AGN Feedback: Simulations of Black Hole

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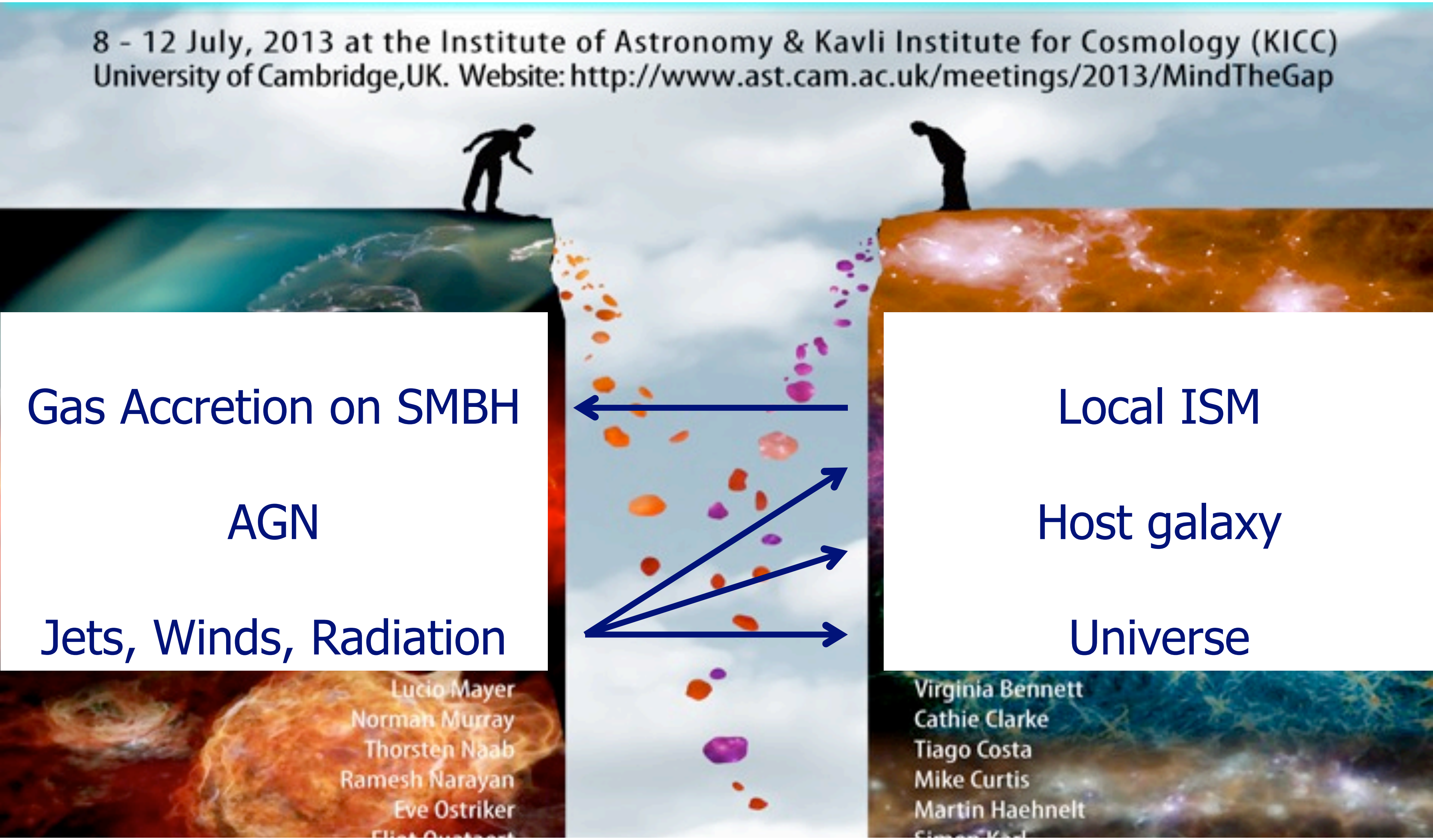
MIND THE OTHER GAP



Gas Accretion on SMBH

AGN

Jets, Winds, Radiation

Local ISM

Host galaxy

Universe

Galactic Nucleus

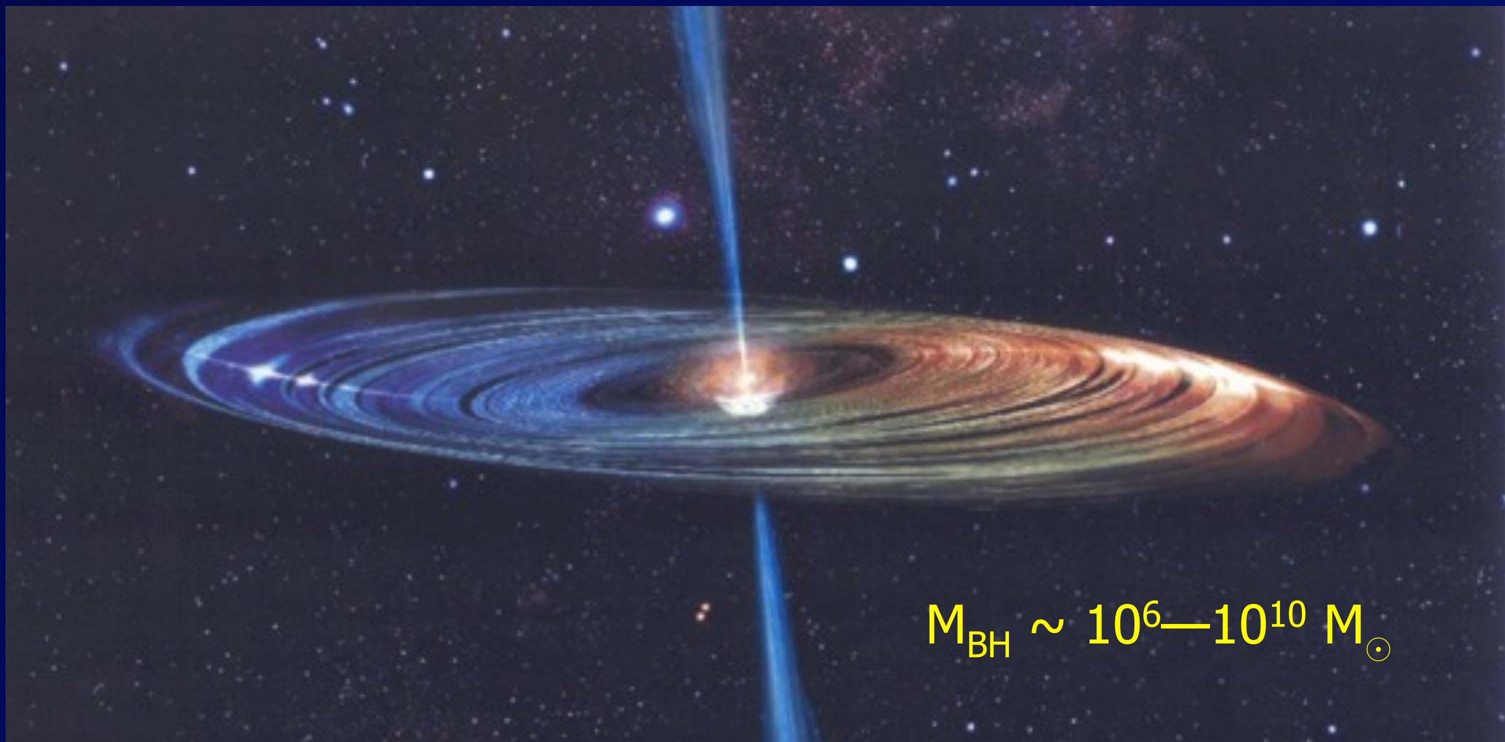


Image credit: Lincoln Greenhill, Jim Moran

Three Accretion Regimes

ADAF/Slim Disk

Super-Eddington, radiation trapped

(Begelman '79; Abramowicz et al. '89)

Thin Accretion Disk

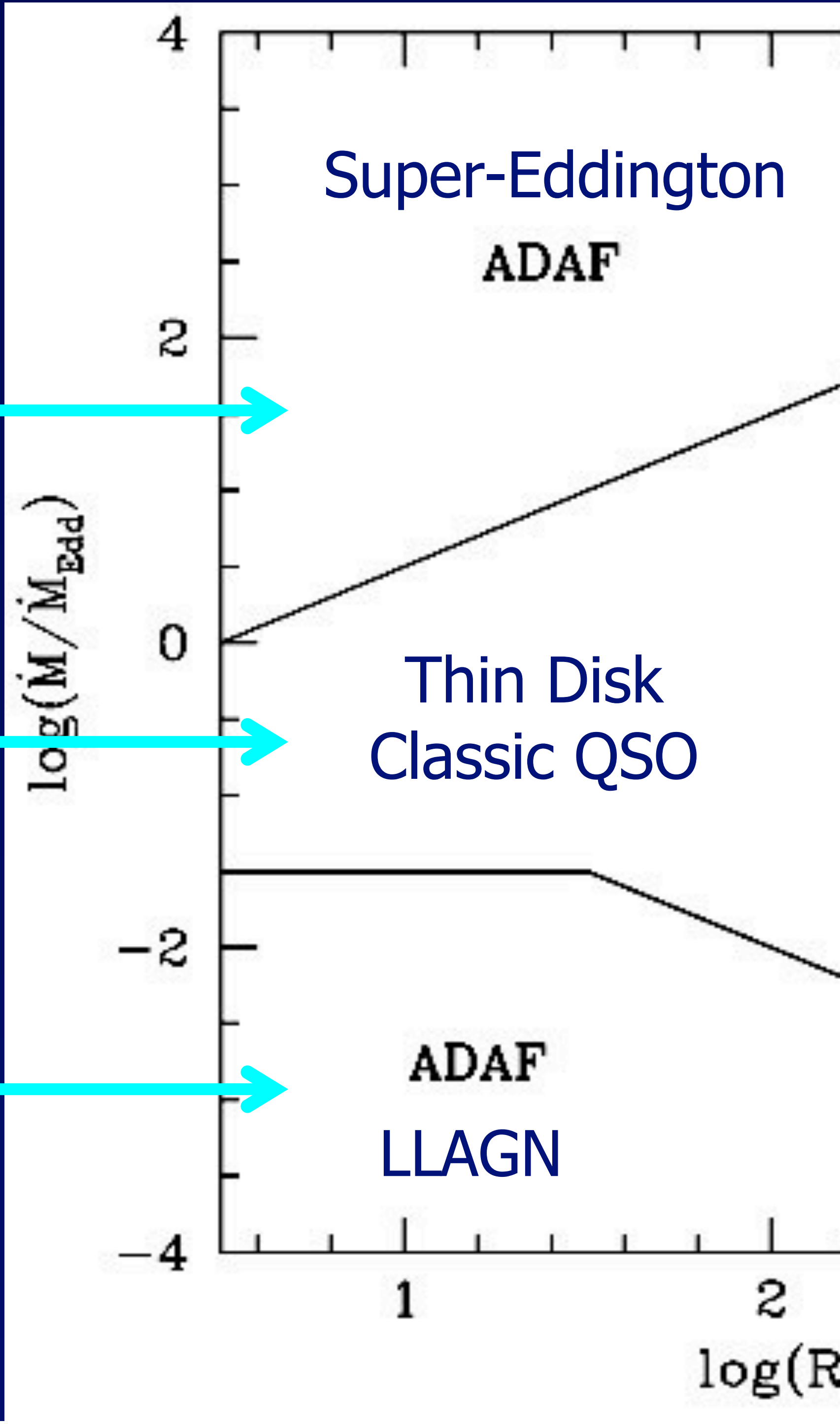
(Pringle & Rees '72; Shakura & Sunyaev '73; Novikov & Thorne '73)

Quasars, XRBs in high soft state

ADAF/RIAF

Radiatively inefficient

(Ichimaru '77; Rees et al. '82; Narayan & Yi '94, '95; Abramowicz et al. '95)



Accretion and Outflows

- Analytic disk theory (1D) is okay for understanding basic physics of accretion
- Jets and outflows involve 2D motions and are beyond analytical theory
- We need numerical simulations:
  - GR (black hole – Kerr metric!) ✔
  - MHD (magnetic fields essential) ✔
  - Radiation (tough problem) ?✔

Numerical Simulations

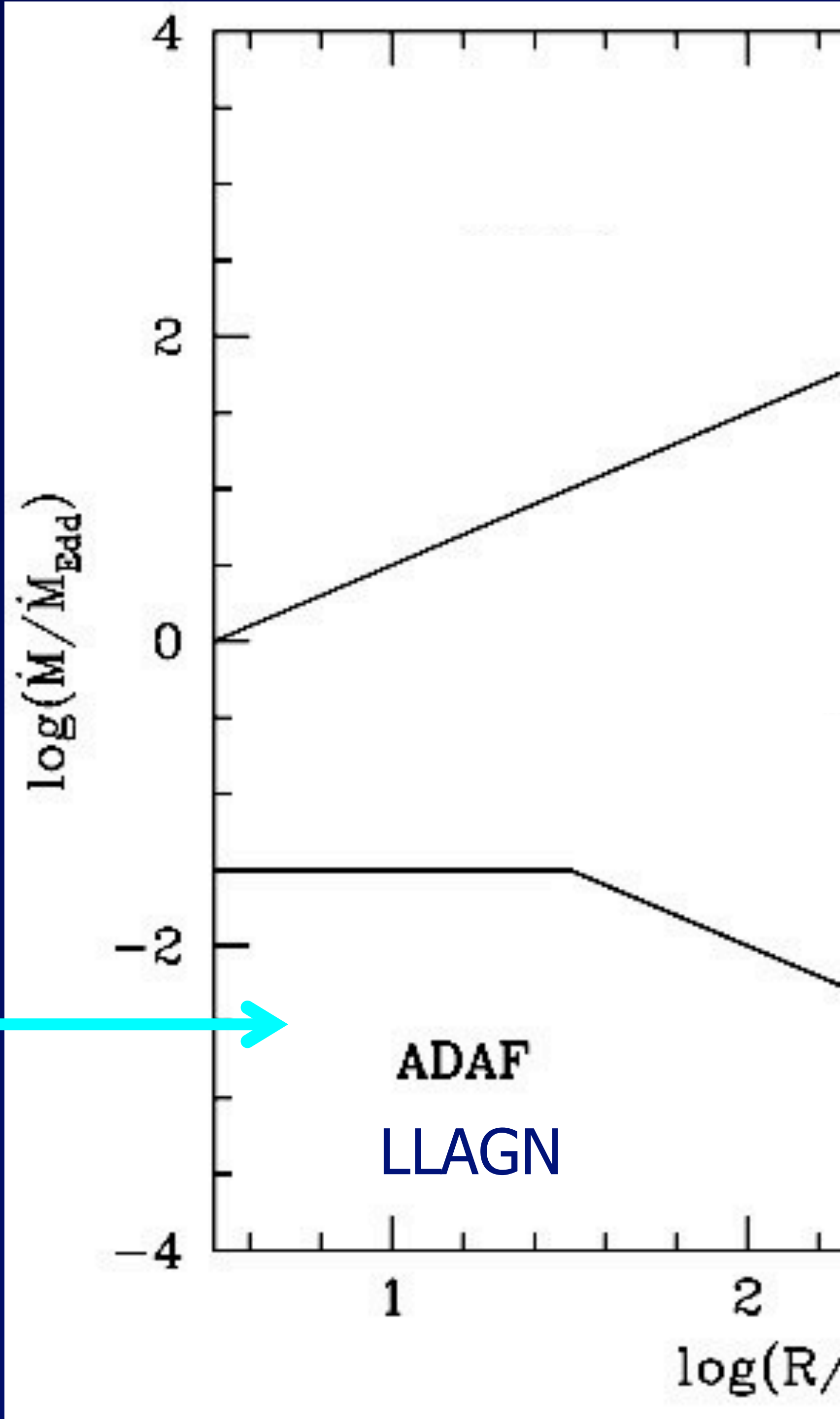
- Simulations of varying degrees of complexity have been done over the years
  - Pseudo-Newtonian hydrodynamics
  - Pseudo-N magnetohydrodynamics (MHD)
  - General Relativistic MHD (GRMHD) **
  - Radiation hydro/MHD → GRRMHD
- **Good news:** GRMHD simulations
  - Produce jets and winds from "generic" initial conditions
  - Provide new insights on accretion/jet physics
  - Provide useful information for AGN feedback

Feedback in Radio Mode/ Maintenance Mode

ADAF/RIAF

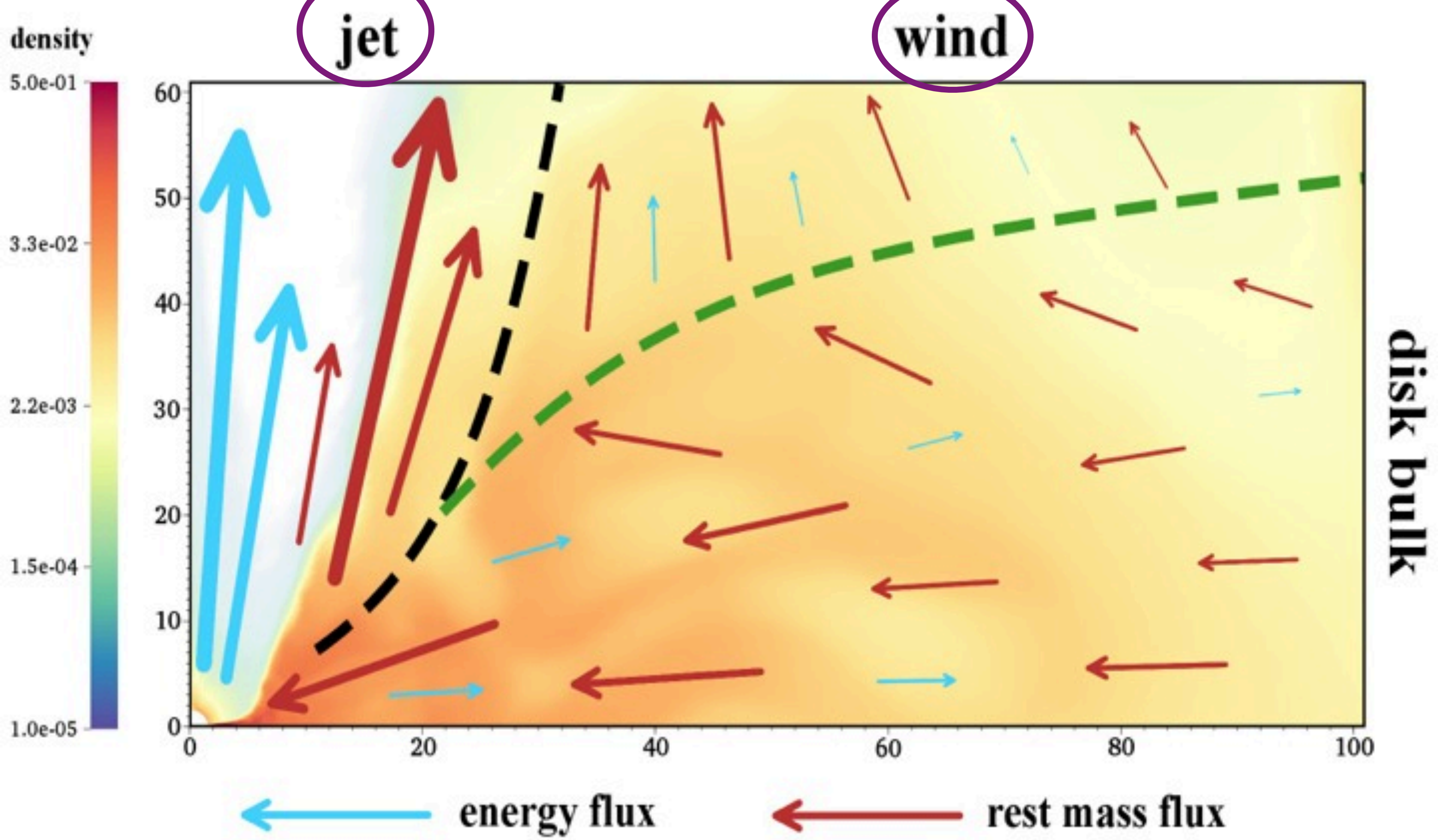
Radiatively inefficient

(Ichimaru '77; Rees et al. '82; Narayan & Yi '94, '95; Abramowicz et al. '95)



GRMHD Simulations of ADAFs

- ADAF/RIAF is the easiest of the three accretion modes to simulate
- We can safely ignore radiation
- Geometrically thick: everything goes fast
- Simulations reach steady state out to fairly large radii
  - ~ few x 100M in the best cases (still << R_B)
- ADAFs readily form jets and outflows



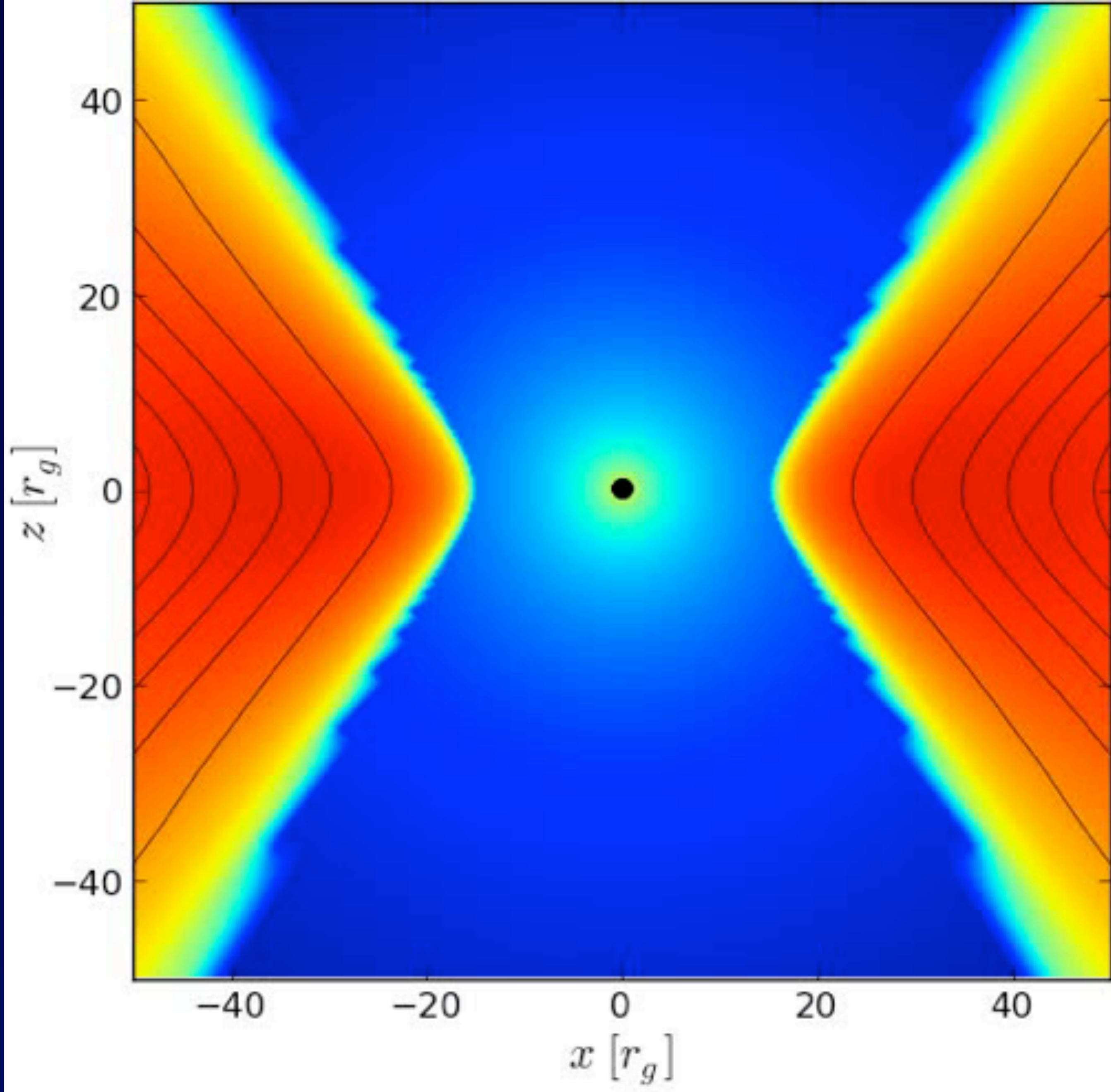
Sądowski et al. (2013)

Two Important Parameters

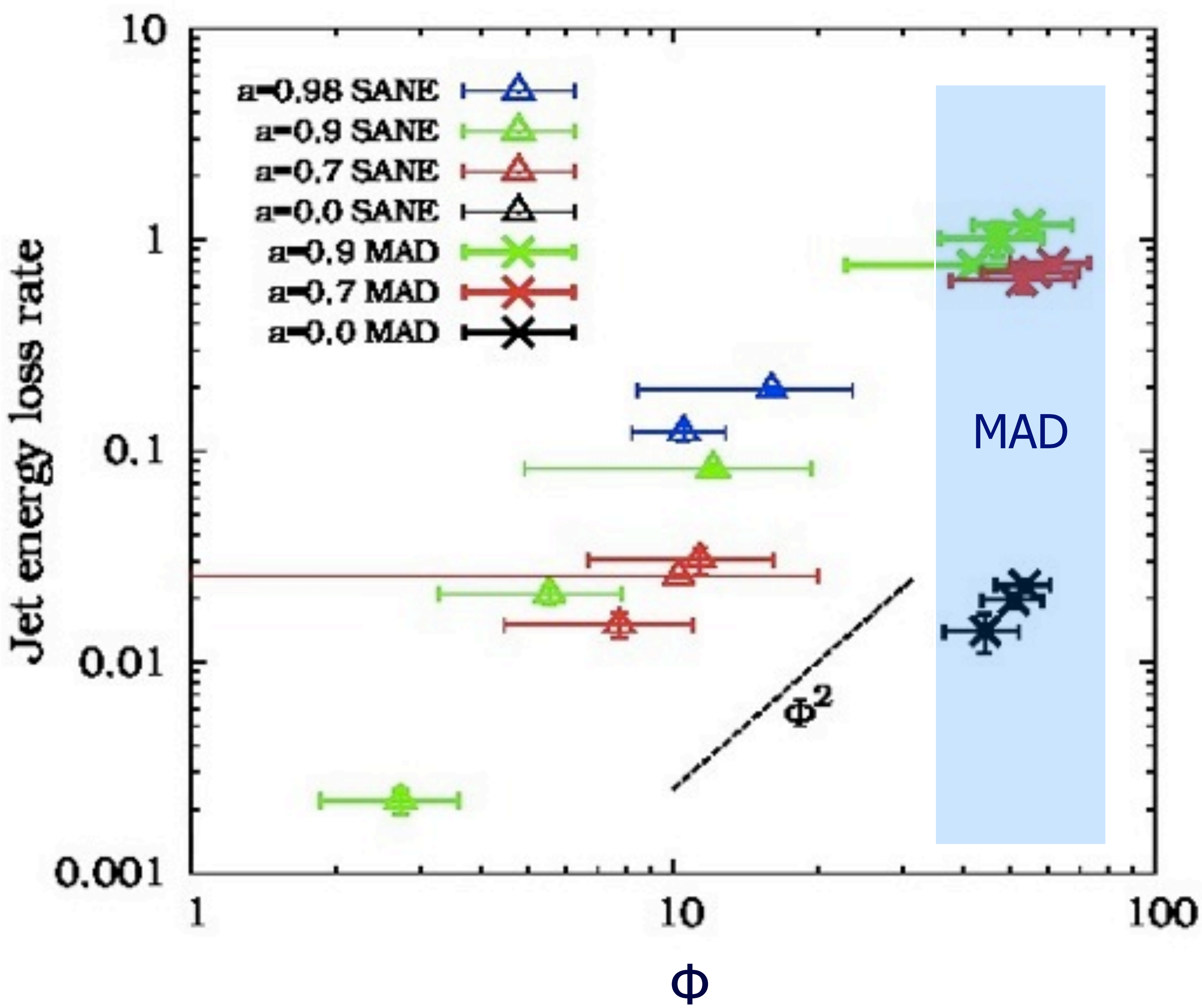
- BH Jet is powered by BH spin energy
- Jet power is sensitive to BH Spin and Magnetic Flux:

$$\boxed{P_{\mathrm{jet}} \approx \Phi^2_{\mathrm{mag}} \Omega^2_{\mathrm{H}} / c}$$

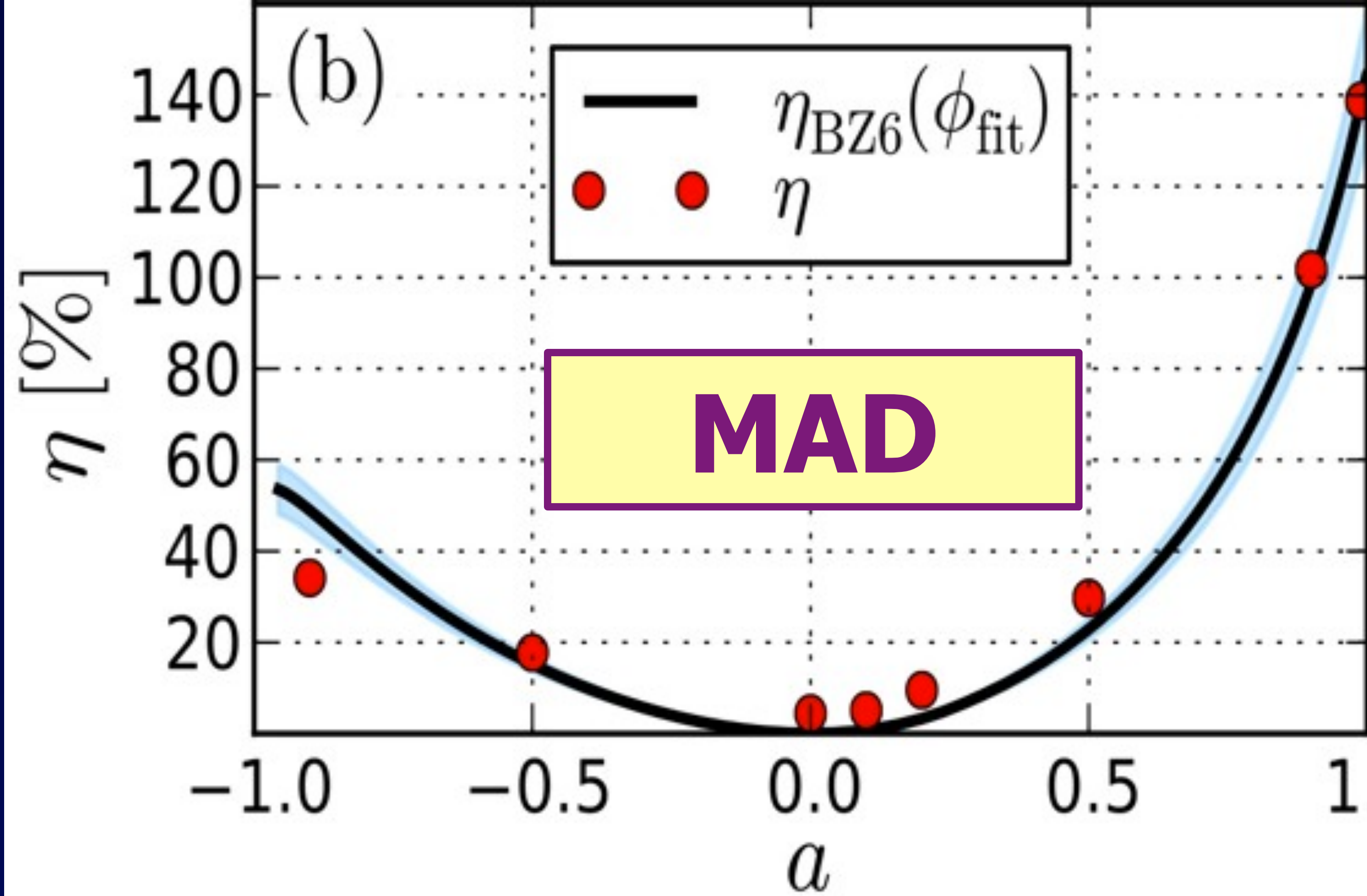
- For a given Mdot, there is a limit to how much Magnetic Flux Φ_{mag} can be pushed into the BH
- System at this limit: Magnetically Arrested Disk (MAD)
- GRMHD simulations of ADAFs readily achieve the MAD limit if sufficient coherent magnetic flux is available
- Jets are highly collimated: feedback efficiency low?



Tchekhovskoy



Sądowski et al. (2013)



BH Jet in MAD state can have a large efficiency: η_{jet} = P_{jet}/Mdot c^2 can even exceed 100% (Tchekhovskoy et al. 2012)

Strong dependence of η_{jet} on spin parameter a_*

Disk Wind

- The Disk Wind is more boring:
  - At best only mildly relativistic: v ~ 0.1-0.2 c
  - Power source is primarily the Disk
  - Power depends modestly on BH spin
  - Power depends modestly on BH Mag Flux
- Large solid angle: ~2π
- Low power in comparison to jet
- Likely to be efficient source of feedback

Maintenance Mode Feedback Efficiency

Feeback efficiency depends on 3 parameters:

$Mdot/Mdot_{Edd}$ (Mdot/M)
Ω_H (range: 0—1)
Φ_{mag} (range: 0—Φ_{max})

Perhaps $\Phi_{mag} \rightarrow \Phi_{max}$ (MAD)

Still, we need Mdot, Ω_H before we can "predict" how much energy or mmtm feedback occurs

Available in principle in

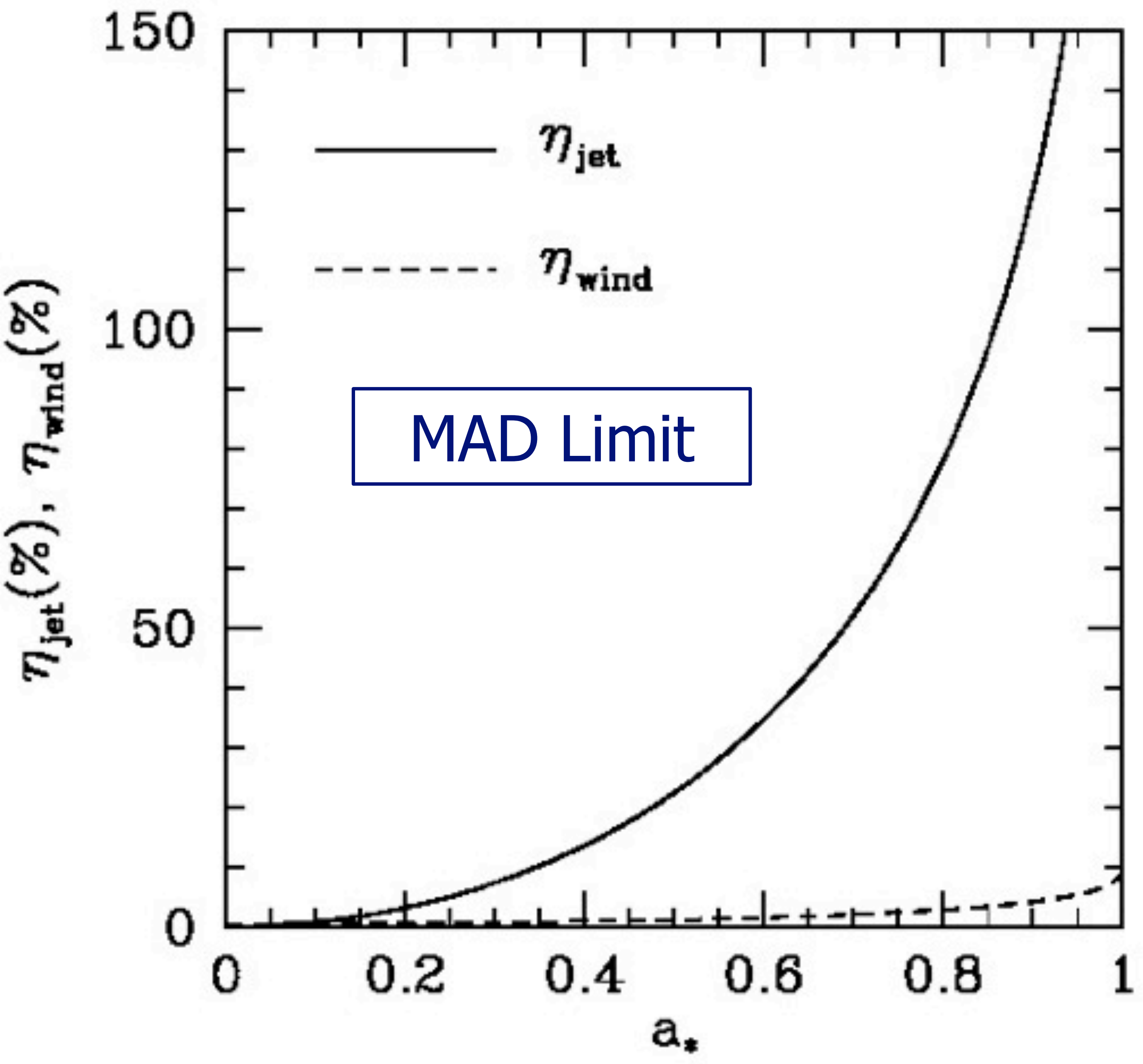
$$\dot{E}_{\rm jet} \approx 0.5\left(\frac{\Phi}{\Phi_{\rm max}}\right)^2\left(\frac{\Omega_{\rm H}}{0.2}\right)^2 \dot{M}c^2$$

$$\dot{E}_{\rm wind} \approx 0.005\left[1+3\left(\frac{\Phi}{\Phi_{\rm max}}\right)^2\left(\frac{\Omega_{\rm H}}{0.2}\right)^2\right] \dot{M}c^2$$

$$\dot{P}_{\rm jet} \approx 0.5\left(\frac{\Phi}{\Phi_{\rm max}}\right)^2\left(\frac{\Omega_{\rm H}}{0.2}\right)^2 \dot{M}c$$

$$\dot{P}_{\rm wind} \approx 0.1\,\dot{M}c$$

Sądowski et al. (2013)



150
100
50
0
η_{jet}
η_{wind}
MAD Limit
$\eta_{jet}(\%)$, $\eta_{wind}(\%)$
0
0.2
0.4
0.6
0.8
1
a_*

Major Caveat

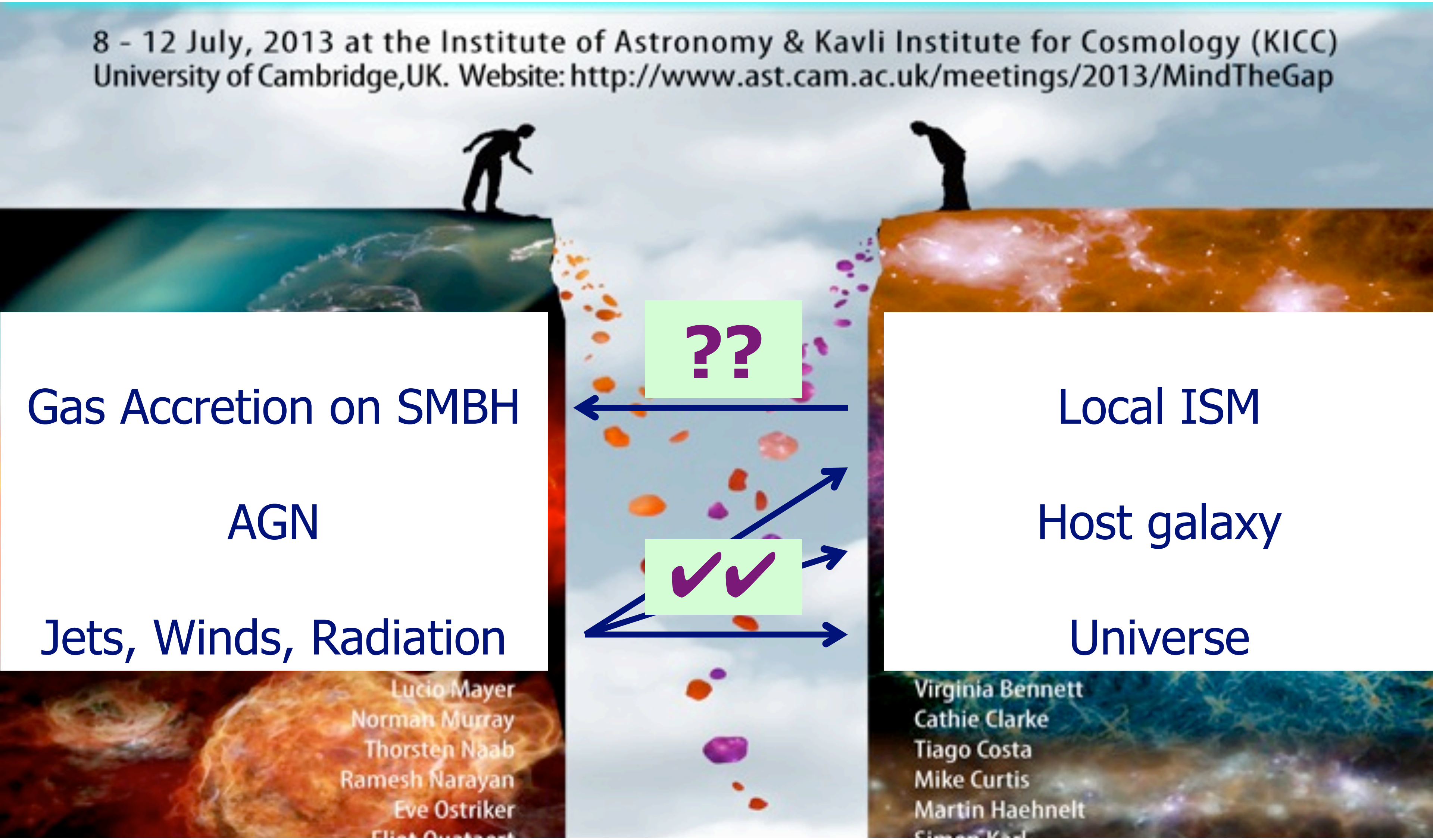
- We do not have very good information on mass loss in the wind
- Serious limitation for feedback estimates

Unless we figure out the mapping between $Mdot_B$ and $Mdot_{BH}$, it will be hard to come up with a predictive prescription for AGN energy/mmtm feedback in the maintenance mode

$$\dot{M}_{\mathrm{wind}} \approx \dot{M}_{\mathrm{BH}} \left(\frac{r}{r_{\mathrm{in}}} \right)^{s}$$

$$\frac{\dot{M}_{\mathrm{BH}}}{\dot{M}_{\mathrm{B}}} \approx \left(\frac{r_{\mathrm{in}}}{r_{\mathrm{B}}} \right)^{s} \ll 1\,??$$

MIND THE OTHER GAP



Gas Accretion on SMBH

AGN

Jets, Winds, Radiation

??

✔✔

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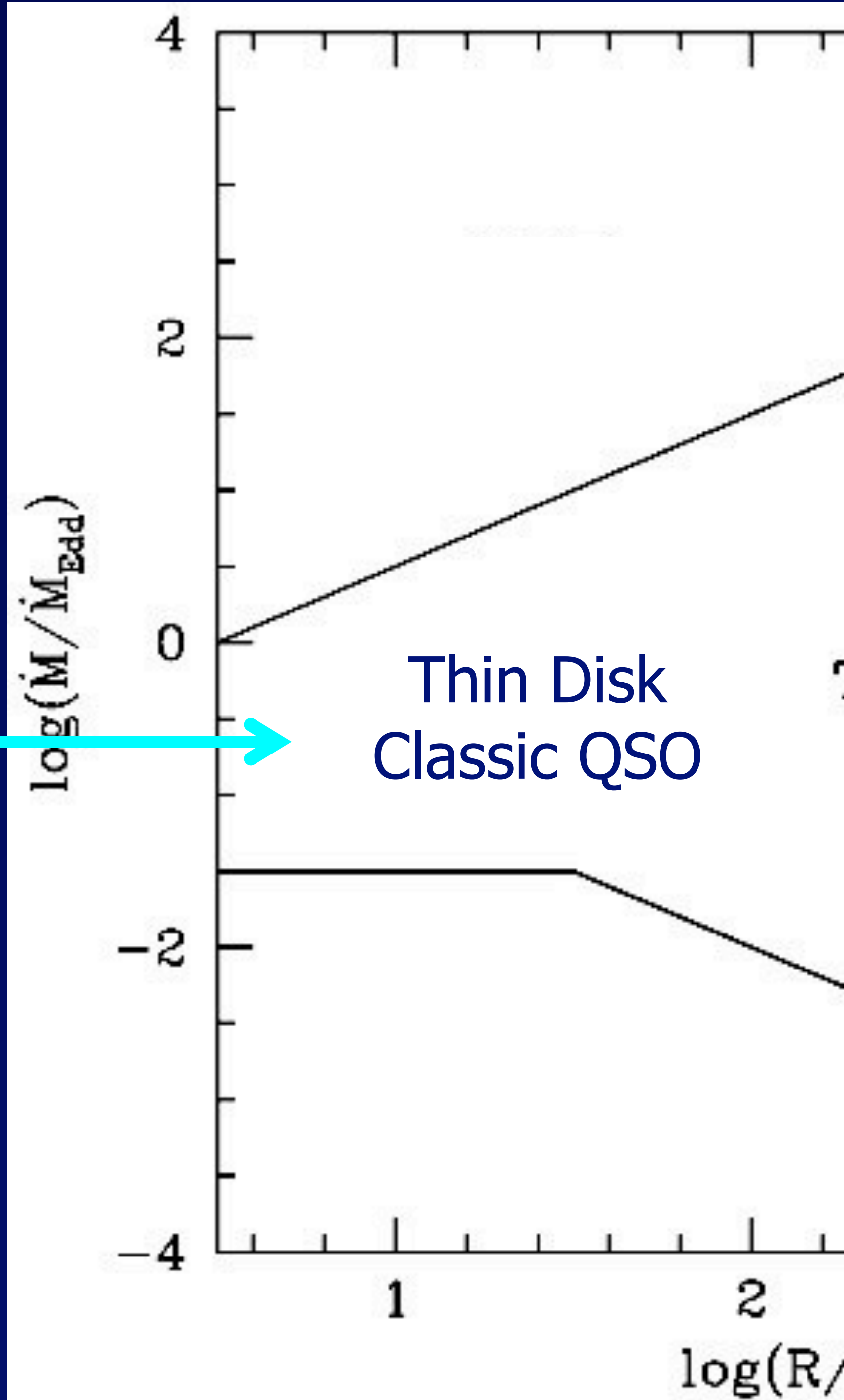
Quasar Mode : I

Thin Accretion Disk

(Pringle & Rees ‘72; Shakura & Sunyaev ‘73; Novikov & Thorne ‘73)

Quasars, XRBs in high soft state



Thin Accretion Disk Model

- Makes robust predictions for the radiative luminosity L_{disk} (no α dependence)
- Radiative feedback is straightforward
  - $\eta_{disk}(a_*)$
- How about mechanical feedback via jets and winds?
- GRMHD simulations have become feasible in recent years, so we can check

No Jets in Simulations of Thin Accretion Disks

- Thin disk simulations do not show anything that looks like a jet
- However:
  - thin disks are hard to simulate
  - models are converged only to $R \sim 20M$
  - No jet or wind out to $20M$
- XRBs in the Thermal-Dominant State (thin disk regime) do not have jets

Quasar Mode : II

ADAF/Slim Disk

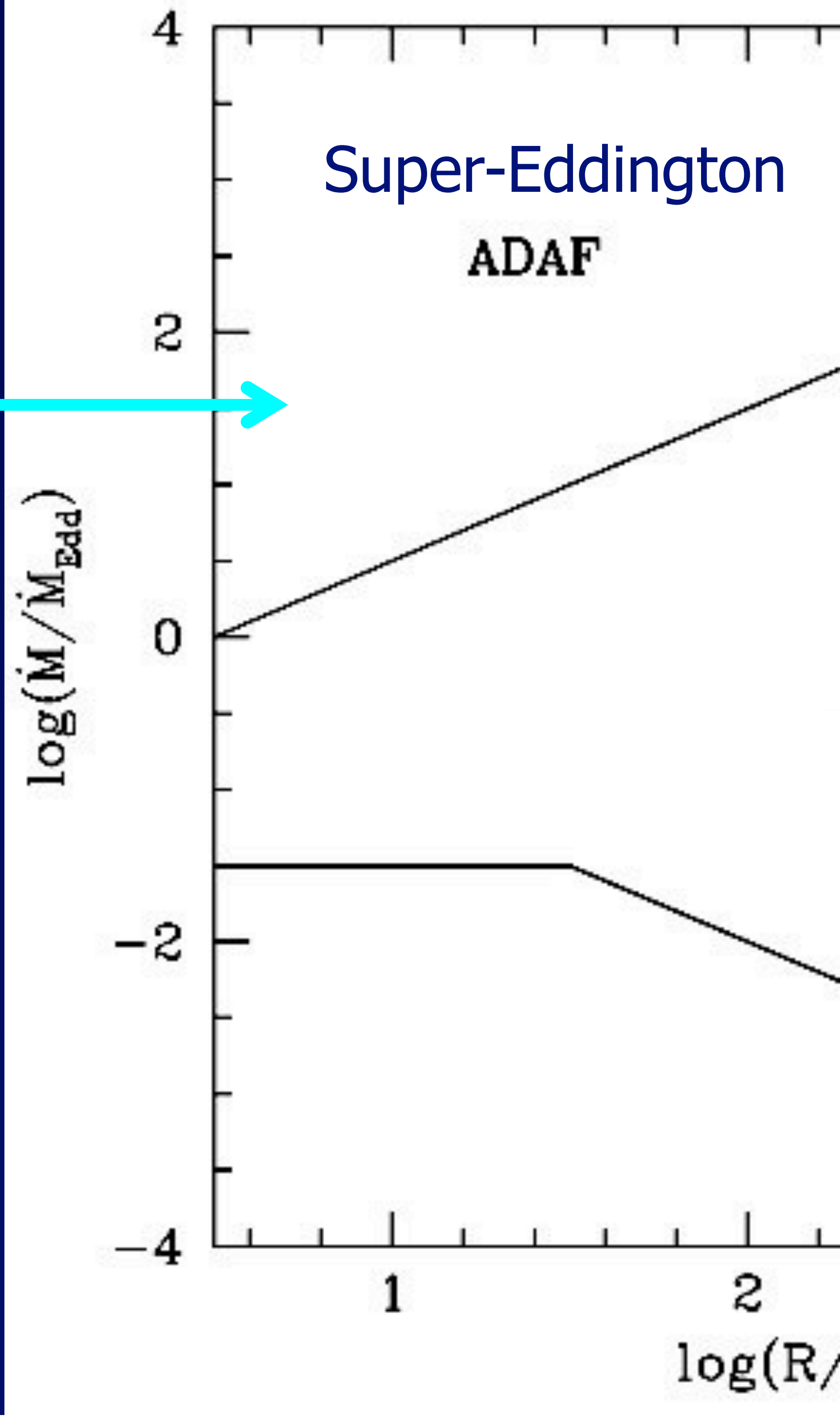
Super-Eddington, radiation trapped
(Begelman '79; Abramowicz et al. '89)

Radiative luminosity should be limited to at most ~ few L_{Edd}

What if Mdot >> Mdot_{Edd}? What happens to all the energy?

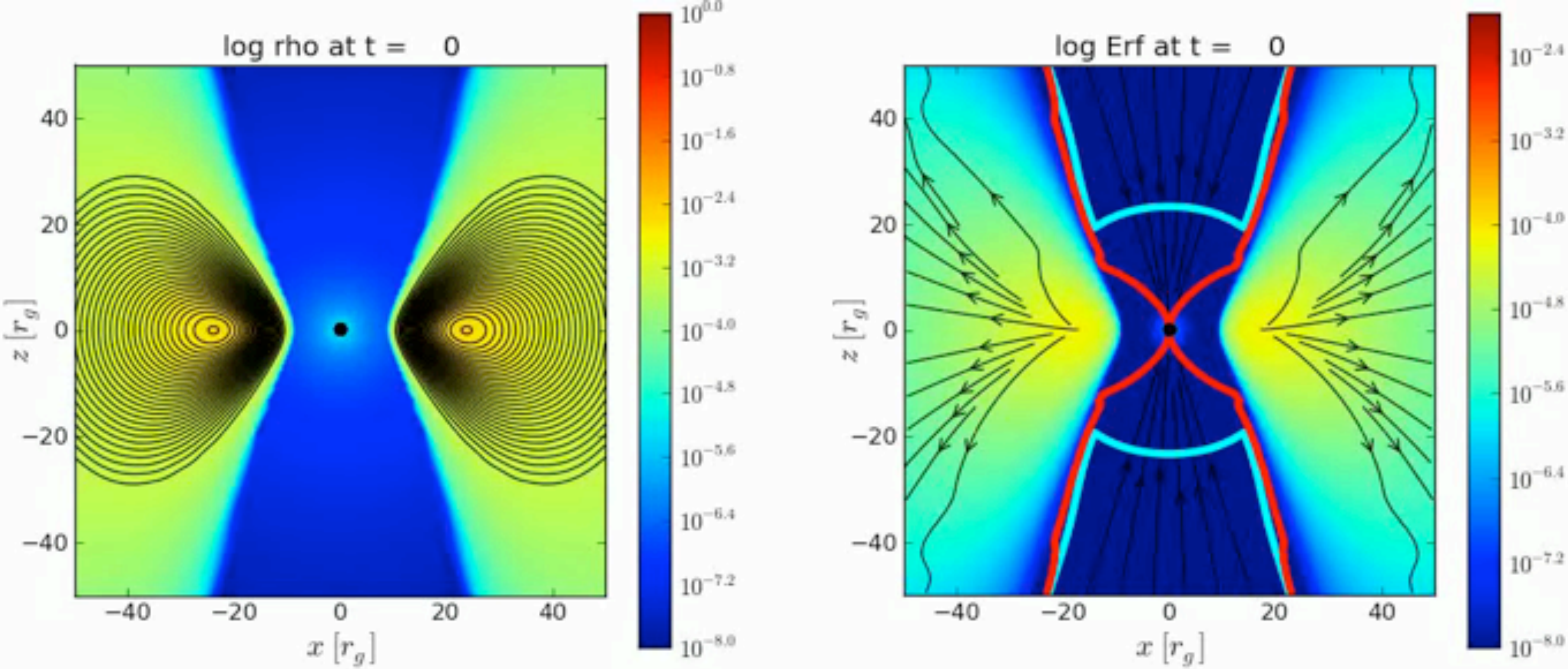
How much energy comes out via a jet or a wind?

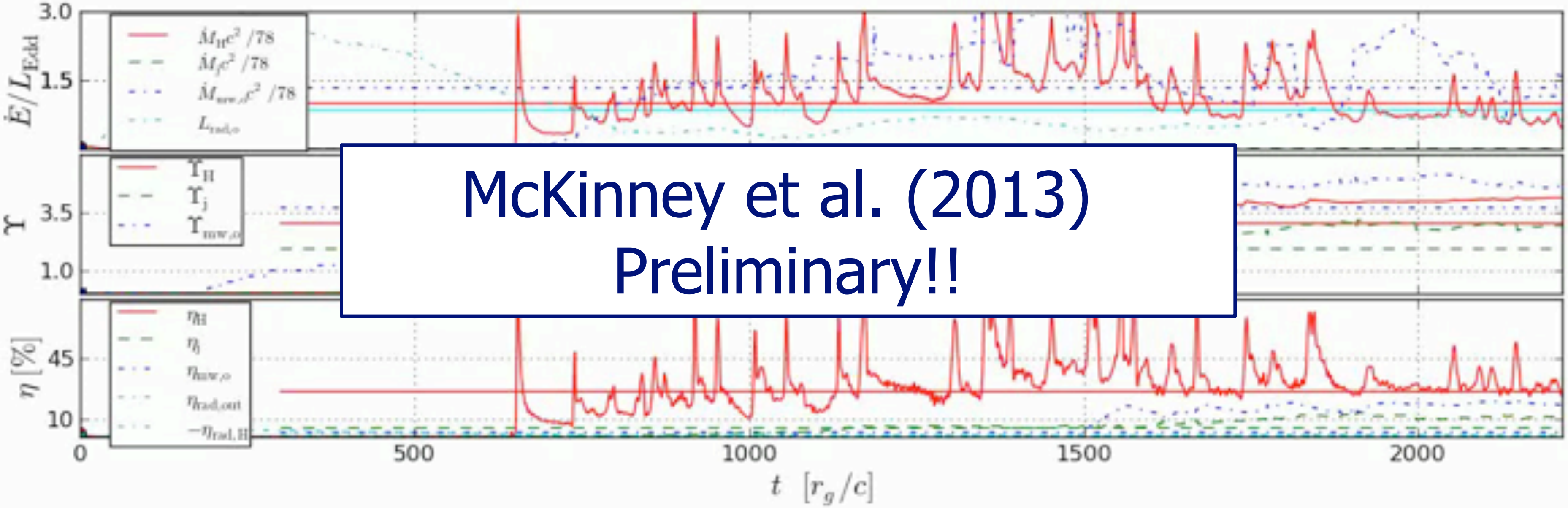
Need 3D Radiation GRMHD simulations



Numerical Simulations of Super-Eddington Accretion

- The field has been dominated by Ohsuga (2003...): Radiation hydro/MHD
- Important results on winds
- However, no GR or even SR
- Recent developments:
  - GR+Hydro+Rad(M1) (Sadowski+ '13)
  - GR+MHD+Rad(M1) (McKinney+ '13)
- First results will be out soon





McKinney et al. (2013)
Preliminary!!

Very Preliminary

$$\dot{M}_{\mathrm{BH}} = 78\, L_{\mathrm{Edd}} / c^2$$

$$L_{\mathrm{radiation}} = 1.1\, L_{\mathrm{Edd}}, \eta_{\mathrm{rad}} = 0.015$$

$$L_{\mathrm{Poynting}} = 9.2\, L_{\mathrm{Edd}}$$

$$L_{\mathrm{matter}} = 2.3\, L_{\mathrm{Edd}}$$

$$L_{\mathrm{total}} = 12.6\, L_{\mathrm{Edd}}, \eta_{\mathrm{total}} = 0.16$$

Summary

- Given M_{BH}, $Mdot_{BH}$, Ω_H, Φ_{mag} ($= \Phi_{max}$?), BH simulators are able to estimate $Edot_{jet}$, $Pdot_{jet}$, $Edot_{wind}$, $Pdot_{wind}$
- What other quantities would you like?
  - Angular distribution of energy/mmtm?
  - Lorentz factor/velocity?
  - SMBH spinup/spindown?
- But major uncertainty: $Mdot_B$ vs $Mdot_{BH}$
  - Prognosis is uncertain

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