GR MHD Simulations of Black Hole Accretion

Dr. P. Chris Fragile
College of Charleston, SC

Collaborators:
Peter Anninos (LLNL), Jay Salmonson (LLNL), Omer Blaes (UCSB), David Meier (JPL), Sera Markoff (Amsterdam), Chris Done (Durham), Jason Dexter (Washington)

Students:
Anna Gillespie, Marco Rodriguez, Julia Wilson, Shikha Chaurasia

ITN 215212: Black Hole Universe

Solid Theoretical Foundation

- Shakura & Sunyaev (1973)/ Novikov & Thorne (1973)
  - thin-disk model
  - thermal spectrum
  - nearly Keplerian profile
  - disk truncates at the ISCO
  - very small radial infall velocity
  - source of angular momentum transport unspecified

$$t_{\phi R} = \alpha P$$

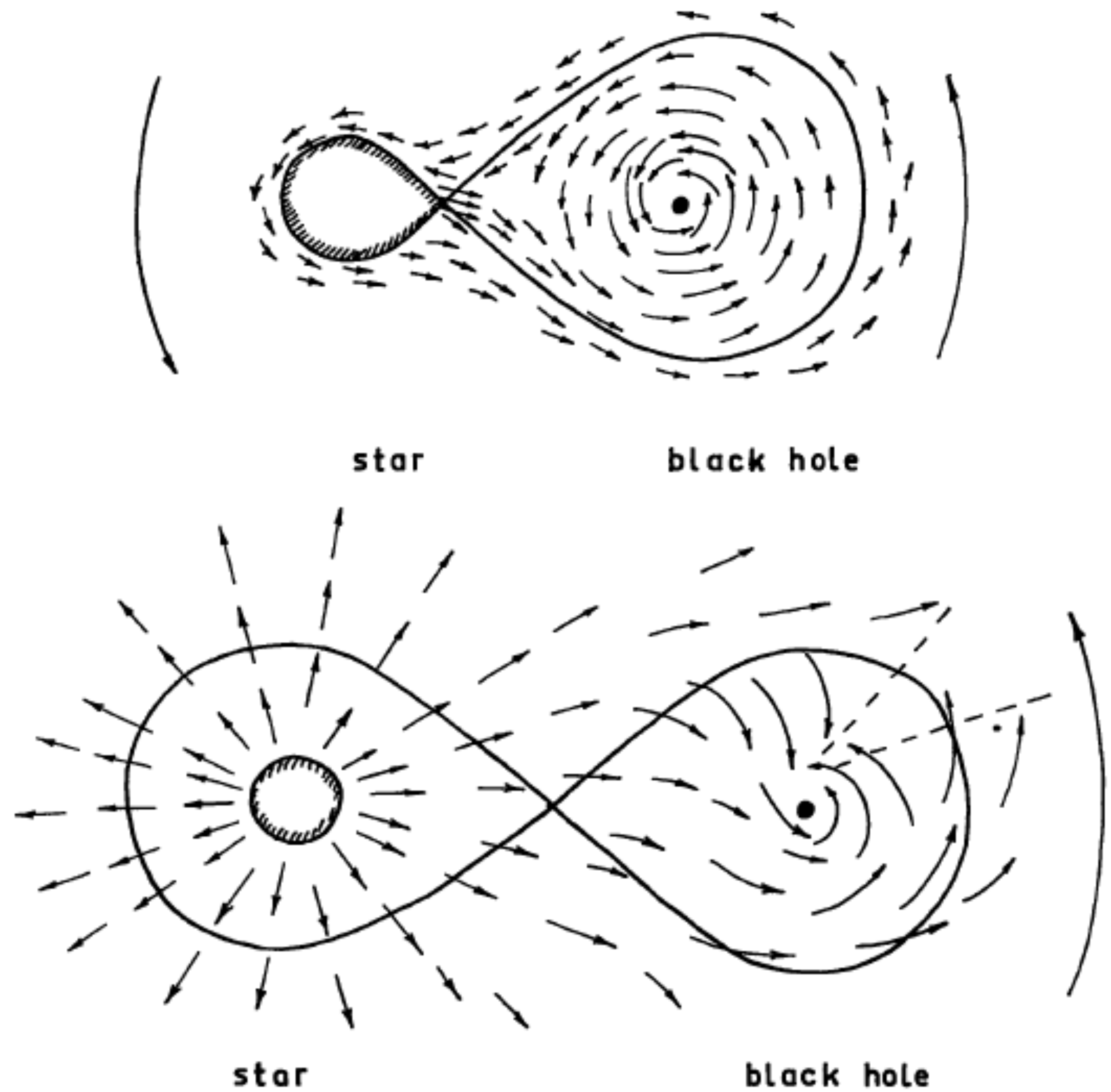
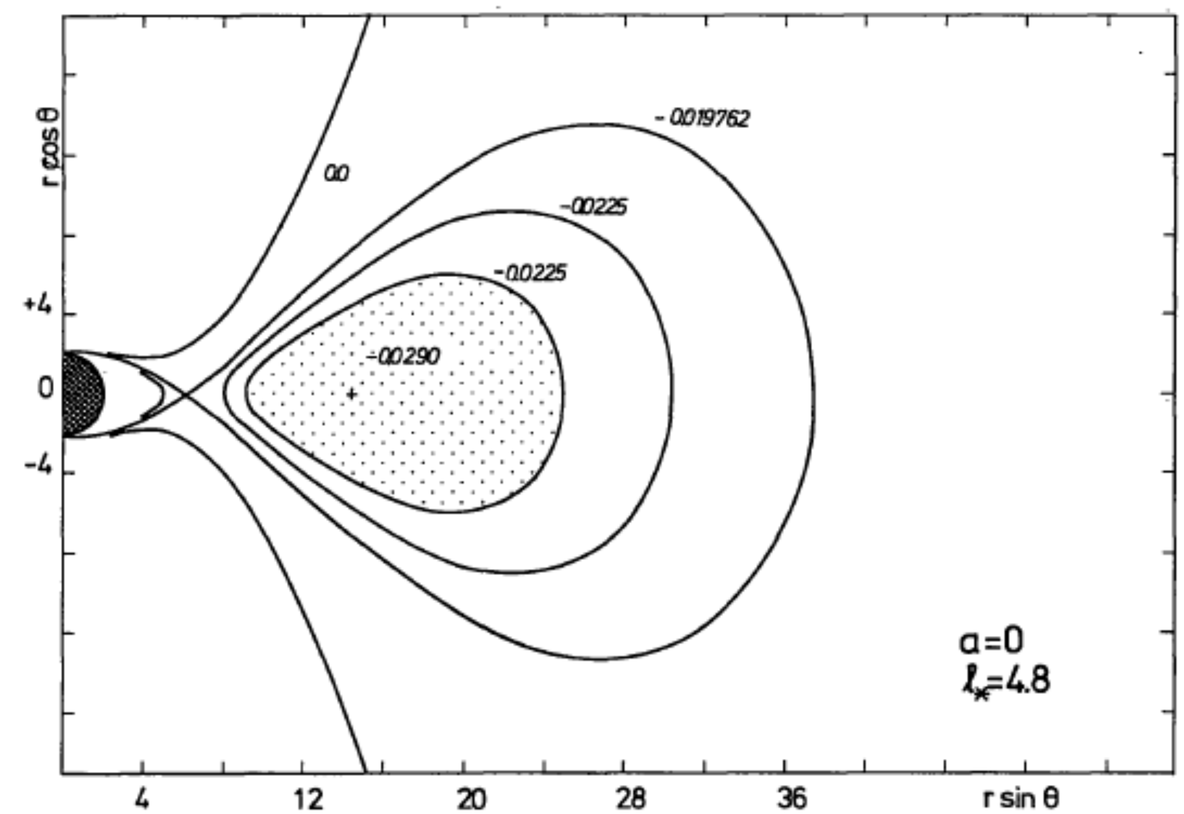
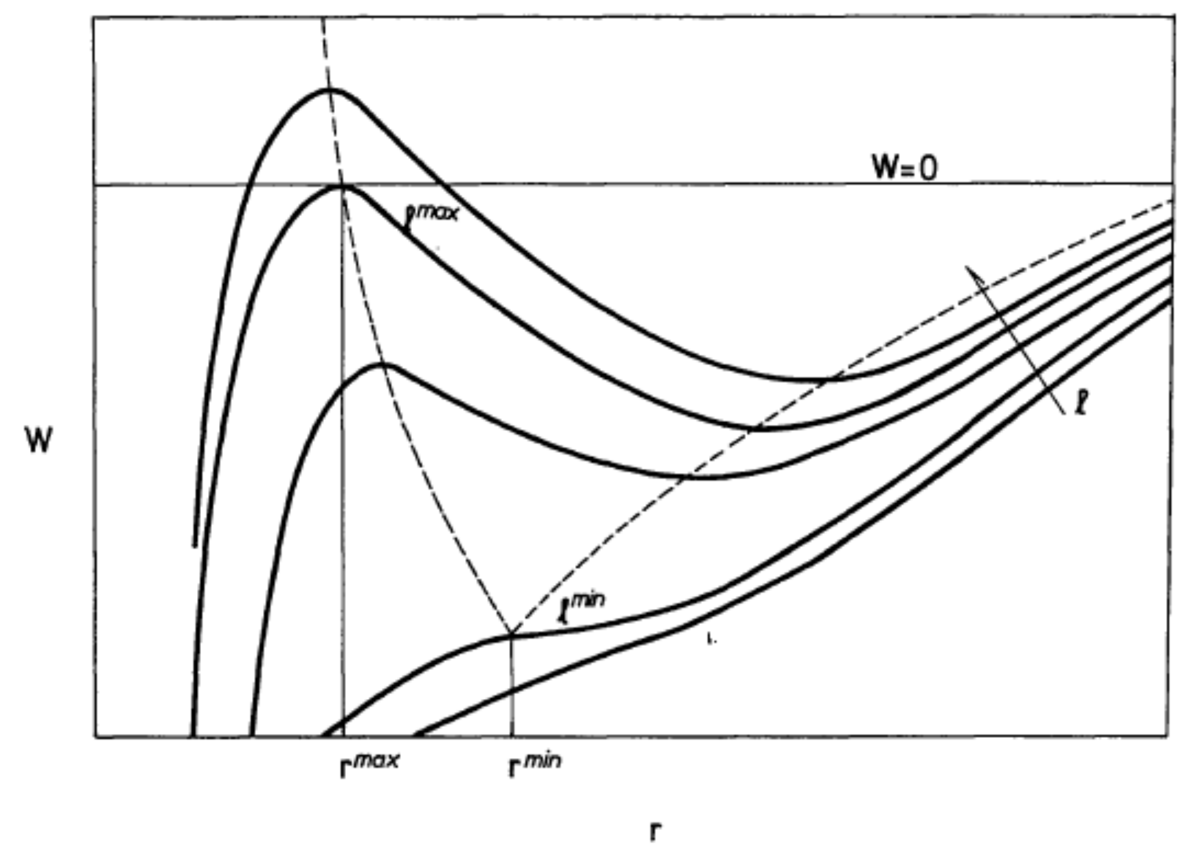


Fig. 1. Two regimes of matter capture by a collapsar: a) a normal companion fills up its Roche lobe, and the outflow goes, in the main, through the inner lagrangian point; b) the companion's size is much less than Roche lobe the outflow is connected with a stellar wind. The matter loses part of its kinetic energy in the shock wave and thereafter, gravitational capture of accreting matter becomes possible

Solid Theoretical Foundation

- “Polish doughnut”
  - “thick-disk” or “fluid torus”
  - Paczyński, Abramowicz et al. (1978)
  - Disk fills equipotential surfaces
  - Cusp in equipotential due to relativity
  - Unlike Shakura-Sunyaev disk,
    - no angular momentum transport
    - “disk” may penetrate inside ISCO
    - non-Keplerian
    - radial pressure gradients



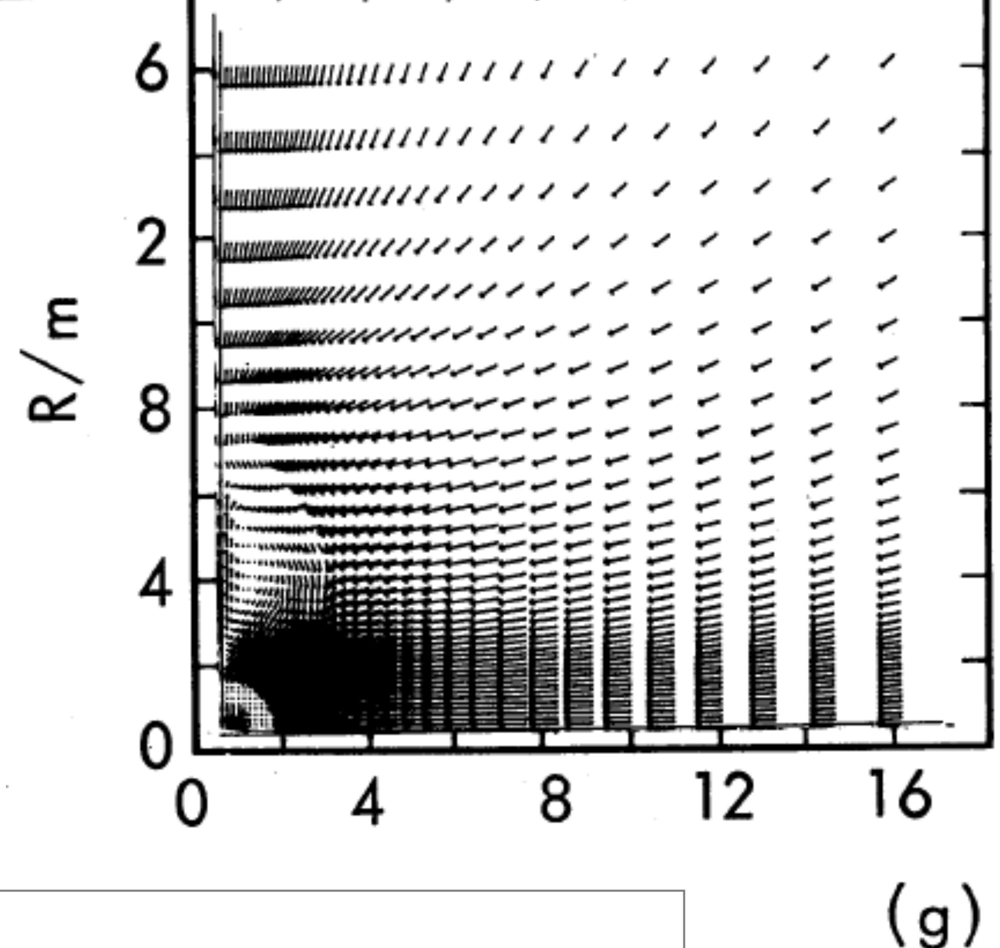


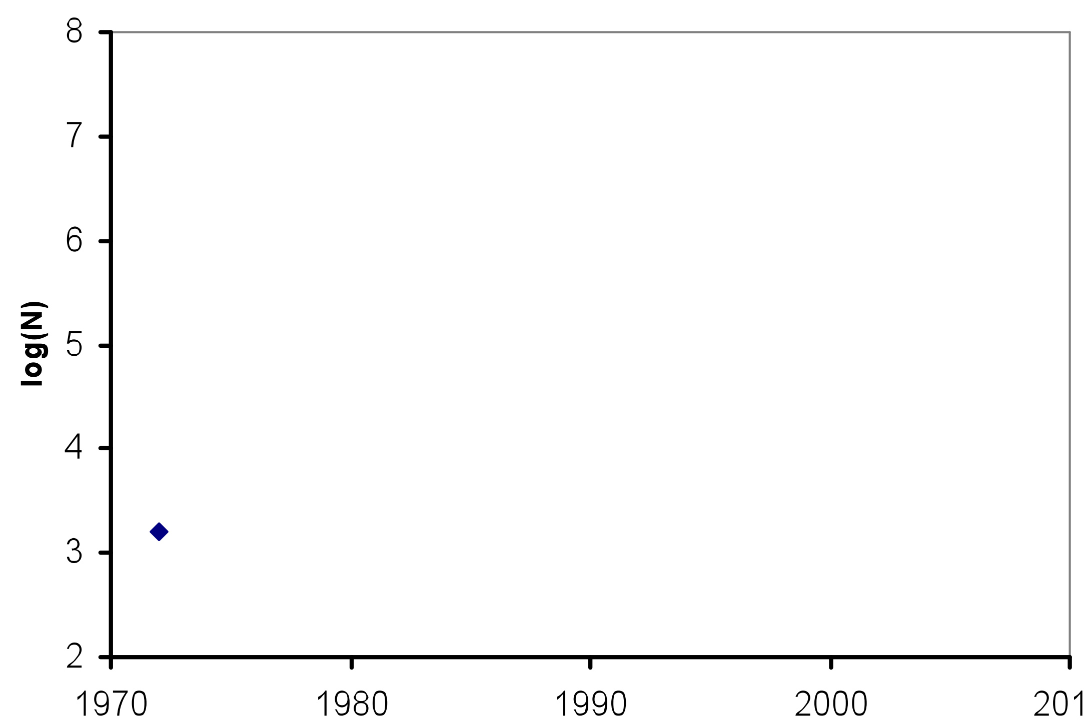
Pioneering numerical work

NUMERICAL STUDY OF FLUID FLOW IN A KERR SPACE*

JAMES R. WILSON
Lawrence Radiation Laboratory, University of California, Livermore
Received 1971 July 12; revised 1971 November 12

James R. Wilson
1922-2007





1980s Rebirth of numerical work

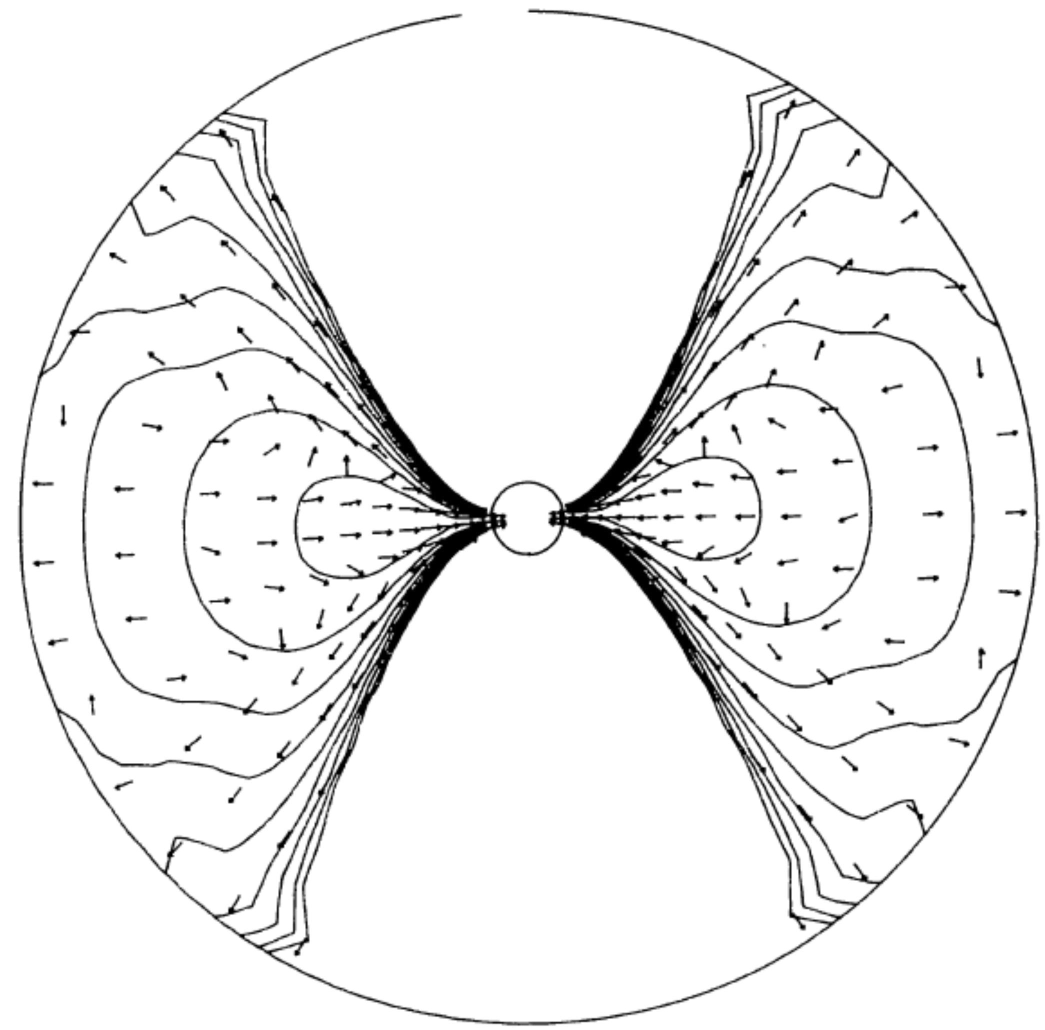
A NUMERICAL STUDY OF NONSPHERICAL BLACK HOLE ACCRETION.
I. EQUATIONS AND TEST PROBLEMS

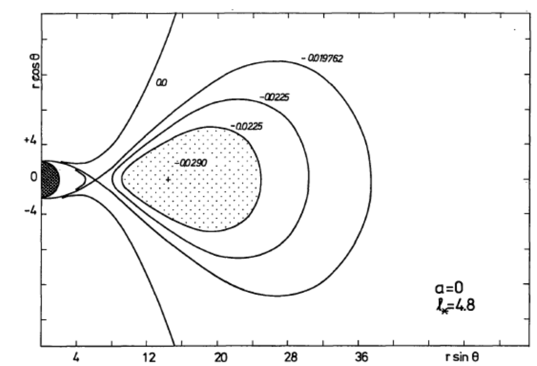
JOHN F. HAWLEY AND LARRY L. SMARR[1]
Department of Astronomy, University of Illinois

AND

JAMES R. WILSON
Lawrence Livermore National Laboratory

Received 1983 April 22; accepted 1983 June 20





1980s Rebirth of numerical work

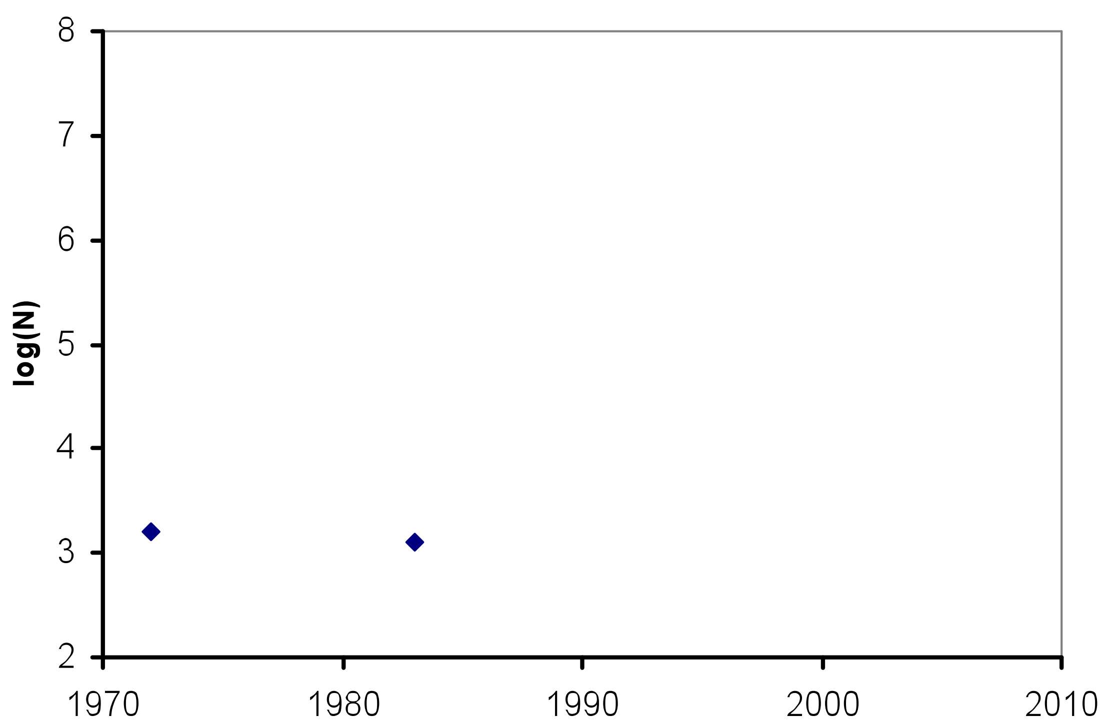
A NUMERICAL STUDY OF NONSPHERICAL BLACK HOLE ACCRETION.
I. EQUATIONS AND TEST PROBLEMS

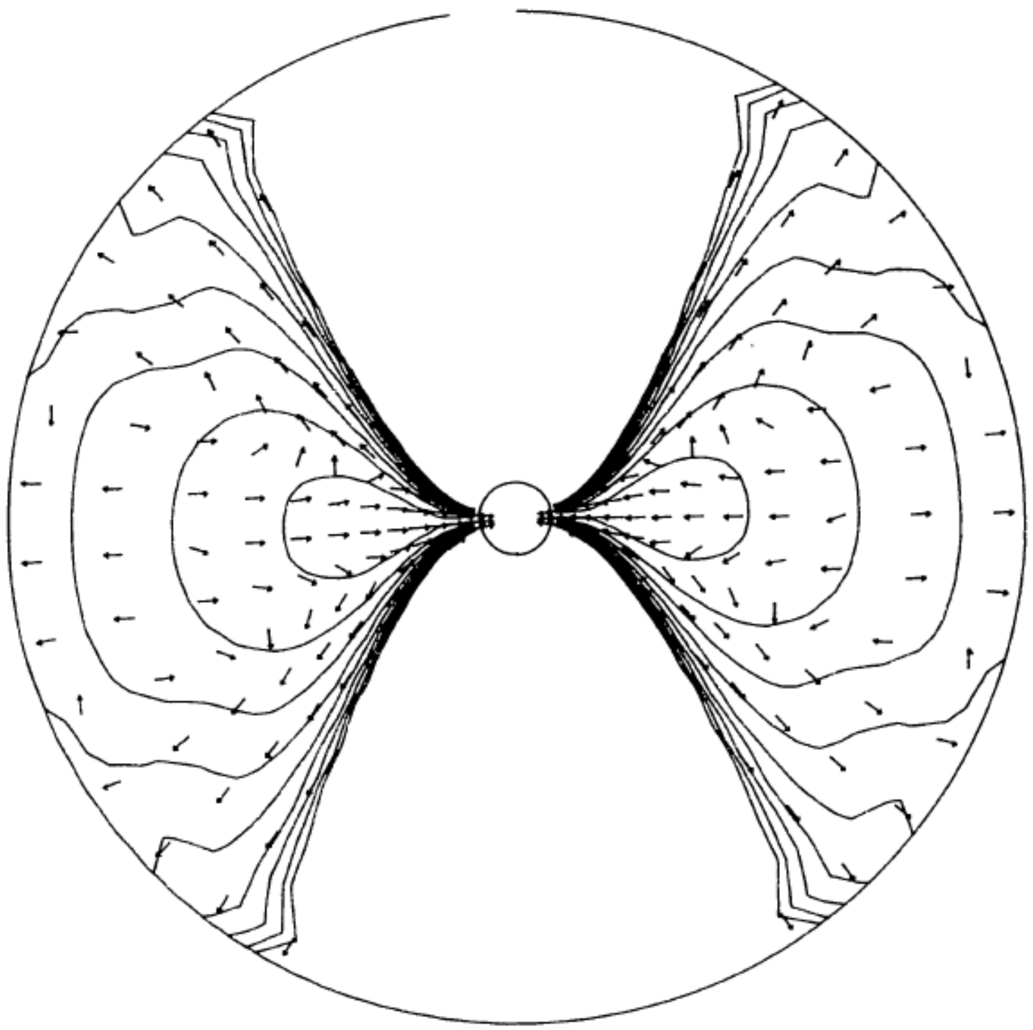
JOHN F. HAWLEY AND LARRY L. SMARR[1]
Department of Astronomy, University of Illinois

AND

JAMES R. WILSON
Lawrence Livermore National Laboratory

Received 1983 April 22; accepted 1983 June 20





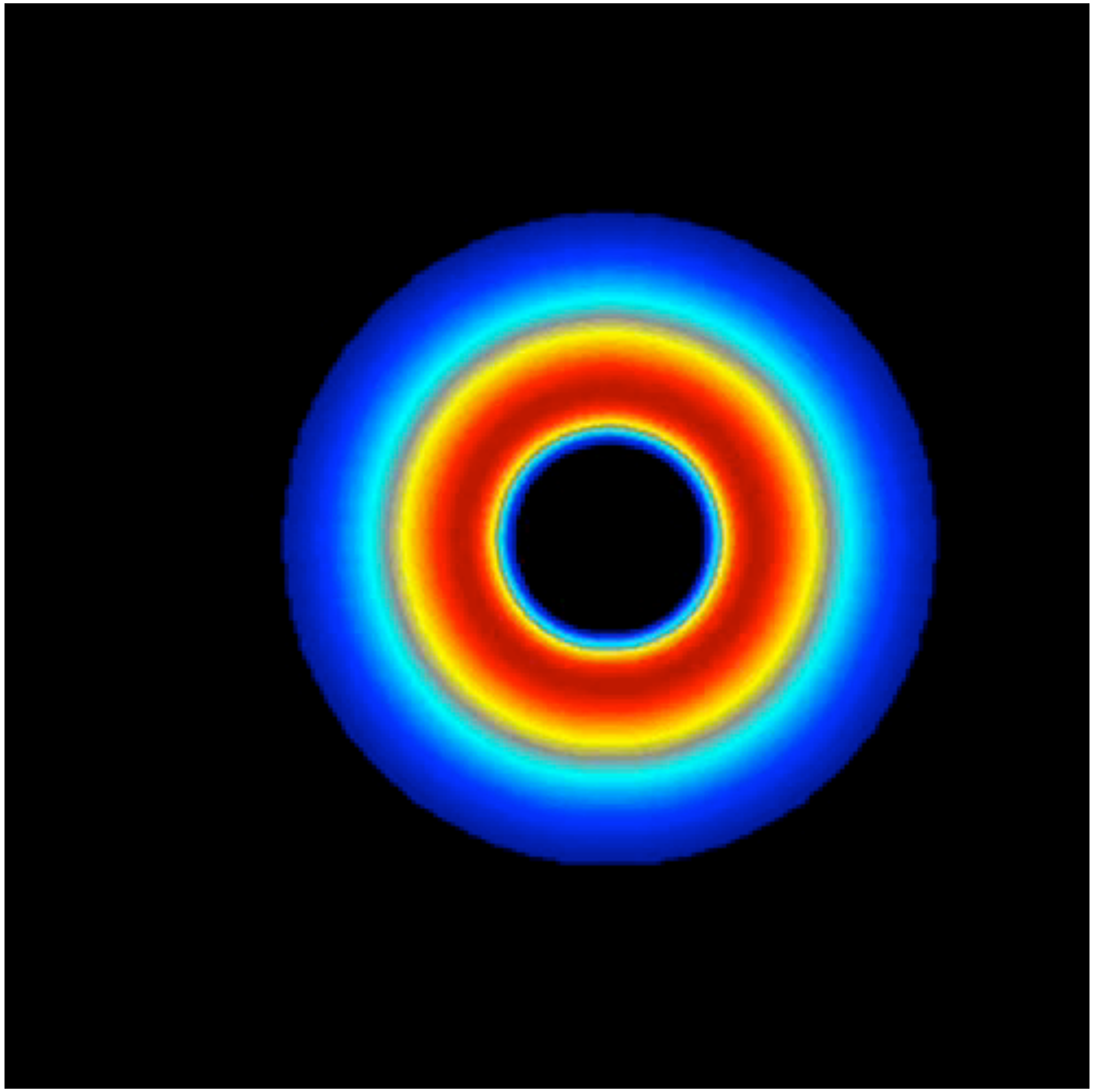
First example of numerical simulations testing theoretical predictions

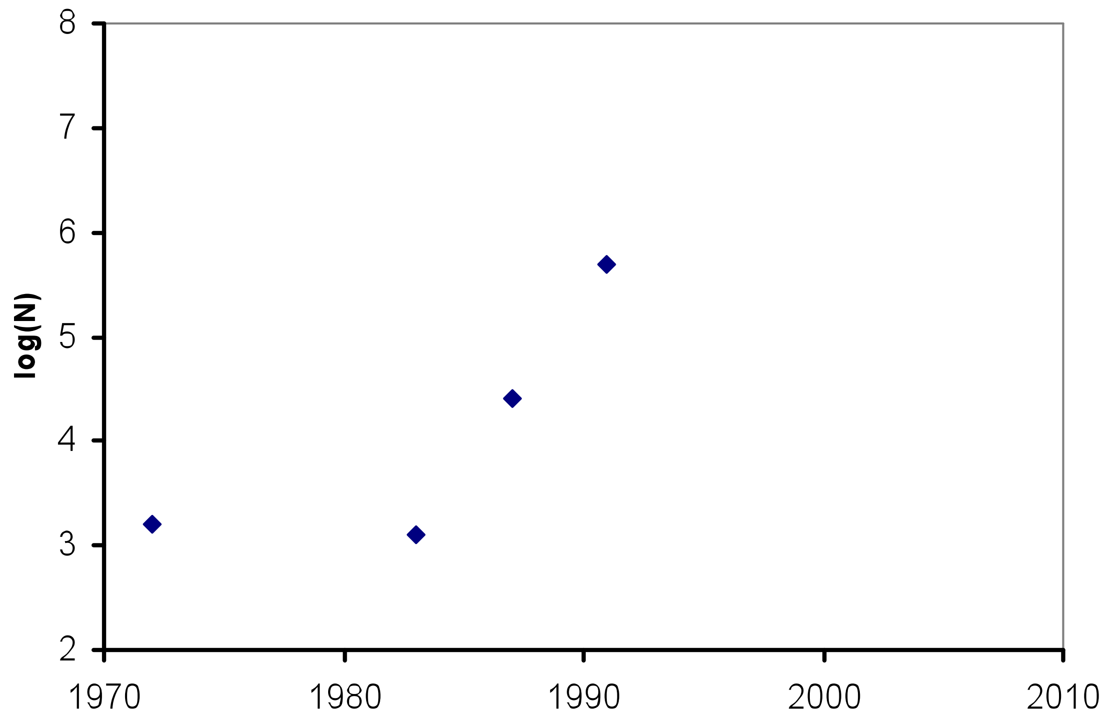
Angular momentum transport

- Papaloizou & Pringle (1984)
  - linear global stability analysis of differentially rotating torus
  - neutrally stable to axisymmetric perturbations
  - unstable to low-order non-axisymmetric modes (PPI)
  - modes grow on dynamical timescale
  - could play a role in angular momentum transport

1980s Angular momentum transport

- Hawley et al. (1987, 1991, 2002)
  - numerical simulations of **non-linear** growth and saturation of PPI
  - PPI suppressed in
    - "wide" tori or
    - when tori connect to hole via accretion



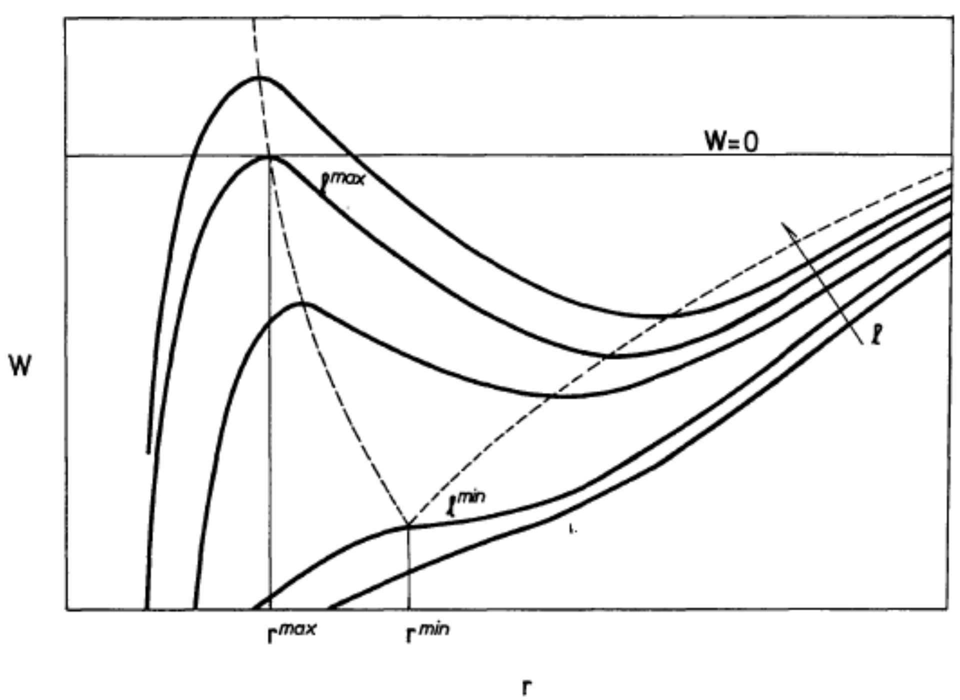


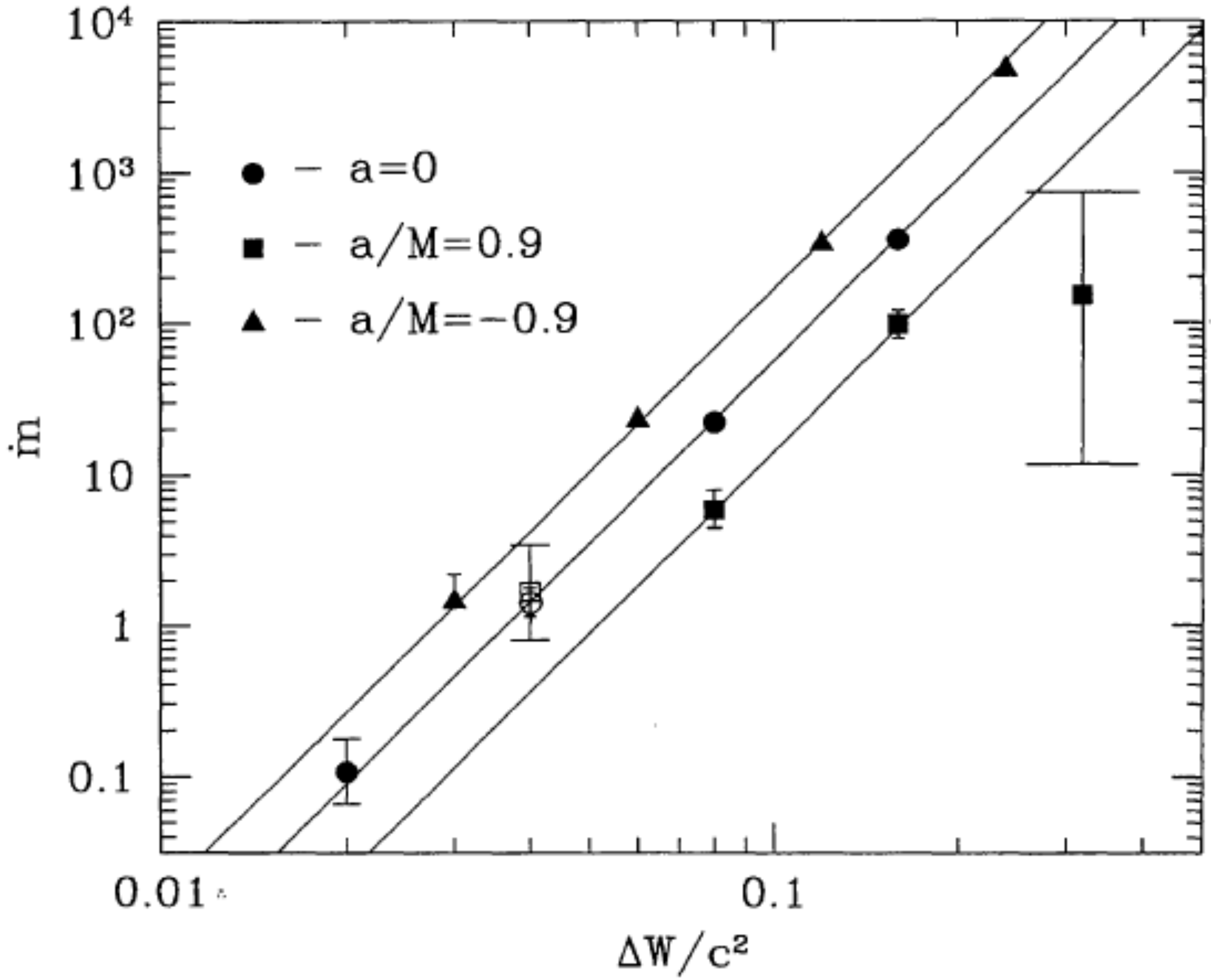
1990s

Slow expansion of numerical work

- Igumenshchev & Beloborodov (1997)
  - mass accretion due to cusp overflow

$$\dot{m} \propto \Delta W^{\Gamma/(\Gamma-1)}$$





1990s

Rediscovery of MRI

- Balbus & Hawley (1991, 1998)
  - previously discovered by Velikhov and Chandrasekhar
  - provided field is weak, only requires

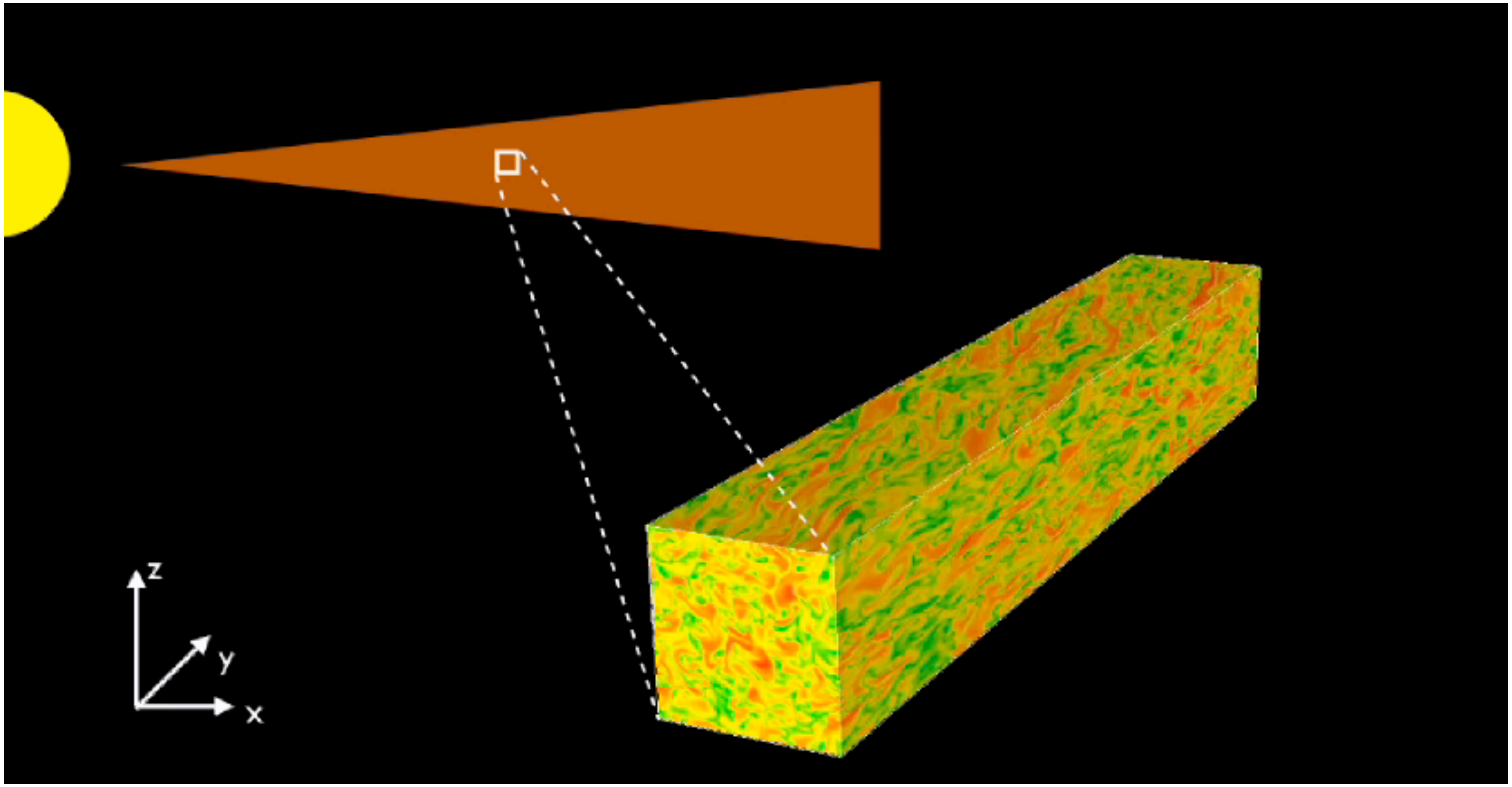
$$\frac{\mathrm{d}\Omega^2}{\mathrm{d}\ln R} < 0$$

  - modes grow on dynamical timescale
  - probably plays a dominant role in angular momentum transport in all ionized astrophysical disks

1990s

Shearing box simulations of MRI

- Unstratified



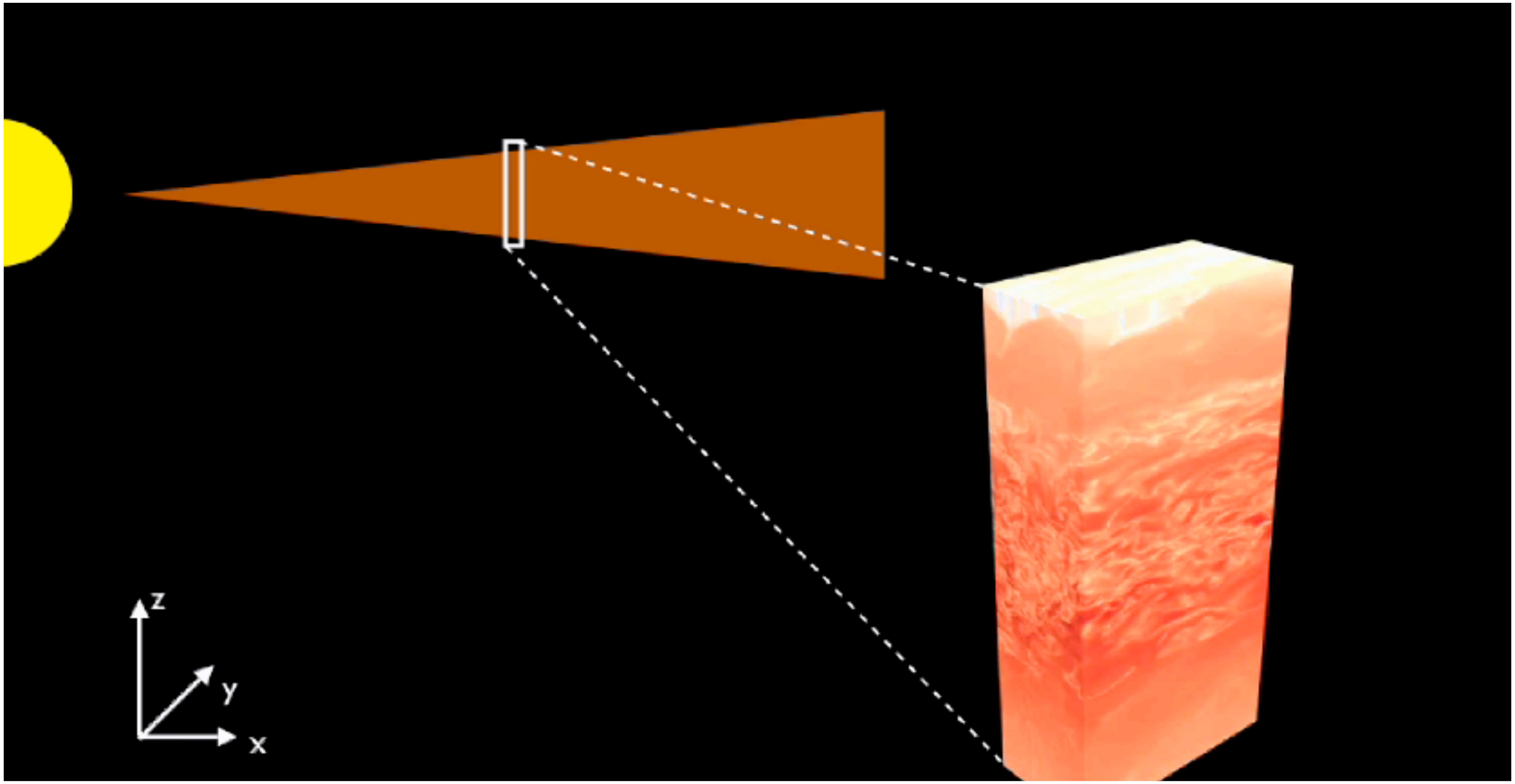
Credit: Jacob Simon

http://jila.colorado.edu/~jasi1566/Unstratified_Shearing_Box_Movie.html

1990s

Shearing box simulations of MRI

- Stratified

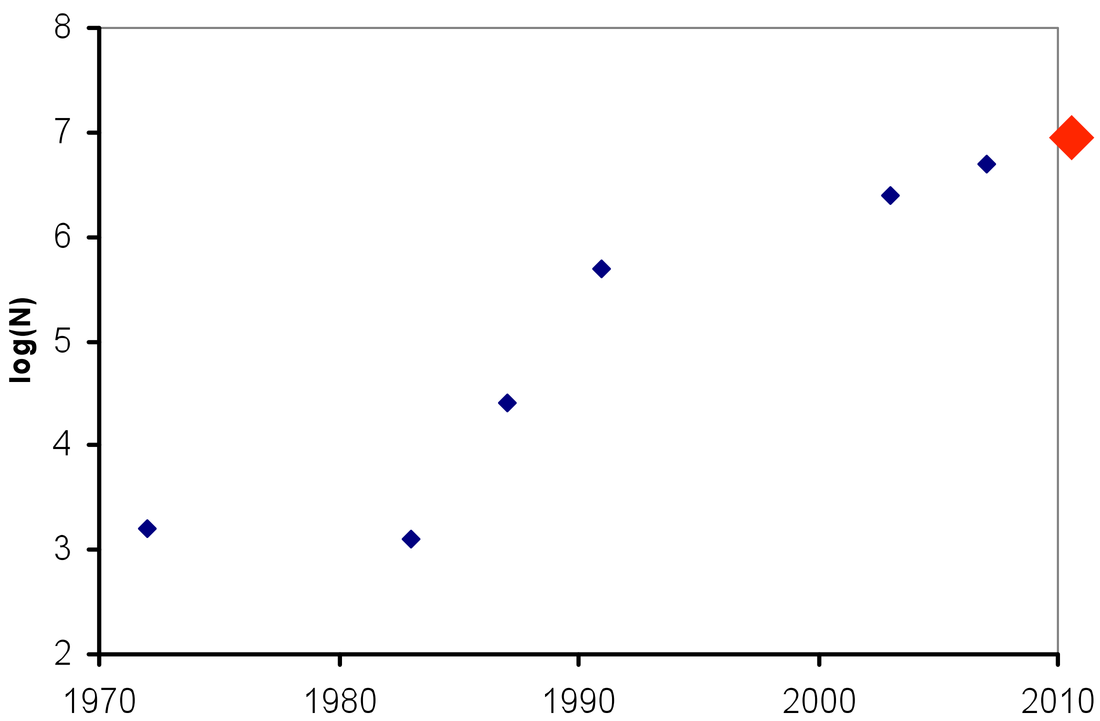


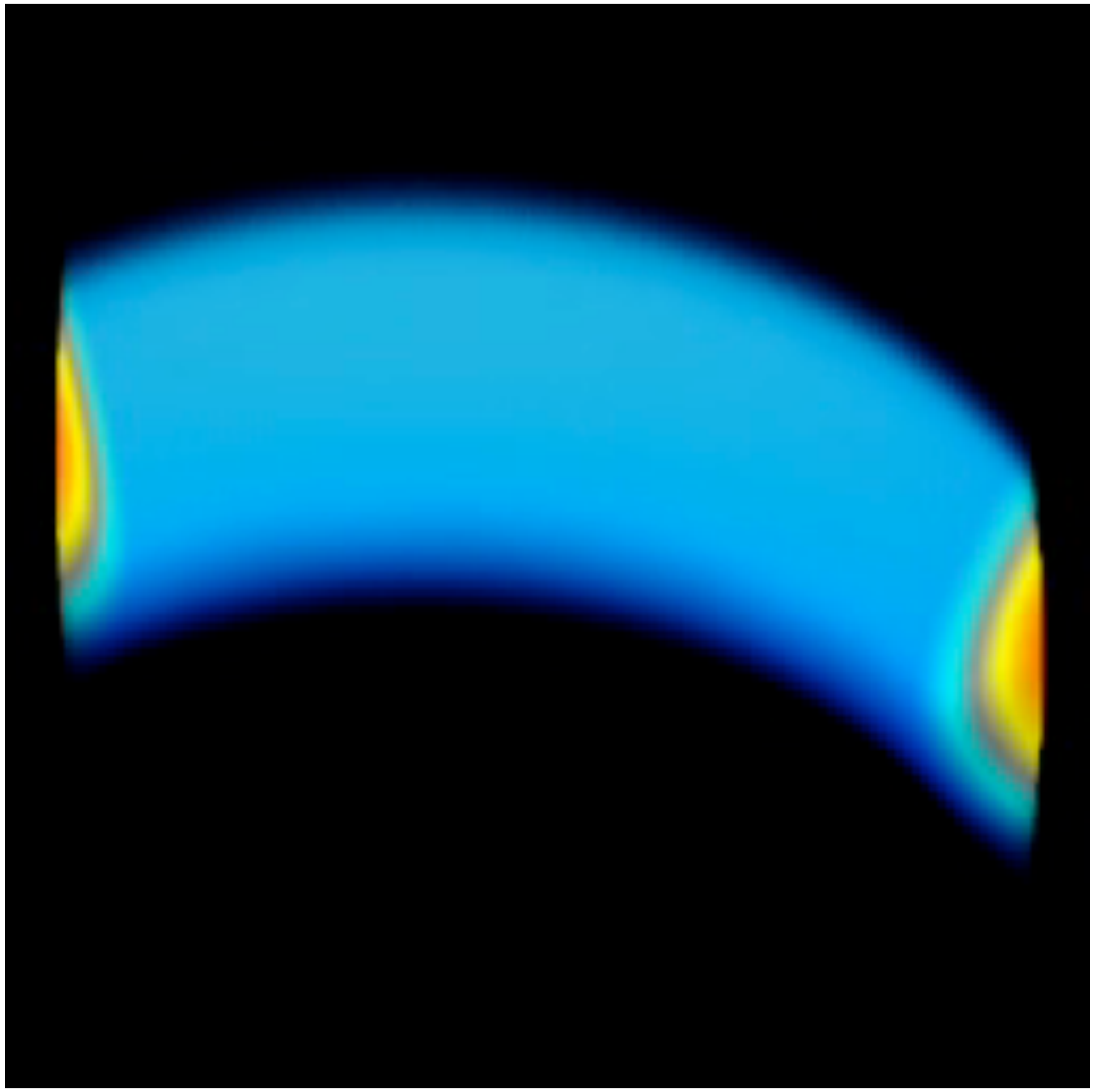
Credit: Jacob Simon

http://jila.colorado.edu/~jasi1566/Stratified_Shearing_Box_Movie.html

Birth of 3D GR MHD simulations

- De Villiers, Hawley & Krolik (2003)
  - start from analytic torus
  - seed with weak magnetic field
  - evolves into something resembling thin, Keplerian disk due to action of MRI





2000s Explosion of numerical work

- Nelson, Papaloizou, ... 1999→
- Stone, Proga, Turner, ... 2001→
- Armitage, Reynolds, Miller, O'Neill, Sorathia, ... 2001→ ↑ Newtonian
- Hawley, Krolik, DeVilliers, Beckwith, Simon, ... 2003→ ↓ GR
- Rezzolla, Font, Zanotti, ... 2003→
- Gammie, McKinney, Noble, Moscibrodzka, ... 2004→
- Fragile, Anninos, Salmonson, ... 2005→
- Ohsuga, Matsumoto, Machida, ... 2005→
- Narayan, Shafee, Tchekhovskoy, Penna, ... 2006→
- Varniere, Tagger, ... 2008→
- plus **many** groups doing shearing box simulations (started in 1990's)
- plus **many** groups doing simulations of accretion in other contexts (proto-planetary disks, neutron stars, etc.)

Numerical “experiments”

Numerical "experiments"

- Simulations of tilted disks
  - Fragile et al. (2007, 2009)

$$128^3$$

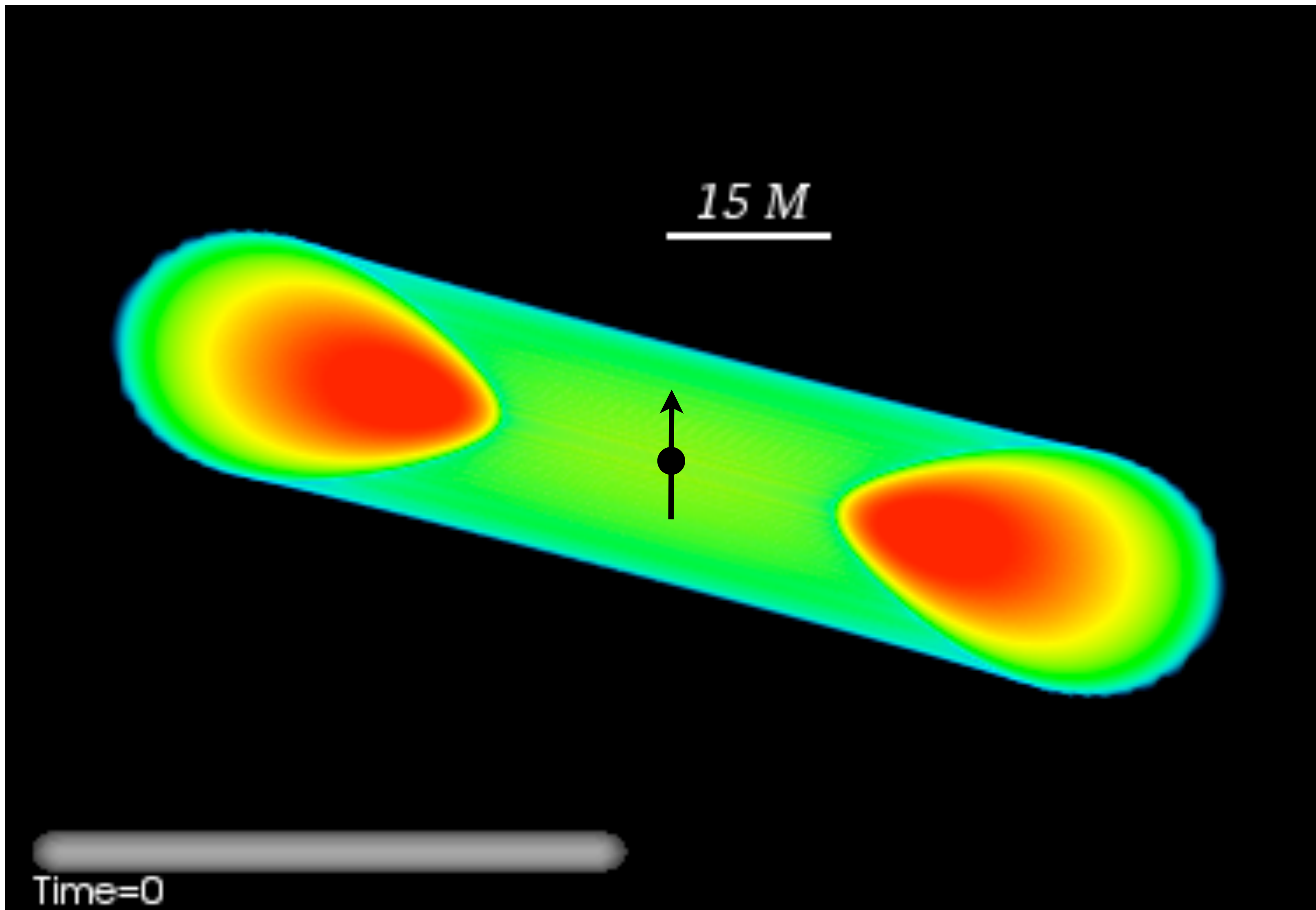
$$\Gamma = 5/3$$

$$r_{P_{\max}} = 25 r_G$$

$$r_{\rm in} = 15 r_G$$

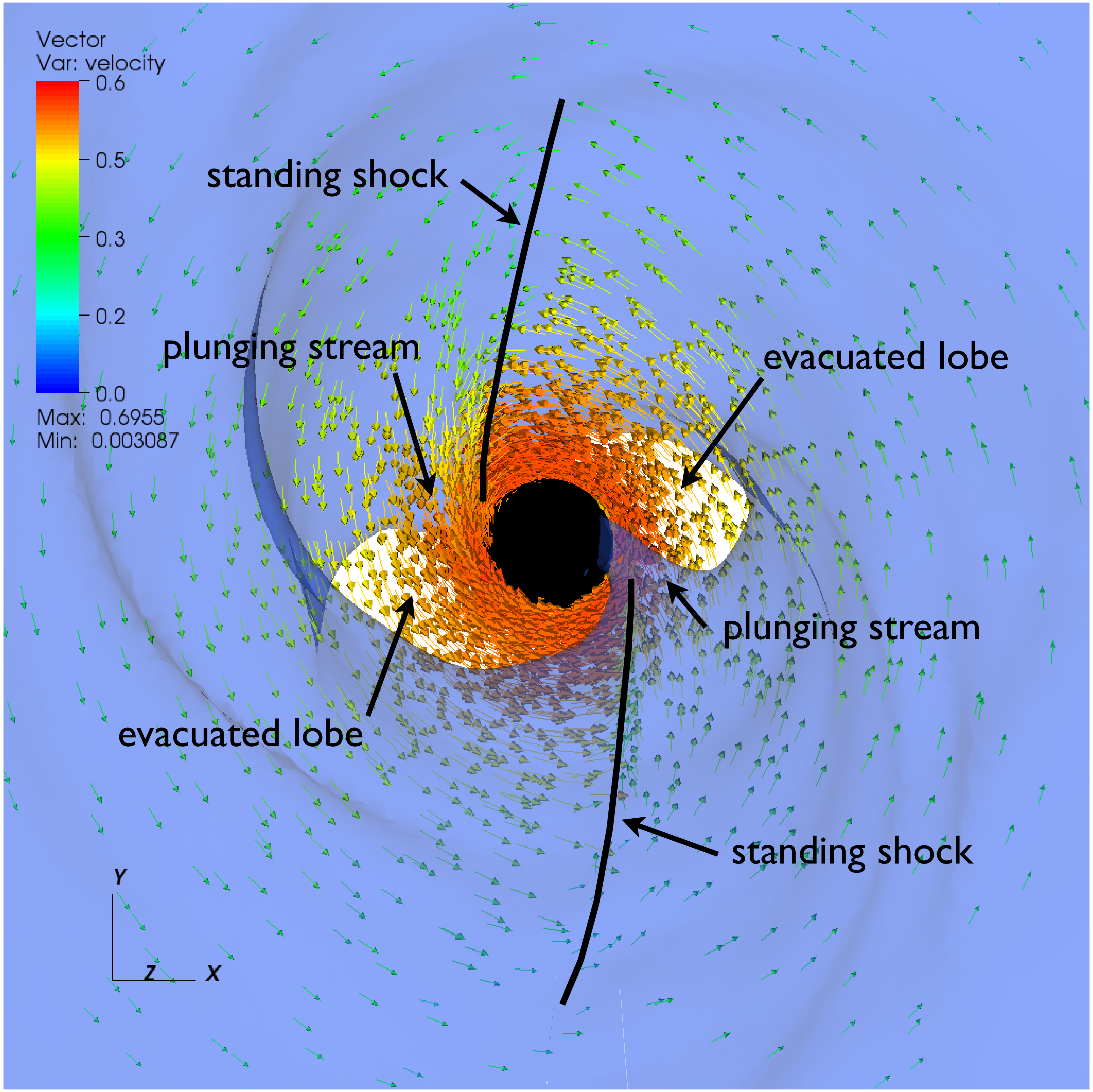
$$a_* = 0.9$$

$$\beta_0 = 15^\circ$$



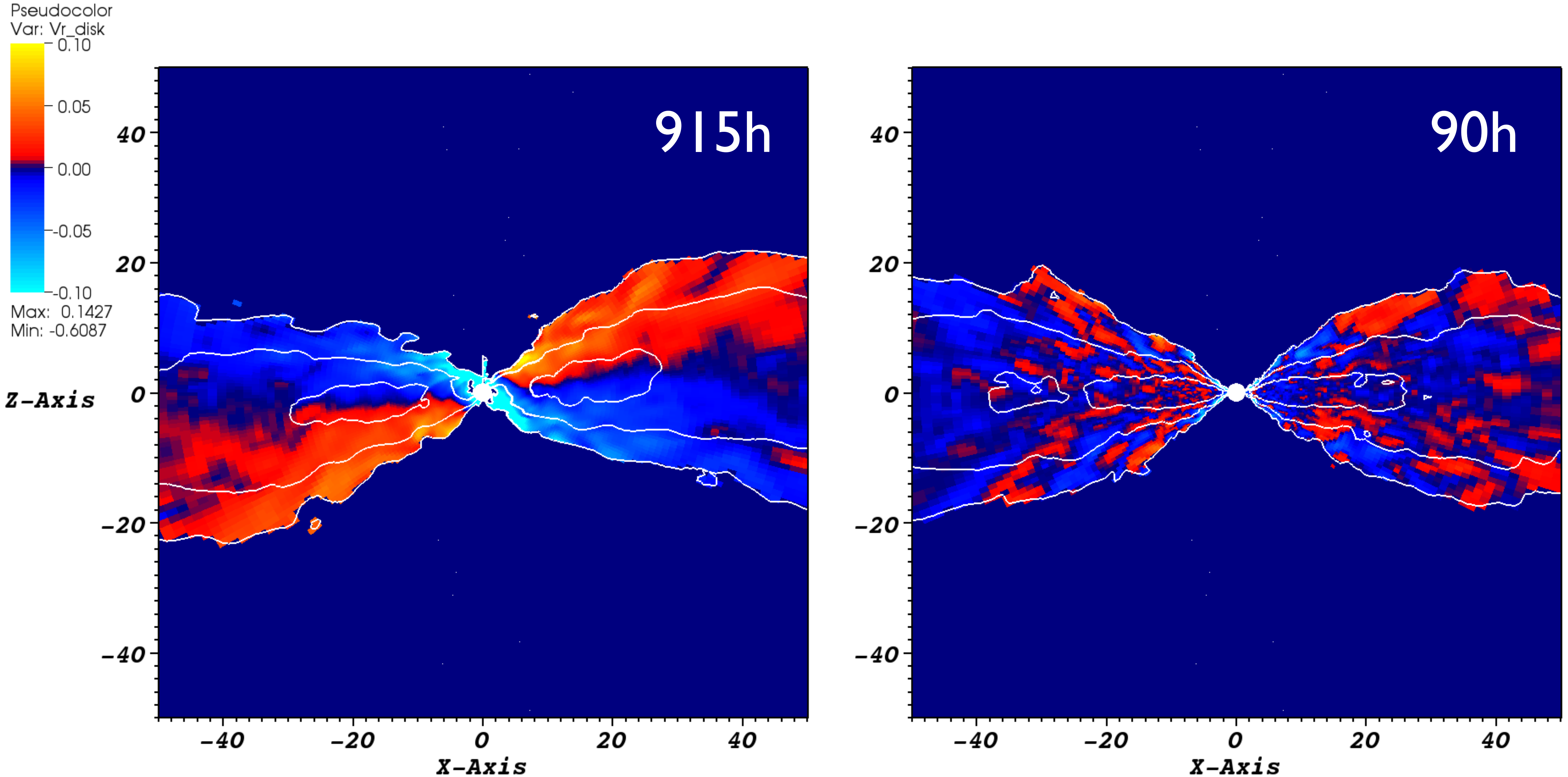
http://fragilep.people.cofc.edu/research/movies/torus3d.m.915h_rho.mov

2000s Standing shocks in tilted disks



(Fragile & Blaes 2008)

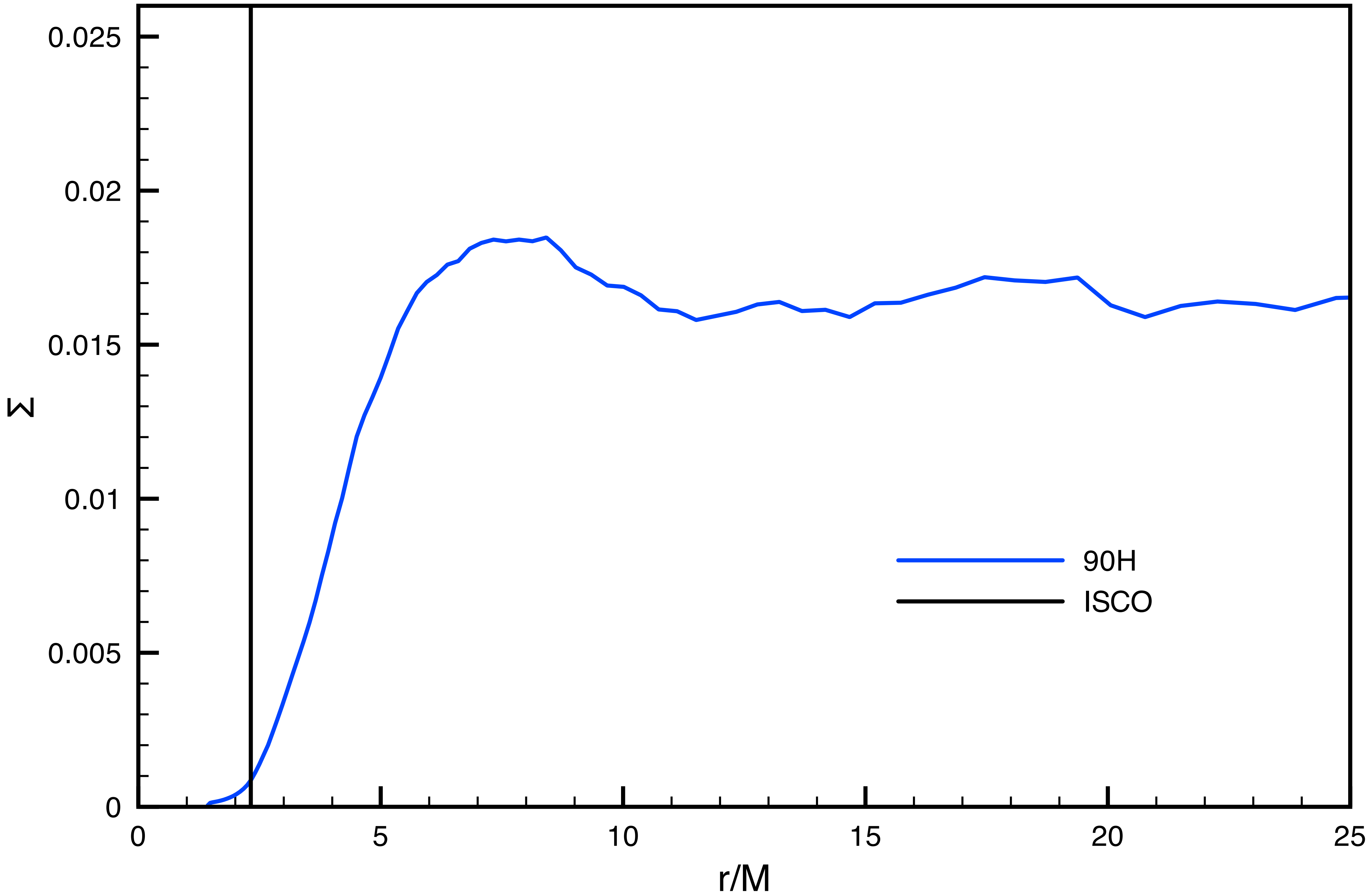
Epicyclic motion in tilted disks



Fragile & Blaes (2008)

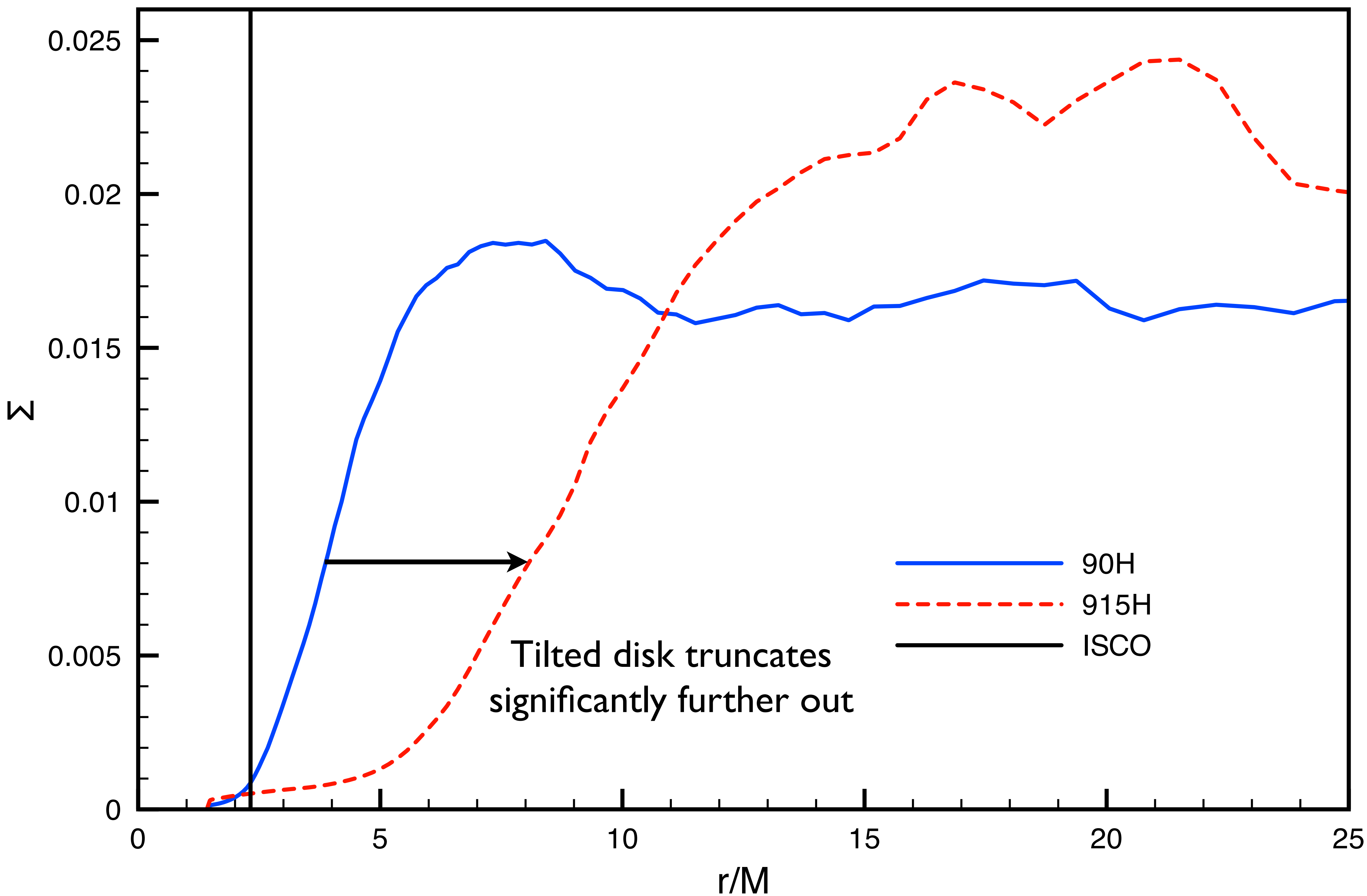
Inner radius of tilted disks

- Surface density



Inner radius of tilted disks

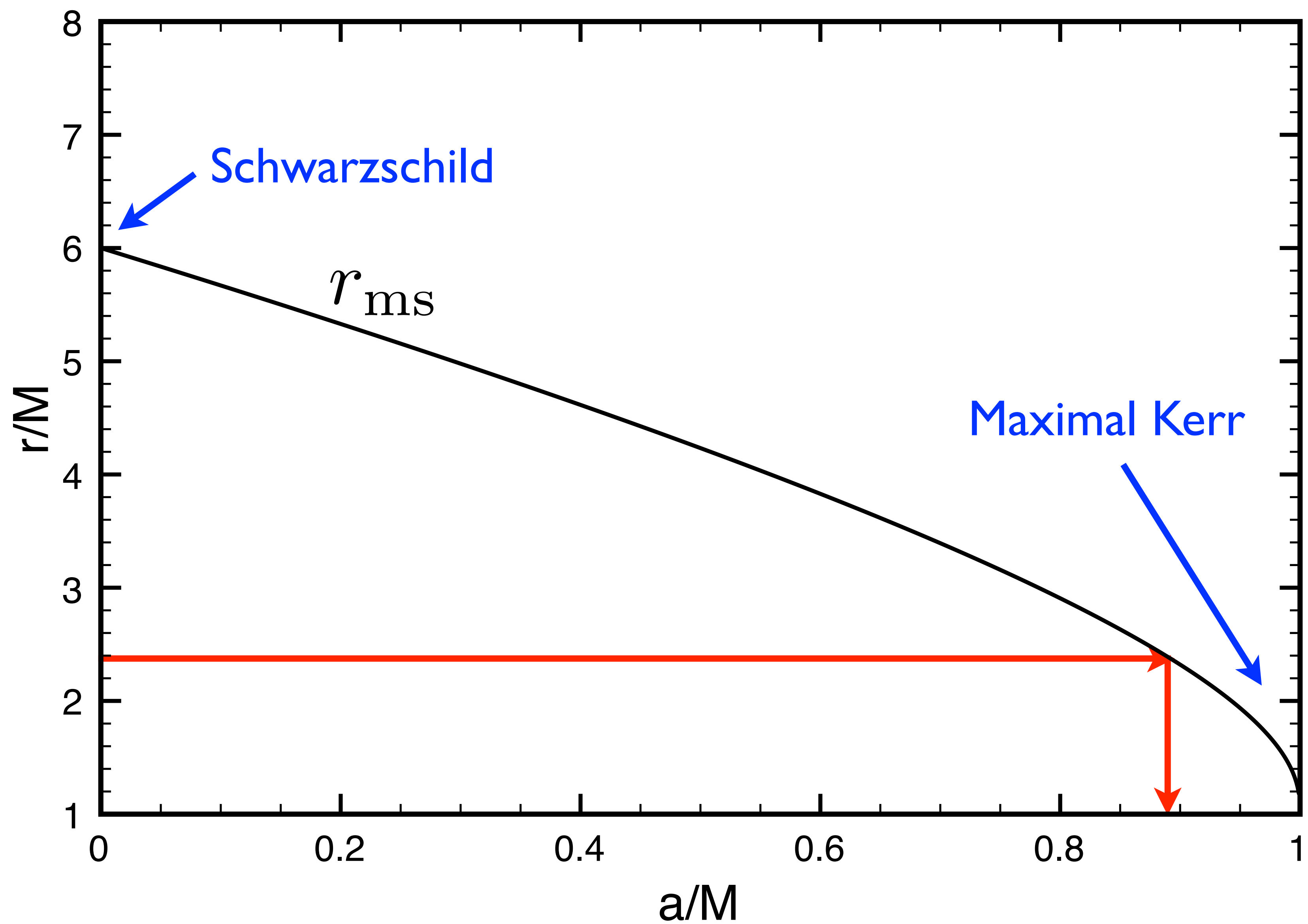
- Surface density



Determining spin of a black hole

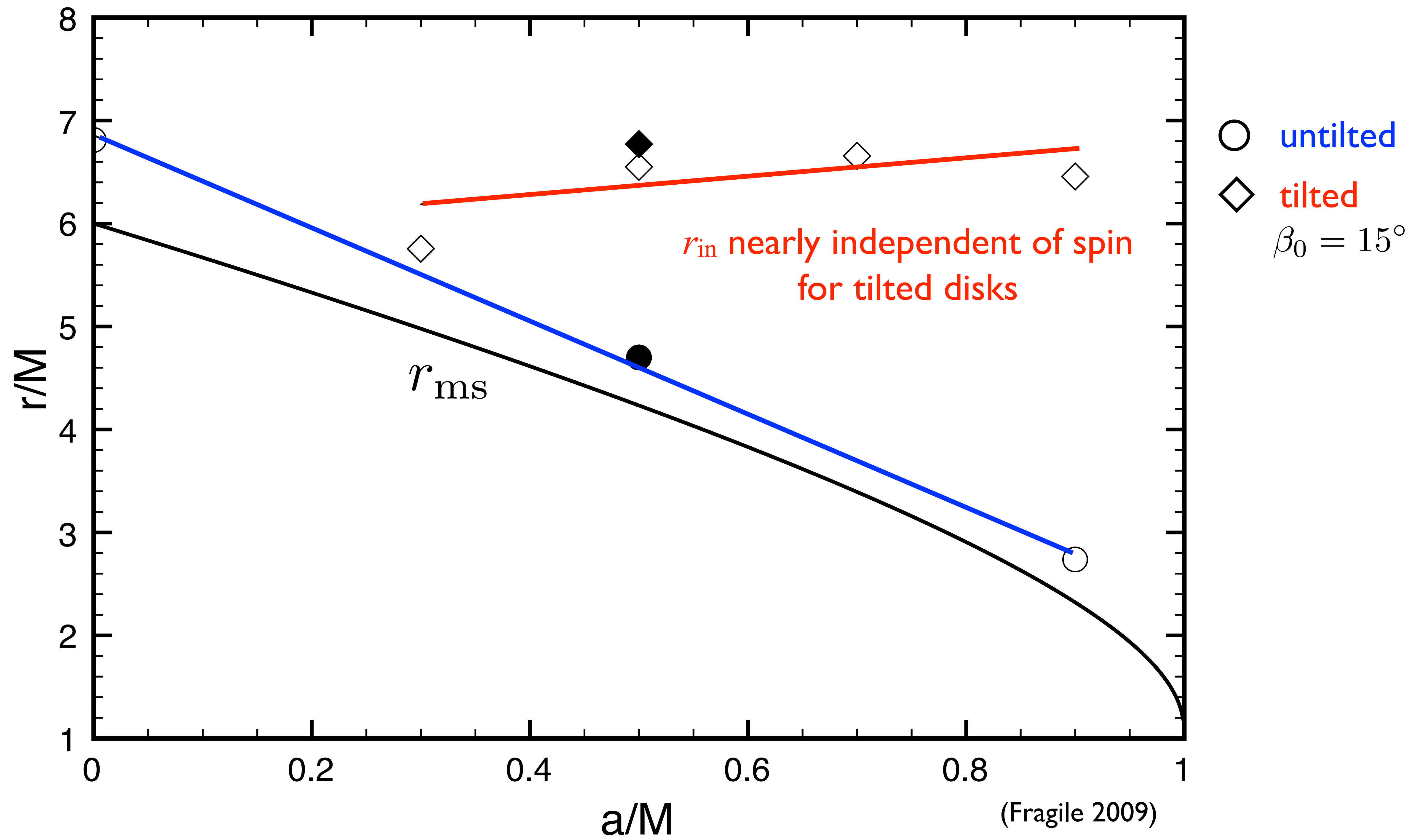
- If $r_{\rm in}$ can be measured
  - continuum fitting
  - Fe α line
- If $r_{\rm in} = r_{\rm ms}$

} can get a directly



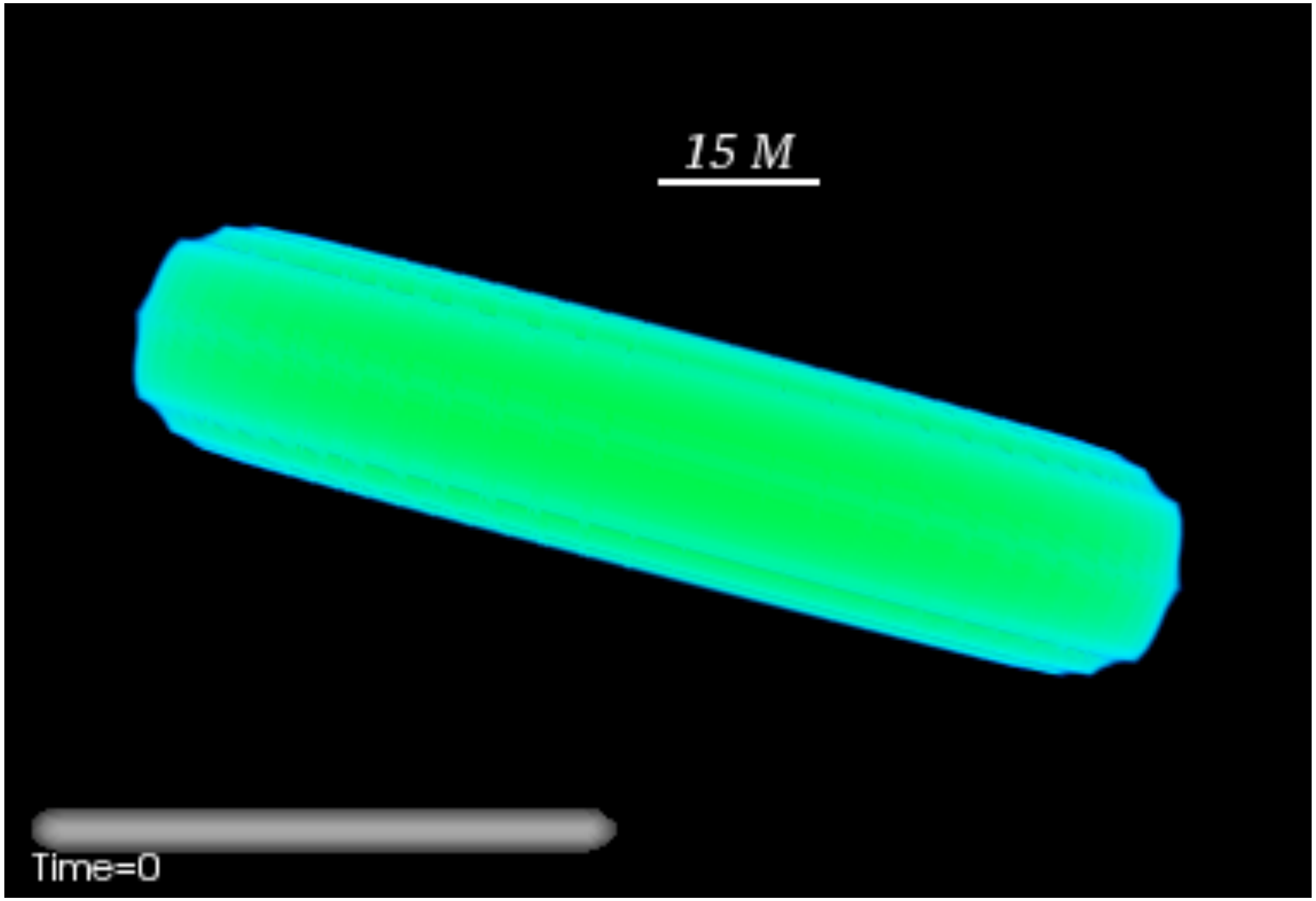
Inner radius of tilted disks

$$\Sigma(r_{\rm in}) = \Sigma_{\rm max}/3e$$



Disk precession

- Torque of BH causes disk to precess
  - After initial twisting phase, disk precesses as solid body



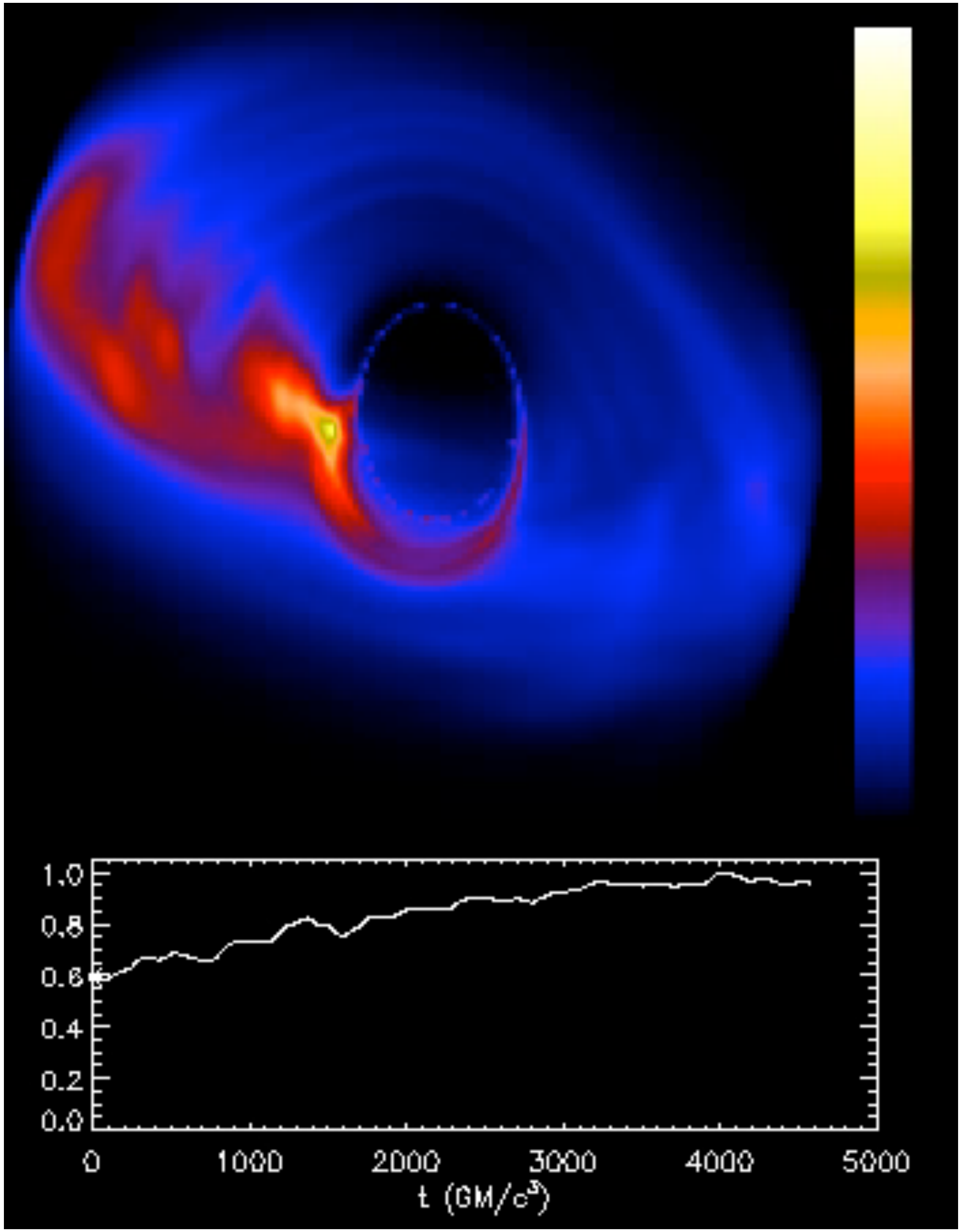
http://fragilep.people.cofc.edu/research/movies/torus3d.m.915m_rho.mov

Matching simulations w/ observations

- "After-the-fact" radiative cooling models
  - Schnittman et al. (2006)
  - Noble et al. (2007); Mościbrodzka et al. (2009)
  - Dexter et al. (2009, 2010)
  - Dexter & Fragile (2011)

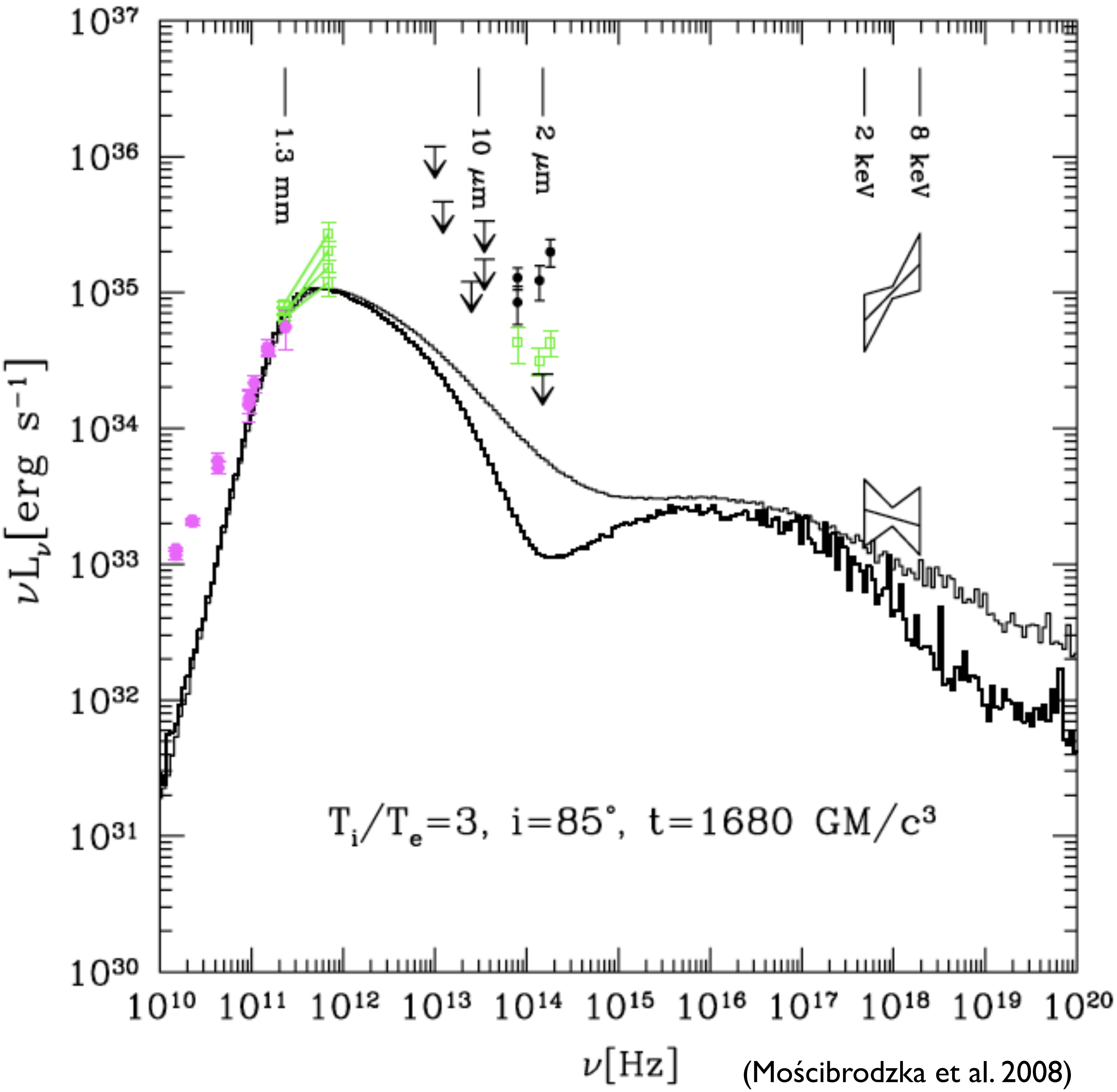
Matching simulations w/ observations

- "After-the-fact" radiative cooling models
  - Schnittman et al. (2006)
  - Noble et al. (2007); Mościbrodzka et al. (2009)
  - Dexter et al. (2009, 2010)
  - Dexter & Fragile (2011)



2000s Matching simulations w/ observations

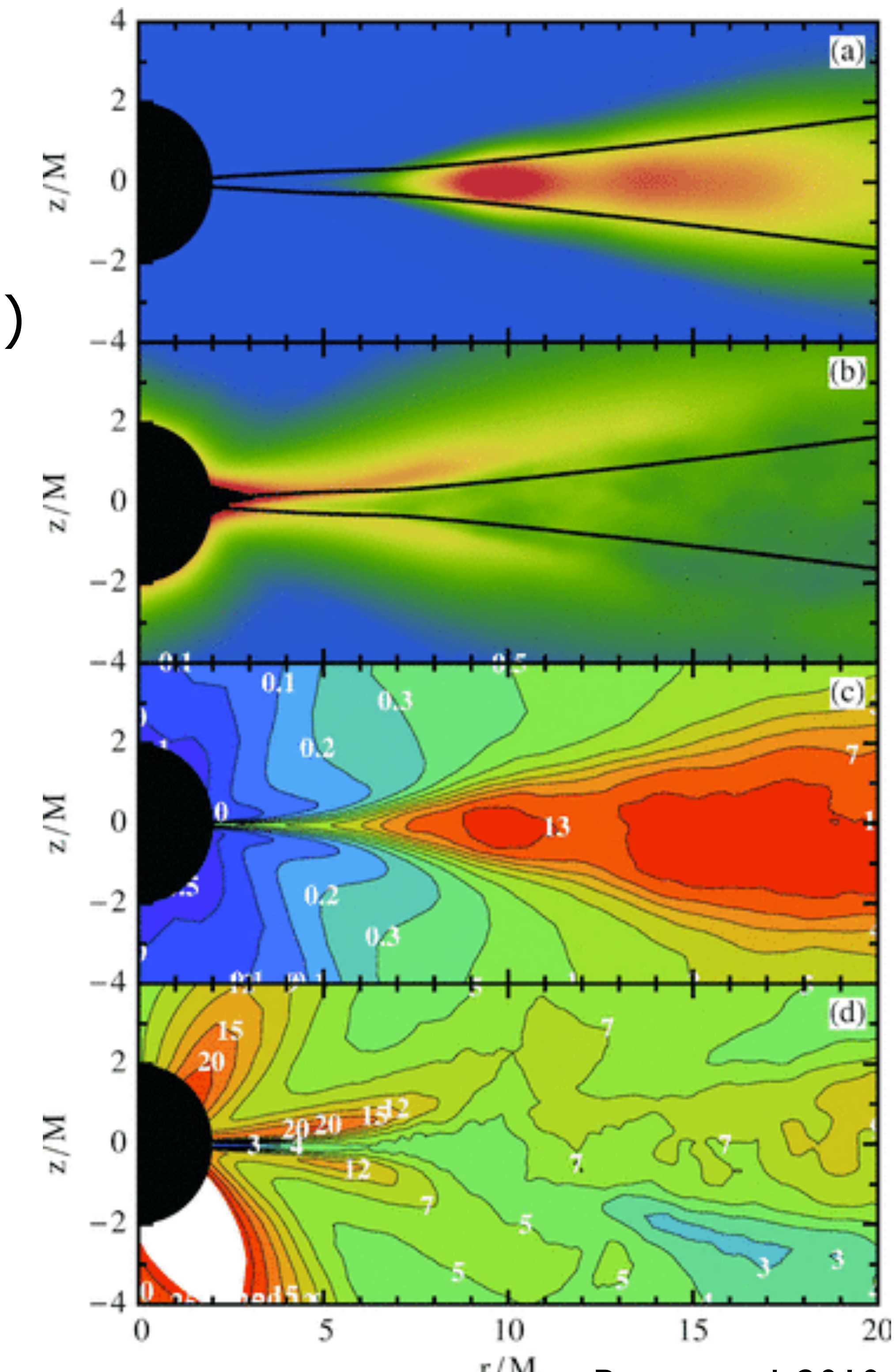
Sgr A*



(Mościbrodzka et al. 2008)

2000s Thermodynamics of simulated disks

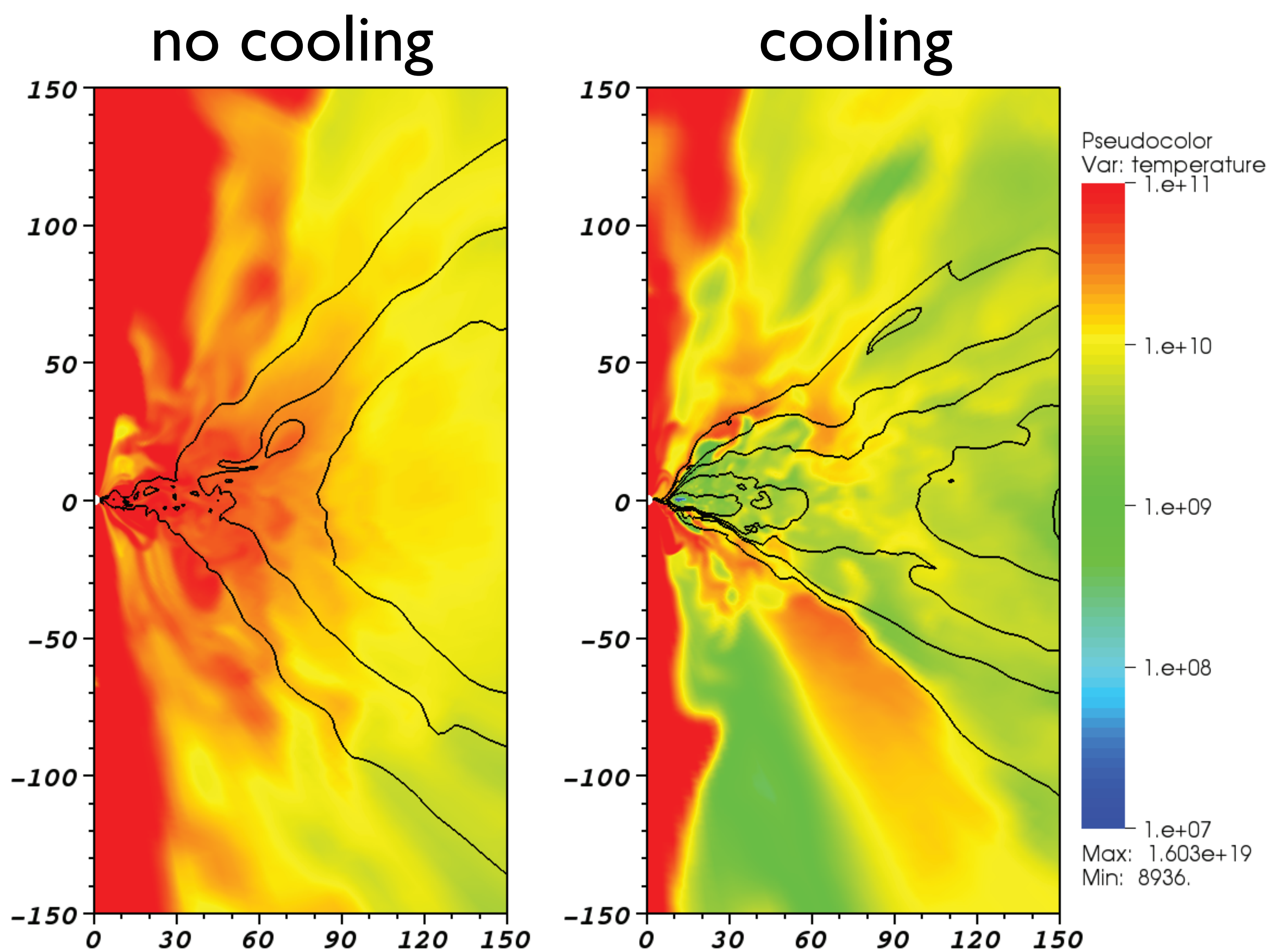
- Geometrically thin (soft state) disks
  - Shafee et al., 2008 & Penna et al., 2010
  - Noble et al., 2009 & 2010
  - cooling ≈ heating (everywhere, locally)
    - matches assumption of Shakura & Sunyaev (1973) and Novikov & Thorne (1973)



Penna et al. 2010

Thermodynamics of simulated disks

- Geometrically thick (hard state) disks
  - Fragile & Meier, 2009
  - physical cooling model based on bremsstrahlung, synchrotron & inverse Compton



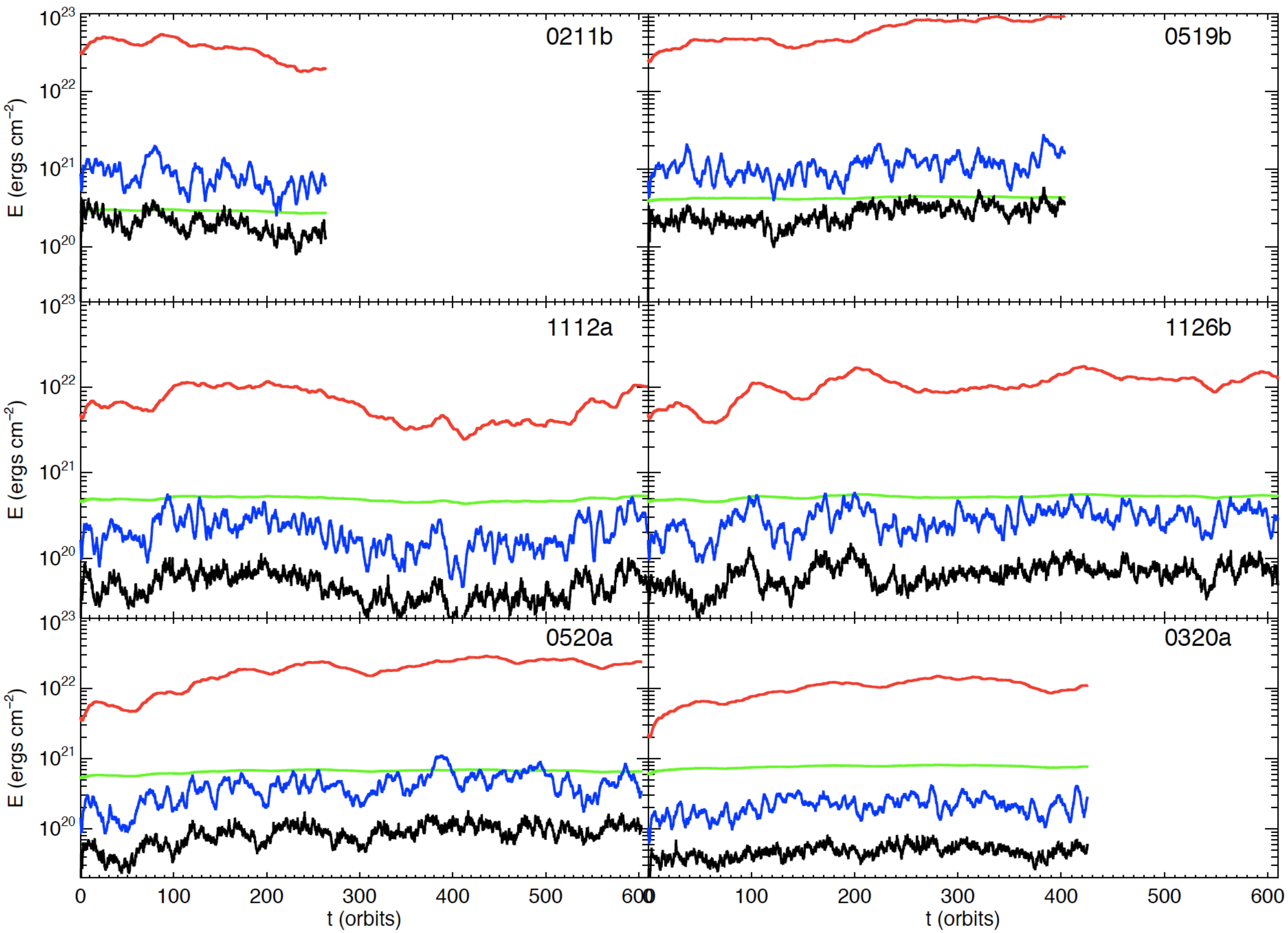
(Fragile & Meier 2009)

Predictions for this decade

- 1970’s - Jim Wilson was “the man”
- 1980’s - Hydrodynamics
- 1990’s - MHD/Relativistic Hydrodynamics
- 2000’s - General Relativistic MHD
- 2010’s - GR Radiation MHD

Radiation MHD in shearing box

- Turner et al (2003); Turner (2004)
- Hirose et al. (2006, 2009)



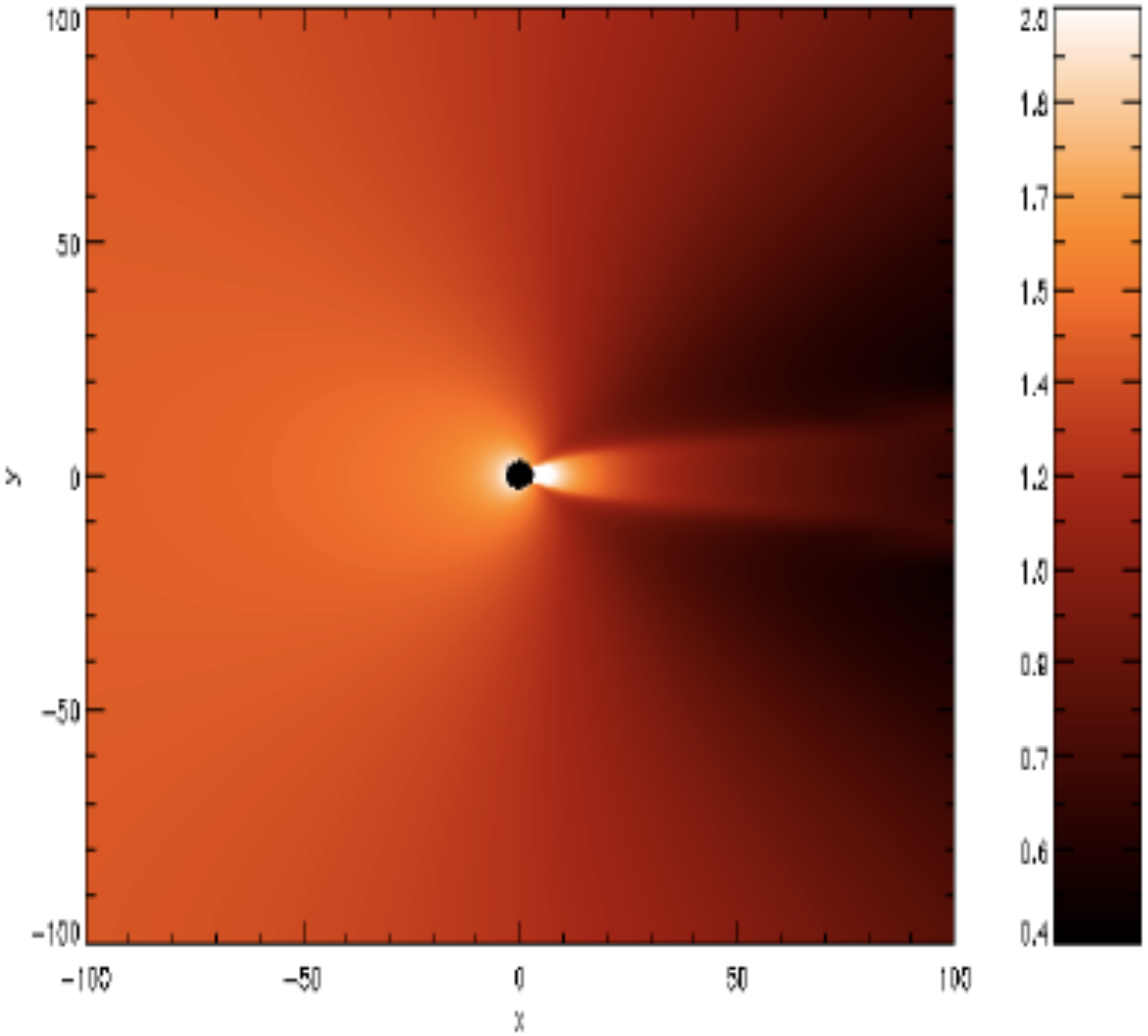
Radiation-pressure dominated disks are thermally stable!

In contradiction with theoretical predictions

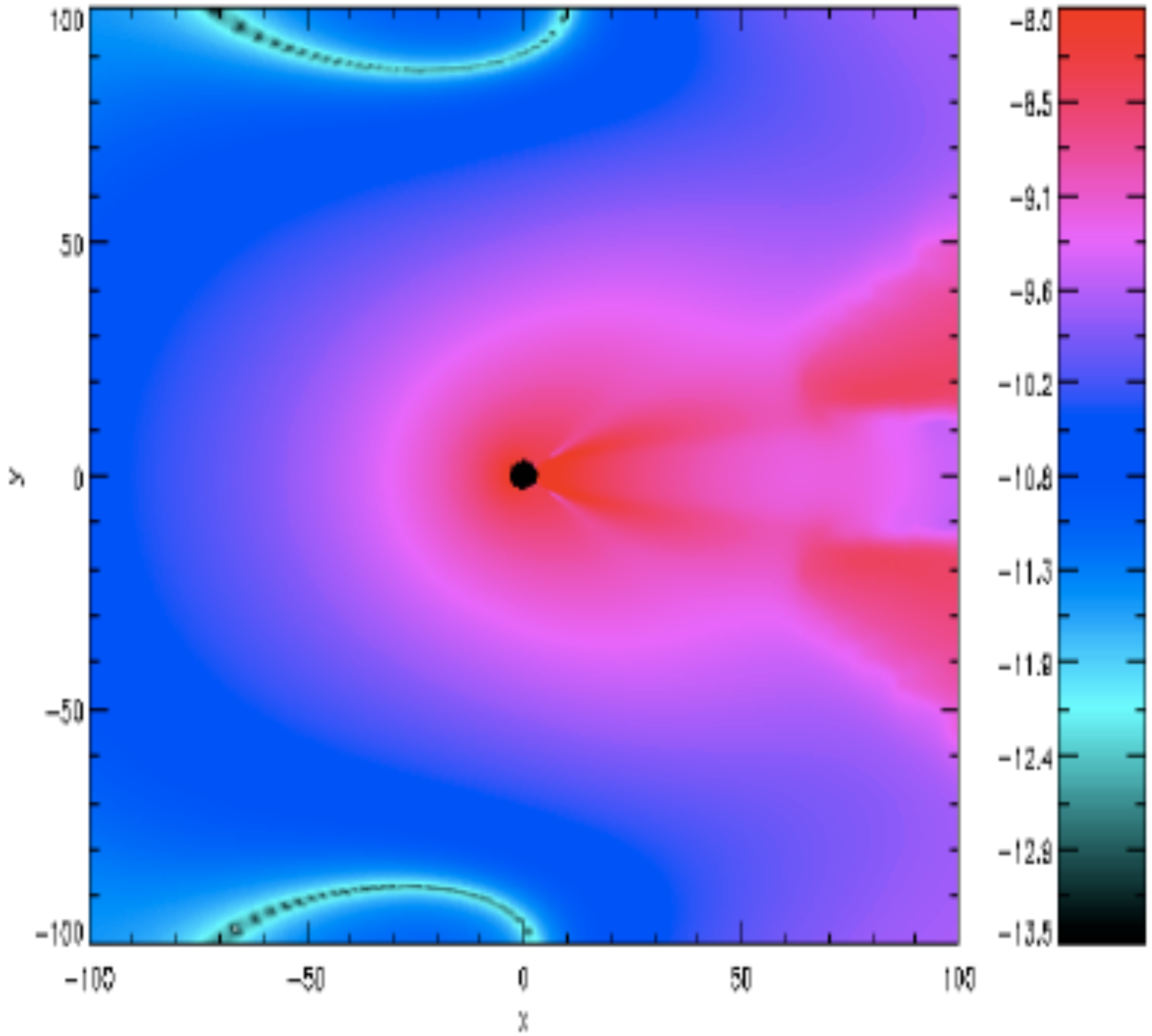
GR Radiation MHD

- Bondi-Hoyle accretion onto black hole
  - Zanotti et al. (2011)

Optical depth



Radiative flux



MHD Simulations Pop Quiz

- What are some of the many uses of MHD simulations of accretion?

  A) testing analytic theory

  B) studying non-linear evolution

  C) "experimenting" with novel scenarios

  D) interpreting observations

  E) All of the above

Acknowledgements

- Thank you to
  - the LOC and SOC
  - NSF
  - ORAU/ORNL
  - SCSGC & SC EPSCoR

nsf

ORAU
OAK RIDGE ASSOCIATED UNIVERSITIES

COLLEGE of CHARLESTON
FOUNDED 1770

OAK RIDGE
National Laboratory

South Carolina
SPACE GRANT

NASA EPSCoR
South Carolina