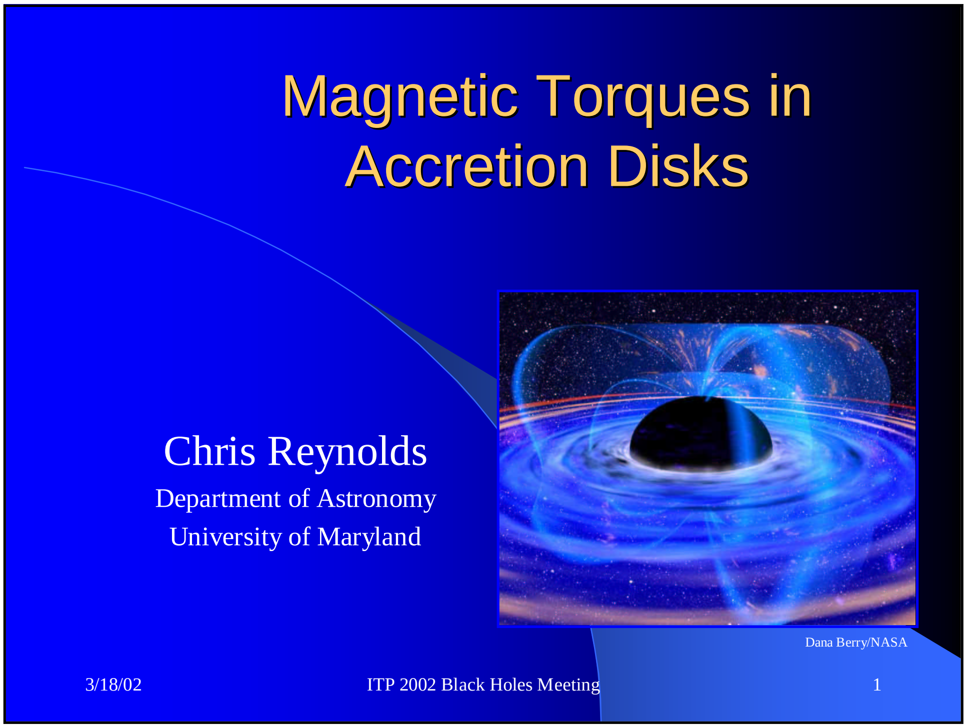
Magnetic Torques in
Accretion Disks
Chris Reynolds
Department of Astronomy
University of Maryland
Dana Berry/NASA
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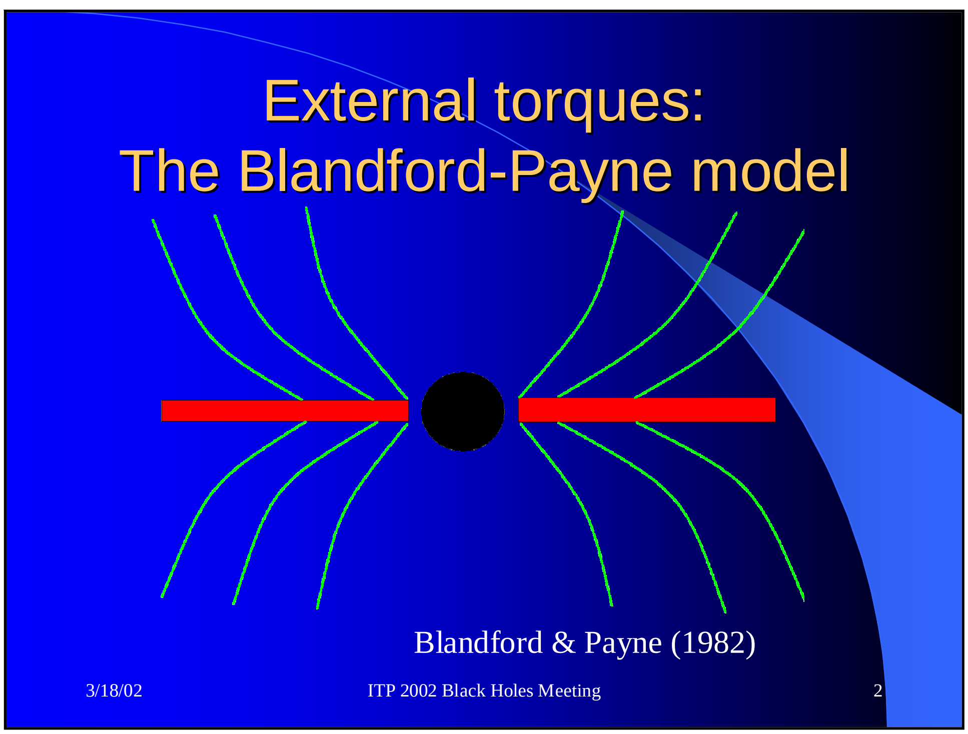
1


External torques:
The Blandford-Payne model
Blandford & Payne (1982)
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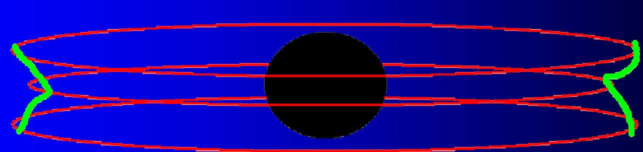
Outline for this talk

- The magneto-rotational instability (MRI)
  - Linear and non-linear properties
  - Local and global simulations
- MHD properties of the innermost disk
  - Inner "edge" of the disk is important!
  - Interesting magnetic/MHD effects occur
  - Simulations (global and cylinderical)
- Reality…some data from XMM-Newton
  - MCG-6-30-15 and XTE J1650-500
- Also see coming talk by **Neal Turner**

I: The Magneto-Rotational Instability (MRI)

- The magneto-rotational instability (MRI)
  - Generic instability in MHD accretion disks
  - Balbus & Hawley (1991) rediscovered this instability and realized importance for accretion disks
  - **The resulting MHD turbulence produces the angular momentum transport that drives accretion**



- Linear theory (Balbus & Hawley 1991)
  - Perturbations of linearized ideal MHD equations with shear
  - Instability if and only if

$$\frac{d\Omega^2}{dr} < 0$$

  - Fastest mode grows on dynamical timescale (independent of magnetic field strength).
  - Fastest growing mode has wavenumber $k \sim \Omega / v_A$
  - Do not get hydrodynamics in limit as $B \rightarrow 0$
- Non-linear evolution
  - Sustained MHD turbulence
  - Investigated in local and global simulations

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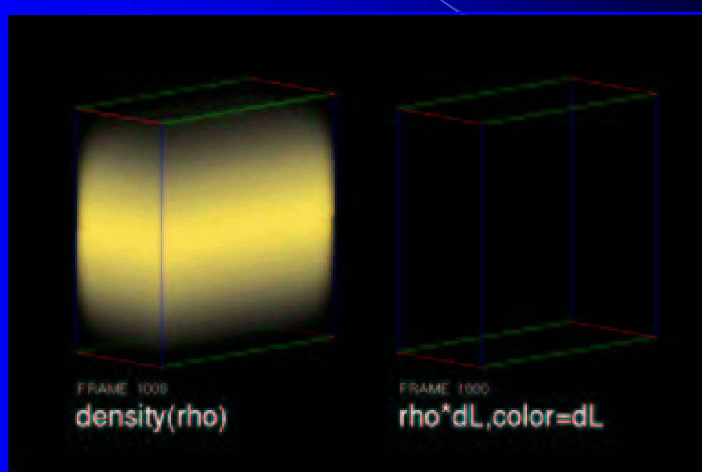
Shearing box (local) models



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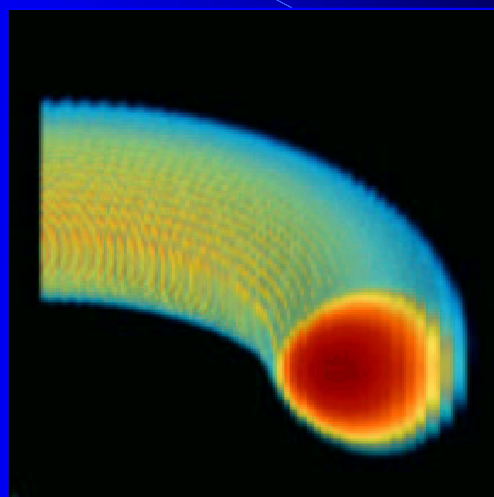
Global disk models



Hawley, Balbus & Stone (2001)

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Summary of simulation results

- Simulations by several groups
  - Armitage, Brandenburg, Gammie, Hawley, Miller, Stone, Turner, and others…
- Local (shearing box simulations)
  - MHD turbulence produced and sustained
  - Angular momentum transport
  - Effective α depends upon net flux threading box
    - α~0.01 for zero net field
    - α~0.1 for significant net field
- Global simulations (zero net field)
  - Can only do relatively hot, adiabatic disks
  - MHD turbulence, with significant power on large scales
  - α~0.1; characteristic of local simulations **with** net field

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II: The innermost regions of the accretion disk

- Properties of inner boundary are extremely important
  - Determines the radiative-efficiency of disk
  - Determines existence/nature of coupling to black hole spin
- "Standard" model (Page, Novikov & Thorne)
  - Generalization of Shakura & Sunyaev (1973) model
  - Assume internal torque goes to zero at ISCO
  - This determines efficiency of disk.

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

$\eta = 0.42$ for maximal Kerr hole

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Analytic arguments

- General arguments (Krolik 1999)
  - Within ISCO (i.e. plunging region), assume
    - Dynamically-weak field frozen into plasma
    - Material pushed into plunging region by magnetic forces
    - [axisymmetry and time-independence]
  - Then…
    - Find that plasma-β decreases rapidly in plunging region
    - Magnetic field will become dynamically significant
    - Can produce interesting effects within plunging region
    - Field could causally-connect plunging region to rest of disk

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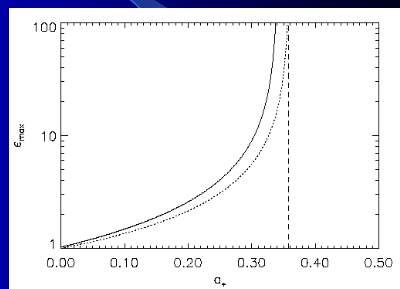
- Particular disk models
  - Gammie (1999)
    - 1-D MHD model of plunging region
    - Significant torques at ISCO
    - Significant enhancement of disk efficiency
  - Agol & Krolik (2000)
    - Extended Page & Thorne model, with torque at ISCO
    - Significant enhancement of efficiency



Agol & Krolik (2000)

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Back to simulations…

- "Toy" model of Schwarzschild accretion disk…
  - Non-relativistic MHD (ZEUS algorithm)
  - Approximate GR using Pseudo-Newtonian potential.

$$\Phi = \frac{M}{r-2M}$$

- Global models
  - Hawley (2000); Hawley & Krolik (2001, 2002)
  - Moderately hot, adiabatic accretion tori
  - Sustained turbulence with effective α~0.1
  - Verified importance of magnetic torques at ISCO

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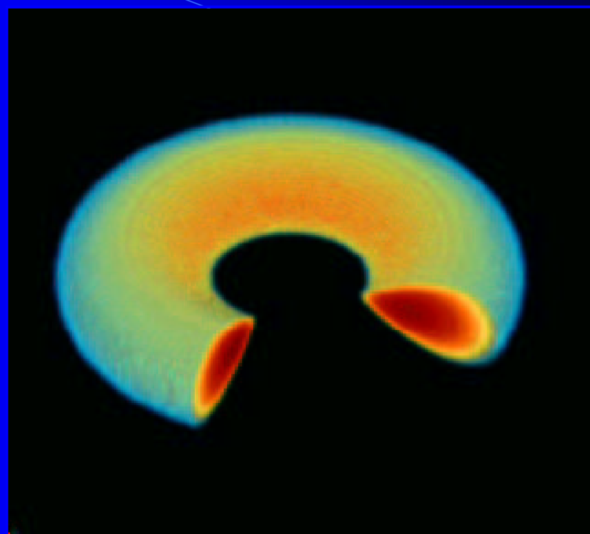

Hawley & Krolik (2001)

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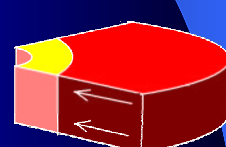
Cylinderical simulations

- Trouble with global simulations…
  - Very computer intensive (no parameter survey yet)
  - Limited spatial resolution in central regions
- Cylinderical simulations
  - Armitage, Reynolds & Chiang (2001); Reynolds & Armitage (2001); Hawley (2001)
  - Distills out essential physics (complements global models)
  - Look at 3-D wedge of disk.
  - Ignore vertical component of gravity
  - Use pseudo-Newtonian potential
  - Isothermal gas, with "h/r"~0.08 at ISCO
  - Use ZEUS-3D & ZEUS-MP codes



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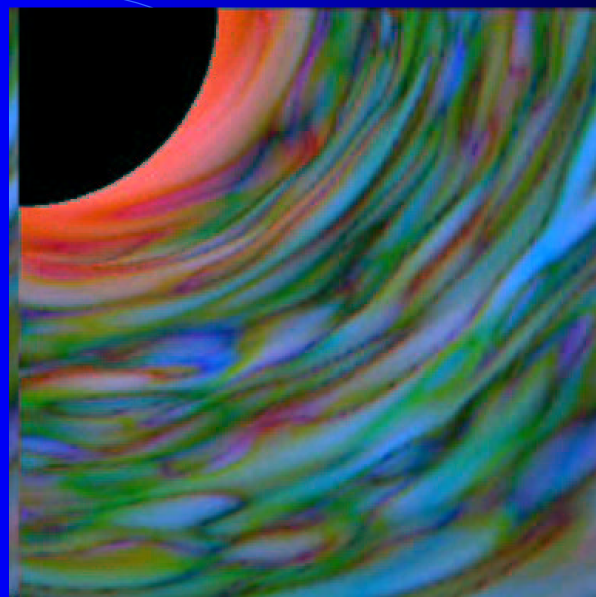
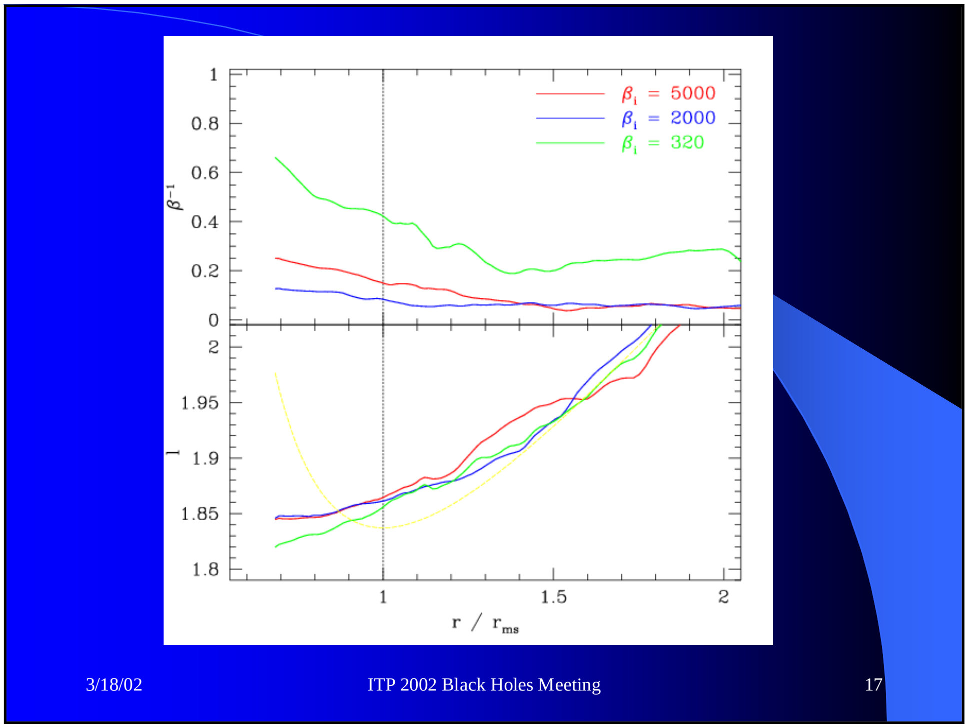


- Perform set of simulations with “tunable” saturation field strengths (Reynolds & Armitage 2001)
  - Tune saturation strength by changing initial vertical fields (hence different net fluxes).
  - Angular-momentum (& energy) transport in plunging region correlates with B-field strength in final turbulent state.
  - ISCO torques tremendously variable on dynamical timescale!
  - Accretion efficiency may vary on short timescales.
- Another way of phrasing this…
  - Saturation field affects value of effective α
  - Presence of ISCO torques correlates with effective α



β_i = 5000
β_i = 2000
β_i = 320
β^-1
l
r / r_ms
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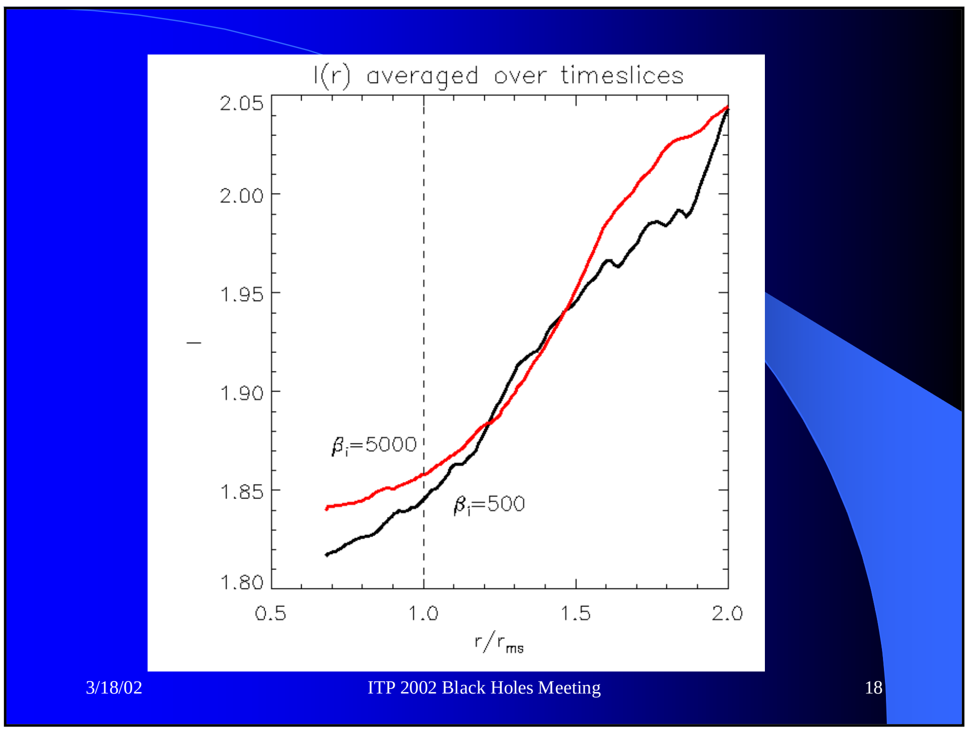

l(r) averaged over timeslices
β_i=5000
β_i=500
l
r/r_ms
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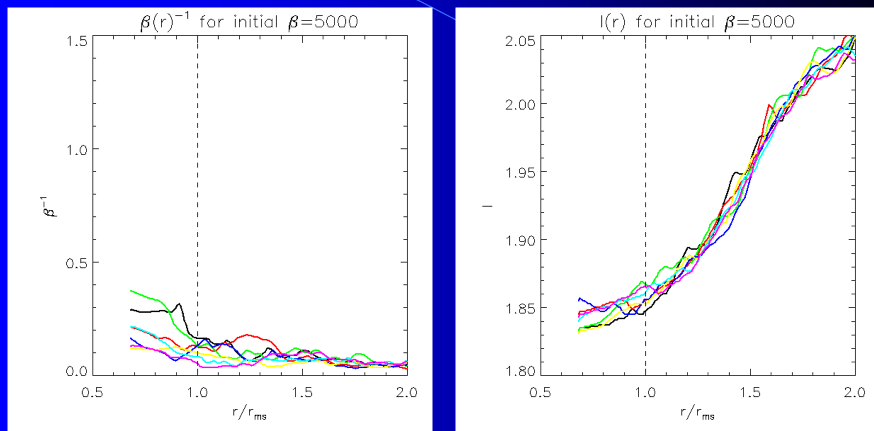

- Significant fluctuations between independent timeslices
- l flattens in plunging region

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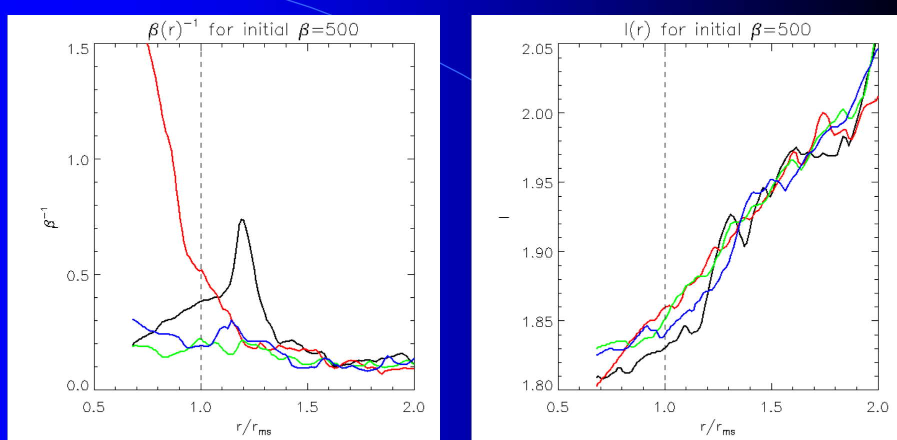

- Larger saturation field $\Rightarrow$ stronger torques in plunging region
- Very large fluctuations
- Especially strong torques in plunging region during red period
- Good agreement with **Hawley & Krolik (2000)** during these times

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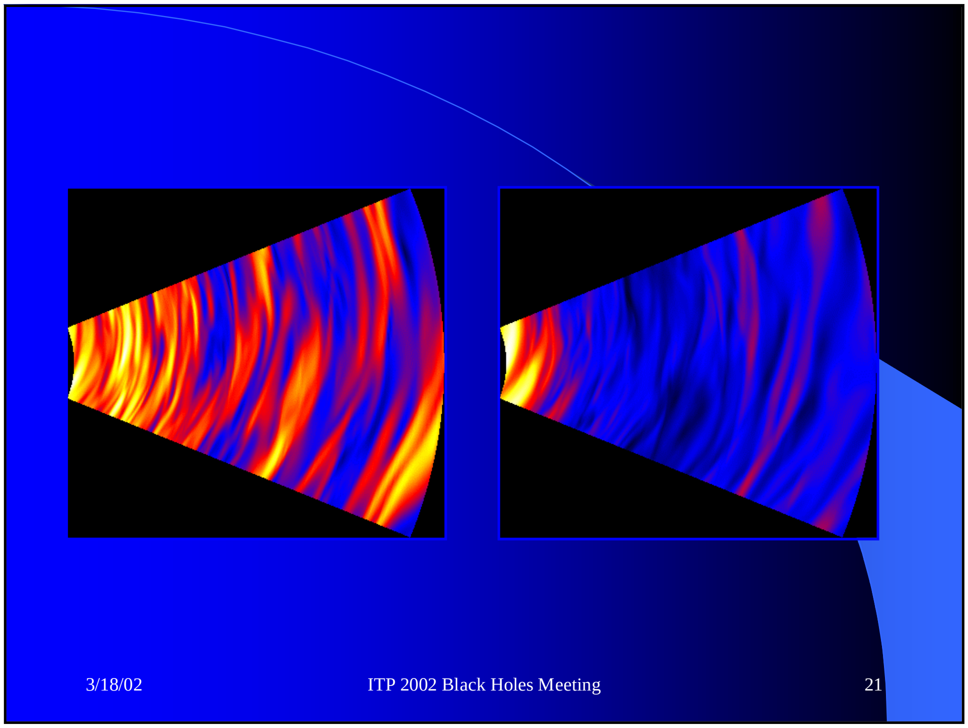
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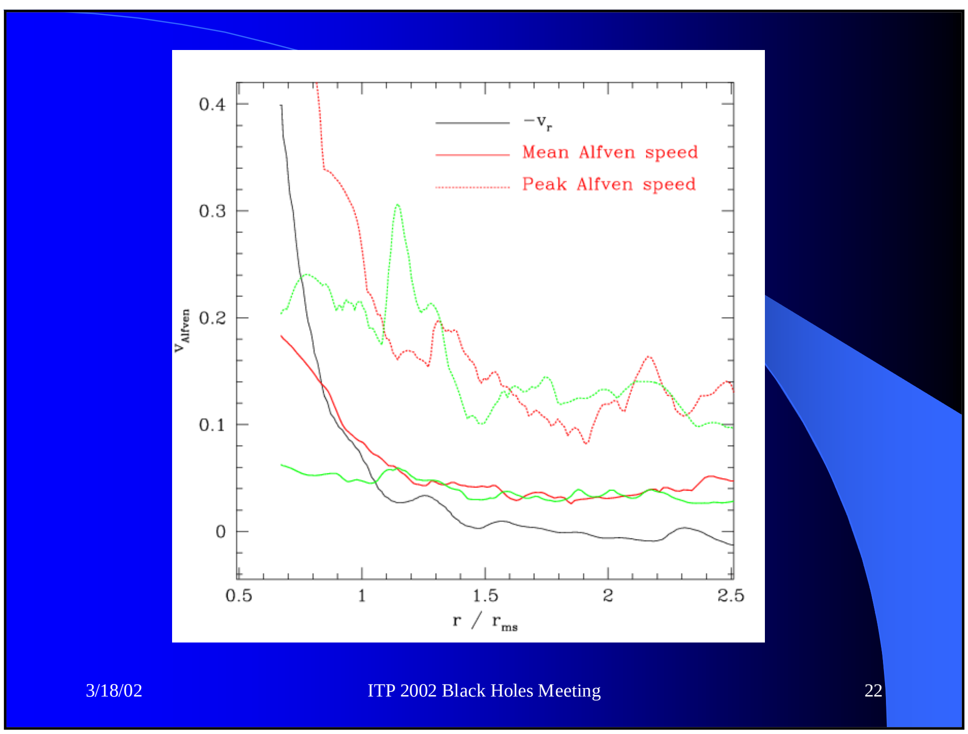
−v_r
Mean Alfven speed
Peak Alfven speed
v_Alfven
0.4
0.3
0.2
0.1
0
0.5
1
1.5
2
2.5
r / r_ms
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22

Beyond the Simulations…

- Relativistic effects around rotating black hole
  - Effects of frame-dragging and gravitational redshifting?
  - Charles Gammie's talk; Koide et al. (1999), Meier et al. (2000)
- What about colder/thinner disks?
  - Do ISCO torques occur in thinner disks?
  - May be limited by reconnection of tightly wound field
- Development of large-scale fields
  - Inverse turbulent cascade, or advection of pre-existing field?
  - Black hole will "integrate" accreted magnetic flux
    - Field strength may be limited by field pressure in body of disk (Ghosh & Abramowicz 1997, Livio et al. 1997)?
    - Much greater fields may be permitted due to inertial confinement by accretion flow in plunging region.

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XMM-Newton observations of MCG-6-30-15

- Wilms, Reynolds, Reeves et al., 2001, MNRAS.
- XMM-Newton satellite
  - Recently launched European X-ray observatory
  - Several co-aligned instruments
    - Reflection Grating Spectrometer (RGS)
    - European Photon Imaging Camera (EPIC)
    - Optical Monitor (OM)
  - Superb for obtaining high S/N spectra of accreting black holes (AGN and GHBCs)

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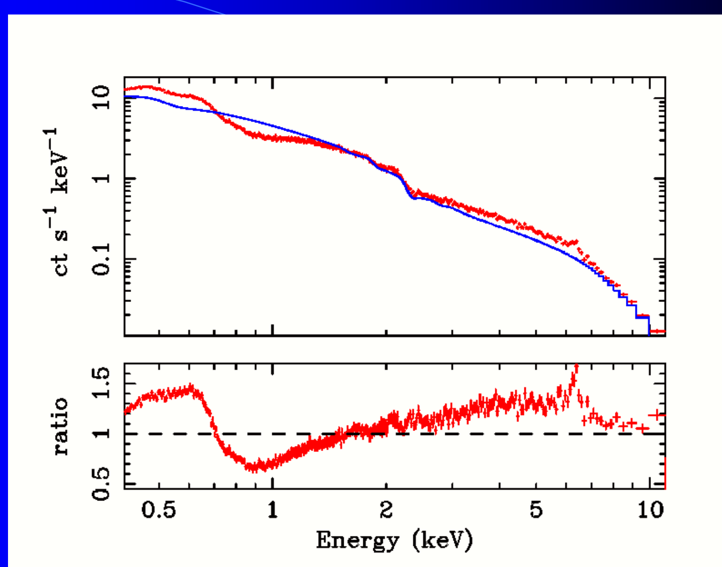

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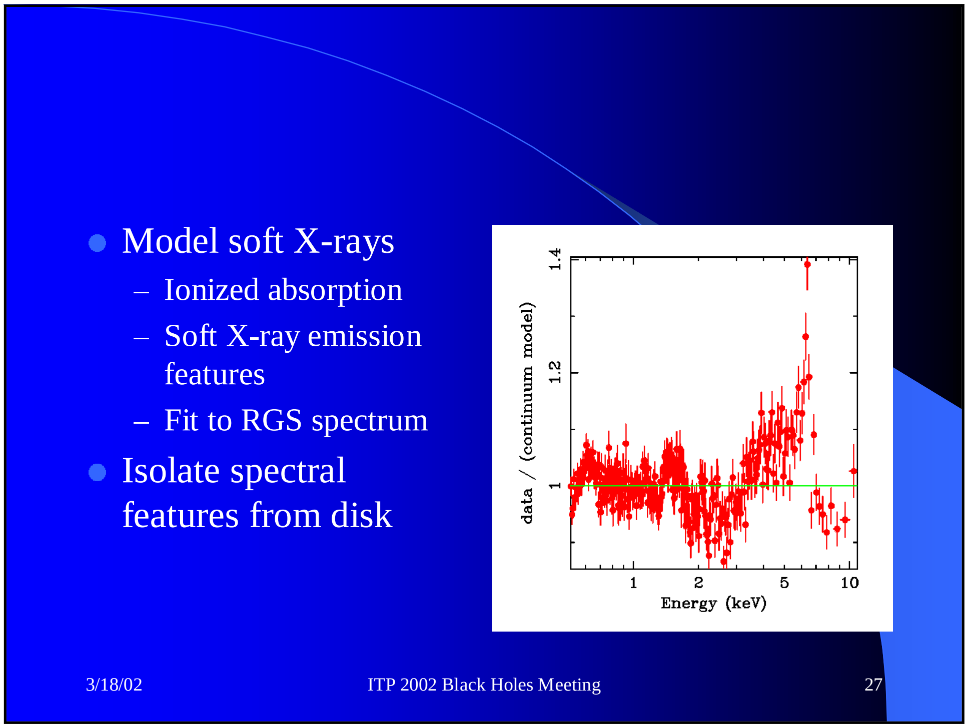

Model soft X-rays
– Ionized absorption
– Soft X-ray emission features
– Fit to RGS spectrum
Isolate spectral features from disk
data / (continuum model)
1.4
1.2
1
1
2
5
10
Energy (keV)
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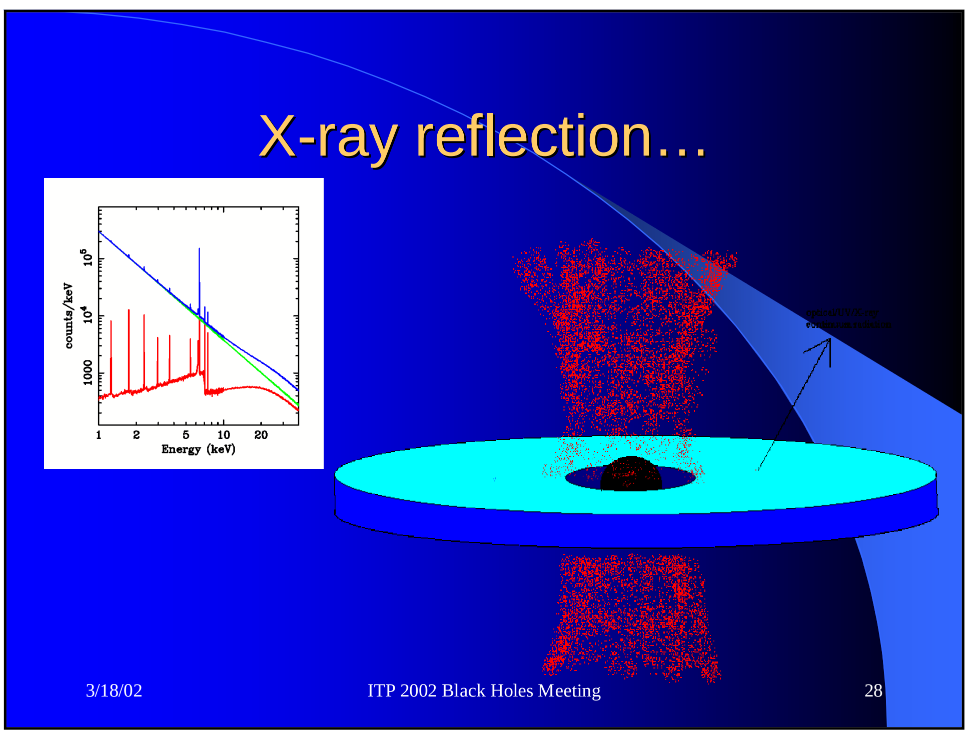
27



X-ray reflection…
counts/keV
10^5
10^4
1000
1
2
5
10
20
Energy (keV)
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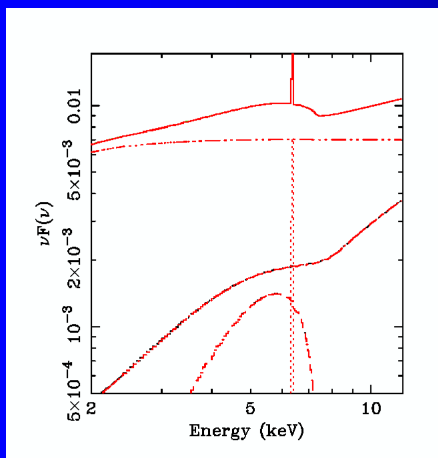
28

Basic result



- Model within context of rapidly rotating BH
  - Requires extreme degree of broadening!
  - Implies very centrally concentrated X-ray source
  - $F(r) \sim r^{-\beta}$, $4.5<\beta<6.0$
  - $R_{in}<2.0\ GM/c^2$
- If BH slowly rotating:
  - more extreme β required
  - Need emission down to $3GM/c^2$

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Spin extraction hypothesis

- Suppose that X-ray emissivity is proxy for disk dissipation profile.
- Spin extraction hypothesis…
  - steep emissivity profile due to torquing of inner disk
  - Inner disk torquing by plunging region in extreme Kerr geometry (Penrose)…
  - …or, torquing by direct magnetic connection between disk and horizon (Blandford-Znajek 1977, Li 2000)
  - In either case, much of extra energy originates from spin of black hole!

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The Tower of Power…

- Suppose X-ray source is **on-axis** above the black hole at r~3GM/c^2 or less.
- Then, gravitational focusing gives
  - Very broad line, **as observed**
  - Very strong reflection signatures (R=4)
- Examined by Martocchia, Matt & Karas (2002).
- But, some potential concerns…
  - Would predict significantly stronger reflection than observed.
  - Marginal disagreement with lack of time-lags observed for this object (Reynolds 2000).

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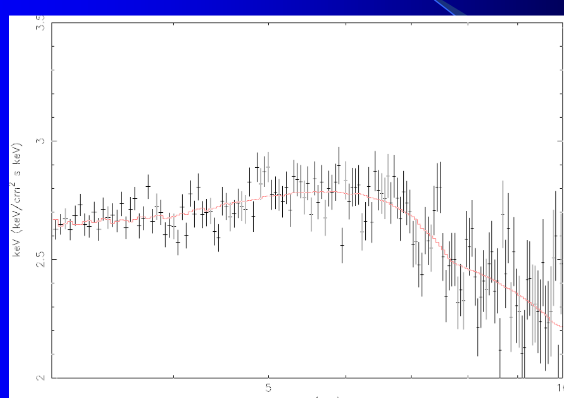
Same thing in a GBHC? XTE1650-500



Miller et al. (2002, astro-ph/0202375)

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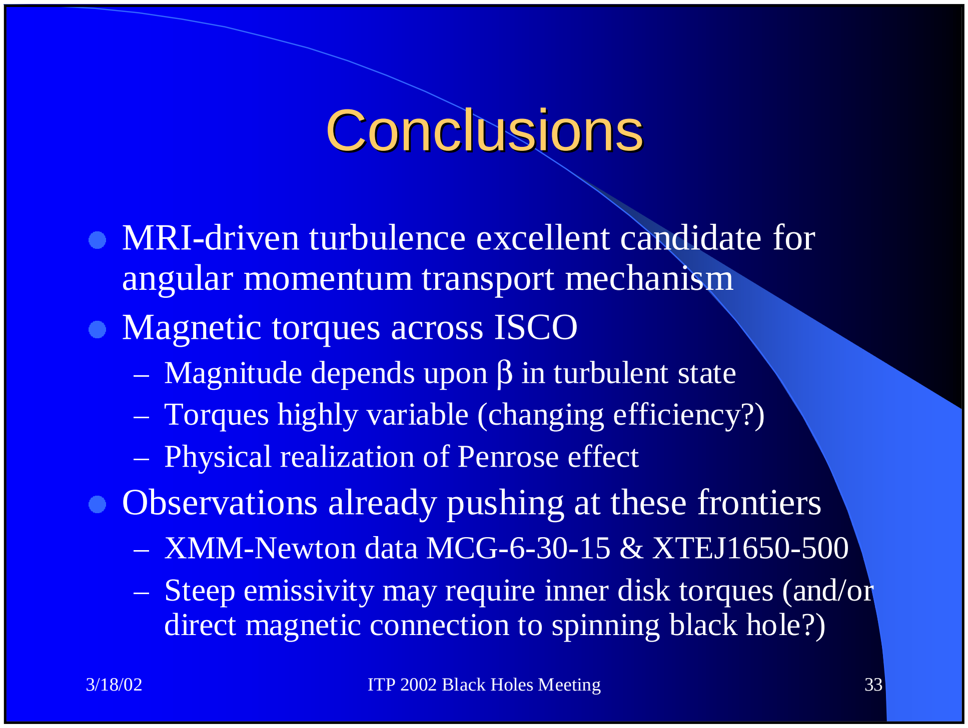
Conclusions
MRI-driven turbulence excellent candidate for angular momentum transport mechanism
Magnetic torques across ISCO
– Magnitude depends upon β in turbulent state
– Torques highly variable (changing efficiency?)
– Physical realization of Penrose effect
Observations already pushing at these frontiers
– XMM-Newton data MCG-6-30-15 & XTEJ1650-500
– Steep emissivity may require inner disk torques (and/or direct magnetic connection to spinning black hole?)
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33