

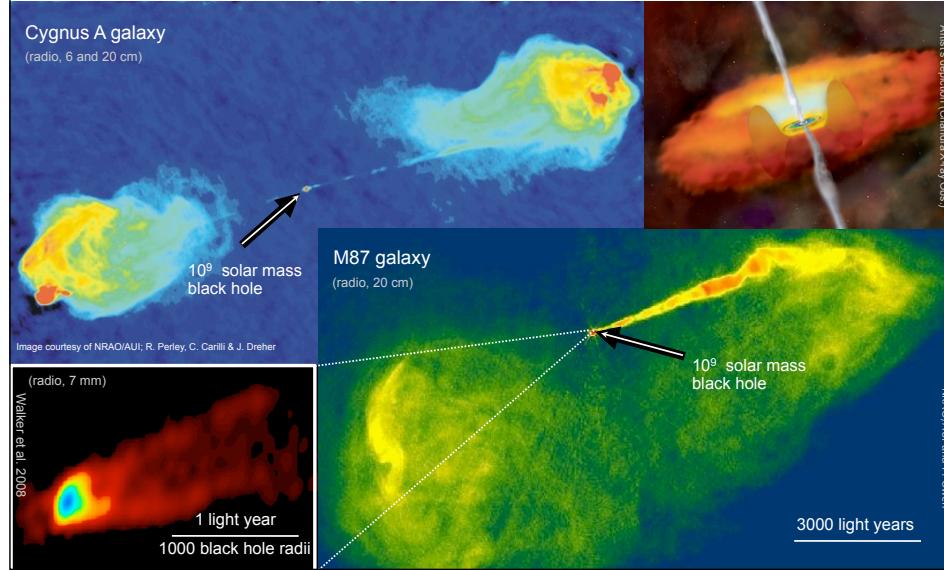
Simulations of Highly Efficient Jets in Active Galactic Nuclei

Alexander (Sasha) Tchekhovskoy

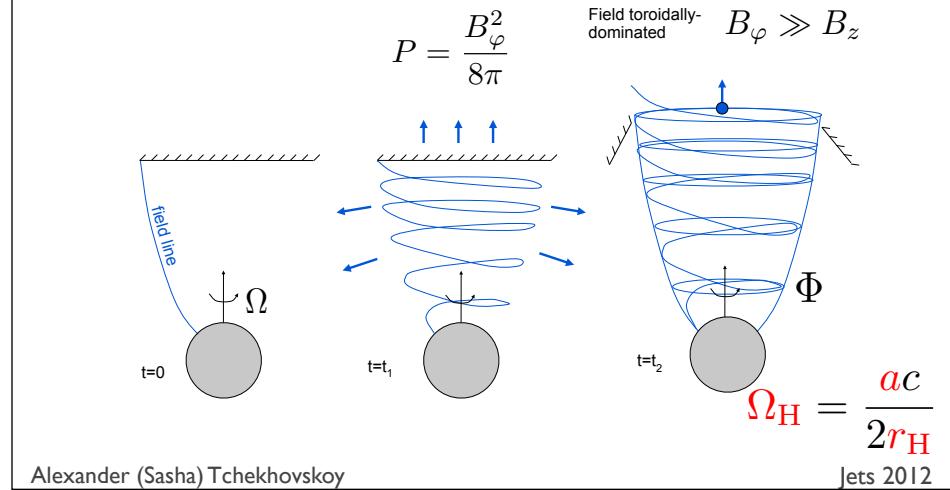
Center for Theoretical Science Fellow
Princeton University

Jonathan McKinney (Stanford, Maryland)
Ramesh Narayan (Harvard)
Roger Blandford (Stanford)

Jets: Beautiful & Challenging



How Do Jets Form?



How Does Jet Power Depend on Spin?

- Proportional to square of flux, Φ , and spin, a :

$$P_{\text{BZ}} = k \Phi^2 \Omega_{\text{H}}^2 / c \quad (\text{Blandford \& Znajek 1977, AT+ 2010, ApJ, 711, 50})$$

- Clearly, $\Phi^2 \propto \dot{M}$
- But, what sets value of the proportionality factor,

$$\phi = \frac{\Phi}{\sqrt{\dot{M} r_g^2 c}},$$

and BH power efficiency,

$$\eta_{\text{BZ}} = \frac{P_{\text{BZ}}}{\dot{M} c^2} = k \phi^2 \left(\frac{\Omega_{\text{H}} r_g}{c} \right)^2 ?$$

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Turn to Simulations

- Jet power depends on magnetic field topology
(McKinney 2005, Beckwith, Hawley & Krolik 2008, McKinney & Blandford 2009)
 - Dipolar geometry gives powerful jet
 - Quadrupolar or toroidal gives weak or no jet
- GR MHD simulations give $\eta_{BZ} \lesssim 20\%$, even for nearly maximally spinning BHs (McKinney 2005, de Villiers et al. 2005, Hawley & Krolik 2006, Barkov & Baushev 2011)
- Can we obtain larger values of η ?
- Observations: some AGN have $\eta \gtrsim 100\%$
(Rawlings & Saunders 1991, Fernandes et al. 2010, Ghisellini et al. 2010, Punsly 2011, McNamara et al. 2011)

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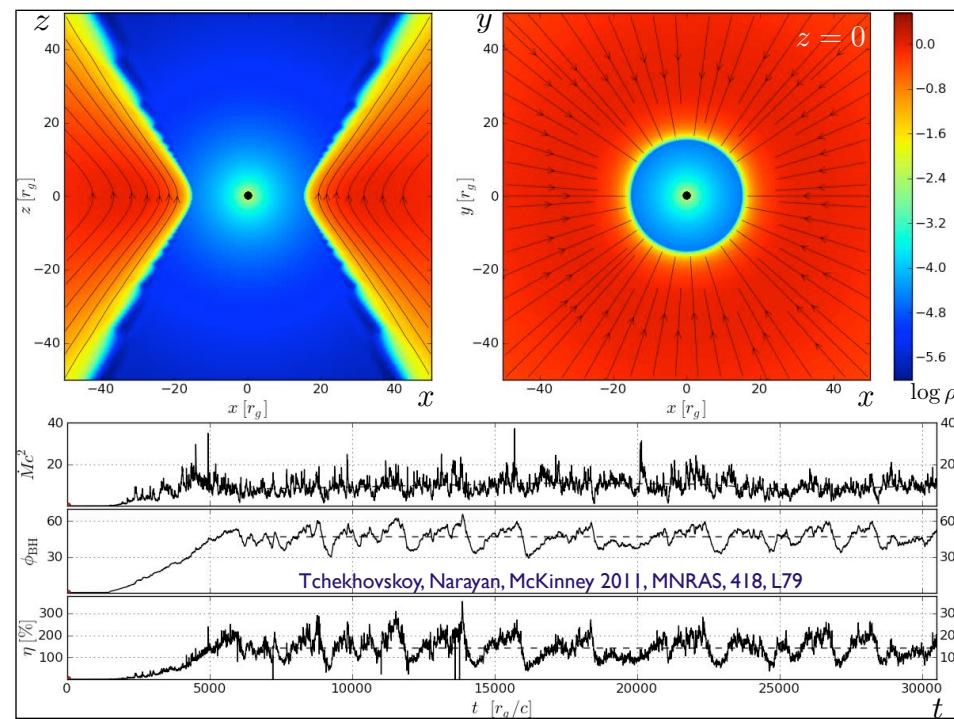
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Jets from MADs

- Jet power increases with increasing BH magnetic flux, Φ .
- Our simulations contain enough magnetic flux to magnetically “overwhelm” the BH:
 - ▶ BH receives more flux than it can take, which maximizes Φ and leads to $\eta > 100\%$.
- Outcome is magnetically-arrested accretion (MAD): matter has to fight its way through the field to get to BH (Igumenshchev et al. 2003, Narayan et al. 2003).
- New physics: high jet power, QPOs, mode of accretion...
- Advanced 3D GR MHD simulations with HARM code: took over 2000 CPU-years! (Gammie et. al. 2003; AT+ 2007)

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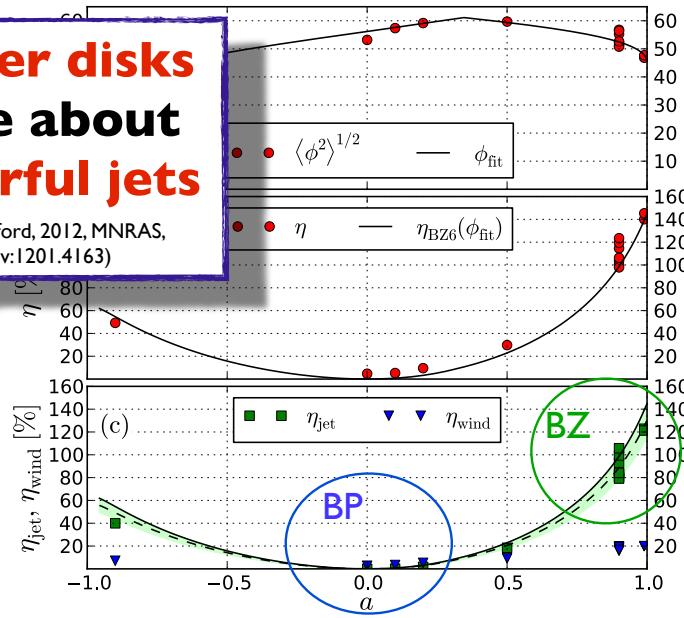
**2x thicker disks
produce about
2x powerful jets**

(McKinney,AT,Blandford, 2012, MNRAS,
submitted, arxiv:1201.4163)

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(AT, McKinney
2012a, MNRAS,
submitted,
arxiv:1201.4385
2012b, in prep.)

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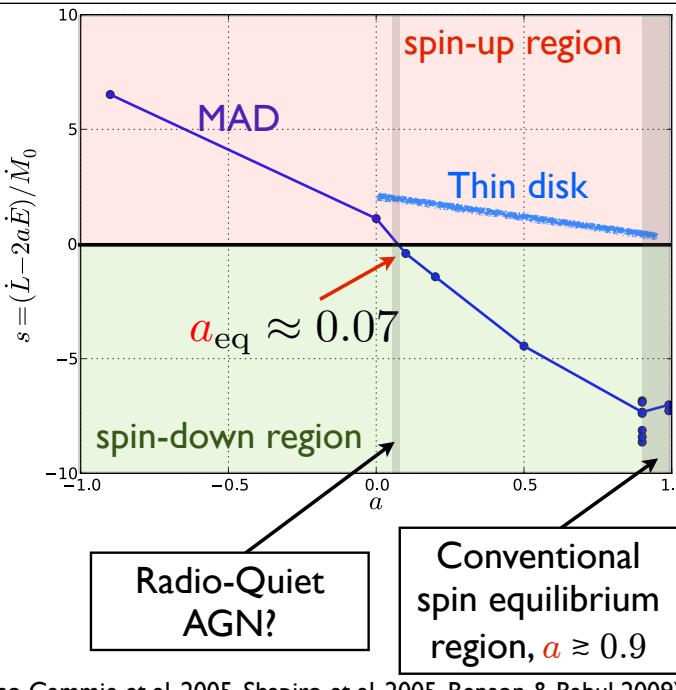


$\eta > 100\%$ unambiguously shows that
net energy is extracted from the BH

Our MADs slow BHs down to a halt

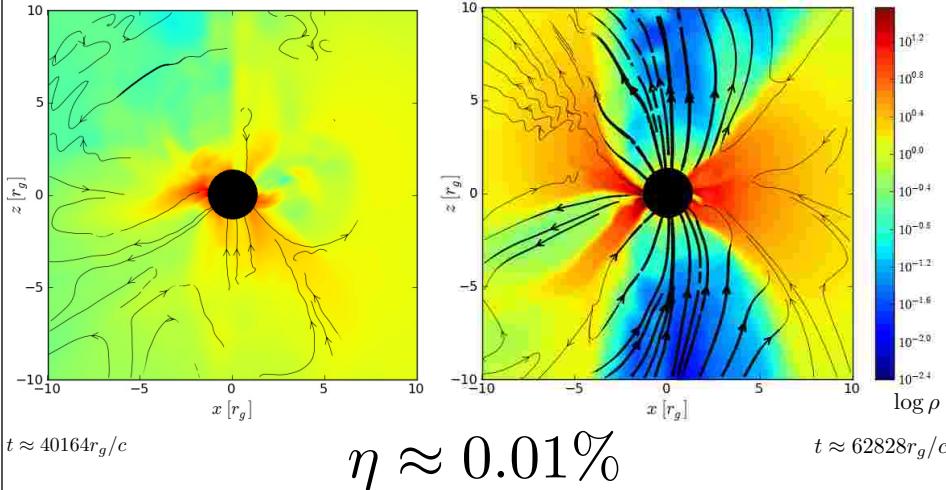
(AT, McKinney
2012a, MNRAS,
submitted,
arxiv:1201.4385,
2012b, in prep.)

(see also Gammie et al. 2005, Shapiro et al. 2005, Benson & Babul 2009)



Anti-MADs: Zero Initial Flux

McKinney, AT, Blandford, 2012, MNRAS, submitted, arxiv:1201.4163



$$\eta \approx 0.01\%$$

Is This The Radio-Quiet AGN?

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Summary

- Simulations maximize $\Phi \rightarrow$ MAD state:
 - ▶ $\eta > 100\%$ for $a \gtrsim 0.9$
 - ▶ MADs slow BHs down to a “halt”, $a \lesssim 0.1$
- Radio-Loud AGN: MADs with $a \approx 1$
- Radio-Quiet AGN:
 - ▶ MADs with “halted” BHs, $a \lesssim 0.1$, or
 - ▶ Low vertical flux accretion for any a
- Retrograde BHs \rightarrow 2-3x less powerful jets
- Thicker disks \rightarrow more powerful jets

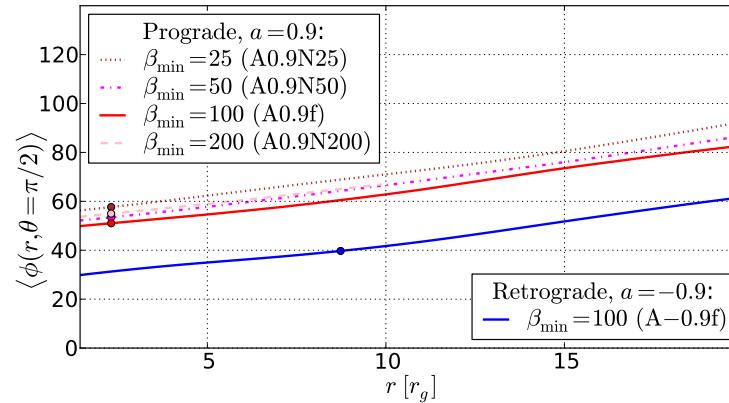
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Initial
flux
does
not
matter!

(Tchekhovskoy,
McKinney
2012a,
MNRAS,
submitted,
arXiv:
1201.4385)

Variation in disk flux by 300%
leads to variation less than 10%
in BH flux and 20% in η



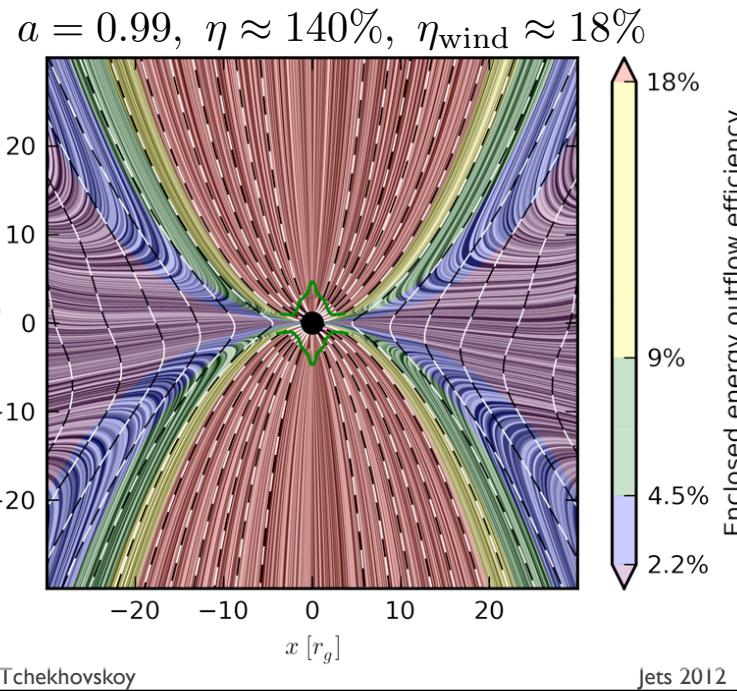
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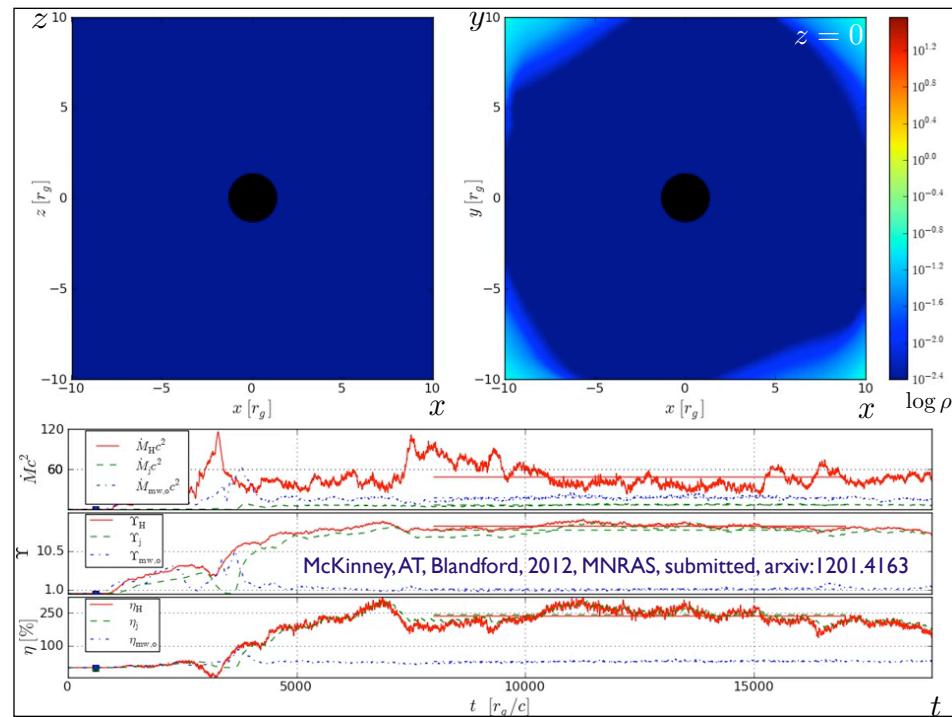
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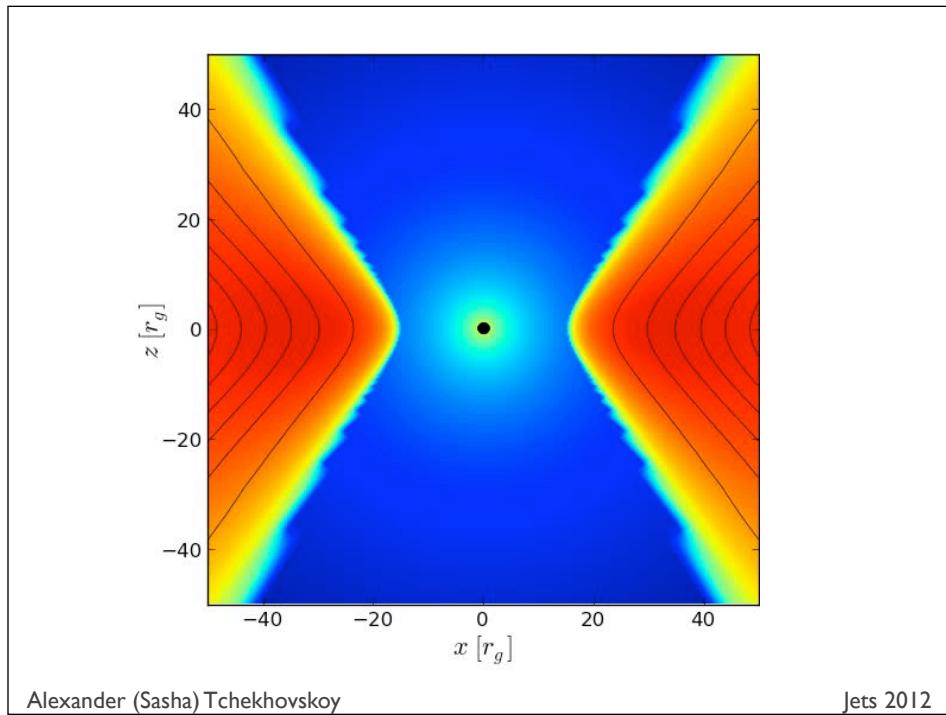
Where
energy
comes
from?
($h/r=0.3$)

(Tchekhovskoy,
McKinney,
in preparation)

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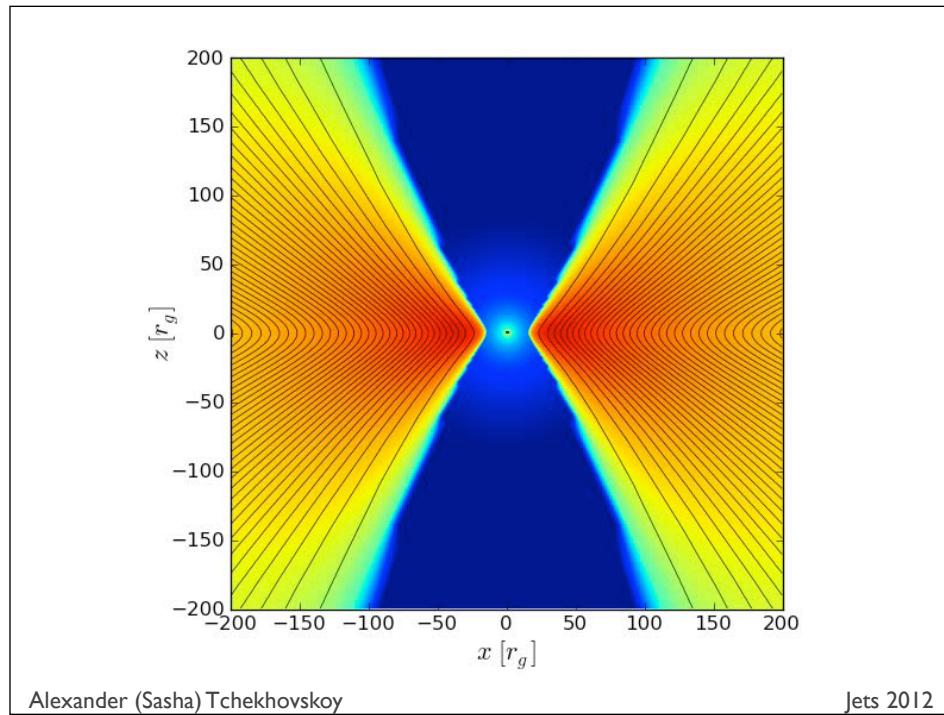






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