# *Relativistic Jets in Super-Eddington Accretion Disks*

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# GRRMHD Simulations are Now Possible

- GRMHD codes were developed in the early 2000s: Koide, Komissarov, De Villiers, Hawley, Gammie, McKinney, Fragile, Tchekhovskoy,…
- Many important applications to relativistic jets
- Ohsuga carried out R(Radiation)MHD simulations of pseudo-Newtonian disks
- Nobody attempted full GR**R**MHD simulations
- Achieved finally in 2014: Sądowski (KORAL) McKinney (HARMRAD)

# *Why is Radiation Hard?*

- Radiation has to be handled as a separate fluid on top of magnetized gas
- Has its own speed, which can be very different
  - Serious problem because of Courant condition
  - Needs implicit techniques
- Have to deal with different opacity regimes
  - Optically thick: diffusion
  - Optically thin: free-streaming

# Actually, GRRMHD is Not so Hard!

- In BH accretion, the magnetized gas is already relativistic
  - Radiation fluid has comparable velocity
  - Fully implicit techniques not needed --- semi-implicit is sufficient
- Relativistic four-notation and technology are actually a major help
  - Energy-momentum conservation is easy
  - No conceptual problems (as in Newtonian)

# How Should We Represent the Radiation Field?

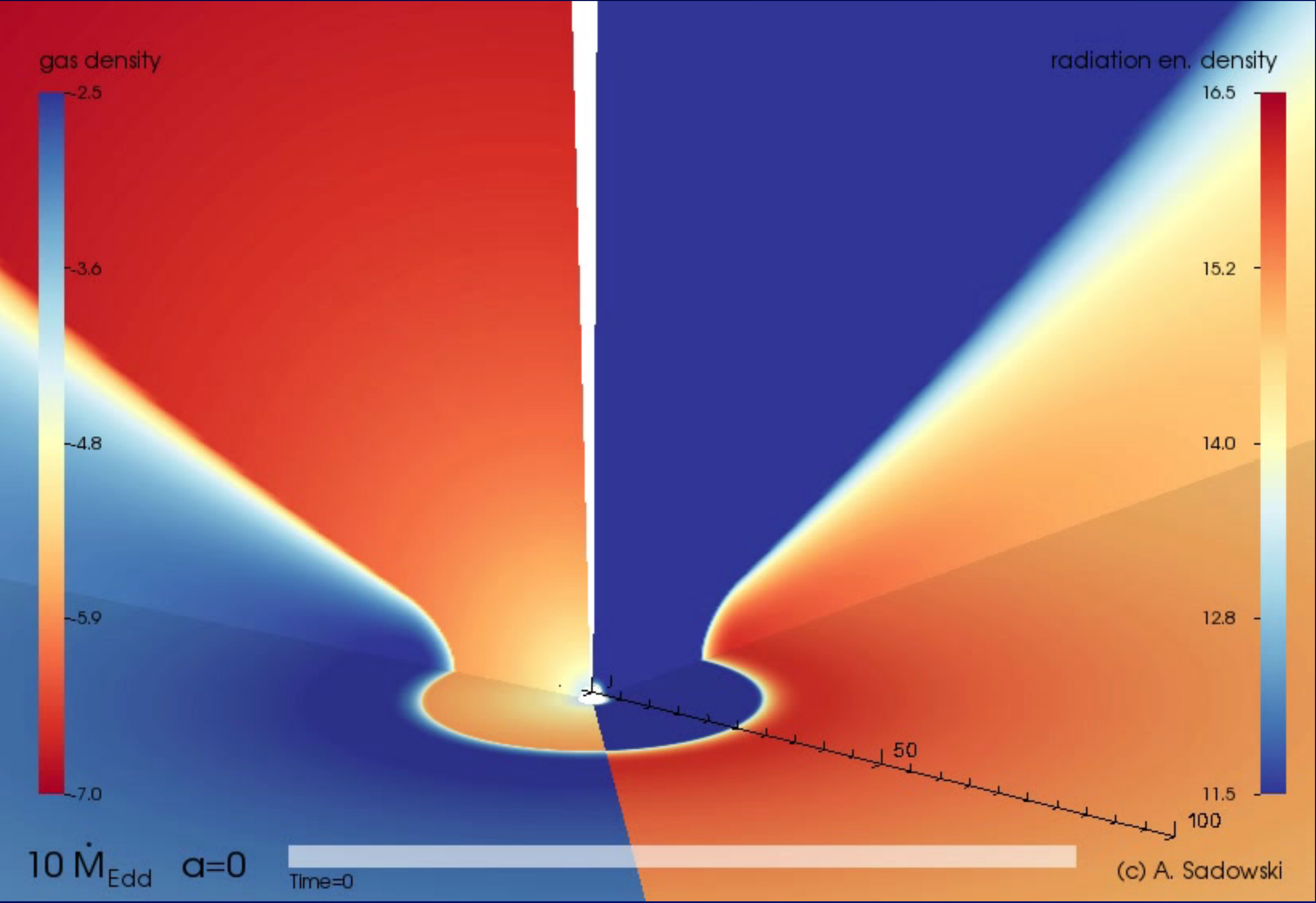
- At each instant, the radiation field is six-dimensional: **r**, **n**, $\nu$
- Impractical to evolve the whole thing
- Simple prescriptions like diffusion or flux-limited diffusion are not good enough
- Simplest consistent scheme is M1: considers four bolometric quantities: U, **F**
- Straightforward closure: stress tensor $\mathbf{R}^{\mu\nu}$

# Gas vs Radiation

- In deriving hydrodynamic equations, we consider $\rho$ , $\rho$ **v**, etc., and close the equations with eqn of state: p( $\rho$ ,T)
- M1 is similar: U, **F** → $\mathbf{R}^{\mu\nu}$
- In hydrodynamics, viscosity has to be added separately via coefficients
- Same in radiation: can add radiation viscosity if needed

# *Super-Eddington Accretion Slim Disk: Hyper-Accretion*

- Mdot > Edd: GR**R**MHD needed
  - Radiation pressure important
  - Disk is optically very thick: $\tau >> 1$
  - Observed radiation comes from $\tau <\sim 1$
  - Advection-dominated
  - Puffed up: geometrically thick

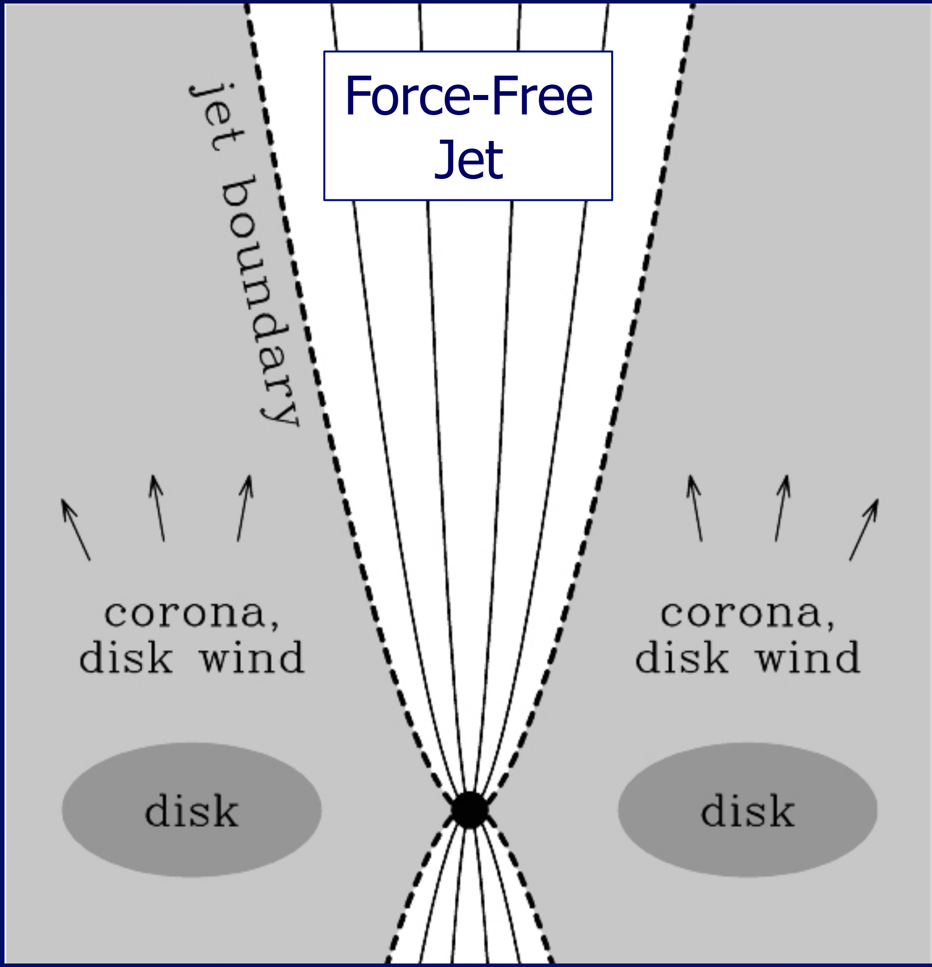

gas density
-2.5
-3.6
-4.8
-5.9
-7.0
radiation en. density
16.5
15.2
14.0
12.8
11.5
50
100
10 $\dot{M}_{Edd}$ a=0
Time=0
(c) A. Sadowski

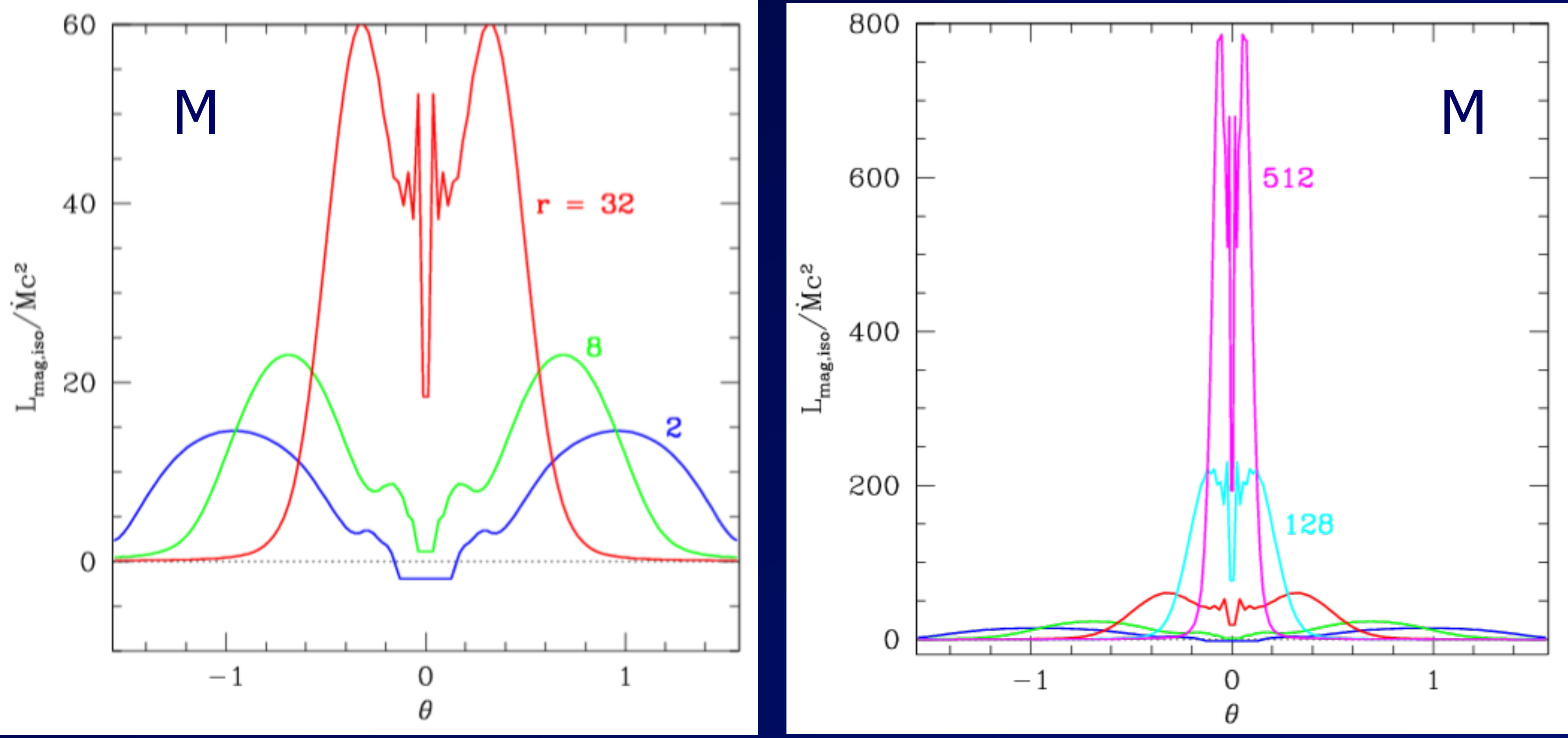
# Results

- All super-Eddington disks seem to have relativistic jets
- If we define $P_{jet} = \eta_{jet}$ Mdot $c^2$
  - Baseline case: Zero BH spin, no strong organized field: modest jet power $\eta_{jet} \sim 0.02$
  - Favorable case: BH spin with MAD field: can get large jet power: $\eta_{jet}$ up to ~1 (?)

# BZ Jet in a Low-Mdot ADAF/RIAF

- Clean problem
- Energy flows from BH via field lines in a force-free/MHD jet
- Mass, energy, ang mmtm are conserved along flux tubes
- Jet collimation concentrates the power into a small solid angle
- Some BH energy goes into the disk

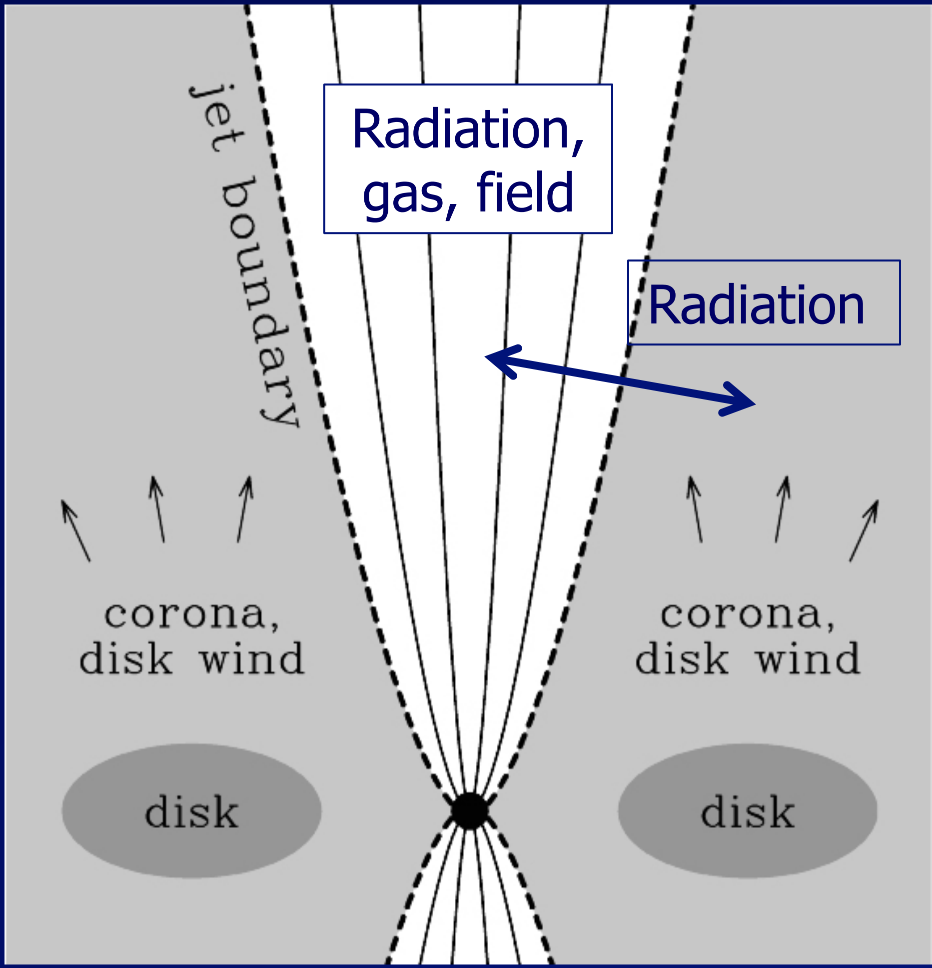


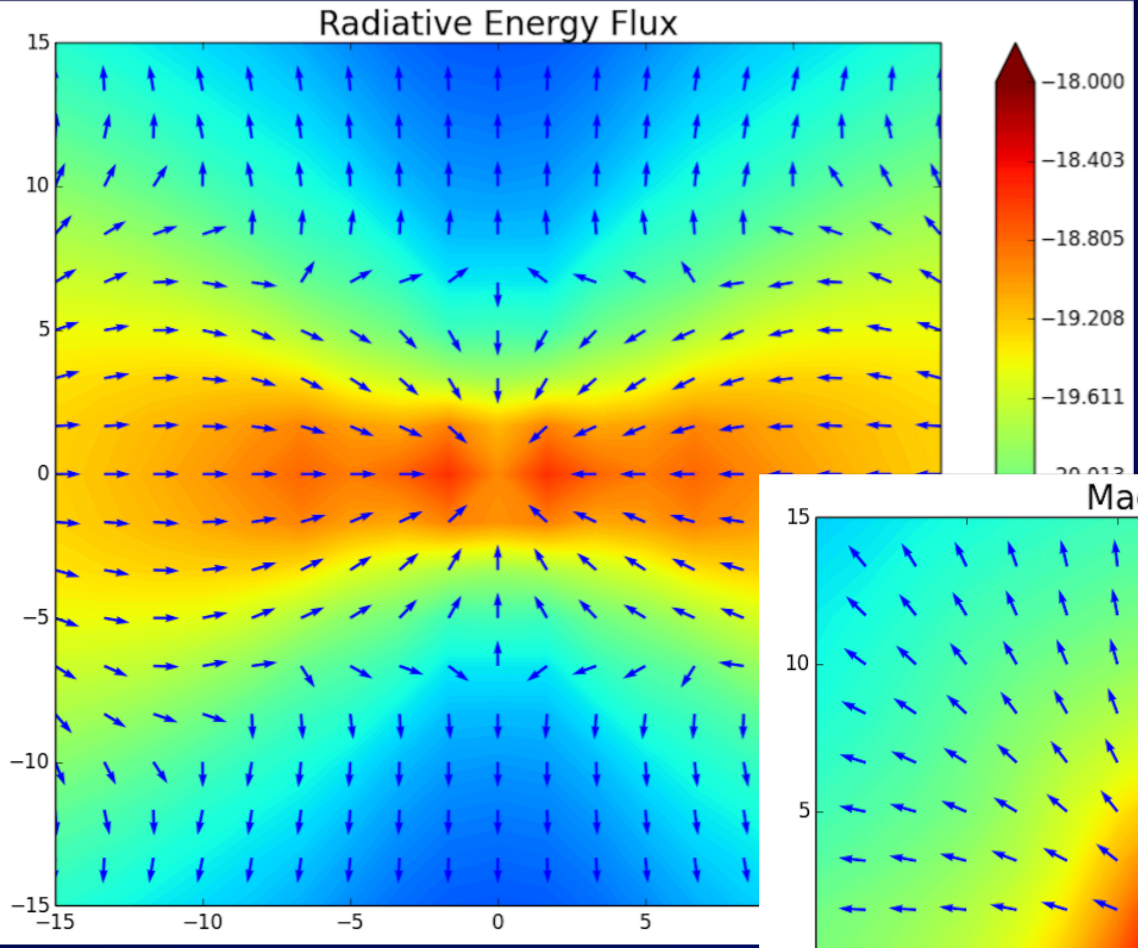



$a_* = 0.9$ simulation of an ADAF in the MAD state (Sądowski et al. 2013)
Jet power is primarily magnetic
Initially, at small r, power is spread over a wide range of angle
At larger r, power becomes focused by jet collimation
At a very large r, magnetic energy → gas kinetic energy

# What About Jets in Super-Eddington Disks?

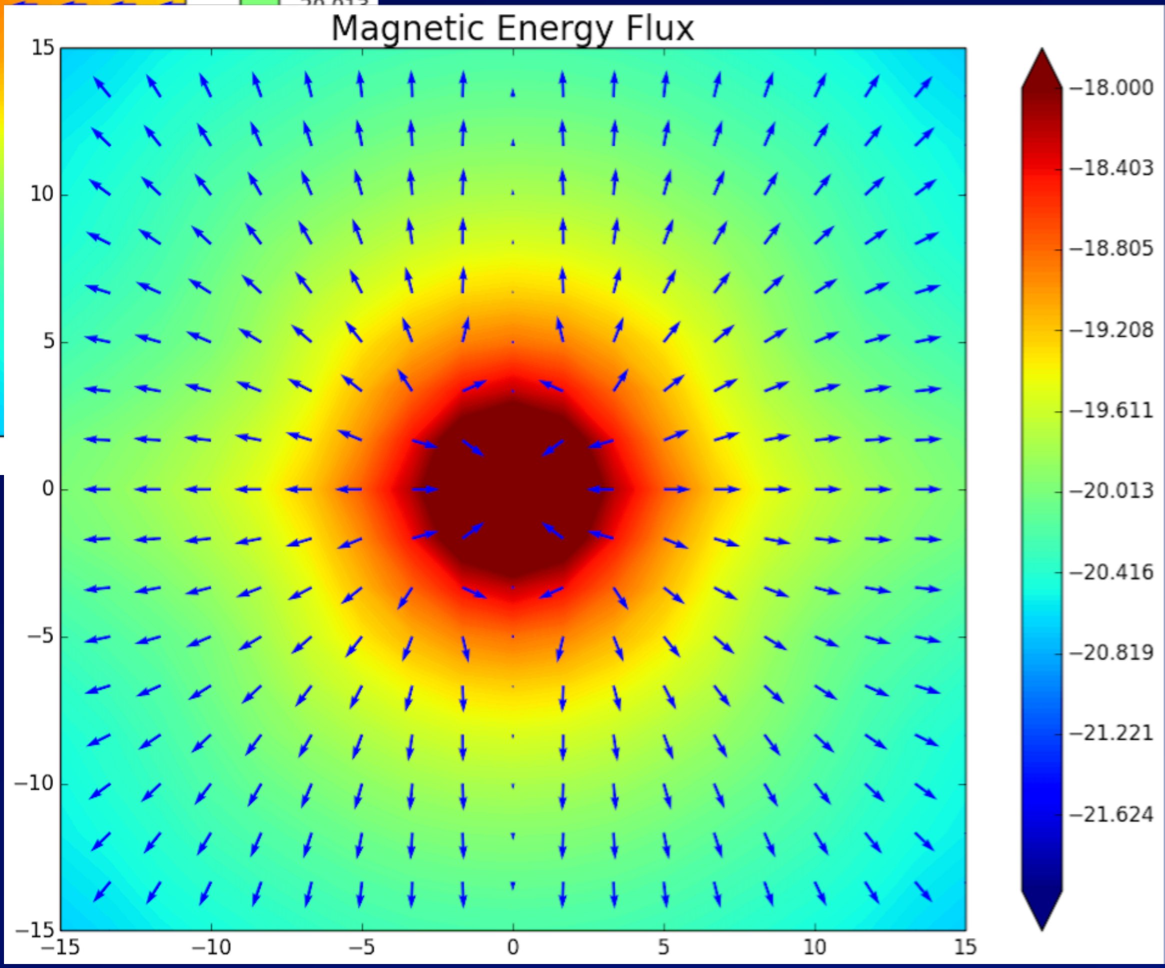
- Less clean situation
- Energy can still flow out of BH via field lines
- But mass, energy, ang mmtm not conserved along flux tubes
- Radiation transfers energy across field lines
- **Energy can flow from disk to jet**
- **Radiation accelerates**



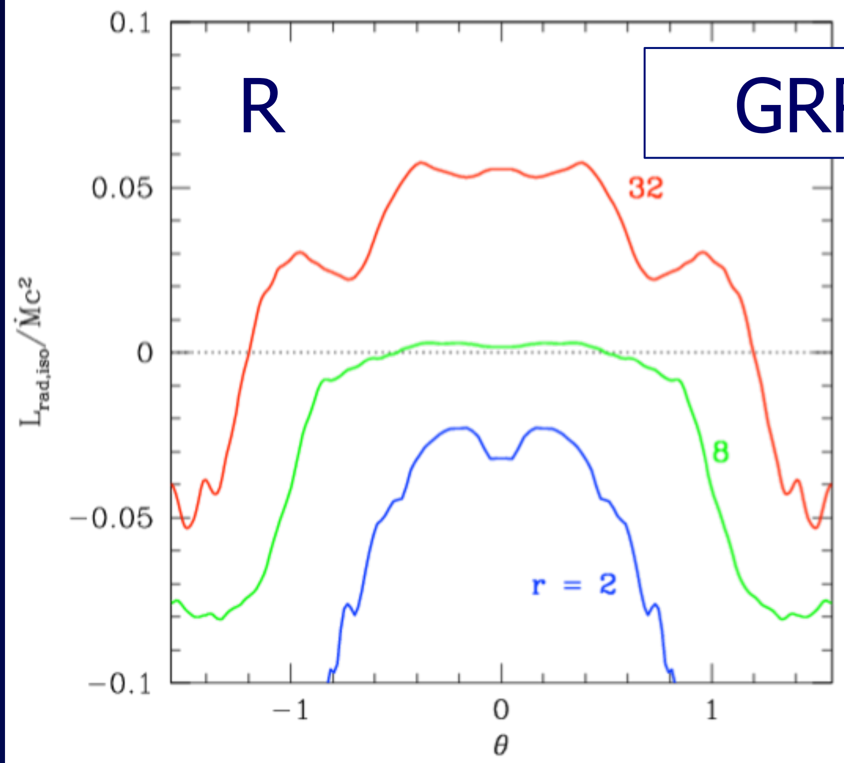


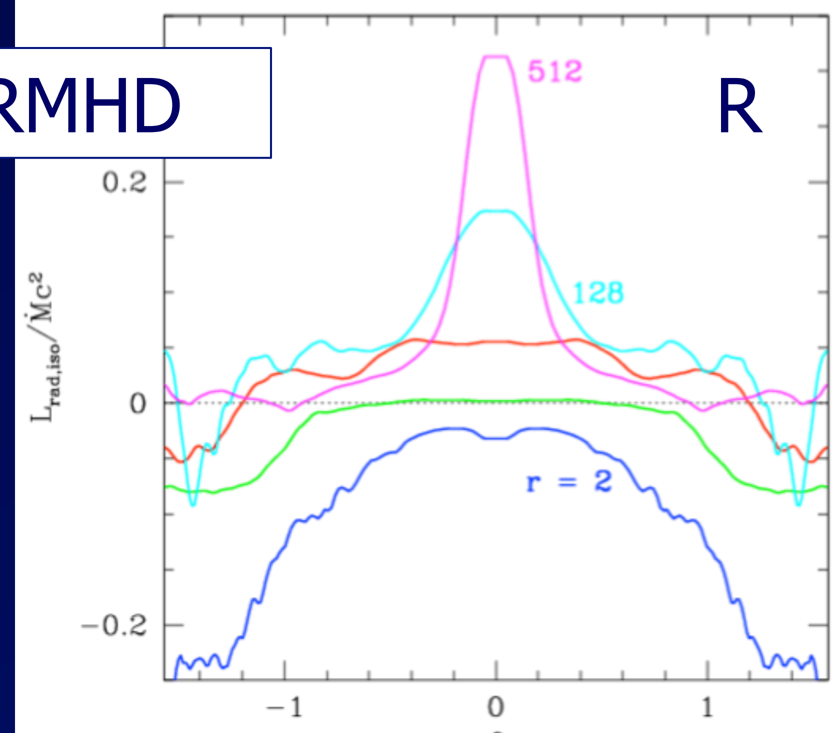

$a_* = 0$

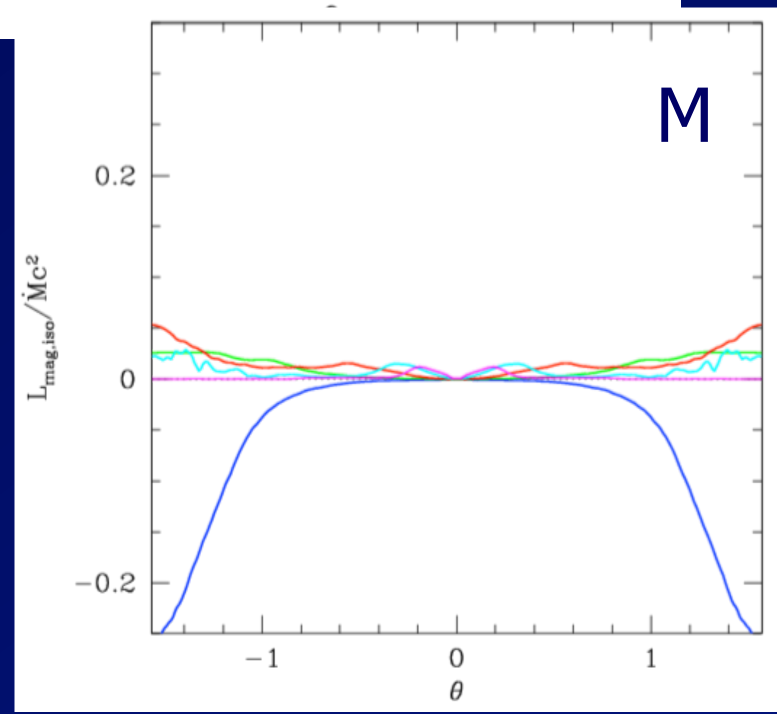
Mdot = 560 Edd



# GRRMHD



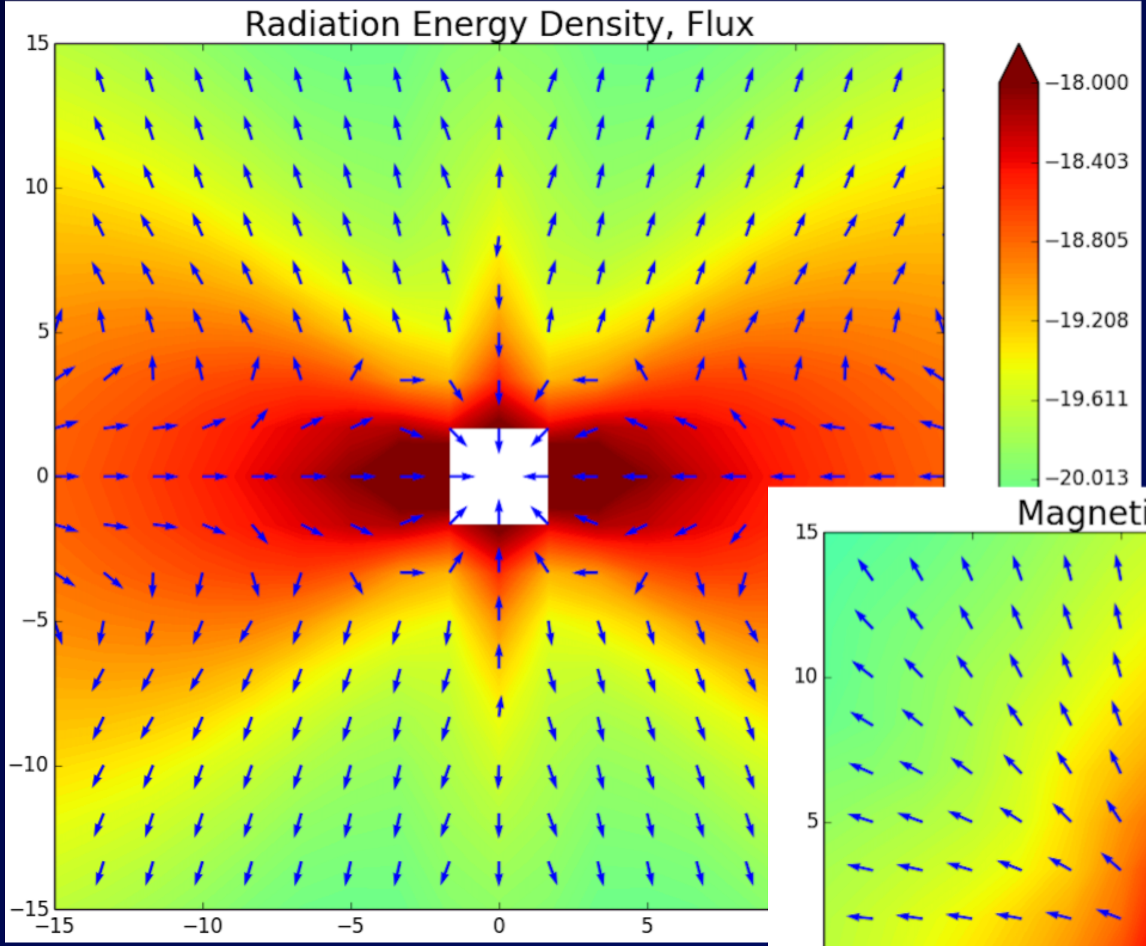

$a_*=0$ BH accreting at ~560 Eddington

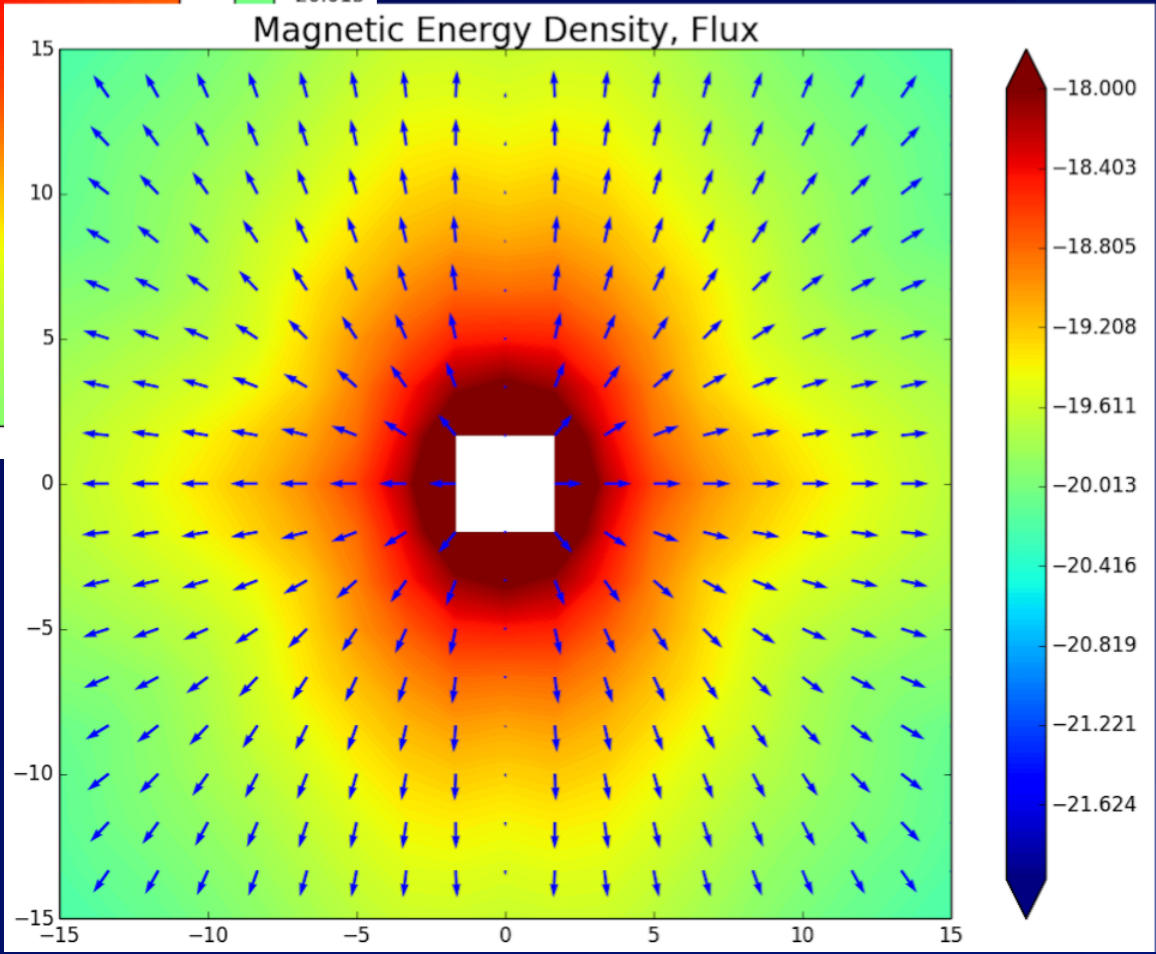
BH magnetic field plays no role in jet

Close to BH, radiation flows into the BH

Jet acquires power later, from the disk

**Jet acceleration by radiation**




$a_* = 0.9$

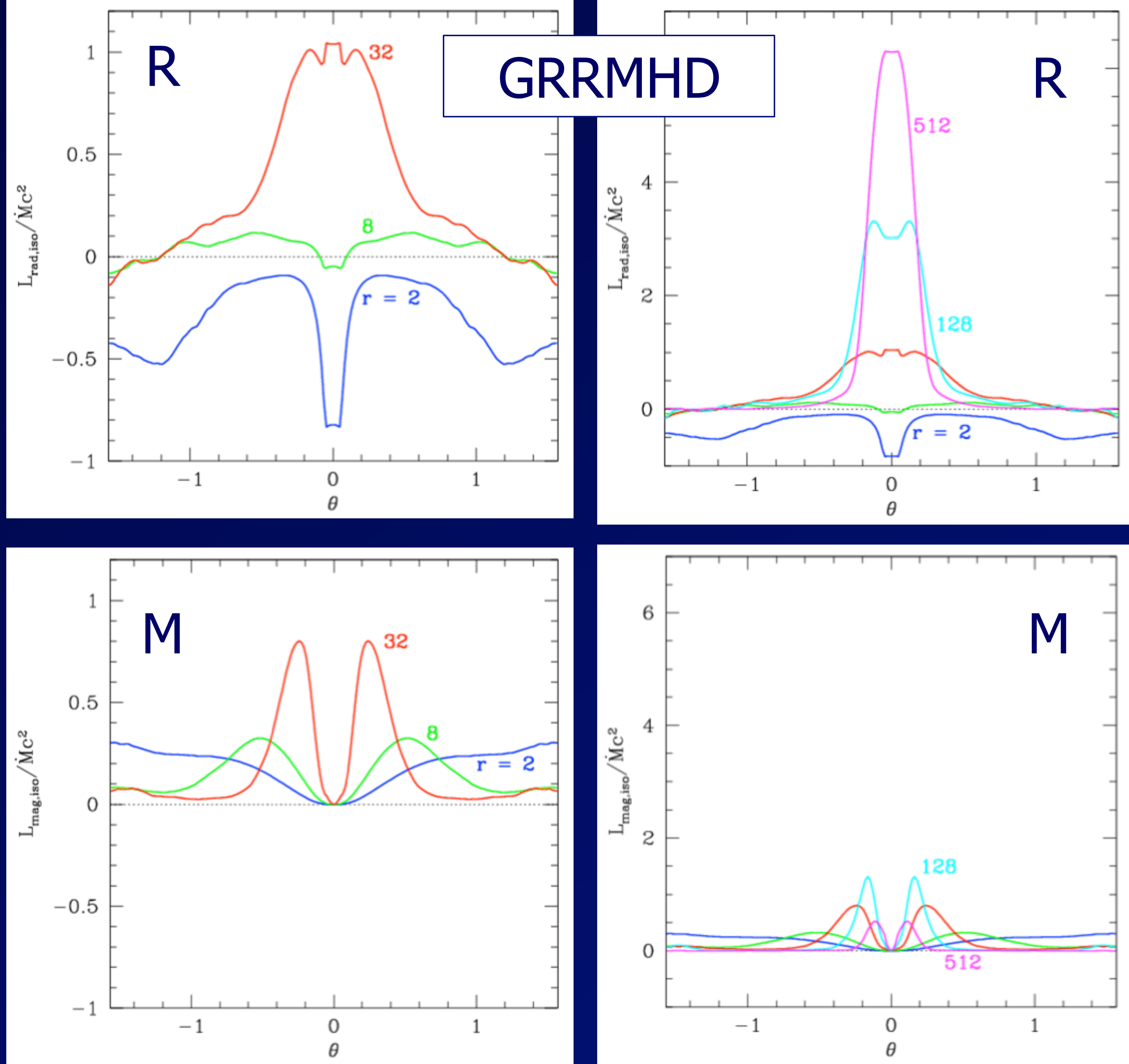
Mdot = 3000 Edd

$a_* = 0.9$

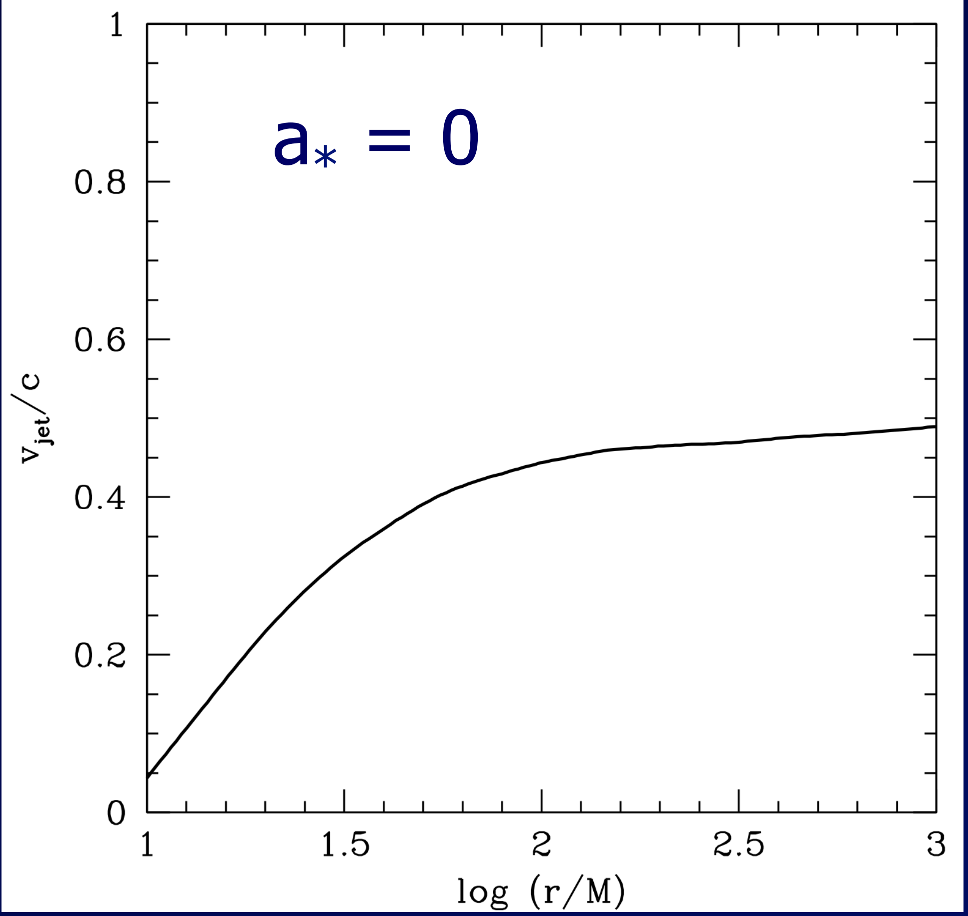
Mdot = 3000 Edd

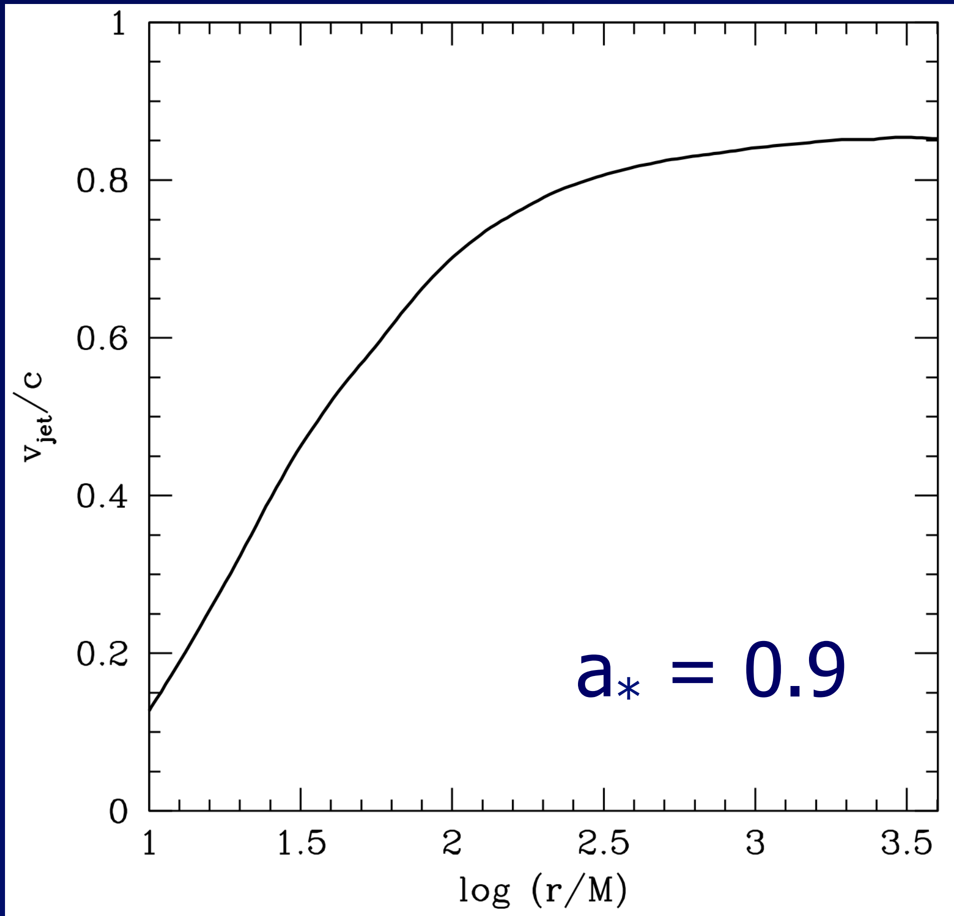
$\eta_{jet} = 0.25$

Acceleration by radiation, augmented (strongly) by magnetic fields (BZ)



Radiative jets are modestly relativistic: $v_{jet} \sim 0.5$—$0.9\ c$



# Quick Summary

- Super-Eddington accretion flows always have jets
- Jet power: $P_{jet}$ ~ (few—100%) Mdot $c^2$
  - **Not Eddington limited!**
- Jet velocity: v <~ 0.9 c
- Jet collimation: $\theta_{jet}$ ~ 0.2 radians
- MAD limit systems have not yet been simulated…
- Strong mass outflows are present

# *Super-Eddington Blazars*

- Are there any blazars that are believed to be super-Eddington systems?
- Are their properties consistent with the "Quick Summary"?
- Are they different in some way from "normal" blazars?

# *Early Growth of SMBHs*

- High z quasars with $M_{SMBH} \sim 10^{10} M_{\odot}$
- Tough with Eddington-limited accretion
- However, if there is enough gas supply(?), the SMBH can have Mdot >> $\text{Mdot}_{Edd}$
- Expect powerful jets: $P_{jet} \gg L_{Edd}$
- Observational consequences?
- Feedback and Mdot regulation?

# *Tidal Disruption Events*

- According to standard models, all TDEs have early super-Eddington accretion
- They should all have powerful jets
  - Reasonably broad beam: $\theta$
  - Fairly modest Lorentz factor: $\gamma$
- Current data are generally consistent…

# Other Applications

- Ultra-Luminous X-ray Sources
  - Any evidence for or against jets?
- SS433, GRS1915+105
- Gamma-ray bursts
- …

# Conclusion

- GR**R**MHD simulations are now possible
- We can study super-Eddington accretion (also radiatively efficient thin disks)
- Jets appear to be universal in super-Eddington disks
- Applications to astrophysical sources are just beginning to be explored