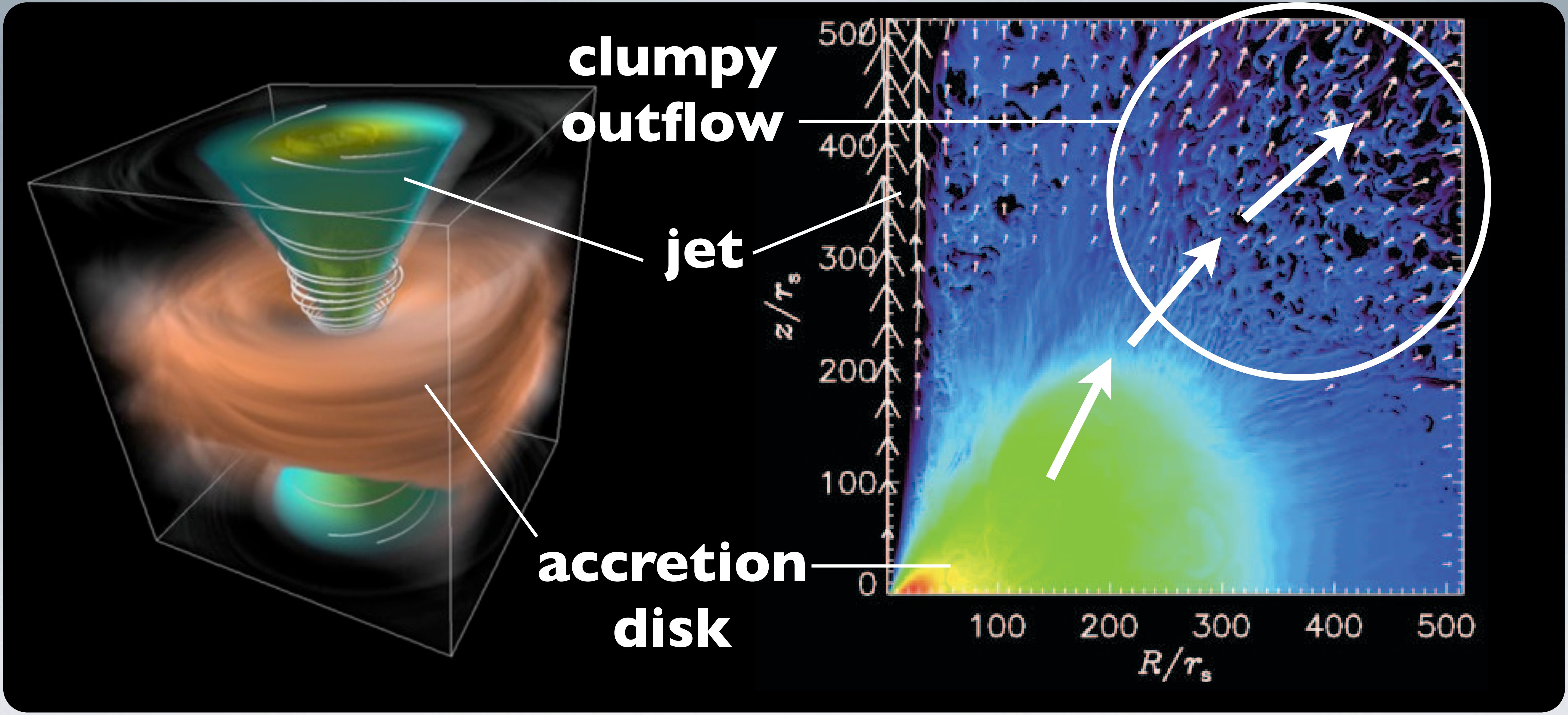
Radiation-MHD Simulations of Black Hole Accretion Flows & Outflows



Ken OHSUGA (NAOJ)

WHY RADIATION-MHD ?

- **Disk viscosity** is magnetic origin.
- Dissipation of the magnetic energy **heats up the gas**.
- Difference of the radiative cooling rate leads to the difference of the **disk structure** (thick or thin, hot or cold).
- Radiation- and/or magnetic pressusure drive **jets and disk outflows**.
- **Clumpy, time-dependent outflow** is produced by thermal instability (that is, radiative cooling).

Performing **radiation-MHD** simulations,
we investigate the **inflow-outflow structure**.

BASIC EQUATIONS OF RADIATION-MHD

$$\frac{\partial \rho}{\partial t} + \boldsymbol{\nabla}\cdot(\rho\boldsymbol{v}) = 0$$

$$\frac{\partial(\rho\boldsymbol{v})}{\partial t} + \boldsymbol{\nabla}\cdot\left(\rho\boldsymbol{v}\boldsymbol{v} - \boxed{\frac{\boldsymbol{B}\boldsymbol{B}}{4\pi}}\right) = -\boldsymbol{\nabla}\left(p + \boxed{\frac{|\boldsymbol{B}|^2}{8\pi}}\right) + \boxed{\frac{\chi}{c}\boldsymbol{F}_0} - \rho\boldsymbol{\nabla}\psi$$

$$\frac{\partial e}{\partial t} + \boldsymbol{\nabla}\cdot(e\boldsymbol{v}) = -p\boldsymbol{\nabla}\cdot\boldsymbol{v} + \boxed{\frac{4\pi}{c^2}\eta J^2} - \boxed{4\pi\kappa B + c\kappa E_0}$$

$$\boxed{\frac{\partial E_0}{\partial t} + \boldsymbol{\nabla}\cdot(E_0\boldsymbol{v}) = -\boldsymbol{\nabla}\cdot\boldsymbol{F}_0 - \boldsymbol{\nabla}\boldsymbol{v} : \mathbf{P}_0 + 4\pi\kappa B - c\kappa E_0}$$

$$\boxed{\frac{\partial \boldsymbol{B}}{\partial t} = \boldsymbol{\nabla}\times\left(\boldsymbol{v}\times\boldsymbol{B} - \frac{4\pi}{c}\eta\boldsymbol{J}\right) \qquad \boldsymbol{J} = \frac{4\pi}{c}\boldsymbol{\nabla}\times\boldsymbol{B}}$$

🟥 RHD terms   🟦 MHD terms

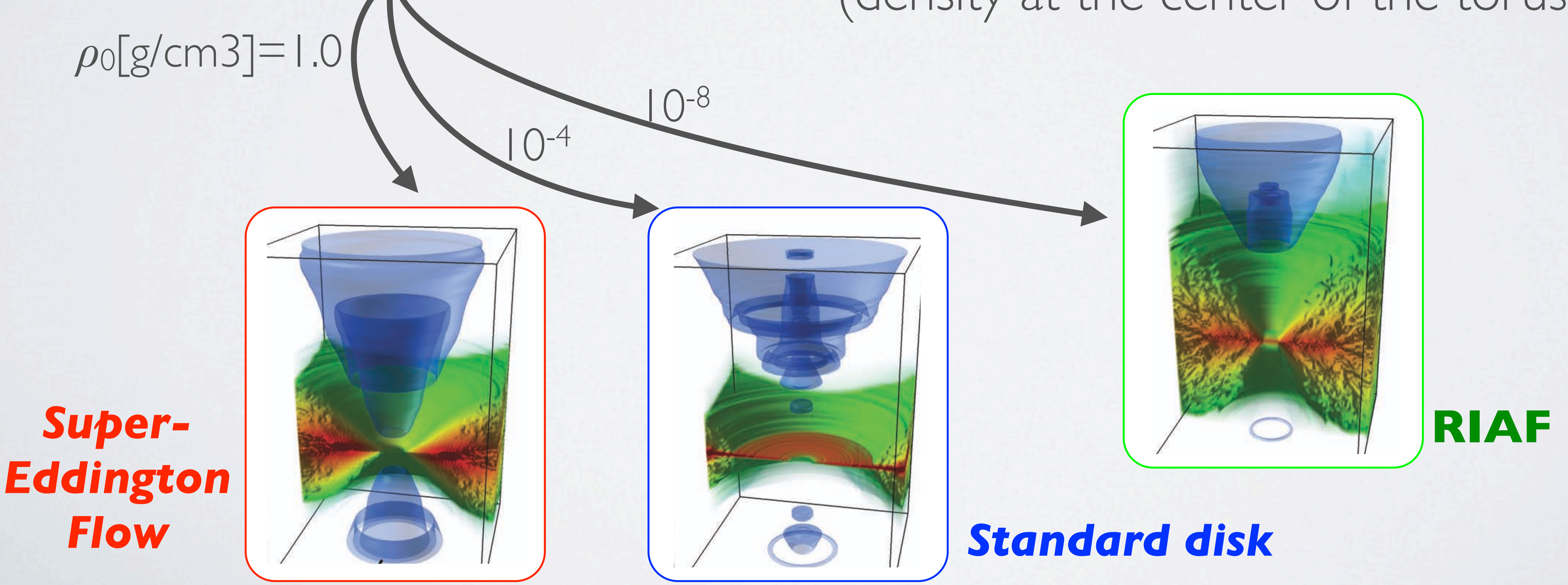
NUMERICAL METHOD

- Cylindrical coordinate (r, ϕ, z); r=2-100Rs, z=0-100Rs
- Axisymmetry & Mid-plane Symmetry
- Initial Conditions & density parameter

-No disk initially !

-Rotating torus (plasma-beta=100, closed poloidal magnetic fields; B_ϕ=0)

-We set the density parameter, ρ_0 (density at the center of the torus).



SUPER-EDDINGTON FLOWS

ρ/ρ_0, [ρ_0=1.0 g cm^{-3}]

Radiation-pressure supported disk + radiatively-driven jet

-$\boldsymbol{M_{\mathrm{dot}}\sim 60 L_{\mathrm{edd}}/c^2}$

-$\boldsymbol{L}_{\mathrm{bol}}\gtrsim\boldsymbol{L}_{\mathrm{edd}}$

-$\boldsymbol{L}_{\mathrm{trap}}\gtrsim\boldsymbol{L}_{\mathrm{edd}}$

Ohsuga et al. 2009, PASJ, 61, L7;
Ohsuga, Mineshige 2011, ApJ, 726, 2

M_{BH}=10Msun

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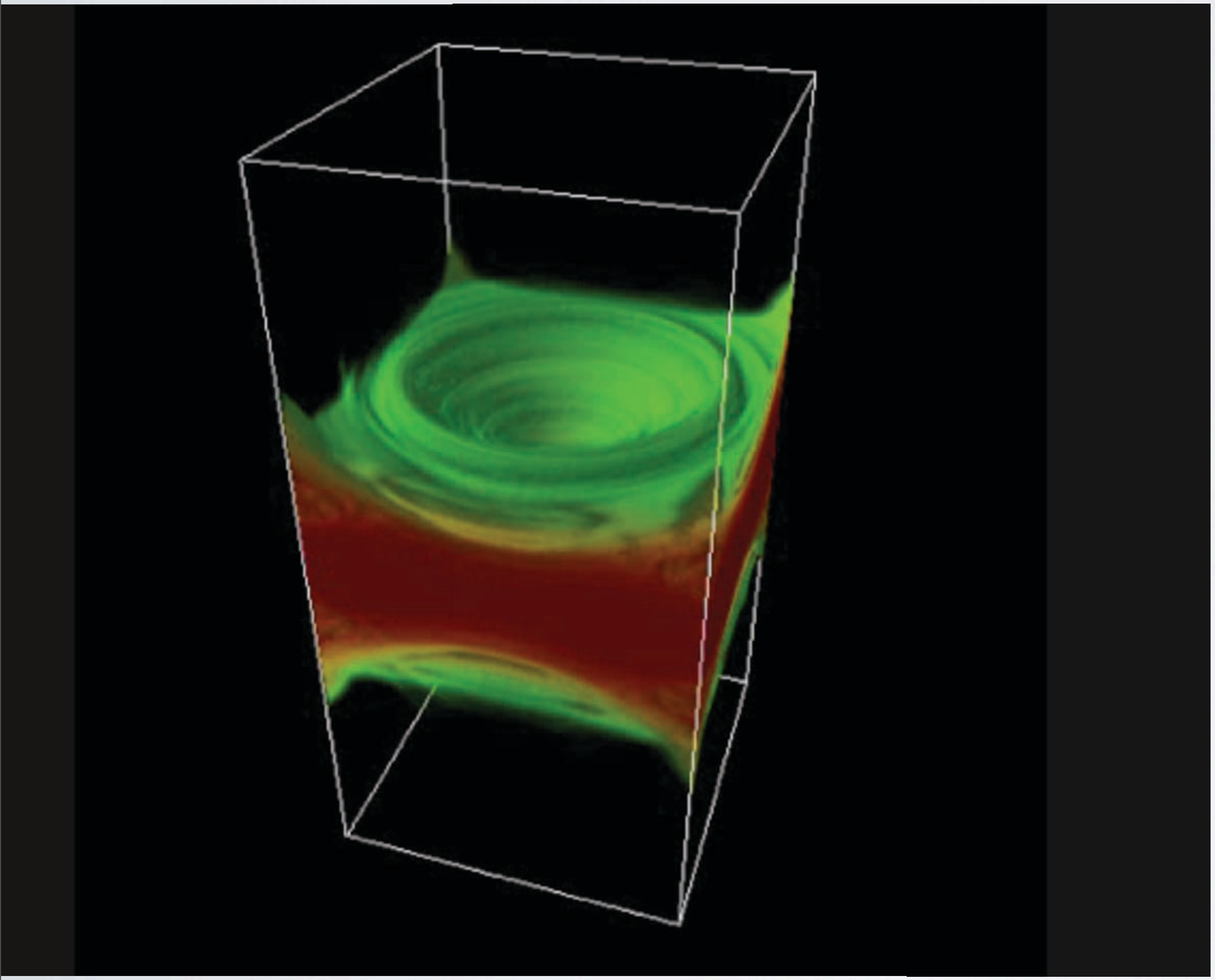

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STANDARD DISK & RIAF

ρ/ρ_0, [$\rho_0=10^{-4}$ g cm^{-3}]

$L_{\mathrm{bol}}\sim 10^{-4}L_{\mathrm{edd}}$, $M\mathrm{dot}\sim 10^{-3}L_{\mathrm{edd}}/c^2$

Cold, thin disk

ρ/ρ_0, [$\rho_0=10^{-8}$ g cm^{-3}]

$L\sim 10^{-12}L_{\mathrm{edd}}$, $M\mathrm{dot}\sim 10^{-5}L_{\mathrm{edd}}/c^2$

Hot, thick disk & magnetic jet

$\mathrm{M_{BH}=10Msun}$

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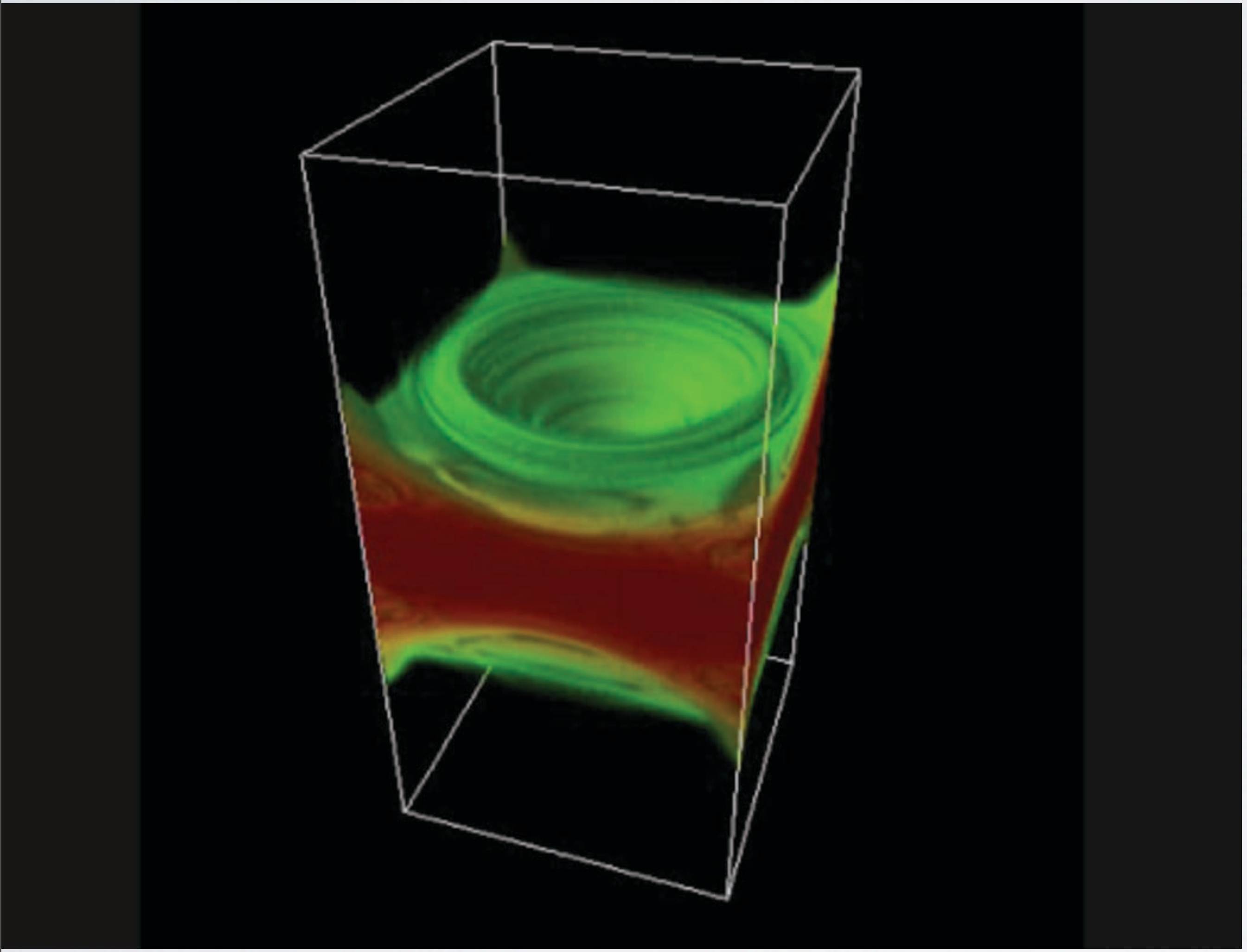

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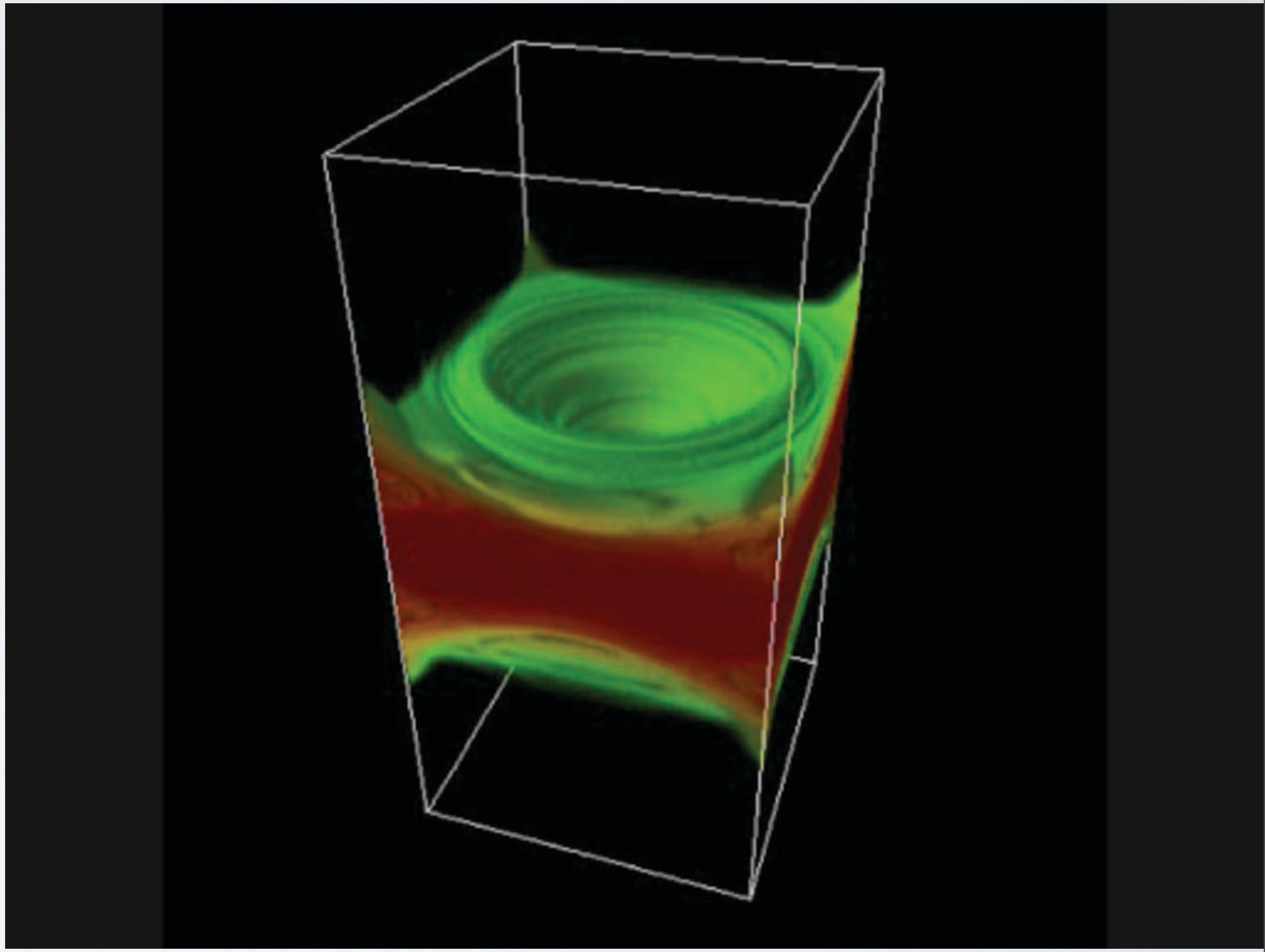

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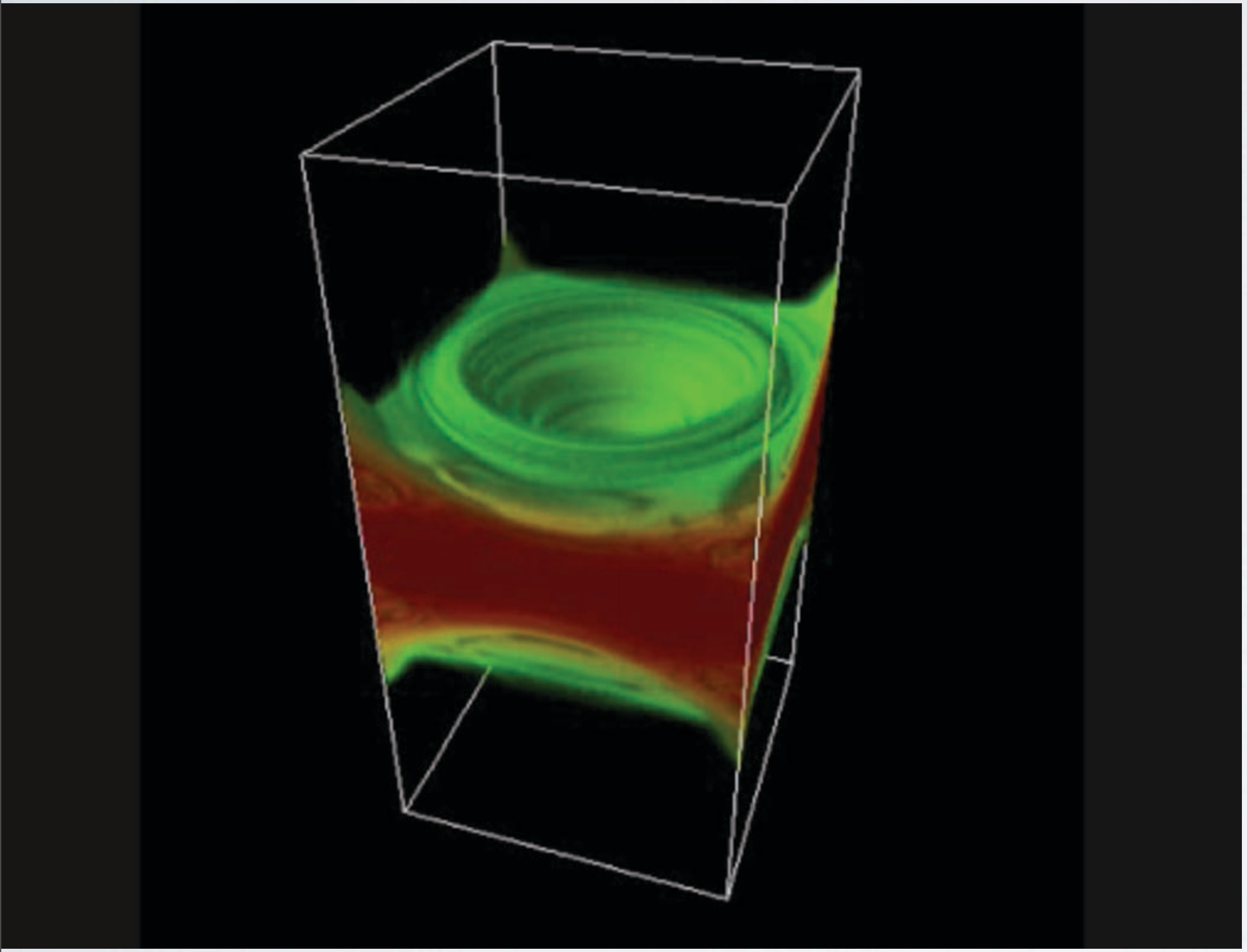

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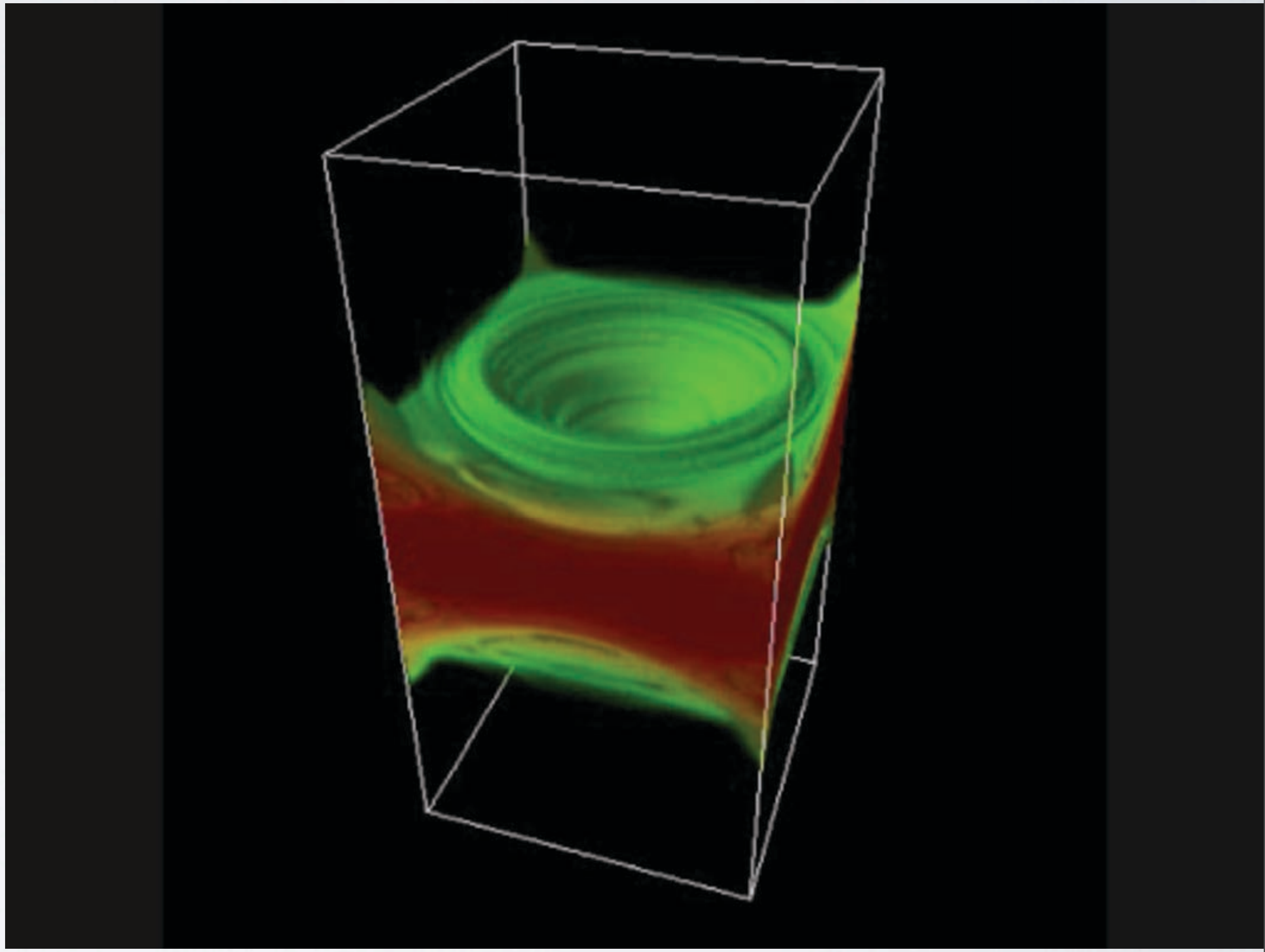

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Cold, thin disk

L~$10^{-12}L_{edd}$, Mdot~$10^{-5}L_{edd}/c^2$

Hot, thick disk & magnetic jet

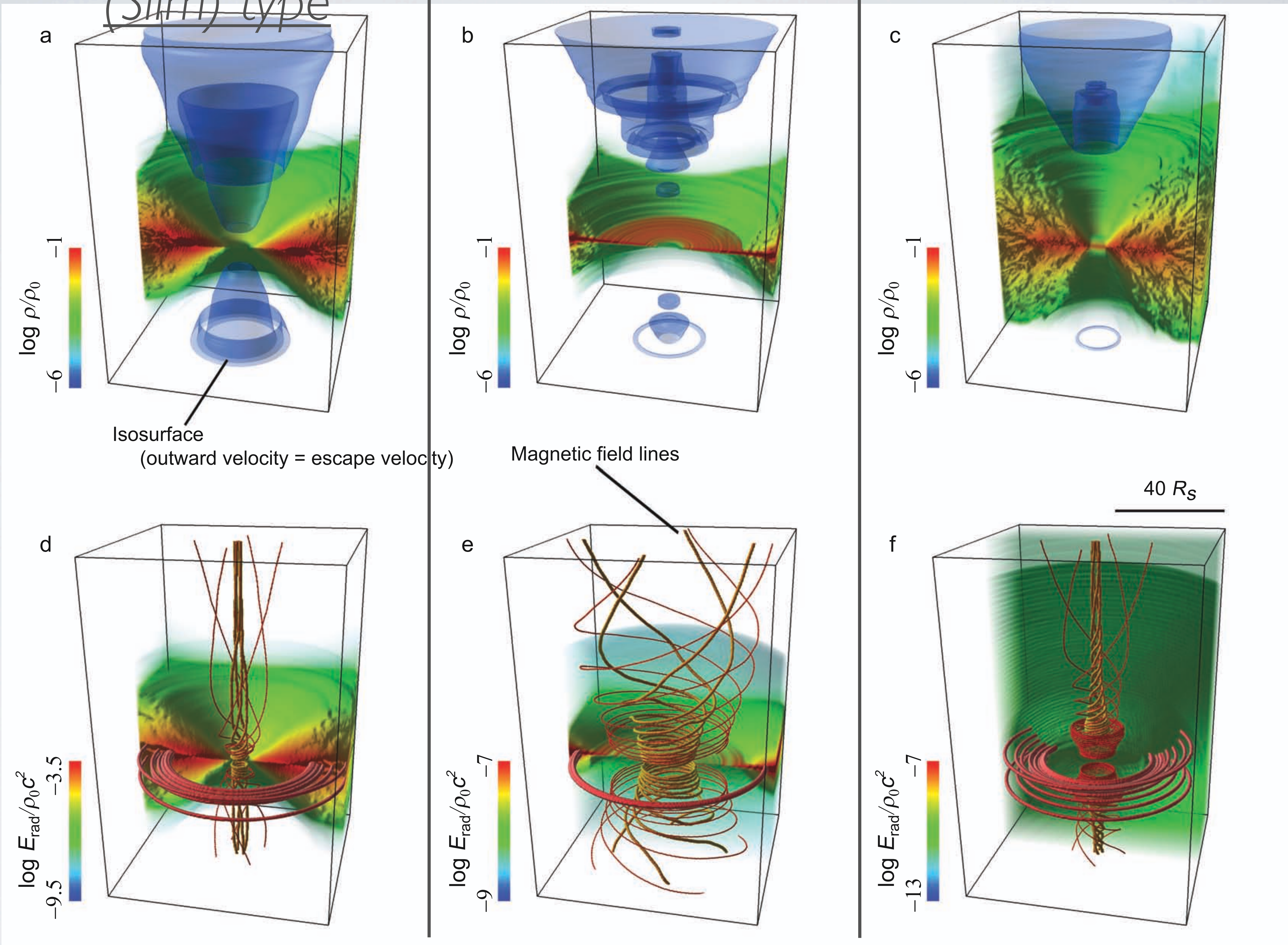
Super-Eddington (Slim) type

Standard type

RIAF type

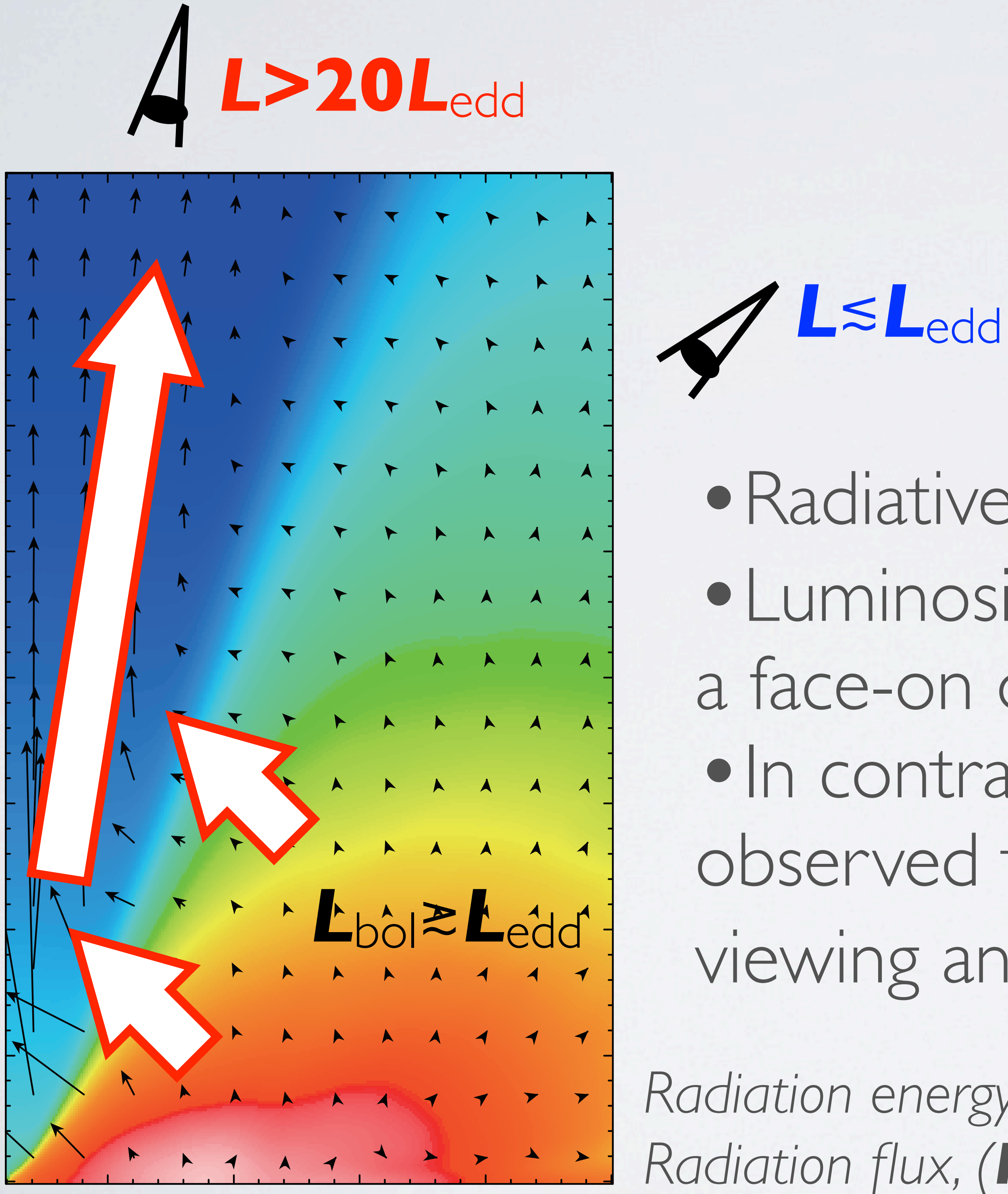
Normalized Densiy

Radiation Energy & Magnetic Fields



Our RMHD simulations succeeded in reproducing three types of flows (Super-Eddington, standard, RIAF)

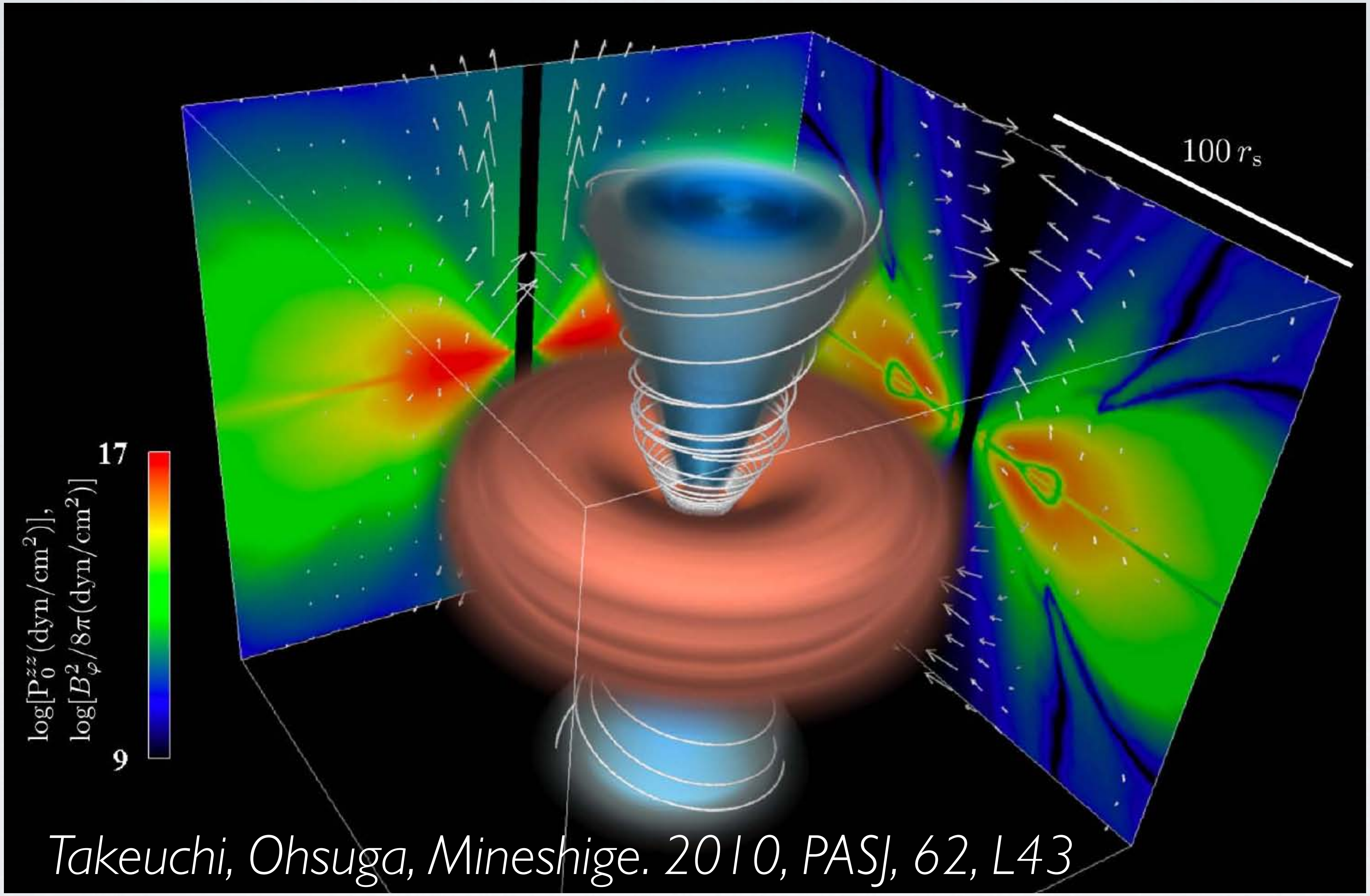
OBSERVED LUMINOSITY



- Radiative Flux is mildly collimated, $\lesssim 20°$
- Luminosity is estimated as $L>20L_{\rm edd}$ for a face-on observer.
- In contrast, the objects might be observed to be $L\lesssim L_{\rm edd}$, if observer's viewing angle is much larger than 20°.

Radiation energy (E_0, color)
Radiation flux, ($\boldsymbol{F}_0$, vector)

RADIATION-MHD JETS



Takeuchi, Ohsuga, Mineshige. 2010, PASJ, 62, L43

Our RMHD simulations reveal a new type of jet;
Radiatively-accelerated and magnetically collimated jet

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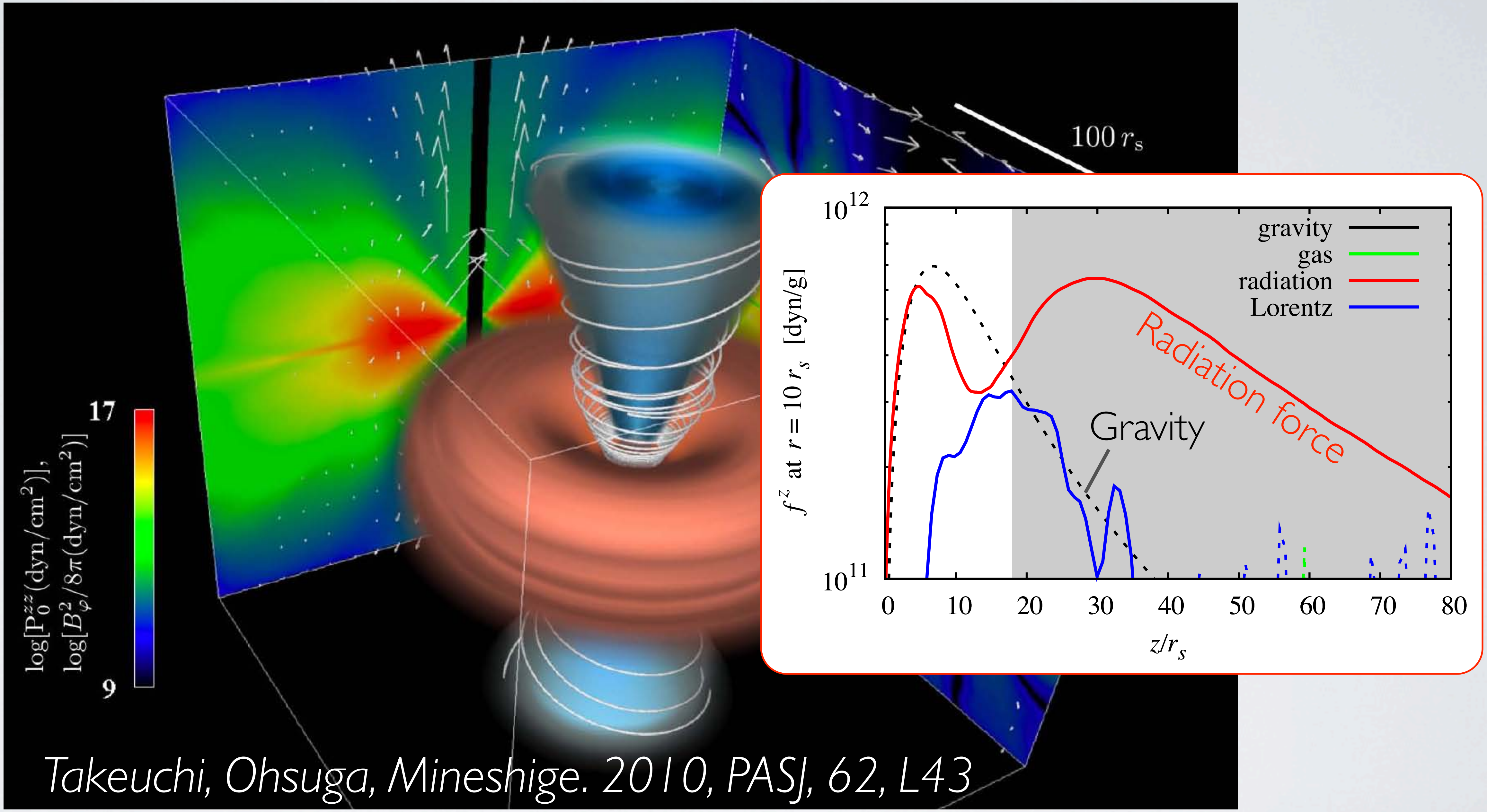

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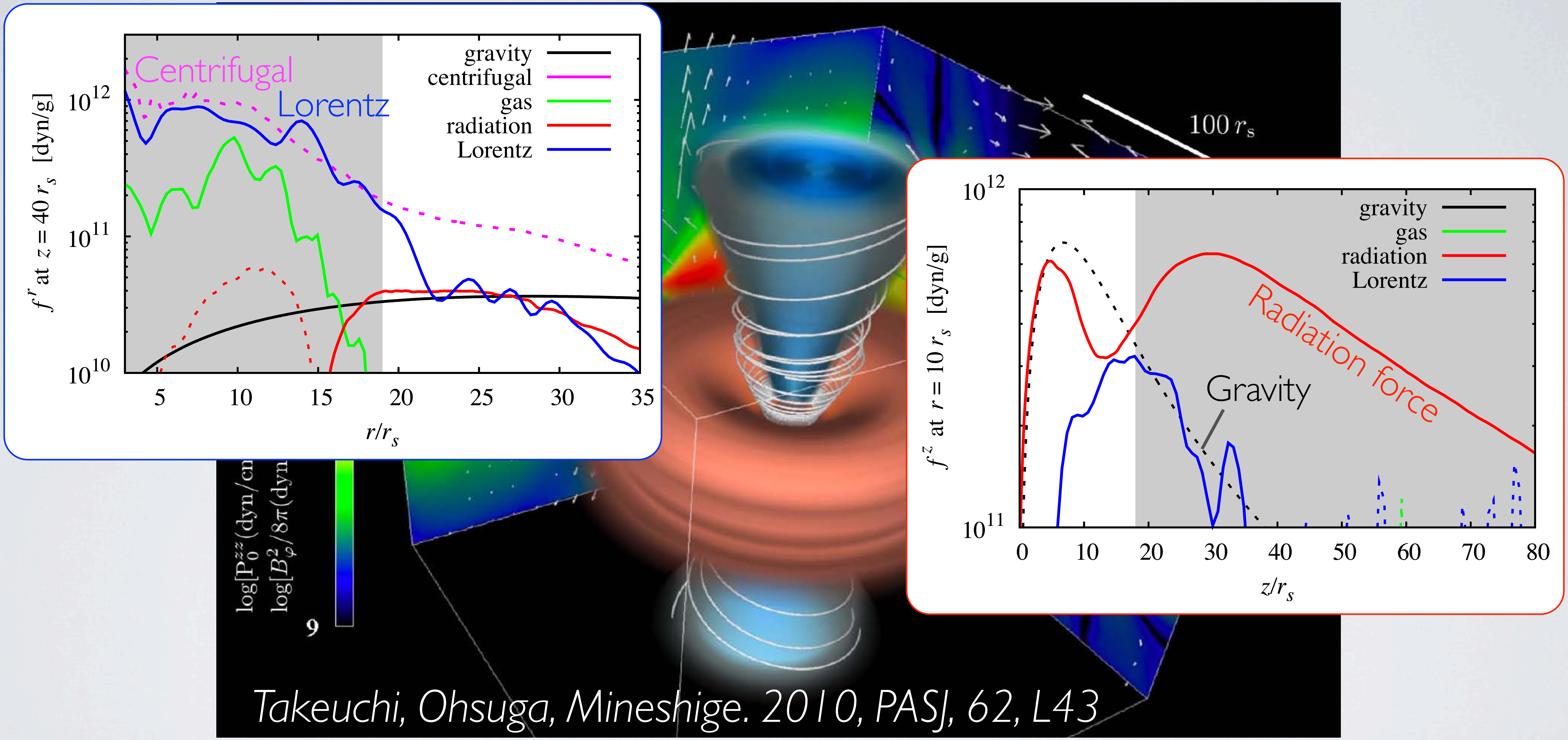

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TIME-DEPENDENT CLUMPY OUTFLOW

Ohsuga in prep.

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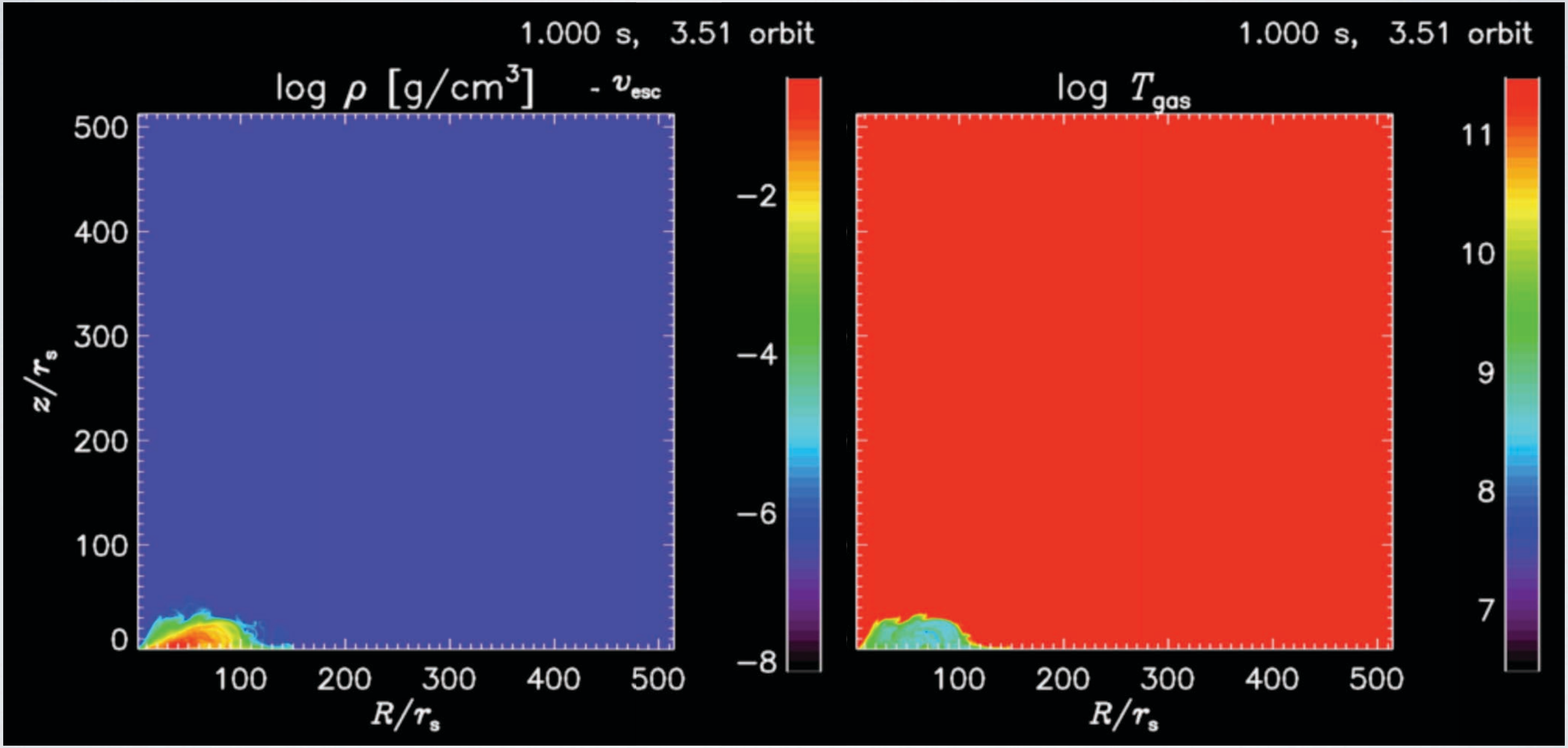

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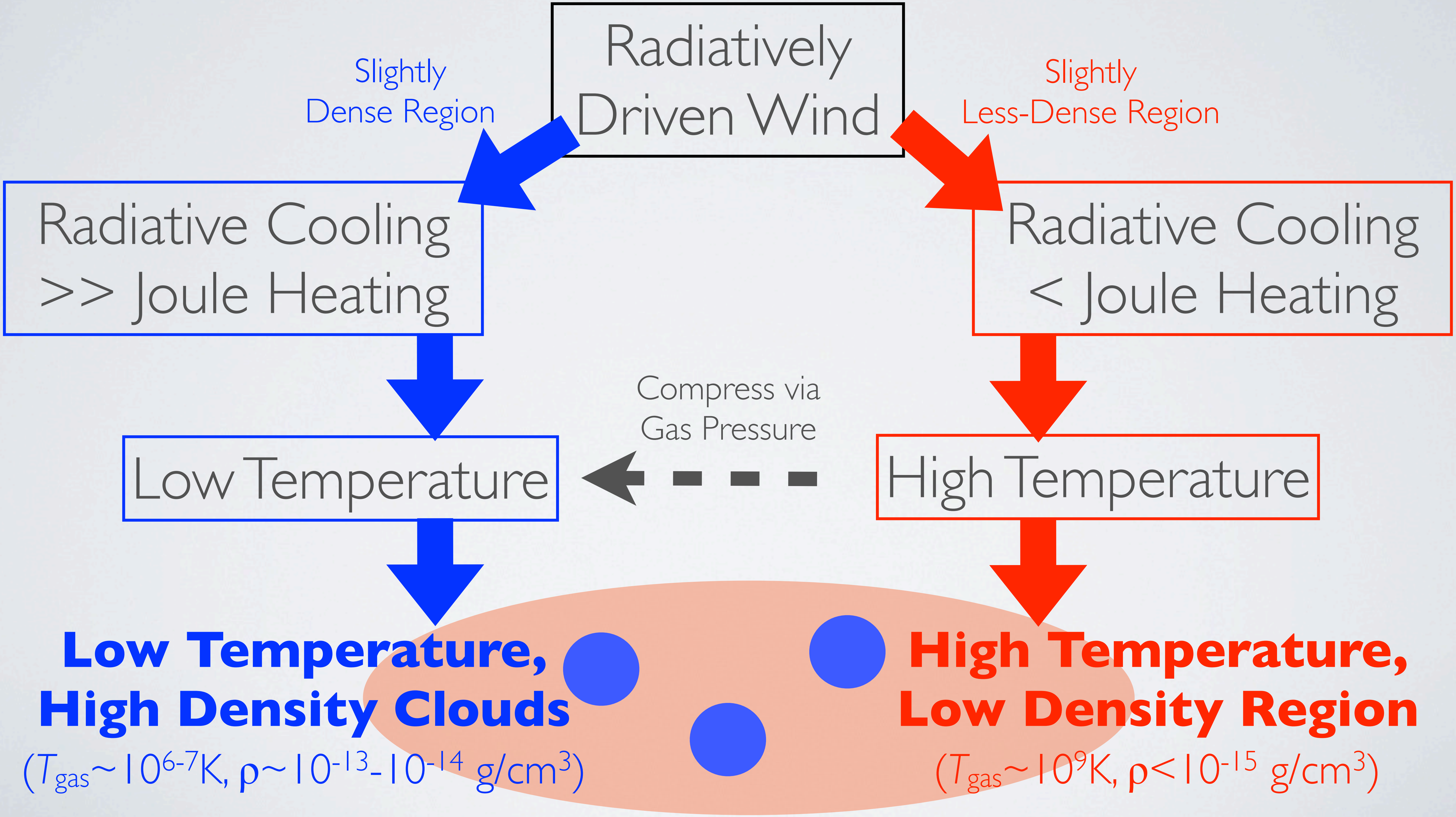
THERMAL INSTABILITY



Radiatively Driven Wind

Slightly Dense Region

Slightly Less-Dense Region

Radiative Cooling >> Joule Heating

Radiative Cooling < Joule Heating

Low Temperature

High Temperature

Compress via Gas Pressure

Low Temperature, High Density Clouds

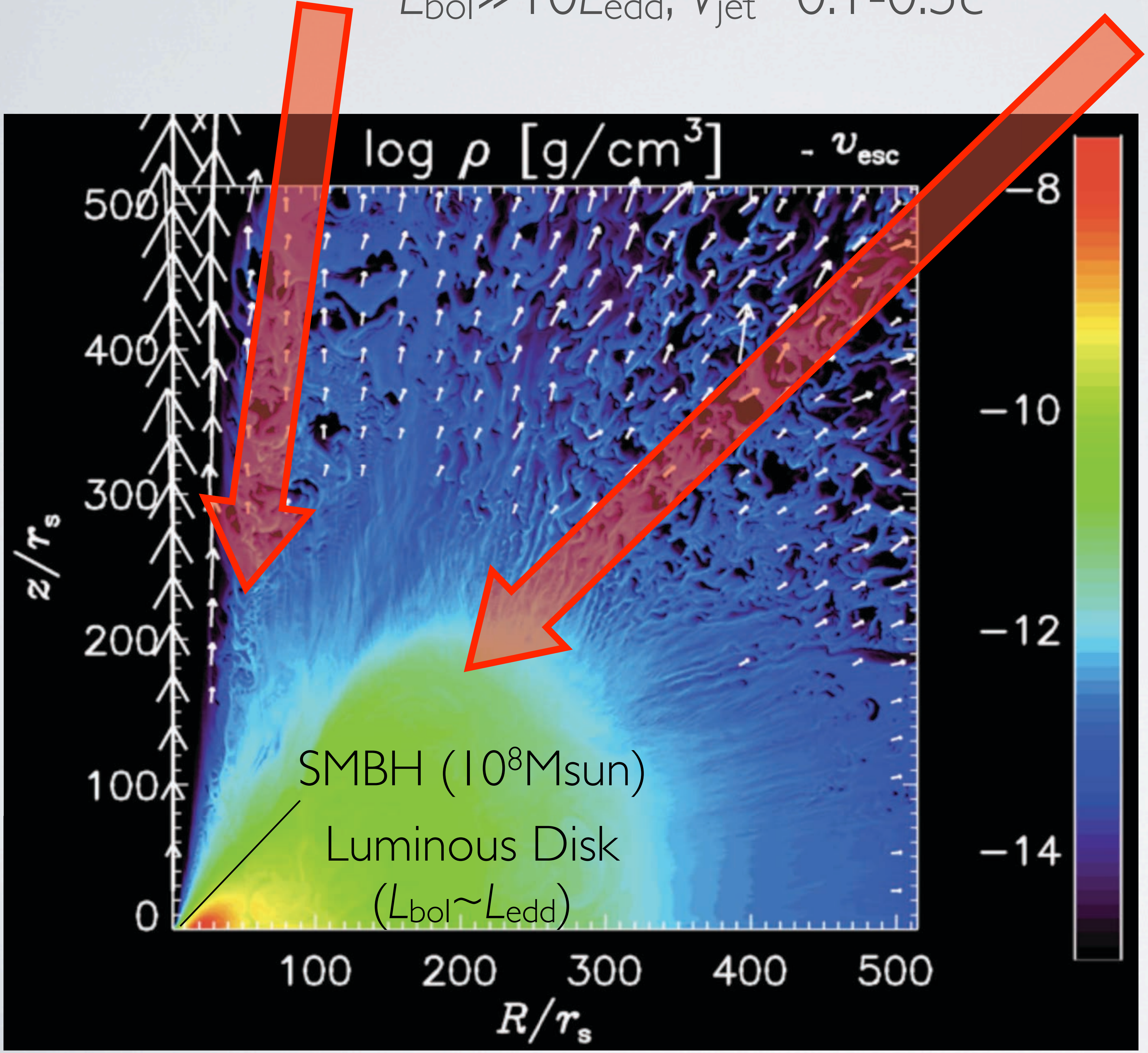
($T_{gas}\sim 10^{6\text{-}7}$K, $\rho\sim 10^{-13}$-10^{-14} g/cm^3)

High Temperature, Low Density Region

($T_{gas}\sim 10^{9}$K, $\rho < 10^{-15}$ g/cm^3)

Super-Eddington objects

$L_{bol} \gg 10 L_{edd}$, $V_{jet} \sim 0.1\text{-}0.5c$



SMBH (10^8Msun)

Luminous Disk ($L_{bol} \sim L_{edd}$)

Time-dependent absorbing feature.

$L_{bol} \lesssim L_{edd}$

$V_{out} \sim 0.03c\text{-}0.1c$

$\text{Log}(N_H) \sim 23\text{-}25$

Super-Eddington objects

$L_{bol} \gg 10 L_{edd}$, V_{jet}~0.1-0.5c

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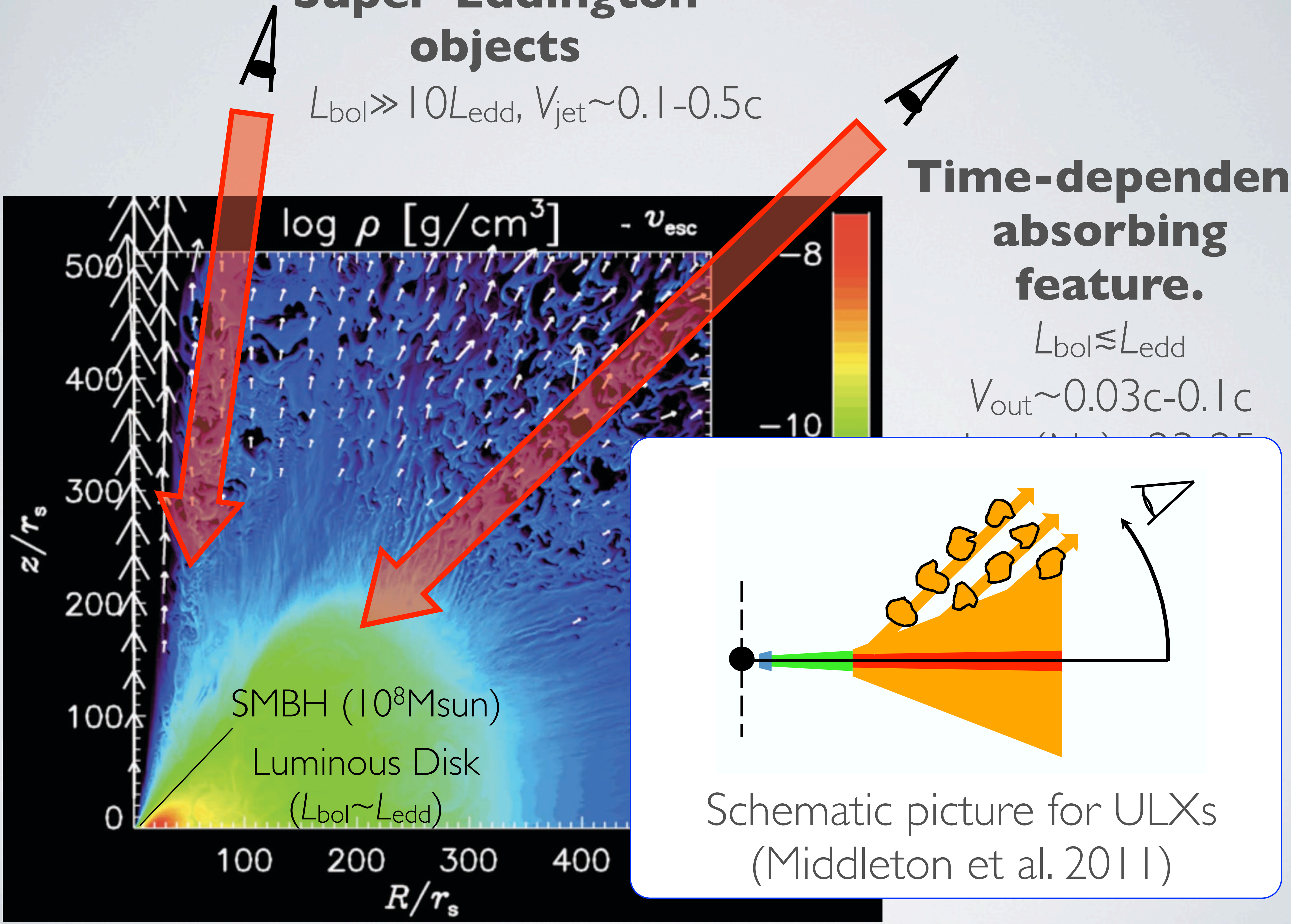
$L_{bol} \lesssim L_{edd}$

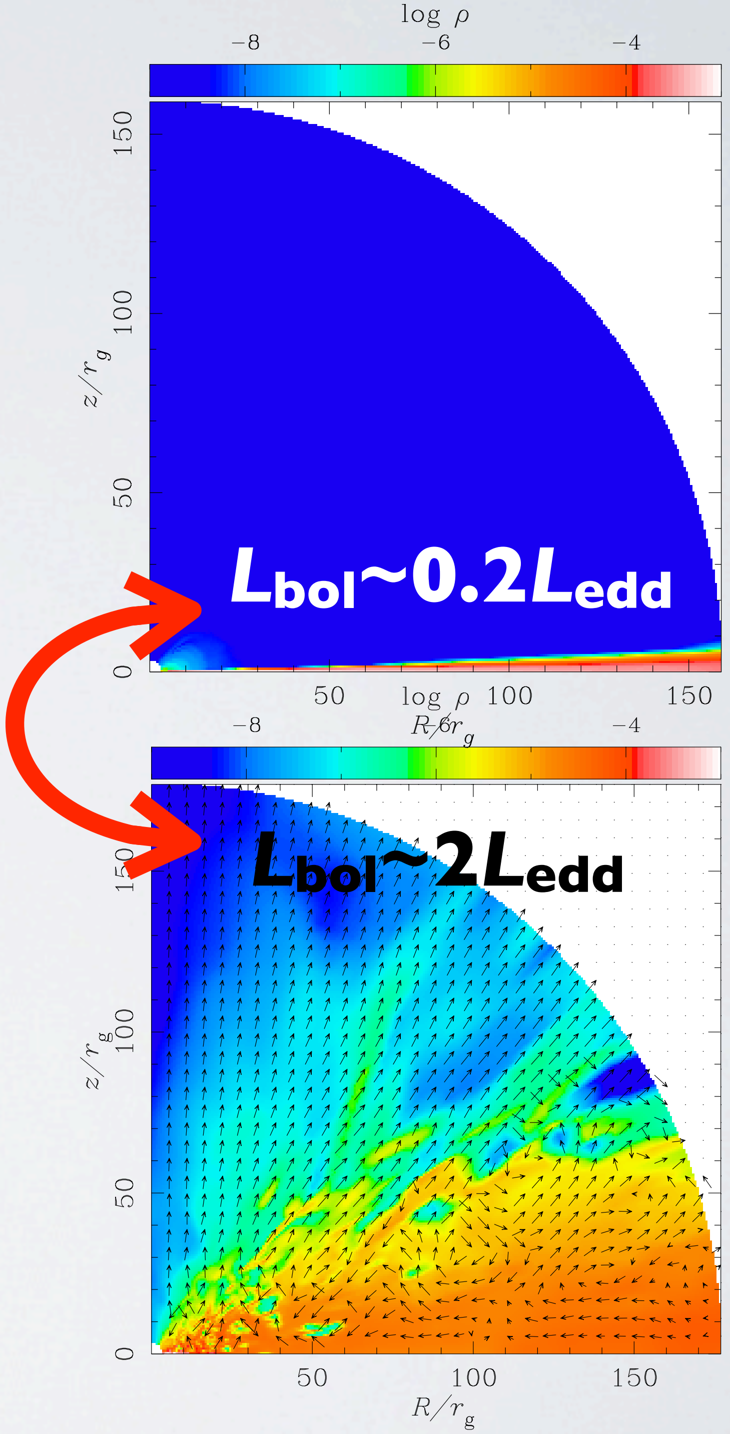
V_{out}~0.03c-0.1c



Schematic picture for ULXs (Middleton et al. 2011)

LIMIT-CYCLE OSCILLATION

Ohsuga 2006, ApJ, 640, 923



Thermal viscous instability induces limit-cycle behavior.

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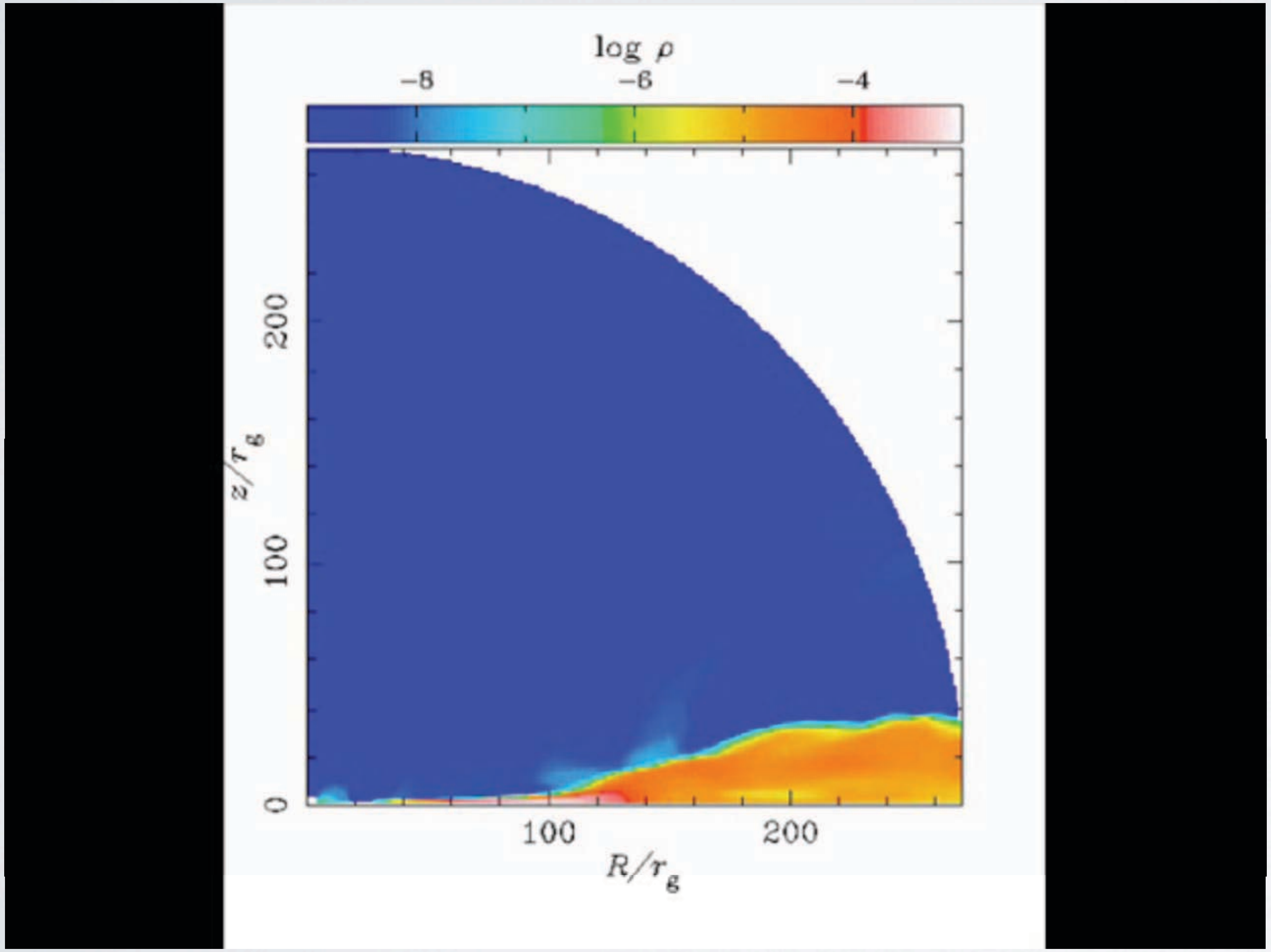

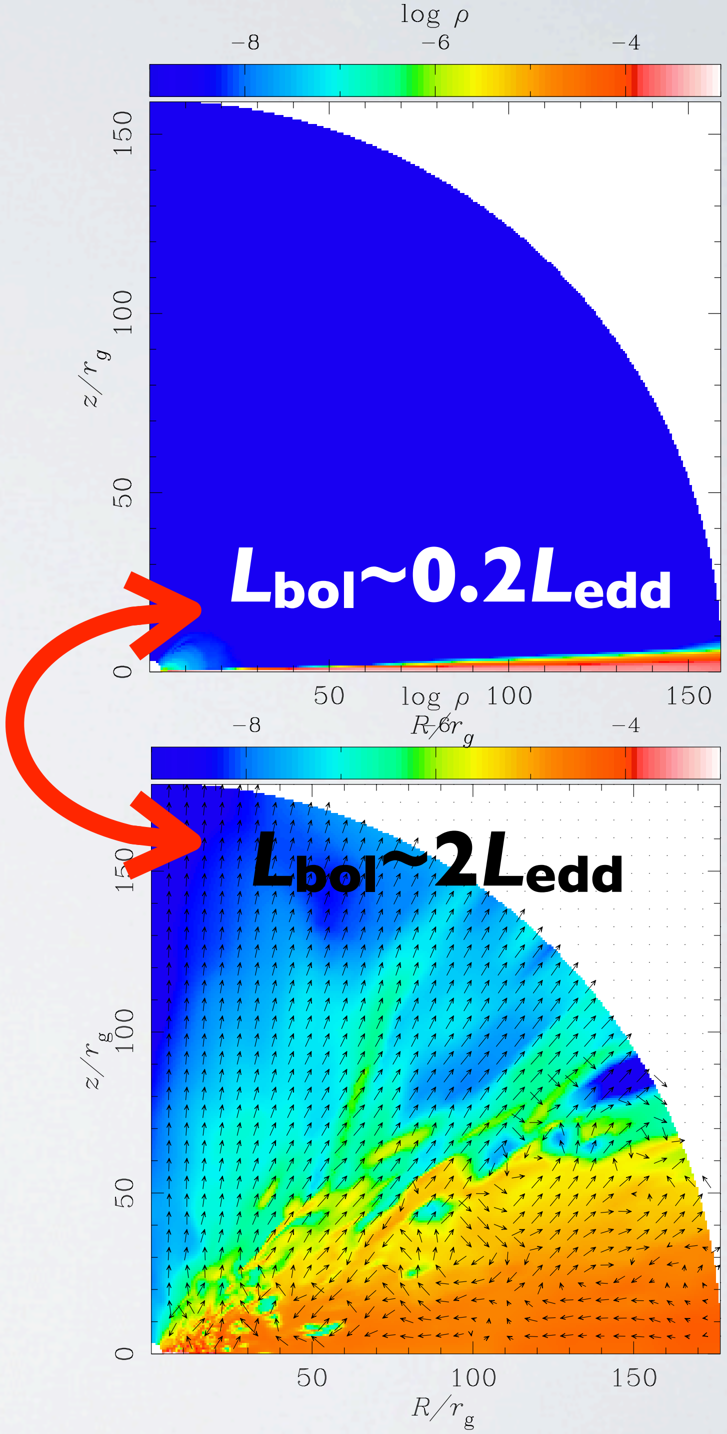

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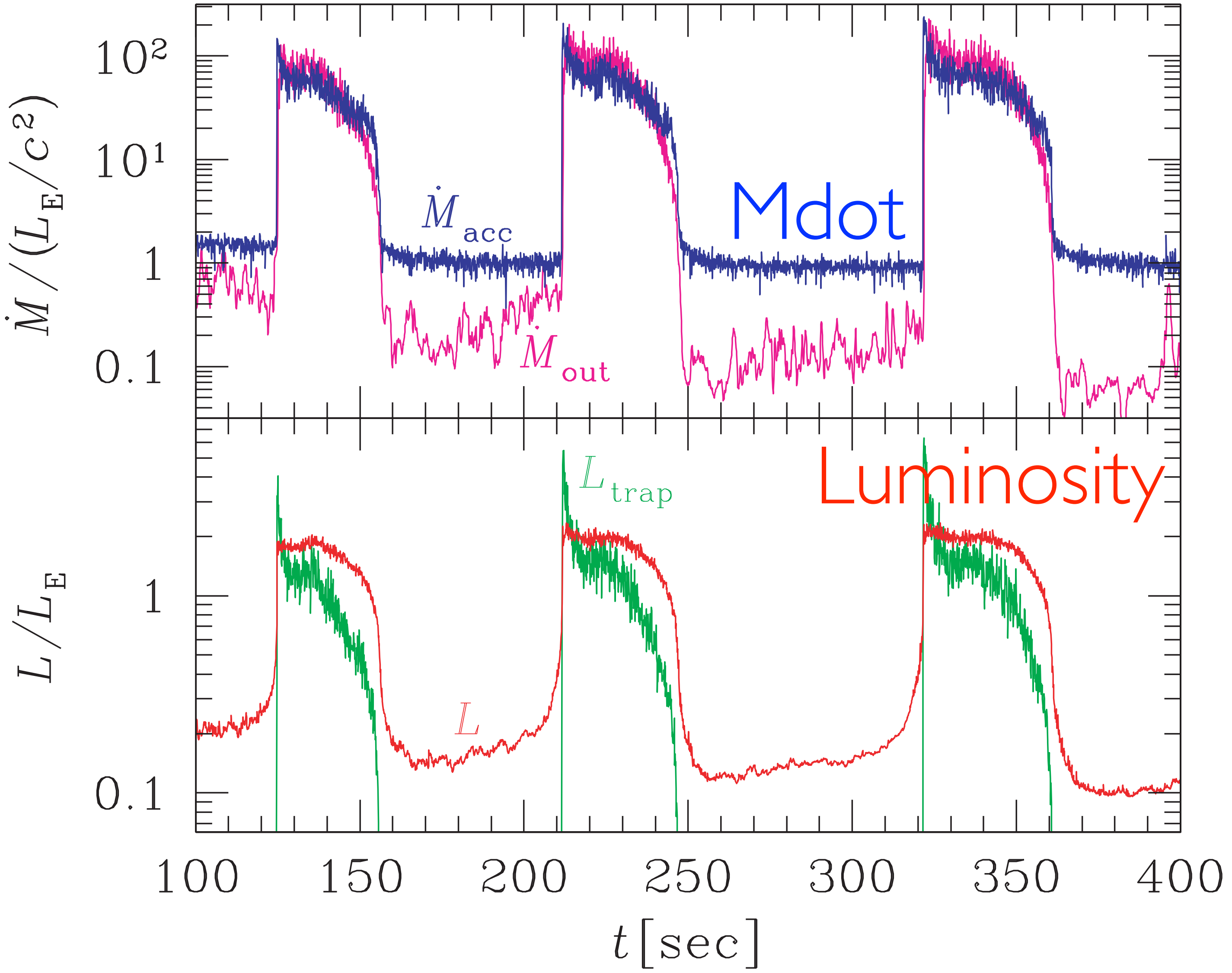
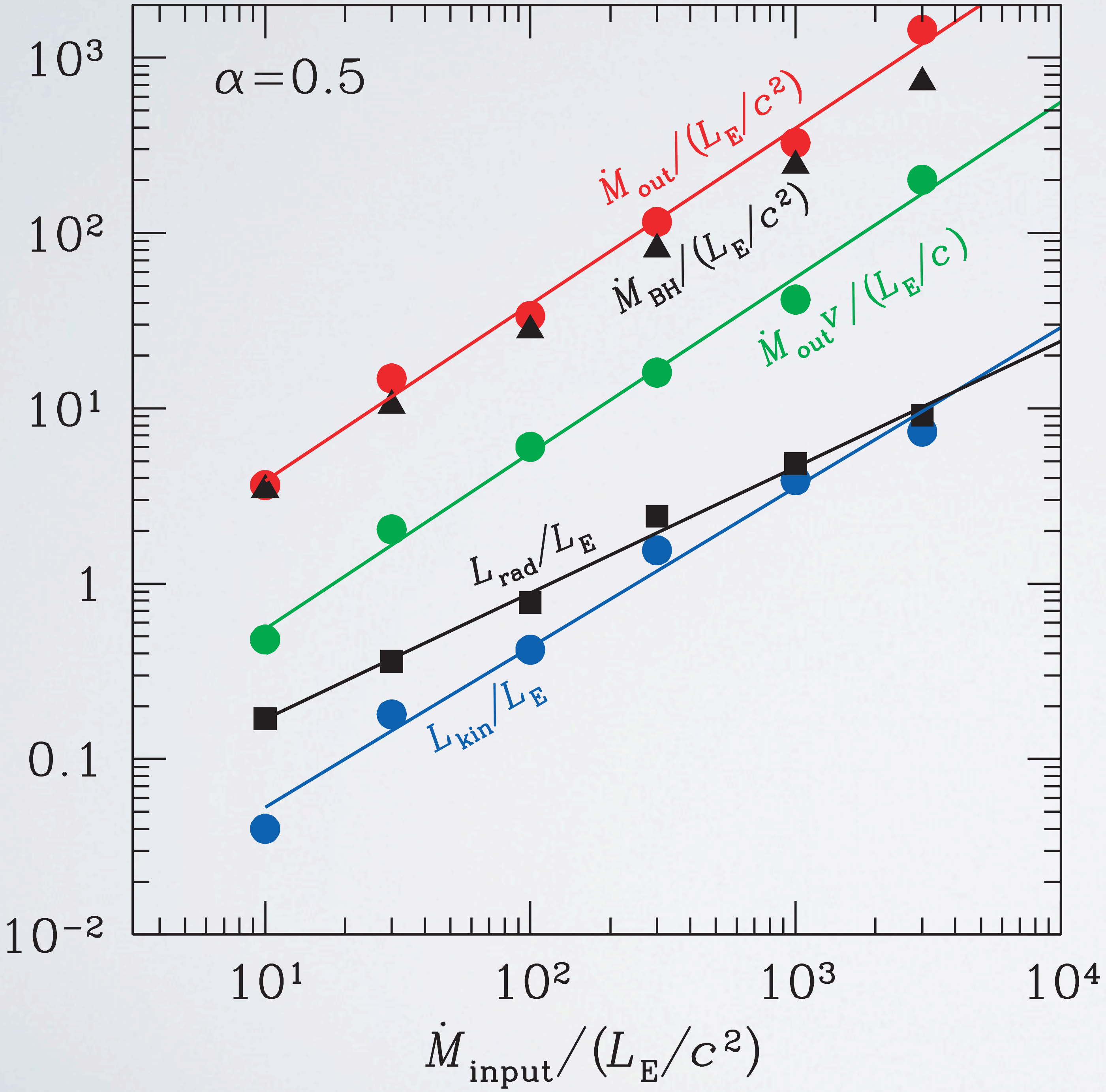


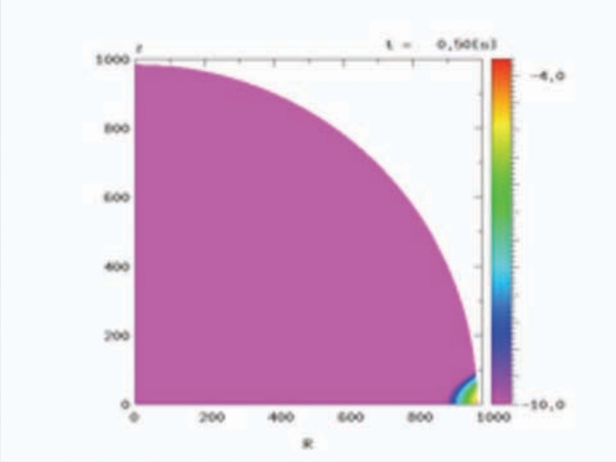
Our simulations nicely fit the observations of microquasar, GRS1915+105.

1. Luminosity variation
   $2L_{\rm edd} \leftrightarrow 0.2L_{\rm edd}$
2. Timescale~several 10 sec.
3. Intermittent outflow.

AGN FEEDBACK



Mass supply rate; from host galaxy to galactic center.



We find that mass outflow-rate can exceed L_{edd}/c^2, and momentum ejection-rate can exceed L_{edd}/c.

Feedback from the super-Eddington flow would affect the evolution of the host galaxy and might contribute to establish '*M*-σ relation' (King 2003).