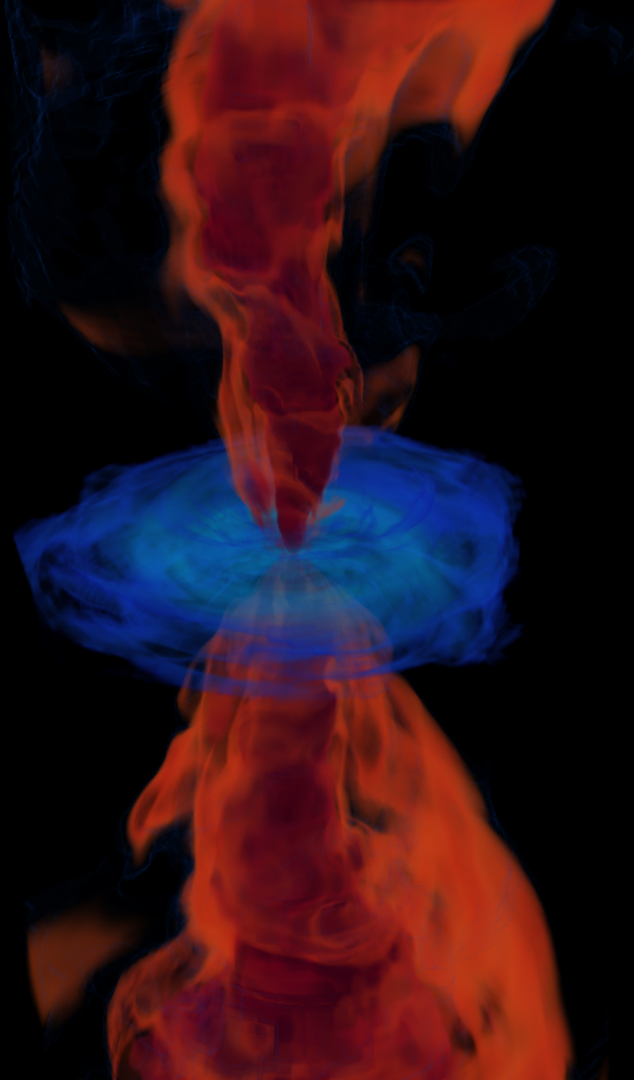


Black hole spin gone MAD

Beverly Lowell
NSF Graduate Research Fellow

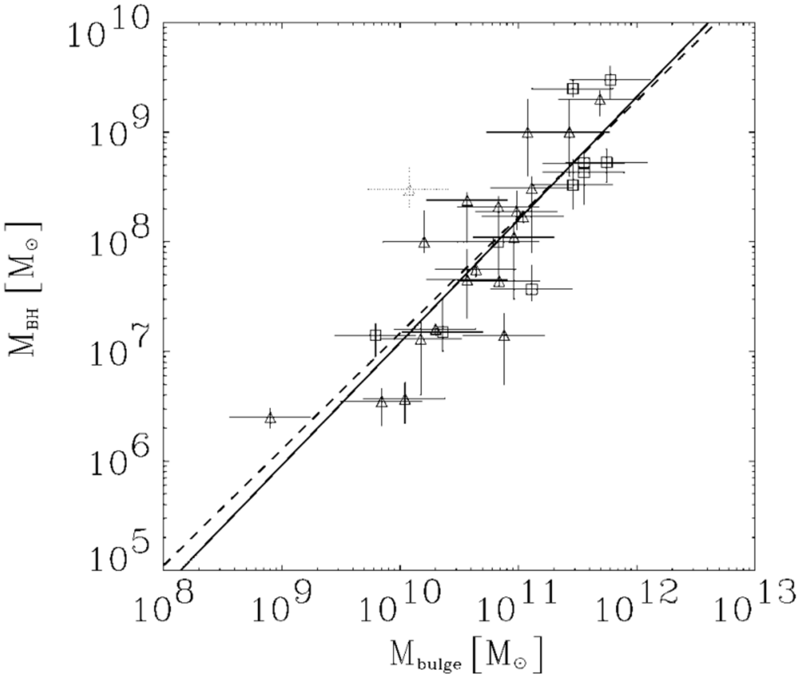
May 20, 2022

With Jonatan Jacquemin Ide,
Matthew Liska, and
Sasha Tchekhovskoy

Northwestern

CIERA
CENTER FOR INTERDISCIPLINARY EXPLORATION AND RESEARCH IN ASTROPHYSICS

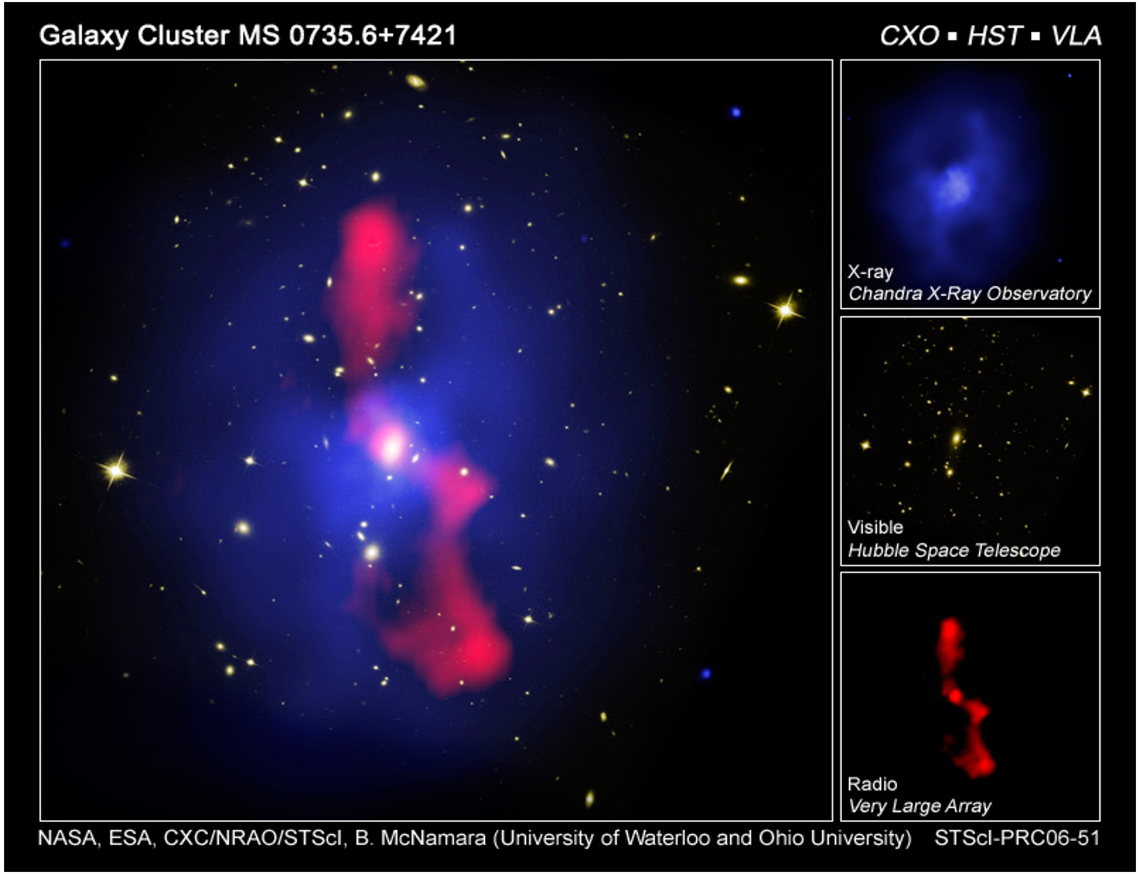
Black hole feedback in action



Häring, N., & Rix, H.-W. 2004, ApJL, 604, L89,

(e.g. Magorrian et al. 1998; Marconi & Hunt 2003)

Outflows efficiently rob black holes of their rotational energy!



Energy of jets: $1.2\times10^{62} erg$

Mean jet power: $1\times10^{46}\ erg/s$

$M_{BH} = 5\times10^{9}M_{\odot}$

Rest mass-energy of SMBH:

$9.0\times10^{63} erg$

Energy of the jet can be comparable to the black hole

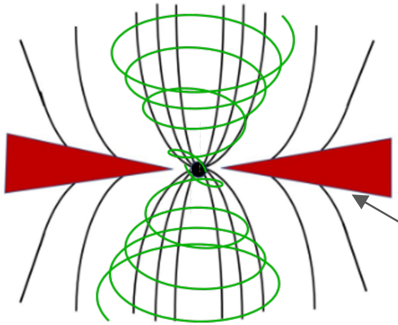
(McNamara et. al., 2009, ApJ, 698, 594)

How does spin evolve in different disk and magnetic field geometries?

Standard disk

Standard Novikov-Thorne disk

Add B-fields



Magnetically-arrested disk (MAD)

Blandford & Payne, 1982

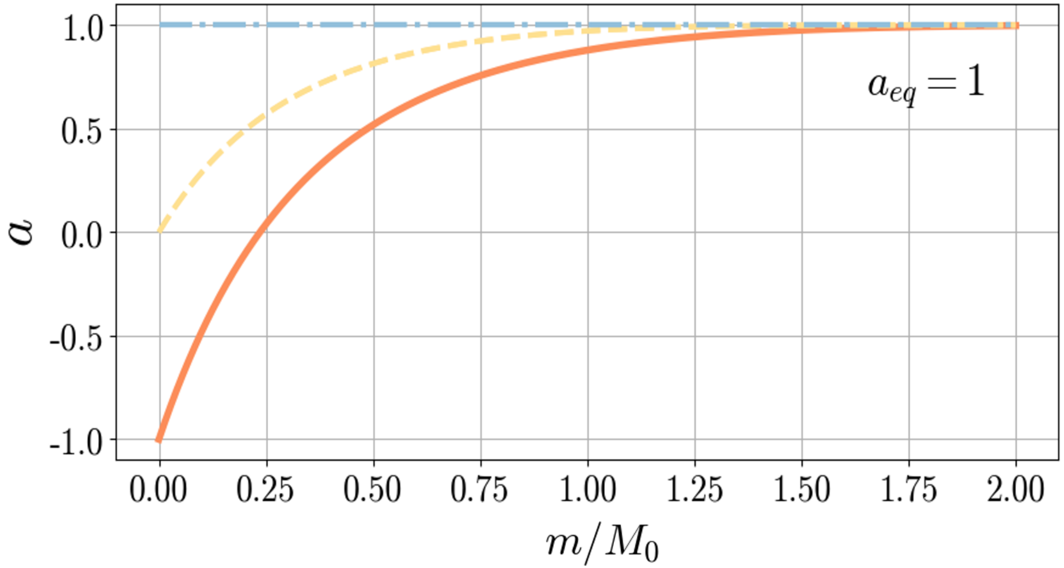
Blandford & Znajek, 1977

Two torques on the black hole: from the jets and from the disk

Modeling black hole spin evolution: analytic thin disk

$$a = \frac{J}{M^2} \qquad -1 \leq a \leq 1$$

Novikov-Thorne disk



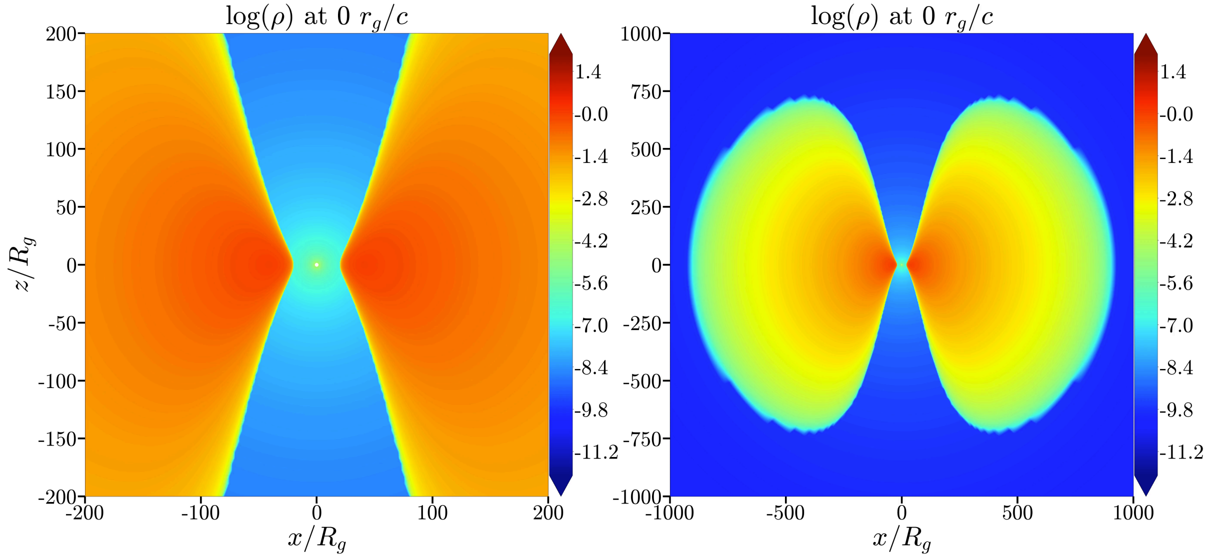
model from Moderski & Sikora, 1996, MNRAS, 283, 854

If accreting at $\dot{M}_{Edd}$, it takes almost 200 Myr to spin up the black hole!

Modeling black hole spin evolution: MADs

General **R**elativistic **M**agneto**h**ydro**d**ynamics (**GRMHD**)

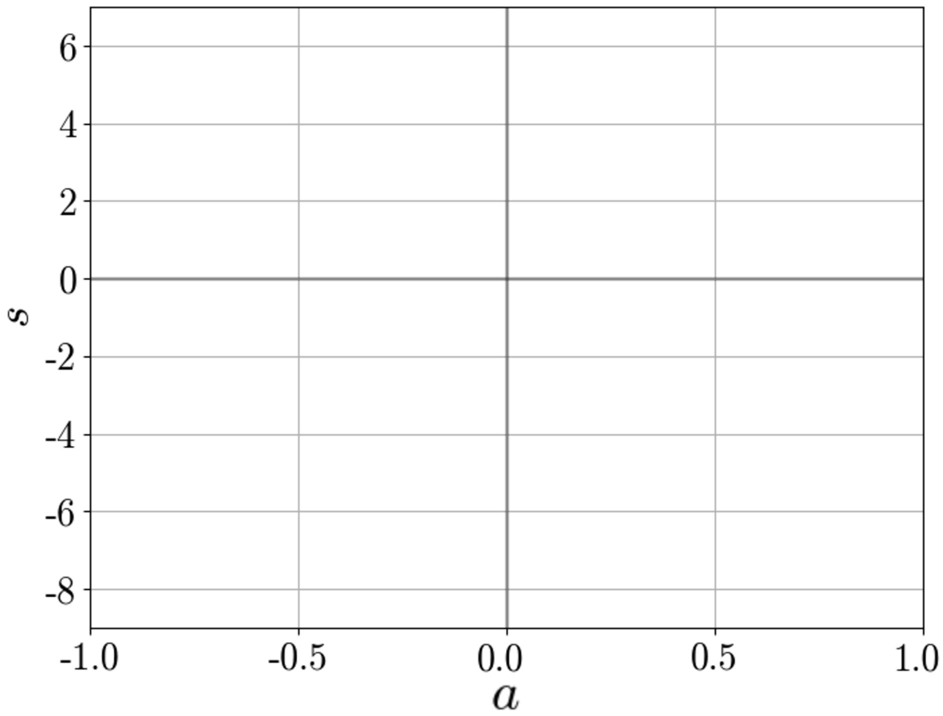
H-AMR (“hammer”, Liska et al 2019)



Problem: BH spin evolves over cosmological time, but a simulation is only a snapshot.
If applied to M87, this long simulation only runs ~100 years.

Solution: Use a catalogue of simulations to model full evolution.

Dimensionless spin-up parameter



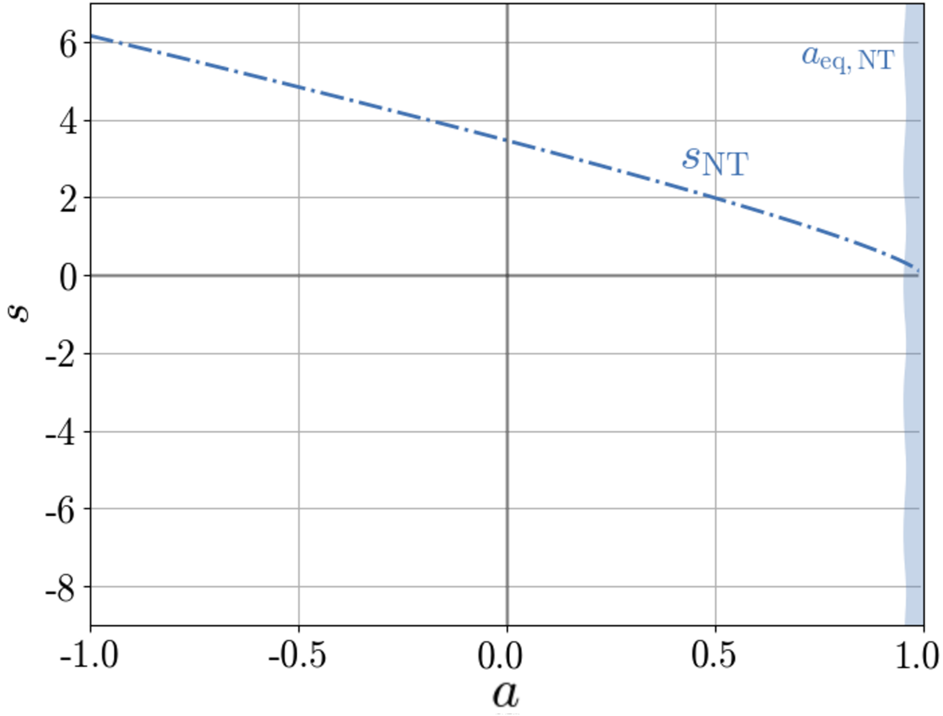
$$s = \frac{da}{dt}\frac{M_{\mathrm{BH}}}{\dot{m}}$$

(Gammie *et al* 2004 *ApJ* 602 312)

$s = 0 \rightarrow a_{eq}$

$s = l_{in} - 2ae_{in}$

Novikov-Thorne disk spins up the black hole



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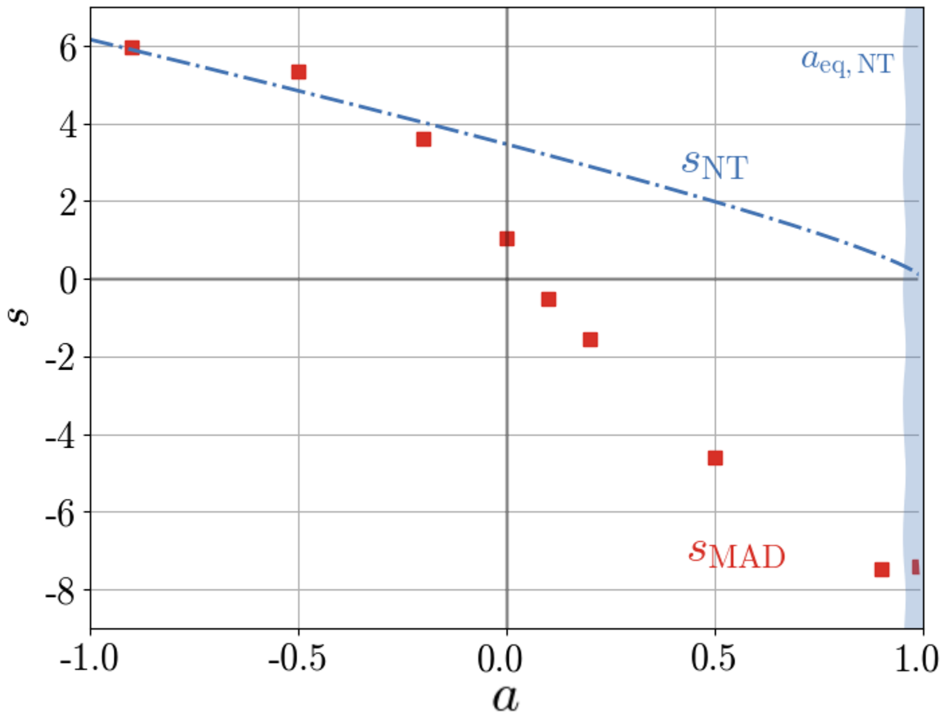

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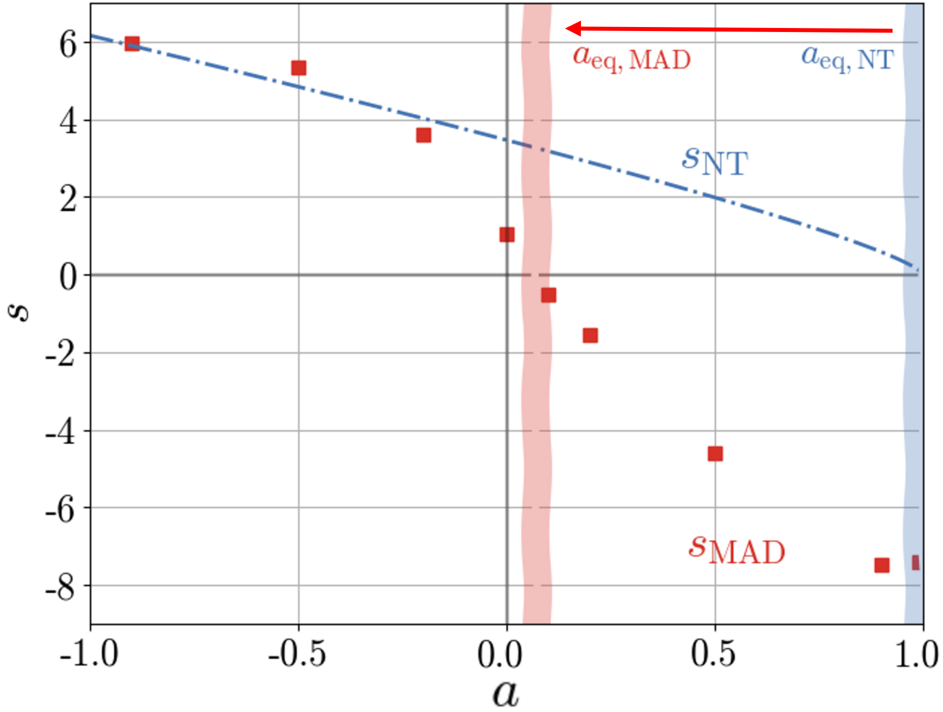
A MAD spins down the black hole



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$a_{\rm eq,MAD} = 0.07$ (Tchekhovskoy 2015)

Another recent MAD spin-down (Narayan et. al. 2022)

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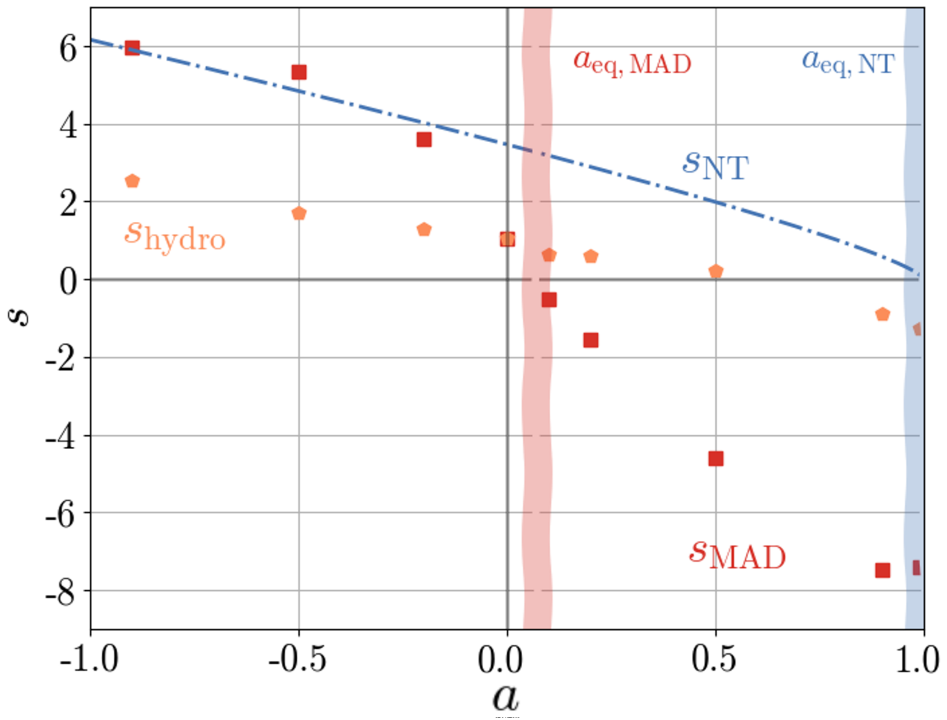

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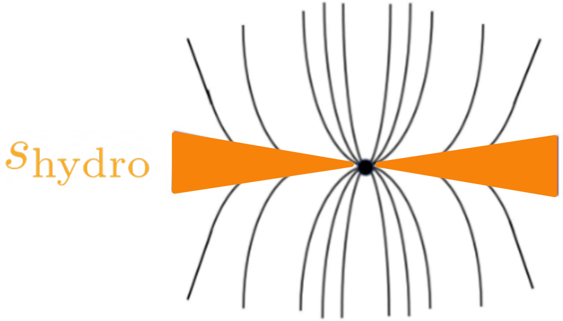

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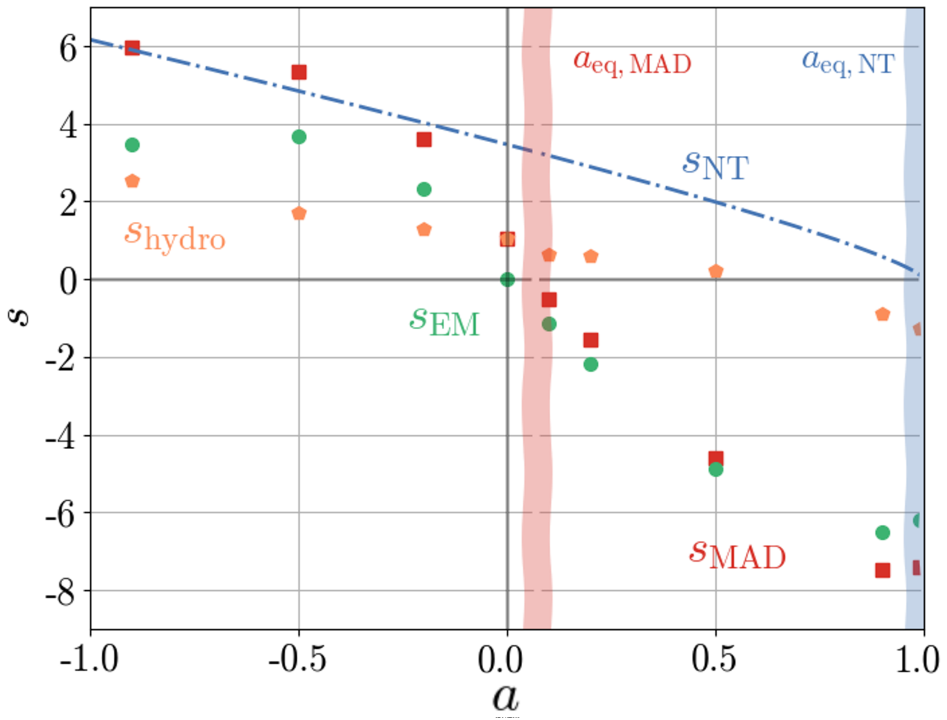

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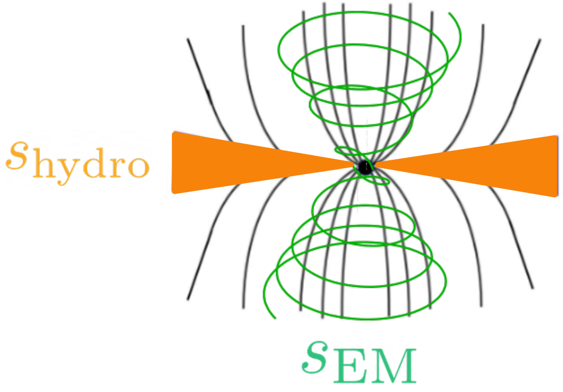

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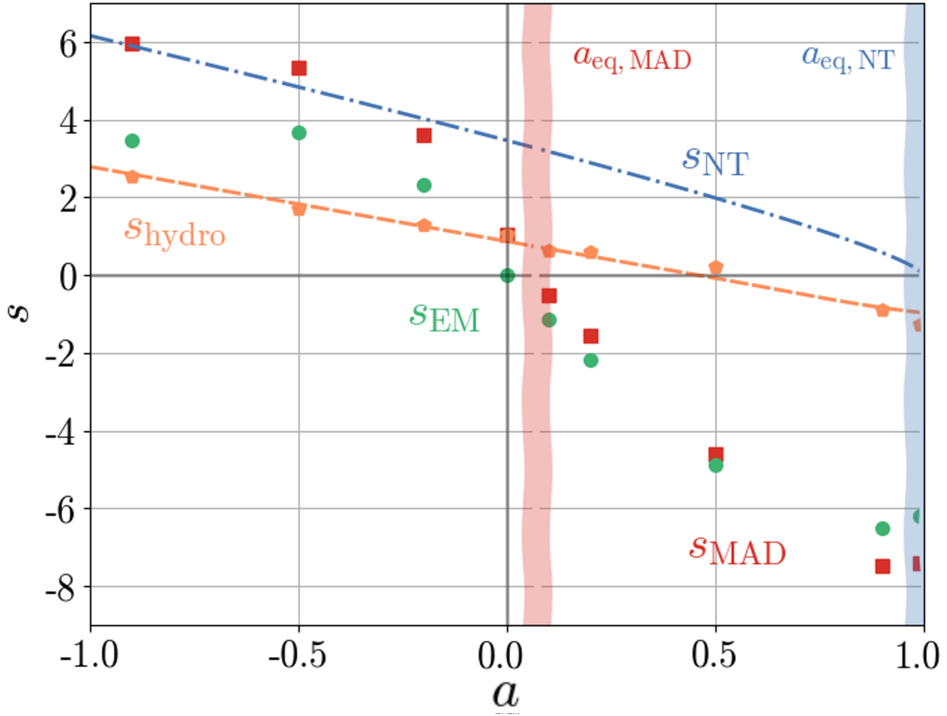

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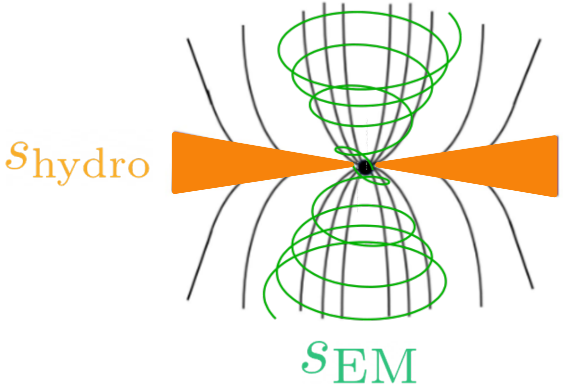

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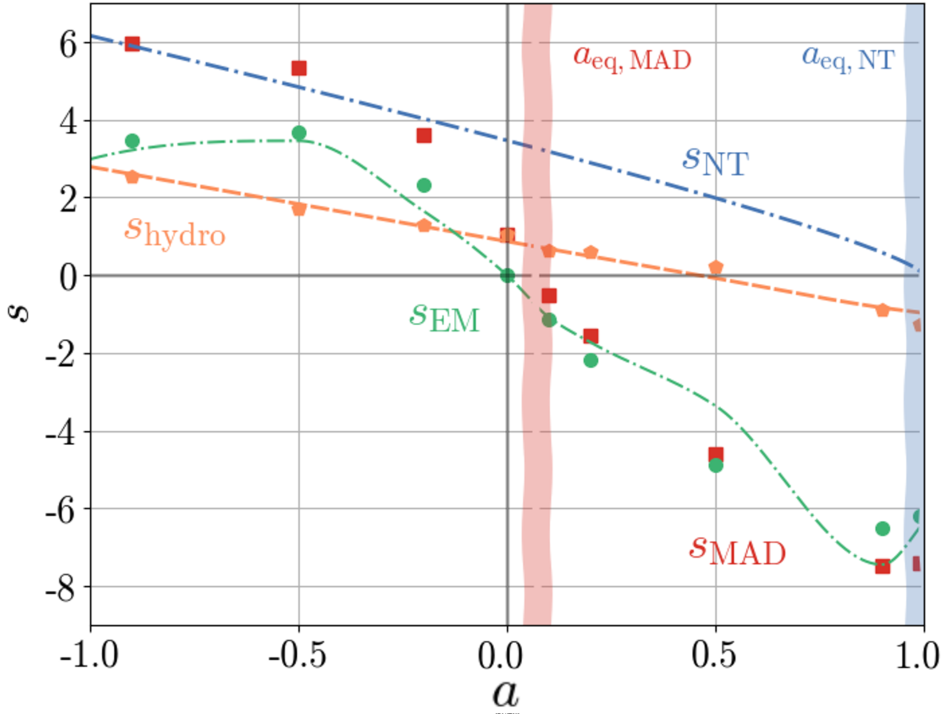

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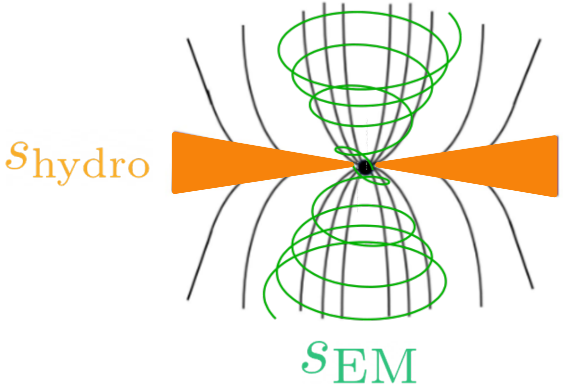

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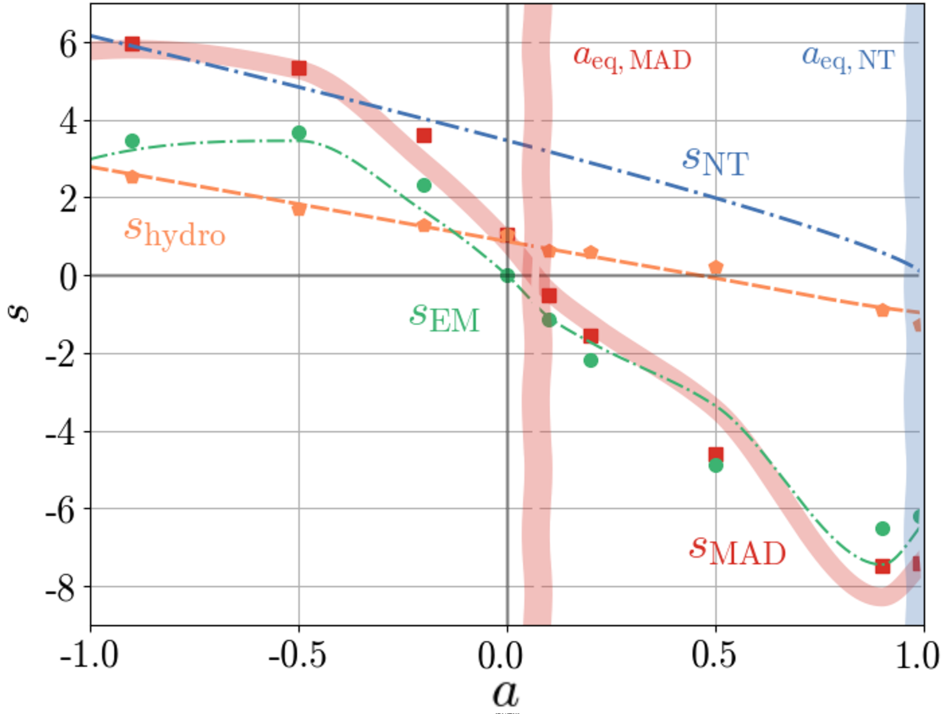

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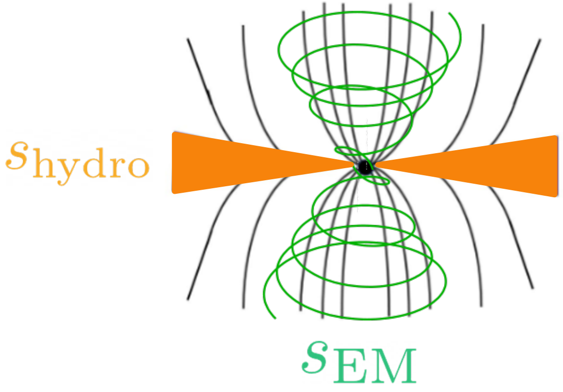
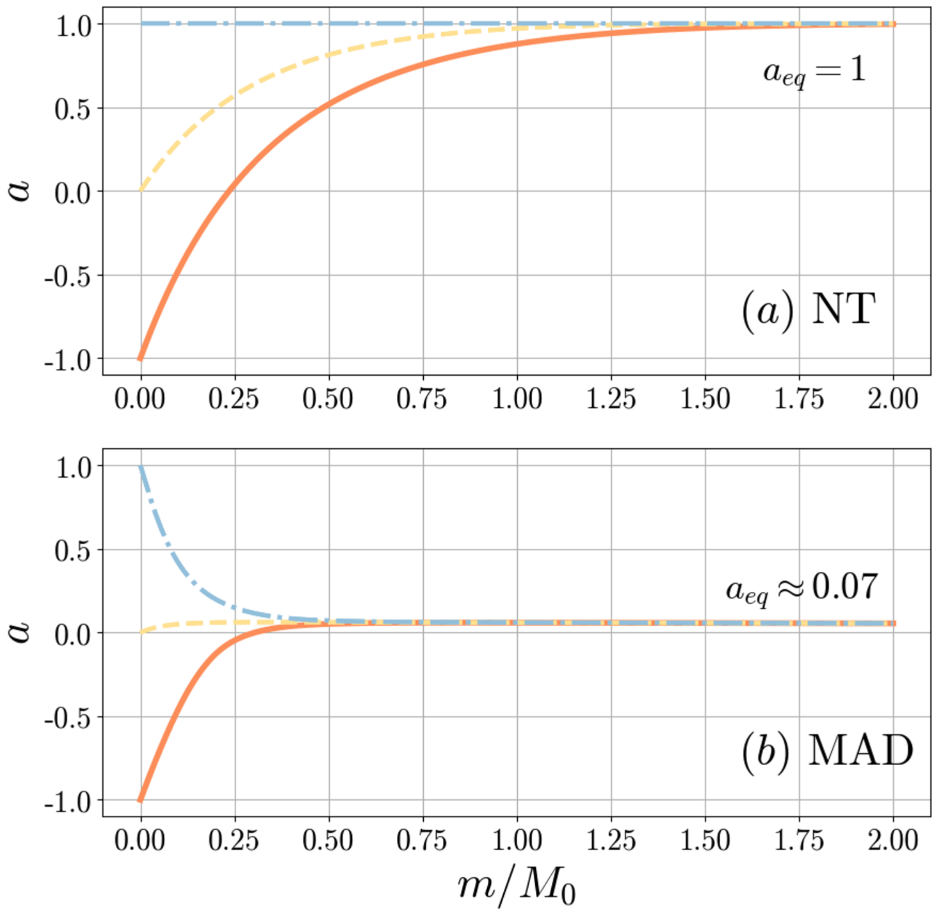


The **first** semi-analytic model to describe black hole spin-down in MADs: Lowell et. al. 2022a (in prep)

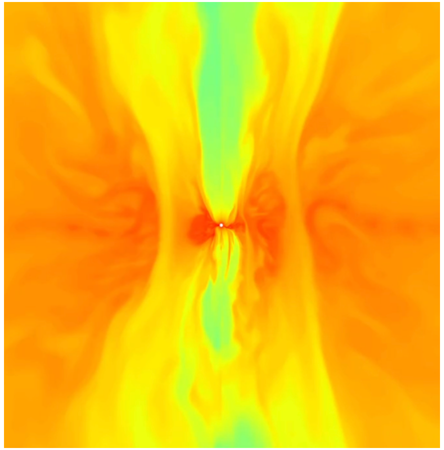
$$s_{\text{MAD}} = s_{\text{hydro}} + s_{\text{EM}}$$

MAD spin-down on a cosmological timescale

- MADs spin down to $a_{eq} \approx 0.07$
- MADs spin down **much faster** than the thin disk
- The black hole will spin down from a=1 to a=0.5 after accreting only 10% of its initial mass (<10 million years if accreting at $\dot{M}_{Edd}$)

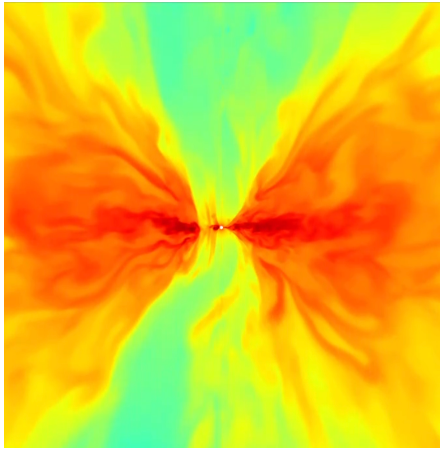


How do torques change for luminous disks?



Thick MADs

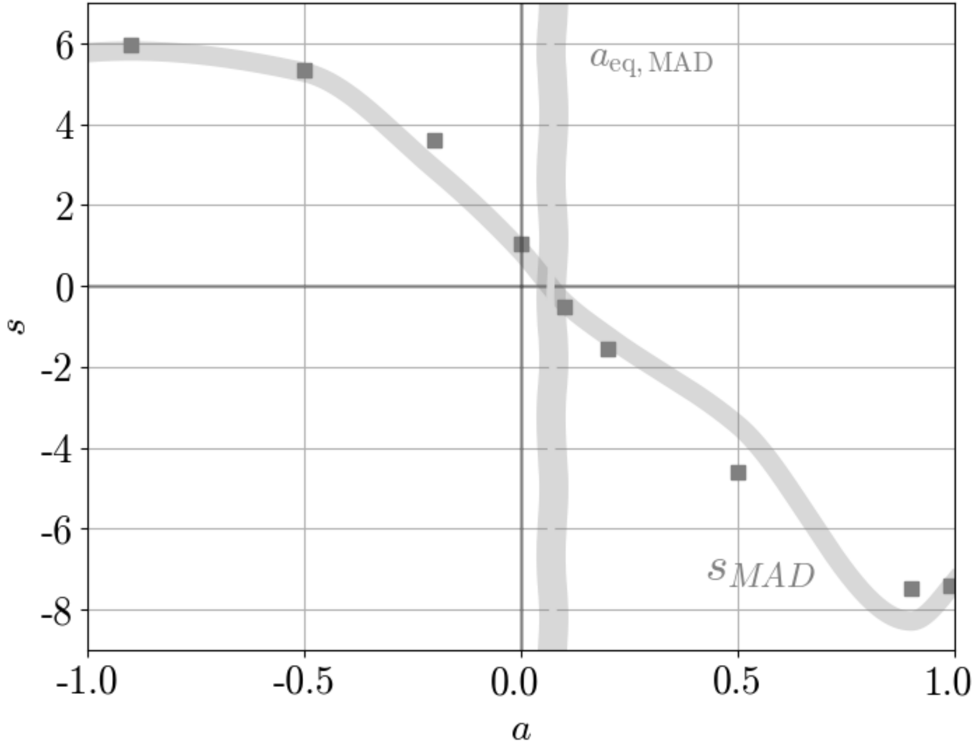
Applies well to super-Eddington accretion



Thin, cooled MADs

Can apply to luminous quasars

How do torques change for luminous disks?



Lowell et al 2022b (in prep)

$h/r = 0.3 : a_{\mathrm{eq,MAD}} = 0.07$

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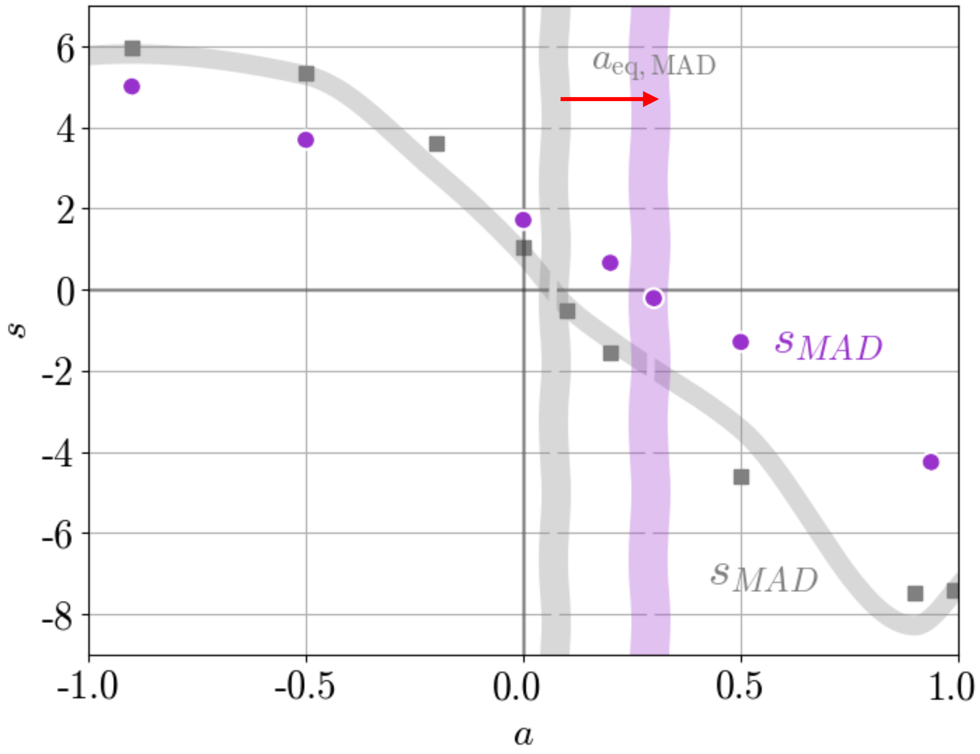


Lowell et al 2022b (in prep)

$h/r = 0.3 : a_{\mathrm{eq,MAD}} = 0.07$

$h/r = 0.1 : a_{\mathrm{eq,MAD}} = 0.3$

Luminous MAD black holes also spin down like **radiatively-inefficient MADs**

Current work:

Thinner, more realistic luminous disks including radiation, $\frac{h}{r} = 0.03$

Extend this model to different accretion rates/Eddington ratios, filling in the $a_{eq} - \dot{M}/\dot{M}_{Edd}$ parameter space

Main takeaways

STAND WITH UKRAINE

- Magnetically arrested disks spin down black holes. The BH only needs to accrete 10% of its mass for the spin to drop to a=0.5.
- Both the black hole AND the inner disk are robbed of angular momentum
- Luminous disks have slightly higher a_{eq}, but qualitatively behave similarly!
- More realistic radiation transport coming soon (preliminary results show similar trend)

Oak Ridge National Laboratory | Leadership Computing Facility

NERSC National Energy Research Scientific Computing Center

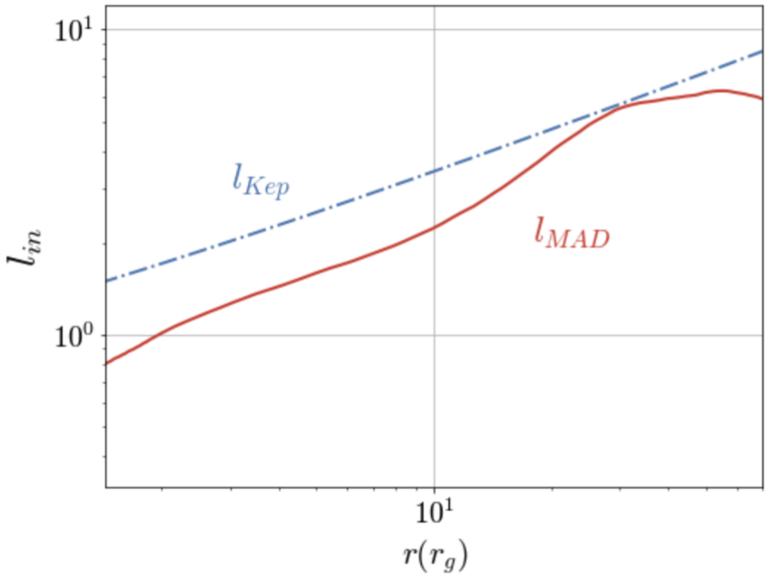
Illinois Space Grant Consortium Est. 1989

NSF Graduate Research Fellowship Program

TACC Texas Advanced Computing Center
Powering Discoveries That Change The World

Model for MAD spin-down

Angular momentum



$$dJ = l_{in} M dm \qquad \mathrm{dM} = e_{in} dm$$

$$s = (l_{\rm hydro} - 2ae_{\rm hydro}) - \eta_{\rm EM}\left(\frac{1}{k\Omega_{\rm H}} - 2a\right)$$

$l_{hydro} = 0.87$ (Independent of spin!)

$e_{hydro} \approx 0.95$

$\eta_{EM}(a)$

$k(a)$