Towards a First Principles Understanding of Black Hole Variability

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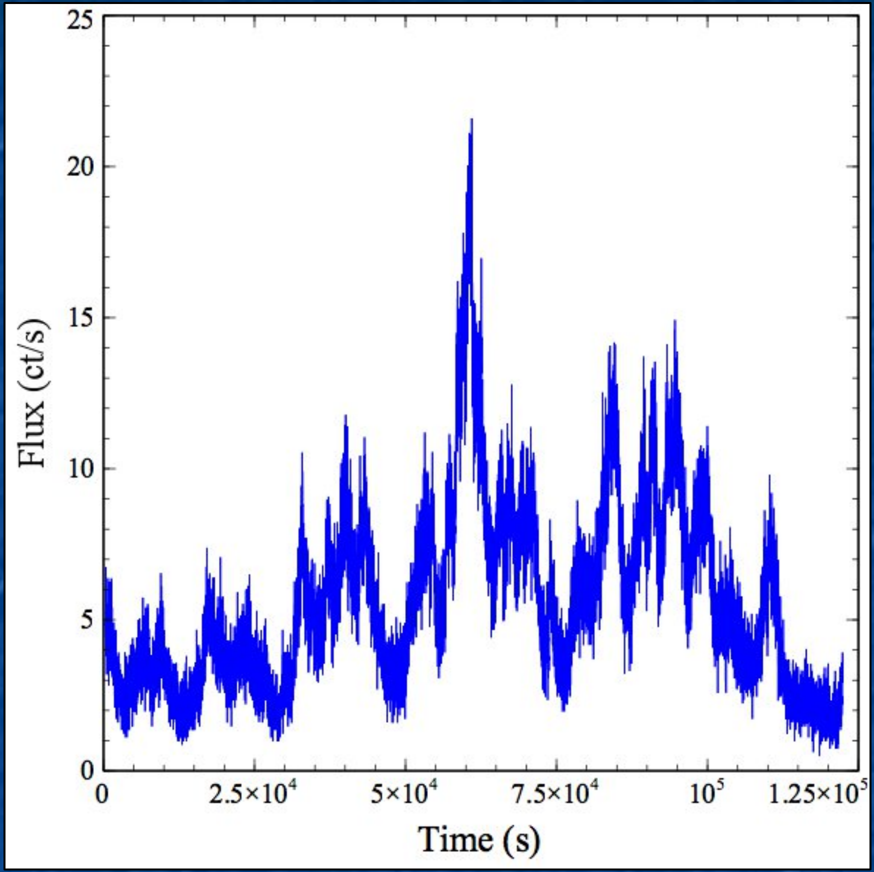
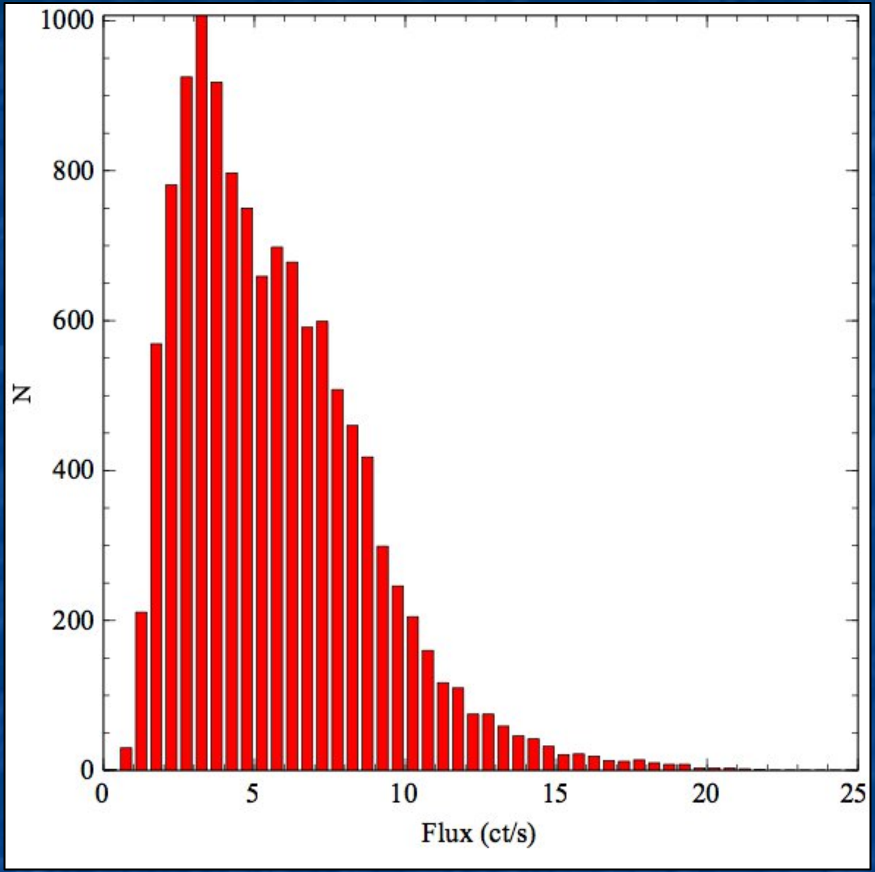
Outline

- The structure of the aperiodic "noise"
  - Propagating fluctuation model
  - Role of dynamo processes
- State transitions
  - The thin-disk/RIAF paradigm
  - First look at structure of truncated disks
- Goal : Use of variability as probe of the underlying accretion physics

I : Rapid aperiodic variability

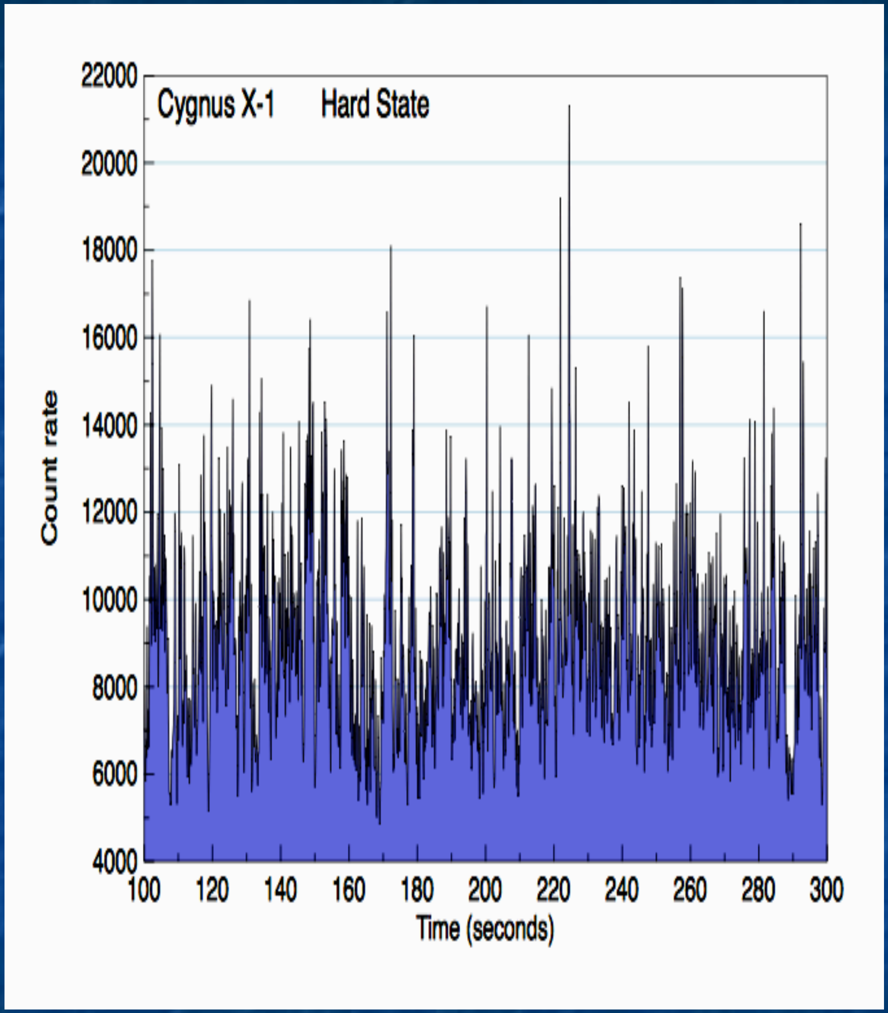
Seyfert galaxy 1H0707-495 (XMM-Newton)



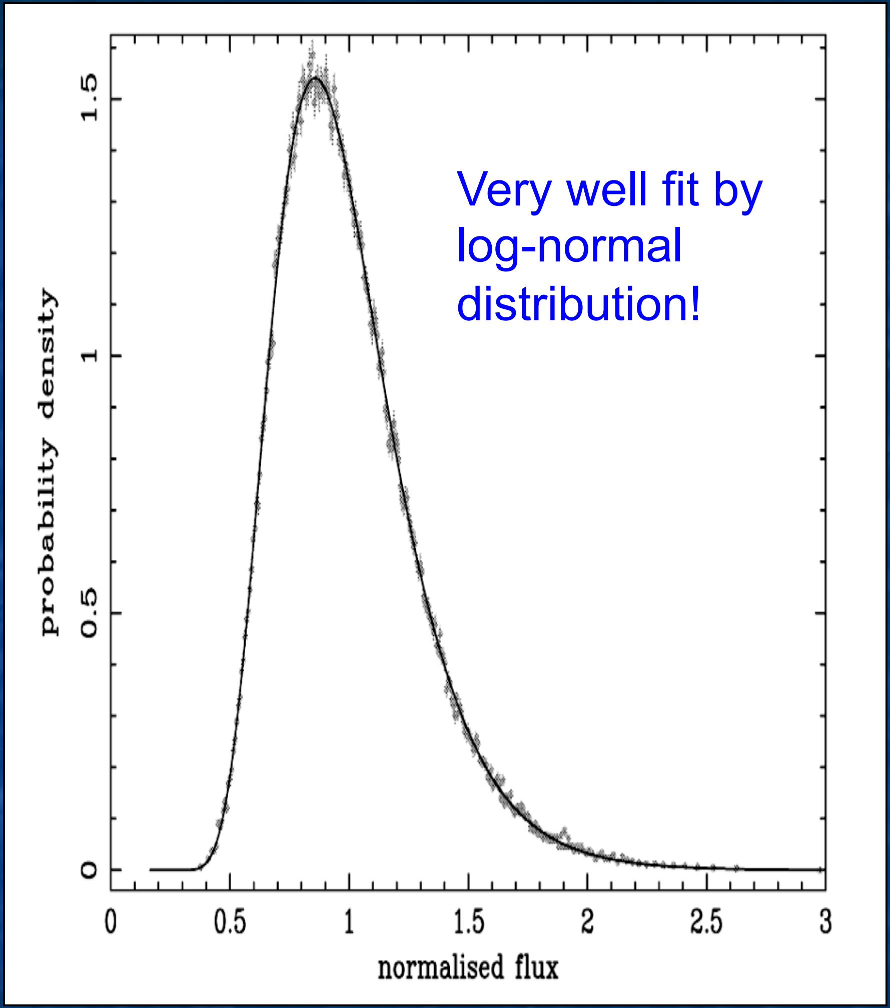


Light curve is “flary”… distribution function of flux measurements skewed to the high end

Cygnus X-1 (RXTE)



Belloni et al. (2010)



Uttley, McHardy & Vaughan (2005)

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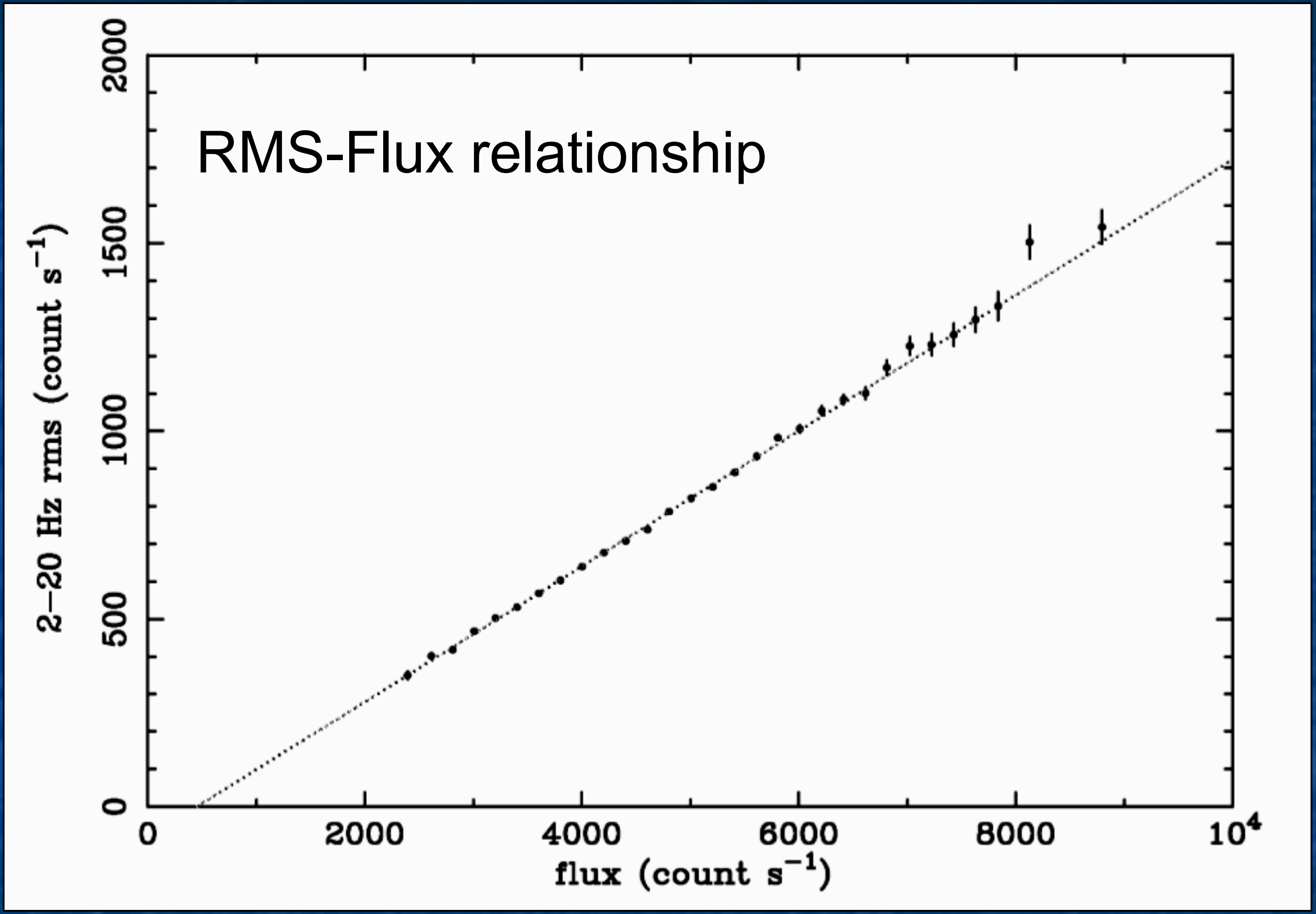

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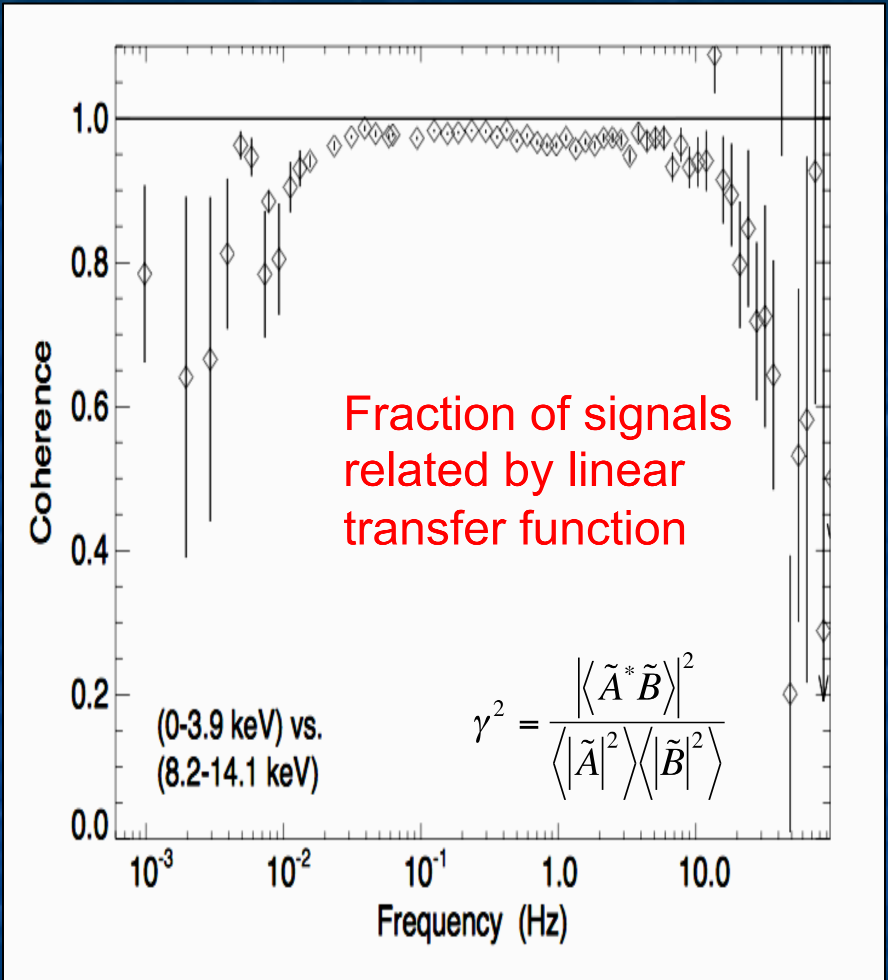
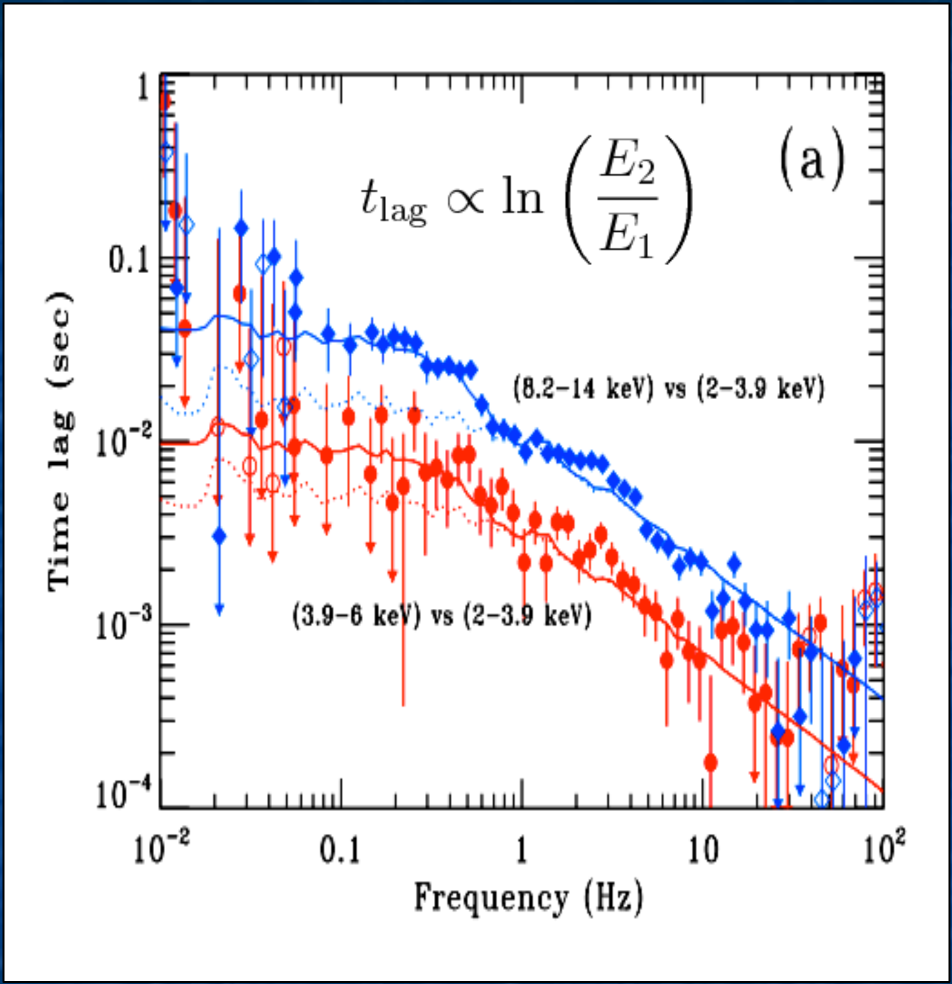
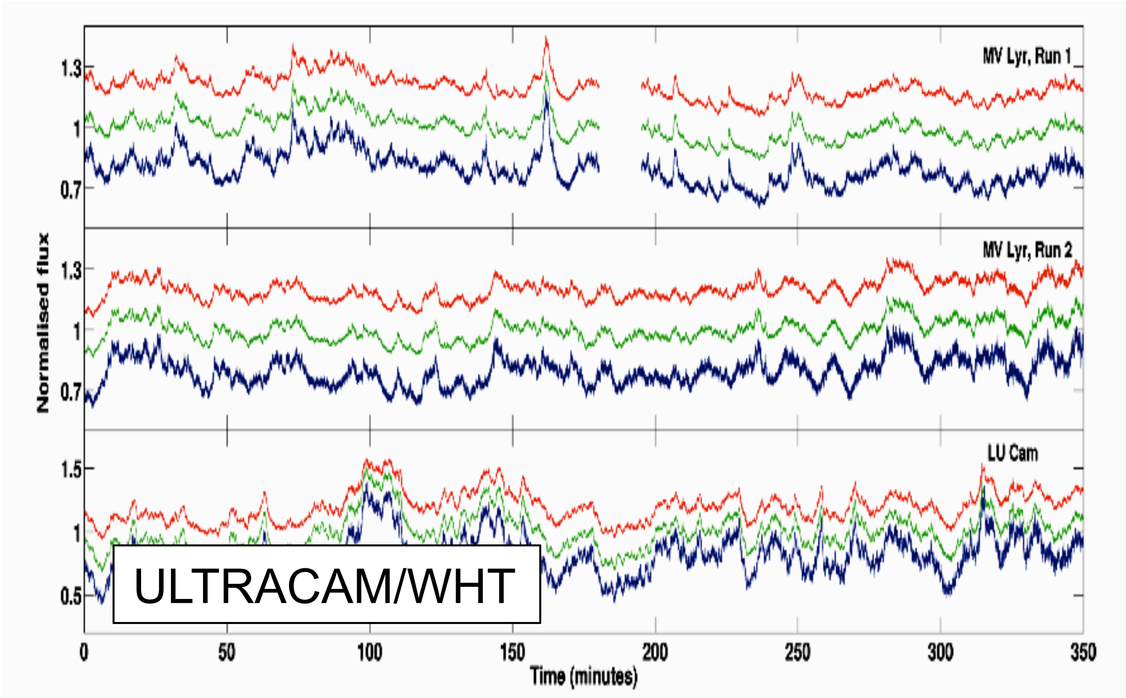
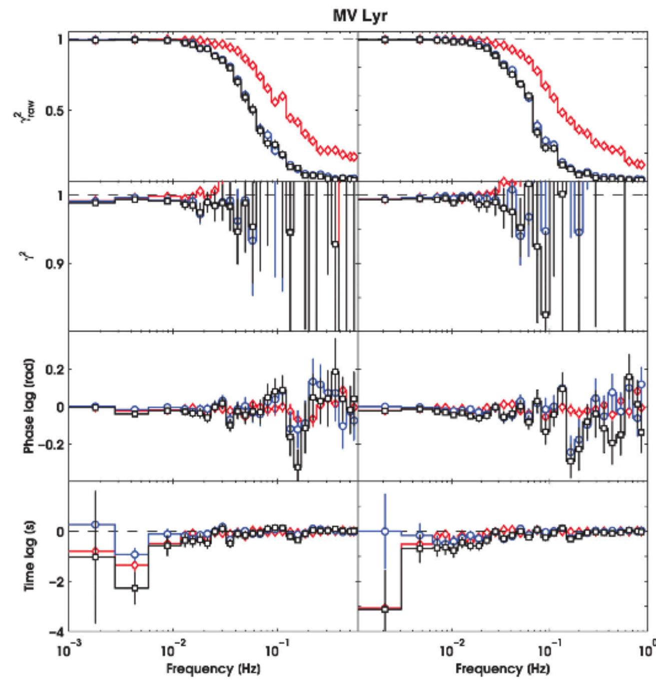




Nowak et al. (1999)

Poutanen (2001)

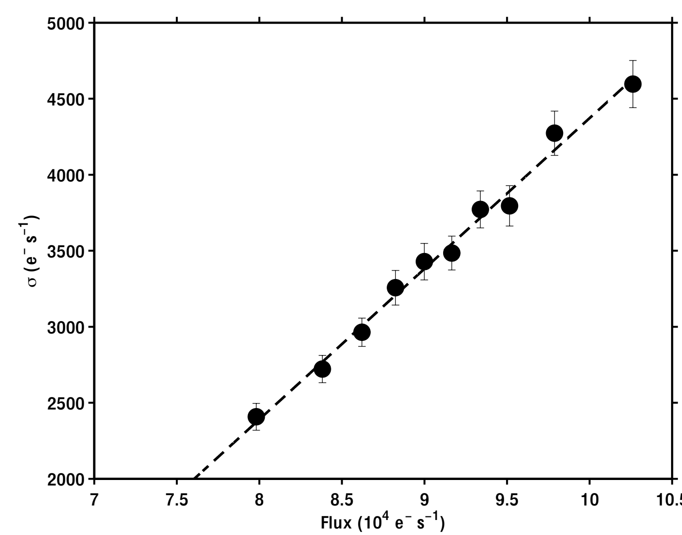




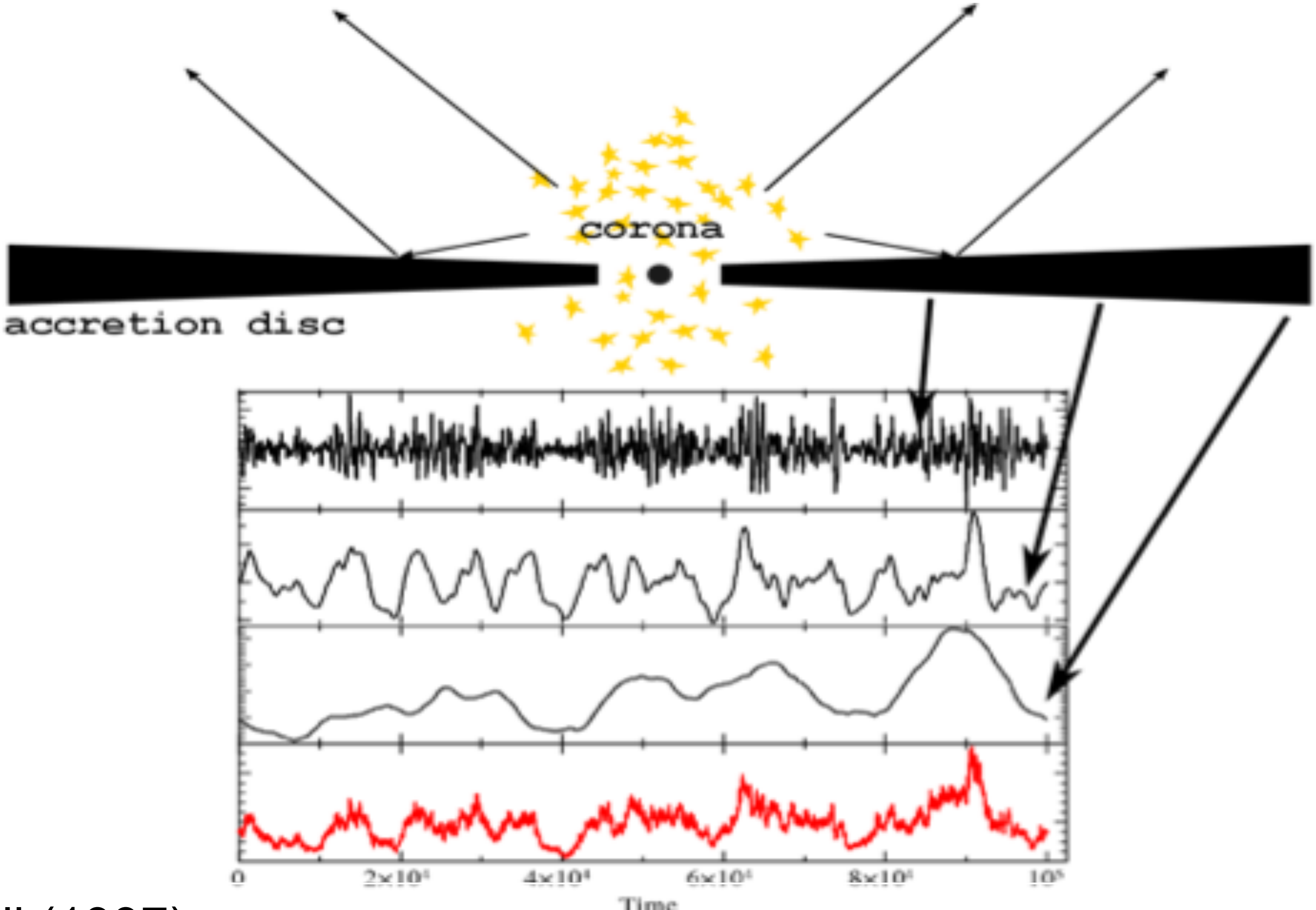
White dwarfs do it too!

Also show rms-flux relation and frequency-dependent time-lags

(Scaringi et al. 2013)



Propagating fluctuations model : Inward propagating multiplicative fluctuations caused by stochasticity in the angular momentum transport mechanism



Lyubarskii (1997);
Kotov, Churazov & Gilfanov (2001);
Uttley, McHardy & Vaughan (2005)

1d viscous disk model with stochastic viscosity

Lyubarskii (1997) linearized problem ➔ got rid of behavior we seek!

Cowperthwaite & Reynolds (2015):
Integrate non-linear disk evolution equation for surface density Σ:

$$\frac{\partial \Sigma}{\partial t} = \frac{3}{R}\frac{\partial}{\partial R}\left[R^{1/2}\frac{\partial}{\partial R}(\nu \Sigma R^{1/2})\right], \qquad \text{(Pringle 1981)}$$

Treat viscosity as stochastic parameter with characteristic frequency ω_0 (mimicking turbulent fluctuations):

$$\nu = \nu_0(1 + \beta)$$

$$d\beta(t) = -\omega_0(\beta(t) - \mu)dt + \xi dW(t)$$

driving frequency

mean (=0)

Normalized Gaussian white noise

1d viscous disk model with stochastic viscosity

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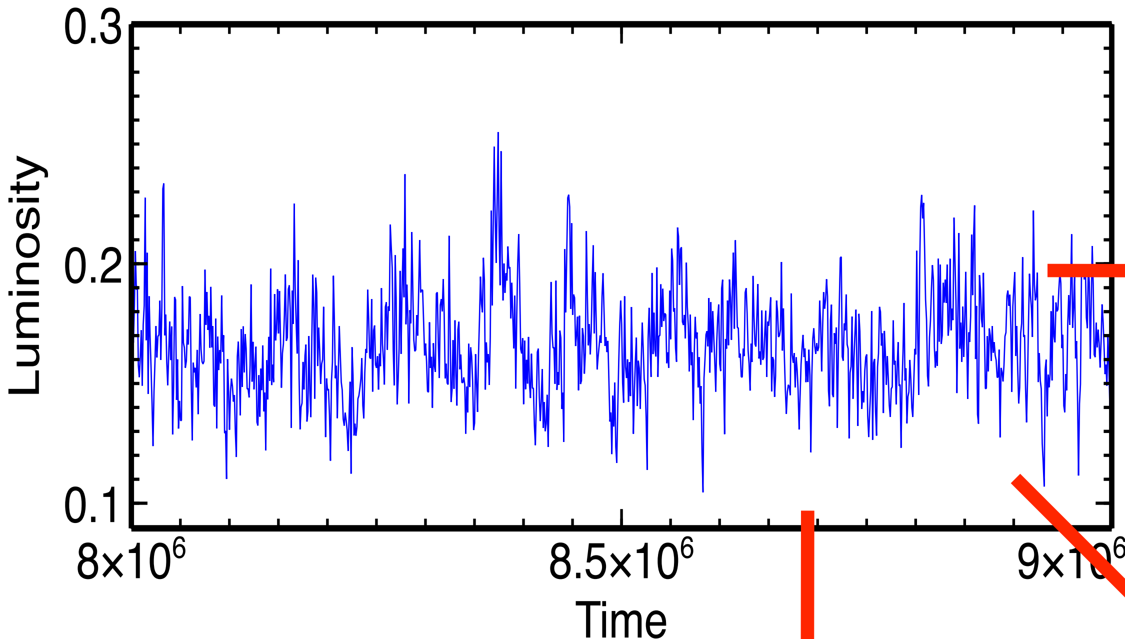
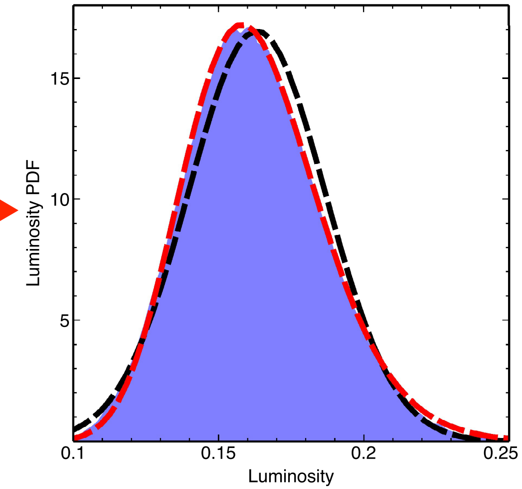
$$d\beta(t) = -\omega_0(\beta(t) - \mu)dt + \xi dW(t)$$

Findings:

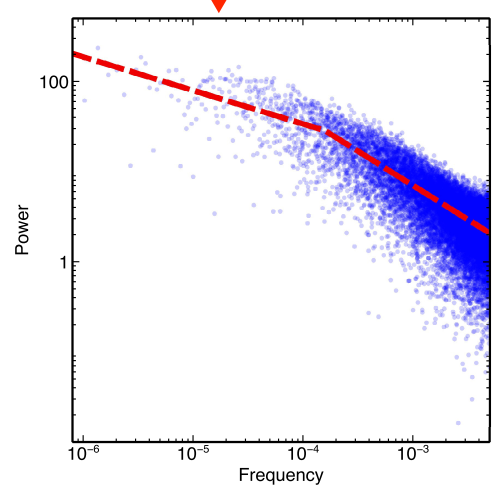
- If fluctuations are slow enough, then recover log-normal light curve, rms-flux relationship, coherence/lags between radii
- But, dynamical timescale fluctuations are too fast… no coherent propagation and no non-linearity in the light curve!

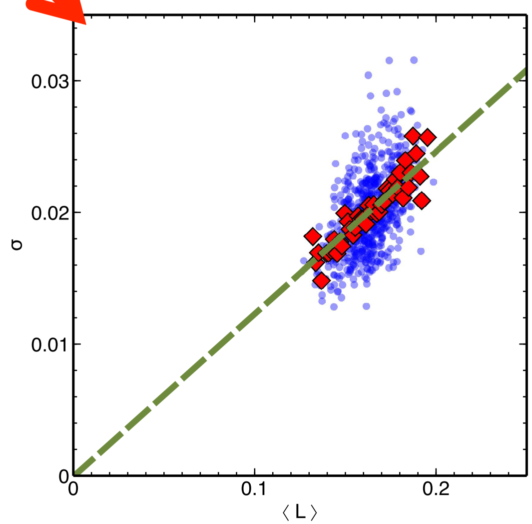
Cowperthwaite & Reynolds (2015)





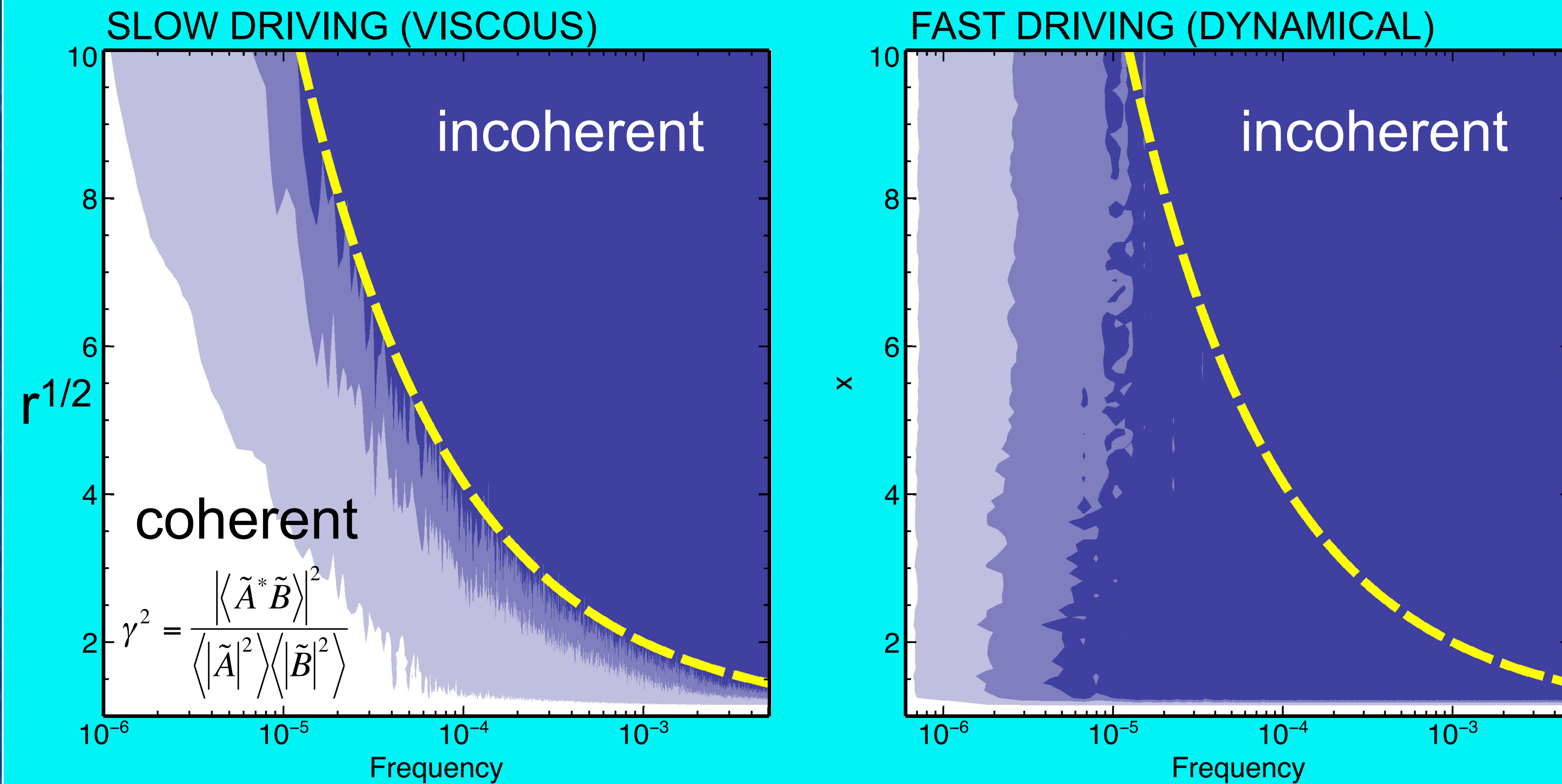
SLOW DRIVING (VISCOUS TIMESCALE)





COHERENCE FUNCTIONS

Cowperthwaite & Reynolds (2015)



Radii are coherent on timescales longer than viscous timescale

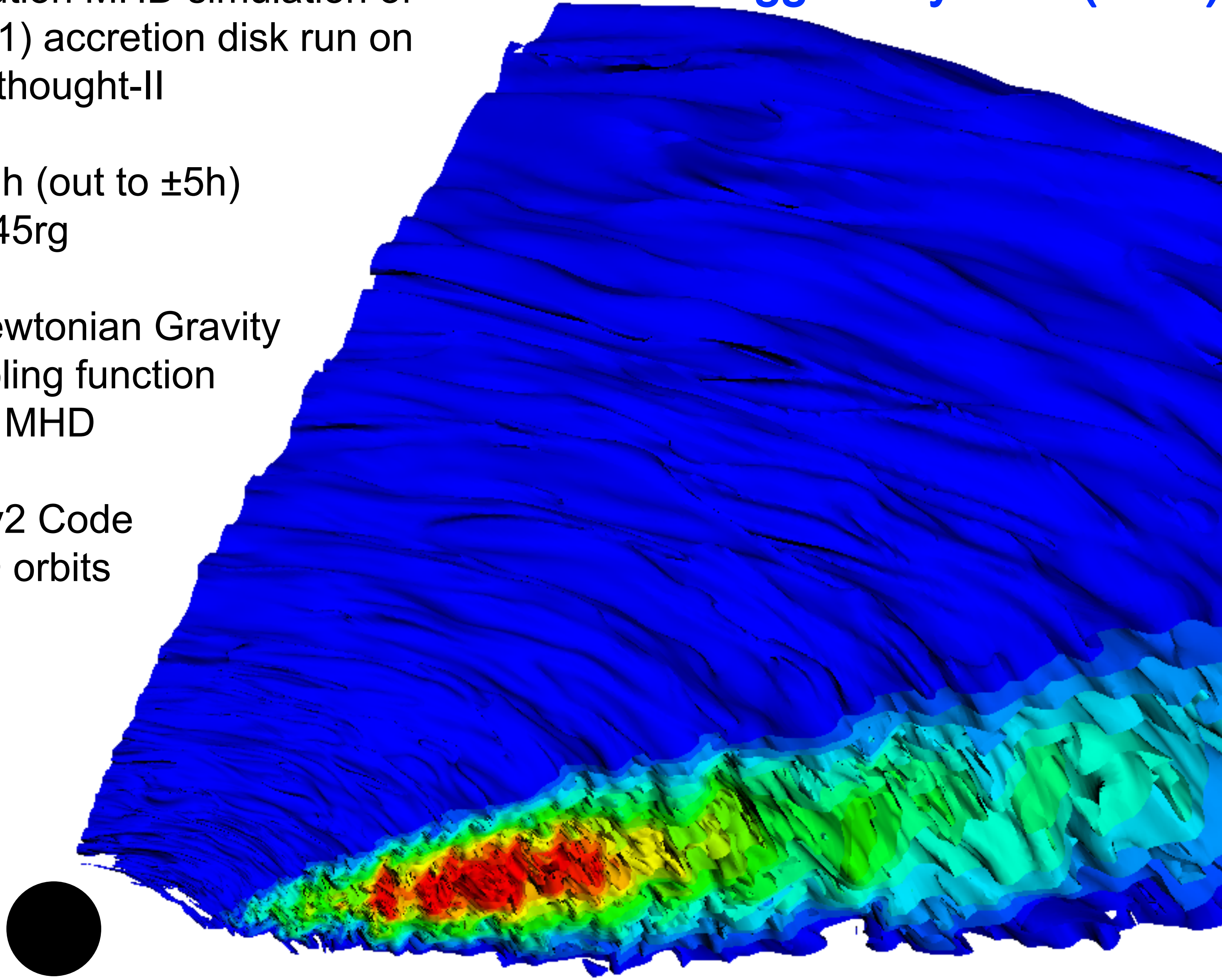
Hogg & Reynolds (2016)

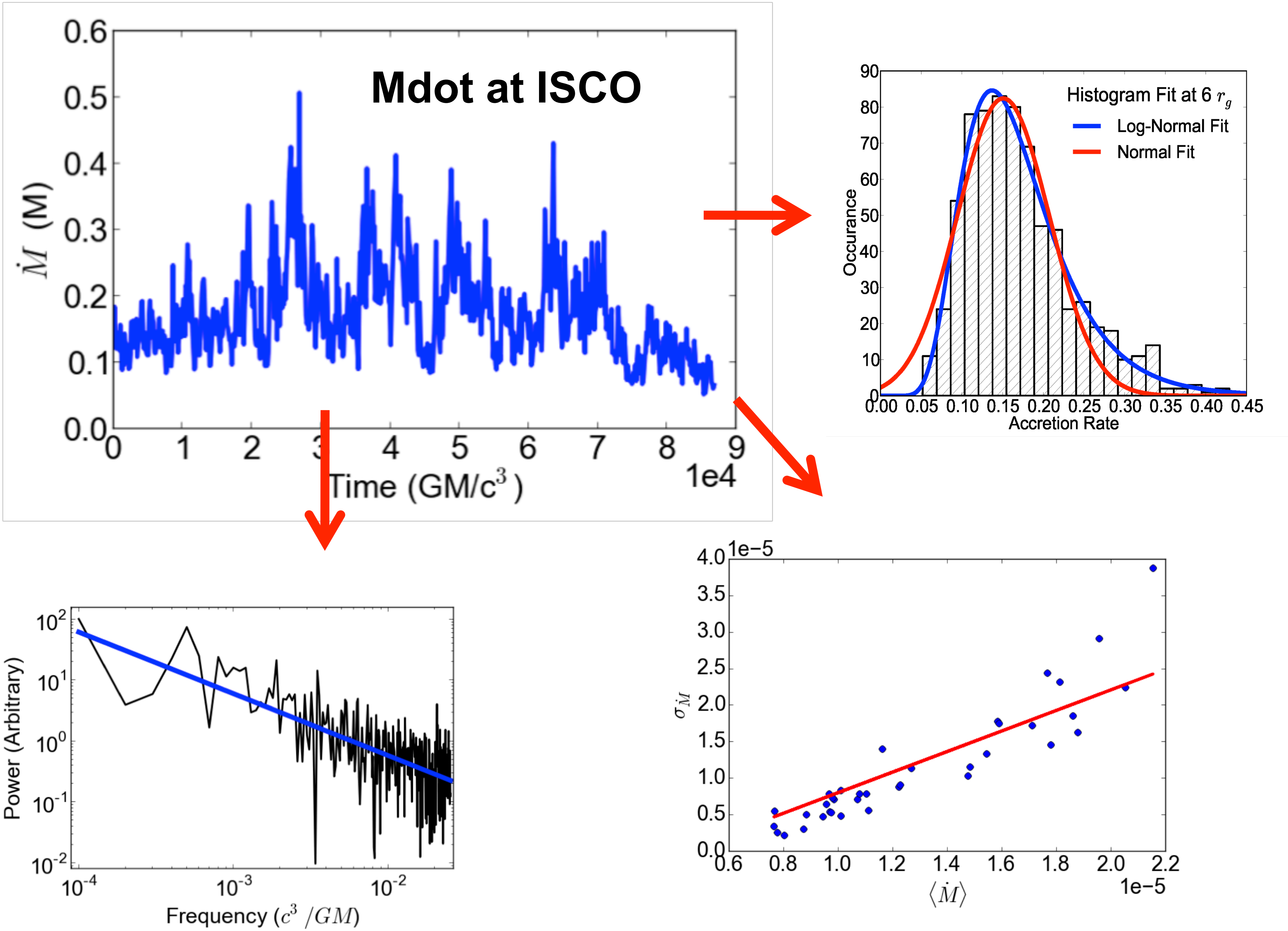
High-resolution MHD simulation of thin (h/r=0.1) accretion disk run on UMd Deepthought-II

30-zones / h (out to ±5h)
R : 4rg➔145rg

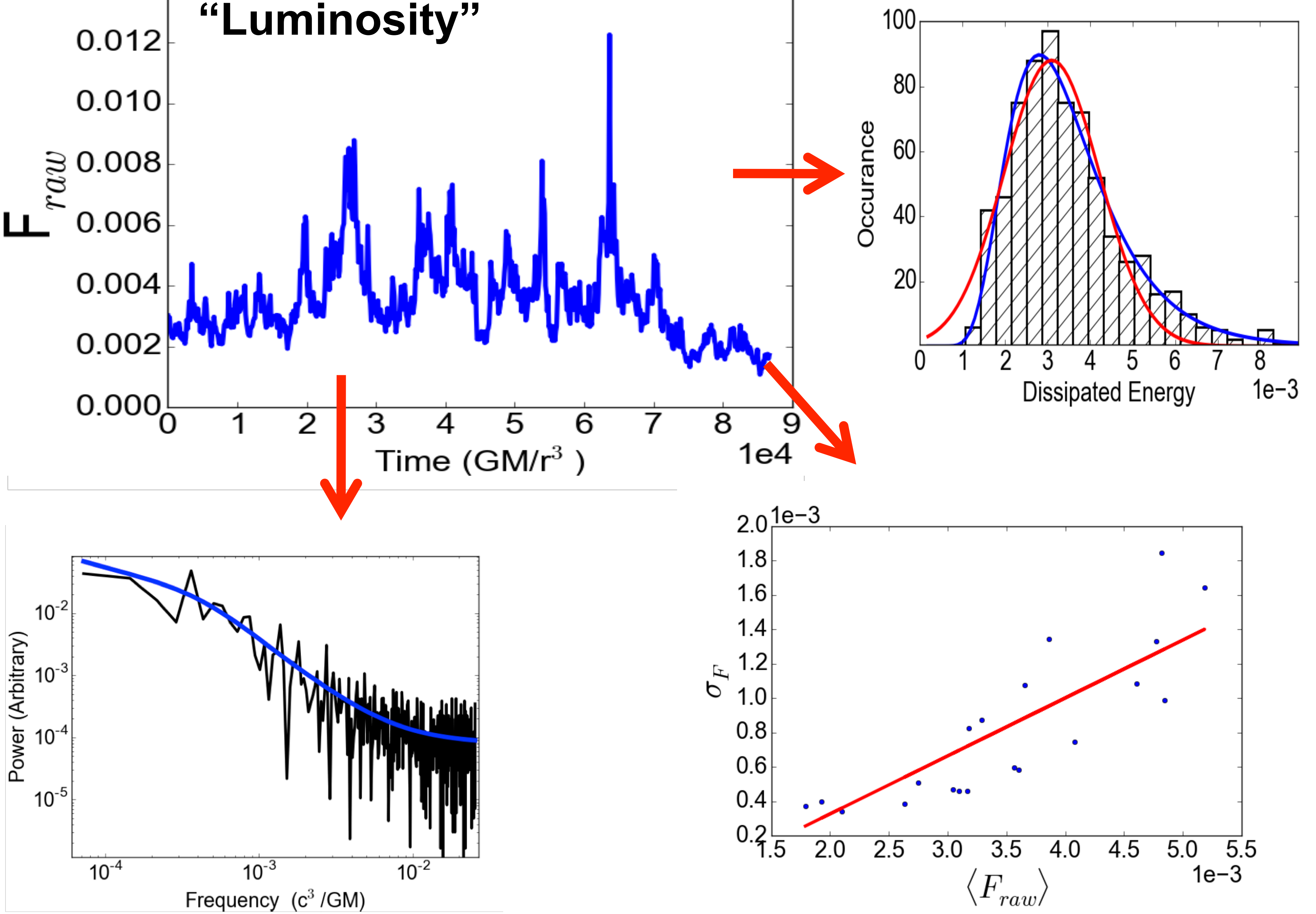
Pseudo-Newtonian Gravity
Simple cooling function
Newtonian MHD

ZEUS-MPv2 Code
2000 ISCO orbits

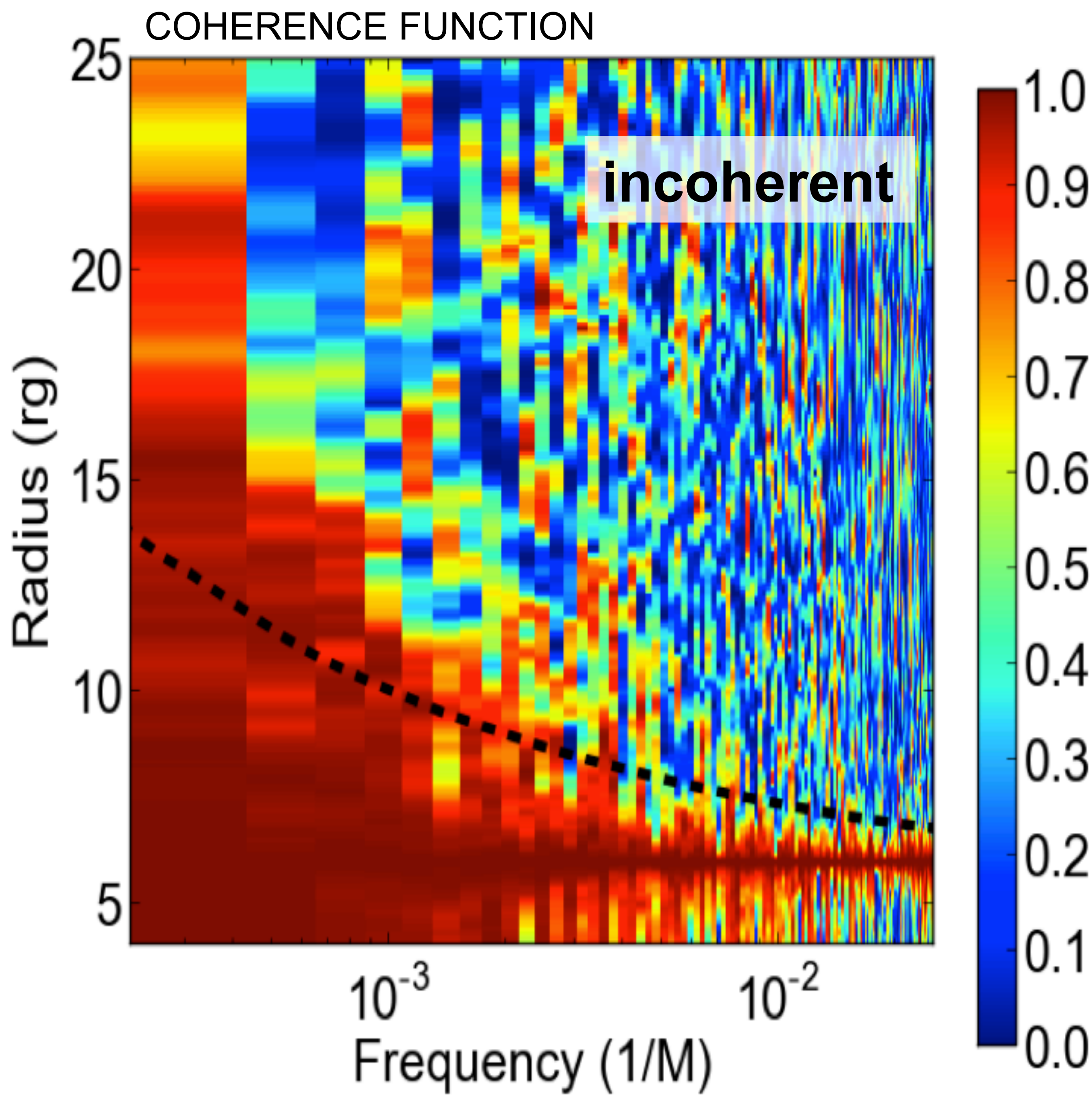



Mdot at ISCO
$\dot{M}$ (M)
Time (GM/c^3)
1e4
Histogram Fit at 6 r_g
Log-Normal Fit
Normal Fit
Occurance
Accretion Rate
Power (Arbitrary)
Frequency (c^3 /GM)
1e−5
$\sigma_{\dot{M}}$
$\langle \dot{M} \rangle$
1e−5

Hogg & Reynolds (2016)



Hogg & Reynolds (2016)



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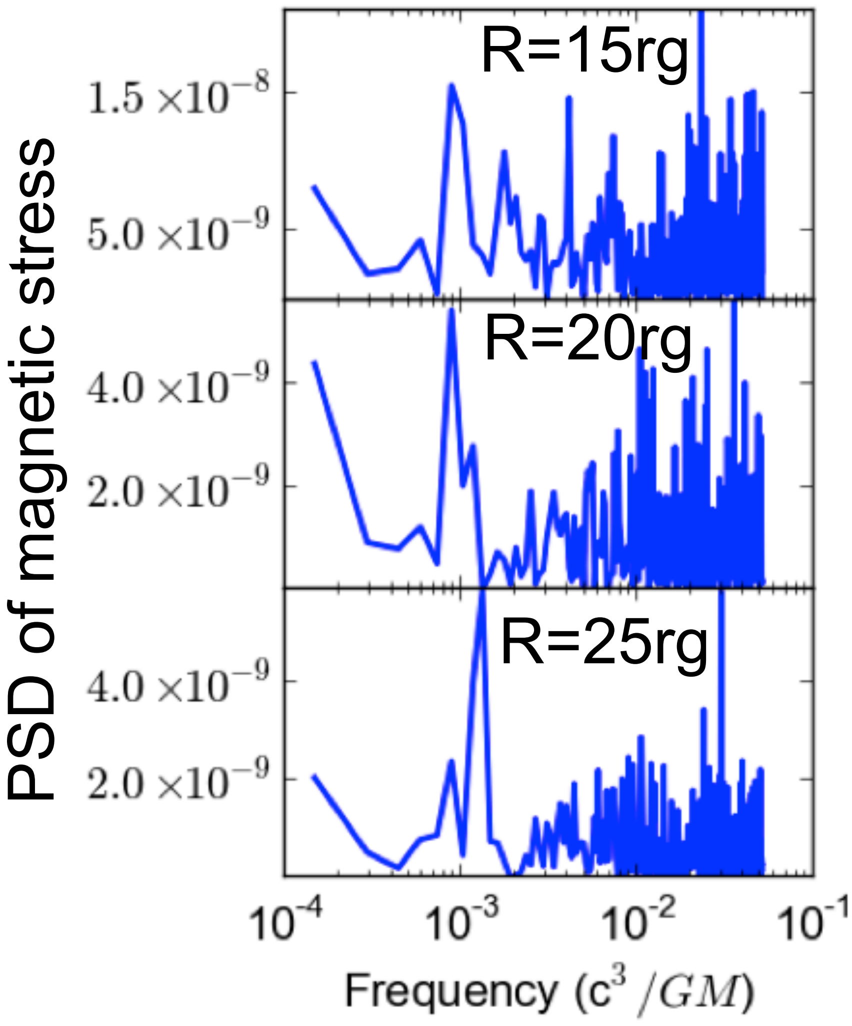
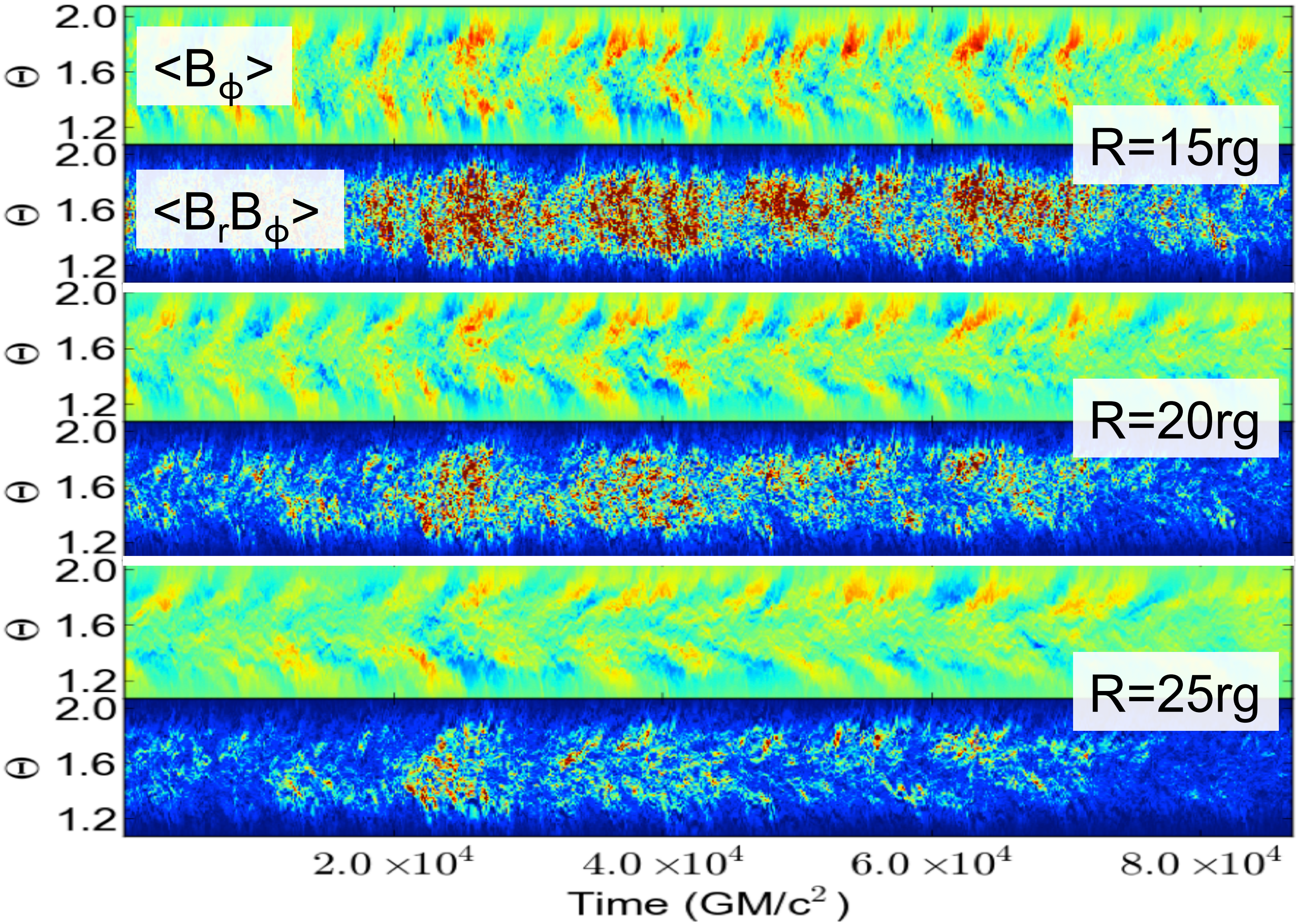


Hogg & Reynolds (2016)



Take home message & WAGs

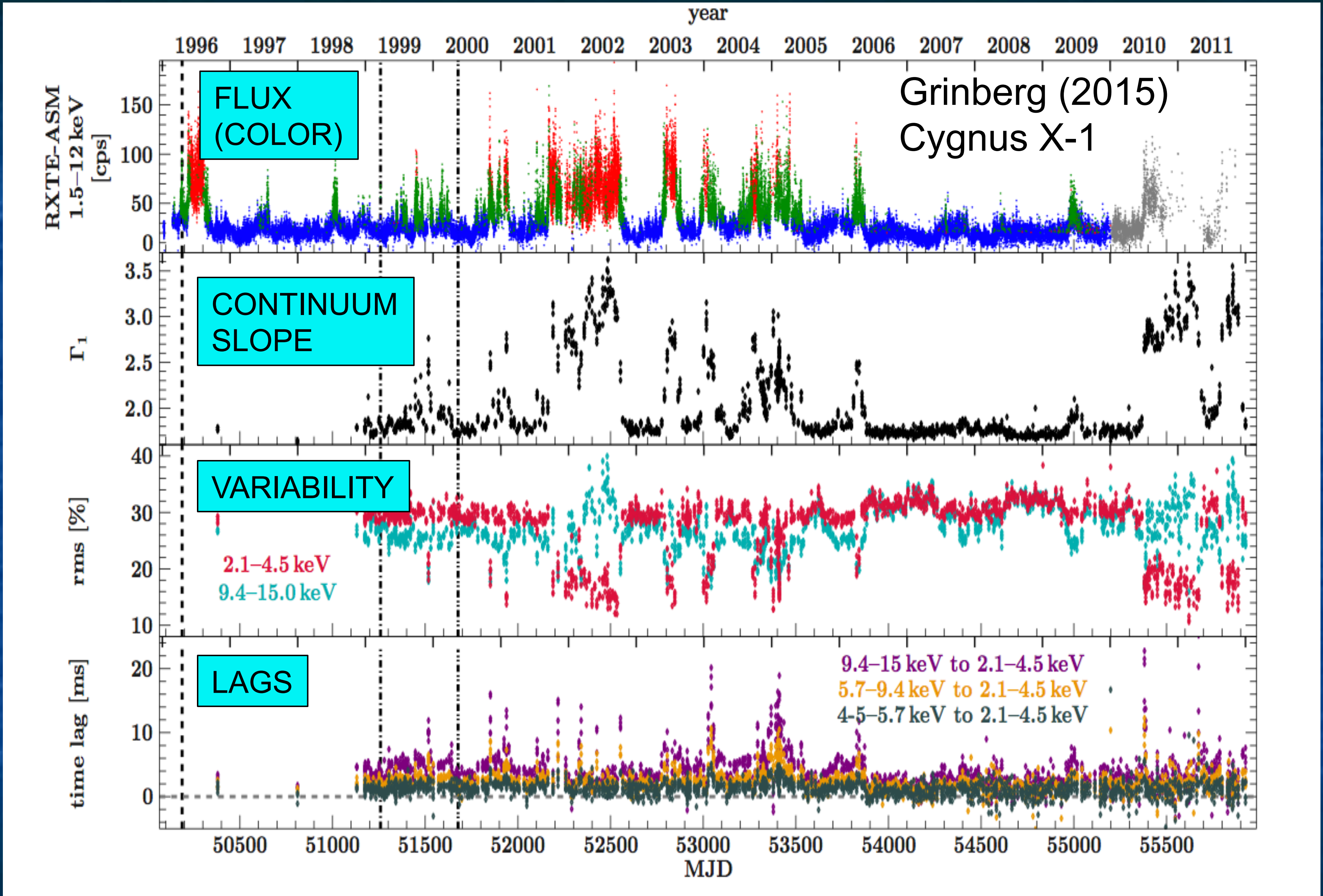
DYNAMO CYCLES → NON-LINEAR VARIABILITY

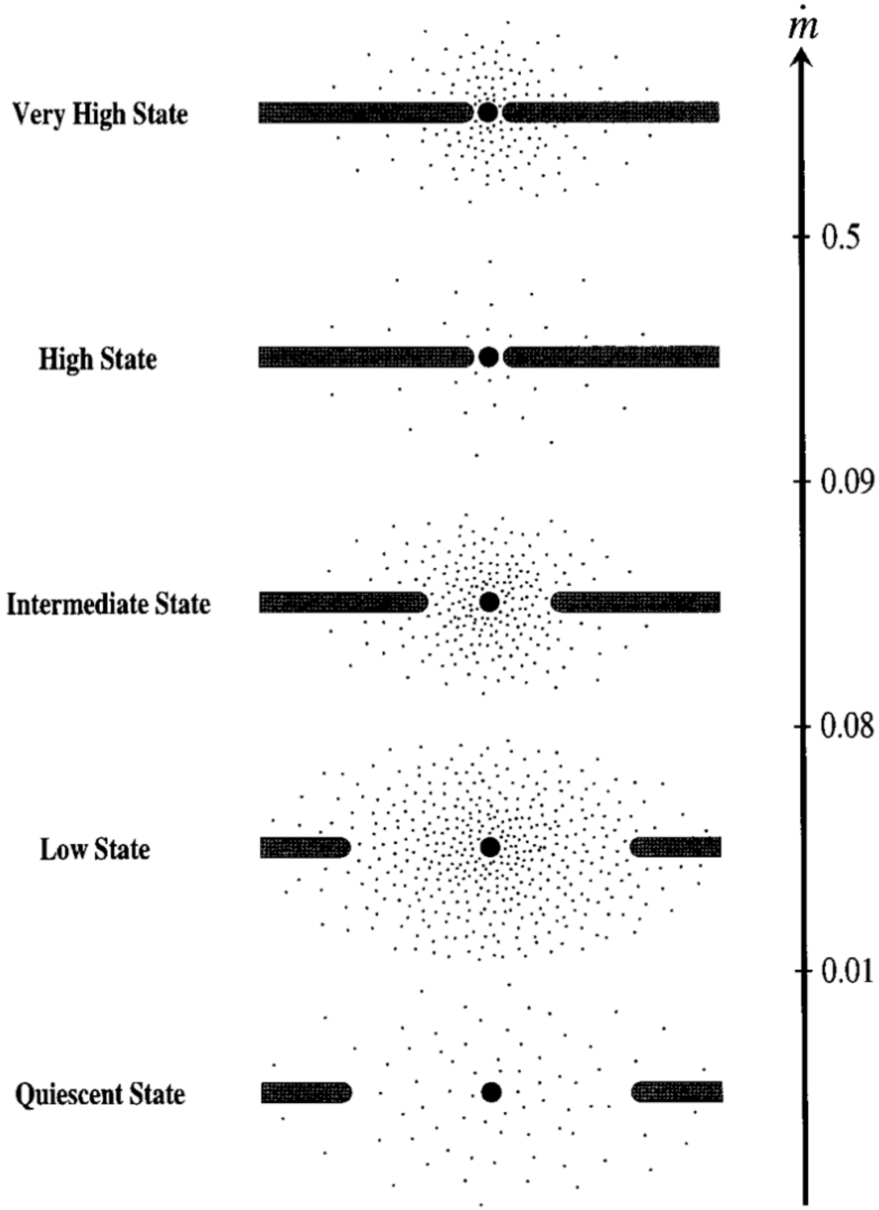
BUT... WWCS? {What Would Chris (Done) Say?}

High-soft state BHBs have very little high-frequency variability at all!

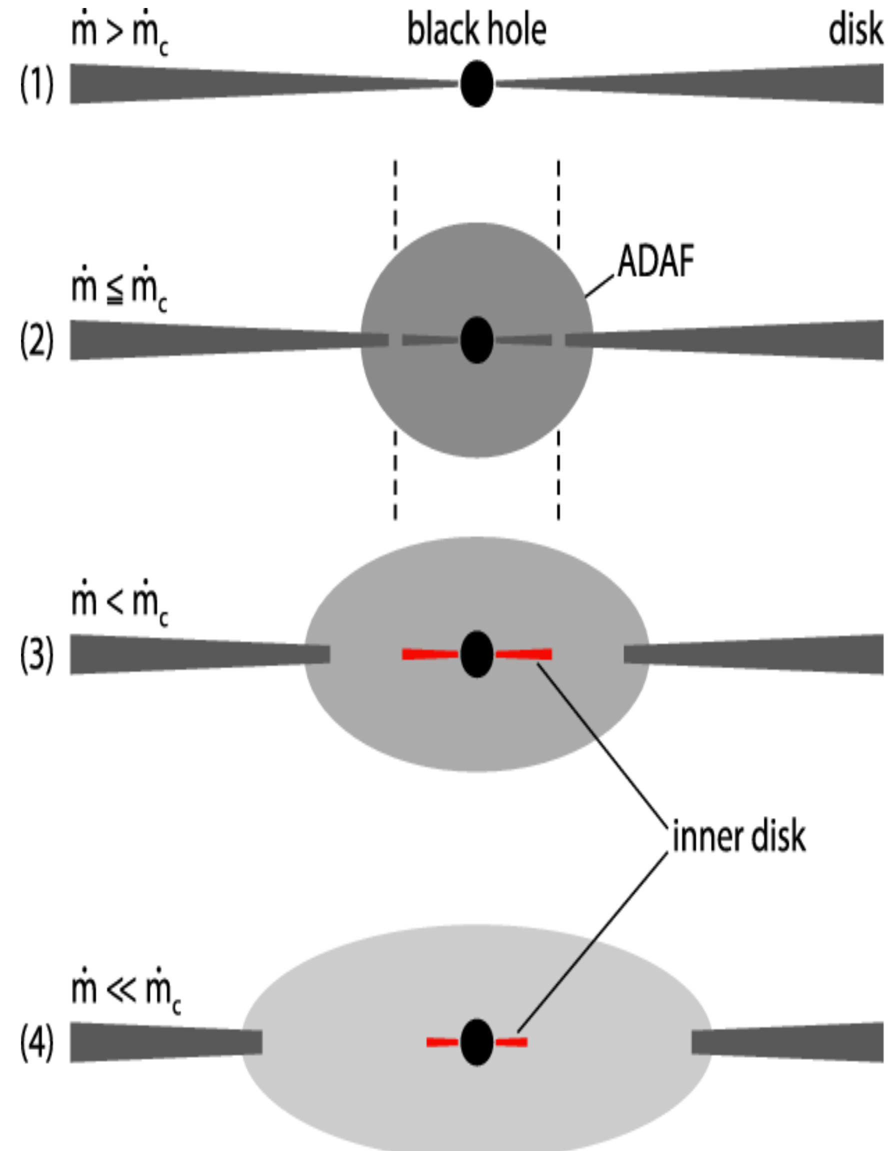
Maybe dynamo is suppressed in the HSS; thermodynamics (maybe Pr_m instability), net magnetic flux...

II : State transitions and the nature of truncated disks


year
1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011
FLUX (COLOR)
Grinberg (2015)
Cygnus X-1
RXTE-ASM 1.5–12 keV [cps]
CONTINUUM SLOPE
Γ1
VARIABILITY
rms [%]
2.1–4.5 keV
9.4–15.0 keV
LAGS
time lag [ms]
9.4–15 keV to 2.1–4.5 keV
5.7–9.4 keV to 2.1–4.5 keV
4-5–5.7 keV to 2.1–4.5 keV
MJD



Esin et al. (1997)



Meyer-Hofmeister et al. (2009)

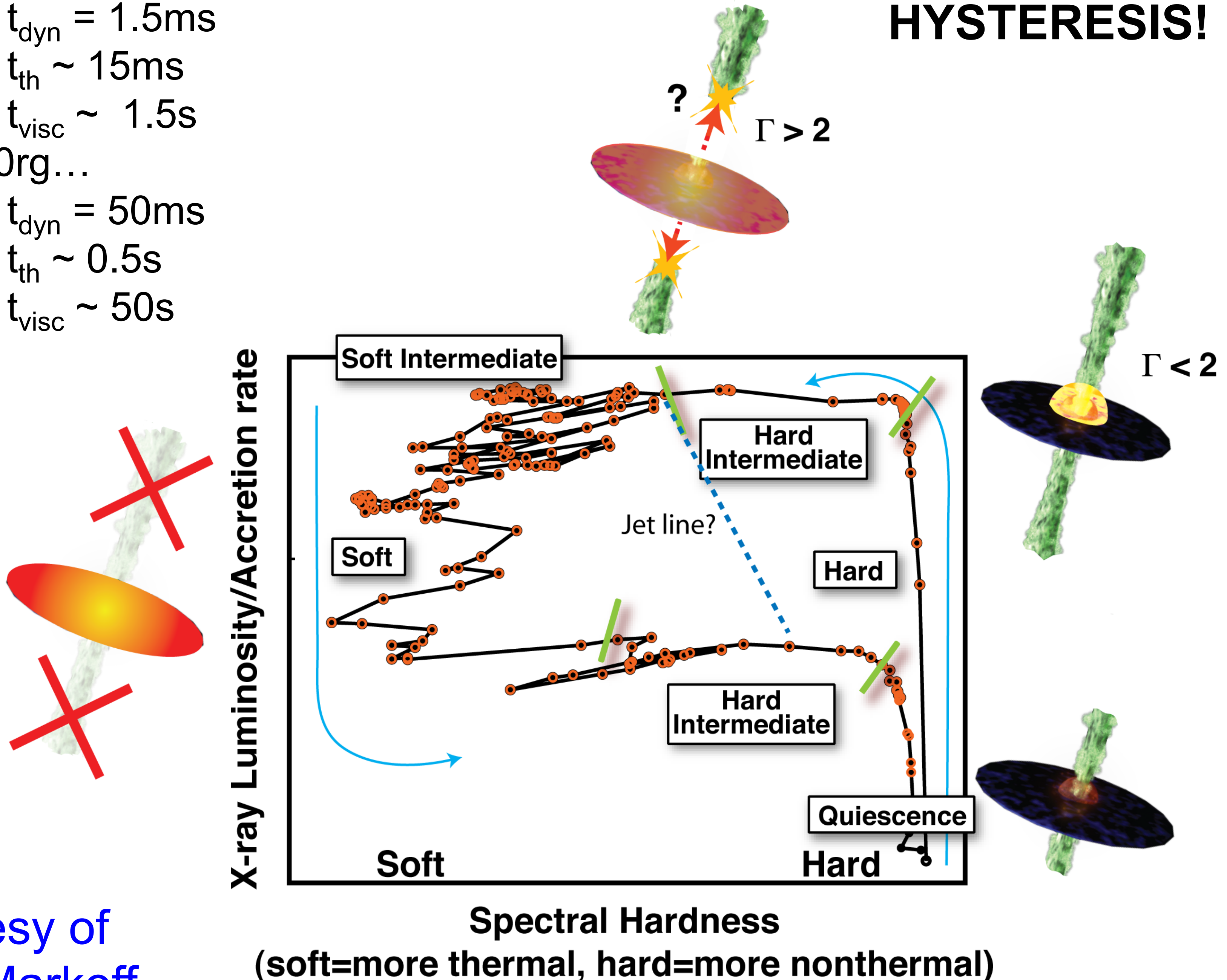
HYSTERESIS!

At r=10rg...

t_{dyn} = 1.5ms
t_{th} ~ 15ms
t_{visc} ~ 1.5s

At r=100rg…

t_{dyn} = 50ms
t_{th} ~ 0.5s
t_{visc} ~ 50s



Courtesy of
Sera Markoff

Begelman & Armitage (2014) model

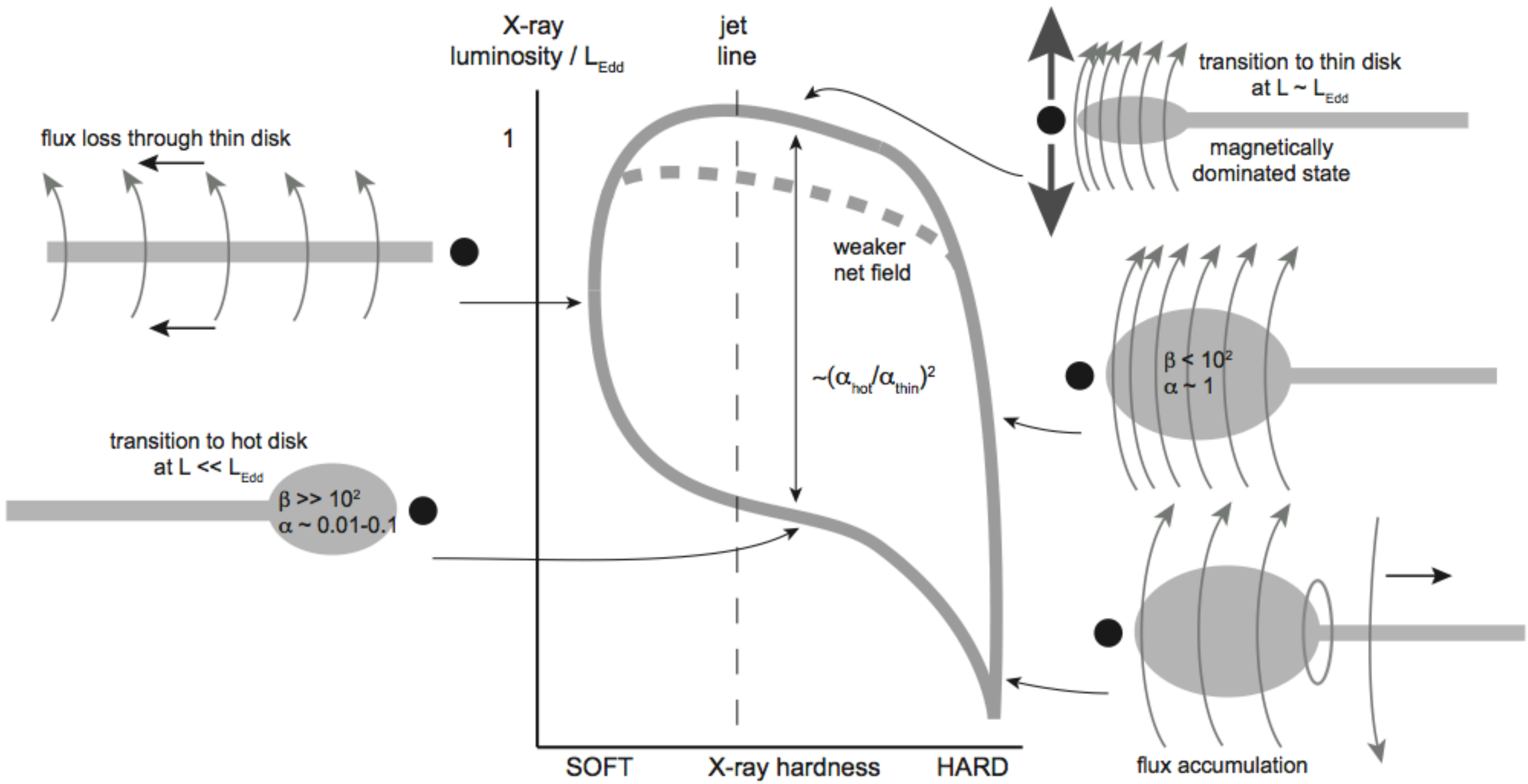


Figure 1. Illustration of the observed evolution of black hole binary disks in L_X versus spectral hardness (simplified from Fender, Belloni & Gallo 2004), and how that relates to the assumed evolution of net magnetic fields in our model. The luminosity of the upper branch of the transition depends on the net accumulated flux, which can vary from cycle to cycle.

Need to understand truncation…

- Before we can understand state changes, we must understand the structure of flows with thin/efficient outer regions and thick/inefficient inner regions. Some issues
  - Can the thin➔thick transition occur over $\Delta r \ll r$?
  - Is a steady flow structure possible?
  - Nature of stresses/energy fluxes across the transition zone?
- Thermal physics driving the radial transition may be complex…
- So, make a toy system with a simple cooling function designed to drive a thermal instability; then study resulting thin➔thick transition

Toy cooling function

- **Design specs** : Want optically-thin cooling which is positive-definite, does not drive viscous instability, but can drive thermal instability. For steady-state and efficient disk, this will balance heating

$$\mathcal{H} = \frac{3}{2}\alpha\mathcal{R}\rho T\Omega_K$$

- Choose $\Lambda = \Lambda_0(T)\rho T^2 f(r),$

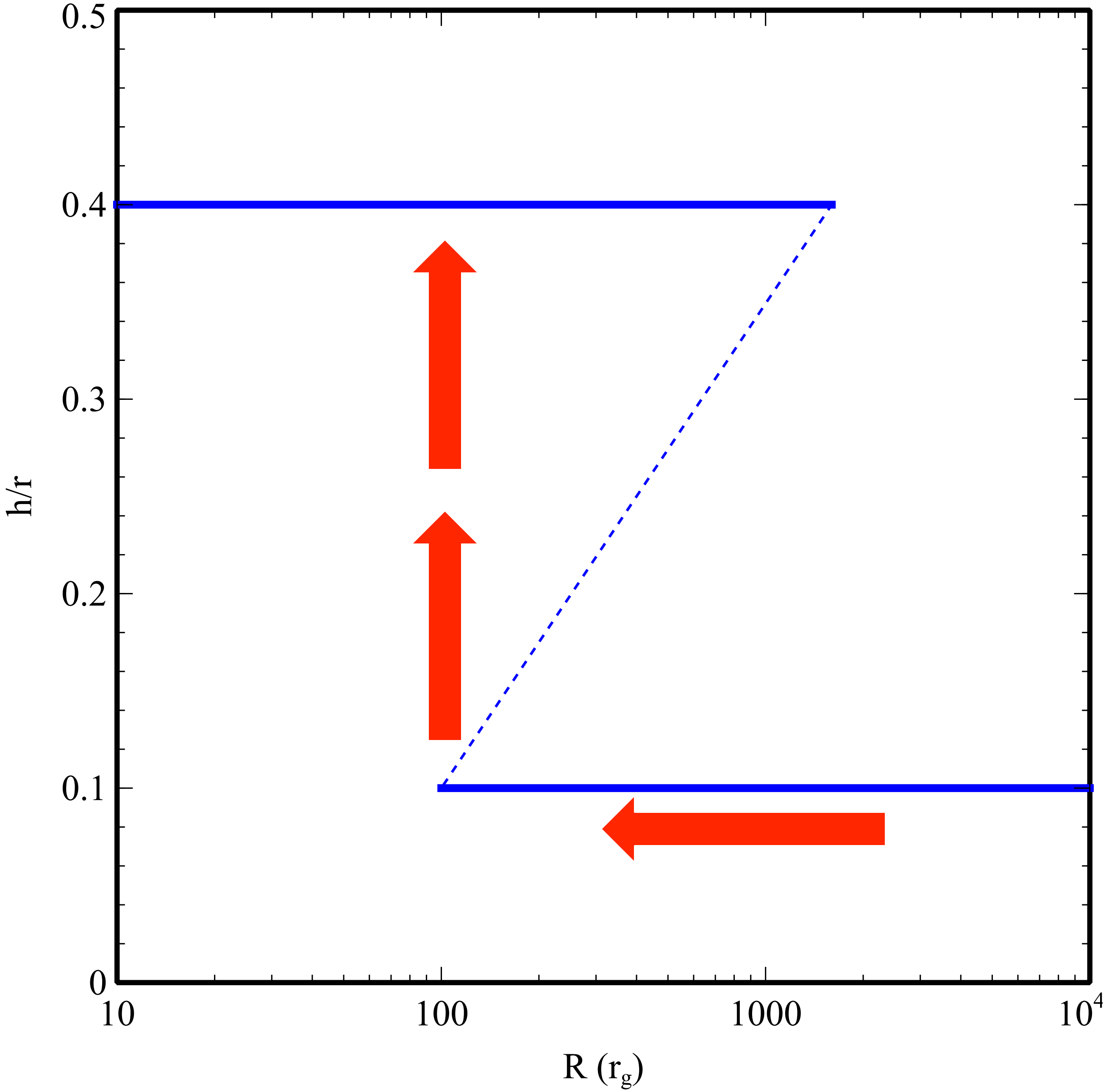
$$\mathcal{H} = \Lambda \quad \rightarrow \quad \frac{h}{r} = \sqrt{\frac{3\alpha}{2\Lambda_0(T)}},$$

NOT a simple Noble et al. style "target-h/r" cooling function!

- Thermal instability introduced by T-dependent Λ_0

$$\Lambda_0(T) = \begin{cases} \Lambda_c & (T < T_T) \\ \Lambda_h & (T \geq T_T) \end{cases}$$

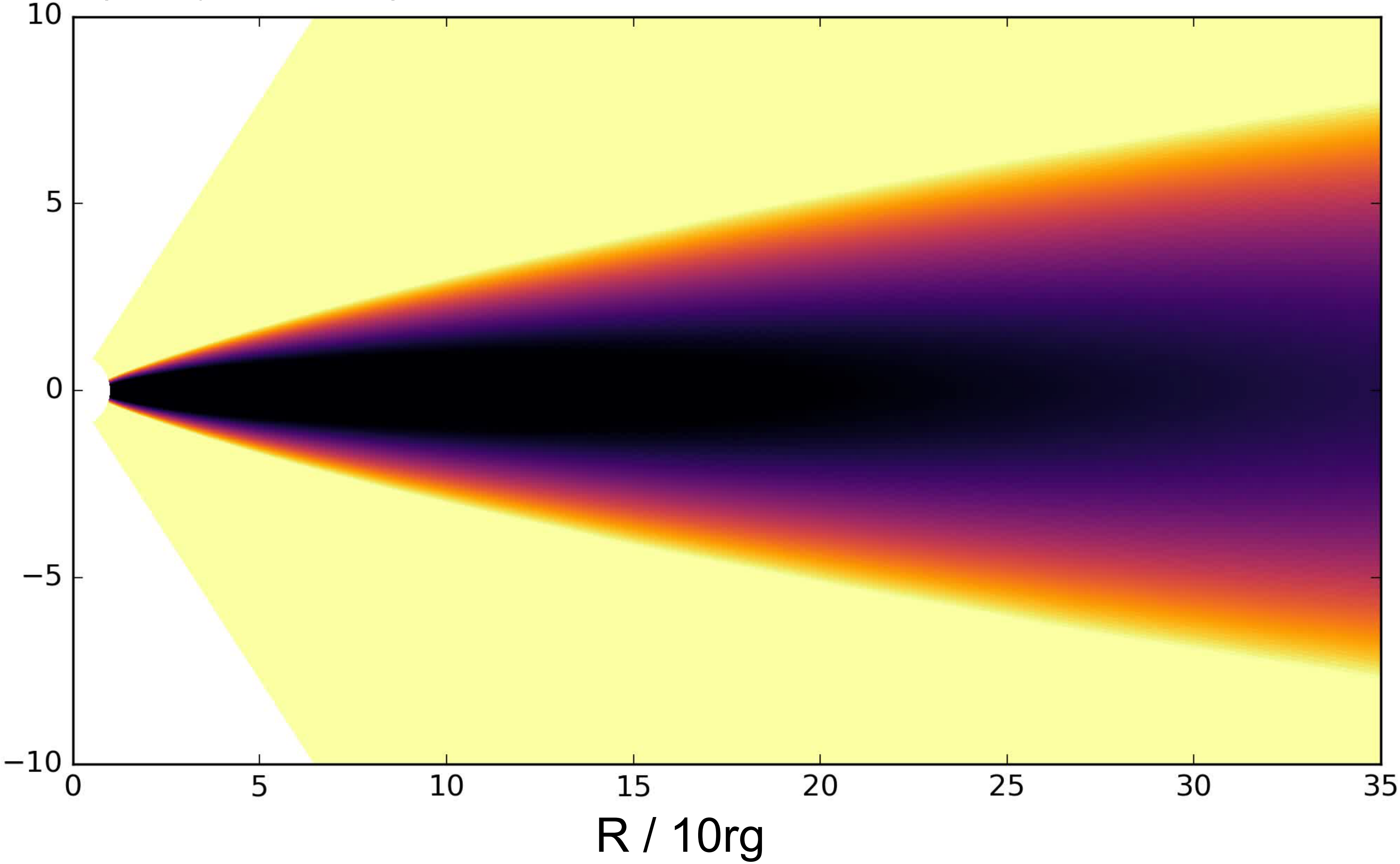
Hogg & Reynolds (submitted)



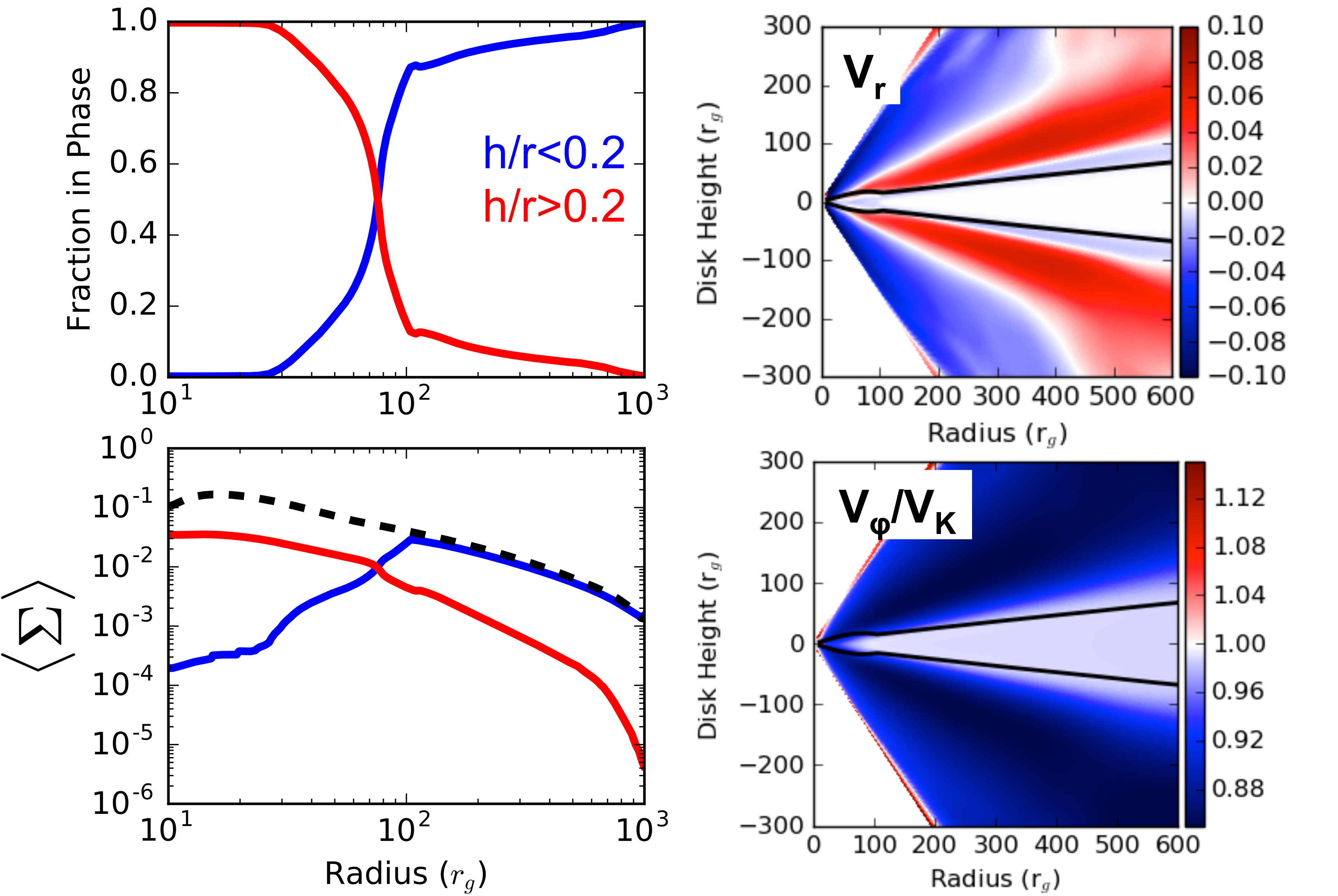
0.5
0.4
0.3
0.2
0.1
0
h/r
10
100
1000
10^4
R (r_g)

Hydro with α-viscosity (axisymmetric)

Hogg & Reynolds (submitted)
Also, Drew's poster!



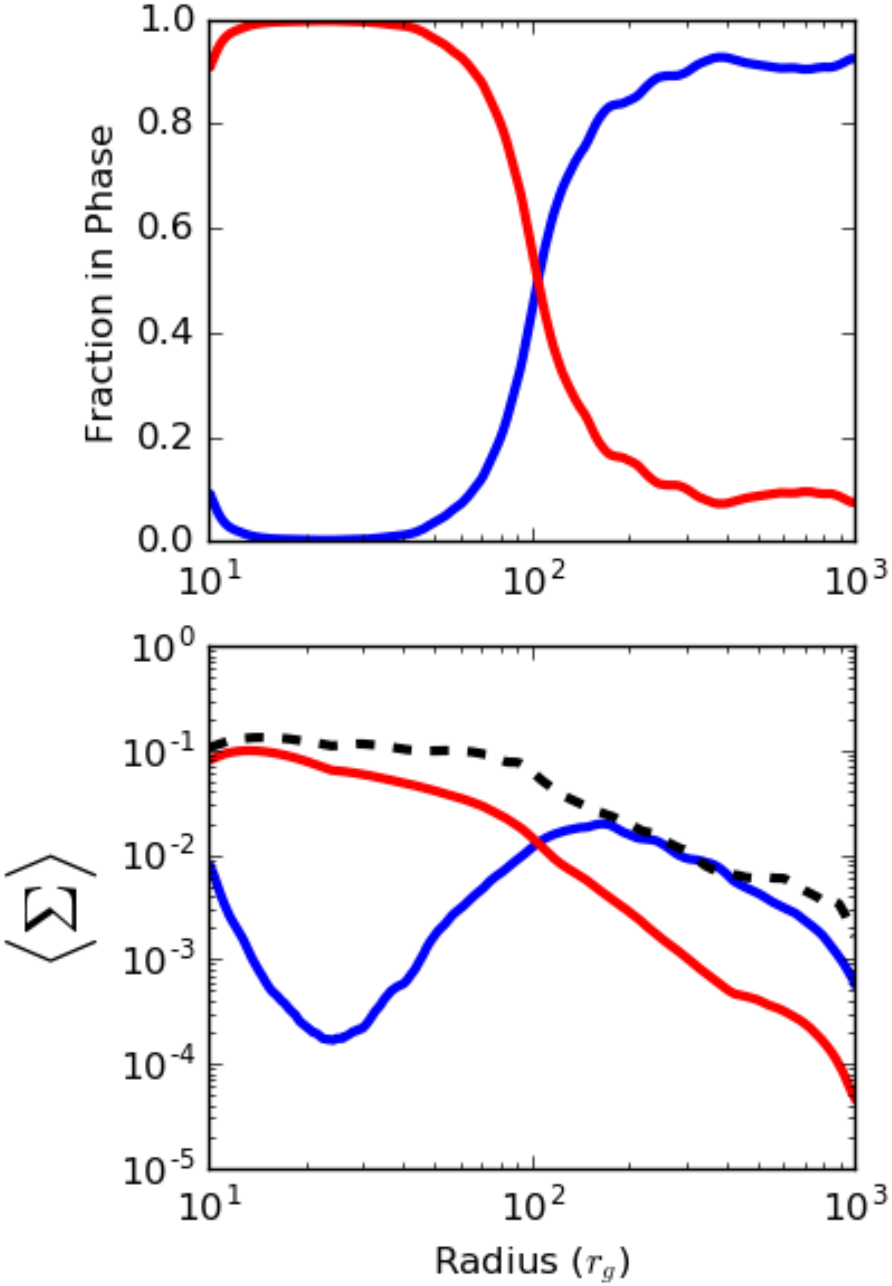
Hogg & Reynolds (submitted)

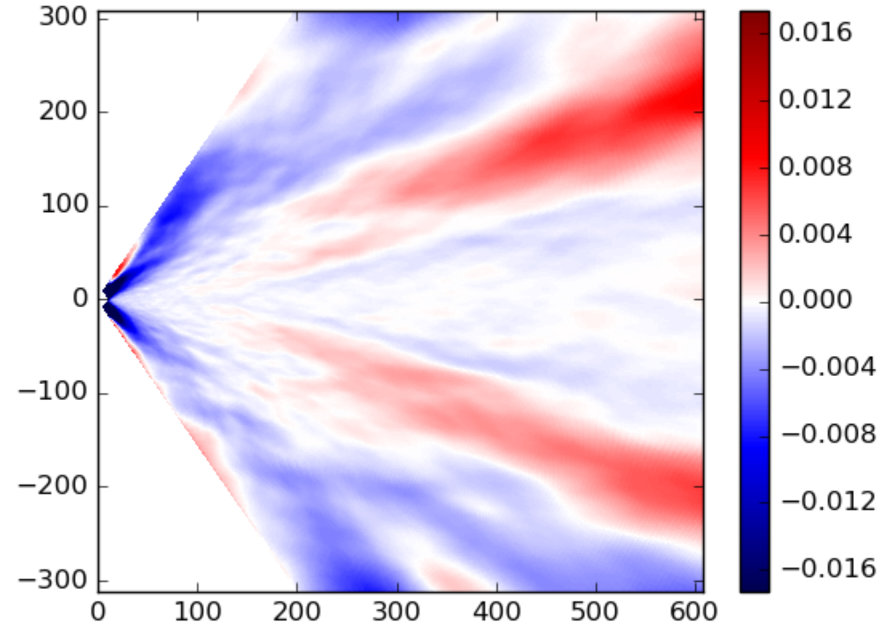


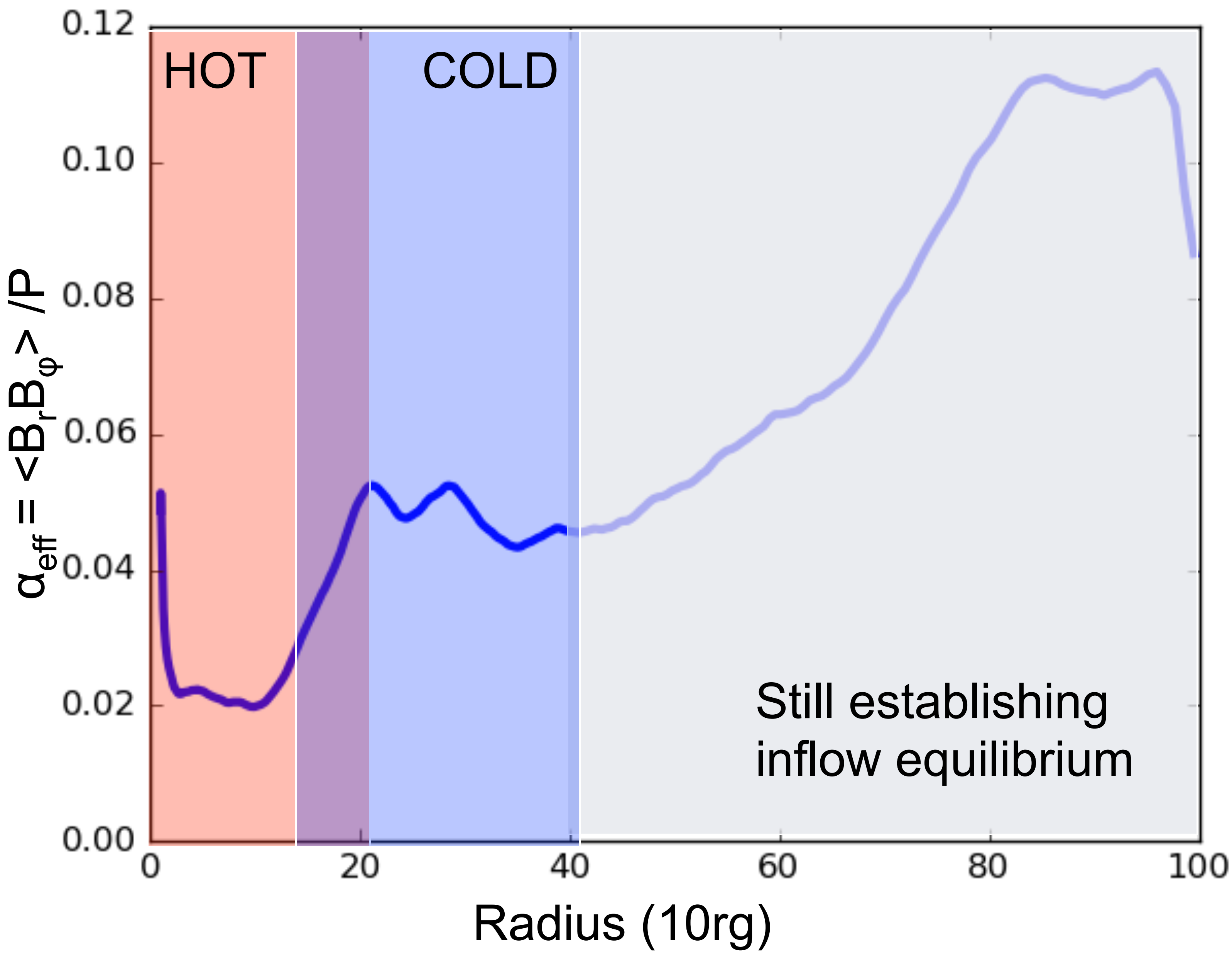
Non-relativistic ideal MHD
3D (π/3 wedge simulation)

PRELIMINARY

Hogg & Reynolds (in prep)






HOT
COLD
Still establishing
inflow equilibrium
0.12
0.10
0.08
0.06
0.04
0.02
0.00
0
20
40
60
80
100
Radius (10rg)
$\alpha_{eff} = \langle B_r B_\varphi \rangle / P$

Conclusions

- Structure of aperiodic variability
  - Propagating fluctuations driven by stochastic changes in the angular momentum transport
  - Dynamical timescale turbulence non-sufficient… slower dynamo drives variability
- Nature of truncated disks
  - Can recover thin→thick transition
  - Viscous HD model… thermal limit cycle, thermal breeze, and significant cold matter interior to transition
  - MHD model (preliminary)… no limit cycle, thermal breeze, little cold matter interior to transition.