TOWARDS UNIFYING BLACK HOLE ACCRETION FLOWS - SIMULATING STATE TRANSITIONS

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ACCRETION ON BLACK HOLES

Compactness allows for extraction of significant fraction of the gravitational energy (up to 40% of accreted rest mass energy)

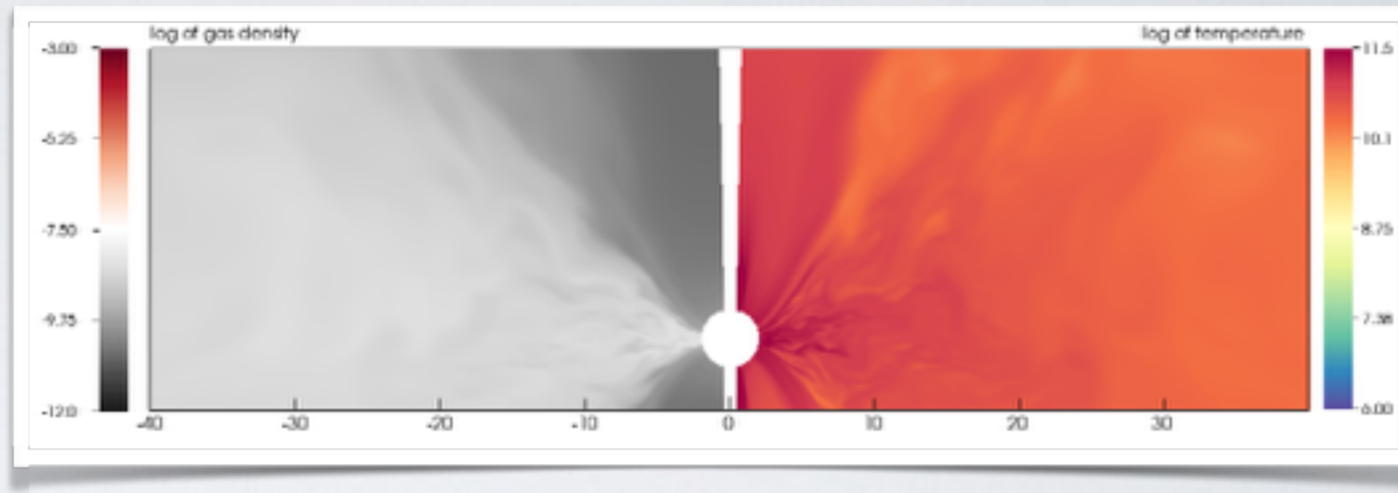
BH accretion is involved in some of the most energetic phenomena:

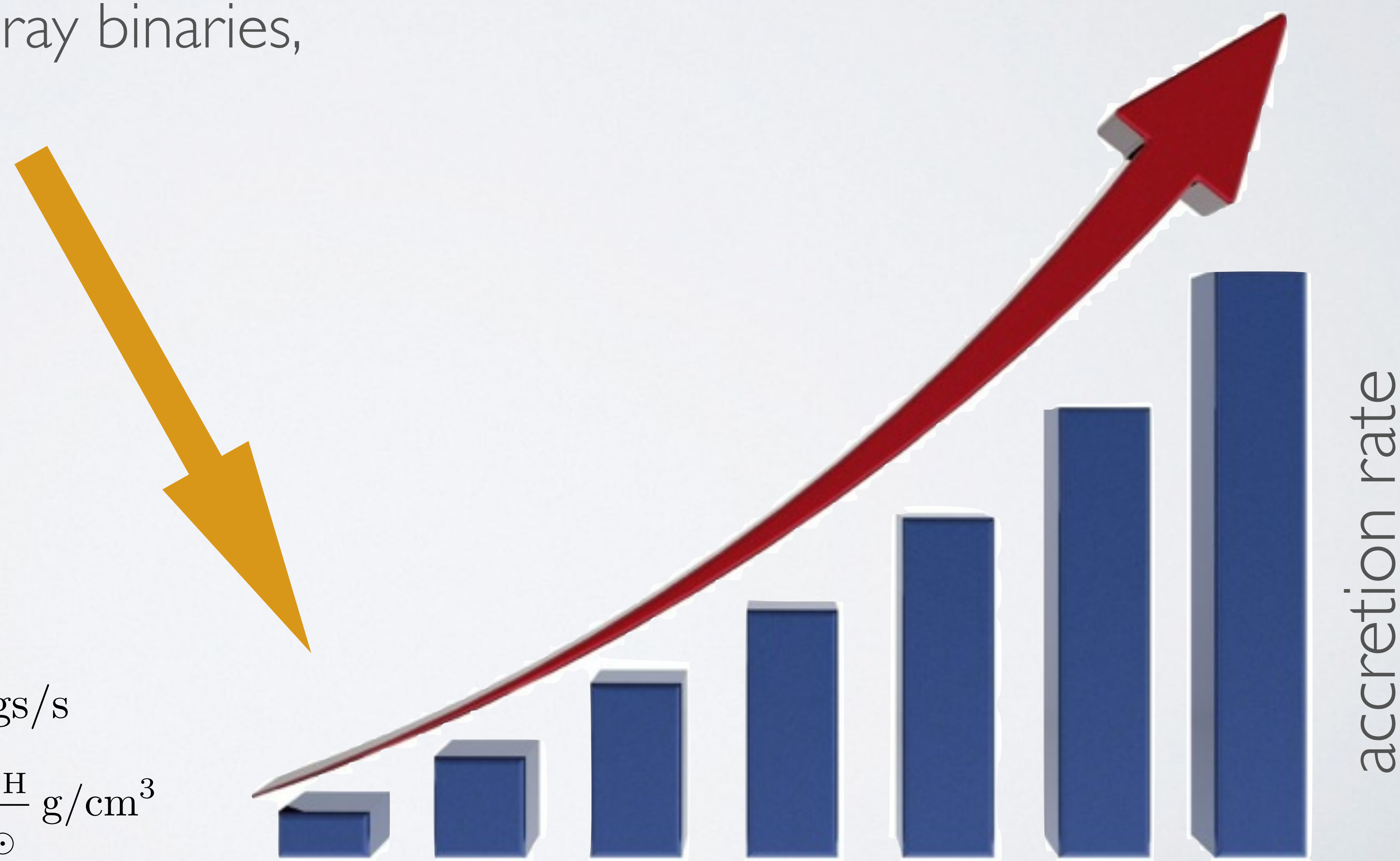
- X-ray binaries
- Active galactic nuclei
- Tidal disruptions of stars
- Gamma ray-bursts
- ULXs

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*

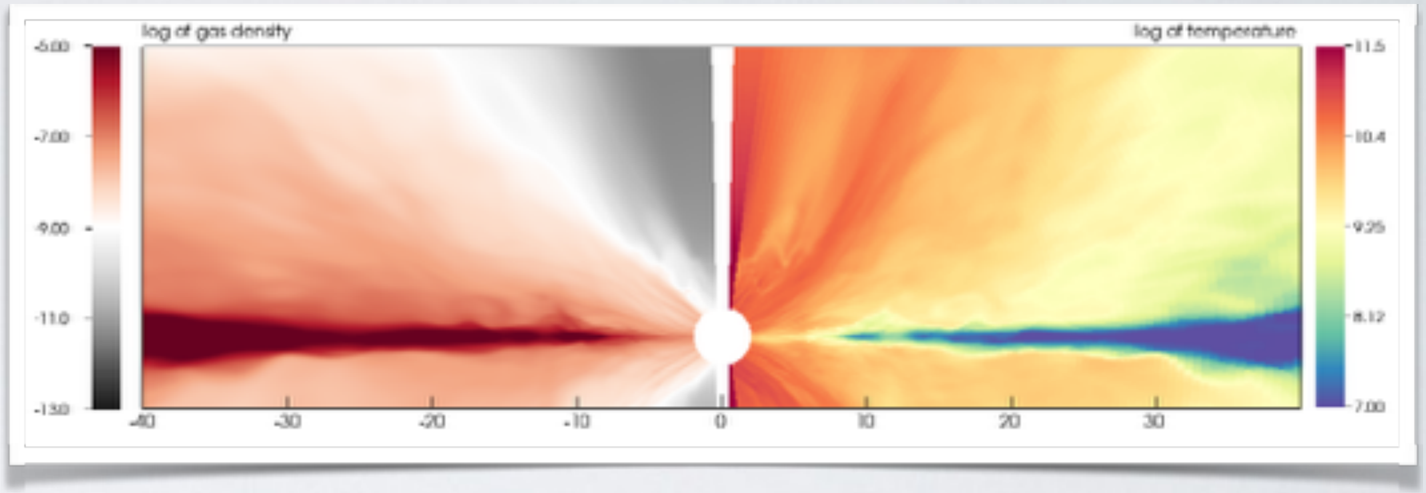




$$L_{\rm Edd} = 1.25 \cdot 10^{38} M/M_\odot \ {\rm ergs/s}$$

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

MODES OF ACCRETION



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

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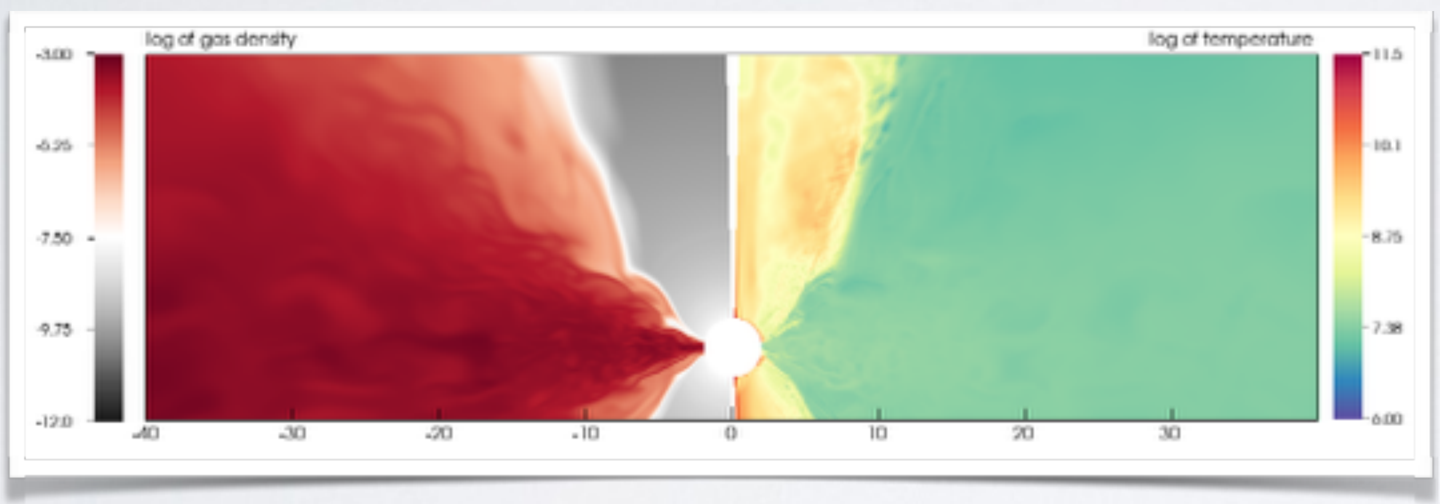
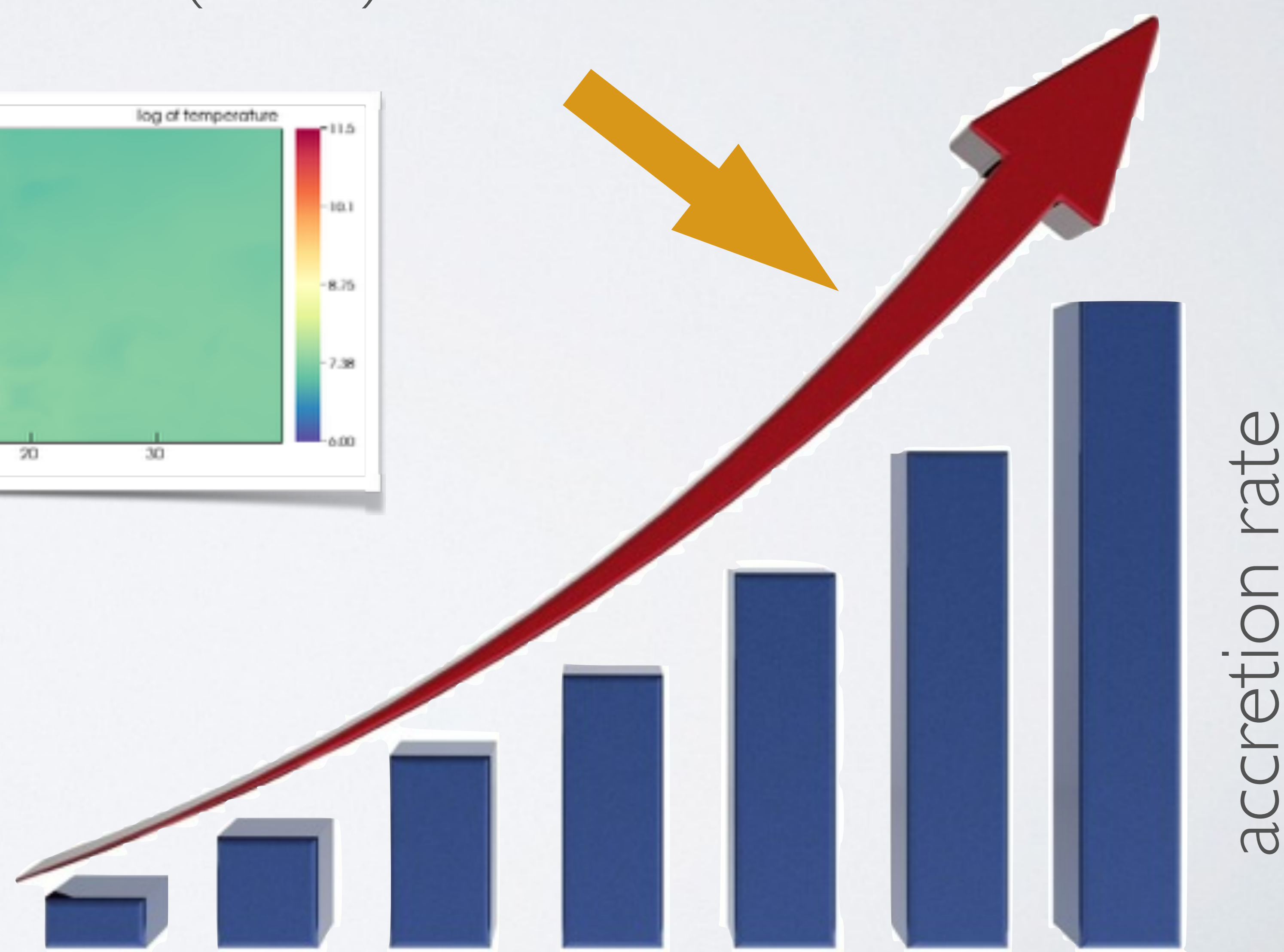
MODES OF ACCRETION

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)





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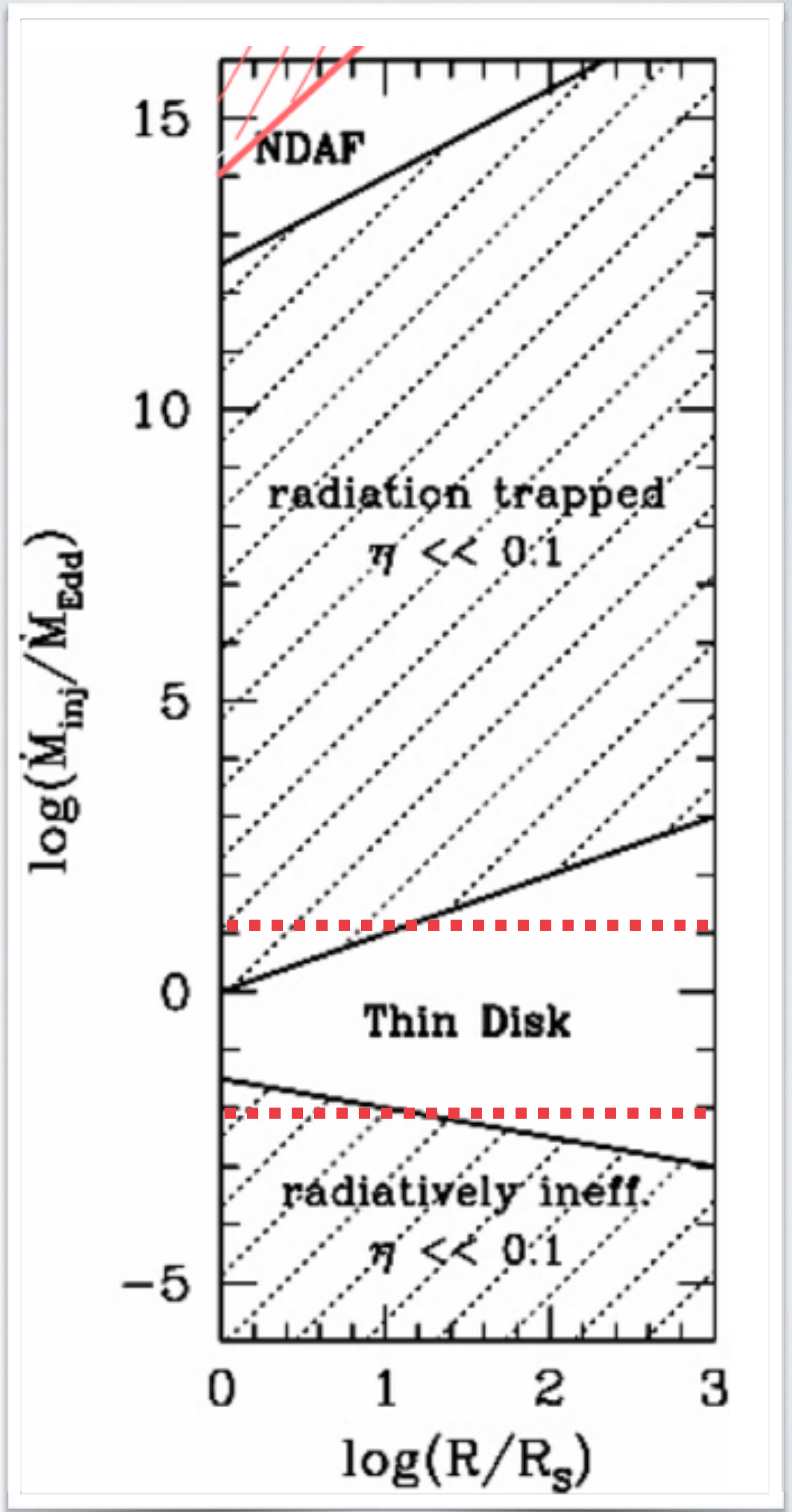
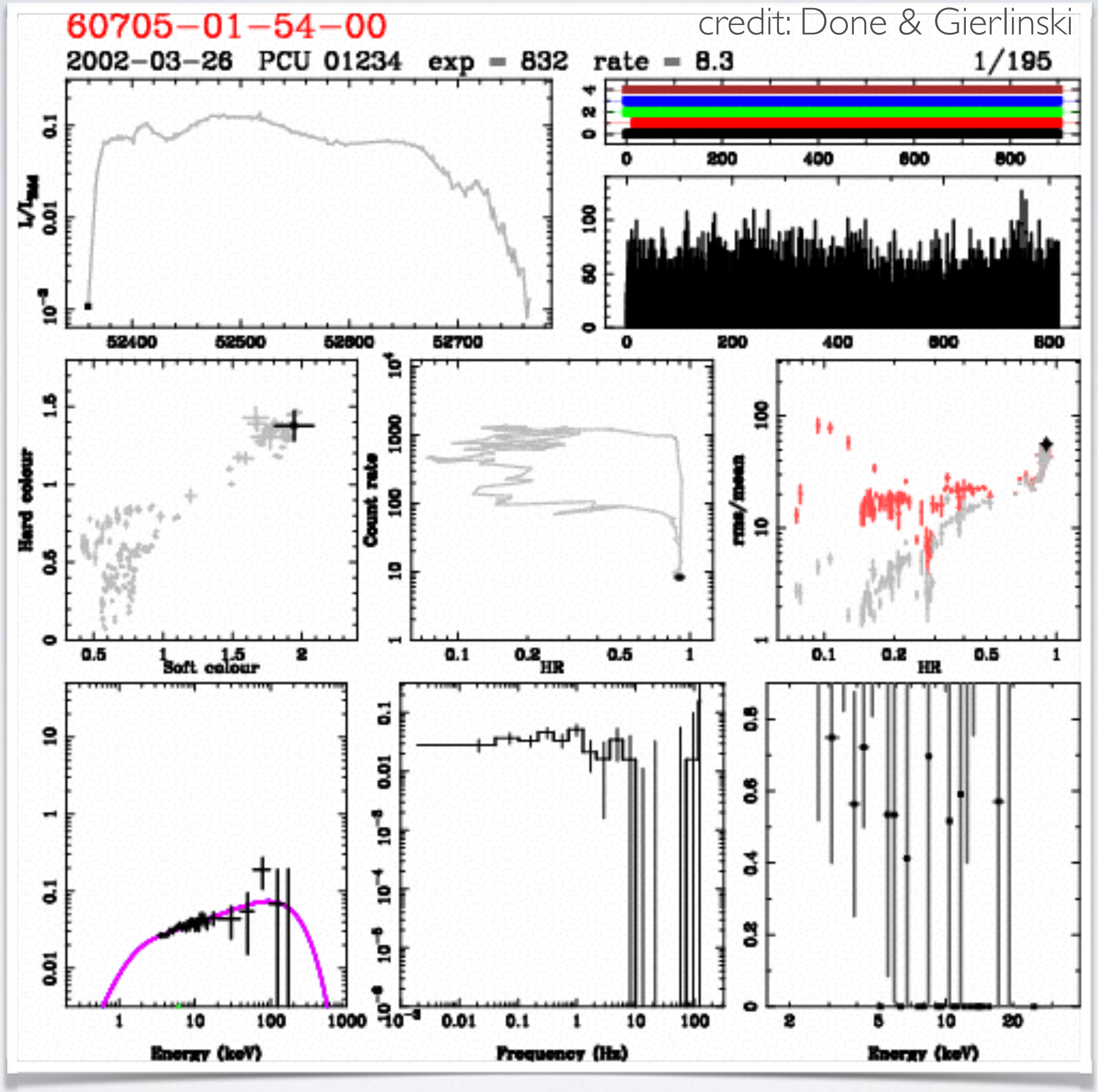
MODES OF ACCRETION

- Transition between equilibrium solutions taking place at different critical accretion rate at different radii
- Combo solutions allowed:
  - thin and slim
  - thin and hot

  at outer/inner regions
- Astrophysical sources change their modes!



STATE TRANSITIONS IN GX 339-4



Optically thin, hot → Optically thick, cold

AGN EFFICIENCY

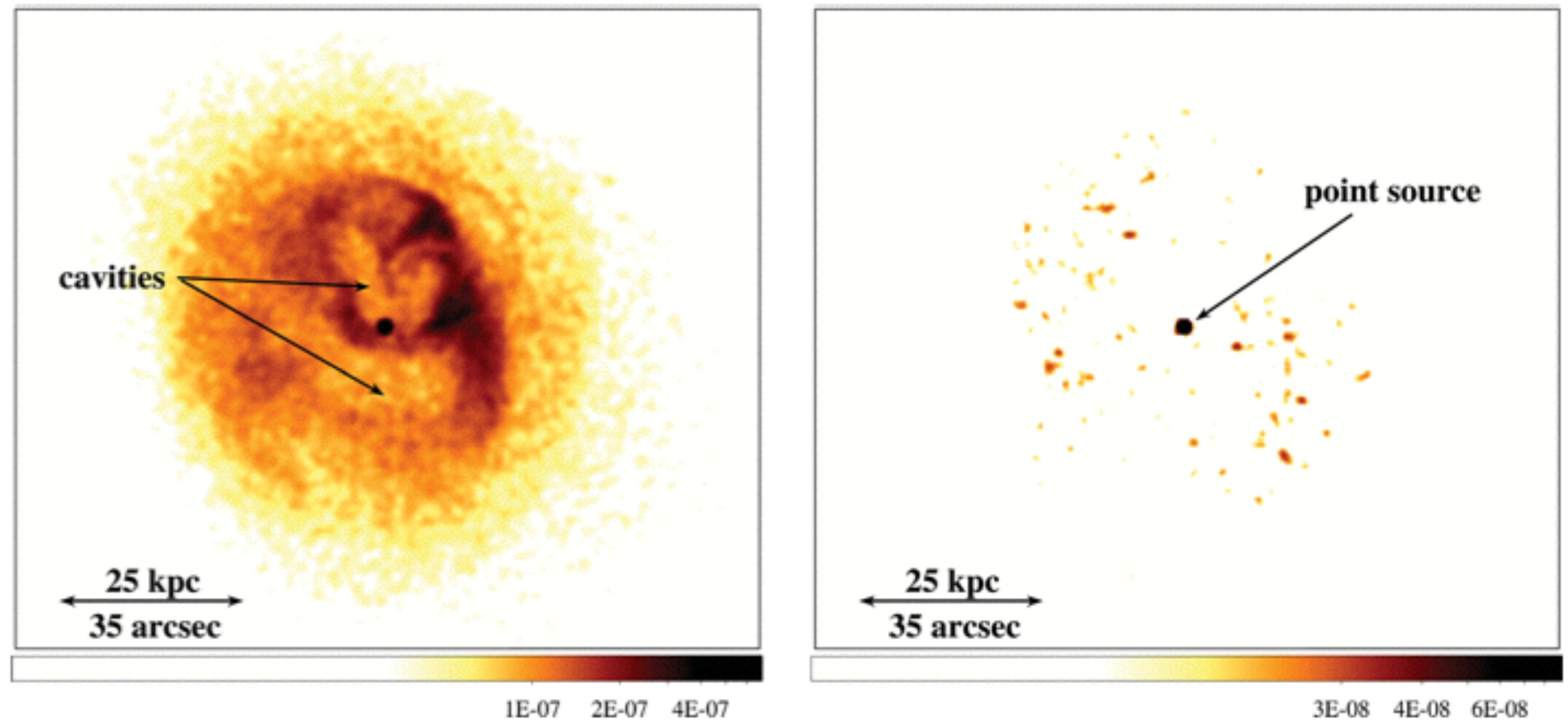
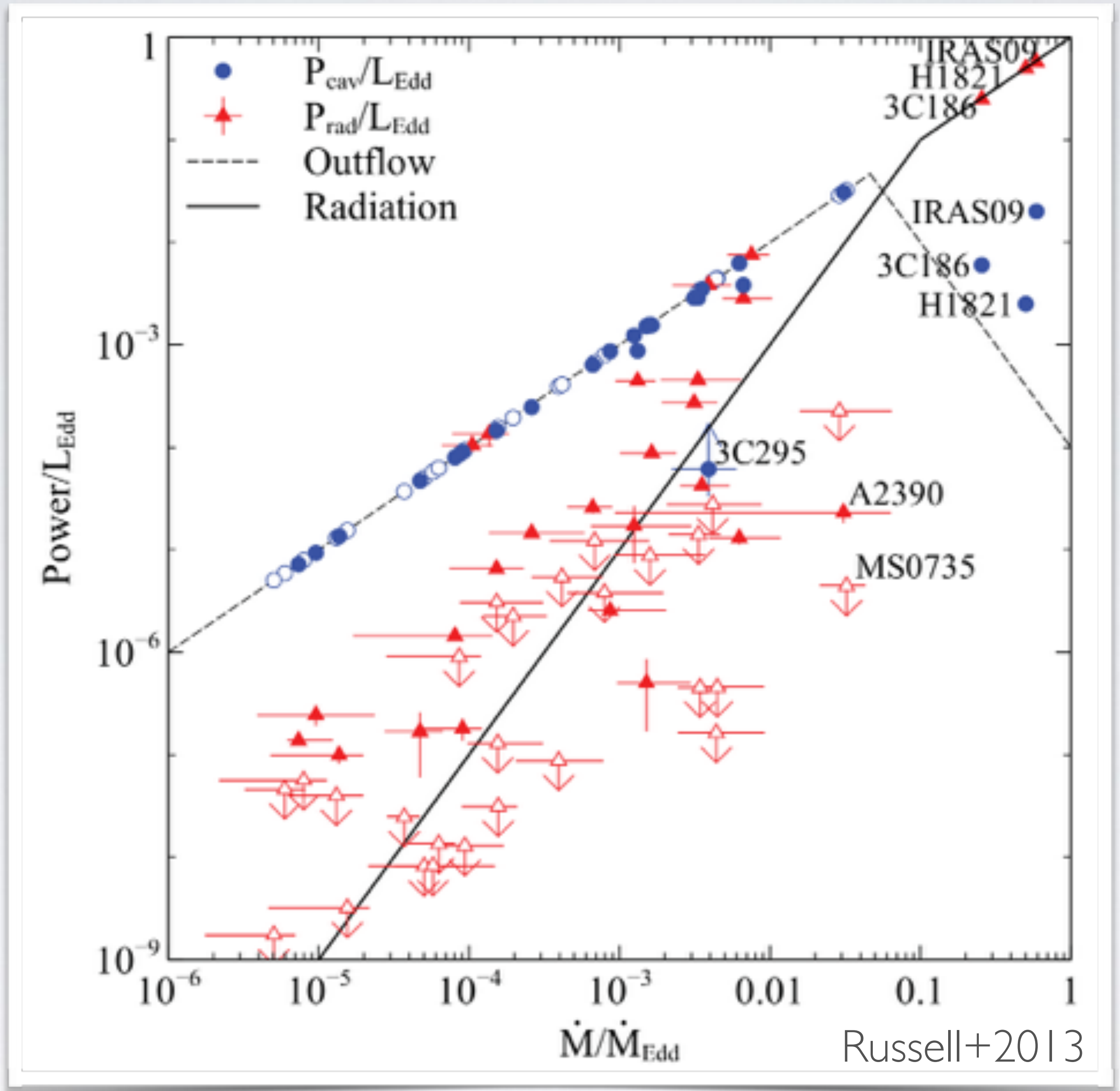


Figure 1. Exposure-corrected *Chandra* images covering the same field of Abell 2052 (see Blanton et al. 2011). The colour bar has units photons cm^{-2} s^{-1} $pixel^{-1}$. Left: 0.5–7 keV energy band showing the X-ray cavities. Right: 3–7 keV energy band showing the AGN point source detection.

Russell+2013

- Quasars radiatively efficient
- However, most AGN dim - but efficient in mechanical luminosity!
- Mechanical output measured from the properties of inflated cavities
- Radiative output measured directly

MODES OF ACCRETION IN AGN



Surveys of AGN confirm this picture:

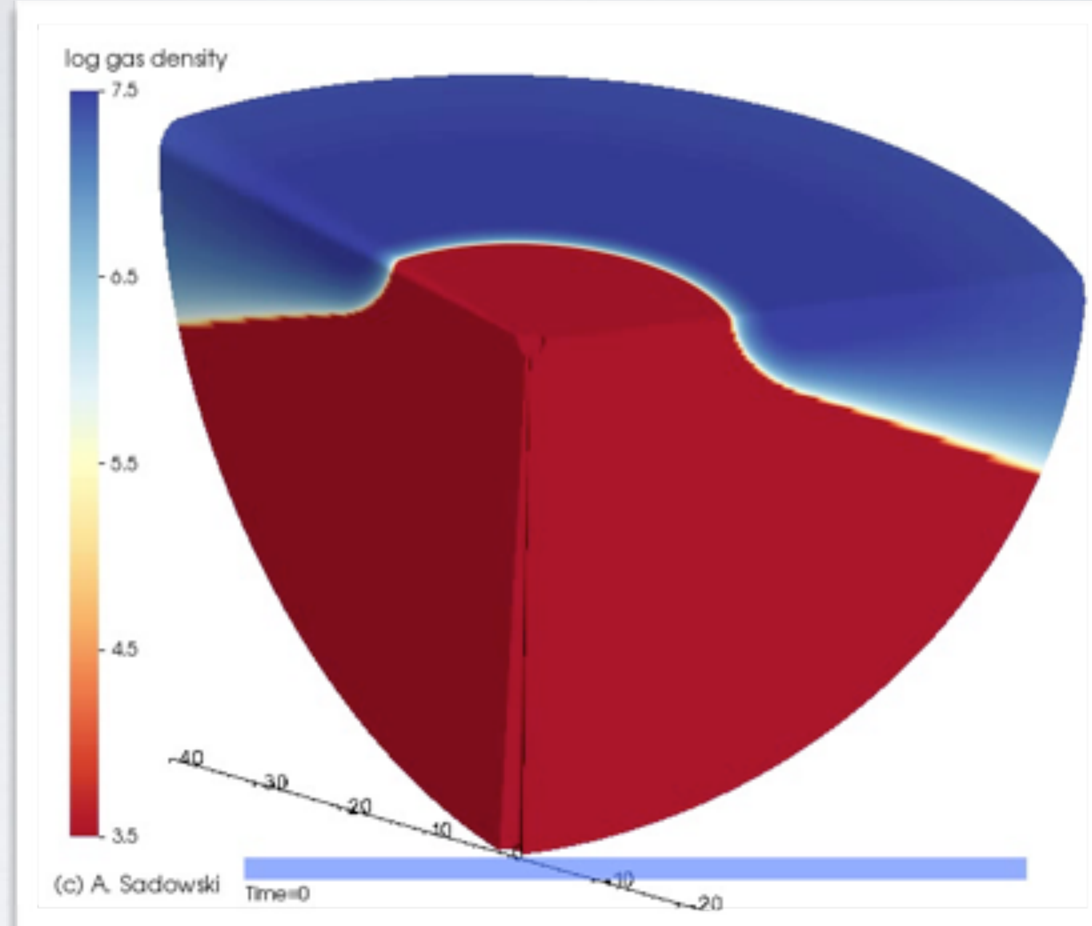
- kinetic output dominates below $10^{-3} L_{\mathrm{Edd}}$
- radiative luminosity dominates above

SIMULATING STATE TRANSITIONS

KORAL (Sadowski+13,14,15)

- GR ideal MHD + div B=0
- Radiation evolved simultaneously providing cooling and pressure
- Radiative transfer under M1 approximation
- Conservation of number of photons (allows for tracking the radiation temperature)
- Comptonization
- Synchrotron and bremmstrahlung Planck and Rosseland opacities dependent on both gas and radiation temperature
- Independent evolution of thermal electrons and ions
- Coulomb coupling
- Self-consistent (depending on electron and ion temperatures) adiabatic index

Sufficient set to study accretion flows at any accretion rate, including the intermediate regime

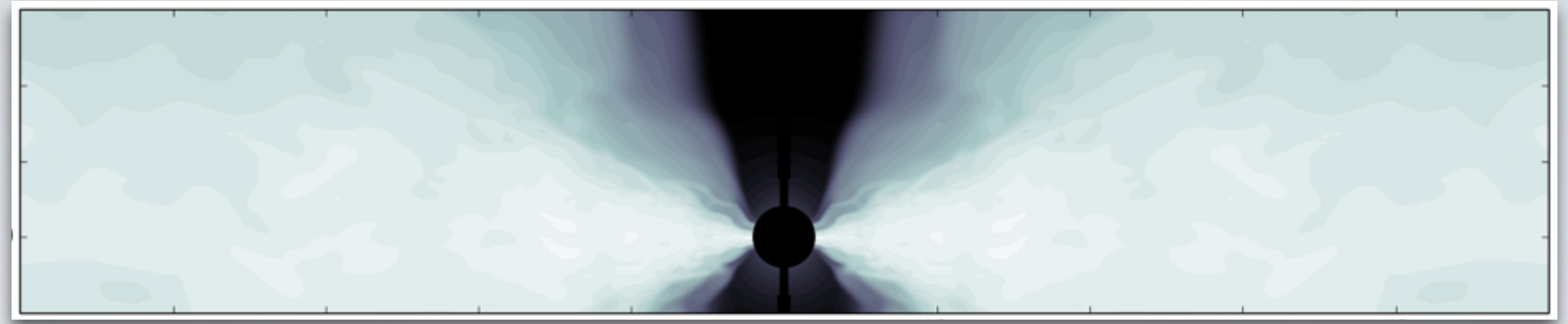


$$
\begin{aligned}
(\rho u^\mu)_{;\mu} &= 0 \\
(T^\mu_\nu)_{;\mu} &= G_\nu, \\
(R^\mu_\nu)_{;\mu} &= -G_\nu. \\
(n u^\mu)_{;\mu} &= \dot{n}.
\end{aligned}
$$

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

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

LOW LUMINOSITY ACCRETION FLOWS IN KORAL

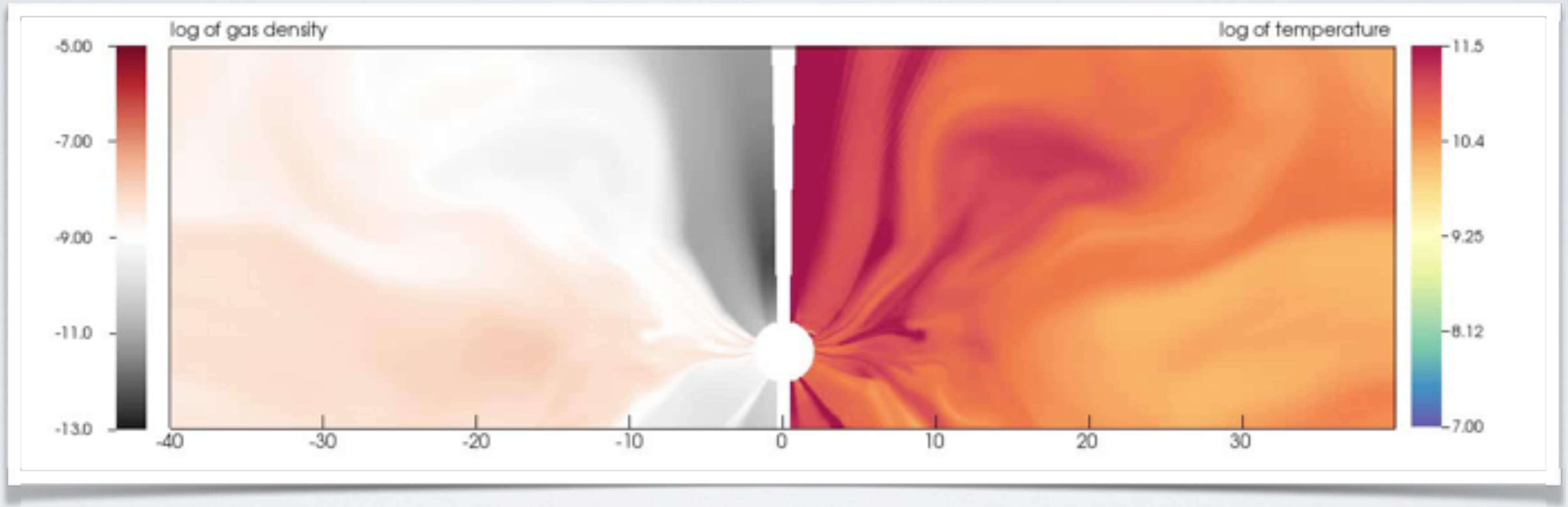


- Set of 2D and 3D simulations of radiative accretion flows in the ADAF/thin transition regime
- Bremmstrahlung + synchrotron + scattering
- Photon number conserving
- <u>Fixed ion to electron temperature ratios</u>
- Resolution: 336x336x32 (pi/2)
- Logarithmic, horizon-penetrating grid
- Initialized by rescaling up solutions for lower accretion rates

LOW LUMINOSITY ACCRETION FLOWS

$$T_{\rm i}/T_{\rm e} = 10$$

$\sim 10^{-4}\dot{M}_{\rm Edd}$



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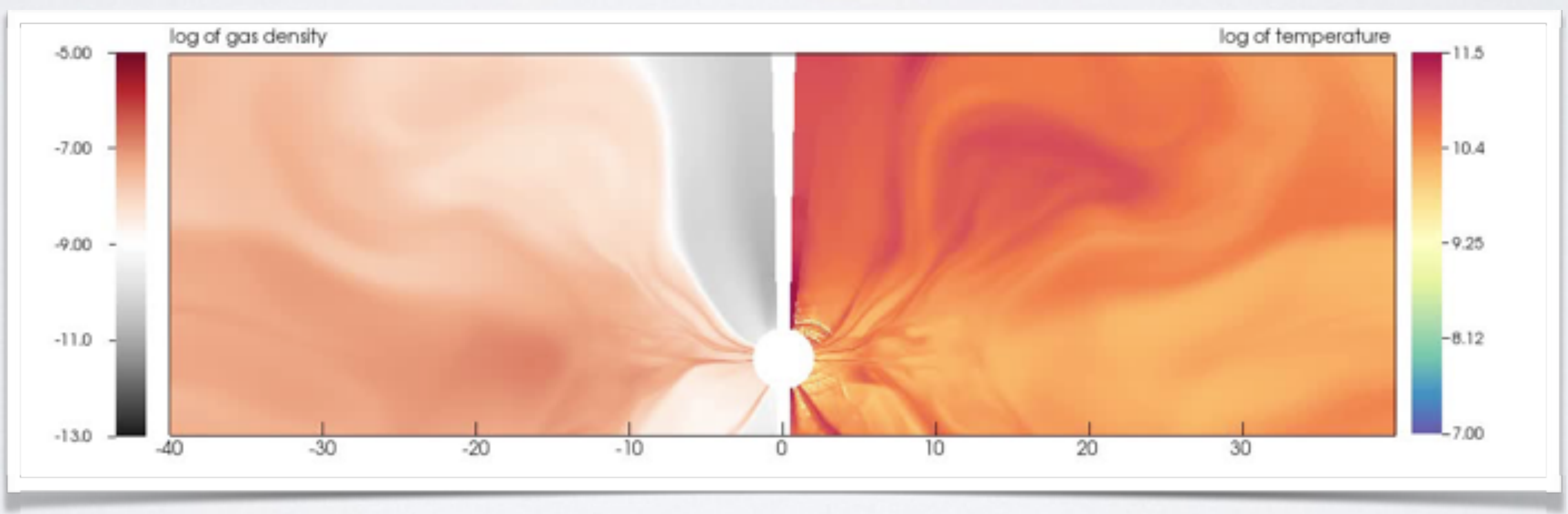

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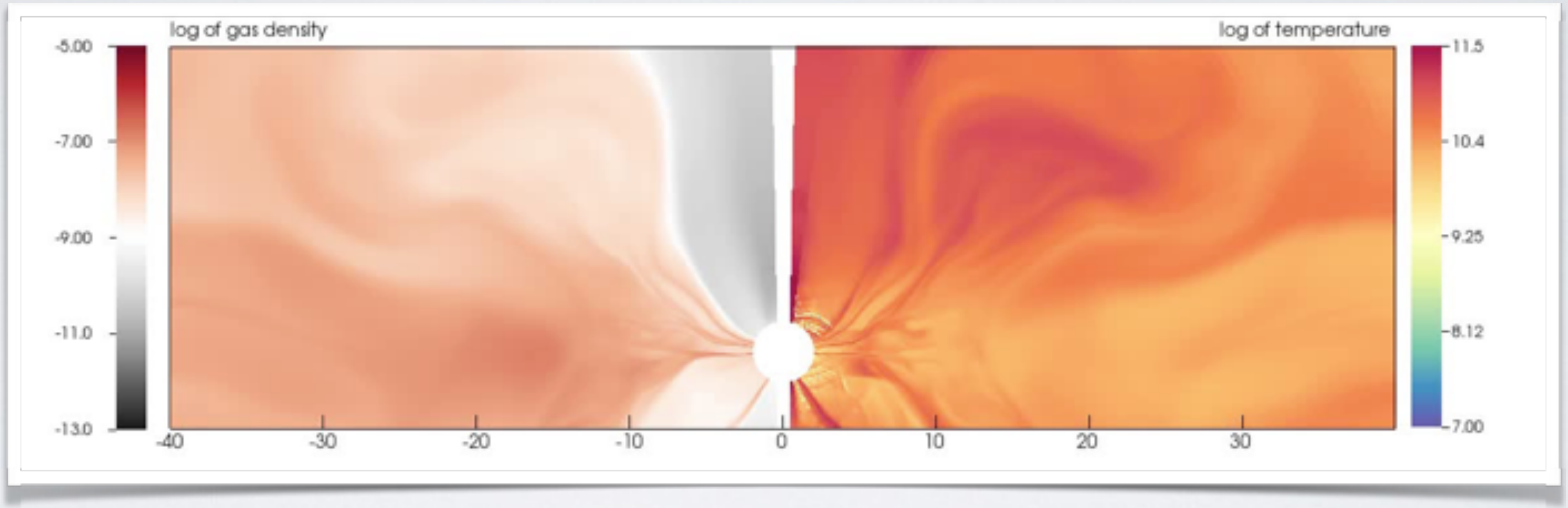
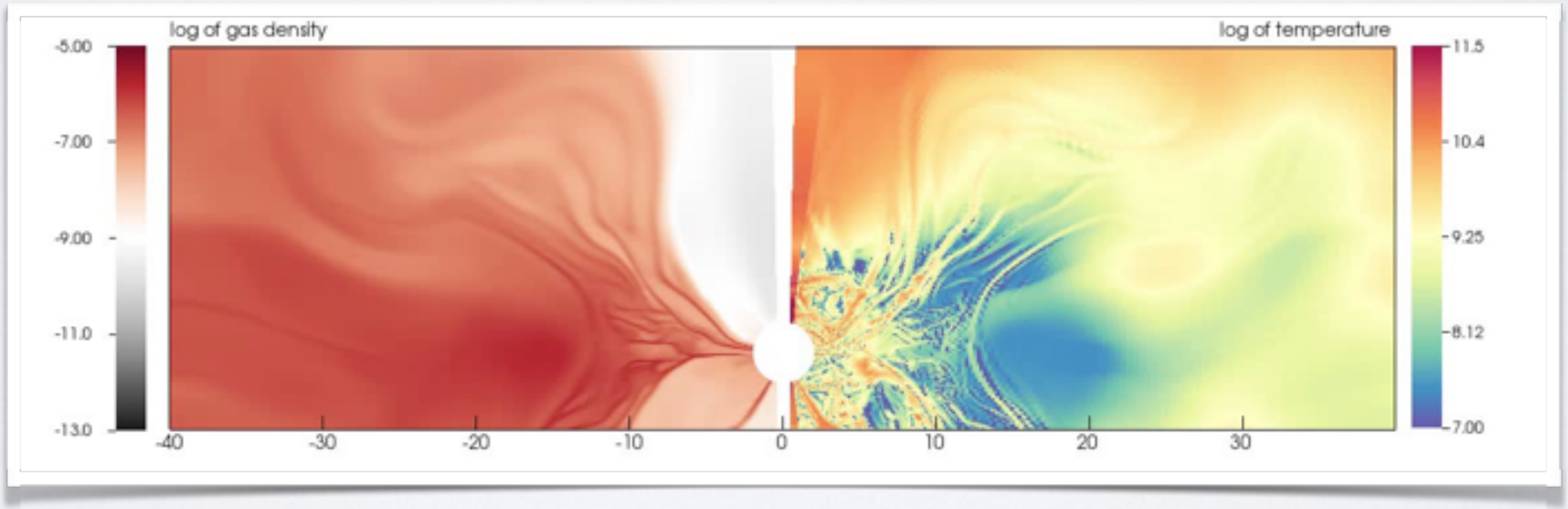
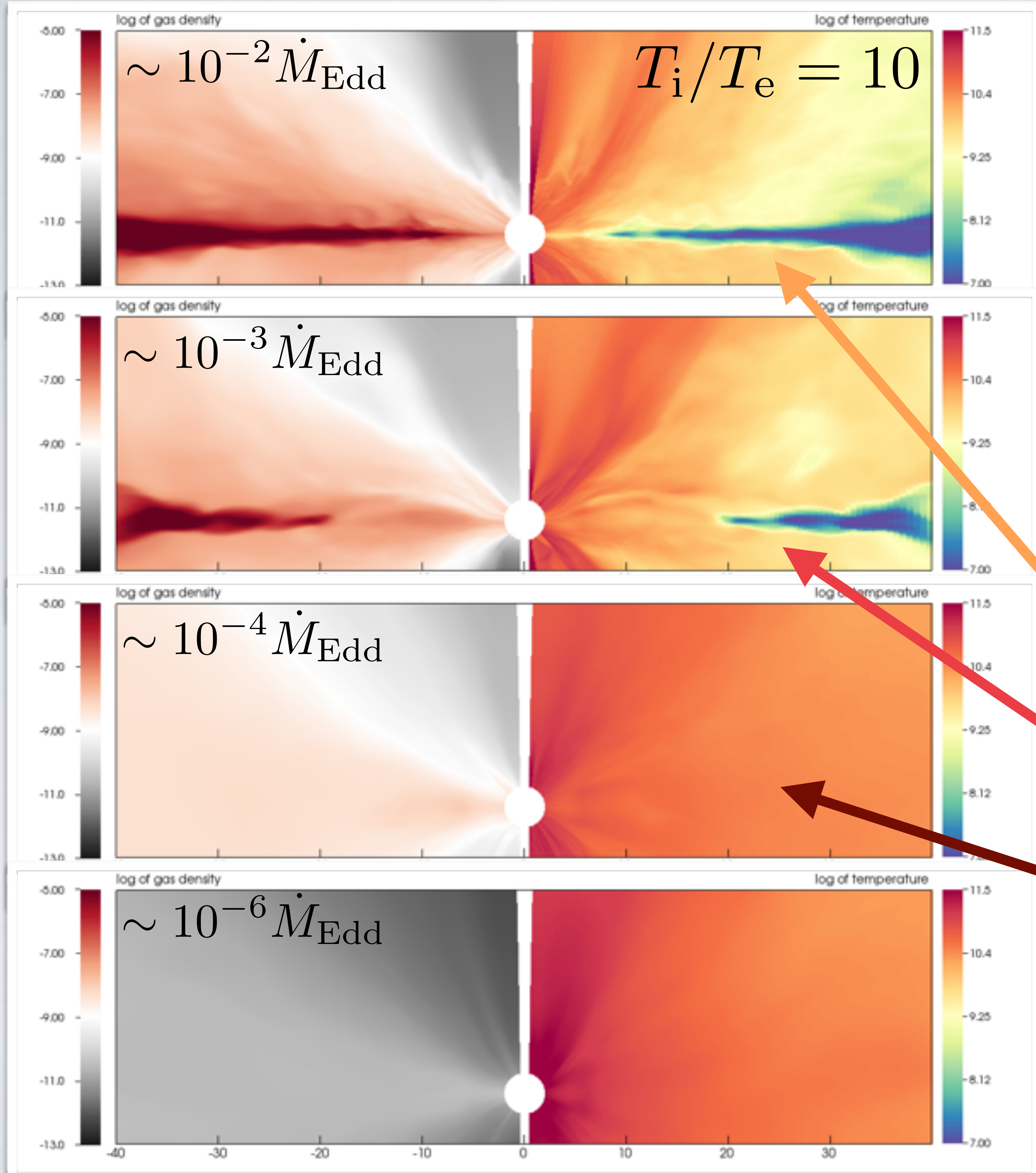
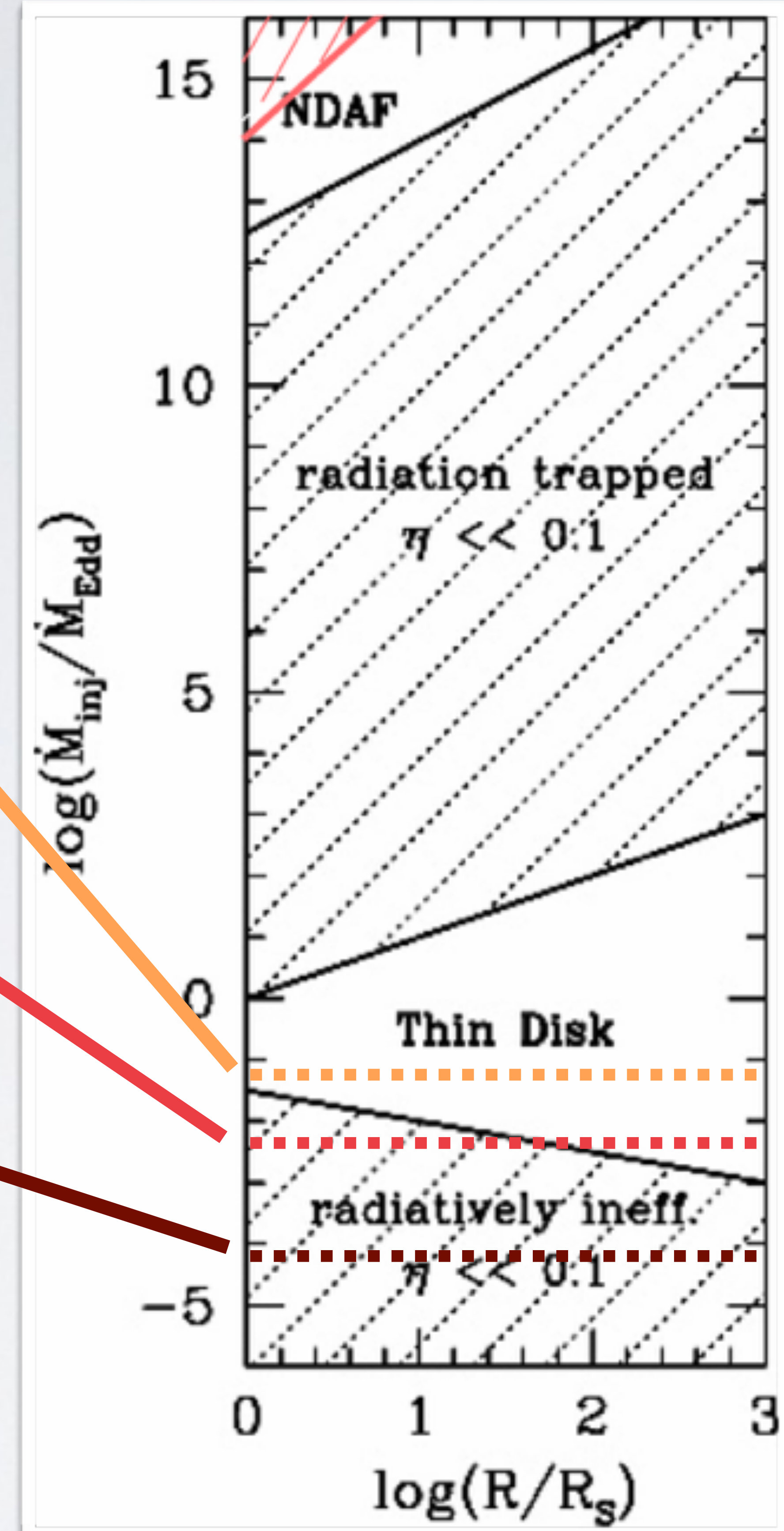


$\sim 10^{-2}\dot{M}_{\rm Edd}$





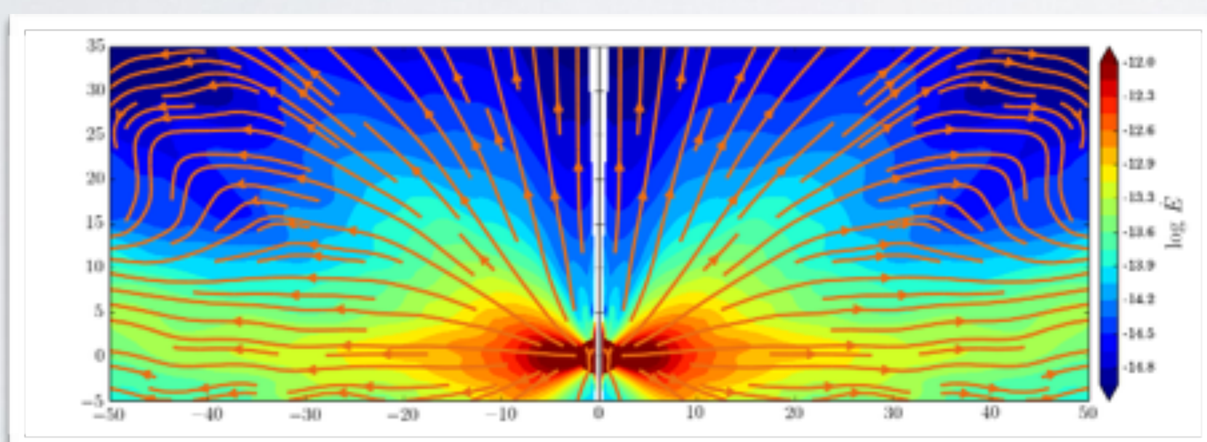
log of gas density
log of temperature
$\sim 10^{-2}\dot{M}_{\rm Edd}$
$T_{\rm i}/T_{\rm e} = 10$
$\sim 10^{-3}\dot{M}_{\rm Edd}$
$\sim 10^{-4}\dot{M}_{\rm Edd}$
$\sim 10^{-6}\dot{M}_{\rm Edd}$
-40 -30 -20 -10 0 10 20 30



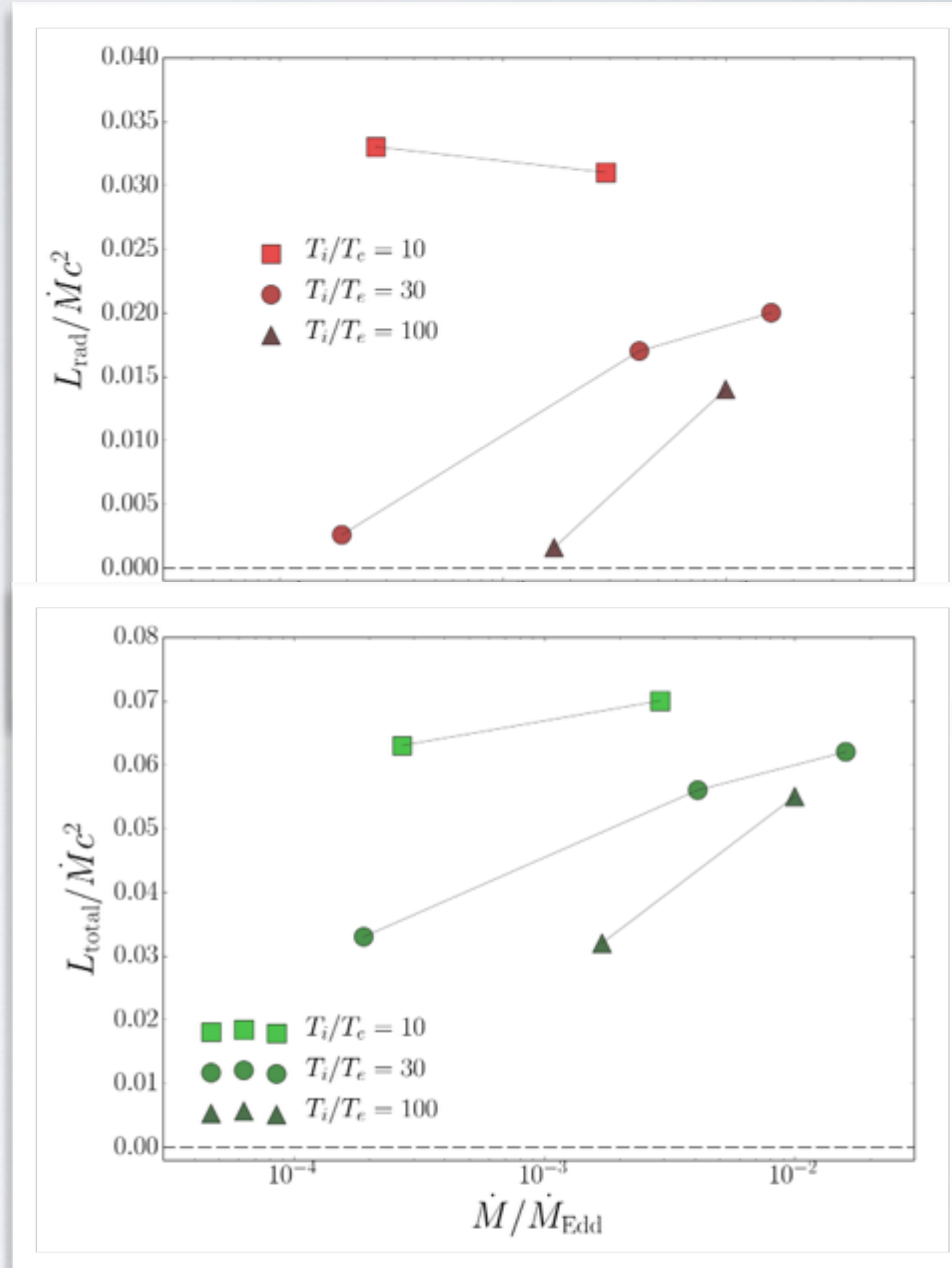
NDAF
radiation trapped
$\eta << 0.1$
Thin Disk
radiatively ineff.
$\eta << 0.1$
$\log(\dot{M}_{\rm inj}/\dot{M}_{\rm Edd})$
$\log(R/R_s)$
15 10 5 0 −5
0 1 2 3

RADIATIVE EFFICIENCY

- Radiative output increases with accretion rate
- The hotter the electrons, the higher the radiative efficiency
- Mechanical efficiency close to the fully optically thin value of 3%

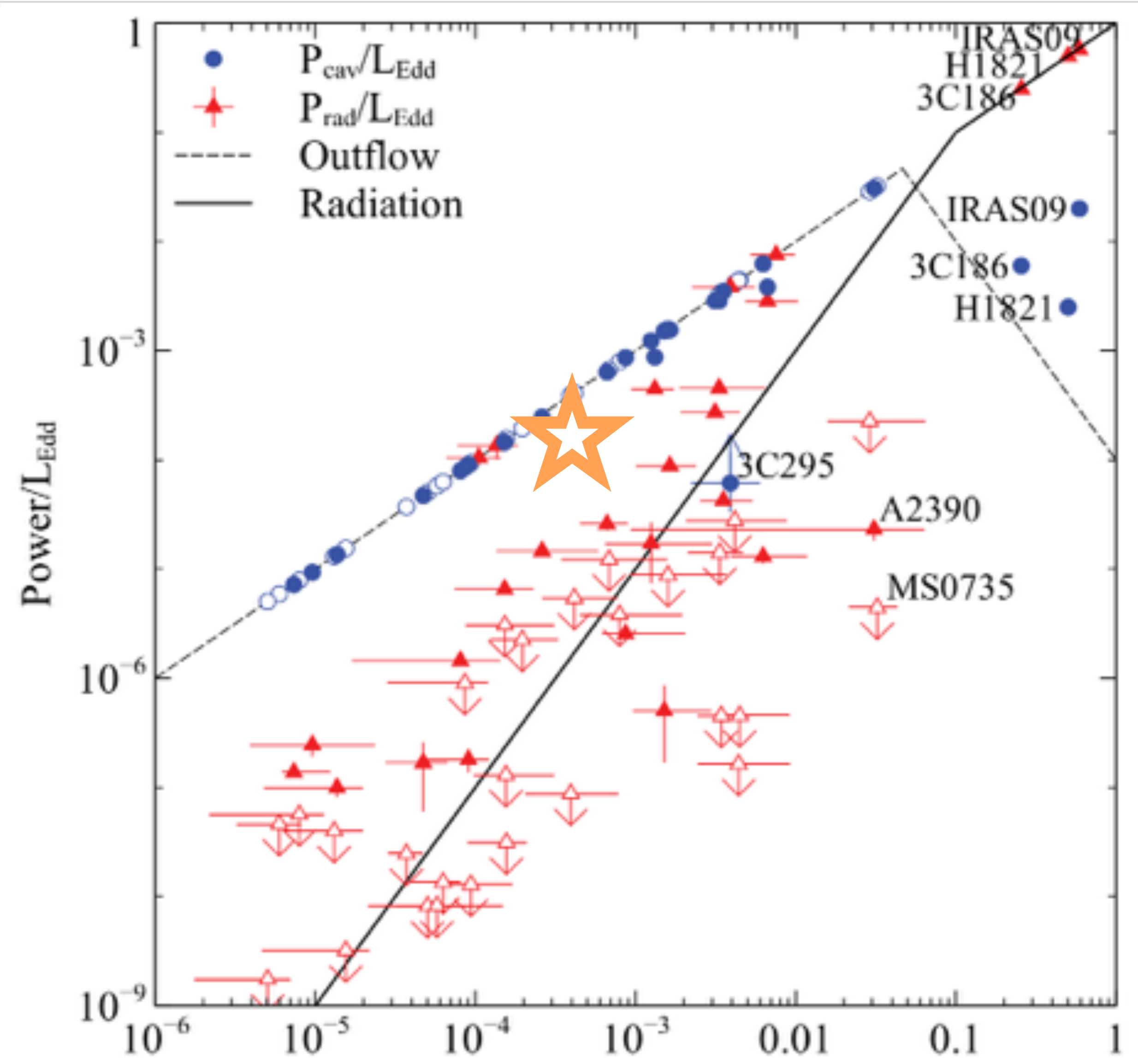


(Sadowski+15)



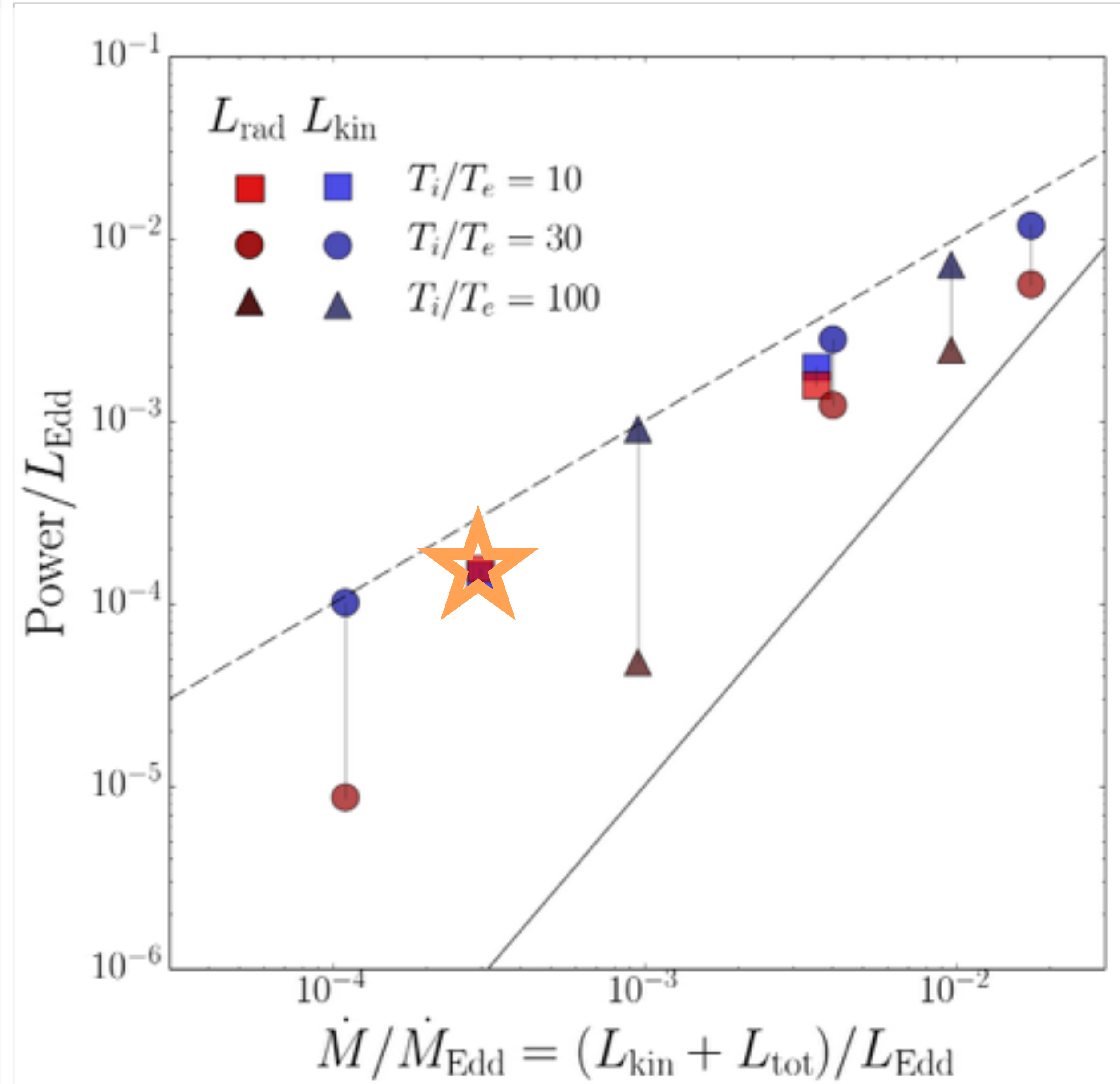
RADIATIVE AND MECHANICAL EFFICIENCIES

Observed



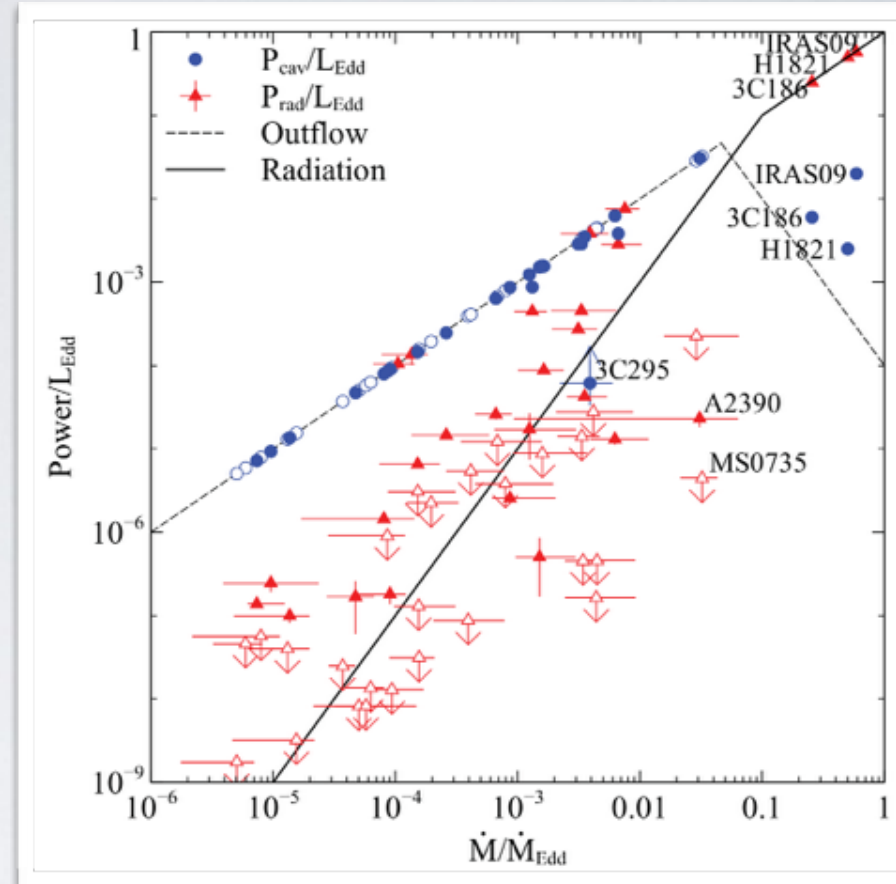
Russell+2013

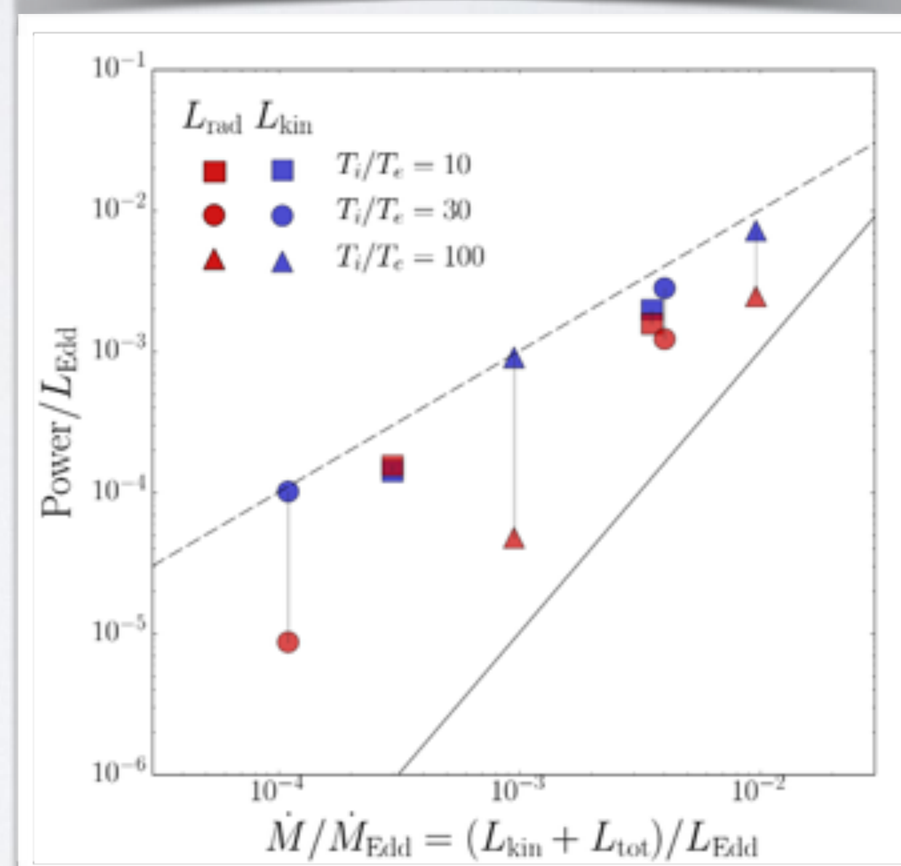
Simulated



RADIATIVE AND MECHANICAL EFFICIENCIES

- $T_\mathrm{i}/T_\mathrm{e} = 10$ gives comparable radiative and mechanical luminosities already at $10^{-4} L_\mathrm{Edd}$ - unphysical!
- $T_\mathrm{i}/T_\mathrm{e} = 30$ and $T_\mathrm{i}/T_\mathrm{e} = 100$ consistent with observational constraints from AGN surveys
- $T_\mathrm{i}/T_\mathrm{e} \gtrsim 30$!



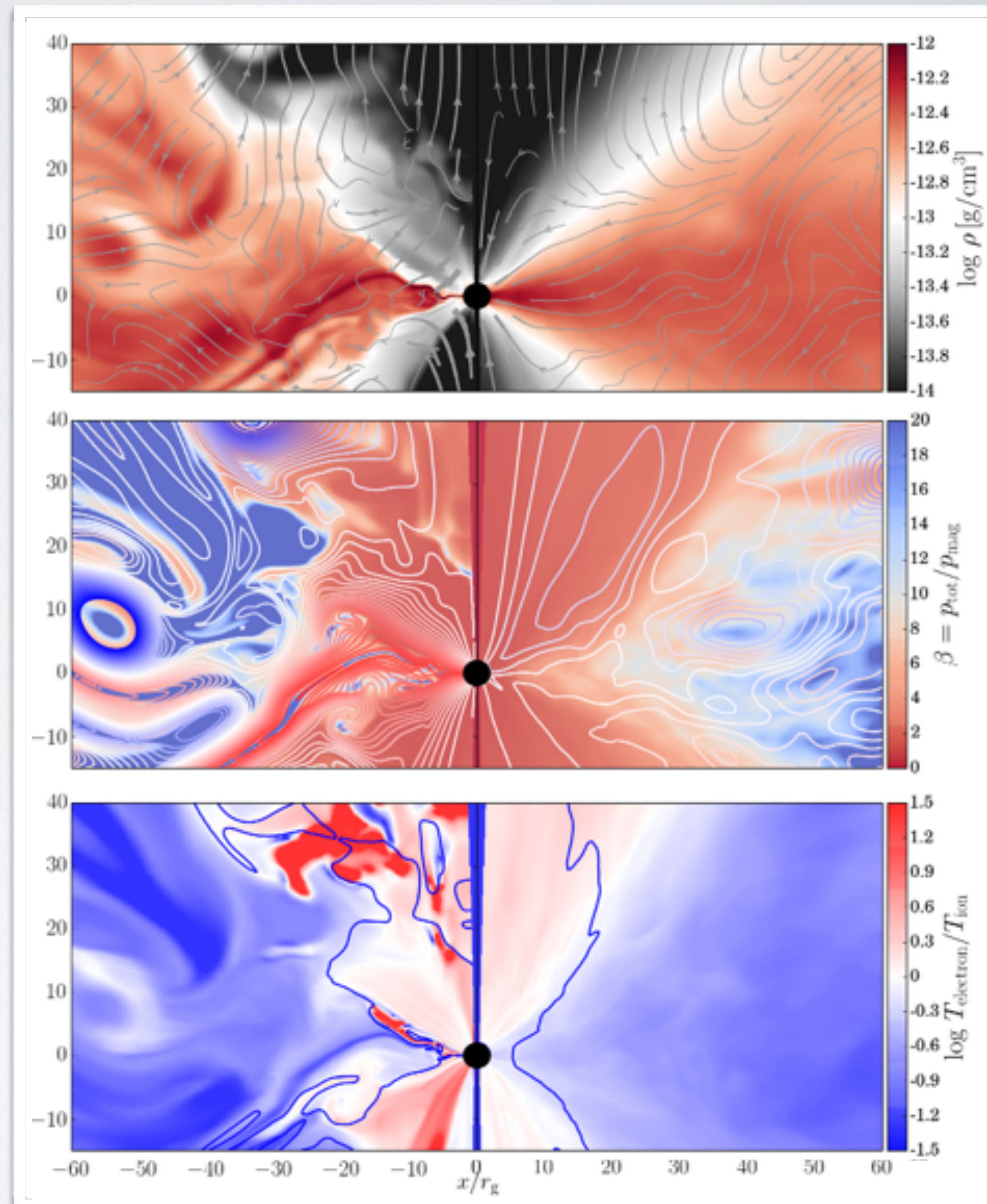


ELECTRON TEMPERATURE

- Radiative properties depend on the electron temperature
- This affected both by adiabatic compression and non-adiabatic dissipation
- If the latter dominates, then,

$$\frac{T_e}{T_i} = \frac{1}{2}\frac{\delta_e}{1-\delta_e}$$

  with δ_e being the fraction of heating going into electrons.
- δ_e a function of gas magnetization.
- Studying transition from radiatively inefficient to efficient state may help constrain disk properties.



SUMMARY

- GR radiative MHD simulations allow for the first time to numerically study the intermediate optical depth regime of BH accretion
- Comparison of the observed and simulated radiative characteristics of accreting gas allows to get insights into the properties of collisionless plasmas and test assumptions behind modeling of truncated disks
- $T_{\rm i}/T_{\rm e} \gtrsim 30$