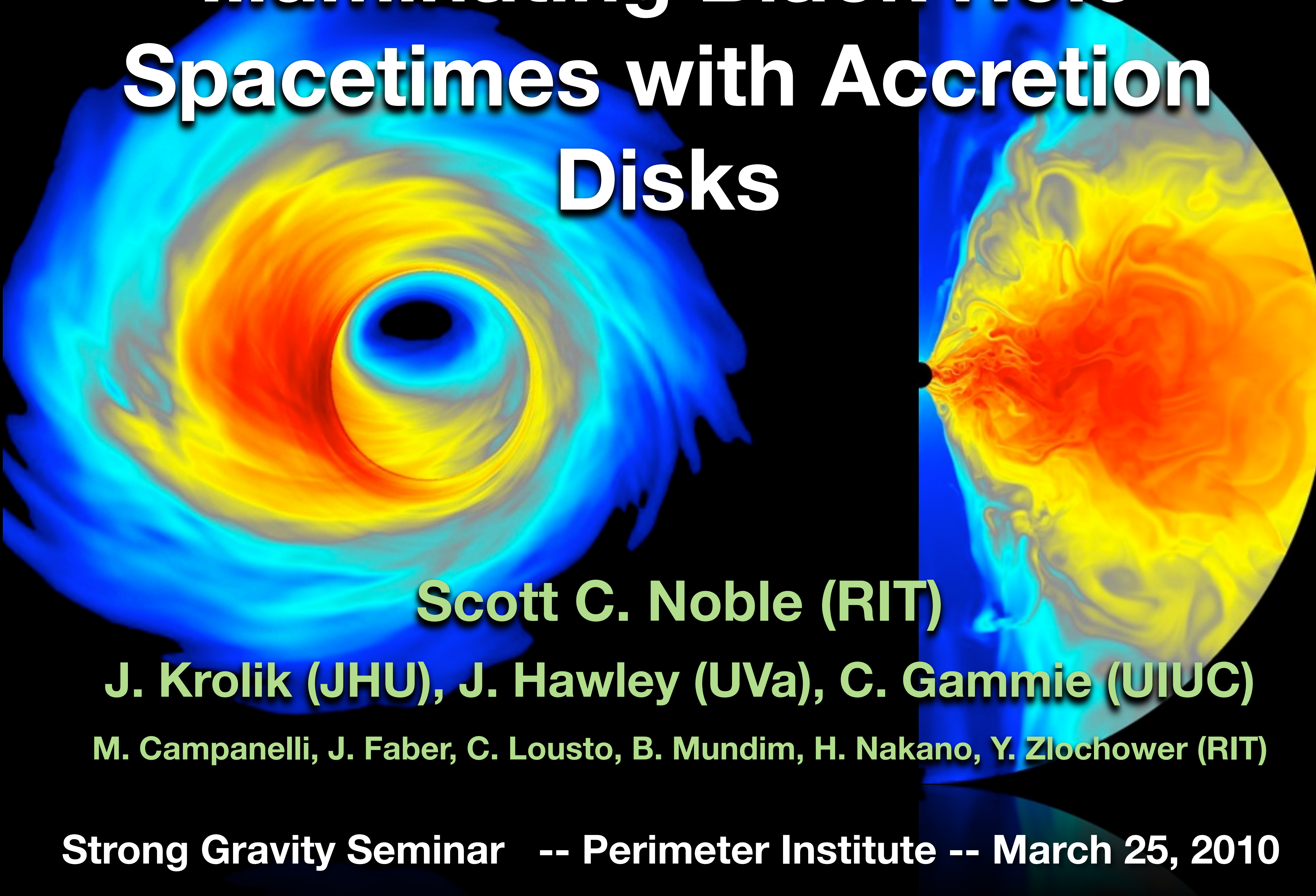
Illuminating Black Hole Spacetimes with Accretion Disks



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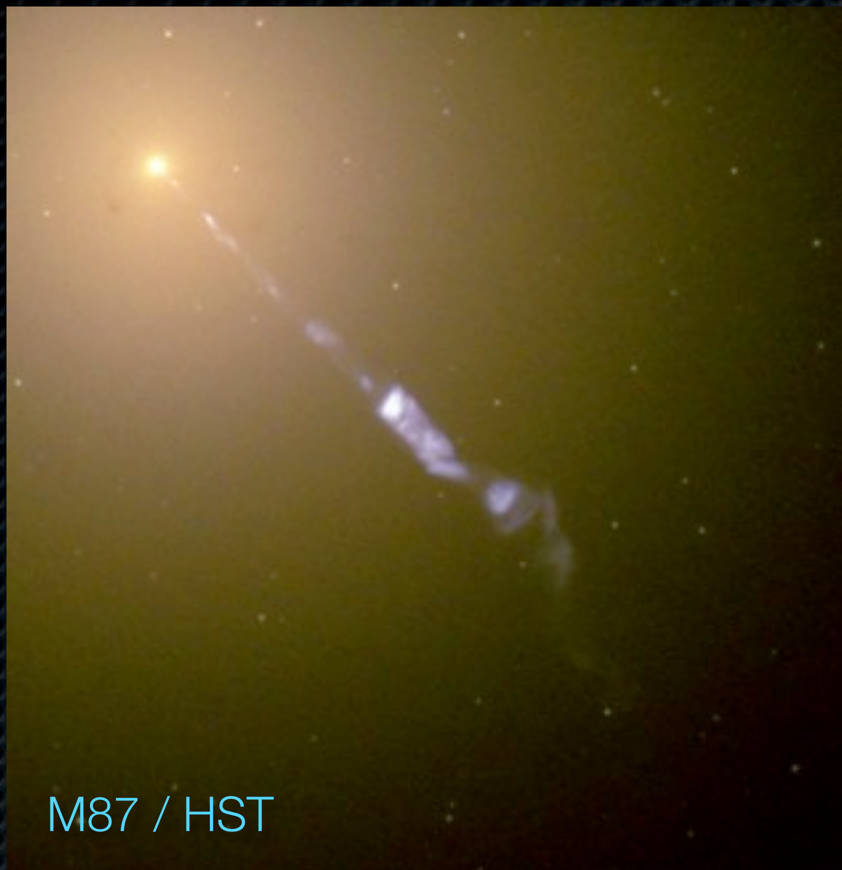
Strong Gravity Seminar -- Perimeter Institute -- March 25, 2010

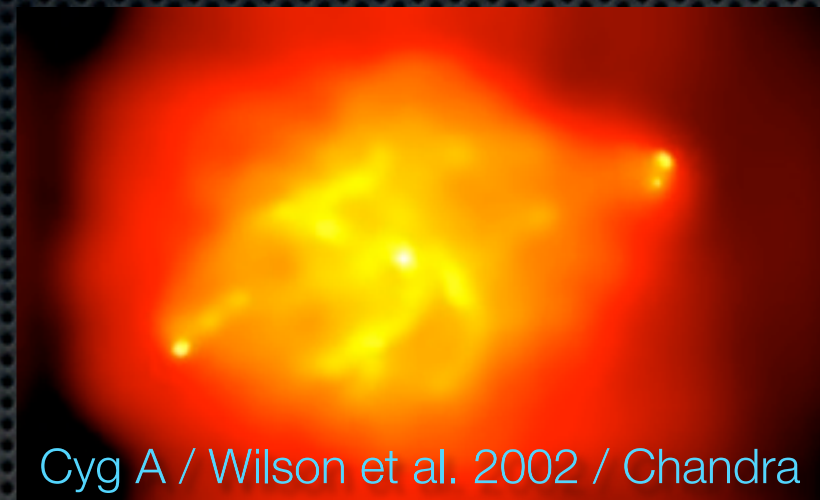
Outline

- Overview of black hole accretion disks
- Brief model/simulation description under the GRMHD paradigm
- Self-consistent models of emission from Sgr A*
- Geometrically thin accretion disks
- Temporal power spectra of coronal X-ray emission
- Future Directions:
  - Further model-space explorations
  - Binary black hole accretion

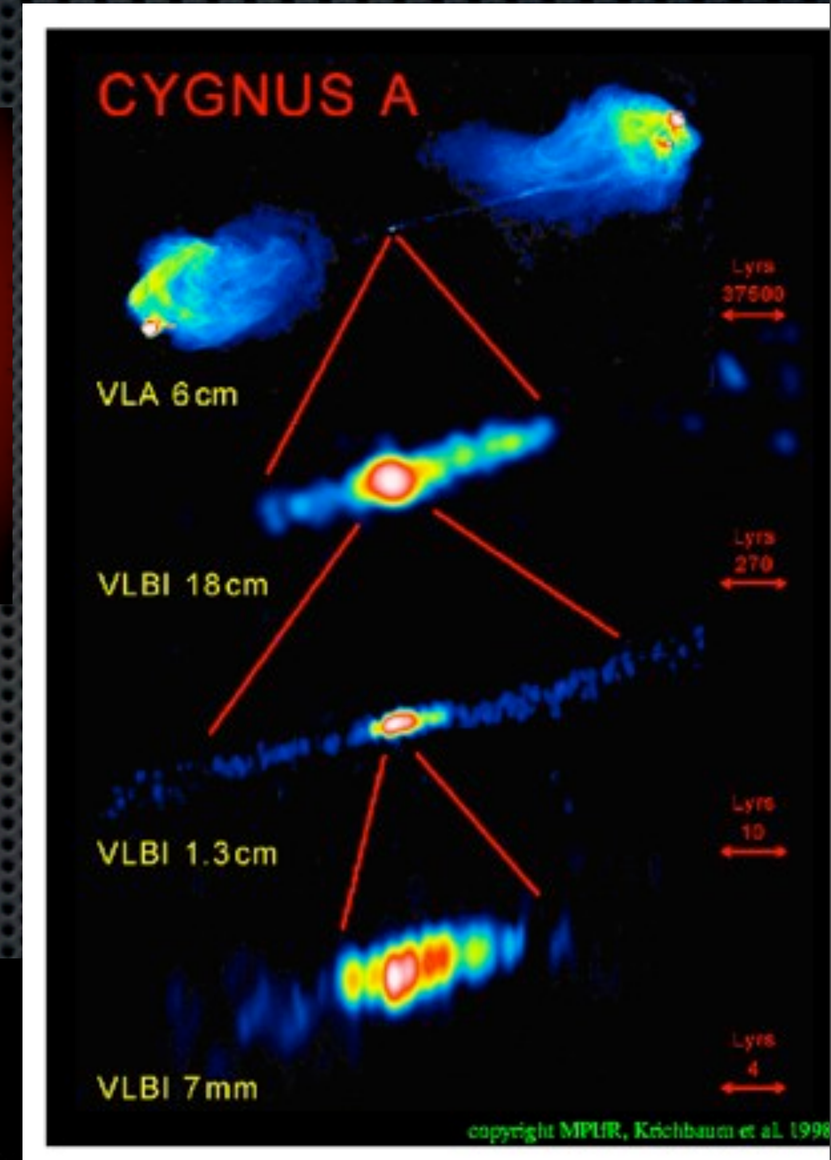
The Exciting World of Black Hole Accretion!

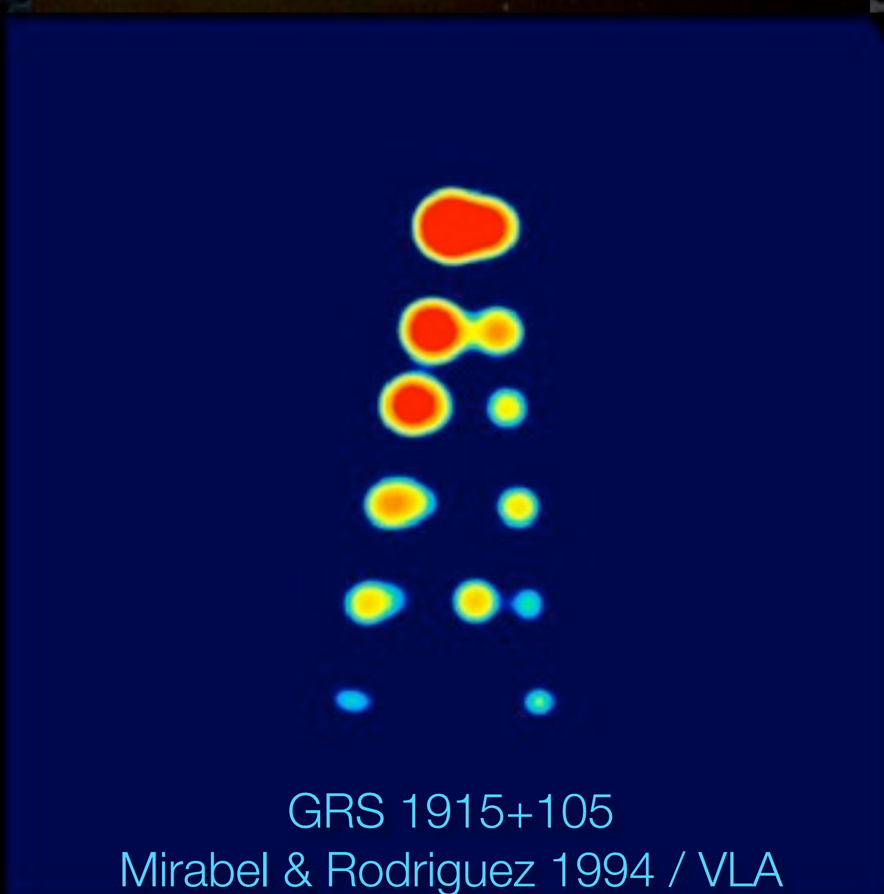


M87 / HST



Cyg A / Wilson et al. 2002 / Chandra



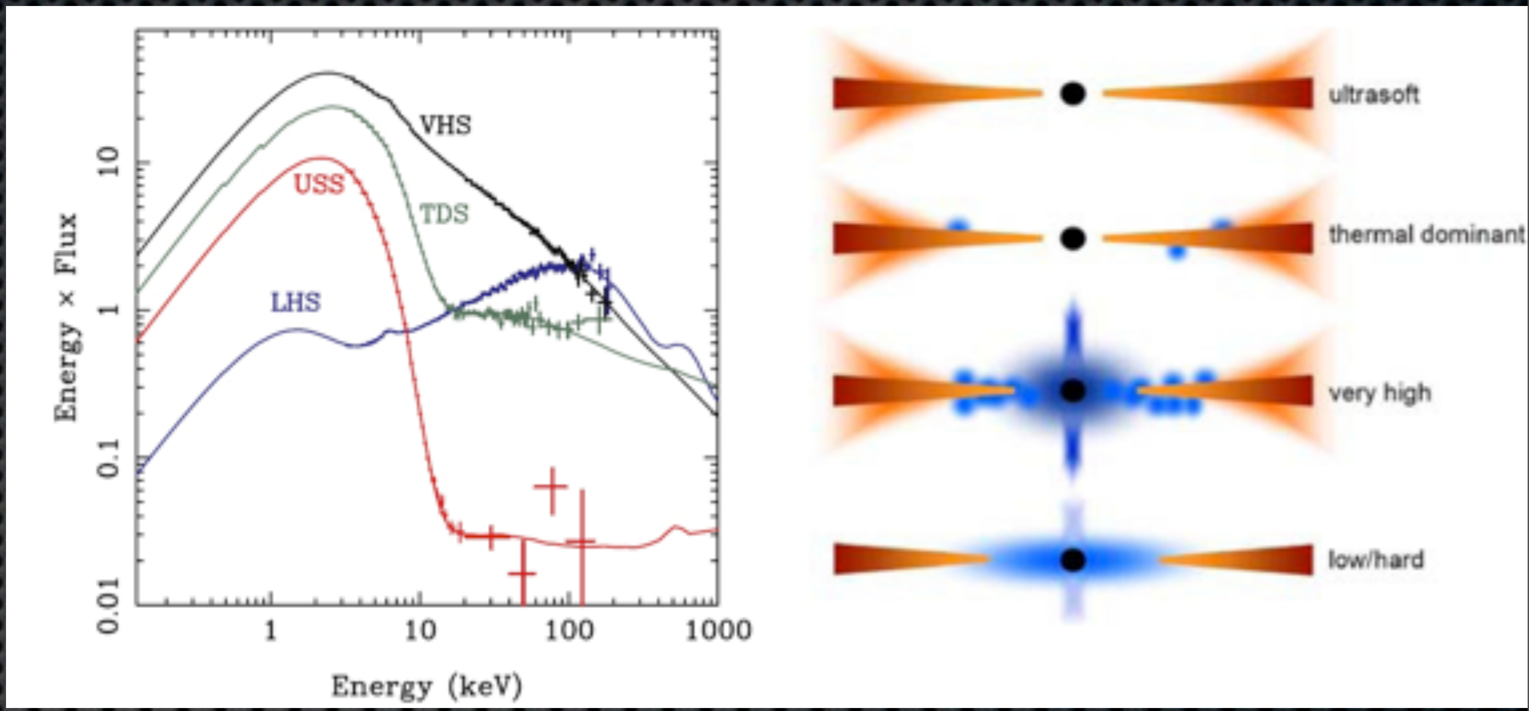


GRS 1915+105
Mirabel & Rodriguez 1994 / VLA

Probing the Spacetime of BHs

- Variability: e.g. QPOs, short time scale fluctuations

Done et al 2007



- Polarization
  (e.g. Schnittman & Krolik 2009)

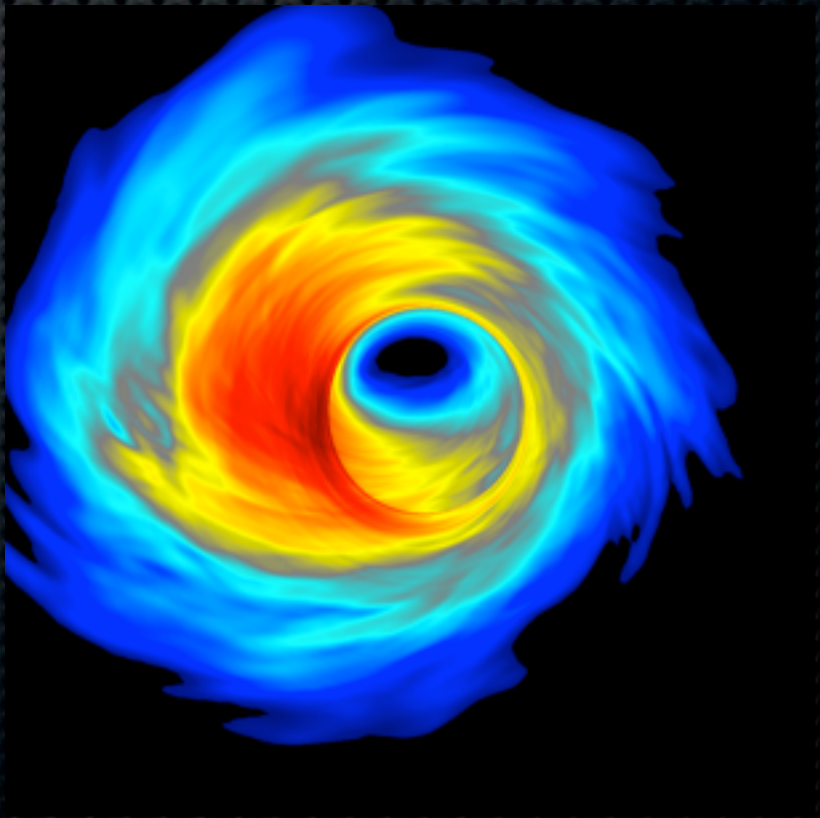
- Spectral Fitting of Thermal Emission

$$L = AR_{\rm in}^2 T_{\rm max}^4 \quad R_{\rm in}^2 = f(a, M)$$

McClintock et al. 2006, Shafee et al. 2006

- Relativistic Iron Lines

- Directly Resolving the BH Silhouette
  - e.g. Sgr A* with sub-mm/mm VLBI



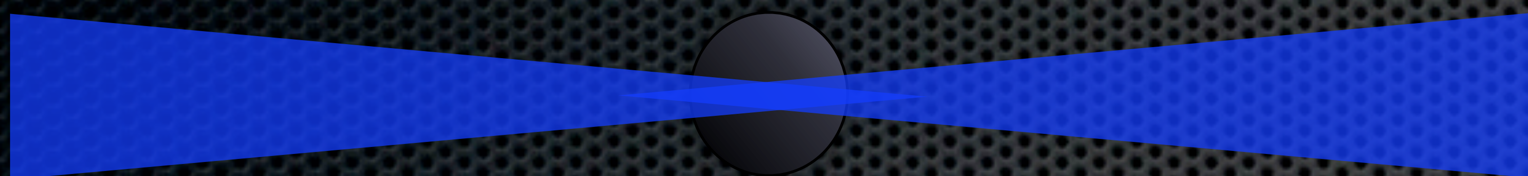
Noble et al. 2007, Mościbrodzka et al 2009,
Broderick et al 2006-2009, Doeleman et al. 2009

Disk "Dichotomy"

Thin Disks:

- Shakura & Sunyaev (1972)
- Novikov & Thorne (1972)

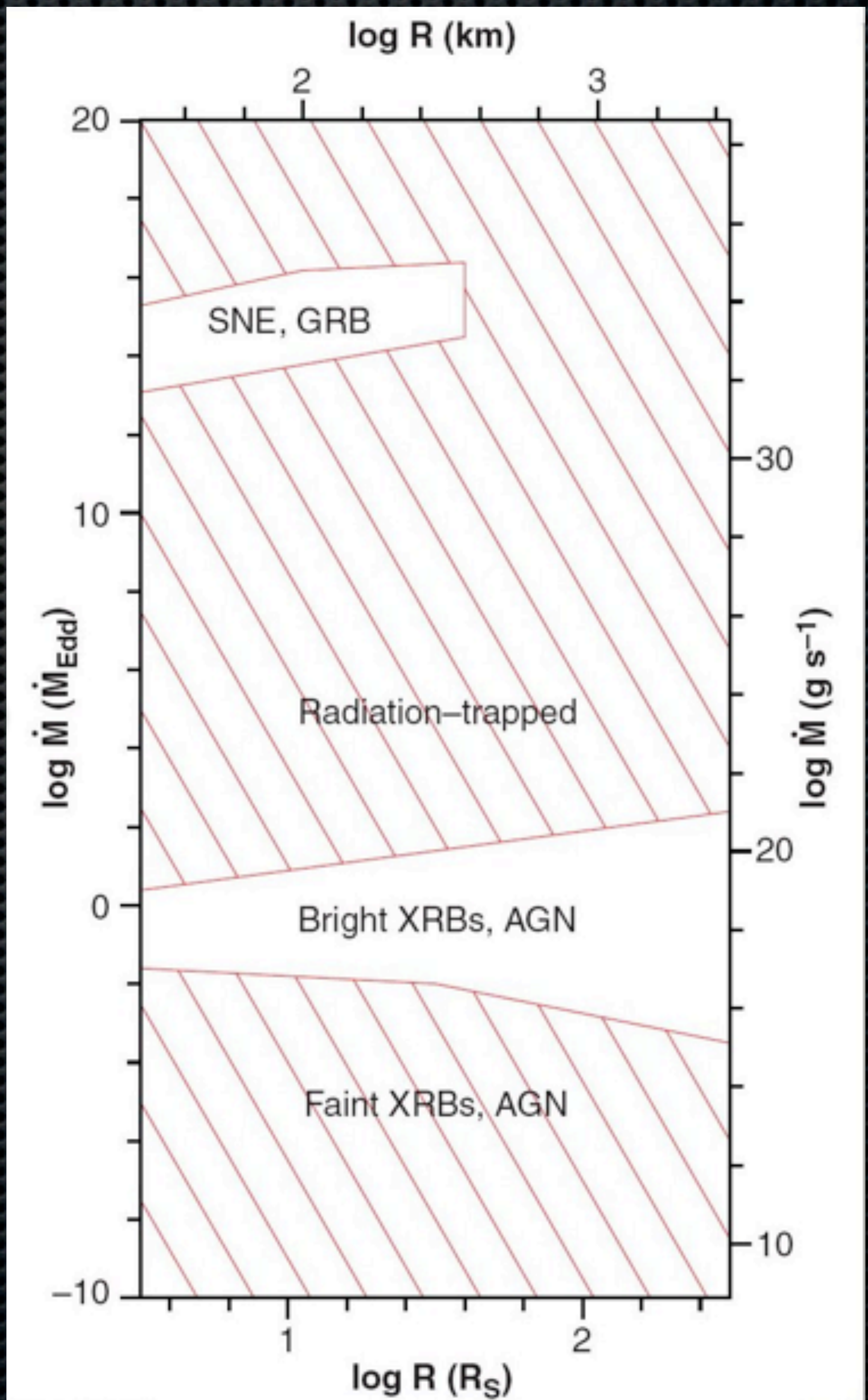
- Dissipation Rate < Cooling Rate
- "Cold" , Optically Thick
- Thermal or Multi-temperature black body



Thick Disks:

- Narayan & Yi (1994-5) (ADAF)
- Blandford & Begelman (1999) (ADIOS)
- Quataert & Gruzinov (2000) (CDAF)

- Dissipation Rate > Cooling Rate
- "Hot" , optically thin, outflows
- 2 Temperature flow, advected heat

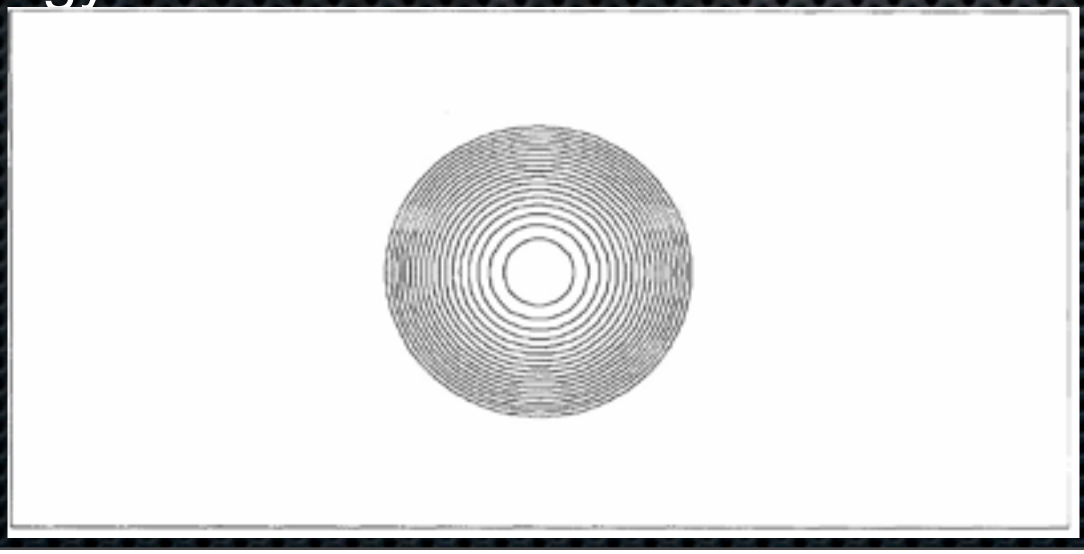


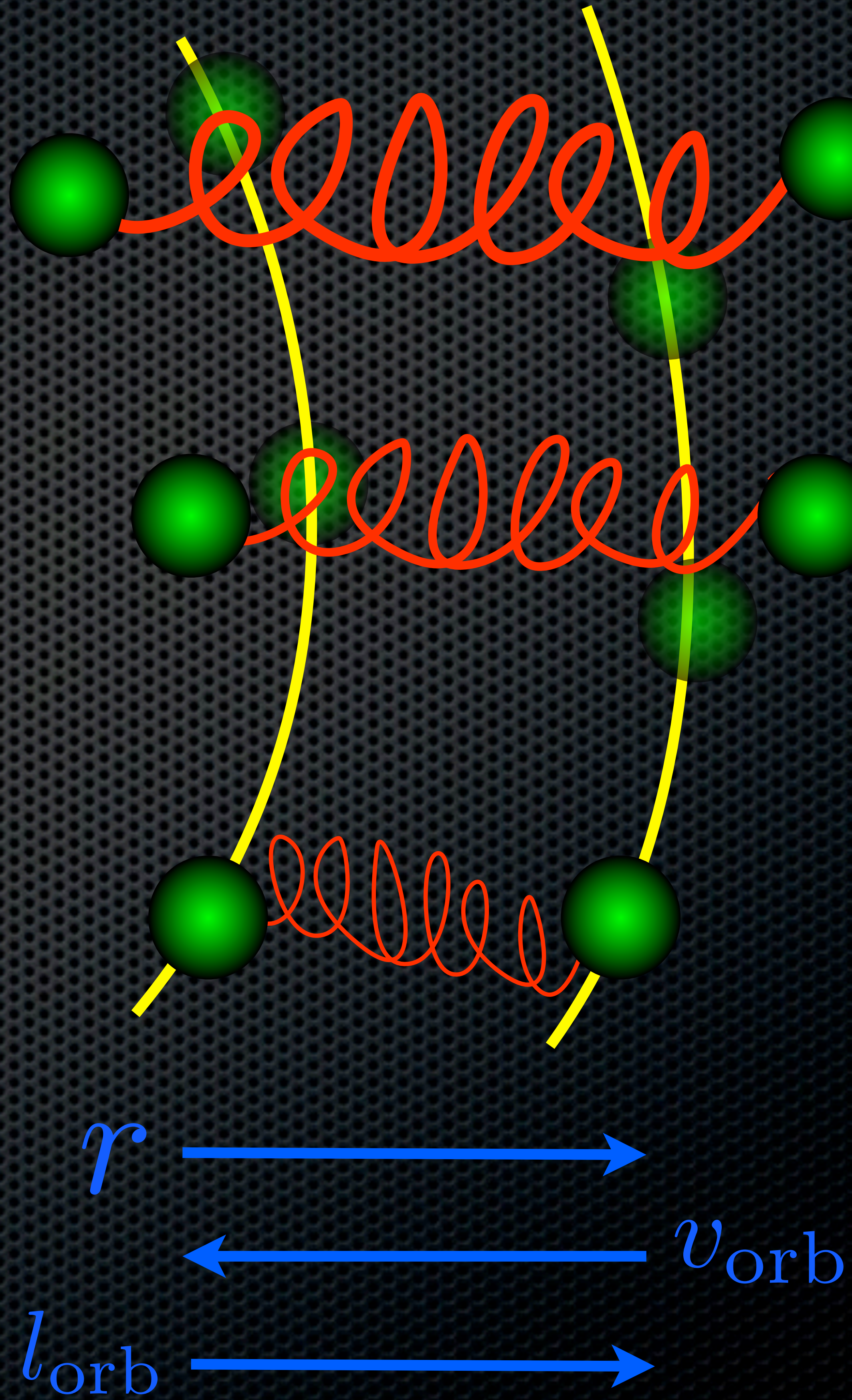
Narayan & Quataert (2005)

Magneto-rotational Instability (MRI)

- Velikhov (1959)
- Chandrasekhar (1960)
- Balbus & Hawley (1991)

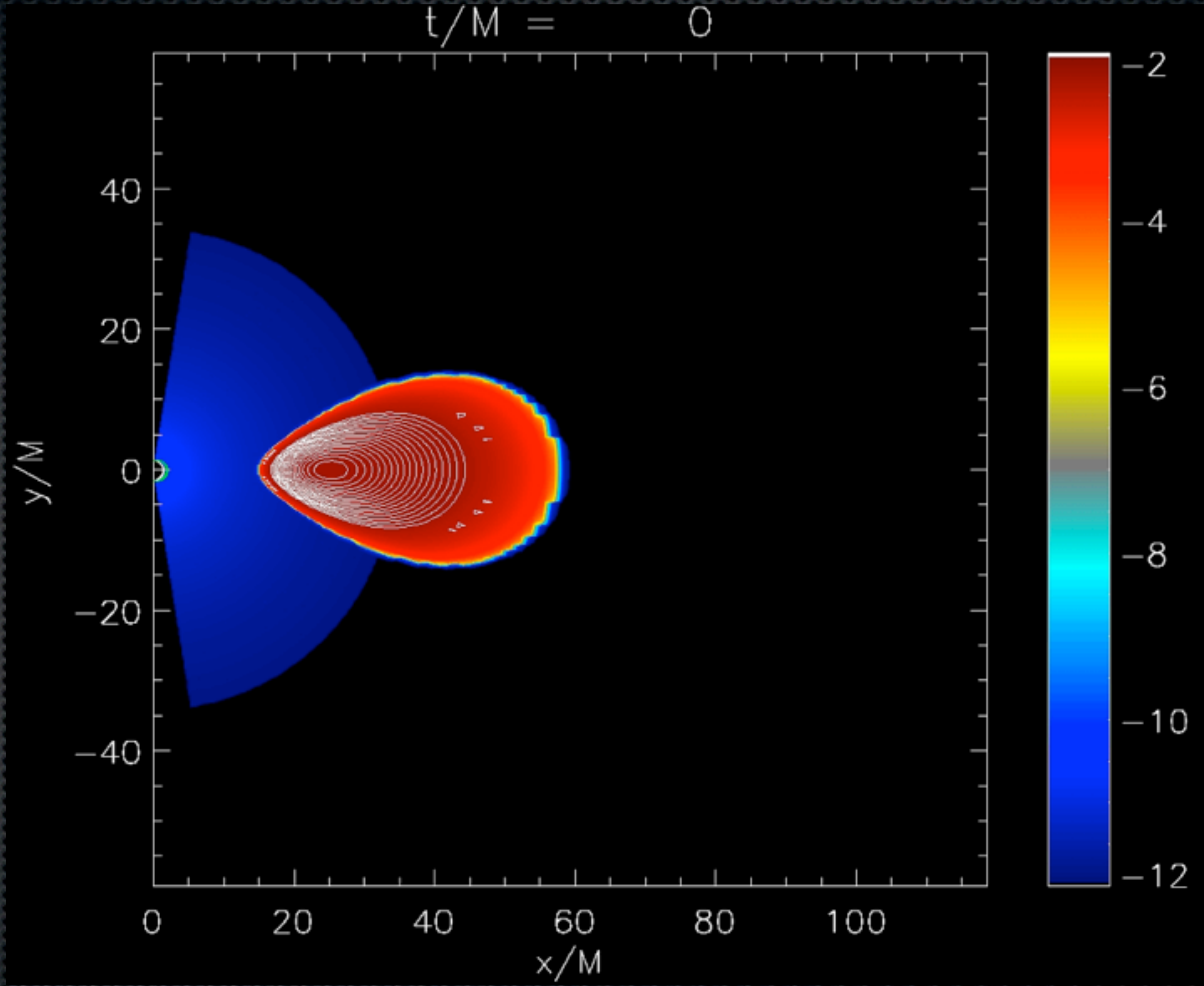
- Growth on orbital time scale.
- MRI develops from weak initial field --- relevant for any (partially) ionized gas.
- Magnetic coupling over different radii is not well described by local viscosity.
- Can explain high accretion rates where hydrodynamic viscosity cannot.
- Fastest instability known that feeds off free energy of differential rotation.





Global Disk Simulations

- Ideal GRMHD EOM
- Kerr-Schild coordinates
- Modern high-res. shock-capturing methods
- Flux (energy) conserving



$$N_r \times N_\theta \times N_\phi$$
$$=$$
$$192 \times 192 \times 64$$
$$r \in [< r_{\rm hor}, 120M]$$
$$\theta \in \pi\,[\delta, 1-\delta]$$
$$\phi \in [0, \pi/2]$$

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- Ideal GRMHD EOM
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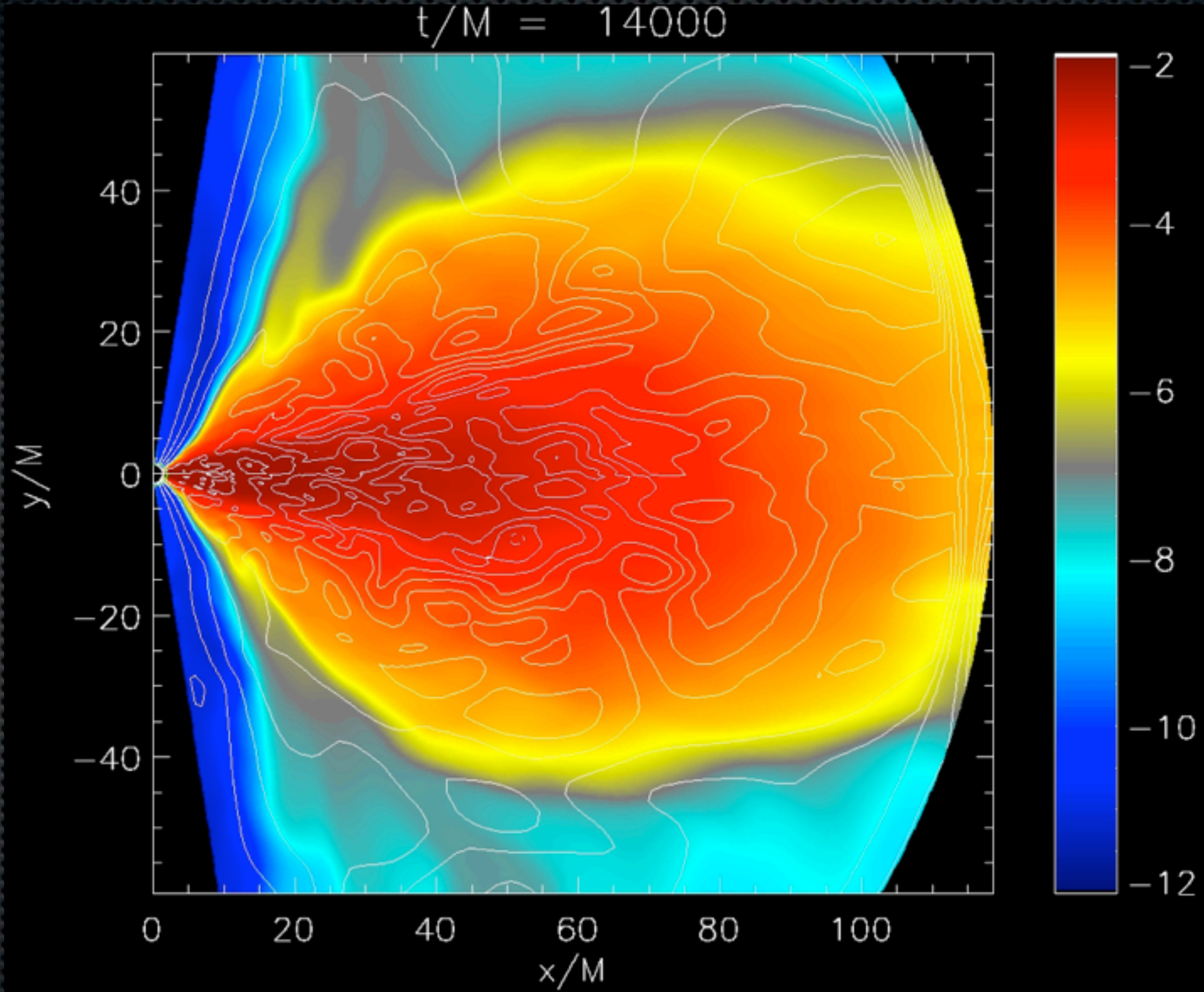

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$$=$$
$$192 \times 192 \times 64$$
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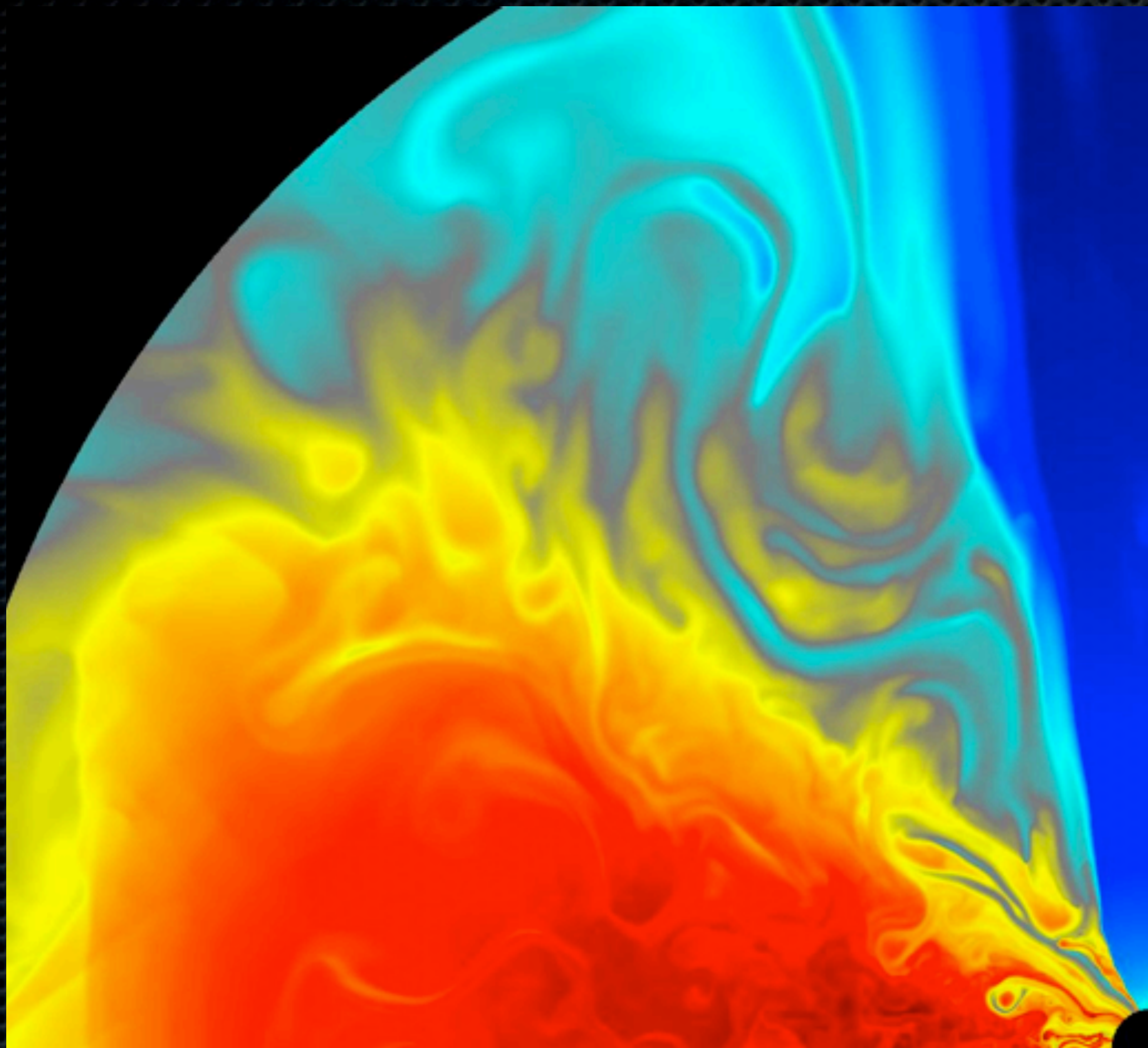
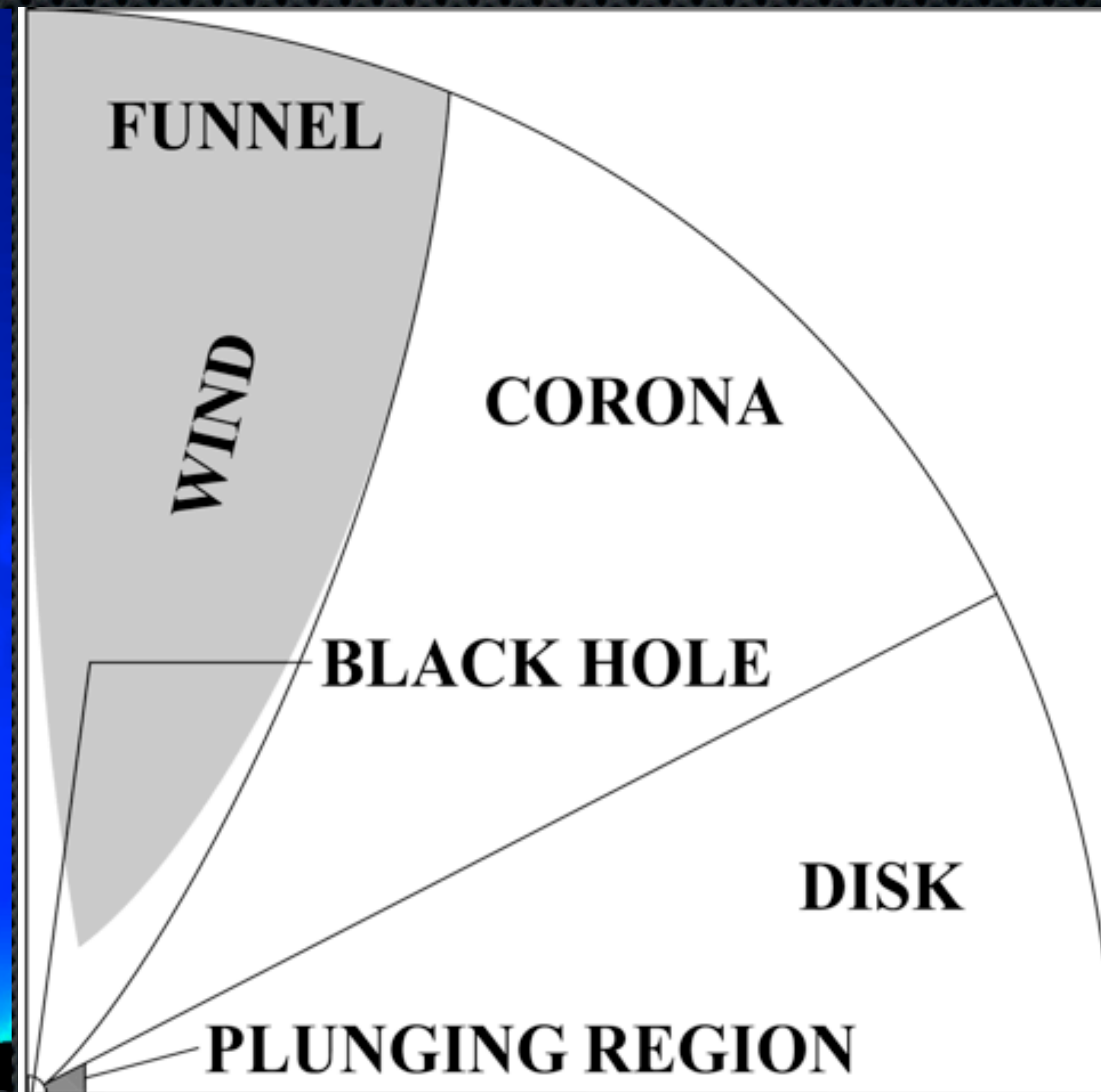
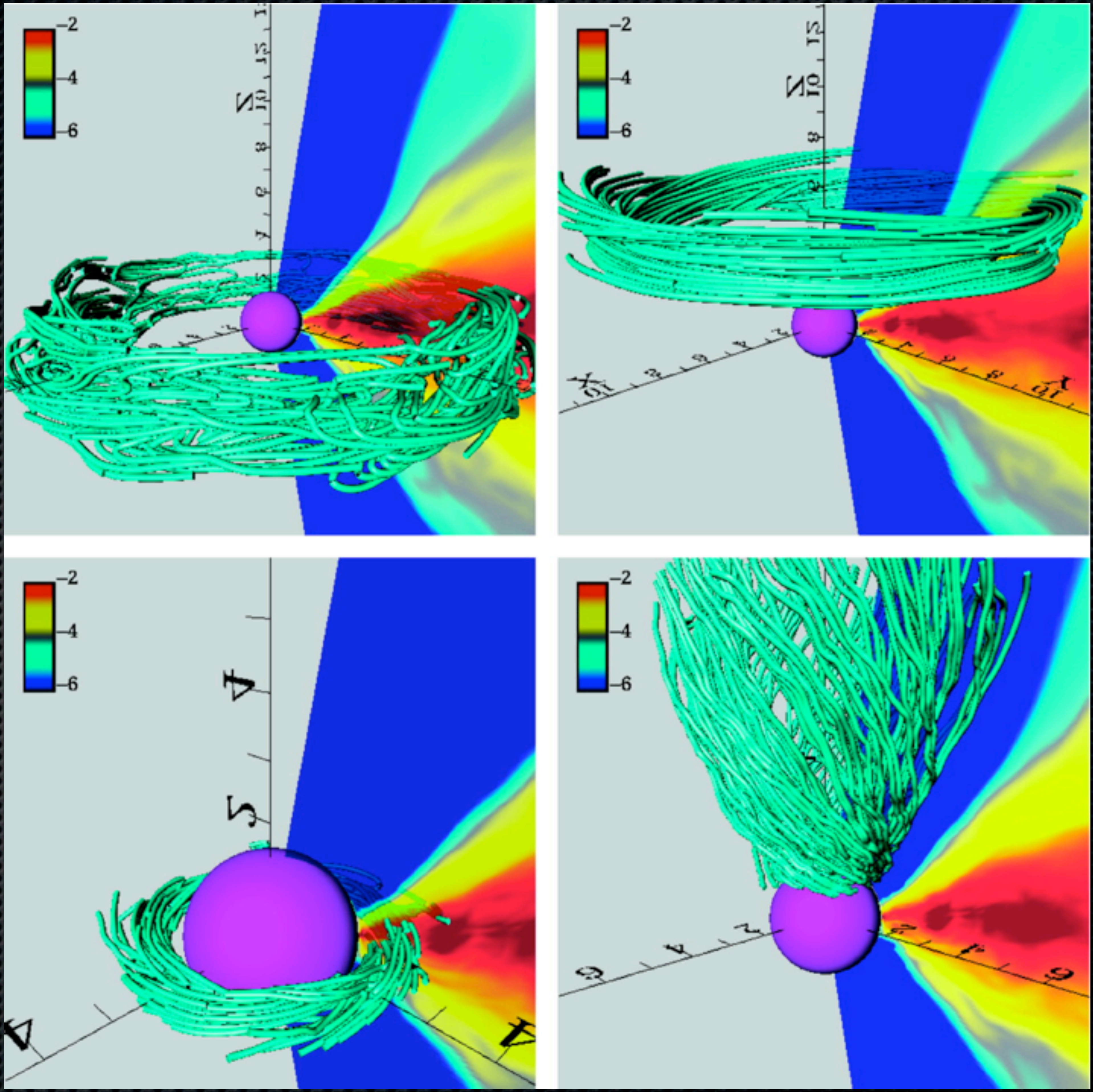
Disk Morphology





McKinney & Gammie (2004)
Hawley, De Villiers, Krolik, Hirose 2003+

Canonical Magnetic Field Distribution



Hirose et al. (2004)

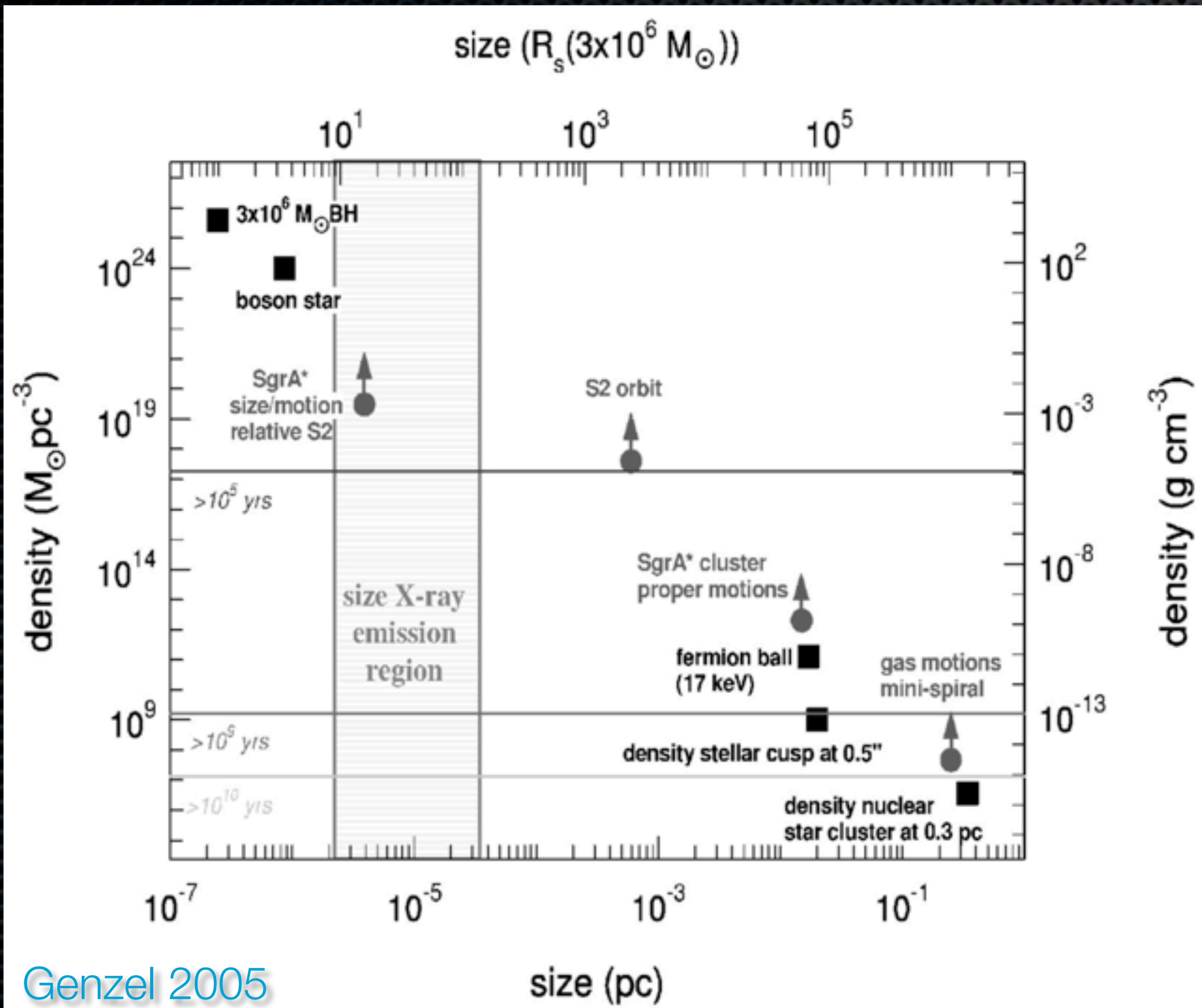
Sagittarius A* (Sgr A*)

Why Study Sagittarius A* (Sgr A*)?

- ☑ Biggest black hole on the sky!
- ☑ #5 out of 25 of David Gross' "Future of Physics" questions (tests of GR)
- ☑ Test masses orbiting it! (post-Newtonian parameters)
- ☑ Luminous plasma orbiting it! (disk theory tests, further gravity tests)

"The black hole at the center of the galaxy is officially On Notice. I don't know where this super massive black hole gets off holding the Milky Way together, nor do I care. It is blatantly challenging The Lord and will be dealt with in time. Does this singularity think God cannot hold our galaxy together on His own? Black hole, you may have swallowed a million suns, but now you're dealing with America! You're On Notice."

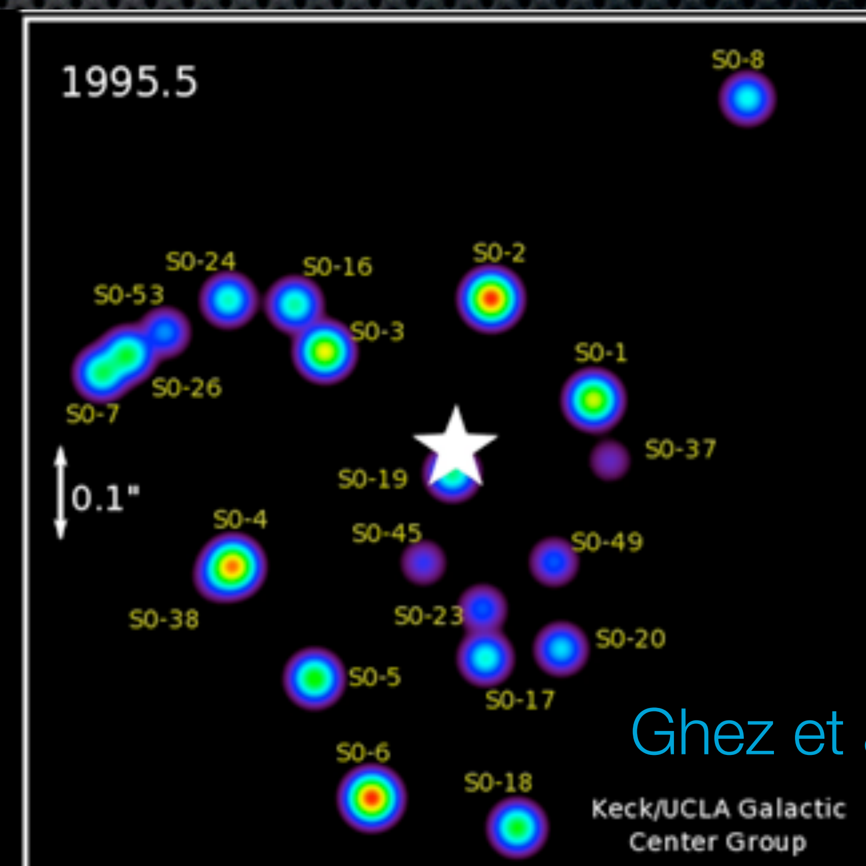
The Central Gravitational Source



Genzel 2005

Ghez et al (2008)
Gillesen et al (2009)

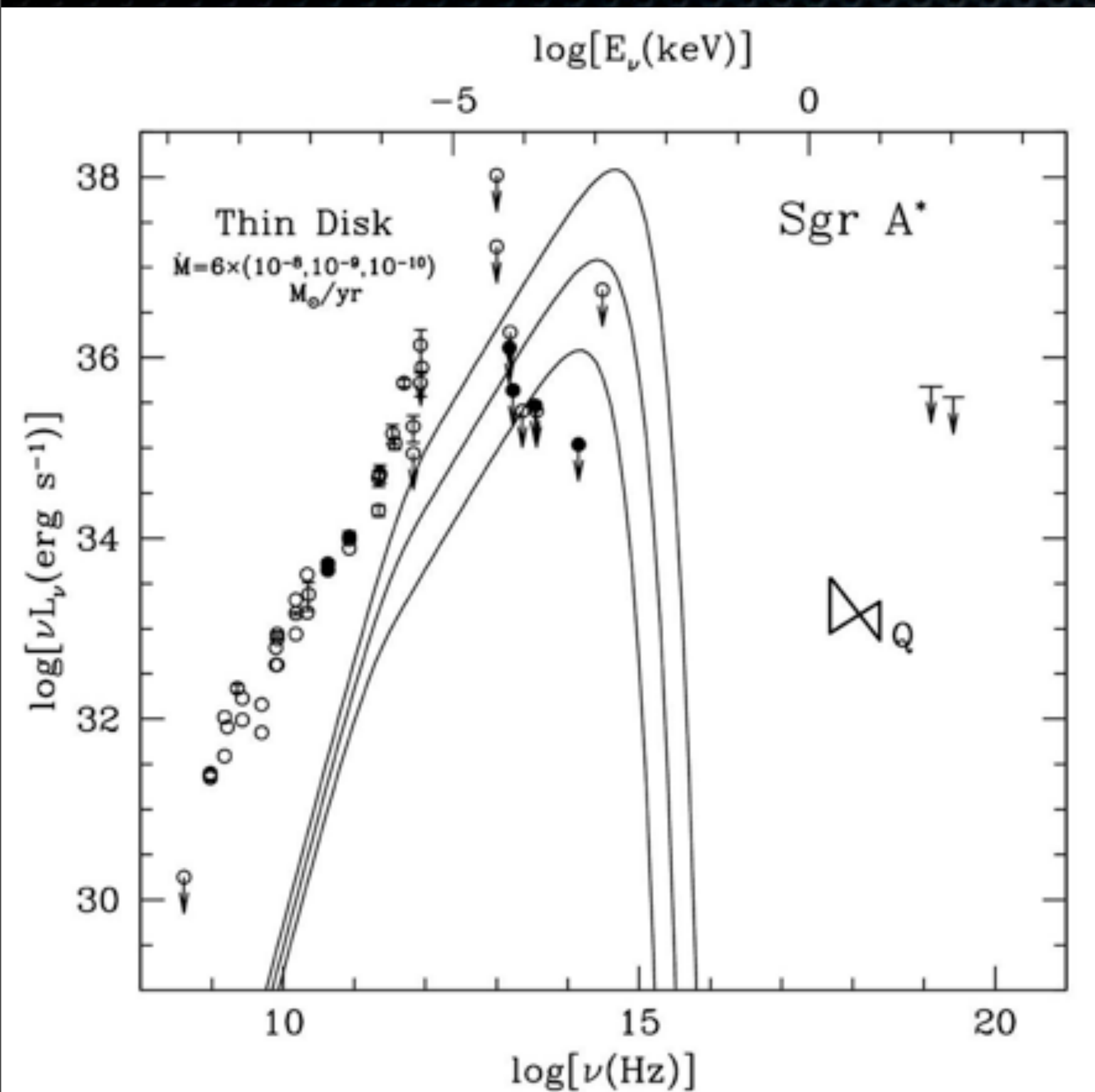
$$D \simeq 8.4\text{kpc}$$
$$M_{\rm BH} \simeq 4.5 \times 10^6 M_\odot$$

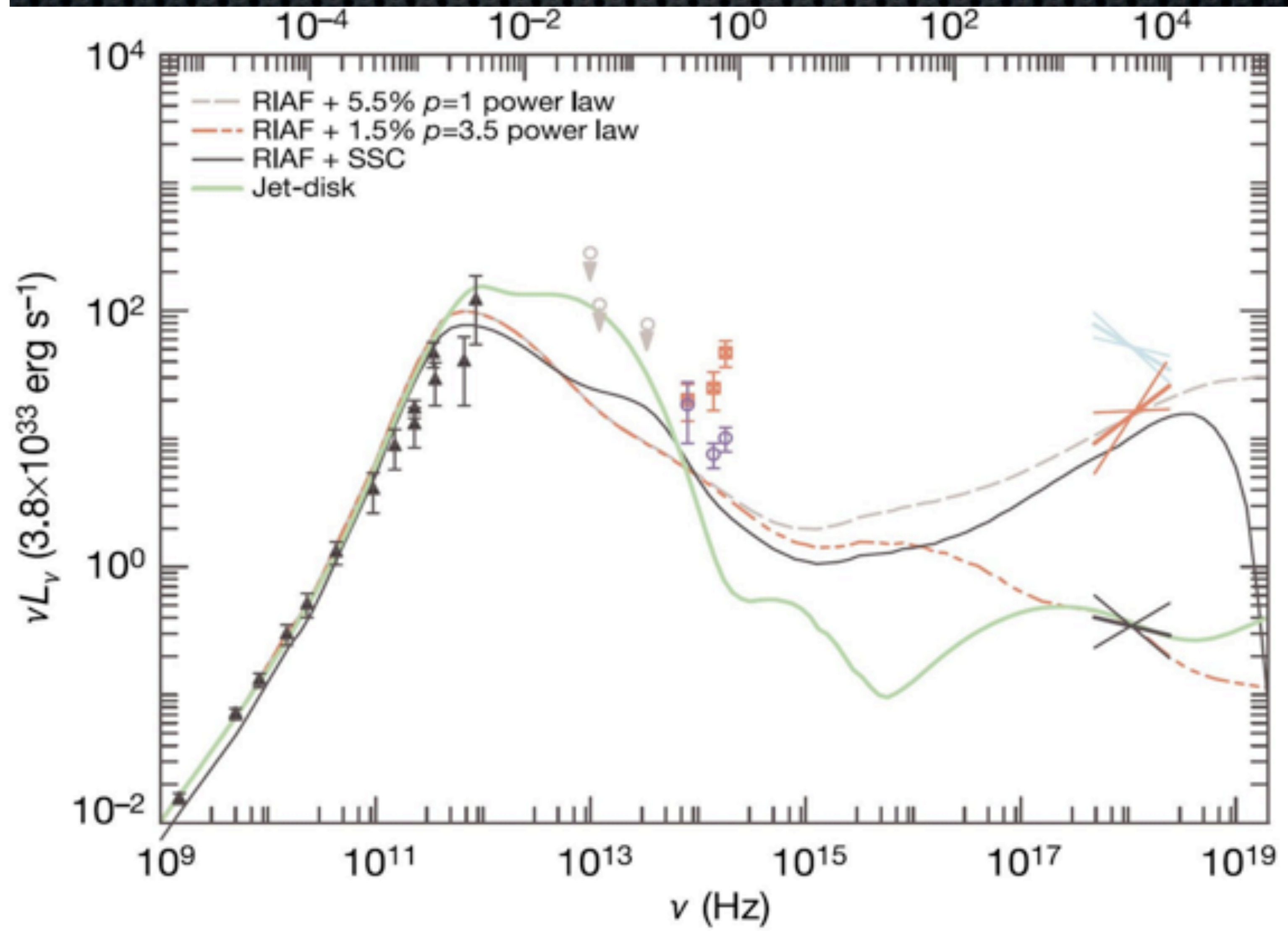


Ghez et al

$$r_s = 1 \times 10^{12}\text{cm} = 3.6 \times 10^{-7}\text{pc} = 0.07\text{AU} = 10\mu\text{as} = 33\text{sec}$$

The Enigmatic Accretor





Narayan astro-ph/0201260

$$\dot{M}_{\rm RM}\,(r \simeq r_s) \simeq 10^{-3}\dot{M}_{\rm X-rays}$$

Marrone et al. 2006

$$L_{\rm SgrA*} = 10^3 L_\odot = 10^{-9} L_{\rm edd} \qquad L_{\rm SgrA*} = 10^{-2}\left(\frac{\eta}{0.1}\right) c^2 \dot{M}_{\rm RM}$$

Much Theoretical Interest!!

Moscibrodzka et al 2010, arxiv 1002.1261

Reference	dynamical model	radiative model	plasma	range of model
Narayan et al. (1998)	stat. rel. ADAF	non-rel. MC	th	$10^5 R_g$
Markoff et al. (2001)	Jet	scaling	non-th	–
Yuan et al. (2003)	stat non-rel. RIAF	non-rel rays	th+non-th	$2 \times 10^5 R_g$
Ohsuga et al. (2005)	MHD-time dep.	non-rel. MC	th	$60 R_g$
Goldston et al. (2005)	MHD-time dep.	polarized non-rel. rays	th+non-th	$512 R_g$
Broderick & Loeb (2006b)	stat. non-rel RIAF	polarized RT	non-th	$2 \times 10^5 R_g$
Mościbrodzka et al. (2007)	MHD-time dep.	non-rel. MC	th+non-th	$2.4 \times 10^3 R_g$
Loeb & Waxman (2007)	Jet	scaling	th+non-th	–
Huang et al. (2007)	stat. RIAF	RT	th	$2 \times 10^5 R_g$
Markoff et al. (2007)	Jet	non-rel rays /w corr	non-th	–
Huang et al. (2009)	stat. rel. RIAF	RT	th	$10^4 R_g$
Broderick et al. (2009)	stat. rel. RIAF	RT	th+non-th	$2 \times 10^5 R_g$
Chan et al. (2009)	MHD-time dep.	non-rel rays /w corr.	th+non-th	$43 R_g$
Yuan et al. (2009)	stat. rel. RIAF	RT	th	$100 R_g$
Hilburn et al. (2009)	GRMHD-time dep.	non-rel MC	th	$40 R_g$
Dexter et al. (2009)	GRMHD-time dep.	RT	th	$40 R_g$
Mościbrodzka et al. (2009)	GRMHD-time dep.	RT + rel. MC	th	$40 R_g$
Noble et al. (2007)	GRMHD-time dep.	RT	th	40 Rg

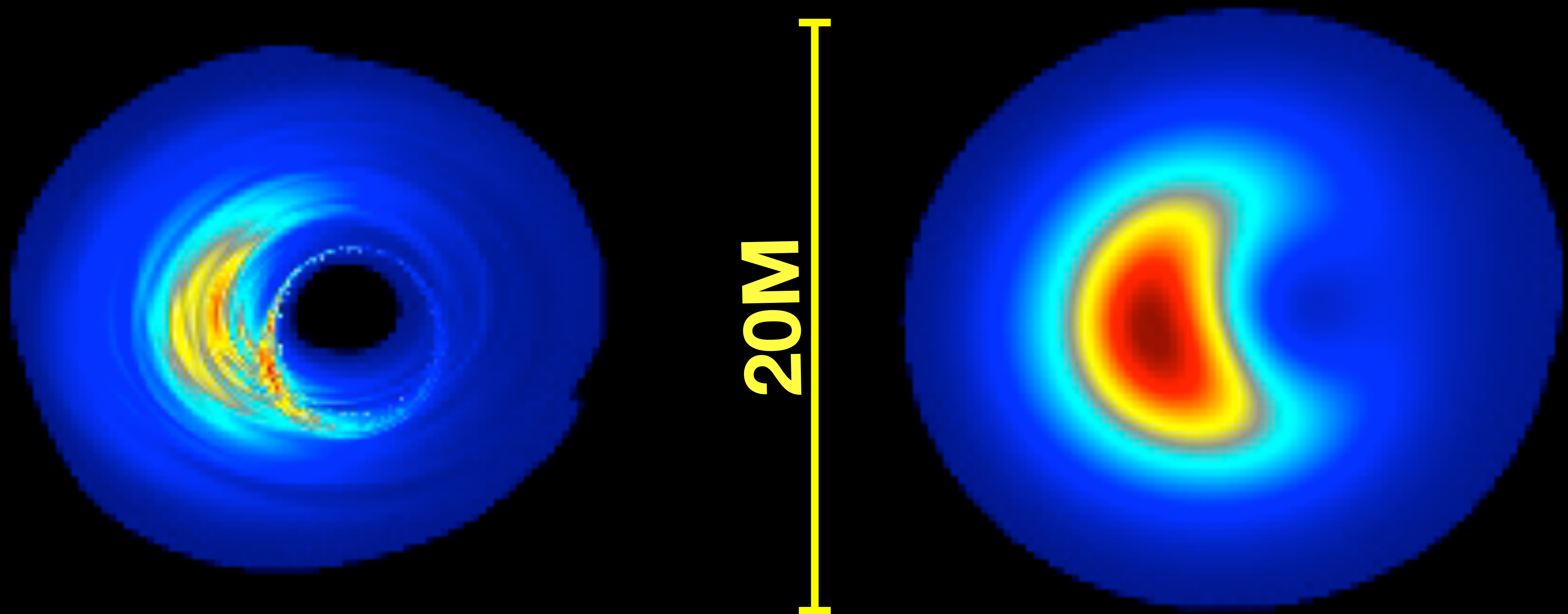
Table 1. Summary of selected models of Sgr A*. Abbreviations: RT-ray tracing, MC-Monte Carlo, GR-general relativistic, RIAF-radiatively inefficient accretion flow, ADAF-advection dominate accretion flow, plasma-particles distribution, th-thermal, non-th-non-thermal, range-model radial range.

SCN, Leung, Gammie, Book (2007)

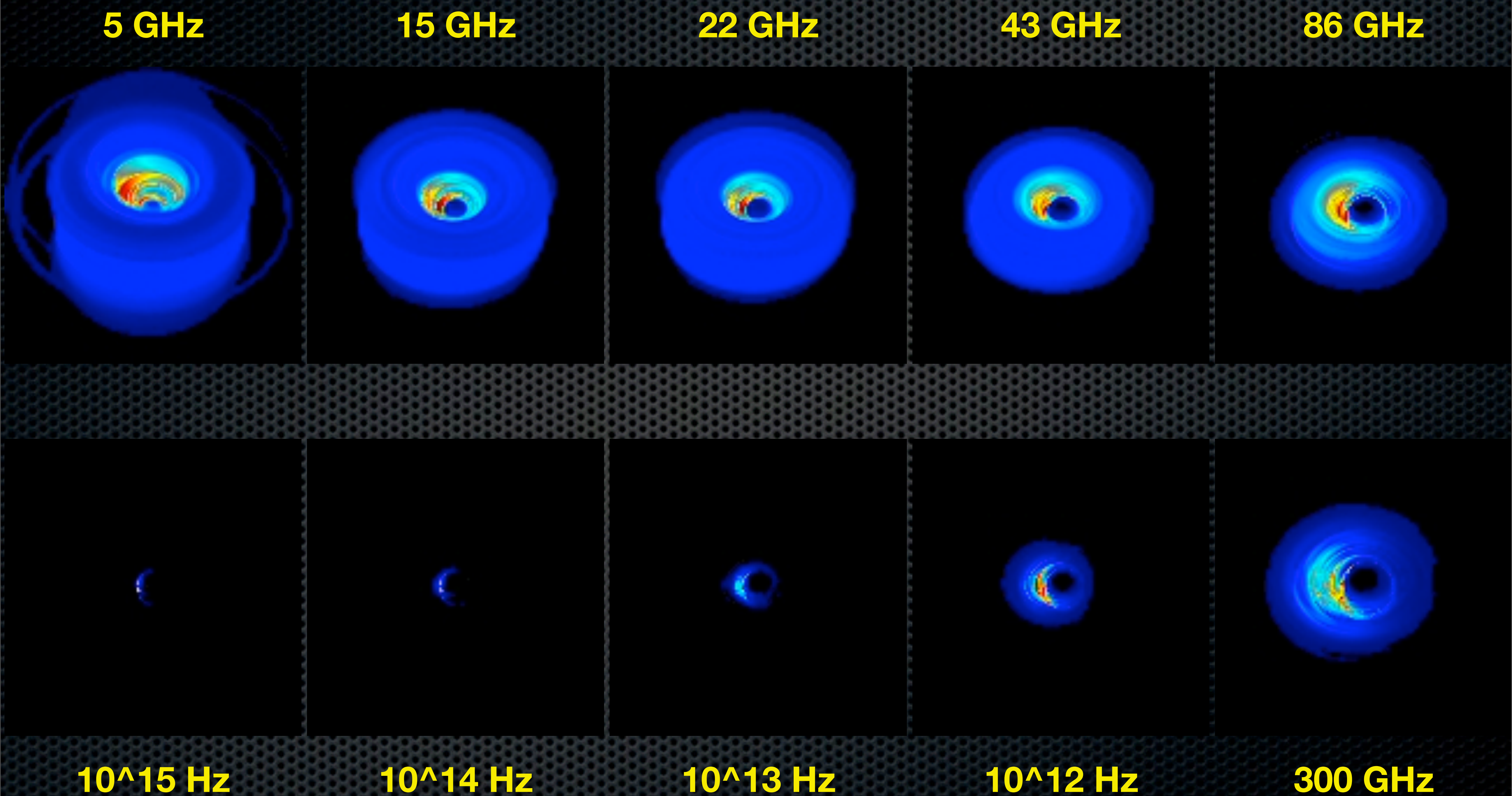
- Axi-symmetric GRMHD Simulations (256x256) w/ HARM
- a = 0, 0.5, 0.75, 0.88, 0.93, 0.97
- Rout = 40M, Pmax at r=10-15M
- Relativistic self-absorbed synchrotron and brems. rad. transfer

Fiducial Model

$$a = 0.94M$$
$$\nu_{\rm obs} = 3 \times 10^{11}\,{\rm Hz(1mm)}$$
$$i = 30^\circ$$
$$\dot{M} = 5 \times 10^{-9} M_\odot {\rm yr}^{-1}$$

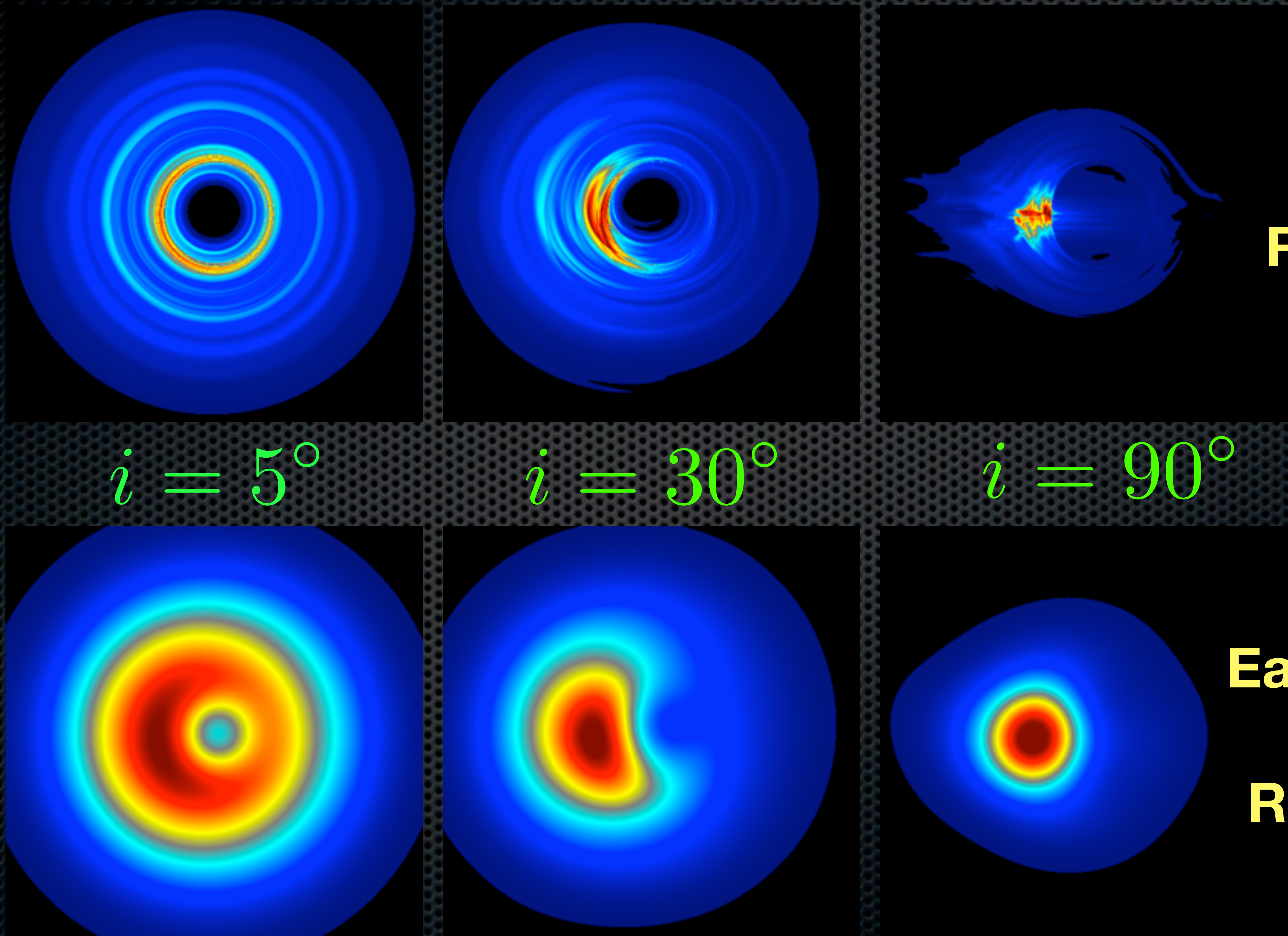


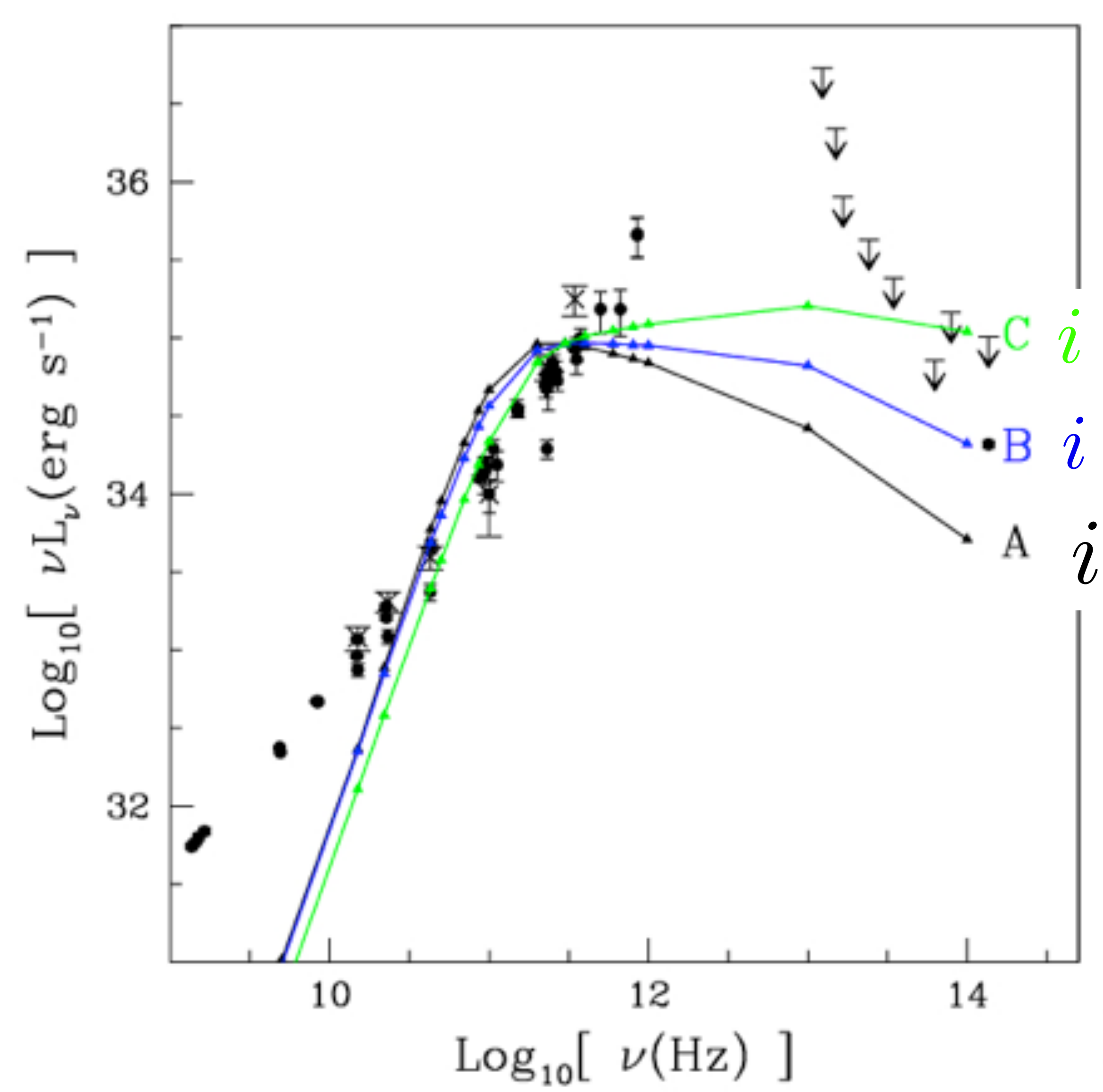
Source Size


5 GHz
15 GHz
22 GHz
43 GHz
86 GHz
10^15 Hz
10^14 Hz
10^13 Hz
10^12 Hz
300 GHz

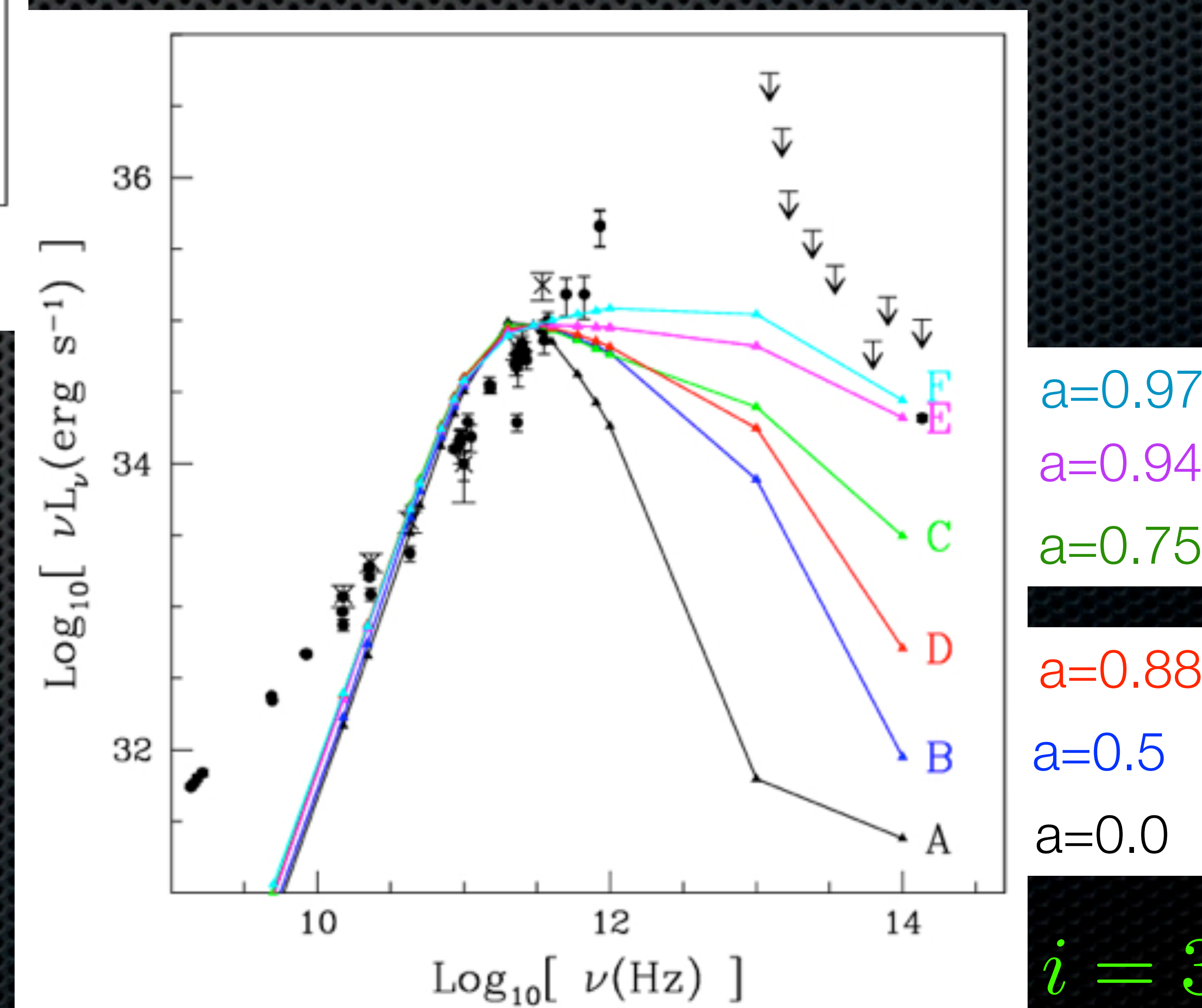
Black Hole Silhouette

- $a = 0.94$
- VLBI Base line = 8000km
- $\lambda = 1\mathrm{mm}$



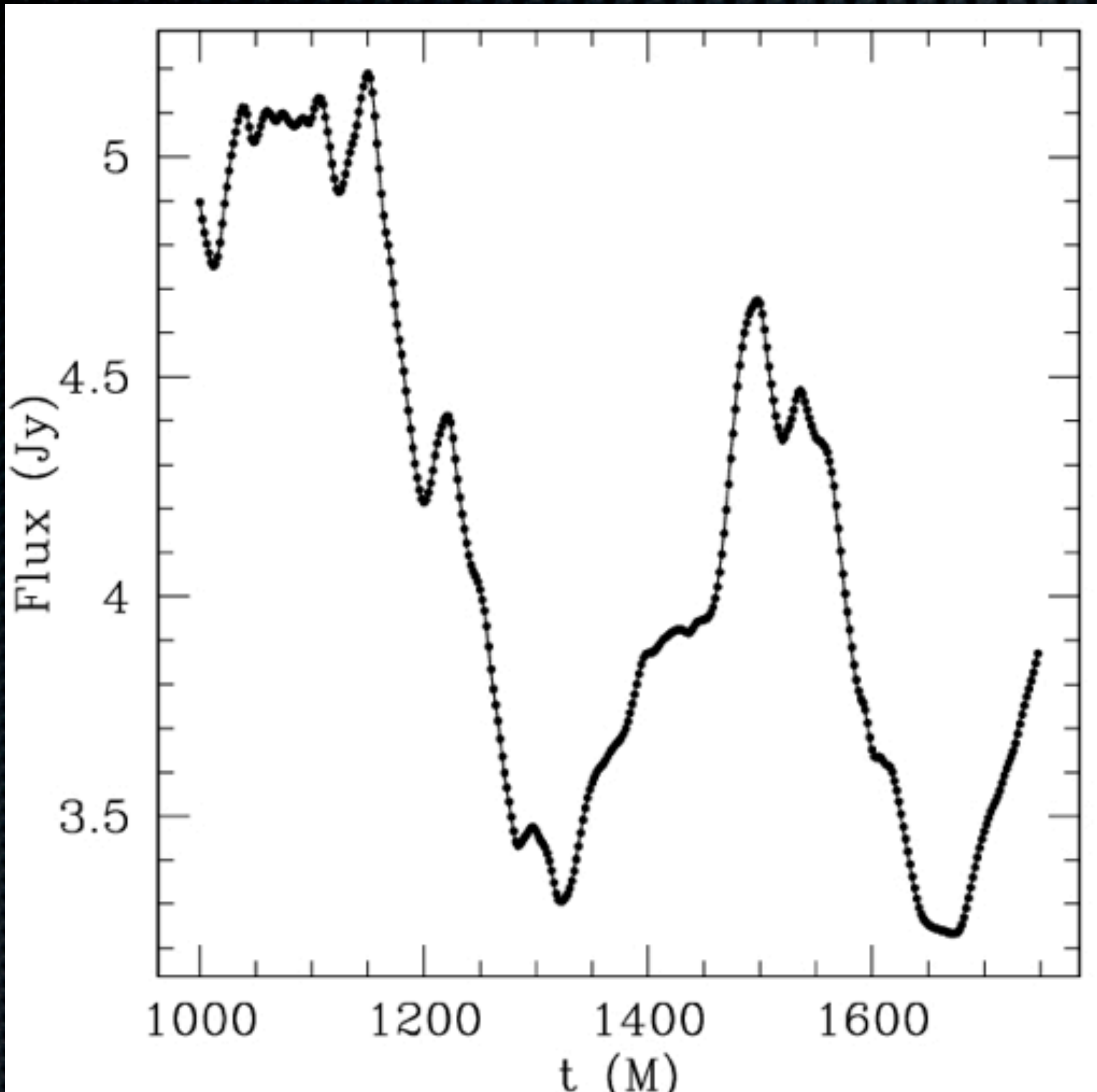


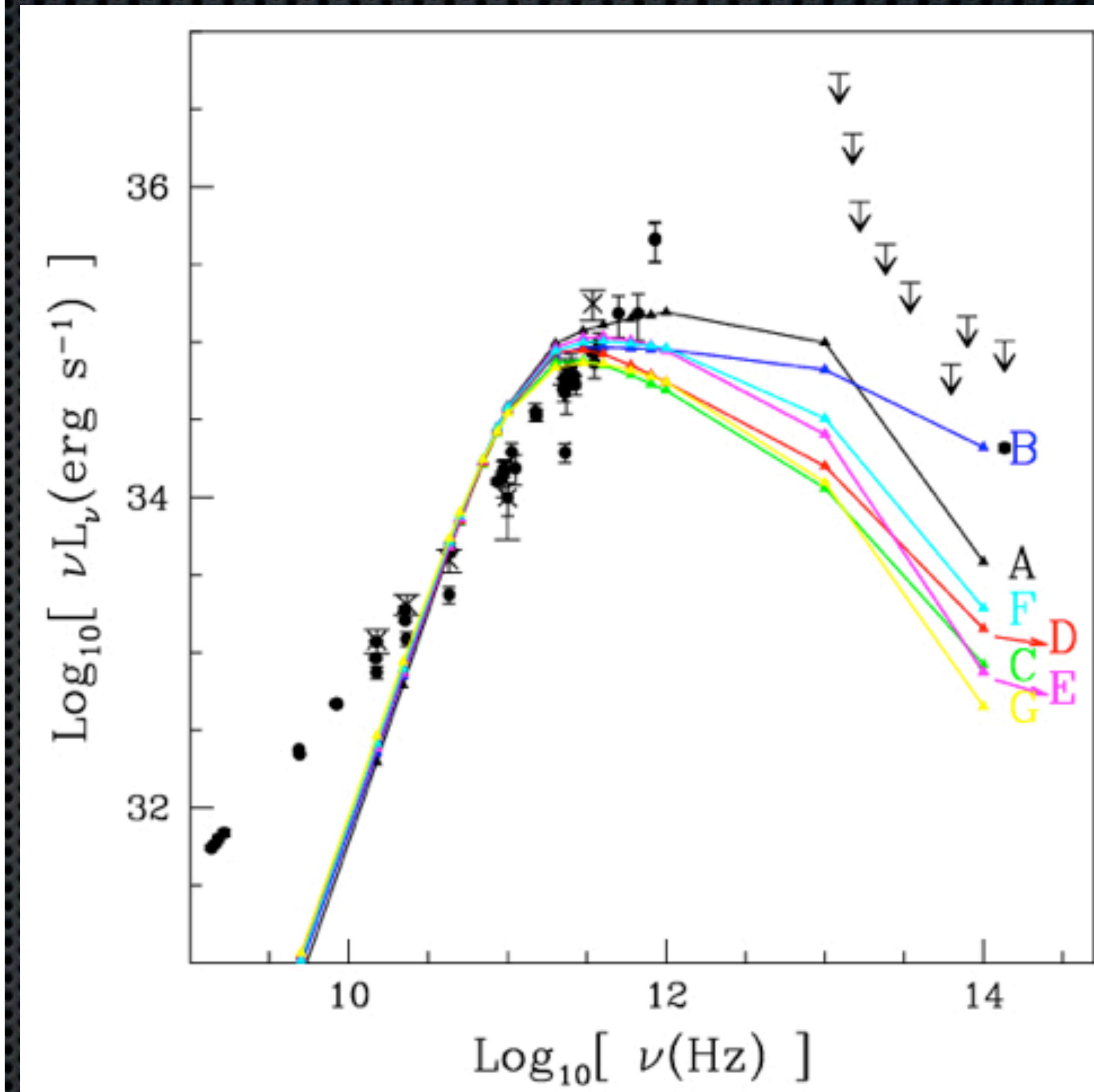
- Relativistic beaming/boosting sensitive to inclination angle;
- Amplifies relative spectral importance of high-T inner region;
- Our model favored smaller inclinations or more "face-on" disks;



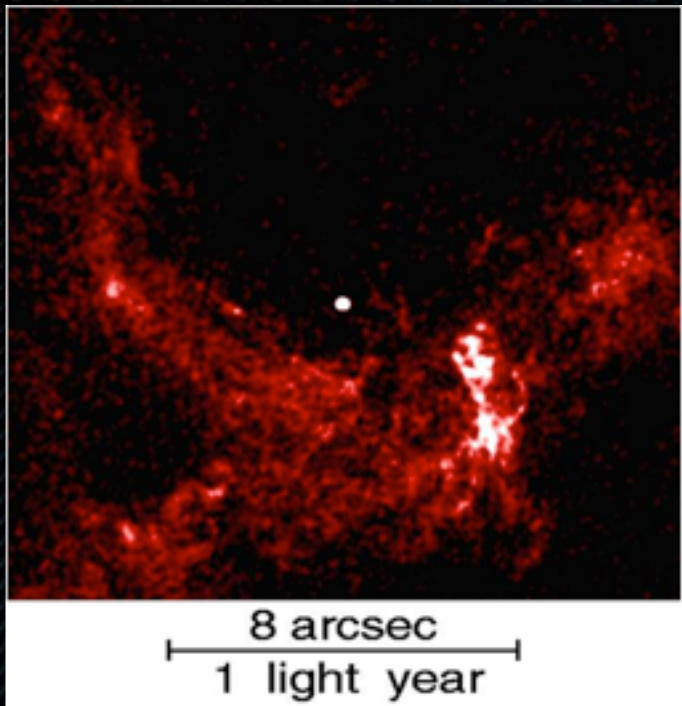
- Largest orbital velocities, temperatures and B-field increase with BH spin;
- Predict a < 0.88

Time-dependence





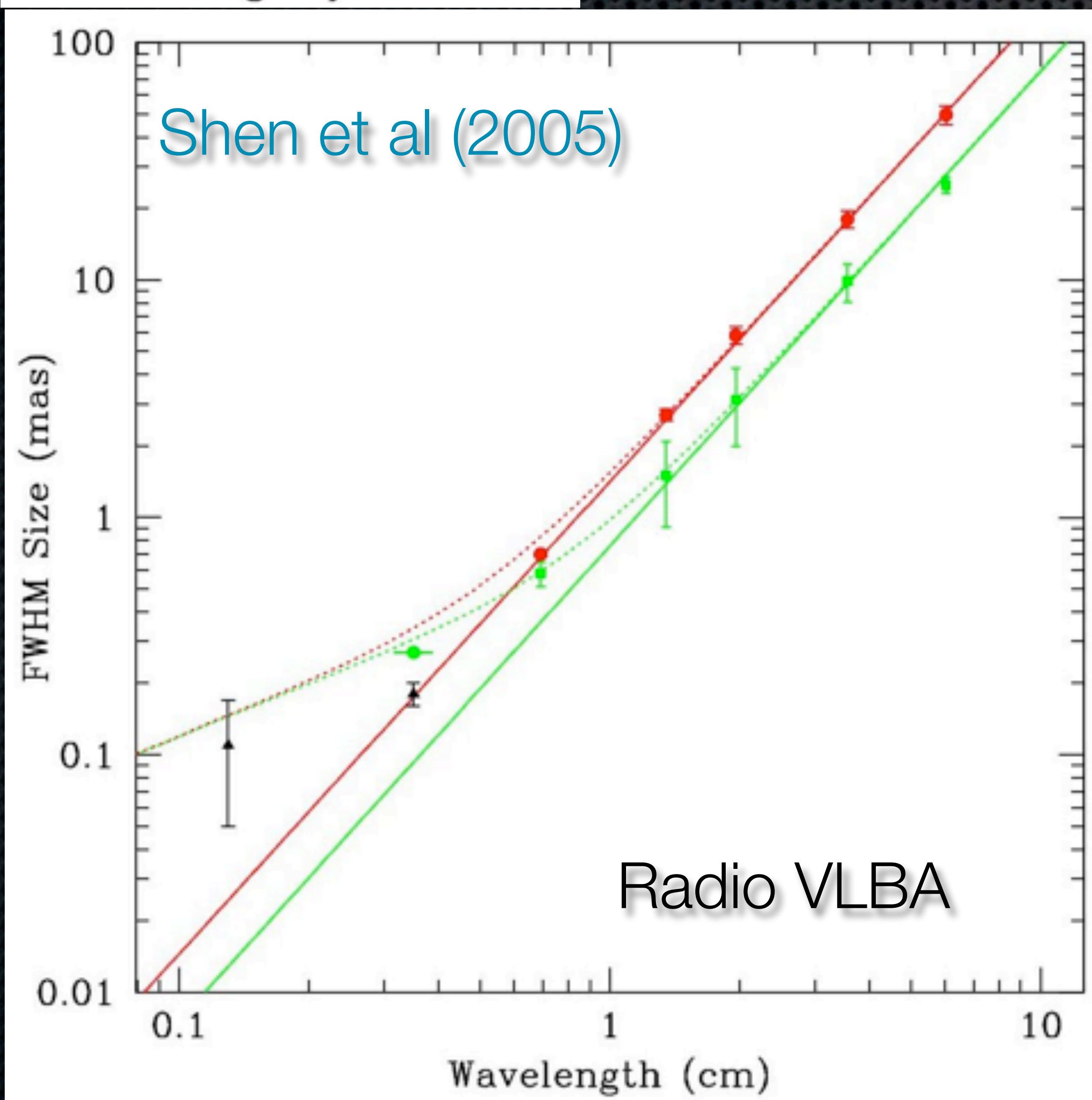
- Variability greatest at optically thin frequencies
- Weaker variability at 1mm consistent with flare events
- Time variation < spin variation
    - Hope for bracketing black hole spin

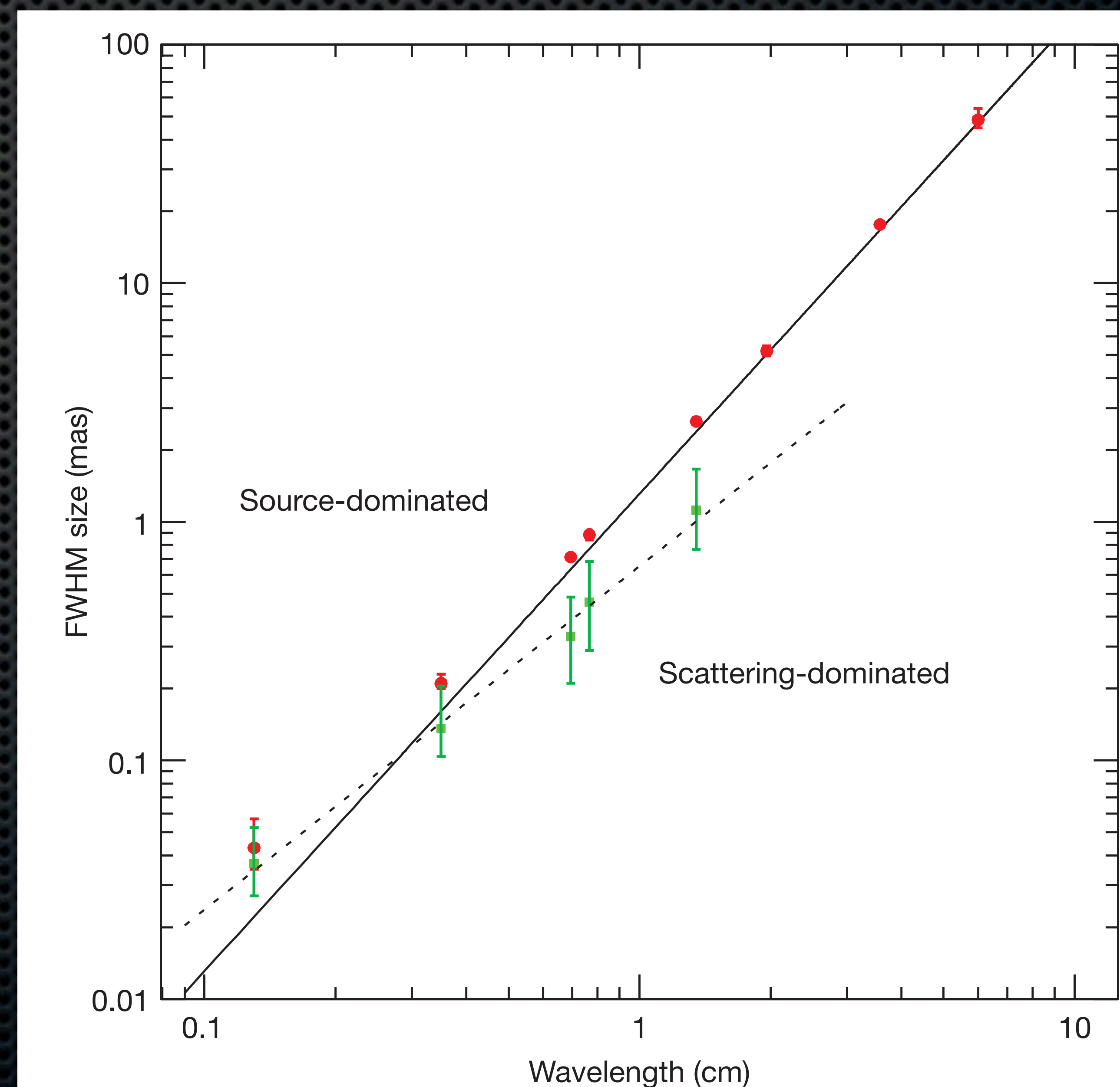


Towards Horizon-scale Observations:

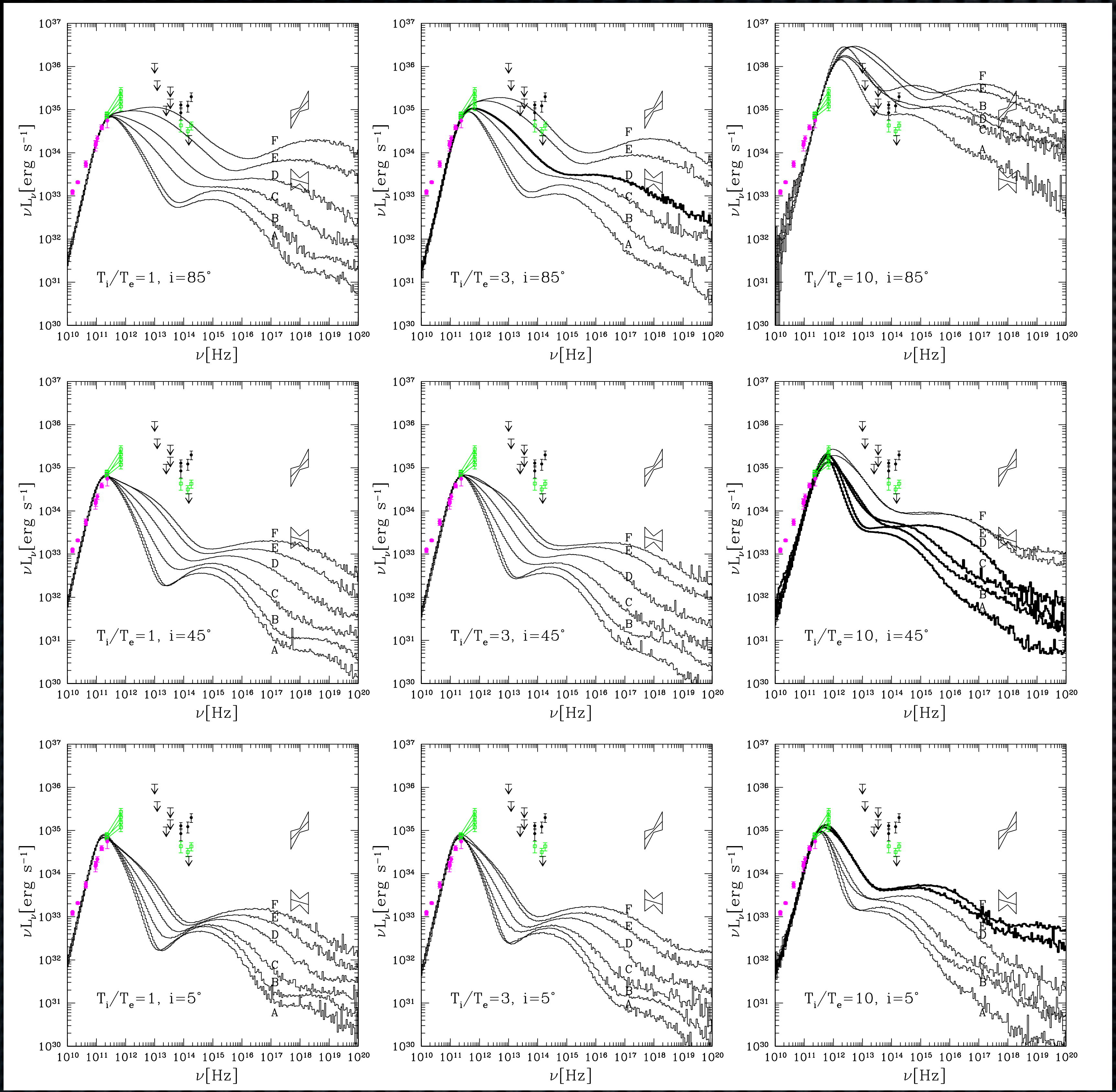
Doeleman et al (2008)

- Observe at freq. where disk becomes transparent;
- ARO/SMT, CARMA, JCMT
- Baseline = 4700km
- $\mathrm{FHWM} \simeq 4r_s$
- Towards the "Event Horizon Telescope"





Moscibrodzka, Gammie, Dolence, Shiokawa, Leung (2009)

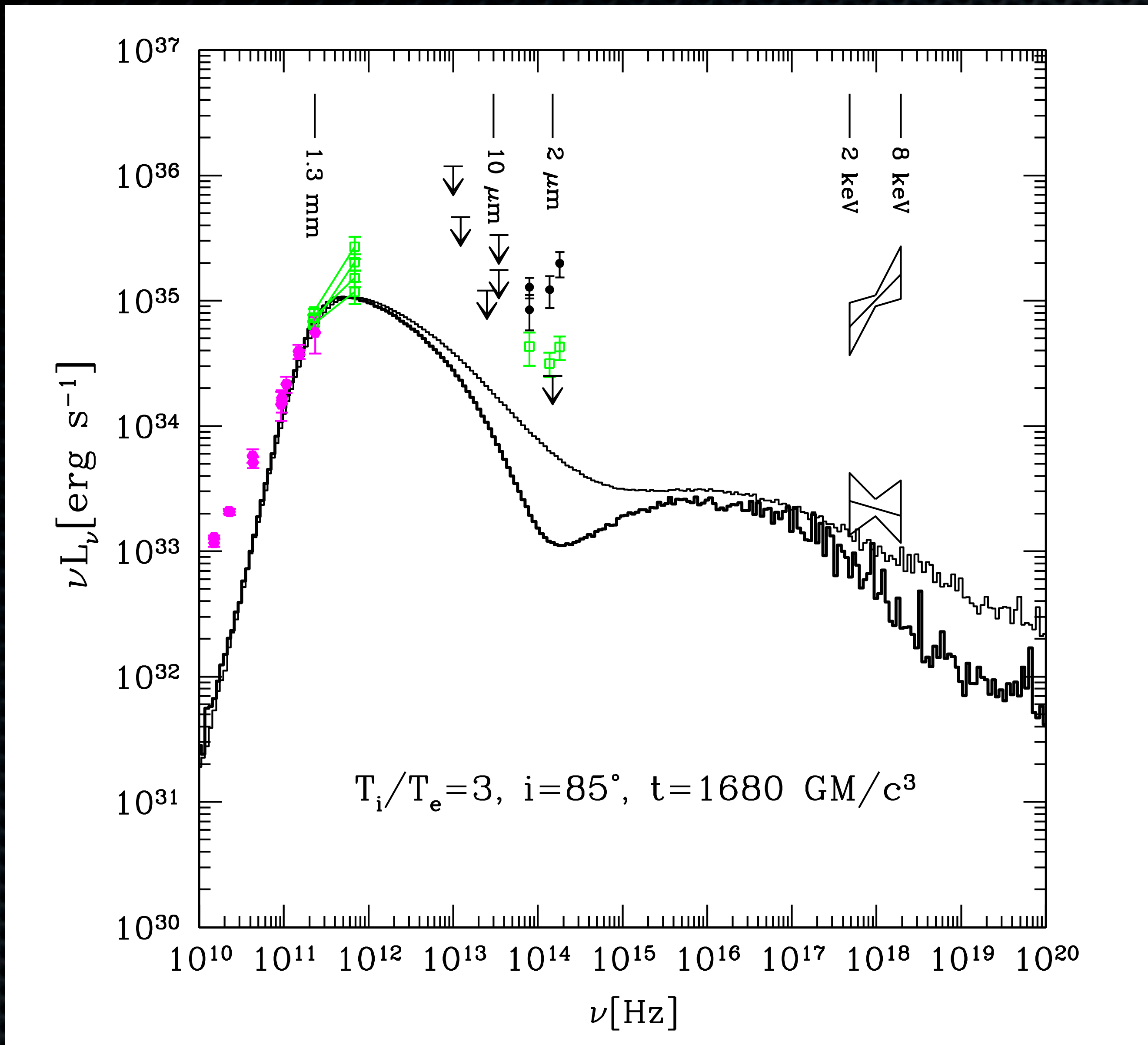


- Relativistic Monte Carlo, necessary for inverse-Compton emission (X-ray)
- Old ray-tracing method for images;
- Constrain time-averaged spectra to:
  - NIR, X-ray quiescent upper limits
  - sub-mm spectral slope
- Constrain time-averaged apparent sizes to mm-VLBI limits [Doeleman et al (2008)] ;

$$F_\nu(230\mathrm{GHz}) = 3.4\mathrm{Jy}$$

$$T_i/T_e = 1, 3, 10 \qquad i = 5°, 45°, 85° \qquad a = 0.5, 0.75, 0.88, 0.94, 0.97, 0.985$$

Moscibrodzka, Gammie, Dolence, Shiokawa, Leung (2009)

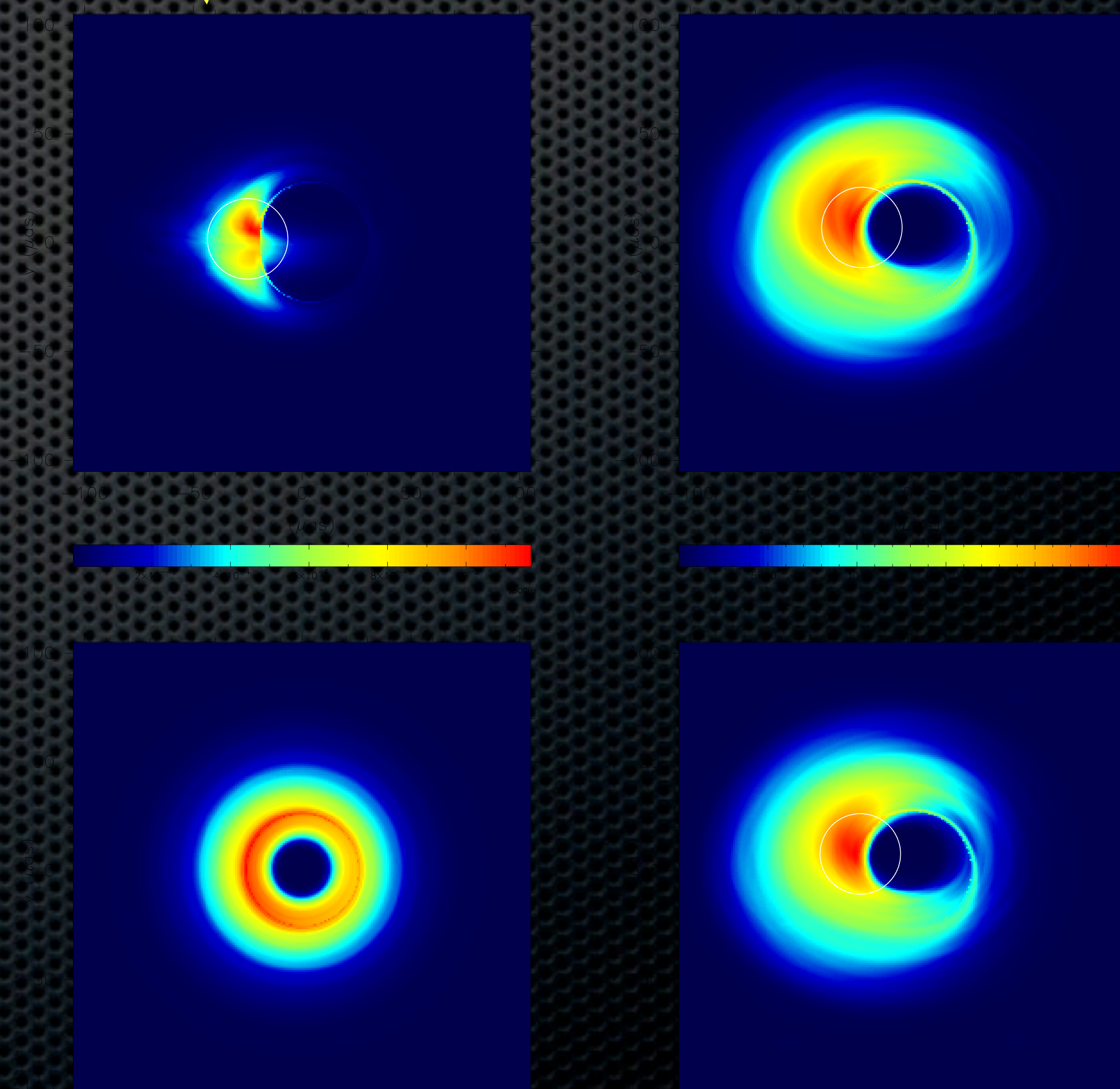


"Best-bet" Model:

$$a = 0.94$$

$$T_i/T_e = 3$$

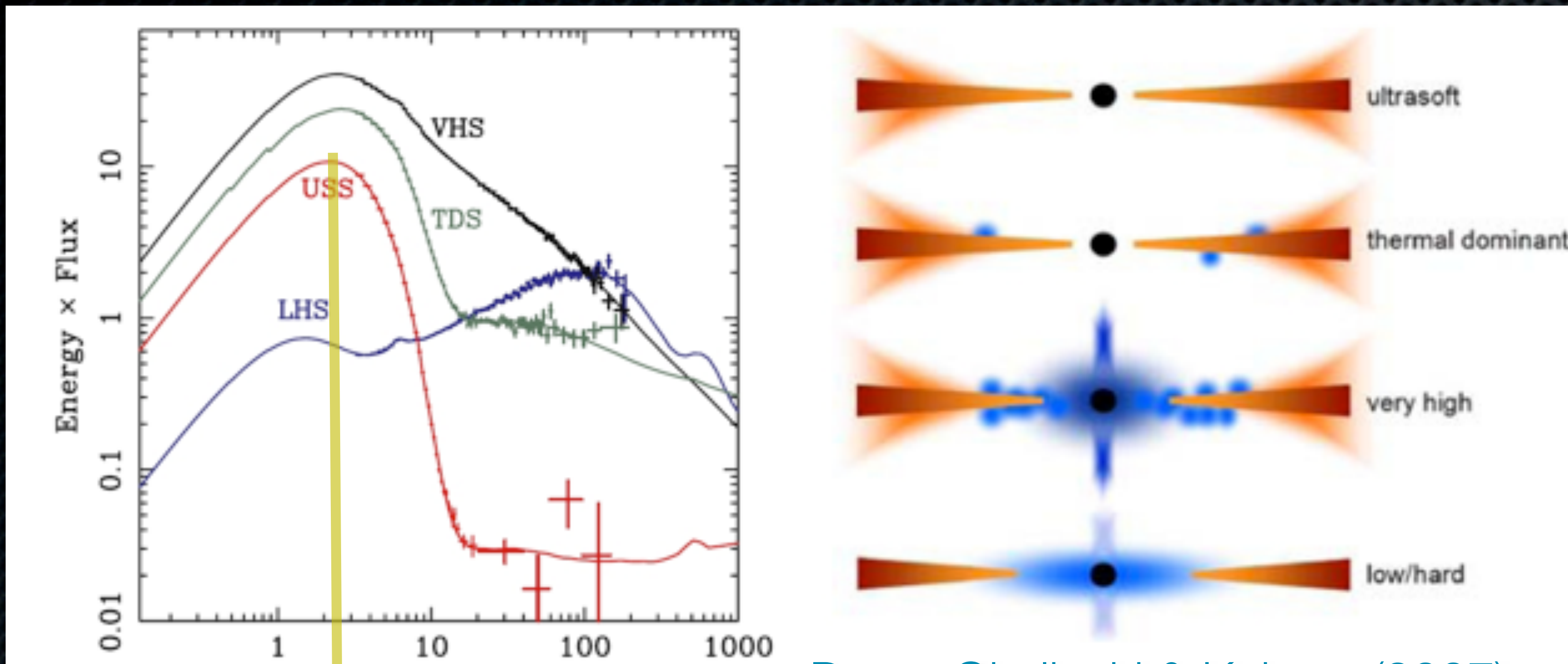
$$i = 85°$$



- Size constraints favor large spin & inclination
- $T_i/T_e = 1$ ruled out by spectra

Thin Disks

Thermal Spectral Fitting for BH Spin



Done, Gierlinski & Kubota (2007)

$T_{\max}$

$$L = A R_{\rm in}^2 T_{\max}^4$$

$$R_{\rm in} = R_{\rm in}(M, a) \simeq R_{\rm ISCO}$$

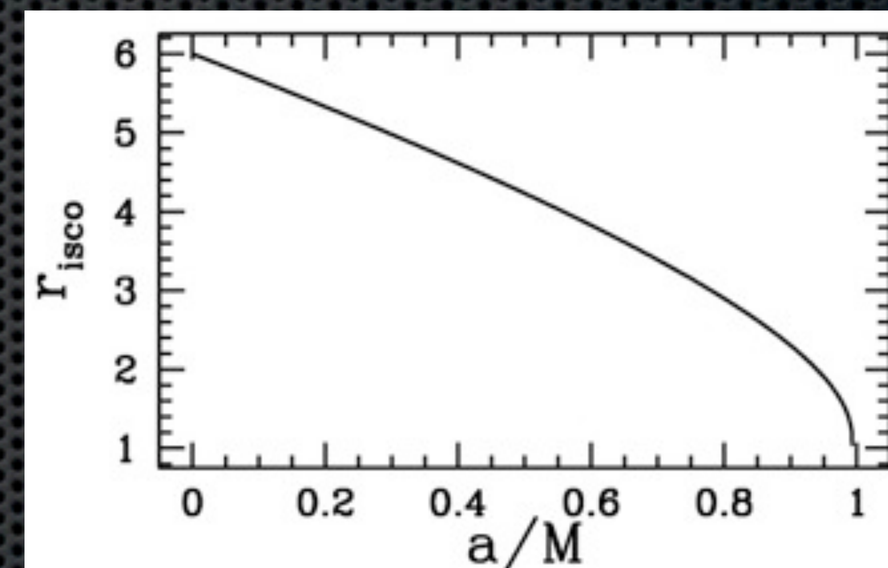


TABLE 1

Black Hole Spin Estimates Using the Mean Observed Values of *M*, *D*, and *i*

Candidate	Observation Date	Satellite	Detector	a_* (D05)	a_* (ST95)
GRO J1655−40	1995 Aug 15	*ASCA*	GIS2	~0.85	~0.8
			GIS3	~0.80	~0.75
	1997 Feb 25–28	*ASCA*	GIS2	~0.75[a]	~0.70
			GIS3	~0.75[a]	~0.7
	1997 Feb 26	*RXTE*	PCA	~0.75[a]	~0.65
	1997 (several)	*RXTE*	PCA	0.65–0.75[a]	0.55–0.65
4U 1543−47	2002 (several)	*RXTE*	PCA	0.75–0.85[a]	0.55–0.65

[a] Values adopted in this Letter.

Shafee et al. (2006)

	Power Law	
Object	Mean	Standard Deviation
GRS 1915+105[a]	0.998	0.001
GRS 1915+105[b]	0.998	0.001

McClintock et al. (2006)

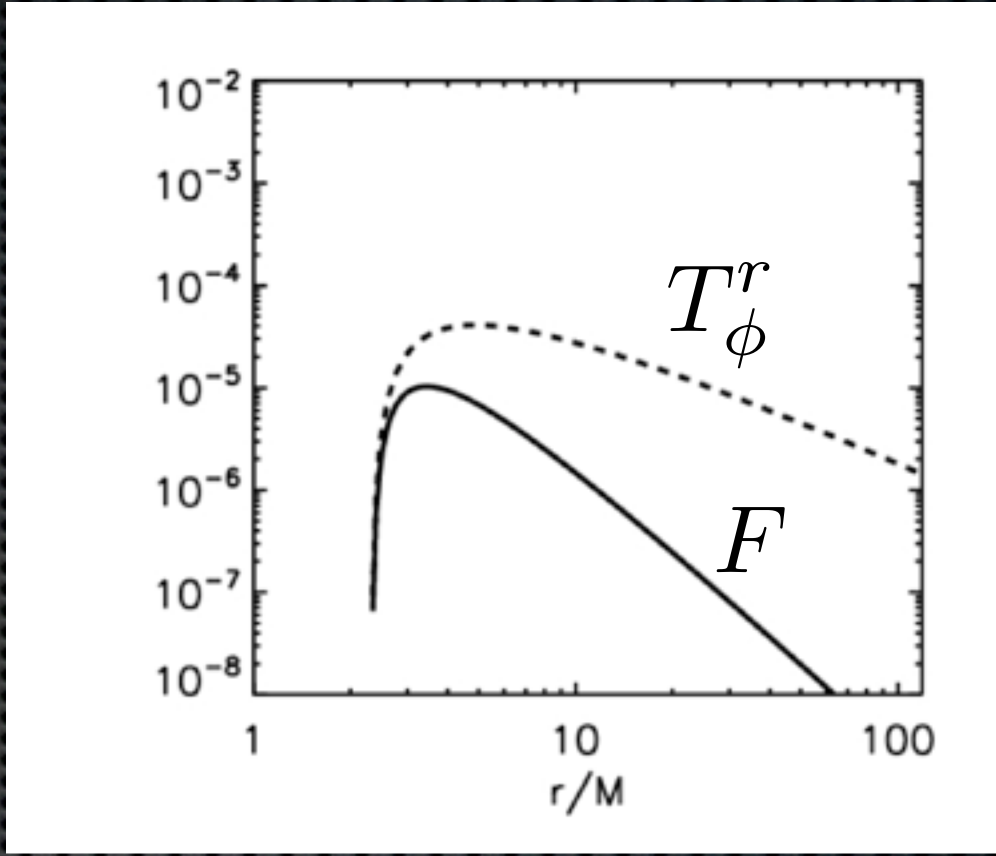
Steady-state Thin Disk Models

Novikov & Thorne (1973)

$$L = \eta \dot{M} c^2$$

$$\eta = 1 - \epsilon_{\rm ISCO}$$

- Stationary gravity
- Perfect radiator
- Work done by stress locally dissipated & radiated
- Zero stress at ISCO as boundary condition
- Luminosity as total liberation of binding energy up until plunge into ISCO



Shakura & Sunyaev (1973)

$$T^r_\phi = -\alpha P \quad P = \rho c_s^2$$

$$t^r_\phi = -\alpha c_s^2$$

No stress at sonic point:

$$\rightarrow R_{\rm in} = R_s \simeq R_{\rm ISCO}$$

Muchotzeb & Paczynski (1982)
Abramowicz et al. (1988)
Afshordi & Paczyncski (2003)

Gammie (1999)

- Magnetized inflow model matched to thin disk
- Efficiency tied to mag. flux BC

Agol & Krolik (2000)

- Magnetic torques at ISCO can affect radiative efficiency

SCN, Krolik & Hawley 2009

- 3D GRMHD thin disk evolution
- Local cooling function to constrain H ~ r
  - Cool when cell because hotter than target temperature
- Save as emissivity for post-processing
- Fully relativistic radiative transfer calculation
- Assume cooling and transfer is optically thin for now
- a = 0.9M

$$\Delta\eta/\eta = 6\%$$

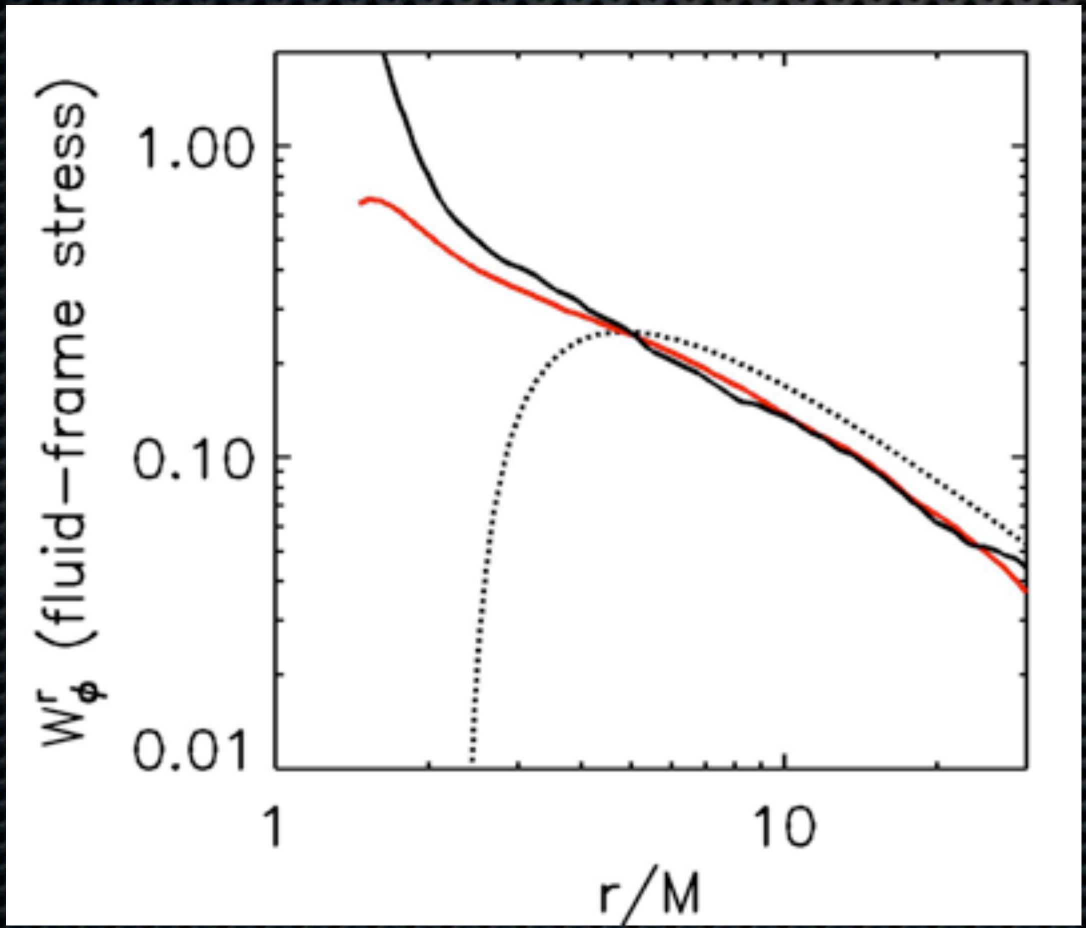
$$\Delta T_{\rm max}/T_{\rm max} = 30\%$$

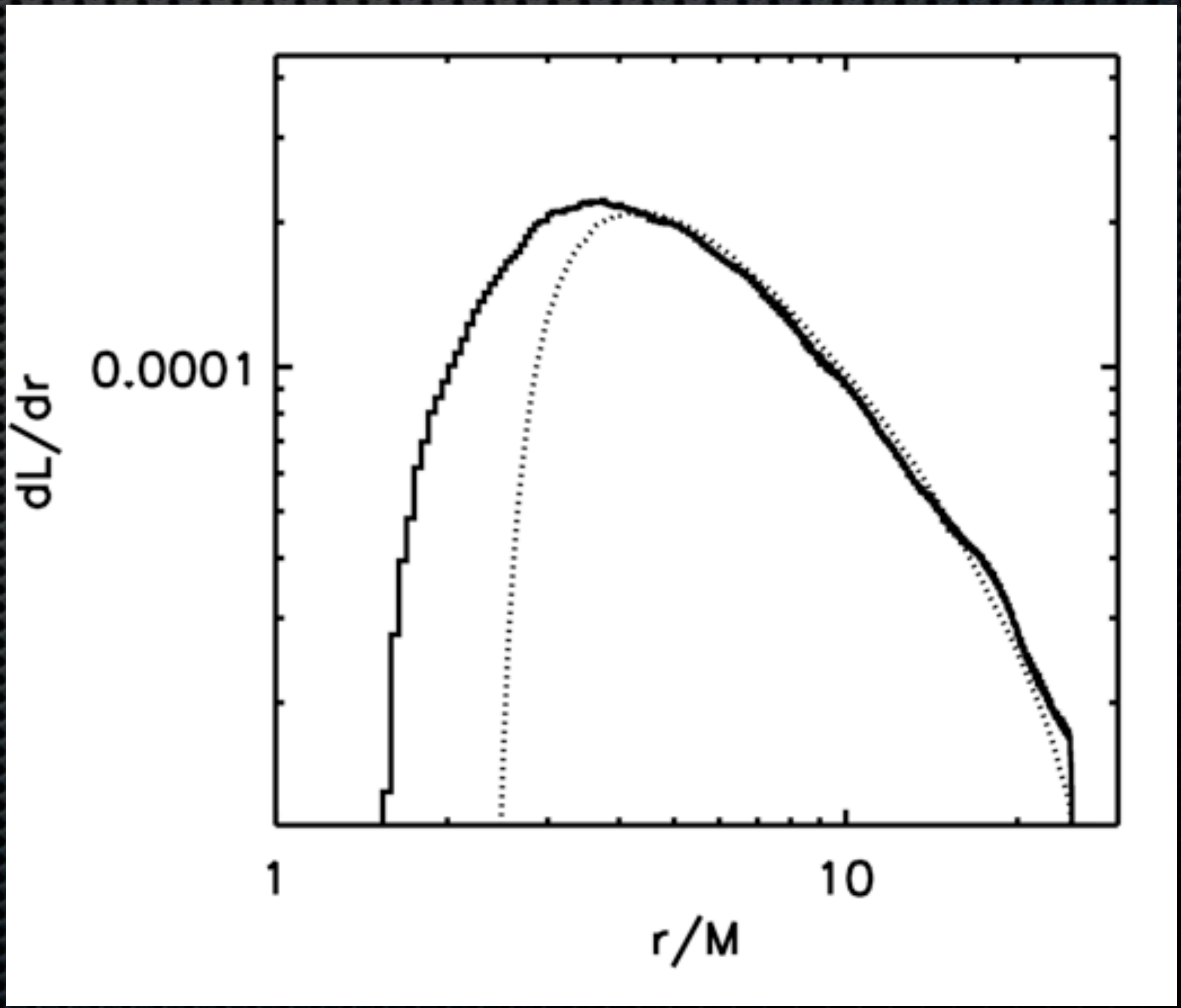
$$\Delta R_{\rm in}/R_{\rm in} = 80\%$$

$$T \to 0 : \Delta\eta/\eta = 20\%$$

Suggests previous spectral fits may overestimate spin

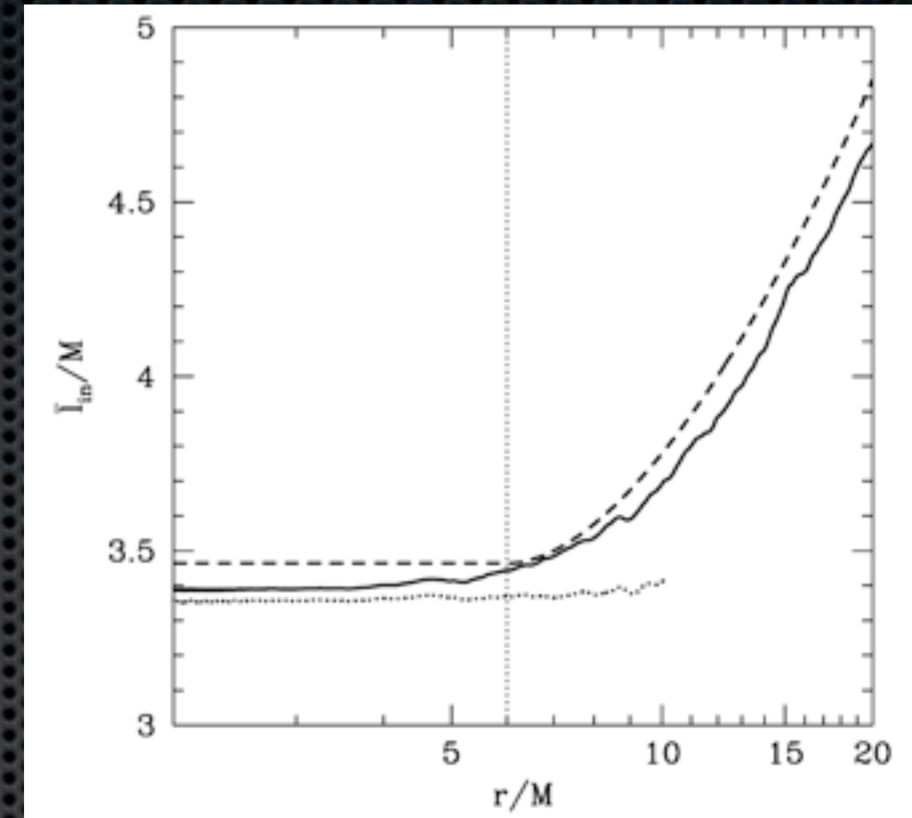
$$L = \eta \dot{M} c^2 \qquad \eta_{\rm NT} = 0.143$$

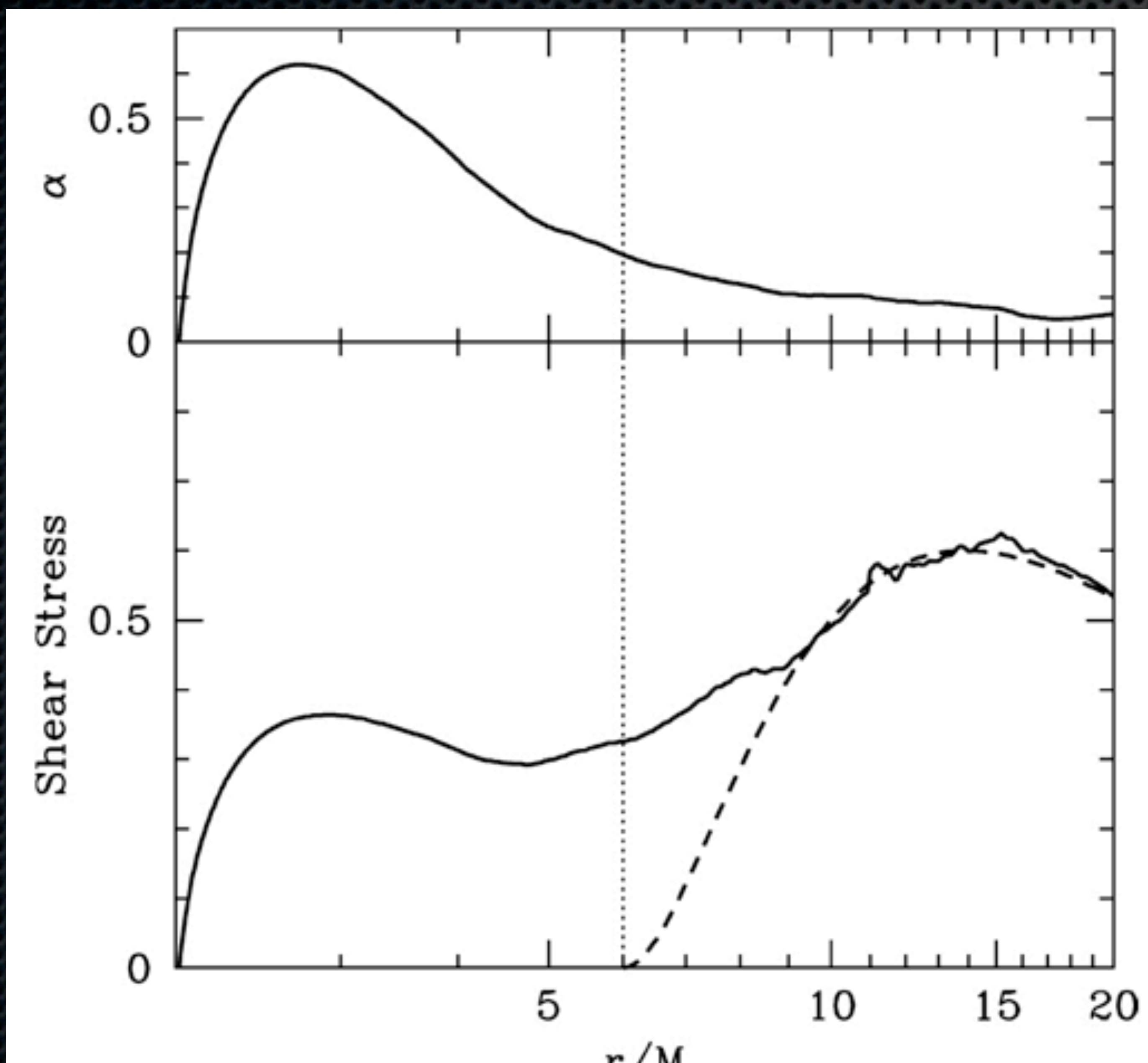




Shafee, McKinney, Narayan, Tchekhovskoy, Gammie, McClintock (2008)

- Cooling function: Drive to constant entropy
- a = 0M





	Shafee et al. 2008	SCN, Krolik, Hawley 2009
a/M	0	0.9
Azimuthal Extent	$\pi/4$	$\pi/2$
# of B Loops	2	1
Size of B Perturbation	2% (50%)	0%
H/R	0.05-0.07	0.07 - 0.13
Code	WHAM	HARM3D
Resolution	512x120x32	192x192x64

ThinHR: H/R = 0.06
912x160x64

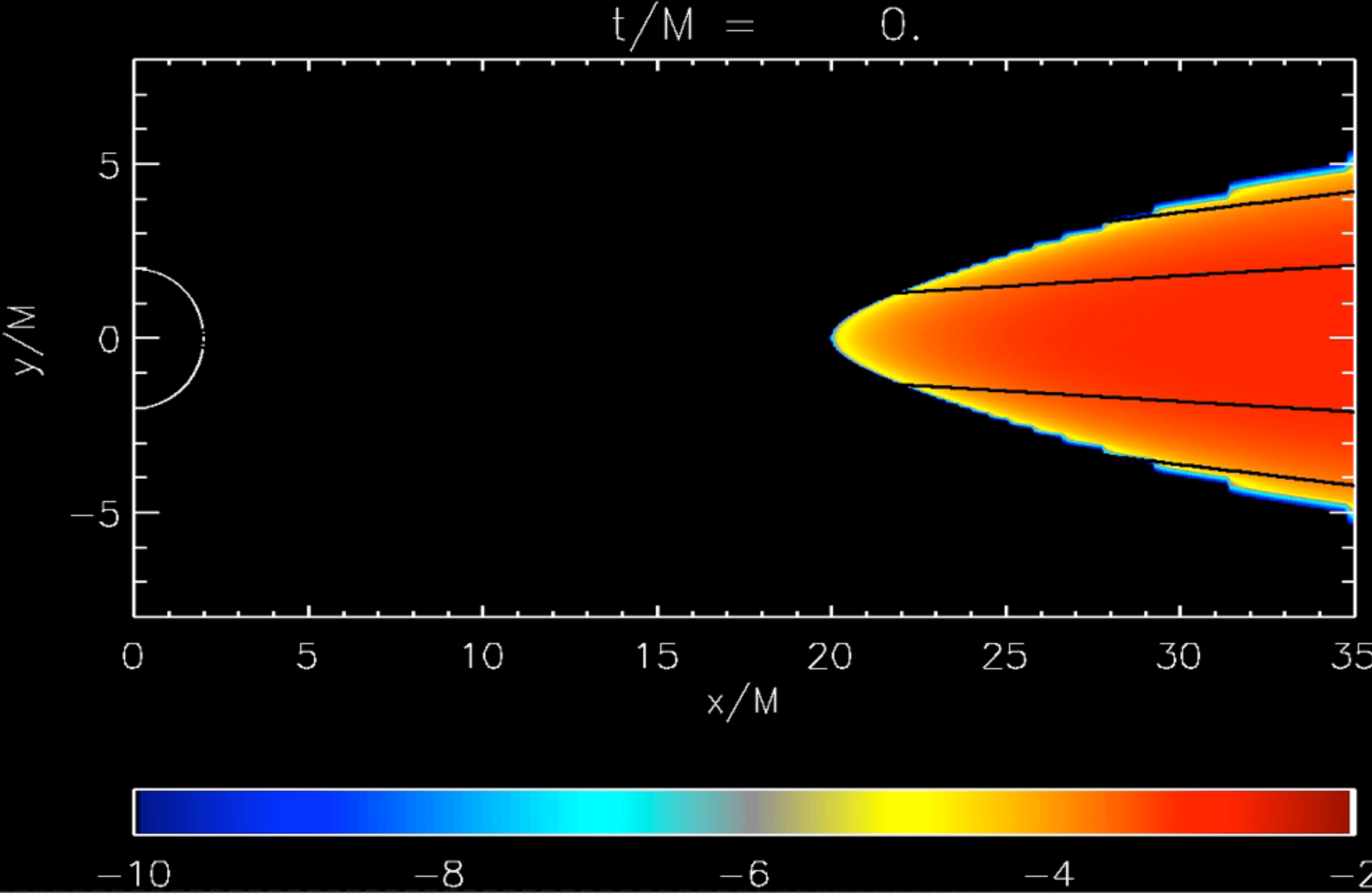
ρ

SCN, Krolik, Hawley 2010

ThinHR: H/R = 0.06
912x160x64

ρ

SCN, Krolik, Hawley 2010

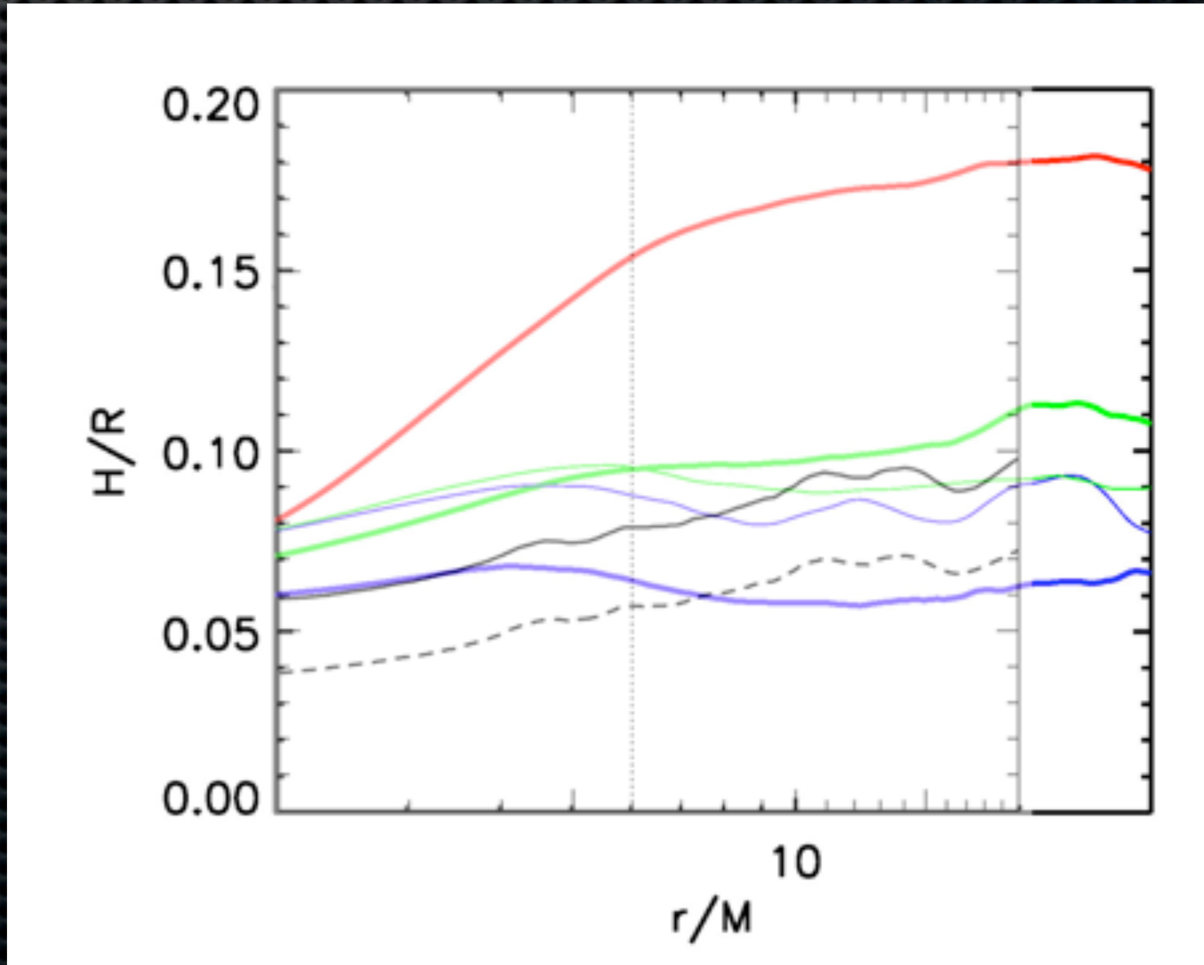


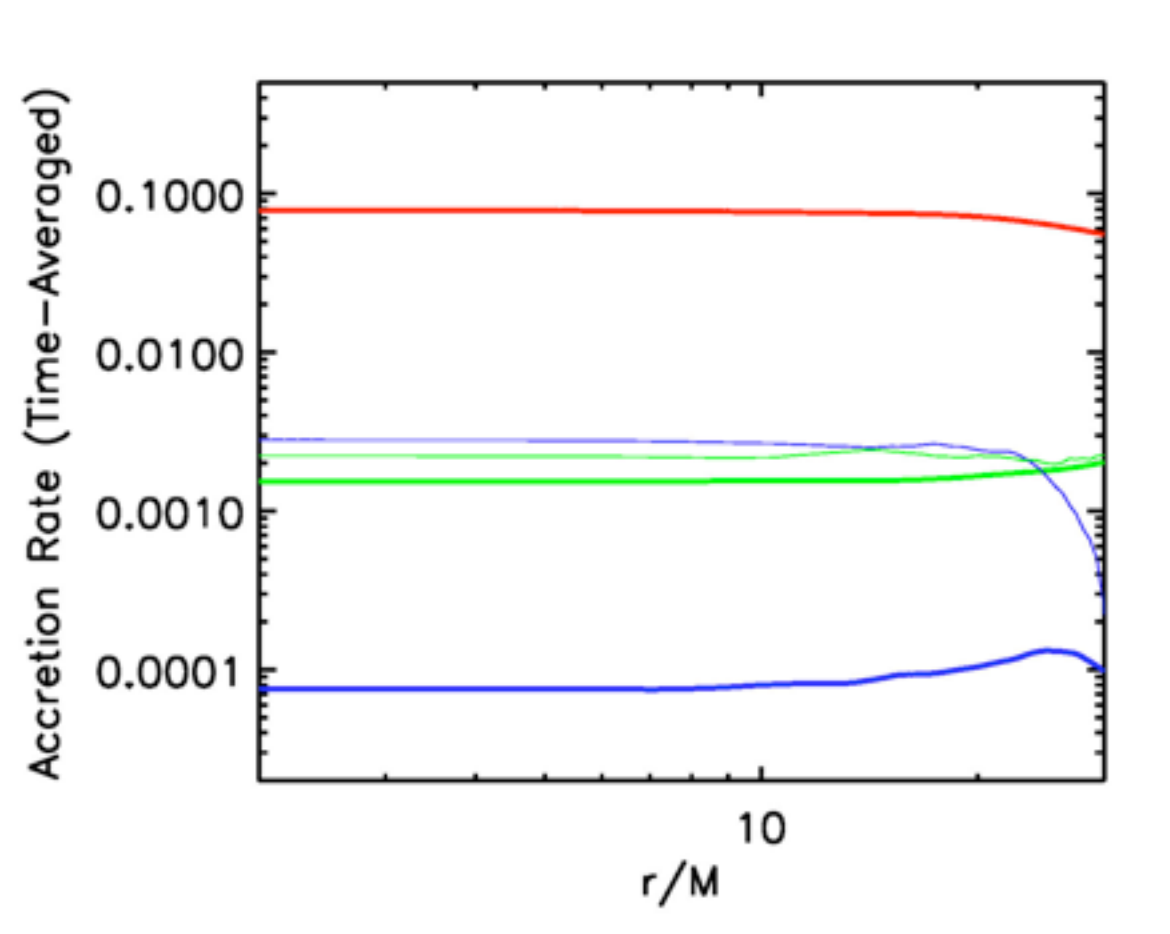
	Shafee et al 2009	Our Original	Thin1	Medium1	Thick1	Thin2	Medium2
BH Spin	a=0.0	a=0.9	a=0.0	a=0.0	a=0.0	a=0.0	a=0.0
Resolution	512x120x32	192x192x64	912x160x64	512x160x64	384x160x64	192x192x64	192x192x64
f Extent	p/4	p/2	p/2	p/2	p/2	p/2	p/2
# of Loops	2	1	1	1	1	1	1
Actual H/R	0.05 - 0.07	0.07 - 0.13	0.06	0.10	~0.17	0.087	0.097
N_{cells} per H/r	44	6 - 30	80	100	40 - 70	60	35
Initial Data	"V. 1"	V. 2	V. 1	V. 1	V. 1	V. 2	V. 2

SCN, Krolik, Hawley 2010

v1: (high resolution), Initial Disk:
- at target thickness
- with inner radius at 20M
- With Pmax at r=35M

v2: (low resolution), Initial Disk:
- at H/r ~ 0.15
- Inner radius at 15M
- Pmax at r=25M



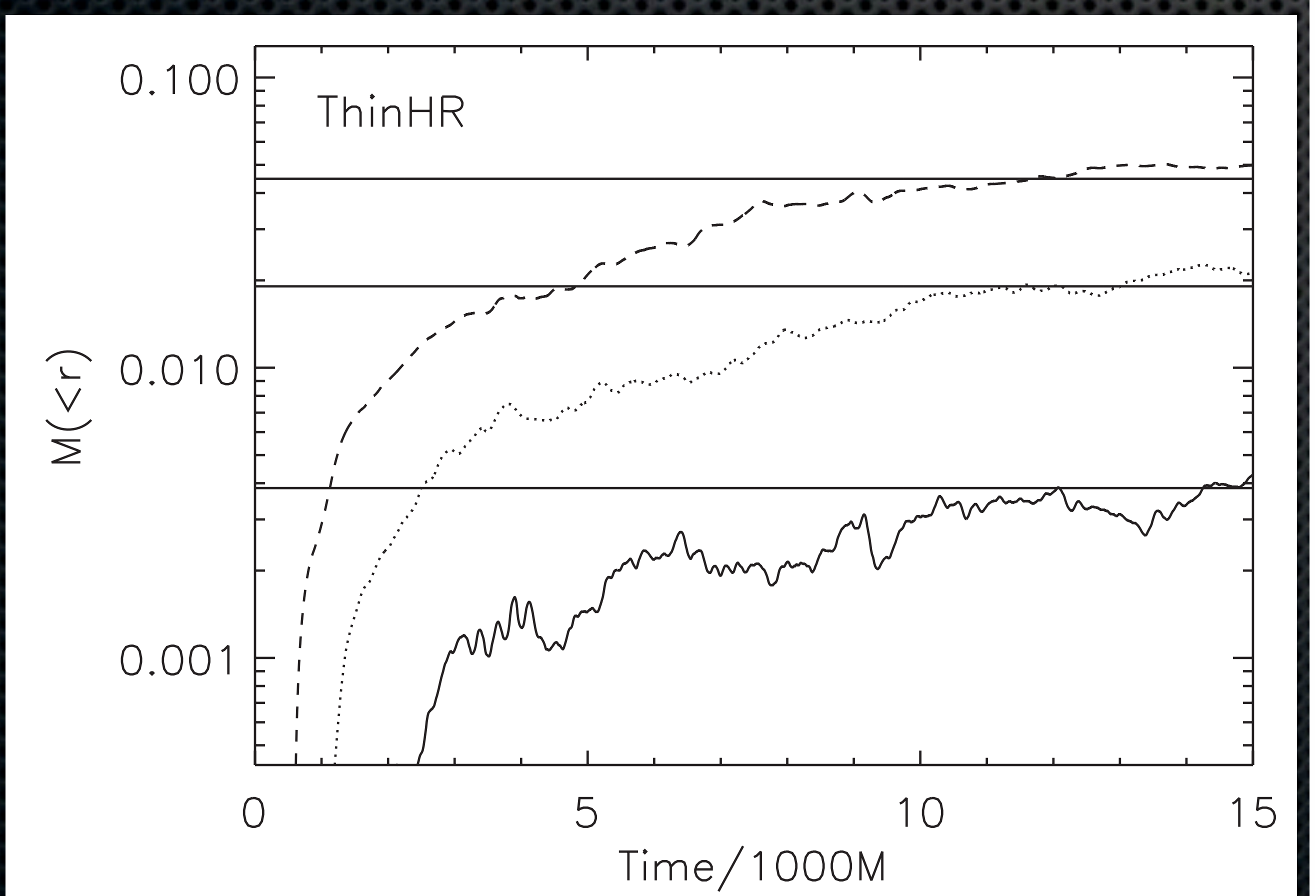


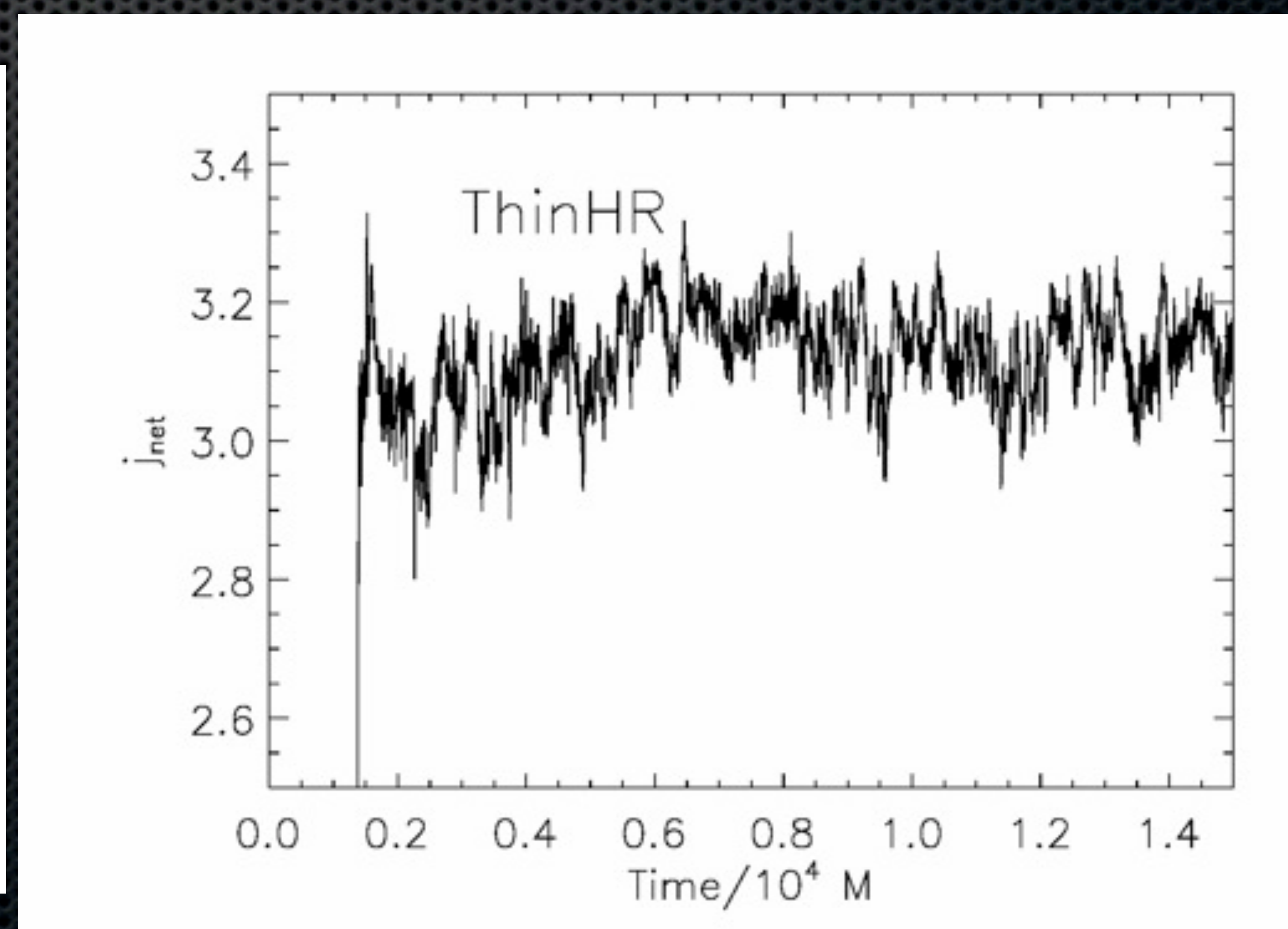
Inflow Equilibrium

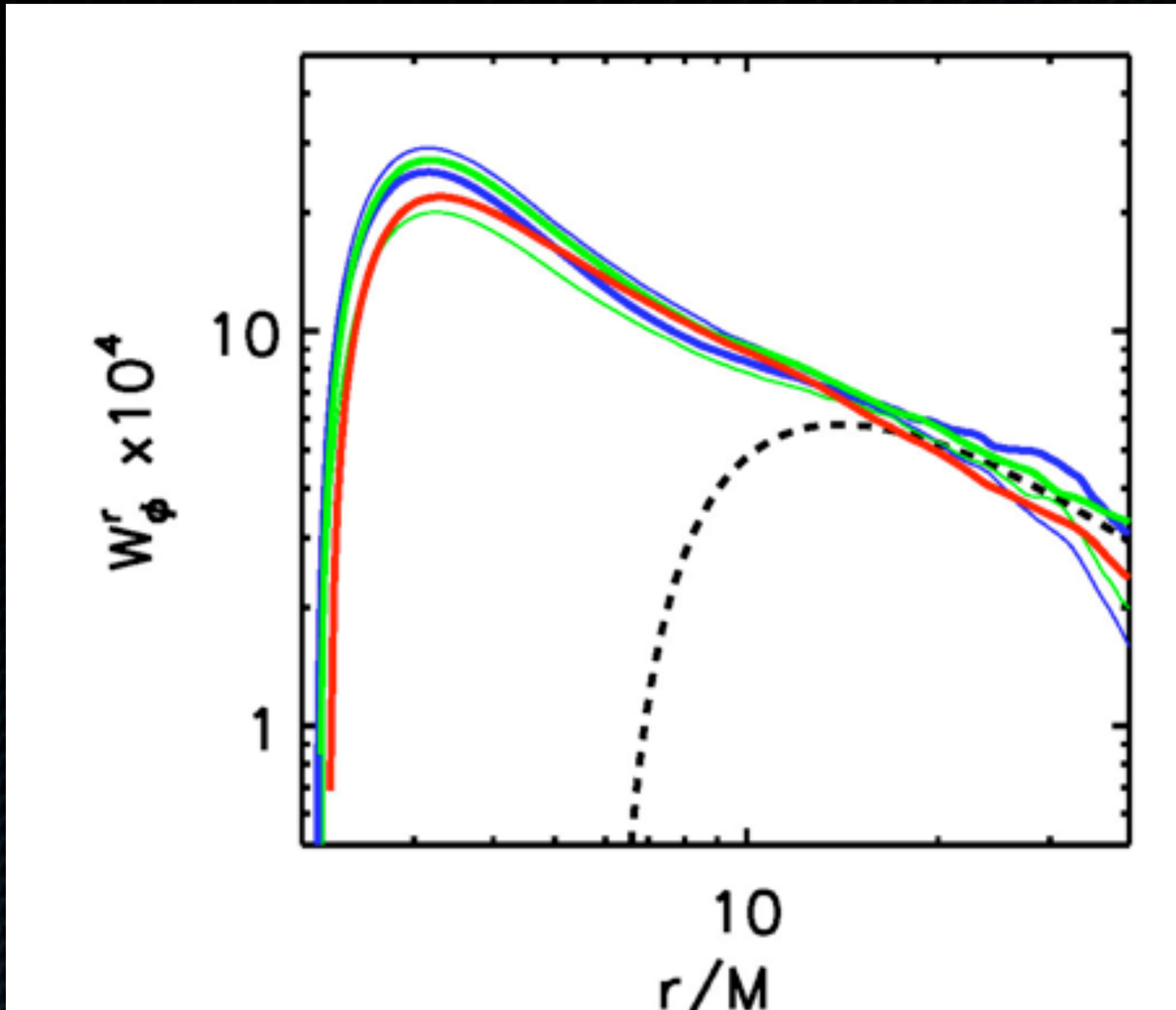
Defined to be when:

1) Accreted specific angular momentum (jnet) is steady;
2) Mass flux shows no trends in time over radius;

Remember these are turbulent MHD flows---they need not reach any kind of steady-state!





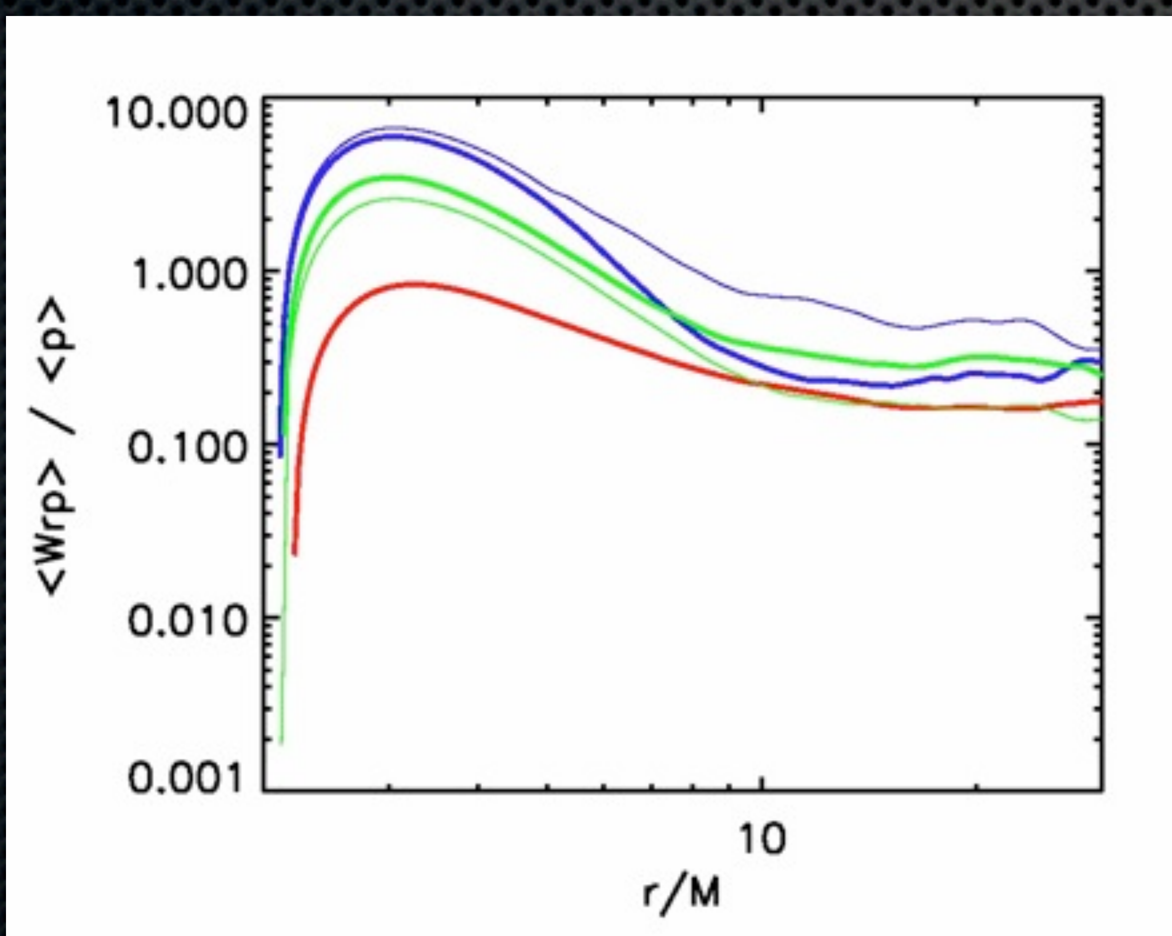


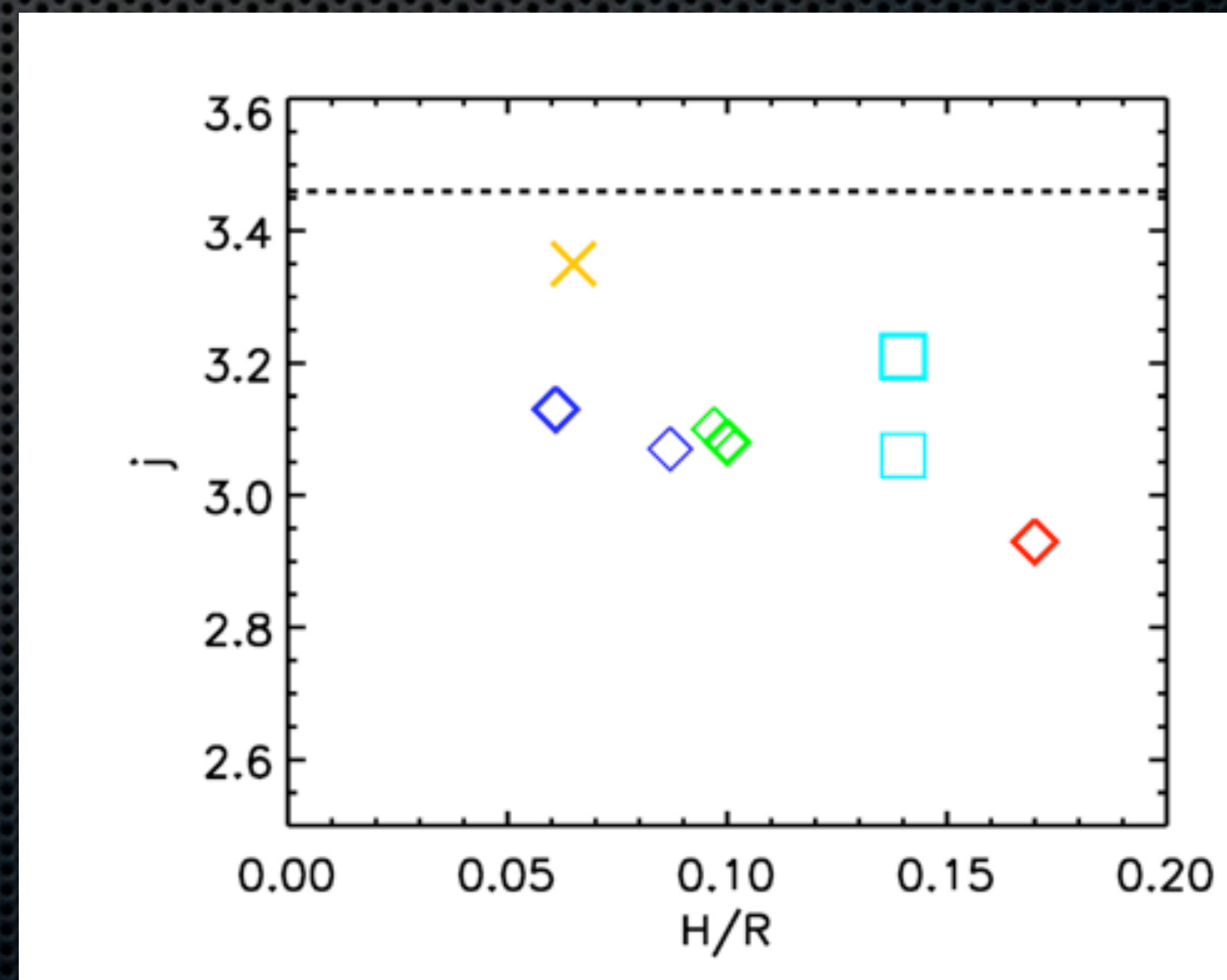
- No trend seen in Maxwell Stress
- Minor “sqrt” trend seen in spec. ang. mom.
    - Due to additional Reynolds stress for thicker disks

De Villiers & Hawley code

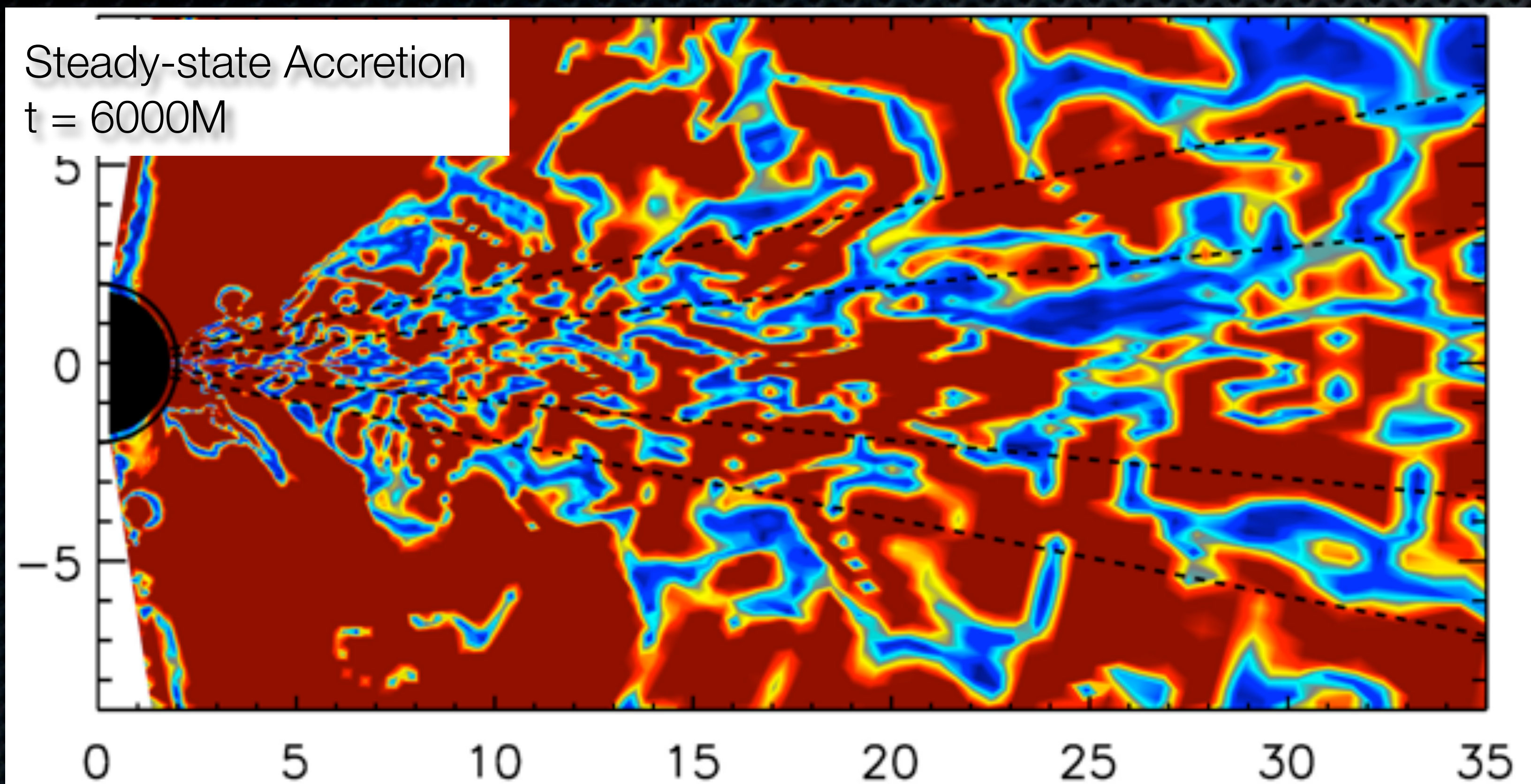
Vertical field with De Villiers & Hawley code

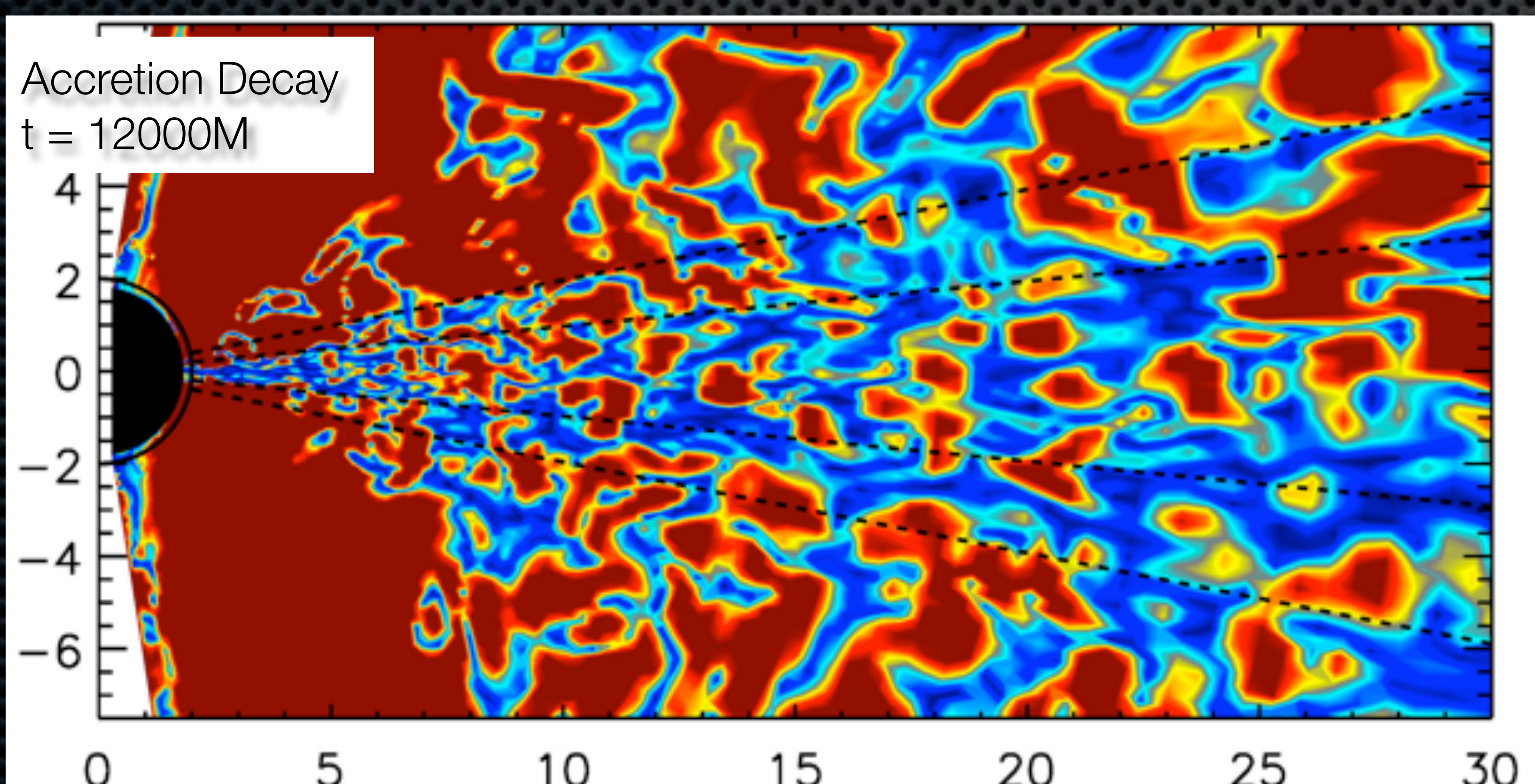
Shafee et al 2008

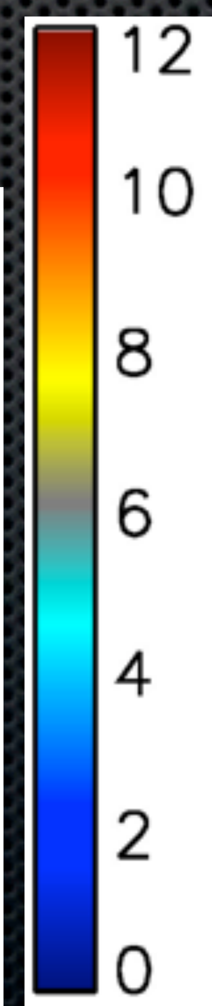




Track MRI Resolution for all time!







Suggestions from local shearing box simulations:

Sano et al. 2004

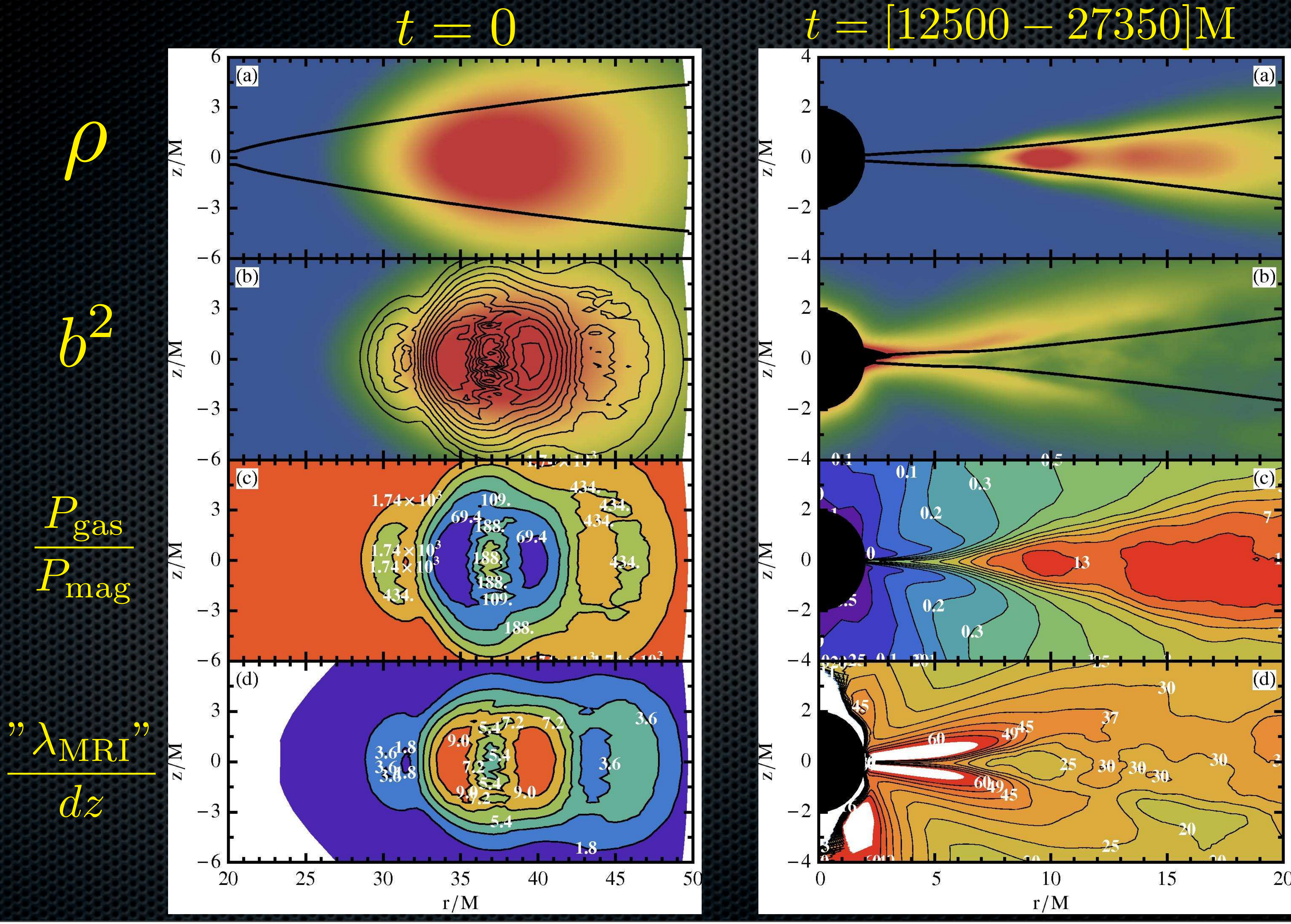
$$\lambda_{\mathrm{MRI}} \equiv \frac{1}{\sqrt{4\pi\rho\Omega(R)}} b_\mu \hat{e}^\mu_{(\theta)}$$

$$\frac{\lambda_{\mathrm{MRI}}}{\Delta z} > 6$$

Davis, Stone, & Pessah 2009

$$\frac{H}{\Delta z} > 60$$

Penna, McKinney, Narayan, Tchekhovskoy, Shafee, McClintock 2010 arxiv:1003.0966



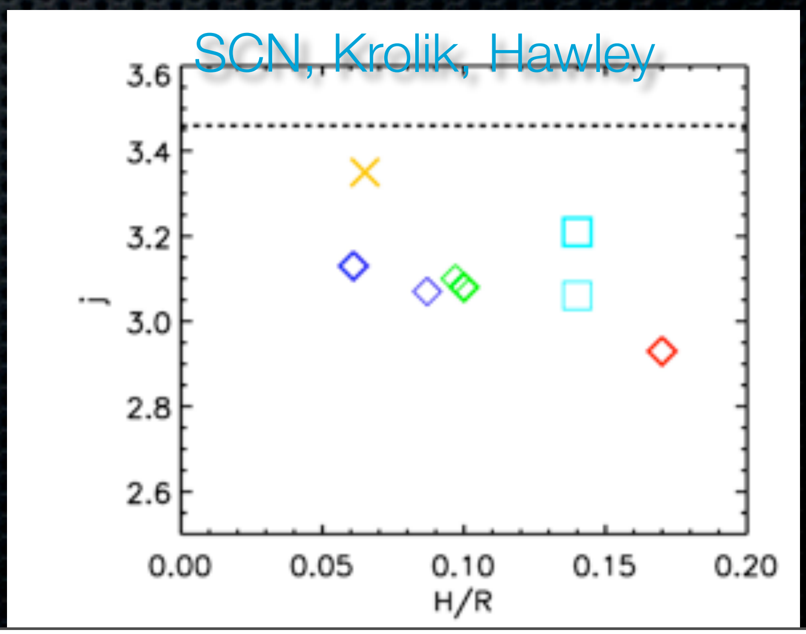
Penna, McKinney, Narayan, Tchekhovskoy, Shafee, McClintock 2010 arxiv:1003.0966

- Resolution, spin, thickness study;
- Canonically use 4 loops of magnetic field;
- Various azimuthal extents and resolutions;
- Perform resolution in w/ grid sizes below ThinHR's (reach same azimuthal grid size only);
- 10 to 44 cells per H/r ;

Model Name	T_i/M-T_f/M	$\frac{a}{M}$	N_r	N_θ	N_ϕ
A0HR07	12500-27350	0	256	64	32
A7HR07	12500-20950	0.7	256	64	32
A9HR07	14000-23050	0.9	256	64	32
A98HR07	14000-19450	0.98	256	64	32
A9HR3	4500-8300	0.9	256	64	32
A98HR3	4500-5100	0.98	256	64	32
C0	6000-10000	0	512	128	32
C1	10400-18900	0	256	64	16
C2	10400-16000	0	256	64	64
C3	10400-20000	0	256	64	16
C4	10400-17700	0	256	64	64
C5	11500-20000	0	256	32	32
C6	10400-15800	0	256	128	32
LOOP1	12900-17300	0	256	64	32

- Show trend toward NT with thickness;
  - Thinnest disks show ~2% deviations from NT even over spin
  - Larger deviations for the 1 Loop configuration

Model Name	$\lvert h/r \rvert$	$\dot{M}$	$\tilde{e}$	$D[\tilde{e}]$	$\jmath$	$D[\jmath]$
$\pm 2\lvert h/r \rvert$						
A0HR07	0.064	0.066	0.058	-0.829	3.363	-2.913
LOOP1	0.069	0.091	0.057	-0.336	3.269	-5.637
All θ						
A0HR07	0.064	0.074	0.054	4.723	3.266	-5.717
LOOP1	0.069	0.106	0.053	7.574	3.093	-10.726

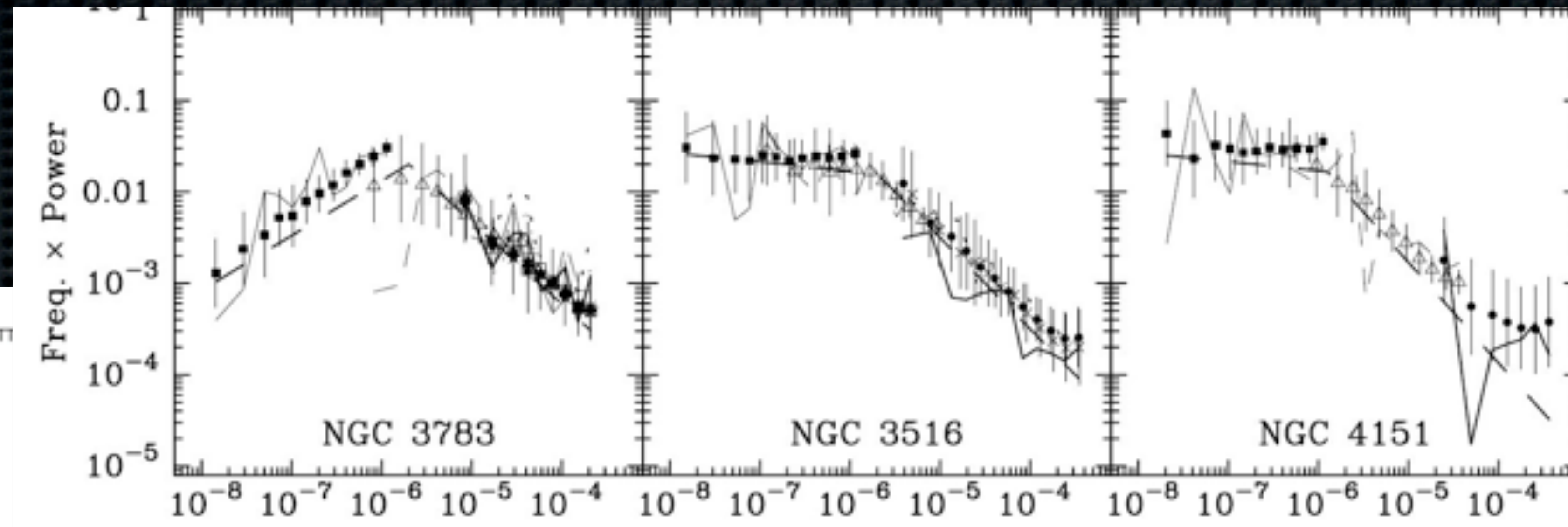


Open Questions:

- What are natural magnetic field topologies?
- What are the convergence criteria for global disk calculations?
- What luminosity profiles do these new models predict?

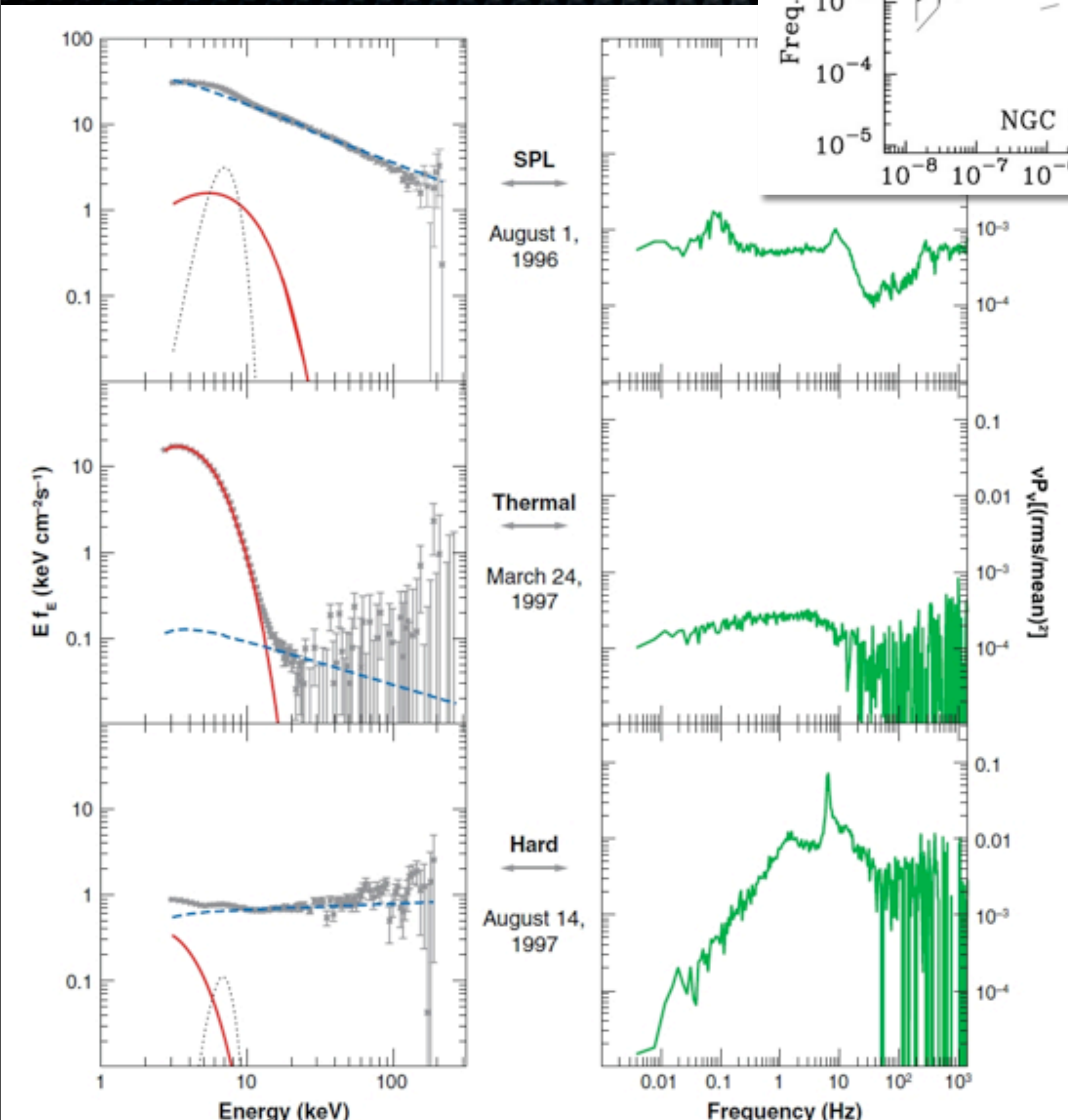
Variability

Coronal X-ray Variability



AGN

Markowitz et al 2003



X-ray Binaries

Remillard & McClintock 2006

X-ray variability:

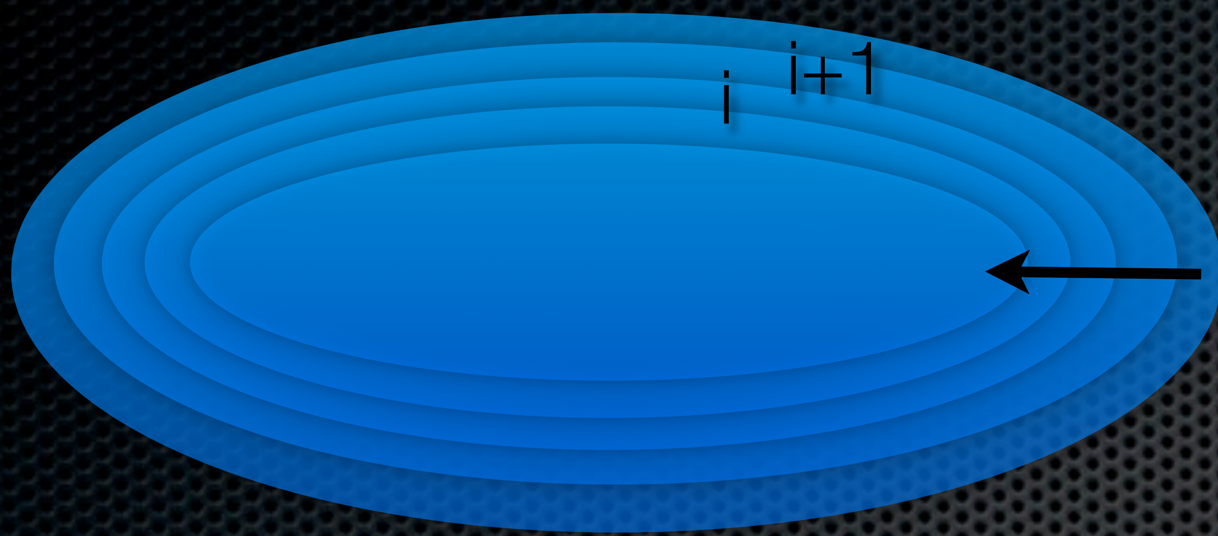
- is always dominated by corona;
- is dependent on spectral state;

$$P \sim \nu^{\alpha}$$

$$-3 < \alpha < -1$$

Variability Models

$$P \sim \nu^{\alpha}$$



Lyubarskii et al 1997

- Total variability is a superposition of independent variability from larger radii modulating interior annuli on inflow (viscous) times scales

Churazov et al 2001

- Outer radius of corona may be cause of (temporal) spectral slope

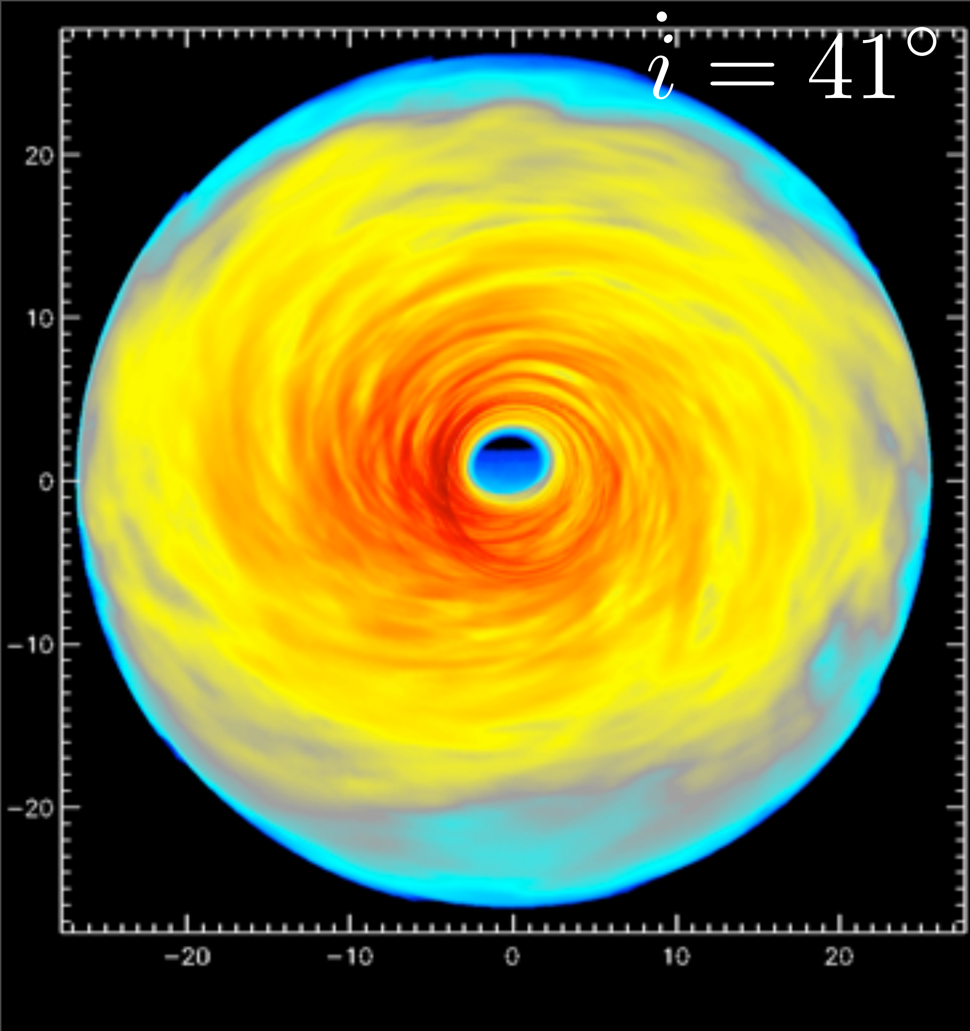
$$\tau_a = \left[\alpha \left(\frac{H}{r} \right)^2 \Omega_K \right]^{-1}$$

- Accretion rate modulation modeled as variability of α (disk parameter)
- Predicts phase coherence at frequencies longer than inverse of inflow timescale

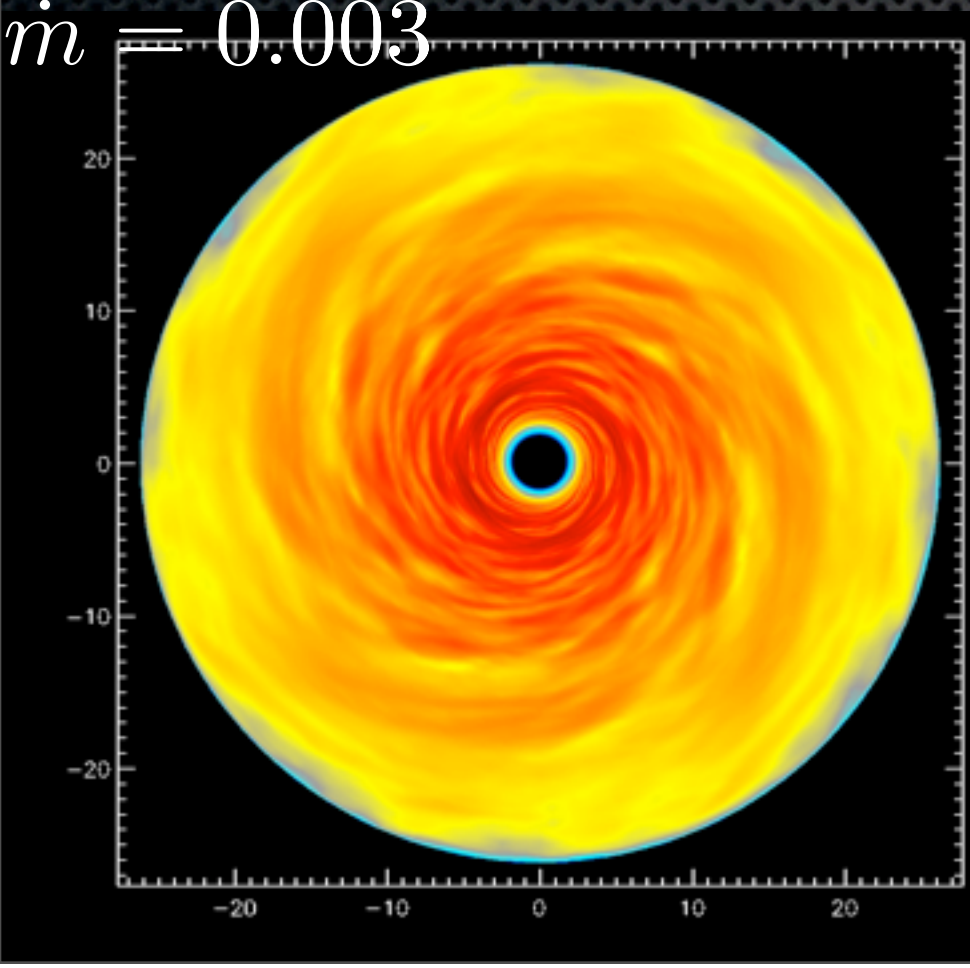
Armitage & Reynolds 2003
Machida & Matsumoto 2004
Schnittman et al 2006
Reynolds & Miller 2009

- Used accretion rate or stress as dissipation proxies
- PLD breaks at local orbital frequency per annulus
- Composite PLD $\rightarrow \alpha \simeq -2$

$i = 41^\circ$

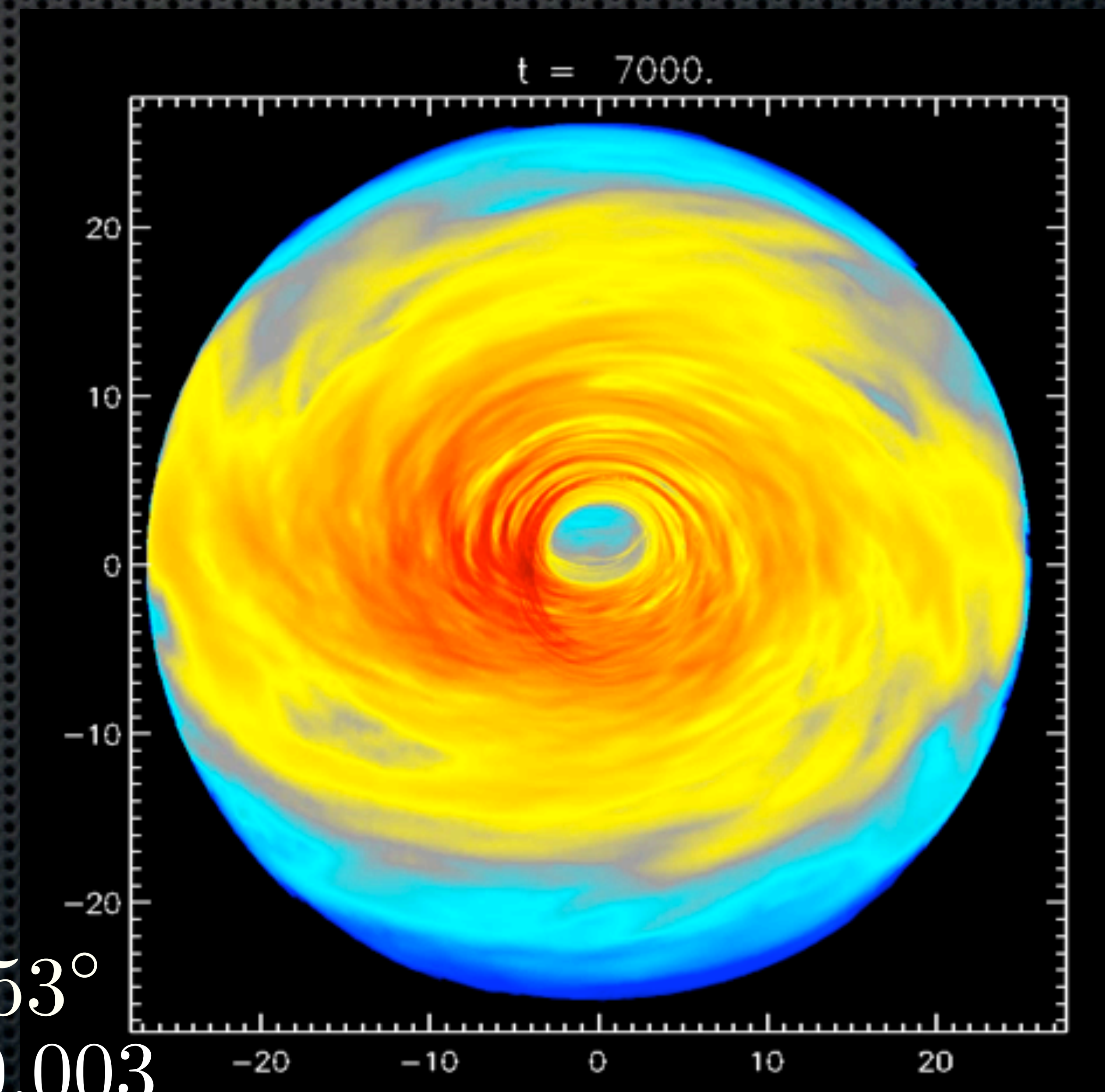


$\dot{m} = 0.003$



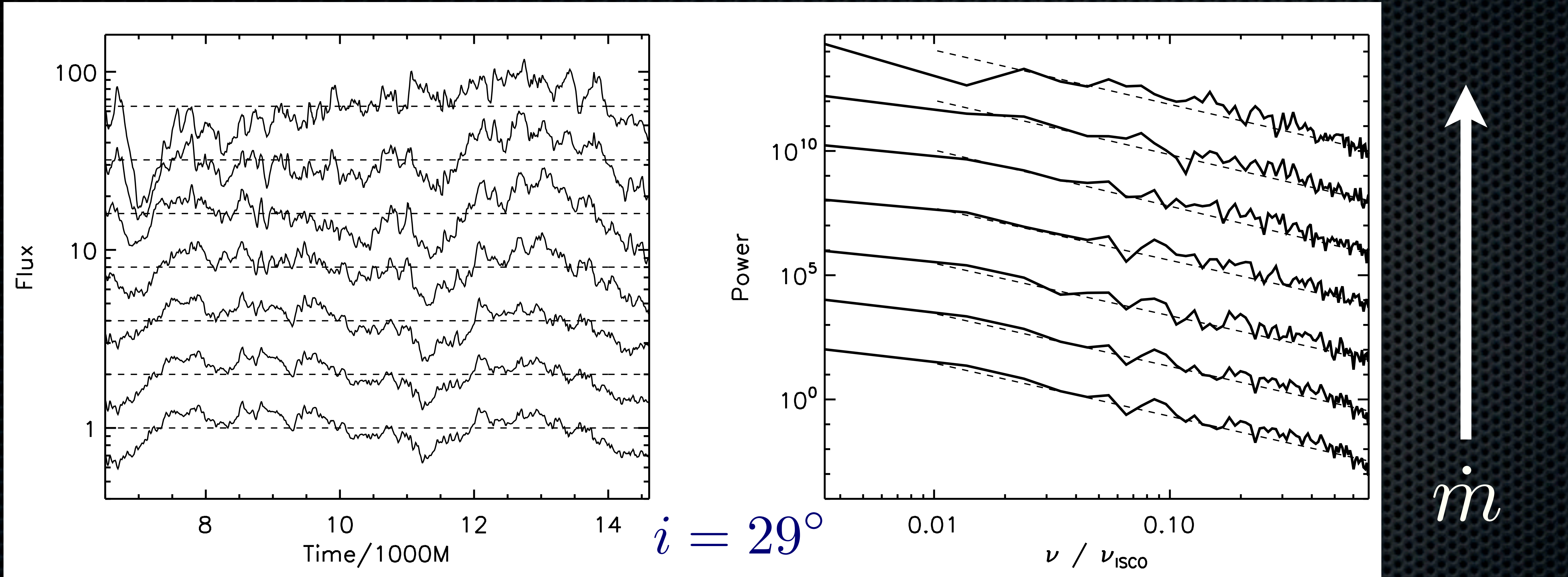
SCN & Krolik 2009

- Use "thin disk" cooling rate in corona as emissivity
- Thomson Opacity model (e- scattering)
- Integrate to photosphere $(\tau = 1)$
- Include finite light speed effect
- Parameterized by accretion rate and inclination

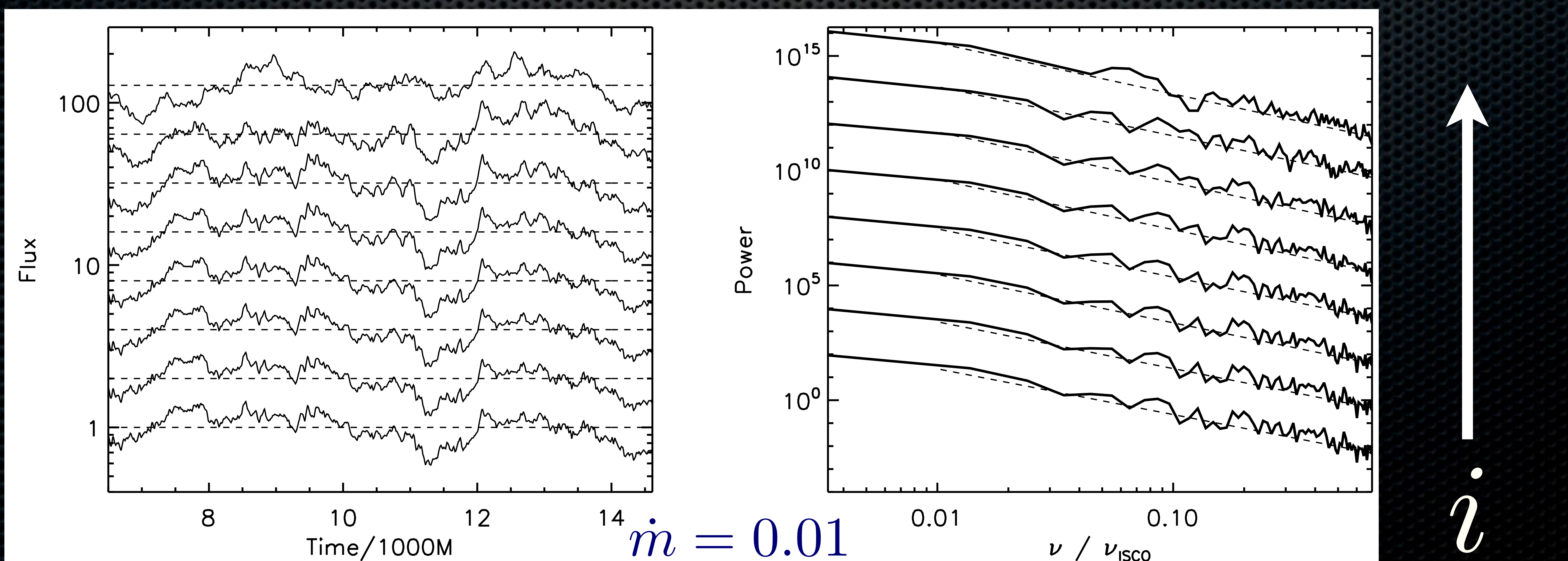


$i = 53^\circ$

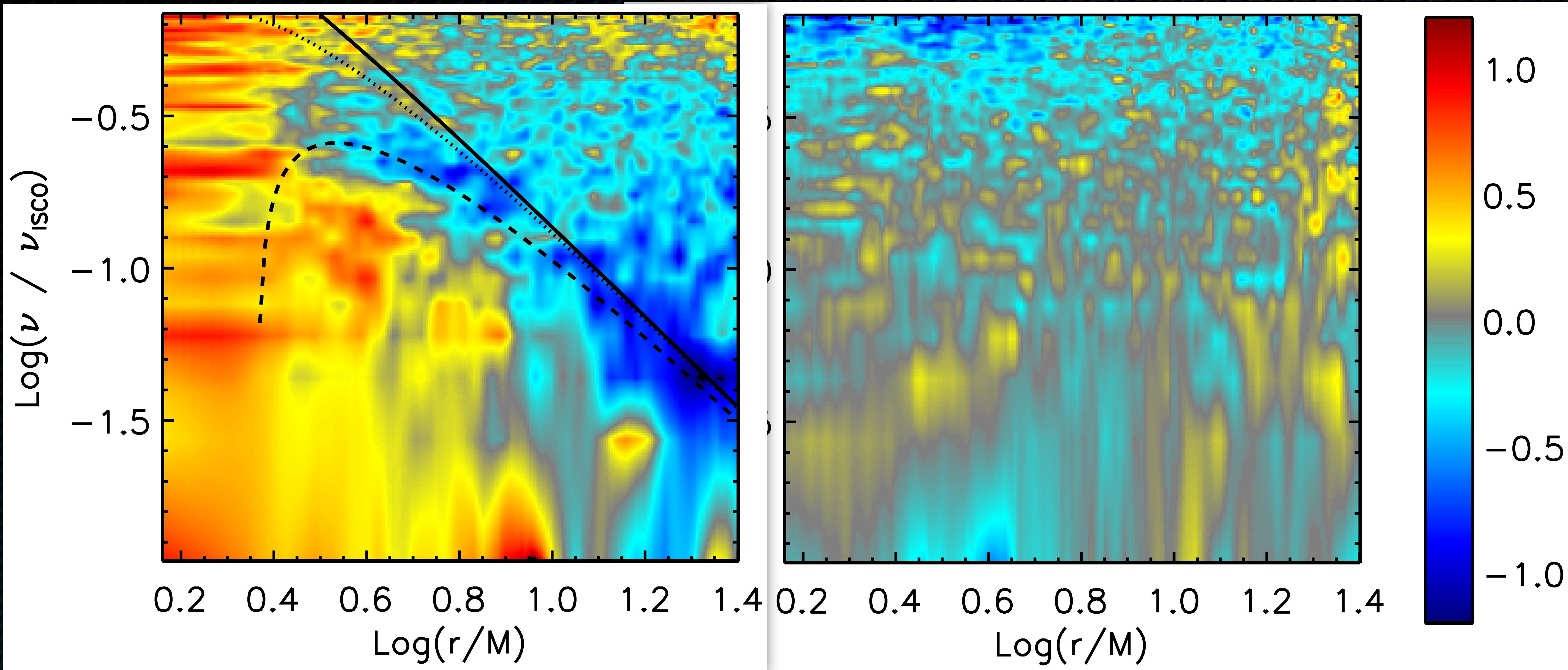
$\dot{m} = 0.003$



Flux
100
10
1
8
10
12
14
Time/1000M
$i = 29^\circ$
Power
10^{10}
10^5
10^0
0.01
0.10
ν / ν_{ISCO}
$\dot{m}$



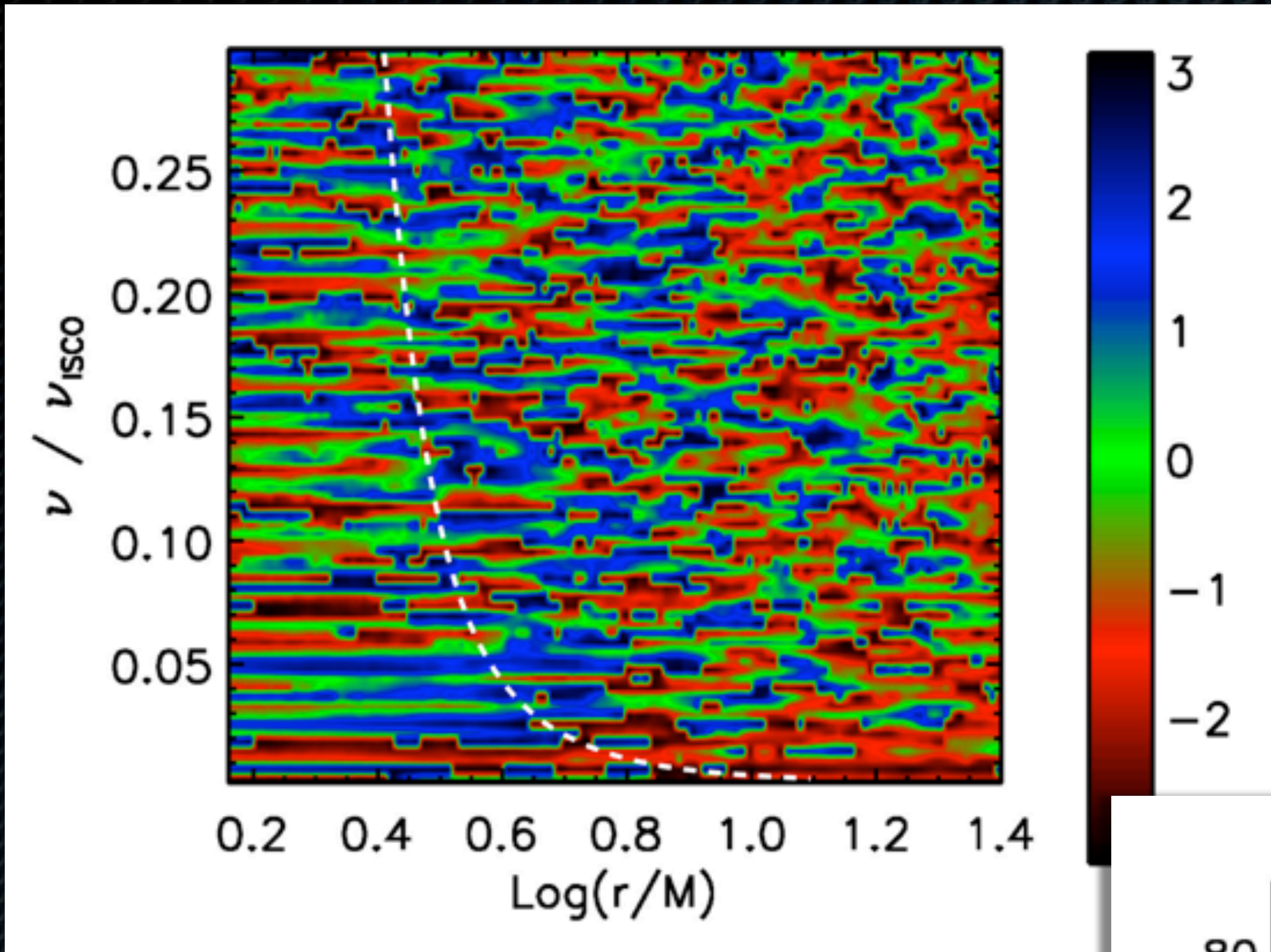
Flux
100
10
1
8
10
12
14
Time/1000M
$\dot{m} = 0.01$
Power
10^{15}
10^{10}
10^5
10^0
0.01
0.10
ν / ν_{ISCO}
i



$$\log \frac{P_{\rm diss}(\nu, r)}{P_{\dot{\rm M}}(\nu, r)}$$

$$\log \frac{P_I(\nu, r)}{P_{\rm diss}(\nu, r)}$$

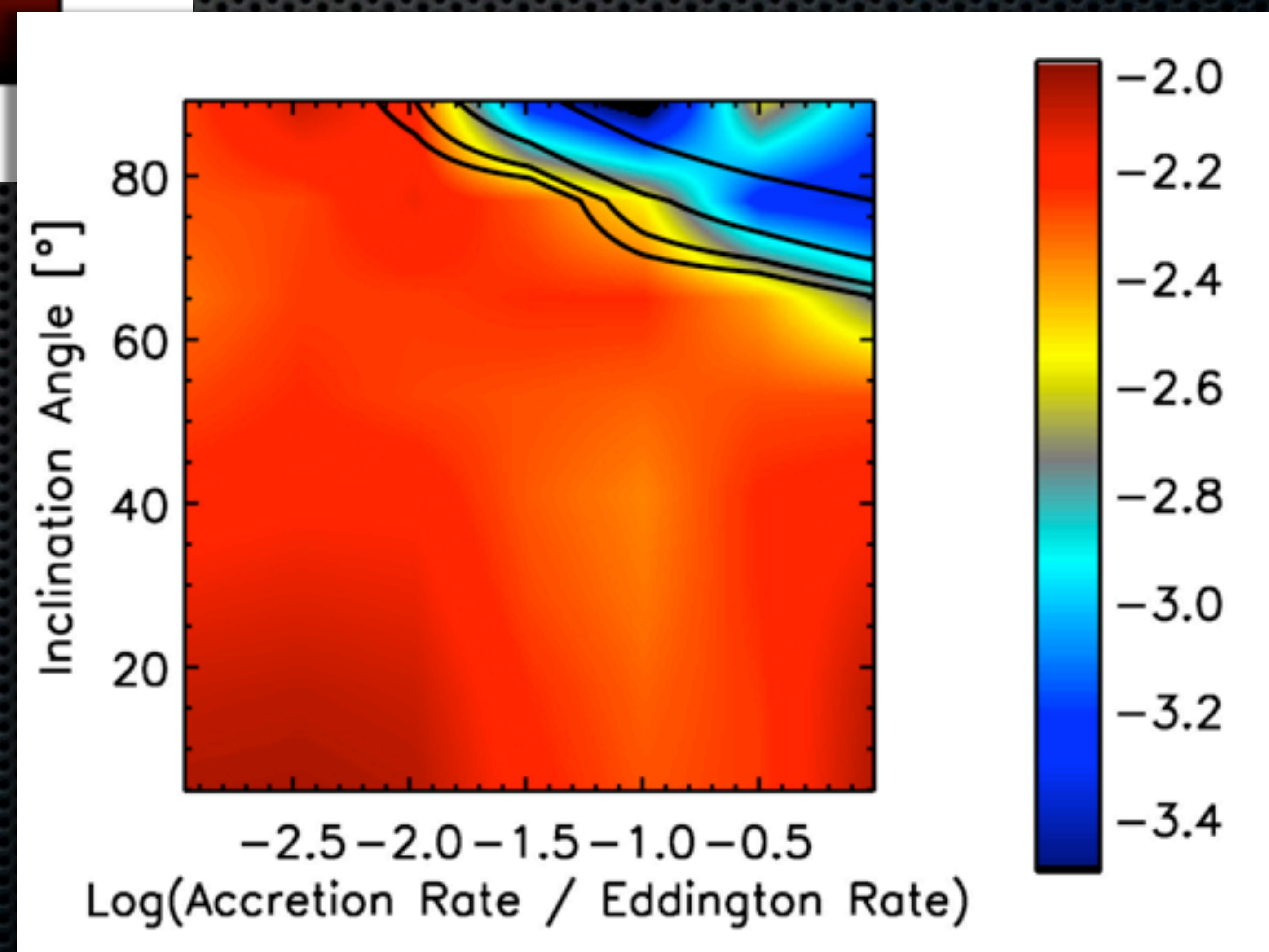
- Dissipation approximately follows accretion rate
- Not all accretion rate modes are dissipated
- Variability at infinity follows local dissipation var.



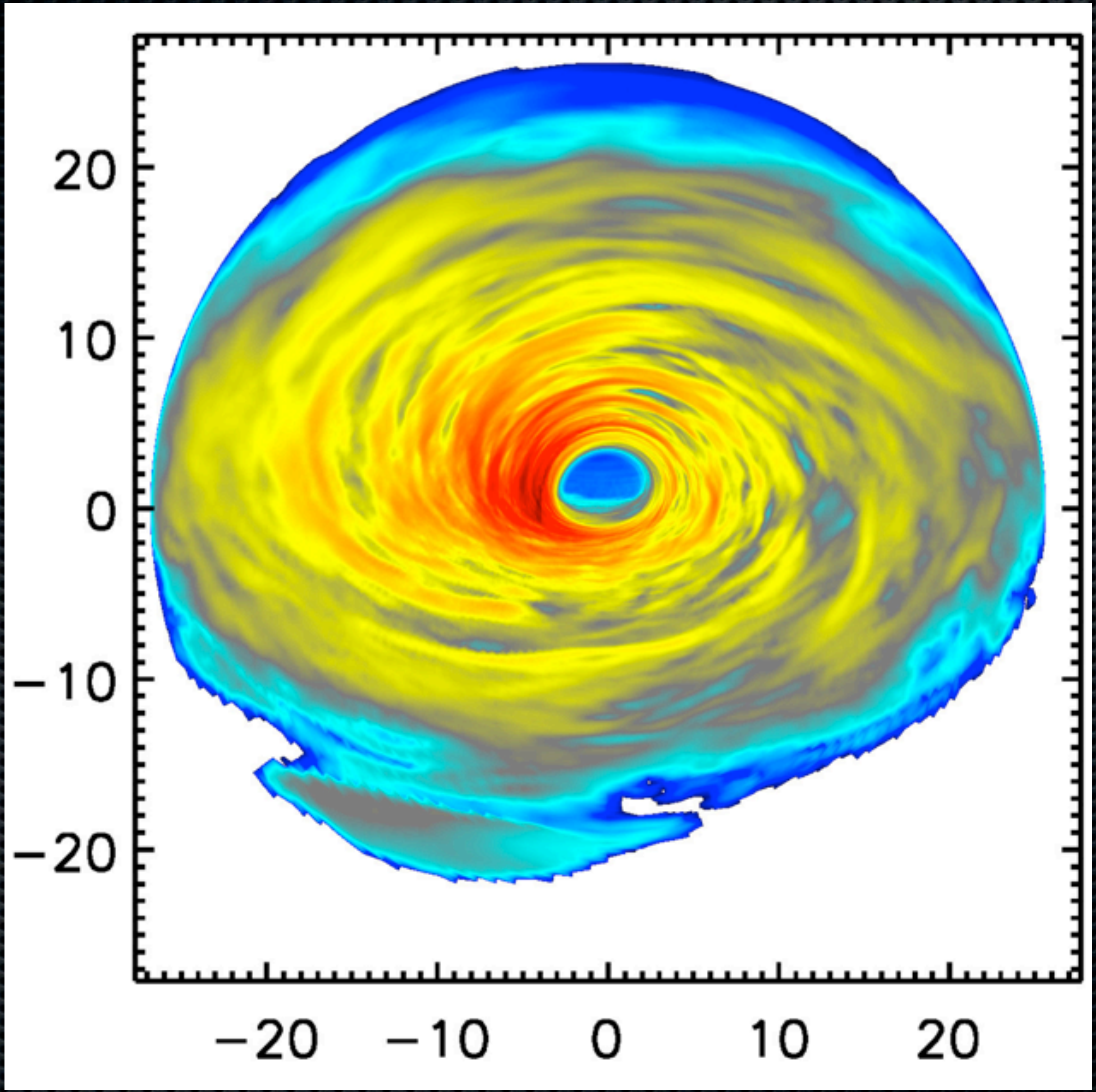
- Mostly incoherent between adjacent radii and frequencies;
- Possible coherence at

$$\nu < 1/T_{\rm inflow}(r)$$

  - Need longer runs to verify;



- Degenerate Result;
- No inclination angle effect;
- Consistent w/ observed power-law exponents
- See no QPOs, though we lie between LFQPO and HFQPO range

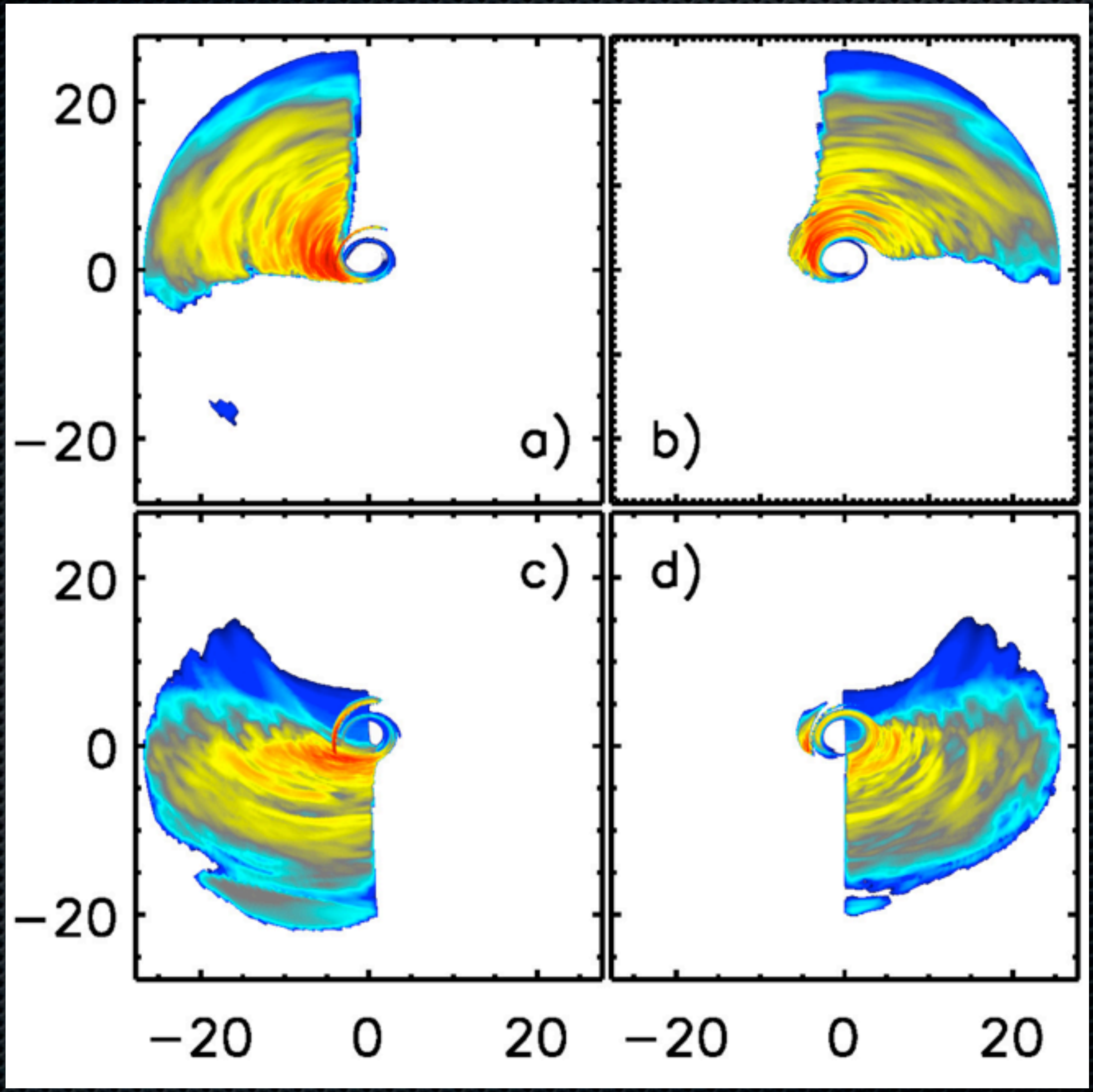


20
10
0
−10
−20
−20
−10
0
10
20

Degeneracy Explanation

$\alpha_a > -2$

$\alpha_b > -2$



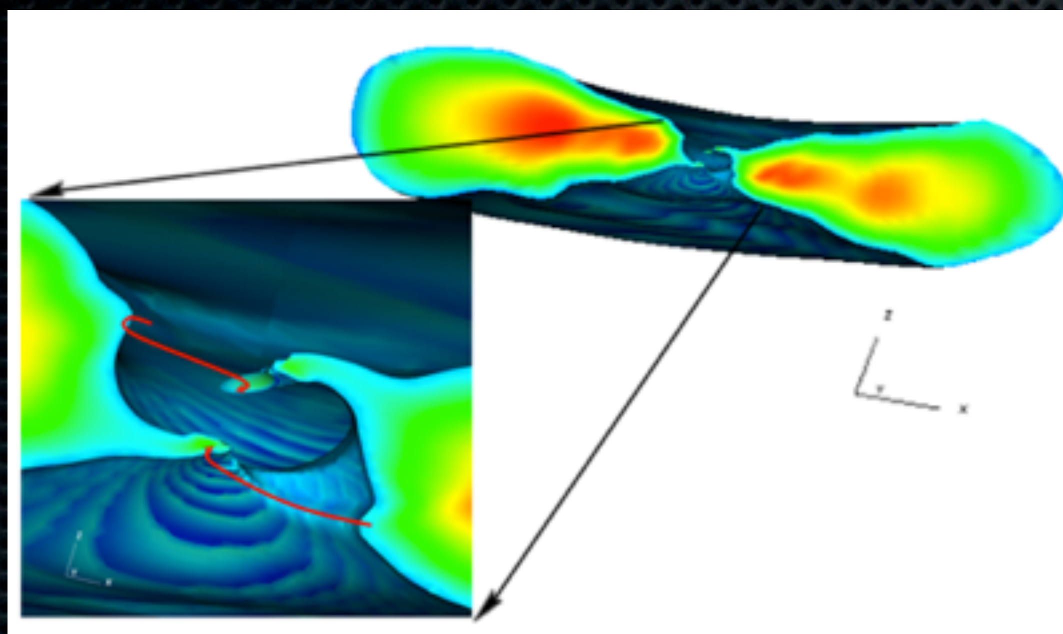
$\alpha_c < -2$

$\alpha_d < -2$

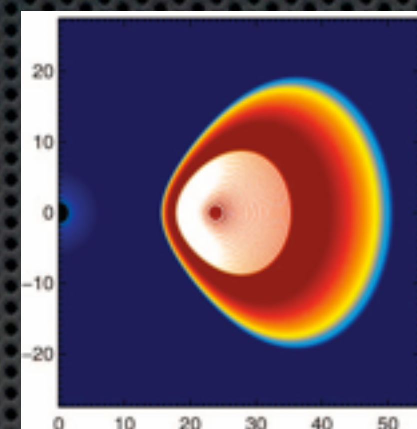
$i \sim 0^\circ$
$\alpha_i \simeq -2$

Out-standing Issues in black hole accretion

Warped Disks   Fragile et al. 2007-2009



Initial Field Topology   Beckwith et al. 2008



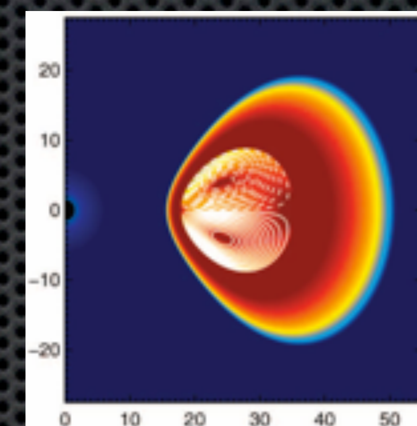
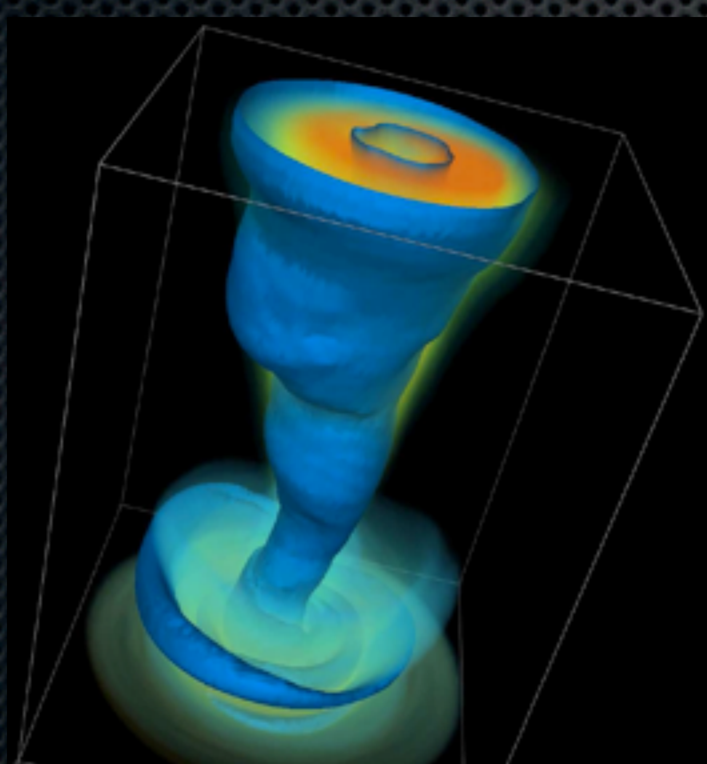


Image Unavailable

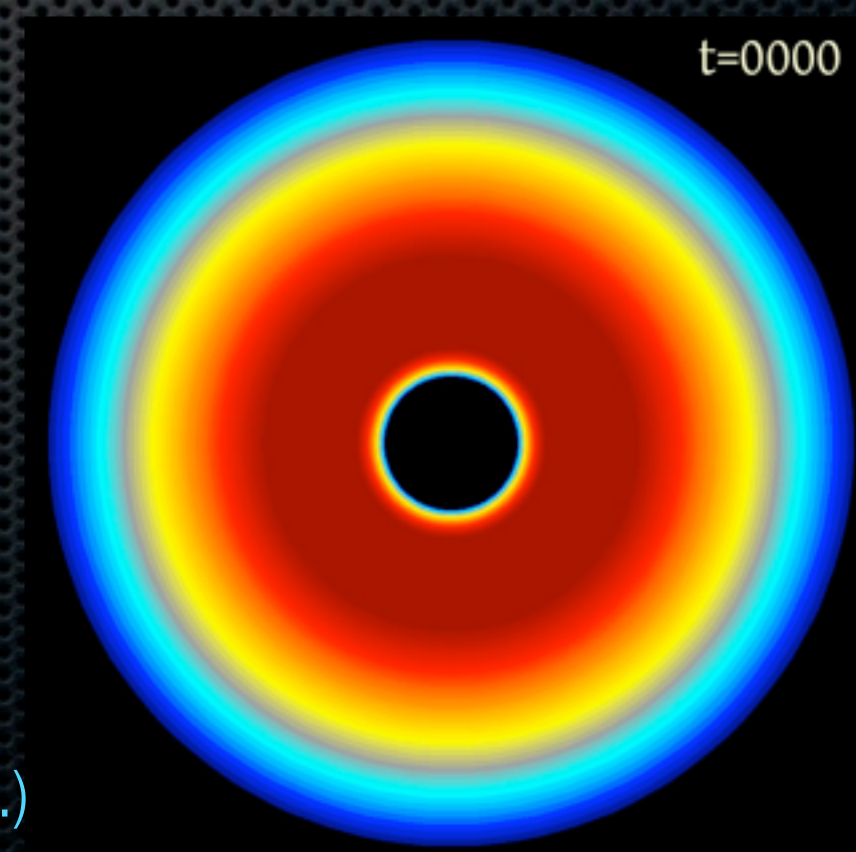
Poloidal	Quadrupolar	Toroidal
Jet	Jet	“No” Jet



McKinney & Blandford 2009

Full 2pi Evolutions
m=1 mode dominance

Gammie et al (unpub.)

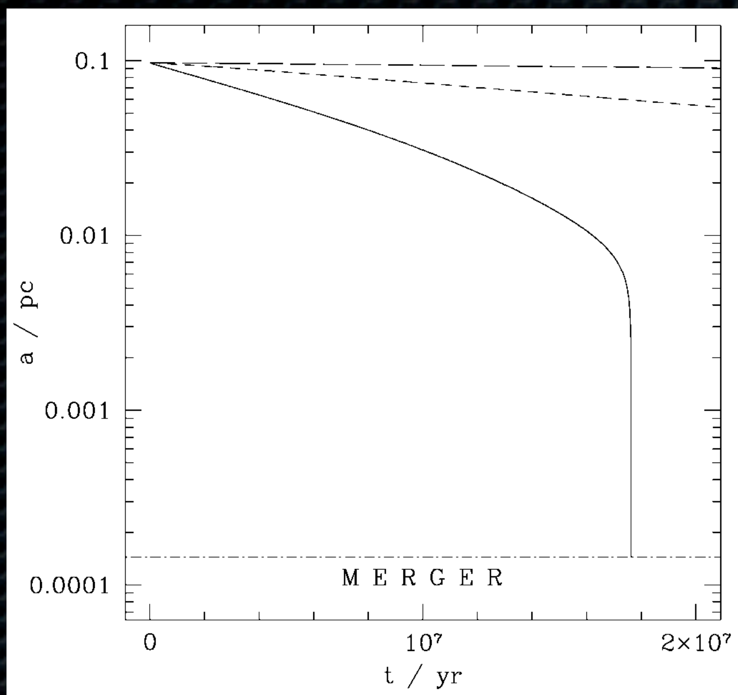


Binary Black Hole Accretion

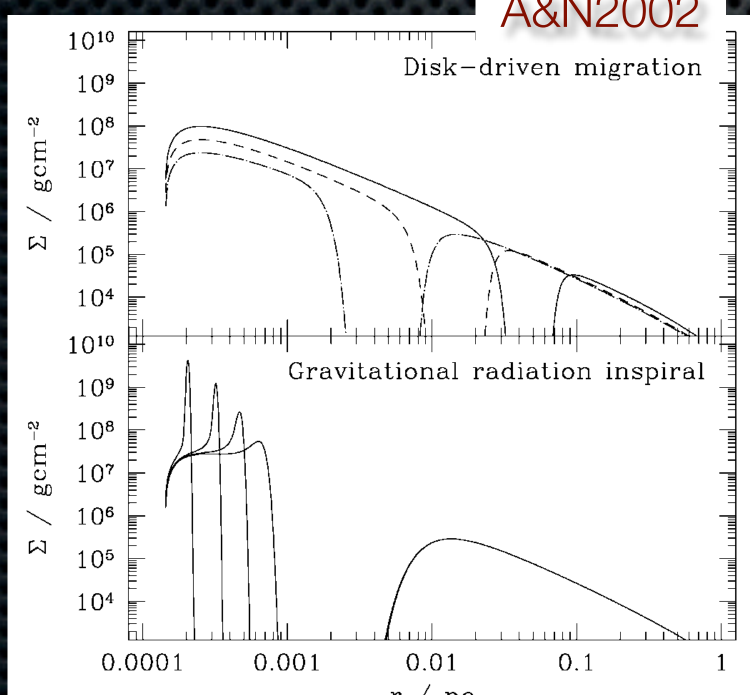
Artymowicz & Lubow 1994

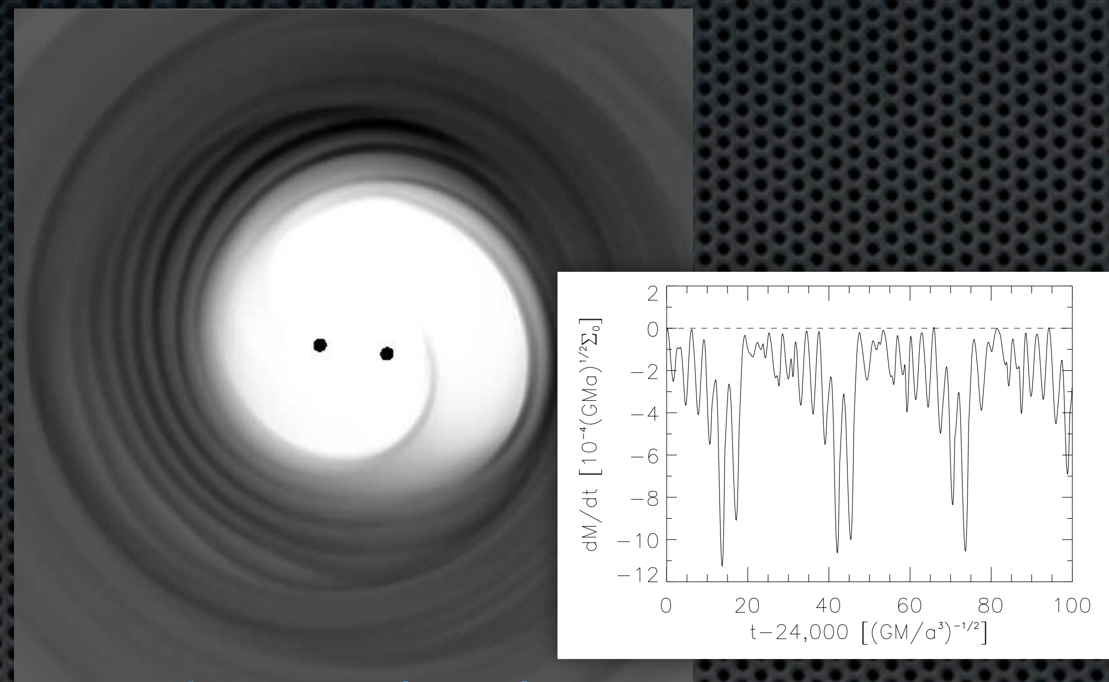
Armitage & Natarajan 2002,2005

Circumbinary Black Hole Disks

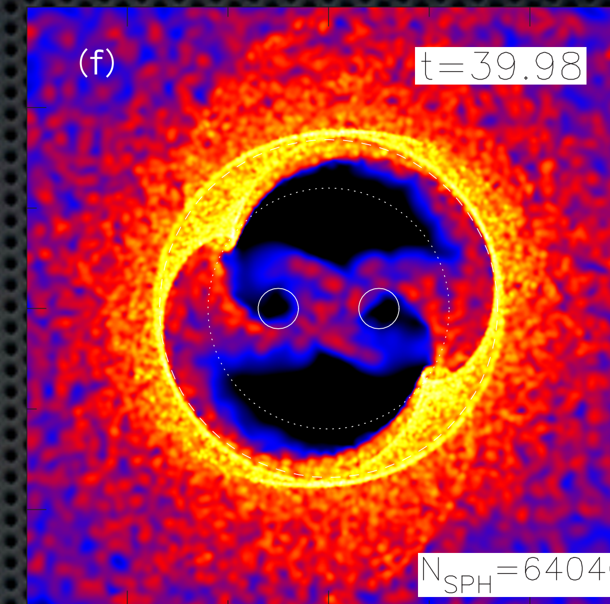


A&N2002

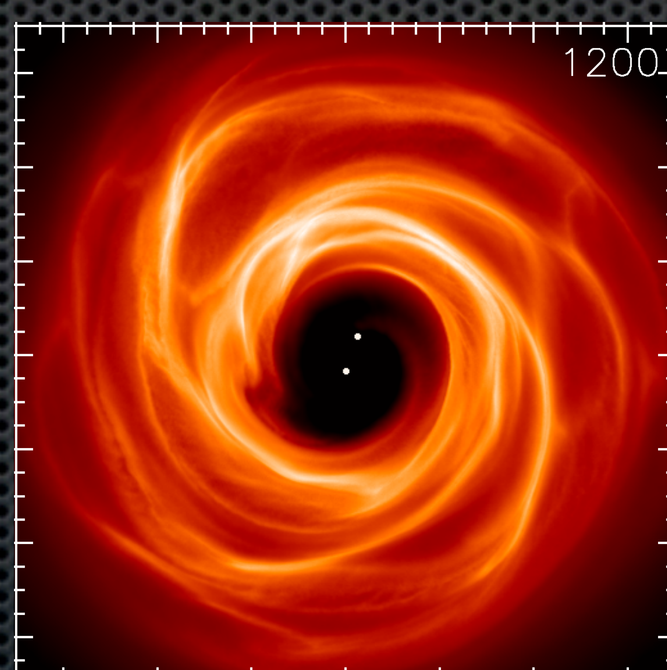




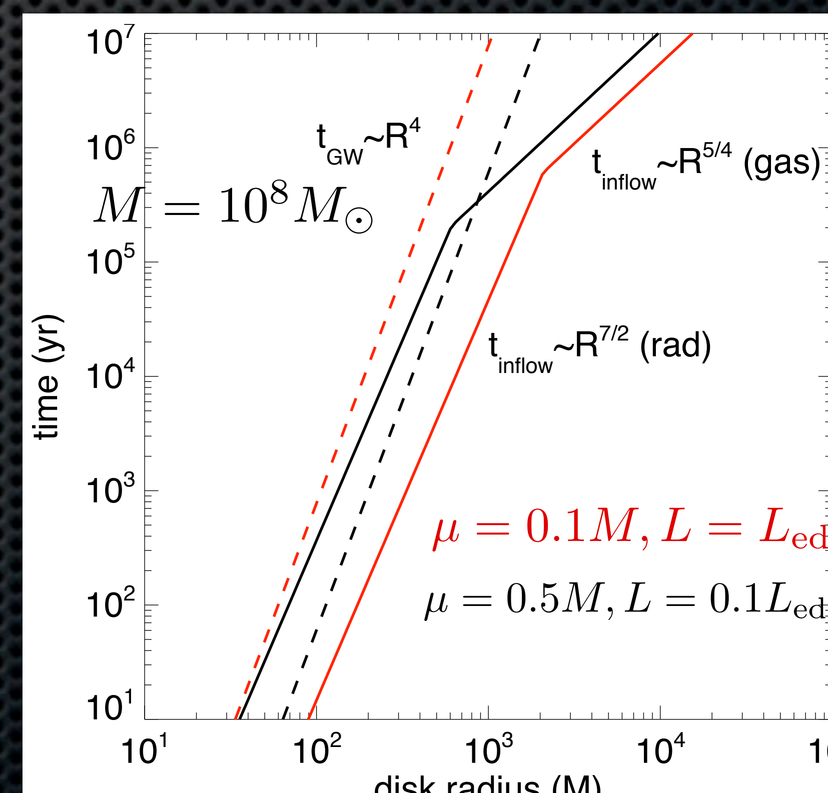
MacFadyen & Milosavljevic 2008



Hayasaki et al 2007

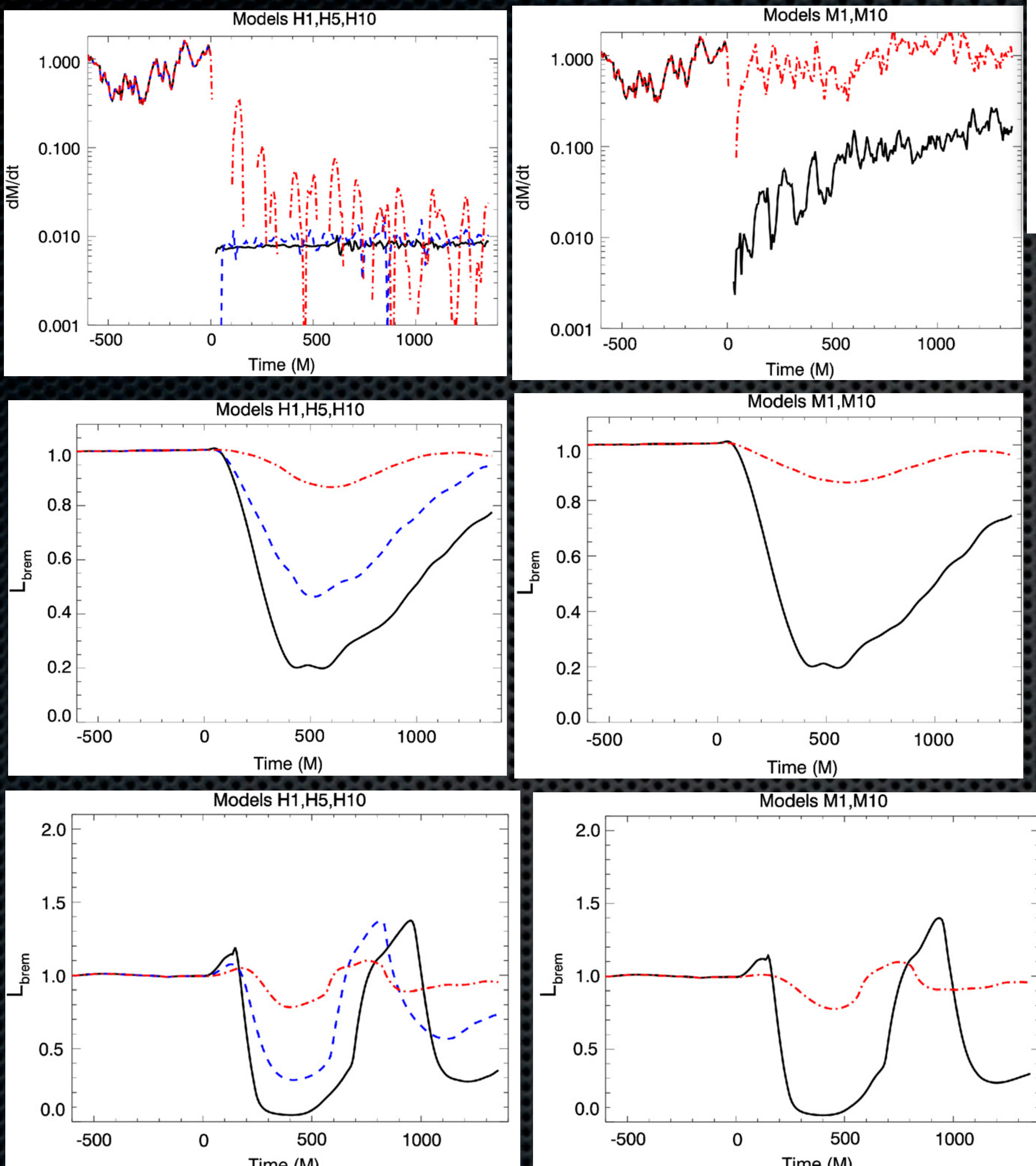


Cuadra et al 2009

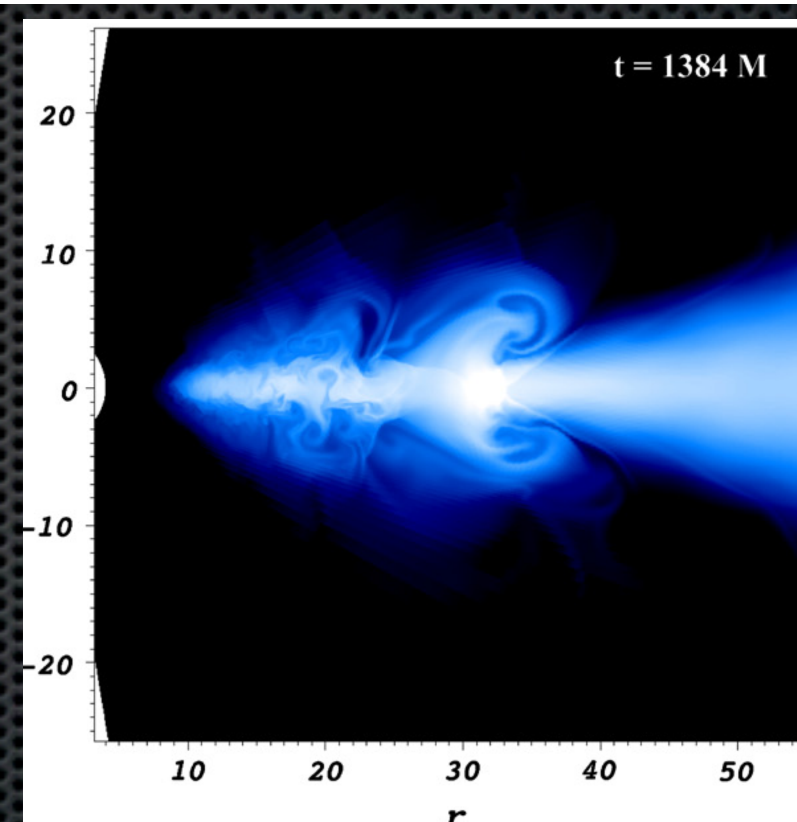


Schnittman & Krolik 2008

O’Neill et al 2009 “Kicked” Thin Disk (near BH)



ID	Type of Simulation[a]	Resolution[b]	ϵ[c]
H10	Hydrodynamic	768 × 256	0.10
M10	MHD	768 × 256 × 32	0.10
H5	Hydrodynamic	768 × 256	0.05
H1	Hydrodynamic	768 × 256	0.01
M1	MHD	768 × 256 × 32	0.01



$$L_{\rm brem} = \int j_{\rm brem} dV$$

$$j_{\rm brem} \propto \rho^2 T^{1/2}$$

- Newtonian Hydro/MHD
- Mass Loss
- Non-conservative Hydro

Summary & Conclusion:

- Moving towards fully self-consistent accretion models
- MRI-driven, uncooled accretion can match the full spectrum of Sgr A*
  - Vital for understanding its evolution and polarization
- Building the analytical tools to evaluate disks' statistical steady-state
- Find that magnetic fields can dramatically change the "thin disk" picture within the ISCO
- MRI turbulence can explain the high frequency X-ray variability in AGN and low/hard state of galactic black holes
  - Emissivity is not trivially dependent on accretion rate

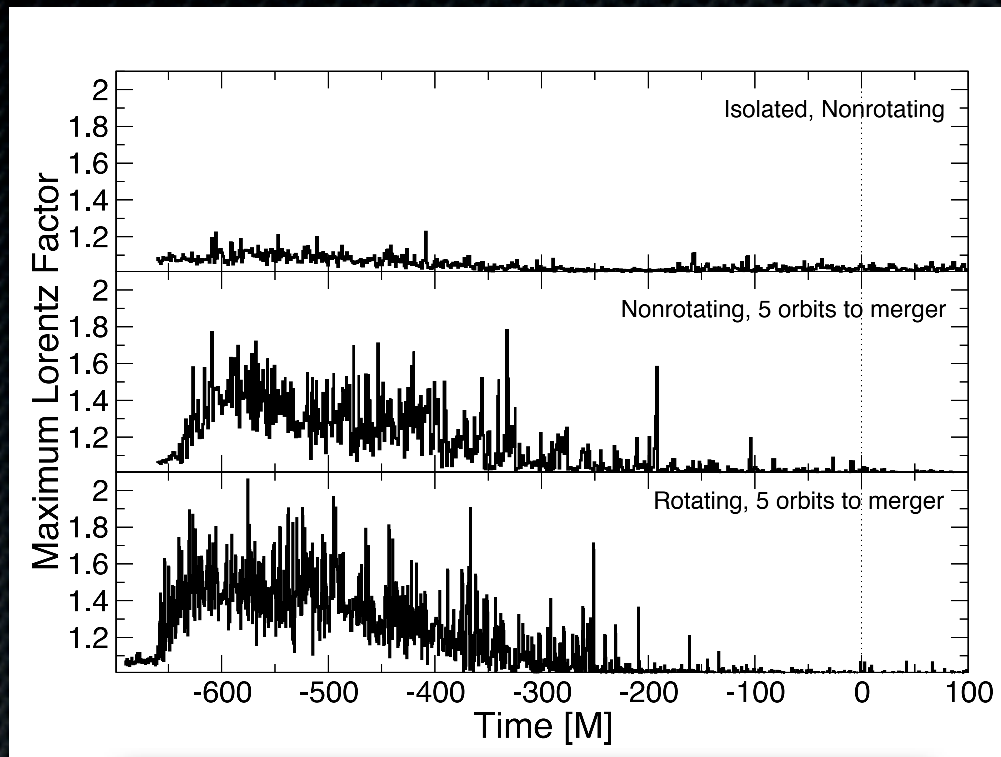
Future Work:

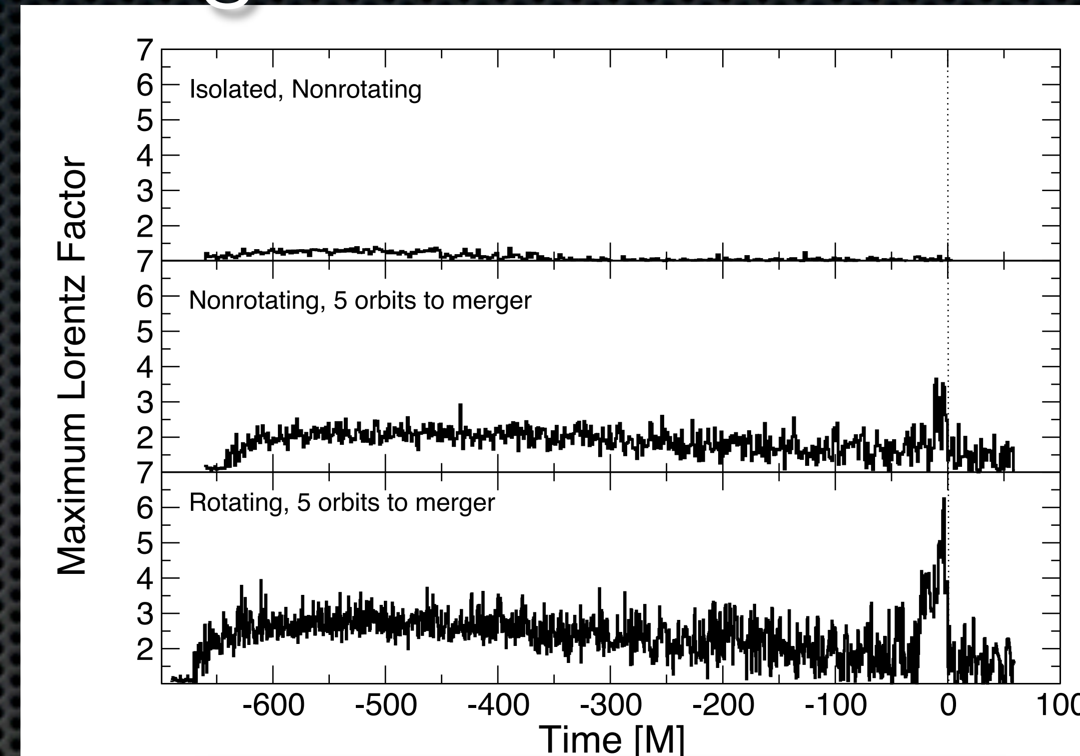
- 3D Sgr A* models
- Inclined disks;
- Further magnetic field topology studies;
- What are "natural" initial disk conditions?
- How does Unary Black Hole accretion physics carry over to Binary Black Holes?

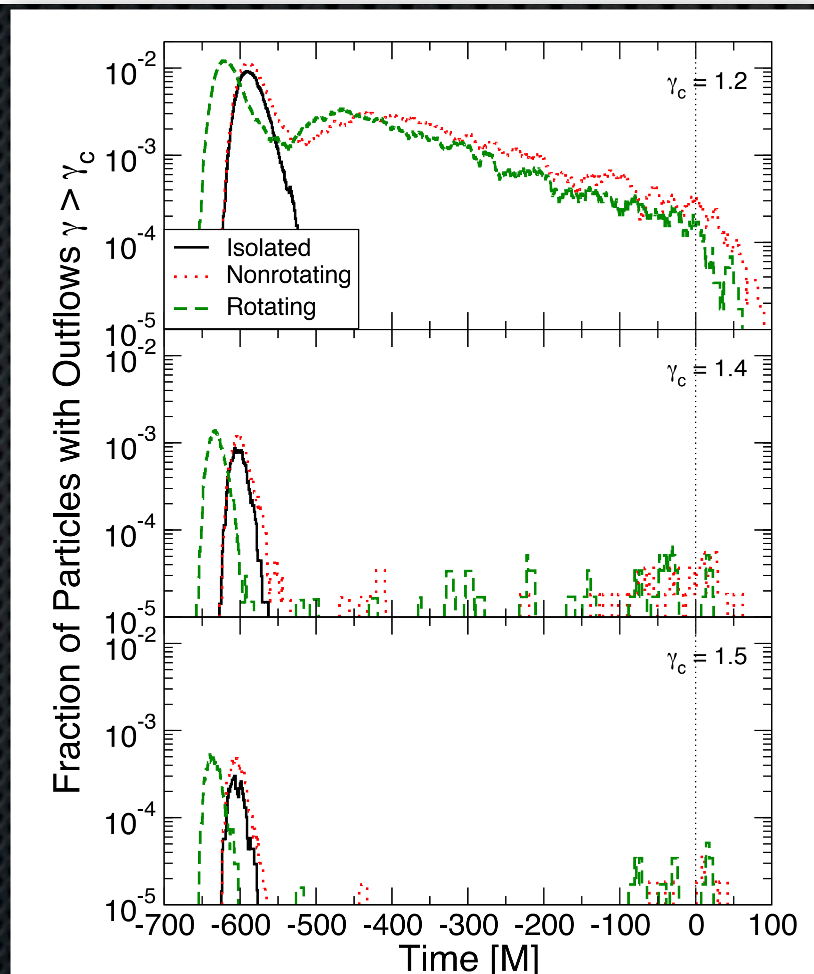
Extra Slides

van Meter et al 2009

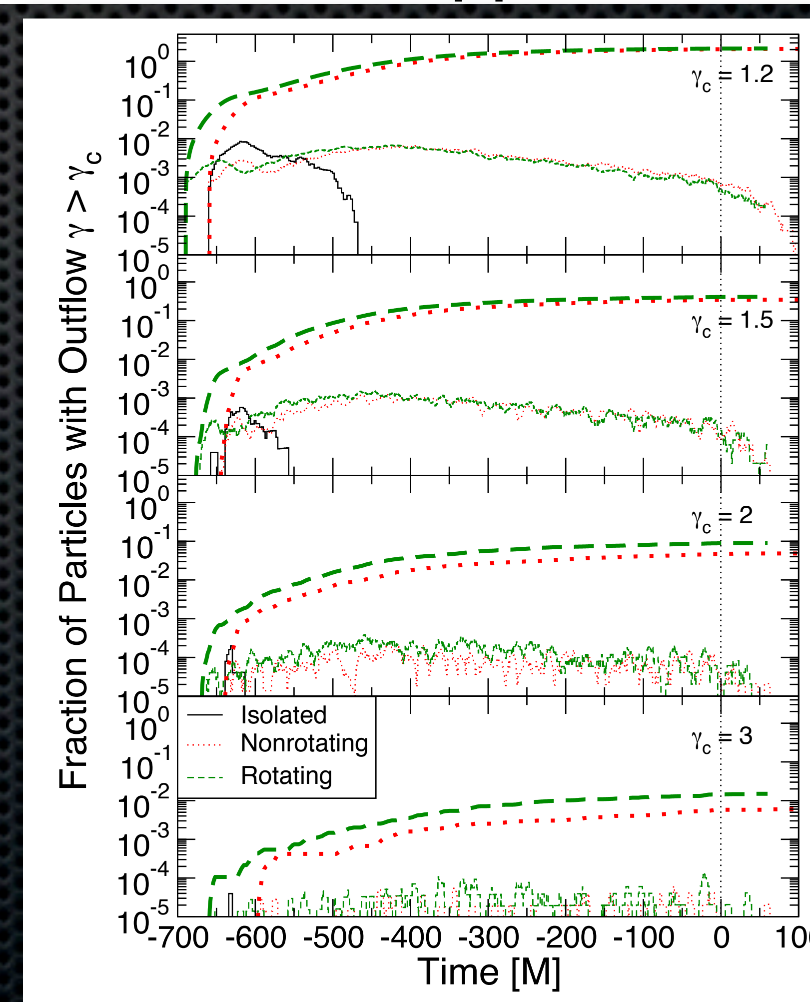
"Stirring Test Particles"







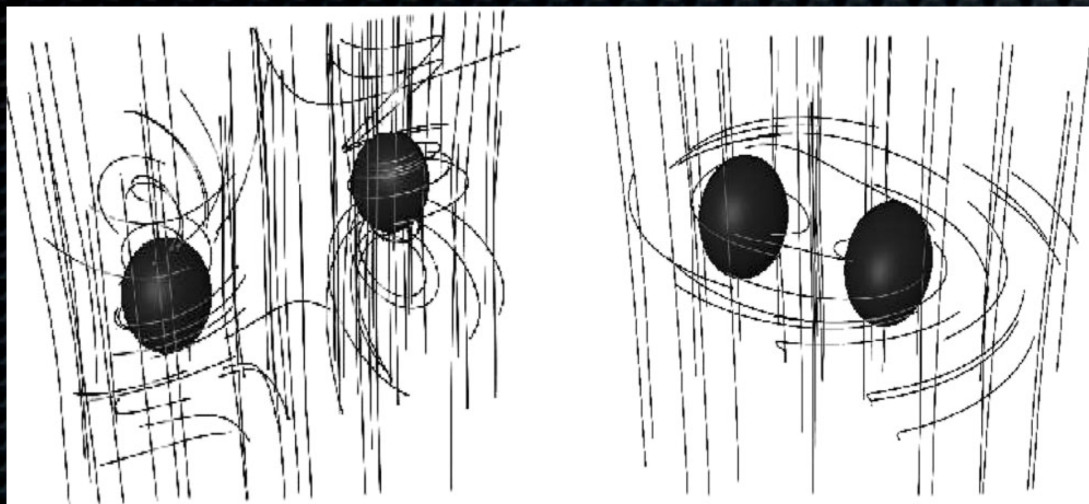
Warm Torus in Orbit

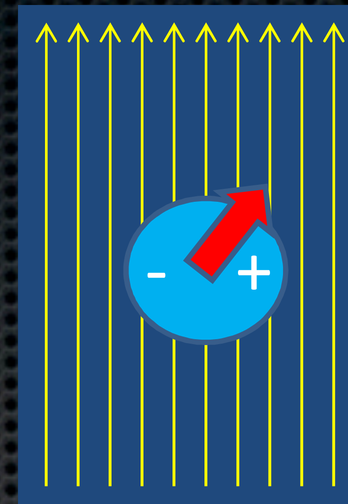


Hot Isotropic Cloud

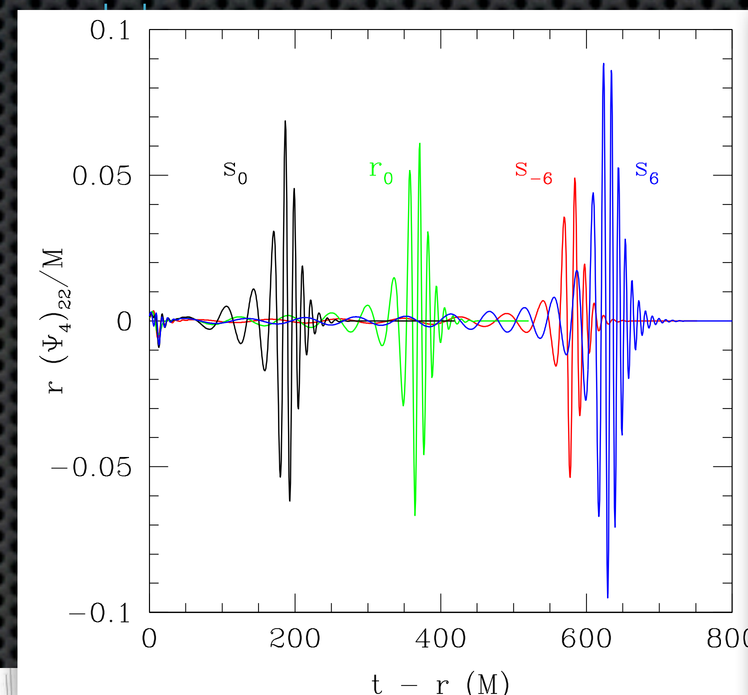
BBH Merger in Magnetic Field

Palenzuela et al 2009

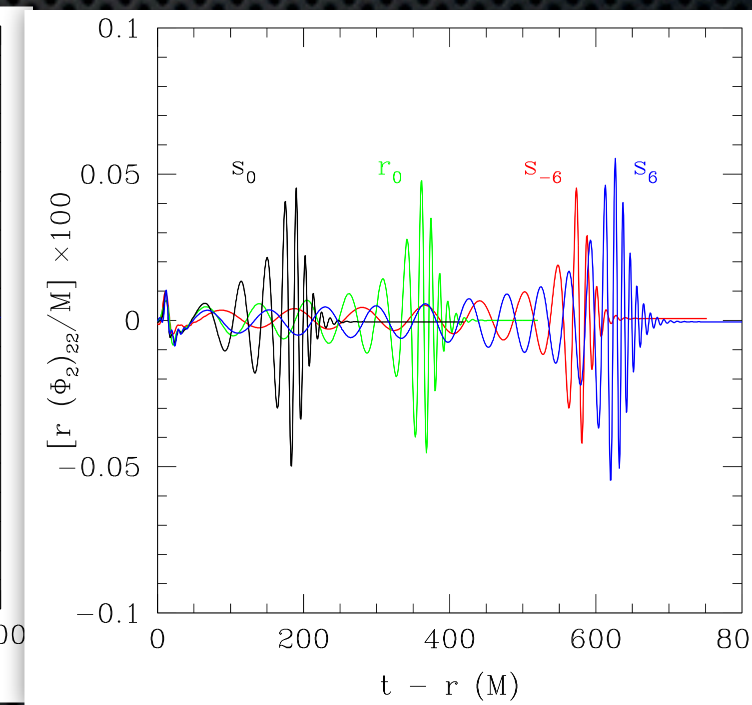




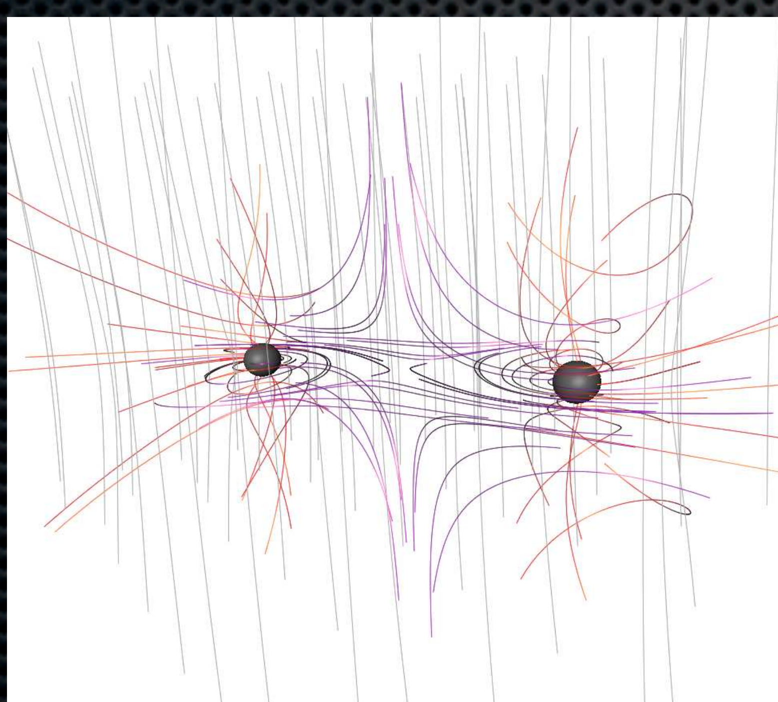
GW

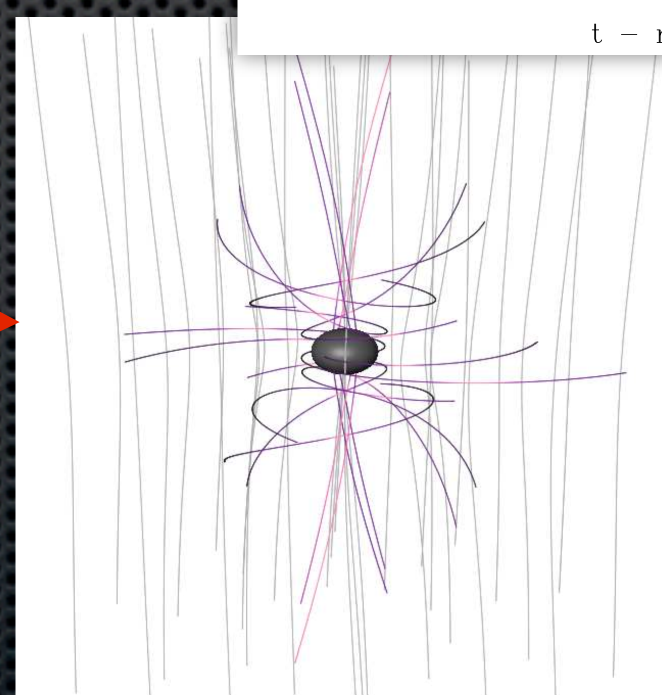


EM



Mosta et al 2009





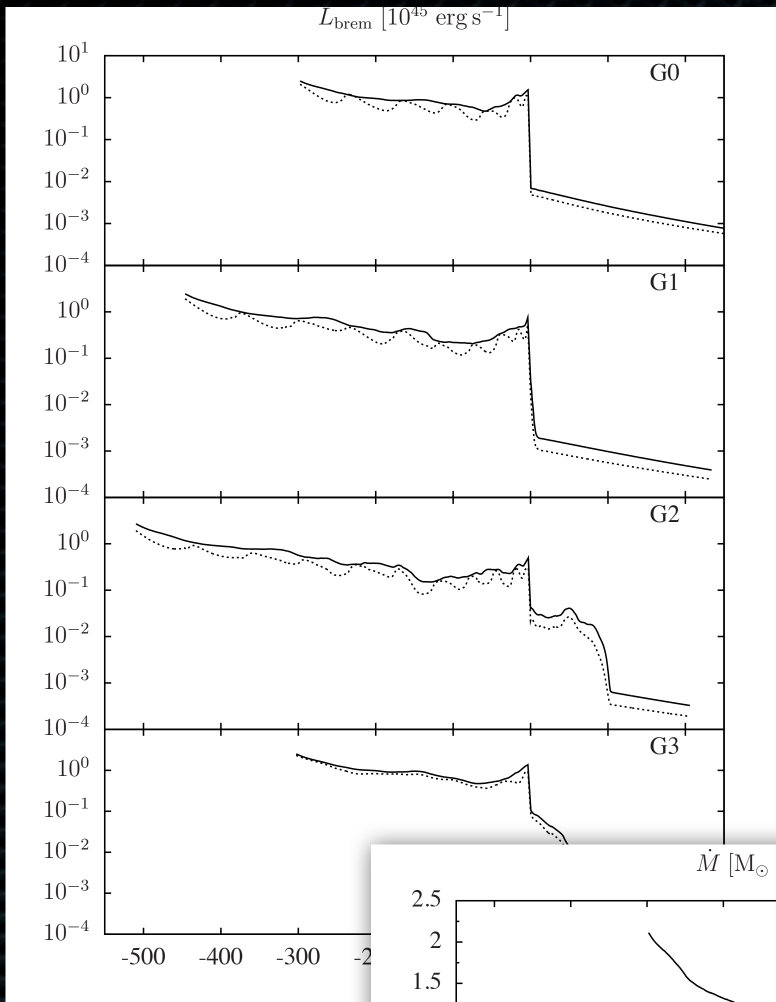
$$\frac{E_{\rm EM}^{\rm rad}}{M} \simeq 10^{-15} \left(\frac{M}{10^8\ M_\odot}\right)^2 \left(\frac{B}{10^4\ \rm G}\right)^2$$

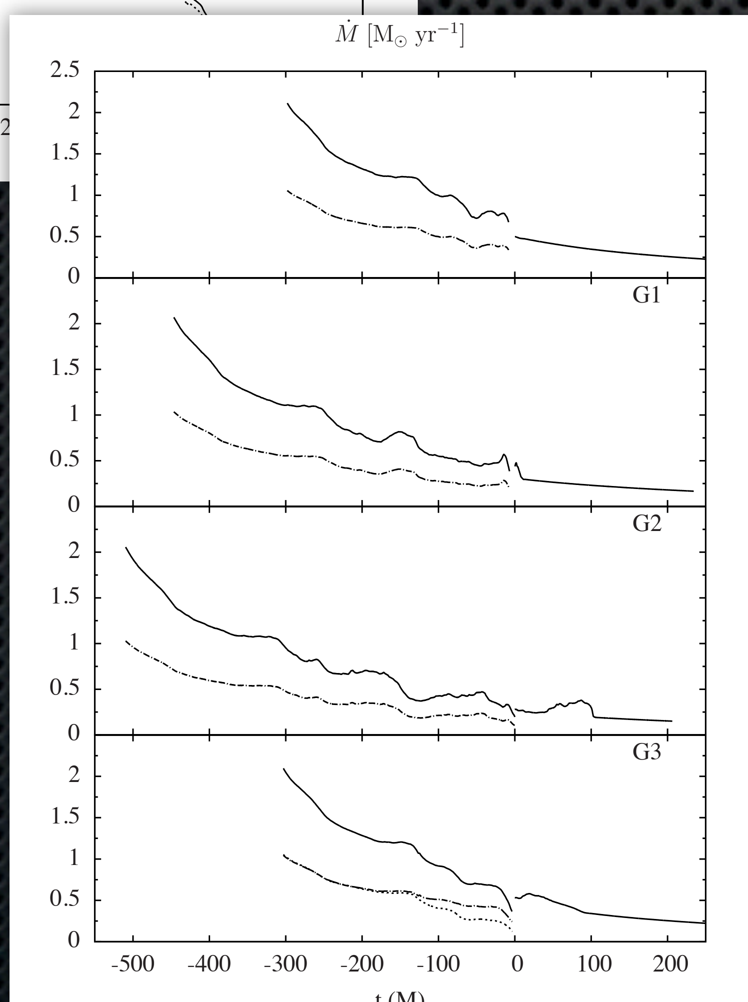
$$L_{\rm EM} \equiv \frac{E_{\rm EM}^{\rm rad}}{\tau} \simeq\ 10^{-4} \left(\frac{B}{10^4\ \rm G}\right)^2 L_{\rm Edd}$$

$$\nu = 10^{-4}(10^8 M_\odot/M)\rm Hz$$

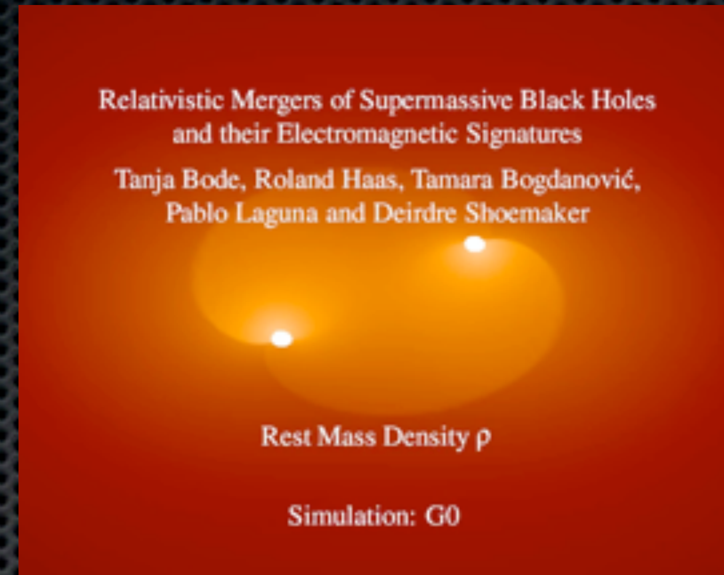
Bode et al. 2009

“Stirring Hot Gas”

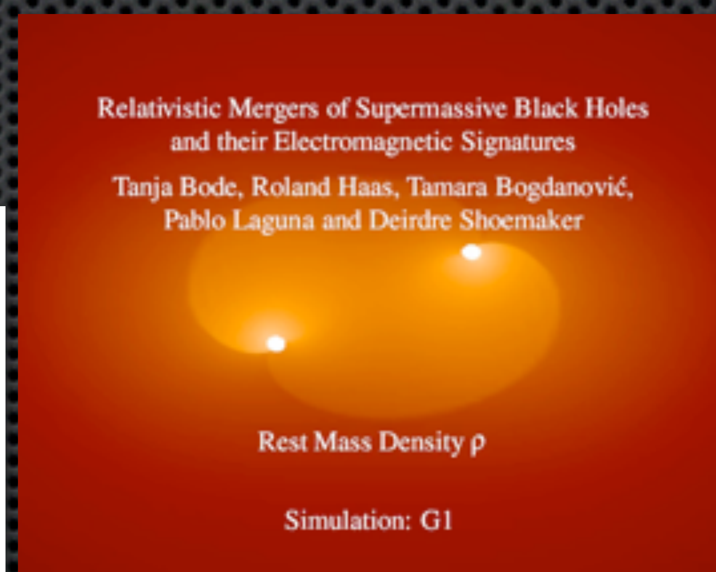




G0



G3



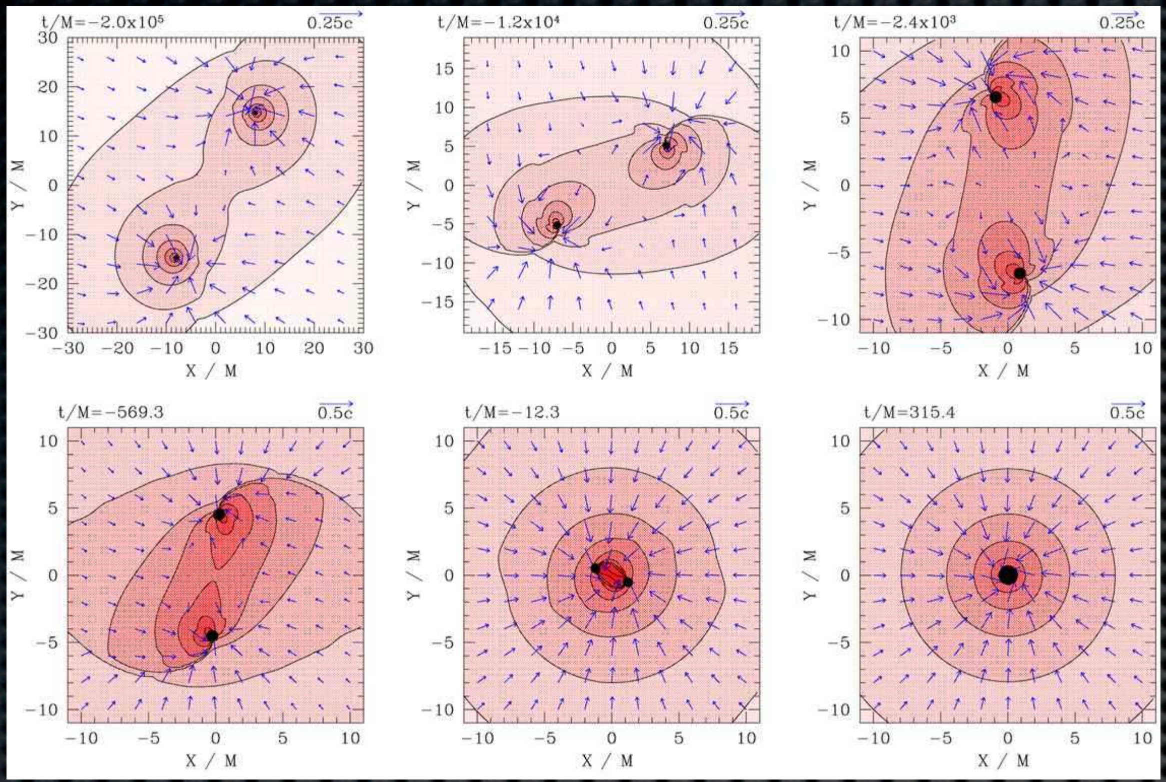
G1

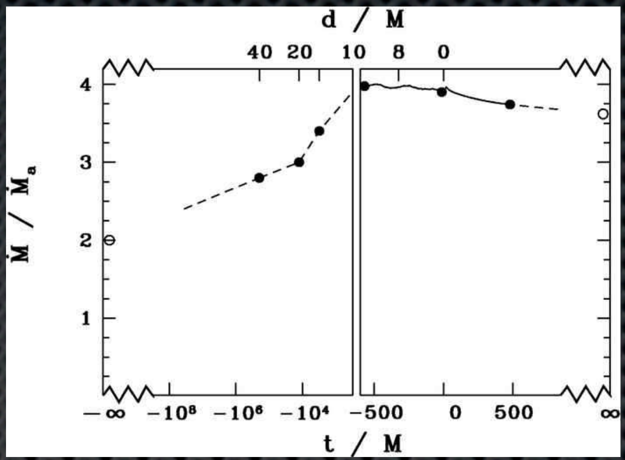
G2

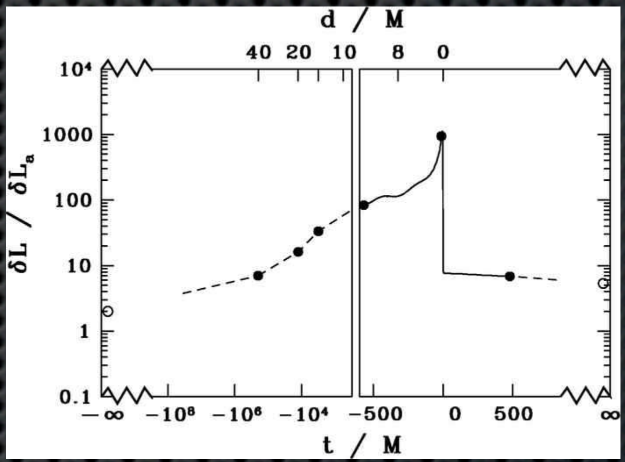
Run	a_1/m	a_2/m	P^x/M	P^y/M	m_i/M	$M_{\rm ADM}/M$
G0	0	0	-2.0902×10^{-3}	0.11237	0.5000	0.9878
G1	+0.4	+0.4	0	0.10862	0.4893	0.9875
G2	+0.6	+0.6	0	0.10677	0.4736	0.9874
G3	+0.4	-0.4	0	0.11237	0.4893	0.9878

Farris, Liu, Shapiro 2009

Binary Bondi-Hoyle-Lyttleton Accretion

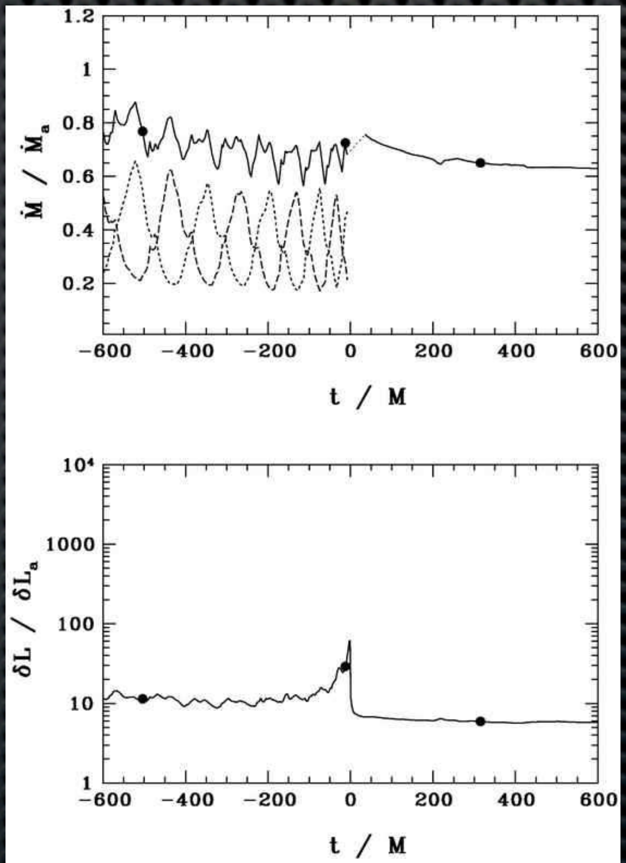


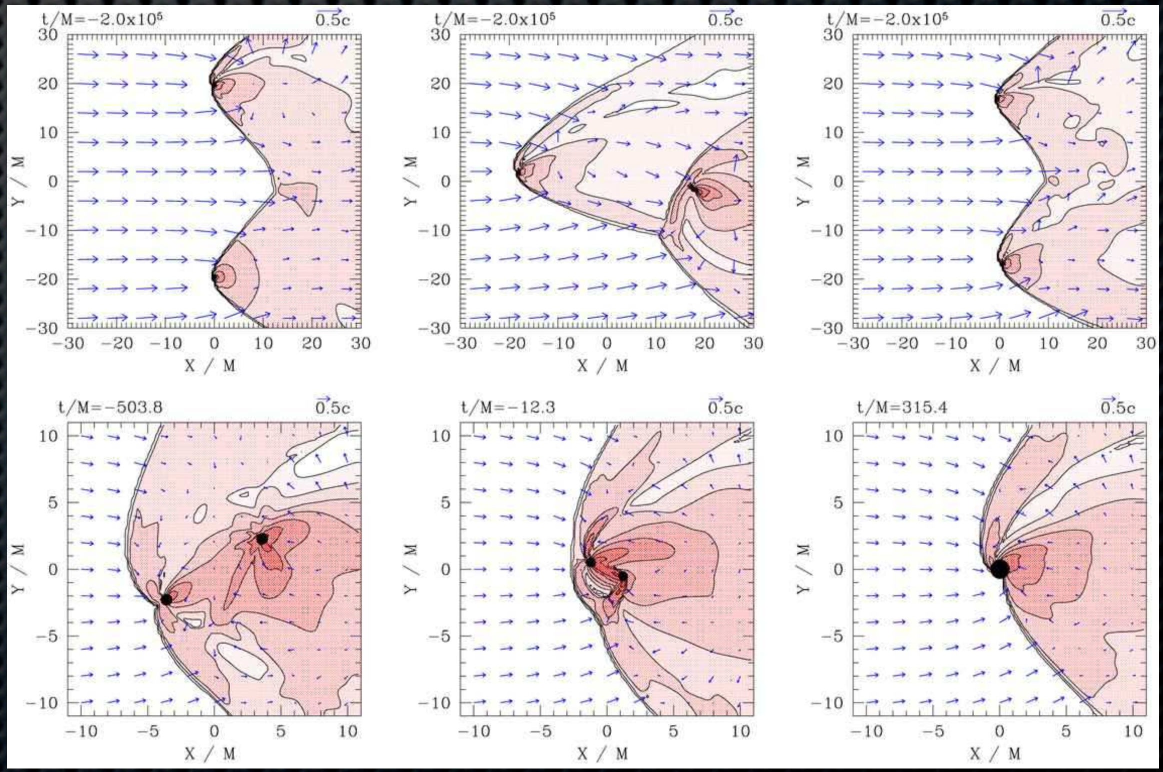




“Prototype”

Boosted Temperature



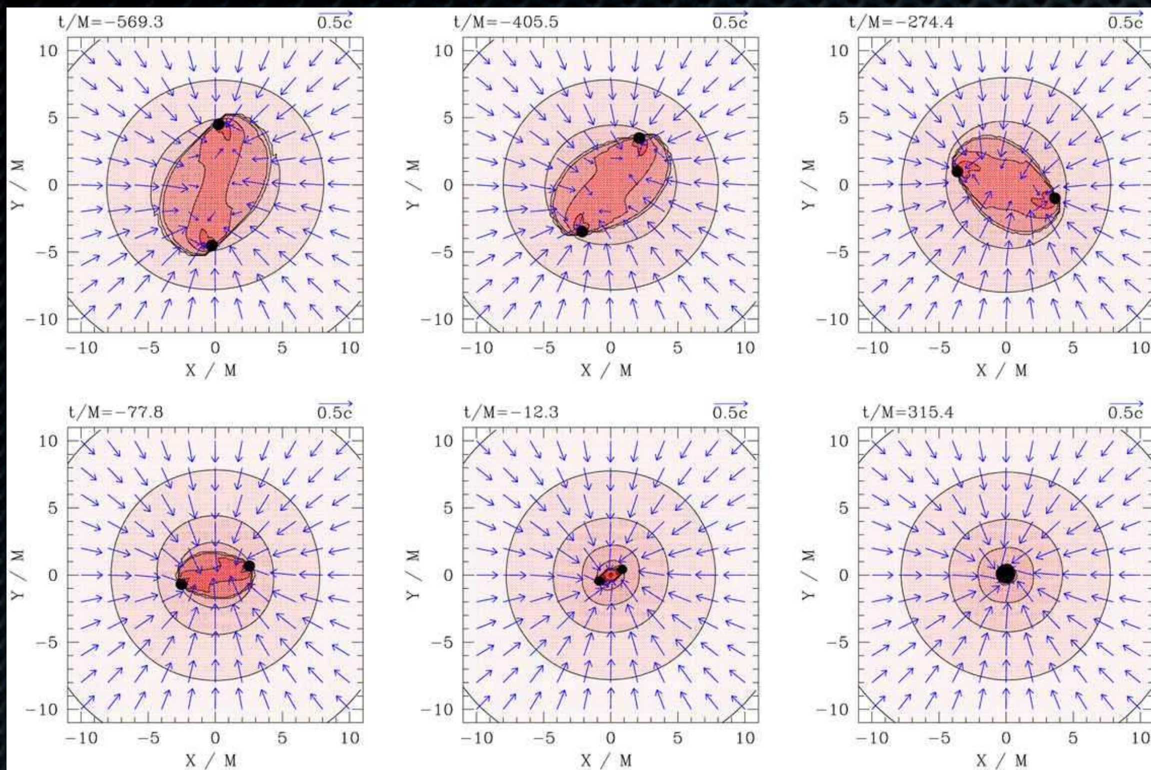


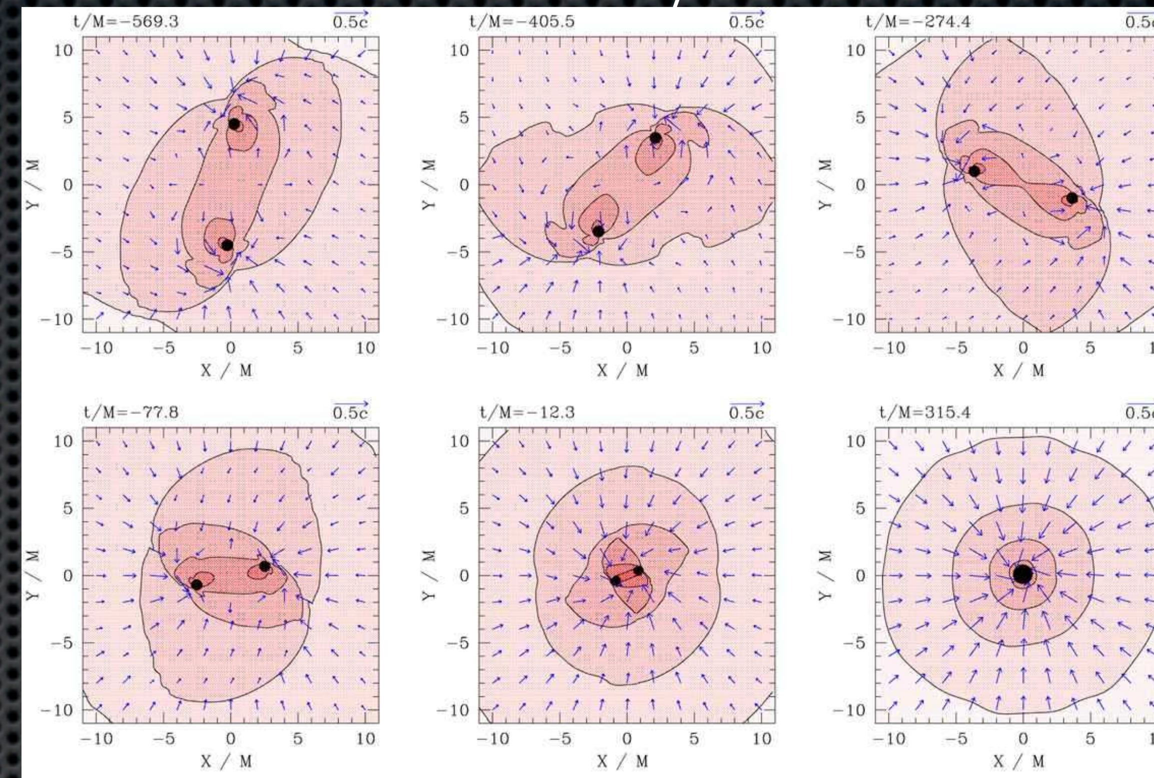
Farris, Liu, Shapiro 2009

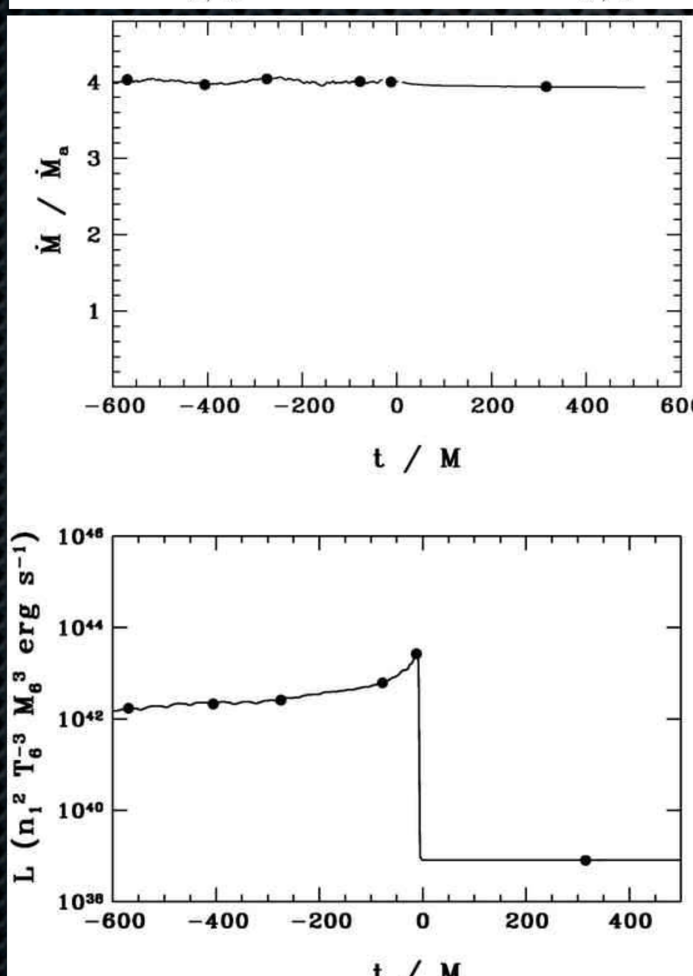
$\Gamma = 5/3 \rightarrow 13/9$

Realistic Temperature

$\Gamma = 5/3$



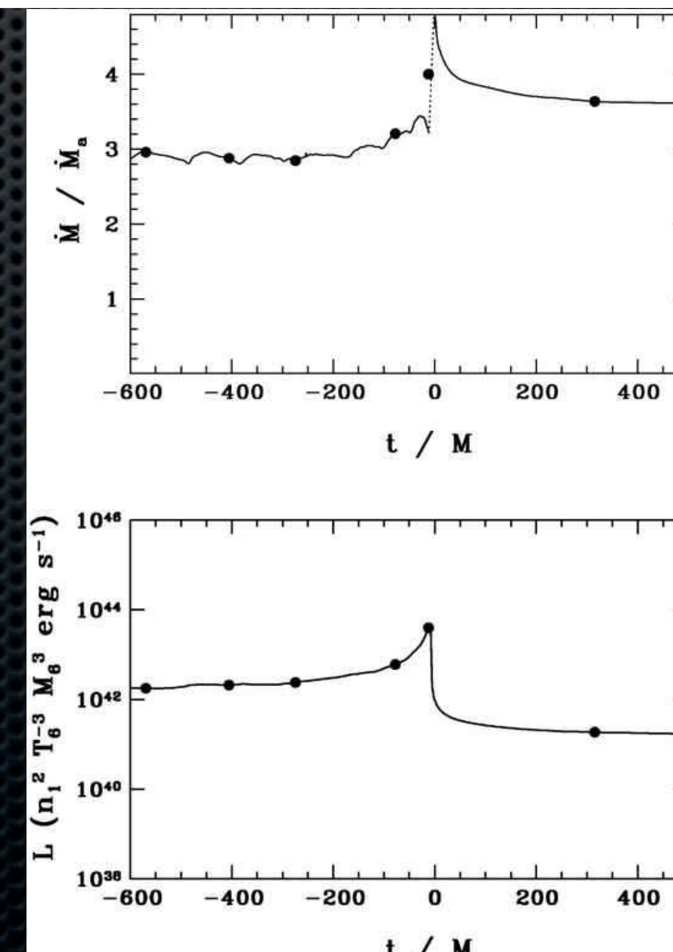




$$L_{ff}^{max} \approx 3\times 10^{37}\ n_1^2\ T_6^{-3} M_6^3\ \mathrm{erg\ s^{-1}}\ ,$$
$$L_{syn}^{max} \approx 3\times 10^{43}\ n_1^2\ T_6^{-3} \beta_1^{-1} M_6^3\ \mathrm{erg\ s^{-1}}$$

$$h\nu_{ff}^{max} \approx \frac{230\ \mathrm{MeV}}{1+z}\ \mathrm{(RA2)}$$

$$h\nu_{syn}^{max} = \frac{100}{1+z}\ n_1^{1/2}\ T_6^{-3/4} \beta_1^{-1/2}\ \mathrm{eV}\ \mathrm{(RA2)}$$



Sub-kpc Resolved Dual Nuclei

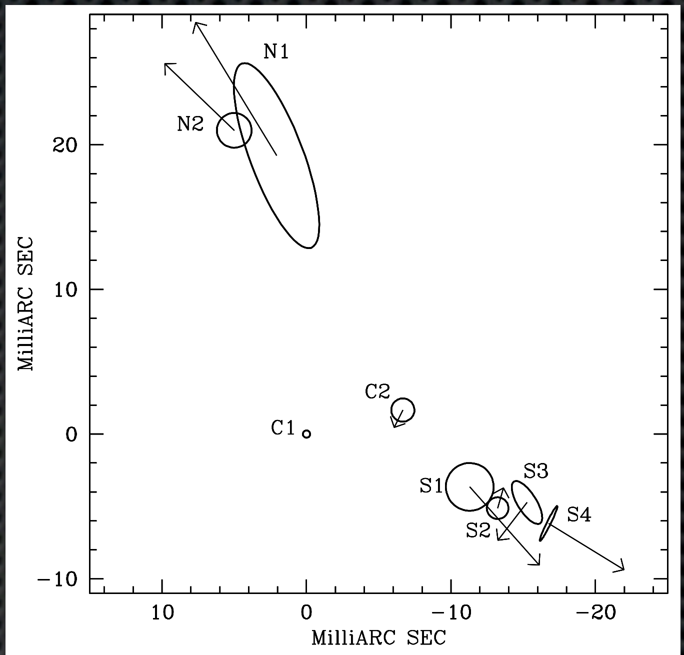
0402+379:

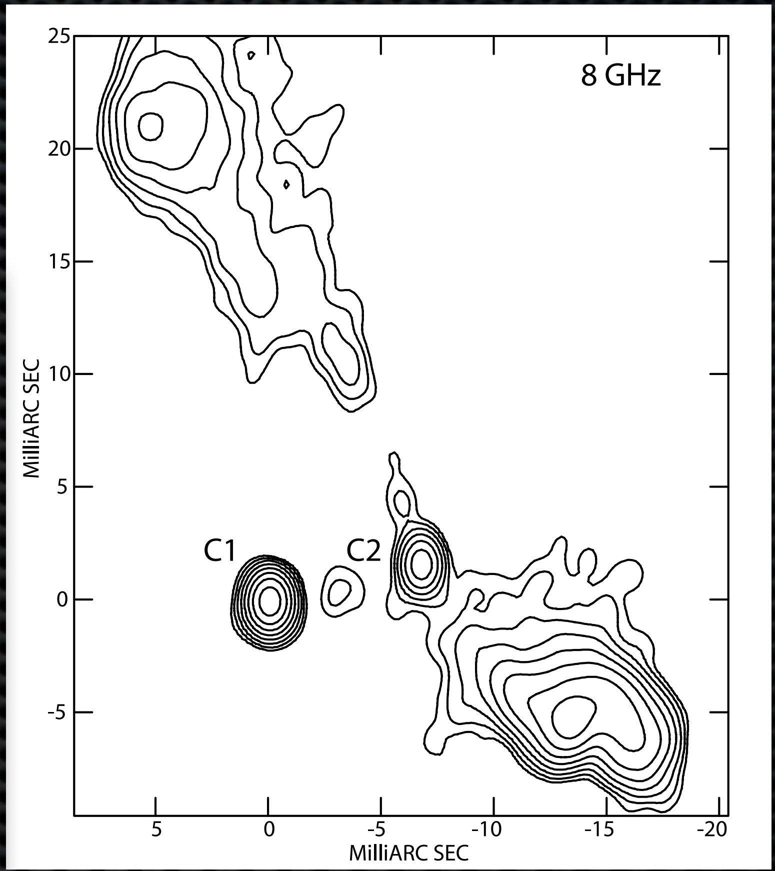
(Xu et al. 1994, Maness et al. 2004, Rodriguez et al. 2006):

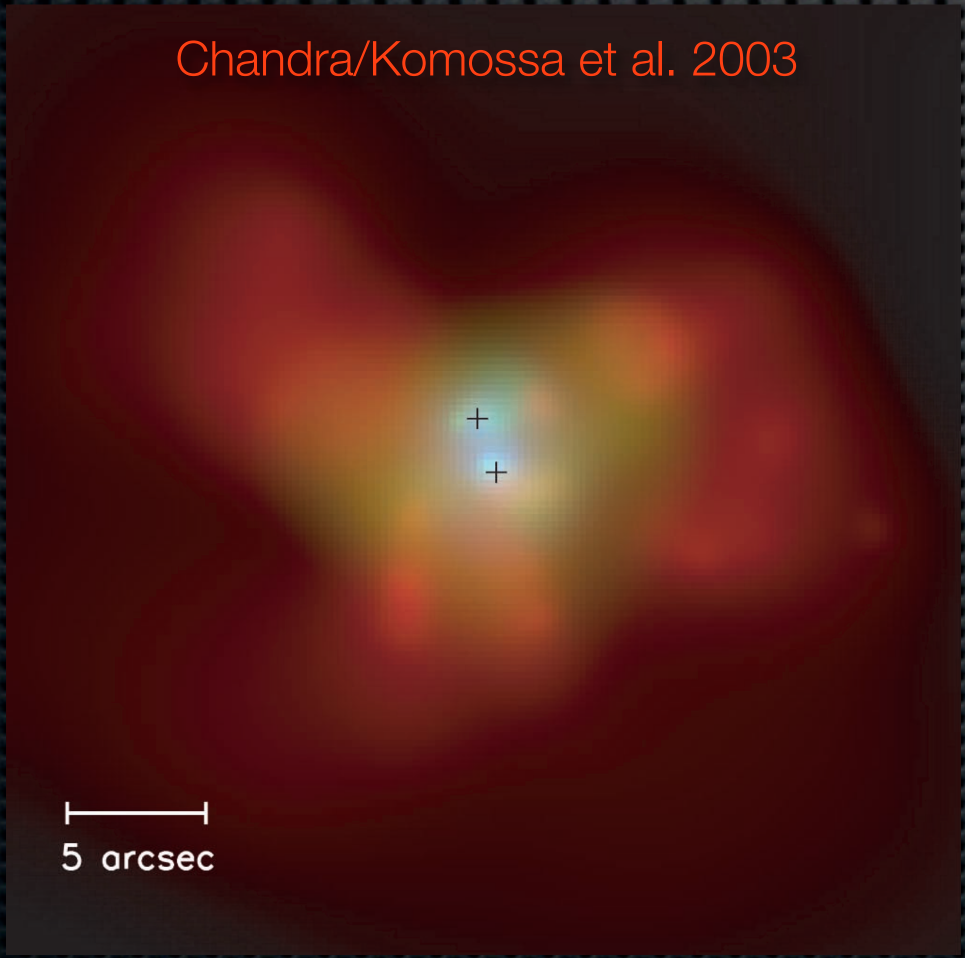
- Radio, Elliptical galaxy host
- z = 0.055, d = 5 pc $M \sim 10^8 M_\odot$

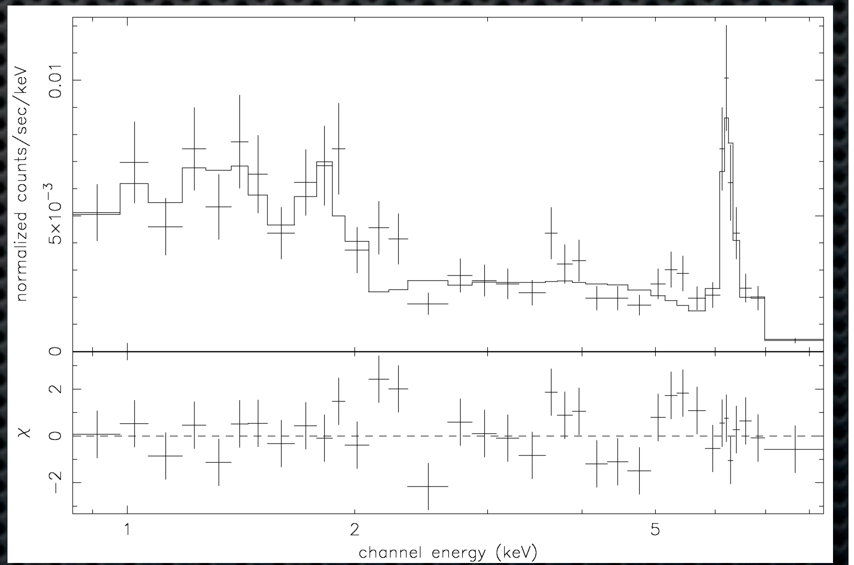
NGC 6240: (Komossa et al. 2003)

- Optical ID: (Fried & Schulz 1983)
- HST, Ultra-lum. IR galaxy host
- z = 0.024   d = 0.5 kpc

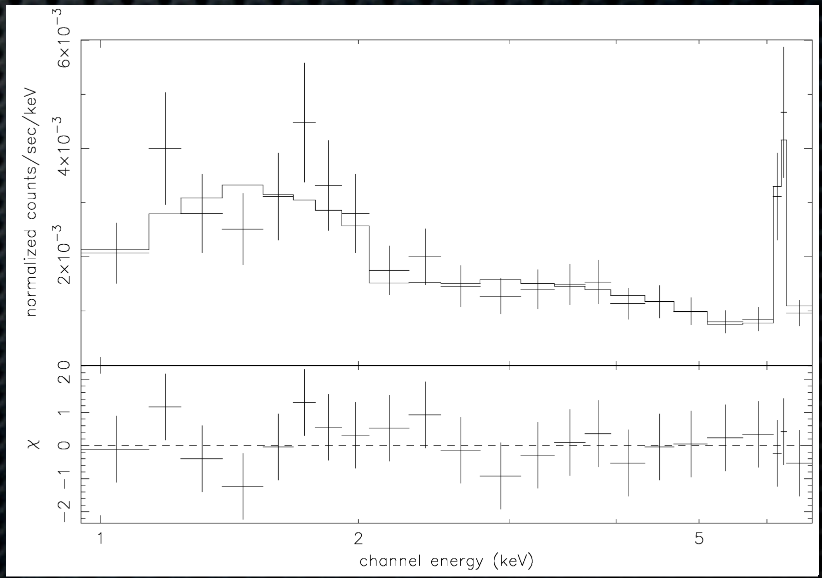








South

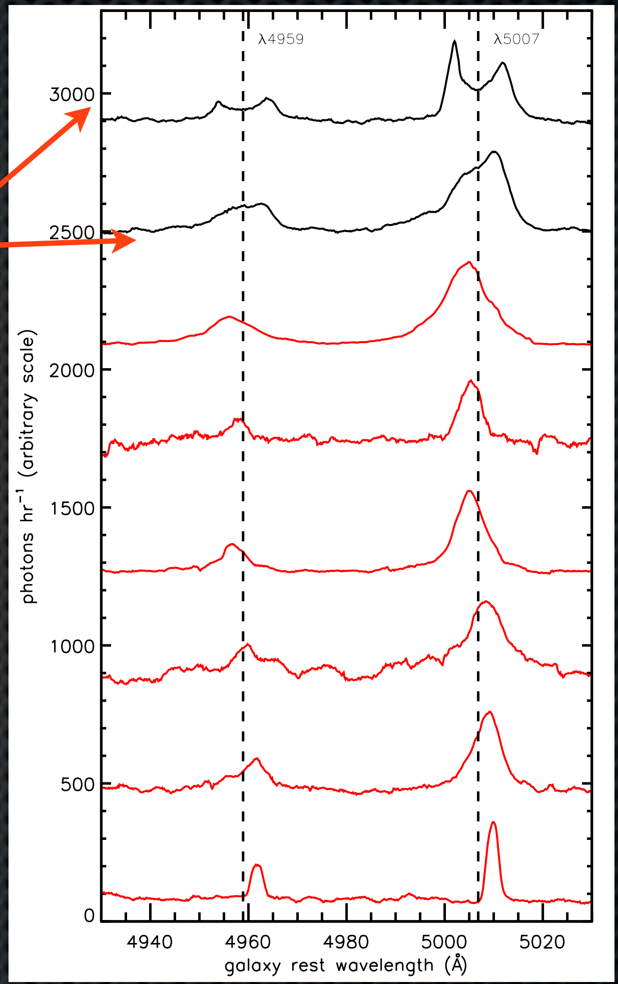


North

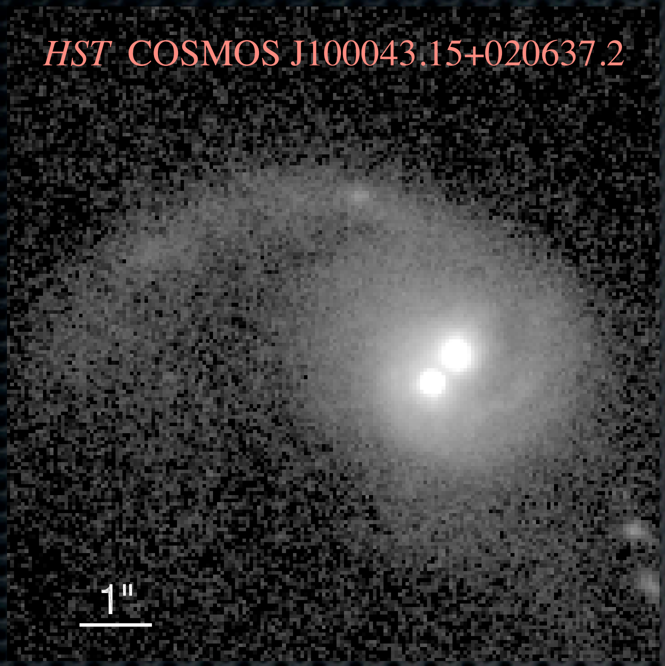
Super kpc Dual Nuclei

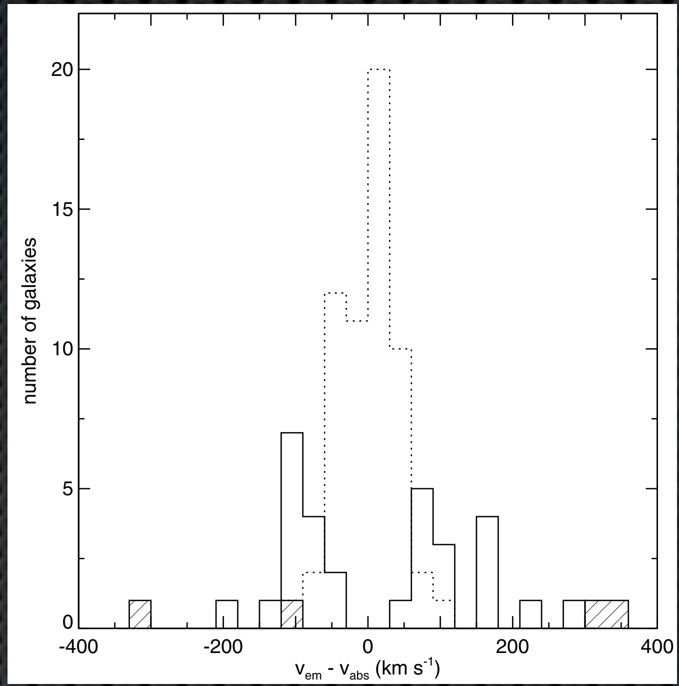
Comerford et al. 2009 x2

DEEP2 Survey
91 AGN: [OIII], HB selected (Seyfert 2)
32 have shifted [OIII] from host
2 have double peaked lines --> “dual” AGN



COSMOS Survey
$d = 1.7\text{kpc}$



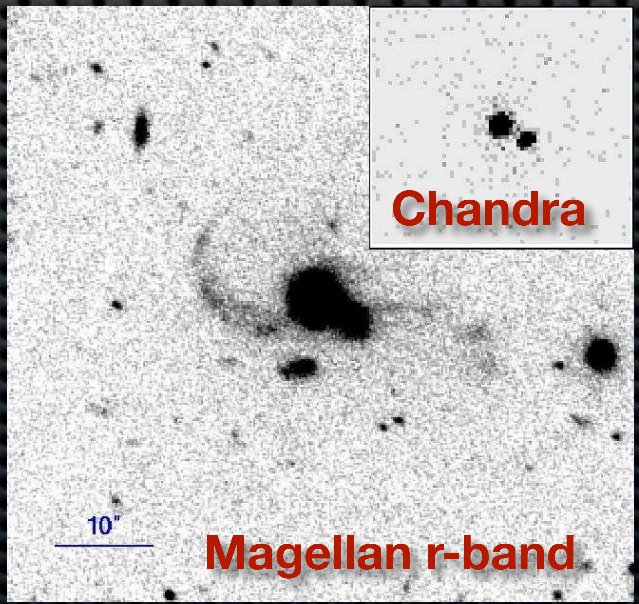


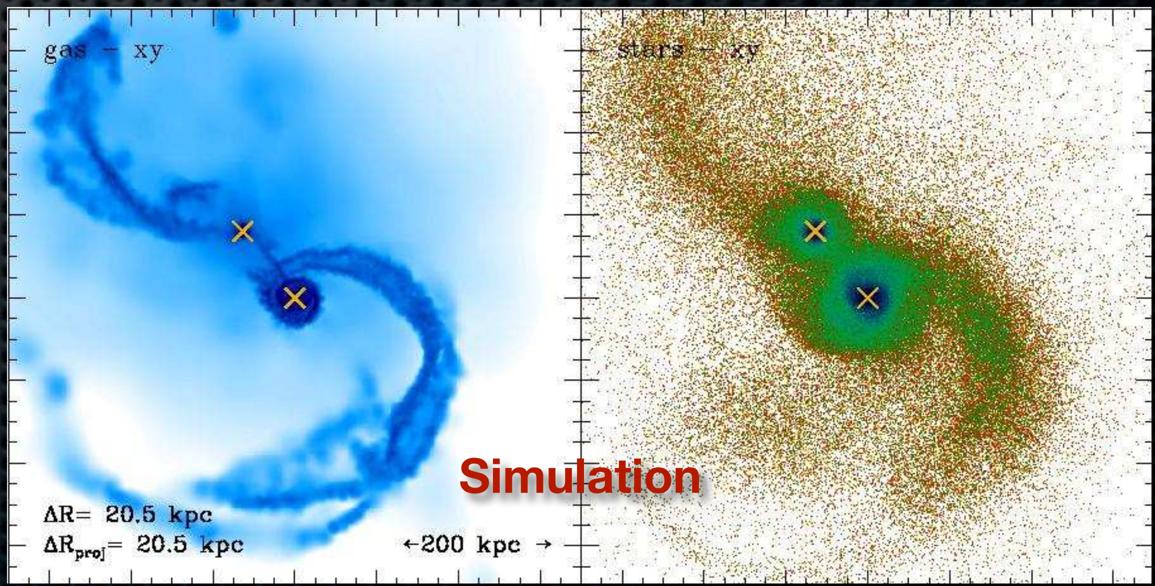
First Spatially Resolved Binary Quasar :
SDSS J1254+0846

Green et al. arxiv1001.1738

$z = 0.44$ $d = 21\text{kpc}$

$\Delta v = 215\text{km/s}$





OJ287: Pre-minor-merger??

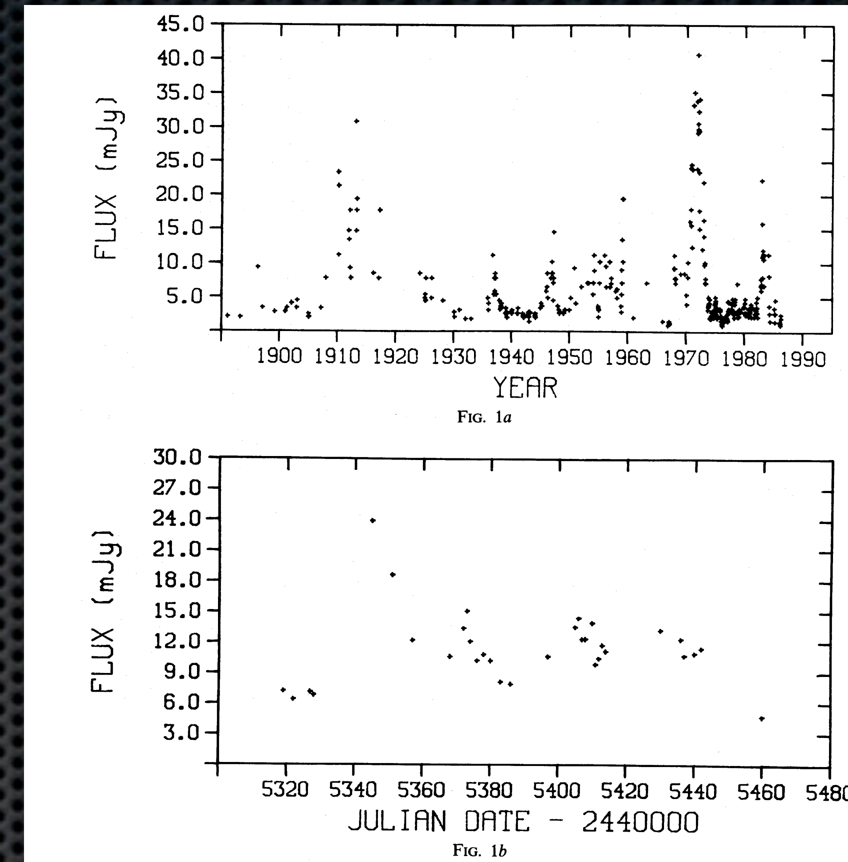
Lehto & Valtonen 1996:

$$M_1 = 1.7 \times 10^{10} M_\odot \qquad M_2 = 10^8 M_\odot$$

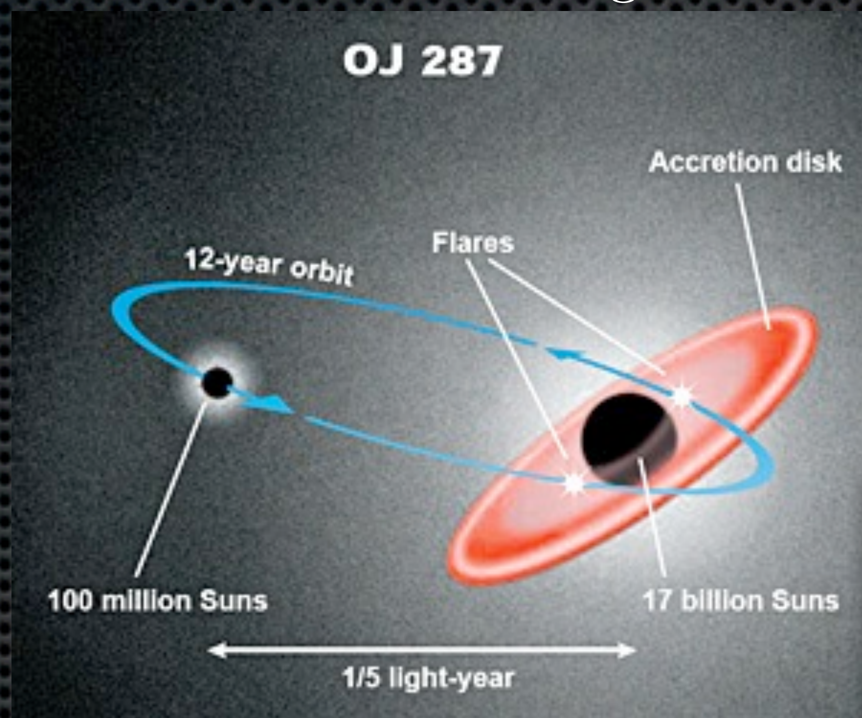
$$T_{\rm orb} = 12.07{\rm yr} \qquad T_{\rm precess} = 130{\rm yr} \qquad T_{\rm merge} \simeq 10^4{\rm yr}$$

$$i_{\rm disk} = 4^\circ$$

$$e = 0.68$$

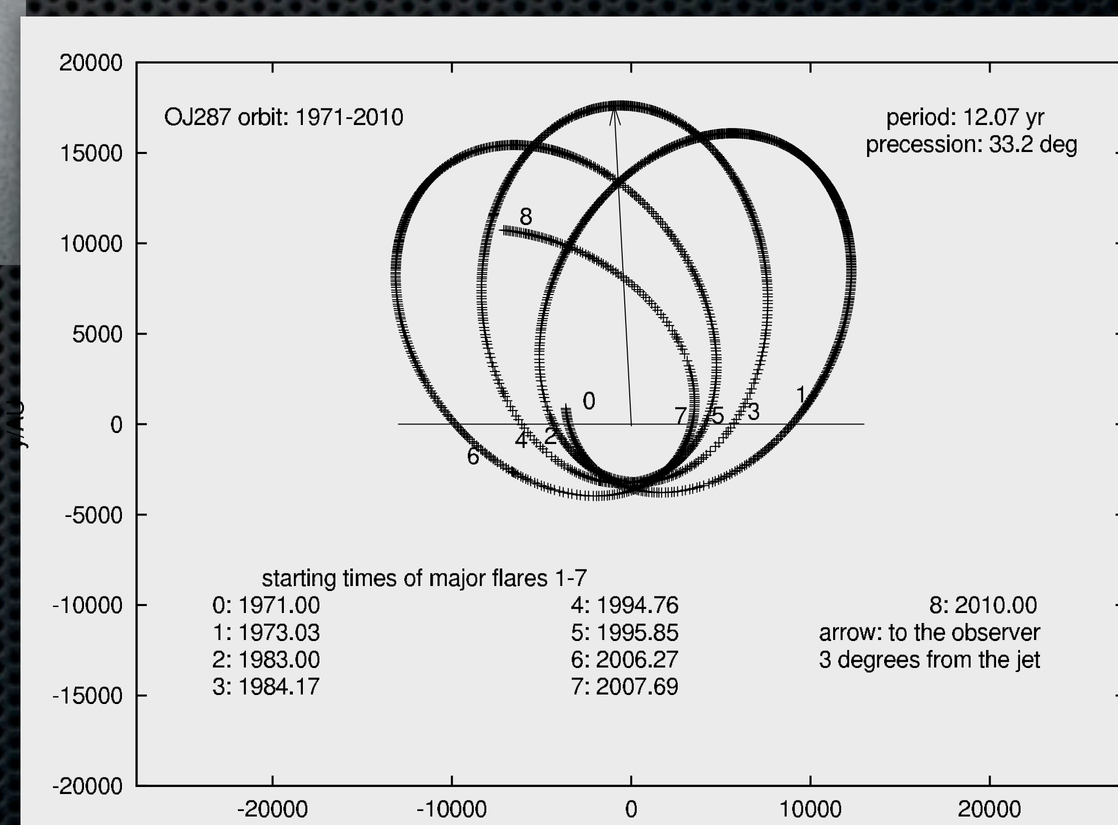


Sillanpaa et al 1988



Valtonen et al Nature 2008:

- 20 days earlier than expected
- Consistent to 10% predicted by radiation decay



Valtonen et al 2010:

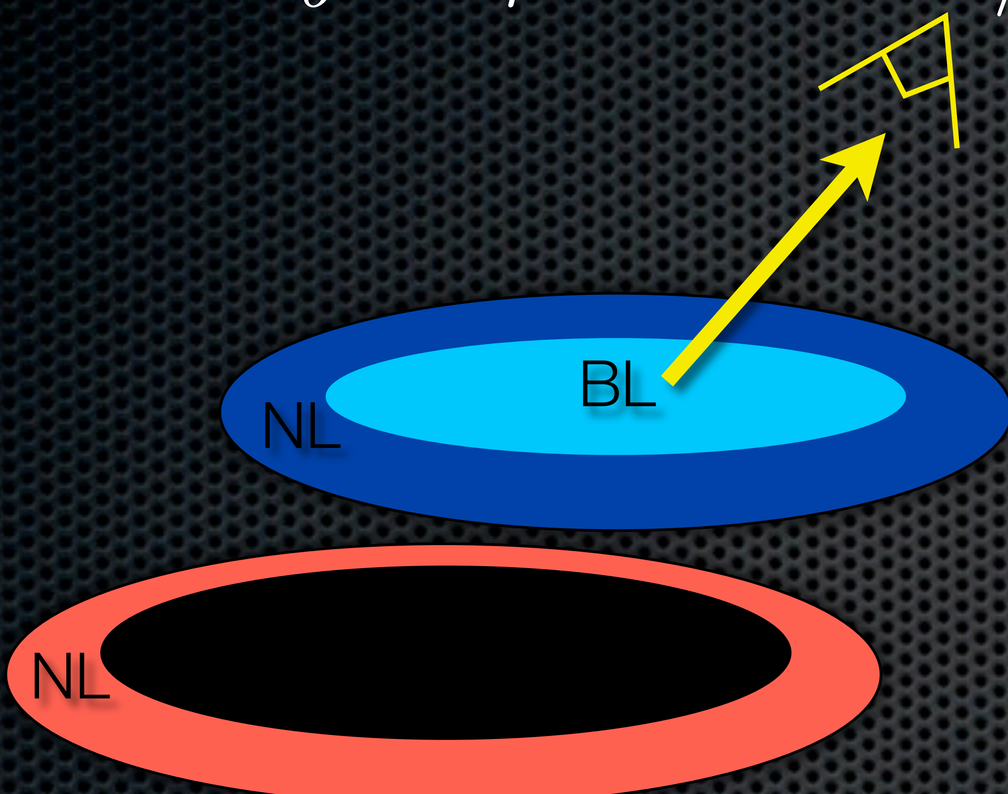
Fit with 2.5PN expansion $\rightarrow a = 0.28 \pm 0.05 M$

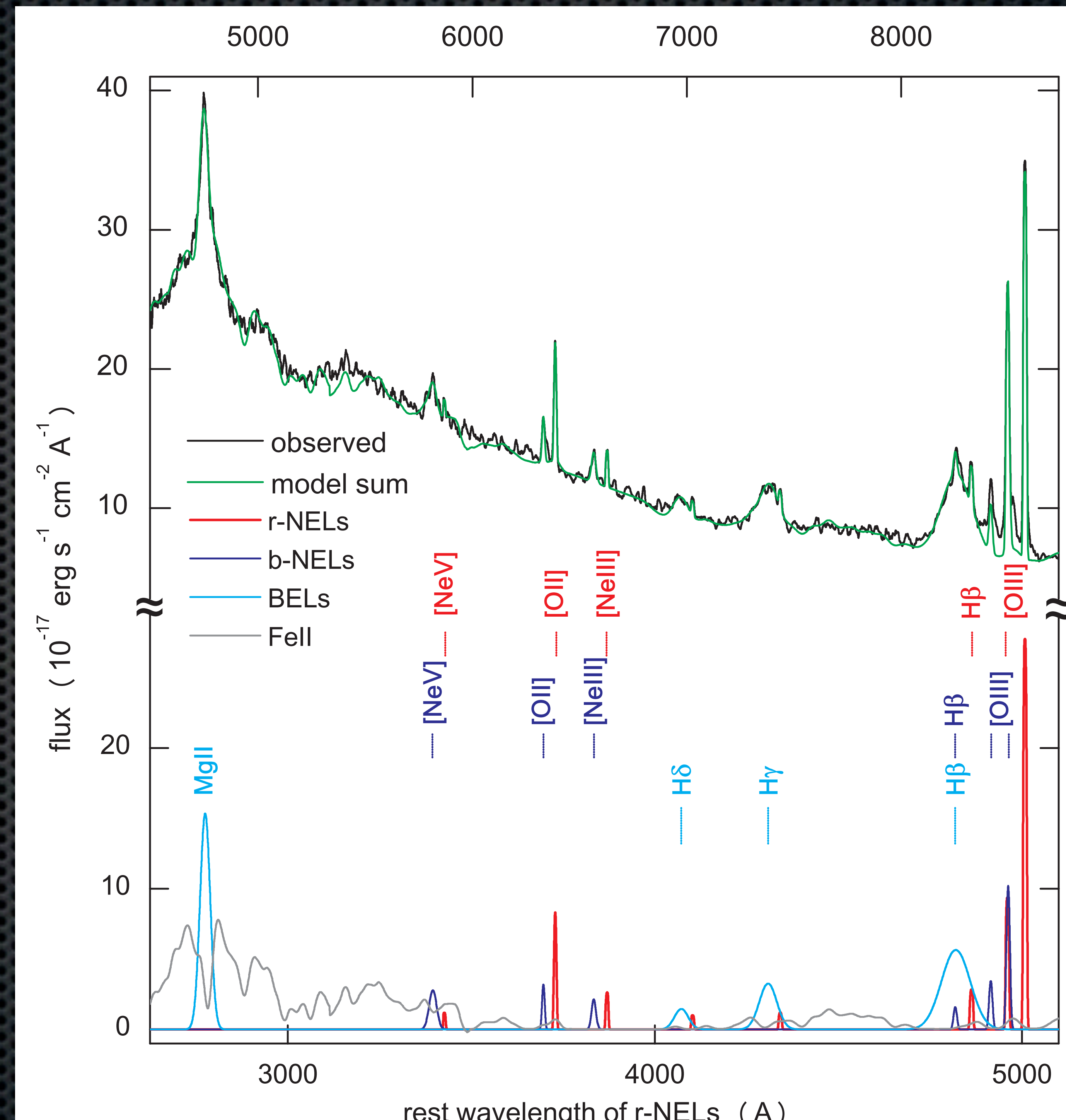
Recoiled SBH? SDSS J0927+2943

Komossa, Zhou, Lu (2008)

$z = 0.713 \qquad r_{\mathrm{BL}} \sim 0.1\mathrm{pc}$

$v_b - v_r = 2650\mathrm{km/s}$





Other Explanations:

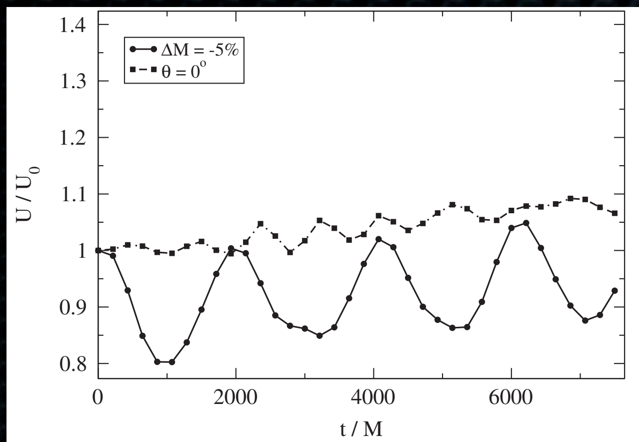
Heckman et al 2009, Shields et al. 2009,
Bogdanovic et al. 2009, Dotti et al. 2009

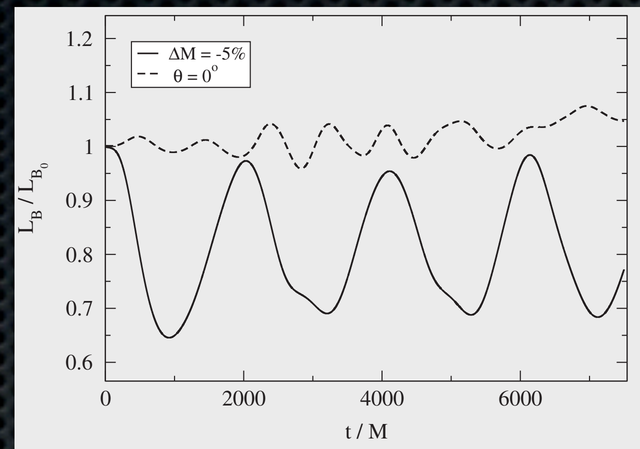
Another Similar Candidate:

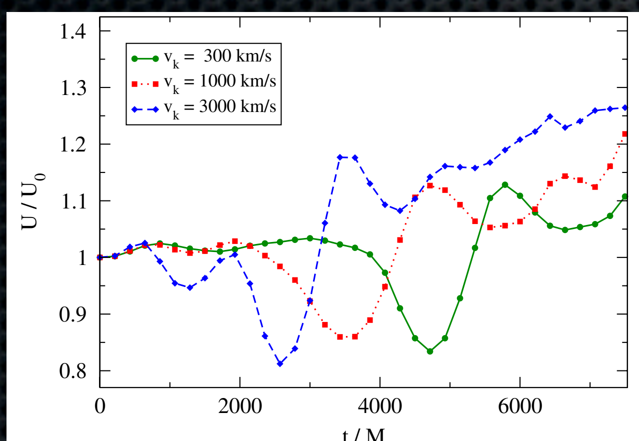
SDSS J105041.35+345631.3 (Shields et al. 2009)

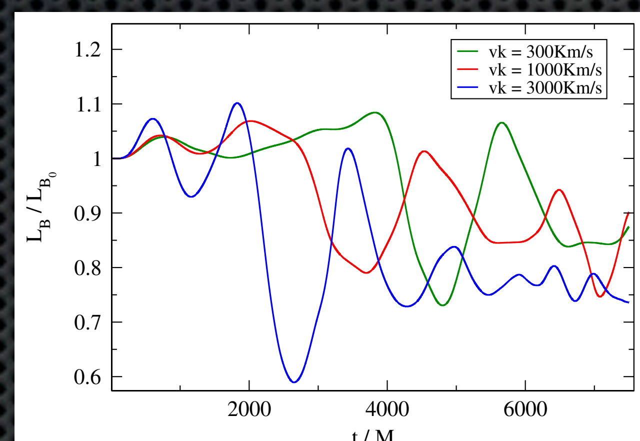
$v_{\mathrm{BL}} - v_{\mathrm{NL}} = 3500\mathrm{km/s}$

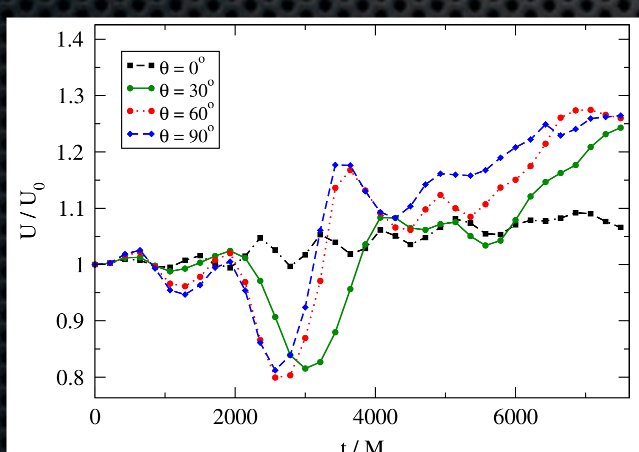
Megevand et al 2009 Kicked Thick Disk (near BH)

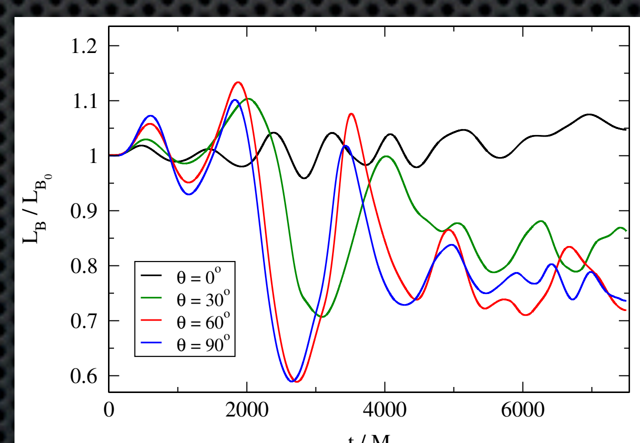


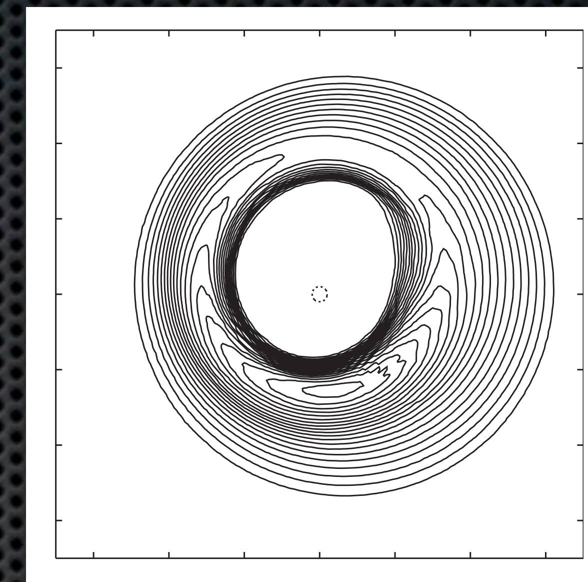


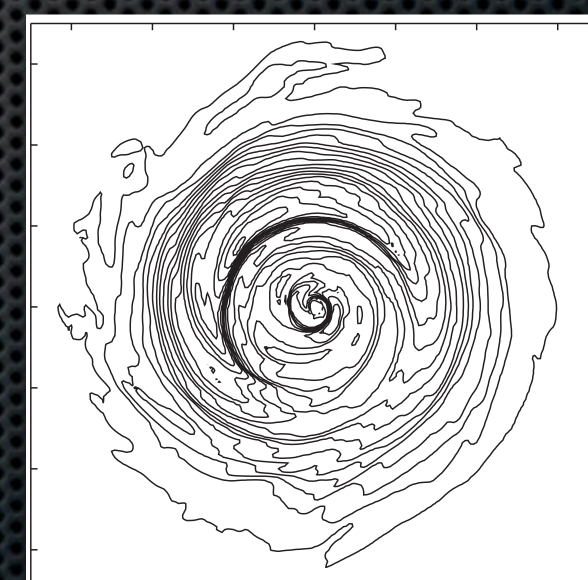




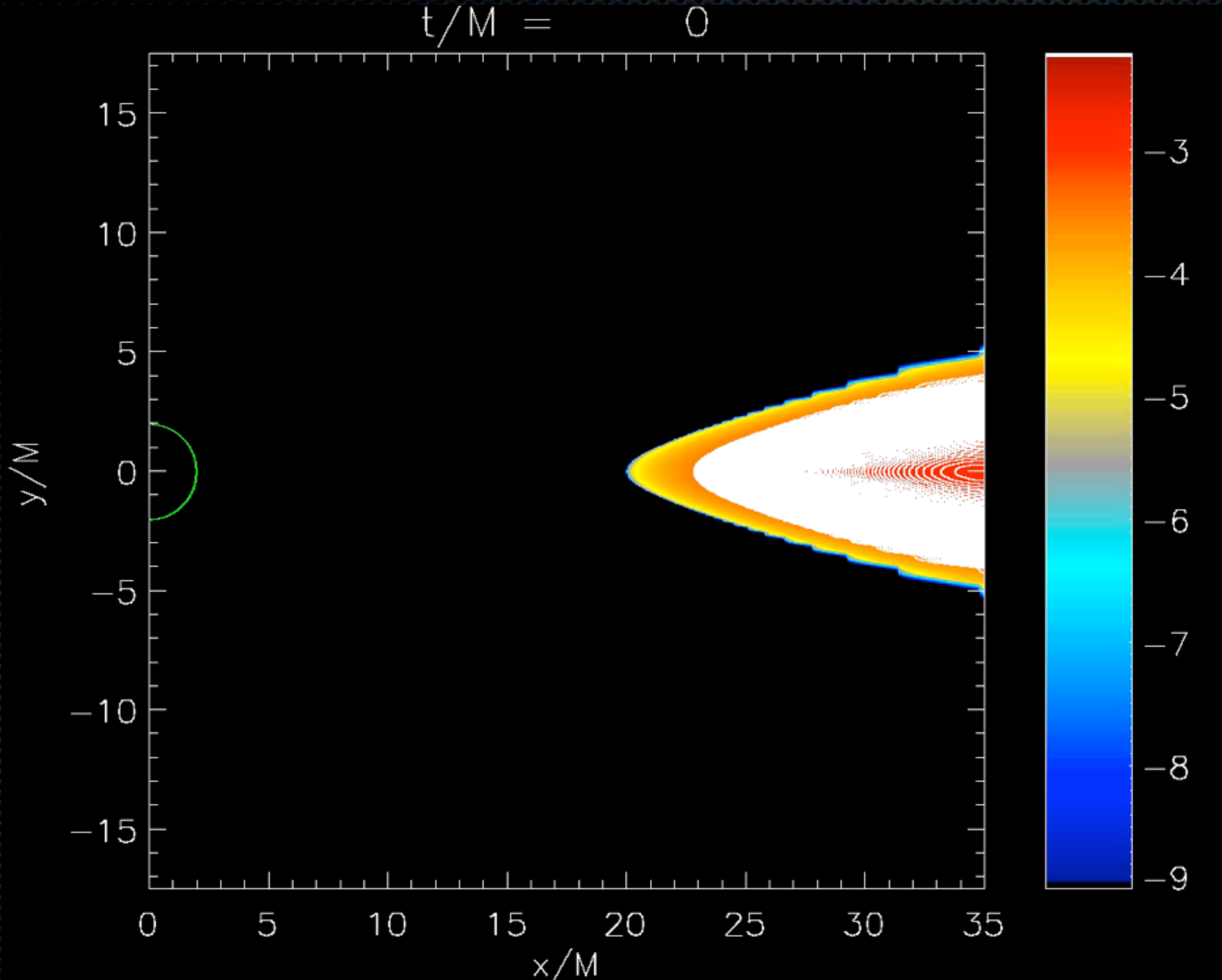








- GR Hydro (not self-gravitating)
- Mass Loss and Kicks
- Conservative Hydro



t/M = 0
y/M
x/M
15
10
5
0
−5
−10
−15
0
5
10
15
20
25
30
35
−3
−4
−5
−6
−7
−8
−9