Title: Getting the Most out of a Black Hole

Date: Mar 04, 2013 01:00 PM

URL: http://www.pirsa.org/13030102

Abstract: As black holes accrete surrounding gas, they often produce relativistic, collimated outflows, or jets. Jets are expected to form in the black hole vicinity making them powerful probes of strong-field gravity. However, how jet properties are connected to black hole and accretion flow properties has been unclear. Recent progress in computer simulations of black hole accretion enables studies of jet formation in unprecedented detail. For the first time, 3D general relativistic magnetohydrodynamic numerical simulations allow one to determine the maximum efficiency with which accretion onto black holes can power relativistic jets. I will present the dependence of this maximum efficiency on black hole spin and discuss how this dependence allows one to probe strong-field gravity. In realistic astrophysical systems, the angular momentum vector of the accretion flow can be tilted relative to the spin of the black hole. I will present the first simulations of jets from such tilted accretion systems and discuss their observational signatures.

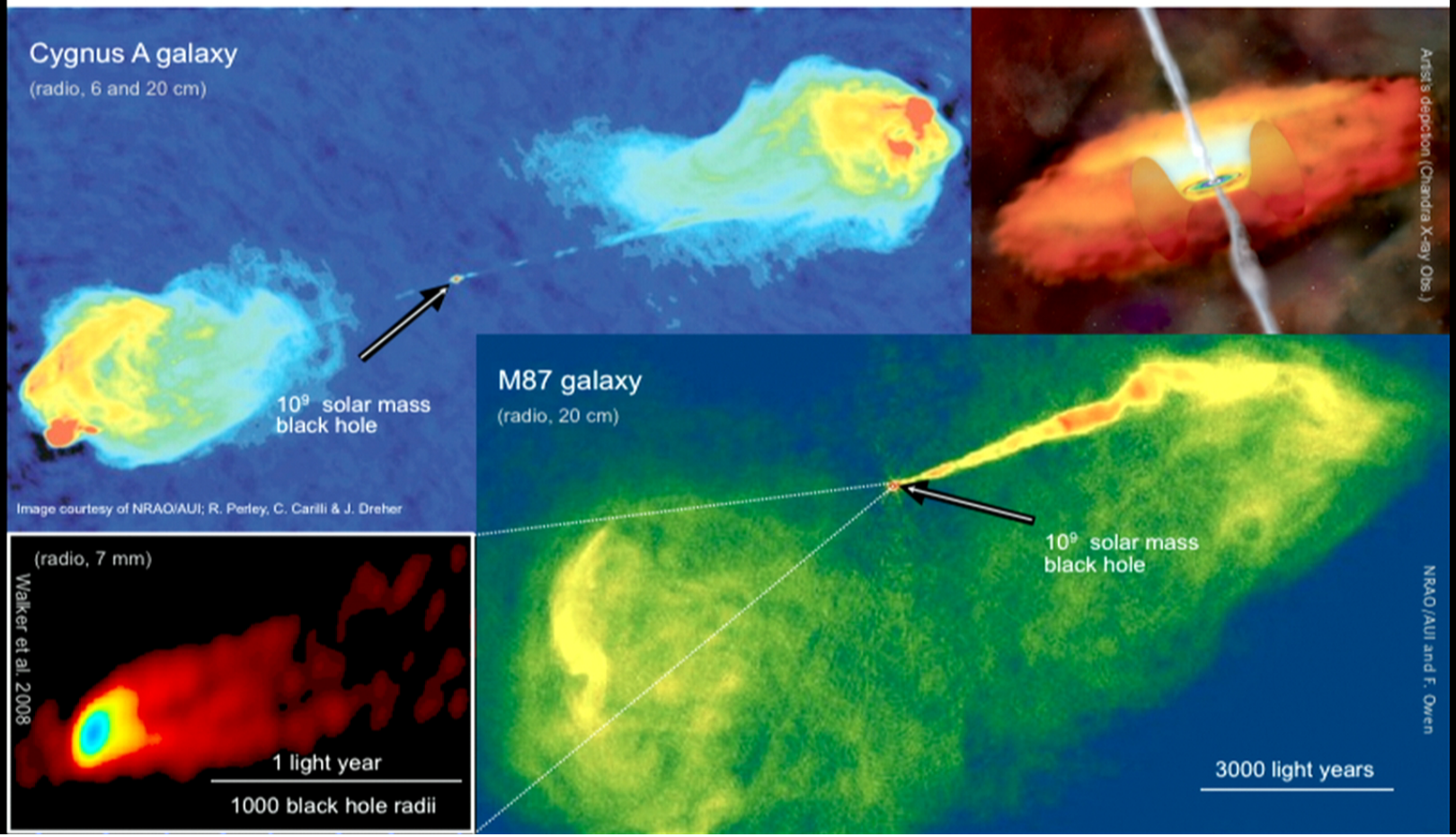
Getting the Most out of a Black Hole

Alexander (Sasha) Tchekhovskoy

Center for Theoretical Science Fellow
Princeton University

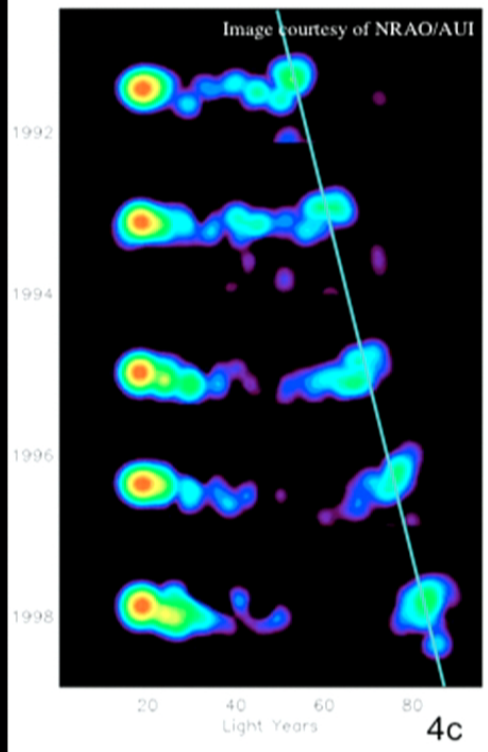
Roger Blandford, Stanford
Dimitrios Giannios, Purdue
Luke Kelley, Harvard
Jason Li, Princeton
Jonathan McKinney, Maryland
Brian Metzger, Columbia
Ramesh Narayan, Harvard
Anatoly Spitkovsky, Princeton

Jets Affect the Environment

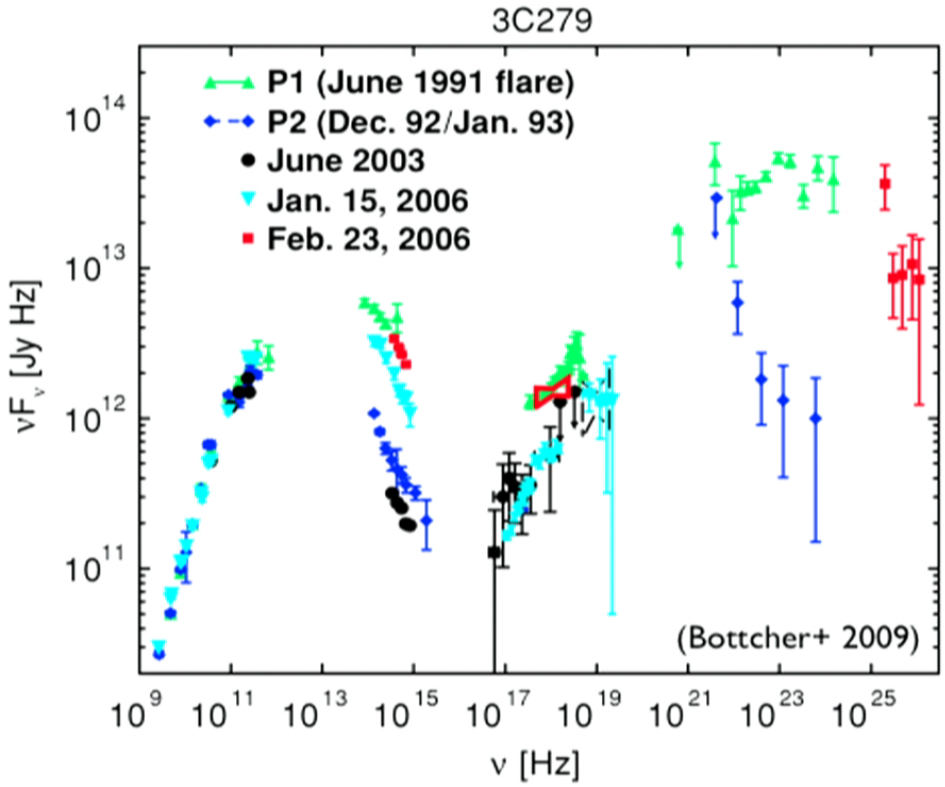


Jets Probe Strong-field Gravity

Active Galaxy with Jet Pointing at us: 3C279

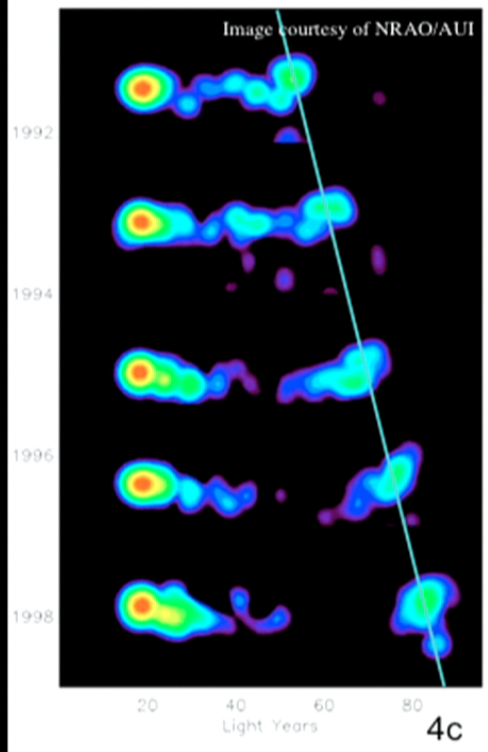


$v \approx 0.997\ c$

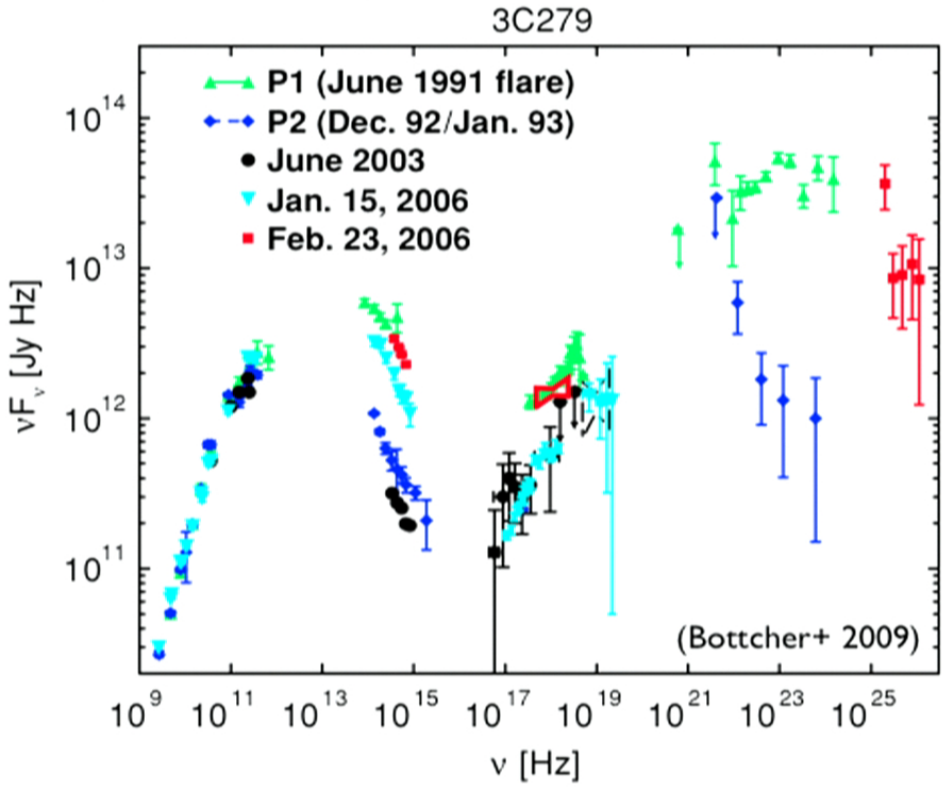


Jets Probe Strong-field Gravity

Active Galaxy with Jet Pointing at us: 3C279



$v \approx 0.997\ c$

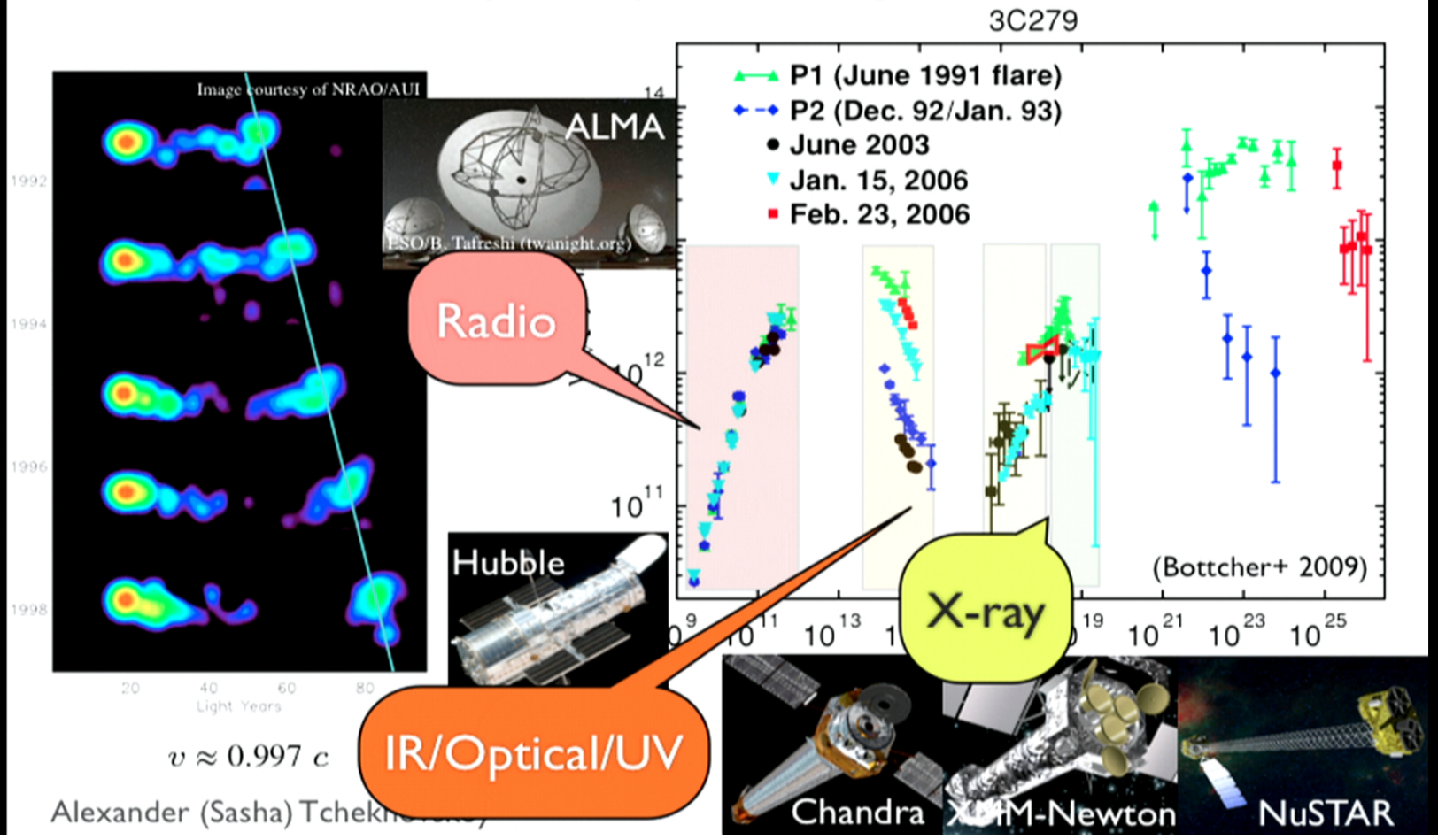


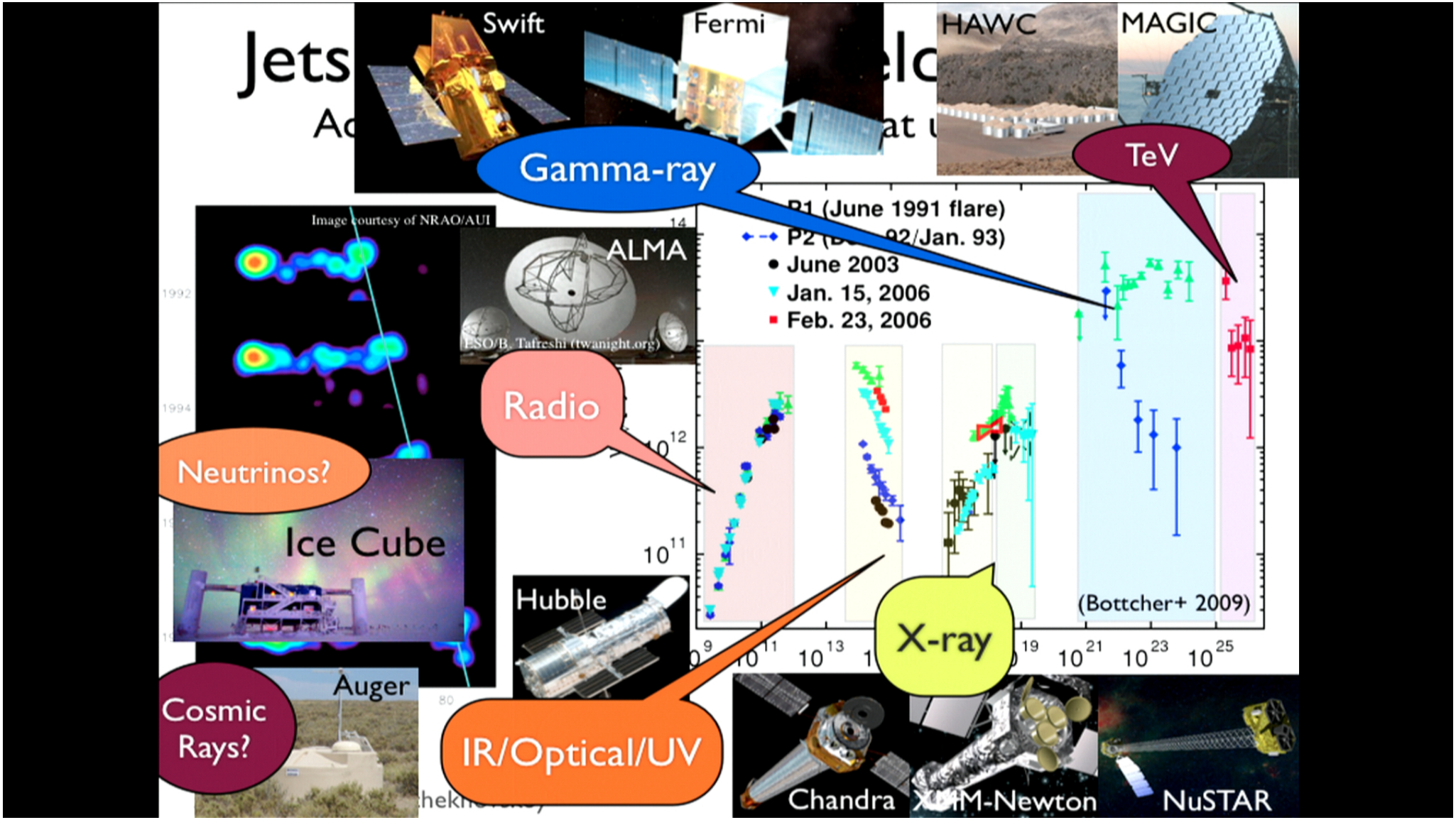
Alexander (Sasha) Tchekhovskoy

Perimeter Institute Seminar

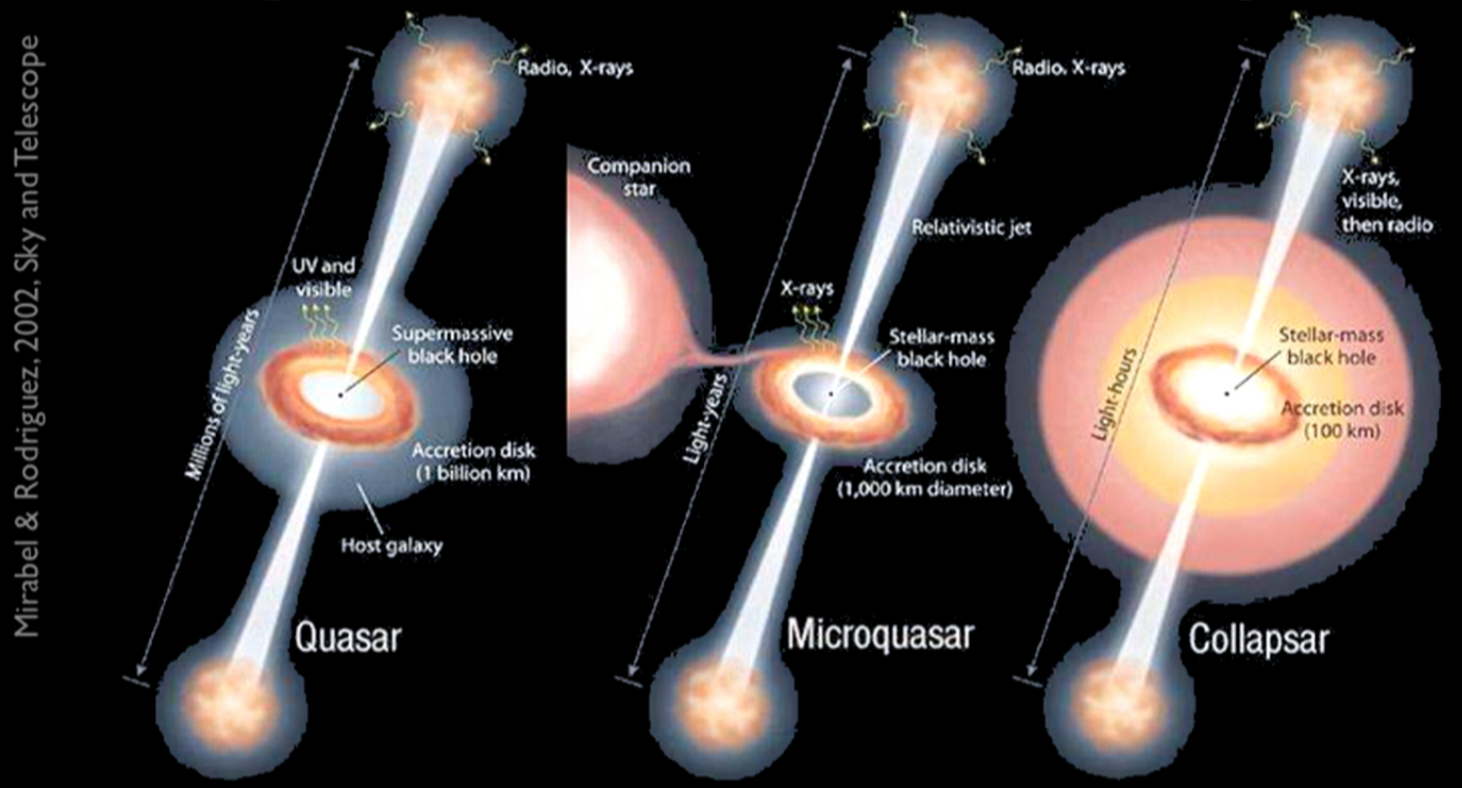
Jets Probe Strong-field Gravity

Active Galaxy with Jet Pointing at us: 3C279




Jets
Swift
Fermi
HAWC
MAGIC
Gamma-ray
TeV
Image courtesy of NRAO/AUI
ALMA
ESO/B. Tafreshi (twanight.org)
Radio
P1 (June 1991 flare)
June 2003
Jan. 15, 2006
Feb. 23, 2006
(Bottcher+ 2009)
Neutrinos?
Ice Cube
Hubble
X-ray
Auger
Cosmic Rays?
IR/Optical/UV
Chandra
NuSTAR

Big or Small: All Make Jets



Active Galactic Nuclei
(e.g., M87,
$M_{BH}=5 \times 10^9 M_\odot$)

Black Hole X-ray Binaries
(e.g., GRS 1915+105,
$M_{BH}=15 M_\odot$)

Gamma-Ray Bursts
($M_{BH} \simeq 5 M_\odot$)

Alexander (Sasha) Tchekhovskoy

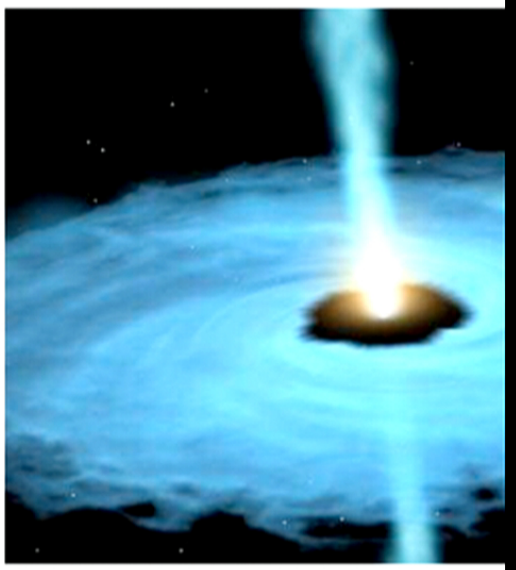
Perimeter Institute Seminar

Fundamental Questions

- What sets the maximum power of jets?
- Are jets powered by black holes or inner regions of accretion disks?
- How does jet power depend on BH spin?
- Does accretion always spin up BHs to high spins?
- Do black holes with tilted disks produce jets? Which way do such jets point?

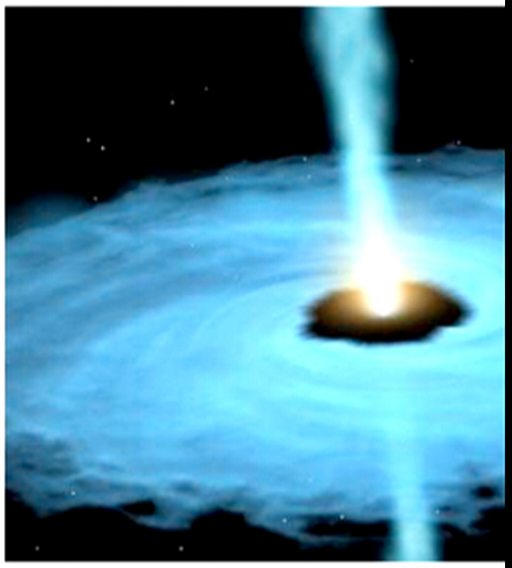
Challenging, Global Multi-scale 3D *GRMHD* Problem

- Disks: small-scale turbulent physics is important
  - magnetic fields → 3D *magnetorotational instability* (*MRI*, Balbus & Hawley 1991) → turbulence & viscosity
    ↪ use 3D *magneto*hydrodynamics (MHD)



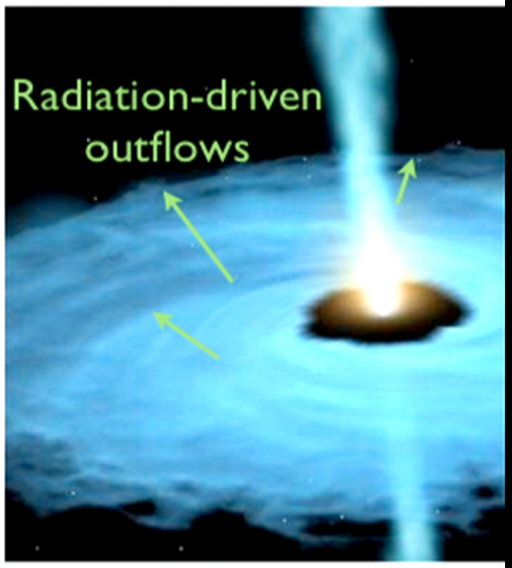
Challenging, Global Multi-scale 3D *GRMHD* Problem

- Disks: small-scale turbulent physics is important
  - magnetic fields → 3D *magnetorotational instability* (*MRI*, Balbus & Hawley 1991) → turbulence & viscosity
    ↳ use 3D *magneto*hydrodynamics (MHD)
- Jets: have a challenging contrast in energy scales
  - relativistically-magnetized: e.g., $E_{\rm M} \sim 10 Mc^2$
    ↳ 10% error in $E_{\rm M}$ → 100% error in Mc^2



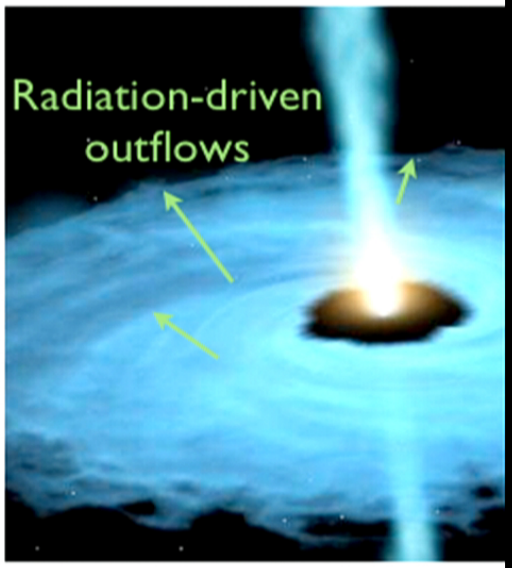
Challenging, Global Multi-scale 3D *GRMHD* Problem

- Disks: small-scale turbulent physics is important
  - magnetic fields → 3D *magnetorotational instability* (*MRI*, Balbus & Hawley 1991) → turbulence & viscosity
    ↳ use 3D *magneto*hydrodynamics (MHD)
- Jets: have a challenging contrast in energy scales
  - relativistically-magnetized: e.g., $E_{\rm M} \sim 10 Mc^2$
    ↳ 10% error in $E_{\rm M}$ → 100% error in Mc^2
- Radiation can dramatically alter disk state



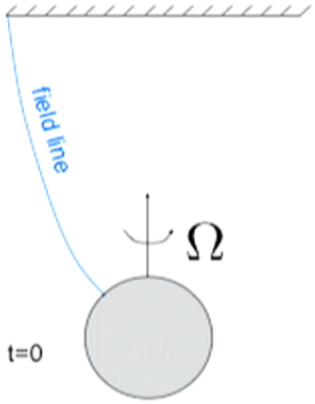
- Radiation+black hole+MHD+3D = 3D *Radiation General Relativistic* MHD

Challenging, Global Multi-scale 3D *GRMHD* Problem



- Disks: small-scale turbulent physics is important
  - magnetic fields → 3D *magnetorotational instability* (*MRI*, Balbus & Hawley 1991) → turbulence & viscosity
    ↳ use 3D *magneto*hydrodynamics (MHD)
- Jets: have a challenging contrast in energy scales
  - relativistically-magnetized: e.g., $E_{\rm M} \sim 10 Mc^2$
    ↳ 10% error in $E_{\rm M}$ → 100% error in Mc^2
- Radiation can dramatically alter disk state
- Radiation+black hole+MHD+3D = 3D *Radiation General Relativistic* MHD
  - *GRMHD* is 5x more expensive than MHD; *RGRMHD* is even more expensive
  - Global simulations that *<u>also</u>* resolve local, small-scale disk microphysics
  - One simulation takes 100 CPU-years = 1 million CPU-hours

How Do Jets Work?



Alexander (Sasha) Tchekhovskoy

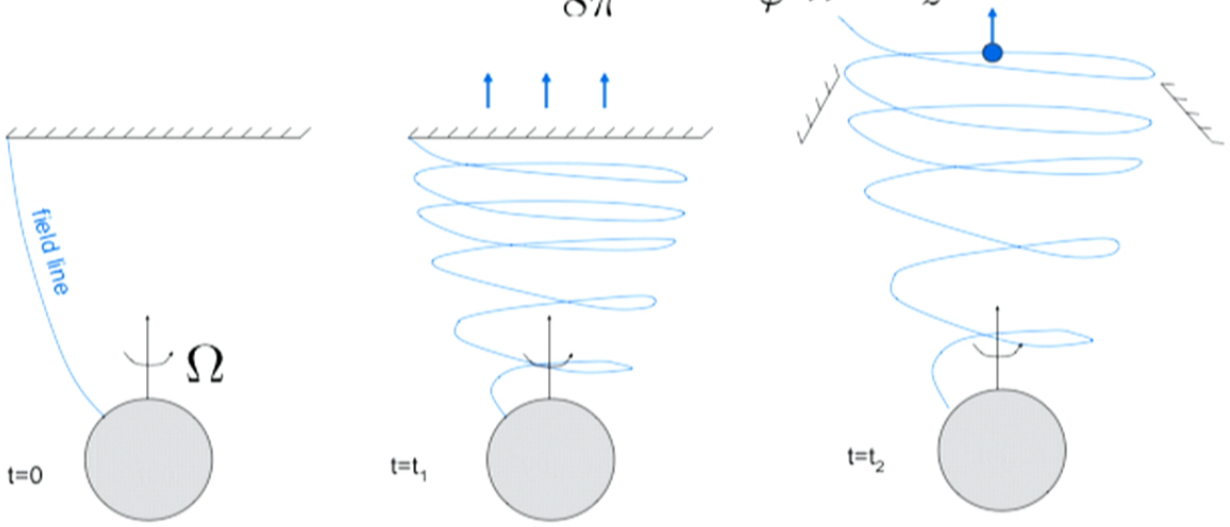
Perimeter Institute Seminar

How Do Jets Work?

$$P = \frac{B_\varphi^2}{8\pi}$$

Field toroidally-dominated

$$B_\varphi \gg B_z$$



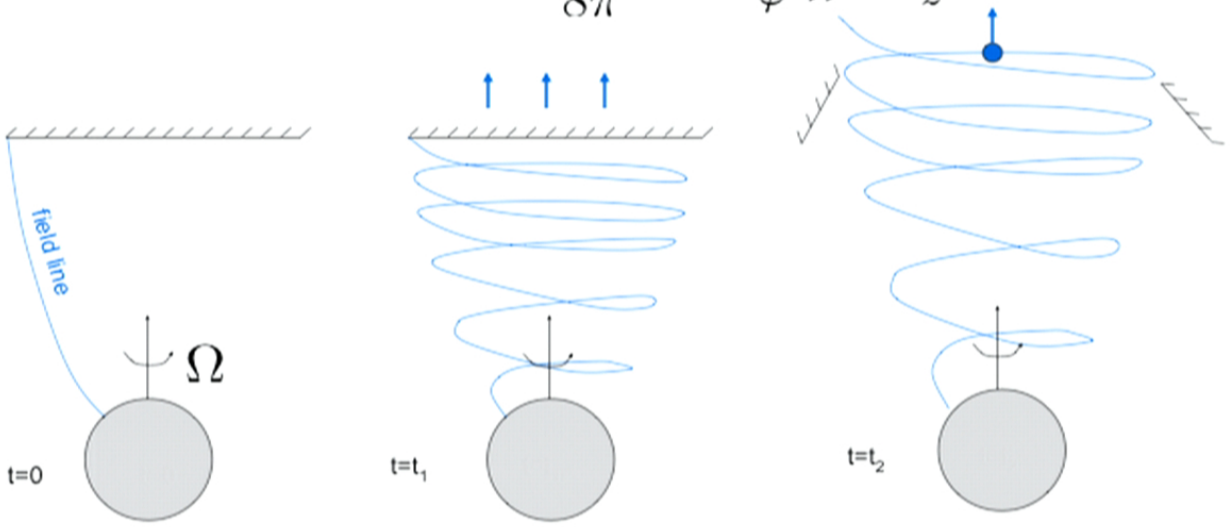
(Beskin & Nokhrina 06, AT+08,09,10, Komissarov 07-10, Lyubarsky 10, many others)

How Do Jets Work?

$$P = \frac{B_\varphi^2}{8\pi}$$

Field toroidally-dominated

$$B_\varphi \gg B_z$$



(Beskin & Nokhrina 06, AT+08,09,10, Komissarov 07-10, Lyubarsky 10, many others)

How Do Jets Work?

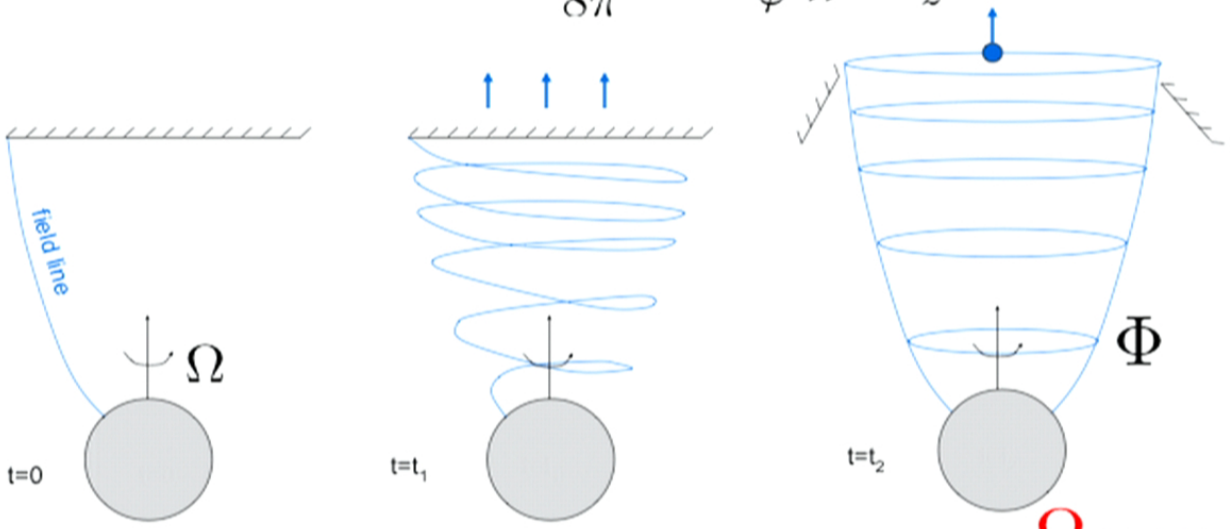
γ-rays, ν, cosmic rays

(Lyutikov 05, Giannios & Spruit 07, Bahcall & Mészáros 08, Broderick & Loeb 08, Beloborodov 09, Narayan, Kumar, AT 11, many others)

$$P = \frac{B_\varphi^2}{8\pi}$$

Field toroidally-dominated

$$B_\varphi \gg B_z$$



(Beskin & Nokhrina 06, AT+08,09,10, Komissarov 07-10, Lyubarsky 10, many others)

$$\Omega_{\rm H} = \frac{ac}{2r_{\rm H}}$$

How Do Jets Work?

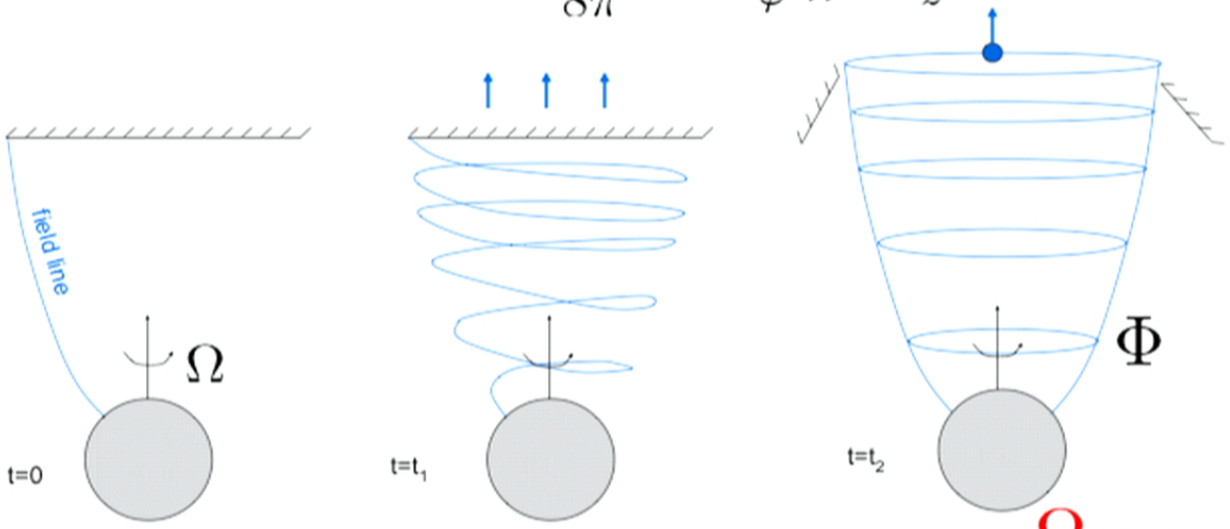
γ-rays, ν, cosmic rays

(Lyutikov 05, Giannios & Spruit 07, Bahcall & Mészáros 08, Broderick & Loeb 08, Beloborodov 09, Narayan, Kumar, AT 11, many others)

$$P = \frac{B_\varphi^2}{8\pi}$$

Field toroidally-dominated

$$B_\varphi \gg B_z$$



(Beskin & Nokhrina 06, AT+08,09,10, Komissarov 07-10, Lyubarsky 10, many others)

$$\Omega_{\rm H} = \frac{ac}{2r_{\rm H}}$$

How Do Jets Work?

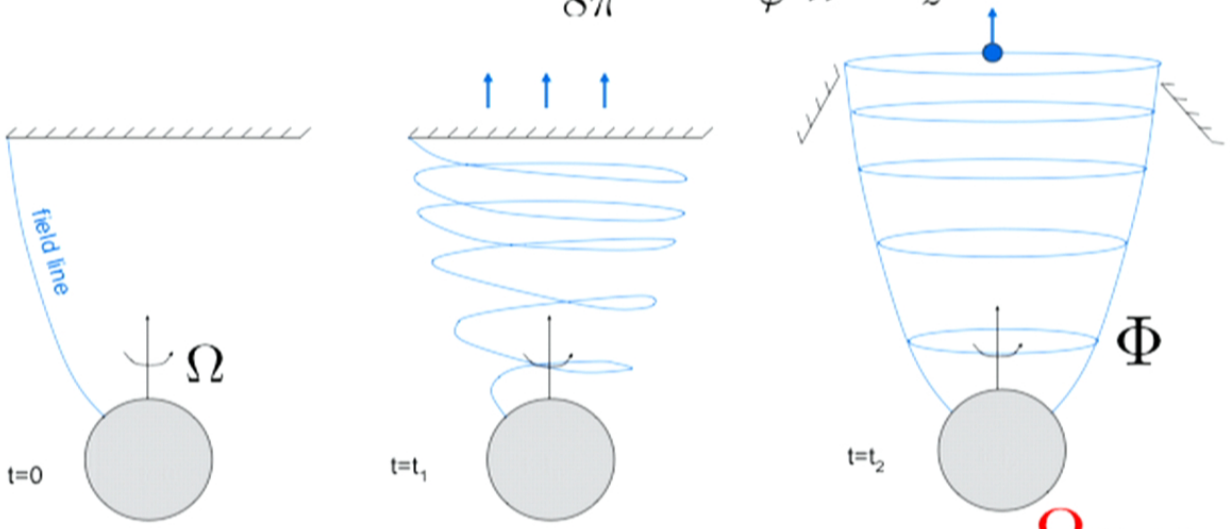
γ-rays, ν, cosmic rays

(Lyutikov 05, Giannios & Spruit 07, Bahcall & Mészáros 08, Broderick & Loeb 08, Beloborodov 09, Narayan, Kumar, AT 11, many others)

$$P = \frac{B_\varphi^2}{8\pi}$$

Field toroidally-dominated

$$B_\varphi \gg B_z$$



(Beskin & Nokhrina 06, AT+08,09,10, Komissarov 07-10, Lyubarsky 10, many others)

$$\Omega_{\rm H} = \frac{ac}{2r_{\rm H}}$$

How Do Jets Work?

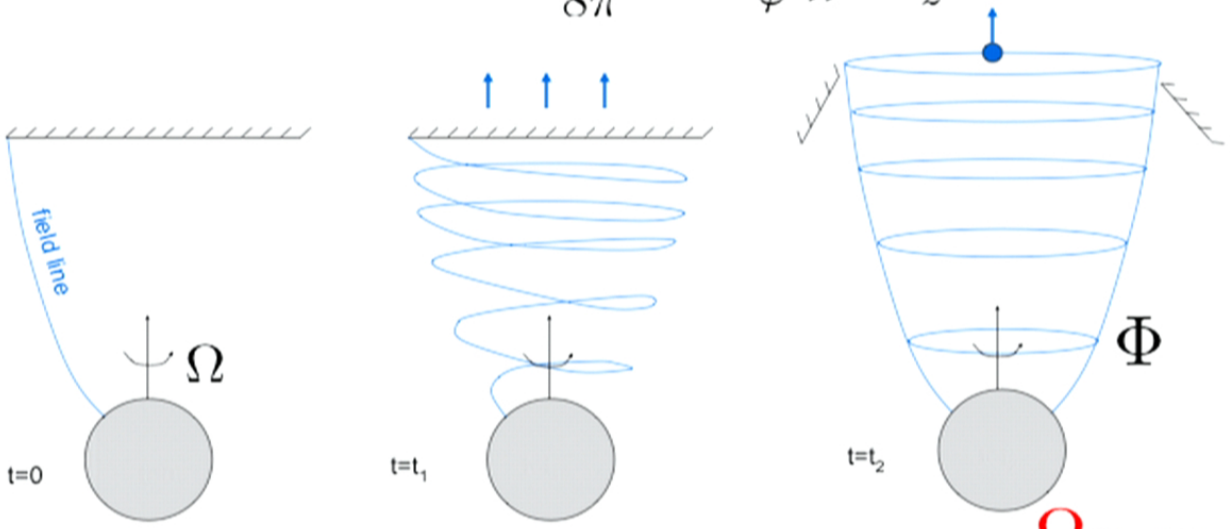
γ-rays, ν, cosmic rays

(Lyutikov 05, Giannios & Spruit 07, Bahcall & Mészáros 08, Broderick & Loeb 08, Beloborodov 09, Narayan, Kumar, AT 11, many others)

$$P = \frac{B_\varphi^2}{8\pi}$$

Field toroidally-dominated

$$B_\varphi \gg B_z$$



(Beskin & Nokhrina 06, AT+08,09,10, Komissarov 07-10, Lyubarsky 10, many others)

$$\Omega_{\rm H} = \frac{ac}{2r_{\rm H}}$$

What Sets BH Power?

- We understand well how BH power depends on Φ and $\Omega_{\rm H}$:

$$P_j = \frac{k}{c}\Phi^2\Omega_{\rm H}^2$$

(Blandford & Znajek 1977, Komissarov 2001, AT+ 2010, ApJ, 711, 50)

What Sets BH Power?

- We understand well how BH power depends on Φ and $\Omega_{\rm H}$:

$$P_j = \frac{k}{c}\Phi^2\Omega_{\rm H}^2$$

(Blandford & Znajek 1977, Komissarov 2001, AT+ 2010, ApJ, 711, 50)

What Sets BH Power?

- We understand well how BH power depends on Φ and $\Omega_{\rm H}$:

$$P_j = \frac{k}{c}\Phi^2\Omega_{\rm H}^2$$

(Blandford & Znajek 1977, Komissarov 2001, AT+ 2010, ApJ, 711, 50)

What Sets BH Power?

- We understand well how BH power depends on Φ and $\Omega_{\rm H}$:

$$P_j \propto \Phi^2 \Omega_{\rm H}^2$$

(Blandford & Znajek 1977, Komissarov 2001, AT+ 2010, ApJ, 711, 50)

What Sets BH Power?

- We understand well how BH power depends on Φ and $\Omega_{\rm H}$:

$$P_j \propto \Phi^2 \Omega_{\rm H}^2$$

$$p_j = \frac{P_j}{\dot{M}c^2} \propto \phi^2 \Omega_{\rm H}^2$$

(Blandford & Znajek 1977, Komissarov 2001, AT+ 2010, ApJ, 711, 50)

What Sets BH Power?

- We understand well how BH power depends on Φ and $\Omega_{\rm H}$:

$$P_j \propto \Phi^2 \Omega_{\rm H}^2$$

$$p_j = \frac{P_j}{\dot{M}c^2} \propto \phi^2 \Omega_{\rm H}^2$$

(Blandford & Znajek 1977, Komissarov 2001, AT+ 2010, ApJ, 711, 50)

What Sets BH Power?

- We understand well how BH power depends on Φ and $\Omega_{\rm H}$:

$$P_j \propto \Phi^2 \Omega_{\rm H}^2$$

$$p_j = \frac{P_j}{\dot{M}c^2} \propto \phi^2 \Omega_{\rm H}^2$$

(Blandford & Znajek 1977, Komissarov 2001, AT+ 2010, ApJ, 711, 50)

- GRMHD simulations give $p_j \lesssim 20\%$, even for nearly maximally spinning BHs

(McKinney 05, de Villiers+ 05, Hawley & Krolik 06, Barkov & Baushev 11)

What Sets BH Power?

- We understand well how BH power depends on Φ and $\Omega_{\rm H}$:

$$P_j \propto \Phi^2 \Omega_{\rm H}^2$$

$$p_j = \frac{P_j}{\dot{M}c^2} \propto \phi^2 \Omega_{\rm H}^2$$

(Blandford & Znajek 1977, Komissarov 2001, AT+ 2010, ApJ, 711, 50)

- GRMHD simulations give $p_j \lesssim 20\%$, even for nearly maximally spinning BHs

(McKinney 05, de Villiers+ 05, Hawley & Krolik 06, Barkov & Baushev 11)

- Observations: some AGN have $p_j \gtrsim 100\%$

(Rawlings & Saunders 91, Fernandes+ 10, Ghisellini+ 2010, Punsly 2011, McNamara+ 2011)

What Sets BH Power?

- We understand well how BH power depends on Φ and $\Omega_{\rm H}$:

$$P_j \propto \Phi^2 \Omega_{\rm H}^2$$

$$p_j = \frac{P_j}{\dot{M}c^2} \propto \phi^2 \Omega_{\rm H}^2$$

(Blandford & Znajek 1977, Komissarov 2001, AT+ 2010, ApJ, 711, 50)

- GRMHD simulations give $p_j \lesssim 20\%$, even for nearly maximally spinning BHs

(McKinney 05, de Villiers+ 05, Hawley & Krolik 06, Barkov & Baushev 11)

- Observations: some AGN have $p_j \gtrsim 100\%$

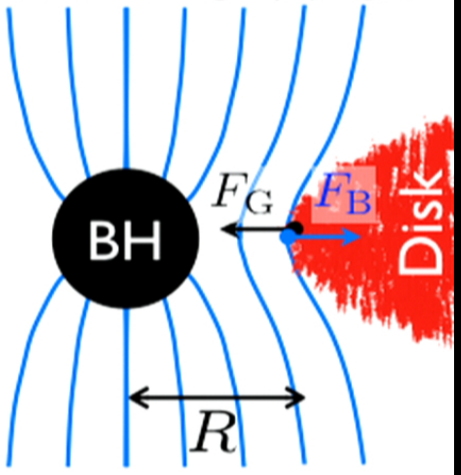
(Rawlings & Saunders 91, Fernandes+ 10, Ghisellini+ 2010, Punsly 2011, McNamara+ 2011)

- Are larger values of p_j even possible in nature?

There Must be Maximum Power

- Gravity limits BH B-field strength (Narayan+ 03):

$$F_{\rm B} \lesssim F_{\rm G}$$

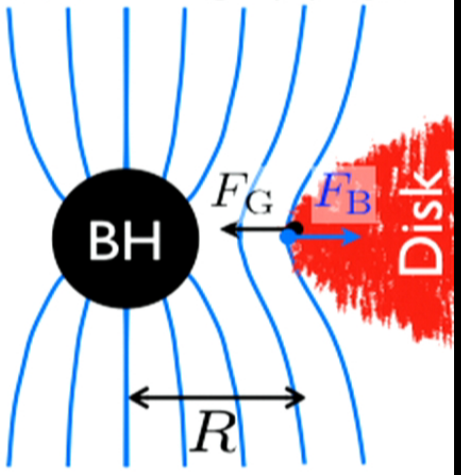


There Must be Maximum Power

- Gravity limits BH B-field strength (Narayan+ 03):

$$F_{\rm B} \lesssim F_{\rm G}$$

$$\frac{B^2}{8\pi} 4\pi R^2 \lesssim \frac{G M_{\rm BH} M_{\rm D}}{R^2}$$



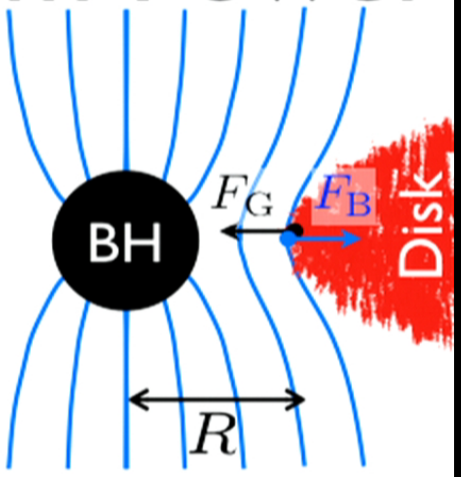
There Must be Maximum Power

- Gravity limits BH B-field strength (Narayan+ 03):

$$F_{\rm B} \lesssim F_{\rm G}$$

$$\frac{B^2}{8\pi} 4\pi R^2 \lesssim \frac{G M_{\rm BH} M_{\rm D}}{R^2}$$

$$B_{\rm max} \sim 10^4\,[{\rm G}] \left(\frac{L}{0.1 L_{\rm Edd}}\right)^{1/2} \left(\frac{M_{\rm BH}}{10^9 M_\odot}\right)^{-1/2}$$



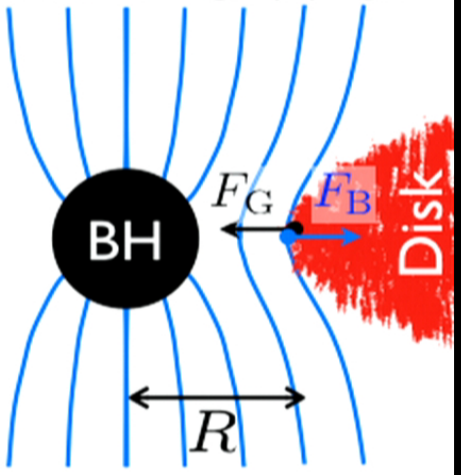
There Must be Maximum Power

- Gravity limits BH B-field strength (Narayan+ 03):

$$F_{\rm B} \lesssim F_{\rm G}$$

$$\frac{B^2}{8\pi} 4\pi R^2 \lesssim \frac{G M_{\rm BH} M_{\rm D}}{R^2}$$

$$B_{\rm max} \sim 10^4\,[{\rm G}] \left(\frac{L}{0.1 L_{\rm Edd}}\right)^{1/2} \left(\frac{M_{\rm BH}}{10^9 M_\odot}\right)^{-1/2}$$



- At $B \gtrsim B_{\rm max}$, a magnetically-arrested disk (MAD) forms:
  - Black hole magnetic flux and jet power are *maximum*
  - B-field is as strong as gravity

(Bisnovatyi-Kogan & Ruzmaikin 74, 76, Igumenshchev+ 03, Narayan+ 03, AT+ 11, AT & McKinney 12a,b, McKinney, AT, Blandford 12)

- How do we get a MAD? Flood the black hole with magnetic flux

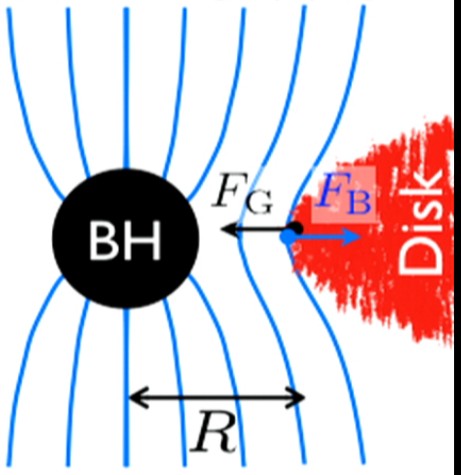
There Must be Maximum Power

- Gravity limits BH B-field strength (Narayan+ 03):

$$F_{\rm B} \lesssim F_{\rm G}$$

$$\frac{B^2}{8\pi} 4\pi R^2 \lesssim \frac{G M_{\rm BH} M_{\rm D}}{R^2}$$

$$B_{\rm max} \sim 10^4\,[{\rm G}] \left(\frac{L}{0.1 L_{\rm Edd}}\right)^{1/2} \left(\frac{M_{\rm BH}}{10^9 M_\odot}\right)^{-1/2}$$

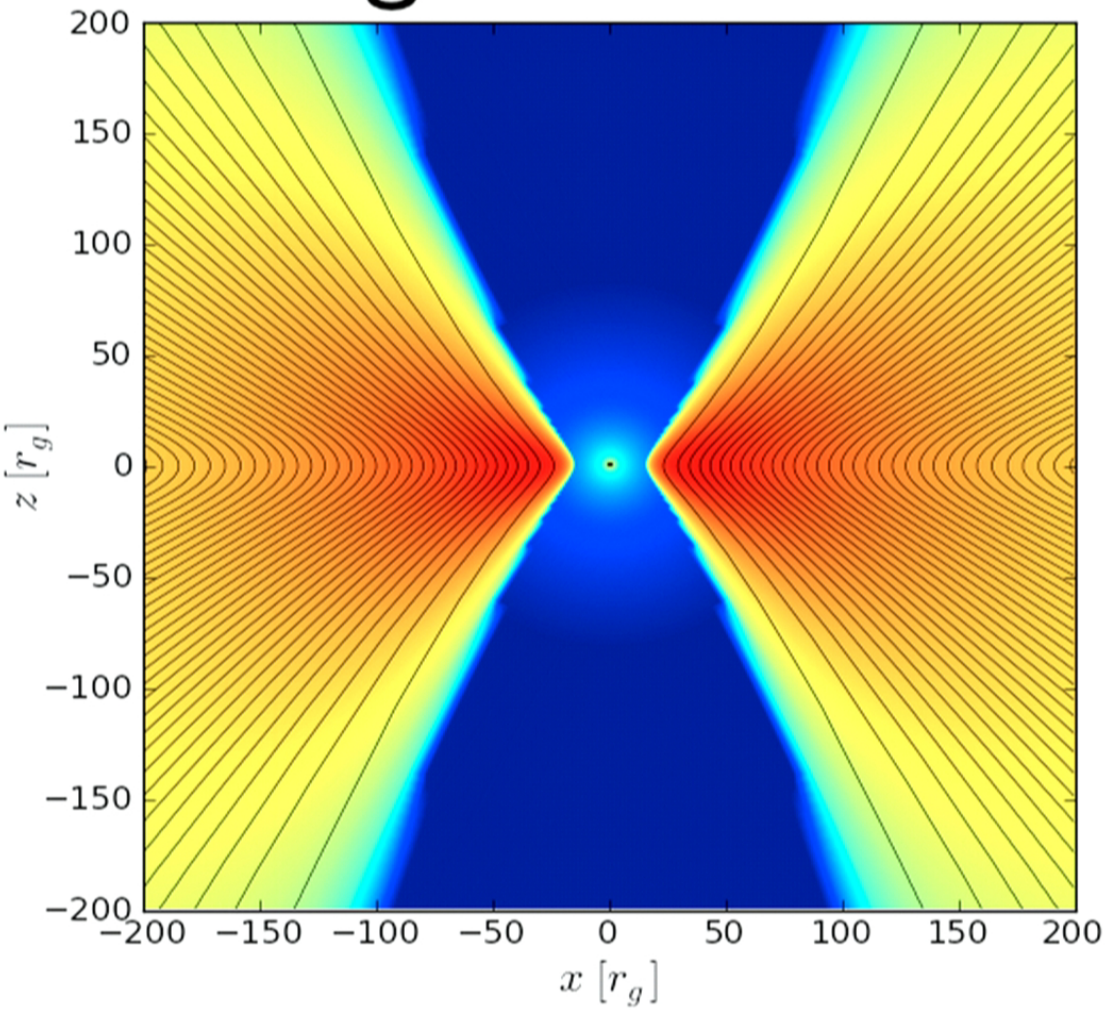


- At $B \gtrsim B_{\rm max}$, a magnetically-arrested disk (MAD) forms:
  - Black hole magnetic flux and jet power are *maximum*
  - B-field is as strong as gravity

(Bisnovatyi-Kogan & Ruzmaikin 74, 76, Igumenshchev+ 03, Narayan+ 03, AT+ 11, AT & McKinney 12a,b, McKinney, AT, Blandford 12)

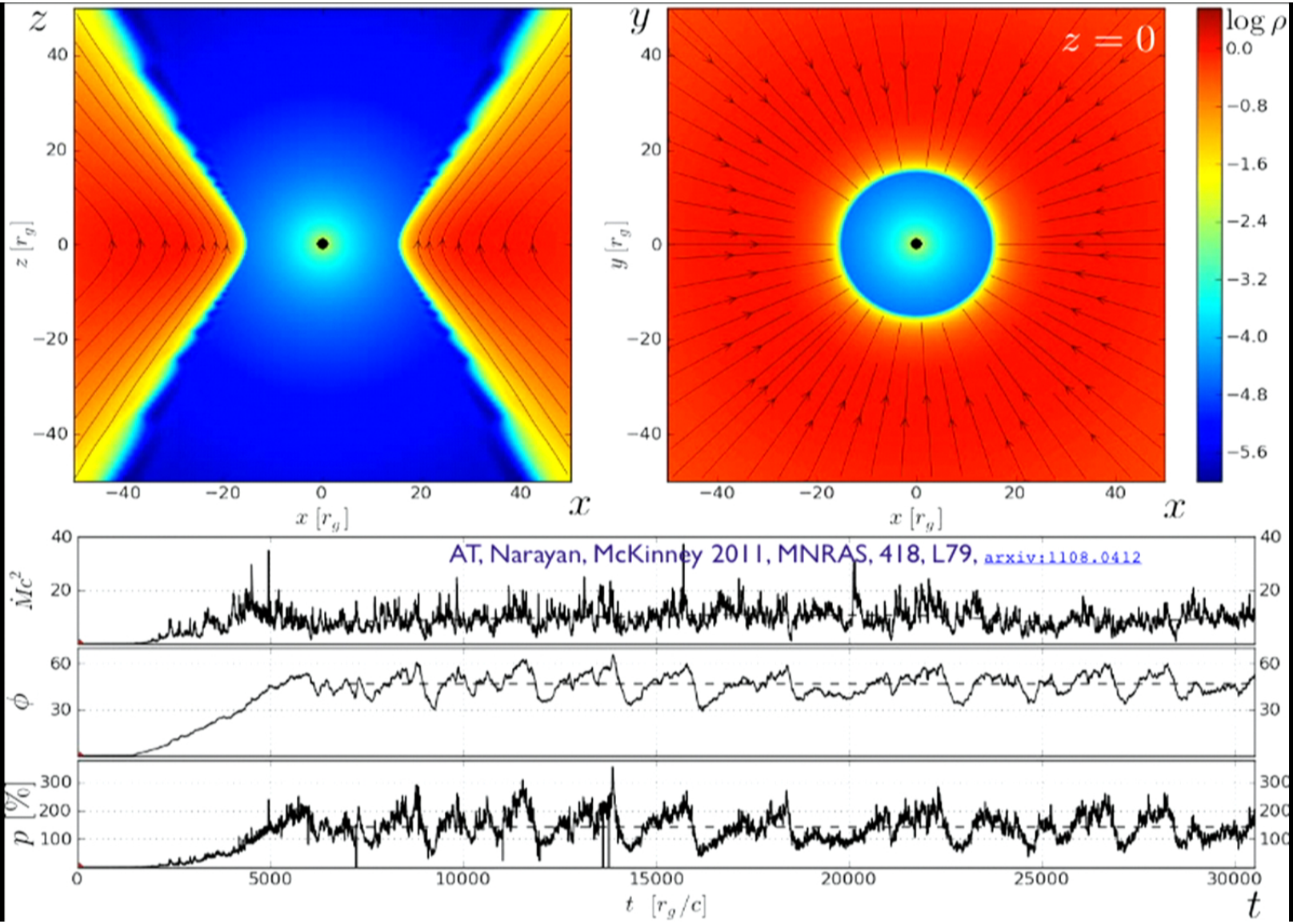
- How do we get a MAD? Flood the black hole with magnetic flux
- Numerical experiments via advanced 3D *GRMHD* simulations with the HARM code (Gammie+03, AT+07, McKinney & Blandford 09): took over 10^3 CPU-years!
- New physics: high jet power and new MAD mode of accretion in which the magnetorotational instability (MRI, Balbus & Hawley 91) is marginally suppressed

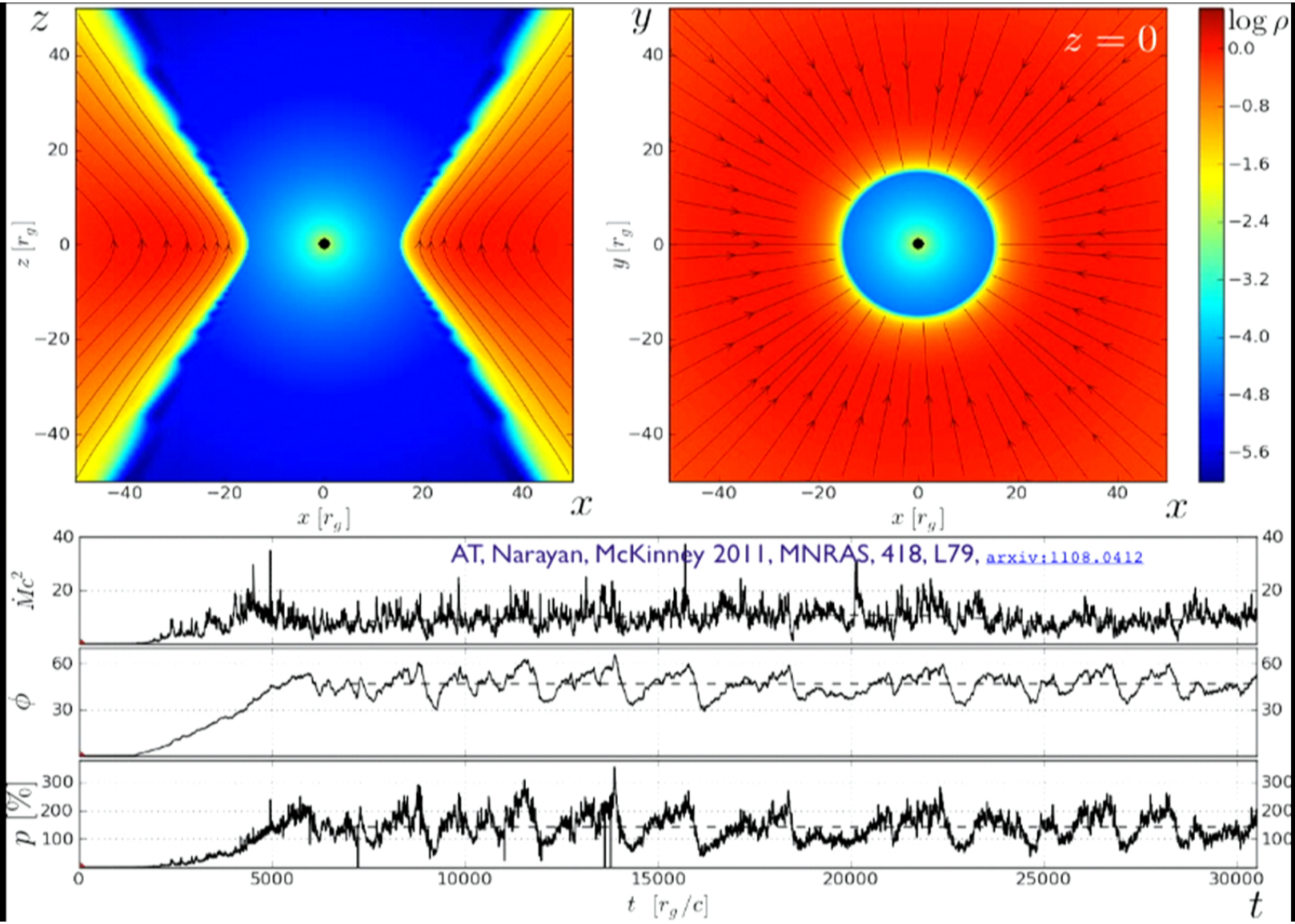
Much Larger Flux than Before

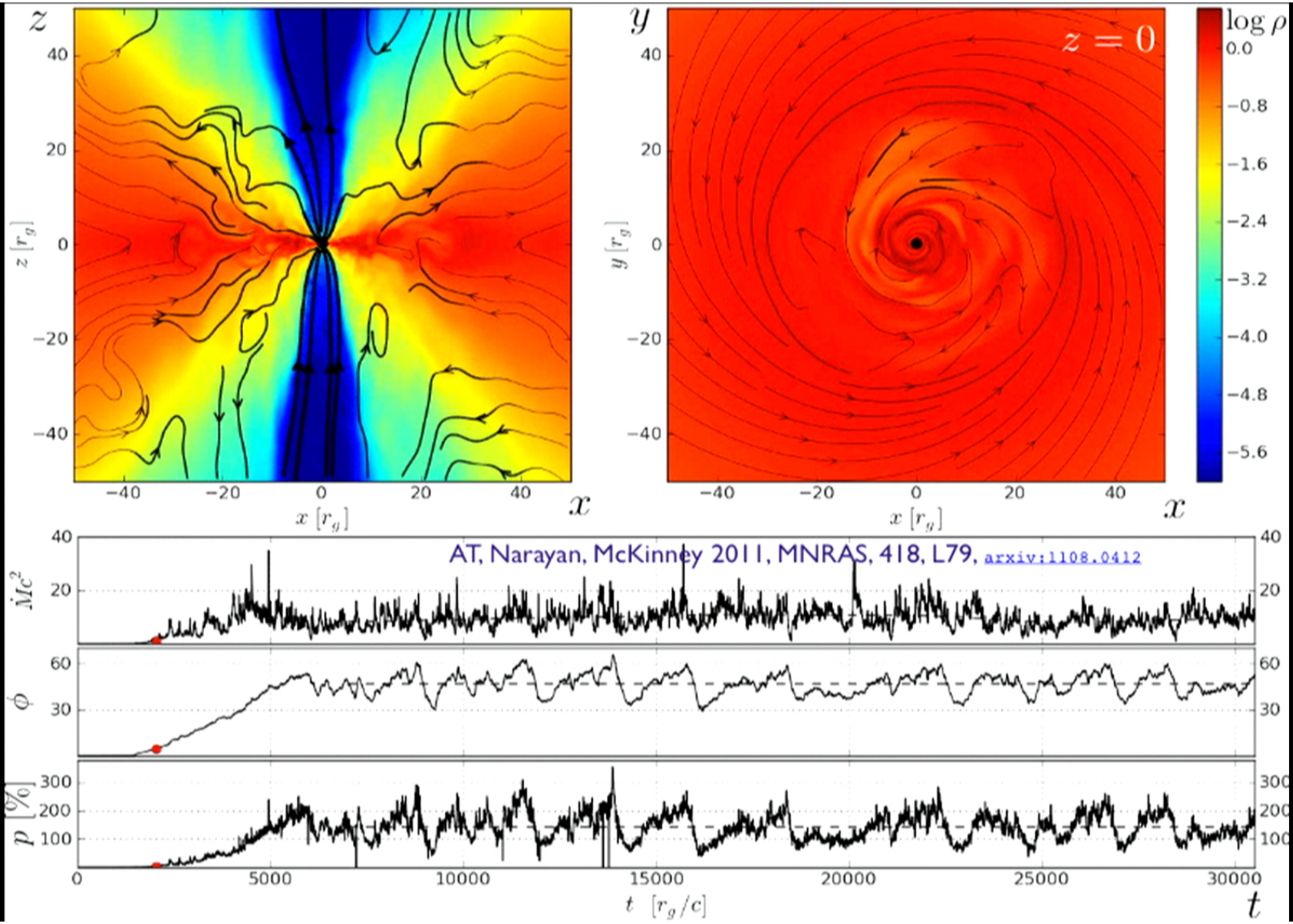


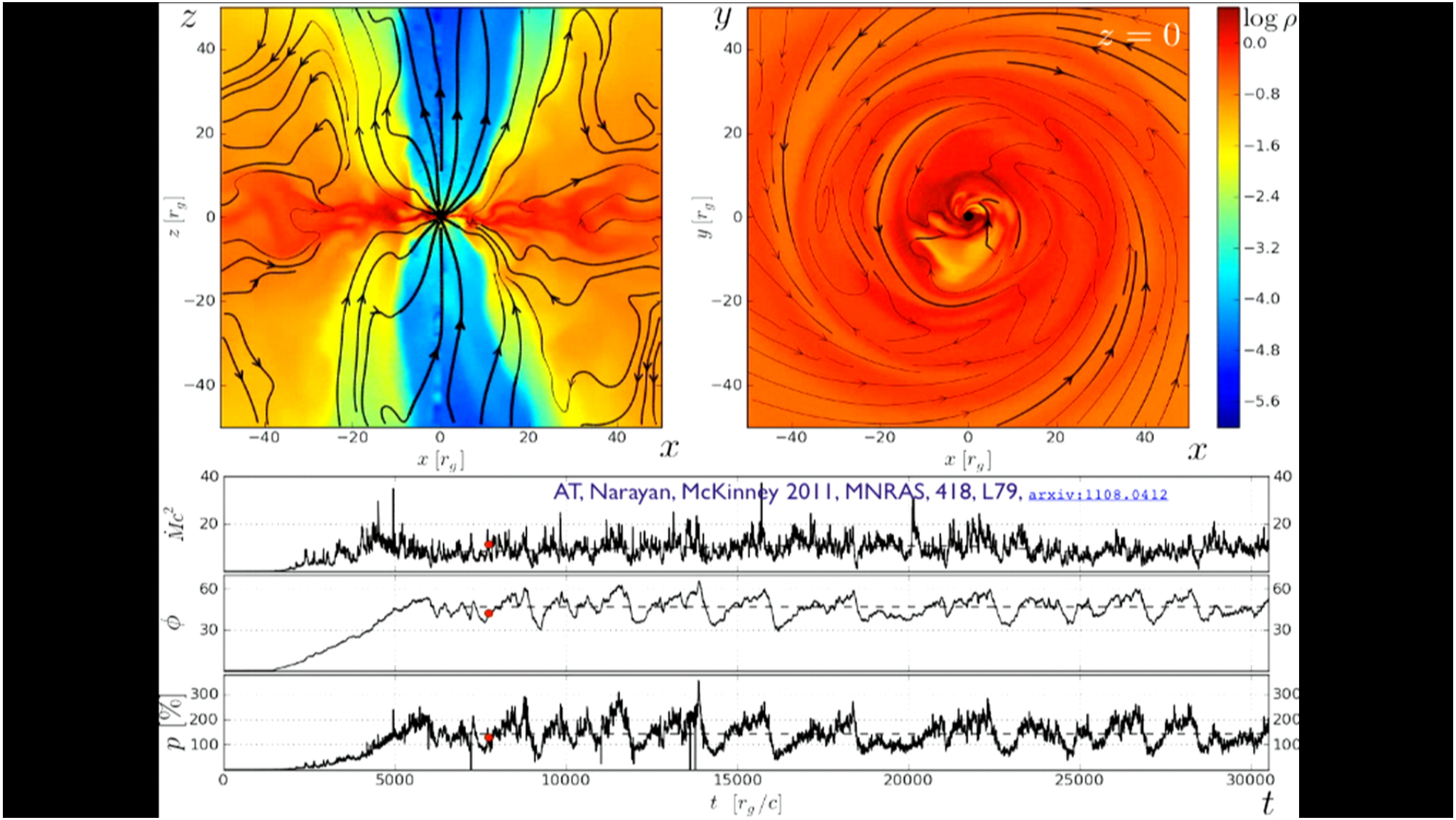
Our grid extends out to $10^5 r_g$

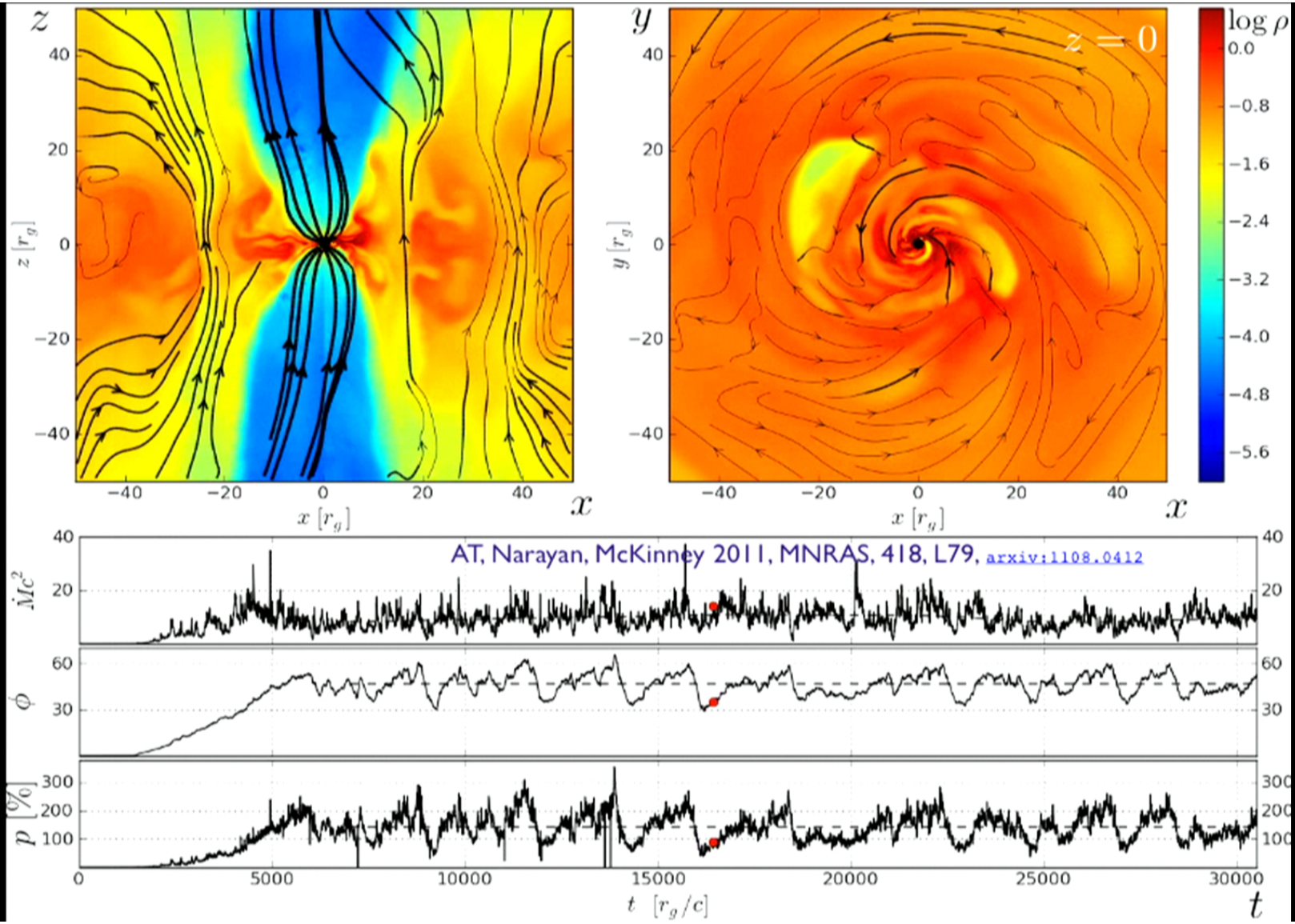
AT, Narayan, McKinney 2011, MNRAS, 478, L79


z
y
$z = 0$
$\log \rho$
0.0
−0.8
−1.6
−2.4
−3.2
−4.0
−4.8
−5.6
$z\ [r_g]$
$y\ [r_g]$
$x\ [r_g]$
x
AT, Narayan, McKinney 2011, MNRAS, 418, L79, arxiv:1108.0412
$\dot{M}c^2$
ϕ
$p\ [\%]$
$t\ \ [r_g/c]$
t


z
y
$z = 0$
$\log \rho$
0.0
−0.8
−1.6
−2.4
−3.2
−4.0
−4.8
−5.6
$z\ [r_g]$
$y\ [r_g]$
$x\ [r_g]$
x
AT, Narayan, McKinney 2011, MNRAS, 418, L79, arxiv:1108.0412
$\dot{M}c^2$
ϕ
$p\ [\%]$
$t\ \ [r_g/c]$
t

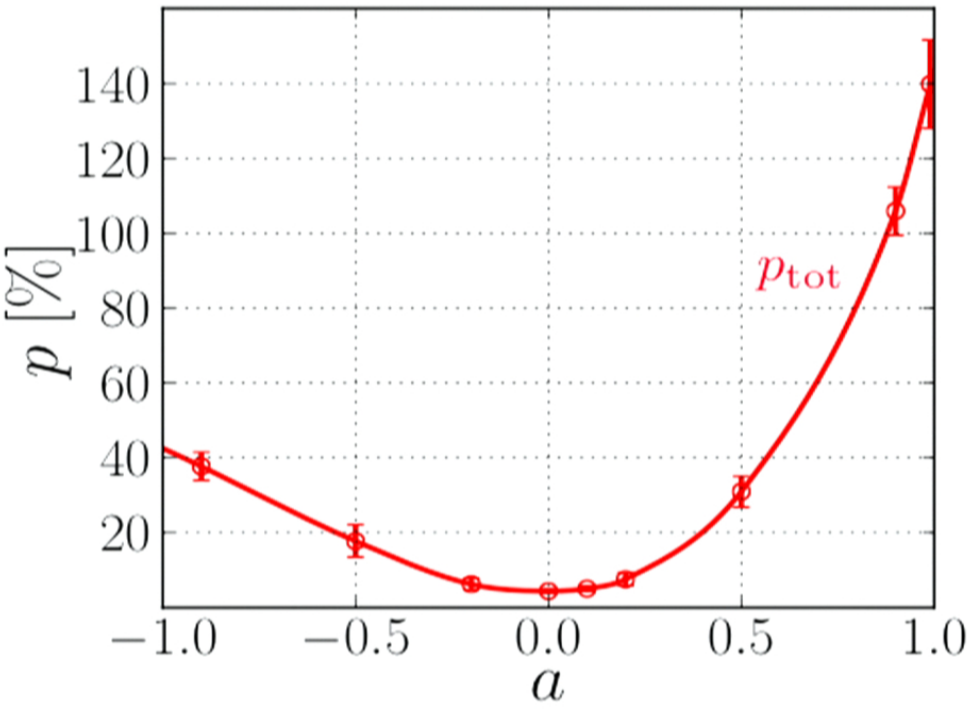

z
y
$z = 0$
$\log \rho$
0.0
−0.8
−1.6
−2.4
−3.2
−4.0
−4.8
−5.6
$z\ [r_g]$
$y\ [r_g]$
$x\ [r_g]$
x
AT, Narayan, McKinney 2011, MNRAS, 418, L79, arxiv:1108.0412
$\dot{M}c^2$
ϕ
$p\ [\%]$
$t\ [r_g/c]$
t


z
y
$z = 0$
$\log \rho$
0.0
−0.8
−1.6
−2.4
−3.2
−4.0
−4.8
−5.6
$z\ [r_g]$
$y\ [r_g]$
$x\ [r_g]$
x
AT, Narayan, McKinney 2011, MNRAS, 418, L79, arxiv:1108.0412
$\dot{M}c^2$
ϕ
$p\ [\%]$
$t\ [r_g/c]$
t


z
y
$z = 0$
log ρ
0.0
−0.8
−1.6
−2.4
−3.2
−4.0
−4.8
−5.6
x [r_g]
z [r_g]
y [r_g]
x
AT, Narayan, McKinney 2011, MNRAS, 418, L79, arxiv:1108.0412
$\dot{M}c^2$
ϕ
p [%]
t [r_g/c]
t

Maximum Jet Power vs. Spin ($h/r \sim 0.3$)

tilted1 2

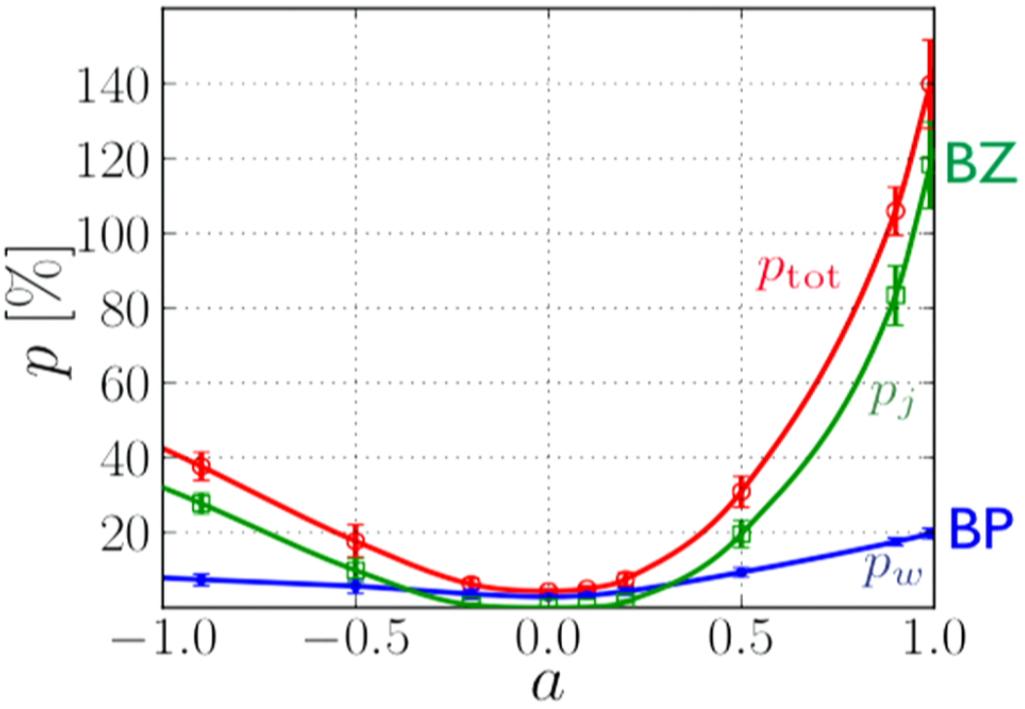


(AT, McKinney 2012a, MNRAS, 423, 55; 2013b, in prep.)

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

Maximum Jet Power vs. Spin ($h/r \sim 0.3$)

tilted1 2



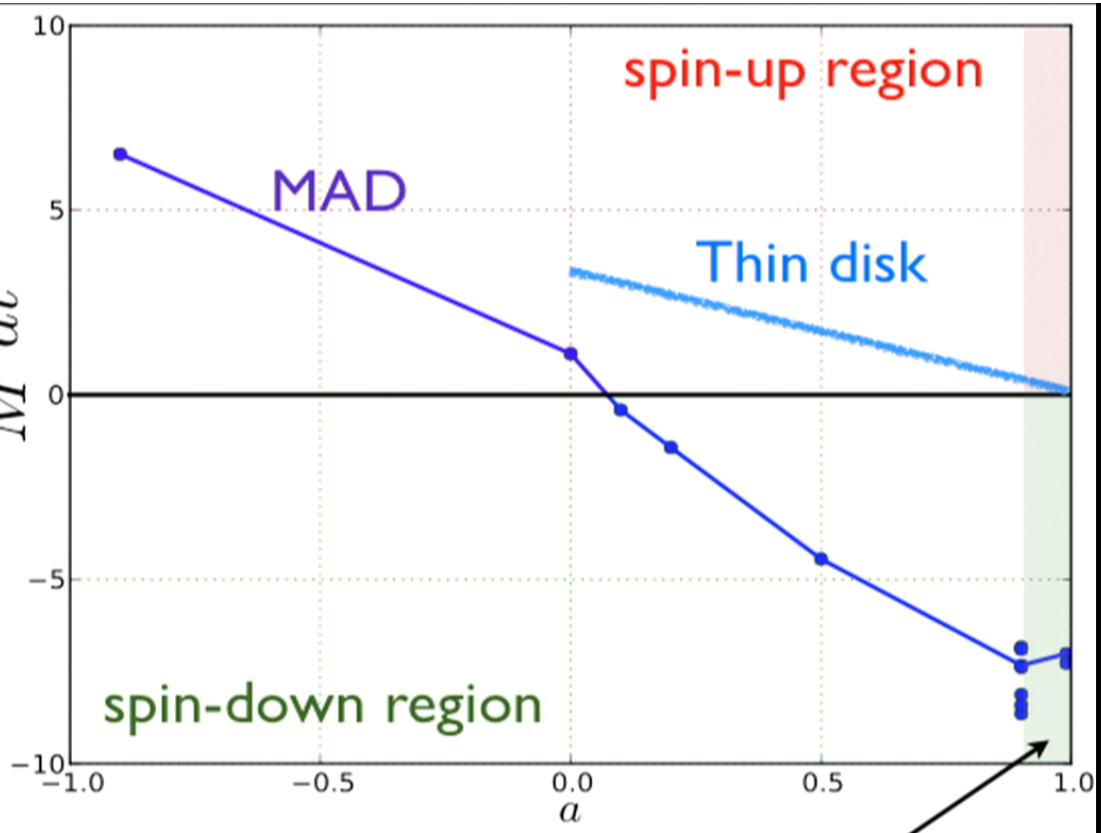
(AT, McKinney 2012a, MNRAS, 423, 55; 2013b, in prep.)

At high spin, most of the power comes from black hole spin (BZ effect).

Our MADs slow BHs down to a halt

tilted1_2

$$s \equiv \frac{M\,da}{\dot{M}\,dt}$$



(AT, McKinney 2012a, MNRAS, 423, 55; 2013b, in prep.)

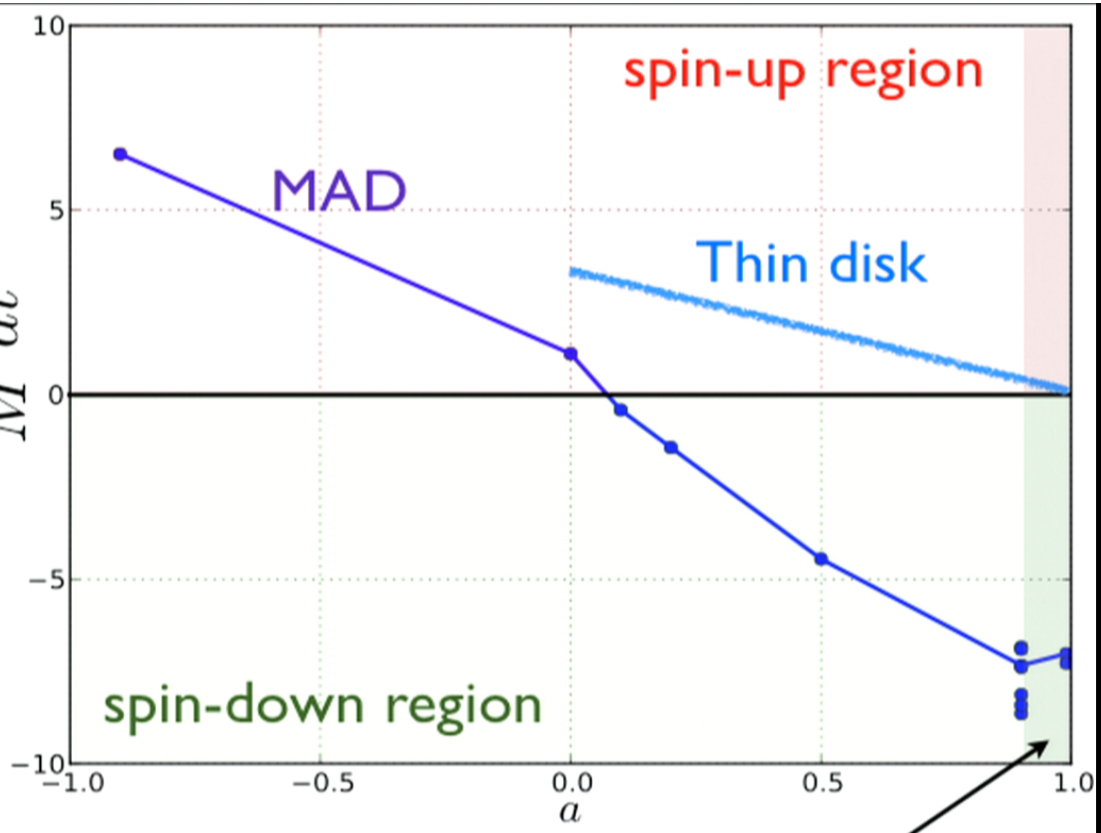
Conventional spin equilibrium region, $a \gtrsim 0.9$

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

Our MADs slow BHs down to a halt

tilted1_2

$$s \equiv \frac{M\,da}{\dot{M}\,dt}$$



(AT, McKinney 2012a, MNRAS, 423, 55; 2013b, in prep.)

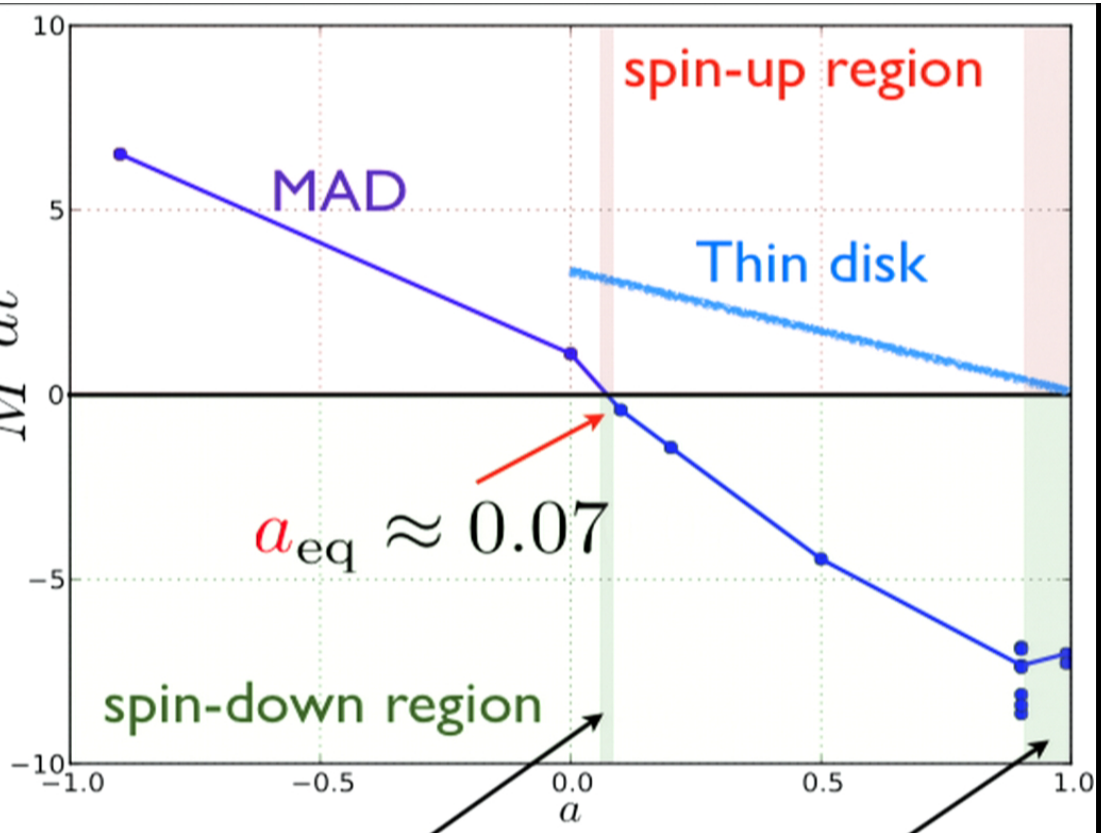
Conventional spin equilibrium region, $a \gtrsim 0.9$

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

Our MADs slow BHs down to a halt

tilted1_2

$$s \equiv \frac{M\,da}{\dot{M}\,dt}$$

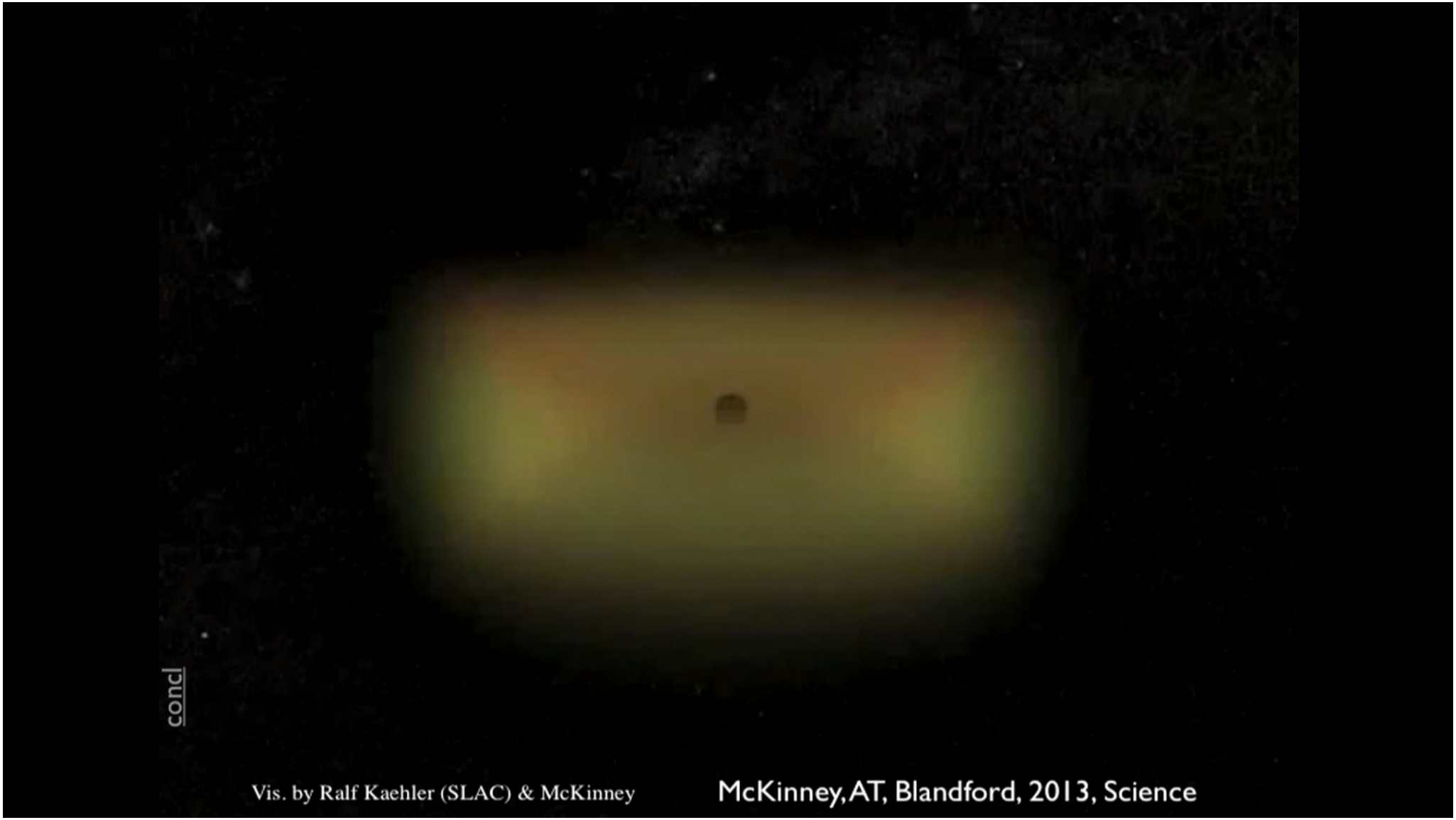


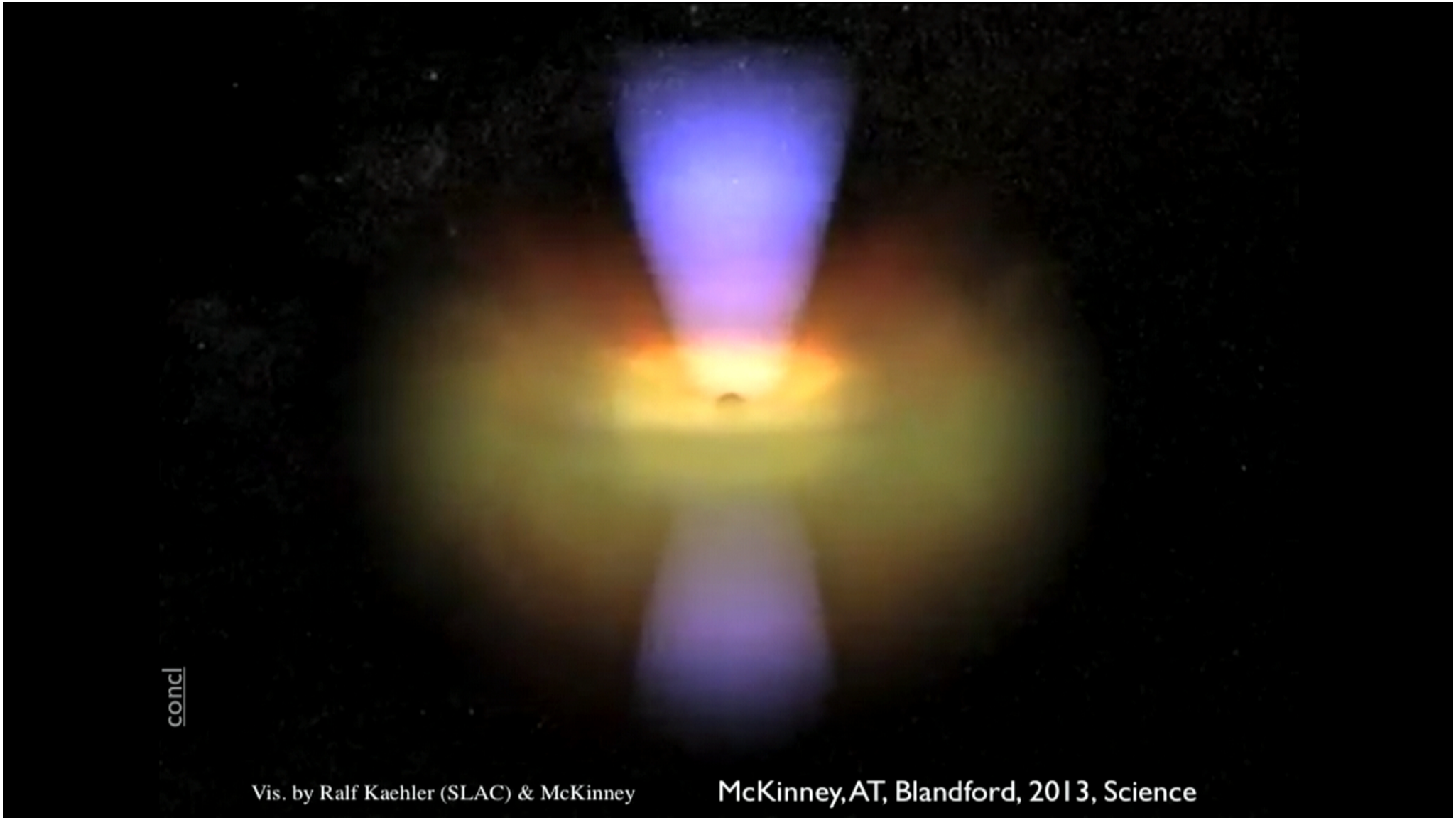
(AT, McKinney 2012a, MNRAS, 423, 55; 2013b, in prep.)

Radio-Quiet AGN?

Conventional spin equilibrium region, $a \gtrsim 0.9$

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


concl
Vis. by Ralf Kaehler (SLAC) & McKinney
McKinney, AT, Blandford, 2013, Science


concl
Vis. by Ralf Kaehler (SLAC) & McKinney
McKinney, AT, Blandford, 2013, Science

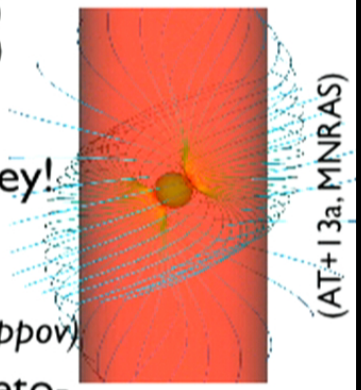
MAD Summary

- Central accumulation of large-scale magnetic flux saturates black holes with flux and leads to MADs

MAD Summary

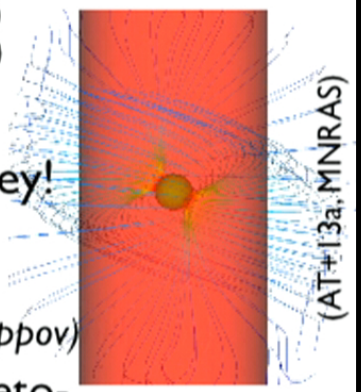
- Central accumulation of large-scale magnetic flux saturates black holes with flux and leads to MADs

Future Directions: 1/3



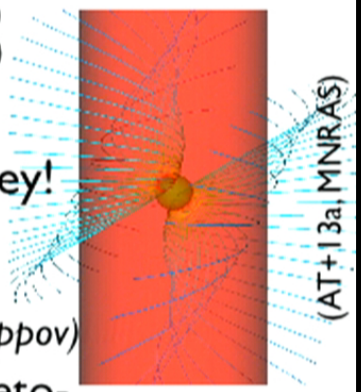
- This is only the beginning of an exciting, fully 3D journey!
- Not only to *black holes* but also *neutron stars:*
  - neutron star magnetospheres *(alignment torques, w/Sasha Philippov)*
  - neutron star accretion, boundary layers, jets, binary magneto-sphere interactions, electromagnetic counterparts to gravitational waves

Future Directions: 1/3



- This is only the beginning of an exciting, fully 3D journey!
- Not only to *black holes* but also *neutron stars:*
  - neutron star magnetospheres *(alignment torques, w/Sasha Philippov)*
  - neutron star accretion, boundary layers, jets, binary magneto-sphere interactions, electromagnetic counterparts to gravitational waves

Future Directions: 1/3



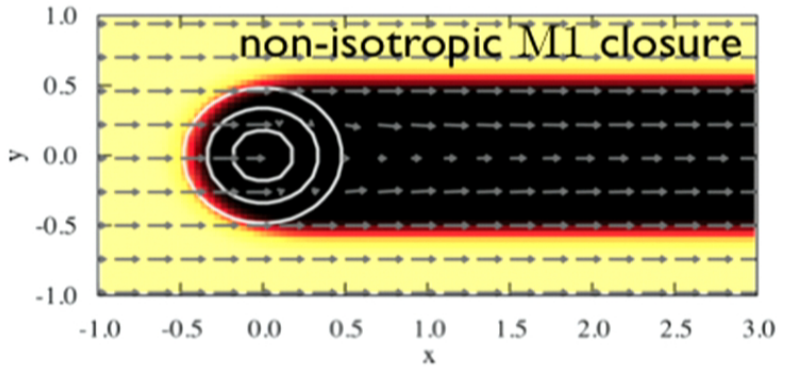
- This is only the beginning of an exciting, fully 3D journey!
- Not only to *black holes* but also *neutron stars:*
  - neutron star magnetospheres *(alignment torques, w/Sasha Philippov)*
  - neutron star accretion, boundary layers, jets, binary magneto-sphere interactions, electromagnetic counterparts to gravitational waves
- Jet propagation/stability in, e.g., active galactic nuclei and core collapse gamma-ray bursts
- Long-standing problem of the origin of large-scale magnetic flux:

Future Directions: 2/3

- Utilize GPUs to attack some of the most ambitious projects, e.g., solve the grand problem of connecting near-black-hole solution to large (feeding) scales
- Implement *radiation* into HARM based on the Koral *radiation GR hydro* code (Sadowski, Narayan, AT, Zhu, 13)

Future Directions: 2/3

- Utilize GPUs to attack some of the most ambitious projects, e.g., solve the grand problem of connecting near-black-hole solution to large (feeding) scales
- Implement *radiation* into HARM based on the Koral *radiation GR* hydro code (Sadowski, Narayan, AT, Zhu, 13)
  - Koral uses M1 radiation moments closure that allows non-isotropic photon distribution in the fluid frame
  - Implementation of radiation into HARM is ongoing *(w/Jon McKinney, Olek Sadowski)*

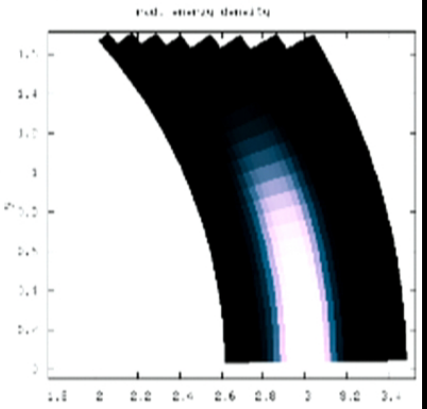


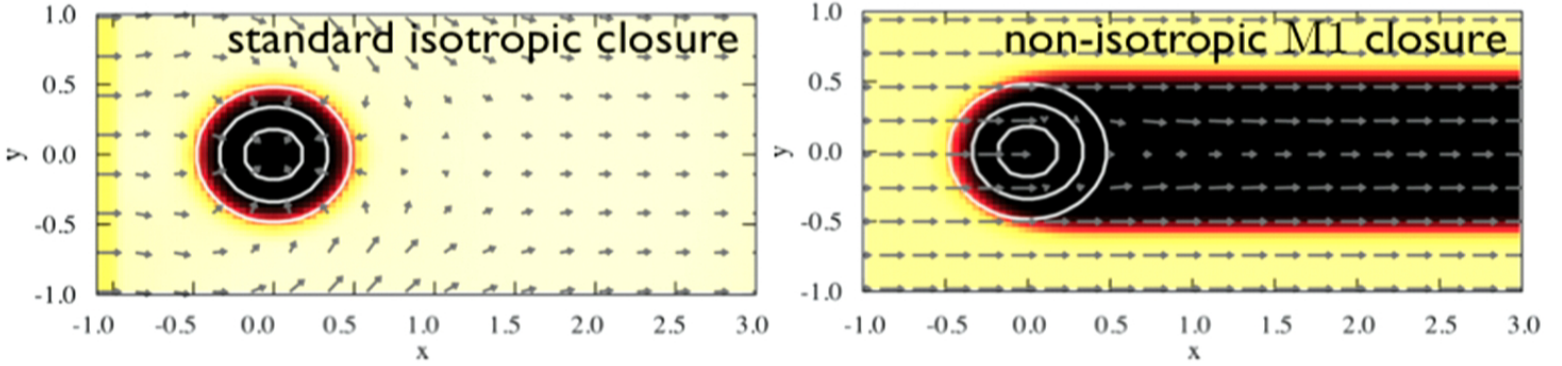
(Sadowski, Narayan, AT, Zhu, 13)

Future Directions: 2/3

- Utilize GPUs to attack some of the most ambitious projects, e.g., solve the grand problem of connecting near-black-hole solution to large (feeding) scales

- Implement *radiation* into HARM based on the Koral *radiation GR hydro* code (Sadowski, Narayan, AT, Zhu, 13)
  - Koral uses M1 radiation moments closure that allows non-isotropic photon distribution in the fluid frame
  - Implementation of radiation into HARM is ongoing *(w/Jon McKinney, Olek Sadowski)*





(Sadowski, Narayan, AT, Zhu, 13)

Future Directions: 3/3

With *radiation*-HARM, I will attack long-standing theoretical and observational problems, e.g.:

Future Directions: 3/3

With *radiation*-HARM, I will attack long-standing theoretical and observational problems, e.g.:

- By how much can accretion luminosity exceed the Eddington limit?