Seeing Spacetime by Proxy:

Binary Black Holes in Gaseous Environments

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Feb. 14, 2010
April APS Meeting 2010

Session G4
Washington DC

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Binary Black Holes in Gaseous Environments

& Unary

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Outline

- Motivation: what can synchronous EM+GW observations do for us?
- Observational Evidence of BBH mergers
- A Love Story of SMBBH Mergers:
  - How do two black hole's find each other in this crazy universe of ours.
- Review of Recent Merger-related Calculations
  - BBH Spark? Efficient EM emission mechanism?
- UBH (unary black hole) Accretion Physics
  - Thoughts on how this may apply to the BBH case

Motivation

GW Observatory	EM Source	GW Range
LIGO/VIRGO/GEO	SN, Pulsars GRBs (BH+NS,NS+NS) ??	1Mpc 50-100Mpc with Adv. LIGO ??
LISA	Galactic Nucleus SMBH + [SMBH,IMBH,BH, NS,WD] ??	z ~ 30, 3, 1, 0.1 ??

Sylvestre 2003

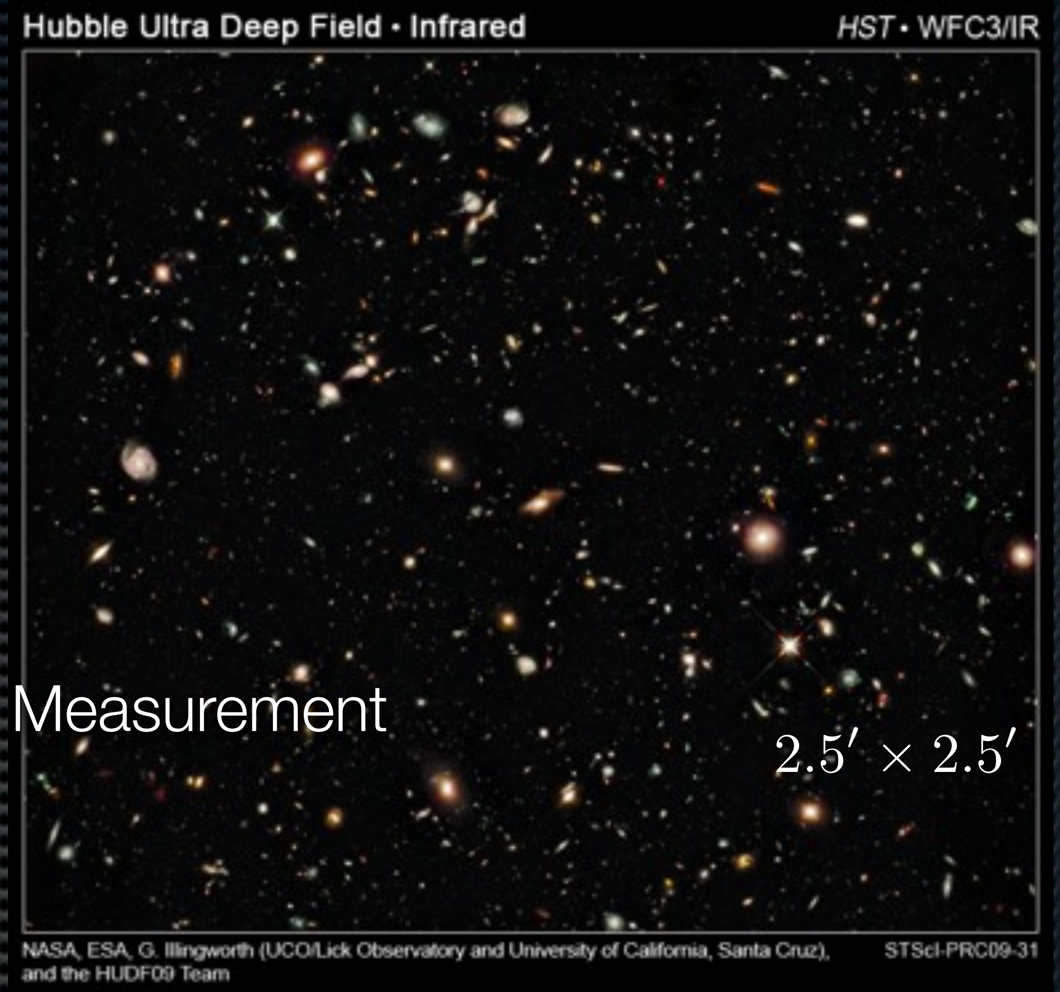
Stubbs 2008

Phinney 2009

- Seeing Coincident GWs and EMWs :
  - Synergy between
    - LIGO/VIRGO/GEO/LISA & LSST/Pan-Starrs/??
    - Improved source identification
  - Multi-messenger/Trans-spectral Astrophysics

Decadal Review White Papers: Bloom et al 2009 Phinney 2009

Motivation

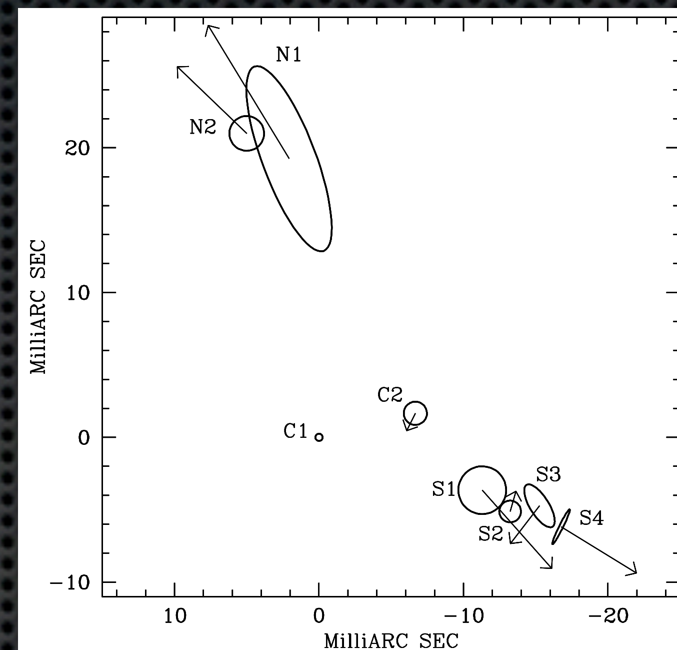


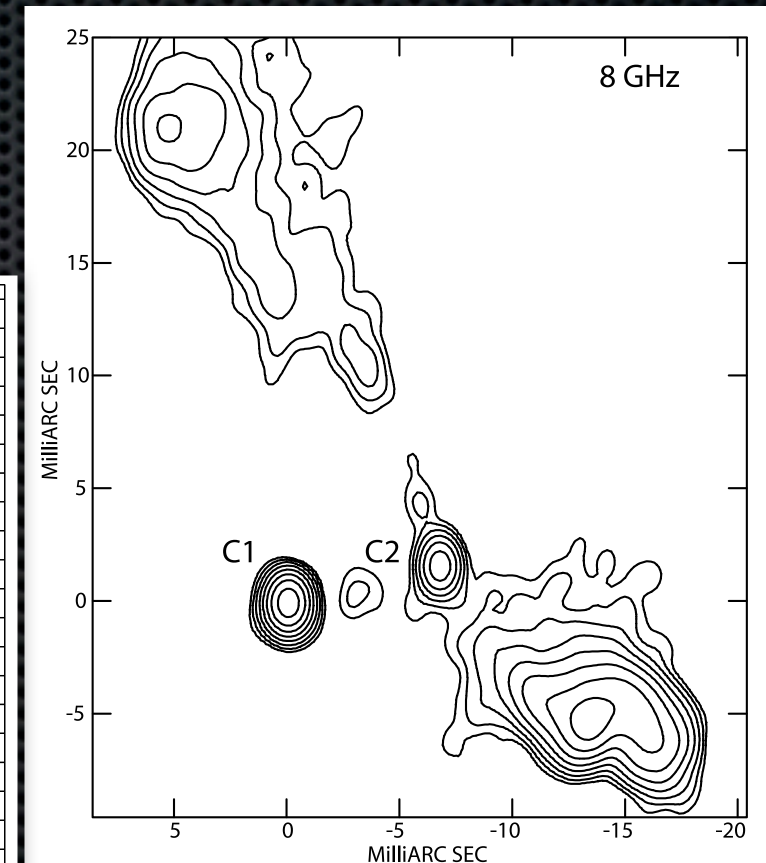
- “Standard Sirens”: New Distance vs. Redshift Measurement
  - Schutz 1986, Holz & Hughes 2005
- Mutual Beneficial Localization
  - LISA localization days in advance: Lang & Hughes 2009 $[10' - 1^\circ] \times [3' - 20'] \times 1\%$
  - EM localization using high-cadence, high-FOV observations Kocsis et al 2007
  - Need dynamical models to predict source variability accurately
  - GW constraints <--> EM constraints
- Connecting robust theoretical predictions to event observations may be first evidence of BBH mergers (hopefully not!)
  - LISA expected to launch in 2020
  - LIGO sensitive to smaller BBHs that are most likely in vacuum
  - BH/NS or NS/NS may require coincidental orientation for observability

Sub-kpc Resolved Dual Nuclei

0402+379:
(Xu et al. 1994, Maness et al. 2004, Rodriguez et al. 2006):

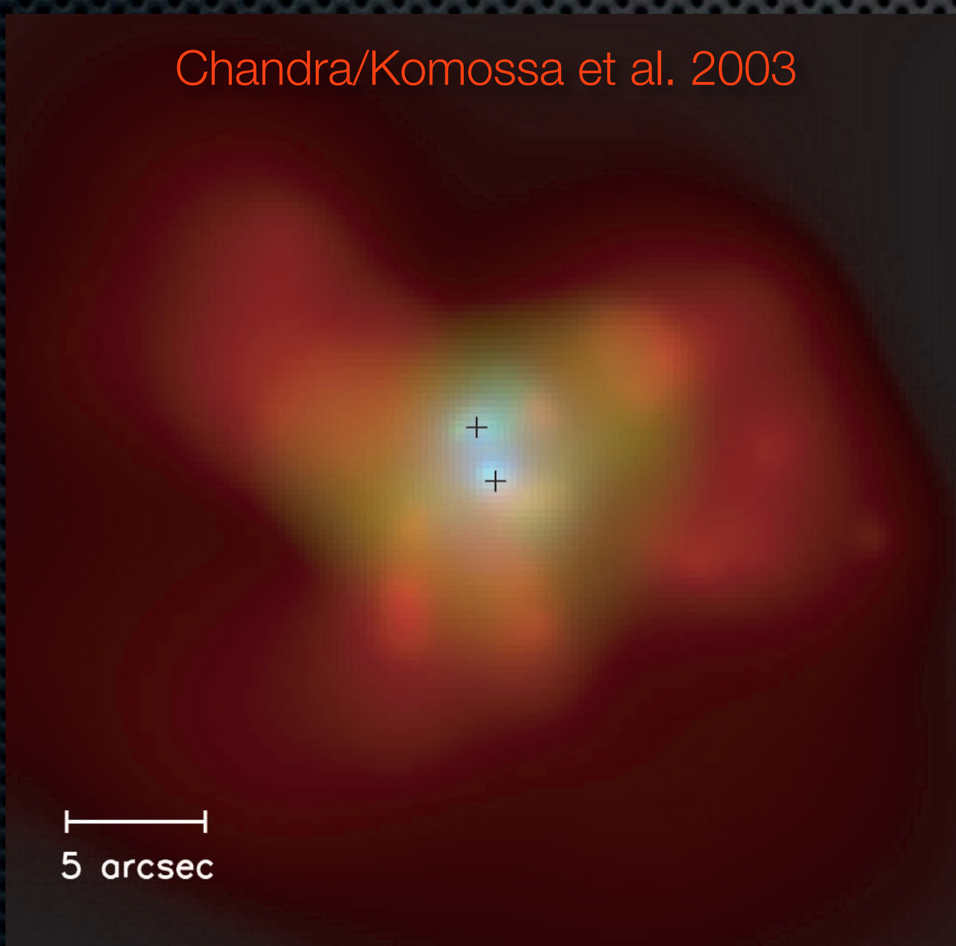
- Radio, Elliptical galaxy host
- z = 0.055, d = 5 pc $M \sim 10^8 M_\odot$

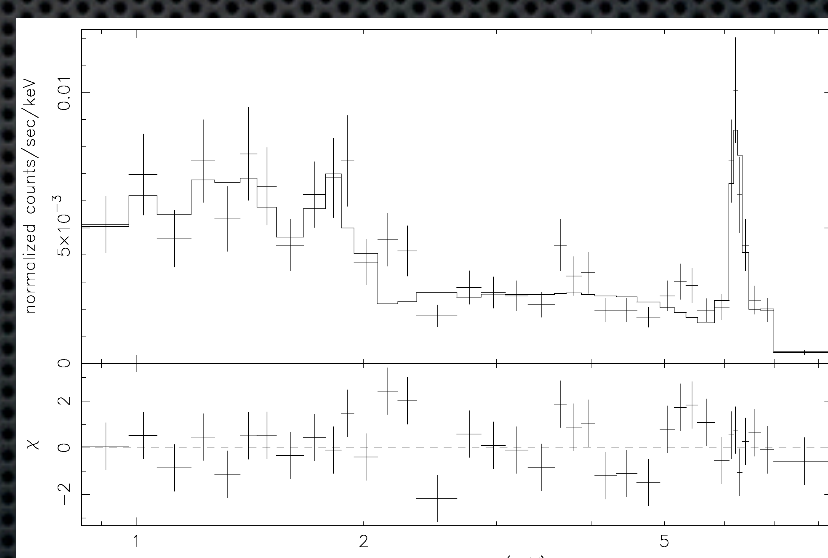




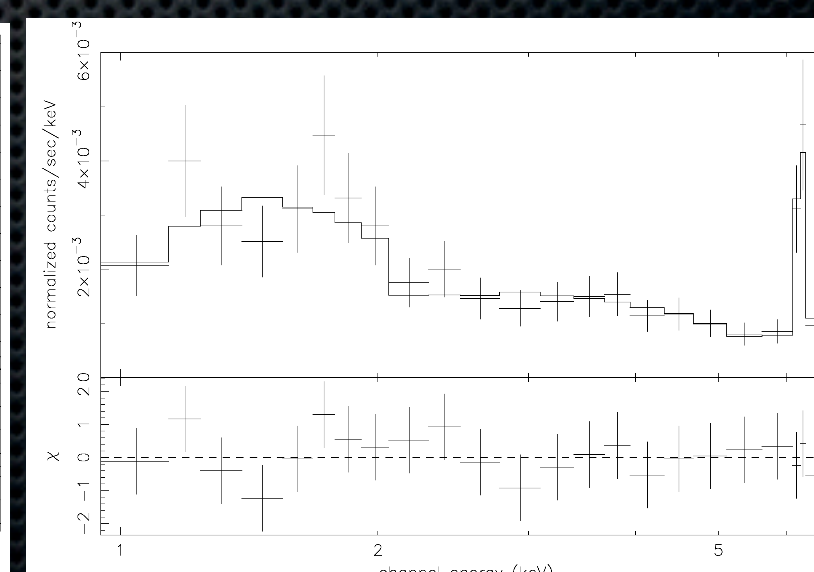
NGC 6240: (Komossa et al. 2003)

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



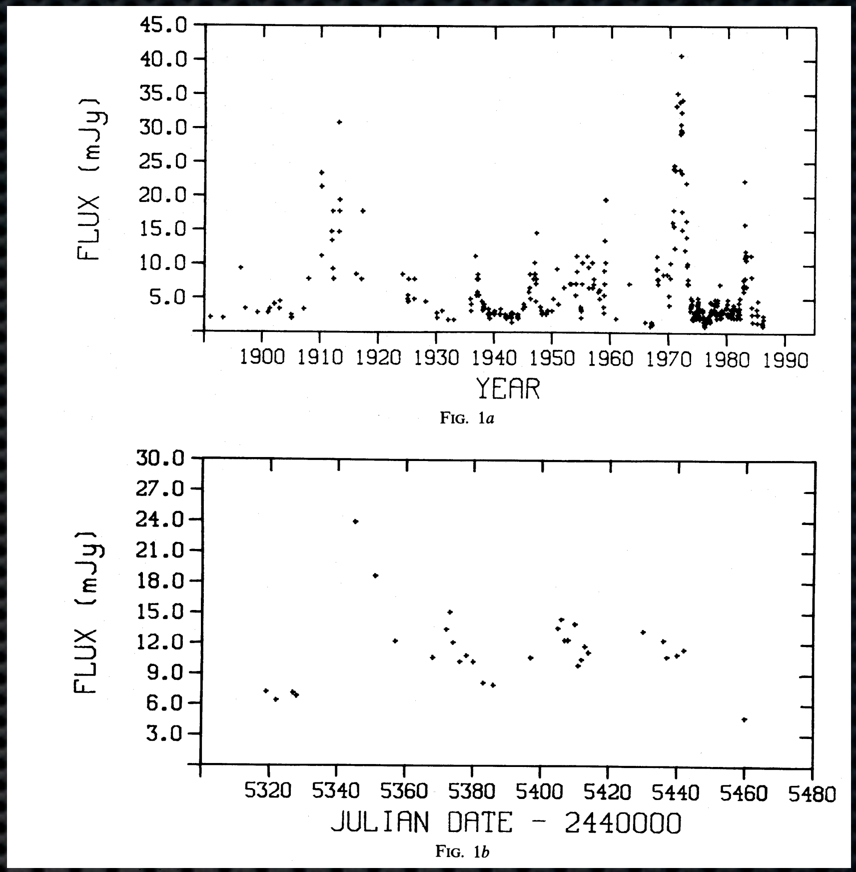


South



North

OJ287: Pre-minor-merger??



Sillanpaa et al 1988

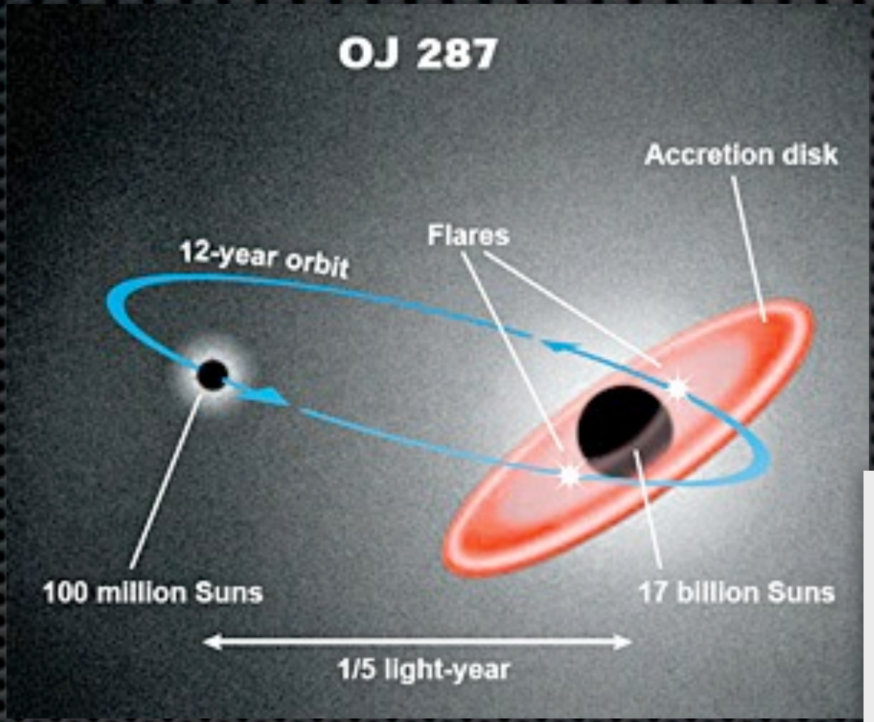
Lehto & Valtonen 1996:

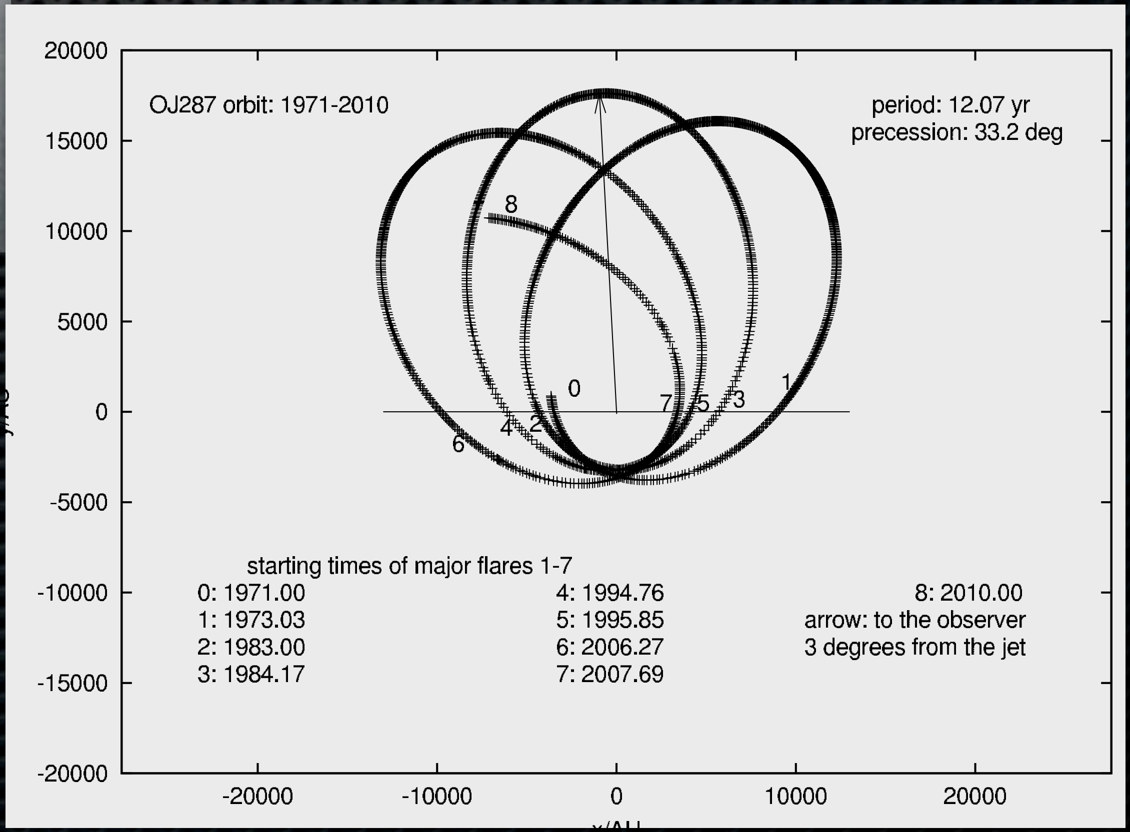
$M_1 = 1.7 \times 10^{10} M_\odot \quad M_2 = 10^8 M_\odot$

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

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

$e = 0.68$





Valtonen et al Nature 2008:

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

Valtonen et al 2010:

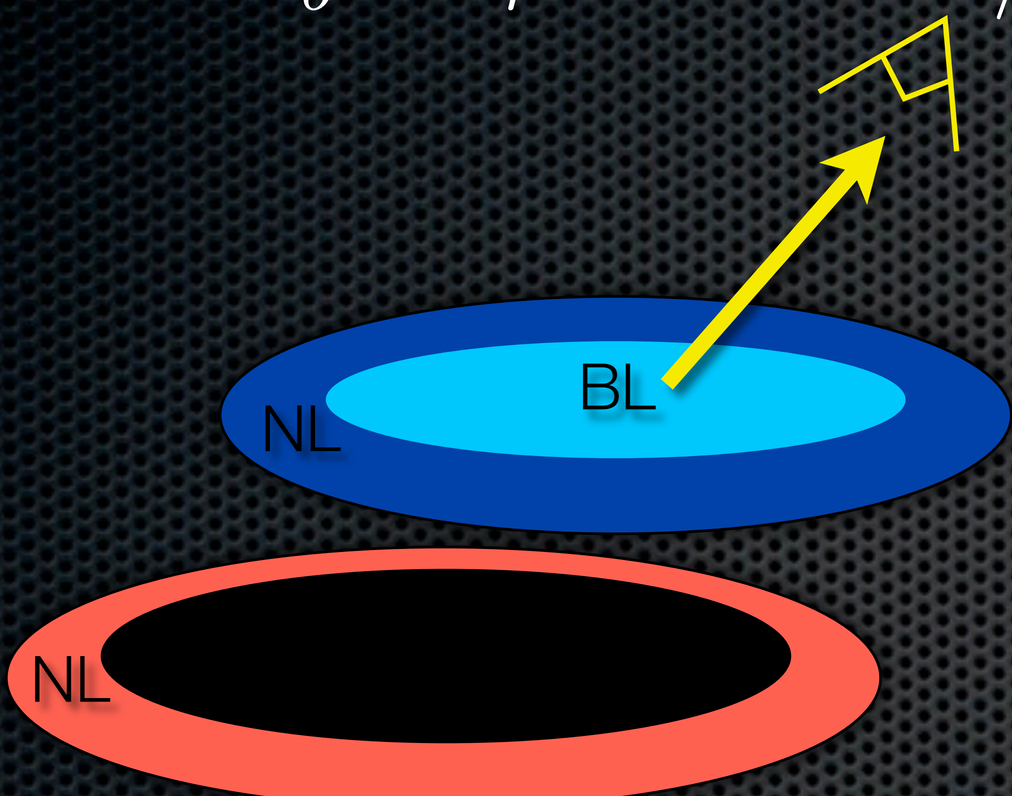
Fit with 2.5PN expansion $\rightarrow a = 0.28 \pm 0.05 M$

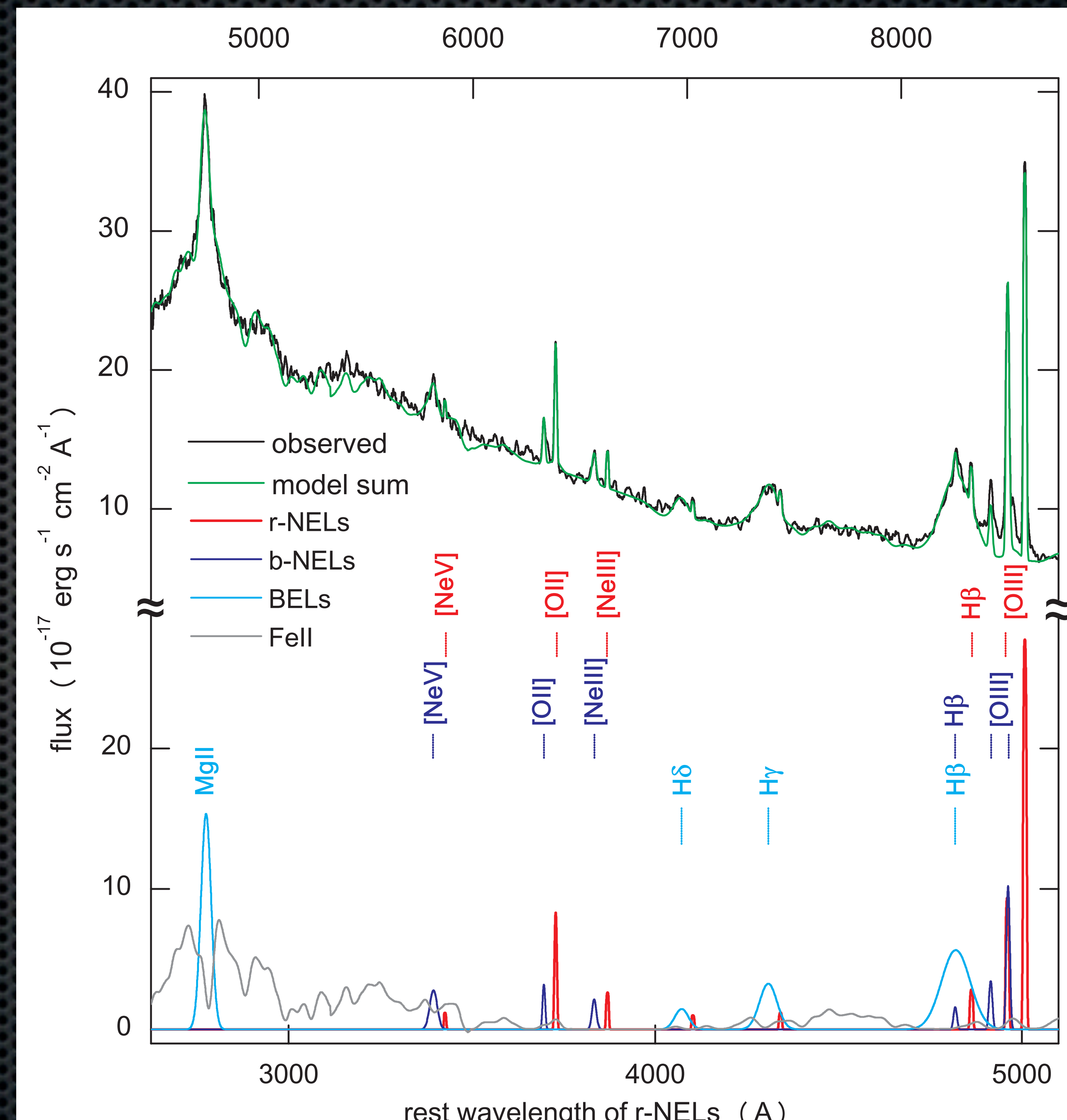
Recoiled SBH? SDSS J0927+2943

Komossa, Zhou, Lu (2008)

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

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





Other Explanations:

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

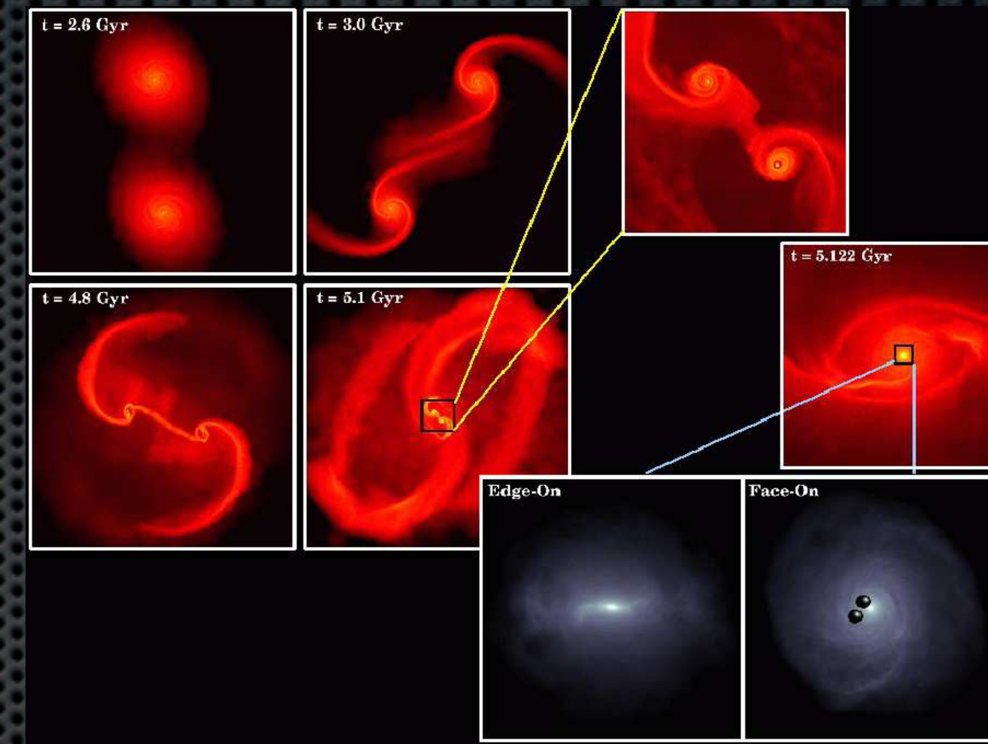
Another Similar Candidate:

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

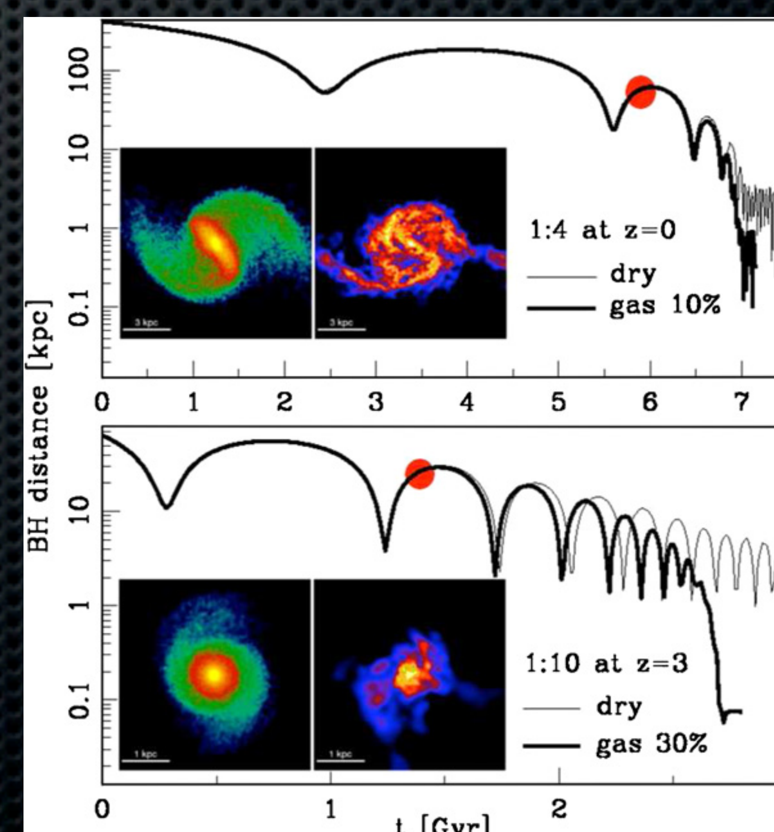
$$v_{\rm BL} - v_{\rm NL} = 3500{\rm km/s}$$

Pre-pre-merger

Hopkins, Hernquist, Springel et al.



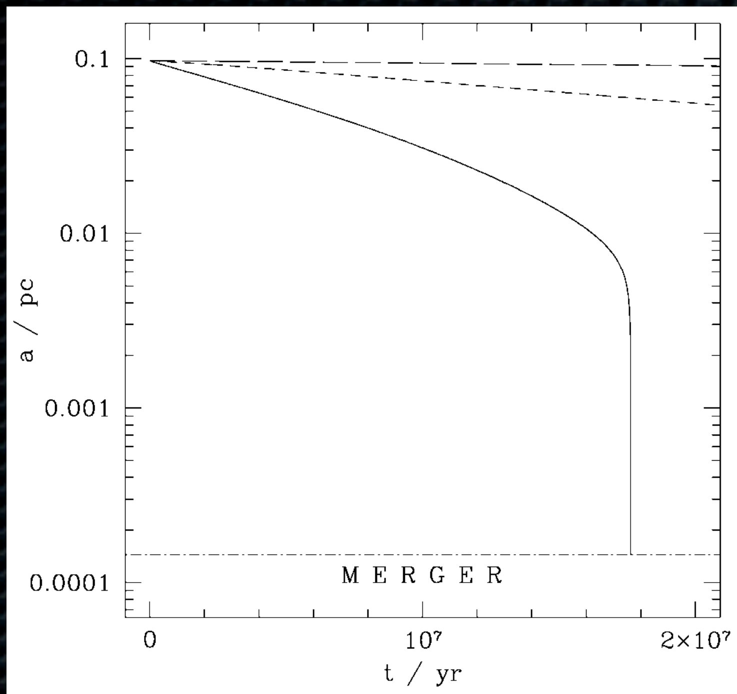
Colpi, et al 2009



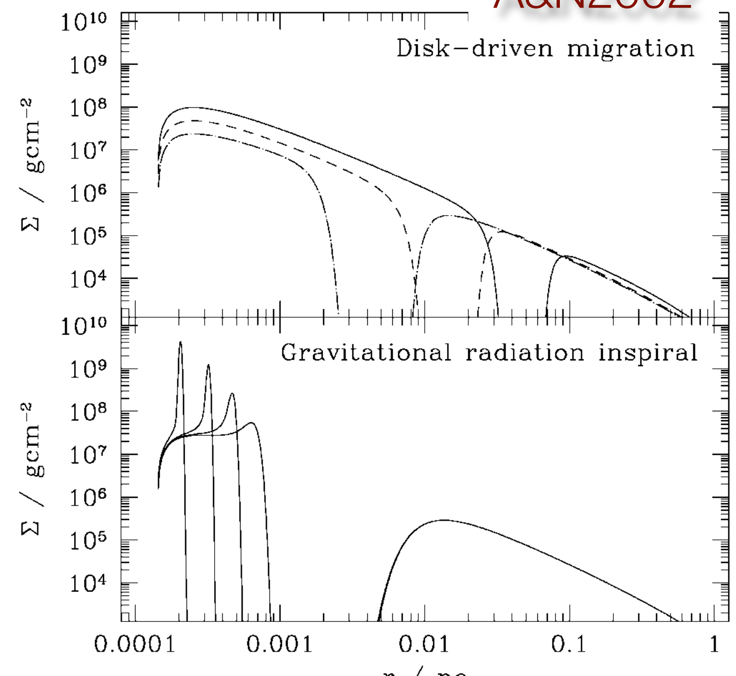
Pre-merger: Circumbinary Disks

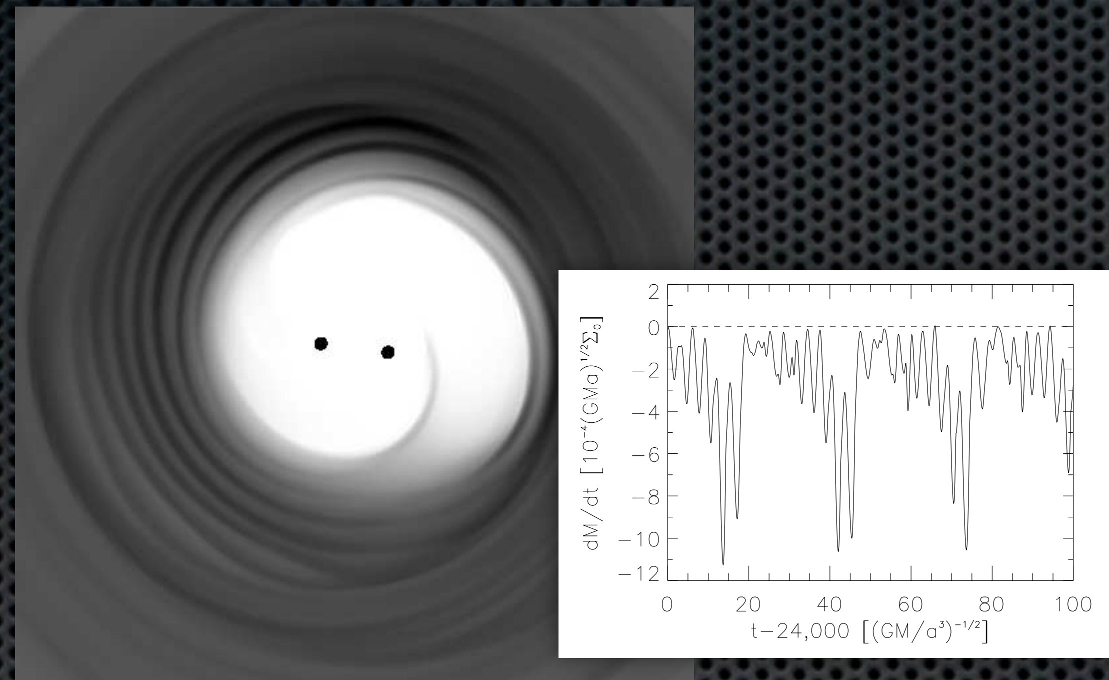
Artymowicz & Lubow 1994

Armitage & Natarajan 2002,2005

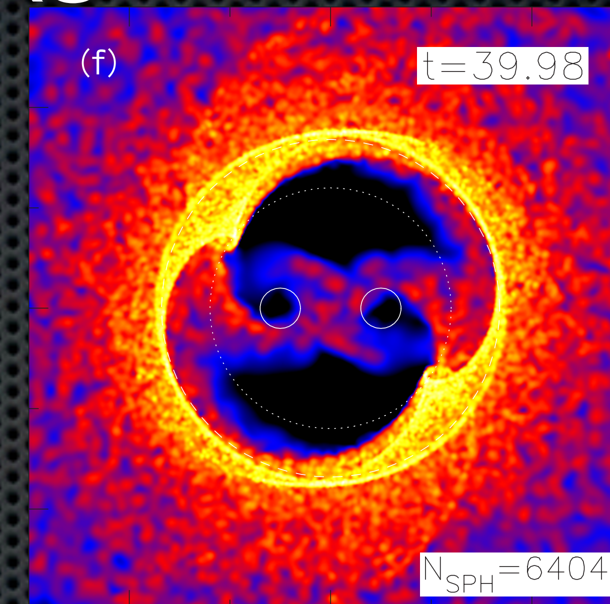


A&N2002

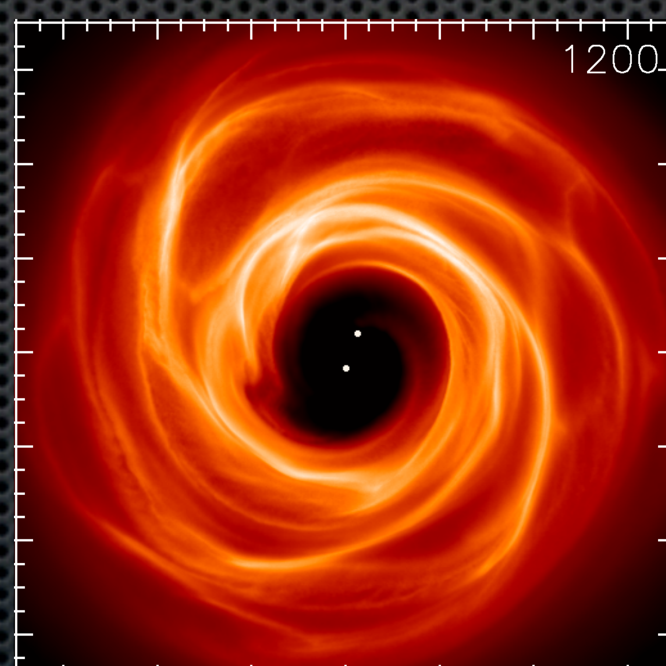




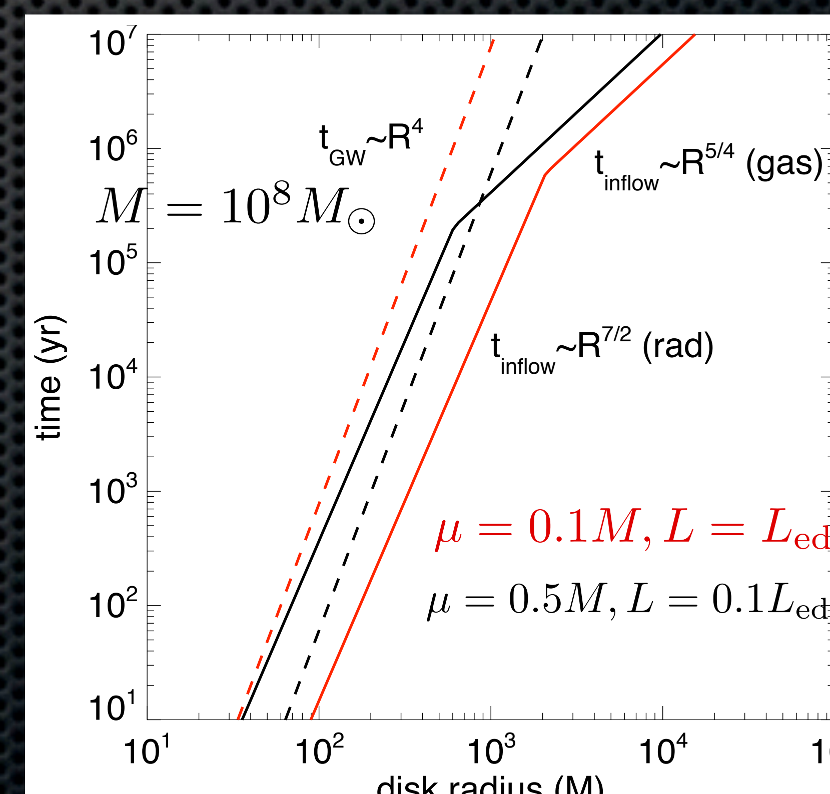
MacFadyen & Milosavljevic 2008



Hayasaki et al 2007



Cuadra et al 2009



Schnittman & Krolik 2008

Post-merger

Mass Loss

Bode & Phinney 2007

O'Neill et al. 2009

Megevand et al 2009

Krolik 2010

Disk's Response to Recoil

Shields & Bonning 2008

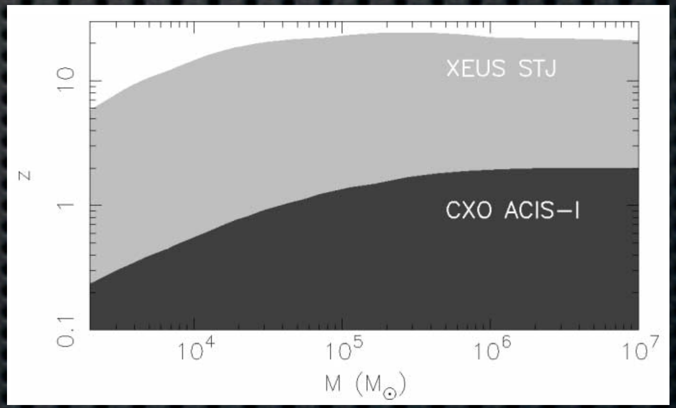
Schnittman & Krolik 2008

Lippai et al 2008

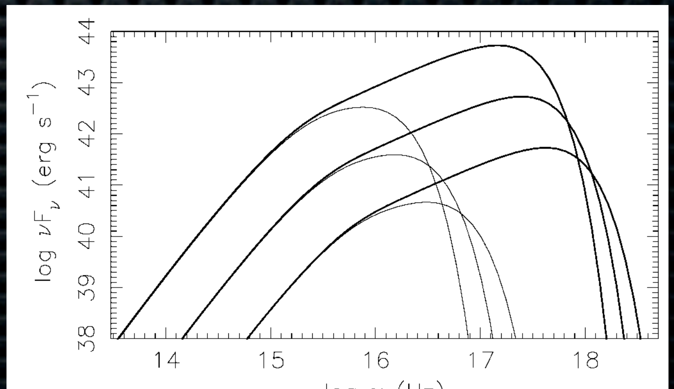
Corrales et al 2009

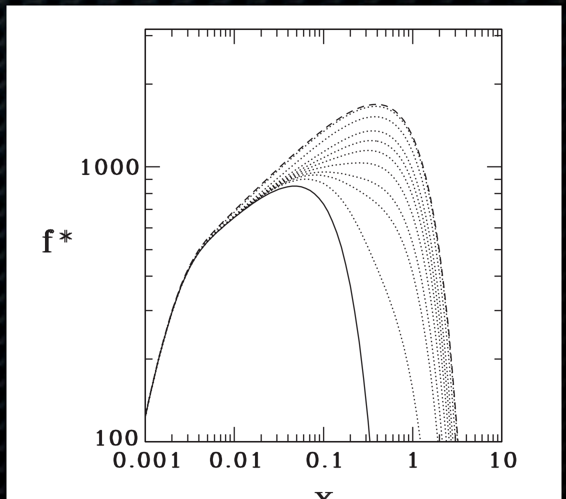
GW Dissipation in Disk

Kocsis & Loeb (2008)



- Gap Refills:
- Milosavljevic & Phinney 2005, Shapiro 2010

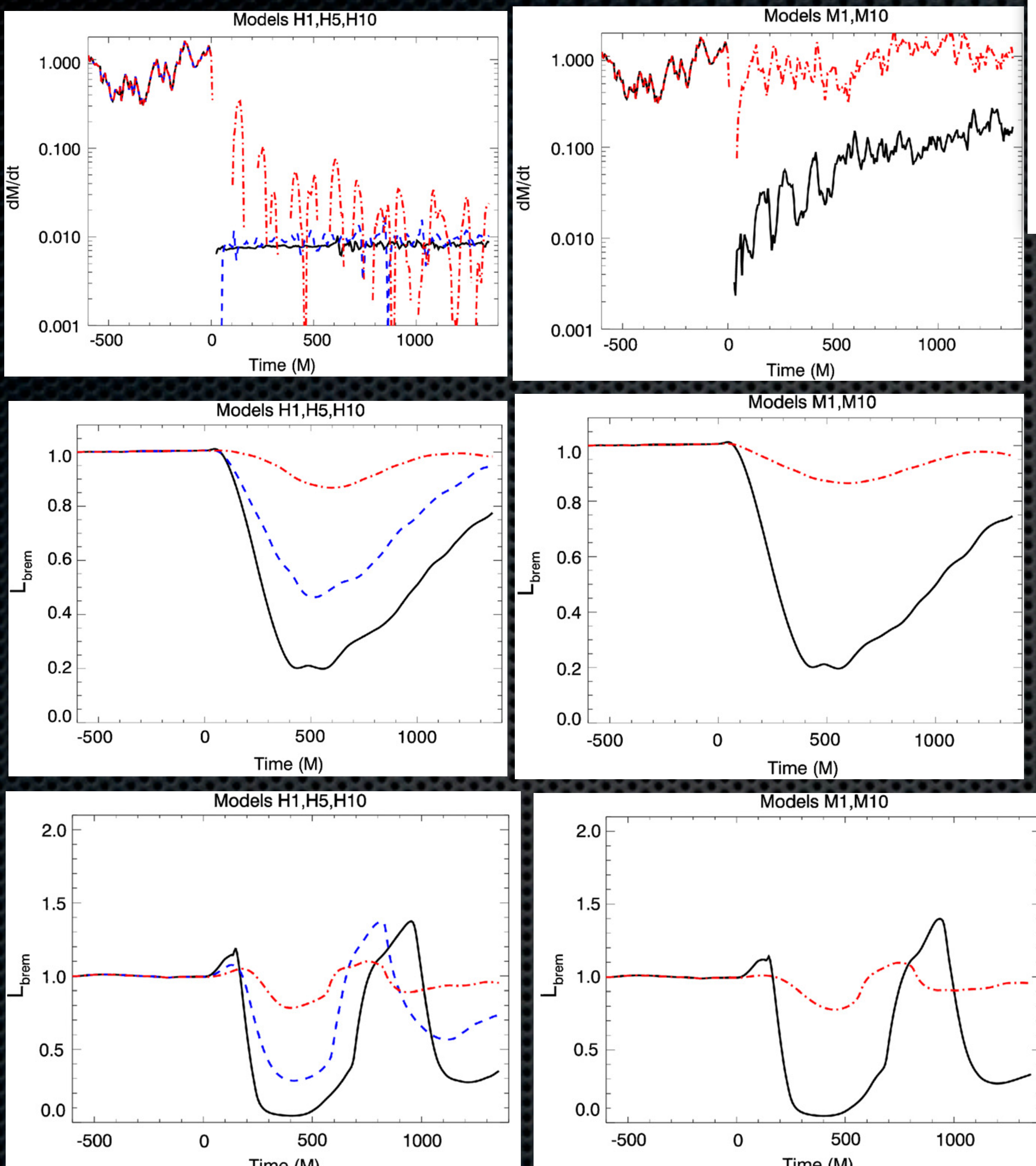




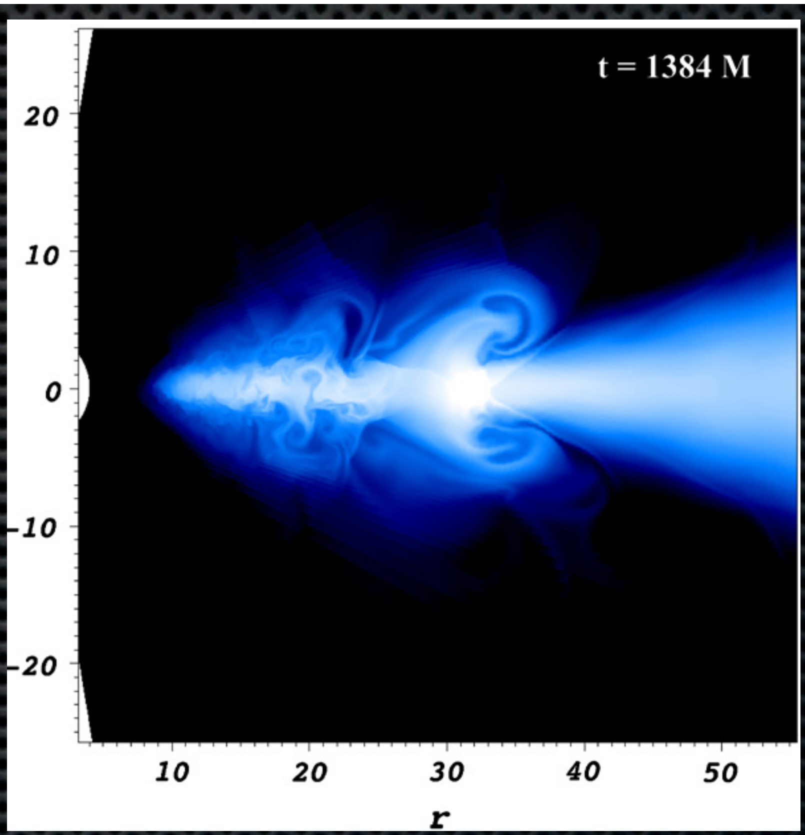
Post-merger: Recoil Consequences

- BBH Mergers recoil with wide range of velocities v < 4000 km/s:
  - (see Hinder arxiv1001.5161 for references)
  - Hyperbolic encounters, e.g. (Healey et al. v~10000km/s) may be unlikely
  - Dry merger ensembles predict sizeable velocities still:
    - Schnittman 2004, Bogdanovic et al 2007, Lousto et al. arxiv-0910.3197
  - Accretion may align the black holes, resulting in smaller kicks:
    - Bogdanovic, Reynolds, Miller 2007, Perego et al. 2009
- Isolated SMBH/AGN :
  - Redmount & Rees 1989
  - Merritt et al 2004, Madau & Quataert 2004
- Off-nucleus Hypercompact Stellar Systems: Merritt, Schnittman, Komossa 2009
- Resurgence of Tidal Disruption Events: Merritt & Komossa 2008a

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	$768 \times 256 \times 32$	0.10
H5	Hydrodynamic	768×256	0.05
H1	Hydrodynamic	768×256	0.01
M1	MHD	$768 \times 256 \times 32$	0.01

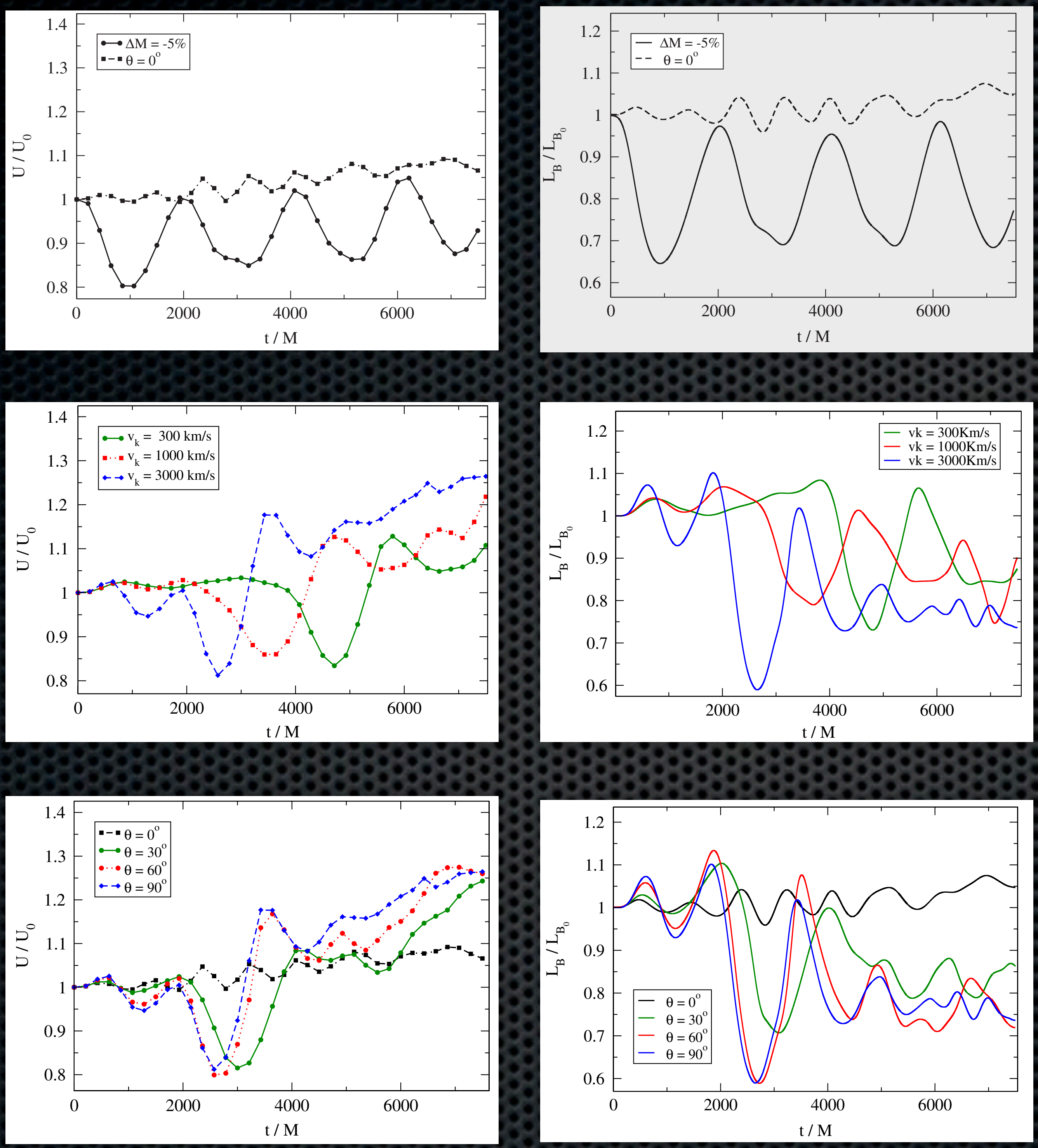


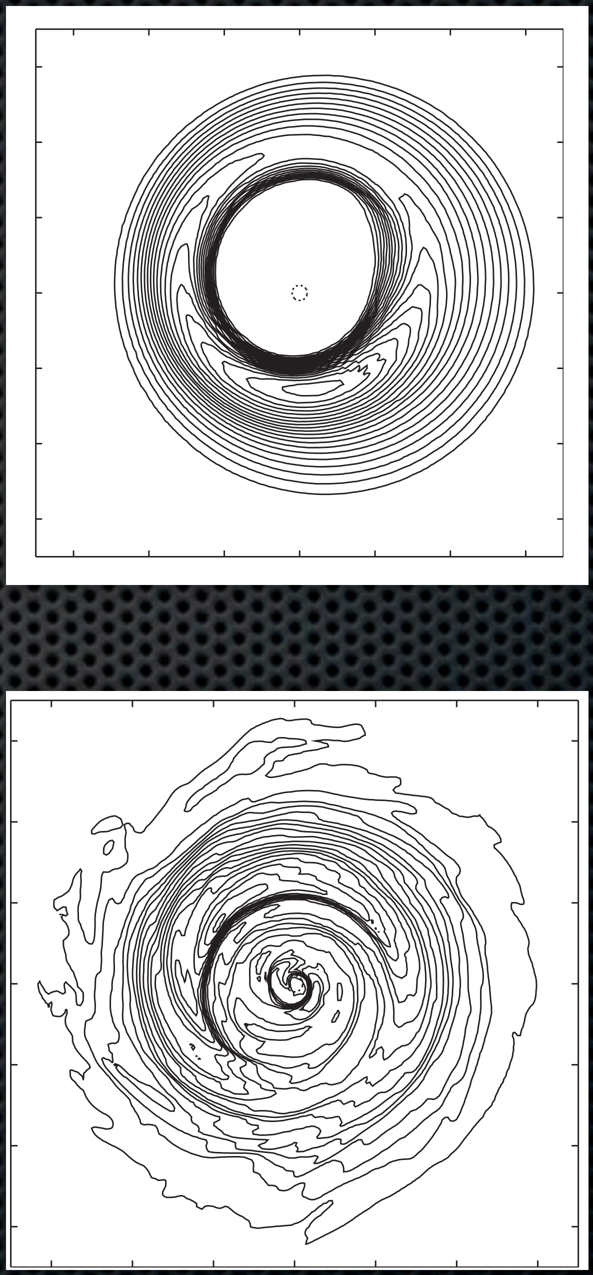
$$L_{\rm brem} = \int j_{\rm brem} dV$$

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

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

Megevand et al 2009 Kicked Thick Disk (near BH)

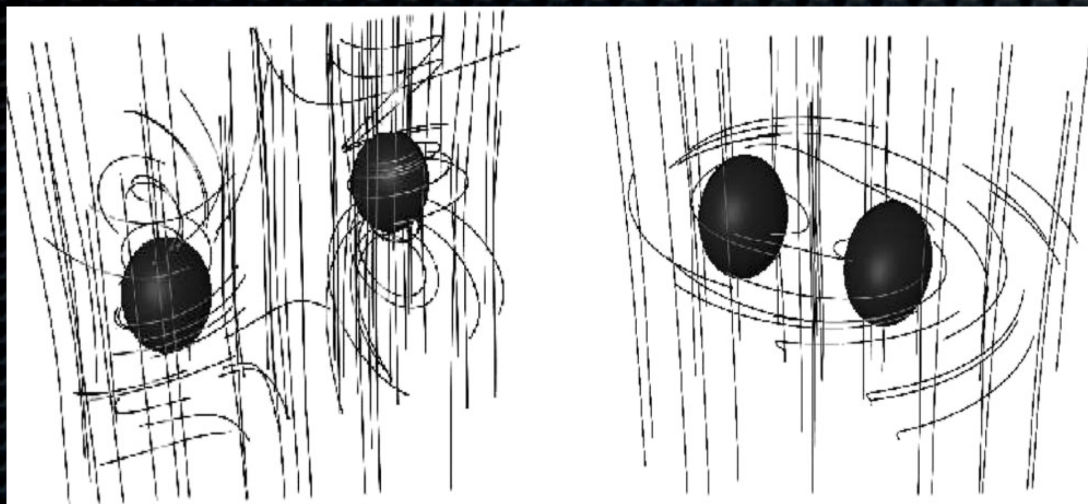


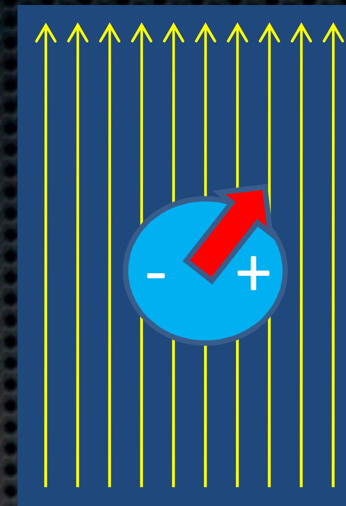


- GR Hydro (not self-gravitating)
- Mass Loss and Kicks
- Conservative Hydro

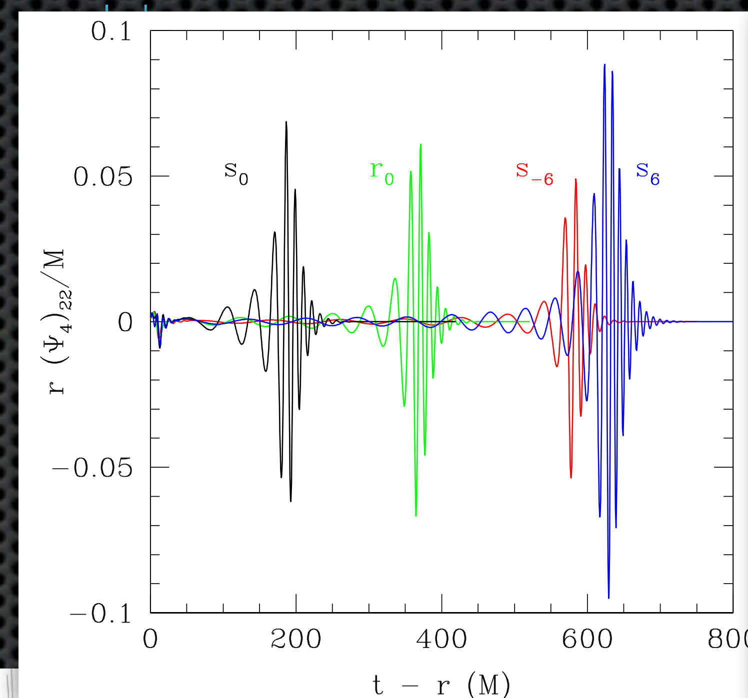
BBH Merger in Magnetic Field

Palenzuela et al 2009

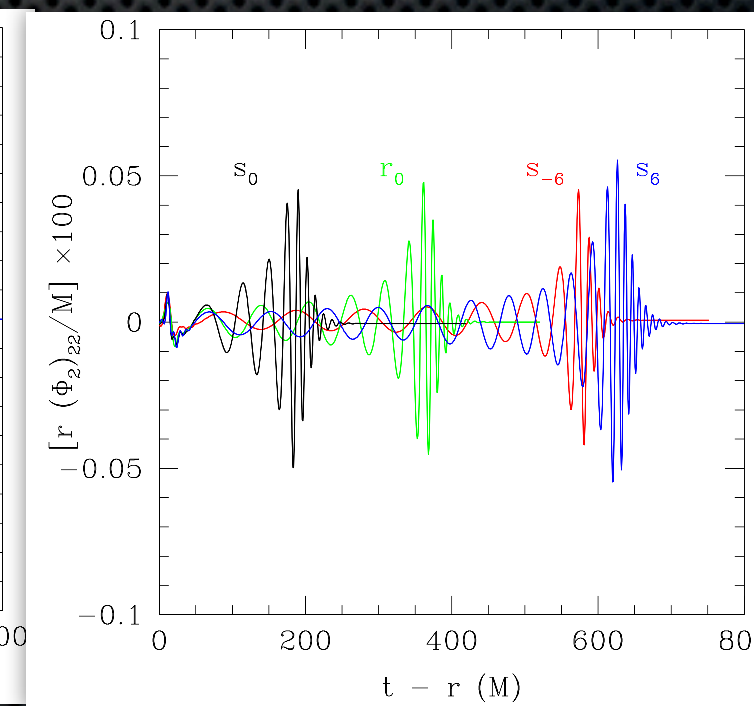




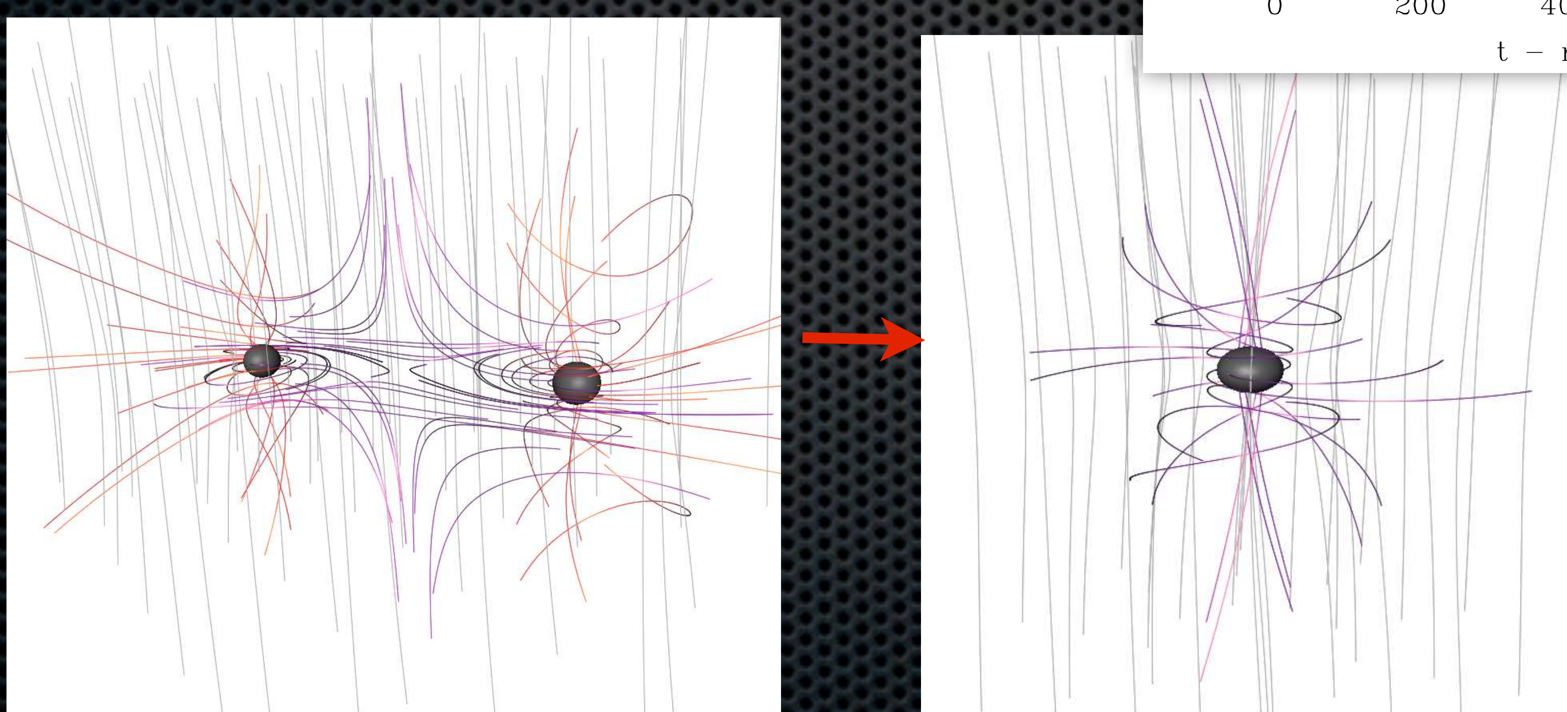
GW



EM



Mosta et al 2009



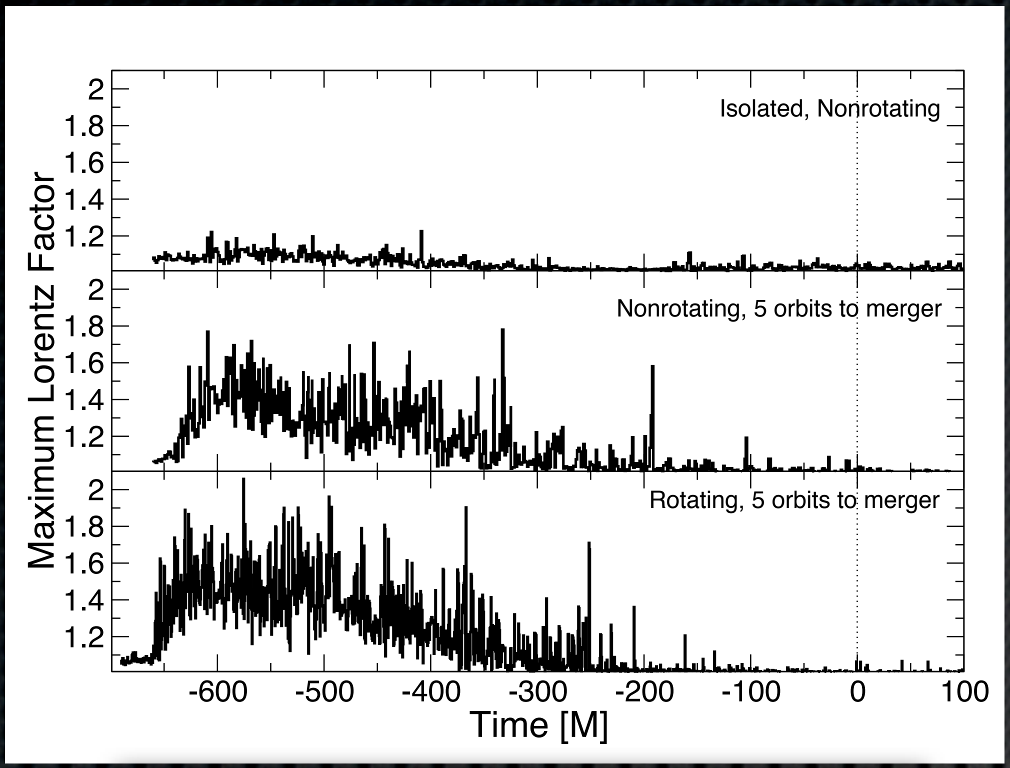
$$\frac{E^{\rm rad}_{\rm EM}}{M} \simeq 10^{-15} \left(\frac{M}{10^8\, M_\odot}\right)^2 \left(\frac{B}{10^4\ {\rm G}}\right)^2$$

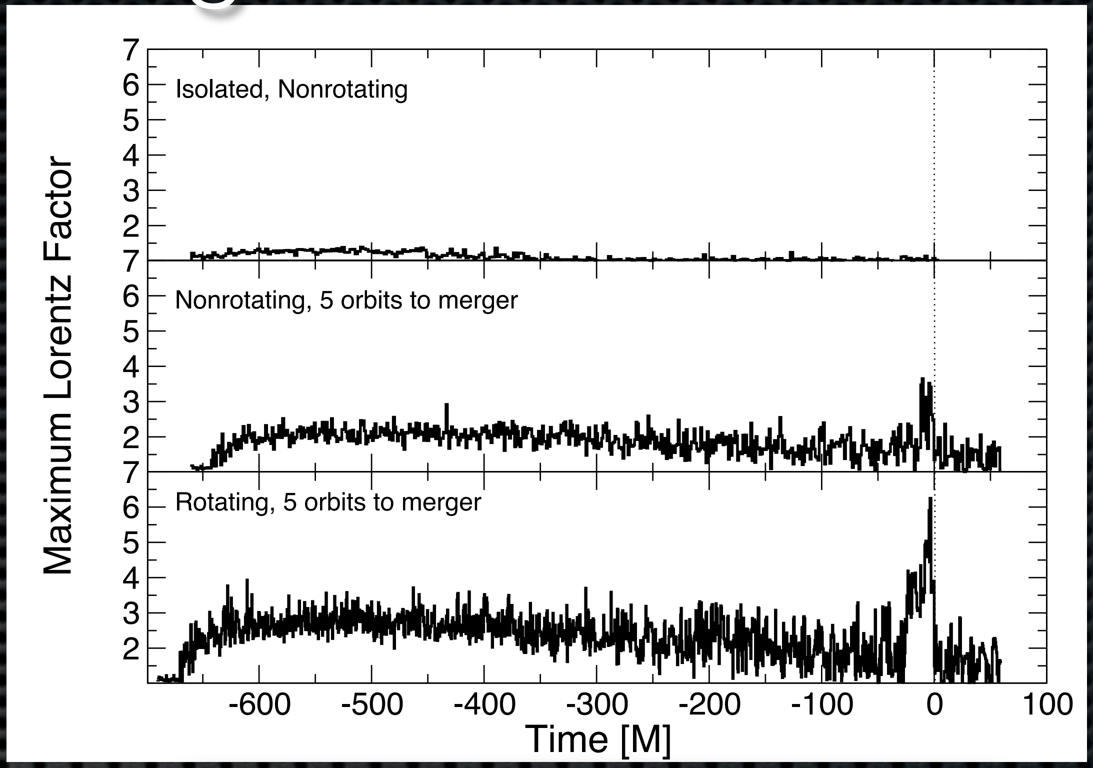
$$L_{\rm EM} \equiv \frac{E^{\rm rad}_{\rm EM}}{\tau} \simeq\ 10^{-4} \left(\frac{B}{10^4\ {\rm G}}\right)^2 L_{\rm Edd}$$

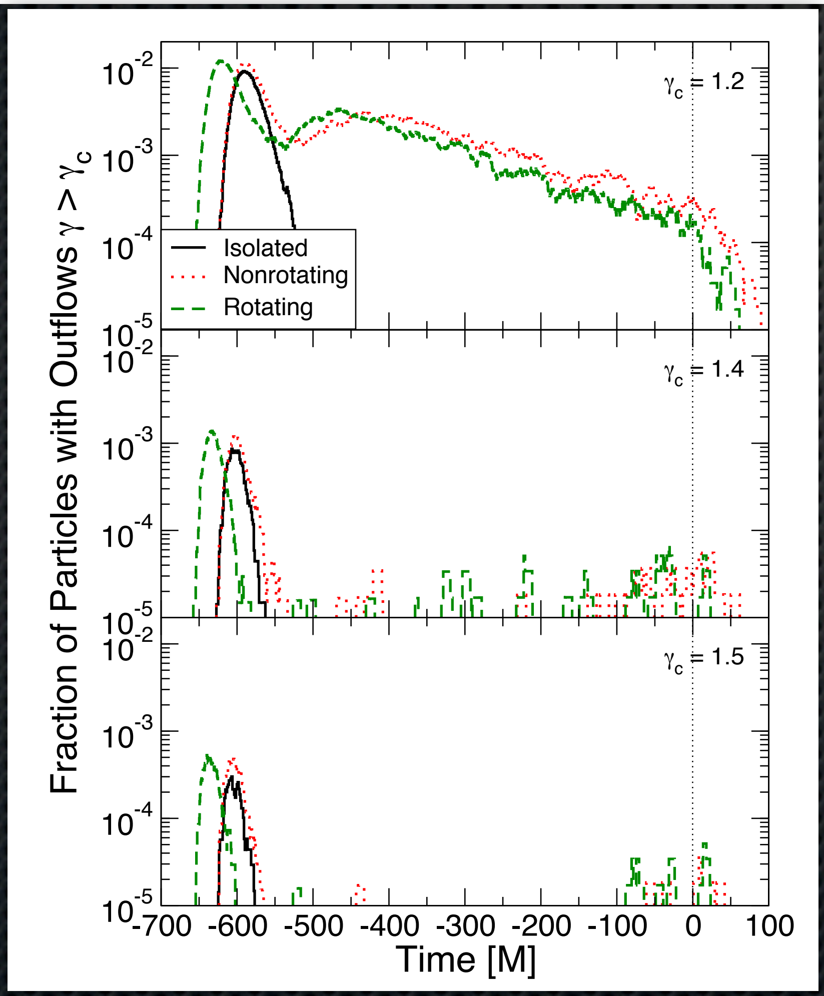
$$\nu = 10^{-4}(10^8 M_\odot/M){\rm Hz}$$

van Meter et al 2009

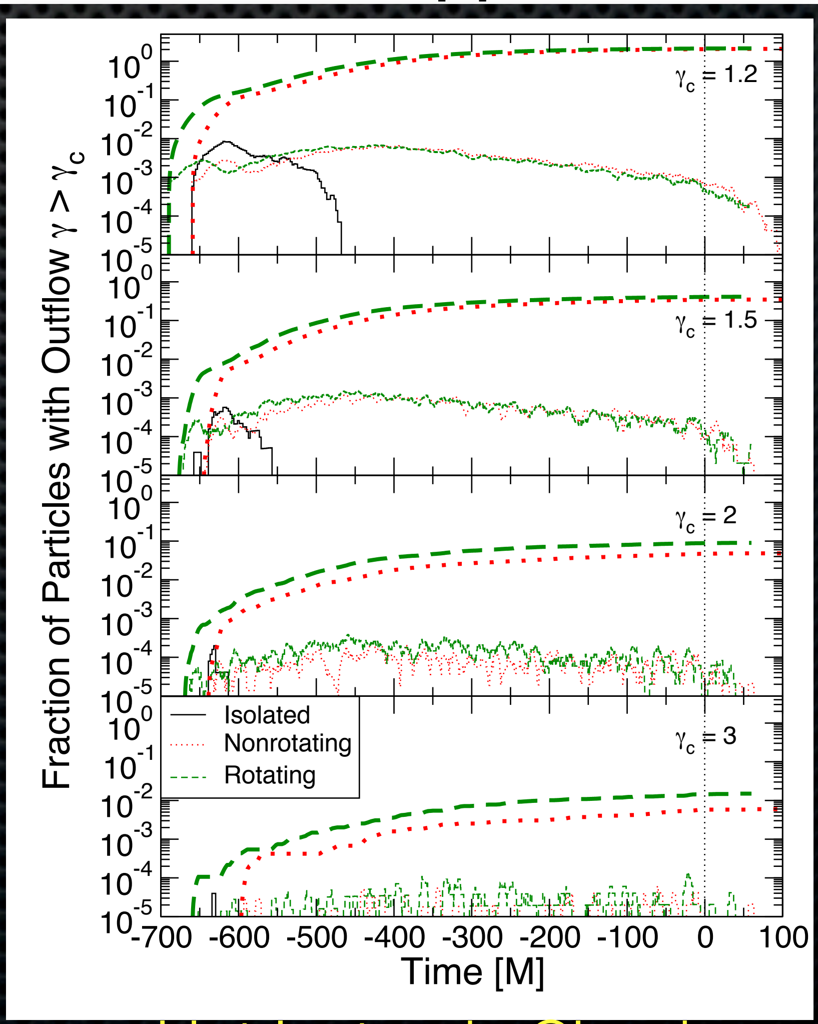
“Stirring Test Particles”







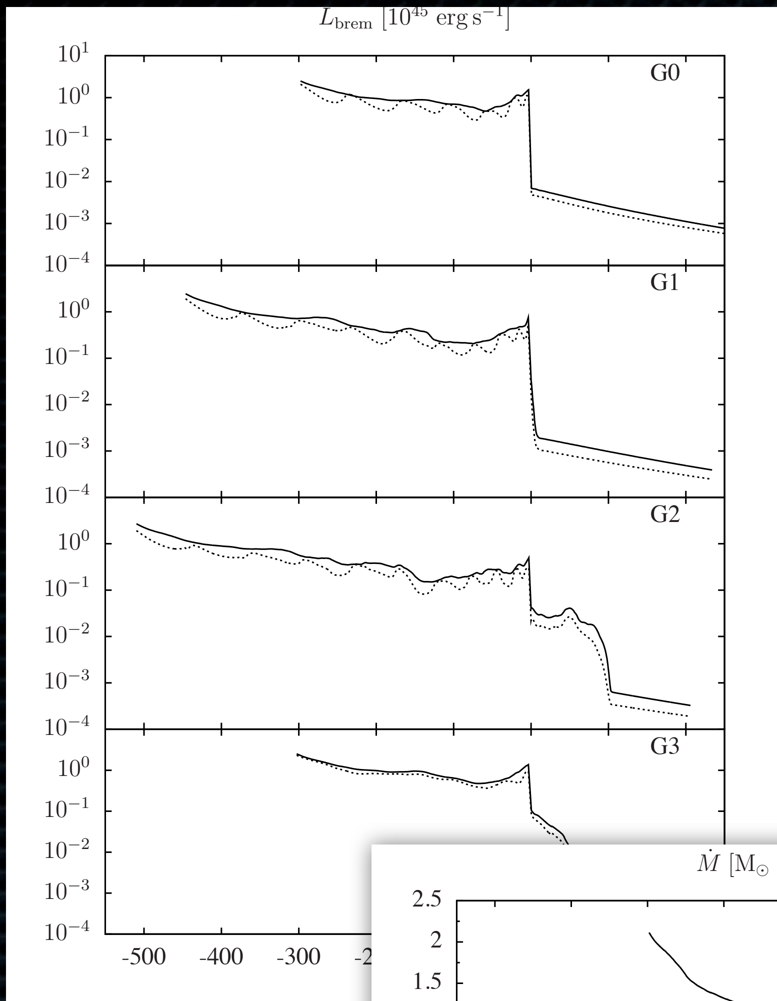
Warm Torus in Orbit

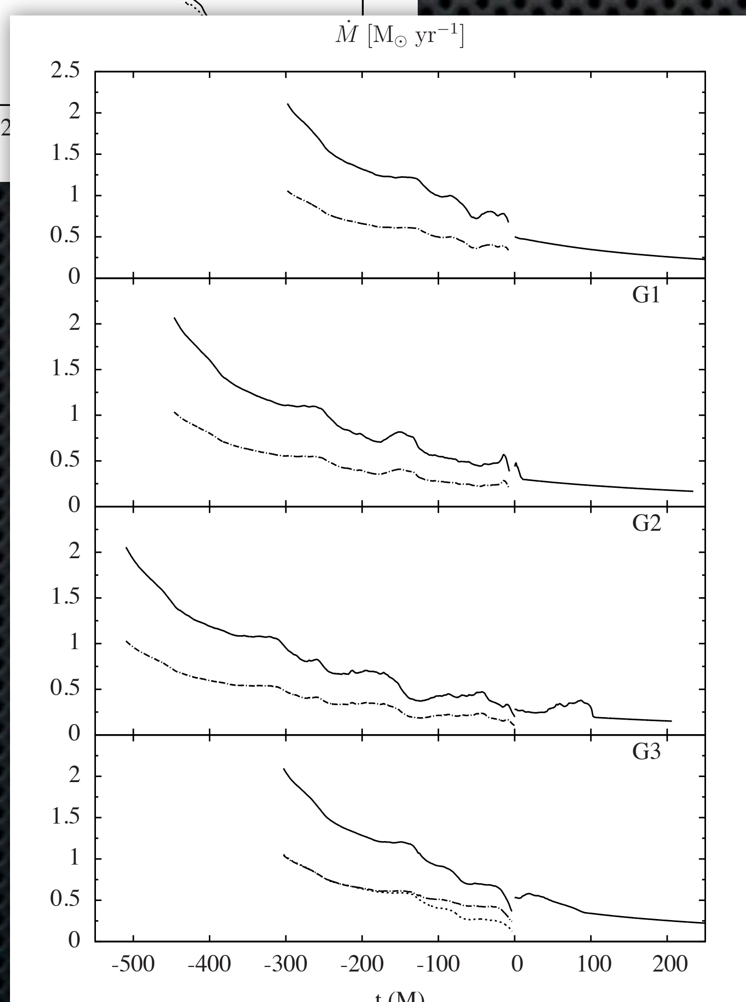


Hot Isotropic Cloud

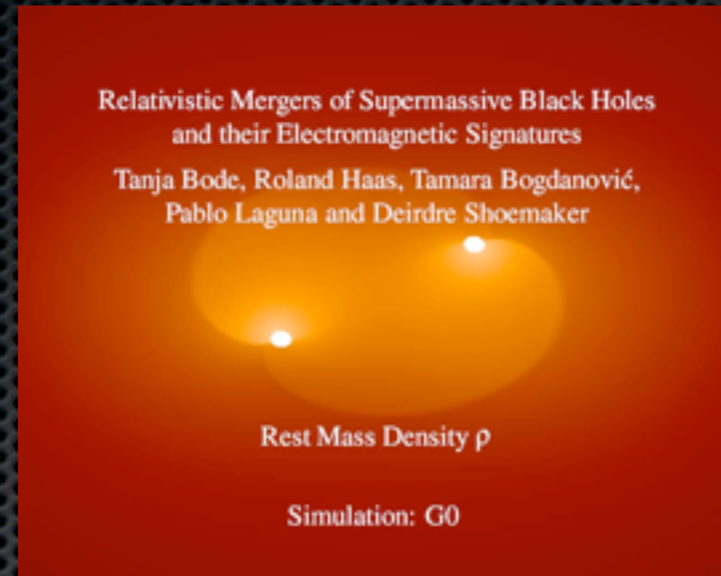
Bode et al. 2009

"Stirring Hot Gas"





G3



G0

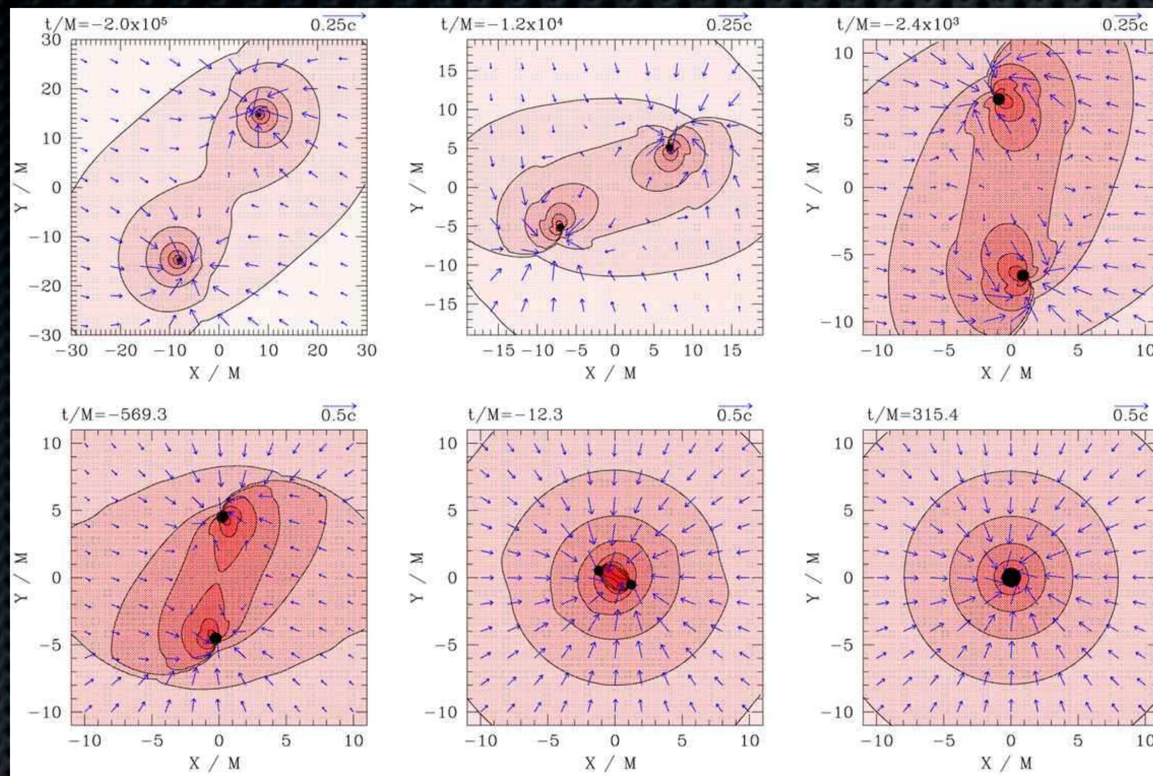
G1

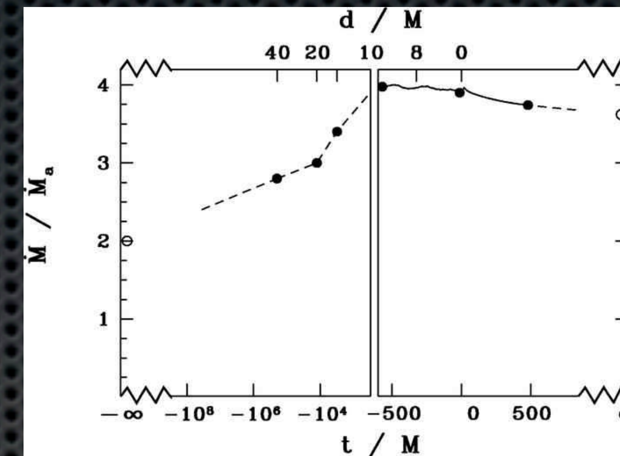
G2

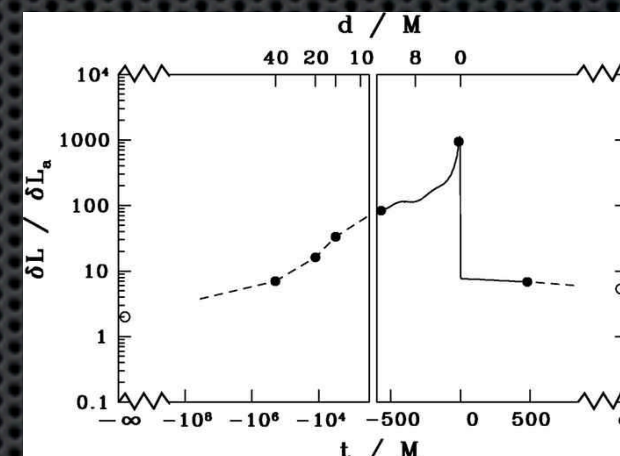
Run	a_1/m	a_2/m	P^x/M	P^y/M	m_i/M	$M_{\rm ADM}/M$
G0	0	0	-2.0902×10^{-3}	0.11237	0.5000	0.9878
G1	+0.4	+0.4	0	0.10862	0.4893	0.9875
G2	+0.6	+0.6	0	0.10677	0.4736	0.9874
G3	+0.4	-0.4	0	0.11237	0.4893	0.9878

Farris, Liu, Shapiro 2009

Binary Bondi-Hoyle-Lyttleton Accretion

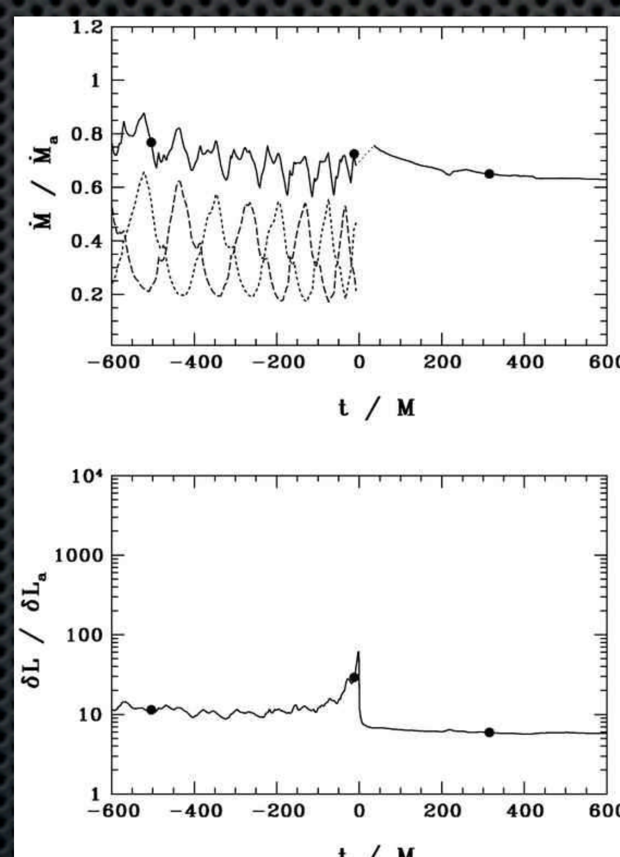


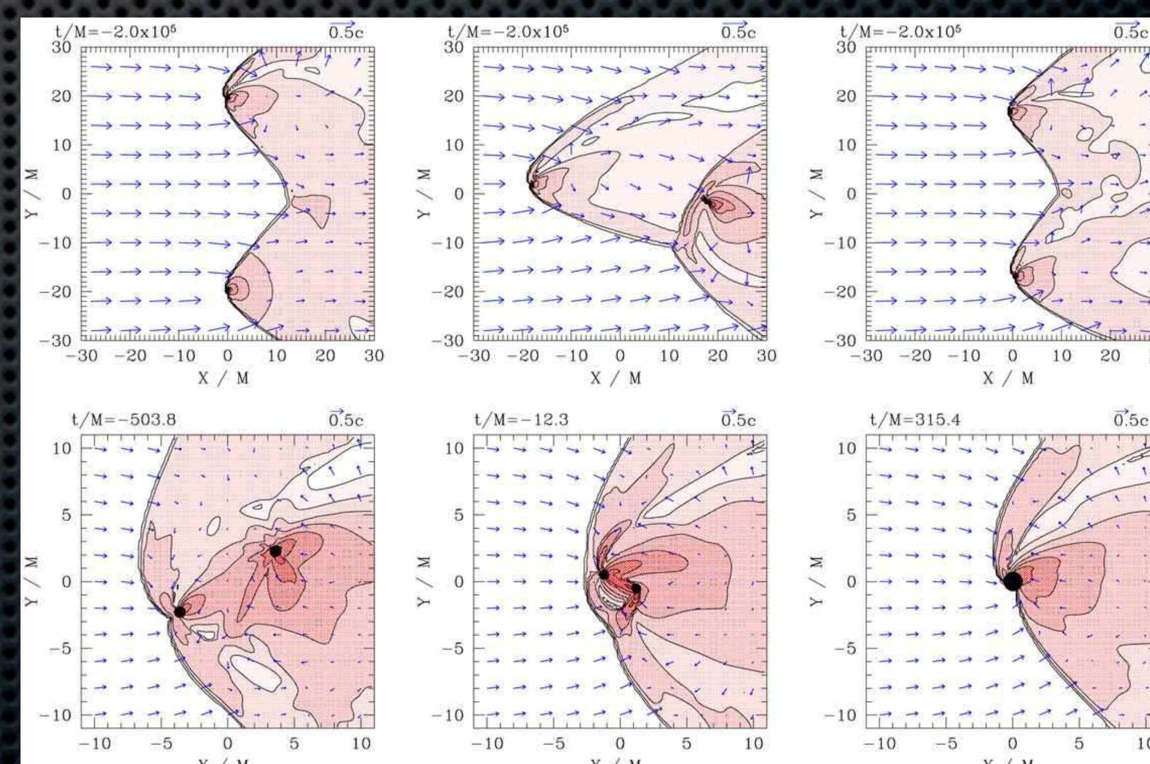




“Prototype”

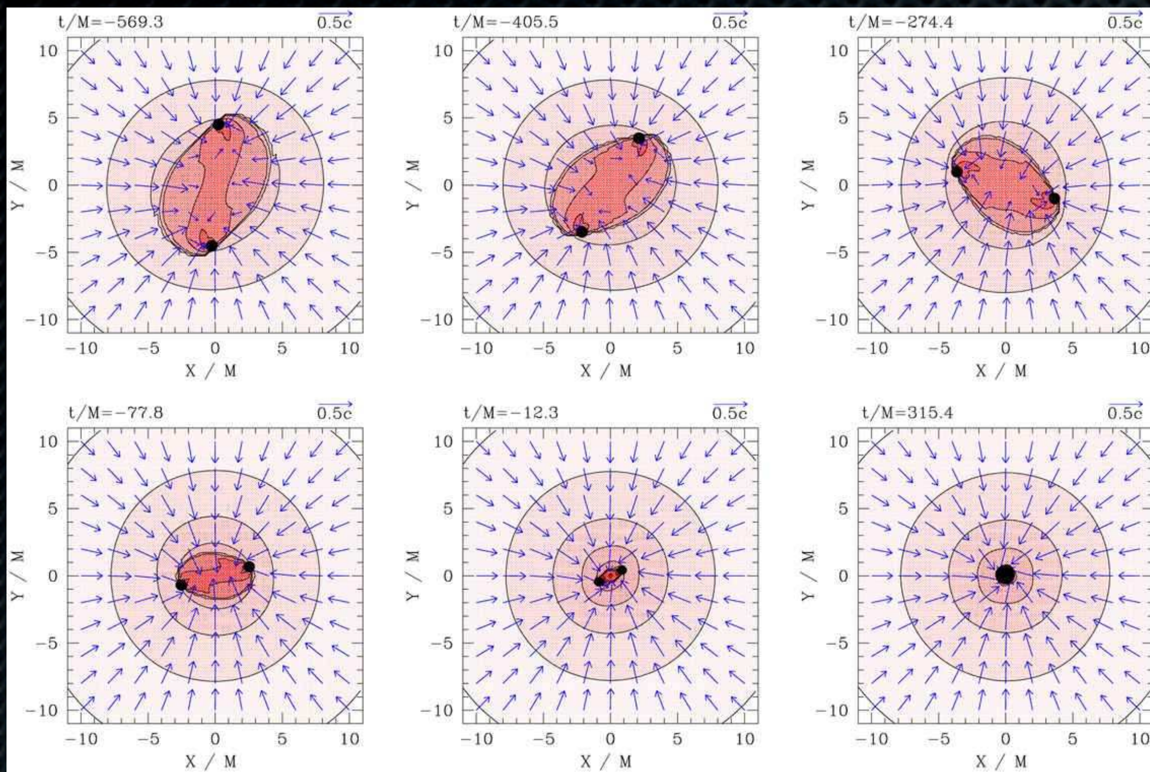
Boosted Temperature

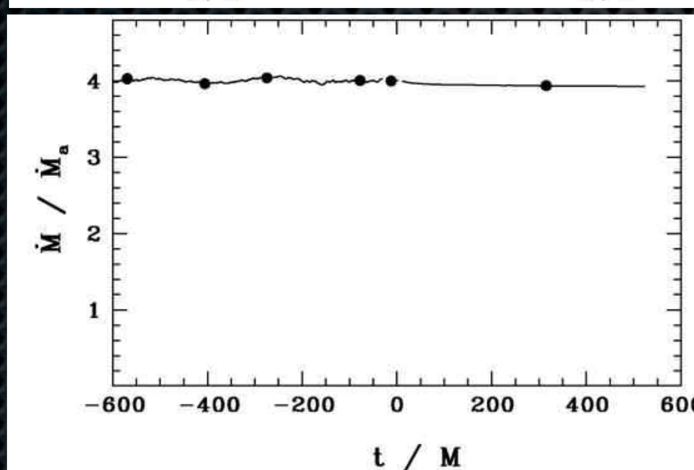


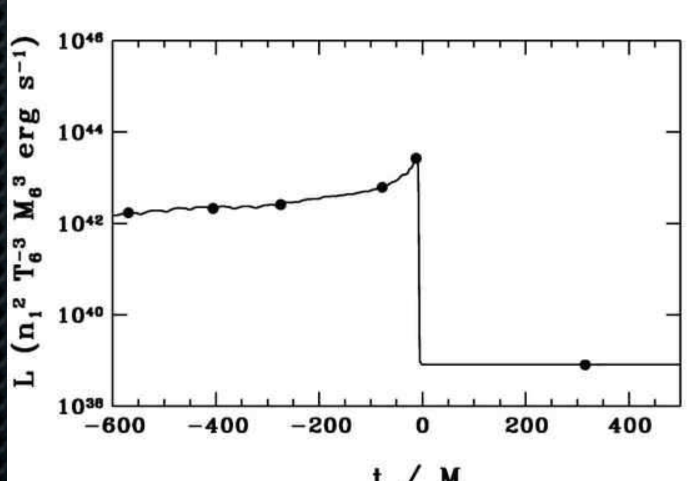


Farris, Liu, Shapiro 2009

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

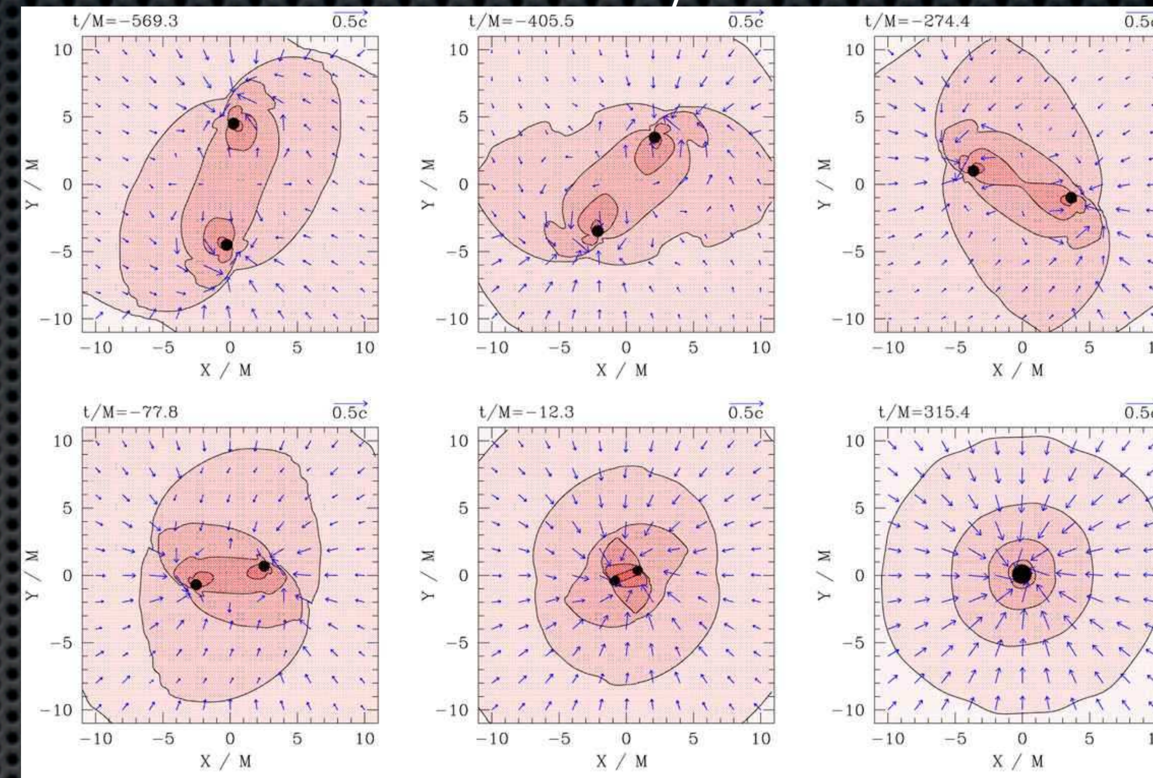


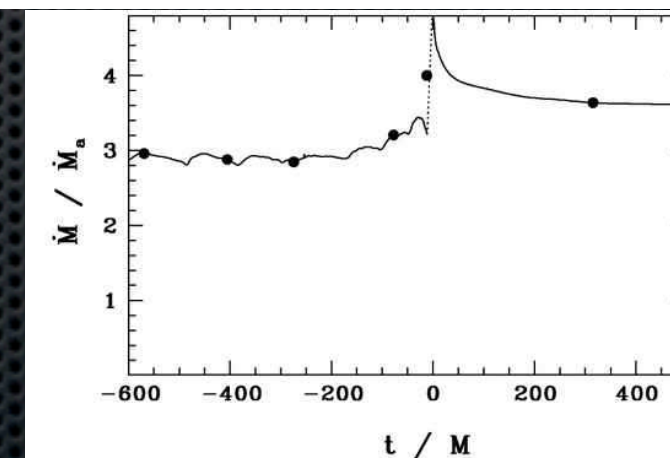


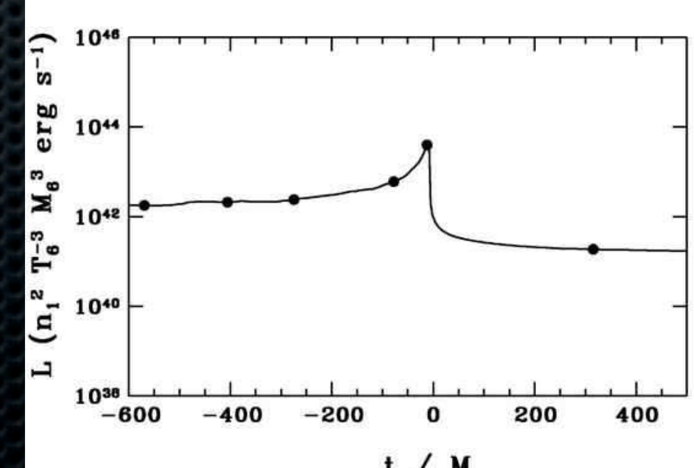


Realistic Temperature

$\Gamma = 5/3$







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

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

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

UBH Accretion

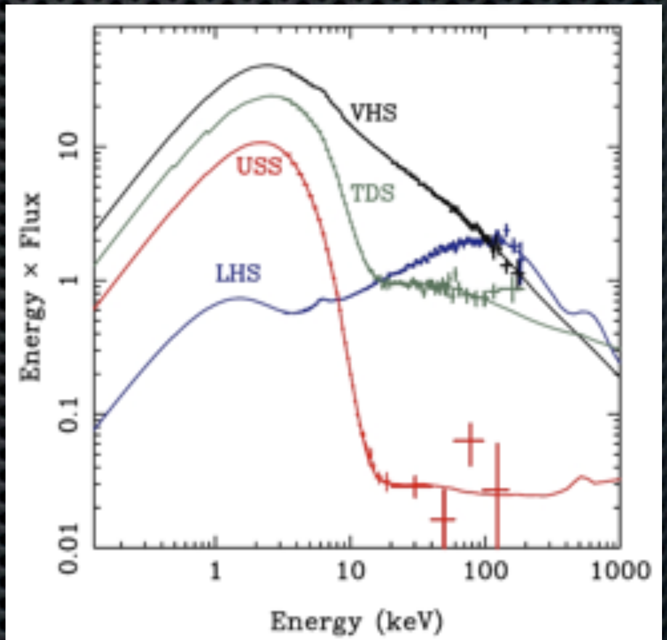
Probing the Spacetime of BHs

- Variability: e.g. QPOs, short time scale fluctuations
- Polarization (e.g. Schnittman & Krolik 2009)
- Spectral Fitting of Thermal Emission

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

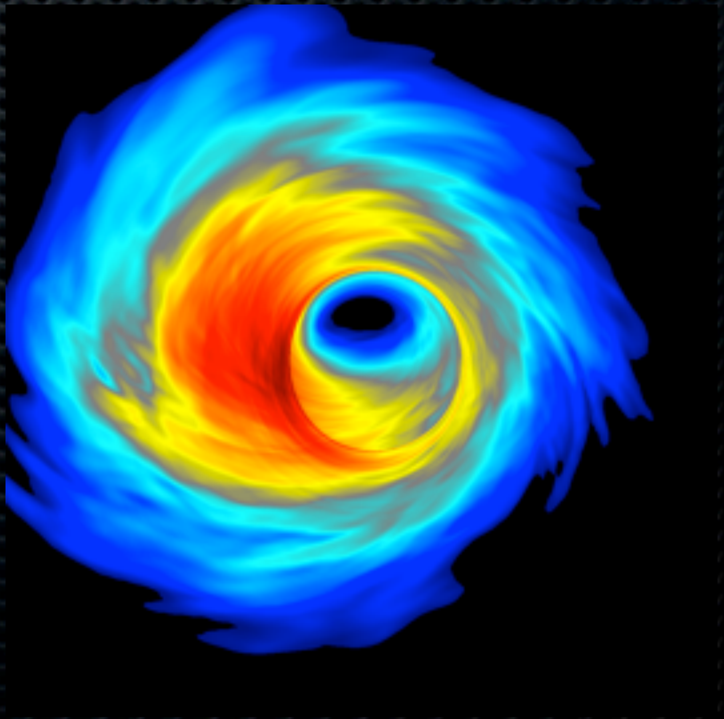
McClintock et al. 2006, Shafee et al. 2006

Done et al 2007



- 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



Thin Disks

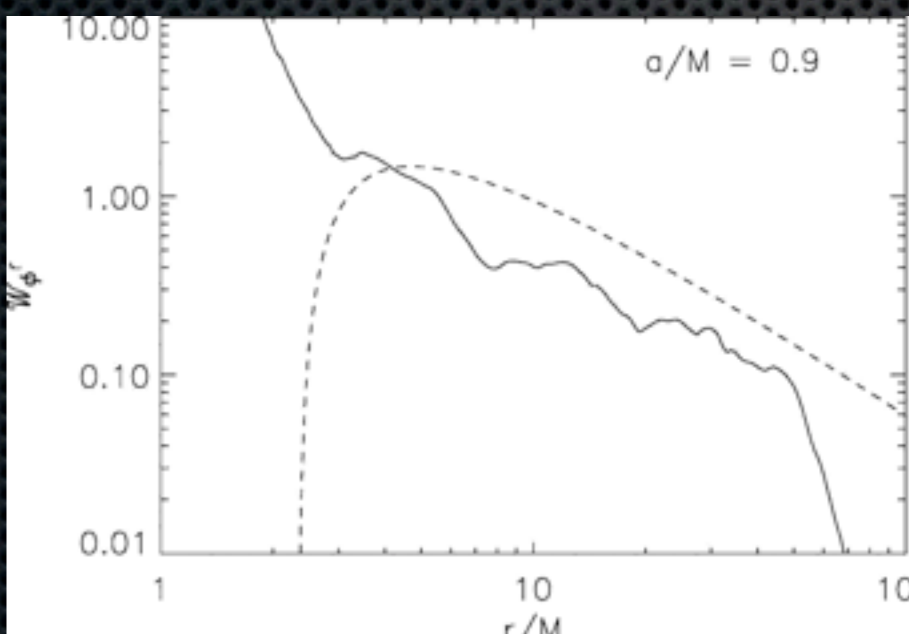
Steady-State Models: Novikov-Thorne 1973, Shakura & Sunyaev 1973

- Efficient radiator, slim profile

$$W_{r\phi} = \alpha p \qquad H/r = \text{const.}$$

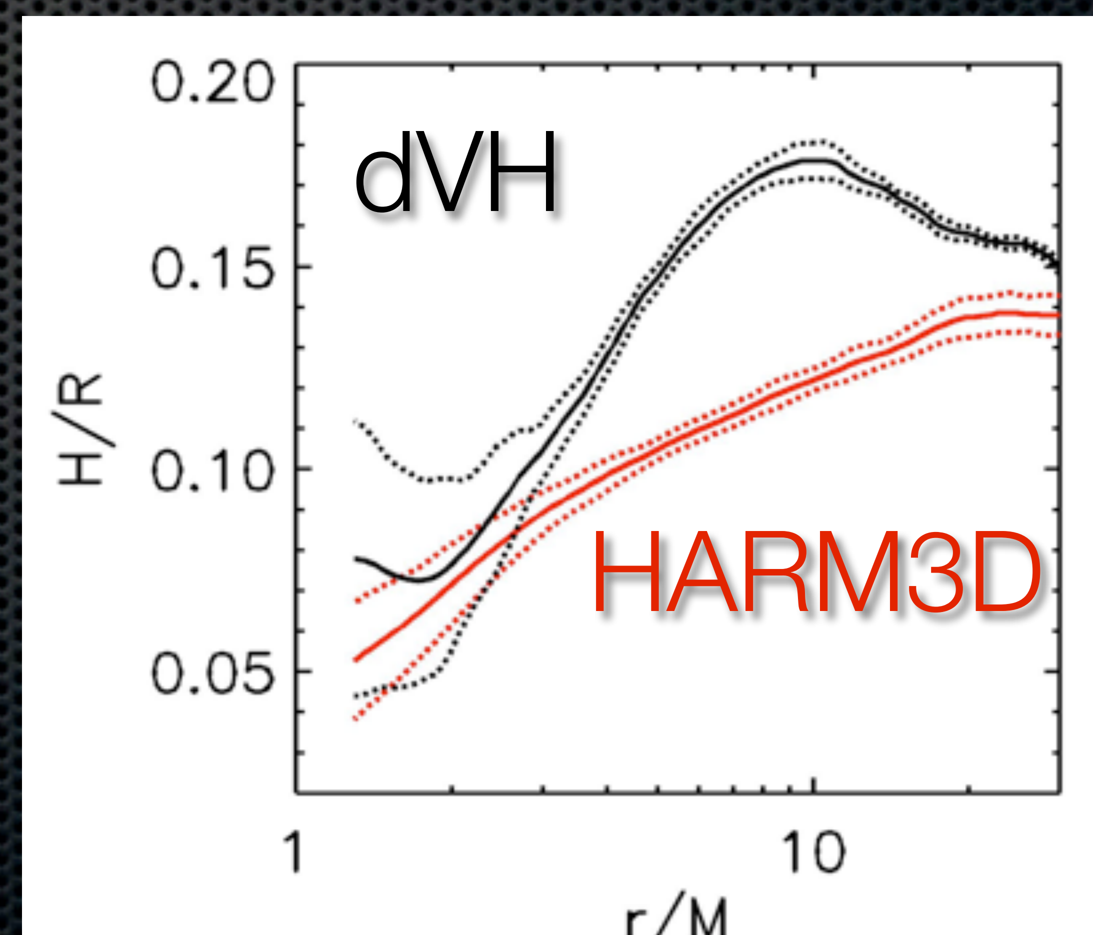
3D GRMHD Disks:

- Include MRI
- “Fully” relativistic
- Eliminate artificial channel solution
- Allow for perpetual turbulence



Krolik, Hawley, Hirose (2005)

de Villiers & Hawley (2003)



SCN, Krolik & Hawley 2009

- 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

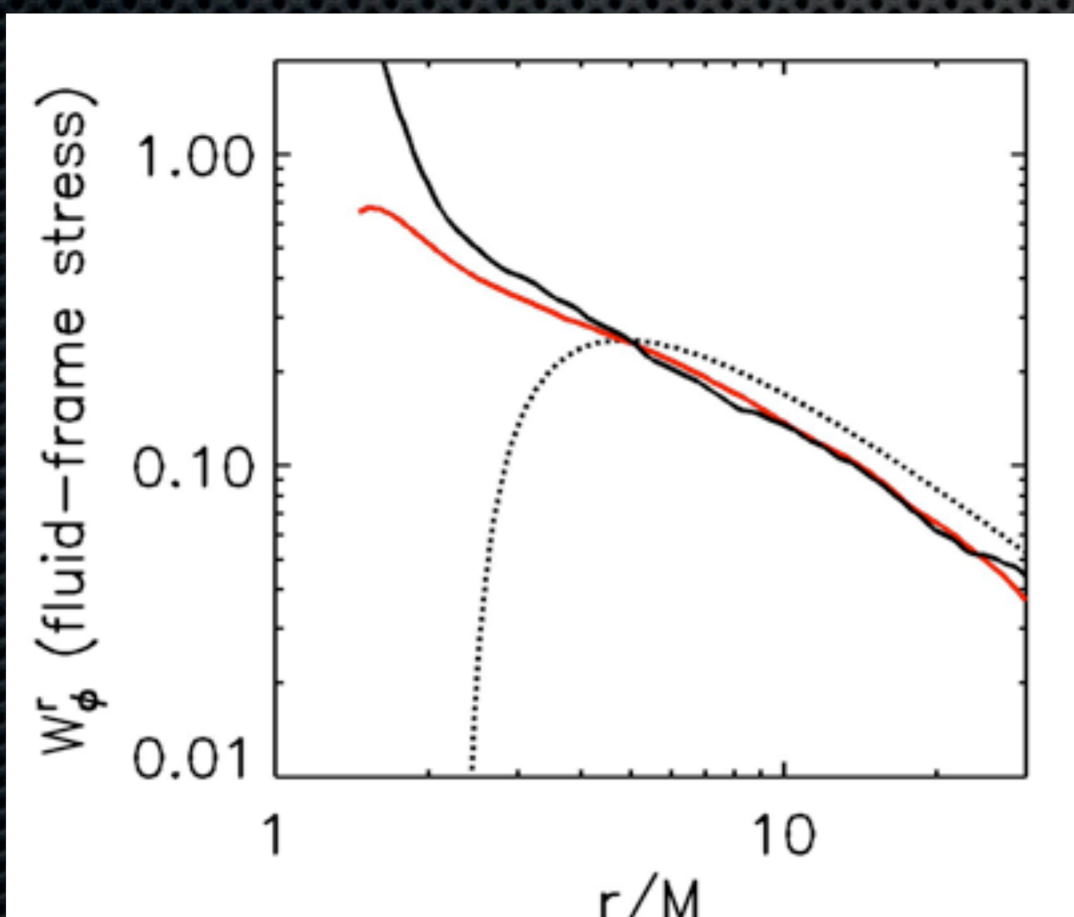
$$\Delta\eta/\eta = 6\%$$

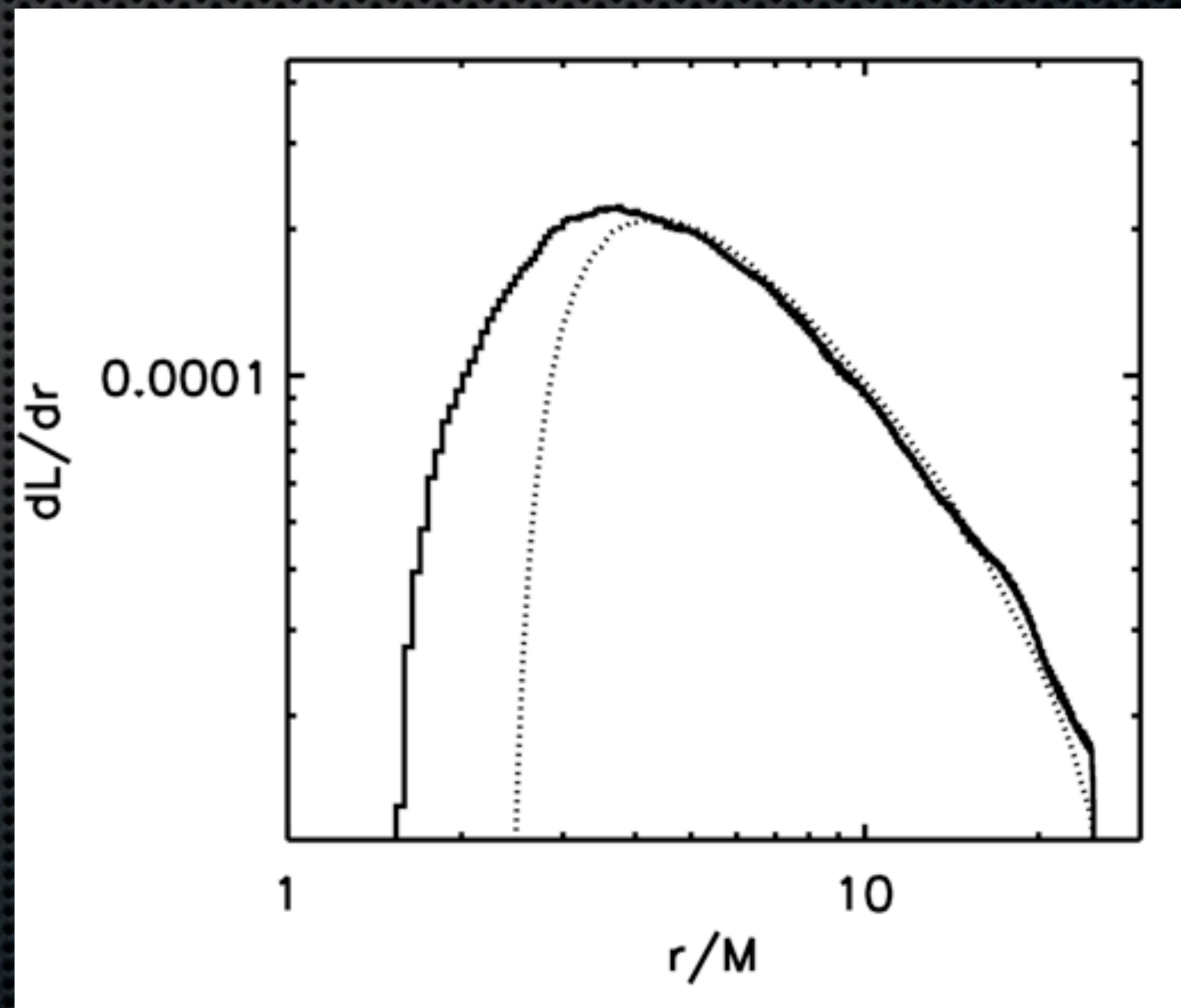
$$\Delta T_{\rm max}/T_{\rm max} = 30\%$$

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

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

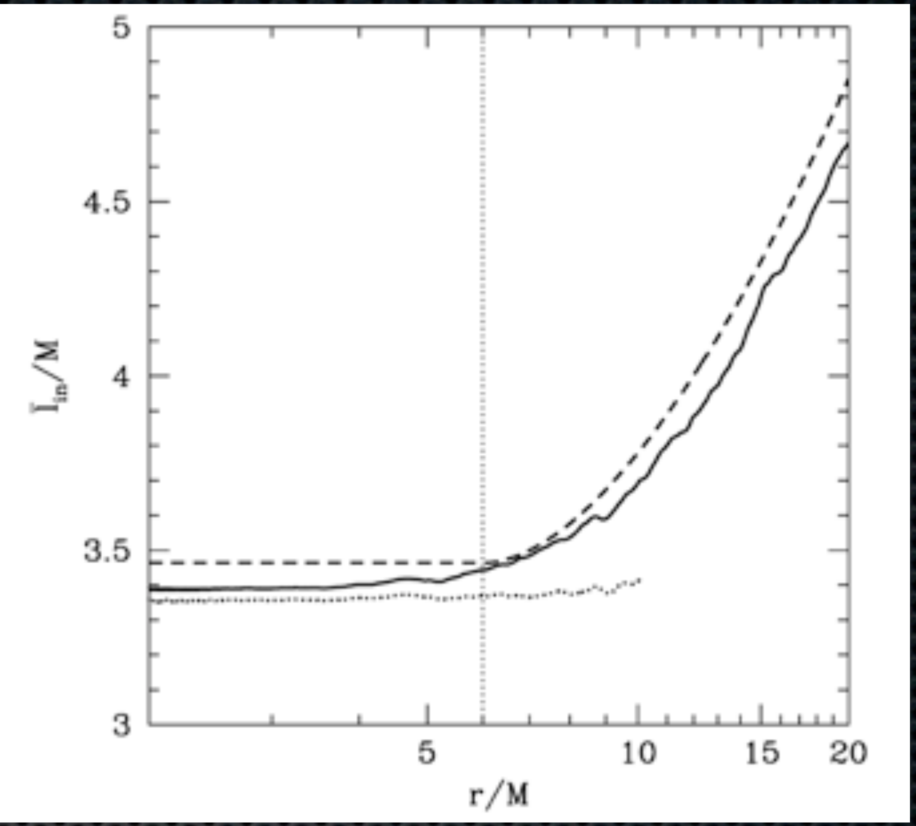
$$L = \eta \dot{M} c^2 \qquad \eta_{\rm NT} = 0.143$$

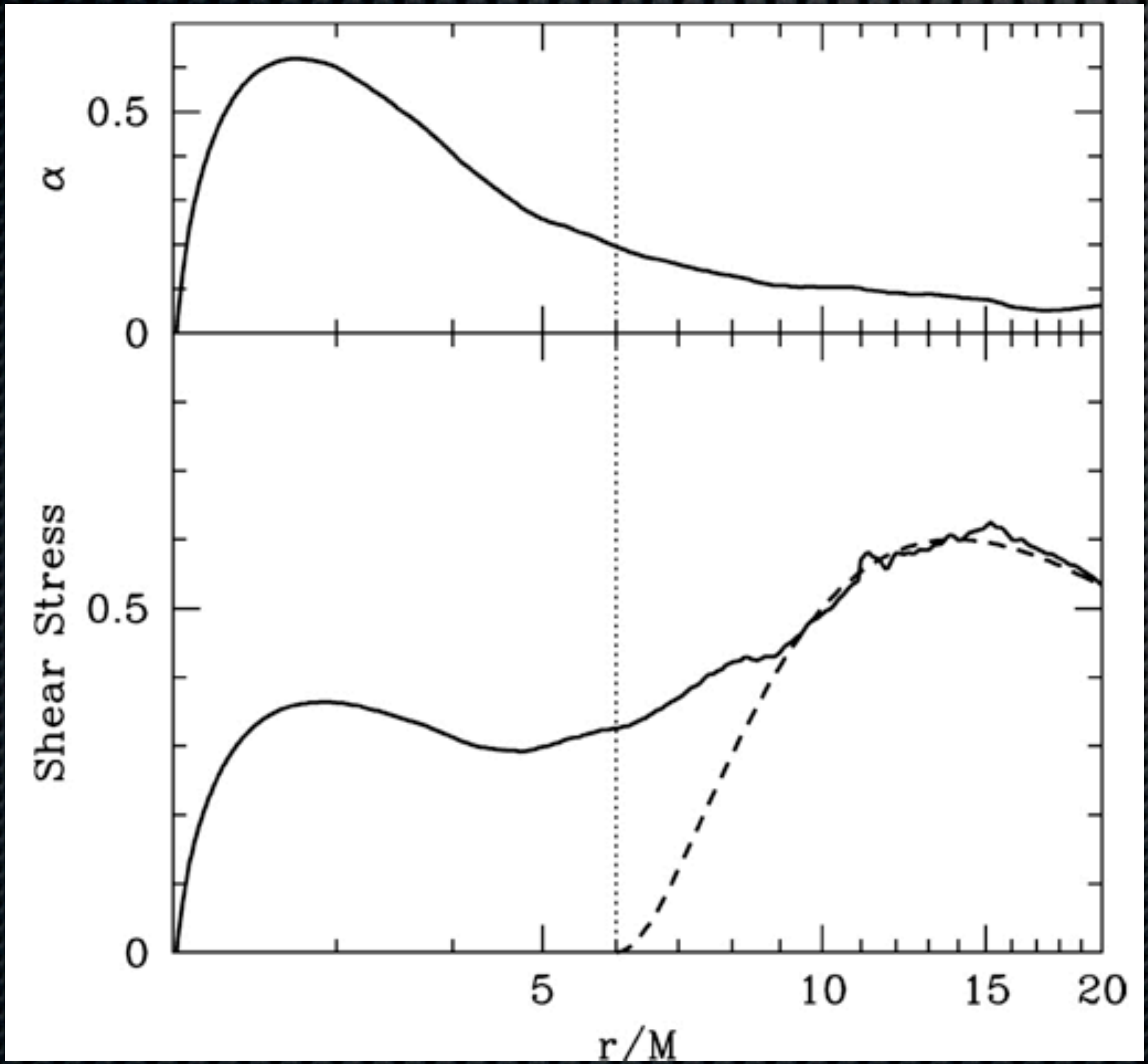




Shafee et al 2009

- 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	10% (or 50%)	0%
H/R	0.05-0.07	0.07 - 0.13
Code	WHAM	HARM3D
Resolution	512x120x32	192x192x64

ThinHR: H/R = 0.06

912x160x64

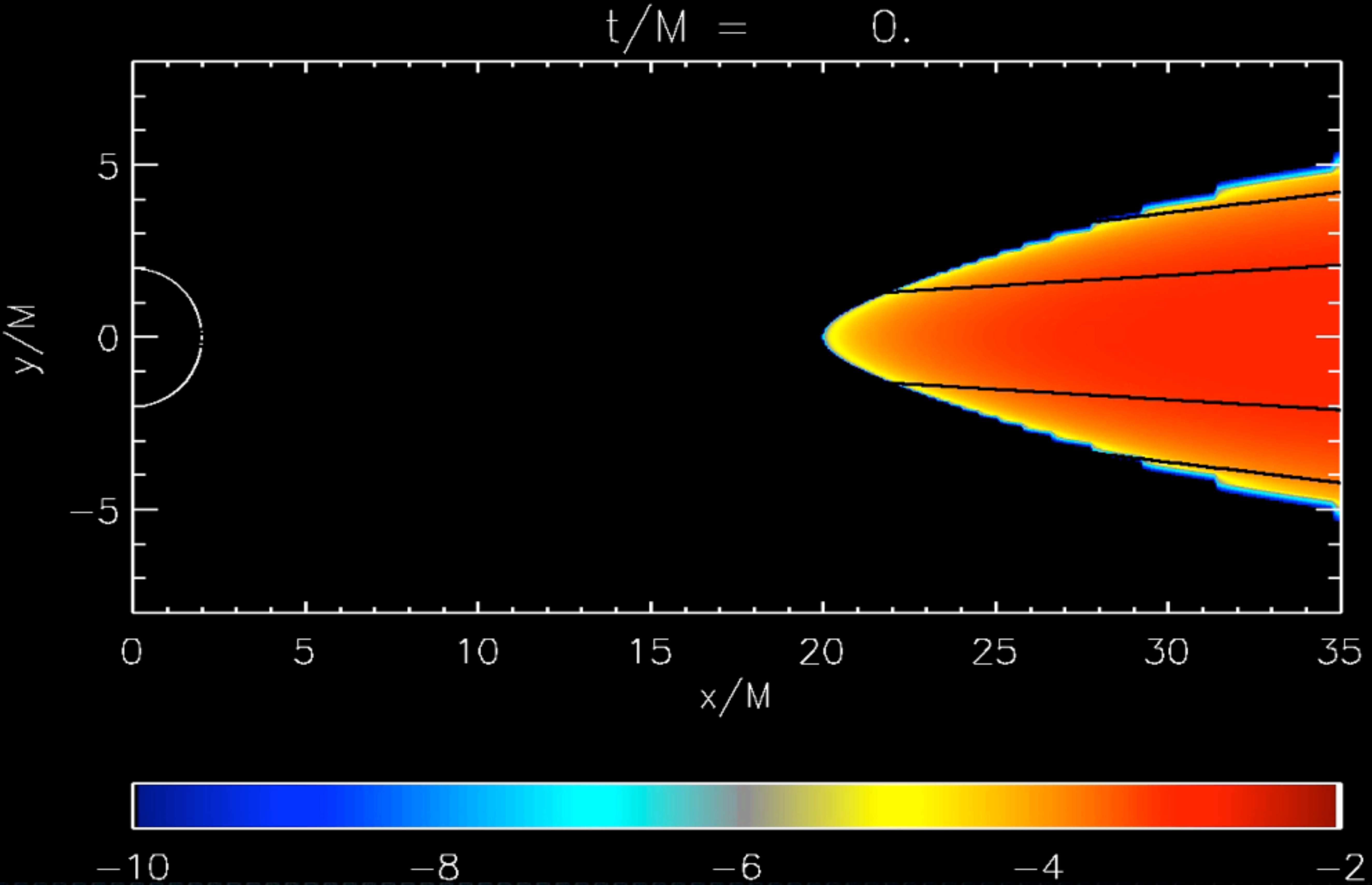
ρ

SCN, Krolik, Hawley 2010

ThinHR: H/R = 0.06
912x160x64

ρ

SCN, Krolik, Hawley 2010



	Theirs	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	~60	6 - 30	80	100	40 - 70	60	35
Initial Data	"V. 1"	V. 2	V. 1	V. 1	V. 1	V. 2	V. 2

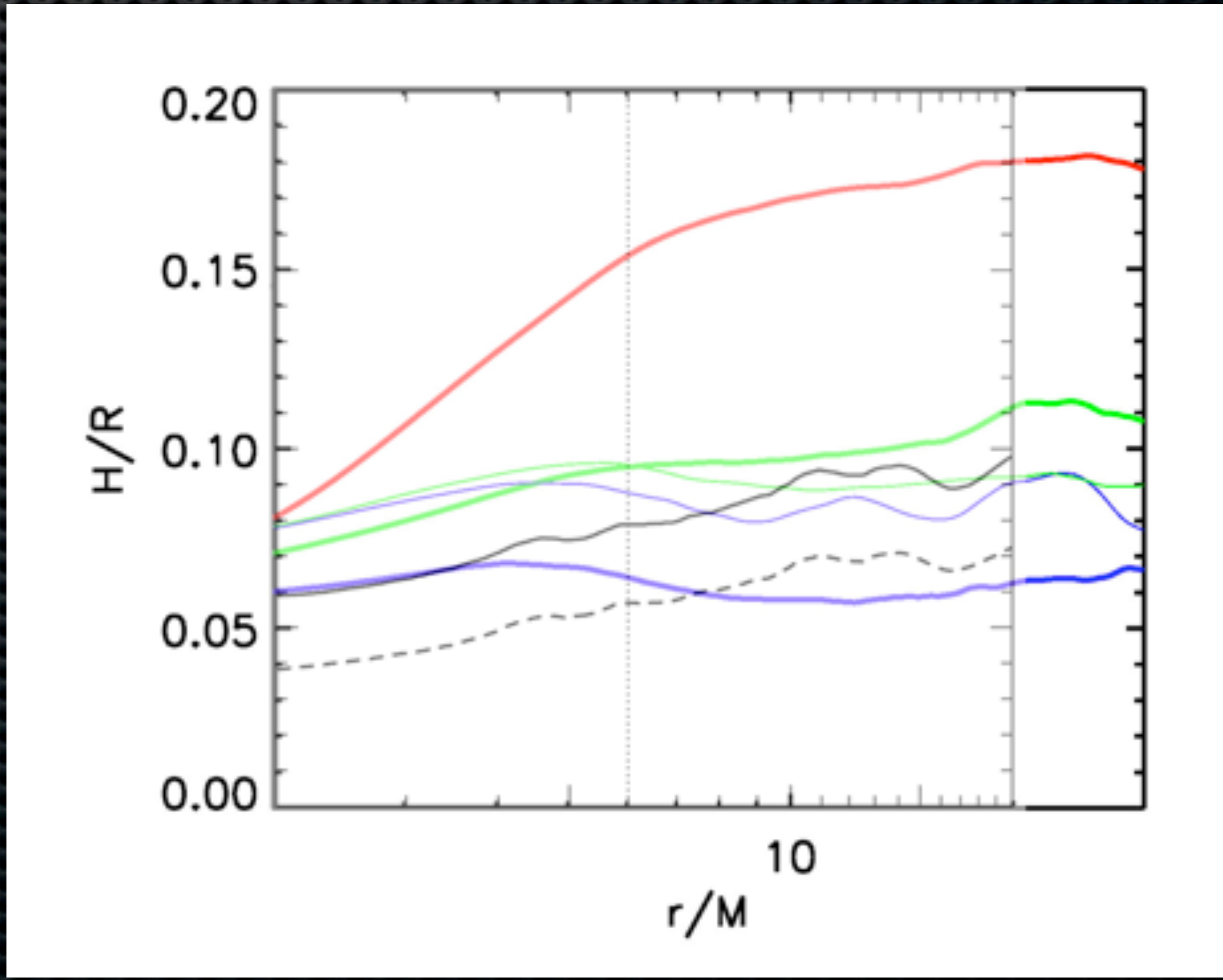
SCN, Krolik, Hawley 2010

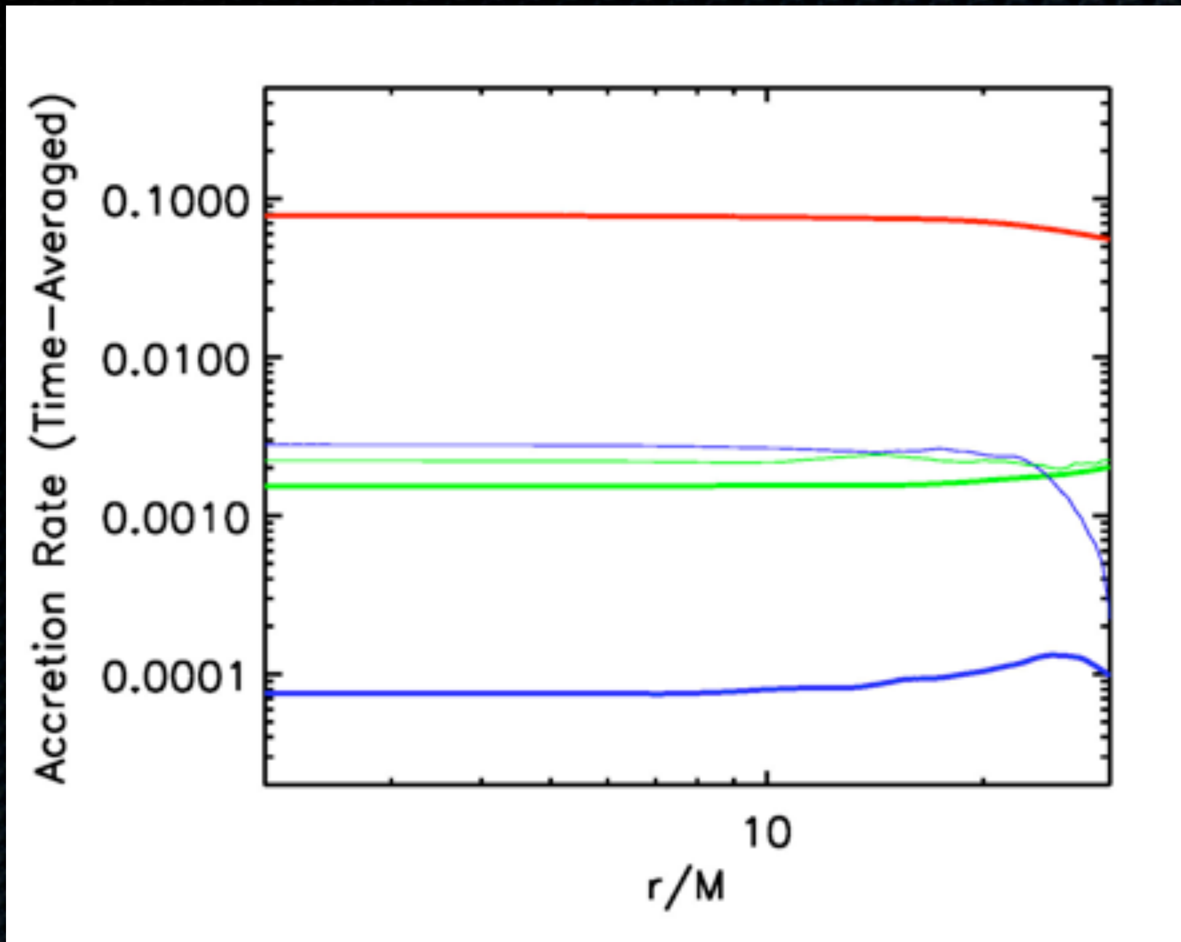
v1: (high resolution), Initial Disk:

- at target thickness
- with inner radius at 20M
- With Pmax at r=35M

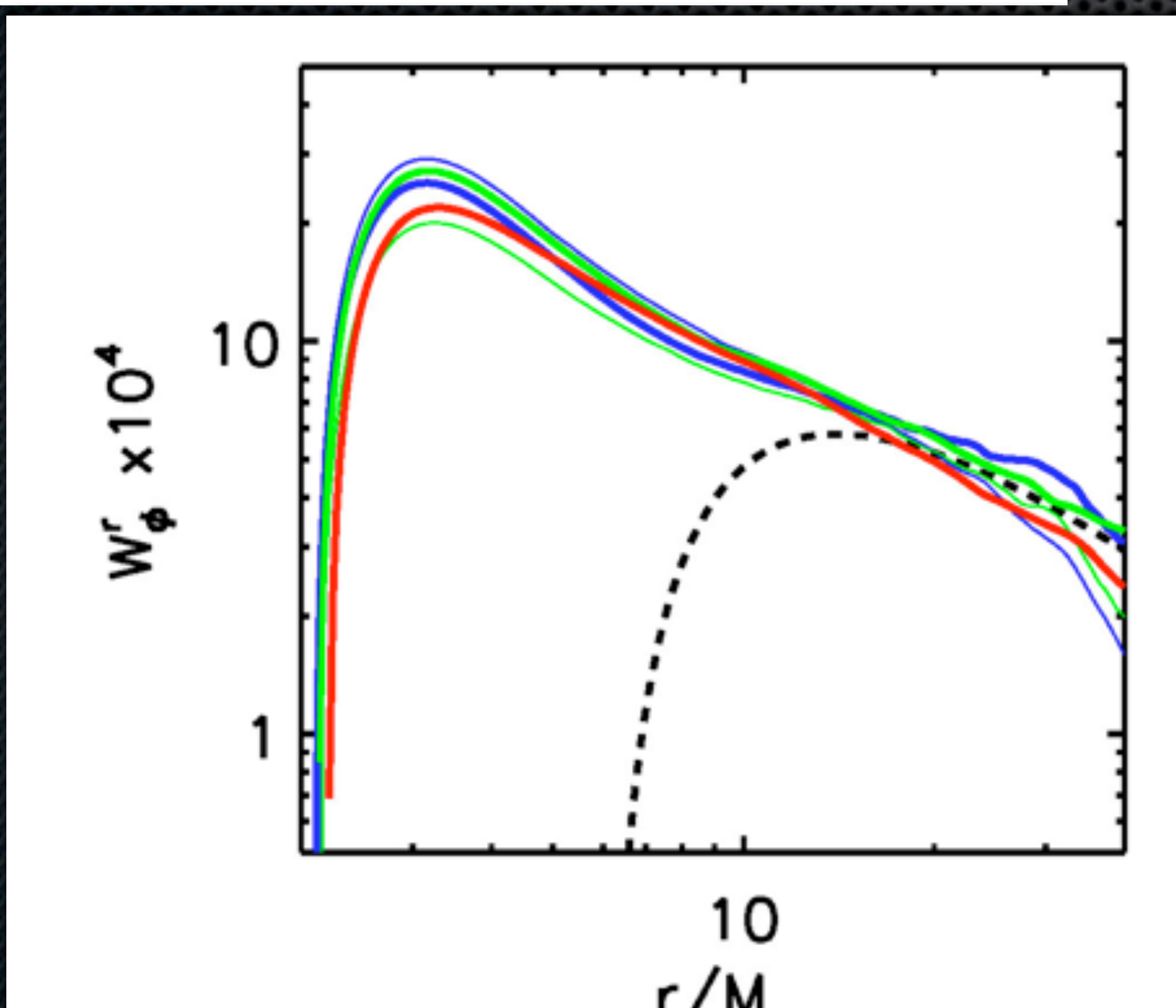
v2: (low resolution), Initial Disk:

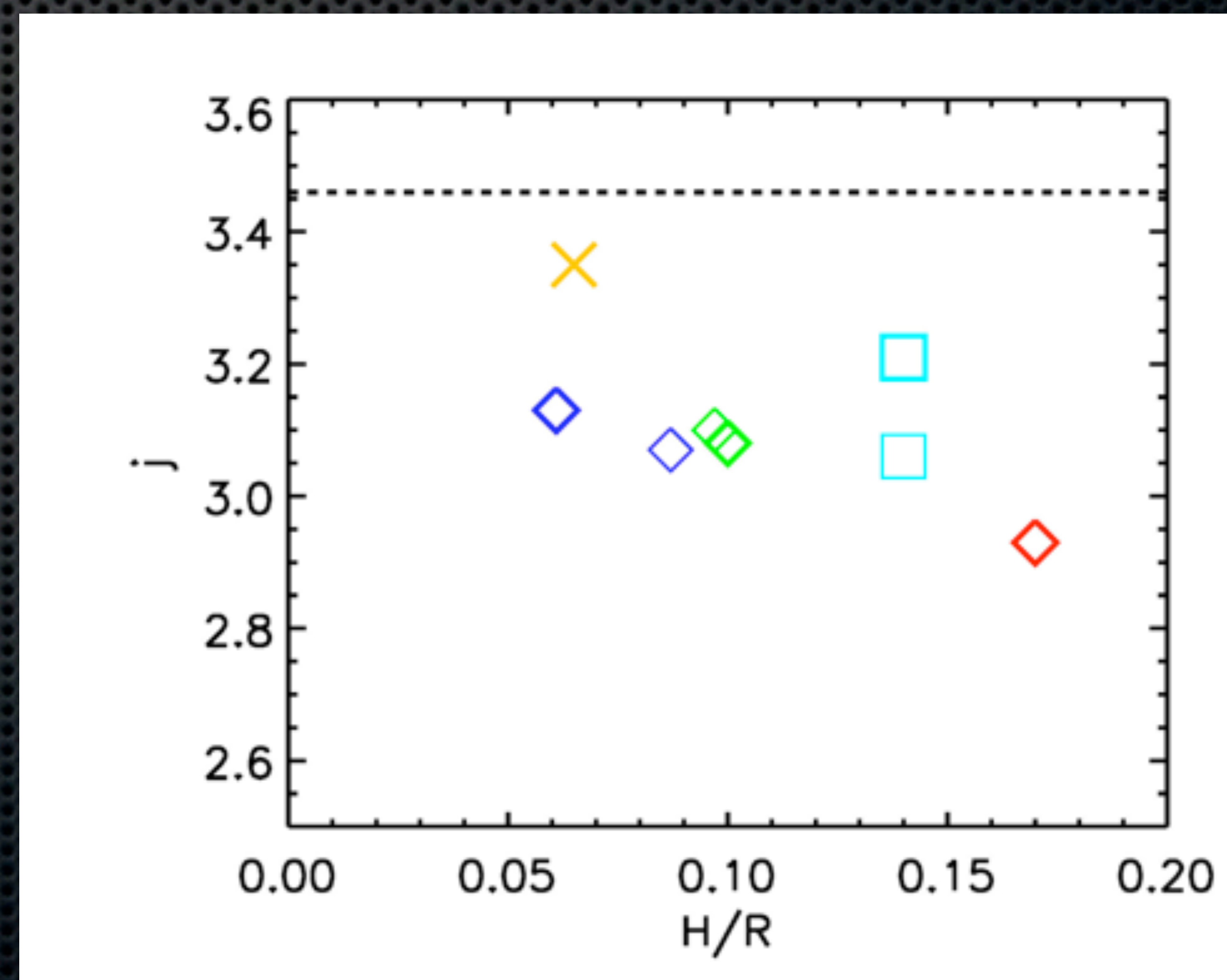
- at H/r ~ 0.15
- Inner radius at 15M
- Pmax at r=25M



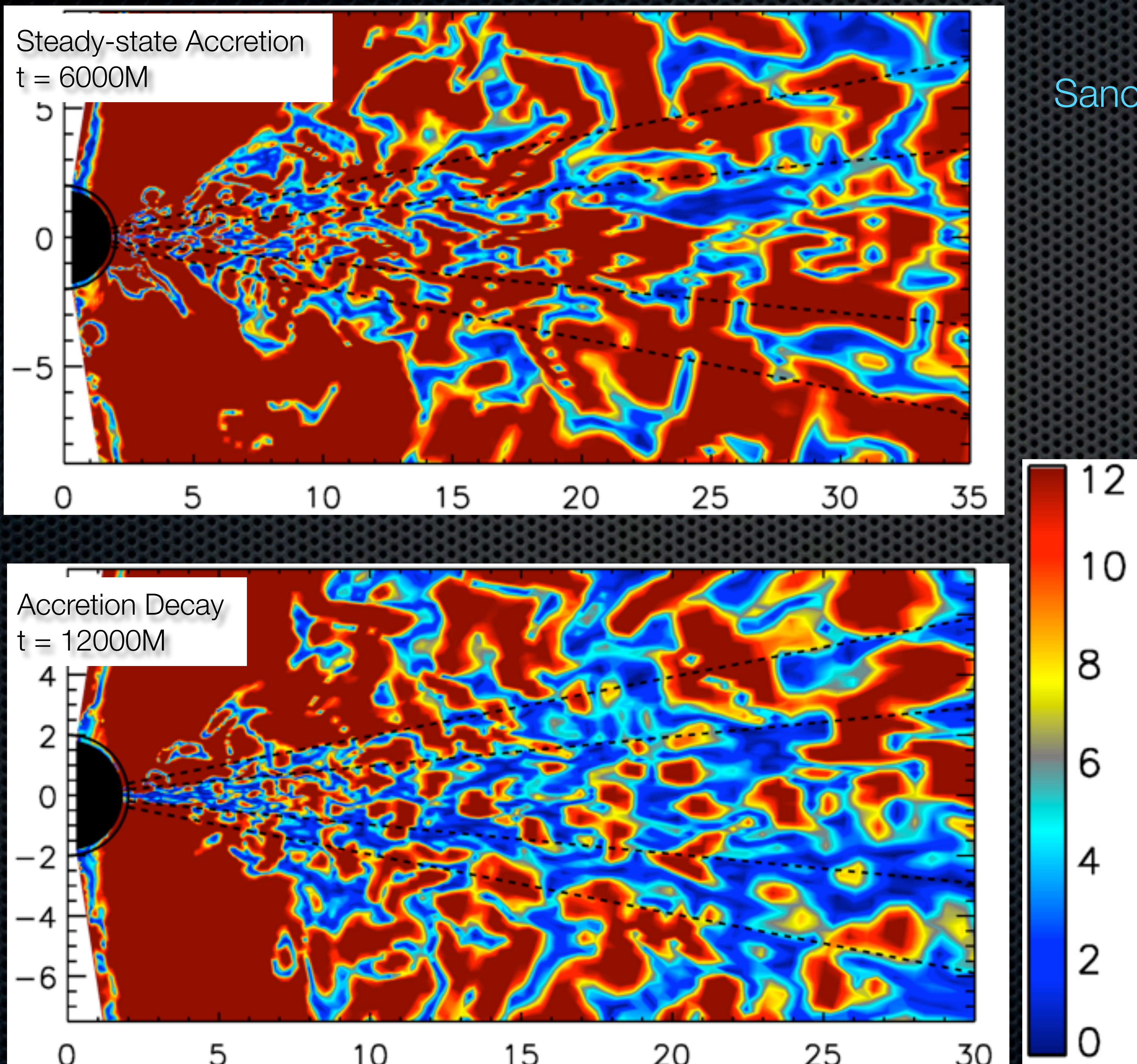


- Much effort to prove time-steady-ness
- No trend seen in Maxwell Stress
- Minor “sqrt” trend seen in spec. ang. mom.
  - Due to additional Reynolds stress for thicker disks
- Large stress within ISCO --> smaller gap in circumbinary disks (TBD)





Track MRI Resolution for all time!



Sano et al. 2004

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

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

Davis, Stone, &
Pessah 2009

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

Coronal X-ray Variability

Variability Driven by Modulations in the Accretion Rate

Lyubarskii et al 1997

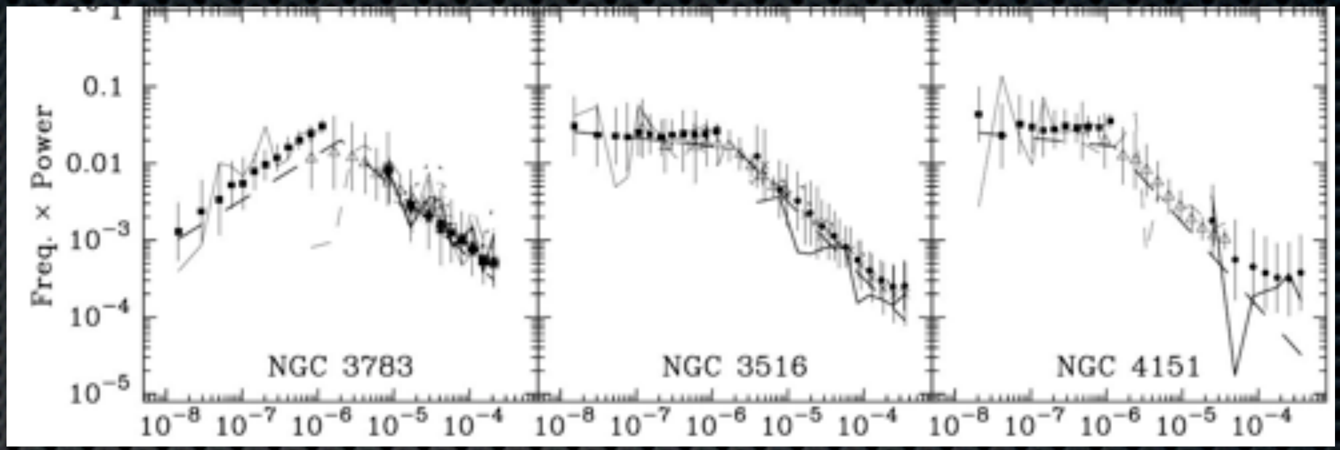
Churazov et al 2001

Armitage & Reynolds 2003

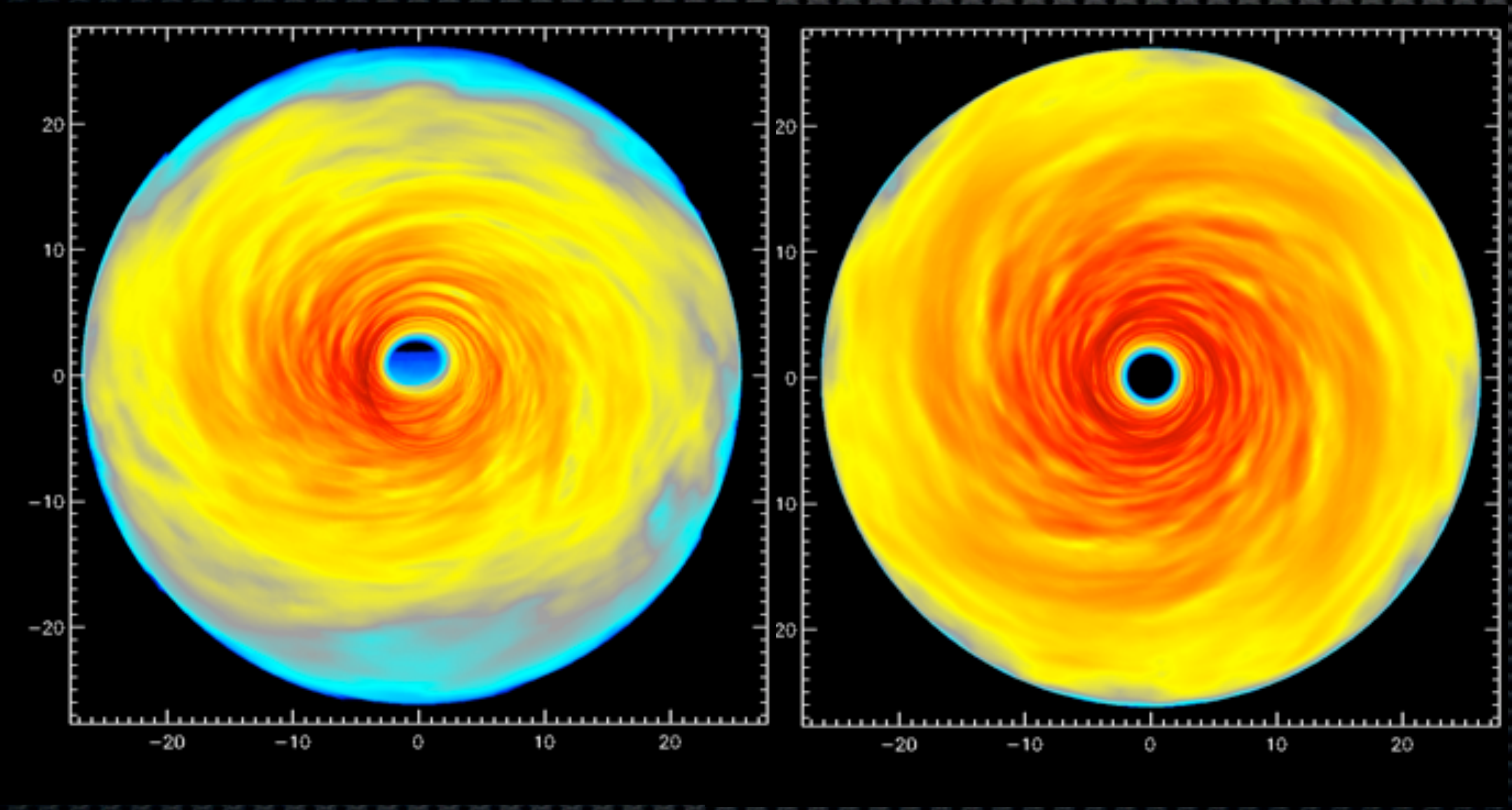
Schnittman et al 2006

Reynolds & Miller 2009

Markowitz et al 2003



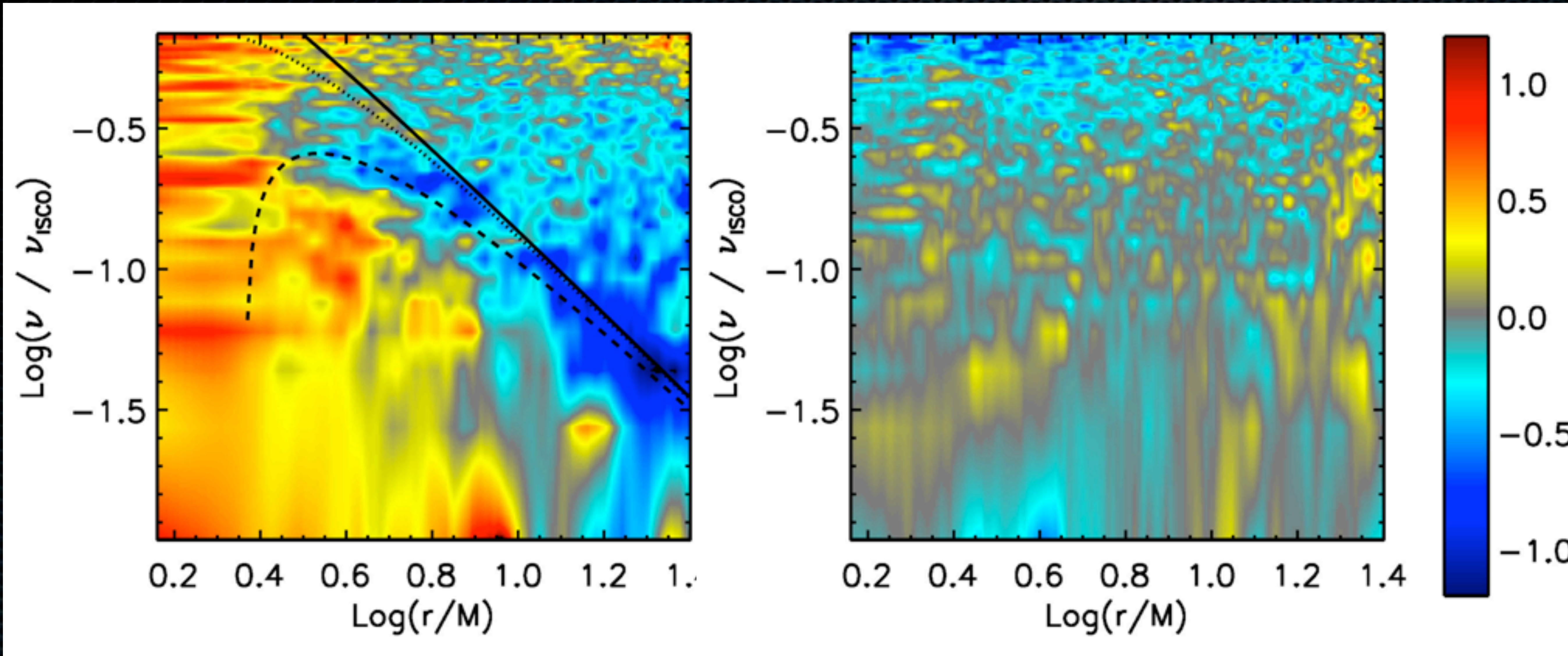
$$-3 < \alpha < -1 \qquad P \sim \nu^{\alpha}$$



$$i = 41^\circ \qquad \dot{m} = 0.003$$

SCN & Krolik 2009

- Use cooling rate in corona as emissivity
- Thomson Opacity (e- scattering)
- Integrate to photosphere
- Include finite light speed effect
- Parameterized by accretion rate and inclination

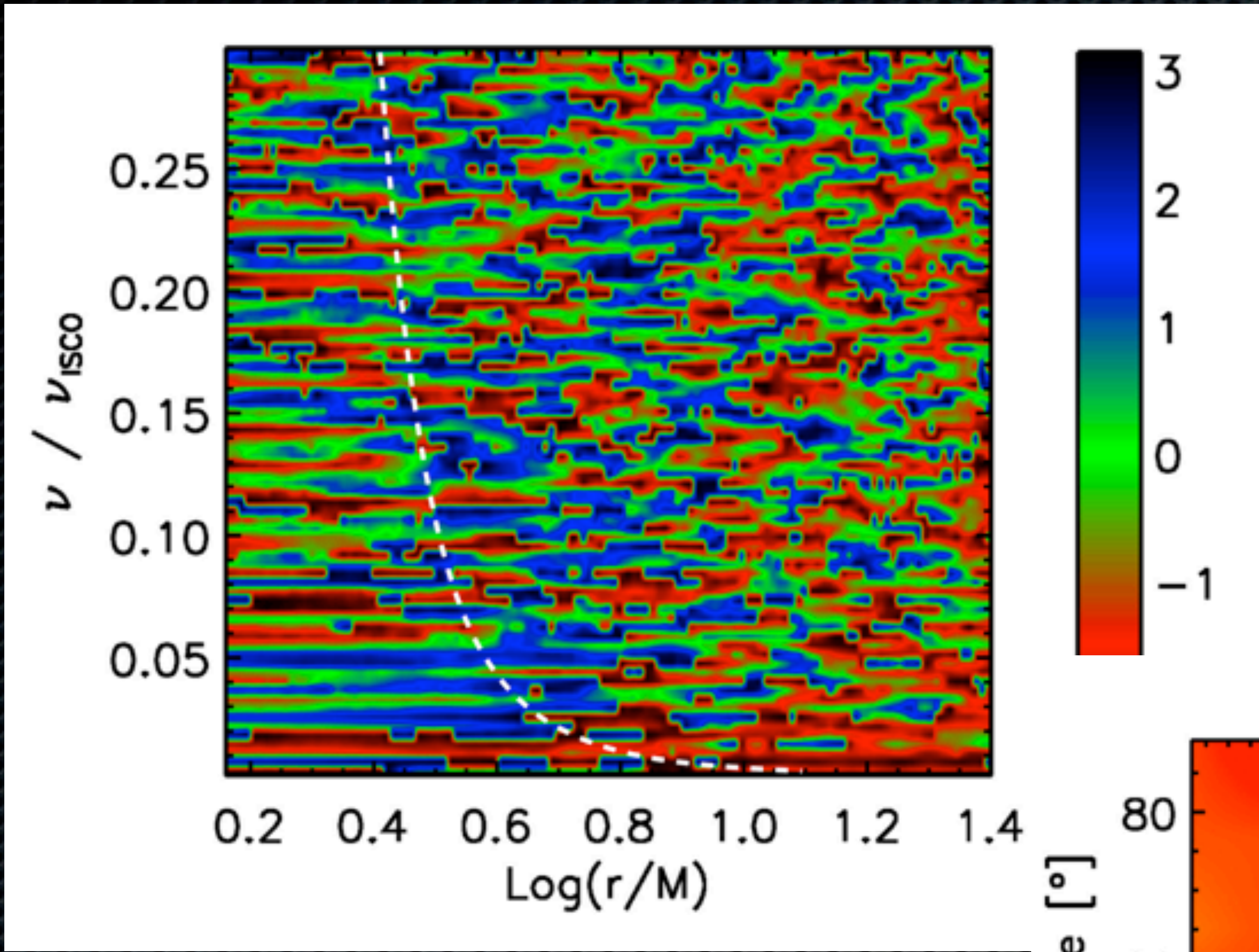


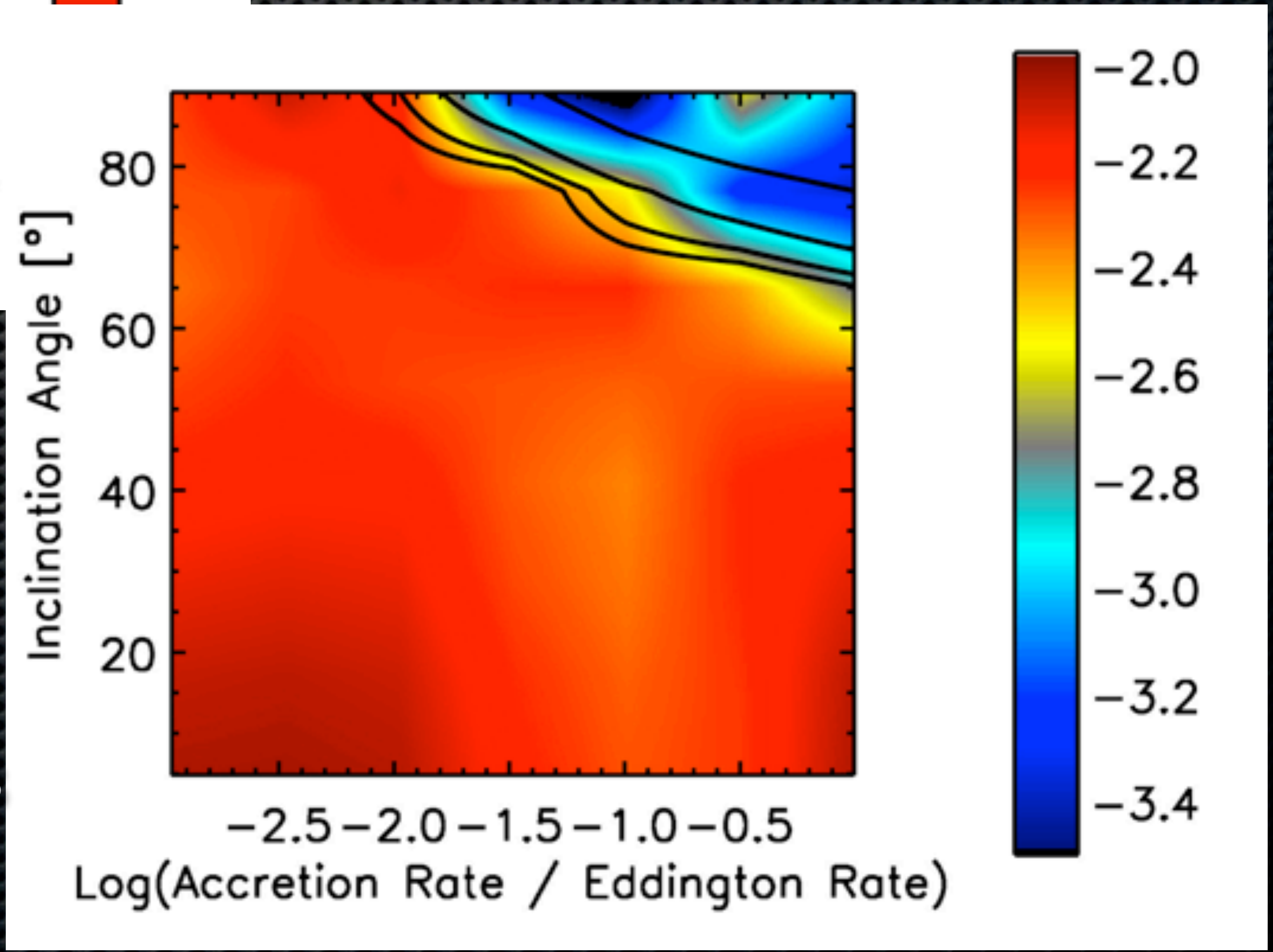
$$\frac{P_{\rm diss}(\nu, r)}{P_{\dot{\rm M}}(\nu, r)}$$

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

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

Phase Incoherence

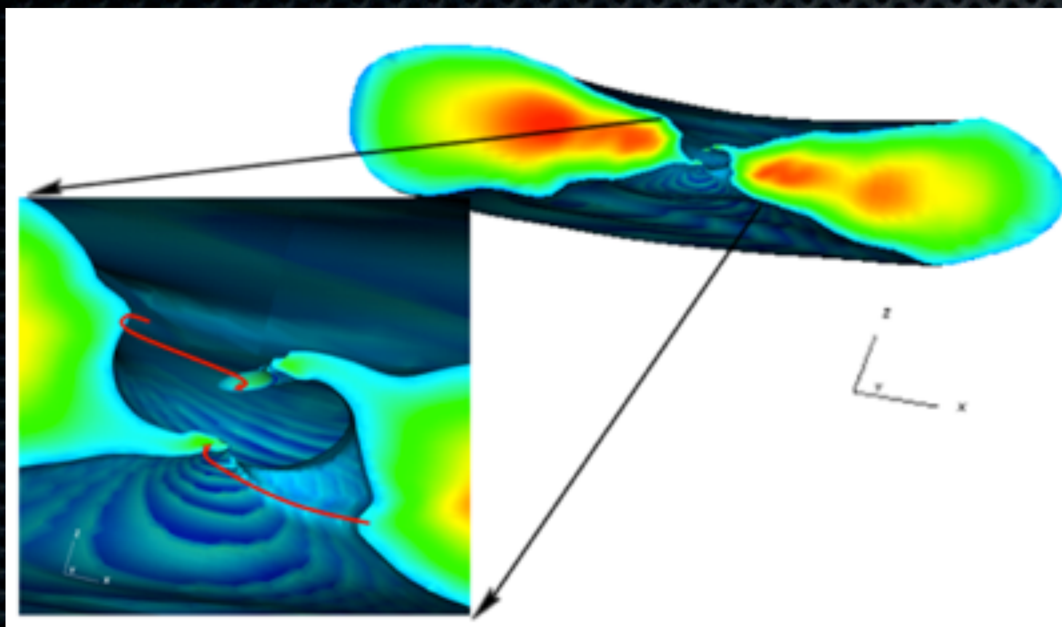




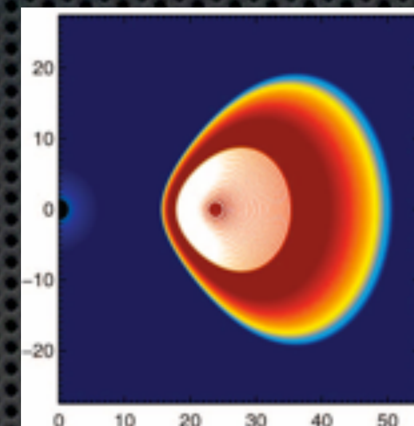
- Degenerate Result
- No inclination angle effect
- Consistent w/ Observations

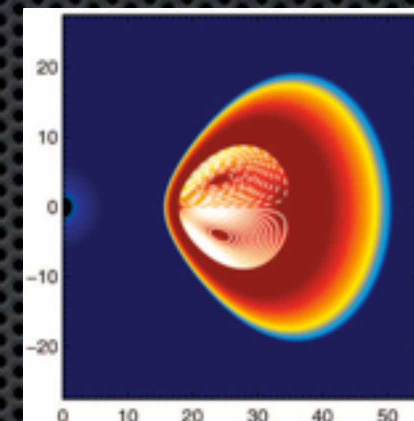
Out-standing Issues in UBH Accretion

Warped Disks Fragile et al. 2007-2009

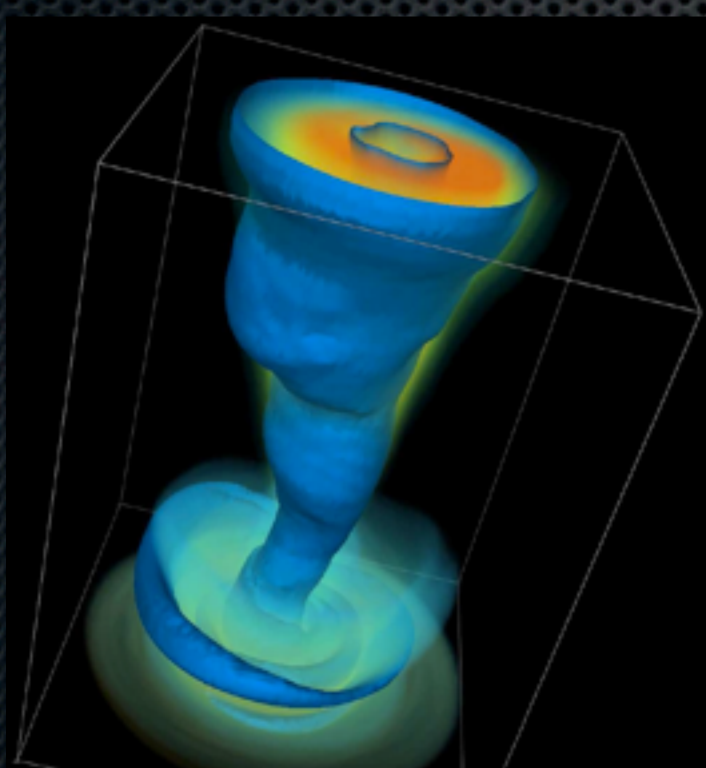


Initial Field Topology Beckwith et al. 2008



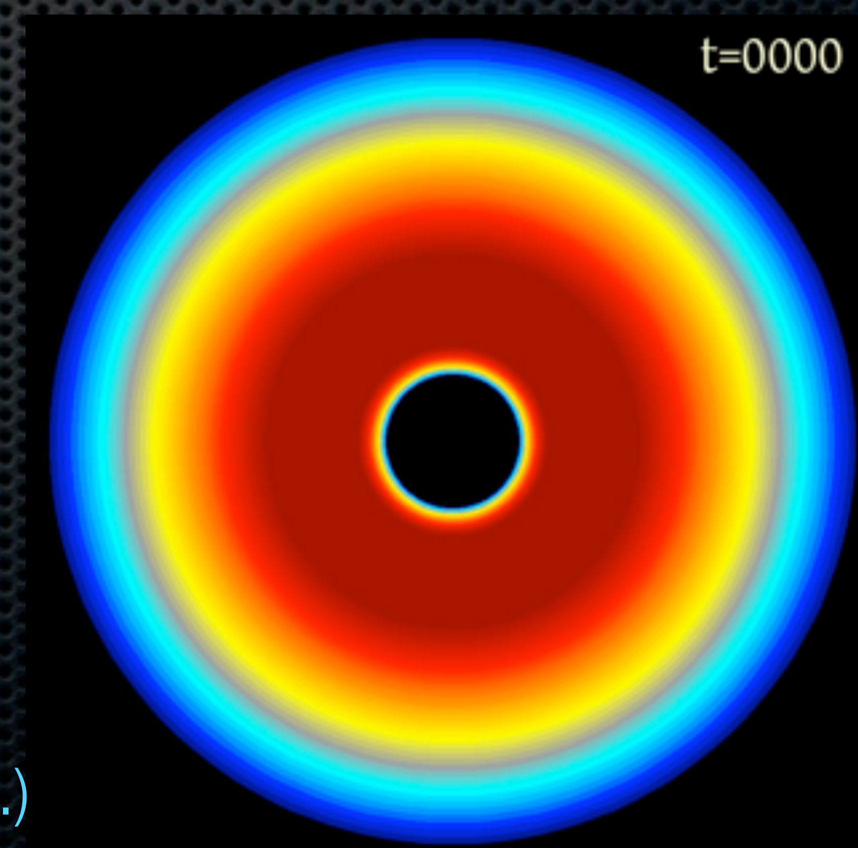


Poloidal	Quadrupolar	Toroidal
Jet	Jet	"No" Jet



McKinney & Blandford 2009

Full 2pi Evolutions
m=1 mode dominance



Gammie et al (unpub.)

Lessons Learned from UBHs

- MHD needed to describe anticipated turbulence
  - Spatio-temporal power spectrum of (EM) fluctuations
  - Leads to significant departures from hydro models
    - e.g. stress within the ISCO
    - Effect on gap location? More efficient accretion?
  - Be careful to resolve the MRI always!
  - Vast space of initial conditions?
- Accurate spectra/variability predictions require radiation transport, but we know how to do it!

What do I want for next Valentine's Day?

- Significant progress in 2009!
  - BBH + [Particles, EM waves, Gas, Bondi]
- Just beginning:
  - Accretion with finite angular momentum
  - MHD
  - Ray-tracing (at least) in dynamical spacetimes
  - Cooling (see Fragile & Meier 2009)
  - Everything above with more mass ratios!!
    - 1:1 may result in an artificially symmetric flow pattern
  - Better initial conditions: "bridge gap" between pre-merger and merger
    - e.g., steady-state disk setup ~100 orbits before merger (~ Farris et al. 2009)

Future is bright for BBH simulations!

Extra Slides

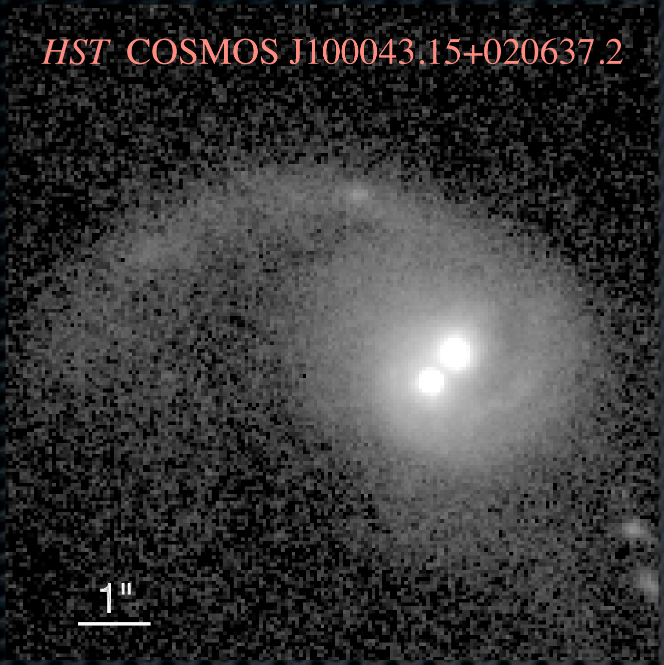
Super kpc Dual Nuclei

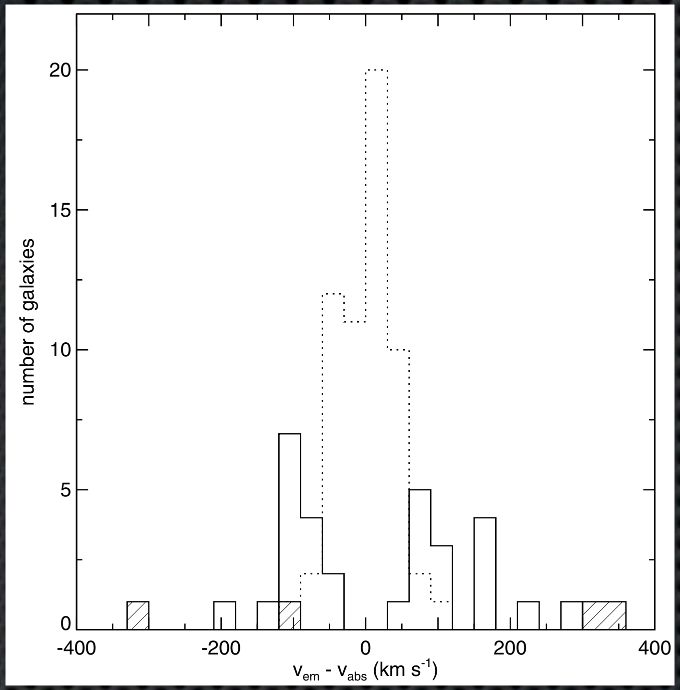
Comerford et al. 2009 x2

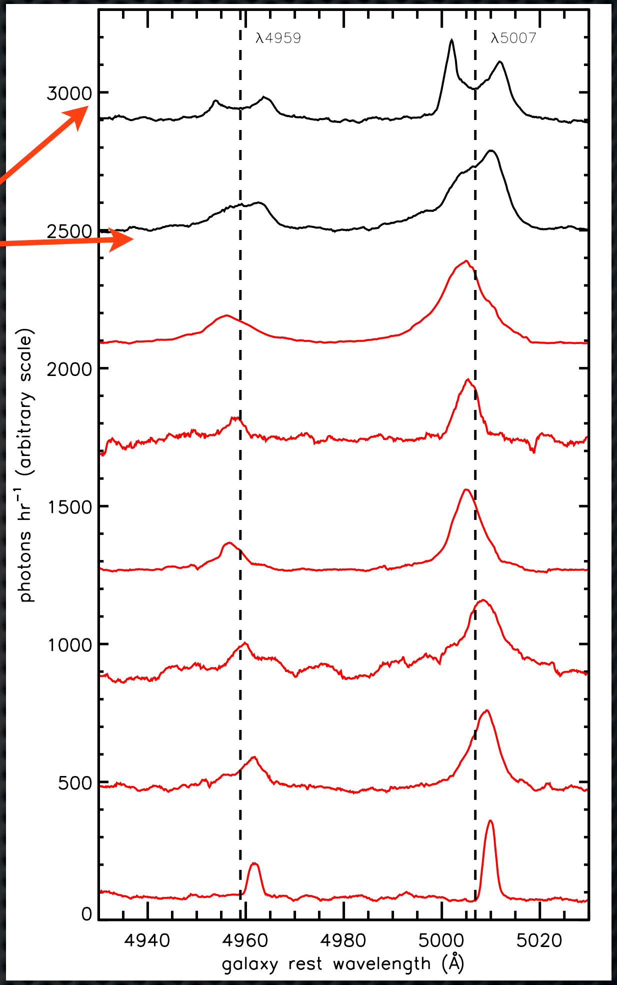
DEEP2 Survey
91 AGN: [OIII], HB selected (Seyfert 2)
32 have shifted [OIII] from host
2 have double peaked lines --> “dual” AGN

COSMOS Survey

$d = 1.7\text{kpc}$





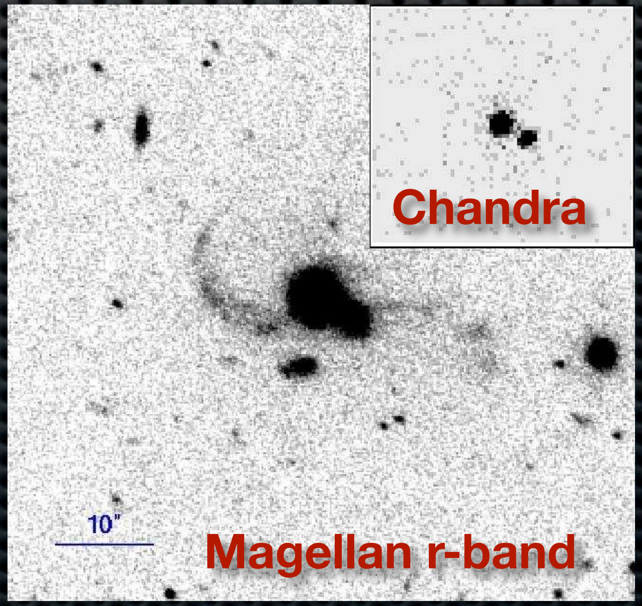


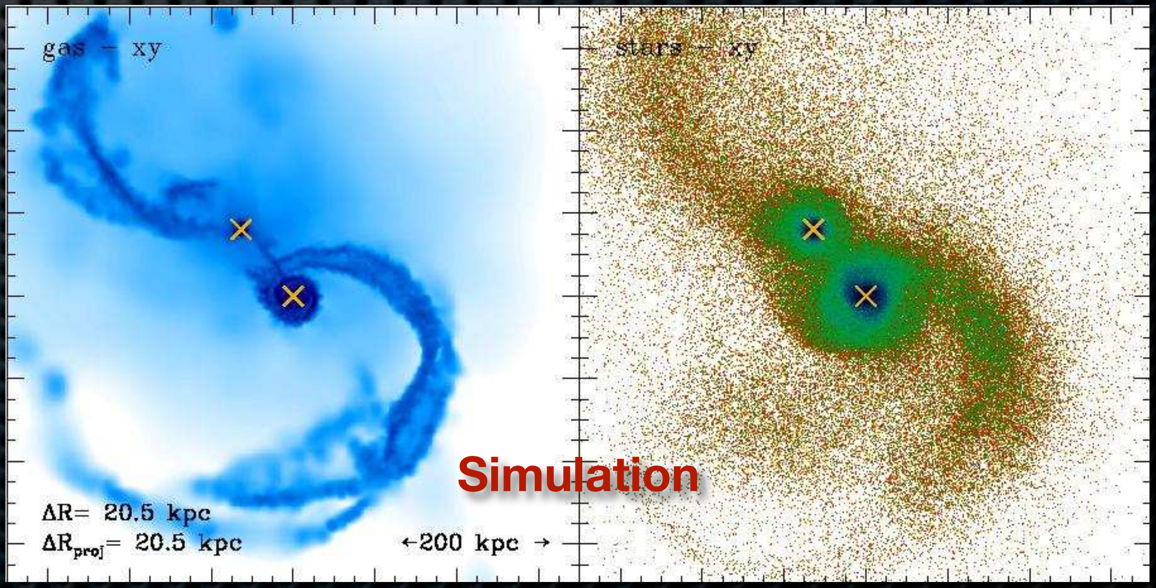
First Spatially Resolved Binary Quasar : SDSS J1254+0846

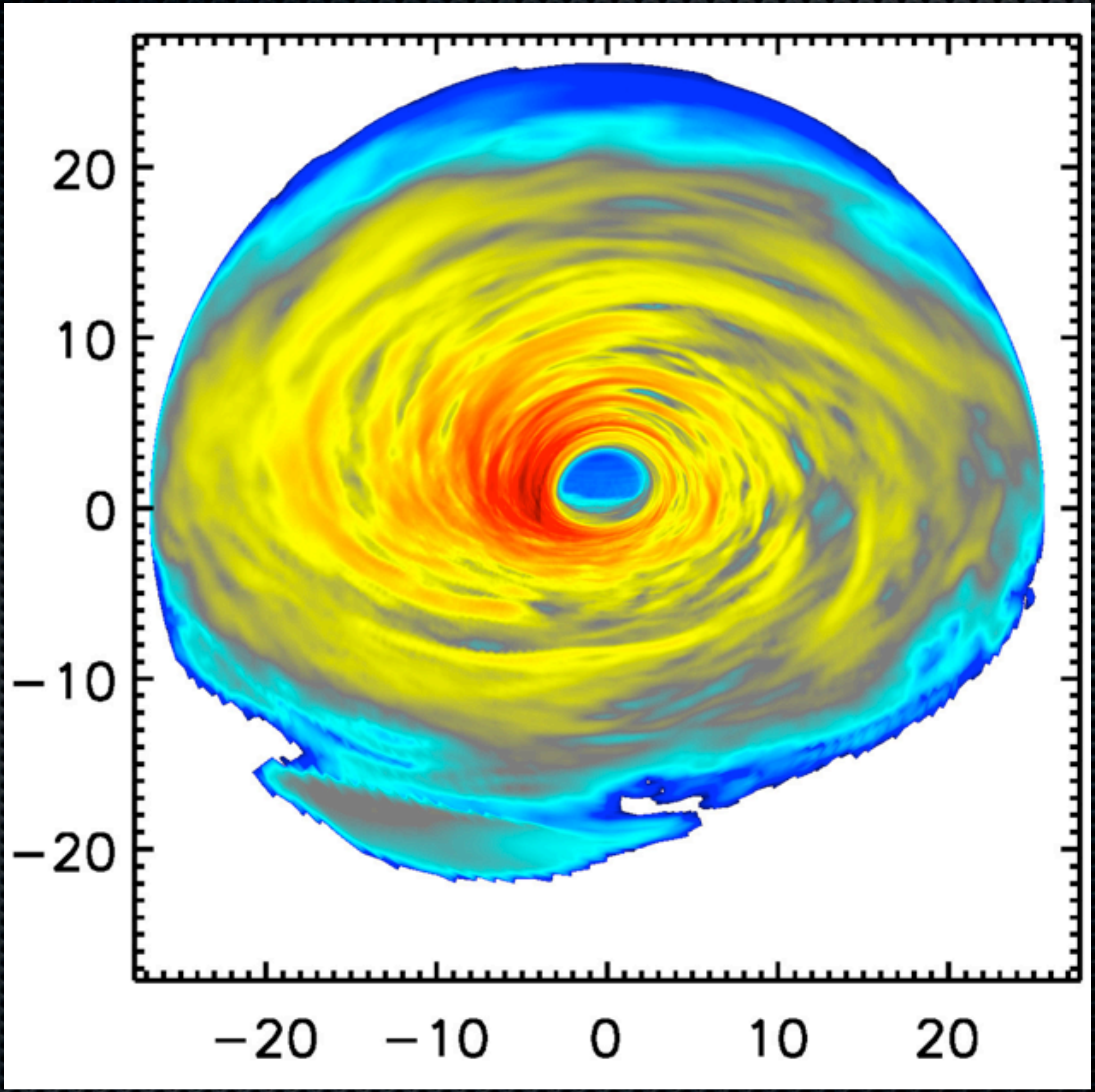
Green et al. arxiv1001.1738

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

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



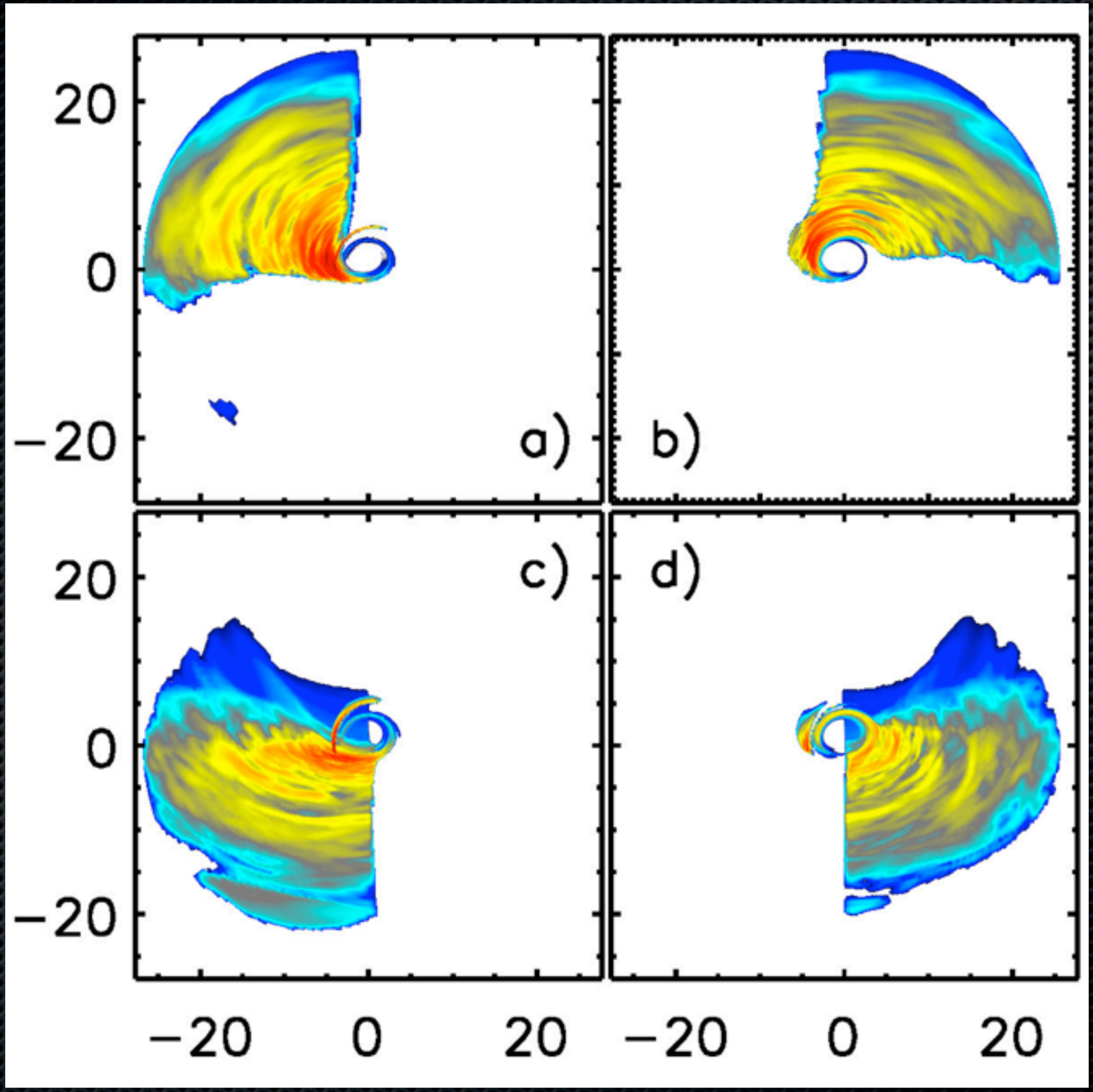



20
10
0
−10
−20
−20
−10
0
10
20

Degeneracy Explanation

$\alpha_a > -2$

$\alpha_b > -2$



$\alpha_c < -2$

$\alpha_d < -2$

$i \sim 0°$

$\alpha_i \simeq -2$