WHAT CAN TIDAL DISRUPTION EVENTS TEACH US ABOUT BLACK HOLE ACCRETION?

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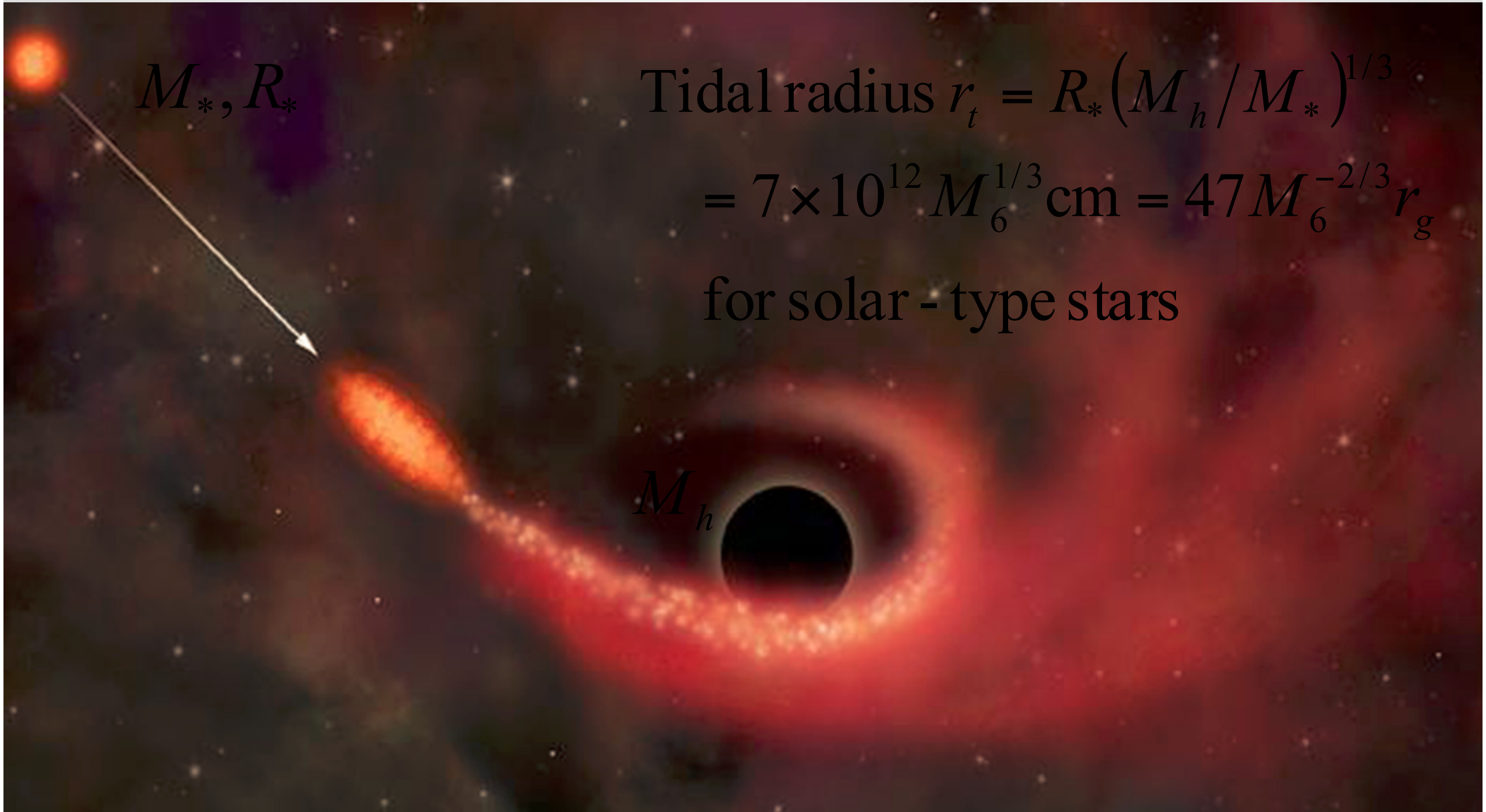
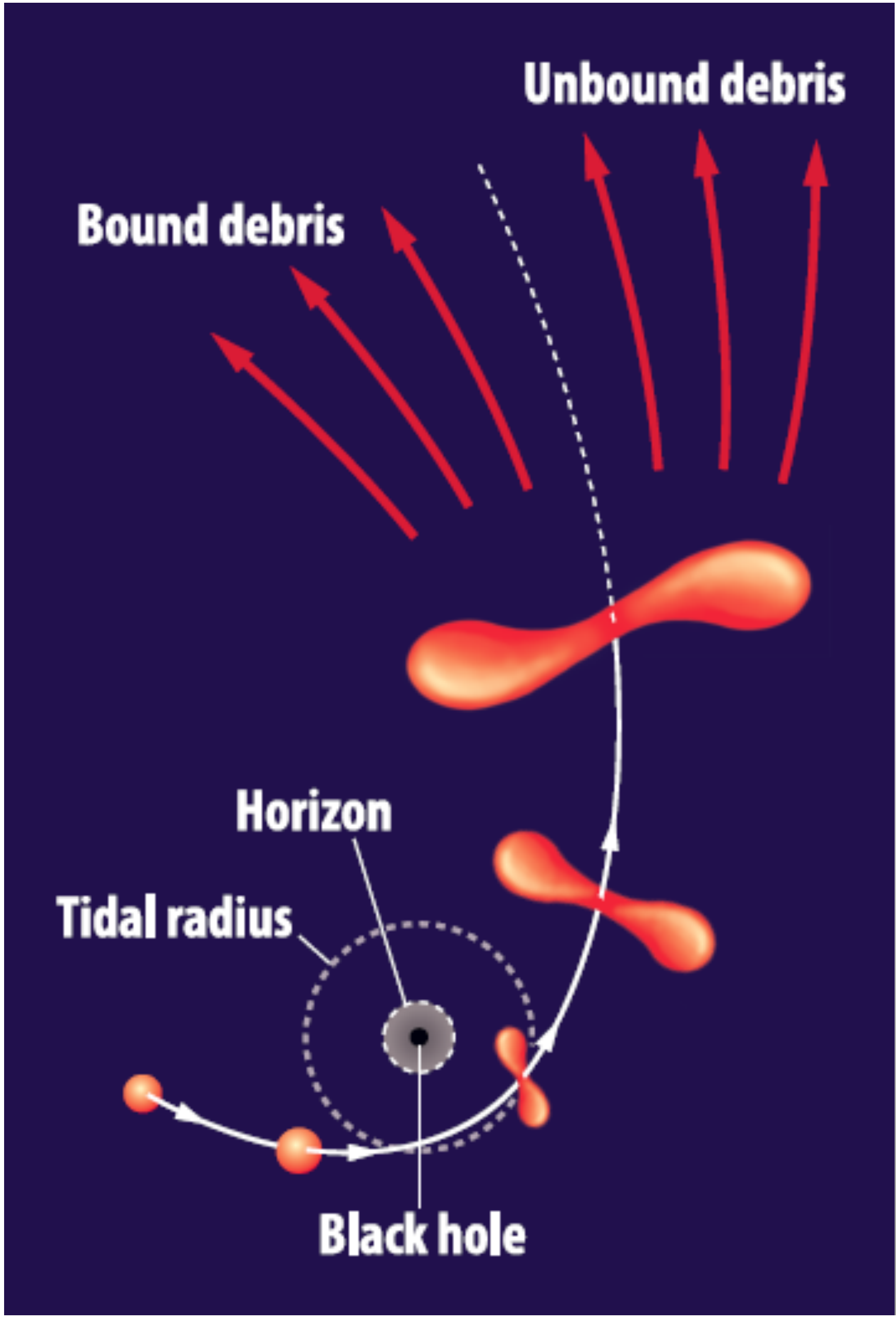
Tidal Disruption Event



$$\text{Tidal radius } r_t = R_* \left(M_h / M_*\right)^{1/3}$$
$$= 7\times10^{12} M_6^{1/3}\,\text{cm} = 47 M_6^{-2/3} r_g$$
for solar - type stars

A star ventures inside the tidal radius of a black hole and is torn apart



Tidal forces …

… unbind ~half the debris

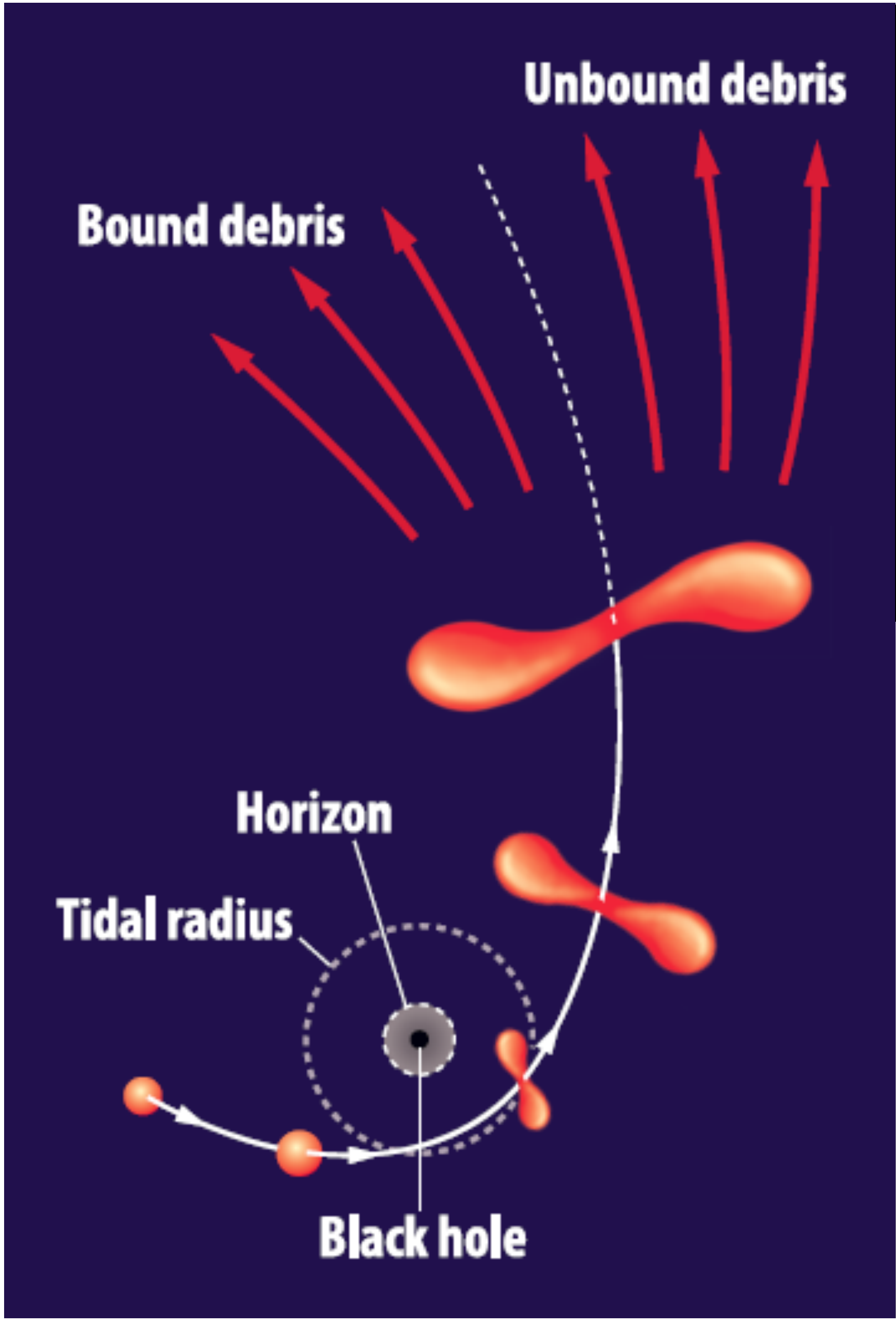
… throw the other half into highly eccentric orbits

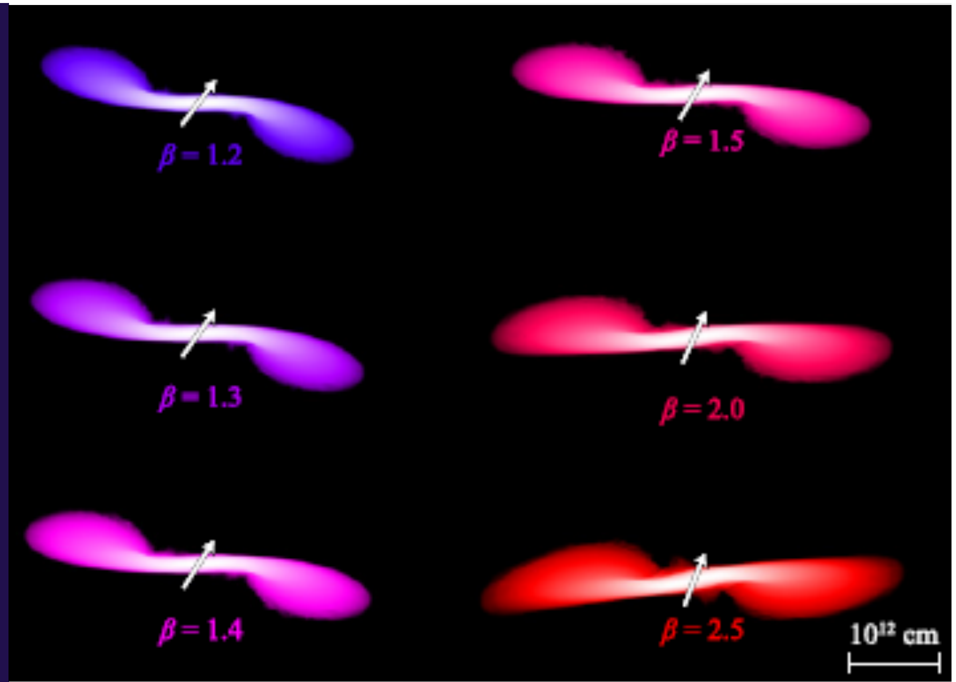
Semi-major axis:

$$r_i \geq \frac{r_t}{2}\left(M_h/M_*\right)^{1/3}$$

$$= 4\times10^{14} M_6^{2/3}\mathrm{cm}$$

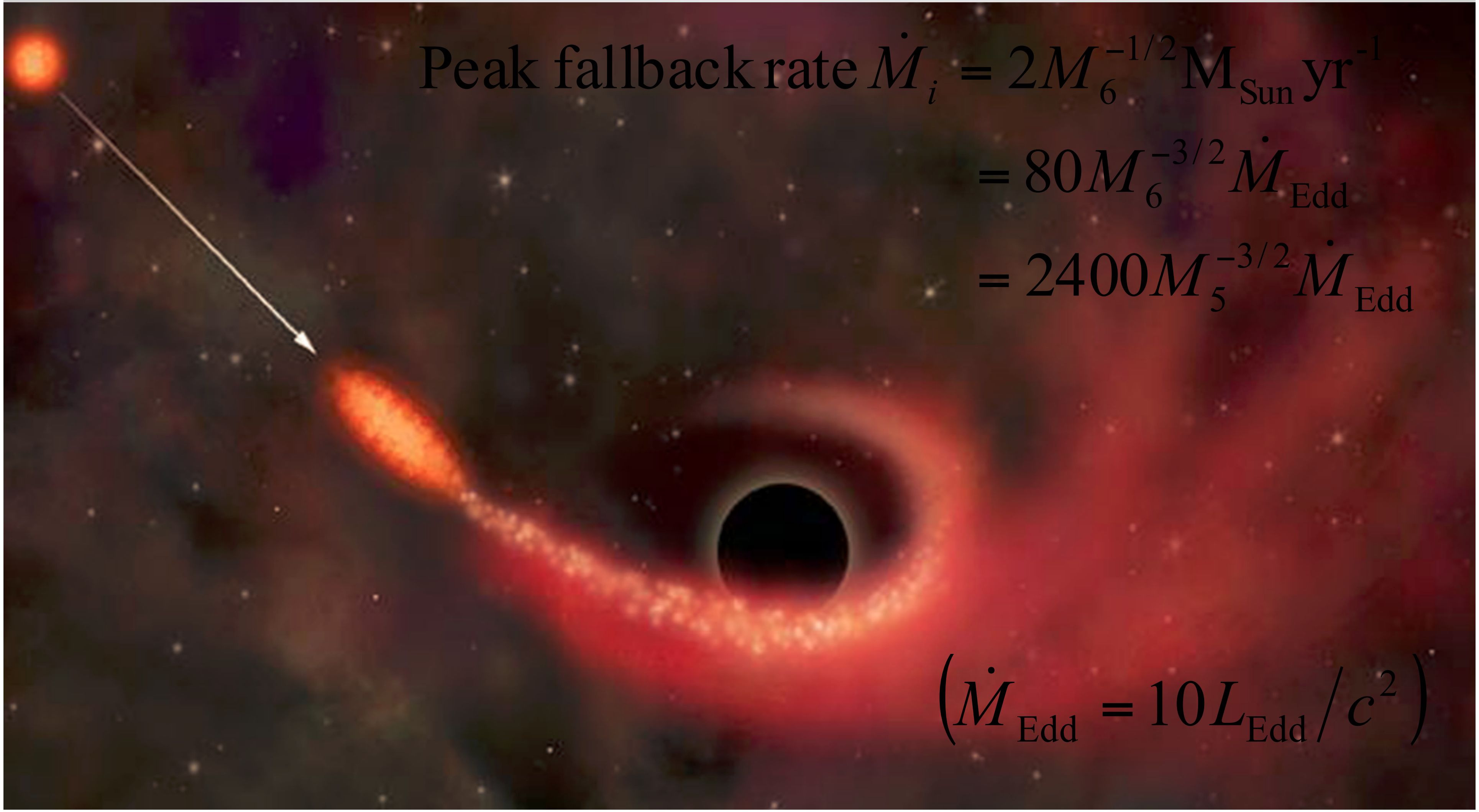
$$= 2400 M_6^{-1/3} r_g$$





Simulations by Guillochon & Ramirez-Ruiz 2013

Initial rise time for fallback $t_i = 0.1 M_6^{1/2}\,\mathrm{yr}$



Peak fallback rate $\dot{M}_i = 2 M_6^{-1/2}\,\mathrm{M_{Sun}\,yr^{-1}}$

$$= 80 M_6^{-3/2}\,\dot{M}_{\mathrm{Edd}}$$

$$= 2400 M_5^{-3/2}\,\dot{M}_{\mathrm{Edd}}$$

$$\left(\dot{M}_{\mathrm{Edd}} = 10 L_{\mathrm{Edd}}/c^2\right)$$

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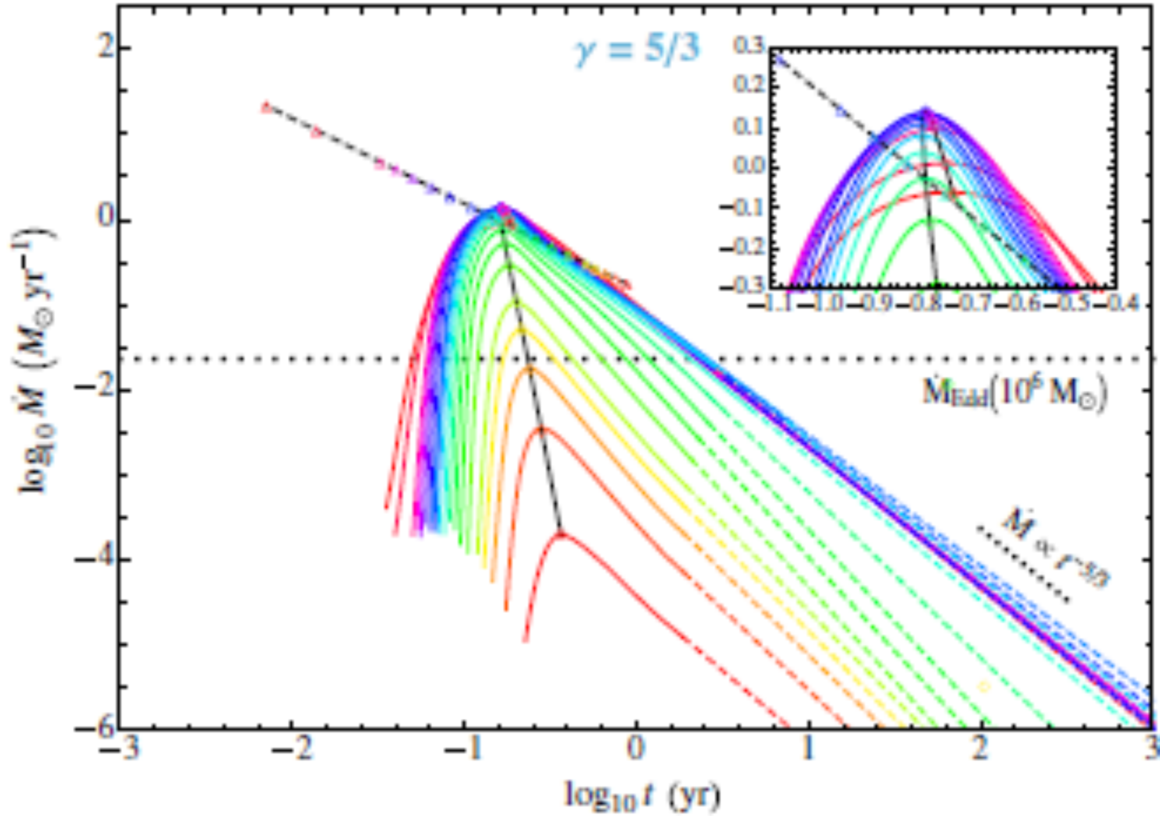
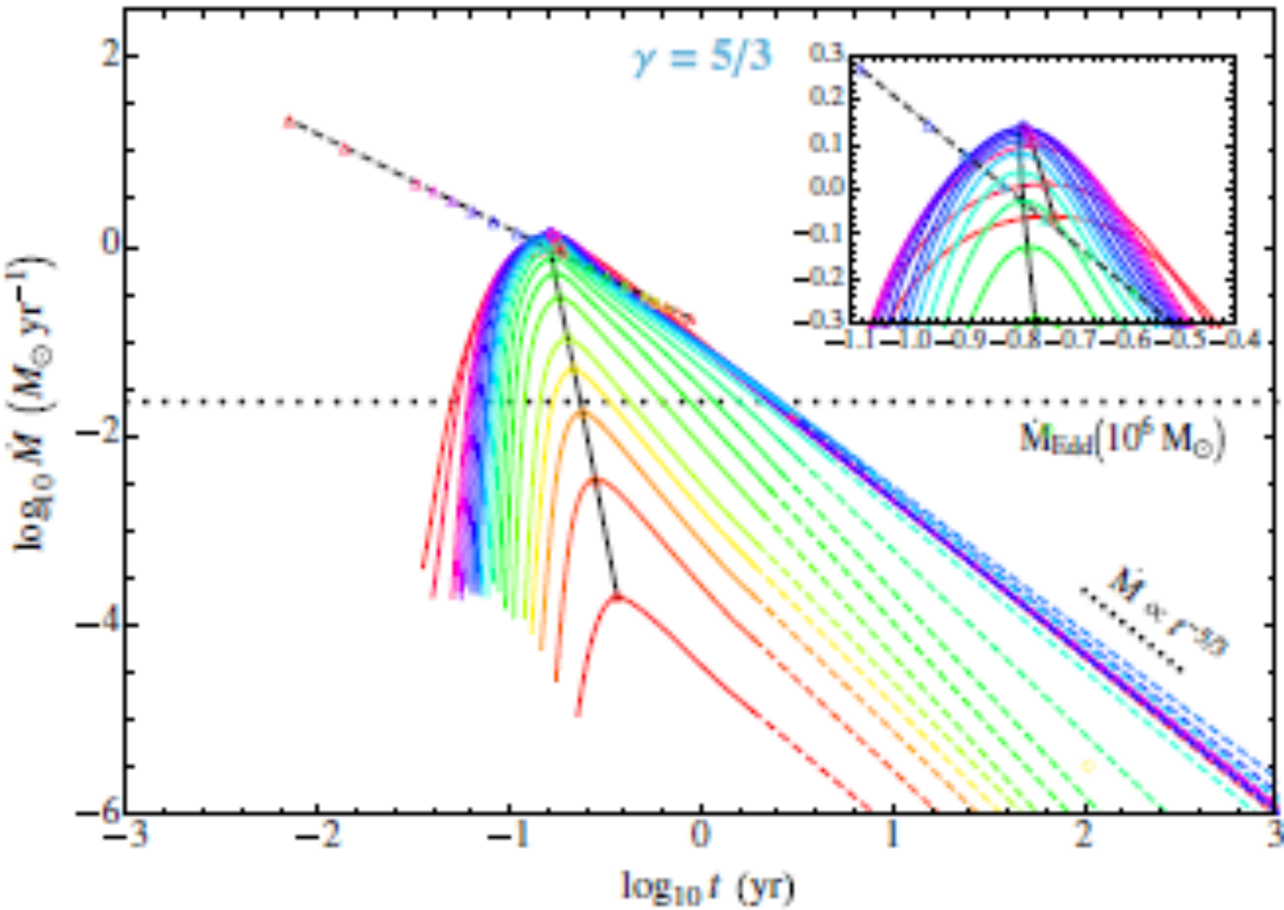


Simulations by Guillochon & Ramirez-Ruiz 2013

Fallback decays as $\dot{M} \propto t^{-5/3} - t^{-2.2}$

$\Rightarrow$ super - Eddington for ~ 1 – 3yr

for $10^5 - 10^6 M_{Sun}$ BH



Tidal disruption leads to hyperaccretion:

- Mass supply rate exceeds Eddington limit:

$$\dot{M} >> \dot{M}_{\rm Edd}$$

- Energy released $\frac{GM\dot{M}}{r} \sim L_E$ at $r \sim 10\left(\dot{M} / \dot{M}_{\rm Edd}\right) r_g$
  = trapping radius where $\tau = \frac{c}{v}$

- Energy accumulates at $r<r_{trap}$

$$r_{\rm trap} = \frac{\dot{M}\kappa}{4\pi c} = 10\left(\dot{M} / \dot{M}_{\rm Edd}\right) r_g$$

HYPERACCRETION:
THE "SLIM DISK" APPROACH

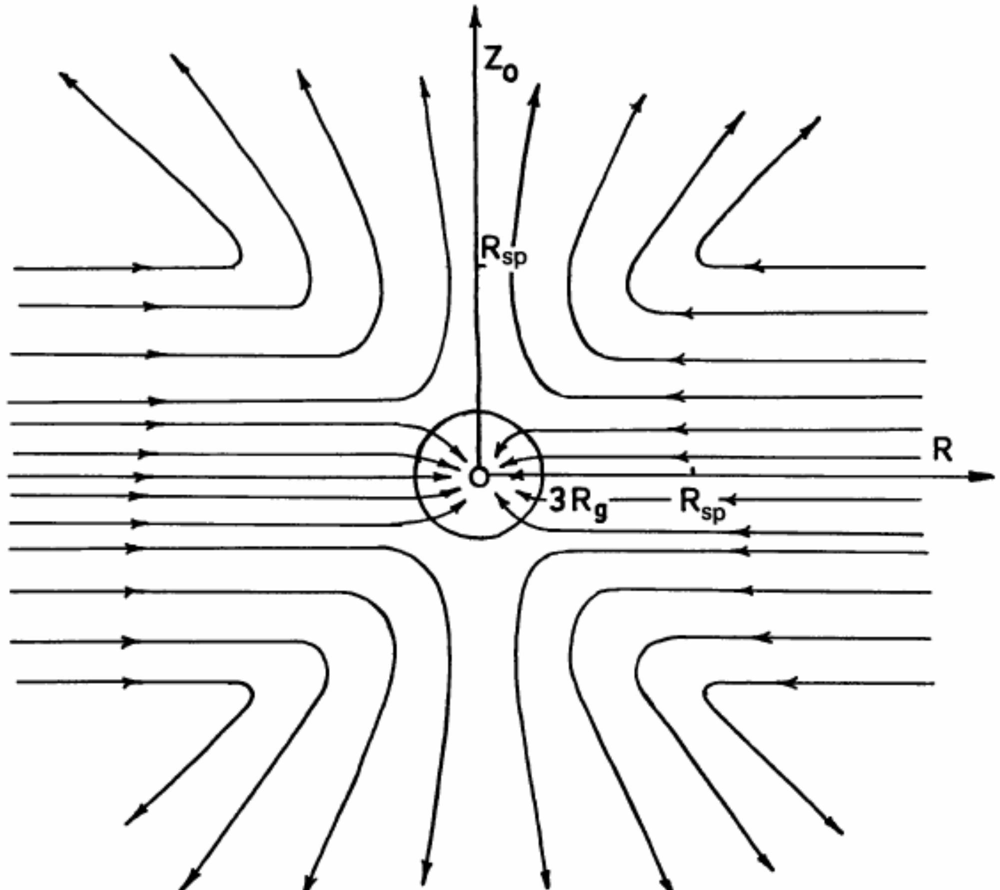
R>R$_{trap}$: $\dot{M} = \mathrm{const.}$

thin Keplerian disk

R<R$_{trap}$: $\dot{M} \propto R$

regulates $L \sim L_E$

Like an "ADIABATIC INLOW-OUTFLOW SOLUTION" (ADIOS) – Blandford & Begelman 1999



Shakura & Sunyaev 73

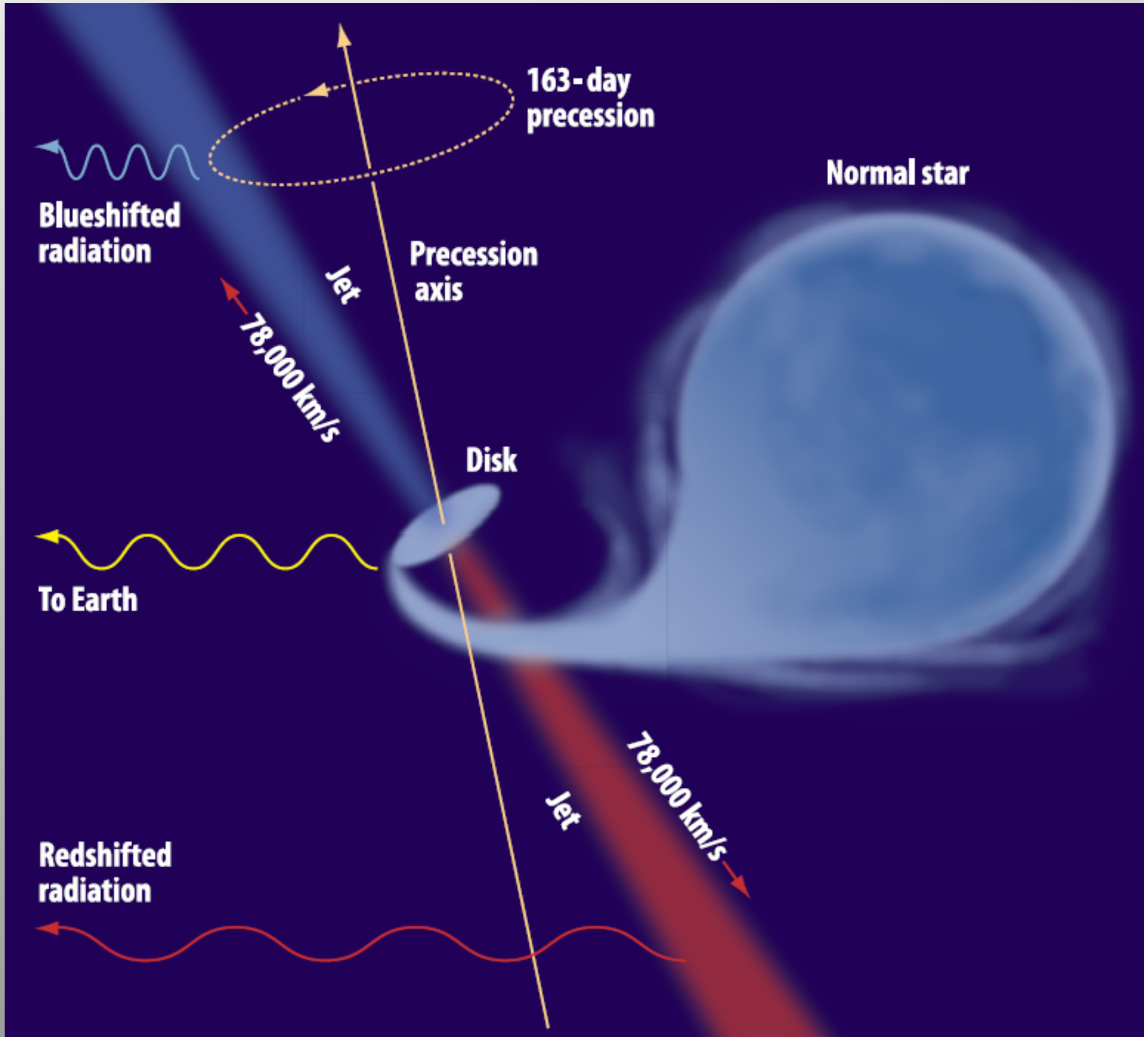
Fig. 8. Lines of matter flow at supercritical accretion (the disk section along the *Z*-coordinate). When $R < R_{sp}$ spherization of accretion takes place and the outflow of matter from the collapsar begins

SS433: A CLASSIC CASE OF HYPERACCRETION

$$\dot{M}_{in} \sim 10^3\ \dot{M}_E$$

$$R_{trap} \sim 10^3 R_g$$

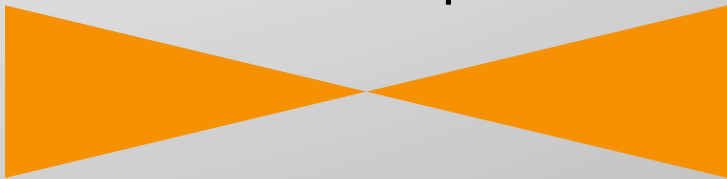
Strong wind from large *R*



DISKLIKE ACCRETION

- Thin disk

  - ~ all dissipated energy radiated away
  - ~ circular Keplerian orbits, vertical structure decouples
  - energy transport: internal torque
- Slim disk

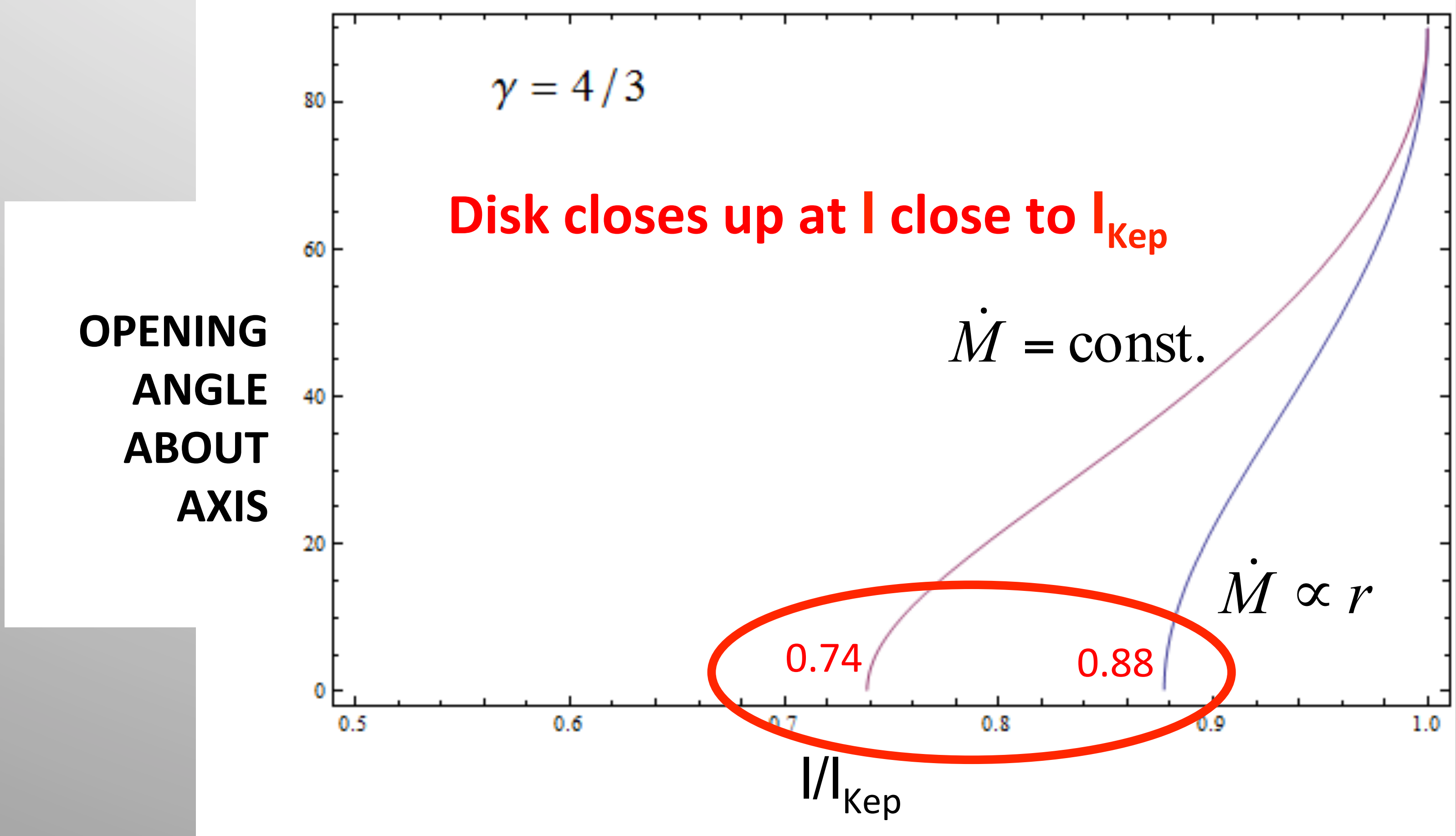


  - gas retains enough pressure to affect radial balance
  - energy transport: torque + advection
- Radiatively inefficient disk
  - Due to low density or high optical depth (Eddington limit)
  - must dispose of extra energy, mass, or angular momentum to avoid becoming unbound
    - Inflow-outflow, circulation, turbulent transport, winds
    - Accretion may be inhibited

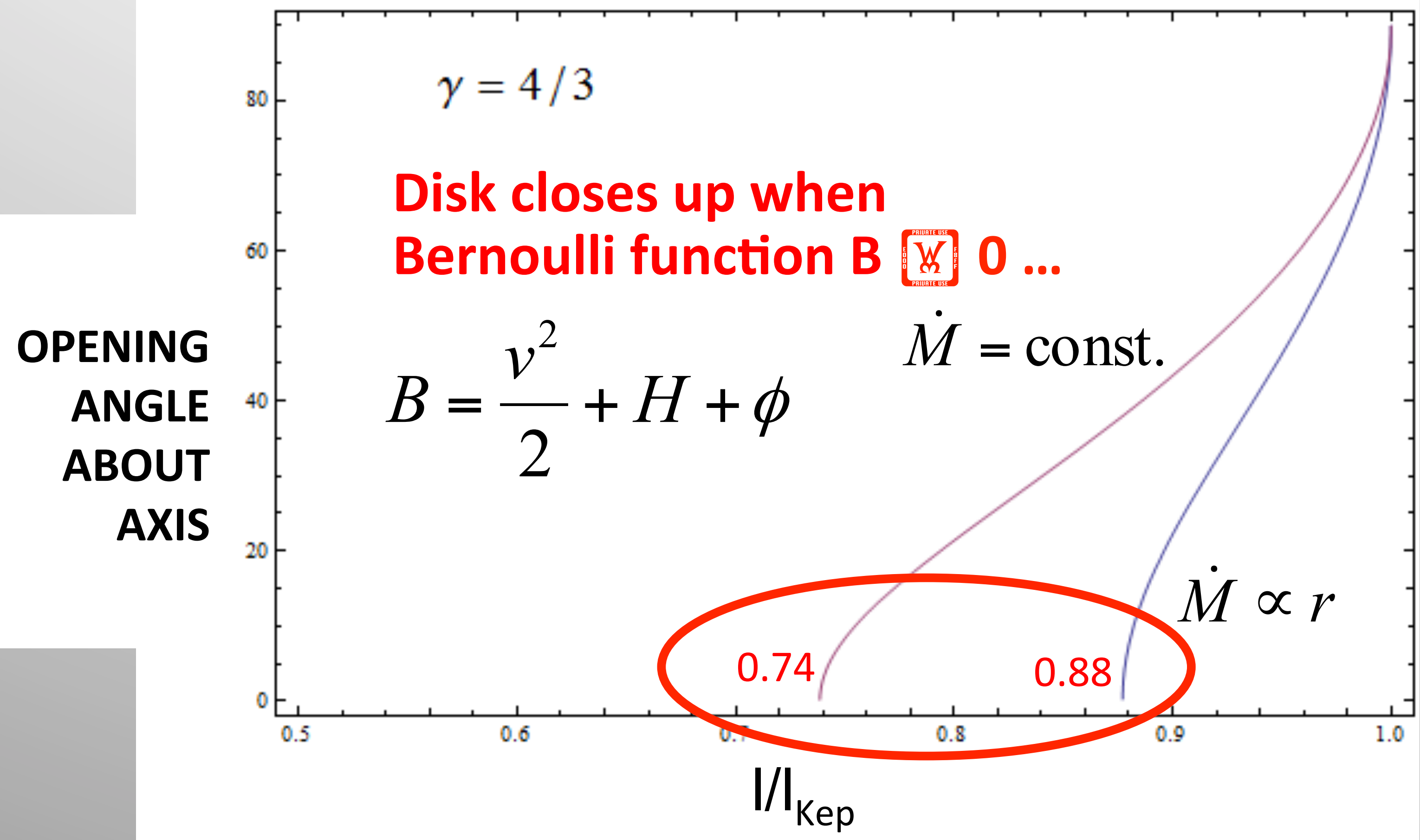
Slim disks: 1D models of 2D (axisymmetric) flows

What happens if we add the second dimension?

2D Slim Disk Models



- Gyrentropes: s(l)
- Quasi-Keplerian



... which occurs if specific angular momentum is too small compared to Keplerian

STARLIKE ACCRETION

- Dynamical conditions don't allow a bound disk-like flow

- Flow reduces B instead by *steepening* density/pressure profiles leads to runaway accretion

Predict:

Sub-Keplerian angular momentum

+

Super-Eddington accretion rate

↓

Failure of self-regulation:

Either violently unstable or star-like flow that produces super-Eddington jet (or accretion from low binding energy orbit)

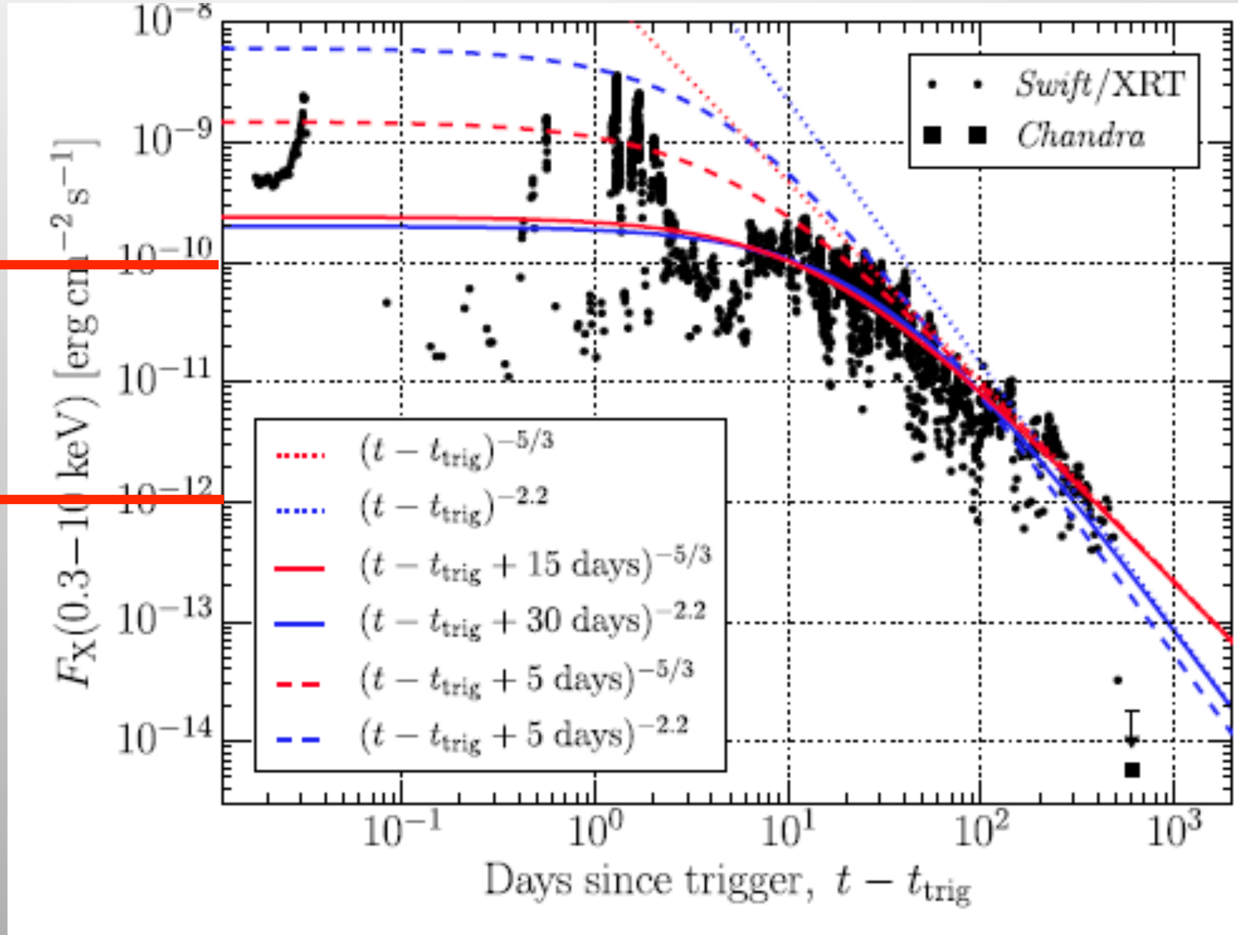
WHAT ACTUALLY HAPPENS?

This is the situation in a super-Eddington TDE

Super-Eddington TDE Swift J1644+57

$\sim 100 L_{\mathrm{Edd}}$

$\sim L_{\mathrm{Edd}}$



Tchekhovskoy et al. 2014

- Swift + Chandra light curves
- L corrected for beaming
- Radio emission suggests jet

Super-Eddington TDE Swift J1644+57

- Angular momentum of debris cloud
  - $R_{circularization} \sim 10^{13} (M/M_\odot)^{-1/3} (M_{BH}/10^6 M_\odot)^{1/3}$ cm
- Radius of debris cloud
  - Set by radiation trapping condition [illegible] $\sim c/v_K$
  - $R_{debris} \sim 10^{15} (M/M_\odot)^{2/5} (M_{BH}/10^6 M_\odot)^{1/5}$ cm
- Hardly rotating
  - $L/L_K \sim (R_{circ}/R_{deb})^{1/2} \sim 0.1 (M_{BH}/10^6 M_\odot)^{2/15}$ initially

Model as evolving sequence of star-like (low l) flows with B~0

Zero Bernoulli Accretion Flow

(Coughlin & MCB 2013)

- Weakly bound envelope
- Narrow rotational funnel
- Density gradient and accretion rate depend on L/L_K

ZEro BeRnoulli Accretion Flow

(Coughlin & MCB 2013)

ZEBRA

- Weakly bound envelope
- Narrow rotational funnel
- Density gradient and accretion rate depend on L/L_K

ZEBRA MODELS:

Equations:

$$\frac{1}{\rho}\frac{\partial p}{\partial r} = -\frac{\partial \phi}{\partial r} + \frac{\ell^2 \csc^2\theta}{r^3}$$

$$\frac{1}{\rho}\frac{\partial p}{\partial \theta} = -\frac{\partial \phi}{\partial \theta} + \frac{\ell^2 \csc^2\theta \cot\theta}{r^2}$$

$$\phi + \frac{\ell^2 \csc^2\theta}{2r^2} + \frac{\gamma}{\gamma - 1}\frac{p}{\rho} = 0$$

General solution: l *any* function of $\phi\, r^2 \sin^2\theta$

Self-similar:

Keplerian potential

([illegible], [illegible], q depend on a)

$$\rho(r,\theta) = \rho_0 \left(\frac{r}{r_0}\right)^{-q} (\sin^2\theta)^{\alpha},$$

$$p(r,\theta) = \beta \frac{G M_h \rho_0}{r} \left(\frac{r}{r_0}\right)^{-q} (\sin^2\theta)^{\alpha},$$

$$\ell^2(r,\theta) = a G M_h r \sin^2\theta,$$

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$$\ell^2(r,\theta) = a G M_h r \sin^2\theta,$$

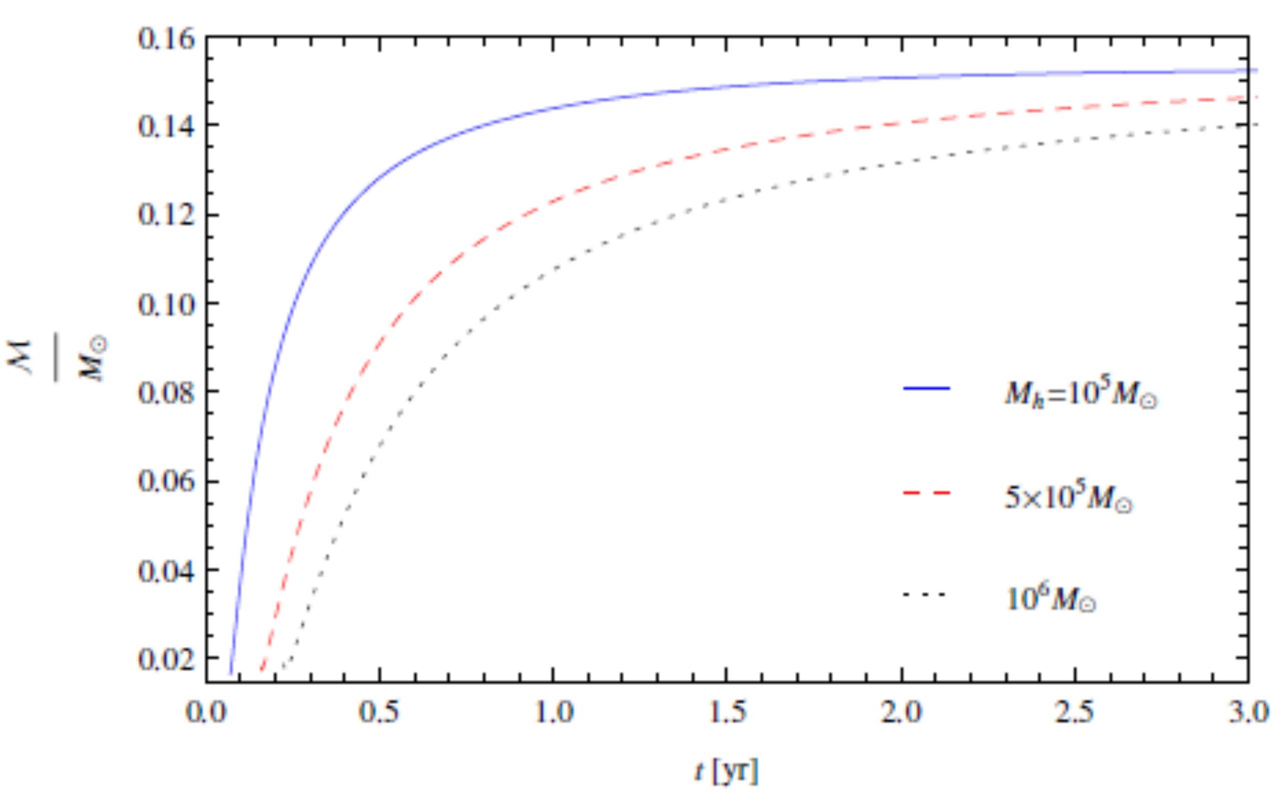
l const. on paraboloids

ZEBRA Evolution

- Accretion (from inner boundary)
  - Less l $\rightarrow$ steeper density slope $\rightarrow$ higher $\dot{M}$
  - $L >> L_E$, no way to self-regulate
  - Energy must escape as jets, or ZEBRA blows up
- BH accretes mass, leaves behind ang. mom.
  - l increases with time, density profile flattens
  - $\dot{M}$ declines, weaker jet
- Time-dependent model fits observed features of Swift J1644

Evolution of envelope mass

- Initially, fallback rate exceeds accretion rate: M incr.
- Later, accretion rate exceeds fallback rate but both decrease
- M levels off at ~15% of stellar mass

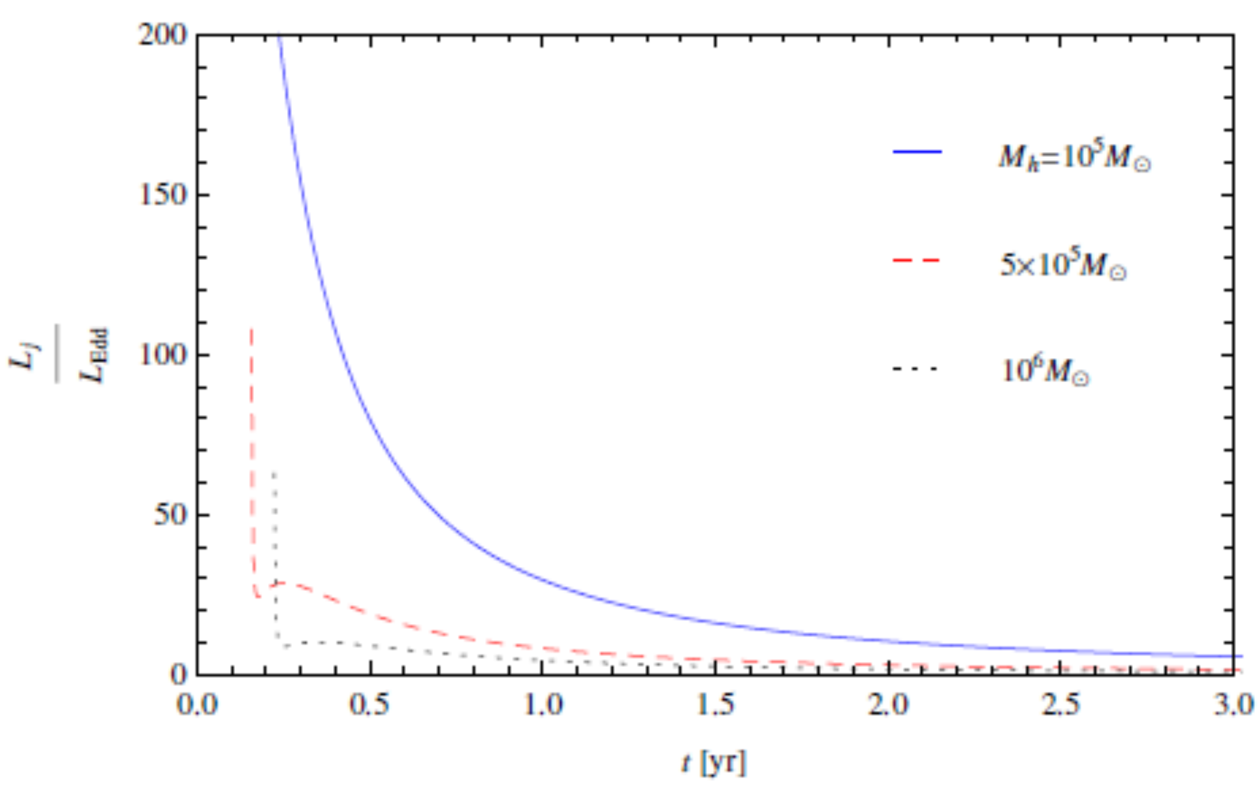


Envelope mass as a function of time, different BH masses

(Coughlin & MCB 2014)

Evolution of jet power

- Proportional to accretion rate w/ fixed efficiency
- Sensitive to density slope
- Reaches L_{Edd} at ~500d, when Swift J1644 X-ray flux plummets

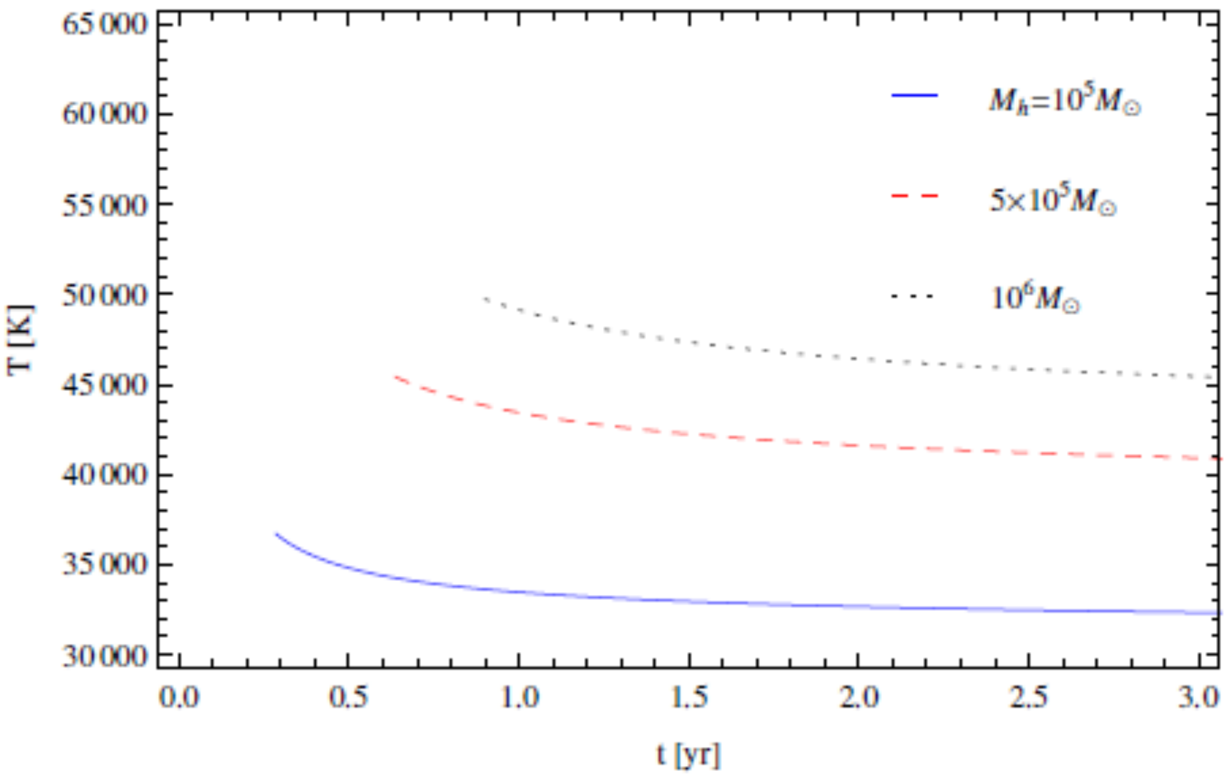


Jet power as a function of time, different BH masses

(Coughlin & MCB 2014)

Envelope effective temperature

- Envelope luminosity ~ $L_{Edd} << L_{jet}$
- $T_{eff} \propto M_*^{-1/5} M_h^{3/20}$
- Far UV



Effective temp. as a function of time, different BH masses

(Coughlin & MCB 2014)

Jets from Tidal Disruption Events

The Magnetic Flux/Spin Paradigm

Angular velocity of engine

Magnetic flux threading engine

$$L_J \sim \frac{\Phi^2 \Omega^2}{c}$$

Jet power limited by amount of flux available

Do TDEs have enough flux?

Transient accretion events have access to a fixed amount of flux…

Tidal Disruption Event candidate Swift J1644+57:

Jet power: $L_j > 10^{45}$ erg $s^{-1} \sim 100\ L_E$

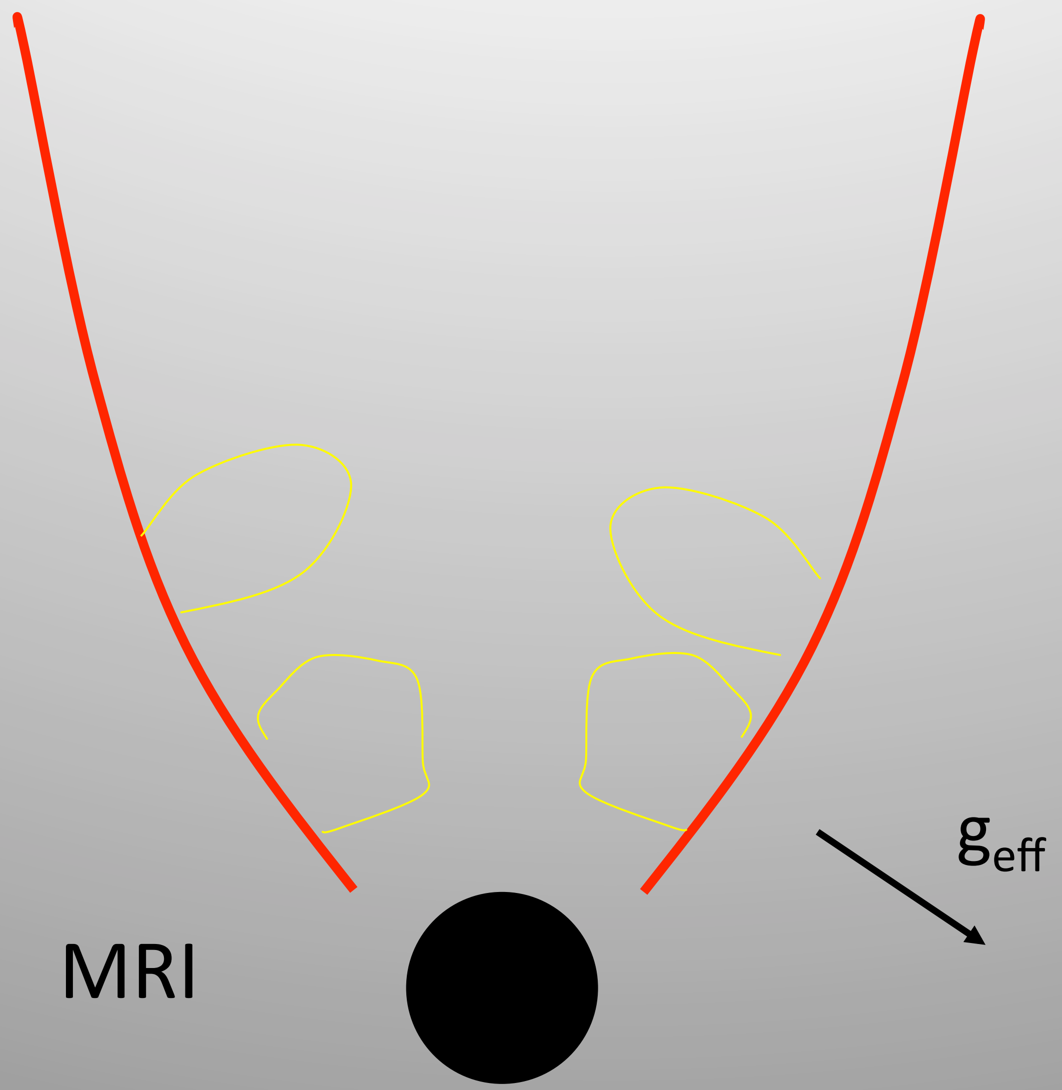
Flux needed: [illegible] $> 10^{30}$ G-cm^2

Flux available: [illegible]$_{\text{[illegible]}} \sim 10^{25} B_3 (R_{\text{[illegible]}}/R_{\text{[illegible]}})^2$ G-cm^2

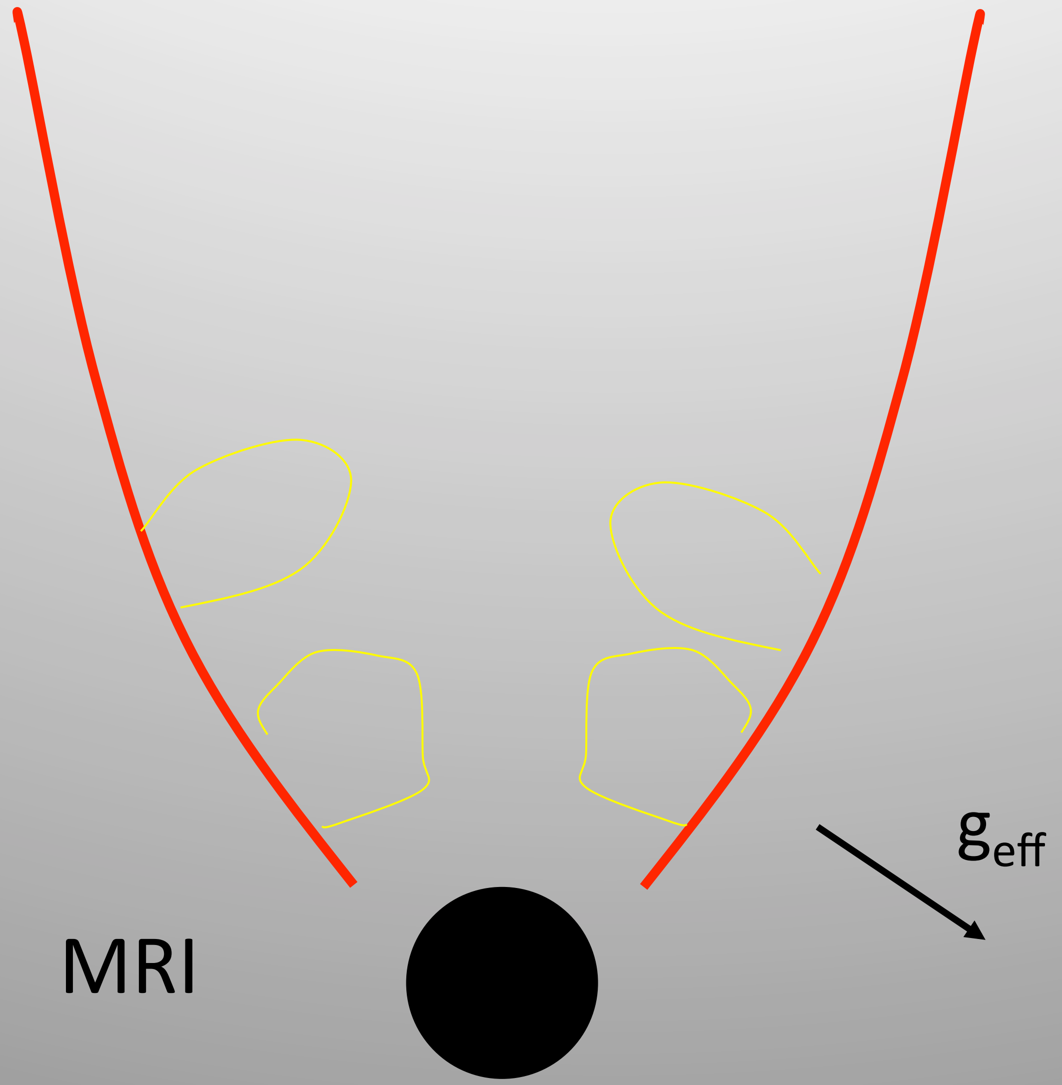
PROBABLY NOT

An Alternate Mechanism for TDE Jets

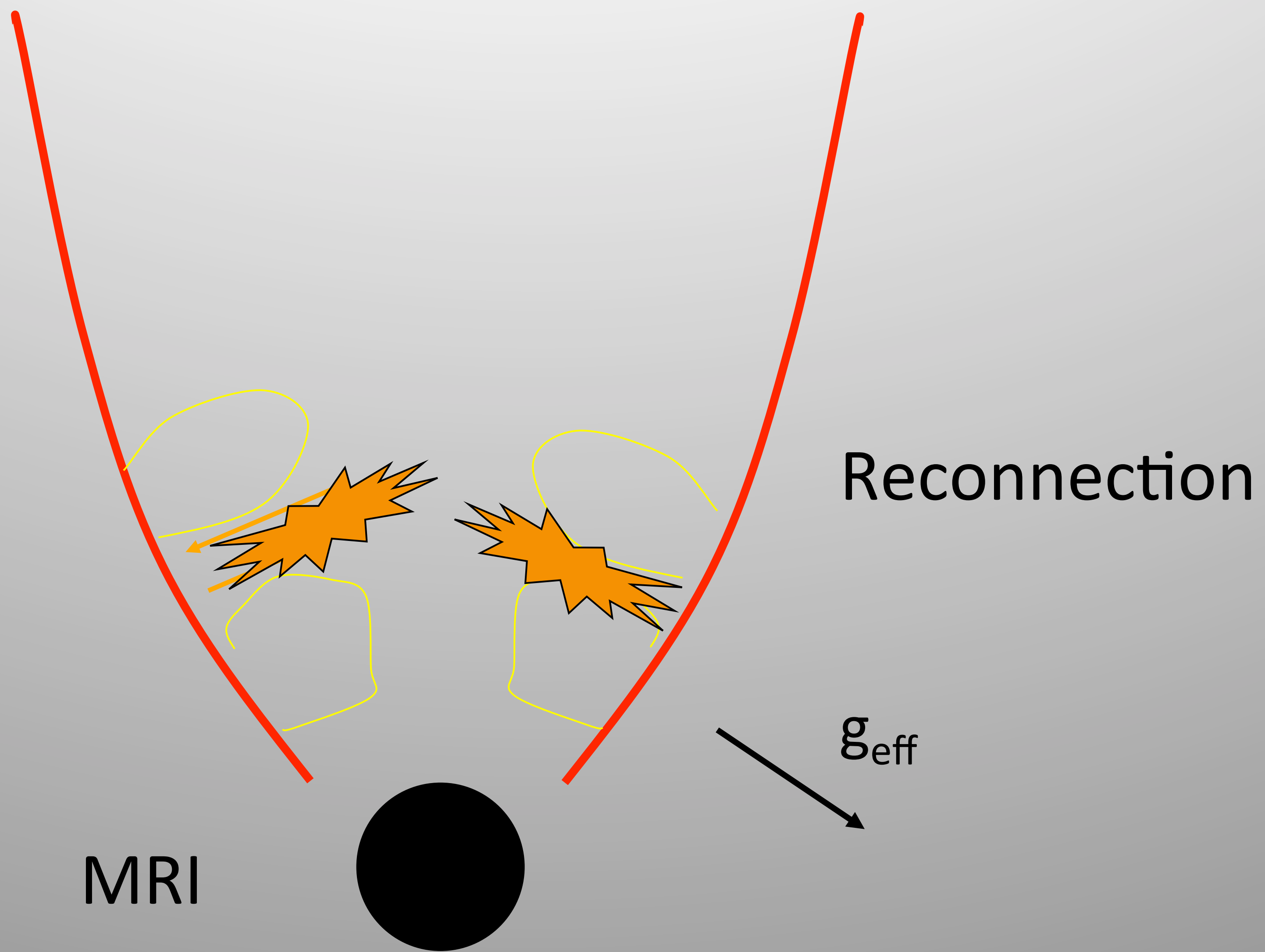
Buoyant loops of B form inward corona

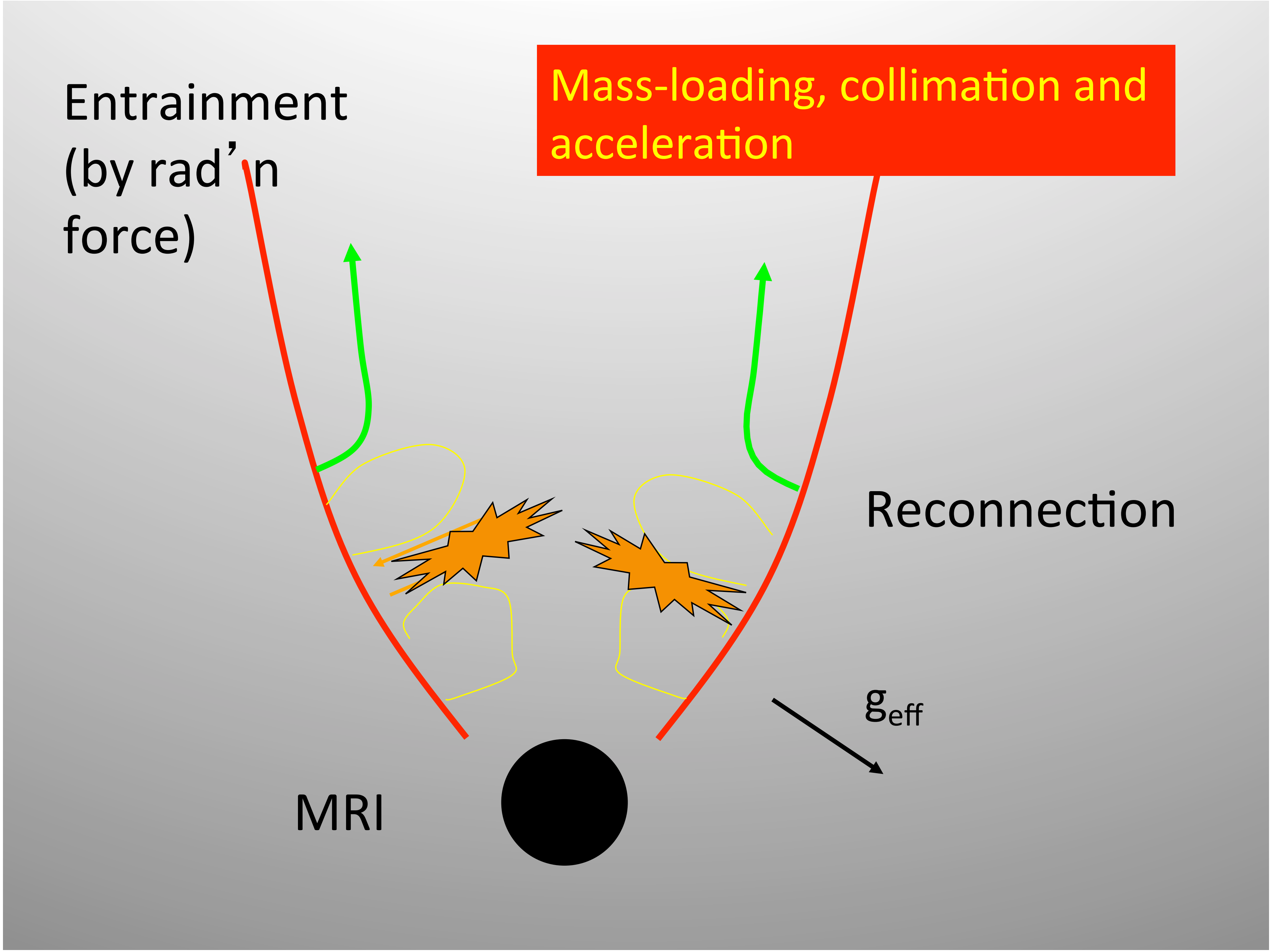


… so jet ultimately powered by dissipation of turbulent B

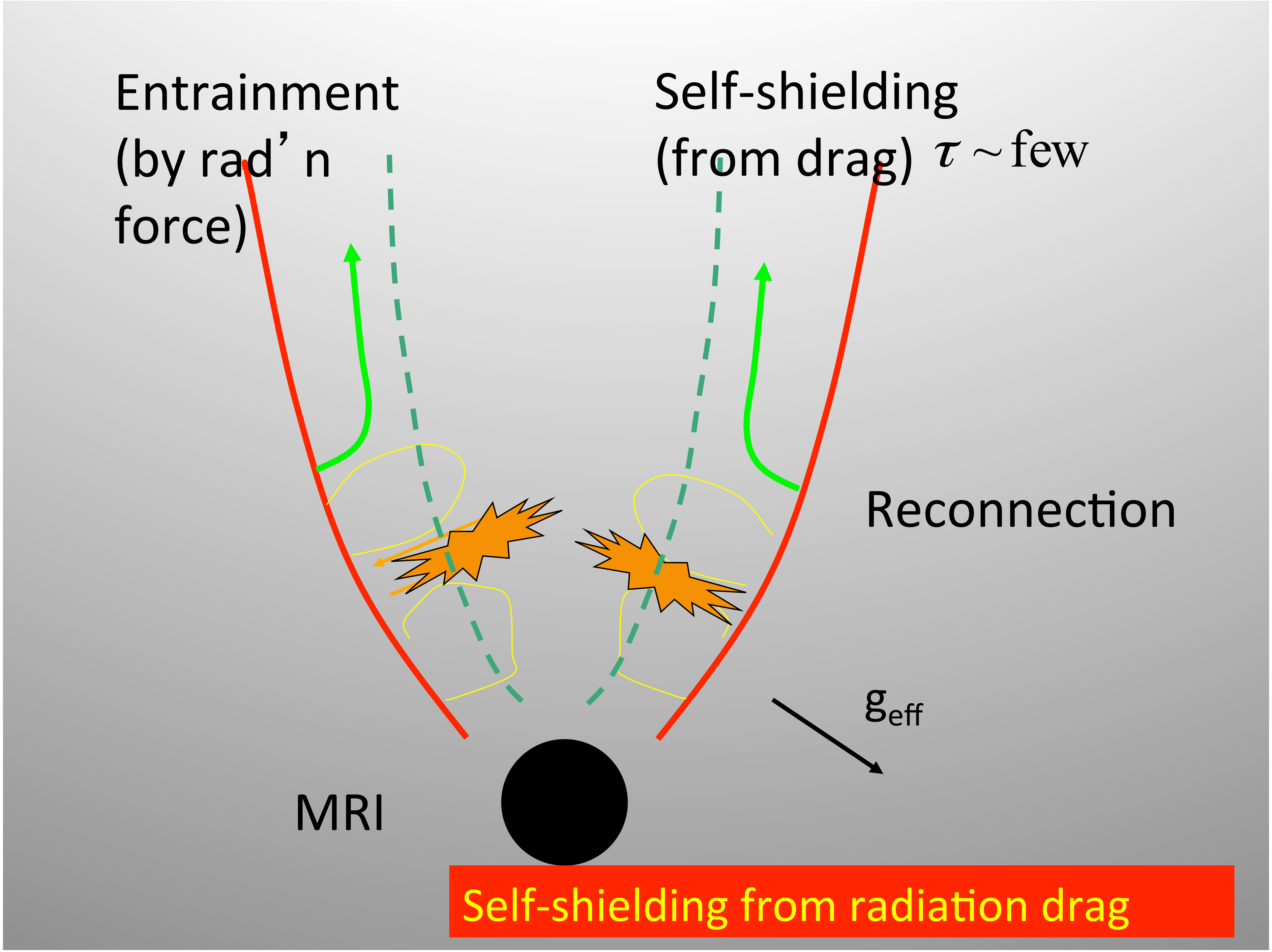


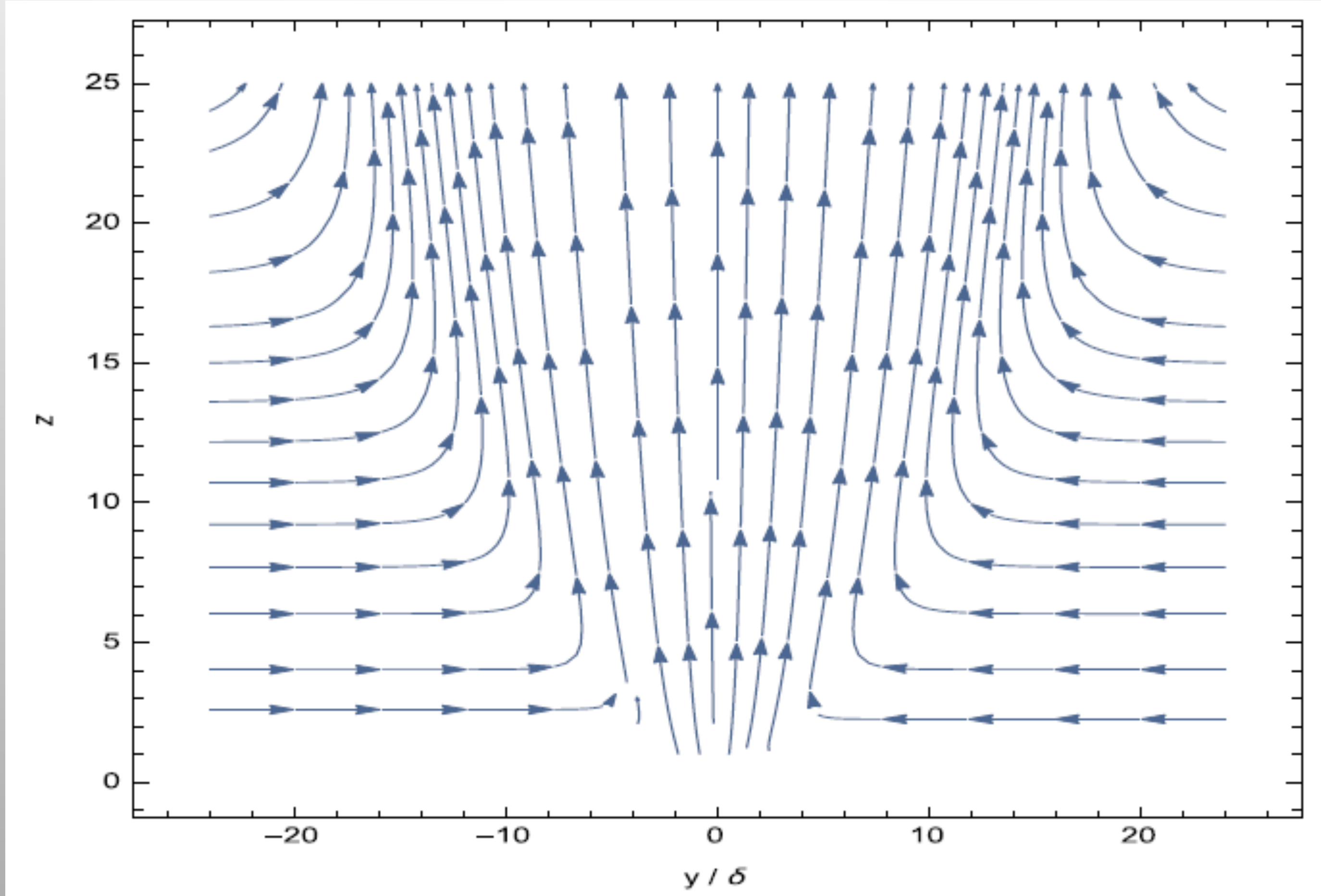
Reconnection converts energy to radiation





Mass-loading, collimation and acceleration
Entrainment (by rad'n force)
Reconnection
g_{eff}
MRI


Entrainment
(by rad' n
force)
Self-shielding
(from drag) $\tau \sim \text{few}$
Reconnection
g_{eff}
MRI
Self-shielding from radiation drag



Relativistic radiation hydrodynamics: entrainment and acceleration by radiation stresses

(Coughlin & Begelman, in prep)

ZEBRA Jets

- Powered by dissipation of turbulent B (from MRI?), not net magnetic flux
- Reconnection → energy converted to radiation
- Acceleration by radiation pressure
- Collimation by rotational funnel
- Mass-loading determined by radiation drag
  - Jets "self-shield"
- L/L_E determines jet Lorentz factor

Broader Implications of ZEBRA Flows

- When do they form?
  - Too much l to fall directly in
  - Too little l/l_{Kep} to maintain disk-like flow
  - Low radiative efficiency
- Where do they form?
  - Tidal Disruption Events
  - Collapsar Gamma-Ray Bursts
  - Supermassive BH seeds accreting from cocoons (quasi-stars)

Do GRBs have enough flux?

Transient accretion events have access to a fixed amount of flux…

Tidal Disruption Event candidate Swift J1644+57:

Jet power: $L_j > 10^{45}$ erg s^{-1} ~ 100 L_E

Flux needed: [illegible] $> 10^{30}$ G-cm^2

Flux available: [illegible]$_{[illegible]}$ ~ 10^{25} B_3 ($R_{[illegible]}$/$R_{[illegible]}$)^2 G-cm^2

Collapsar Gamma-Ray Burst:

Jet power: $L_j > 10^{50}$ erg s^{-1} ~ 10^{11} L_E

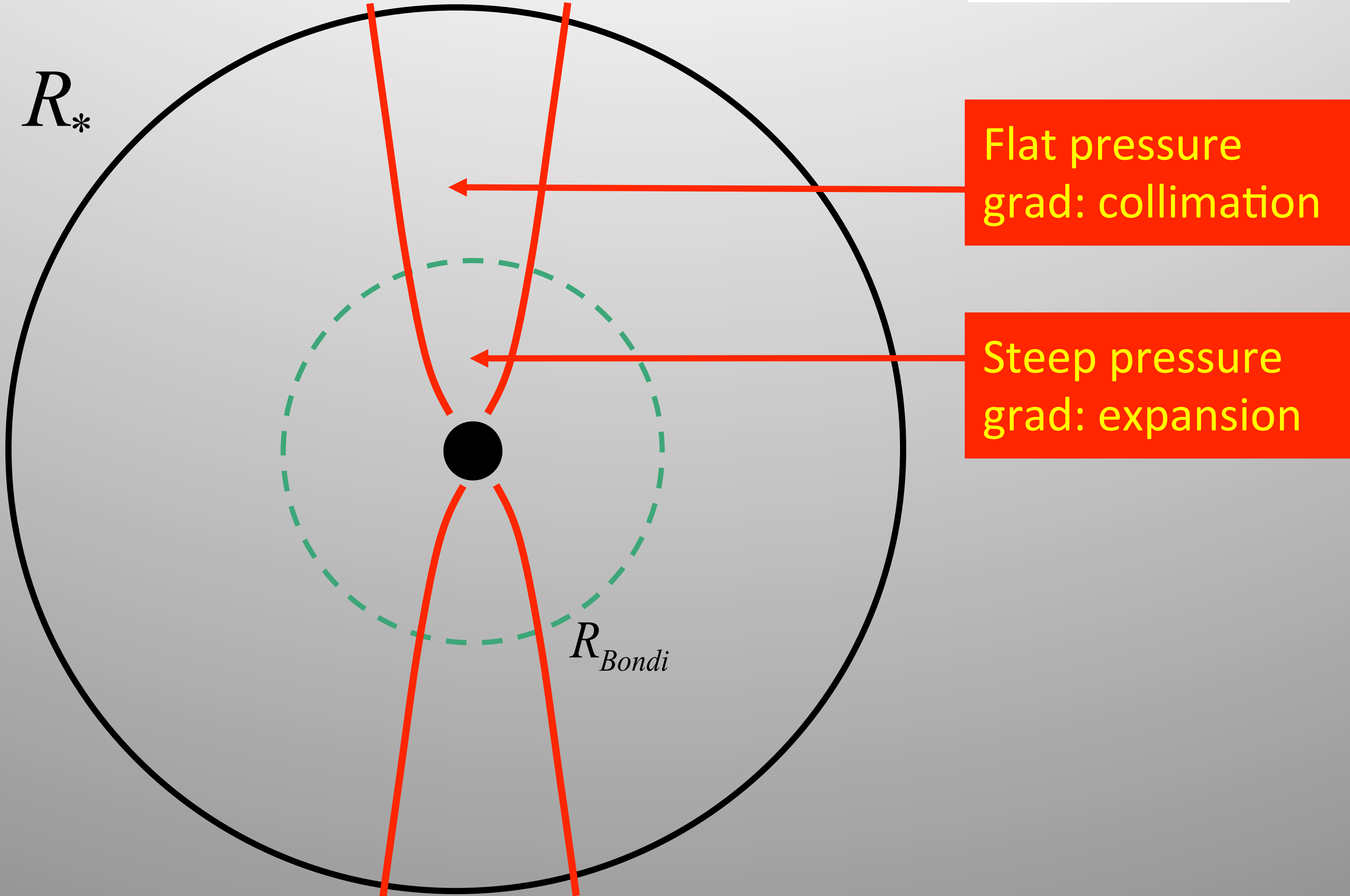
Flux needed: [illegible] $> 10^{28}$ G-cm^2

Flux available: [illegible]$_{[illegible]}$ ~ 10^{25} B_3 ($R_{[illegible]}$/$R_{[illegible]}$)^2 G-cm^2

Generalize ZEBRAs to self-gravitating envelopes:

I *any* function of $\phi\, r^2 \sin^2\theta$

General solution: I *any* function of $\phi\, r^2 \sin^2 \theta$



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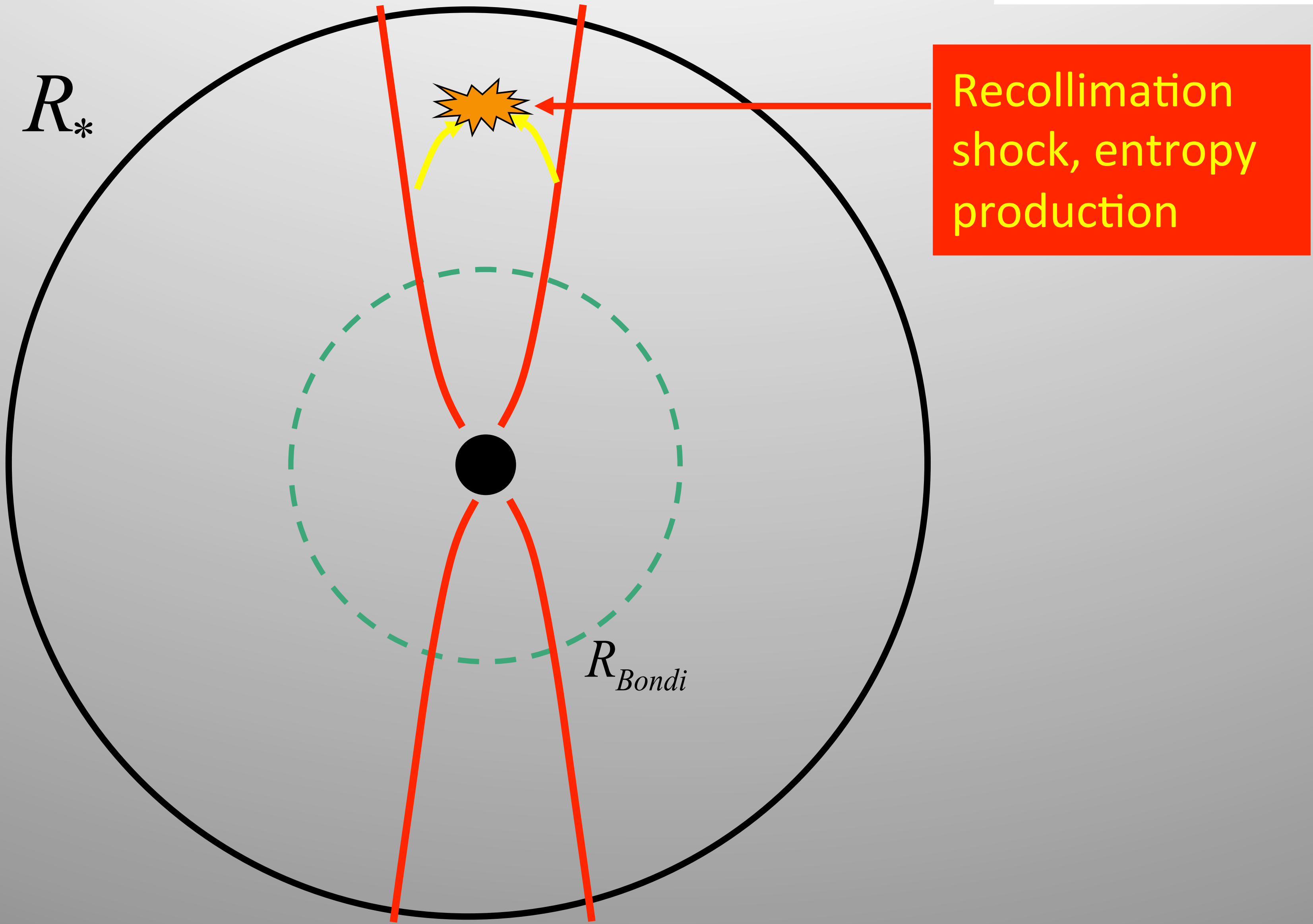
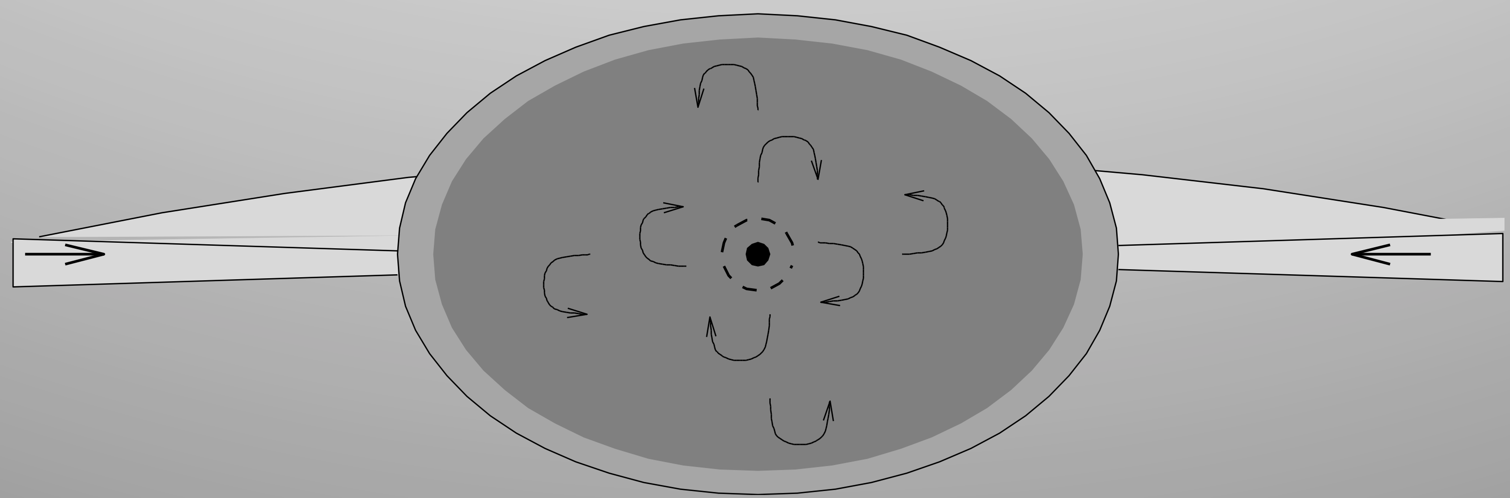


Consequences for GRB Jets

- Dissipation at recollimation shock could explain jet entropy needed for thermal origin of prompt emission
- Lorentz factor ~ $(L/L_E)^{\text{small power (\sim 1/4??)}}$
  - Extreme $L/L_E \sim 10^{11}$ ~ 100 - 1000

"QUASISTAR"

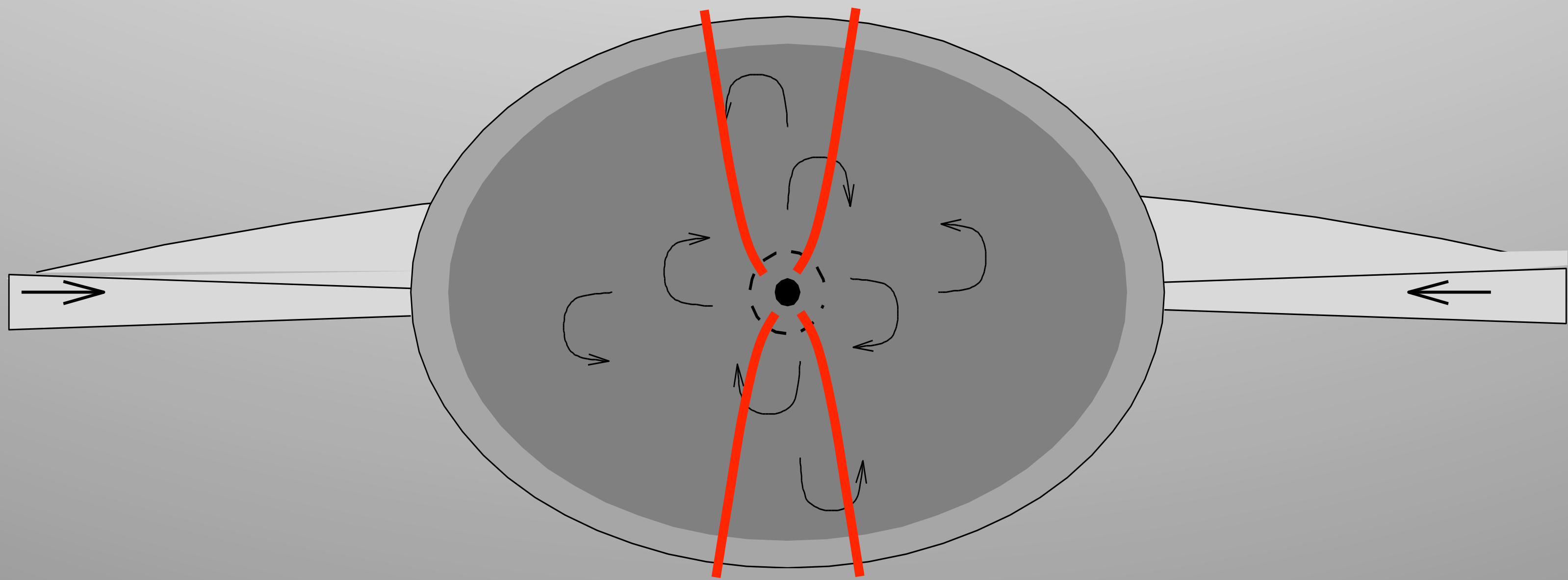
- Remnant envelope around newly formed SMBH seed
- Black hole accretes from envelope, releasing energy
- Envelope absorbs energy and expands
- Accretion rate decreases until energy output = Eddington limit – supports the "star"



Begelman, Volonteri & Rees 2006;Begelman, Rossi & Armitage 2008

QUASISTAR JETS?

- Similar situation to collapsar after expansion
- Self-gravity more important: envelope >~ 100 x BH mass
- Importance of magnetic flux unknown
- Detectability of quasistars at z~5-10?



So what can tidal disruption events teach us about black hole accretion?

- Rotating accretion flows need not resemble disks
- Not all hyperaccreting systems can regulate their energy outputs to the Eddington limit
- Not all jets need be magnetically propelled