RADIATIVE AND MECHANICAL EFFICIENCIES OF BLACK HOLE ACCRETION
-
BLACK HOLE FEEDBACK

Olek Sądowski - MIT
Massimo Gaspari - Princeton

Einstein Fellows

KITP, February 2017

1. EFFICIENCY OF BLACK HOLE ACCRETION

2. AGN FEEDBACK

3. SUBGRID

ACCRETION ON BLACK HOLES

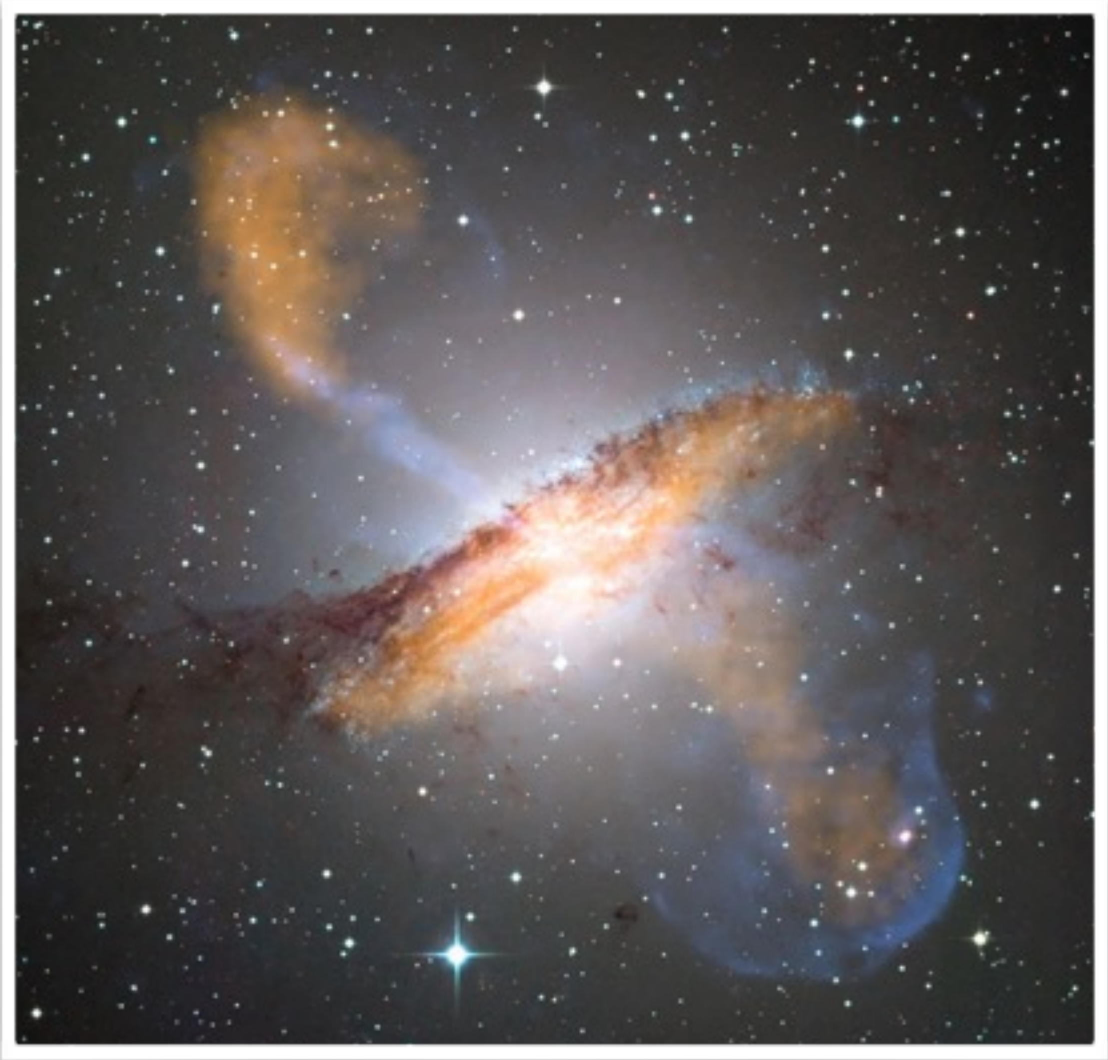
Black holes are most compact - this **compactness** allows for extraction of significant fraction of the gravitational energy (up to 40% of accreted rest mass energy for a BH!)

BH accretion is involved in some of **most energetic** phenomena:

- X-ray binaries
- Active galactic nuclei
- Tidal disruptions of stars
- Gamma ray-bursts
- Ultraluminous X-ray Sources

(NASA)

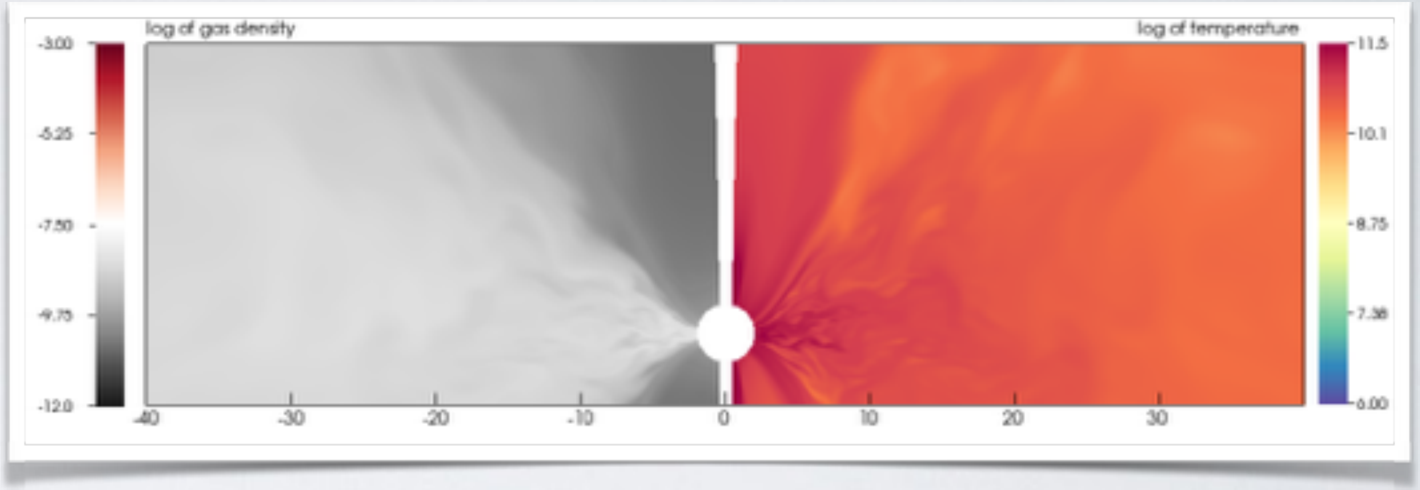
Copyright (C) 2005, by Fahad Sulehria, http://www.novacelestia.com.

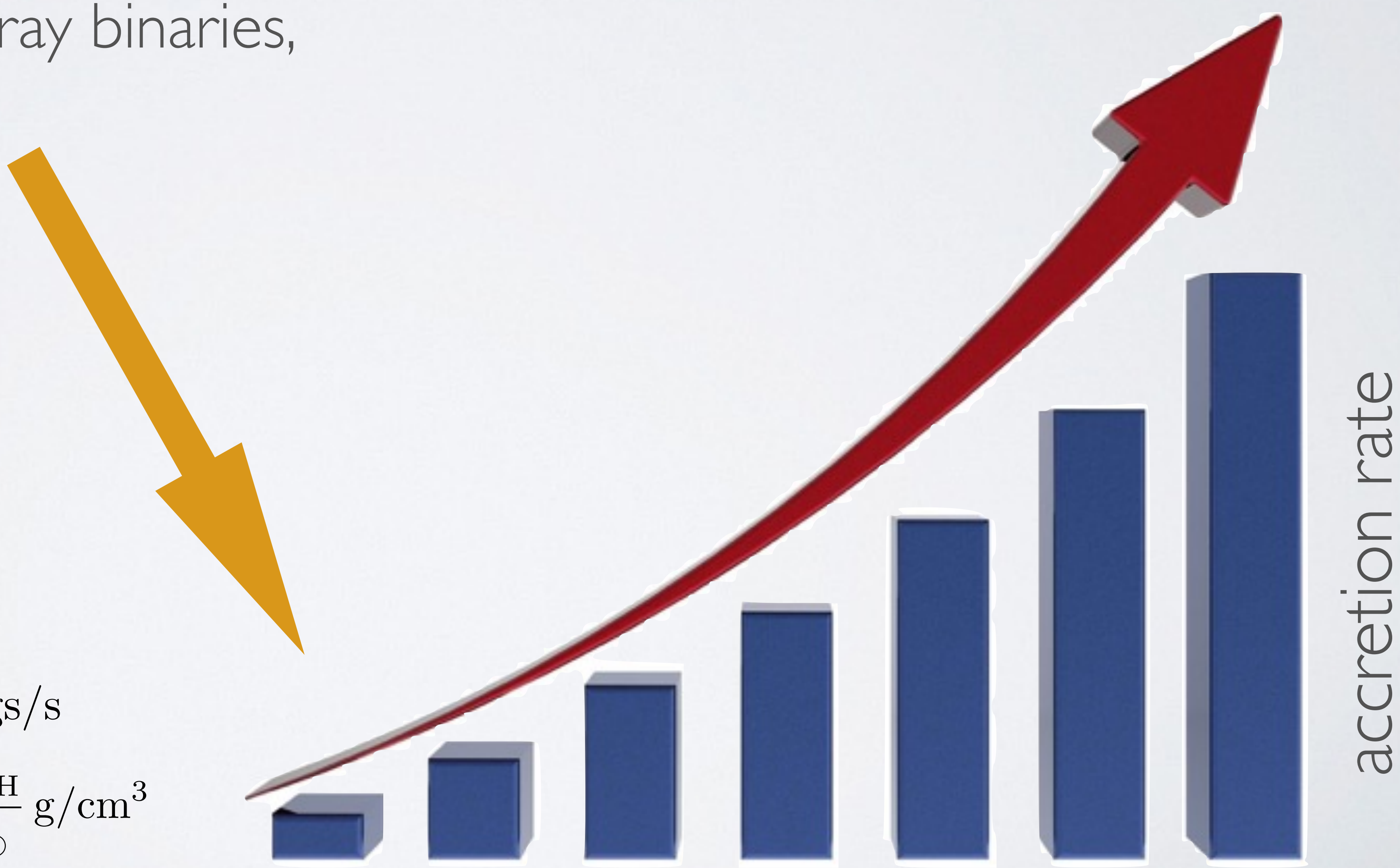


MODES OF ACCRETION

Thick and hot (ADAF)

- Lowest accretion rates $\dot{M} \lesssim 10^{-3} \dot{M}_{\rm Edd}$
- Optically thin, hard spectrum
- Geometrically thick
- low/hard state of X-ray binaries, LLAGN, **Sgr A***





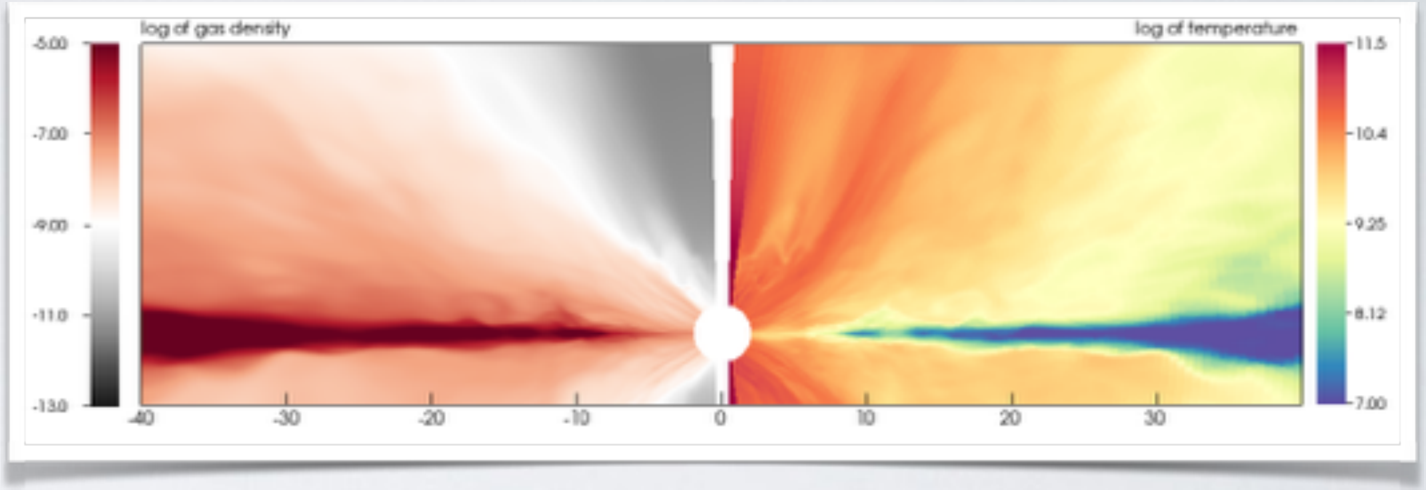
$$L_{\rm Edd} = 1.25 \cdot 10^{38} M/M_{\odot} \text{ ergs/s}$$

$$\dot{M}_{\rm Edd} = \frac{L_{\rm Edd}}{\eta c^2} = 2.4 \cdot 10^{18} \frac{M_{\rm BH}}{M_{\odot}} \text{ g/cm}^3$$

MODES OF ACCRETION

Thin disks

- moderate accretion rates $10^{-3}\dot{M}_{\rm Edd} \lesssim \dot{M} \lesssim 1\dot{M}_{\rm Edd}$
- optically thick, soft spectrum
- geometrically thin
- high/soft state of X-ray binaries, quasars



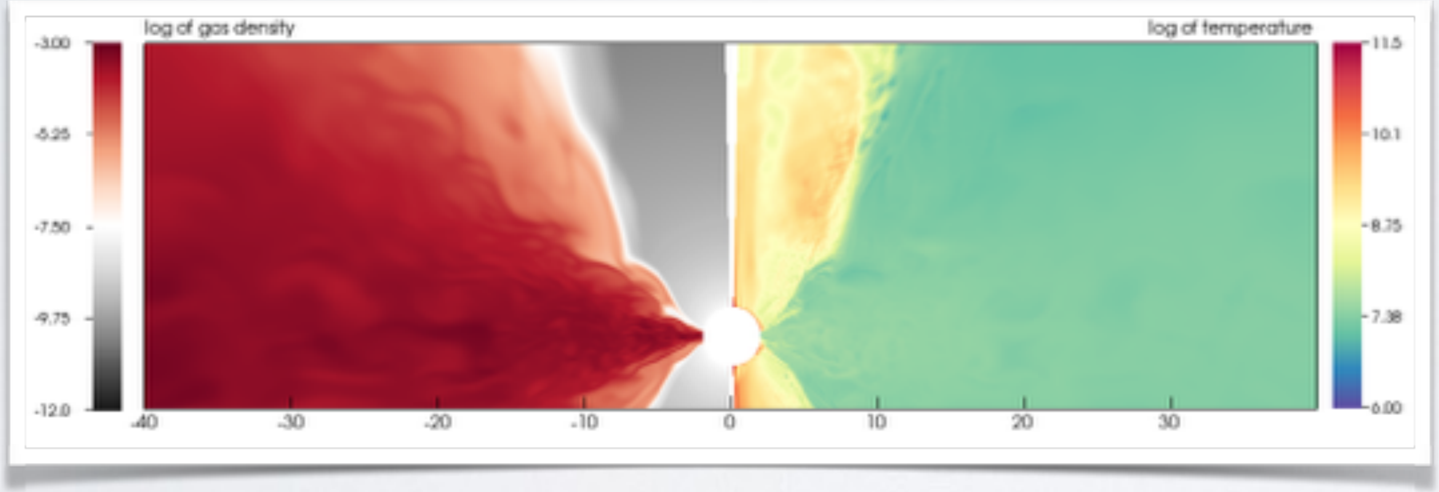
$$L_{\rm Edd} = 1.25 \cdot 10^{38} M/M_\odot \;{\rm ergs/s}$$

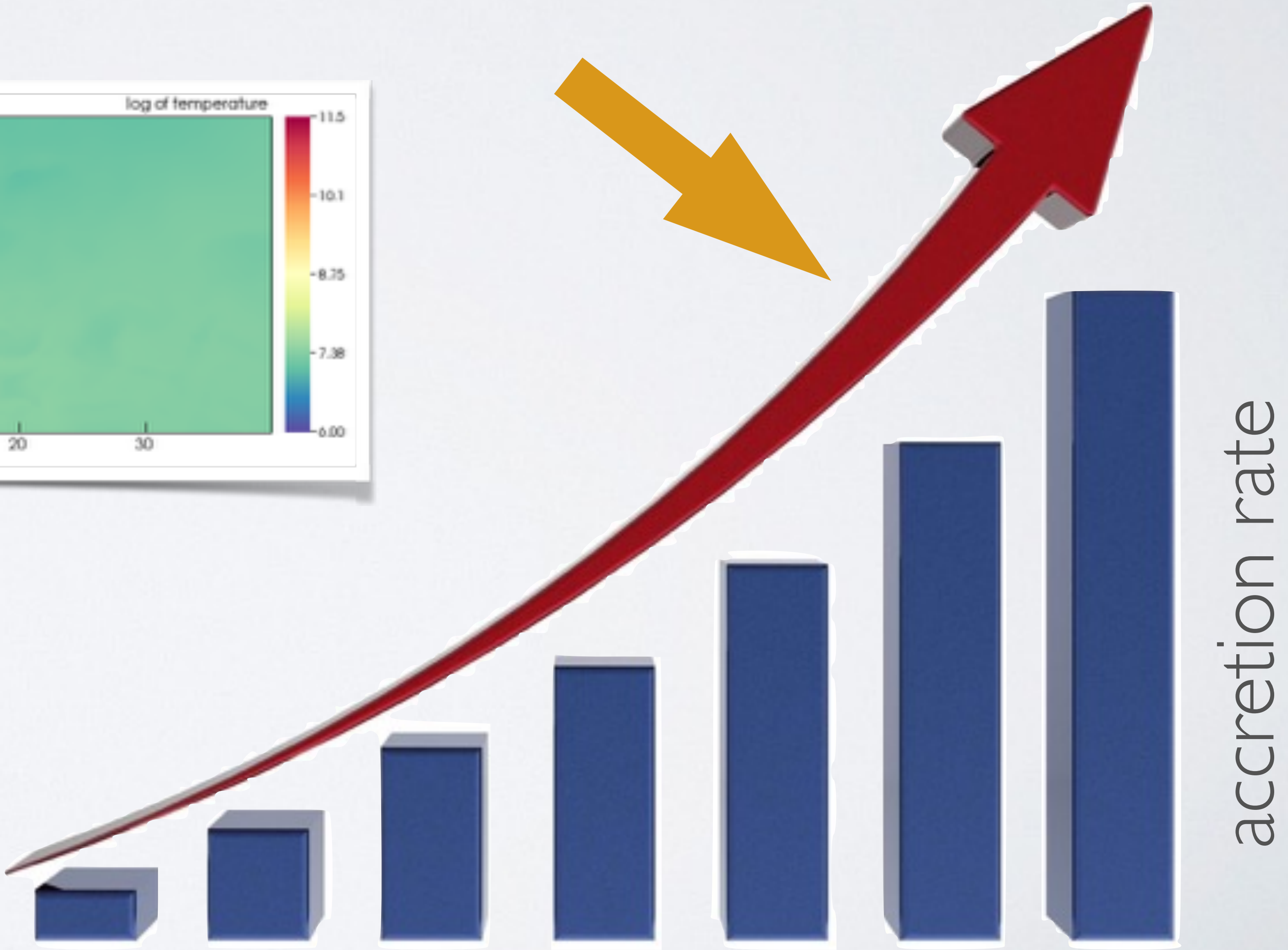
$$\dot{M}_{\rm Edd} = \frac{L_{\rm Edd}}{\eta c^2} = 2.4 \cdot 10^{18} \frac{M_{\rm BH}}{M_\odot} \;{\rm g/cm^3}$$

MODES OF ACCRETION

Super-critical

- highest accretion rates $\dot{M} \gtrsim 1\dot{M}_{\rm Edd}$
- optically and geometrically thick
- ultraluminous X-ray sources (ULX), gamma ray bursts (GRB), tidal disruptions of stars (TDEs)



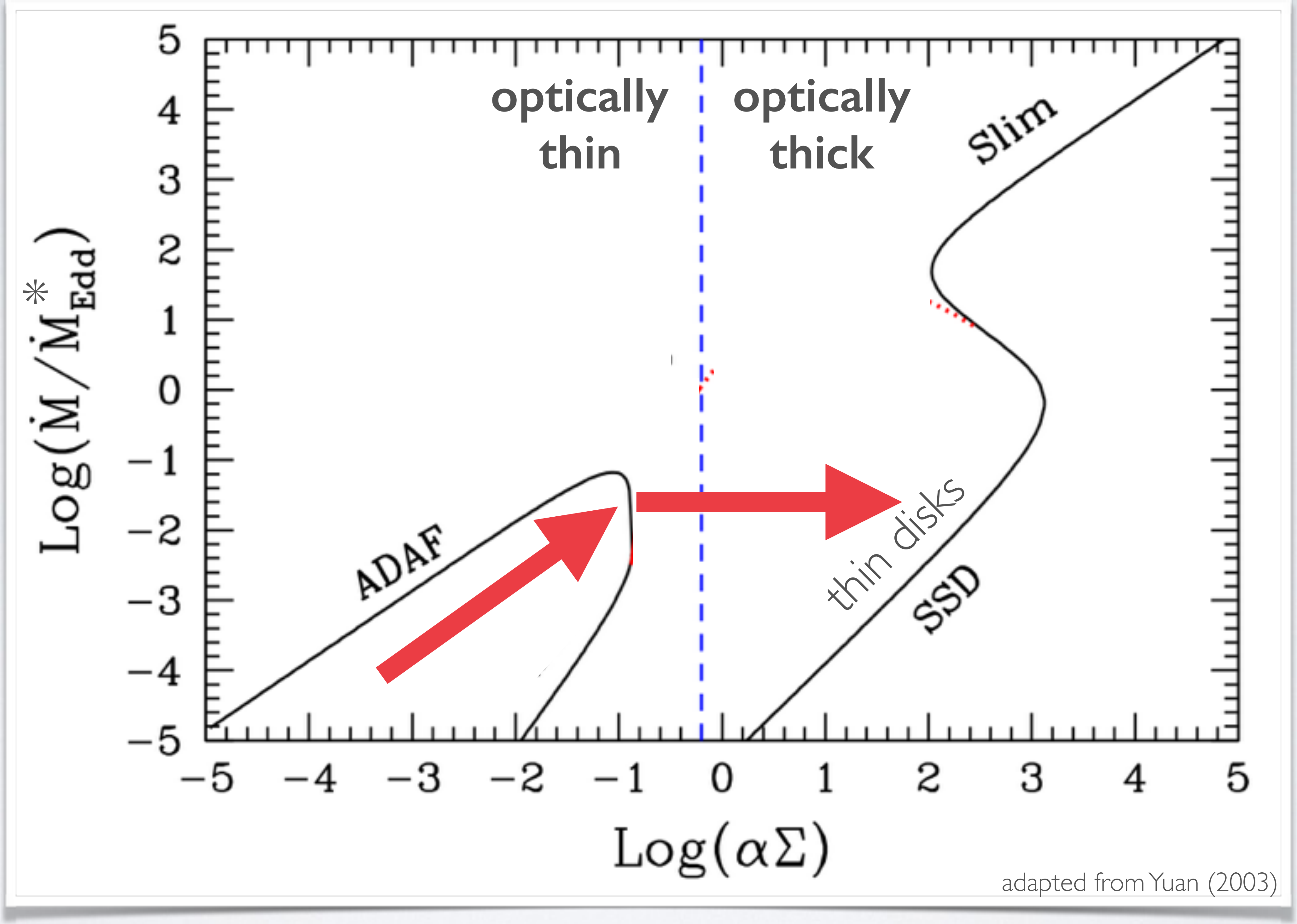


$$L_{\rm Edd} = 1.25 \cdot 10^{38} M/M_{\odot}\, {\rm ergs/s}$$

$$\dot{M}_{\rm Edd} = \frac{L_{\rm Edd}}{\eta c^2} = 2.4 \cdot 10^{18} \frac{M_{\rm BH}}{M_{\odot}}\, {\rm g/cm^3}$$

TRANSITION REGIME

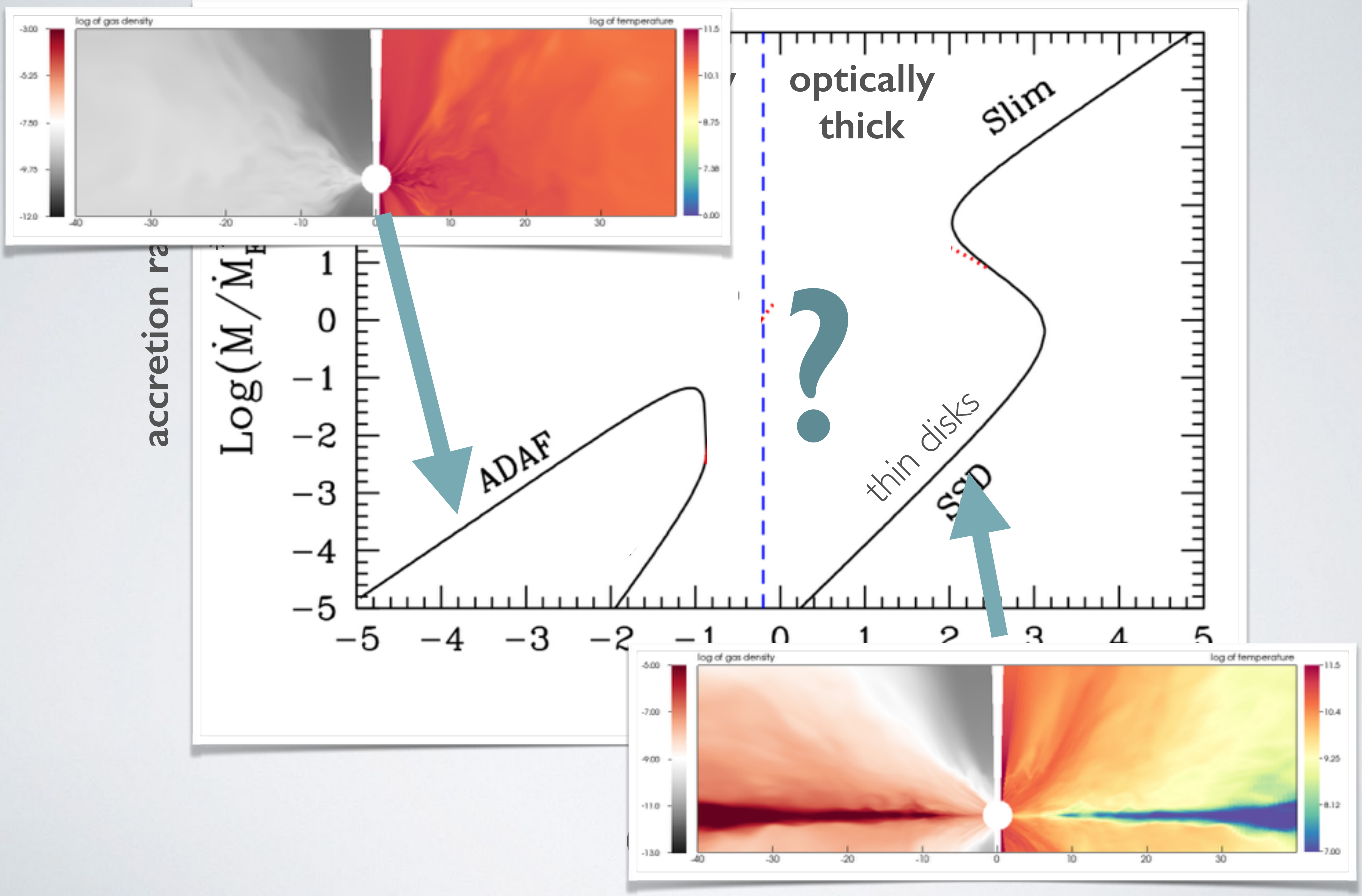
accretion rate



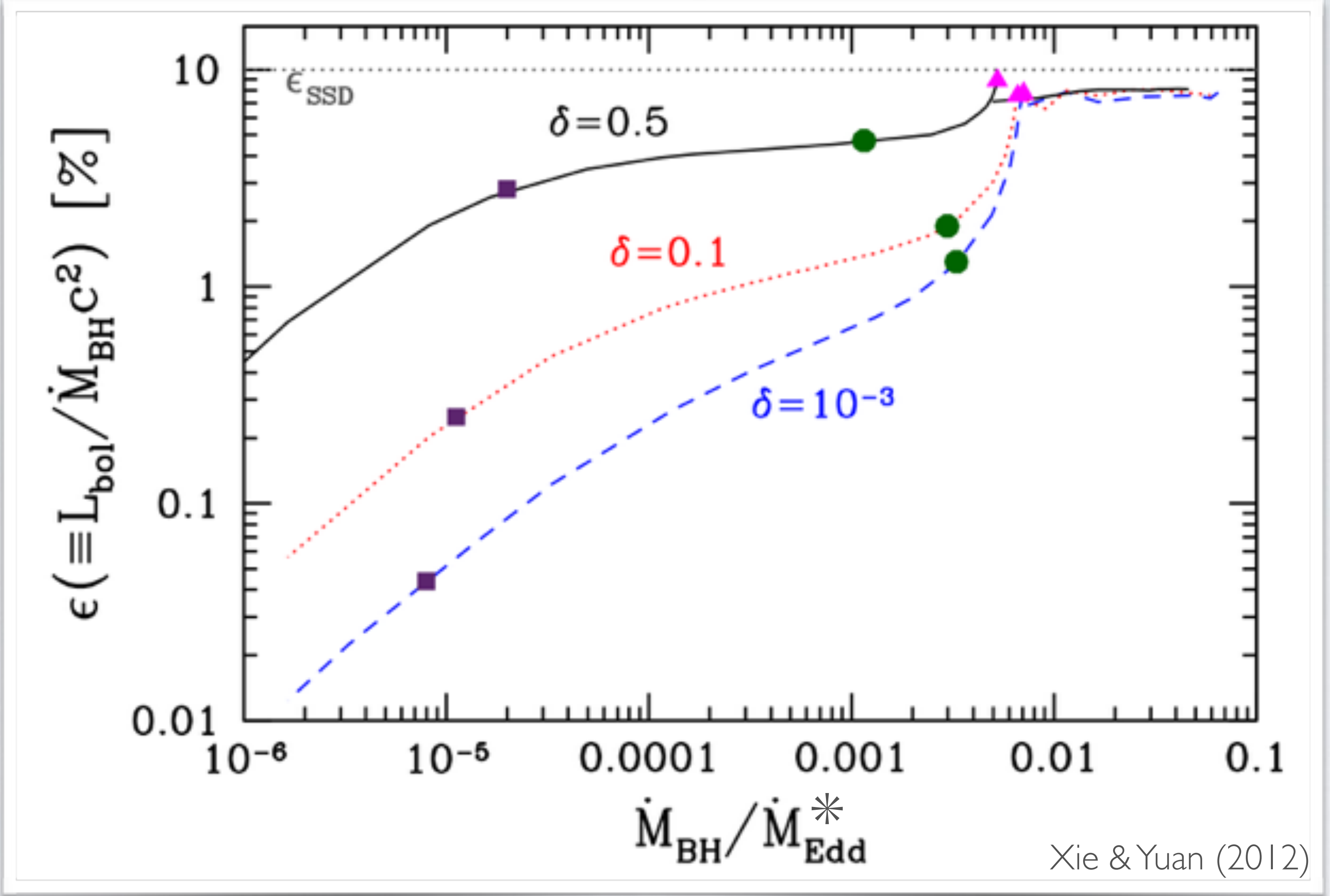
adapted from Yuan (2003)

surface density
(~optical depth)

TRANSITION REGIME



TRANSITION REGIME



Xie & Yuan (2012)

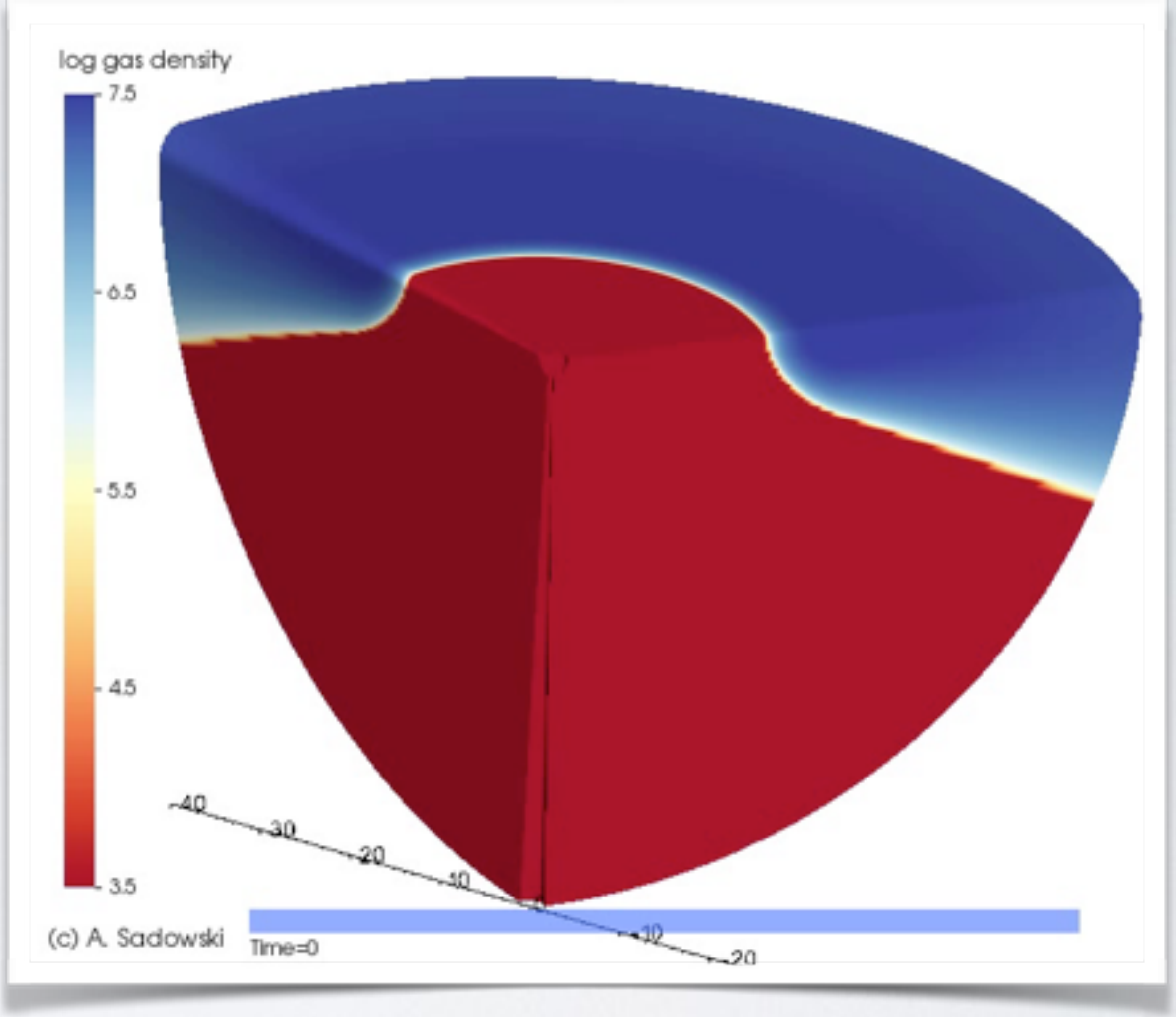
- Radiative output increases with accretion rate
- Radiative efficiency depends on electron heating (here described through the electron heating fraction δ_{e})

SIMULATIONS

SIMULATING BH ACCRETION

Essential components:

- space-time:
  (GR, Kerr-Schild metric)
- magnetized, fully ionized gas:
  ideal MHD
- photons:
  radiation transfer (simplified)
- electrons:
  thermal & non-thermal
- radiative postprocessing:
  spectra, images
- multidimensional fluid dynamics solver

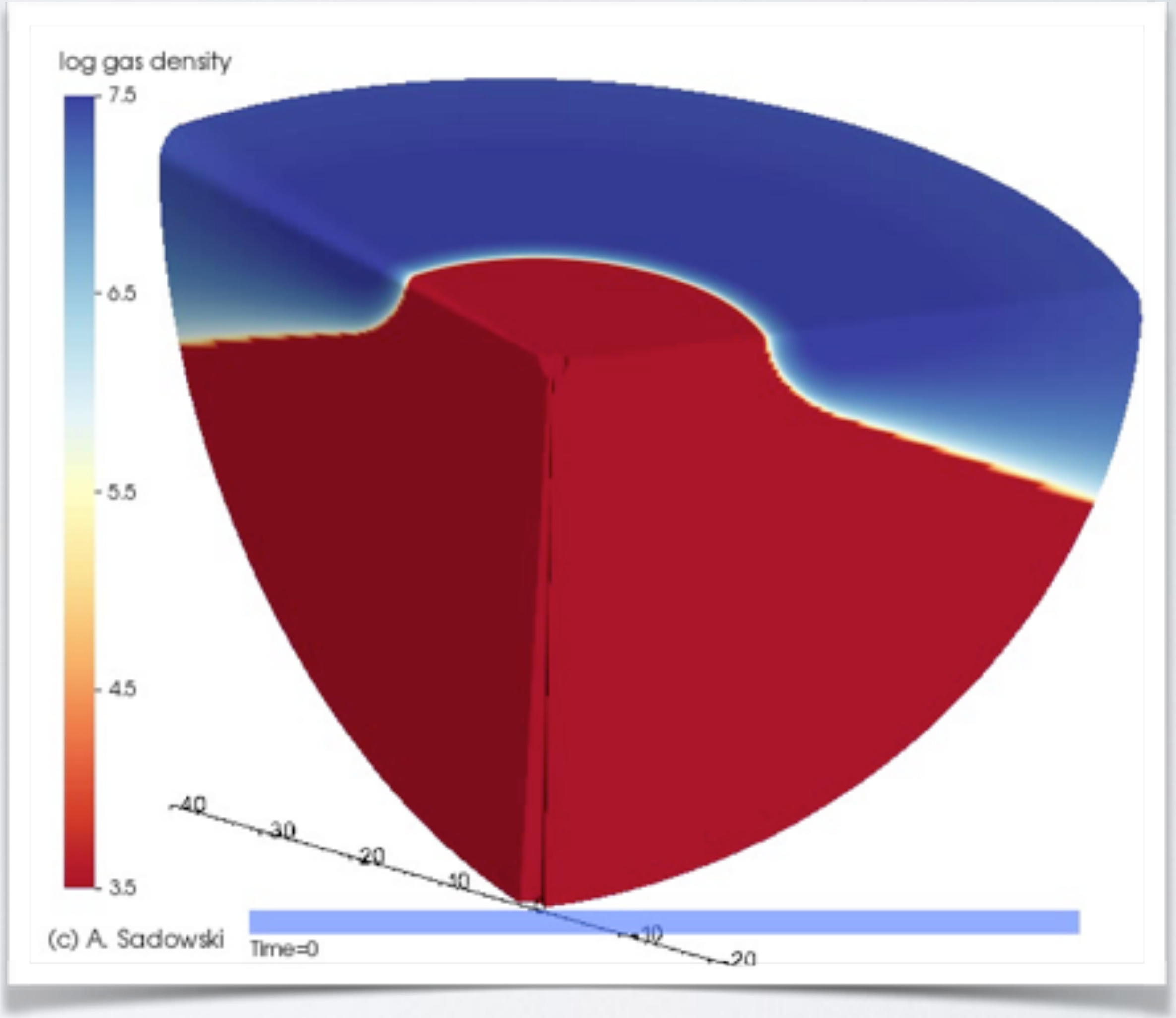


(c) A. Sadowski

SIMULATING BH ACCRETION

Essential components:

- space-time:
  (GR, Kerr-Schild metric)
- magnetized, fully ionized gas:
  ideal MHD
- photons:
  radiation transfer (simplified)
- electrons:
  thermal & non-thermal
- radiative postprocessing:
  spectra, images
- multidimensional fluid dynamics solver



KORAL (Sadowski+13,14,15)

- **Finite-difference, explicit + implicit**, conserving scheme for solving GR ideal RMHD
- **Radiation** evolved under two-moment approximation, provides cooling and pressure
- Grey but conservation of **number of photons** (allows for tracking the radiation temperature)
- **Comptonization**
- **Synchrotron and bremmstrahlung** Planck and Rosseland opacities
- Independent evolution of thermal **electrons and ions**
- **Coulomb** coupling
- **Non-thermal** electrons

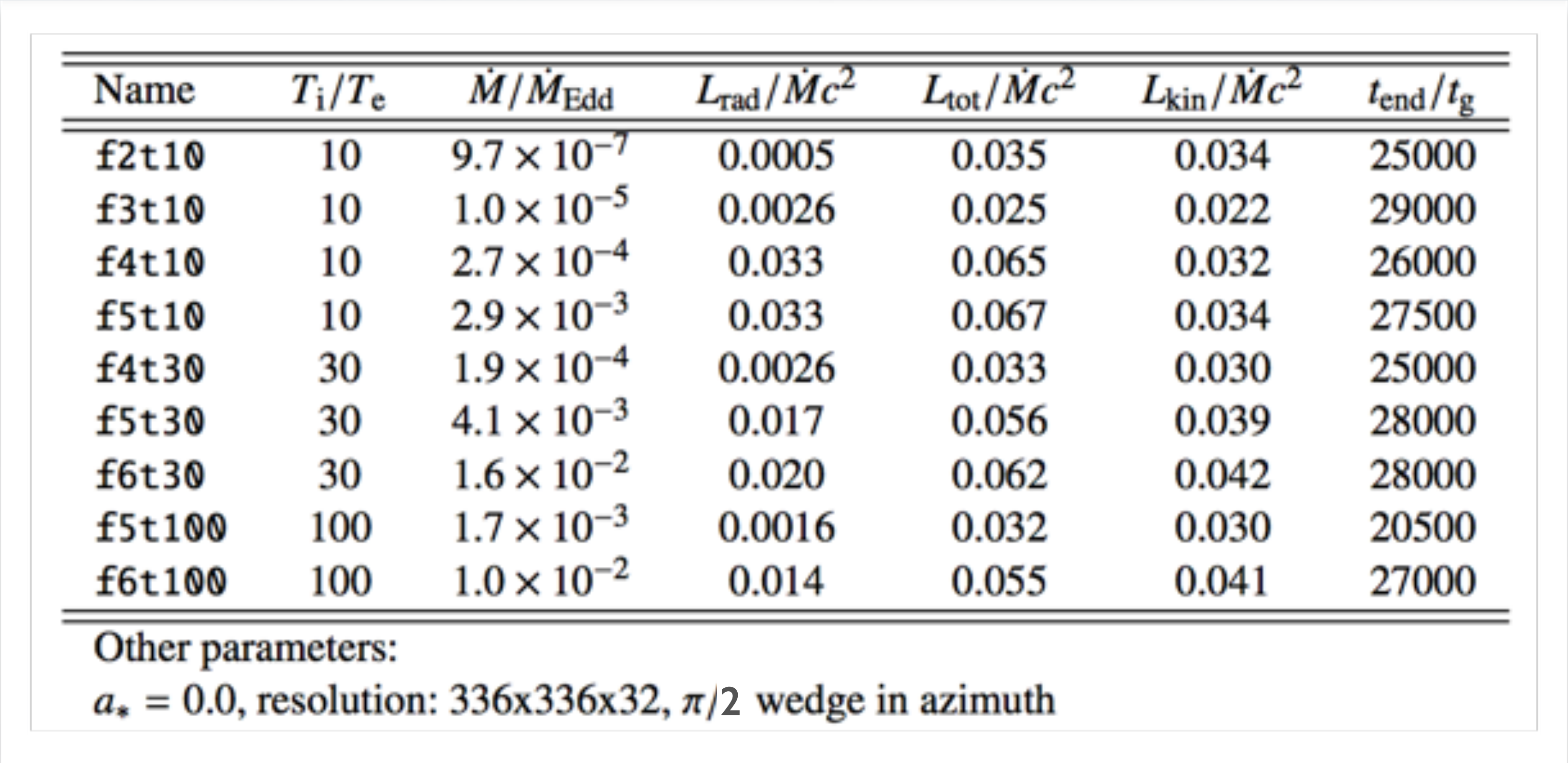
$$\begin{aligned} (\rho u^{\mu})_{;\mu} &= 0 \\ (T^{\mu}_{\nu})_{;\mu} &= G_{\nu}, \\ (R^{\mu}_{\nu})_{;\mu} &= -G_{\nu}. \\ (n u^{\mu})_{;\mu} &= \dot{n}. \end{aligned}$$

$$F^{*\mu\nu}_{;\nu} = 0$$

$$\begin{aligned} T_{\rm e}(n_{\rm e} s_{\rm e} u^{\mu})_{;\mu} &= \delta_{\rm e} q^{\rm v} + q^{\rm C} + G_t \\ T_{\rm i}(n_{\rm i} s_{\rm i} u^{\mu})_{;\mu} &= (1-\delta_{\rm e}) q^{\rm v} - q^{\rm C}, \end{aligned}$$

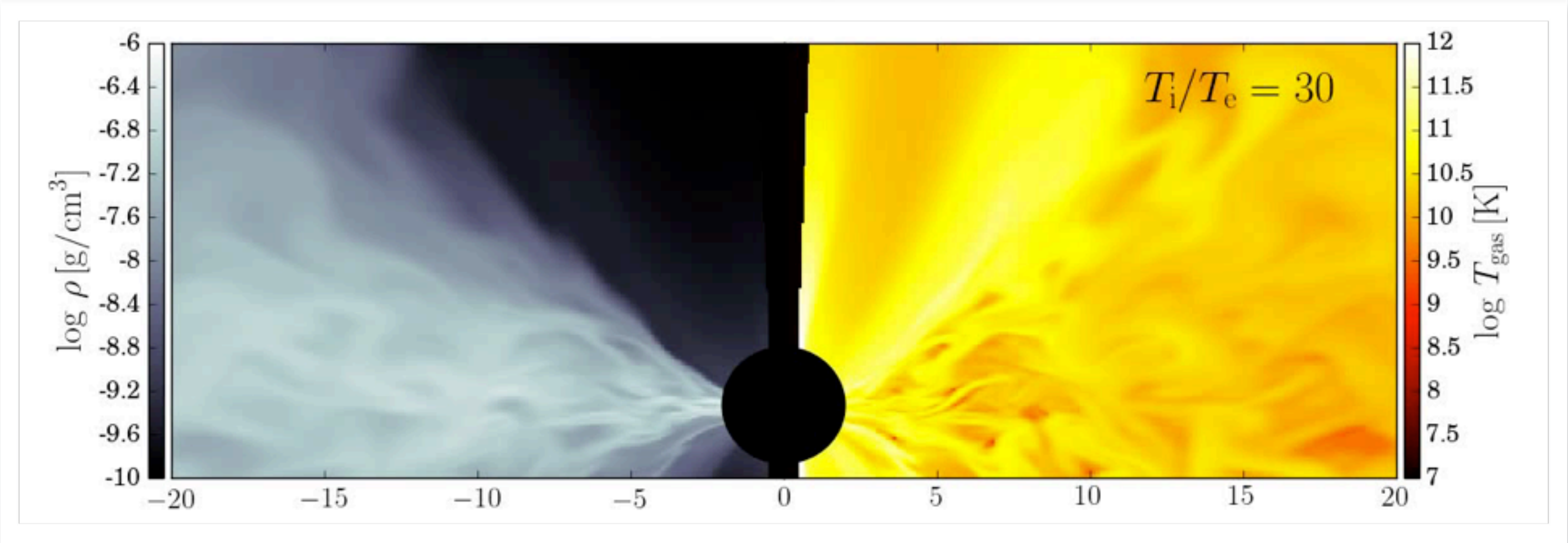
Sufficient set to study accretion flows at any accretion rate!

SIMULATIONS

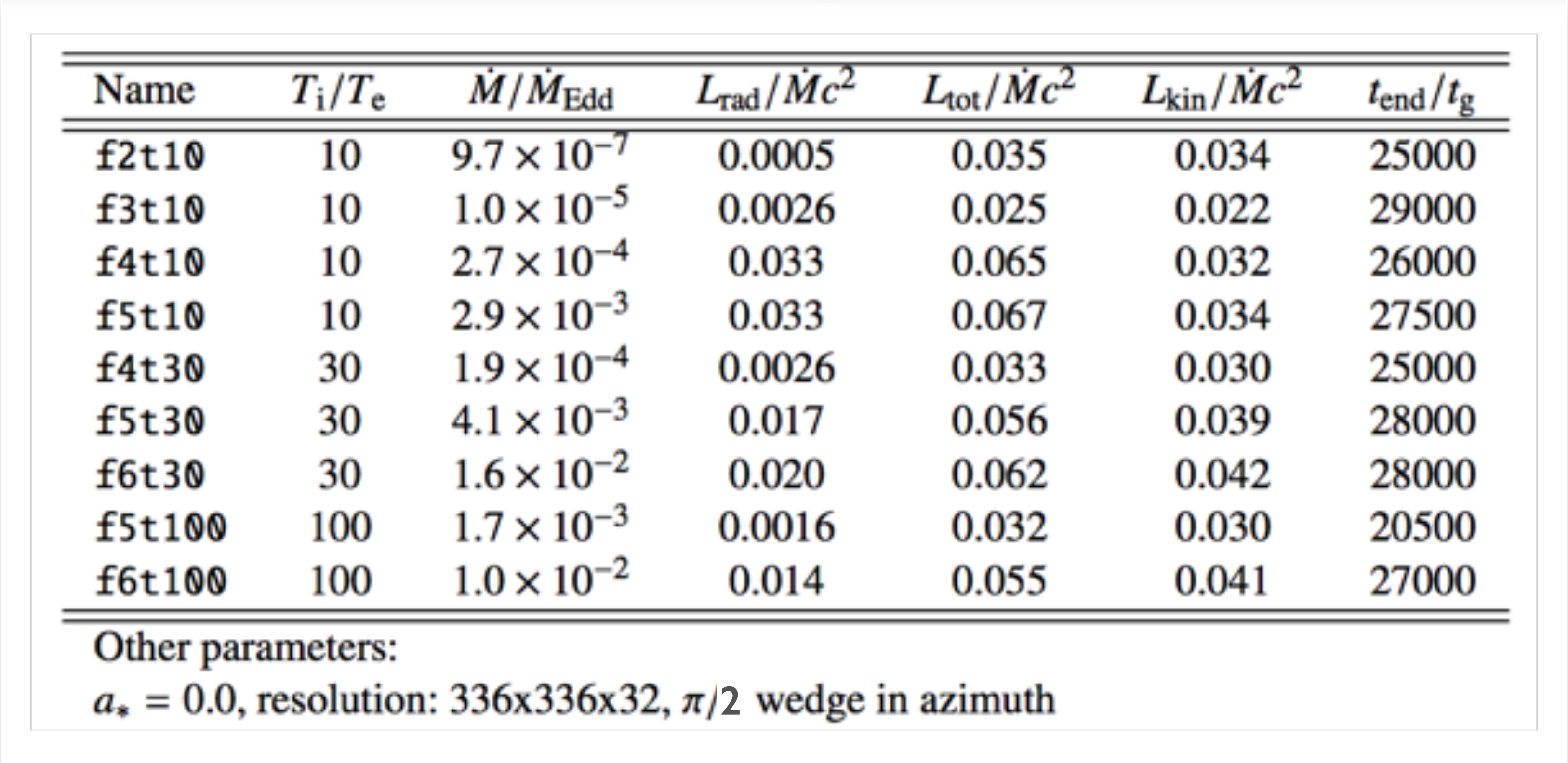


Name	$T_\mathrm{i}/T_\mathrm{e}$	$\dot{M}/\dot{M}_\mathrm{Edd}$	$L_\mathrm{rad}/\dot{M}c^2$	$L_\mathrm{tot}/\dot{M}c^2$	$L_\mathrm{kin}/\dot{M}c^2$	$t_\mathrm{end}/t_\mathrm{g}$
`f2t10`	10	9.7×10^{-7}	0.0005	0.035	0.034	25000
`f3t10`	10	1.0×10^{-5}	0.0026	0.025	0.022	29000
`f4t10`	10	2.7×10^{-4}	0.033	0.065	0.032	26000
`f5t10`	10	2.9×10^{-3}	0.033	0.067	0.034	27500
`f4t30`	30	1.9×10^{-4}	0.0026	0.033	0.030	25000
`f5t30`	30	4.1×10^{-3}	0.017	0.056	0.039	28000
`f6t30`	30	1.6×10^{-2}	0.020	0.062	0.042	28000
`f5t100`	100	1.7×10^{-3}	0.0016	0.032	0.030	20500
`f6t100`	100	1.0×10^{-2}	0.014	0.055	0.041	27000

Other parameters:
$a_* = 0.0$, resolution: 336x336x32, $\pi/2$ wedge in azimuth



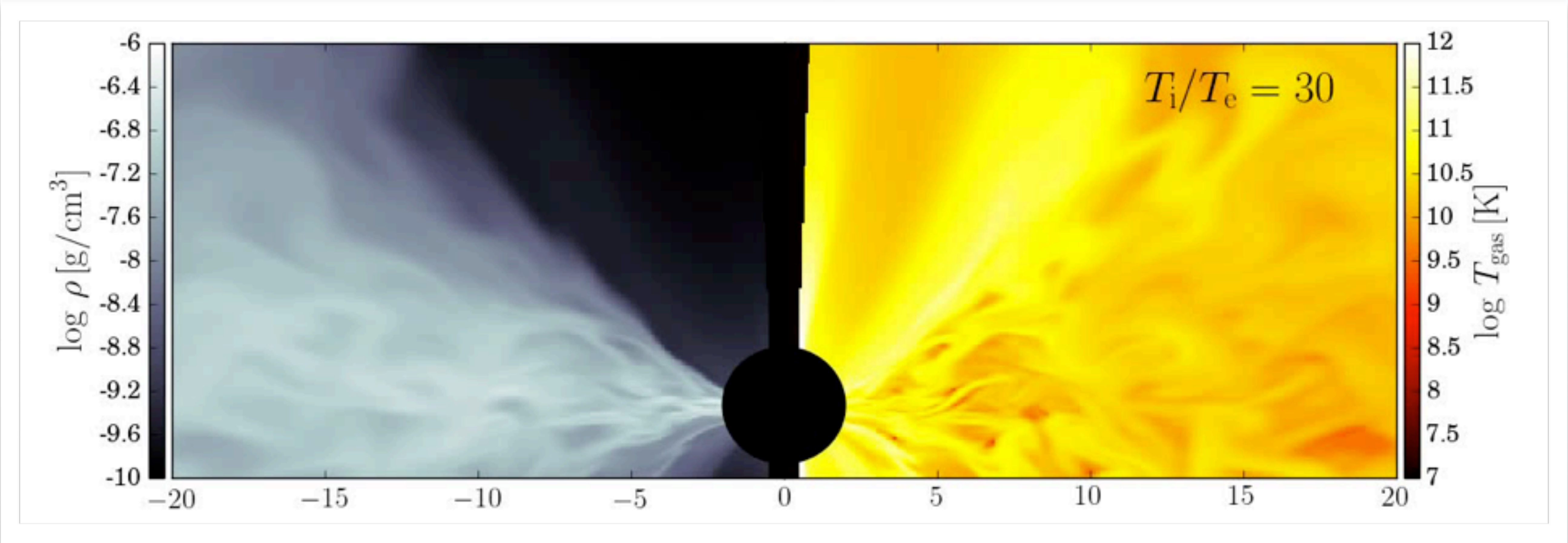
SIMULATIONS



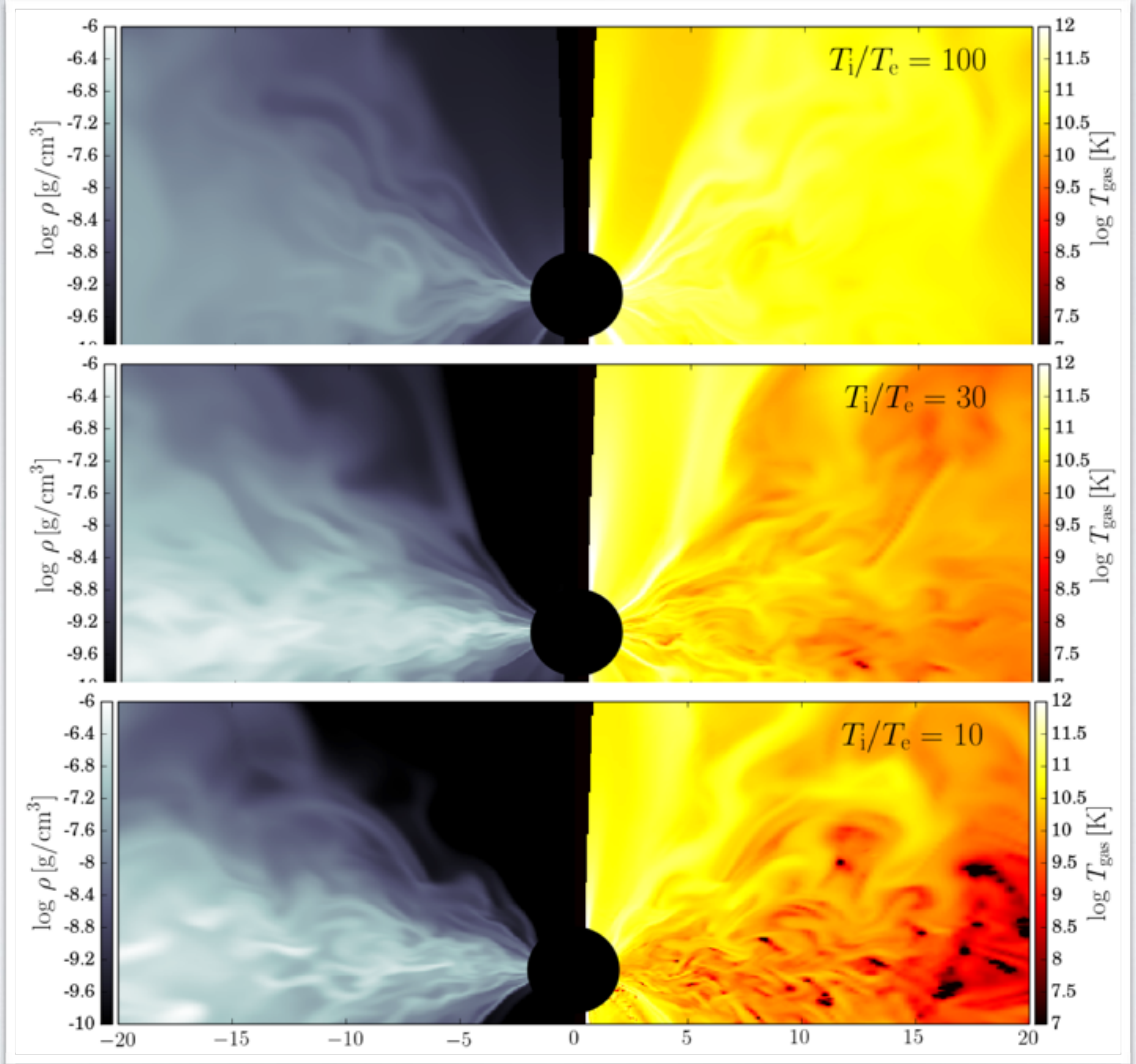
Name	T_i/T_e	$\dot{M}/\dot{M}_{Edd}$	$L_{rad}/\dot{M}c^2$	$L_{tot}/\dot{M}c^2$	$L_{kin}/\dot{M}c^2$	t_{end}/t_g
`f2t10`	10	9.7×10^{-7}	0.0005	0.035	0.034	25000
`f3t10`	10	1.0×10^{-5}	0.0026	0.025	0.022	29000
`f4t10`	10	2.7×10^{-4}	0.033	0.065	0.032	26000
`f5t10`	10	2.9×10^{-3}	0.033	0.067	0.034	27500
`f4t30`	30	1.9×10^{-4}	0.0026	0.033	0.030	25000
`f5t30`	30	4.1×10^{-3}	0.017	0.056	0.039	28000
`f6t30`	30	1.6×10^{-2}	0.020	0.062	0.042	28000
`f5t100`	100	1.7×10^{-3}	0.0016	0.032	0.030	20500
`f6t100`	100	1.0×10^{-2}	0.014	0.055	0.041	27000

Other parameters:

$a_* = 0.0$, resolution: 336x336x32, $\pi/2$ wedge in azimuth

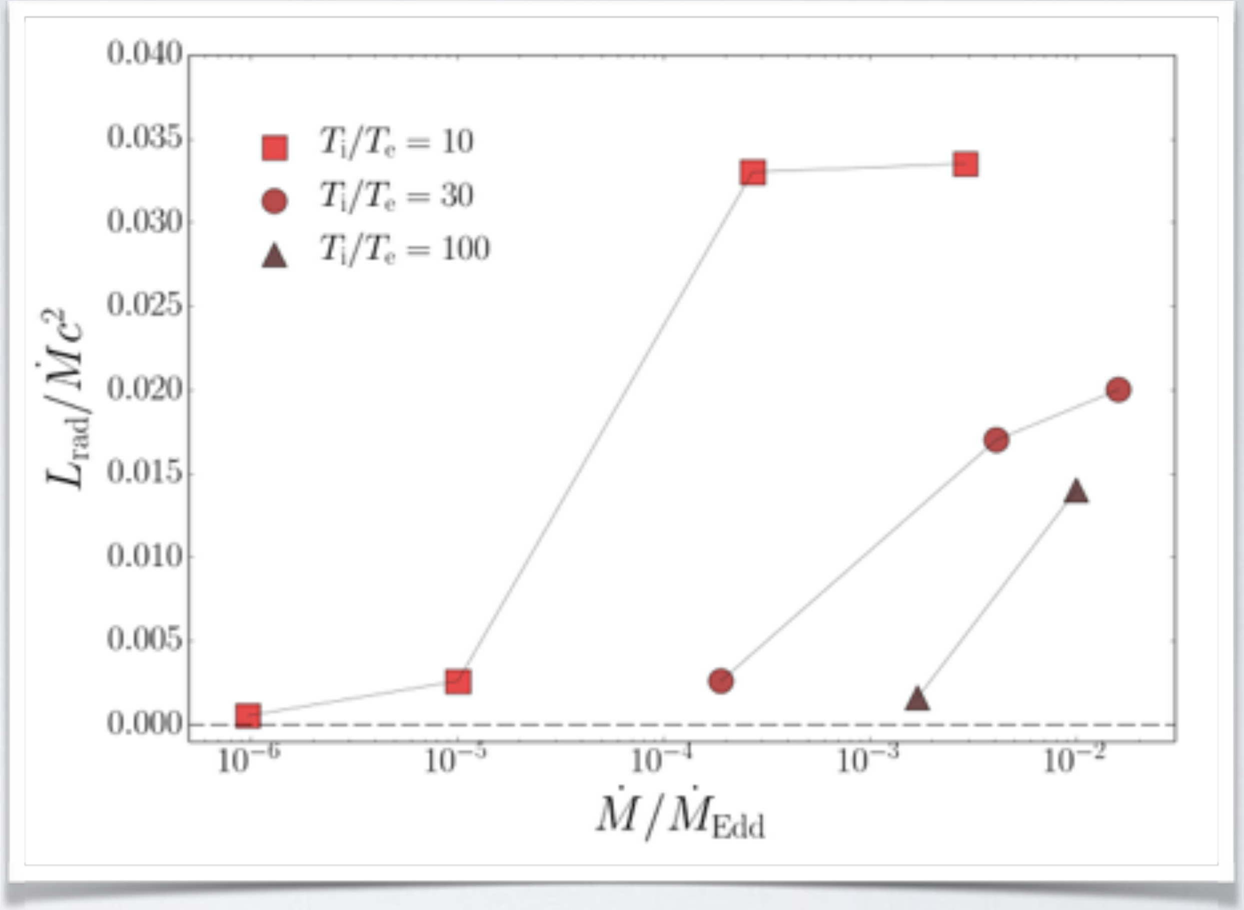


Density Temperature



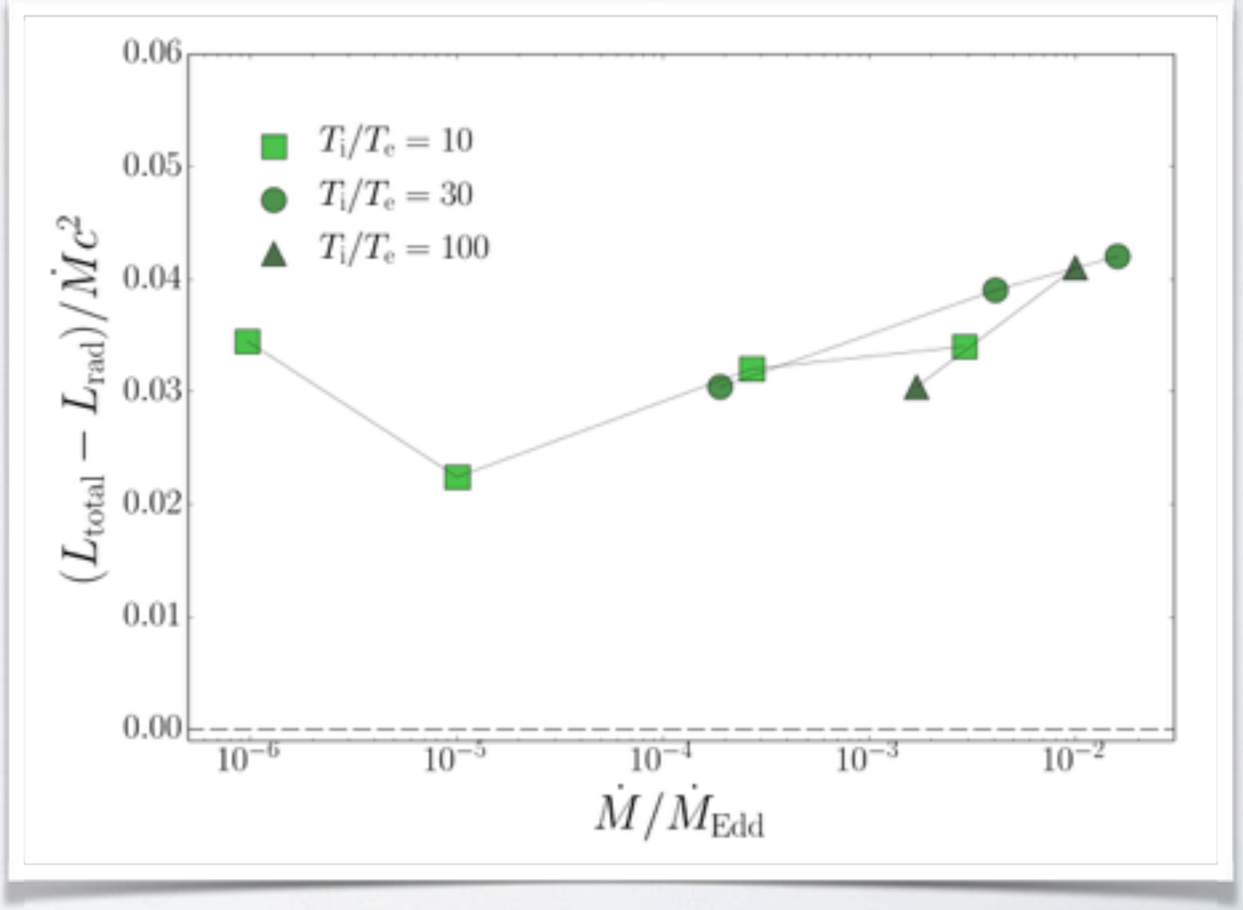
Radiative efficiency:

- increases with accretion rate
- reaches few % already at 1e-3 Eddington
- significant radiative emission from geometrically thick but optically thin disk



Kinetic efficiency:

- mechanical output insensitive to the mass transfer rate
- **for a non-rotating BH close to 3%**
- kinetic energy likely to dissipate and heat ISM



1. EFFICIENCIES OF BLACK HOLE ACCRETION

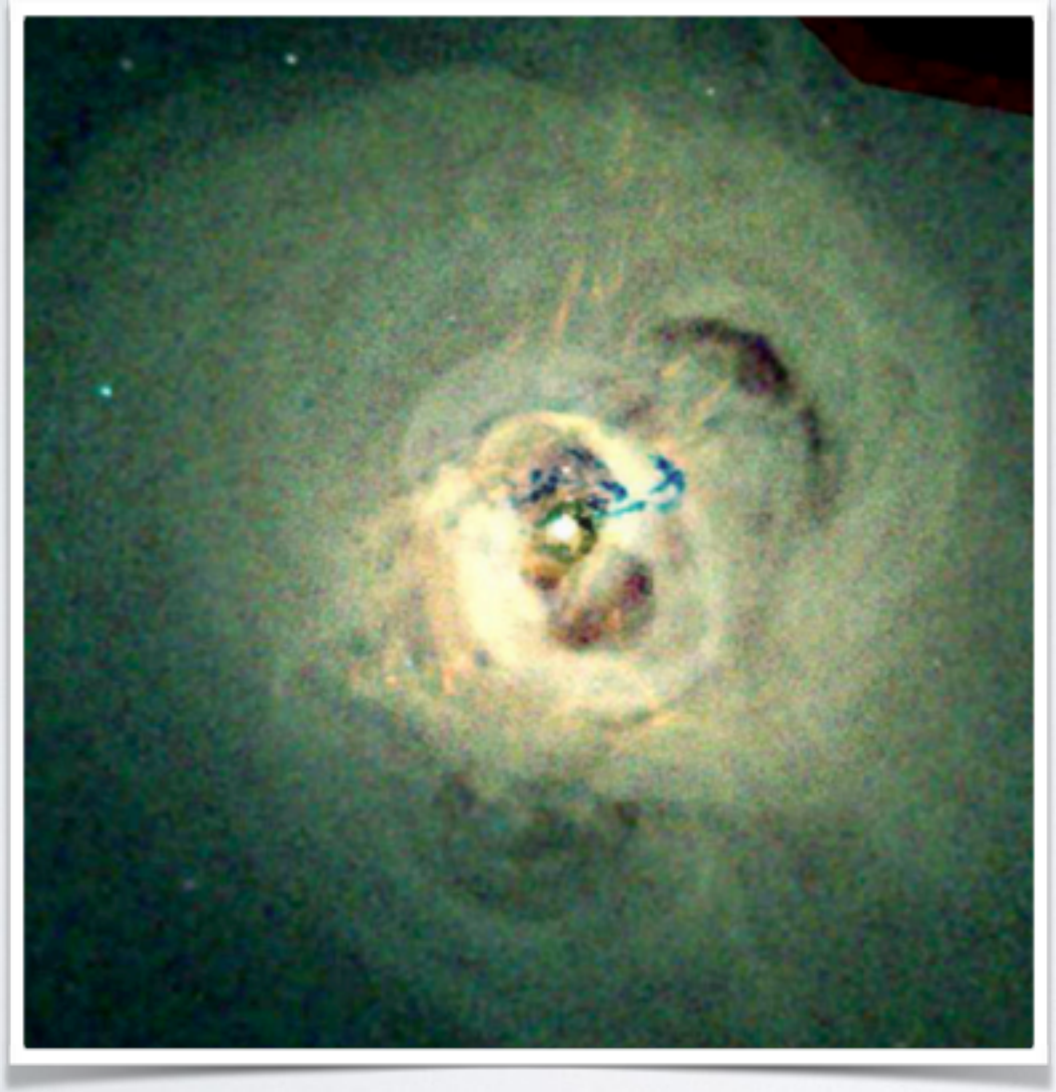
2. **AGN FEEDBACK**

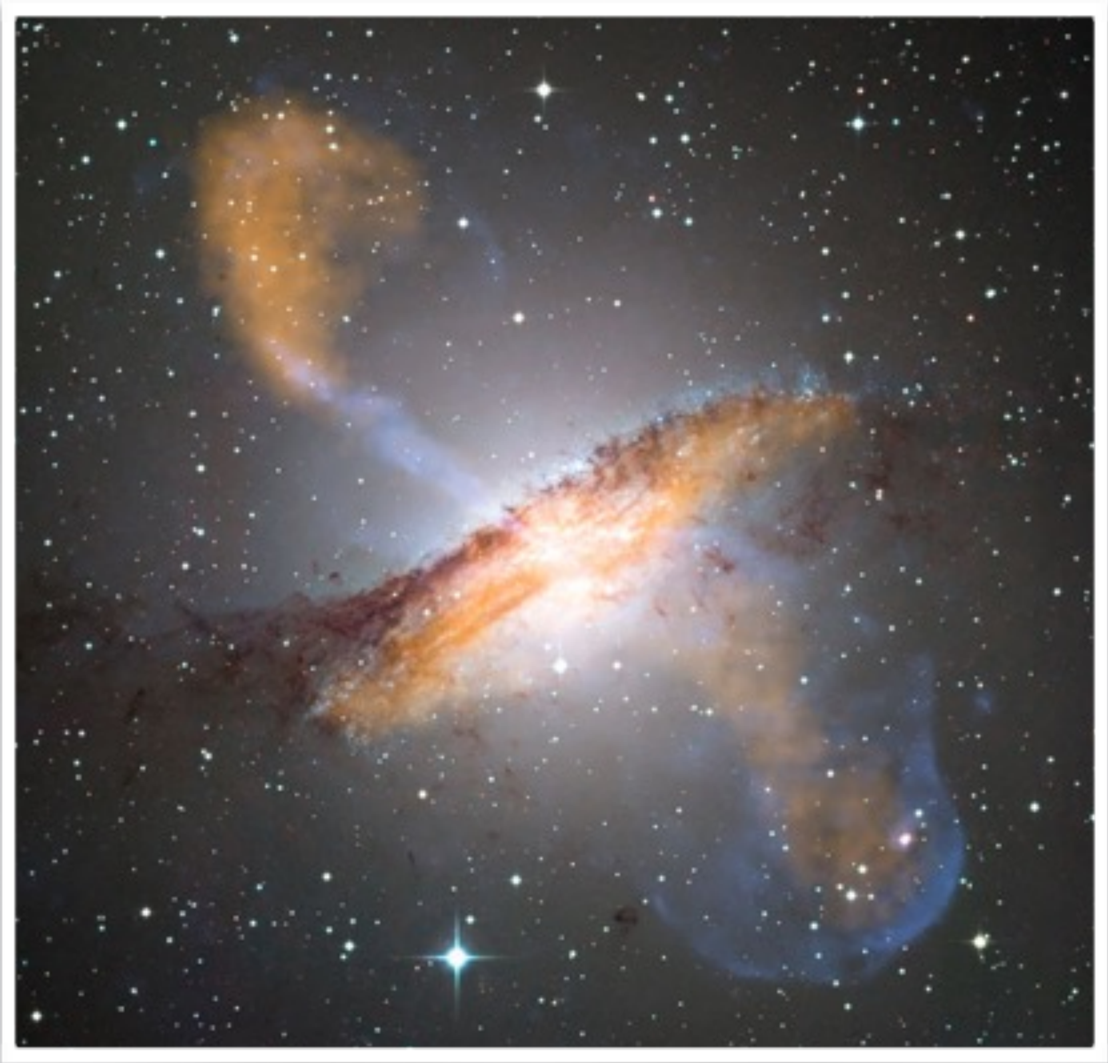
3. SUBGRID

SMBHS AFFECT GALAXIES

Growing evidence for the importance of SMBH feedback :

- suppression of star formation rate for most massive galaxies
- SMBH mass - velocity dispersion relation
- observations of cavities inflated by AGN outflows
- ….

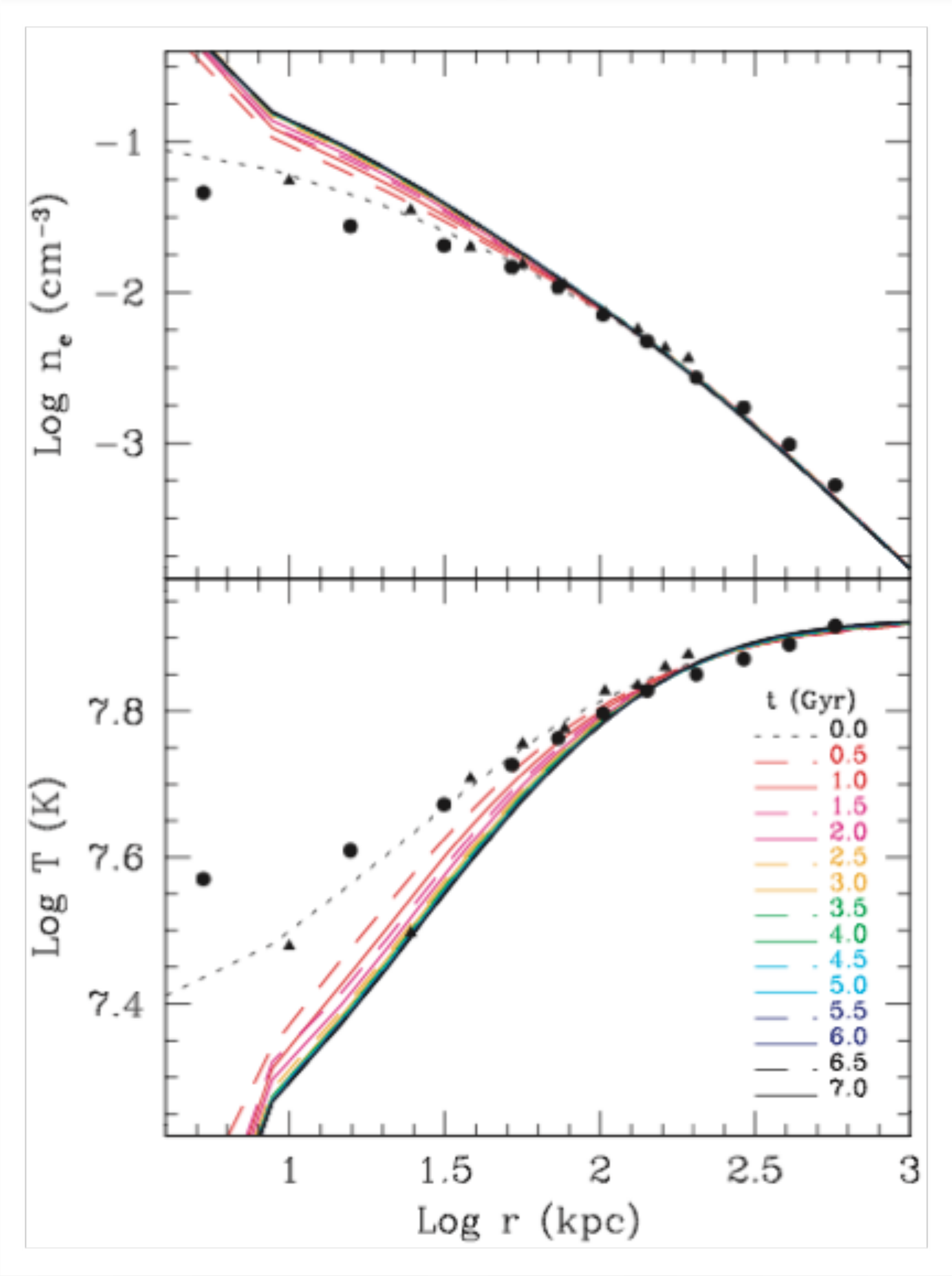




HEATING THE CORE

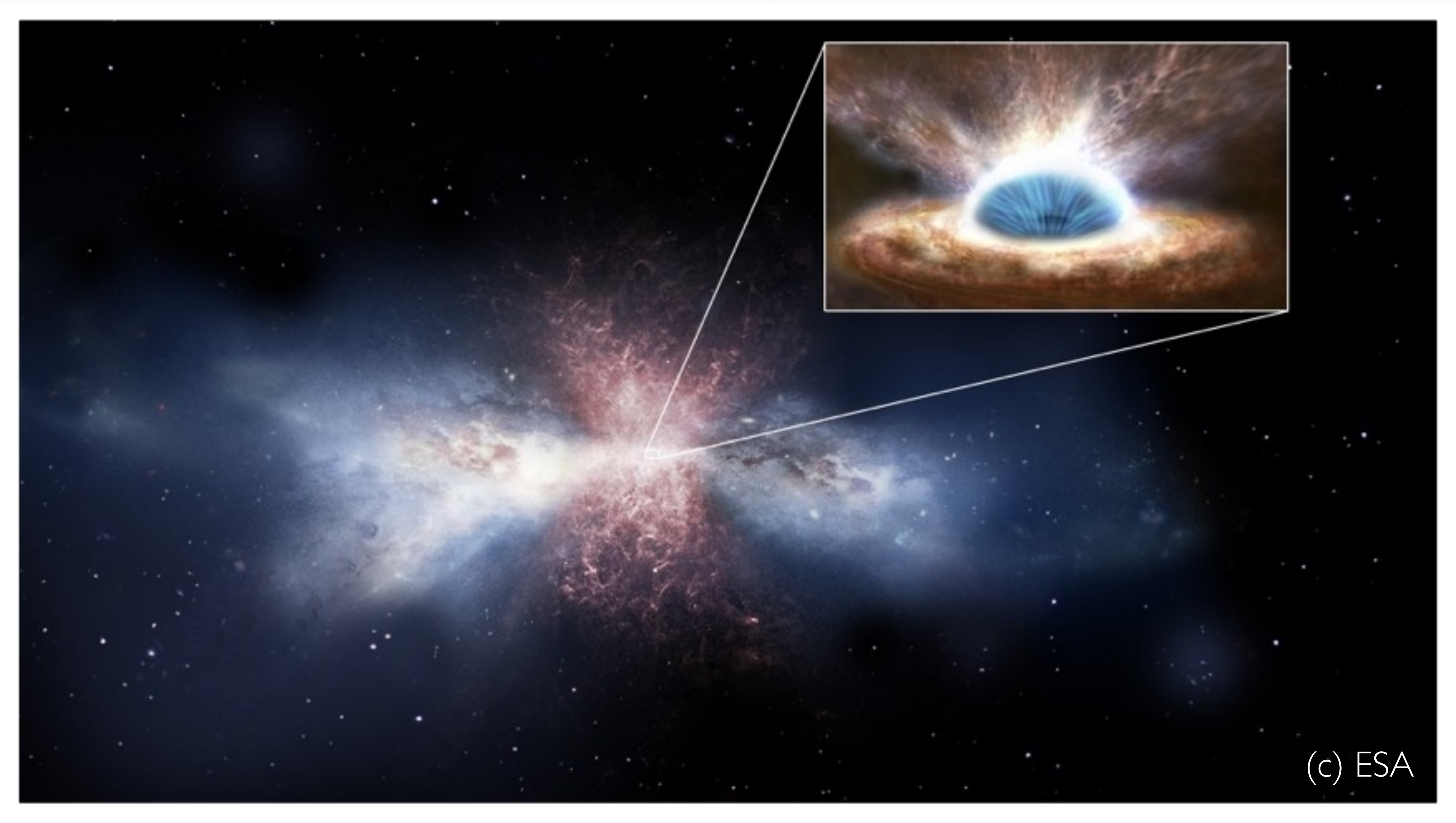
- without external heating cores of clusters cool down very quickly
- implied SFR too high
- AGN heating provides the necessary energy source to explain the observed temperature profiles

$$L_{\rm x} \simeq 6 \times 10^{43}\,(T_{\rm x}/2.2\,{\rm keV})^3\ {\rm erg\,s^{-1}}$$



Gaspari + 12

FEEDING THE SMBH



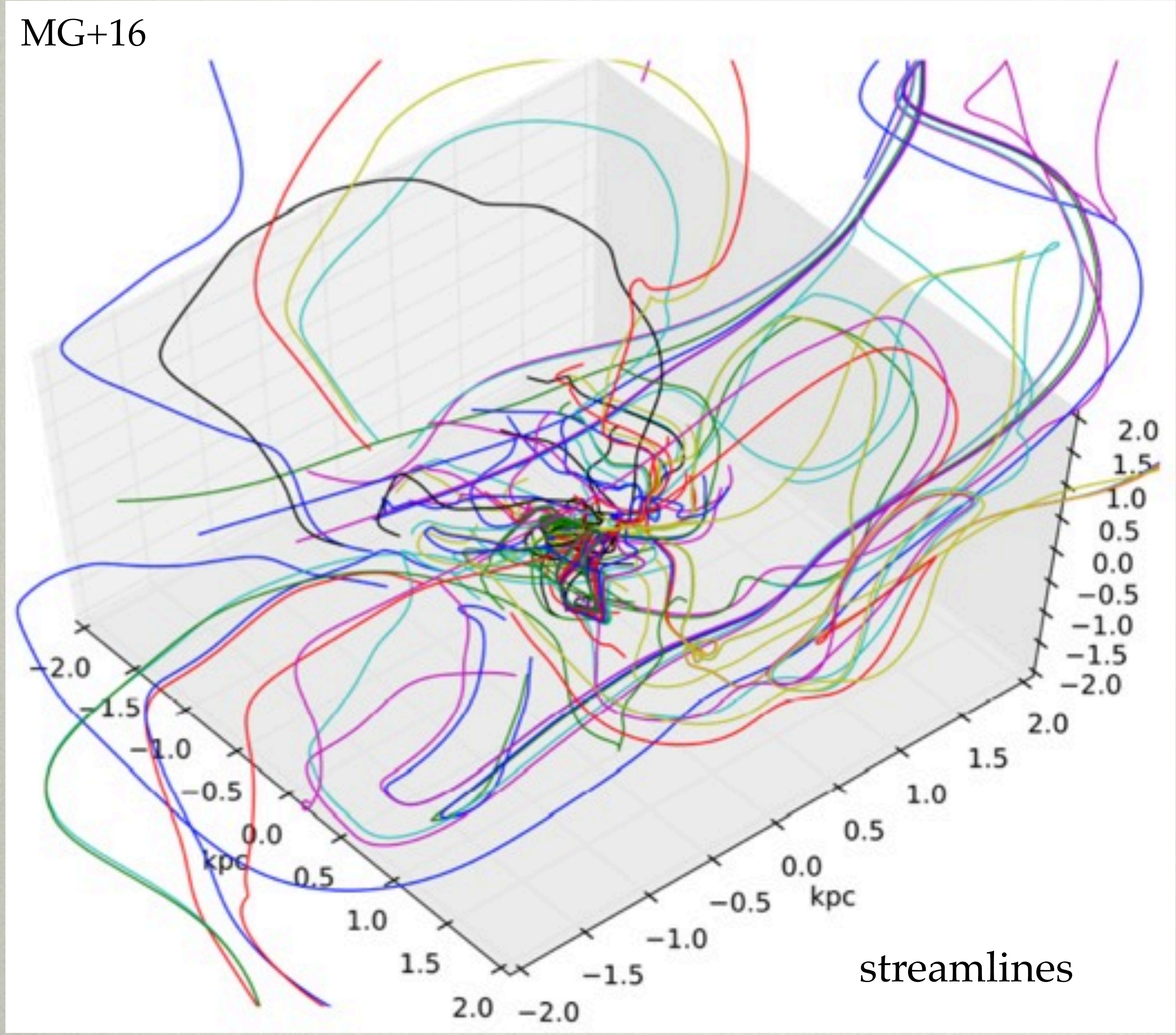
(c) ESA

MULTIPHASE CCA

DYNAMICS

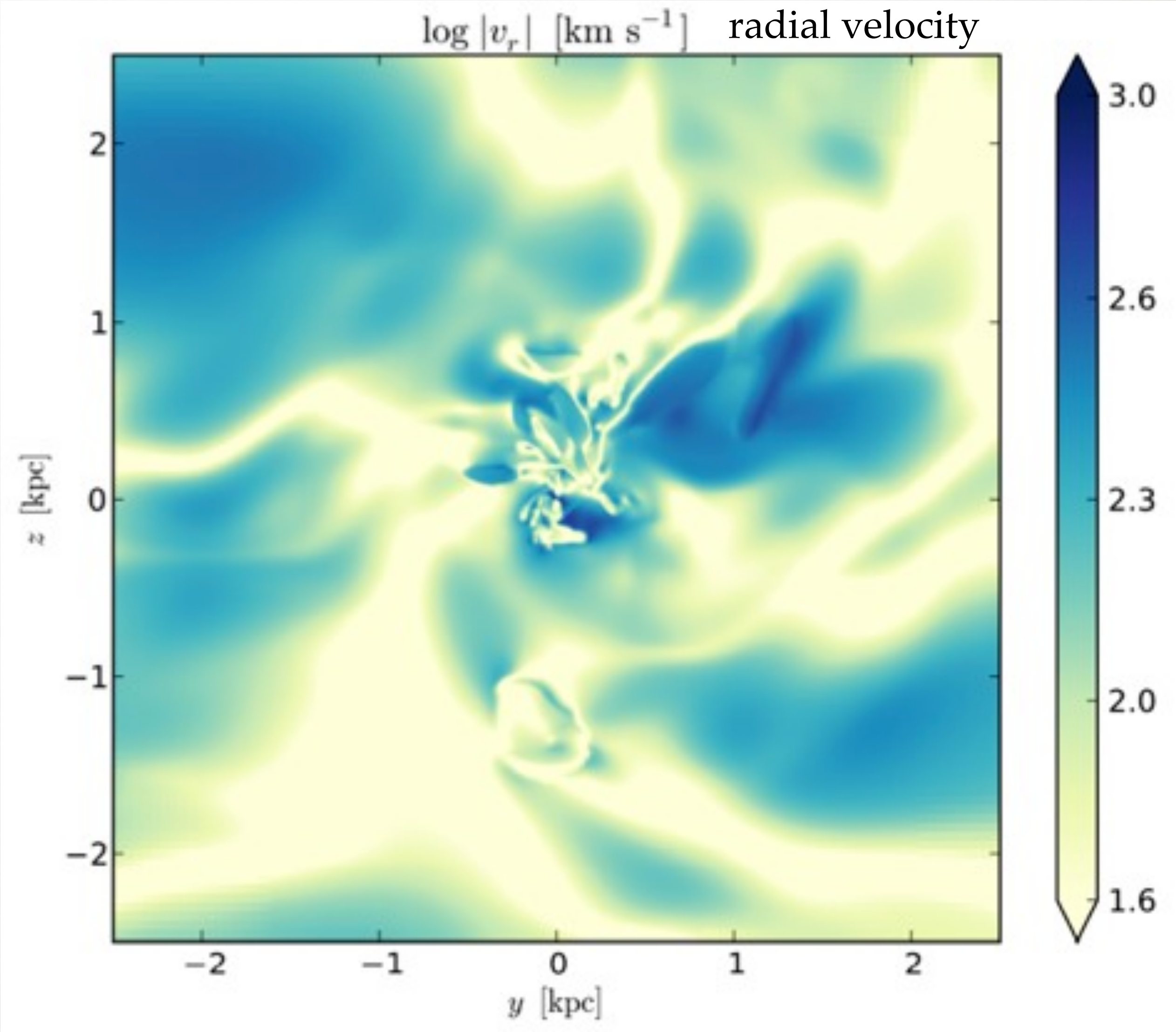
ROTATION + COOLING + TURBULENCE + AGN HEATING => Chaotic Cold Accretion [CCA]

$\sigma_v \sim 160$ km/s $\qquad \mathcal{H} \sim \langle \mathcal{L} \rangle$


MG+16

streamlines

chaotic motions => recurrent multiphase gas interactions


radial velocity

turbulent eddies

injected turbulence ~160 km/s
(similar to *Hitomi* detection)

AGN FEEDBACK CYCLE VIA CCA FUELING:

$$\mathcal{L} > \mathcal{H}$$

↓

top-down multiphase condensation →

↓

CCA feeds SMBH

chaotic collisions

↓

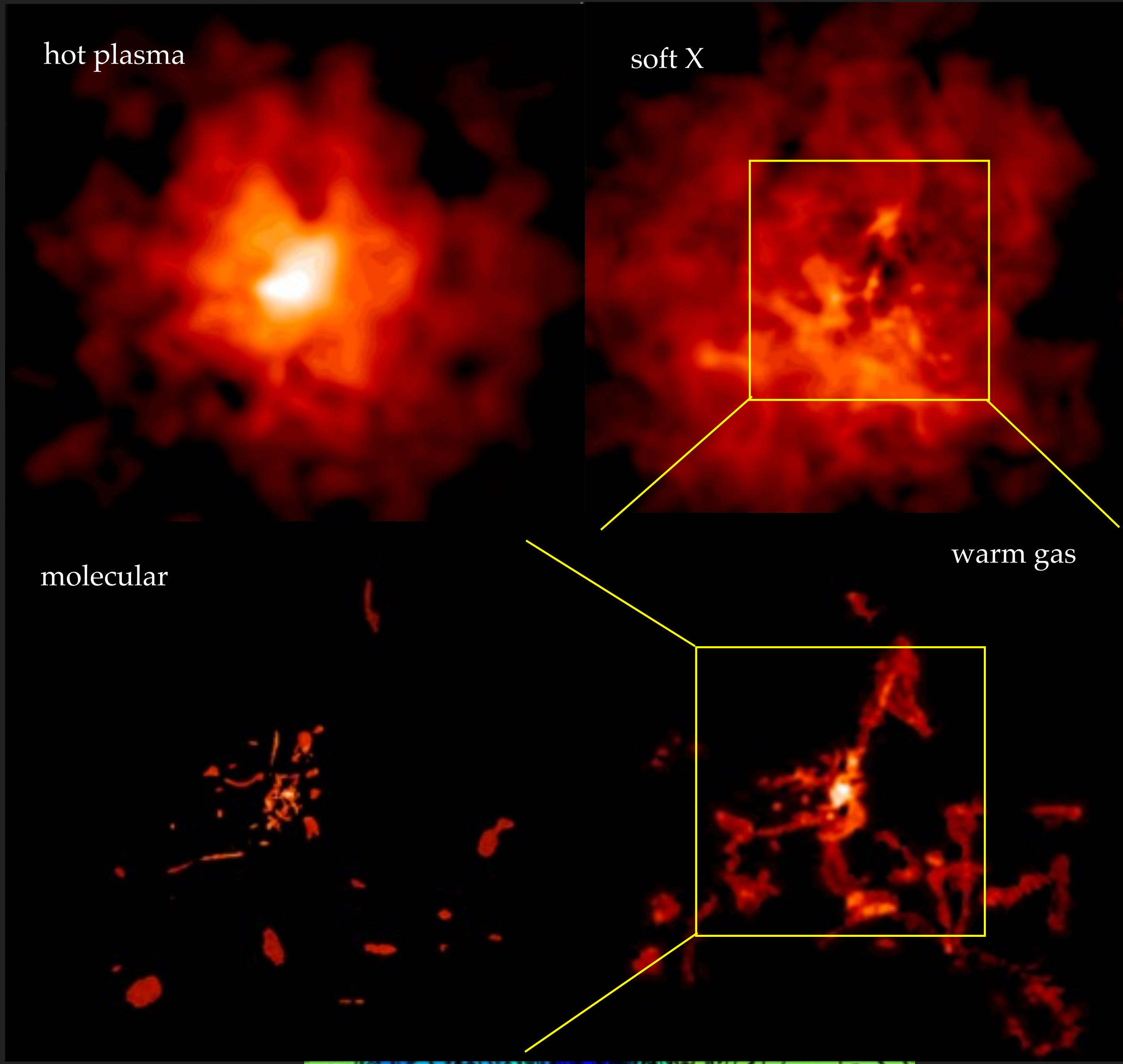
AGN outflows boosted

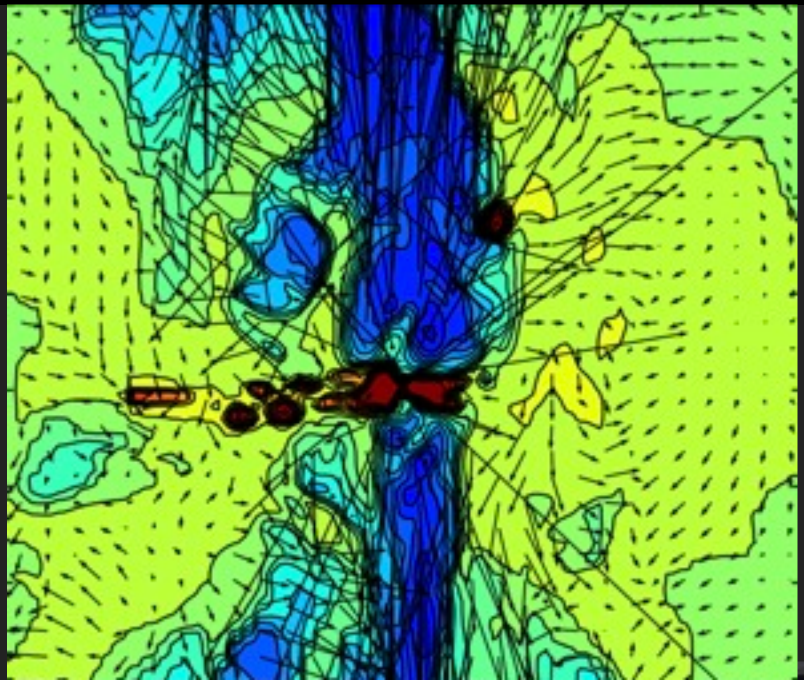
$$P_{\rm out} = \epsilon\, \dot{M}_{\rm BH} c^2$$ →

↓

$$\mathcal{L} < \mathcal{H}$$

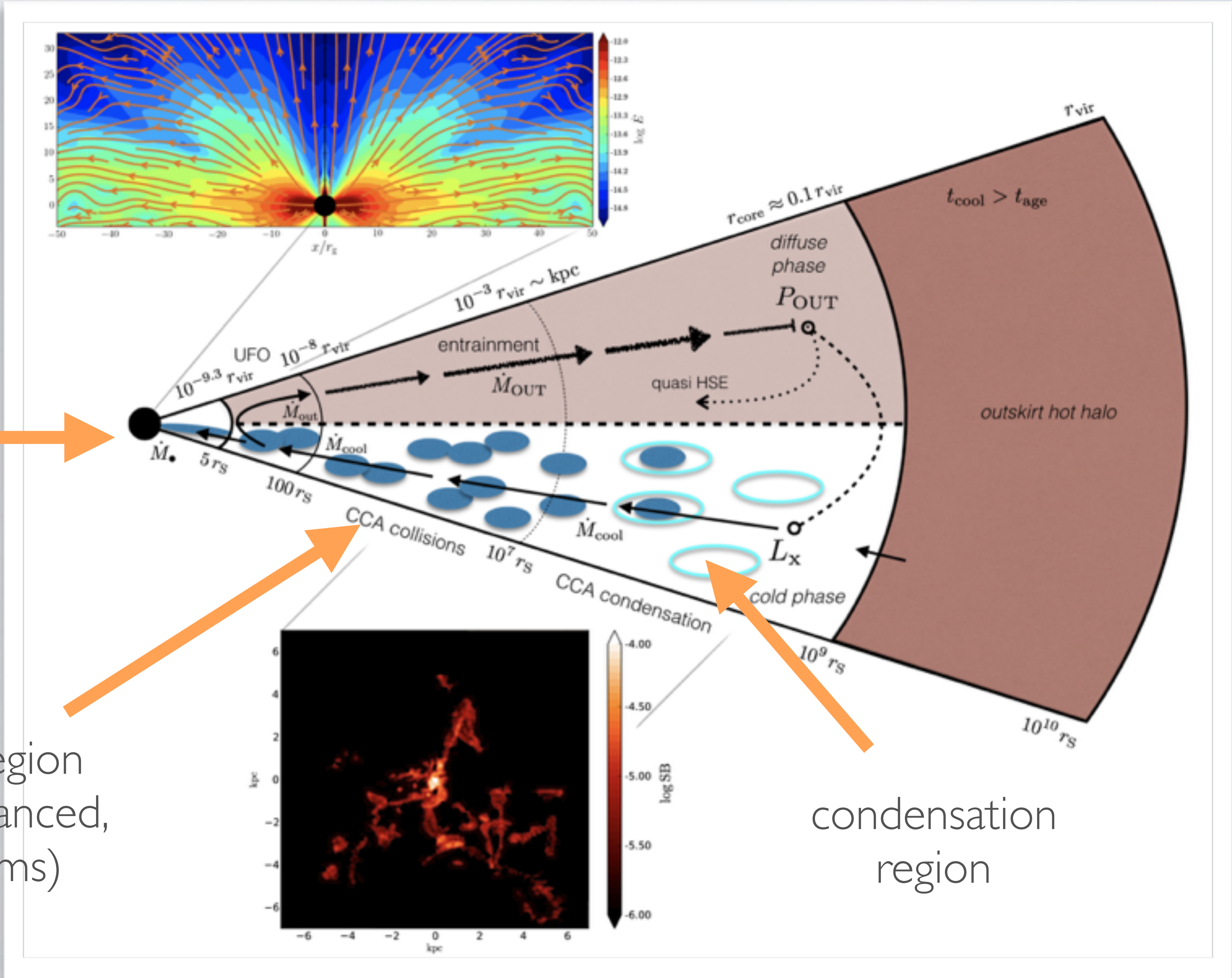
MG+16





long-term and large-scale sims

INFLOWS



horizon region (inflow only)

collision region (inflow enhanced, CCA forms)

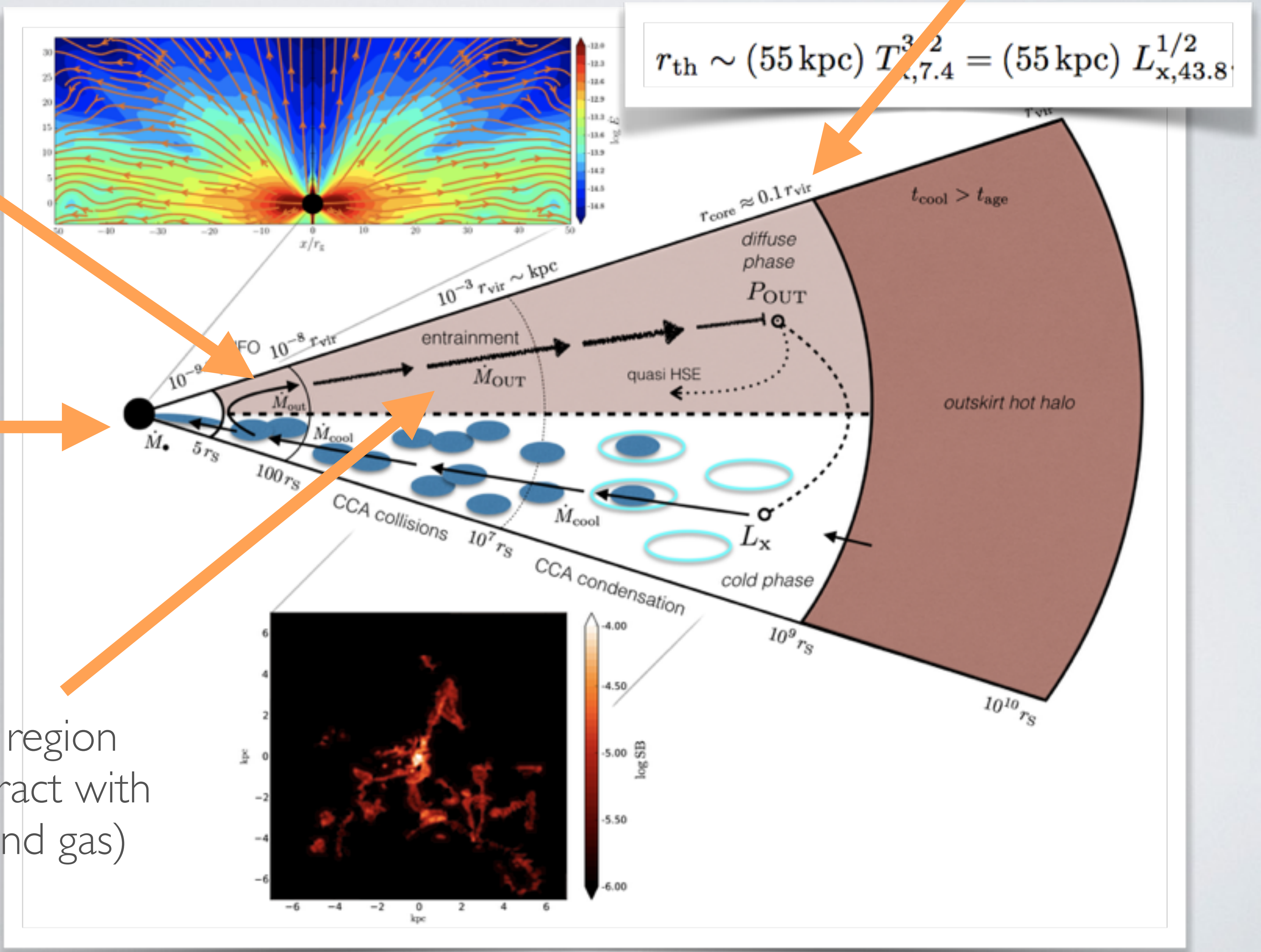
condensation region

OUTFLOWS

thermalization region
(outflows stop,
energy deposited)

UFO region
(outflows
generated)

horizon region
(inflow only)



$$r_{\rm th} \sim (55\,{\rm kpc})\; T_{{\rm x},7.4}^{3/2} = (55\,{\rm kpc})\; L_{{\rm x},43.8}^{1/2}$$

entrainment region
(outflows interact with
the background gas)

ENERGY BALANCE

$$P_{\rm out} = P_{\rm OUT} = L_{\rm x}$$

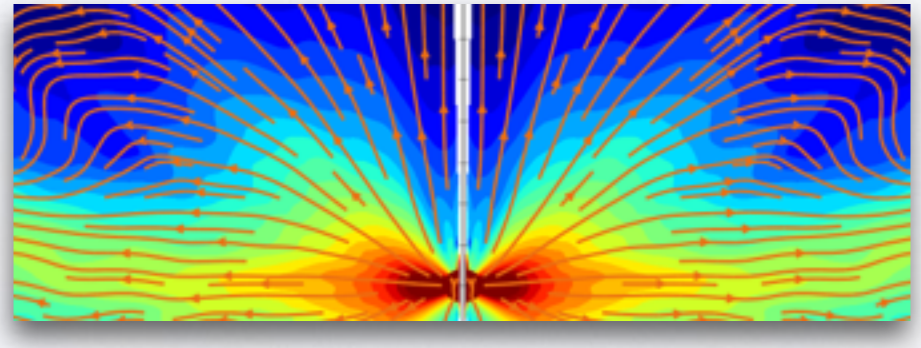
$$L_{\rm x} \simeq 6 \times 10^{43}\,(T_{\rm x}/2.2\,{\rm keV})^3\ {\rm erg\,s^{-1}}$$

$$P_{\rm out} = \varepsilon_\bullet \dot{M}_\bullet c^2,$$

$$\varepsilon_\bullet \simeq 0.03 \pm 0.01,$$

Growth rate of the BH:

$$\begin{aligned}\dot{M}_\bullet = \frac{L_{\rm x}}{\varepsilon_\bullet c^2} &\simeq (0.04\ {\rm M_\odot\,yr^{-1}})\ L_{\rm x,43.8}\\ &= (0.04\ {\rm M_\odot\,yr^{-1}})\ T^3_{\rm x,7.4}.\end{aligned}$$



OUTFLOW PROPERTIES

Quenched cooling flow -
the rate at which clumps of gas fall into the innermost
region due to Chaotic Cold Accretion (based on obs. + sim., see Gaspari+)

$$\dot{M}_{\rm cool} \simeq (1.1\ {\rm M}_\odot\,{\rm yr}^{-1})\, T_{{\rm x},7.4}^{2} = (1.1\ {\rm M}_\odot\,{\rm yr}^{-1})\, L_{{\rm x},43.8}^{2/3},$$

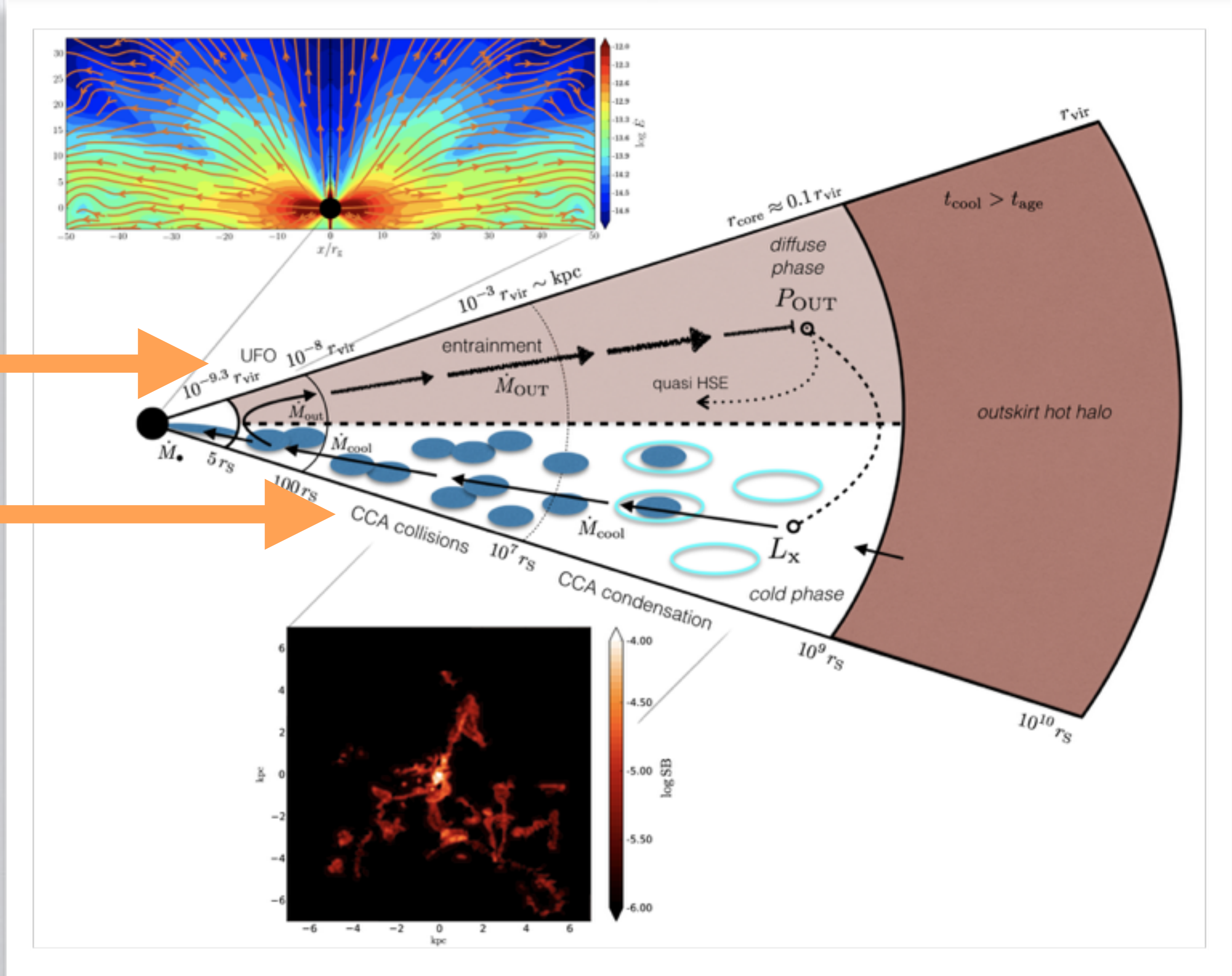
Mechanical power:

(induced by the accretion flow)

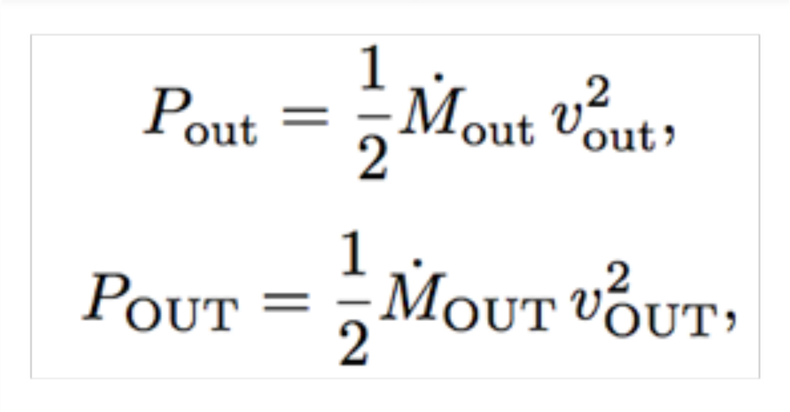
$$P_{\rm out} = \frac{1}{2}\dot{M}_{\rm out}\, v_{\rm out}^{2},$$

$$P_{\rm OUT} = \frac{1}{2}\dot{M}_{\rm OUT}\, v_{\rm OUT}^{2},$$

(affected by interaction with
external gas - entrainment)



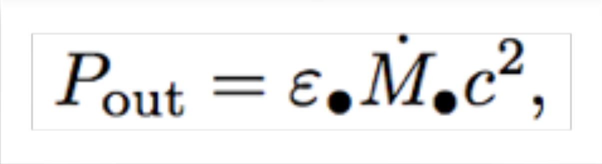
(INNER) OUTFLOW VELOCITY



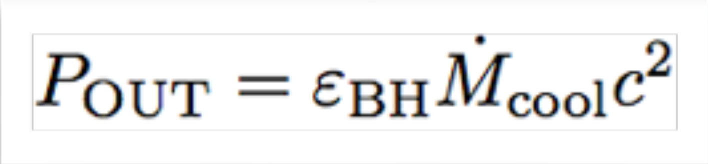
$$P_{\rm out} = \frac{1}{2}\dot{M}_{\rm out}\, v_{\rm out}^2,$$

$$P_{\rm OUT} = \frac{1}{2}\dot{M}_{\rm OUT}\, v_{\rm OUT}^2,$$

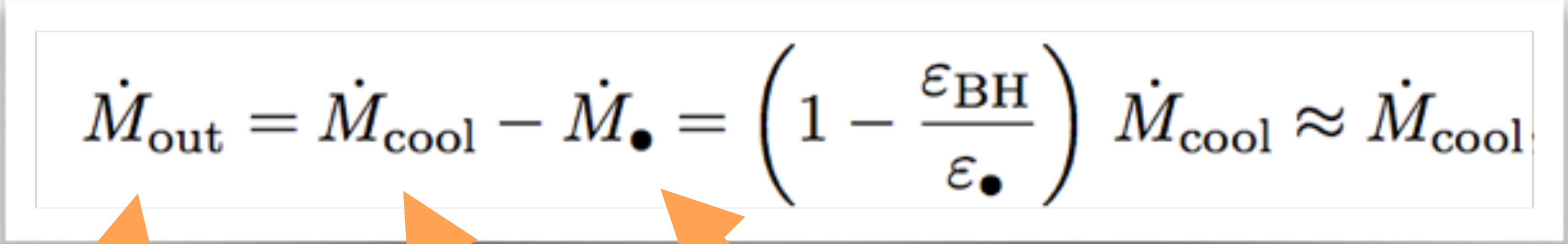
$$P_{\rm out} = P_{\rm OUT} = L_{\rm x}$$



$$P_{\rm out} = \varepsilon_\bullet \dot{M}_\bullet c^2,$$



$$P_{\rm OUT} = \varepsilon_{\rm BH} \dot{M}_{\rm cool} c^2$$



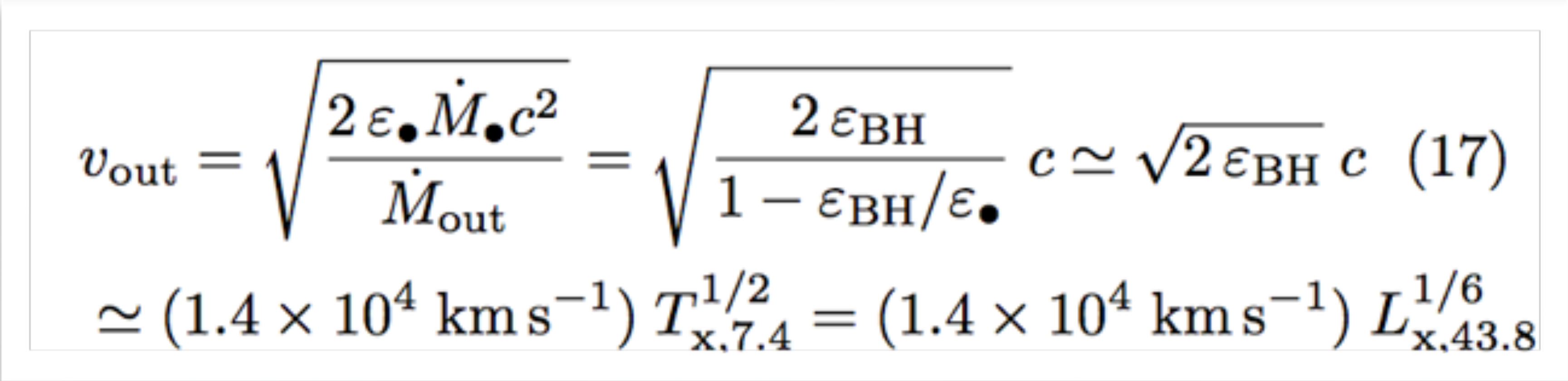
$$\dot{M}_{\rm out} = \dot{M}_{\rm cool} - \dot{M}_\bullet = \left(1 - \frac{\varepsilon_{\rm BH}}{\varepsilon_\bullet}\right) \dot{M}_{\rm cool} \approx \dot{M}_{\rm cool}$$

accretion flow
generated outflows

large scale
CCA inflow

horizon
inflow rate

Velocity of
outflows - UFOs:



$$v_{\rm out} = \sqrt{\frac{2\,\varepsilon_\bullet \dot{M}_\bullet c^2}{\dot{M}_{\rm out}}} = \sqrt{\frac{2\,\varepsilon_{\rm BH}}{1-\varepsilon_{\rm BH}/\varepsilon_\bullet}}\, c \simeq \sqrt{2\,\varepsilon_{\rm BH}}\, c \quad (17)$$

$$\simeq (1.4\times10^4\ {\rm km\,s^{-1}})\, T_{\rm x,7.4}^{1/2} = (1.4\times10^4\ {\rm km\,s^{-1}})\, L_{\rm x,43.8}^{1/6}$$

INFLOW VS OUTFLOW TRANSFER RATE

$$P_{\rm out} = \frac{1}{2}\dot{M}_{\rm out}\, v_{\rm out}^2,$$

$$P_{\rm OUT} = \frac{1}{2}\dot{M}_{\rm OUT}\, v_{\rm OUT}^2,$$

$$P_{\rm out} = P_{\rm OUT} = L_{\rm x}$$

$$P_{\rm out} = \varepsilon_\bullet \dot{M}_\bullet c^2,$$

$$\dot{M}_{\rm out} = \dot{M}_{\rm cool} - \dot{M}_\bullet = \left(1 - \frac{\varepsilon_{\rm BH}}{\varepsilon_\bullet}\right)\dot{M}_{\rm cool} \approx \dot{M}_{\rm cool}$$

accretion flow
generated outflows

large scale
CCA inflow

horizon
inflow rate

fraction of large scale
inflow reaching
the horizon:

$$\dot{M}_\bullet = \frac{\varepsilon_{\rm BH}}{\varepsilon_\bullet}\dot{M}_{\rm cool}.$$

$$\frac{\varepsilon_{\rm BH}}{\varepsilon_\bullet} \approx 10^{-2} - 10^{-1}$$

ENTRAINMENT REGION

$$\dot{M}_{\rm OUT} = \eta\, \dot{M}_{\rm out}$$

outflow transfer rate
at large scale
(after interacting with the
background gas)

entrainment
factor

accretion flow
generated outflows
(small scales)

$$v_{\rm OUT} = \sqrt{\frac{2P_{\rm OUT}}{\dot{M}_{\rm OUT}}} = \eta^{-1/2}\, v_{\rm out}$$

assuming 1/r density scaling:

Entrainment factor:

$$\eta = \left(\Omega \rho_0 r_0\, r\, \frac{v_{\rm out}}{\dot{M}_{\rm out}}\right)^{2/3}$$

ENTRAINMENT REGION

$$\dot{M}_{\mathrm{OUT}} = \eta\, \dot{M}_{\mathrm{out}}$$

assuming 1/r density scaling:

$$\eta = \left(\Omega \rho_0 r_0\, r\, \frac{v_{\mathrm{out}}}{\dot{M}_{\mathrm{out}}} \right)^{2/3}$$

Entrainment factor for multi-phase gas:

$$\eta_{\mathrm{hot}} \simeq 40\; T_{\mathrm{x},7.4}^{-1}\, r_{1\,\mathrm{kpc}}^{2/3}$$

$$\eta_{\mathrm{warm}} \simeq 183\; T_{\mathrm{x},7.4}^{-1}\, r_{1\,\mathrm{kpc}}^{2/3}$$

$$\eta_{\mathrm{cold}} \simeq 850\; T_{\mathrm{x},7.4}^{-1}\, r_{1\,\mathrm{kpc}}^{2/3}$$

(OUTER) OUTFLOW VELOCITY
VERIFICATION

$$v_{\rm OUT} = \sqrt{\frac{2P_{\rm OUT}}{\dot{M}_{\rm OUT}}} = \eta^{-1/2}\, v_{\rm out}$$

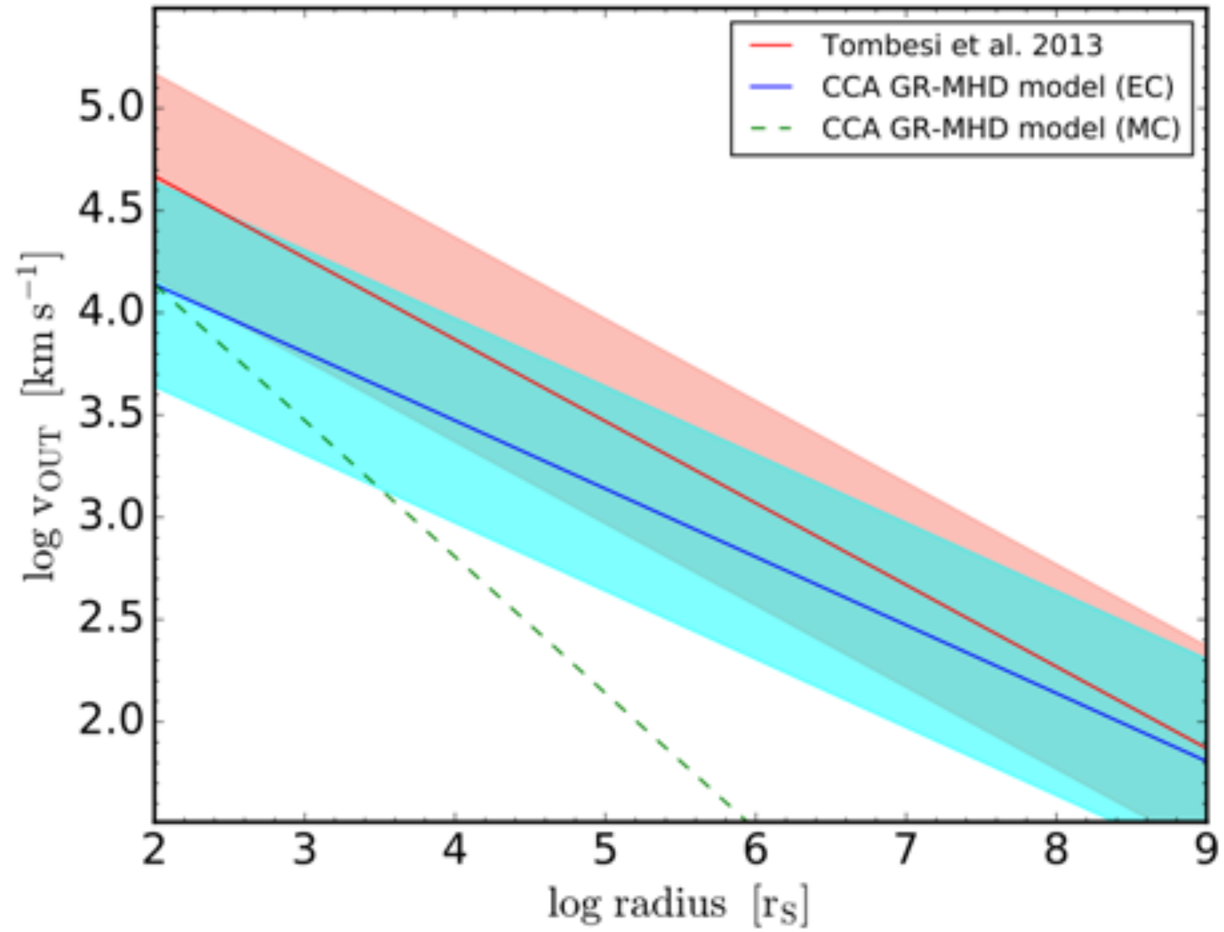


Figure 2. Outflow velocity as a function of radial distance (normalized to the Schwarzschild radius $r_{\rm S}$) for the unified UFO plus warm absorber X-ray data (red; Tombesi et al. 2013) and the prediction of our energy-conserving CCA GR-RMHD model (blue; §3). The dashed green line shows the (inconsistent) purely momentum-driven outflow. The region within $100\,r_{\rm S}$ is the UFO generation region, where most of the inflow mass is ejected. At larger radii, the UFO entrains progressively more mass, slowing down. The adopted background profile slope is $\alpha = 1$. The proposed model, based on linking the horizon/GR-RMHD and macro/CCA efficiencies, well reproduces the data within scatter.

1. EFFICIENCIES OF BLACK HOLE ACCRETION

2. AGN FEEDBACK

3. SUBGRID

AGN FEEDBACK MODEL FOR STRUCTURE FORMATION

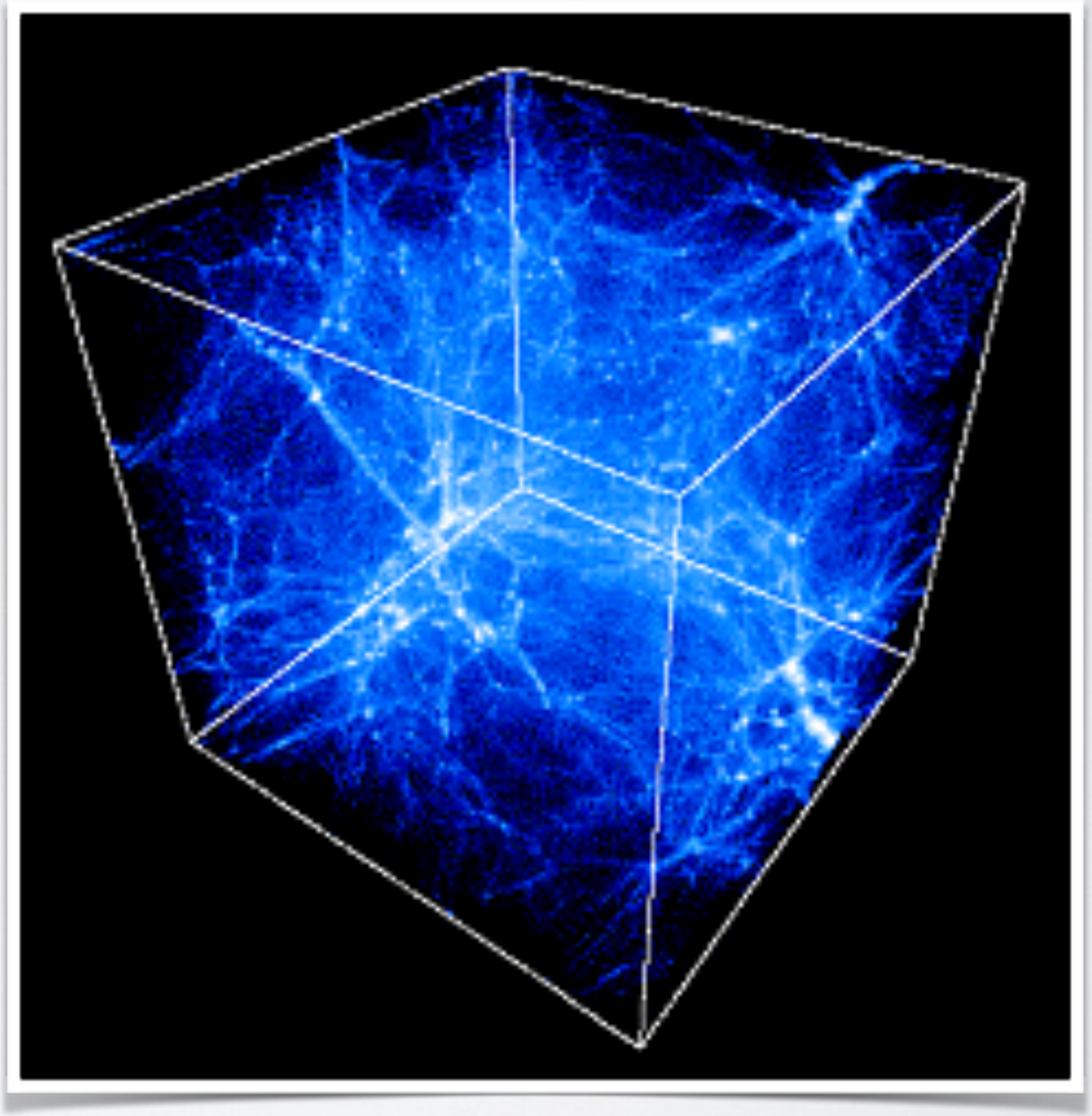
What is typically done:

$$P_{\rm fb} = \epsilon_1 \dot{M}_\bullet c^2$$
$$\dot{M}_\bullet = \epsilon_2 \dot{M}_{\rm Bondi}$$

$\epsilon_1, \ \epsilon_2$ - some numbers, chosen in a way to make the simulation work right

Power put directly into thermal energy

One can do better!



AGN FEEDBACK MODEL FOR STRUCTURE FORMATION

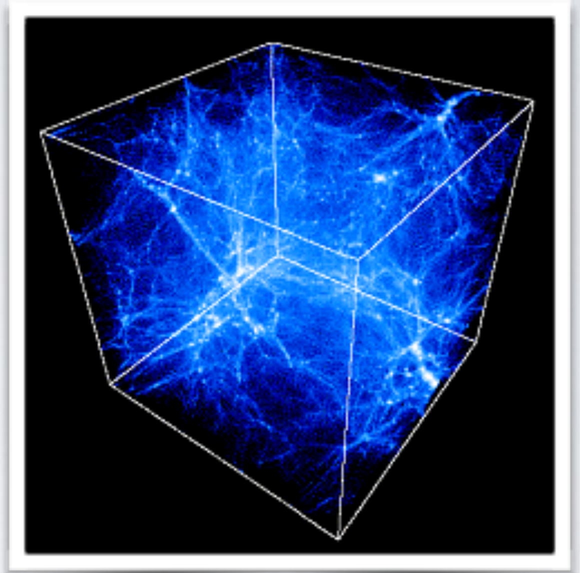
Low-res (dR>10kpc)

- Estimate halo cooling rate, inject it back as thermal energy

$$L_{\rm x} \simeq 6 \times 10^{43}\,(T_{\rm x}/2.2\,{\rm keV})^3\ {\rm erg\,s^{-1}}$$

- Grow BH with:

$$\begin{aligned}\dot{M}_\bullet &= \frac{L_{\rm x}}{\varepsilon_\bullet c^2} \simeq (0.04\ {\rm M}_\odot\,{\rm yr}^{-1})\ L_{{\rm x},43.8}\\ &= (0.04\ {\rm M}_\odot\,{\rm yr}^{-1})\ T^3_{{\rm x},7.4}.\end{aligned}$$



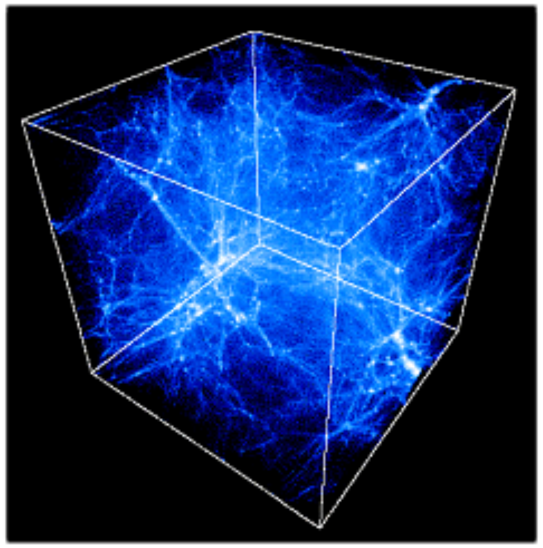
AGN FEEDBACK MODEL FOR STRUCTURE FORMATION

Low-res (dR>10kpc)

$$L_x \simeq 6 \times 10^{43}\,(T_x/2.2\,\mathrm{keV})^3\ \mathrm{erg\,s^{-1}}$$

- Estimate halo cooling rate, inject it back as thermal energy
- Grow BH with:

$$\dot{M}_\bullet = \frac{L_x}{\varepsilon_\bullet c^2} \simeq (0.04\ \mathrm{M_\odot\,yr^{-1}})\ L_{x,43.8}$$
$$= (0.04\ \mathrm{M_\odot\,yr^{-1}})\ T^3_{x,7.4}.$$



Super-high-res (dR~Rbondi)

- Estimate halo cooling rate
- Inject outflow with:

$$P_{\rm out} = P_{\rm OUT} = L_x$$

$$v_{\rm out} = \sqrt{\frac{2\,\varepsilon_\bullet \dot{M}_\bullet c^2}{\dot{M}_{\rm out}}} = \sqrt{\frac{2\,\varepsilon_{\rm BH}}{1-\varepsilon_{\rm BH}/\varepsilon_\bullet}}\,c \simeq \sqrt{2\,\varepsilon_{\rm BH}}\,c \quad (17)$$
$$\simeq (1.4 \times 10^4\ \mathrm{km\,s^{-1}})\ T^{1/2}_{x,7.4} = (1.4 \times 10^4\ \mathrm{km\,s^{-1}})\ L^{1/6}_{x,43.8}$$

- Grow BH with:

$$\dot{M}_\bullet = \frac{L_x}{\varepsilon_\bullet c^2} \simeq (0.04\ \mathrm{M_\odot\,yr^{-1}})\ L_{x,43.8}$$
$$= (0.04\ \mathrm{M_\odot\,yr^{-1}})\ T^3_{x,7.4}.$$

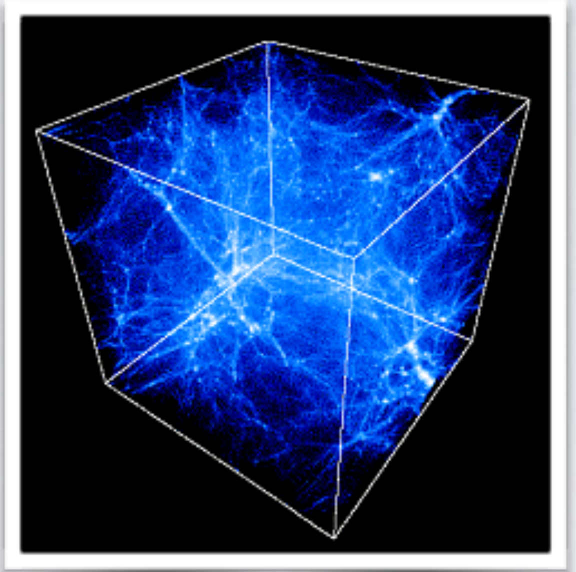
AGN FEEDBACK MODEL FOR STRUCTURE FORMATION

Typical resolution (dR~1kpc)

- Estimate halo cooling rate
- Grow BH with:

$$\dot{M}_\bullet = \frac{L_\mathrm{x}}{\varepsilon_\bullet c^2} \simeq (0.04\ \mathrm{M_\odot\ yr^{-1}})\ L_{\mathrm{x},43.8}$$
$$= (0.04\ \mathrm{M_\odot\ yr^{-1}})\ T^3_{\mathrm{x},7.4}.$$

- Inject mass-loaded outflow:



$$\dot{M}_\mathrm{OUT} = \eta\, \dot{M}_\mathrm{out}$$

$$v_\mathrm{OUT} = \sqrt{\frac{2P_\mathrm{OUT}}{\dot{M}_\mathrm{OUT}}} = \eta^{-1/2}\, v_\mathrm{out}$$

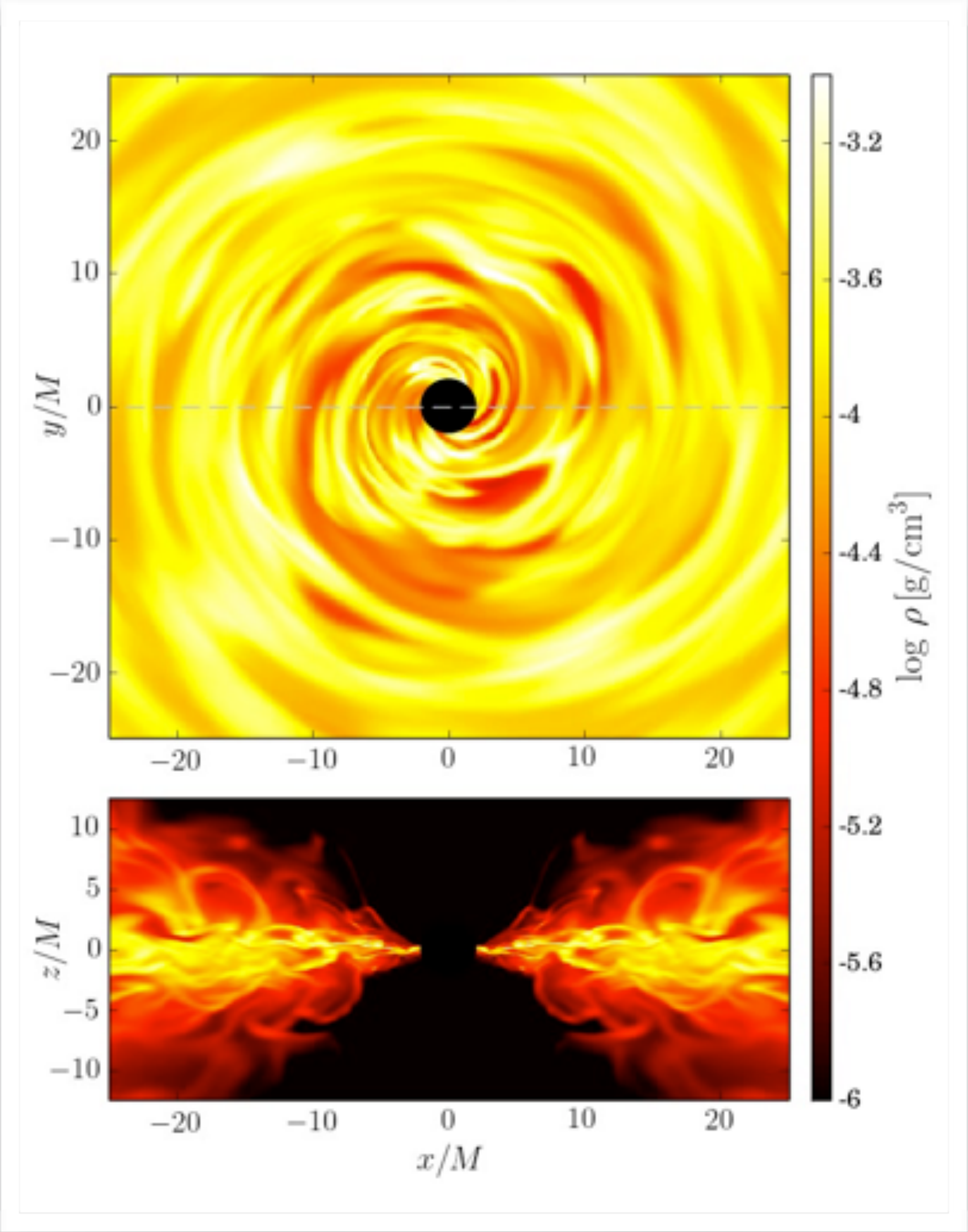
$$\eta_\mathrm{hot} \simeq 40\ T^{-1}_{\mathrm{x},7.4}\, r^{2/3}_{1\,\mathrm{kpc}}$$

$$\eta_\mathrm{warm} \simeq 183\ T^{-1}_{\mathrm{x},7.4}\, r^{2/3}_{1\,\mathrm{kpc}}$$

$$\eta_\mathrm{cold} \simeq 850\ T^{-1}_{\mathrm{x},7.4}\, r^{2/3}_{1\,\mathrm{kpc}}$$

SUMMARY

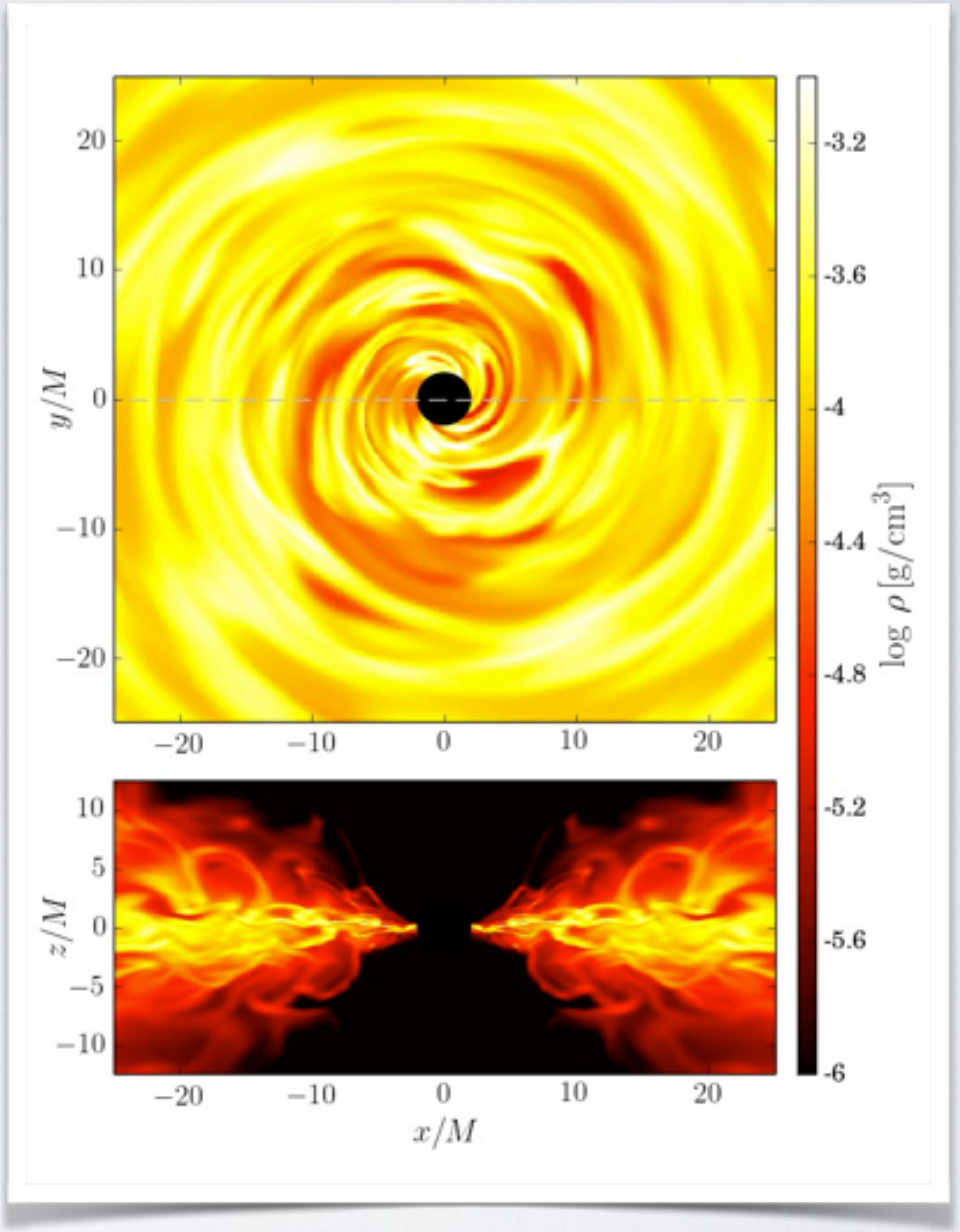
- GR radiative MHD simulations allow for the first time to numerically study the **intermediate regime** of BH accretion
- Radiative efficiency can reach few % of the rest mass energy flux even for thick and optically thin disks (~**luminous hot** accretion flows - LHAFs)
- **Mechanical efficiency ~3%** for zero BH spin, independent of the accretion rate for thick disks
- Coupling micro- and macro-scale efficiencies allows for **constraining the outflow properties** in AGN
- First physical **sub grid model** for AGN feedback!



self-advertisement:
"Thin accretion discs are stabilized by a strong magnetic field", Sadowski 2016

SUMMARY

- GR radiative MHD simulations allow for the first time to numerically study the **intermediate regime** of BH accretion
- Radiative efficiency can reach few % of the rest mass energy flux even for thick and optically thin disks (~**luminous hot** accretion flows - LHAFs)
- **Mechanical efficiency ~3%** for zero BH spin, independent of the accretion rate for thick disks
- Coupling micro- and macro-scale efficiencies allows for **constraining the outflow properties** in AGN
- First physical **sub grid model** for AGN feedback!



self-advertisement:
"Thin accretion discs are stabilized by a strong magnetic field", Sadowski 2016