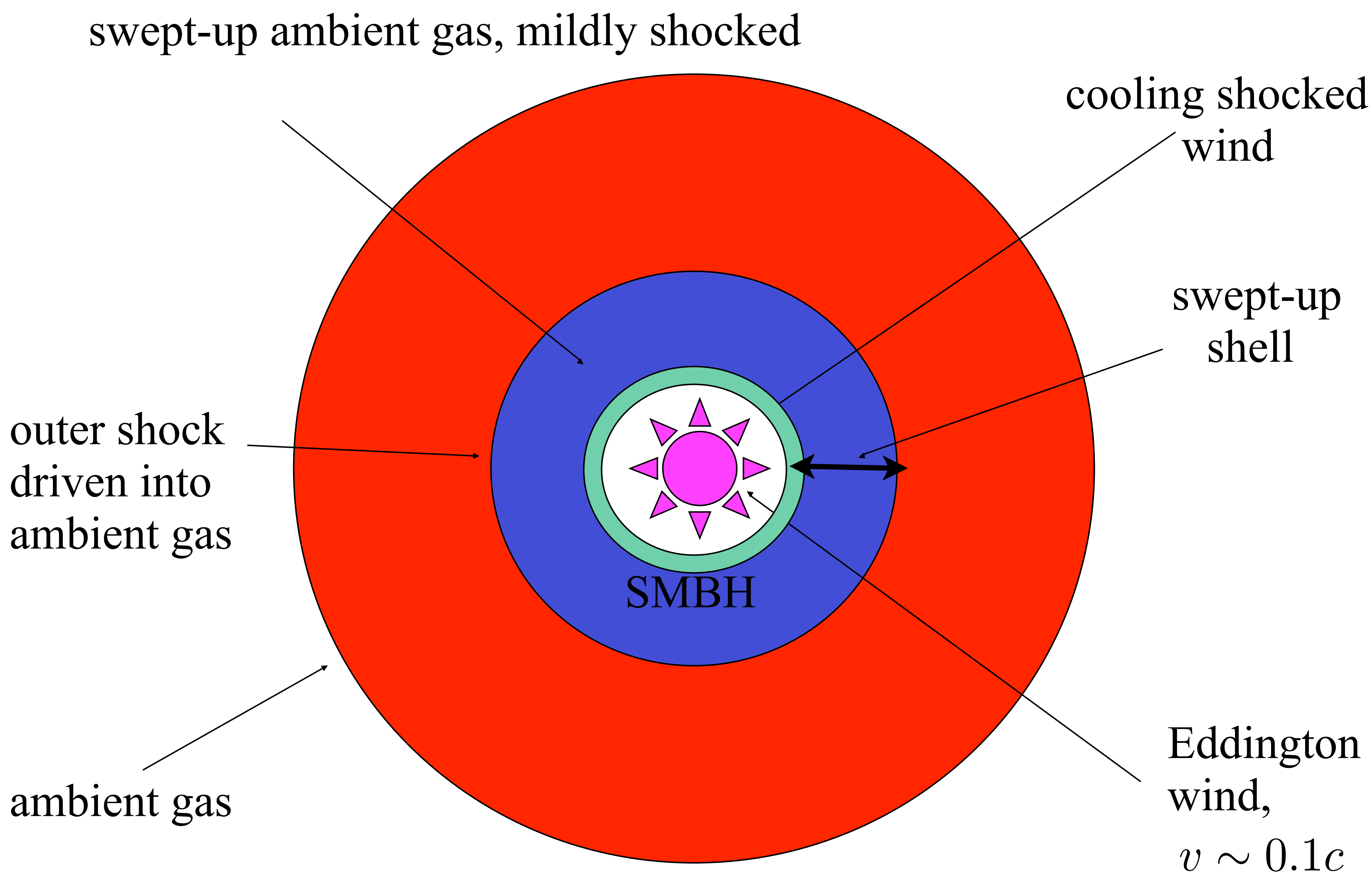


Figure 2. Impact of a wind from an SMBH accreting at a super-Eddington rate on the interstellar gas of the host galaxy: schematic view of the radial dependence of the gas density ρ, velocity u and temperature T. At the inner shock, the gas temperature rises strongly while the wind density and velocity, respectively, increase (decrease) by factors of $\sim$4. Immediately outside this (adiabatic) shock, the strong Compton cooling effect of the quasar radiation severely reduces the temperature, and slows and compresses the wind gas still further. This cooling region is very narrow compared with the shock radius (see Fig. 1), and may be observable through the inverse Compton continuum and lower excitation emission lines. The shocked wind sweeps up the host ISM as a 'snowplough'. This is more extended than the cooling region (cf. Fig. 1), and itself drives an outer shock into the ambient ISM


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

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

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

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

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

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

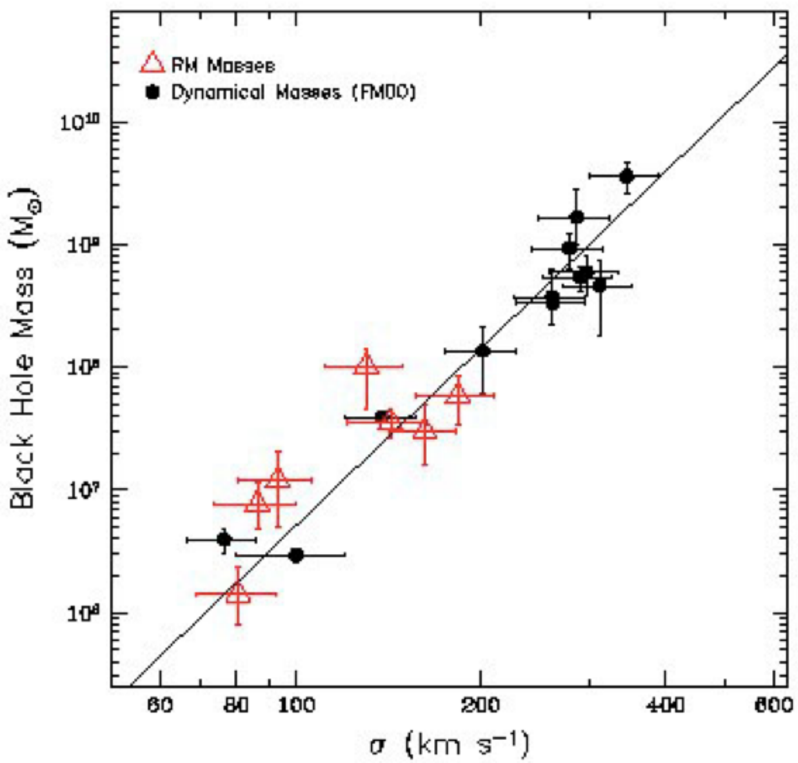
if $M < M_\sigma$, no solution at large R (rhs < 0)

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

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

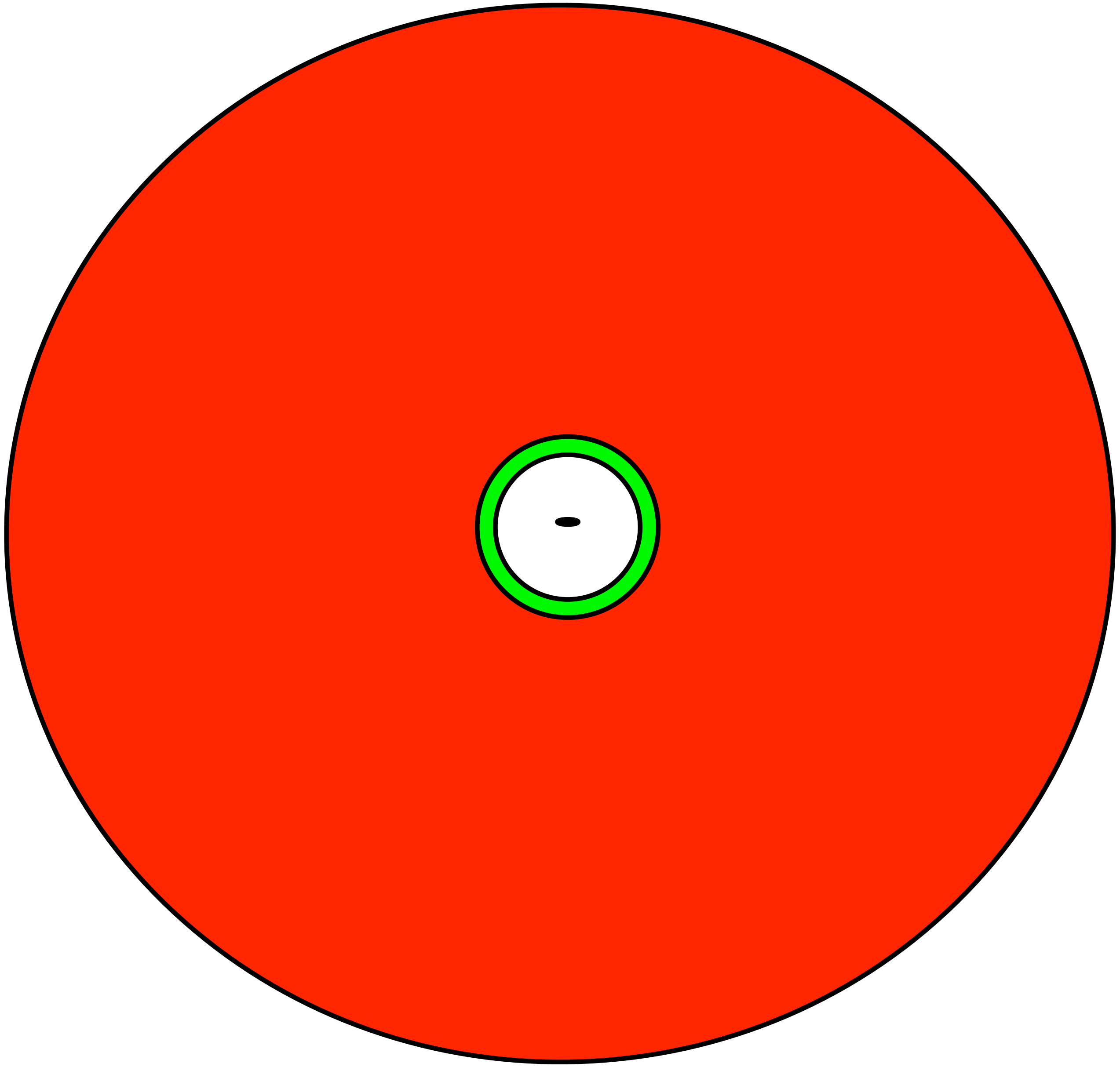
remarkably close to observed $M-\sigma$ relation despite effectively no free parameter $(f_g \sim 0.1)$ (King, 2003; 2005)



SMBH mass grows until Eddington thrust expels gas feeding it

**

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



UFO winds are episodic

X-ray absorption through wind measures column density

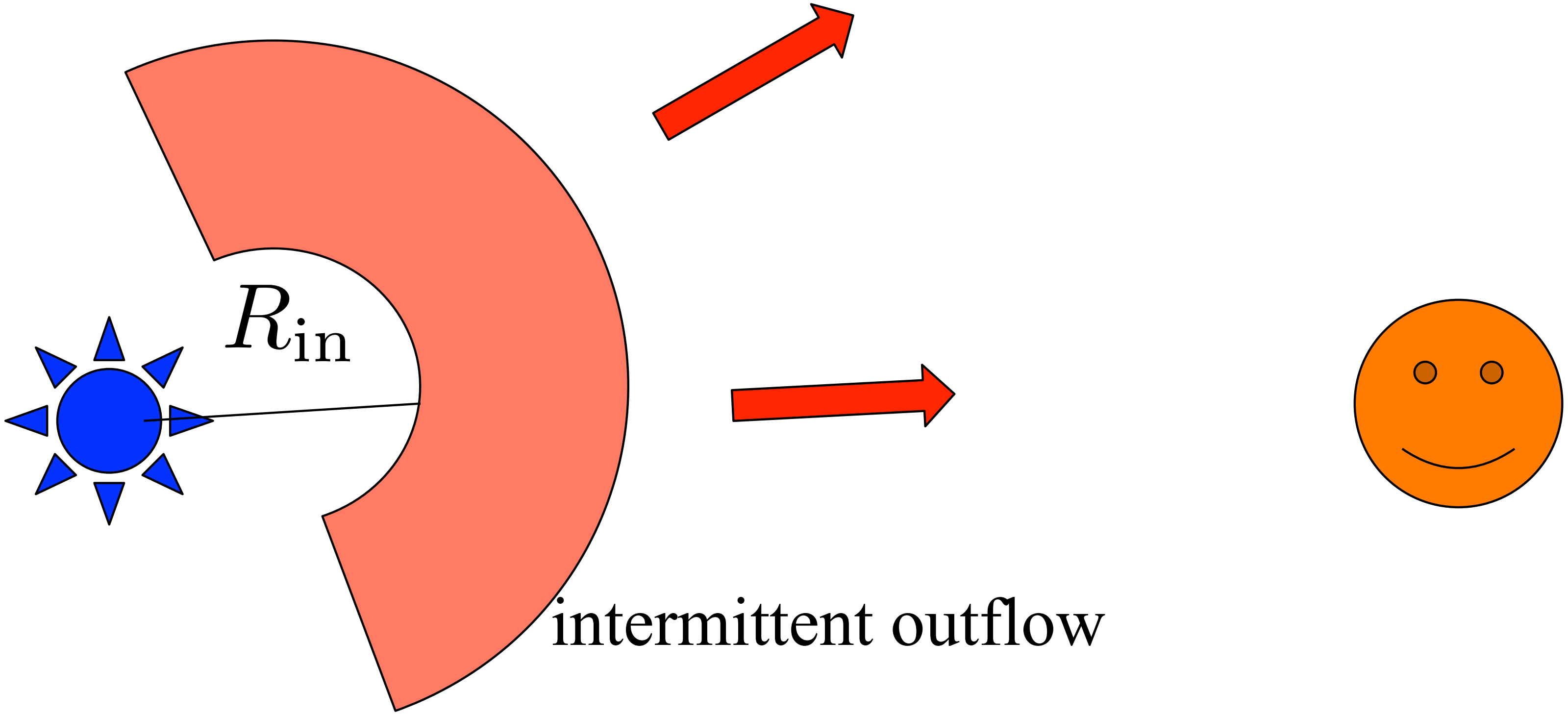
$$N_H = \int \frac{\rho}{m_p} \mathrm{d}r = \int_{R_{\rm in}}^{\infty} \frac{\dot{M}_{\rm out}}{4\pi m_p r^2 v} \mathrm{d}r$$

so $$N_H = \frac{\dot{M}_{\rm out}}{4\pi m_p R_{\rm in} v}$$

but $R_{\rm in} = vt$, where t is time since wind switched off

a full Eddington wind from vicinity of SMBH has Thomson optical depth of order 1, so that $N_H \simeq 10^{24}\,\mathrm{cm}^{-2}$

a smaller column => inner edge of wind is further from SMBH:



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

$$N_H = \frac{GM}{bv^2 R_{\rm in}\sigma_T}, \text{ using } \dot{M}_{\rm out}v = L_{\rm Edd}/c$$

so if outflow stopped a time $t_{\rm off} = R_{\rm in}/v$ ago, we have

$$t_{\rm off} = \frac{GM}{bv^3 N_H \sigma_T} \simeq 0.25 \frac{M_8}{v_{0.1}^3 N_{23} b} \text{ yr}$$

recent!

transition to energy-driven flow once M_σ reached

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

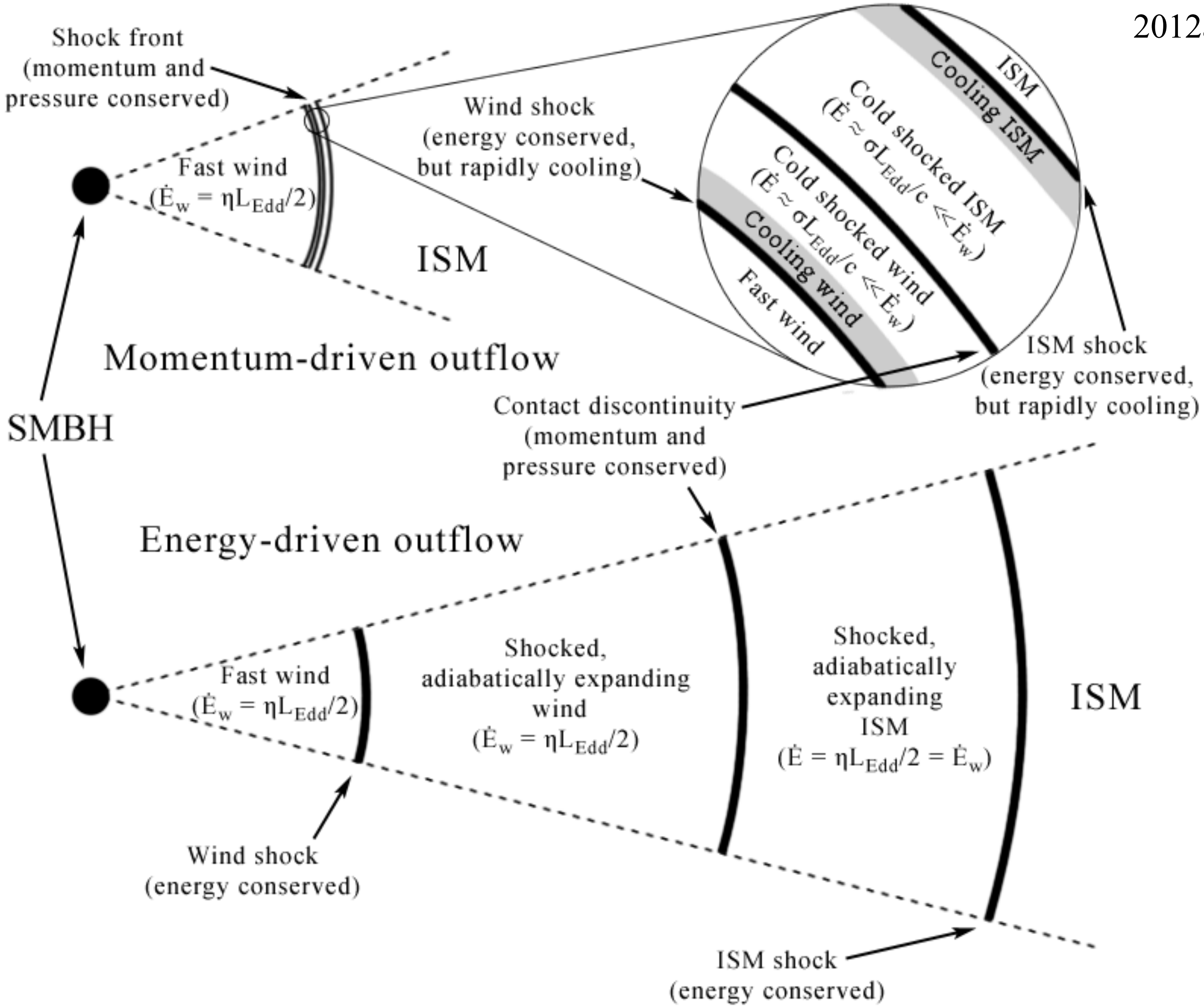
but once $M > M_\sigma$, R can exceed R_C: wind shock no longer cools

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

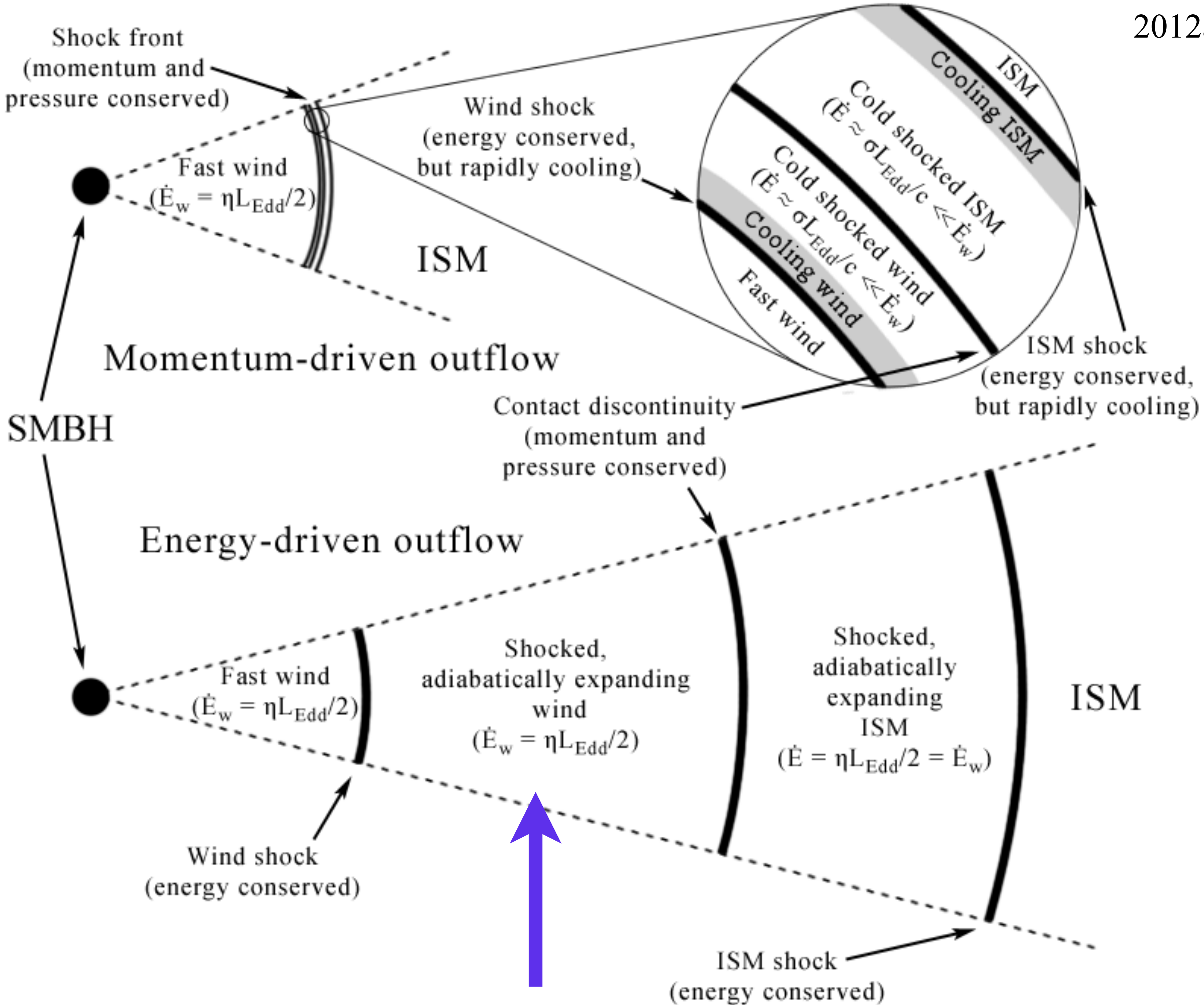
eqn of motion now contains *total* postshock pressure P (gas plus ram)

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

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

energy equation is

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

where

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

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

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

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

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

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

(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

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

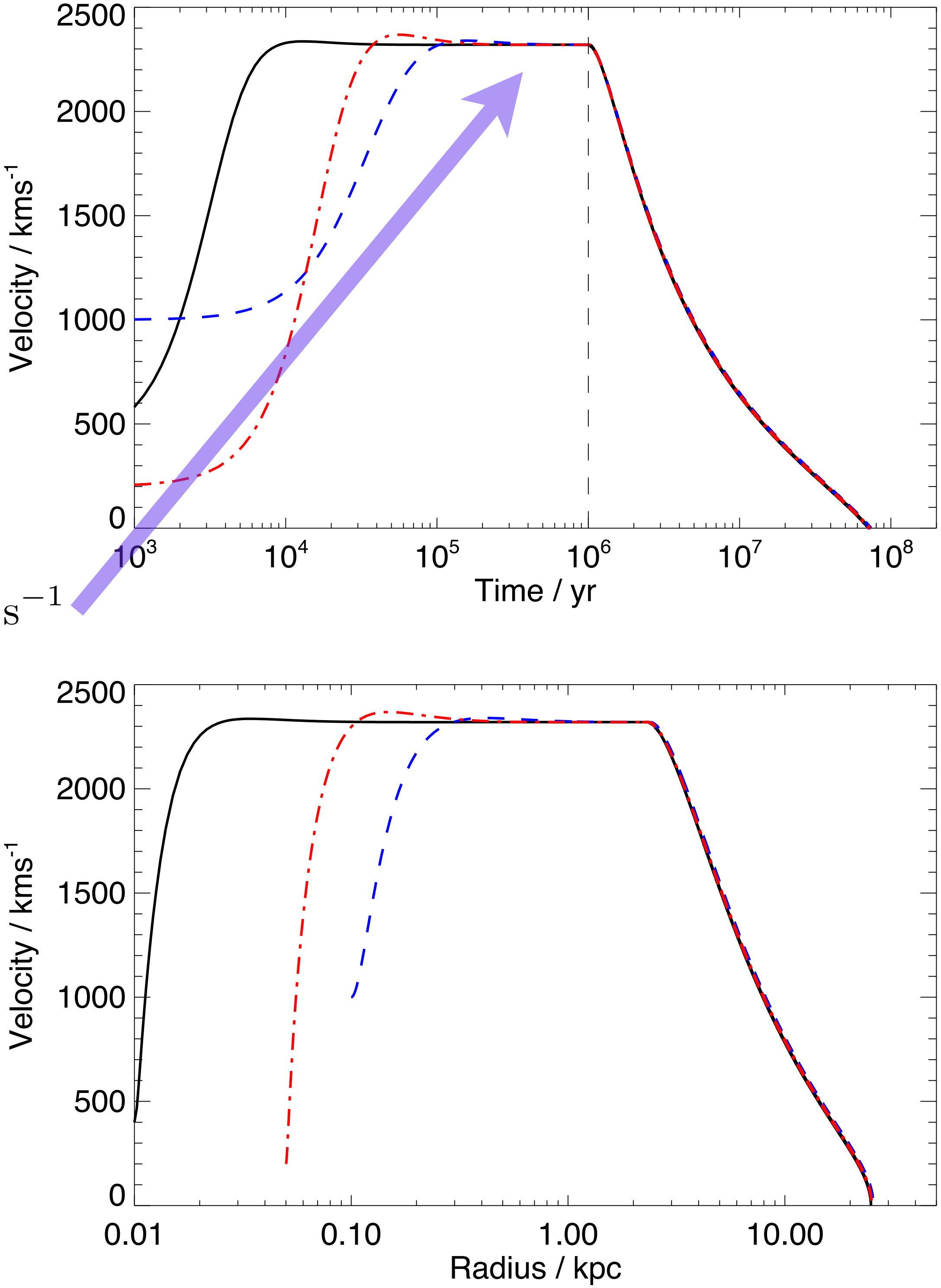
where $r = R/R_0 \geq 1$

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

(King, Zubovas & Power, 2011)

energy--driven outflows rapidly converge to

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



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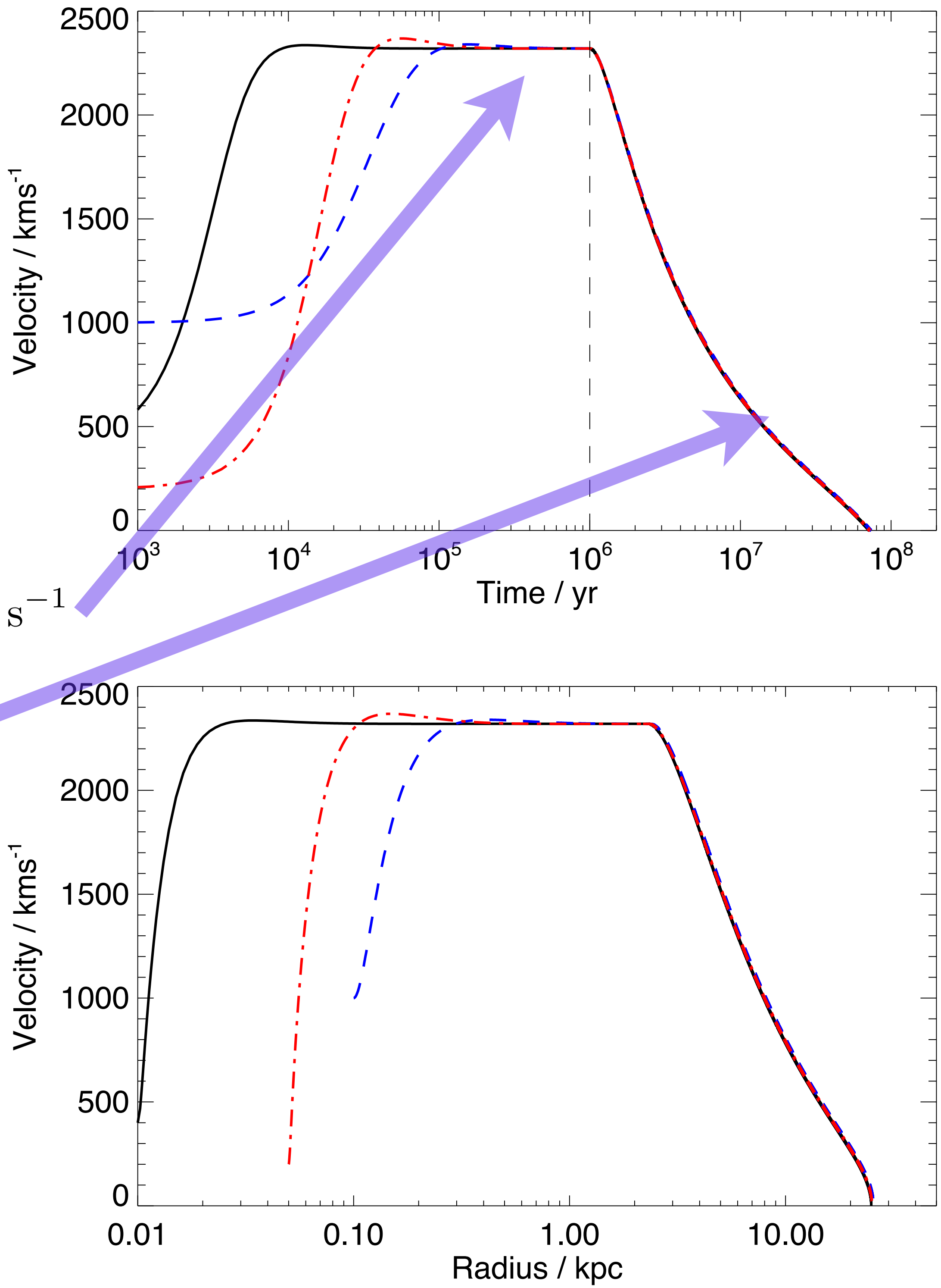
and persist even after central quasar turns off



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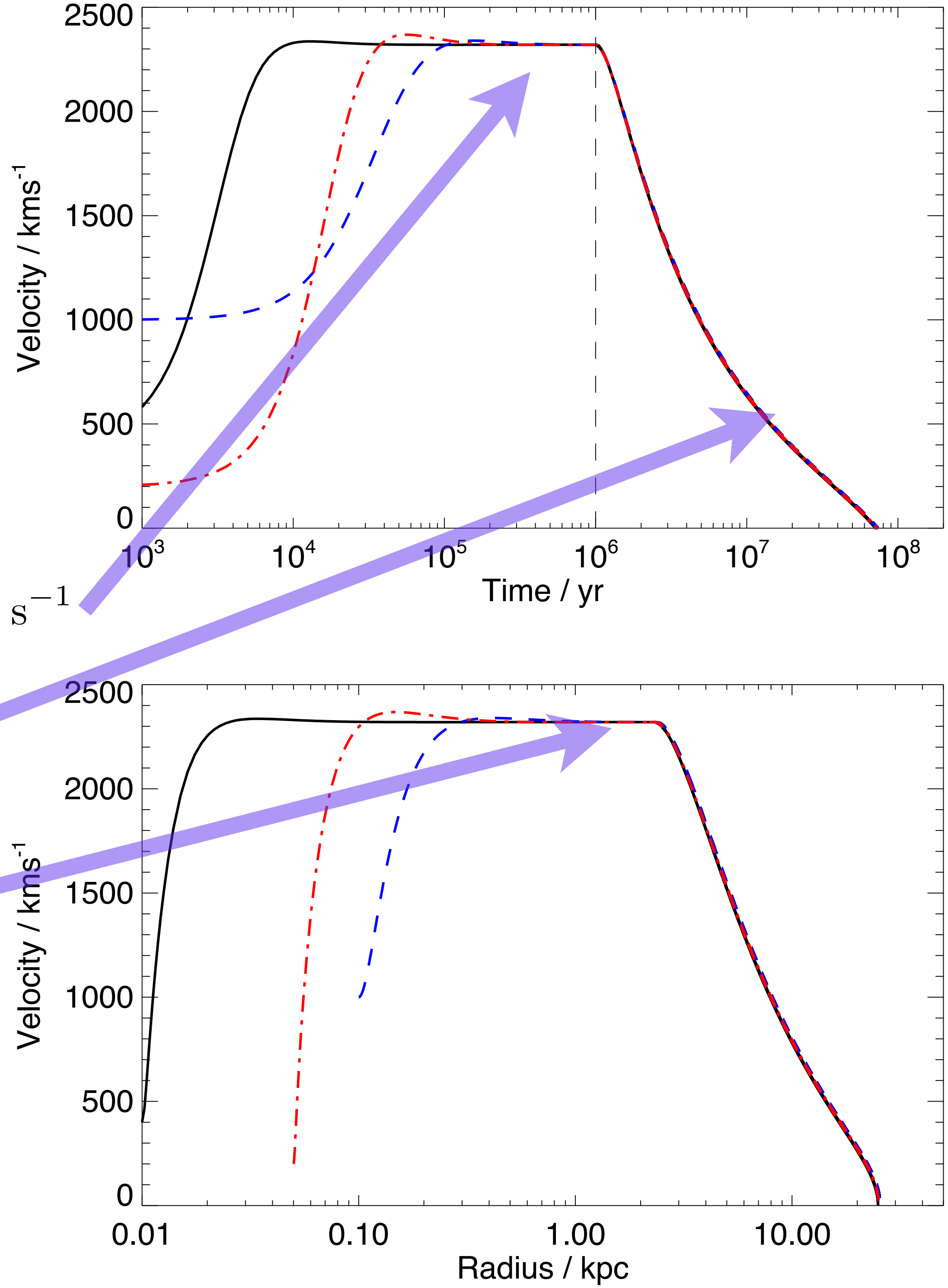
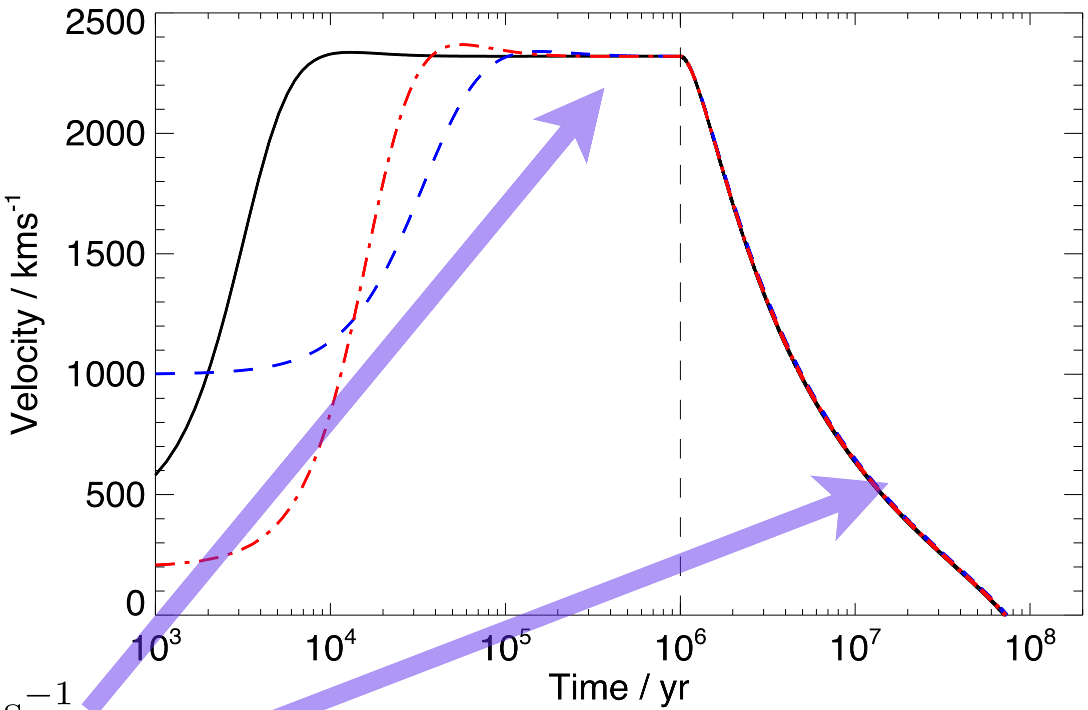
high velocity outflow at large radius



energy--driven outflows rapidly converge to

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



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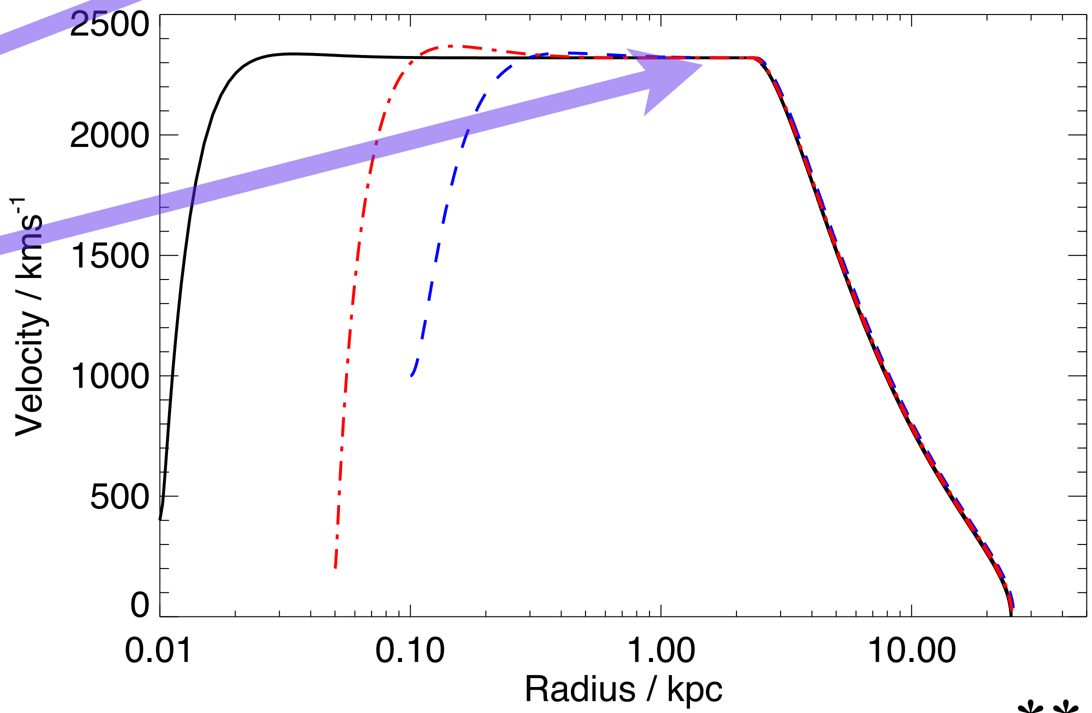

also for other potentials: Zubovas & King, 2012b

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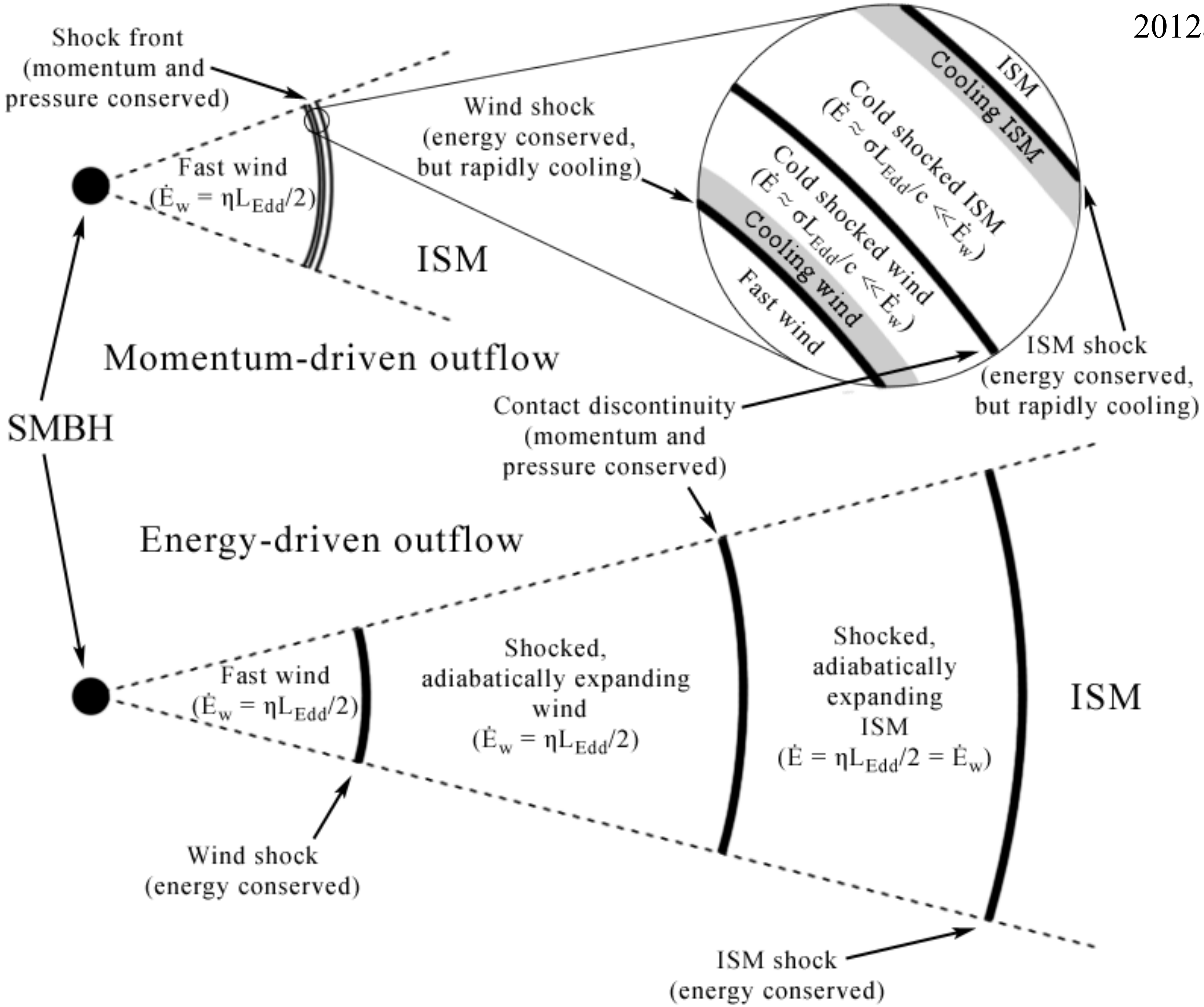
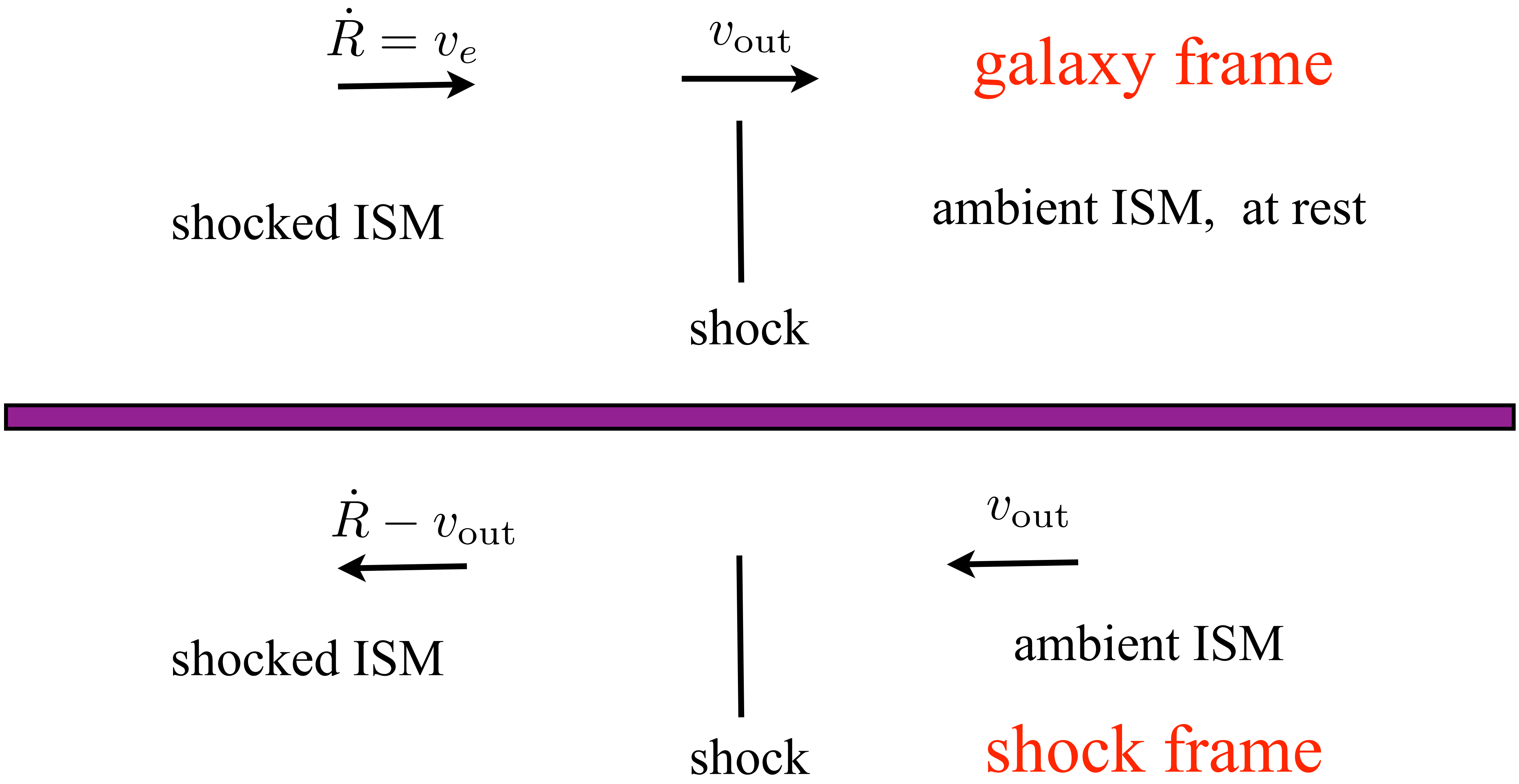
Zubovas & King,
2012a



forward shock speed



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

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

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

and radius as

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

outflow rate of shocked interstellar gas is

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

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

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

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

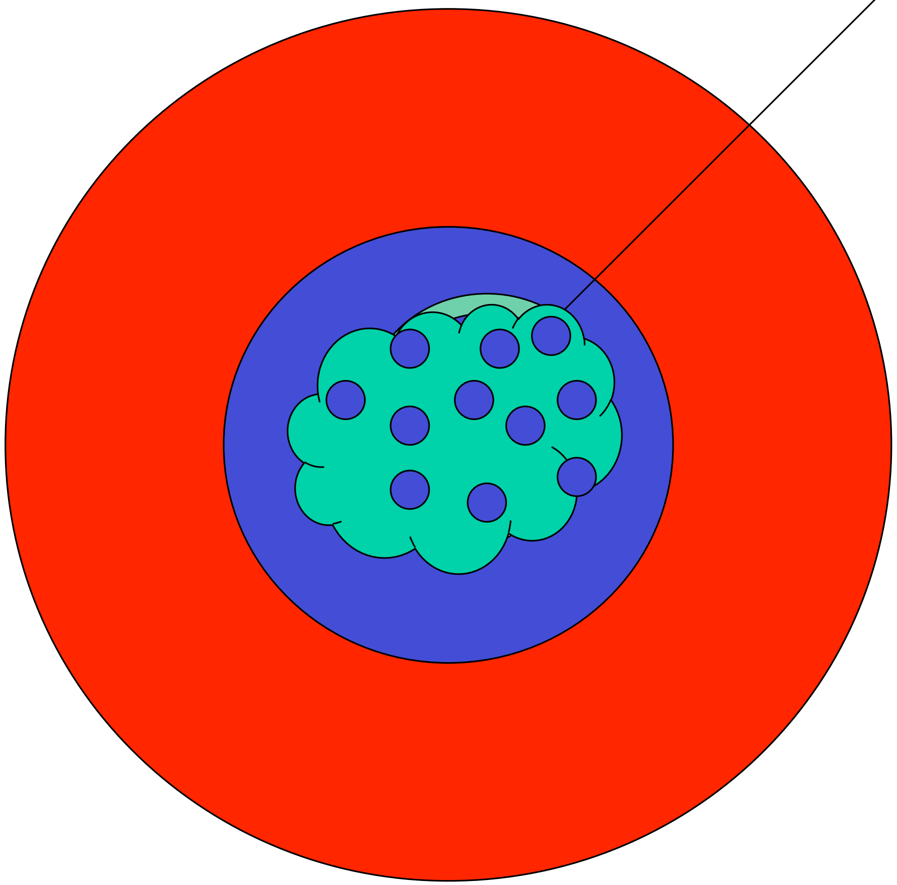
$$\dot{P}_{\rm out} = \dot{P}_{\rm w}\left(\frac{\dot{M}_{\rm out}}{\dot{M}_{\rm w}}\right)^{1/2} \sim 20\sigma_{200}^{-1/3}l^{1/6}\frac{L_{\rm Edd}}{c}$$

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*

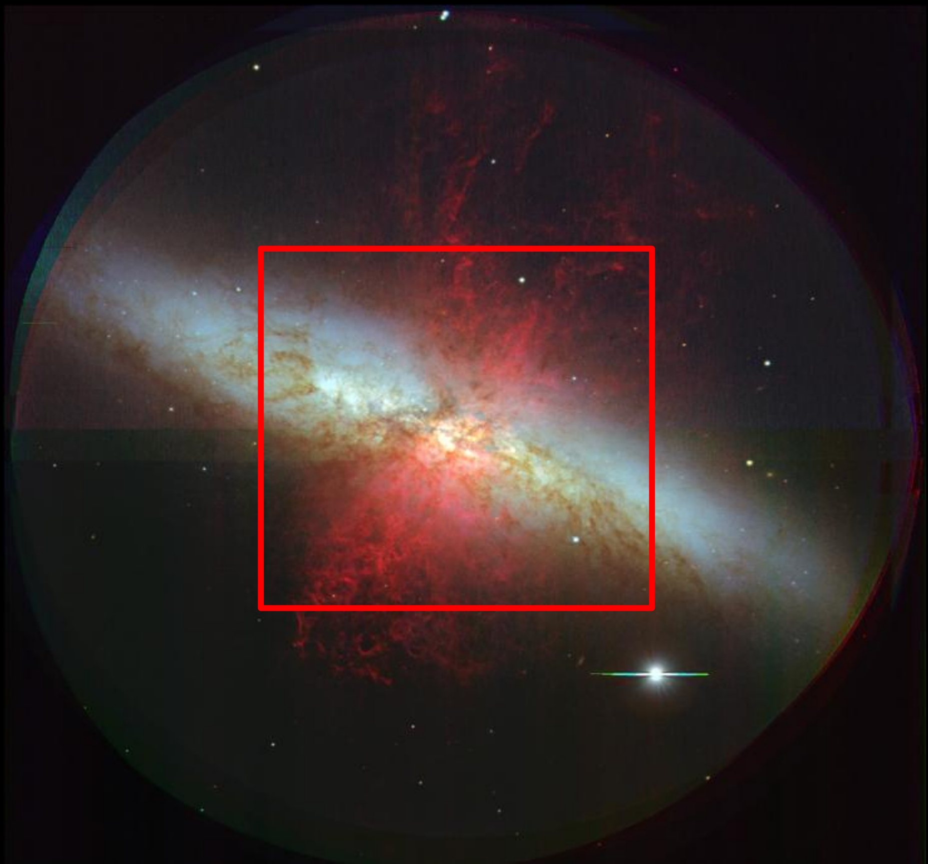


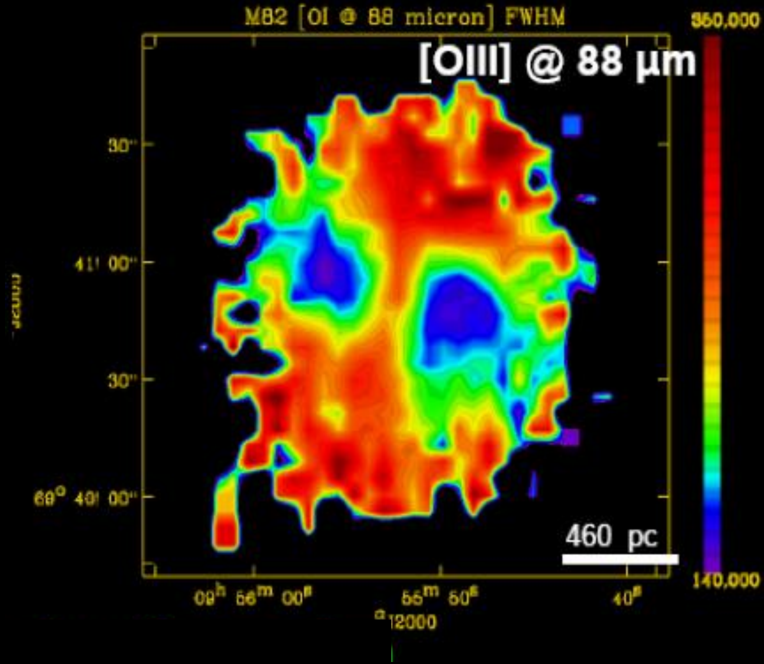
two—phase medium: gamma—rays and molecular emission mixed

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

galaxy bulge should produce gamma-ray emission

M82

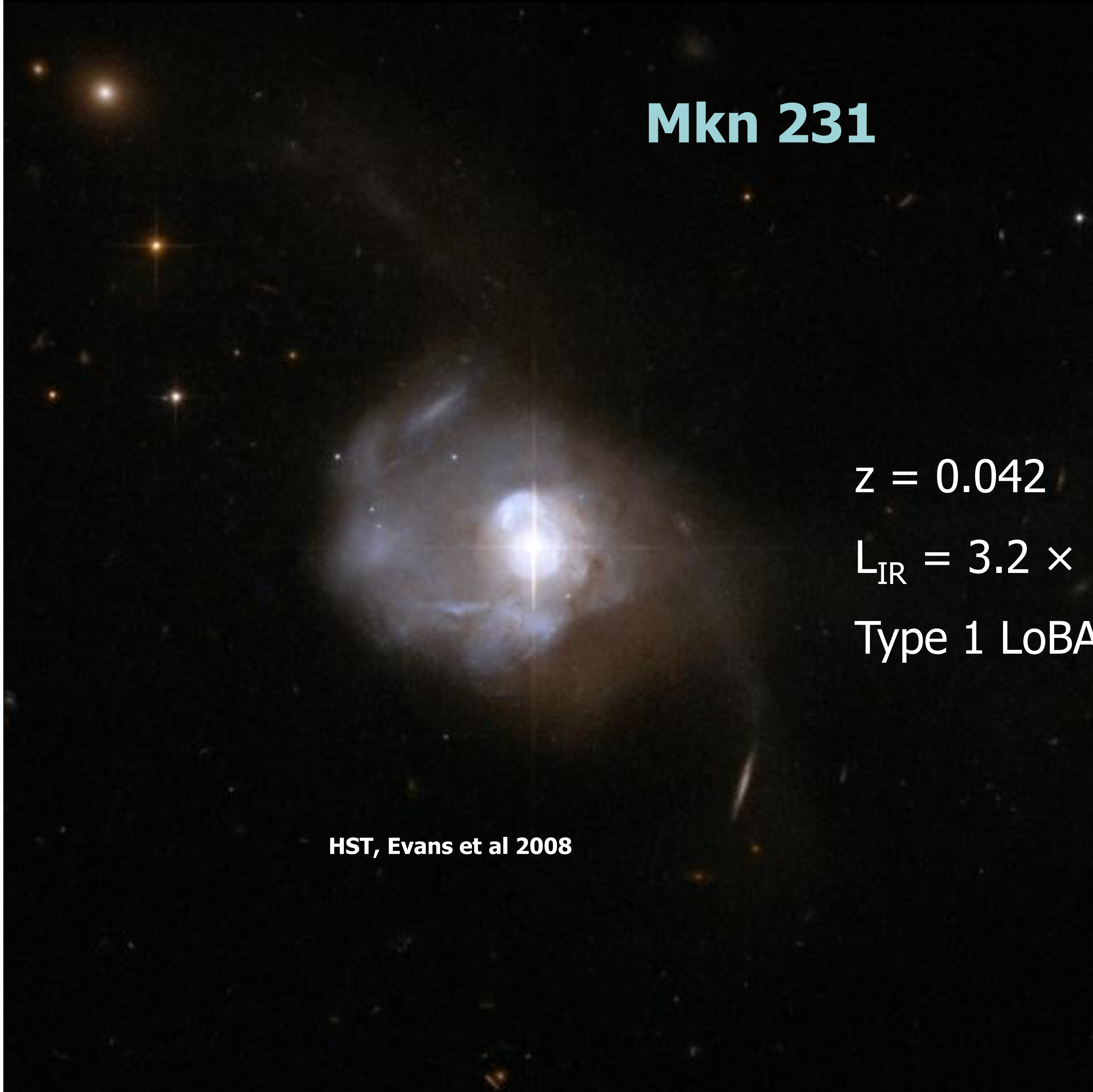




Contursi+ 2012

AGN feedback: Herschel (molecular outflows)

Mkn 231



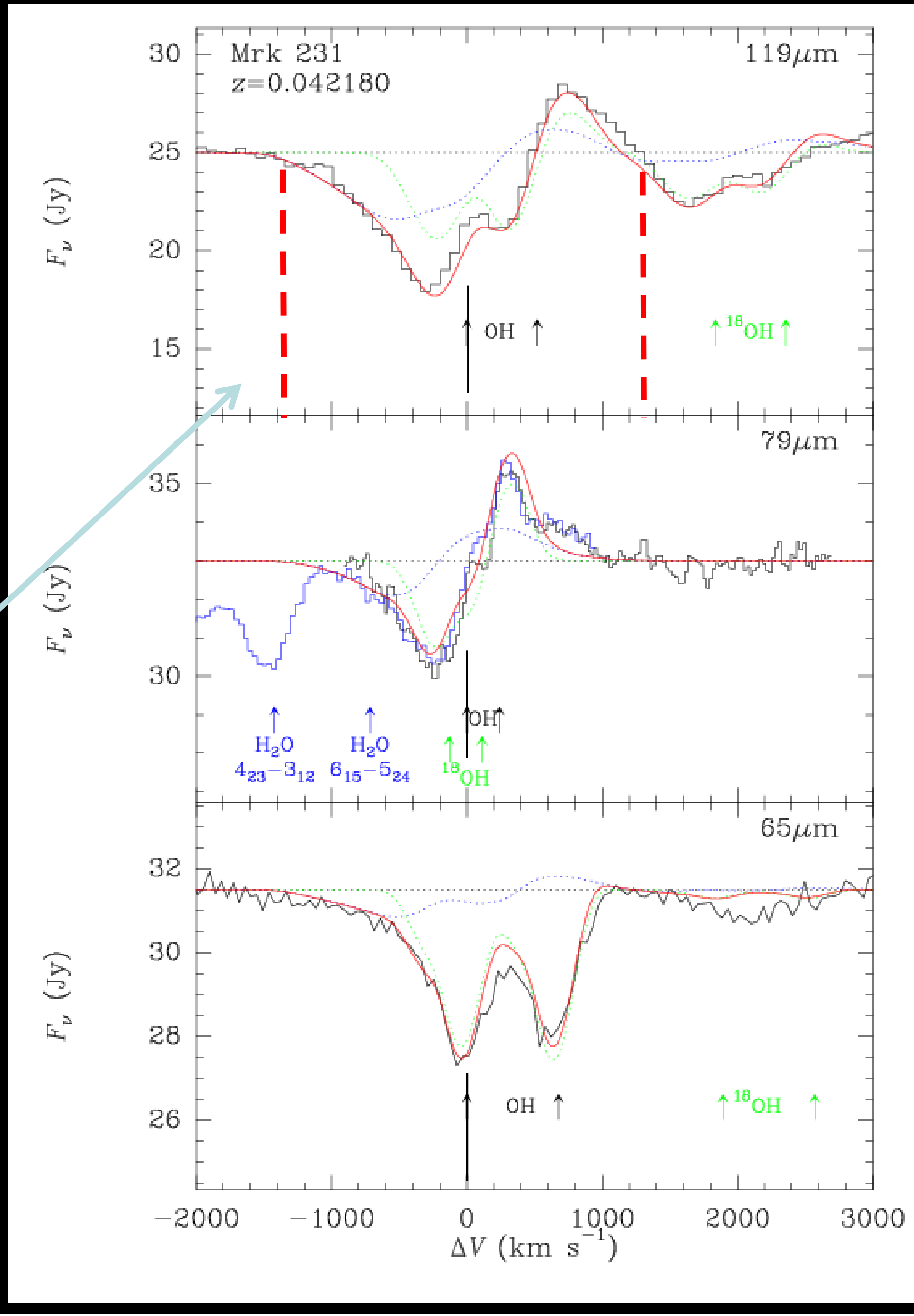
HST, Evans et al 2008

$z = 0.042$

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

Type 1 LoBAL AGN

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

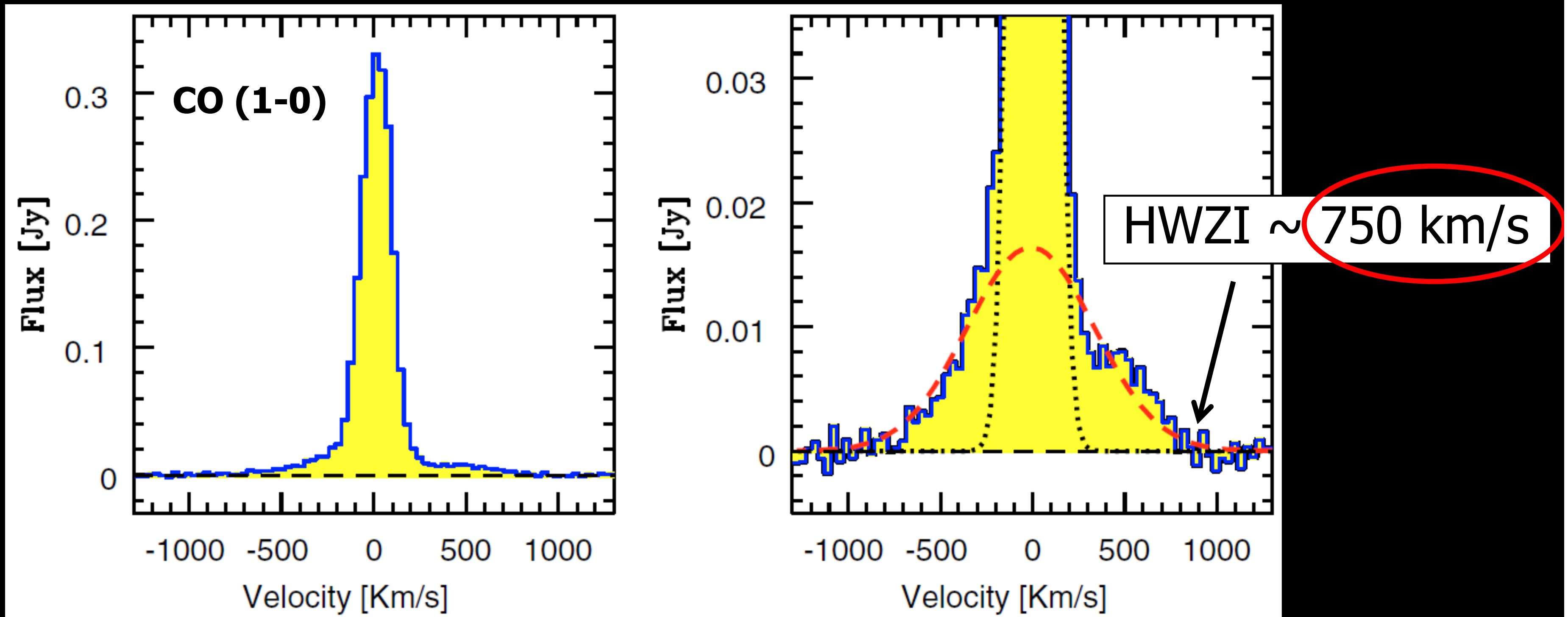
mechanical energy: ≥ 10^{56} ergs

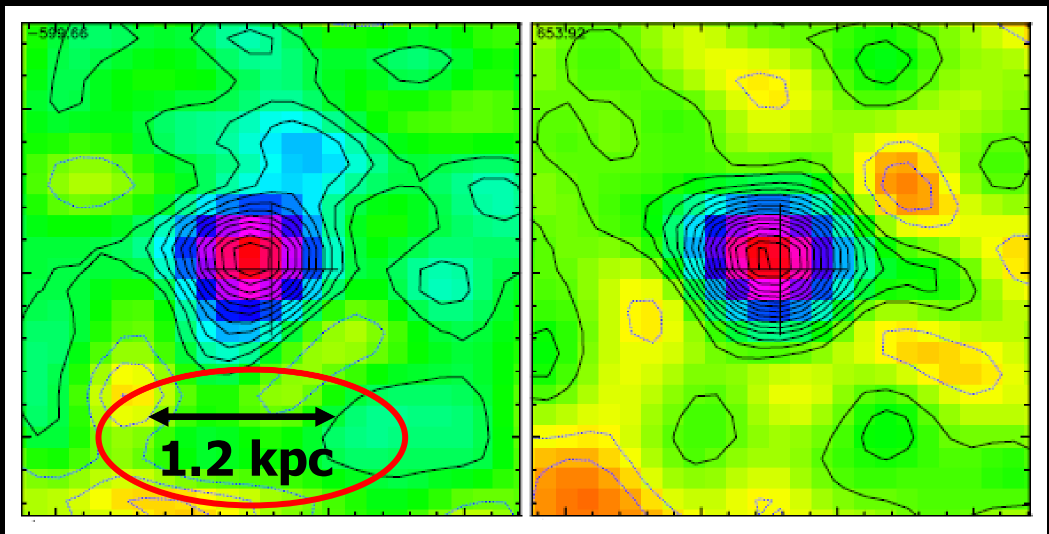
$$T = \frac{1}{2} M_{\rm gas} v^2$$

mechanical luminosity: ≥ 1% L_{IR}

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

Mrk 231 – CO Outflow

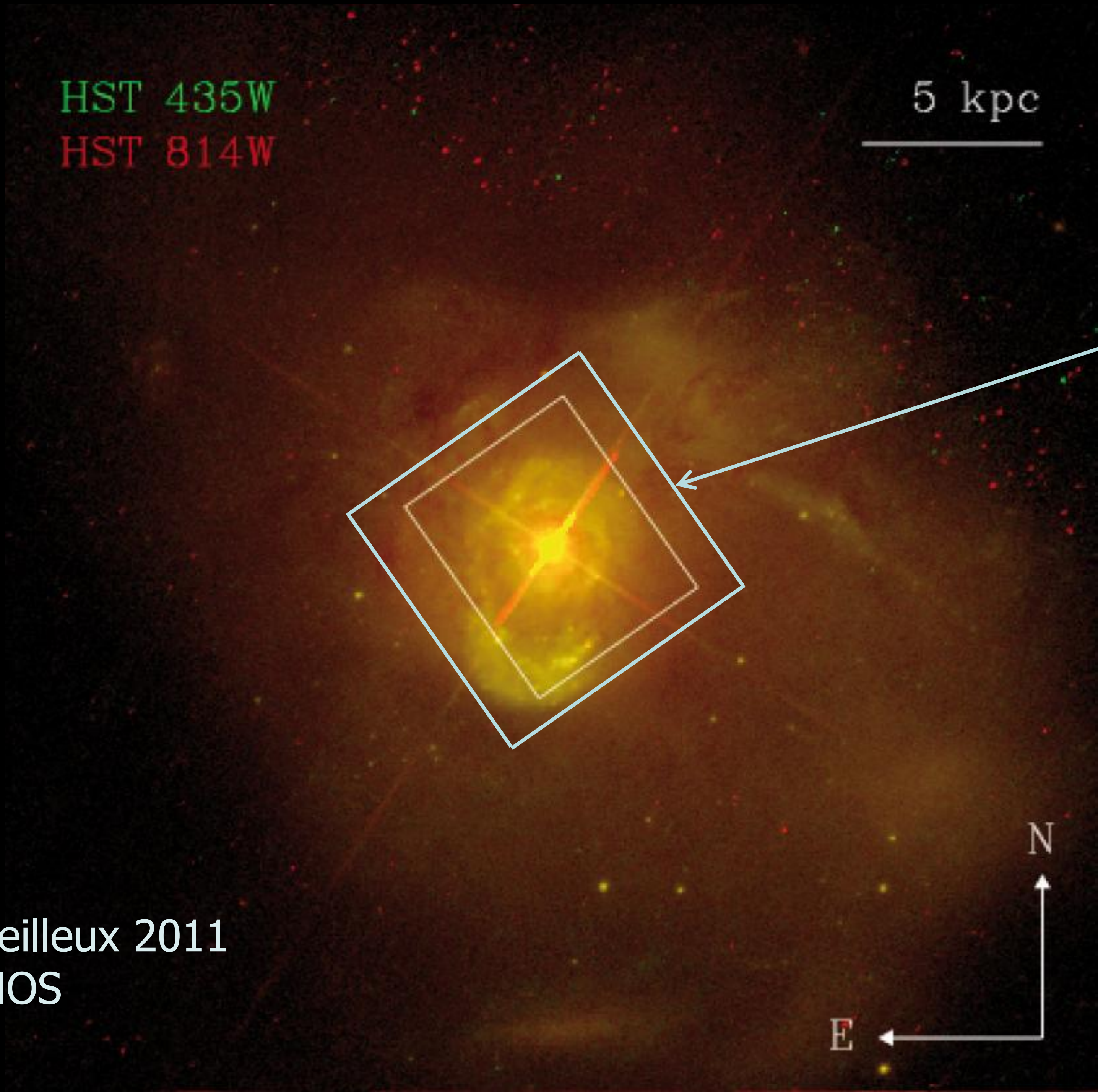




Feruglio+2010

outflow mass of 5.8 x 10^8 $M_\odot$
outflow rate of $\gtrsim$ 700 $M_\odot$/yr

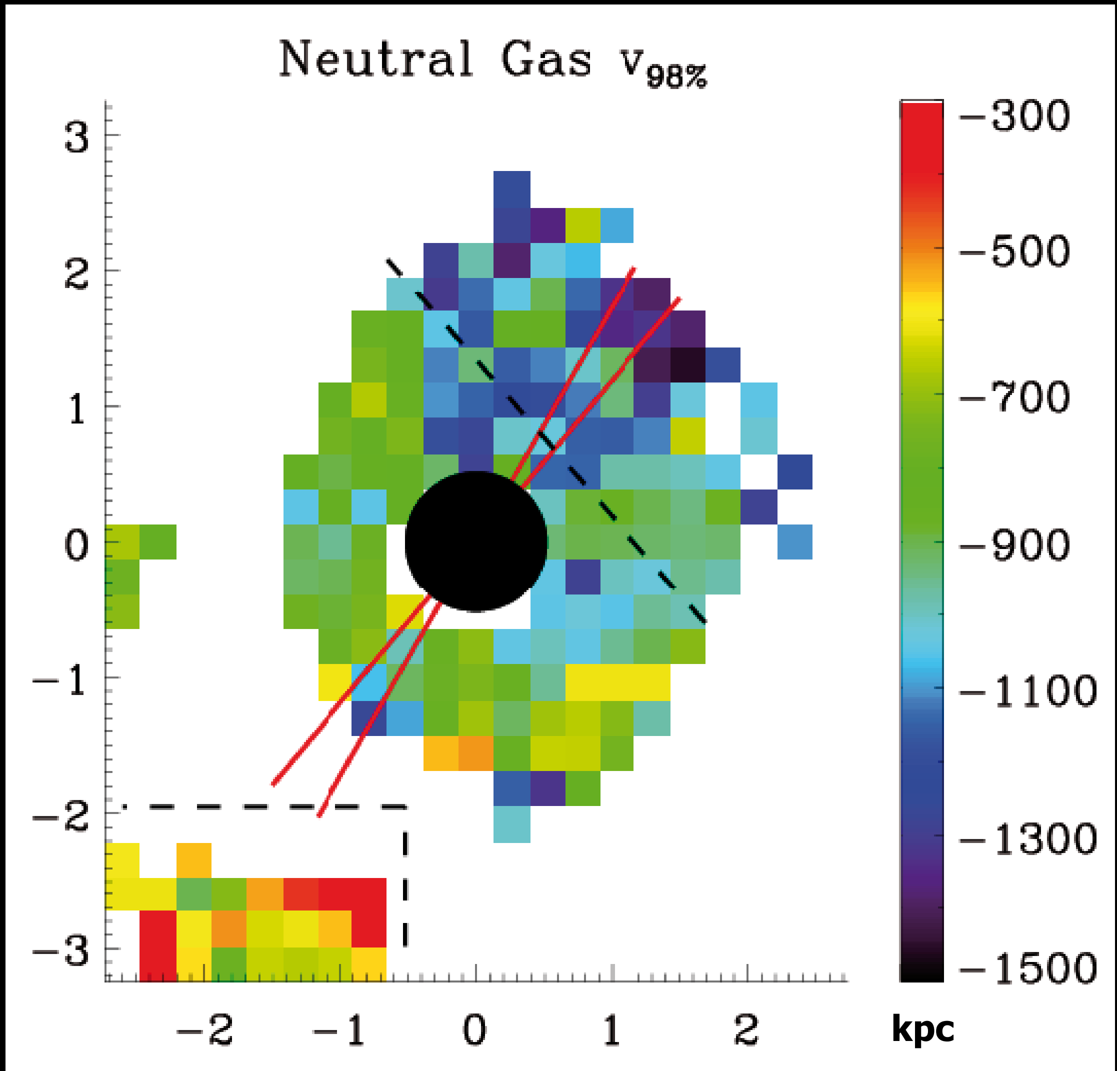
Mrk 231 – Na I D Outflow



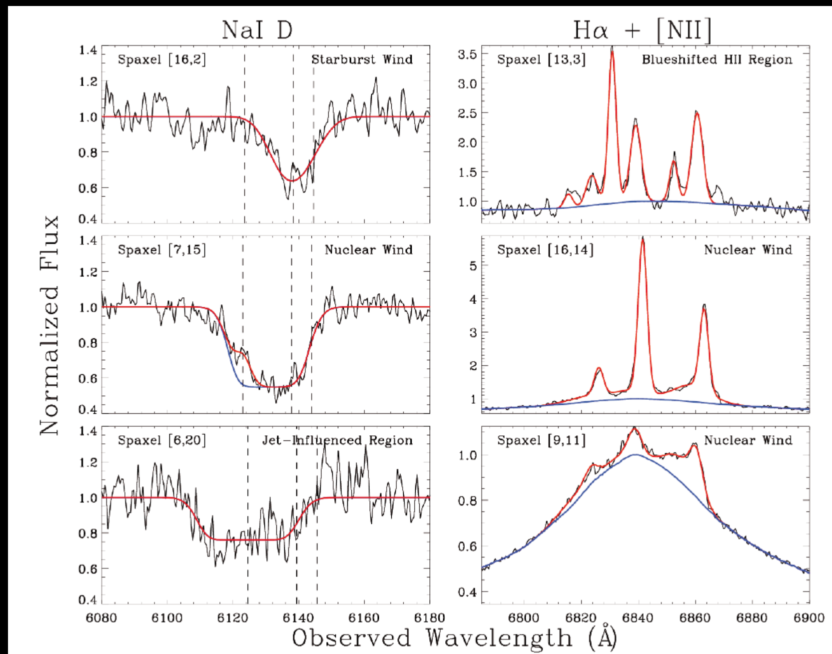
Pacs
spaxel

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

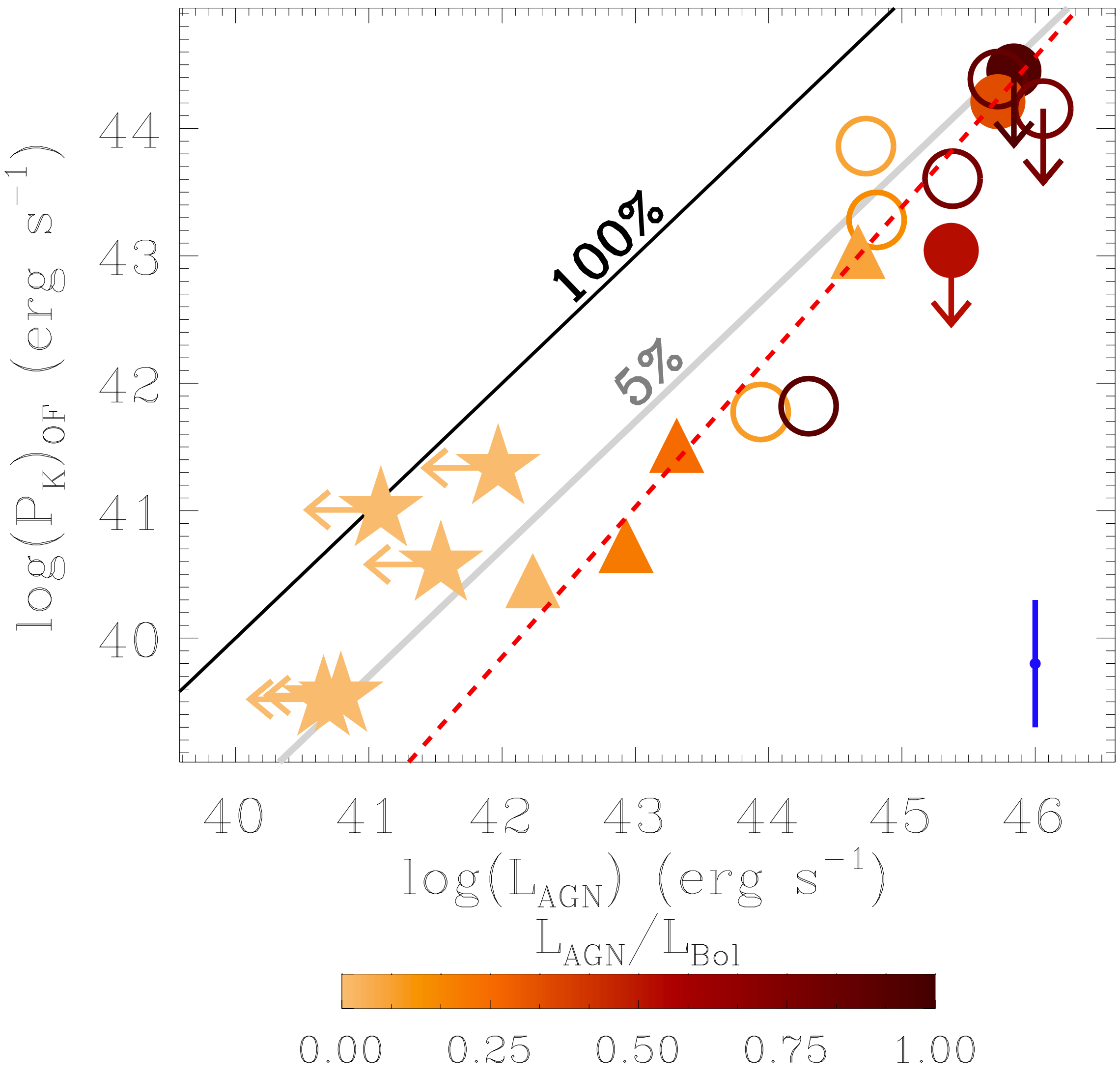


Fig. 12. Correlation between the kinetic power of the outflow and the AGN bolometric luminosity. Symbols and colour-coding as in Fig. 8. The grey line represents the theoretical expectation of models of AGN feedback, for which $P_{\mathrm{K,OF}} = 5\% L_{\mathrm{AGN}}$. The red dashed line represents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

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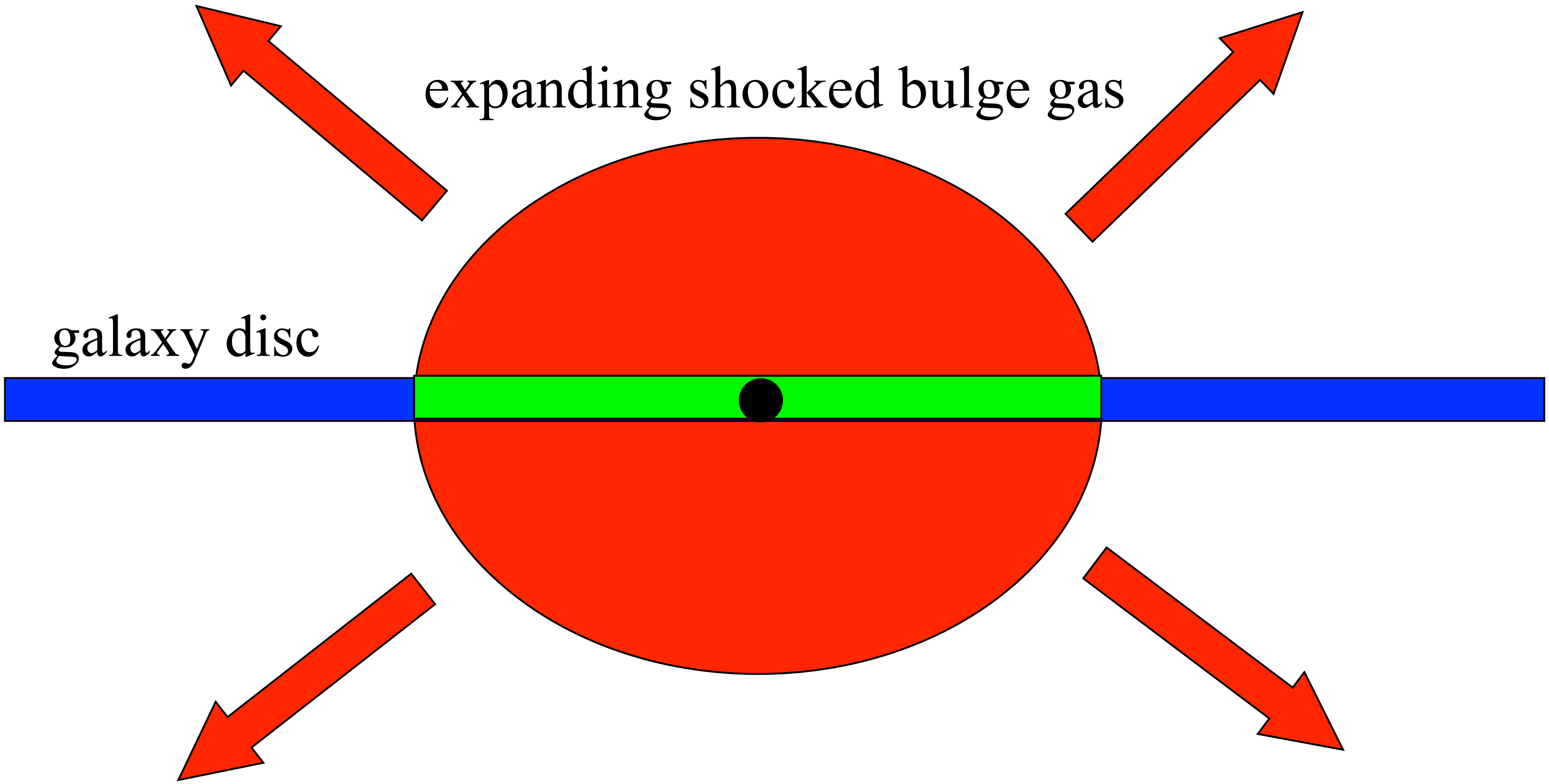
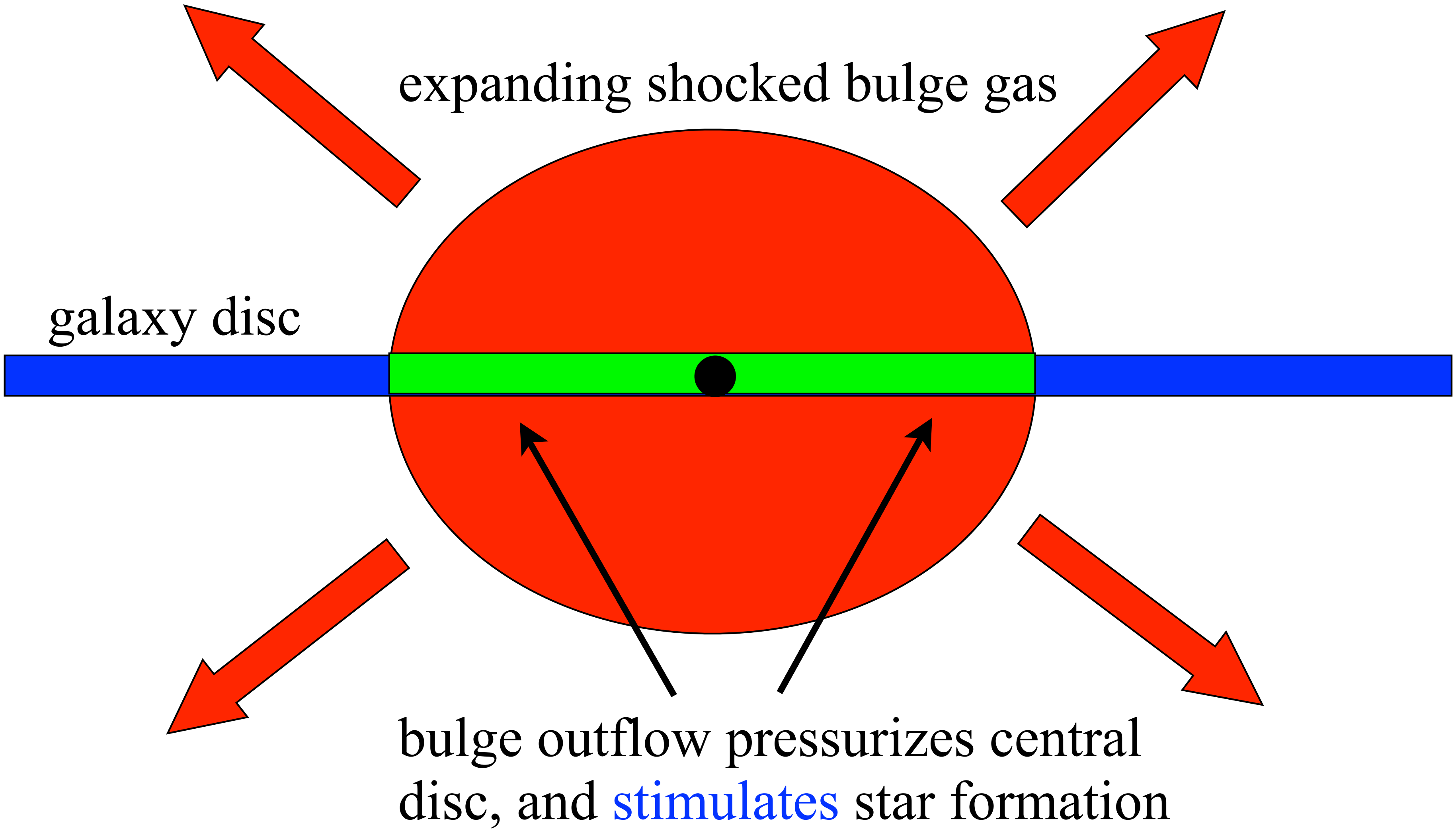
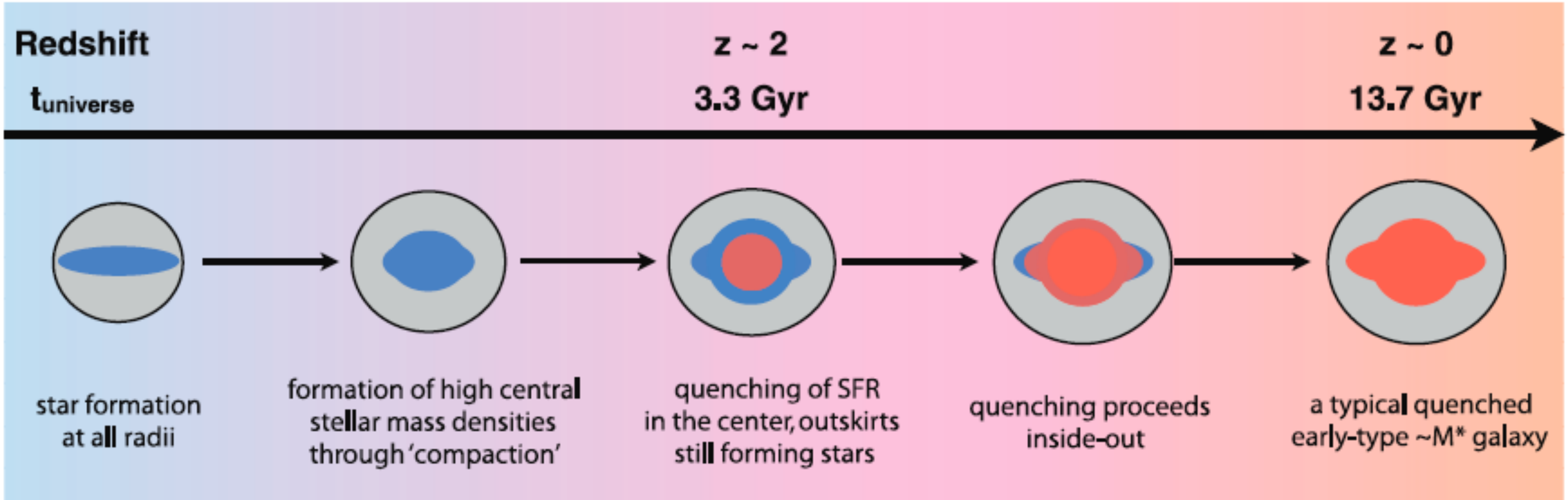
spirals: outflow pressure => star formation in disc



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

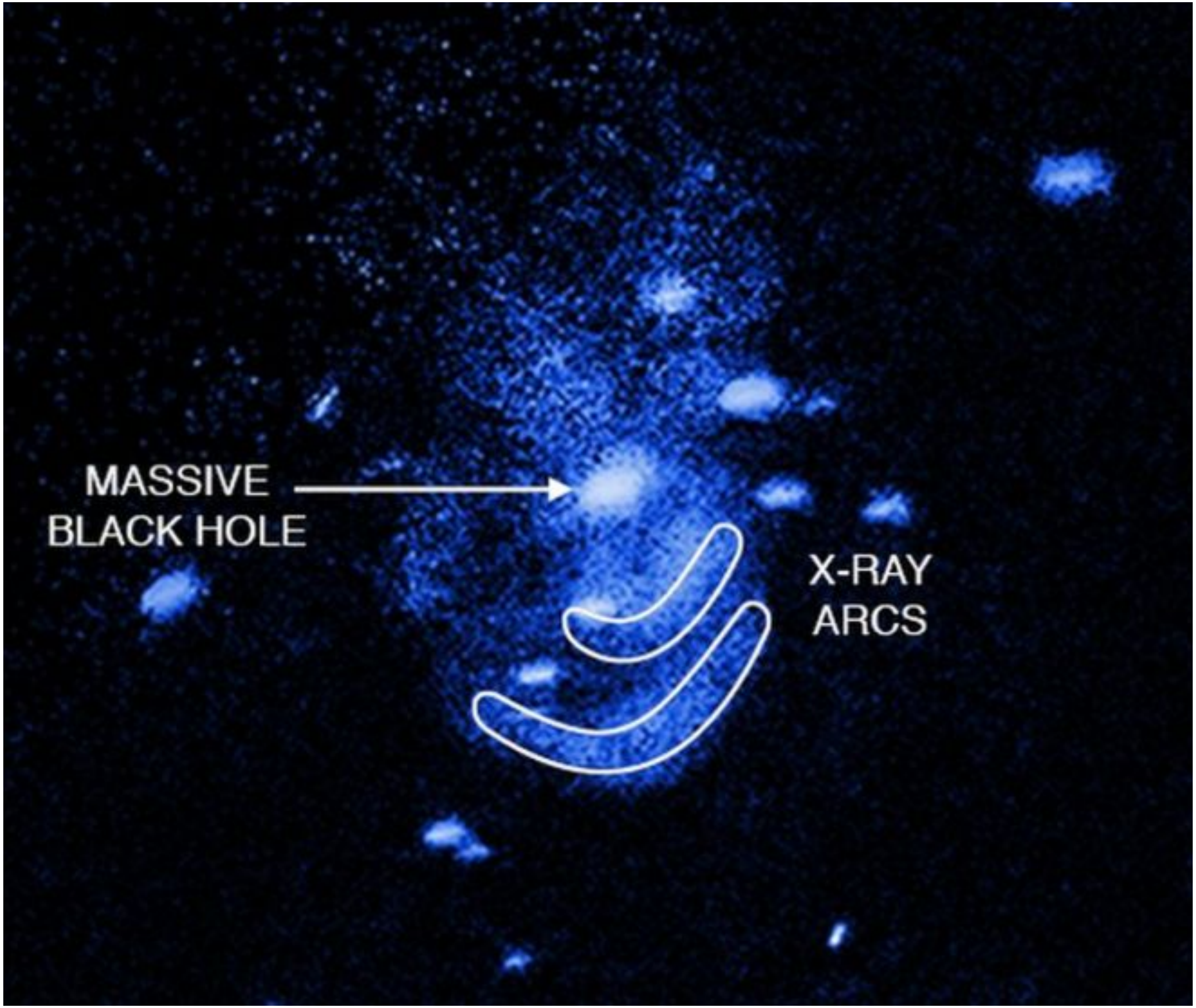
$$M_d \lesssim \frac{H}{R} M_{\rm BH} \simeq 10^{-3} M_{\rm BH}$$

so characteristic variation (`flicker') timescale is

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

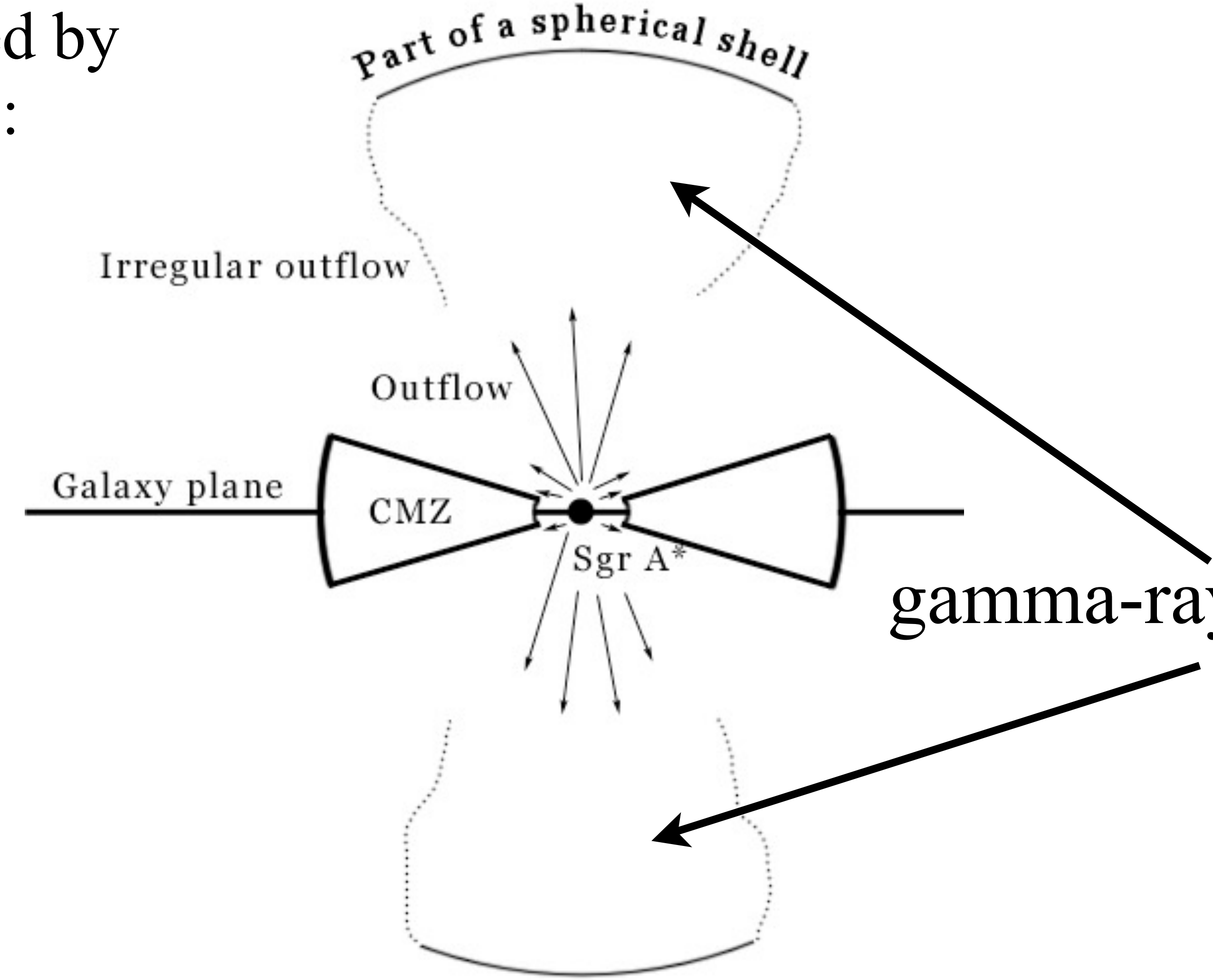
duty cycle $\lesssim 10^8\,{\rm yr}$ (most galaxies are not AGN, but all have SMBH)
(K & Pringle, 2006; K & Nixon 2015; Schawinski + 15)

progress of outflow may be slower than measured velocity



(Schlegel et al., 2016)

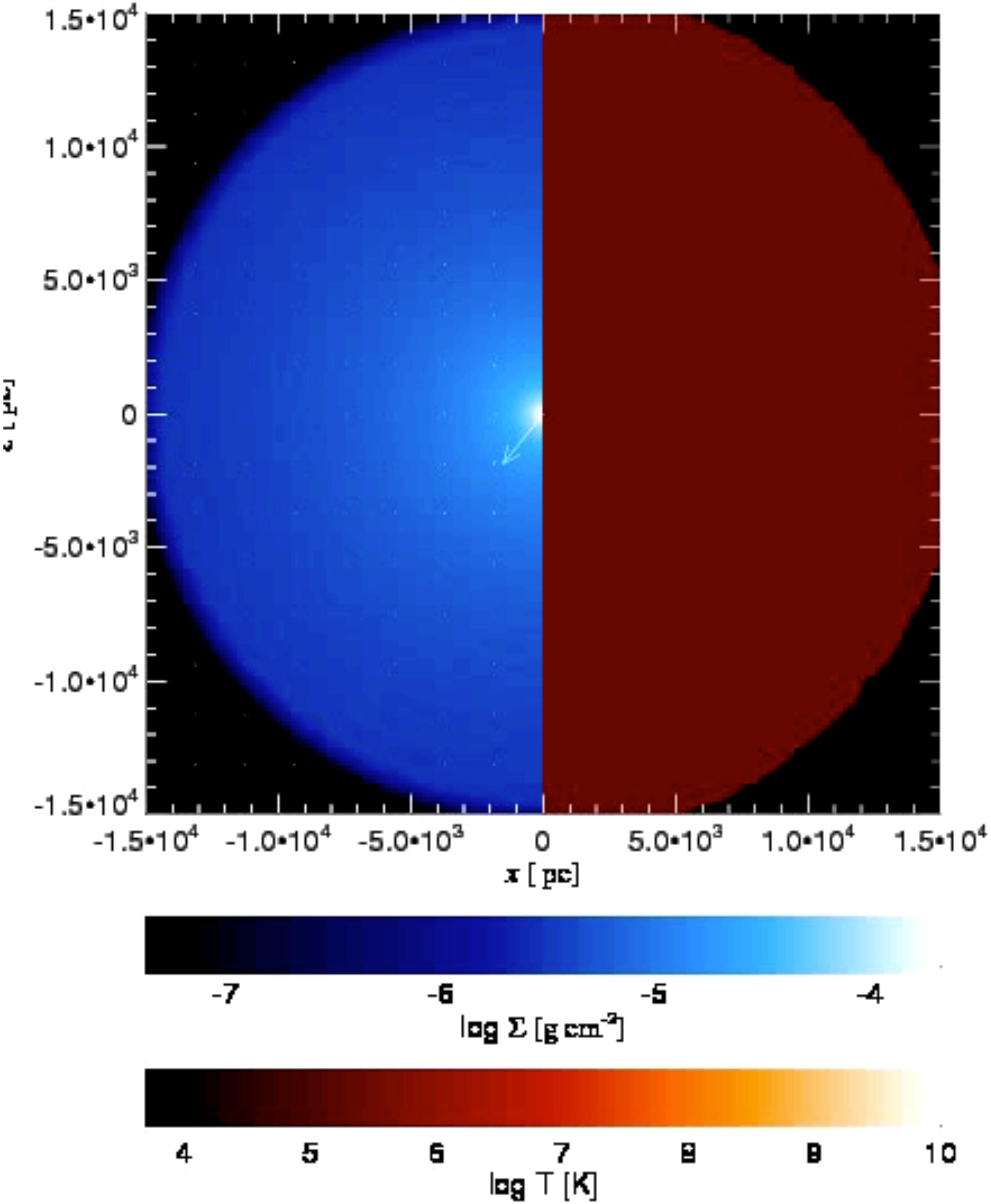
outflow blocked by
galaxy disc:



gamma-ray emission

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

Fermi gamma--ray bubbles in Milky Way?



1.5•10^4
1.0•10^4
5.0•10^3
0
-5.0•10^3
-1.0•10^4
-1.5•10^4
-1.5•10^4
-1.0•10^4
-5.0•10^3
0
5.0•10^3
1.0•10^4
1.5•10^4
x [pc]
-7
-6
-5
-4
log Σ [g cm^-2]
4
5
6
7
8
9
10
log T [K]

alternative interpretation: Fermi bubbles result from jets?

alternative interpretation: Fermi bubbles result from jets?

main problem:

no reason why jets should be symmetrical about galaxy plane

BH spin and inner disc do not know about galaxy plane

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

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

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

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

the $M - M_b$ relation is `acausal' - M, M_b follow *parallel* feedback relations, but do not influence each other but note the nature of this relation:

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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

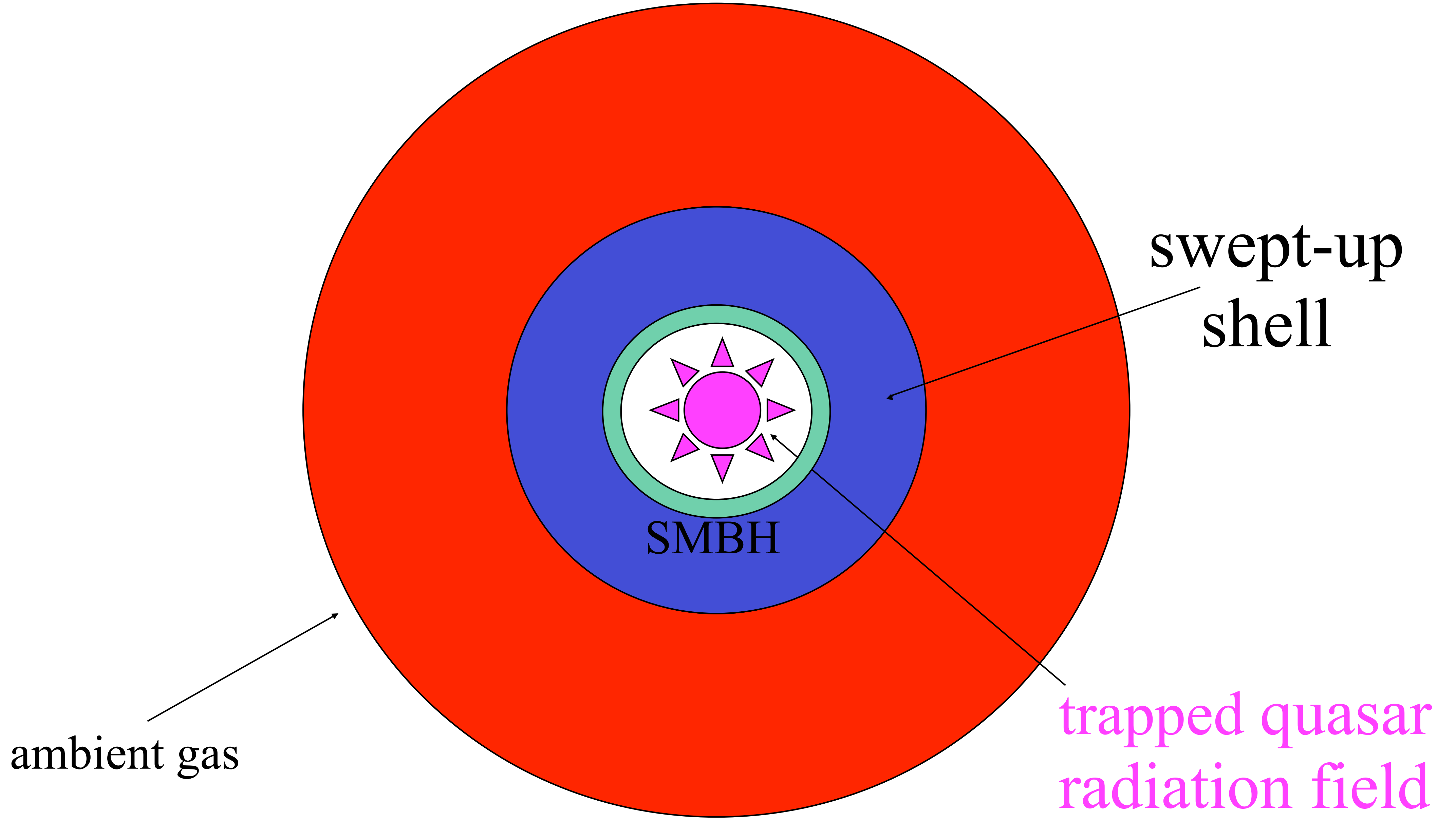
so the luminosity is trapped at small R

=> 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)

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

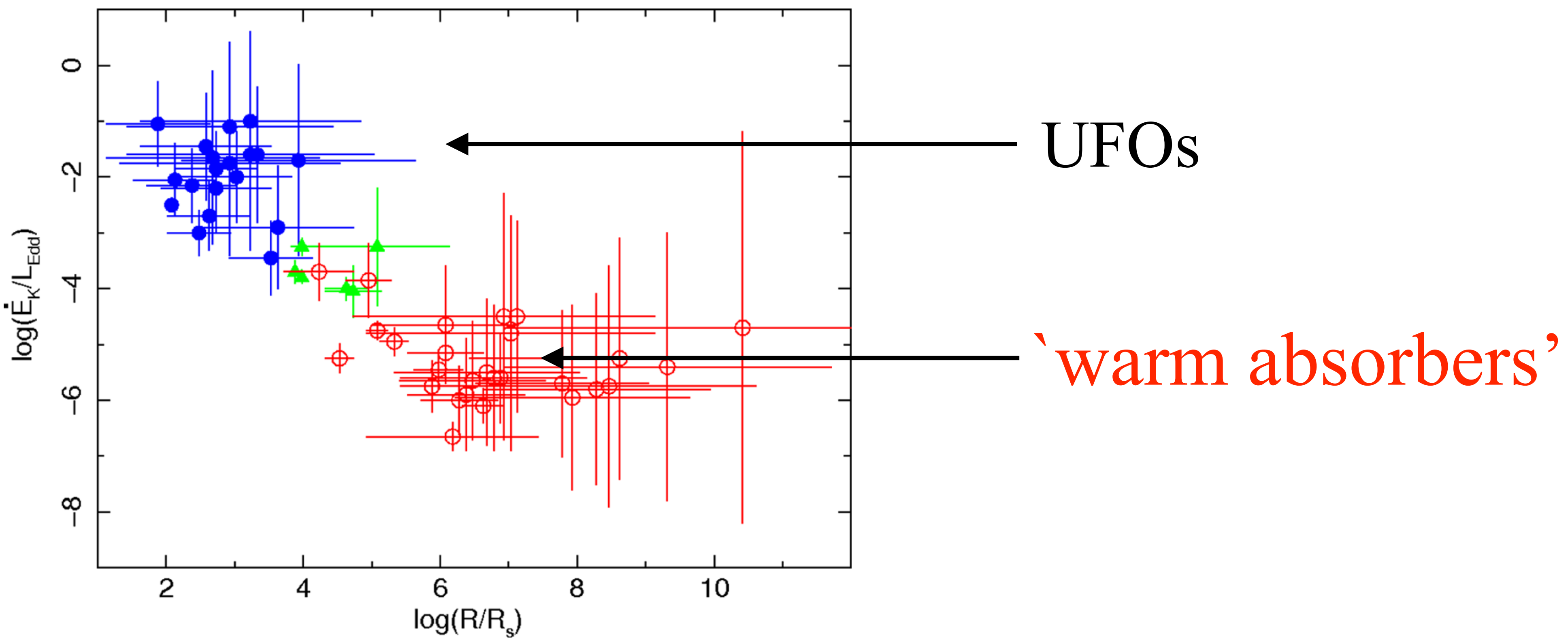
this becomes optically thin (=> radiation can escape) once R reaches

\`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'



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 for a review of outflows, M - sigma before the Saas-Fee book comes out, see

King & Pounds, Annual Reviews of Astronomy and Astrophysics, (2015) 53, 115

GW150914: the most energetic event directly observed:

$$E_{\rm GW} \simeq 3M_{\odot}c^2 \simeq 6 \times 10^{54}\,{\rm erg}\,(\simeq 10^{32}\,{\rm Mt!})$$

but close to GW detection limits: distance ~ 410 Mpc

claimed near-simultaneous electromagnetic (EM) counterpart

now generally discounted —

problem — have to make 2nd BH during merger

is a *later* EM event possible, and if so, observable?

a later event requires positional information, since we cannot use simultaneity to identify it with the GW event

must wait for upcoming GW detectors — e.g. KAGRA (Japan), etc to give better GW error boxes

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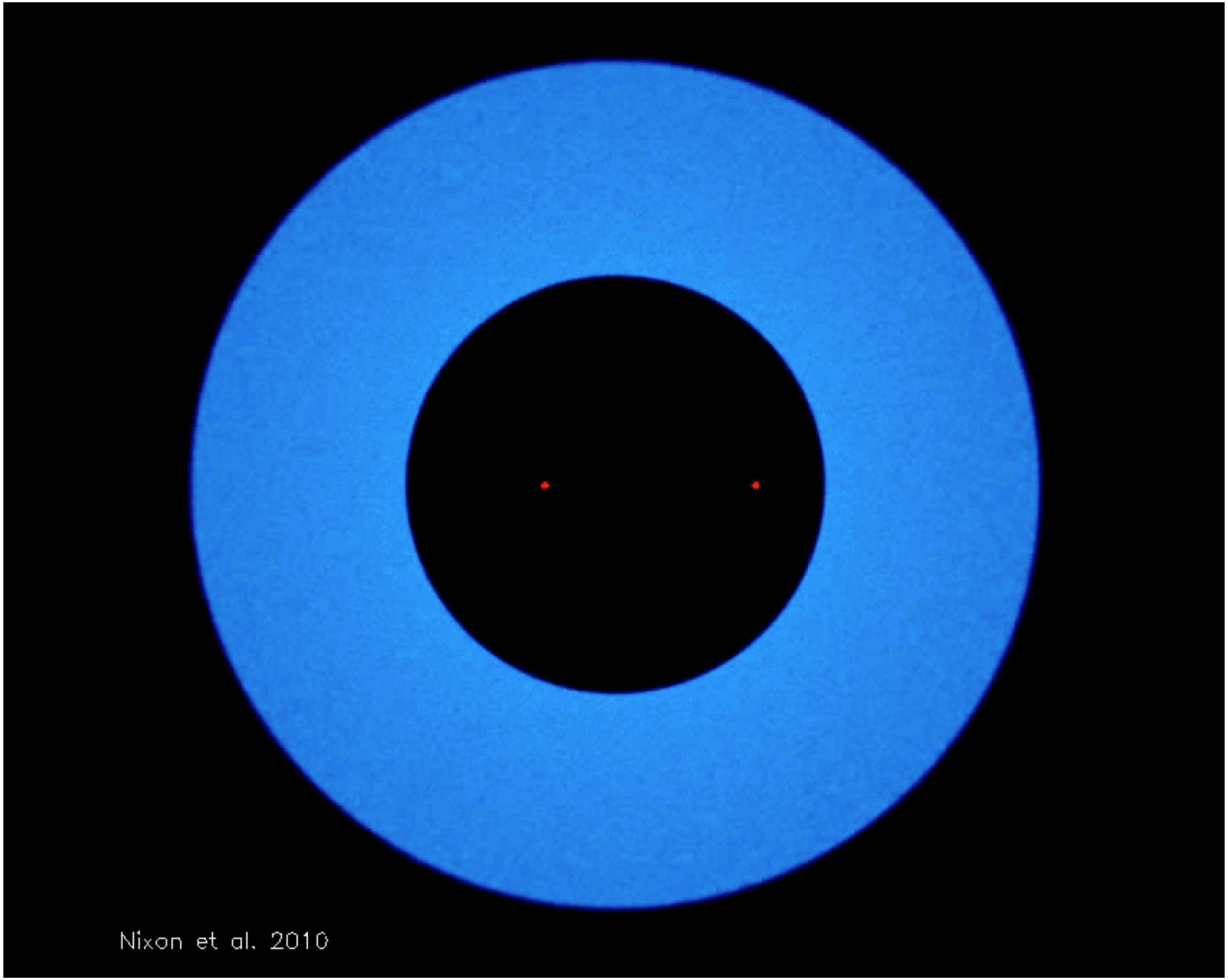
best candidate for a later event — GW event disrupts a

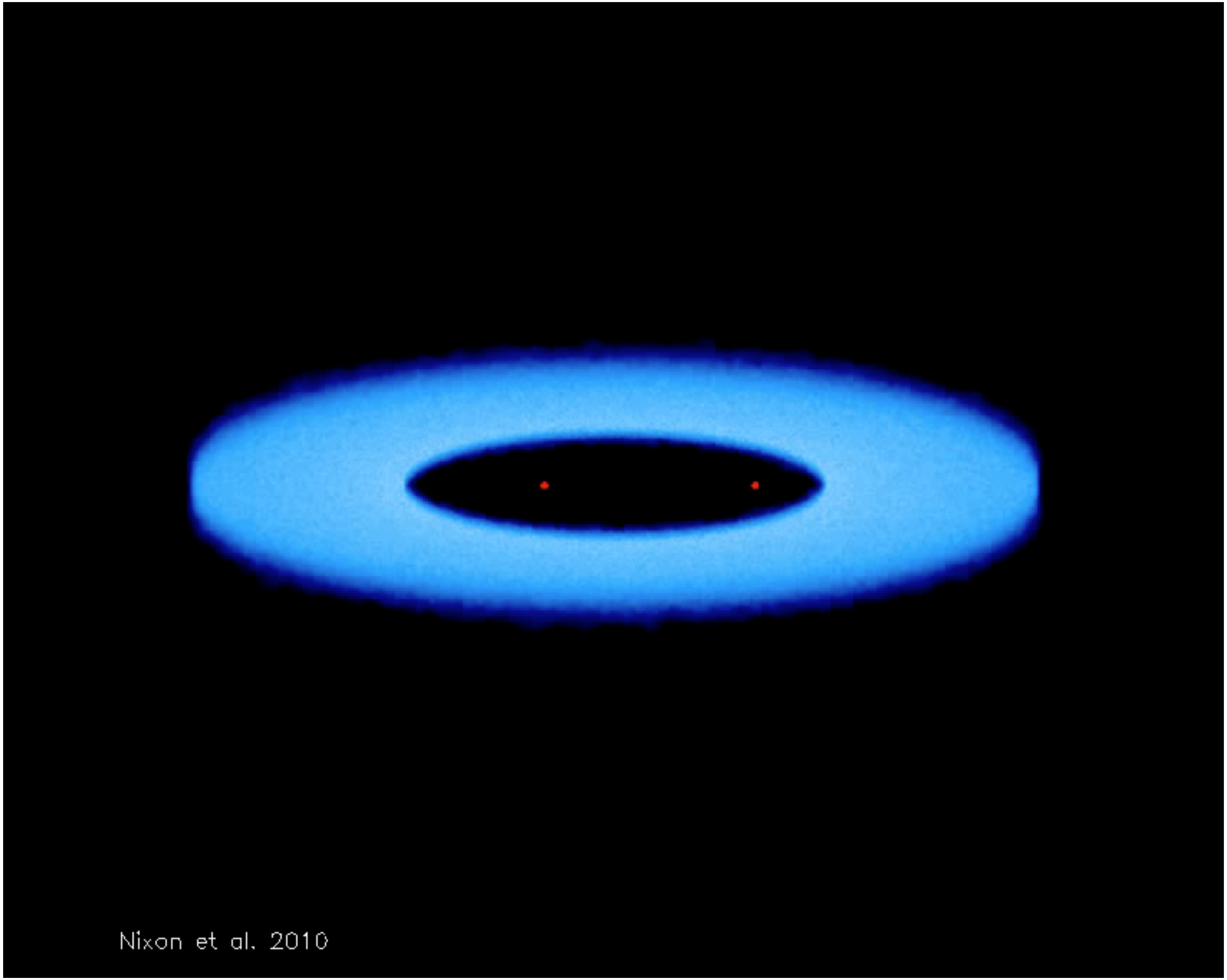
circumbinary disc

left over from the pre—merger binary evolution

cf e.g. circumbinary material around SS433 (Blundell + 2001, 2009), talk by Linial at this meeting

retrograde: Nixon et al. (2011)




Nixon et al. 2010

GW merger disturbs circumbinary disc

Rossi et al., 2010 — supermassive case

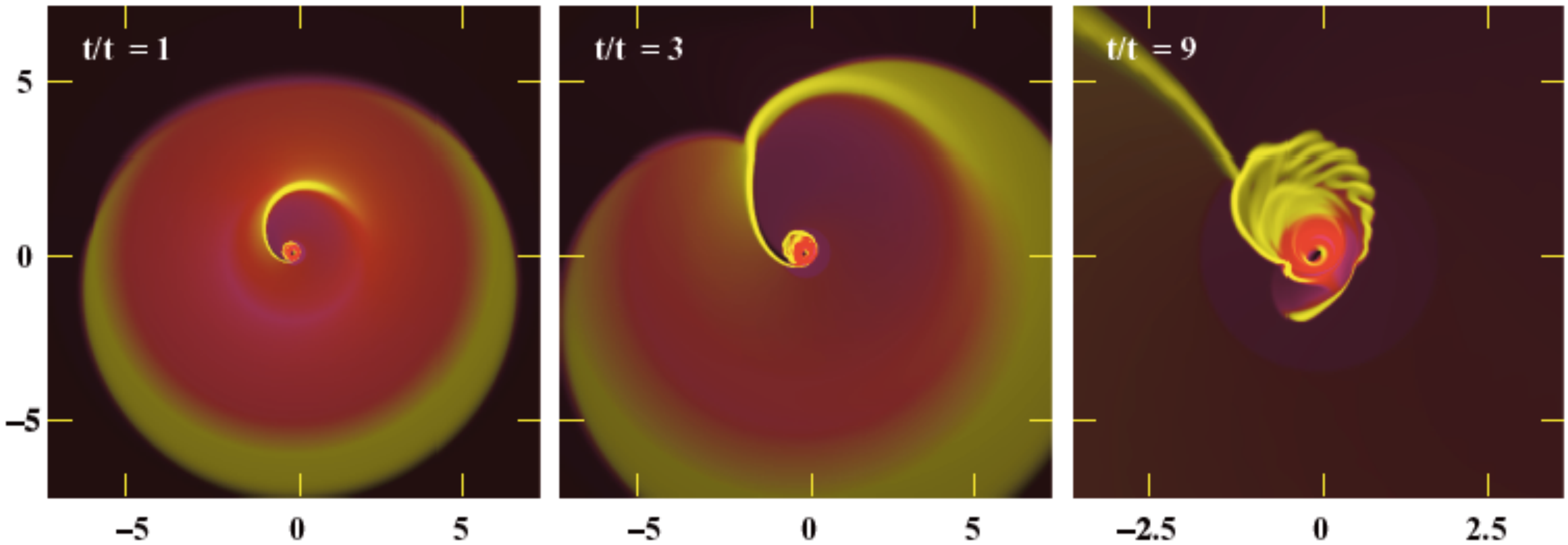


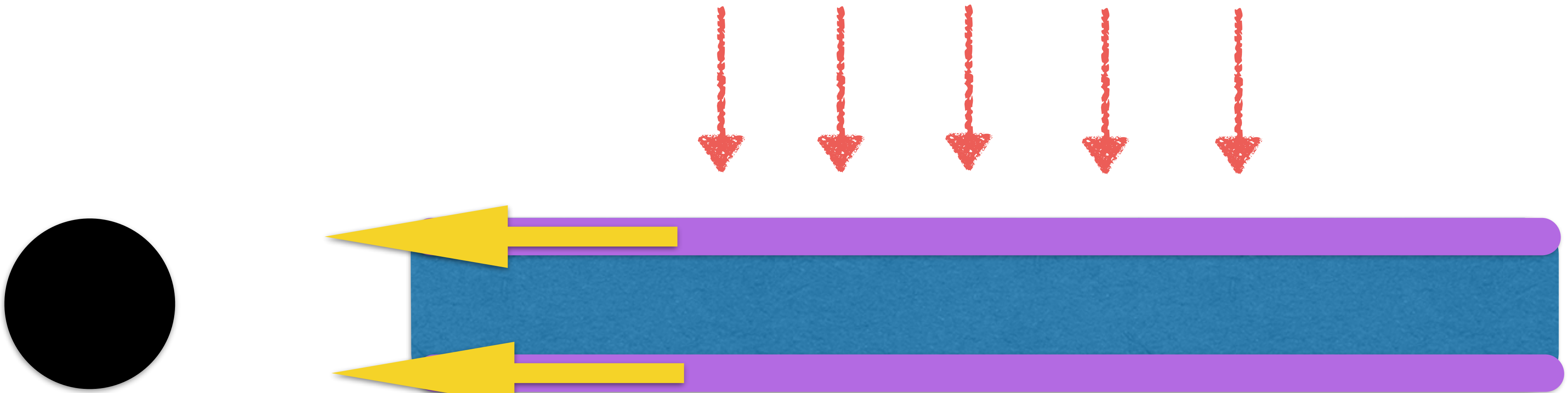
Figure 9. Rendering showing the evolution of the surface density of the disc following an in-plane kick. In this high resolution simulation, the disc extends up to $r = r_{\rm ub}$. During the peak phase of energy dissipation (left-hand panel), energy is dissipated at successively larger disc radii as an outward moving wave propagates through the gas. The outer part of the disc is unbound and escapes ballistically. After the wave reaches the outer edge of the disc (centre panel), the rate of decay of the energy dissipation rate steepens markedly. At late times (right-hand panel, spatial and colour scale adjusted to show structure in the innermost regions) low angular momentum gas continues to accrete onto the bound remnant of the original disc, releasing energy at a low level and forming a highly non-axisymmetric accretion flow.

can a circumbinary disc survive?

after 2nd BH forms, disc must be extremely cold; ~ protoplanetary

without ionization disc is `dead' — *no* motion

outer parts of protoplanetary discs have `dead zones', plus regions where local cosmic ray flux ionizes a skin, with $\alpha \simeq 10^{-2}$



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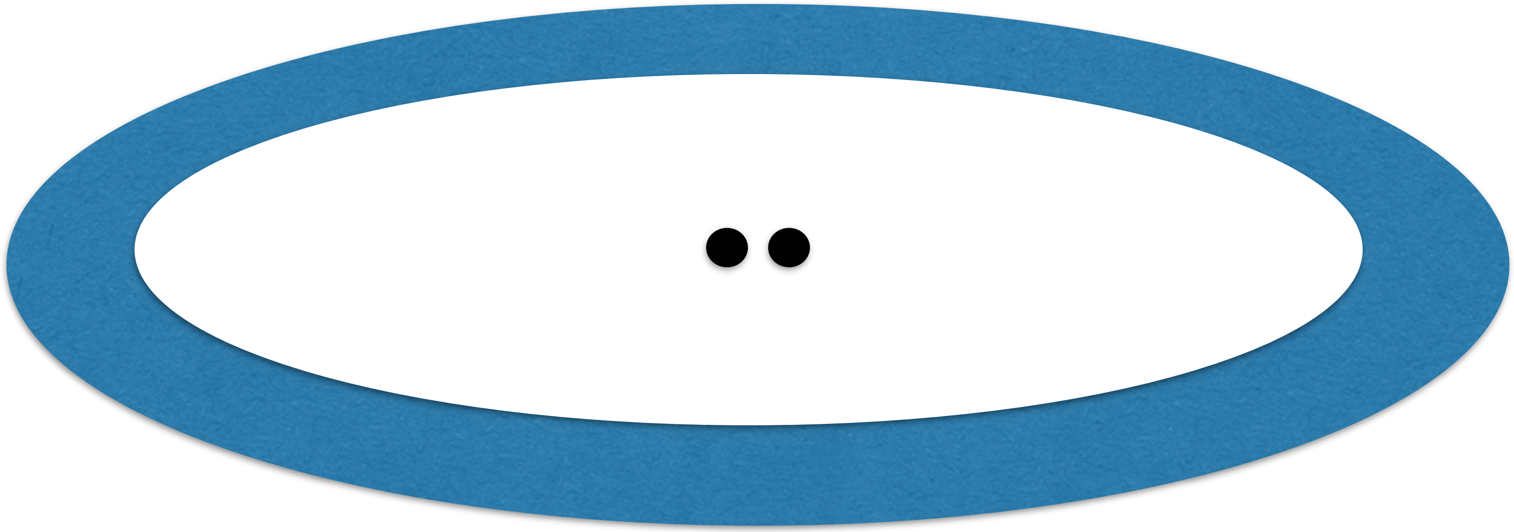
resulting $\dot{M}(R)$ decreases with R, so inward—moving gas piles up in dead zones, and resonances hold up accretion; suggests

inner radius $R_{\rm in}$ of disc where $$t_{\rm visc} = \frac{1}{\alpha}\left(\frac{R}{H}\right)^2\left(\frac{R^3}{GM}\right)^{1/2} = t_{\rm GW}$$

=> $R_{\rm in} \simeq \text{few } 10^{10}\ \rm cm$

remnant disc mass *very* uncertain: parametrize as $M_d \sim 10^{-3} M$

de Mink & King 2016



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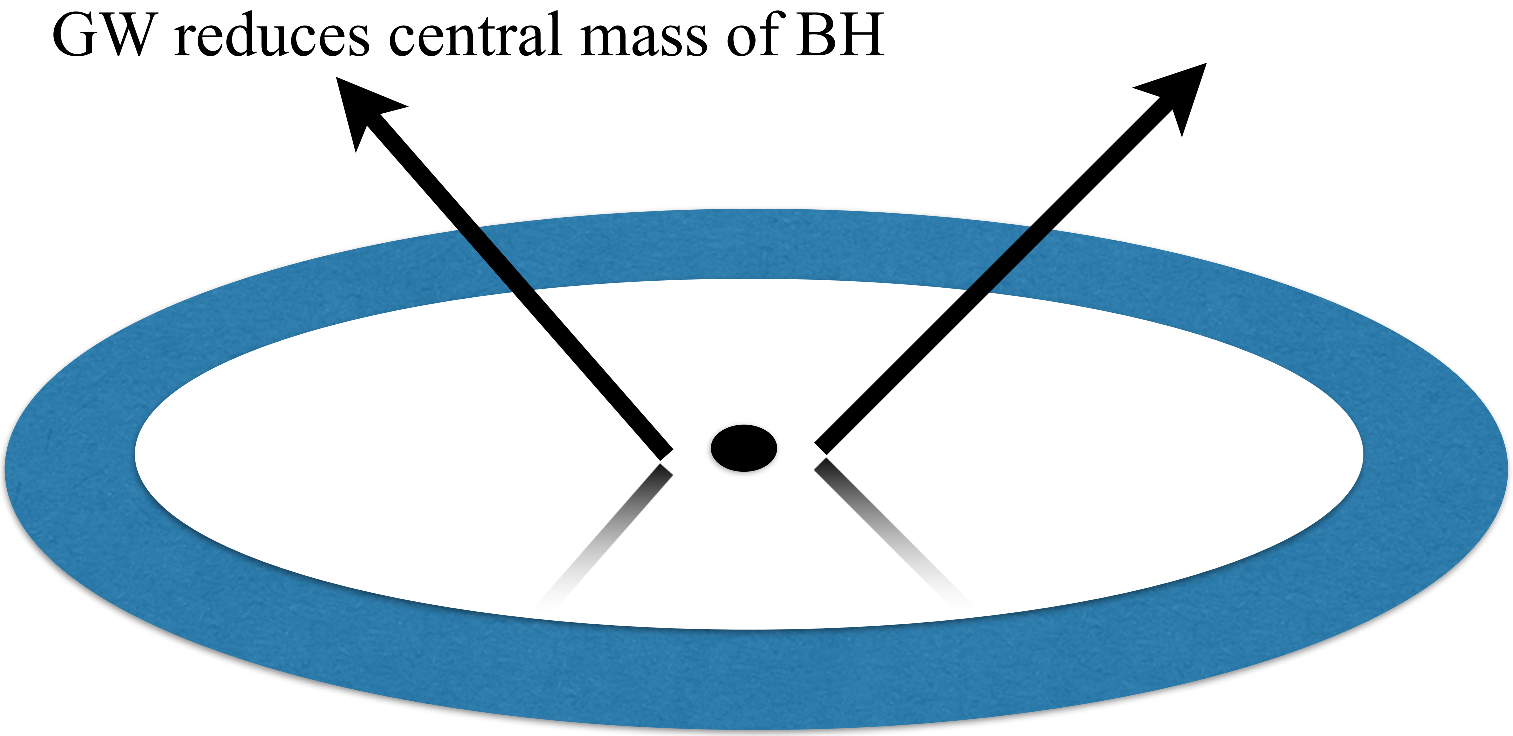
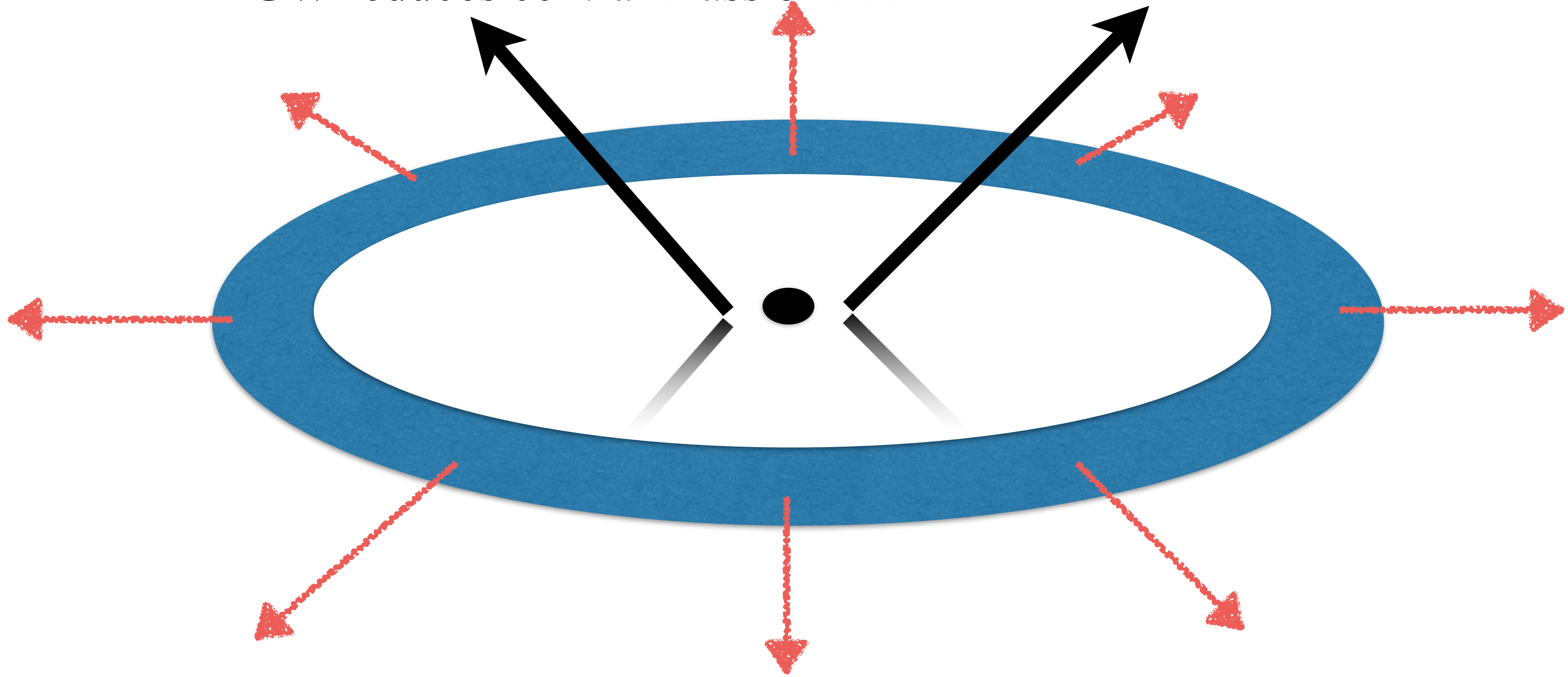


de Mink & King 2016

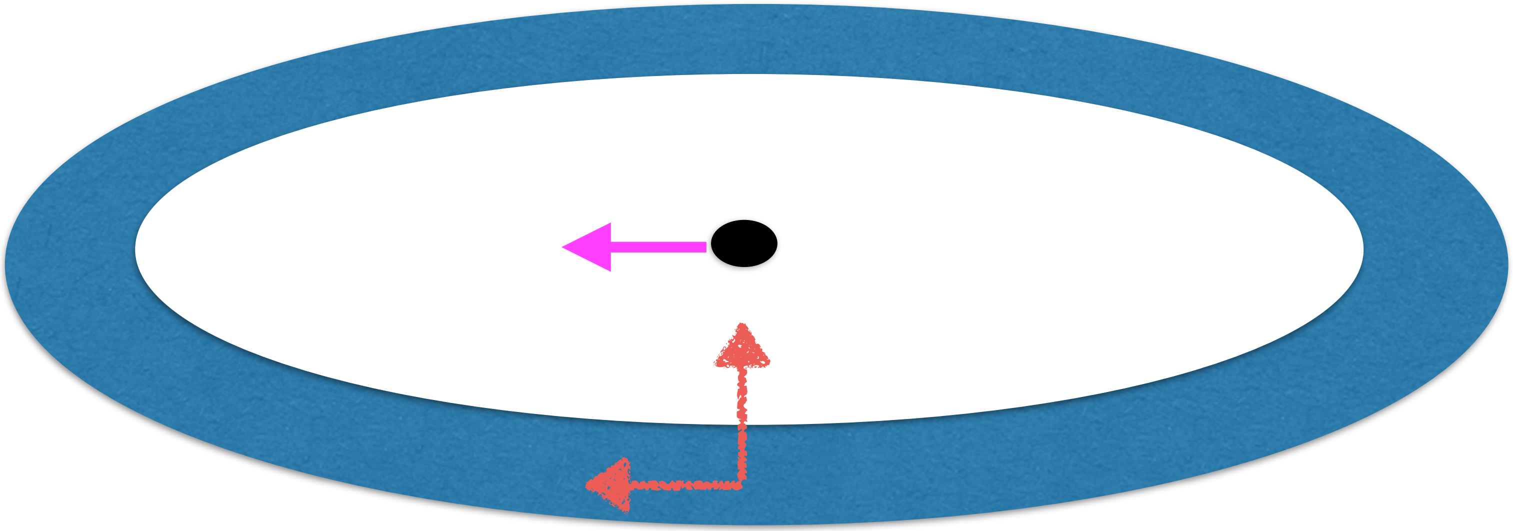
GW reduces central mass of BH



as GW passes, disc responds to mass loss by expanding;
disc orbits become eccentric and intersect => shocks

de Mink & King 2016

merged BH may acquire a kick (anisotropic GW emission)



as GW passes, disc responds to mass loss by expanding;
disc orbits become eccentric and intersect => shocks

disc responds to any *in-plane* kick v at e.g. 9 o'clock by *falling inwards* at *6* o'clock (positive disc rotation)

luminosities, temperatures, spectra, light curves

estimated luminosity

$$L_{\rm EM} \simeq 10^{42} v_3^5 \left(\frac{M_d}{10^{-3}M}\right) {\rm erg\,s^{-1}}$$

(same as for supermassive BH mergers!)

timescale

$$t \sim {\rm few}\,\frac{GM}{v^3} \sim 2.2 \left(\frac{M}{60 M_\odot v_3^3}\right)\,{\rm hr}$$

with $v_3 = v/1000\,{\rm km\,s^{-1}}$ suggest EM counterparts should be easily observab
(temperature estimates => appear in X-rays — IR),
but depend strongly on v_3: in-plane kick may give gamma-rays

[*v* is greater of kick velocity and Kepler velocity at inner disc edge]

luminosities, temperatures, spectra, light curves

mass infall from disc: $$\dot{M} = \frac{\mathrm{d}M}{\mathrm{d}R}\frac{\mathrm{d}R}{\mathrm{d}t}$$

steady disc => $$\frac{\mathrm{d}M}{\mathrm{d}R} = 2\pi R\Sigma, \quad \Sigma \sim R^{\beta}, \quad \beta \sim -0.7$$

infall time (dynamical) $$R \propto t^{2/3}$$

so $$\dot{M} \propto t^{2(1+\beta)/3-1/3} \propto t^{-0.133}$$

flat EM light curves (unlike TDEs, with $L \propto t^{-5/3}$)

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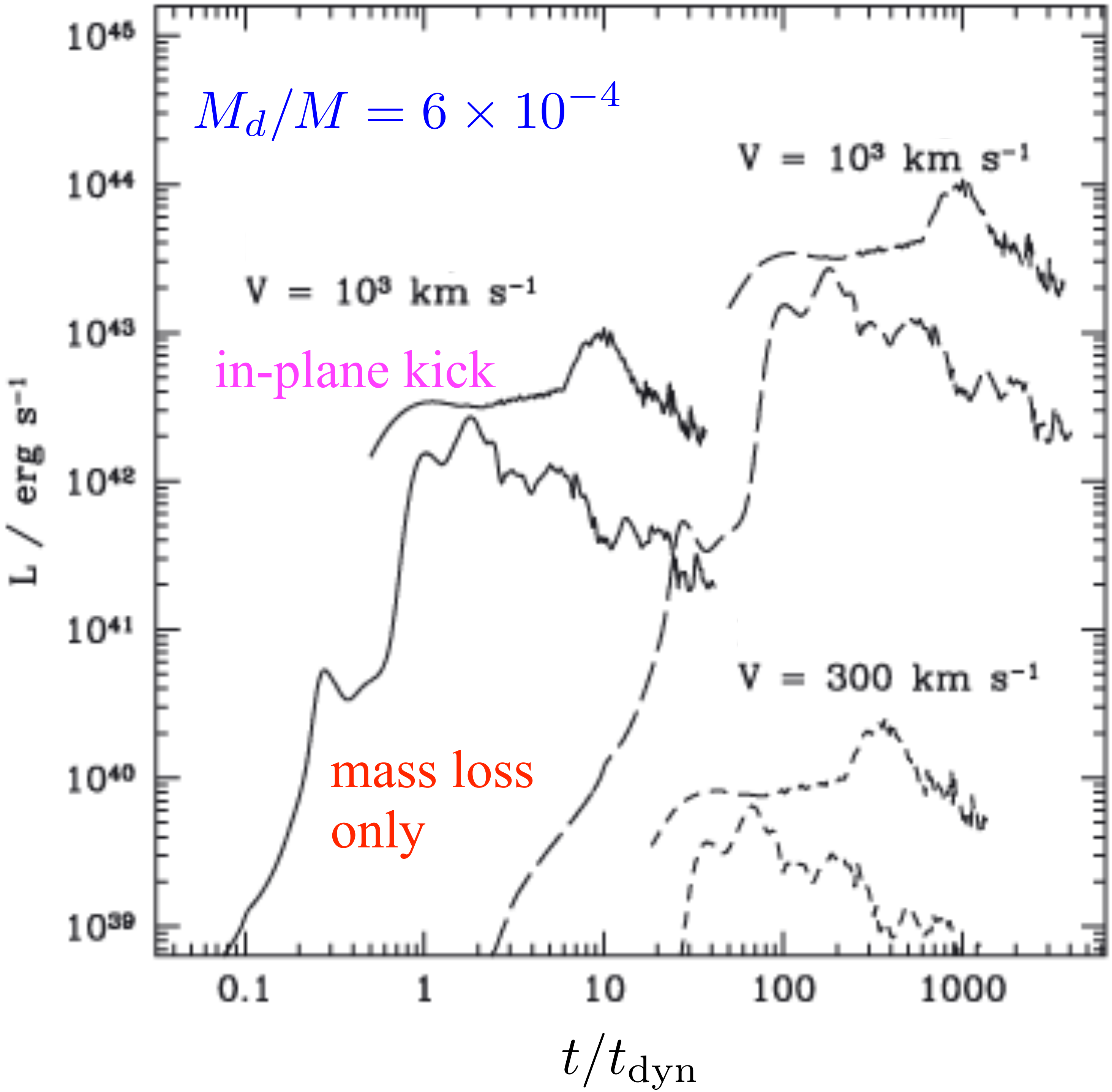
flat EM light curves (unlike TDEs, with $L \propto t^{-5/3}$)

could we detect `orphan' GW mergers?

have we already?

were some known (anomalous) GRBs/afterglows EM counterparts of GW mergers?

Rossi et al., 2010



GW 170104: afterglow of possible EM counterpart

(Stalder et al., arXiv: 1706.00175)

`right' delay and light curve……

and in same (very large!) region of the sky questions

0. were known GRBs/afterglows GW mergers?

astrophysical:

1. which (if any) binary evolution scenario applies?

2. what does this imply for spin magnitudes and directions?

3. does the circumbinary disc survive? — planets?

4. what is M_d/M ?

GR: test predictions for $\mathbf{v}(\mathrm{BH\,spins})$?