Accretion disks: Simulations and Observations

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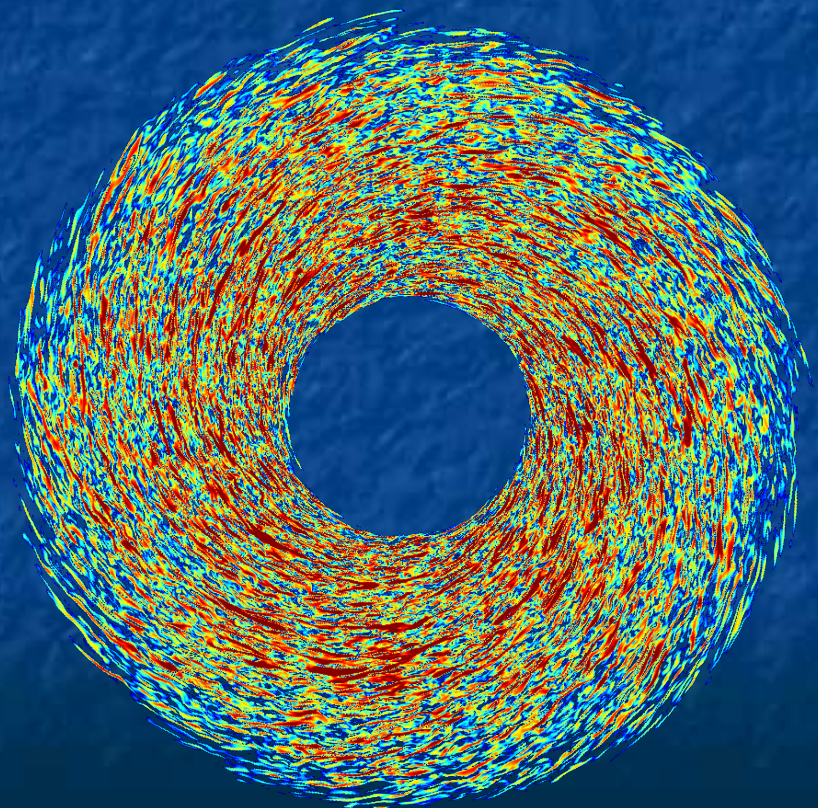
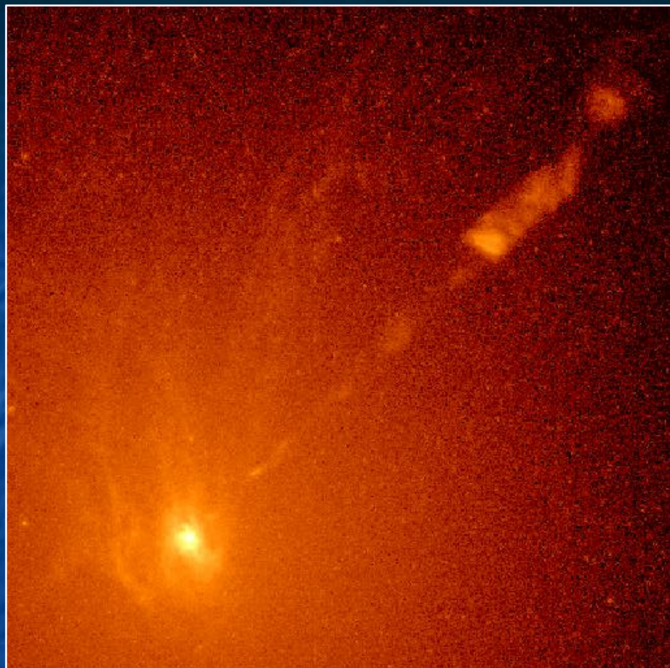
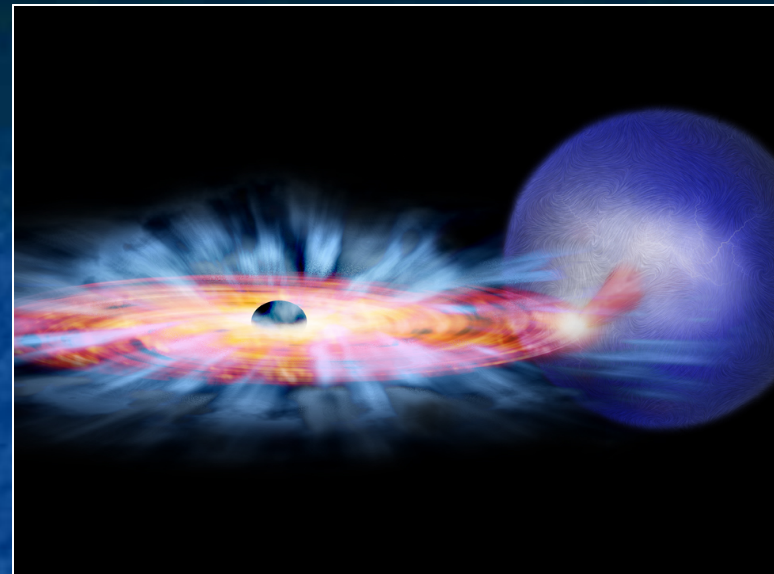


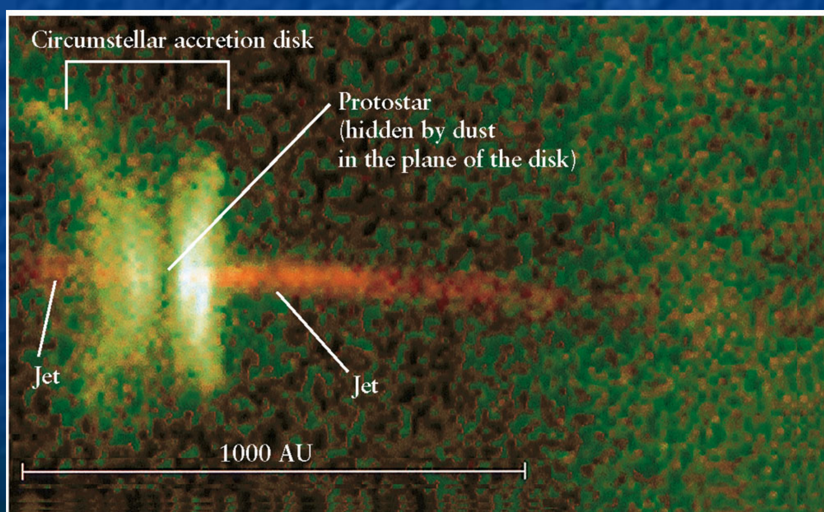
Krakow 2011

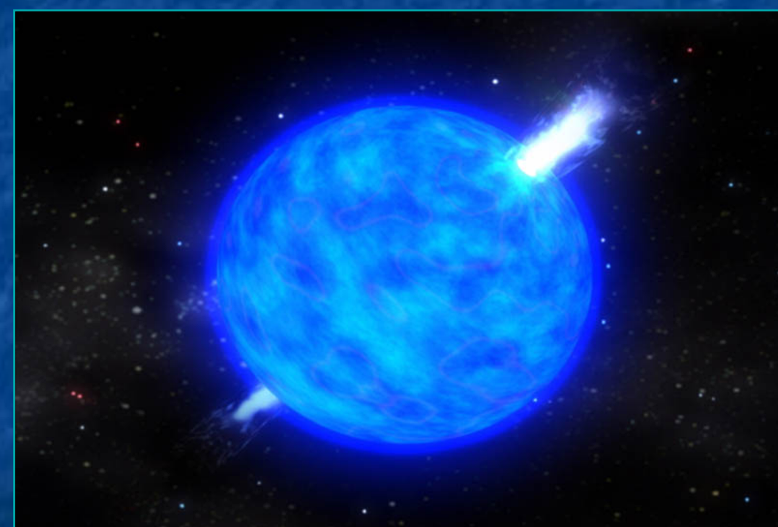
Collaborators

- Simulation work
  - Phil Armitage
  - Kris Beckwith
  - Cole Miller
  - Sean O'Neill
  - **Kareem Sorathia**
  - Jim Stone
  - TERAGRID/Ranger
- Observational work
  - Laura Brenneman
  - Andy Fabian
  - **Anne Lohfink**
  - Jon Miller
  - Mike Nowak
  - **Rubens Reis**
  - Margaret Trippe






Circumstellar accretion disk
Protostar
(hidden by dust
in the plane of the disk)
Jet
Jet
1000 AU



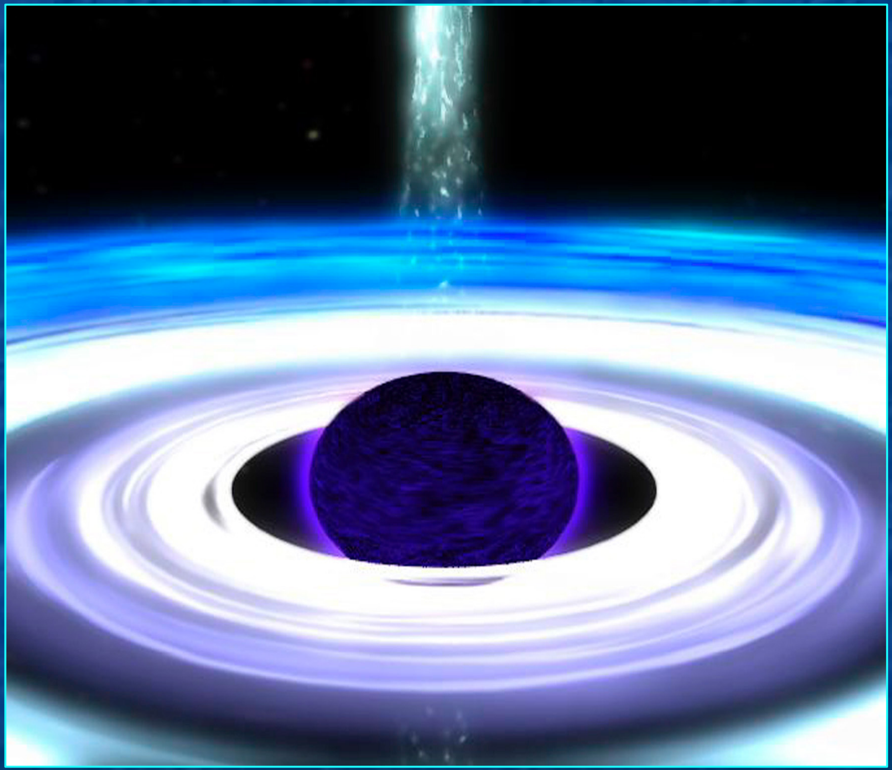
Outline

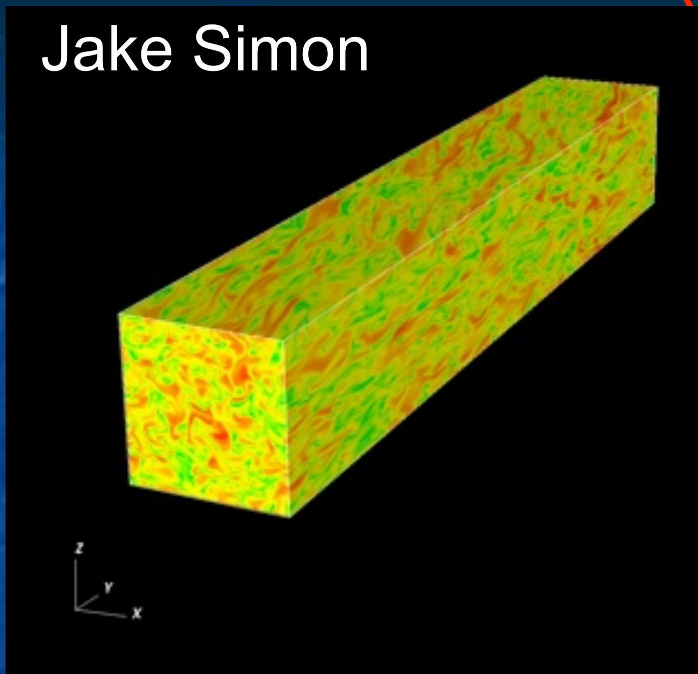
- Why do accretion disks actually accrete?
  - MHD turbulence paradigm for angular momentum transport
  - Going beyond a “local” view of disk physics
- Why are accreting systems so variable?
  - Aperiodic and quasi-periodic phenomena
  - Insights into LFQPOs and HFQPOs from global simulations
- Black hole physics… how rapidly are BHs spinning, and how does inner accretion disk respond to spin?
  - Broad iron line probes of the inner accretion disk
  - Accretion flow properties close to the ISCO

I : Why do accretion disks actually accrete?

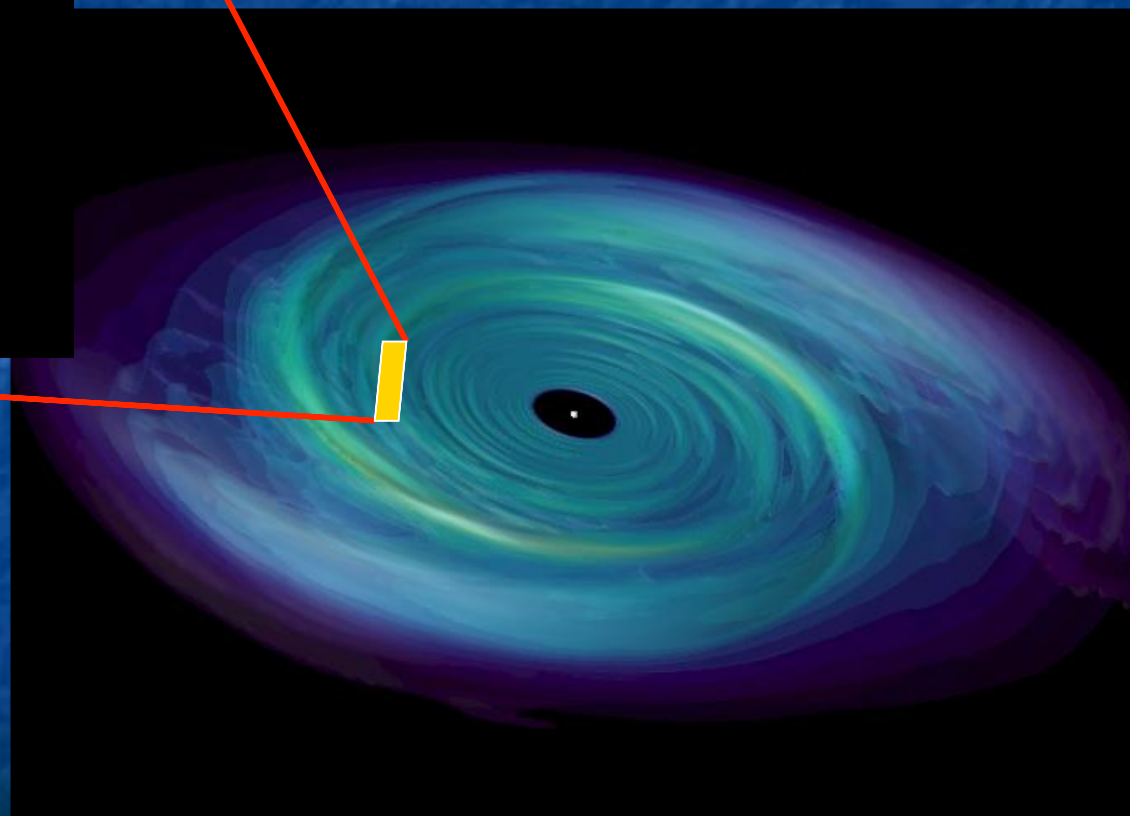
- **The problem** : Need to transport angular momentum in a very very high Re-number flow

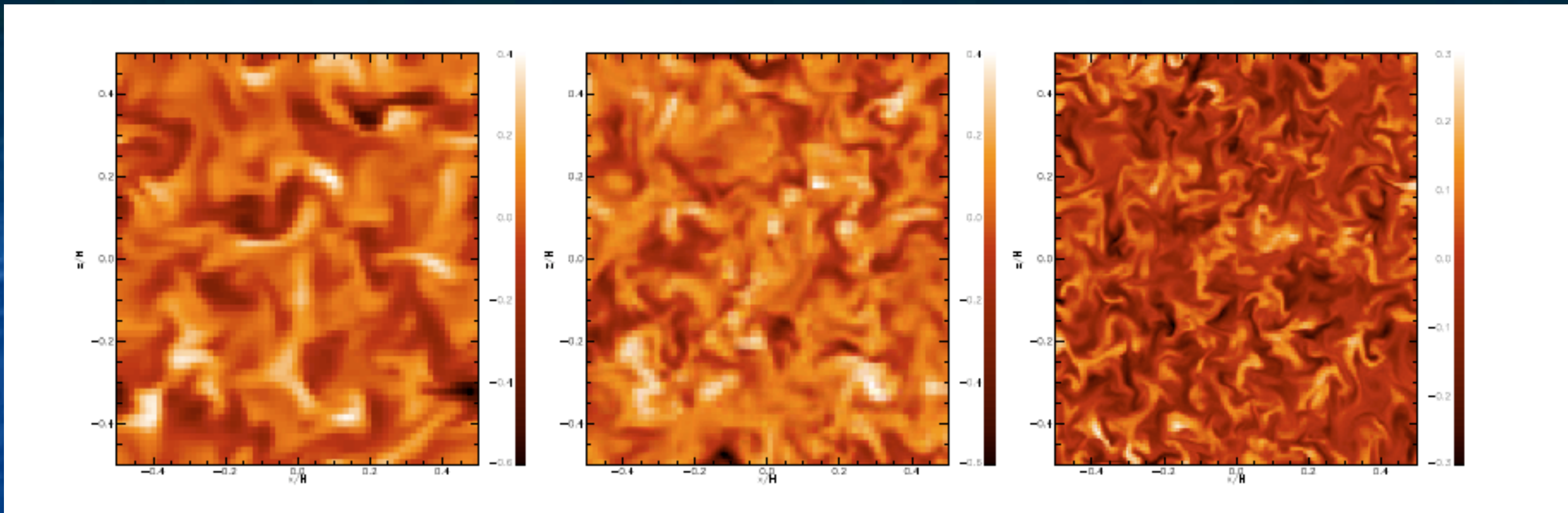
- **Current paradigm** : Magneto-rotational instability (MRI) drives turbulence; correlations in the turbulence transports angular momentum (Balbus & Hawley 1991)

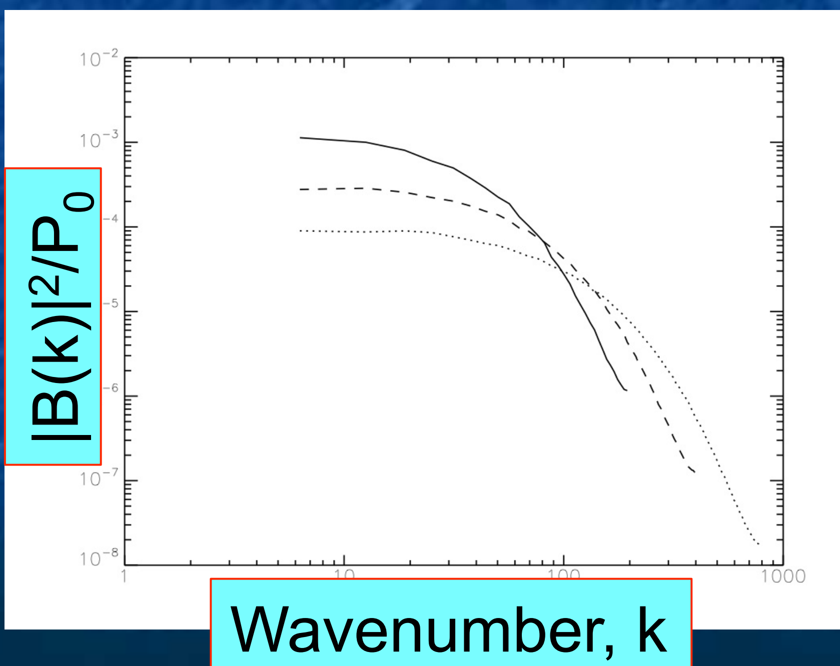




$$\alpha_{eff} = -\left\langle \frac{B_r B_\varphi}{4\pi P} \right\rangle \sim 0.01 - 0.1$$



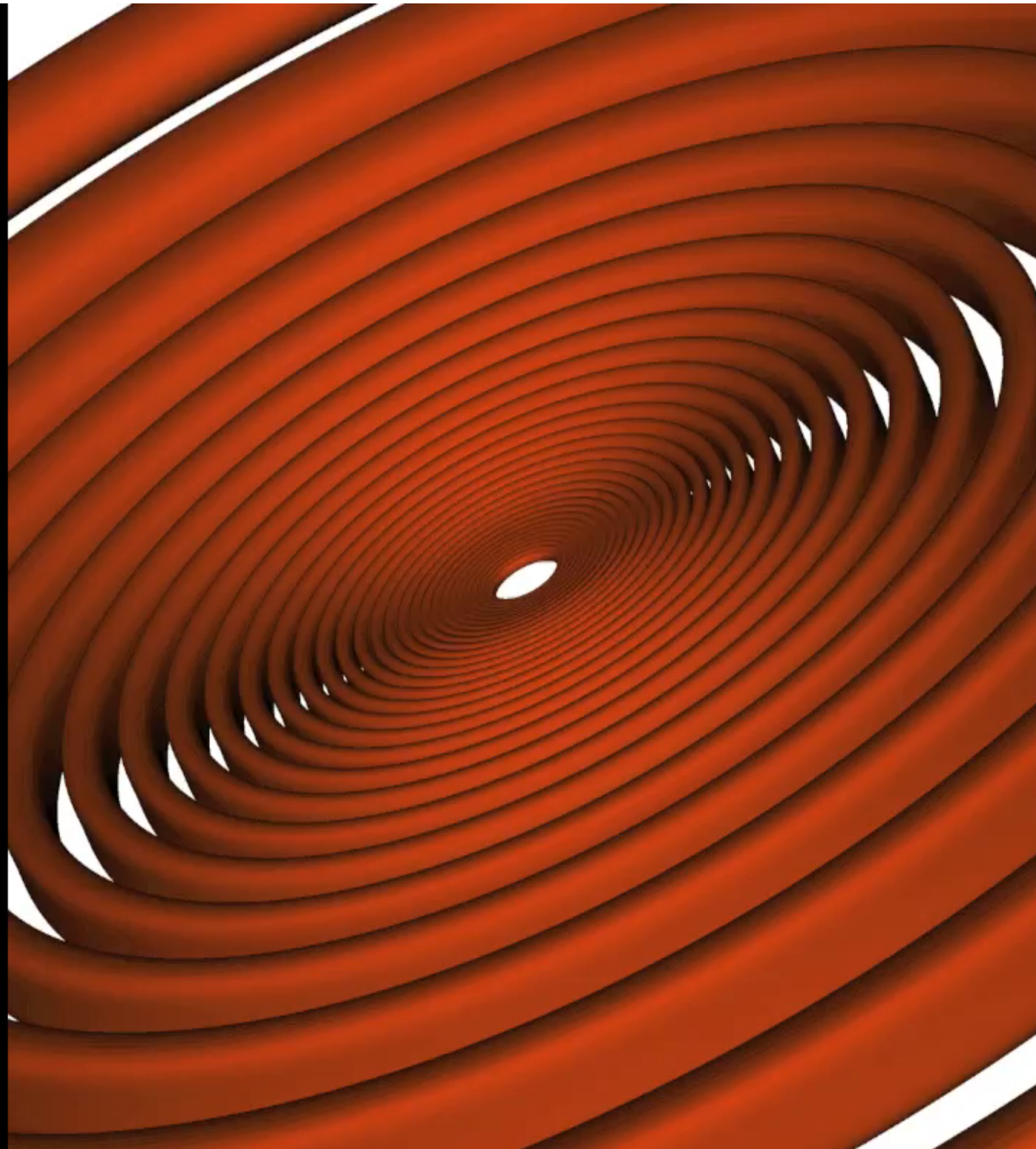




Non-convergence of local, unstratified, zero net-flux models

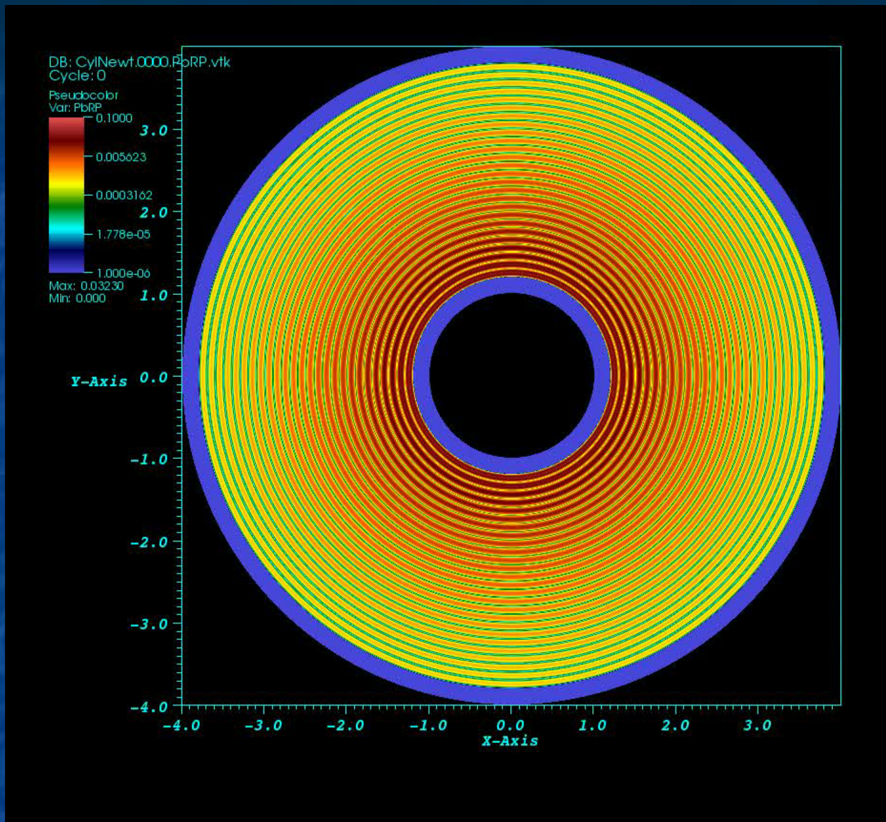
Fromang & Papaloizou (2007)

Non-convergence is fragile… achieve convergence by adding net-flux, stratification, or explicit dissipation

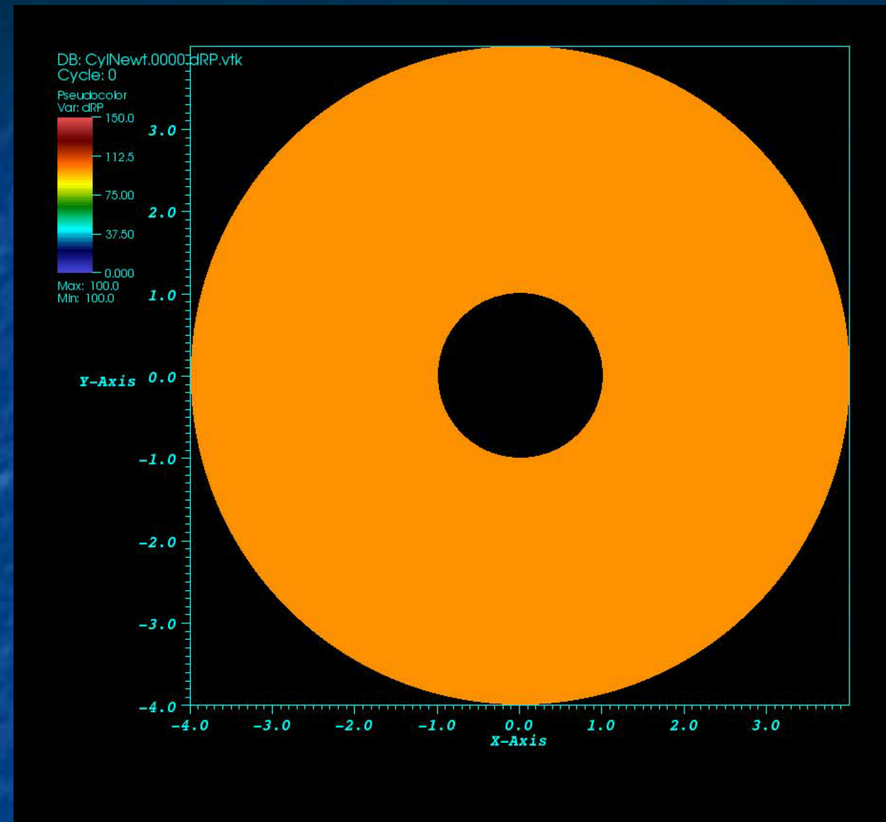


Simulation by Sean O'Neill (rendering shows magnetic field strength)
Visualization by Philip Cowperthwaite & Brett Morris (UMd-undergrads)
Krakow 2011

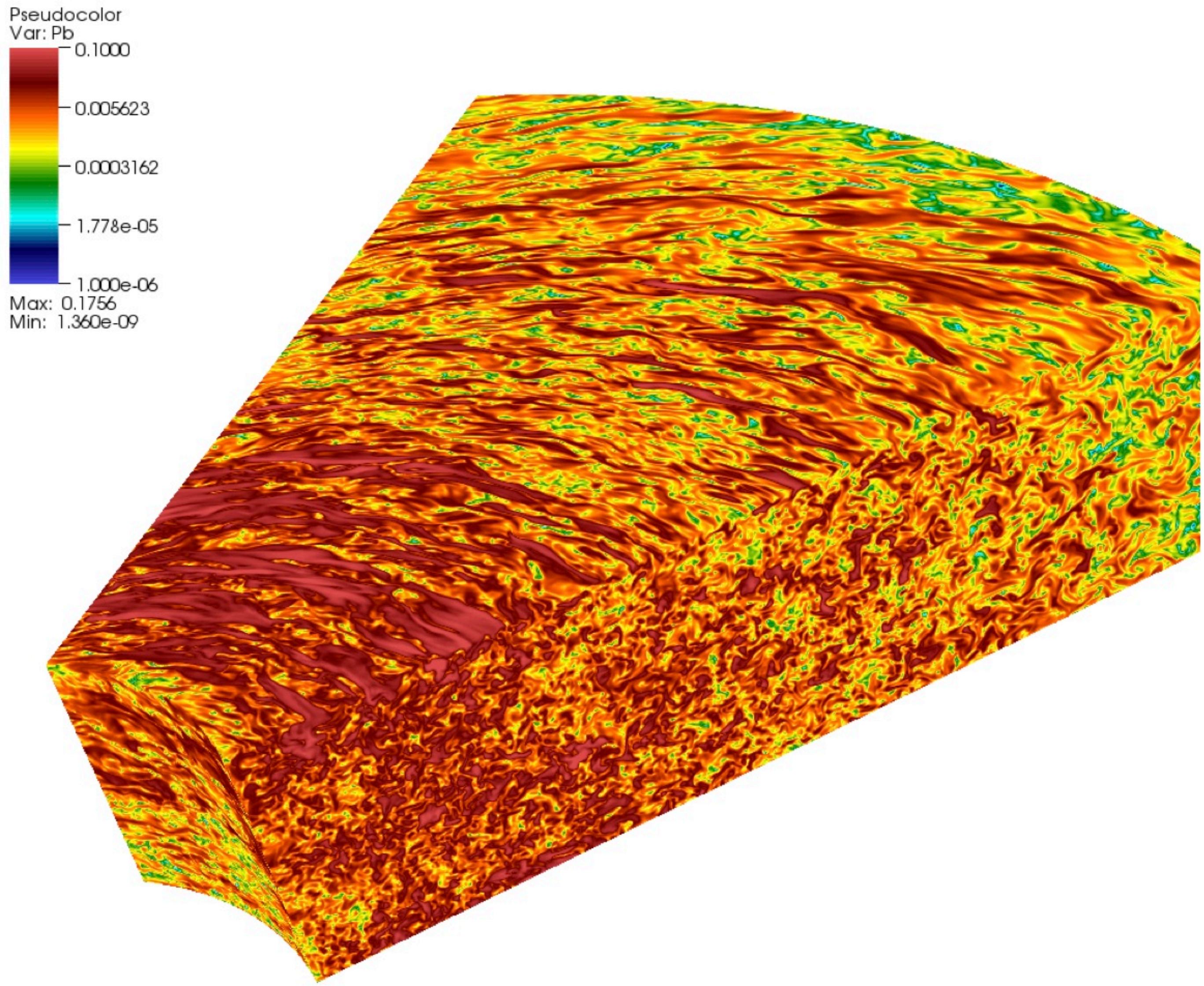
Magnetic Pressure (midplane)

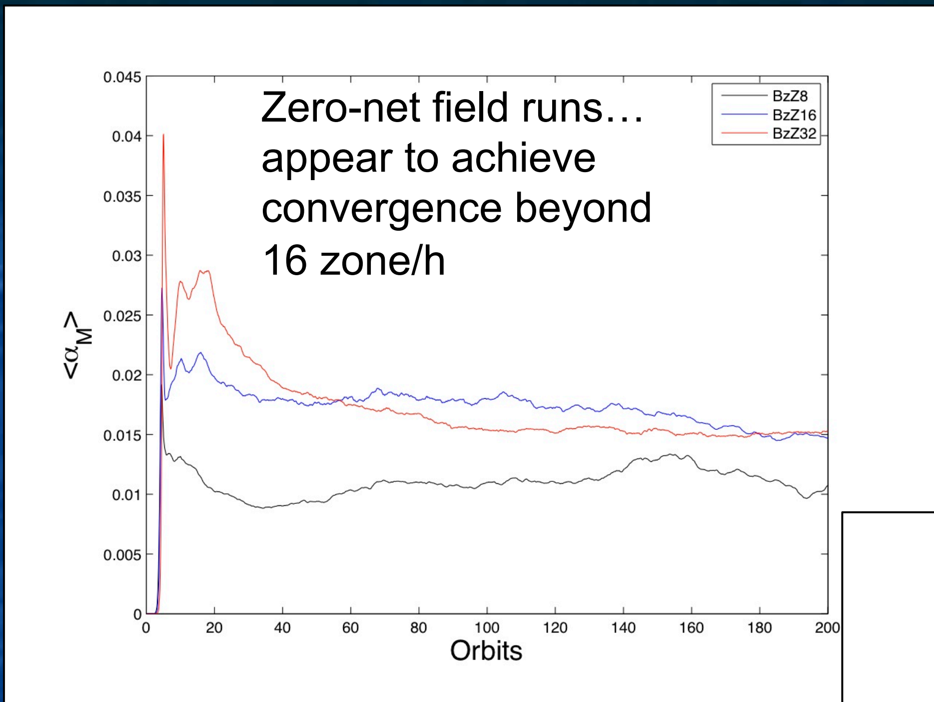


Density (midplane)

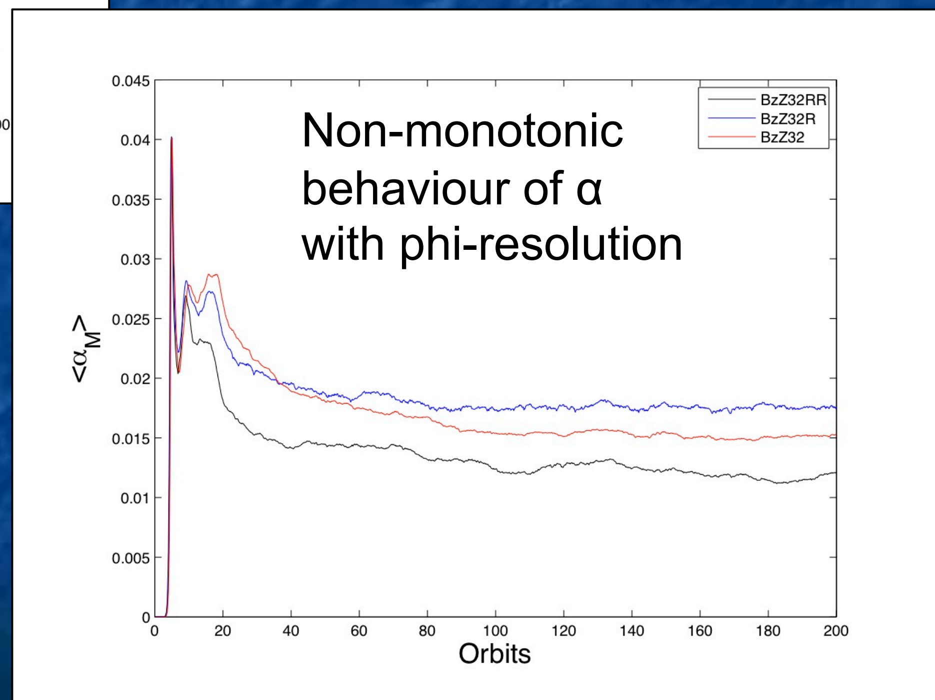


- Global convergence study of vertically unstratified Newtonian disks
- Implement orbital advection in Athena; speed up calculation by factor 20
- **Effective h/r=0.1; 8/16/32/64 z-zones/h at the fiducial radius**
- First models to achieve high resolution in vertical direction AND not cheat in terms of azimuthal resolution (Sorathia, Reynolds et al. 2011)

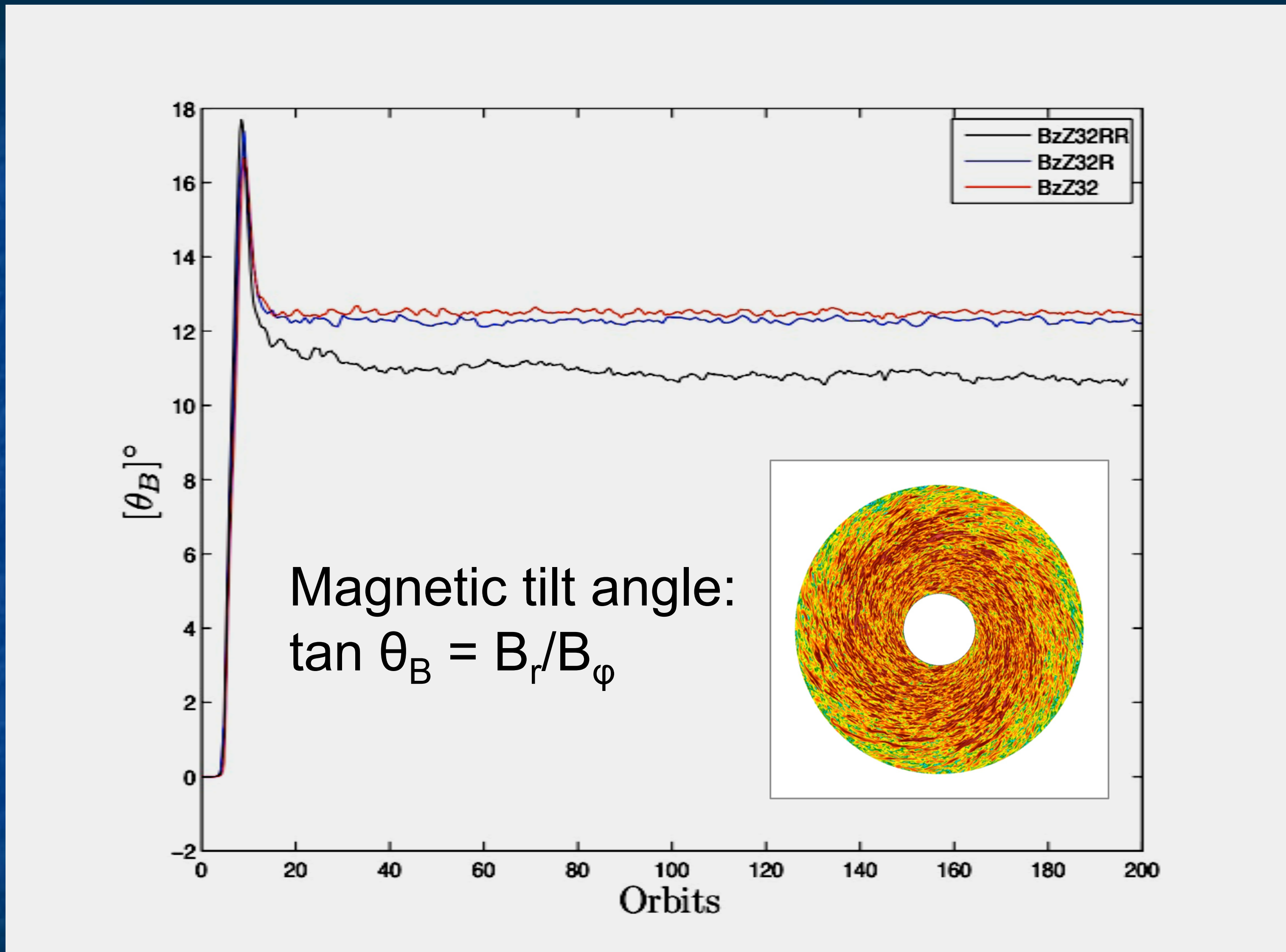

Pseudocolor
Var: Pb
0.1000
0.005623
0.0003162
1.778e-05
1.000e-06
Max: 0.1756
Min: 1.360e-09



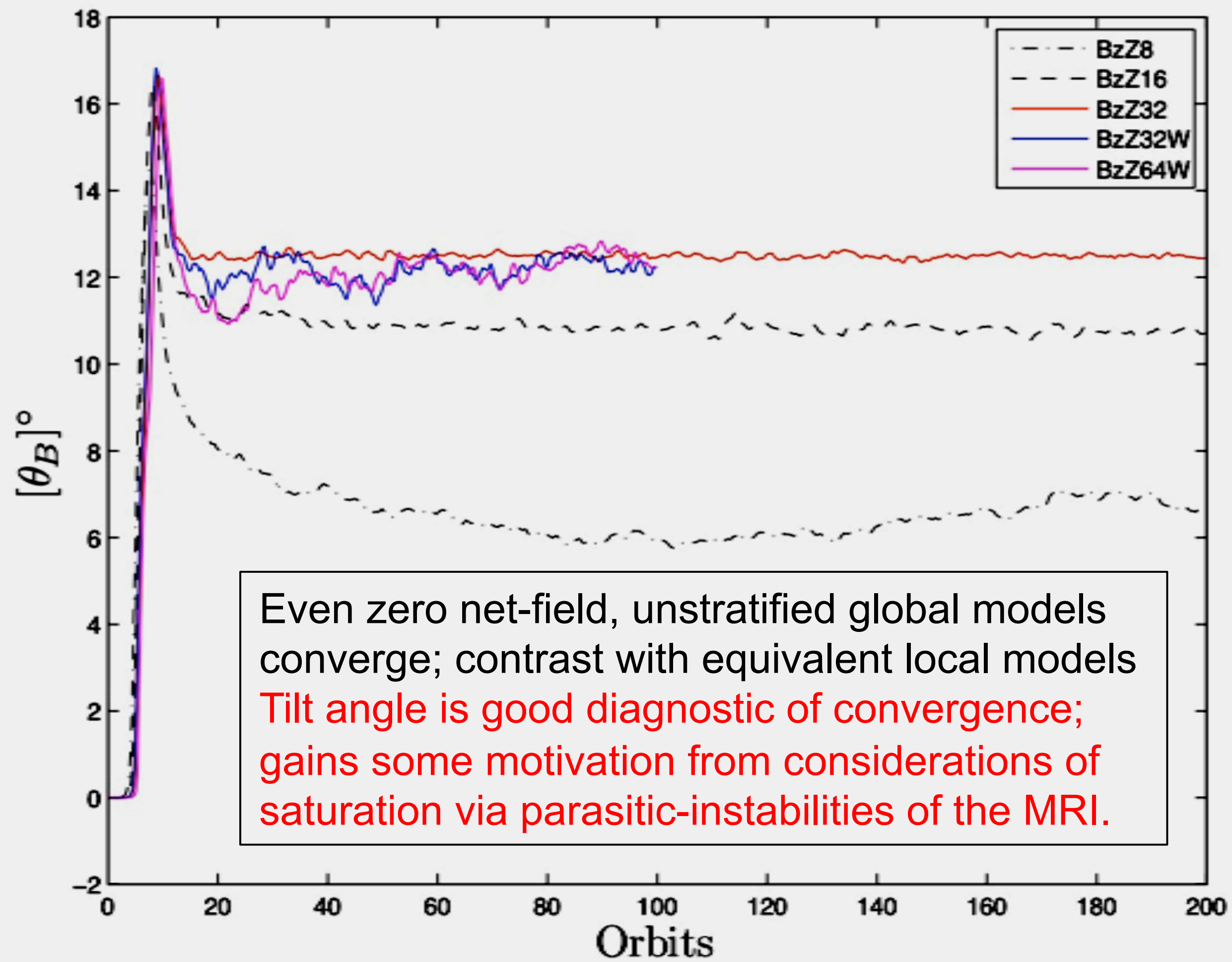
Convergence in a global simulation is subtle… its requires more than just resolving the linear modes of the MRI.



Sorathia et al. (in prep)



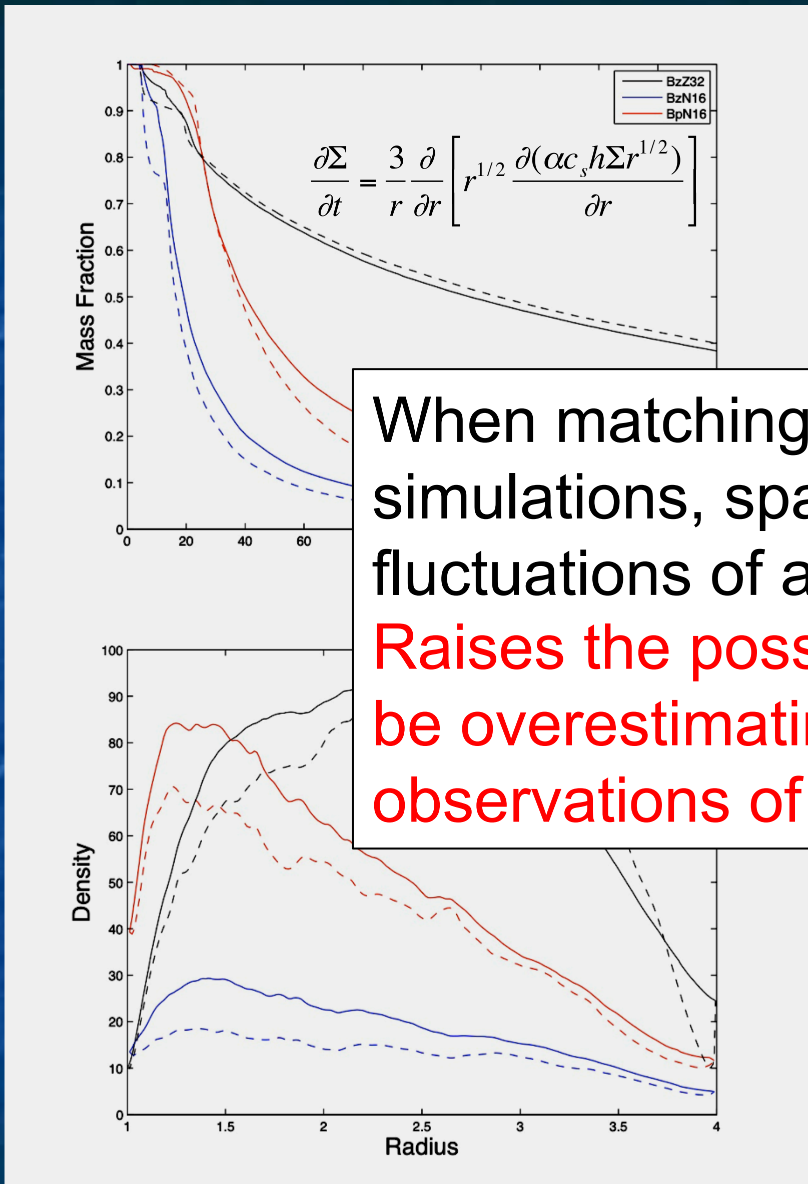
Sorathia et al. (in prep)

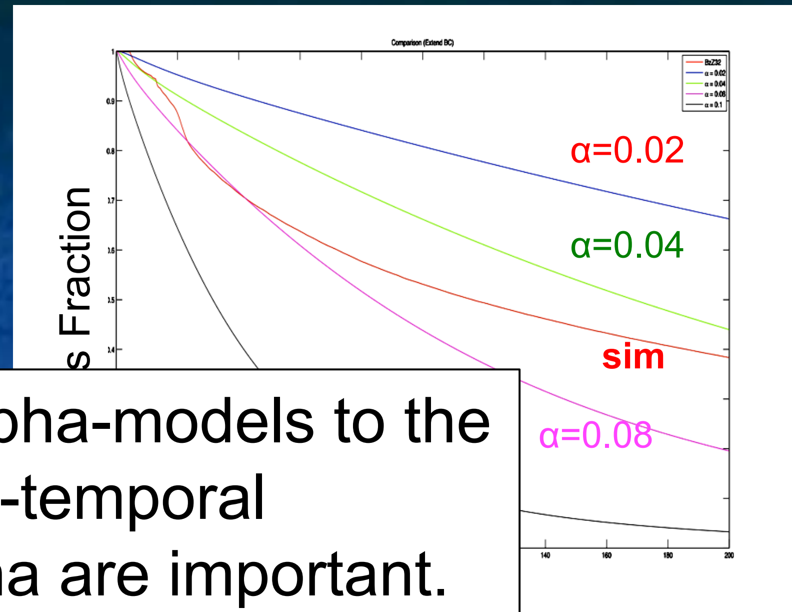


Even zero net-field, unstratified global models converge; contrast with equivalent local models

Tilt angle is good diagnostic of convergence; gains some motivation from considerations of saturation via parasitic-instabilities of the MRI.

Sorathia et al. (in prep)





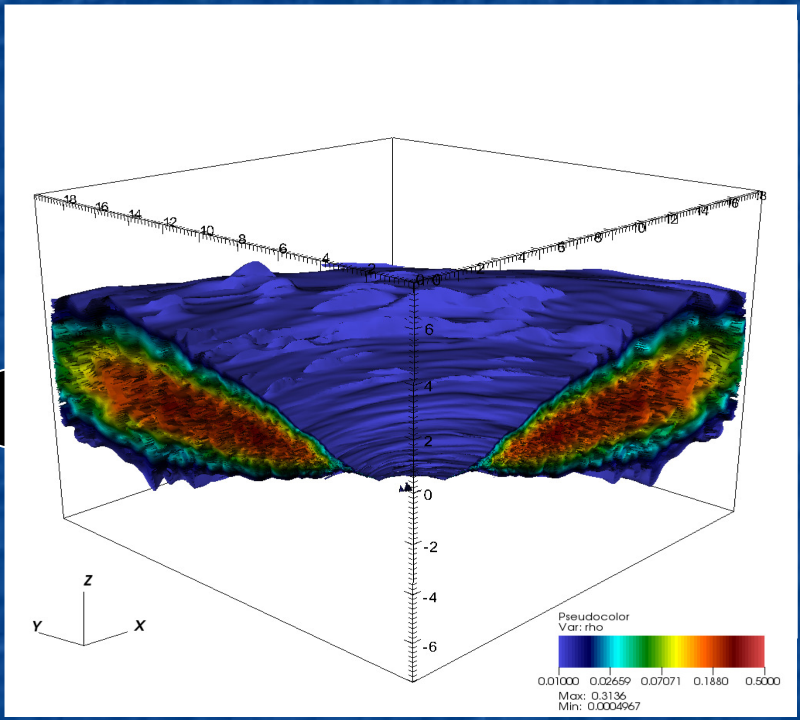
When matching alpha-models to the simulations, spatio-temporal fluctuations of alpha are important.
Raises the possibility that we may be overestimating alpha from observations of dwarf novae

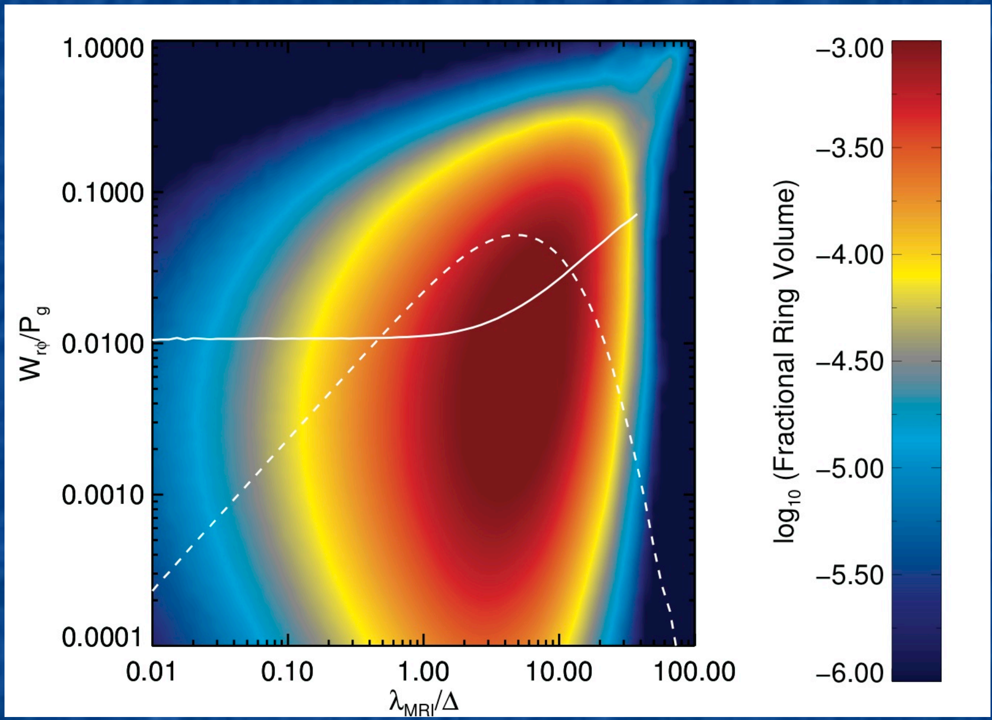
stant-α models

Comparison of 1-d alpha model with full simulation, where α=α(r,t) is measured from the simulation itself

Sorathia et al. (in prep)

Stresses in a thin disk are largely determined by “magnetic connectivity” of the disk (via the corona). This gives the corona previously unrecognized dynamical significance

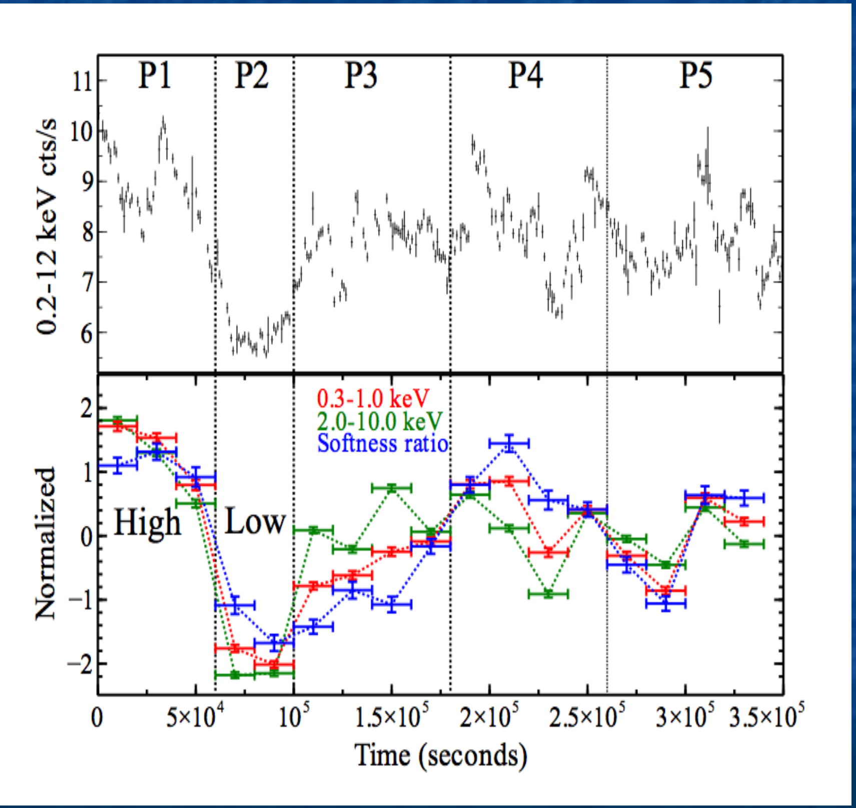




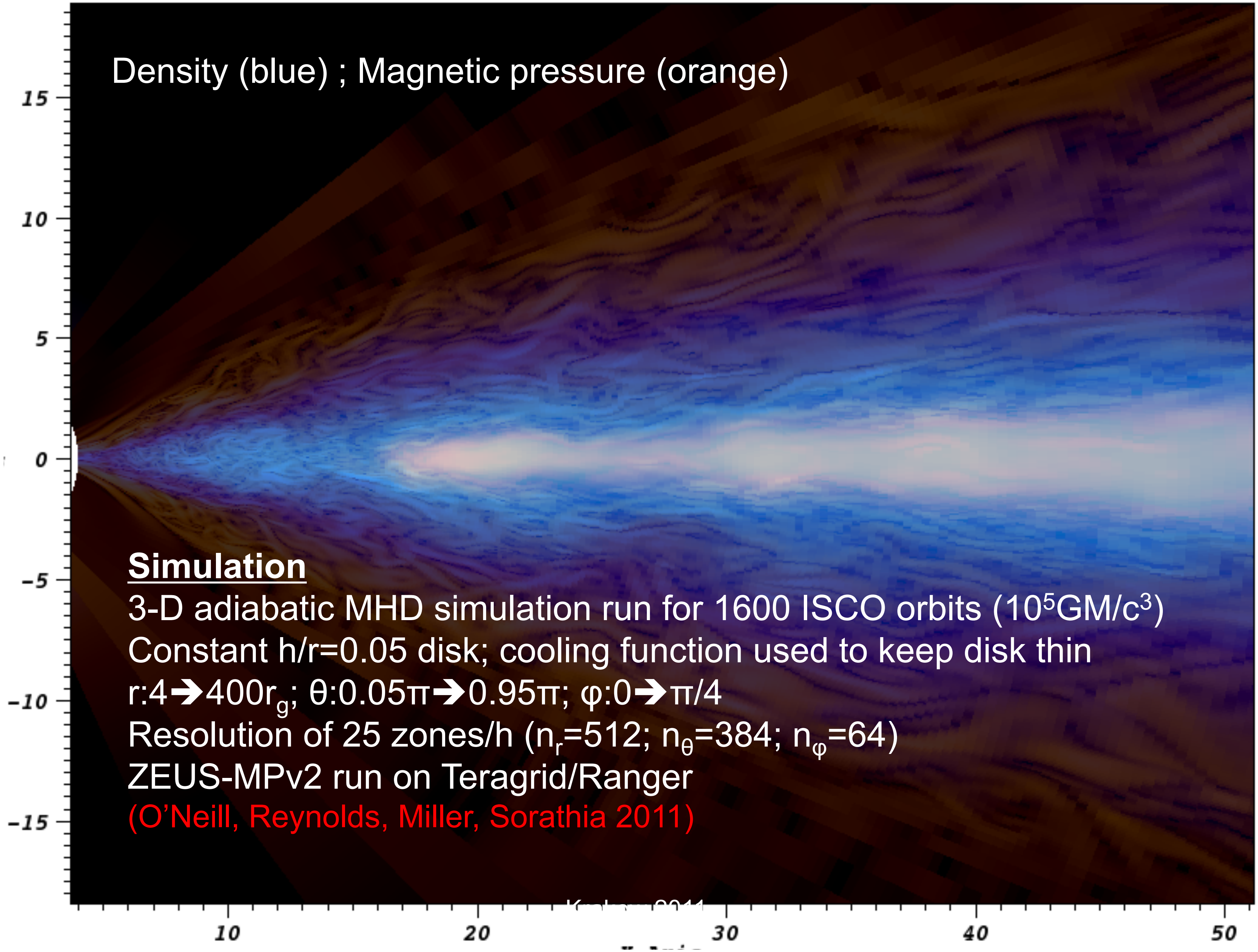
Sorathia, Reynolds & Armitage (2010)
Beckwith, Armitage & Simon (2011)

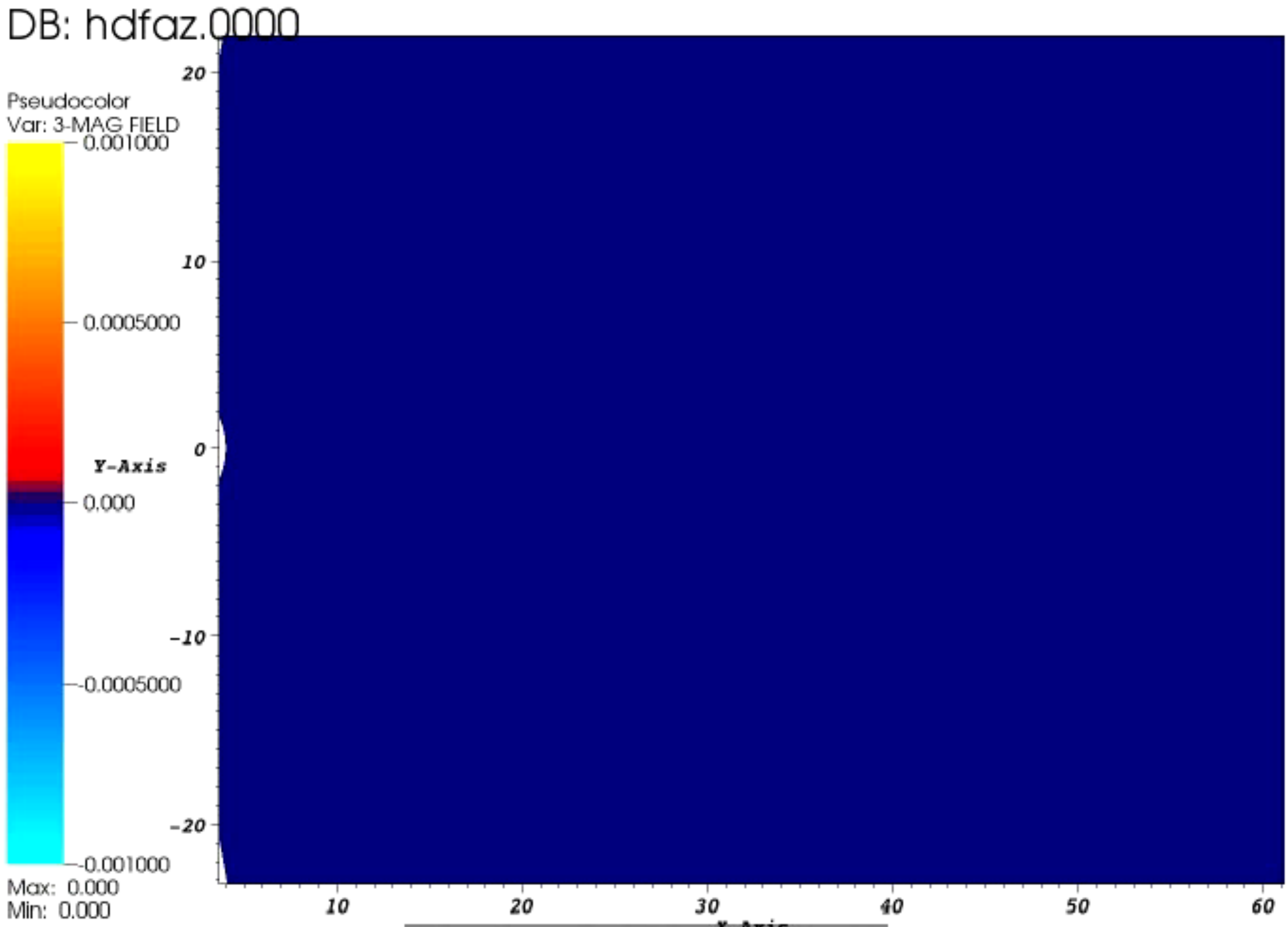
II : What is the nature of variability in accreting systems?

- Strong variability is generic feature of accreting systems
  - Not surprising since these are turbulent MHD systems
- Both aperiodic and quasi-periodic variability seen
  - QPOs especially interesting since they may be revealing fundamental frequencies of the system

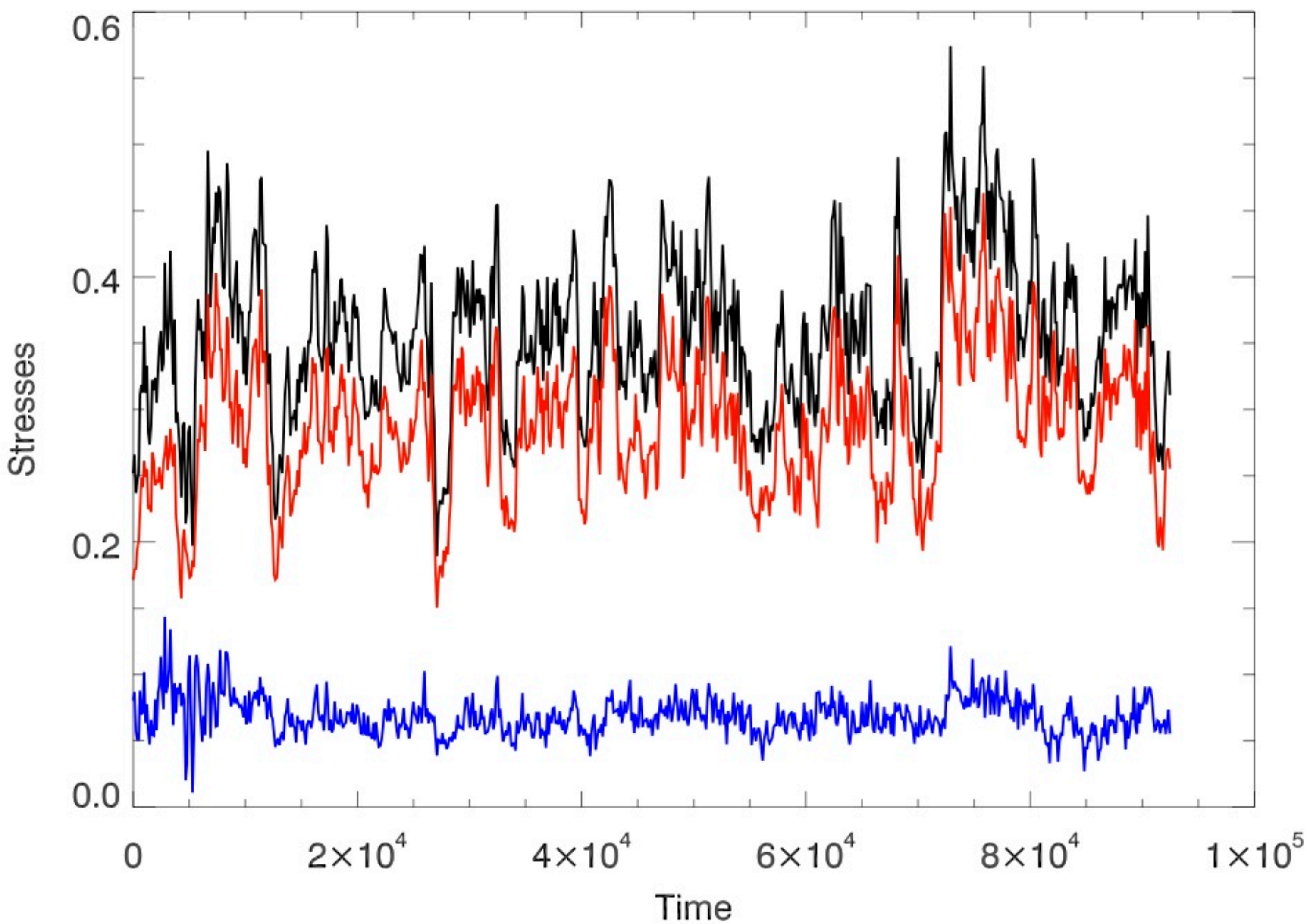


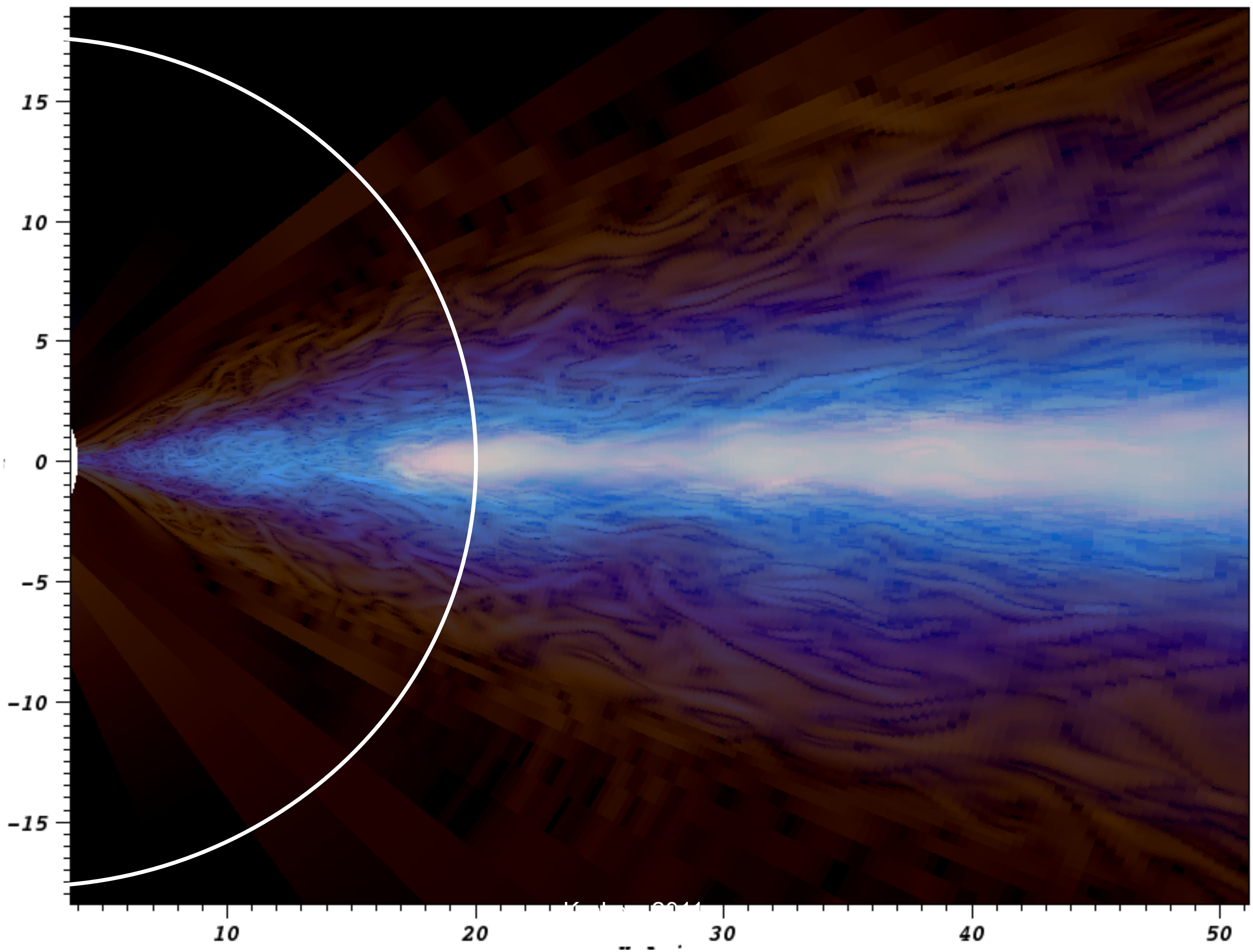
NGC3783 (Reis et al. 2011)


Density (blue) ; Magnetic pressure (orange)
Simulation
3-D adiabatic MHD simulation run for 1600 ISCO orbits (10^5GM/c^3)
Constant h/r=0.05 disk; cooling function used to keep disk thin
r:4→400r_g; θ:0.05π→0.95π; φ:0→π/4
Resolution of 25 zones/h (n_r=512; n_θ=384; n_φ=64)
ZEUS-MPv2 run on Teragrid/Ranger
(O'Neill, Reynolds, Miller, Sorathia 2011)
15
10
5
0
−5
−10
−15
10
20
30
40
50

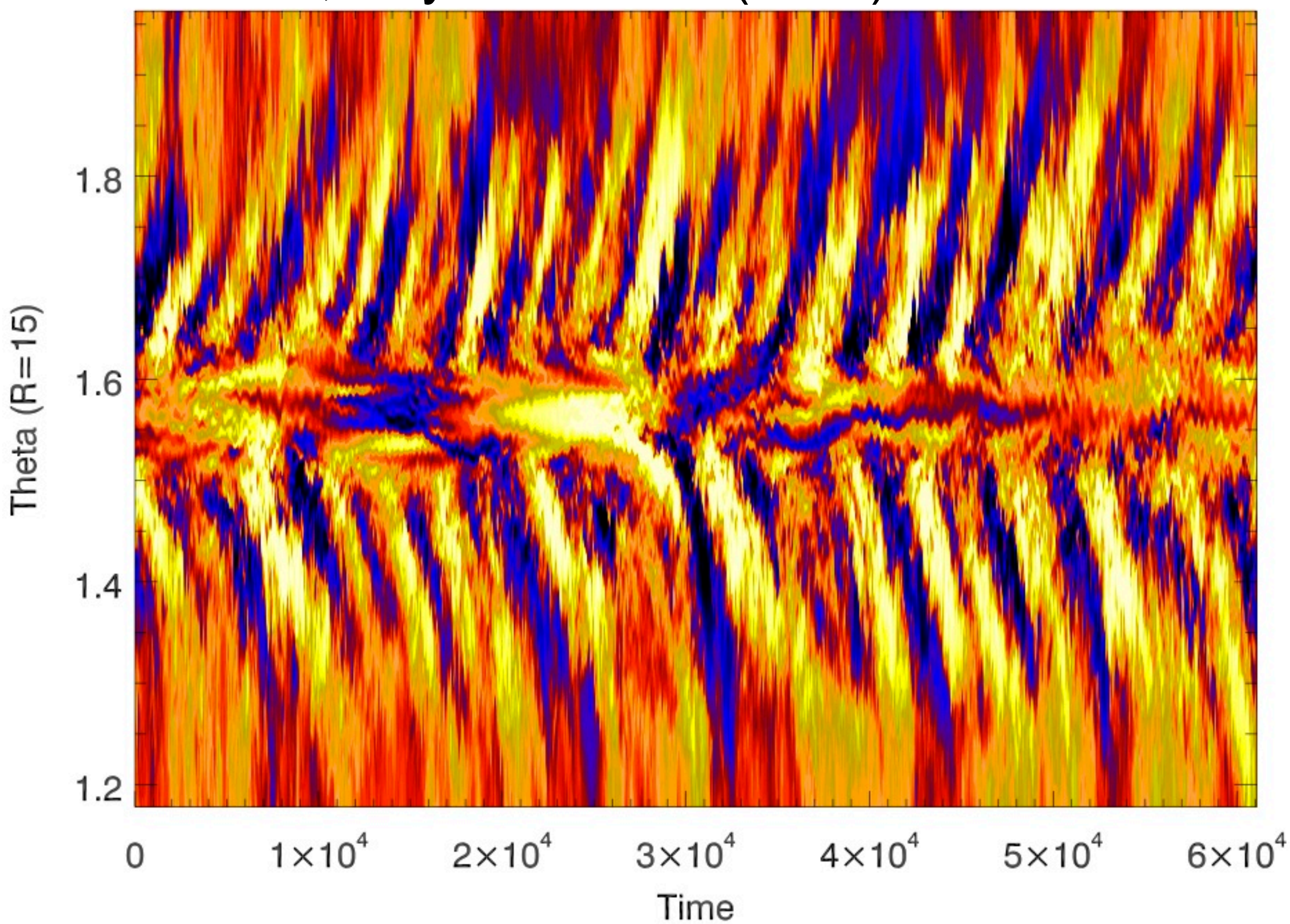

DB: hdfaz.0000
Pseudocolor
Var: 3-MAG FIELD
0.001000
0.0005000
0.000
-0.0005000
-0.001000
Max: 0.000
Min: 0.000
Y-Axis
20
10
0
-10
-20
X-Axis
10
20
30
40
50
60

Stresses (Reynolds, Maxwell, Total)

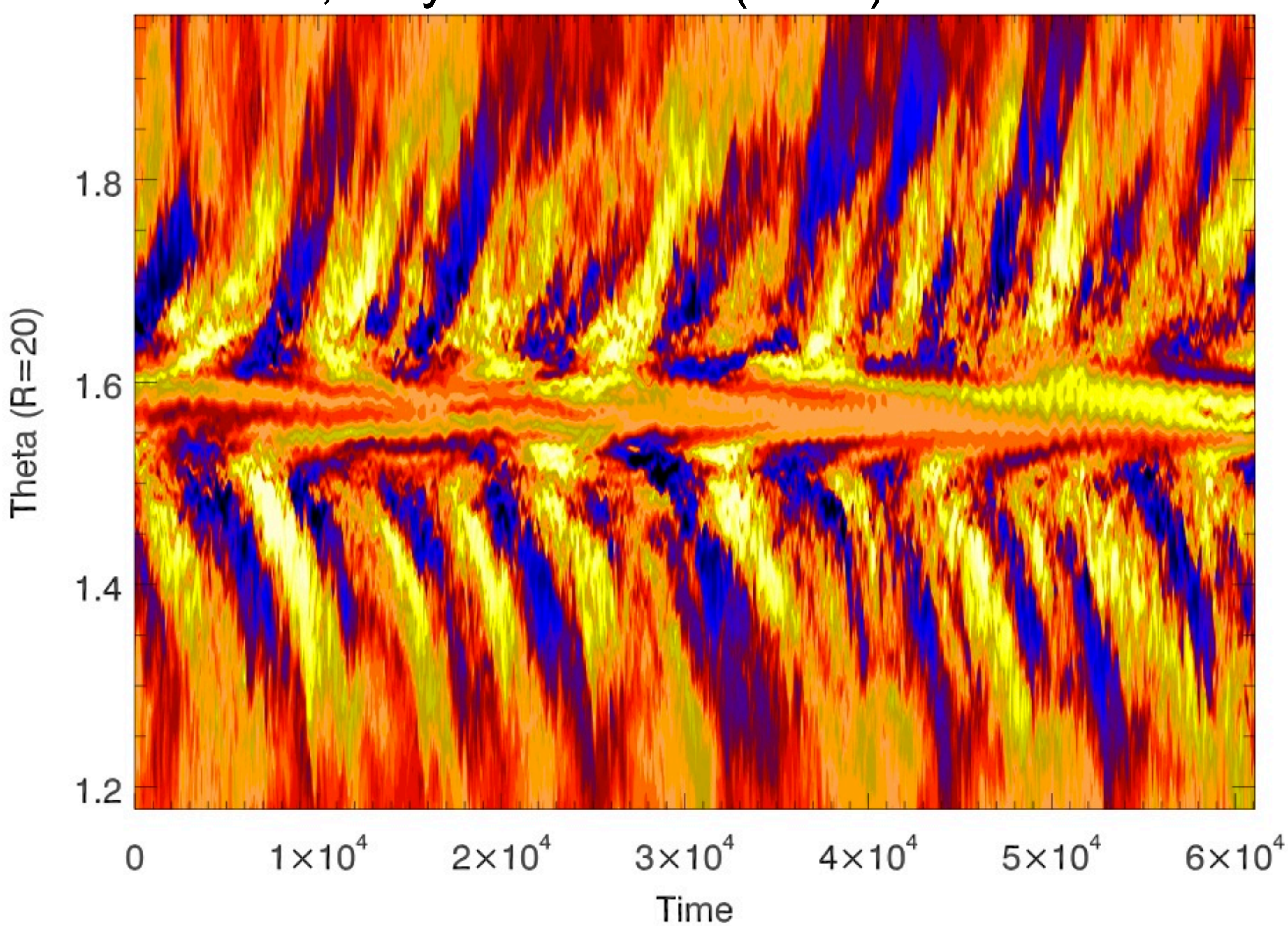



15
10
5
0
−5
−10
−15
10
20
30
40
50

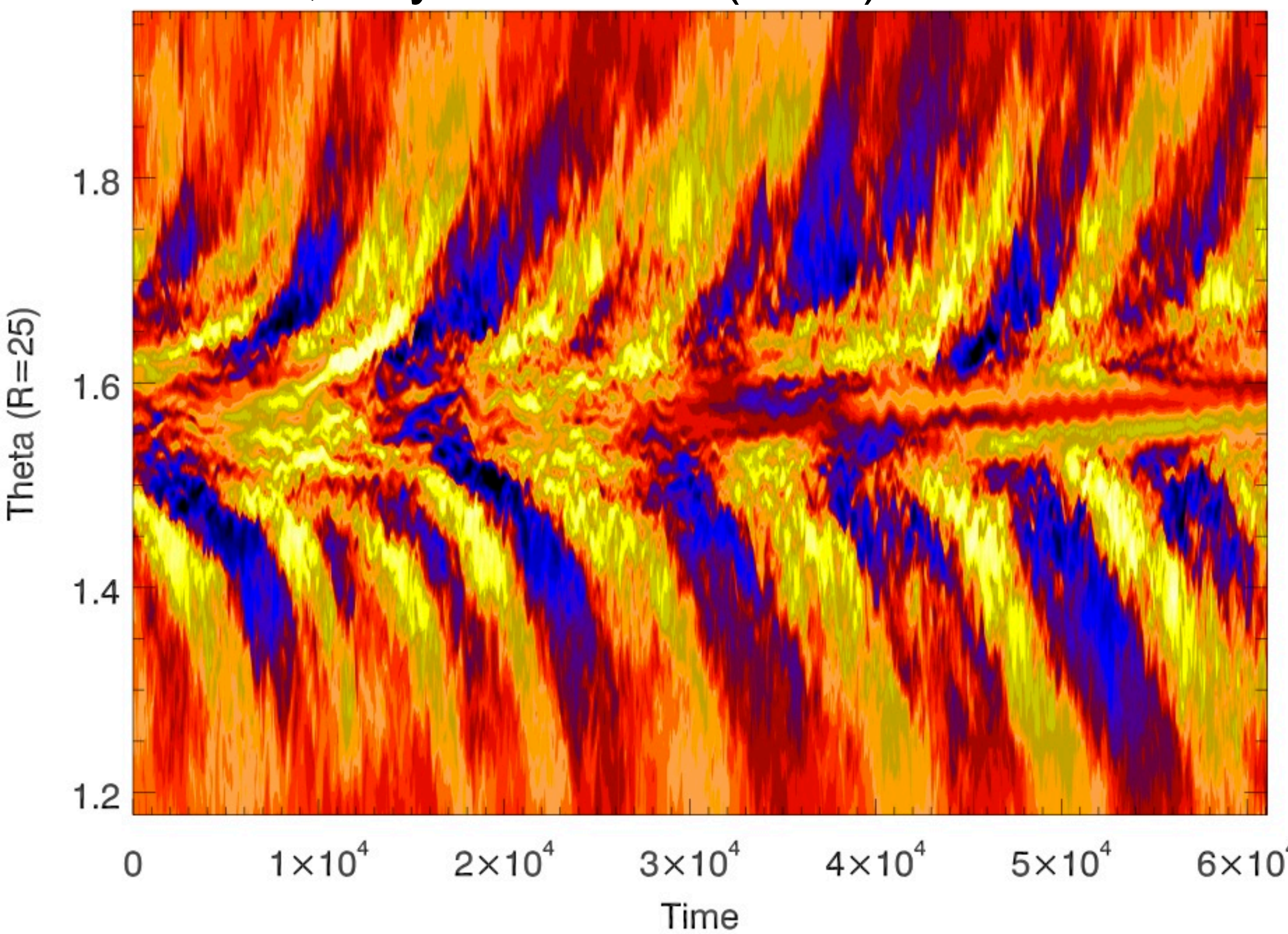
O'Neill, Reynolds et al. (2011)



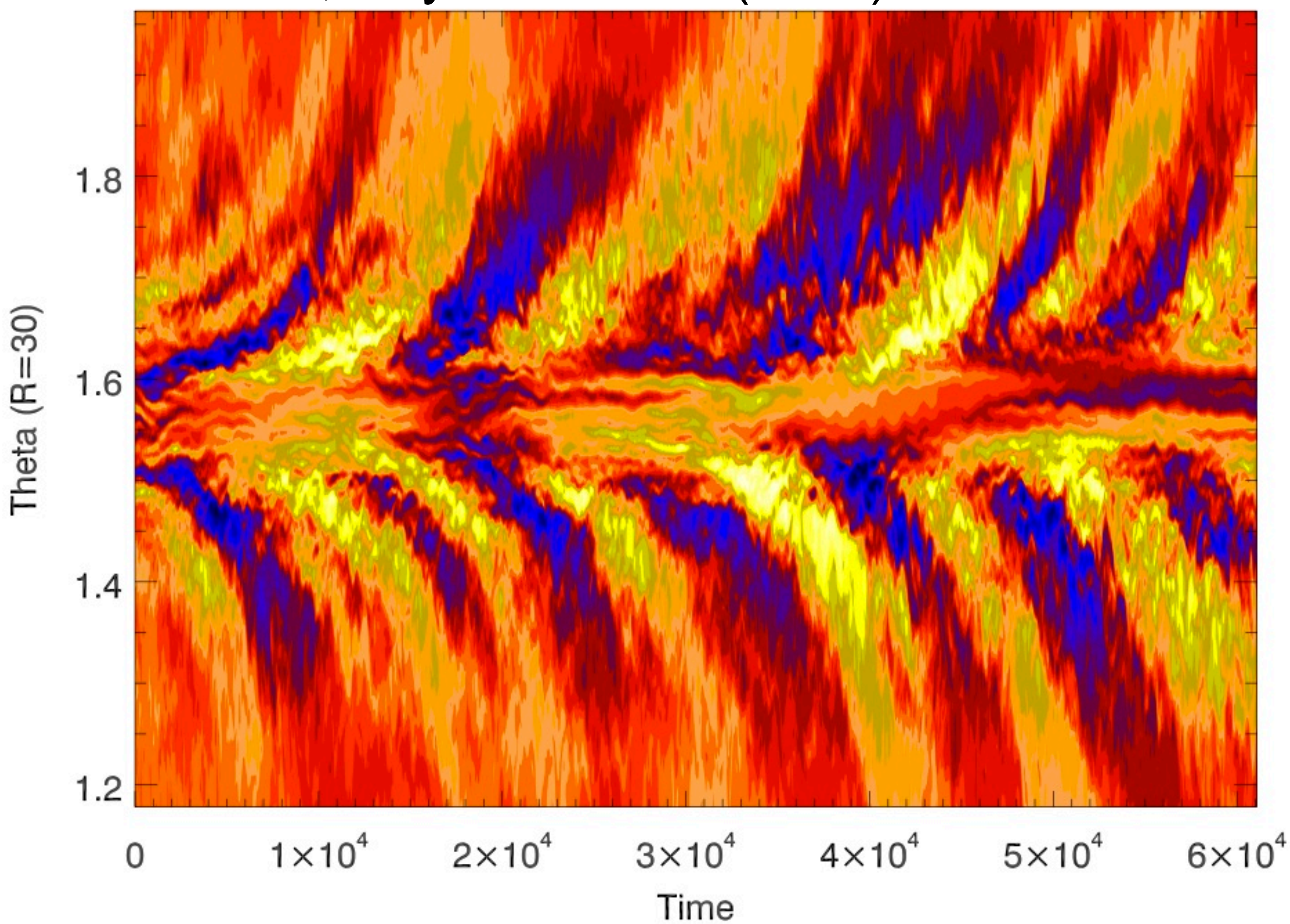
O'Neill, Reynolds et al. (2011)

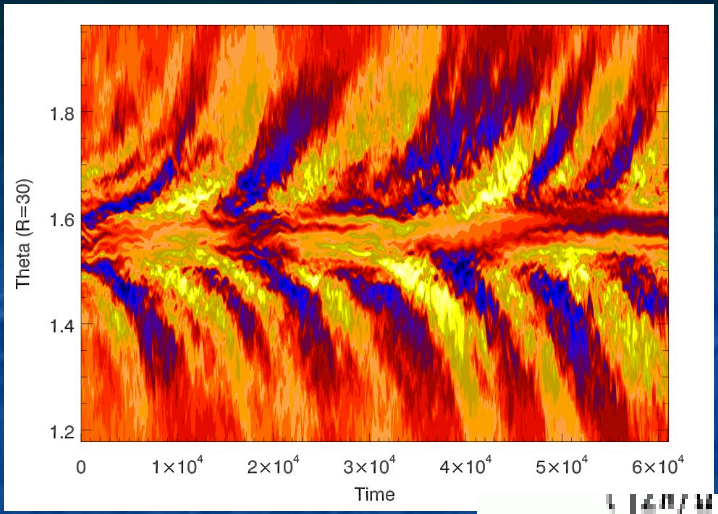


O'Neill, Reynolds et al. (2011)



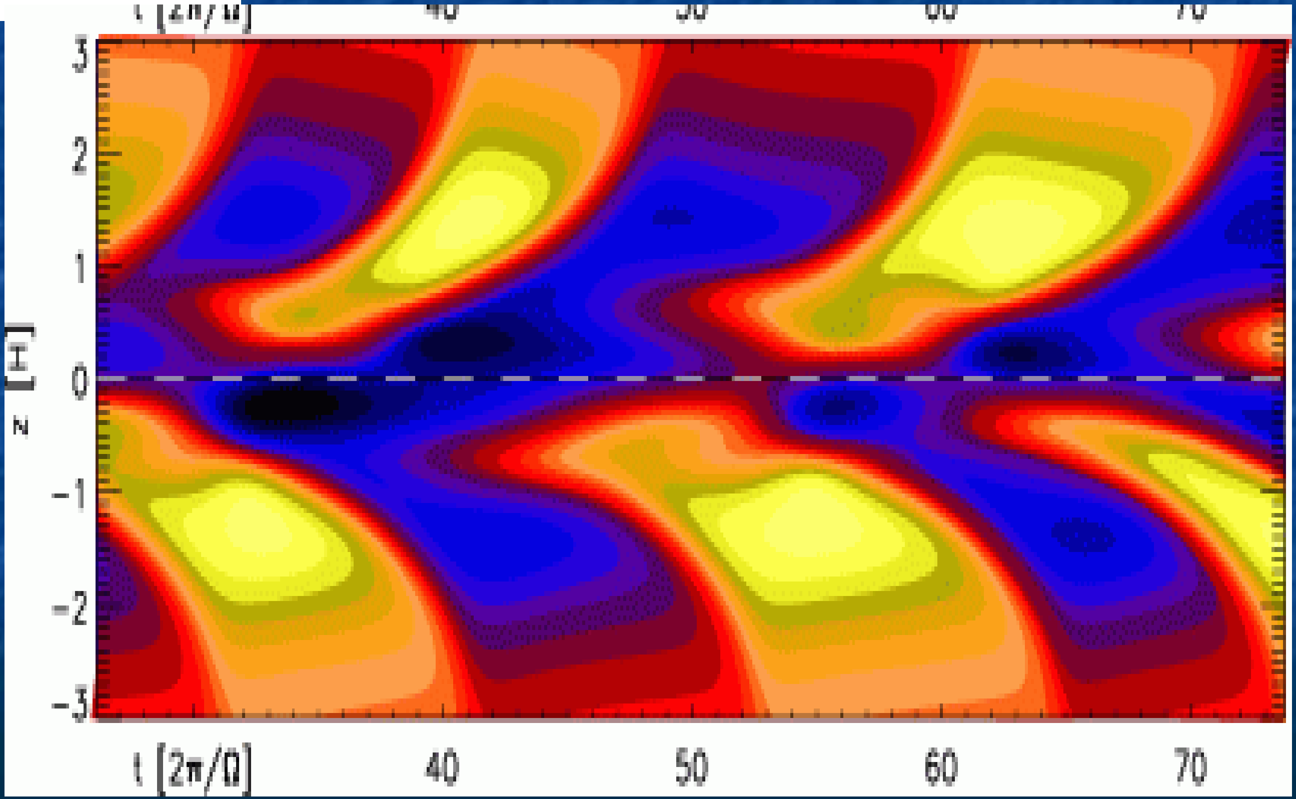
O'Neill, Reynolds et al. (2011)

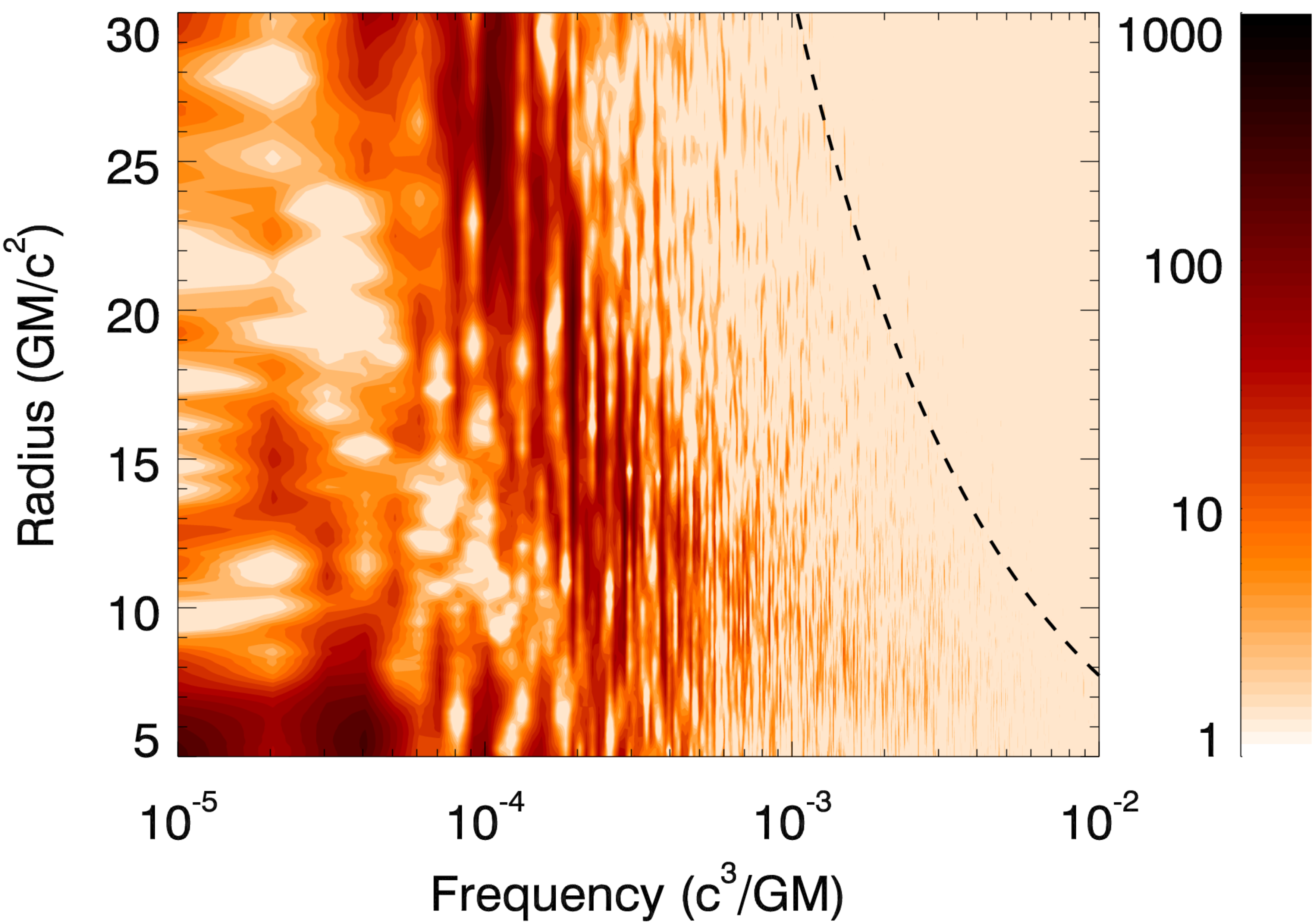




We are seeing a dynamo cycle!

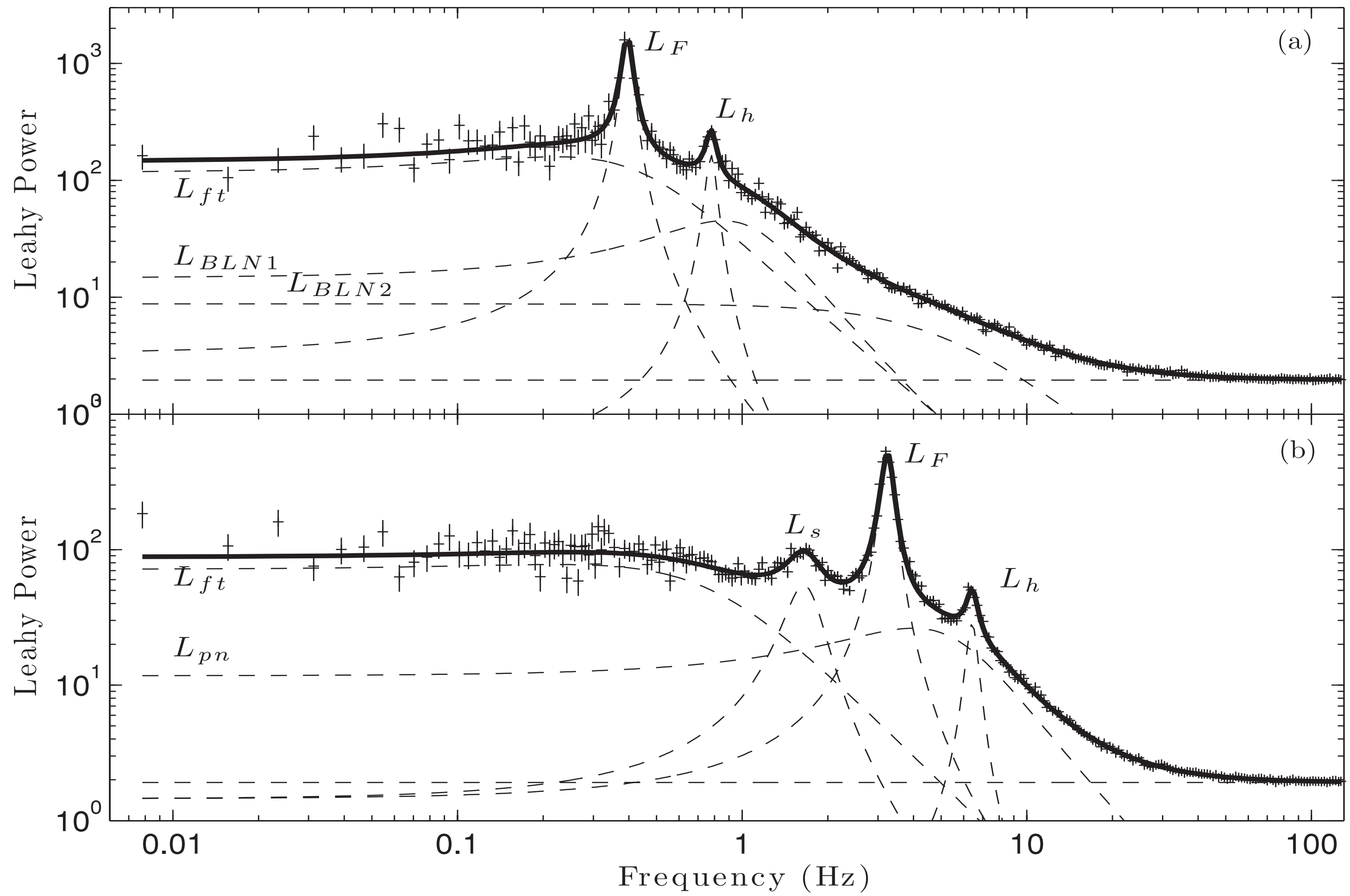
Mean field dynamo model
(Gressel 2010)

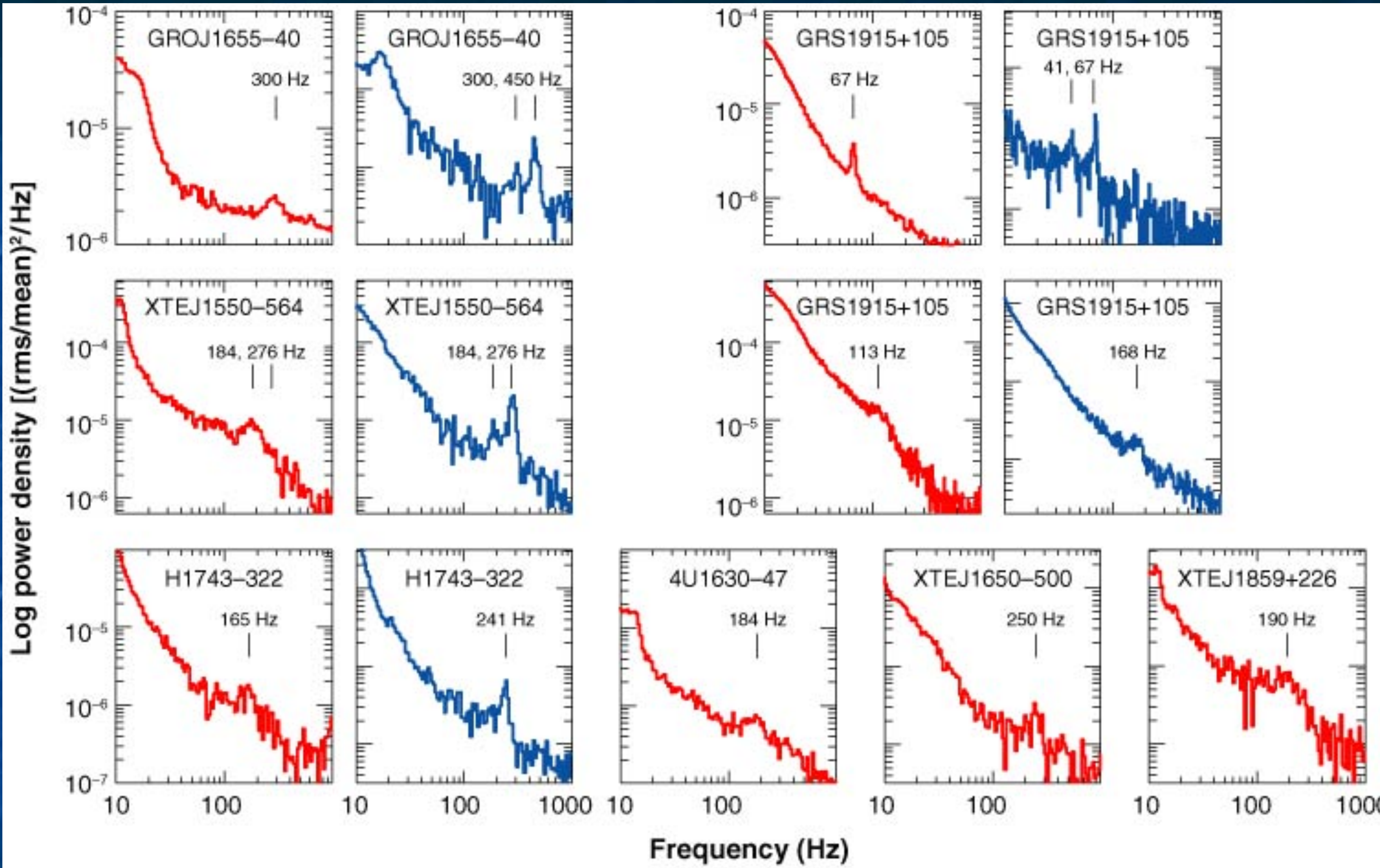




O'Neill, Reynolds et al. (2011)

XTEJ1550-564; Rao et al. (2010)



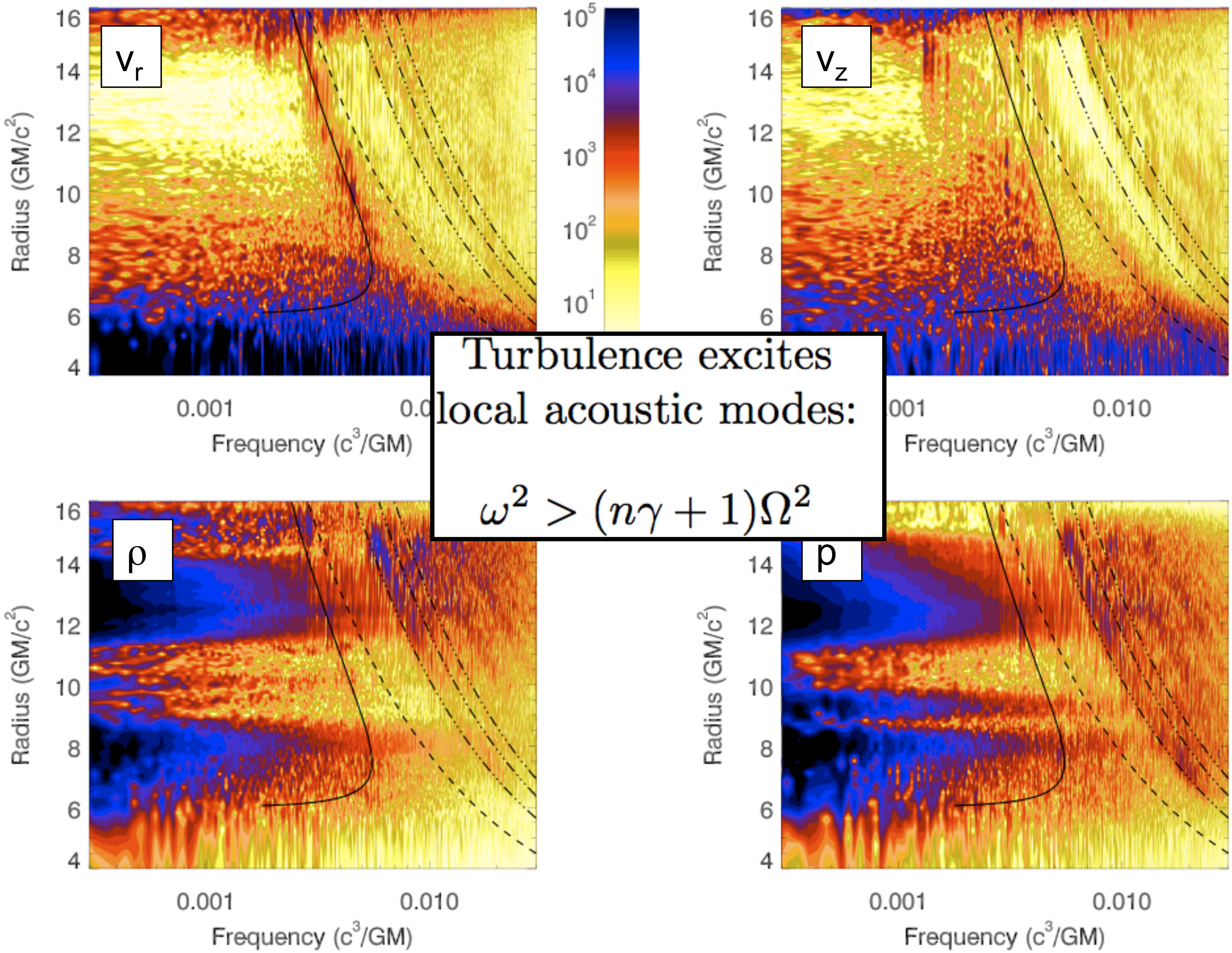


Remillard RA, McClintock JE. 2006.
Annu. Rev. Astron. Astrophys. 44:49–92

High-frequency QPOs

Turbulence excites local acoustic modes:

$$\omega^2 > (n\gamma + 1)\Omega^2$$



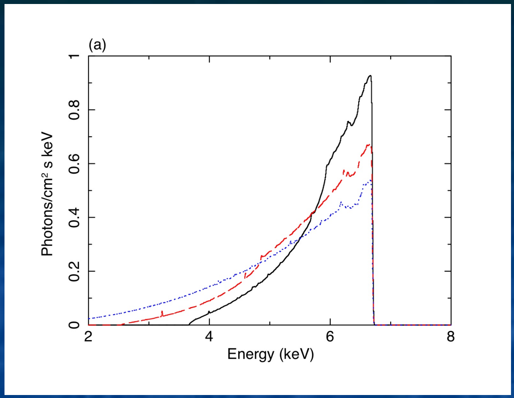
III : Black hole physics…

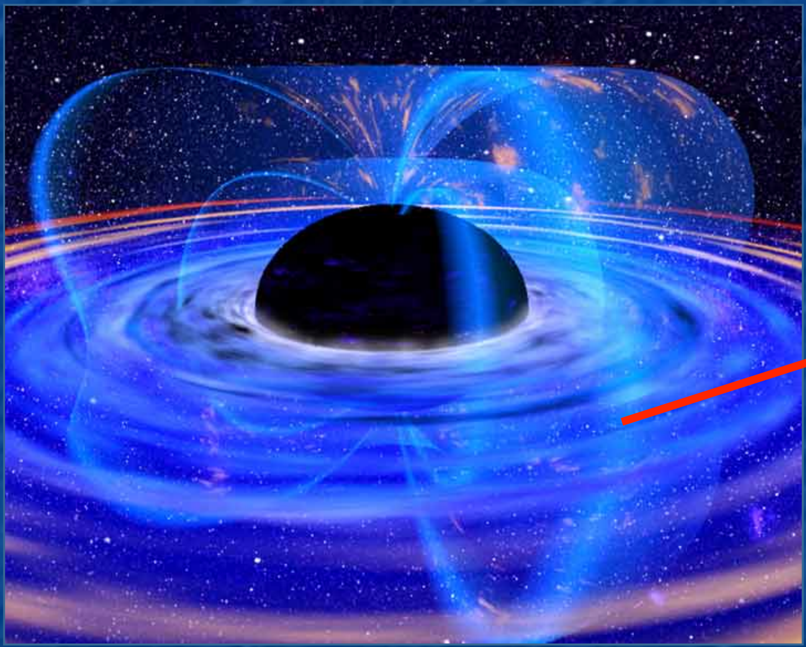
- To date, only way to study black hole itself is to look at accretion-related phenomena

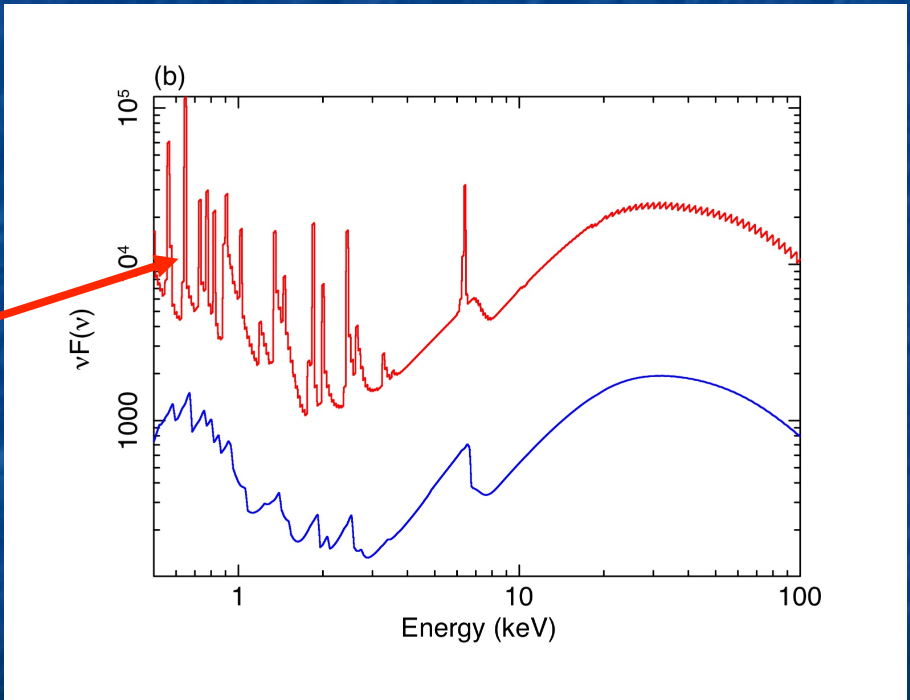
- Will address two specific questions
  - How fast are black holes spinning?
  - What is interaction of spin with inner accretion disk?

- Will focus discussion on the use of X-ray reflection spectroscopy (and some targeted simulations) to address these questions

X-rays from corona/jet irradiate accretion disks… creates a backscattered spectrum rich in spectral features

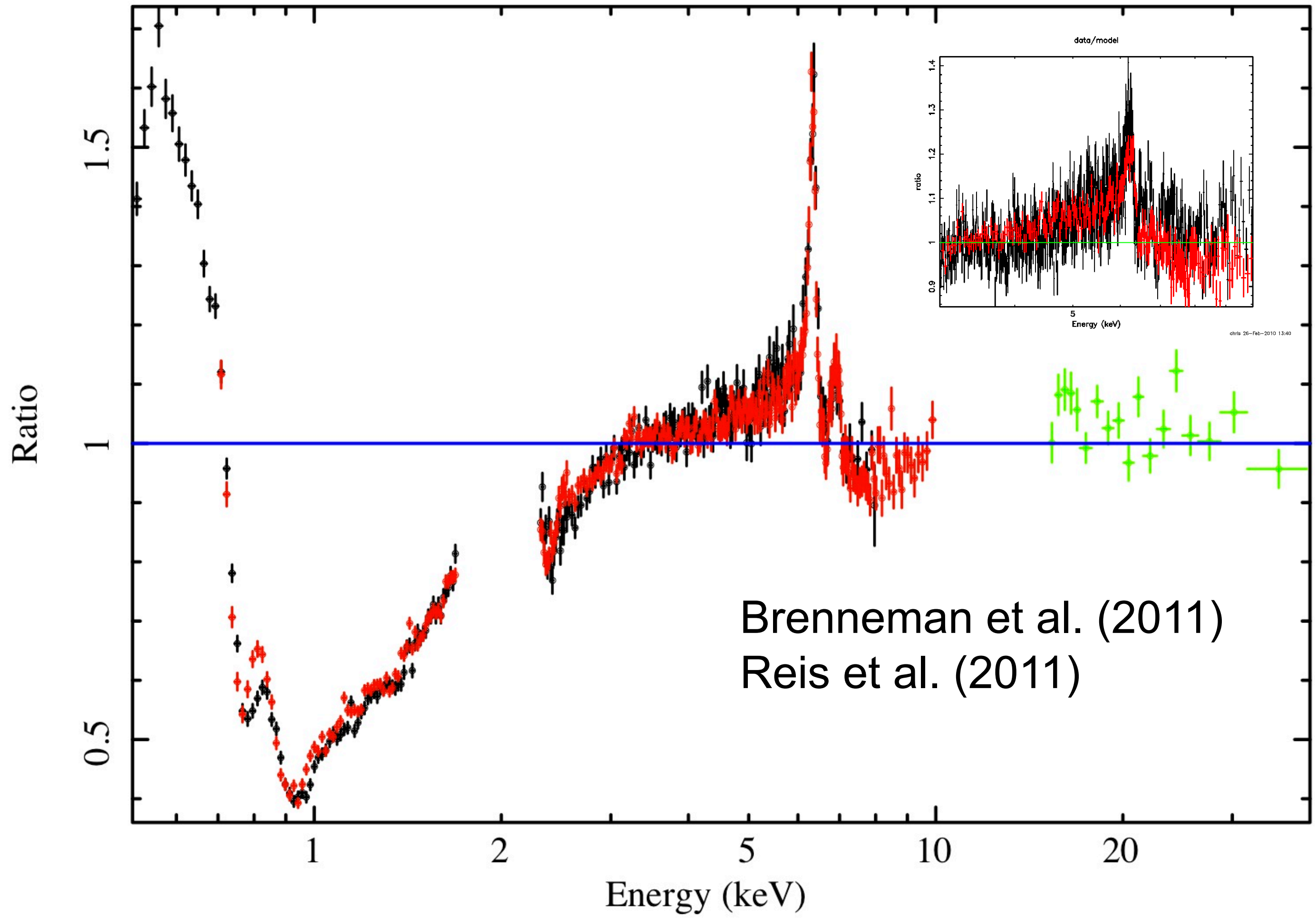




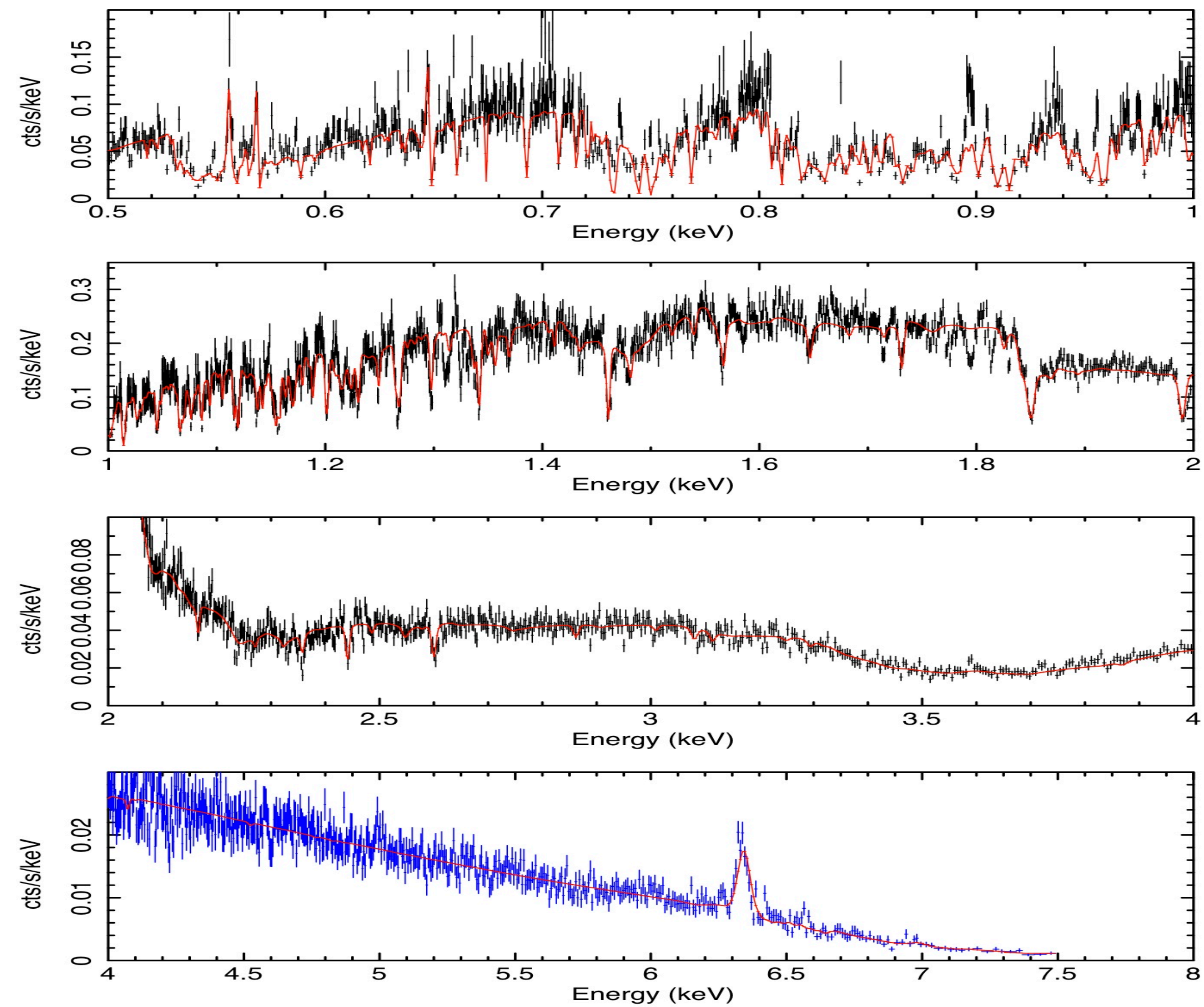


Calculations of spectrum emitted by accretion disk in response to X-ray irradiation (Ross & Fabian 2005)

NGC3783 (Suzaku Key Project; PI Reynolds)

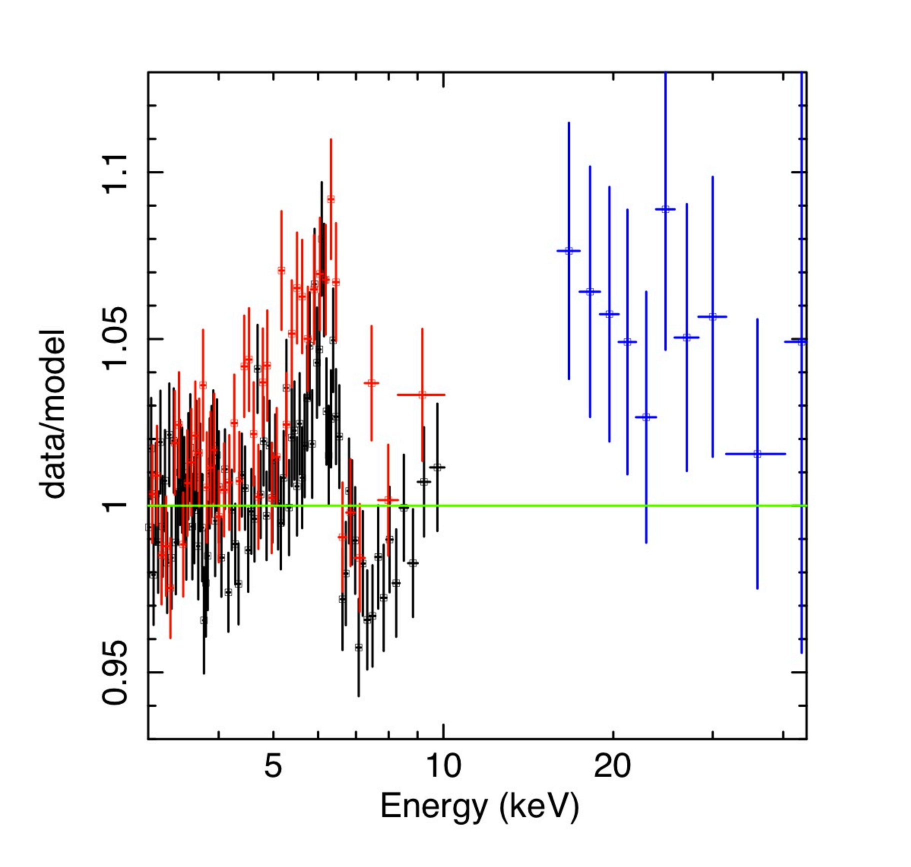


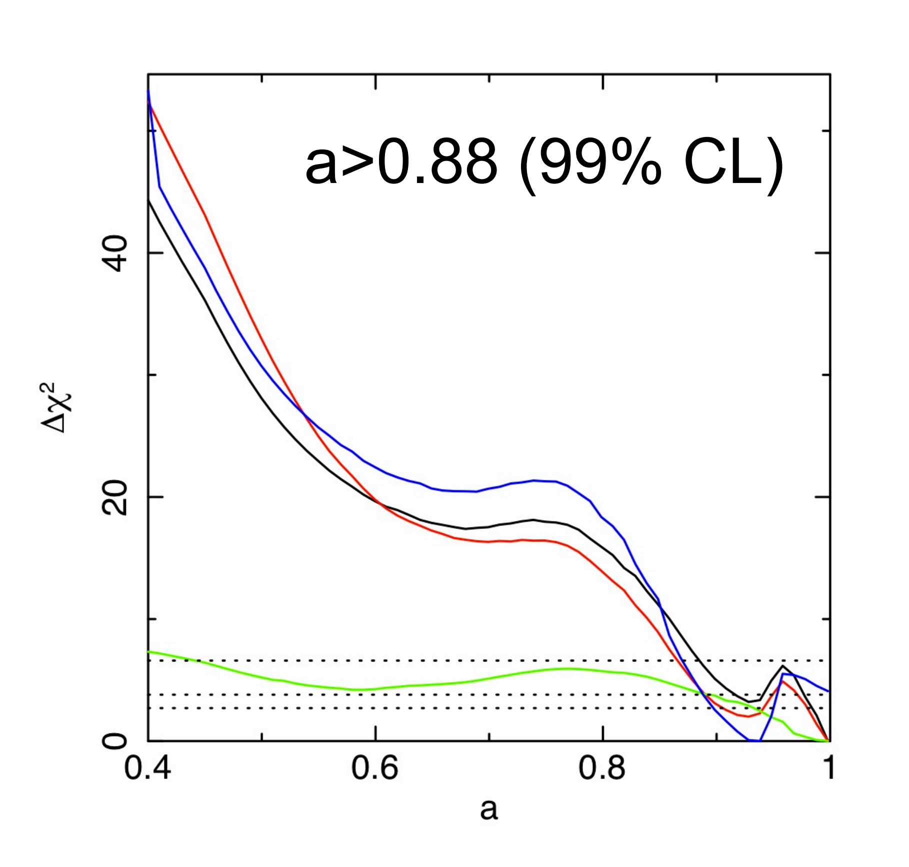
900ks Chandra/HETG (e.g. see Krongold et al. 2003, Netzer et al. 2003)



Krakow 2011

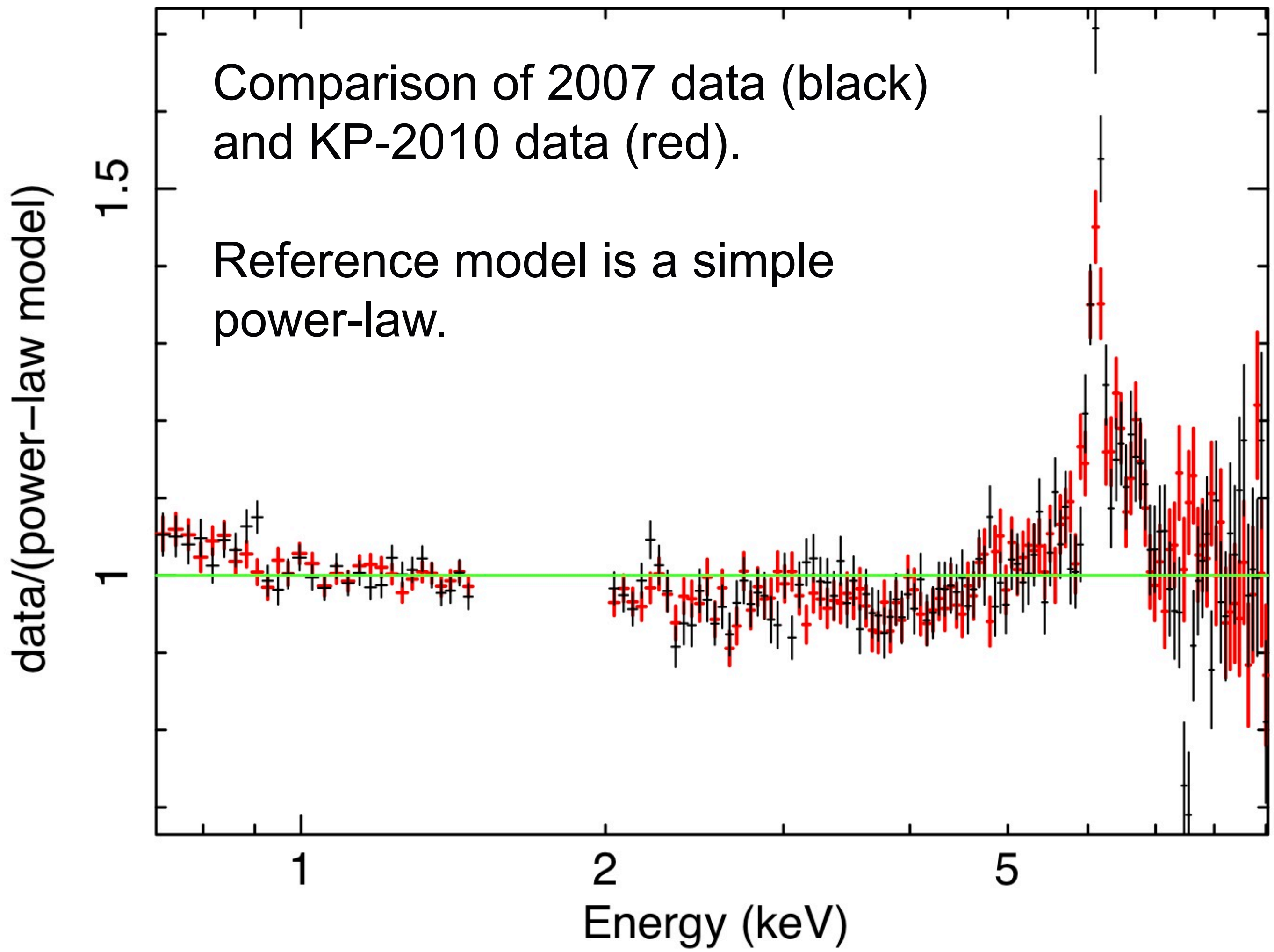
Constraints on BH spin

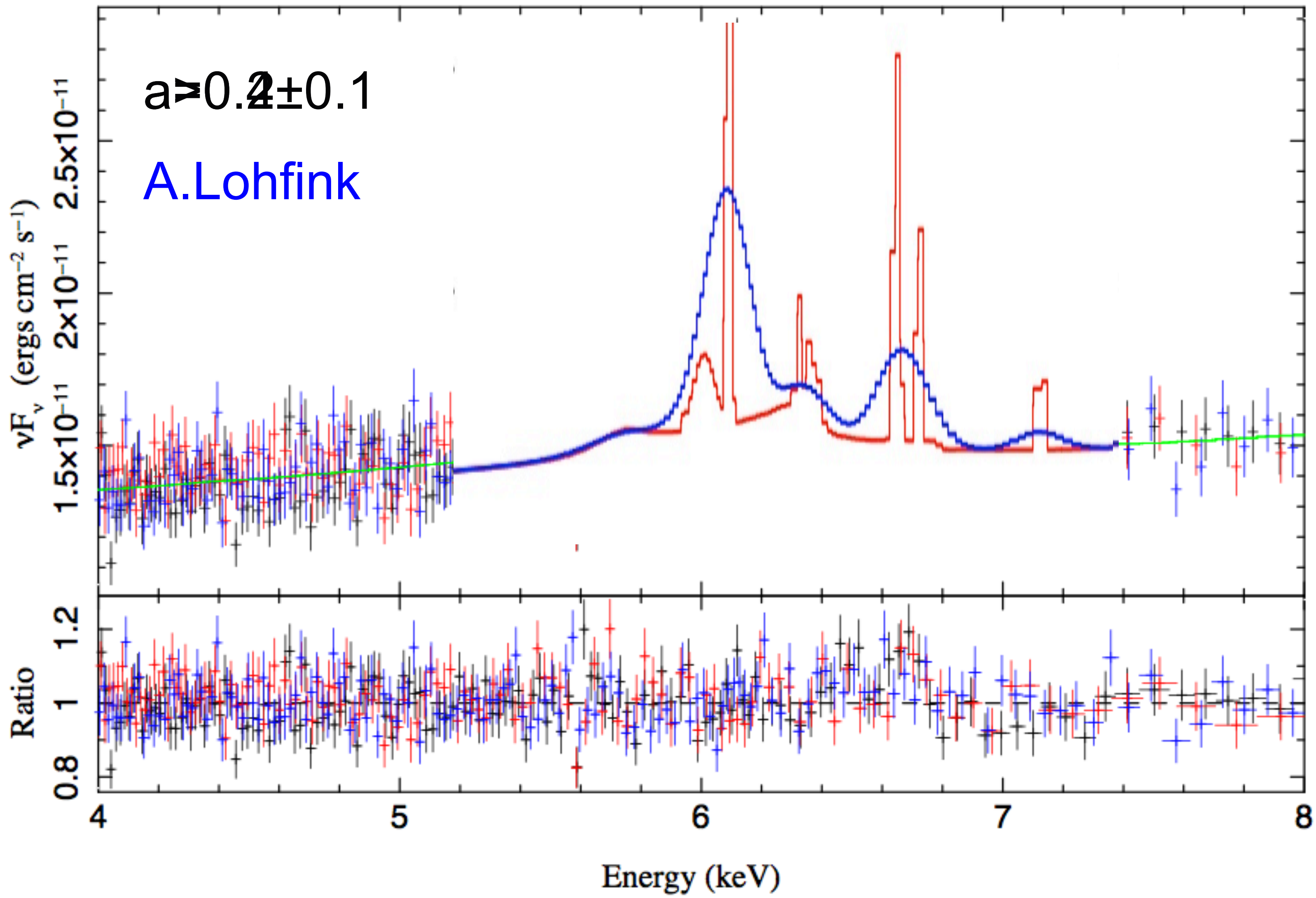




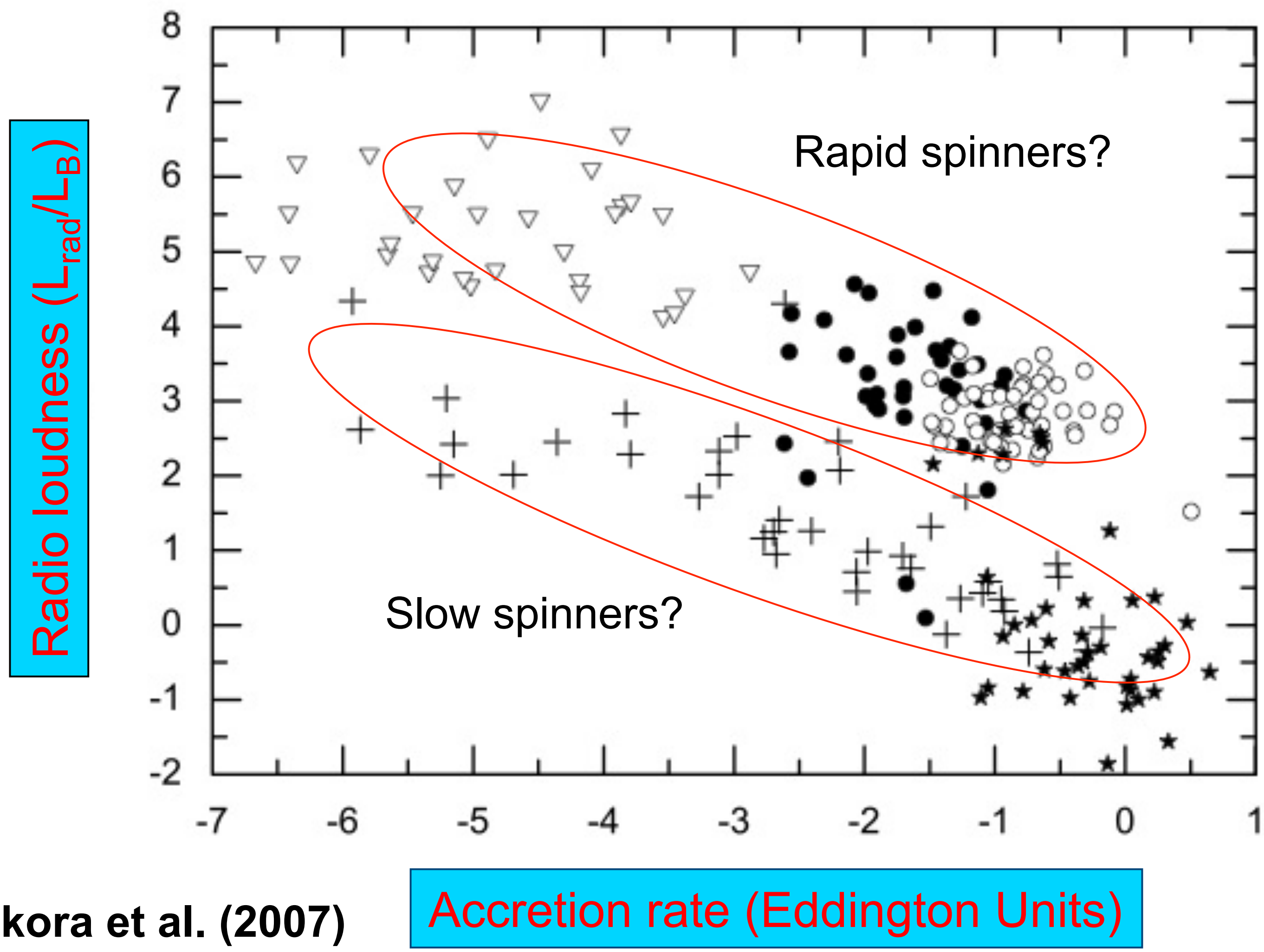
Relativistically smeared disk reflection robustly detected (even including a partial covering multizone warm absorber, strong residuals remain if we don't include disk component)

Fairall 9


Comparison of 2007 data (black)
and KP-2010 data (red).
Reference model is a simple
power-law.
data/(power−law model)
1.5
1
1
2
5
Energy (keV)

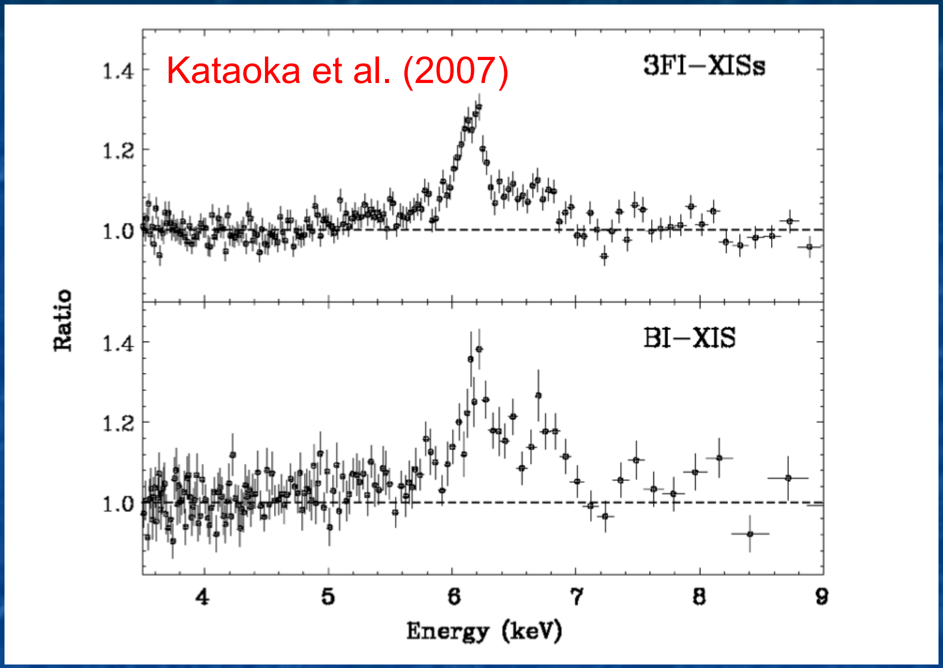

a=0.2±0.1
a>0.4
A.Lohfink
νFν (ergs cm⁻² s⁻¹)
1.5×10⁻¹¹
2×10⁻¹¹
2.5×10⁻¹¹
Ratio
0.8
1
1.2
4
5
6
7
8
Energy (keV)

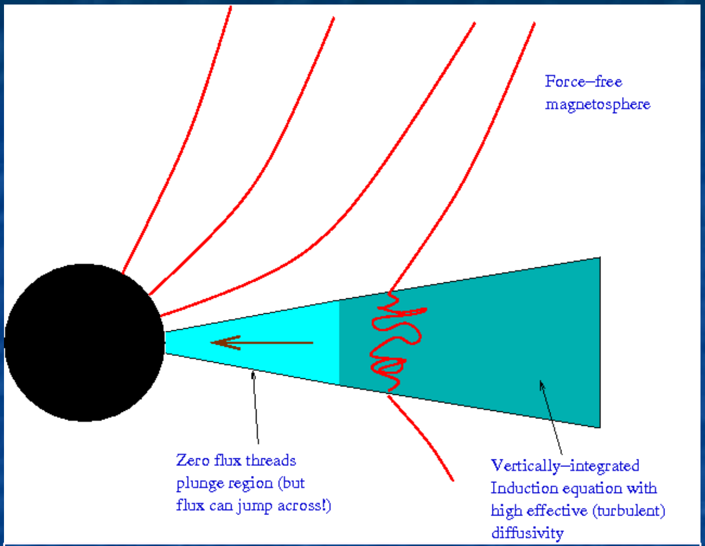
The radio-quiet/radio-loud dichotomy in AGN



Sikora et al. (2007)

RL AGN : 3C120





Reynolds, Garofalo & Begelman (2006)
Garofalo (2009)

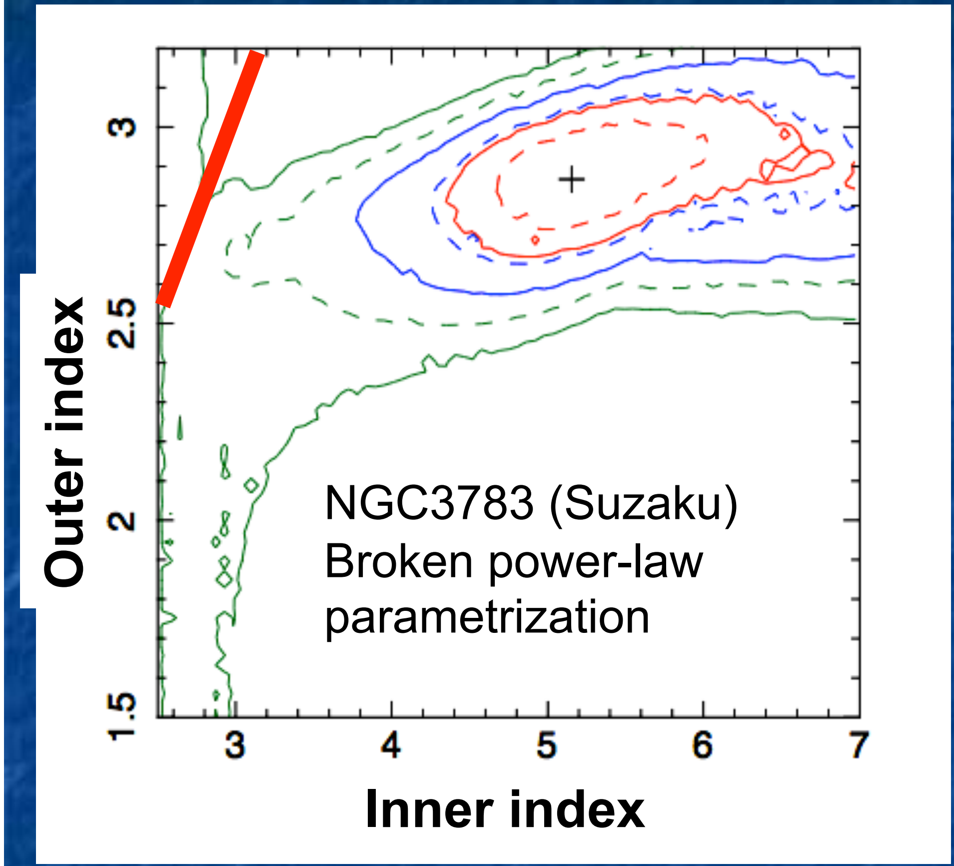
Superluminal motion (8c) ➔ jet-axis <14 degrees from l-o-s

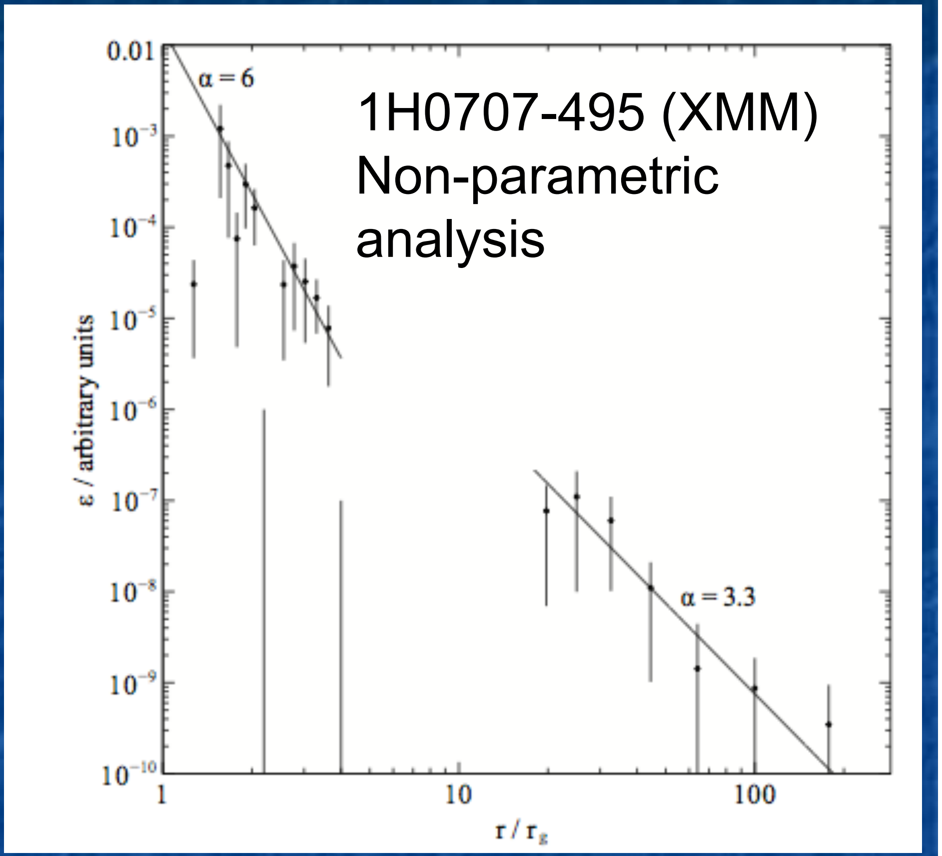
Current Suzaku data :
- i ≈10 degrees ; consistent with jet aligned with disk
- $r_{in} \approx 10 r_g$, ISCO around a rapidly rotating retrograde black hole

Probing disk physics with X-ray reflection spectroscopy

- Several handles on the inner disk from relativistically smeared disk reflection
  - Existence of reflection features → optically-thick disk
  - Ionization state of inner disk (Ballantyne et al. 2011)
    - Finds $\xi \sim L_{bol}/L_{edd}$
    - Flatter than predicted by simple disk theory, $\xi \sim (L_{bol}/L_{edd})^3$
  - Radial run of X-ray irradiation of disk ("emissivity profile")
  - Relative strength of reflection & direct continuum ("R")

Irradiation profiles



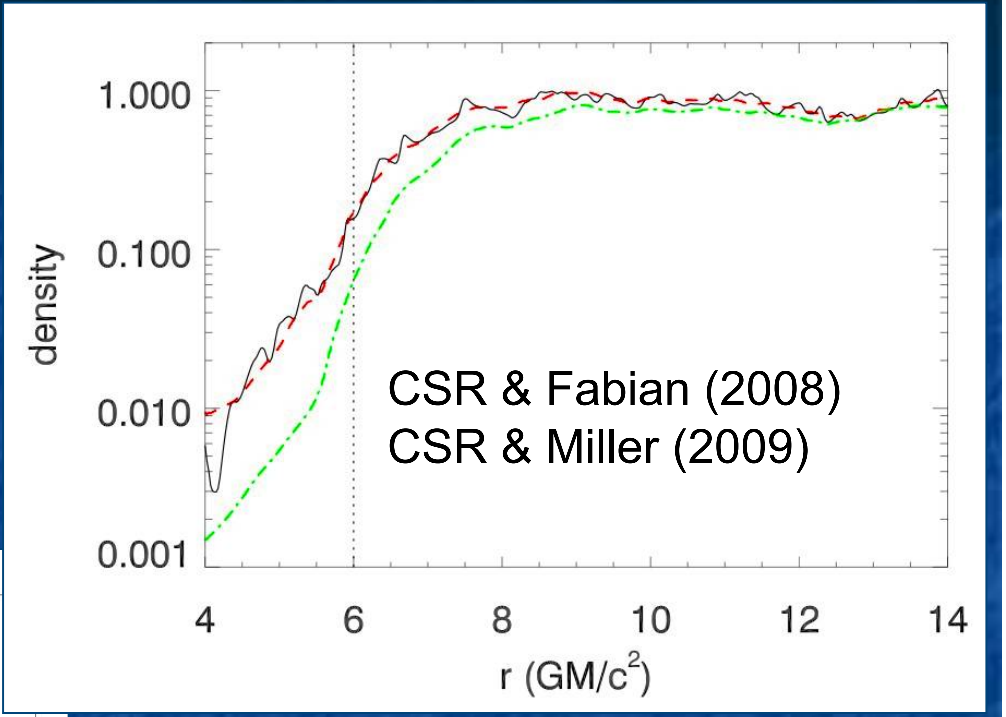


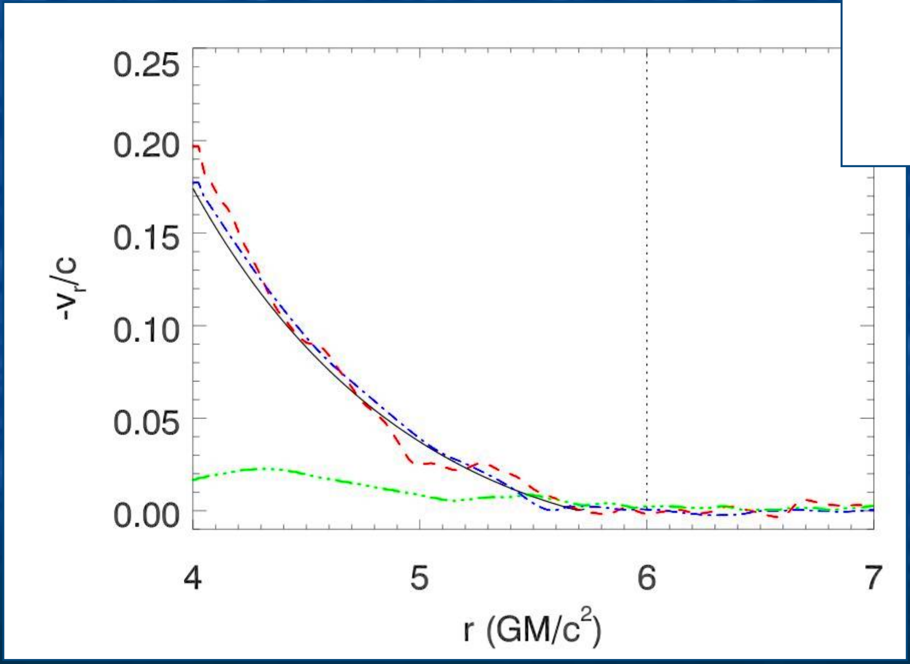
Brenneman, CSR et al. (2011)
[also Wilms, CSR et al. 2001]

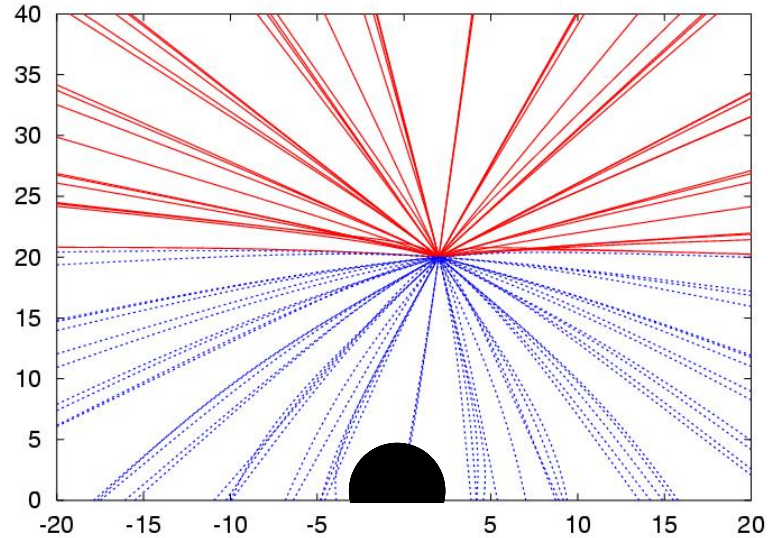
Wilkins & Fabian (2011)

- What does a steep emissivity profile mean?
- Local X-ray corona above "standard" Novikov-Thorne disk
  - Then, need fraction of energy dissipated in corona decreases strongly with radius
- Local corona which receives some fixed fraction of the energy dissipated in underlying disk
  - Then, need dissipation to increase strongly with decreasing radius (strong stress at ISCO?)
  - Subject of debate whether this notion is supported by simulations (Noble et al. 2010; Penna et al. 2010)
- X-rays from high-altitude structure
  - Gravitational light bending naturally gives centrally concentrated emissivity profile

Truncation of iron line at ISCO depends on density – the debate over stress at the ISCO is largely irrelevant to iron line spin measurements!



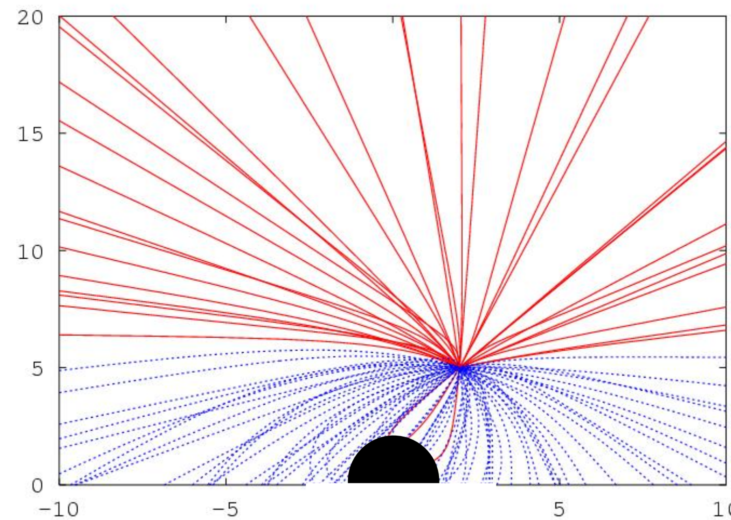


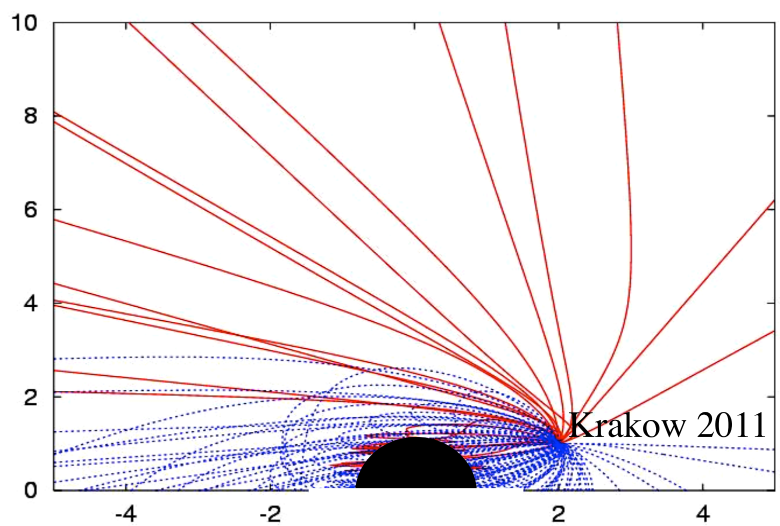


Primary source at h = 20 r_g
isotropy and R = 1

Red = escaping photons

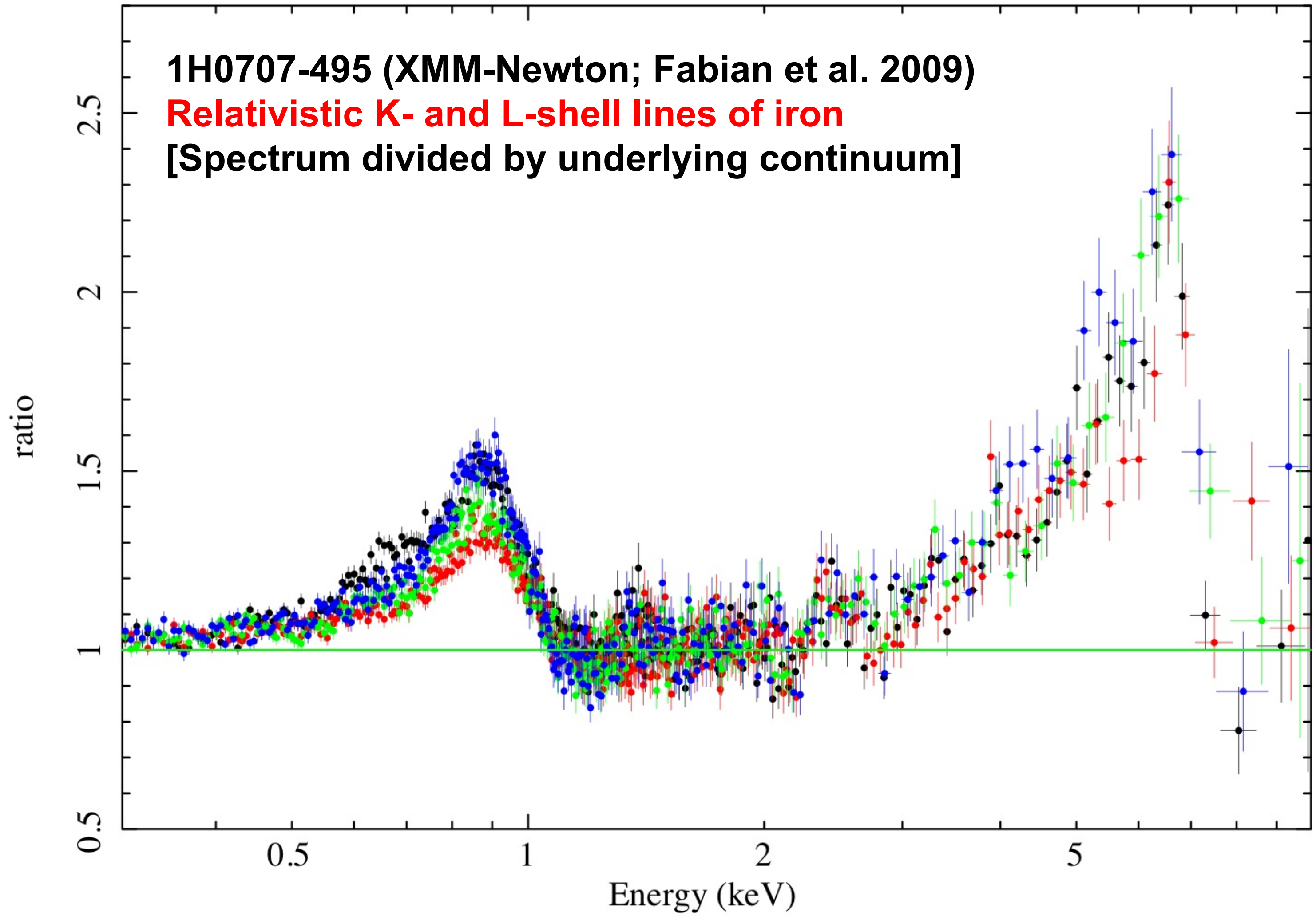
Primary source at h = 5 r_g
anisotropy and R > 1

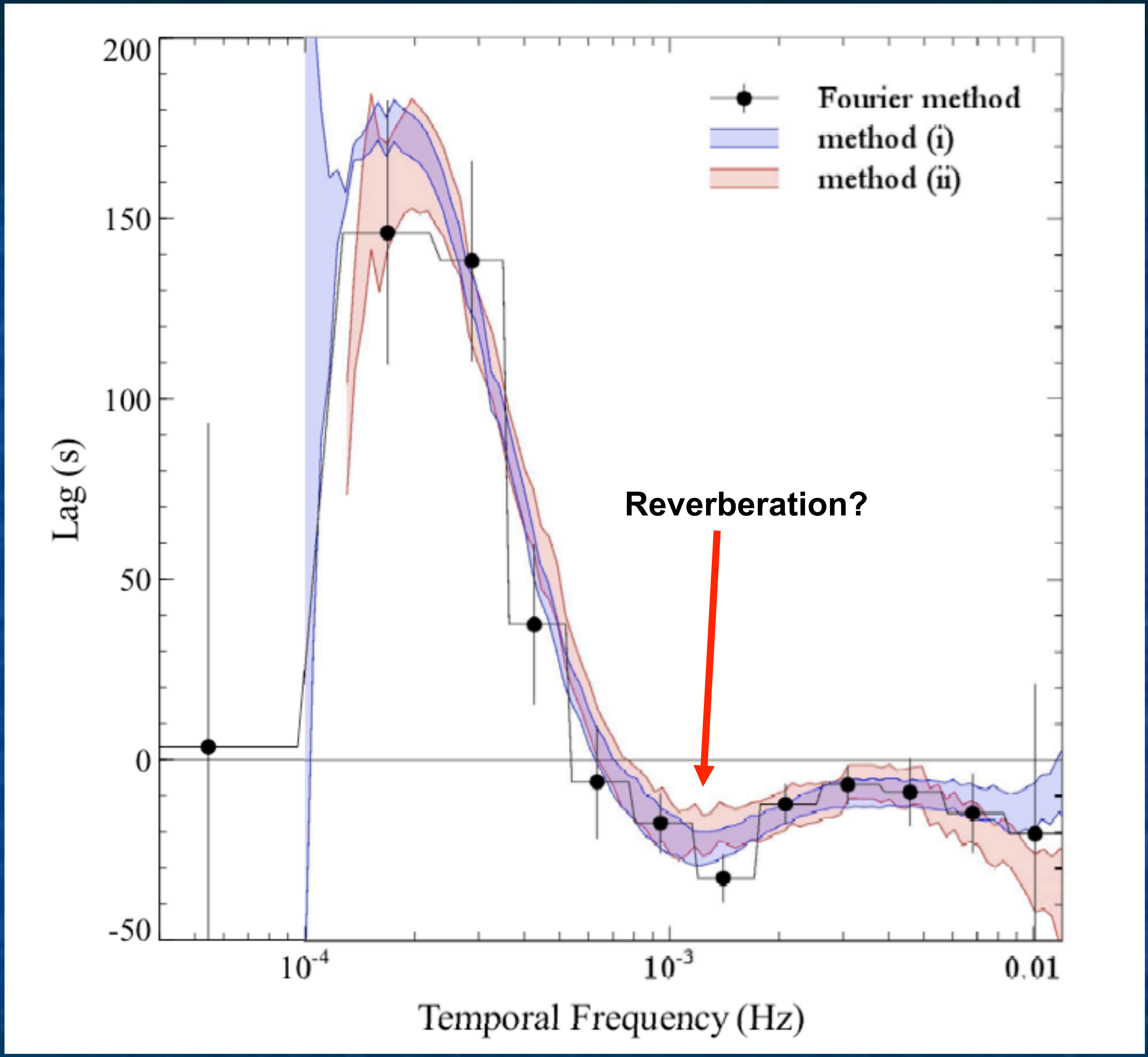




Primary source at h = 1 r_g
anisotropy and R >> 1

1H0707-495 (XMM)





Iron-L line vs continuum in 1H0707; Zoghbi et al. (2009)

Summary

- Disks accrete!
  - Global models do converge, but diagnosing convergence is subtle
  - Magnetic connectivity of disk important in determining stresses
  - When extracting alpha from decay curve, spatio-temporal fluctuations may skew result
- Time variability
  - Dynamo cycles are possible interesting source of LFQPOs
  - HFQPOs remain mysterious… global g-modes and resonances not supported by simulations
- Inner disk and spin-related astrophysics
  - Spin measurements from X-ray reflection spectroscopy
  - Very steep irradiation profiles in inner disk… evidence points to light bending effects, at least in some sources