“TOP 10” PROBLEMS: JETS, OUTFLOWS AND DISKS

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CAVEAT I:

THEY’RE NOT IN ORDER

...BUT THEY ARE NUMBERED

CAVEAT II:

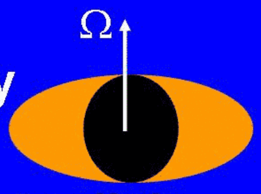
THEY’RE NOT INDEPENDENT

Often it’s worth asking the same question several different ways.

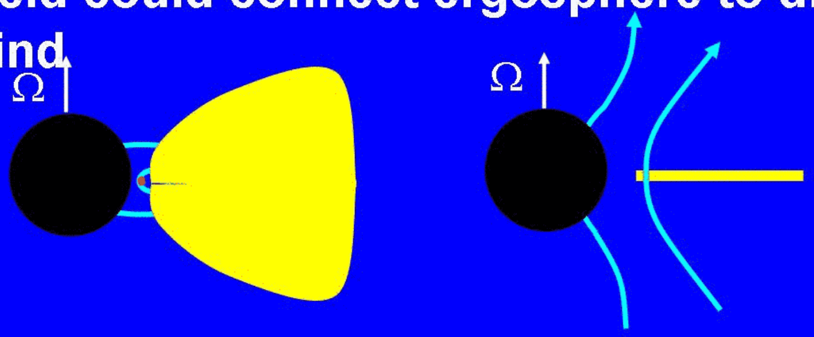
1

CAN BLACK HOLES POWER JETS?

What we know:



- BH spin extractible magnetically
  - up to 0.29 M available
- Field could connect ergosphere to disk, wind

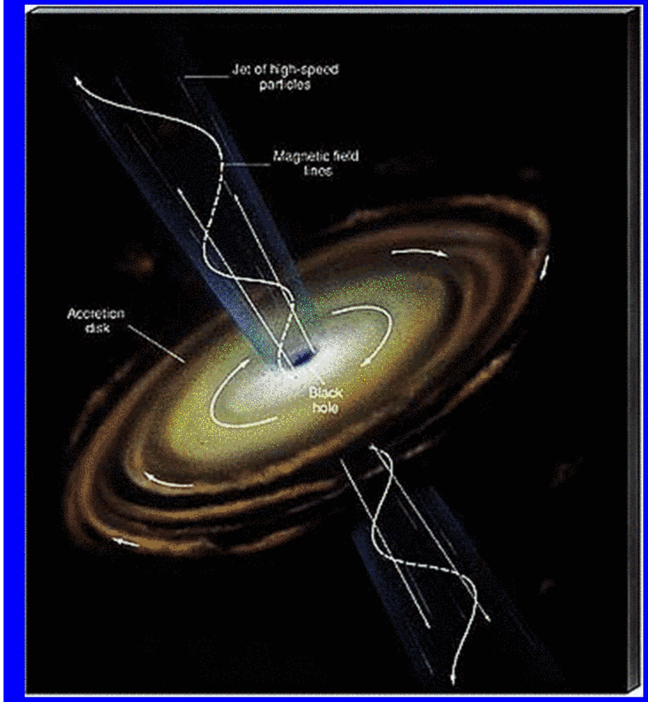


- Stress may → be appreciable in plunge region of disk higher efficiency than ISCO
- Iron line profiles powered partly by spin?

Approaches:

- **Analysis:**
  - Estimate field strengths, relate to disk structure (thick vs. thin, radiation vs. gas pressure)
- **Computation:**
  - GRMHD
  - Integration times getting interesting
- **Observation:**
  - Iron line spectroscopy
  - Variability

Electromagnetic Formation of Jets



(Blandford-Znajek effect)

Corotating observer sees energy flow inwards at horizon; conserved energy flux in non-rotating frame is outward.

For a quasar jet:

$B \sim 10^4$ G; $M \sim 10^9\ M_O$

$E \sim \Omega\ \Phi \sim 10^{20}$ V

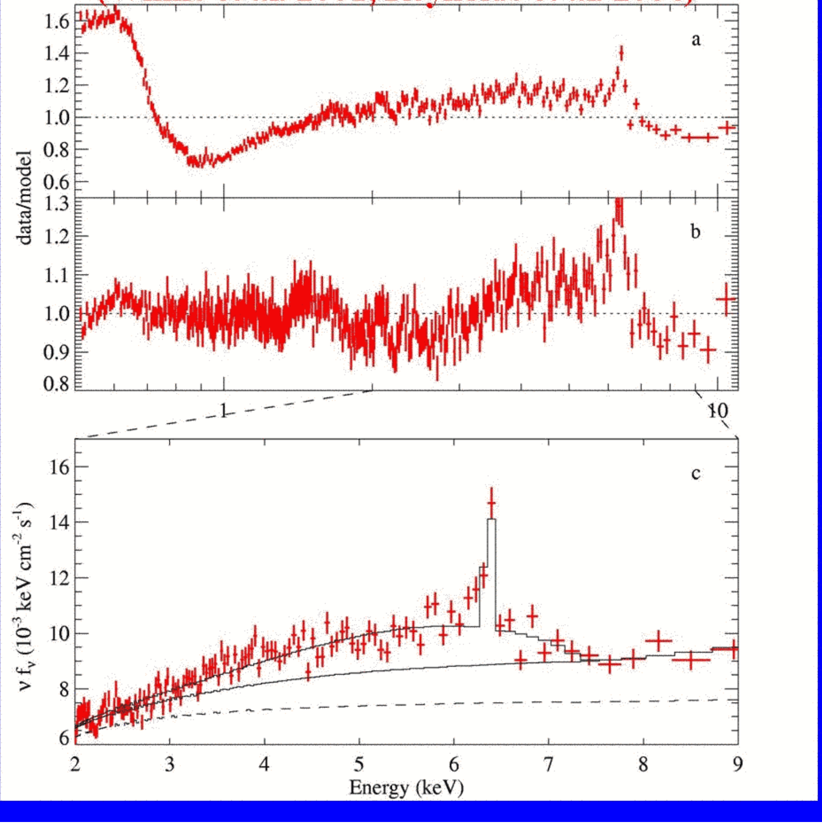
$R_{in} \sim R_{out} \sim 100\ \Omega$

$I \sim V / R \sim 10^{18}$ A

$P \sim E\ I \sim 10^{38}$ W

XMM-Newton/EPIC Observations of the AGN MCG-6-30-15

(Wilms et al. 2001, Reynolds et al. 2004)



Challenges:

- Analysis:
  - Field geometries, coronae, reconnection
    - Open field vs. connected to disk
    - Ω_F vs. Ω_{BH}
  - Jet composition: pairs vs. normal plasma
- Computation:
  - GRMHD with better microphysics
  - Even longer integration times
- Observation:
  - Broader spectral coverage to pin down Fe line profiles, Compton bump
  - Reverberation mapping (Con-X, XEUS)
  - Imaging?

2

HOW RELATIVISTIC CAN A JET GET?

What we know:

- Blazars → $\Gamma \sim 10$
- GRBs → $\Gamma \sim 100\text{'s}$ emerging from dense environment
- Pulsar jets ?→ $\Gamma \sim 10^6$
- Probably acceleration by coherent EM fields in all cases
- Relativistic speeds robust over large distances
- Jets are generic, but speed depends on grav. potential (or can you launch a rel. jet far from a BH?)

Approaches:

- **Analysis:**
  - Jet composition, mass loading
  - Disk-jet correlation
- **Computation:**
  - GRMHD
  - Integration times getting interesting
- **Observation:**
  - Time-dependence, mass scaling, disk-jet interaction from microquasars (multi-wavelength)
  - High-resolution, time → dependent studies via VLBI
  - Variable gamma rays (TeV), 100 kpc X-ray

Challenges:

- Analysis:
  - – Improvements on MHD
    - rel. force-free approx? eg, Blandford-Lyutikov
    - anisotropic pressures, charge-starvation
  - – Jet composition: pairs vs. normal plasma
- Computation:
  - – More GRMHD (jet production – which b.c.?)
  - – Special Rel. MHD (adaptive mesh) to study jet propagation
- Observation:
  - – Distinguish pattern speeds from bulk speed
  - – Hadronic processes, UHE neutrinos, UHECR?
  - – Imaging?

3

HOW AND WHERE DO JETS GET ACCELERATED AND COLLIMATED?

(see prob. 2)

What we know:

- Jet in M87 already relativistic and collimated at r~50 M
- EM acceleration tends to be slow
  - Especially highly relativistic flows
  - Magnetic tension, E-field tend to inhibit accel.
  - Efficient accel. may require dissipation
- Crab jet kinetically dominated?
- Don’t forget radiation pressure
  - BAL winds, SS 433

M87 RADIO MONTAGE

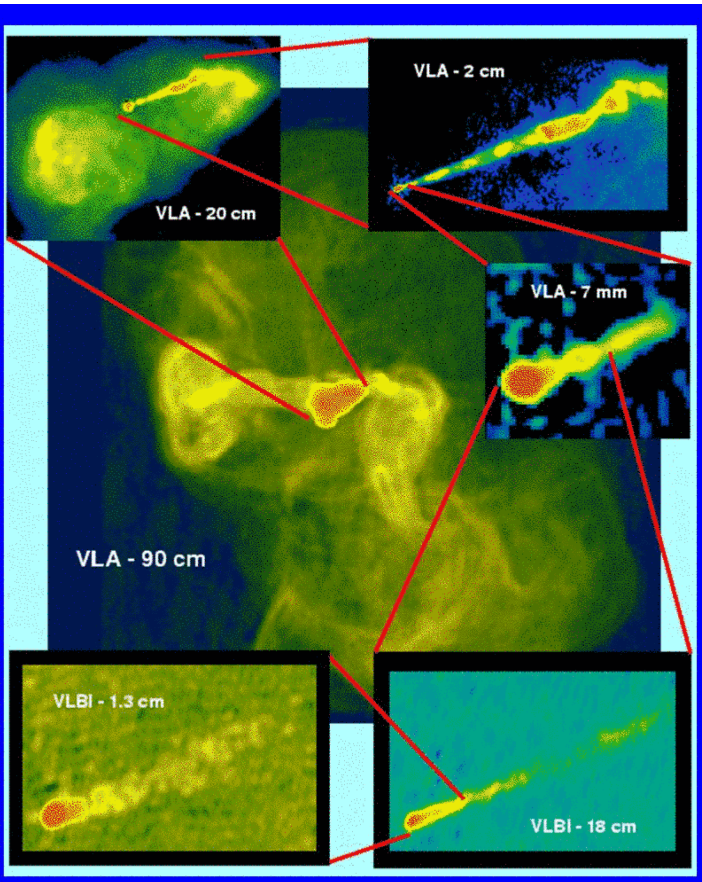
F. Owen (NRAO),
J. Biretta (STScI),
J. Eilek (NMIMT)
1999

$$M_{BH} \sim 3\times10^{9} M_{Sun}$$

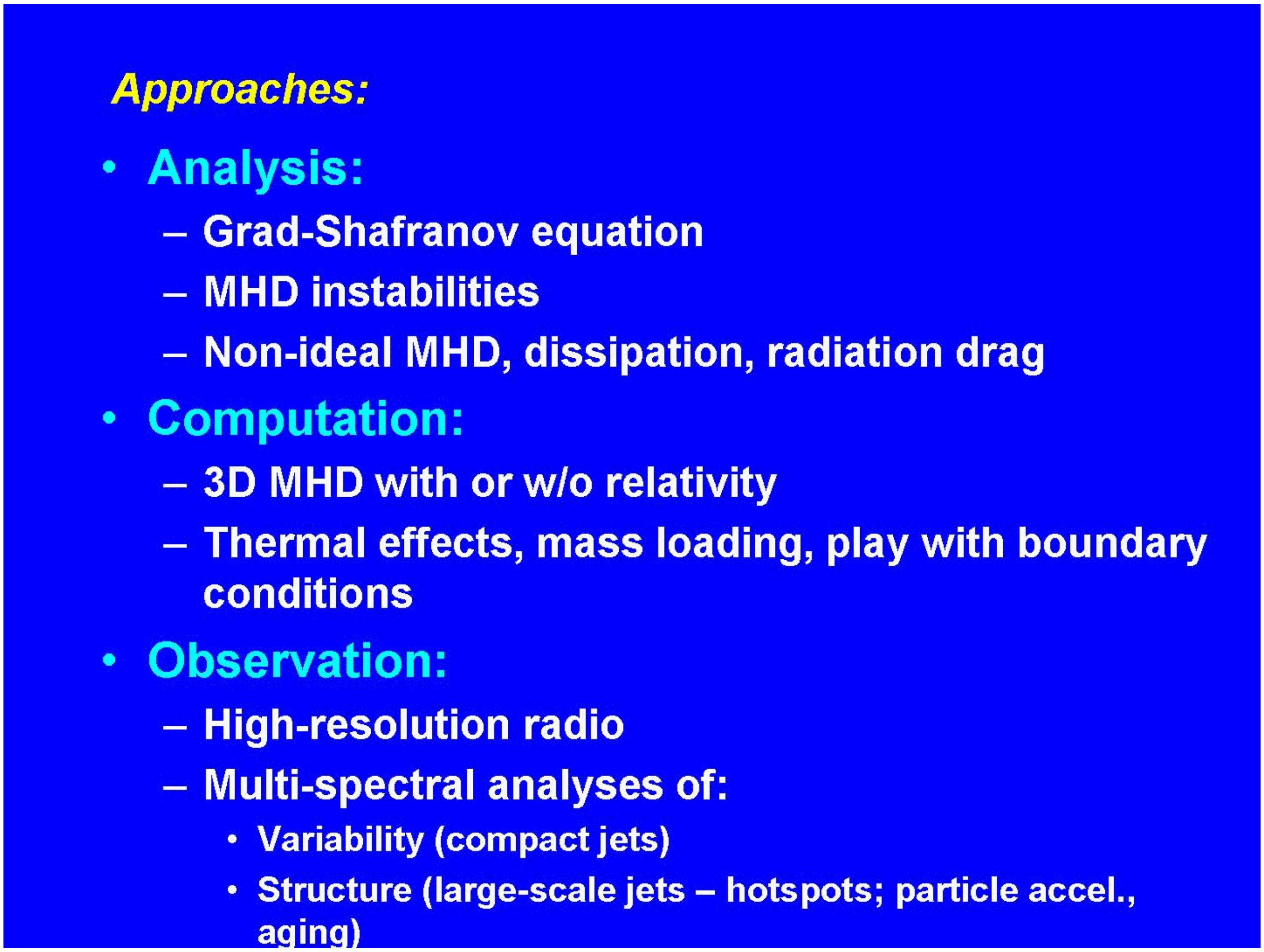
Jet already exists at

$$R < 100m$$

Superluminal motion $\sim 6c$ seen with HST
(Biretta et al. 1999)

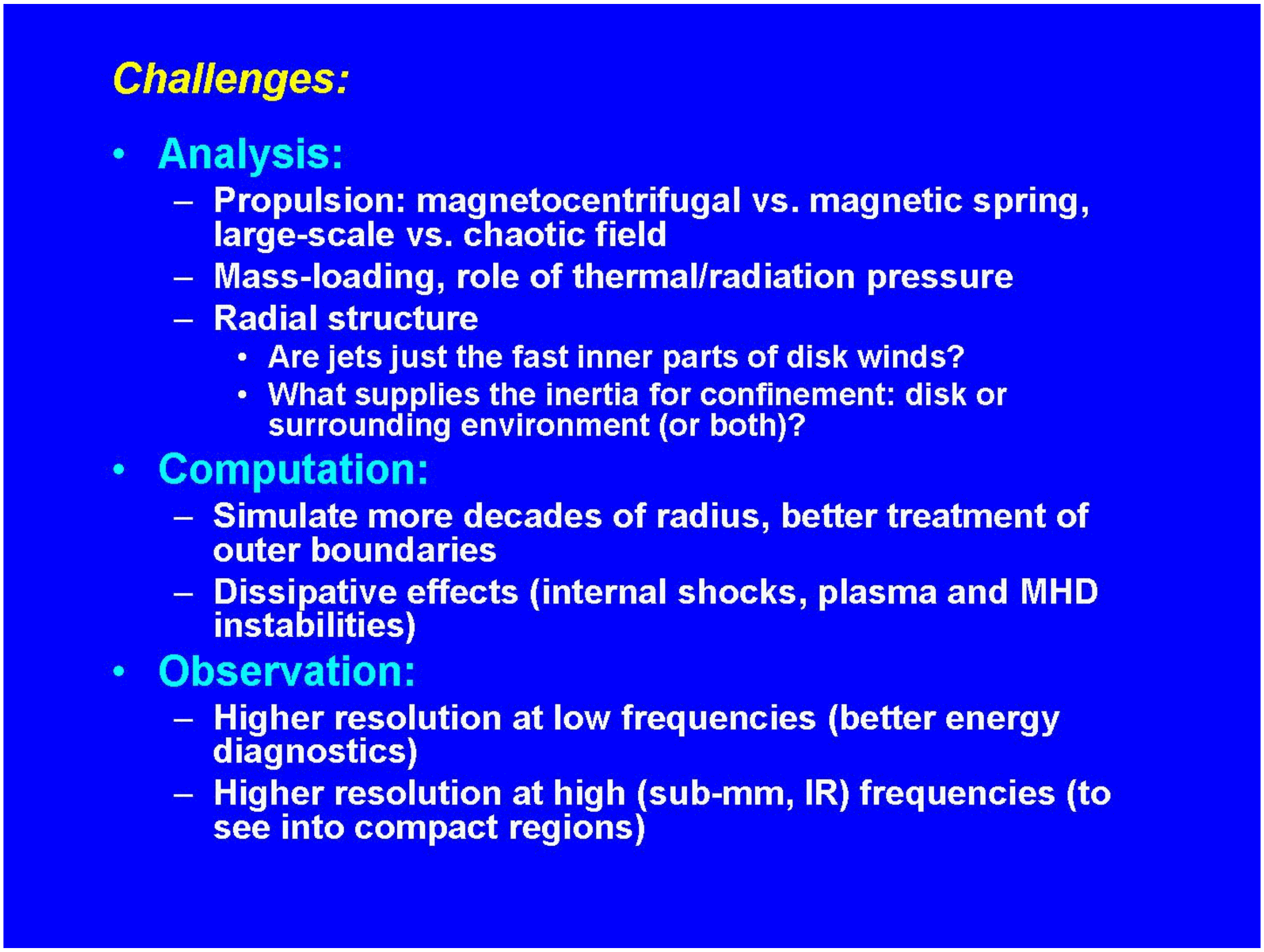


www.nrao.edu/~fowen/M87.html



Approaches:

- Analysis:
  - – Grad-Shafranov equation
  - – MHD instabilities
  - – Non-ideal MHD, dissipation, radiation drag
- Computation:
  - – 3D MHD with or w/o relativity
  - – Thermal effects, mass loading, play with boundary conditions
- Observation:
  - – High-resolution radio
  - – Multi-spectral analyses of:
    - Variability (compact jets)
    - Structure (large-scale jets – hotspots; particle accel., aging)



Challenges:

- Analysis:
  - – Propulsion: magnetocentrifugal vs. magnetic spring, large-scale vs. chaotic field
  - – Mass-loading, role of thermal/radiation pressure
  - – Radial structure
    - Are jets just the fast inner parts of disk winds?
    - What supplies the inertia for confinement: disk or surrounding environment (or both)?
- Computation:
  - – Simulate more decades of radius, better treatment of outer boundaries
  - – Dissipative effects (internal shocks, plasma and MHD instabilities)
- Observation:
  - – Higher resolution at low frequencies (better energy diagnostics)
  - – Higher resolution at high (sub-mm, IR) frequencies (to see into compact regions)

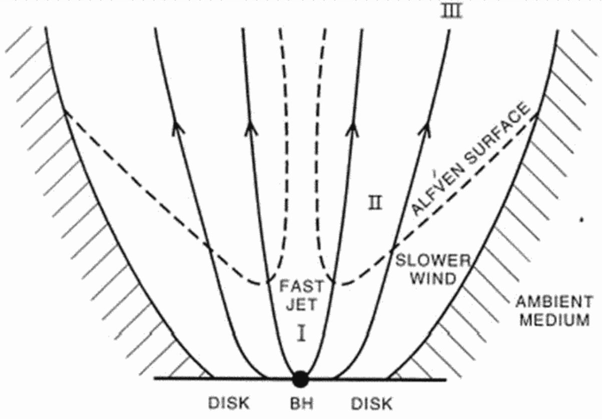
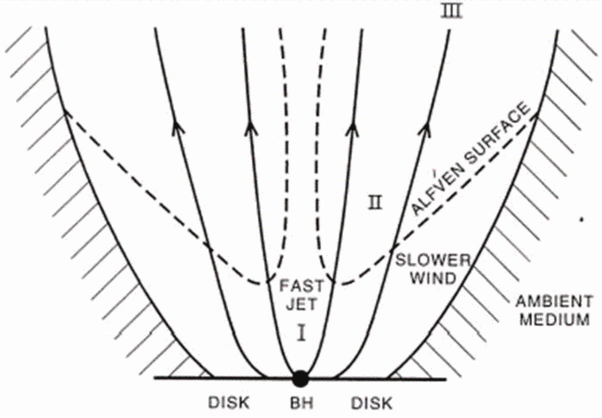


FIG. 1. Possible configuration of a fast jet core surrounded by a slower wind. Between the source of the flow and Alfvén surface (region I), the jet core can be collimated by magnetic stresses transmitted from the disk. In region II, magnetic pinching of the outer wind collimates the jet core. In region III, the flow is collimated by the pressure in the ambient medium. The filled black circle represents the central black hole (BH), the rotation of which could power the fast inner jet.

(MCB, *PNAS* 1995)



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Between the source of the flow and Alfvén surface (region I), the jet core can be collimated by magnetic stresses transmitted from the disk.

(MCB, *PNAS* 1995)

4

DO DISKS REALLY SUPPORT DYNAMOS?

What we know:

- MRI, MRI, MRI!
  - You got a problem with that?

What we know:

- **MRI**, but…
  - Does the disk field “remember” the polarity of the field at ∞ ?
    - On what scales?
    - Is field ever “dragged in” by accretion, or is the structure essentially local?
  - Does MRI create a large-scale disk field, or a chaotic one?
  - Ditto for corona
  - Ditto for jet, wind ….
  - What about disks where MRI is partly suppressed?

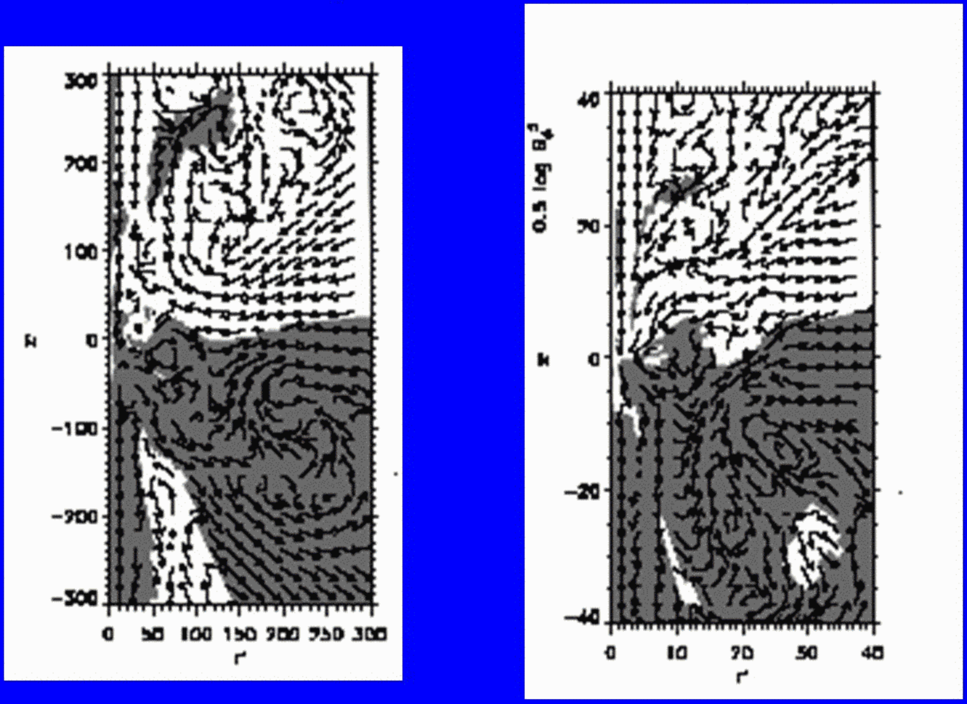
Approaches:

- Computation:
  - Simulate 3D MHD turbulence resulting from MRI
  - Shearing box, stratified box, a few full disk simulations w/ limited radial resolution/dynamic range
  - Difficult to simulate thin disks
  - Limited control of microphysics (reconnection, dissipative heating)

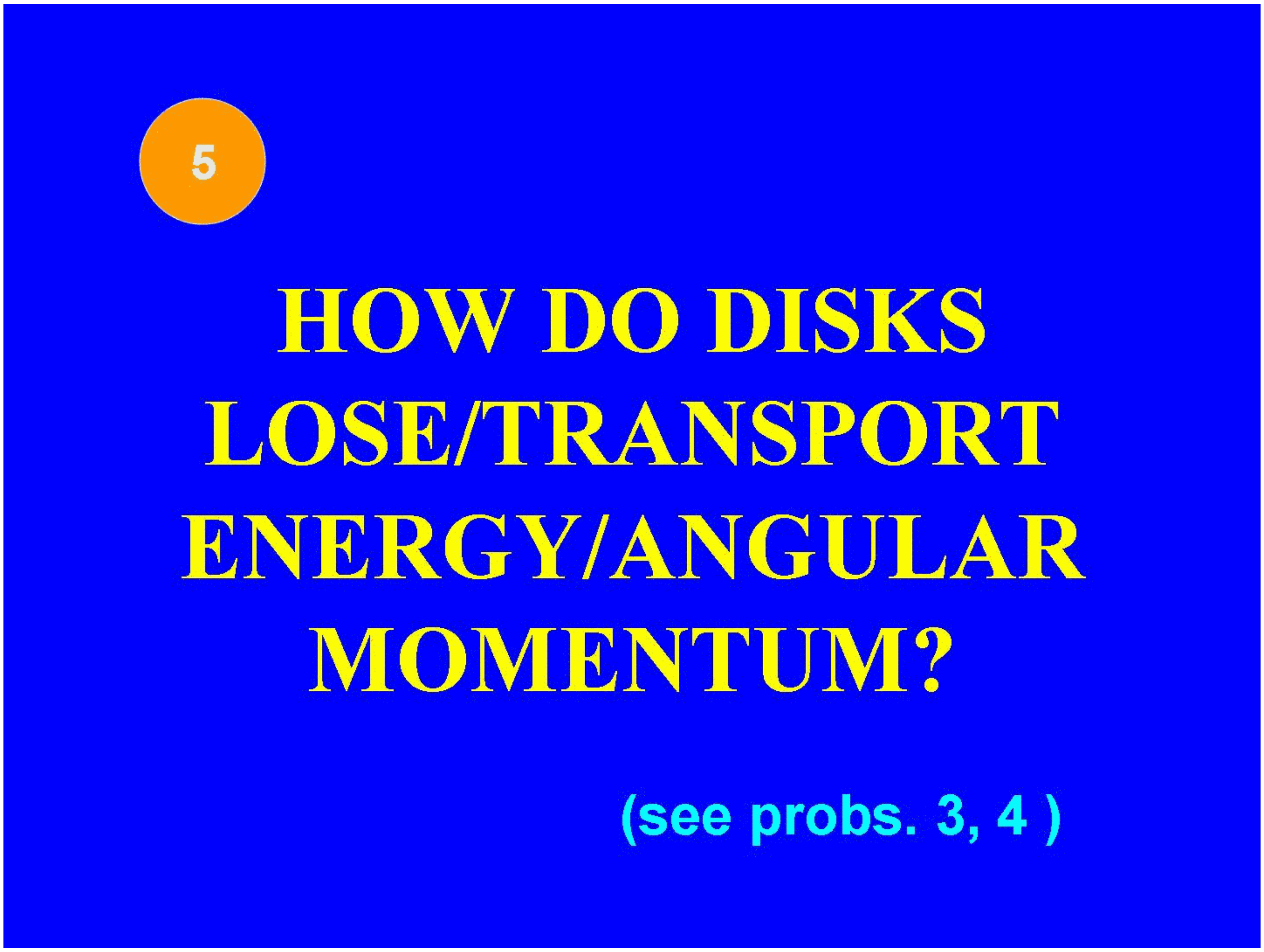
Challenges:

- Computation:
  - Greater radial, vertical dynamic range
  - Improve treatment of boundary conditions, dissipative effects
- Observation:
  - Can polarity flips of B-field be observed?
    - Circular polarization, variability of linear pol.?

Persistence of B_φ? (OK, it's 2D)



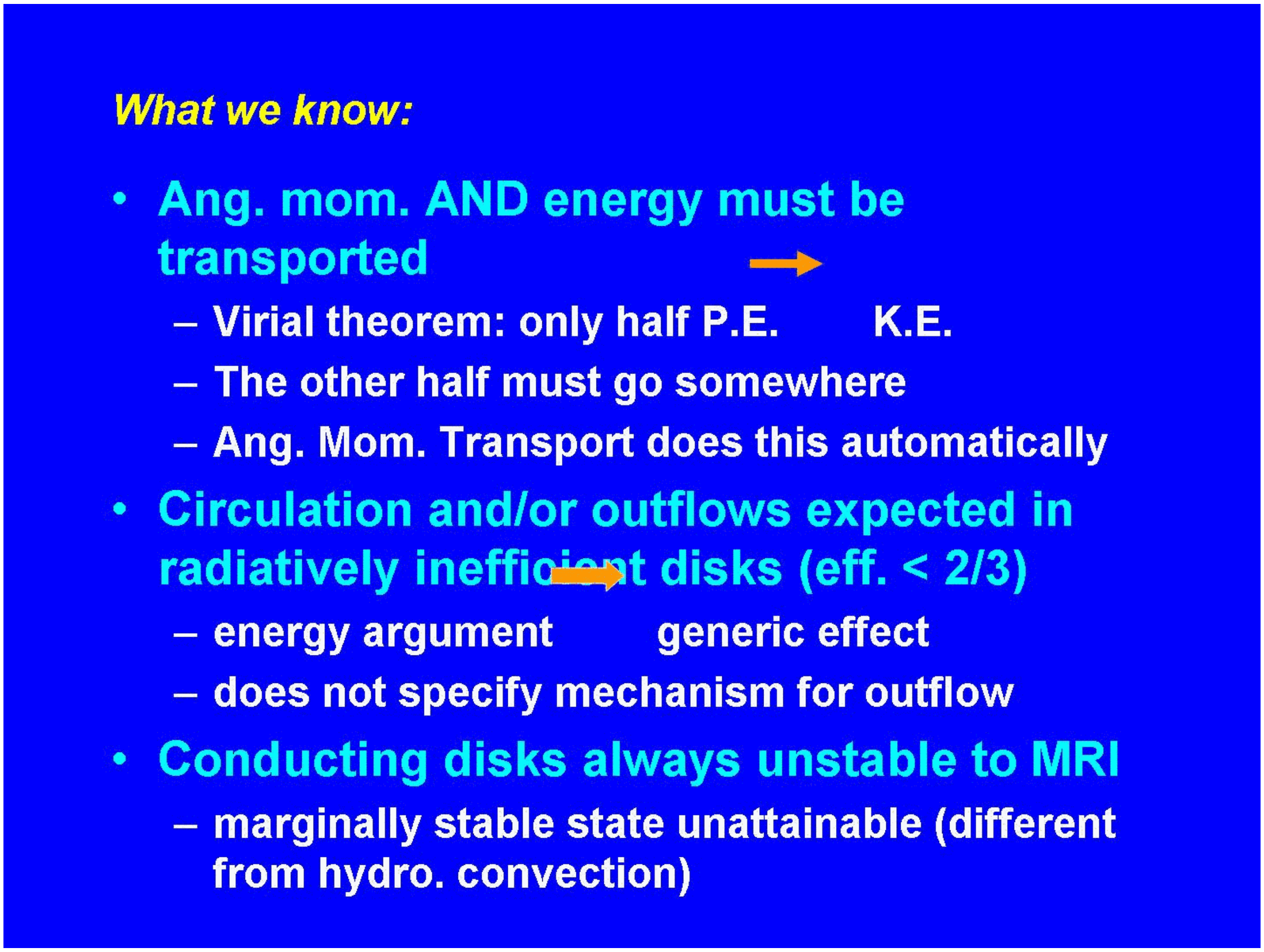
(Proga et al. 2004)



5

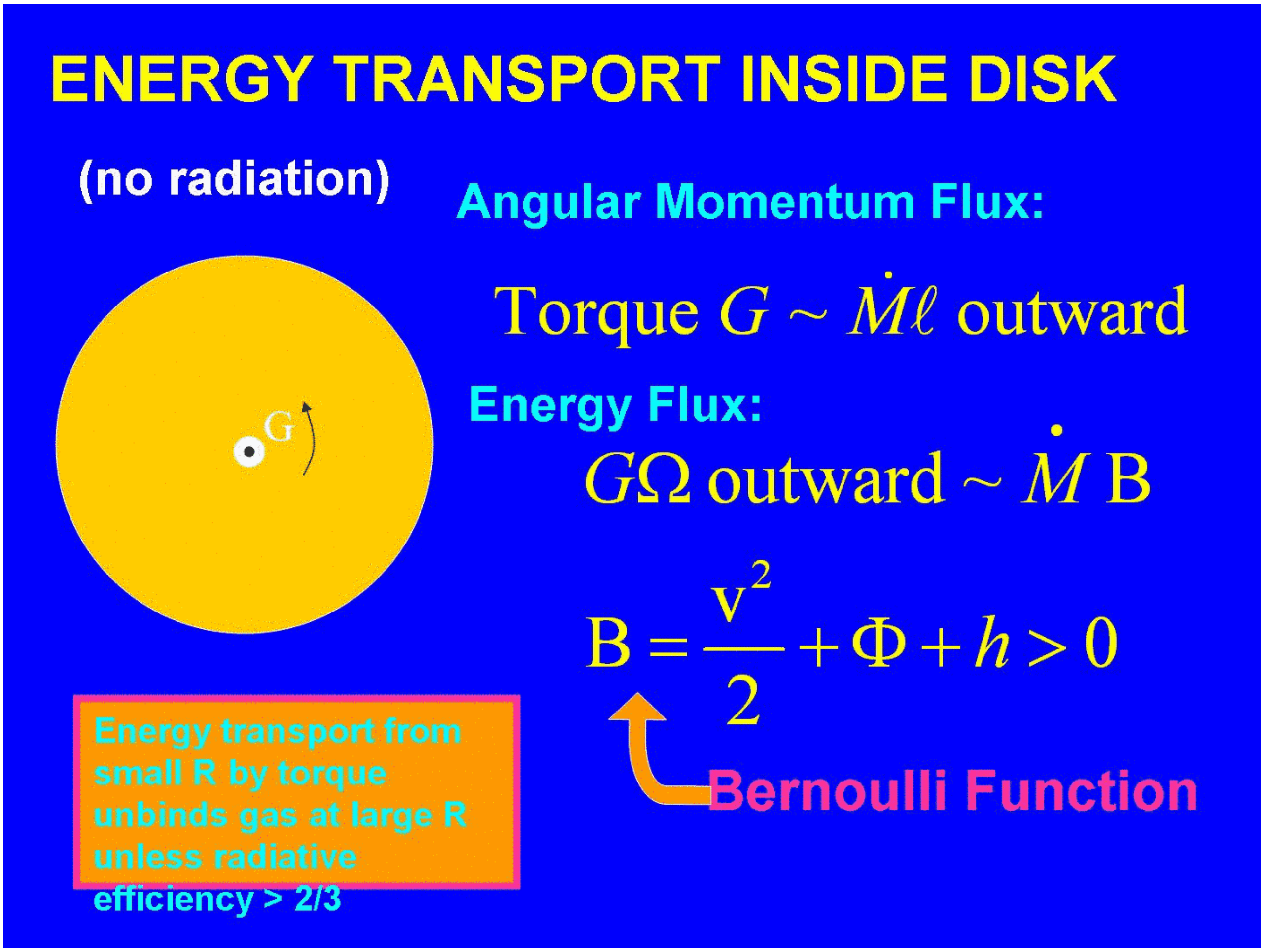
HOW DO DISKS LOSE/TRANSPORT ENERGY/ANGULAR MOMENTUM?

(see probs. 3, 4)



What we know:

- Ang. mom. AND energy must be transported
  - Virial theorem: only half P.E. → K.E.
  - The other half must go somewhere
  - Ang. Mom. Transport does this automatically
- Circulation and/or outflows expected in radiatively inefficient disks (eff. < 2/3)
  - energy argument → generic effect
  - does not specify mechanism for outflow
- Conducting disks always unstable to MRI
  - marginally stable state unattainable (different from hydro. convection)



ENERGY TRANSPORT INSIDE DISK

(no radiation)

Angular Momentum Flux:

Torque $G \sim \dot{M}\ell$ outward

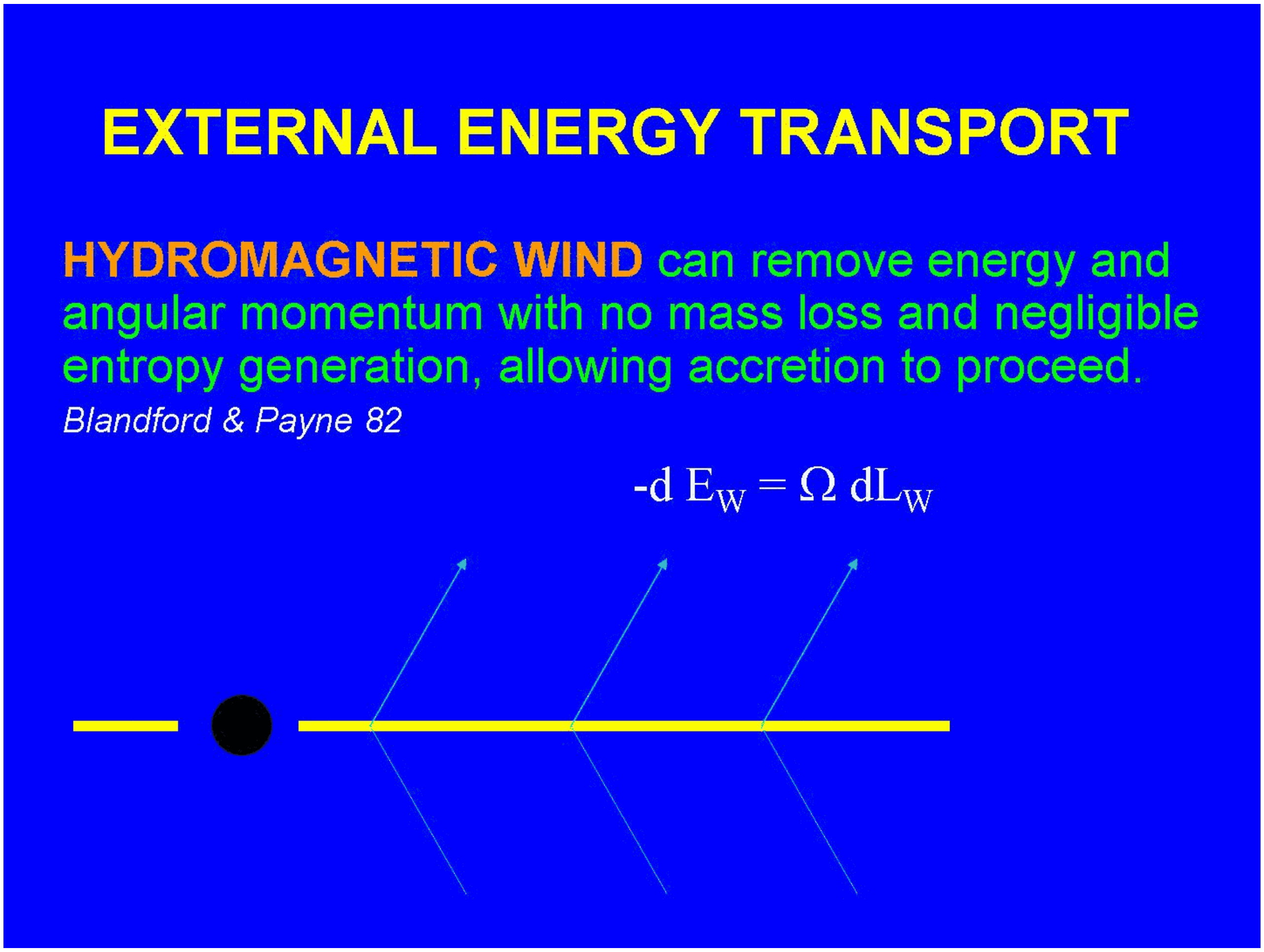
Energy Flux:

$$G\Omega \text{ outward} \sim \dot{M}\,\mathrm{B}$$

$$\mathrm{B} = \frac{v^2}{2} + \Phi + h > 0$$

Bernoulli Function

Energy transport from small R by torque unbinds gas at large R unless radiative efficiency > 2/3



EXTERNAL ENERGY TRANSPORT

HYDROMAGNETIC WIND can remove energy and angular momentum with no mass loss and negligible entropy generation, allowing accretion to proceed.

Blandford & Payne 82

$$-d\,E_W = \Omega\, dL_W$$

BAL Outflows in X-ray Absorption

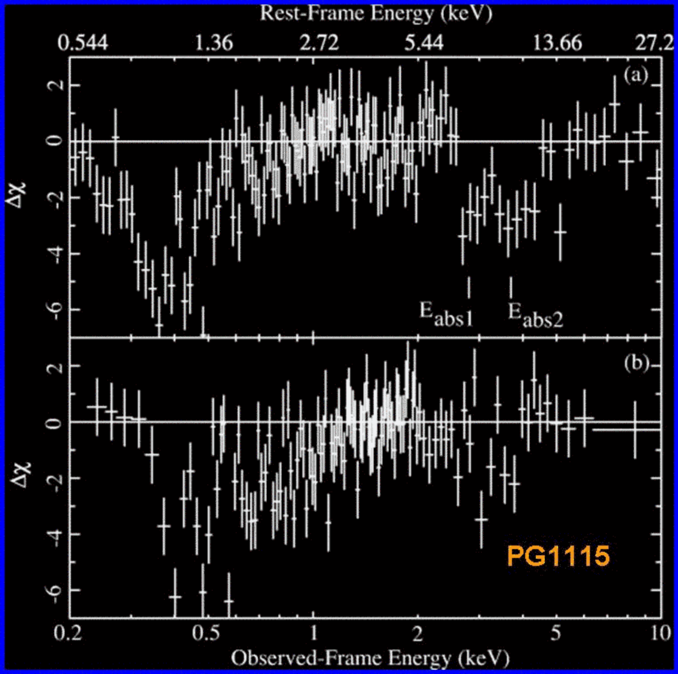
...driven by
radiation pressure?

$N_H \sim 10^{23}\ cm^{-2}$

$v \sim 0.2\ c$

$\Omega \sim 4\pi/10$

$$\frac{L_{KE}}{L_{Bol}} \sim 0.1\left(\frac{r_{abs}}{10^{17}\,cm}\right)$$



Chartas et al. 2003

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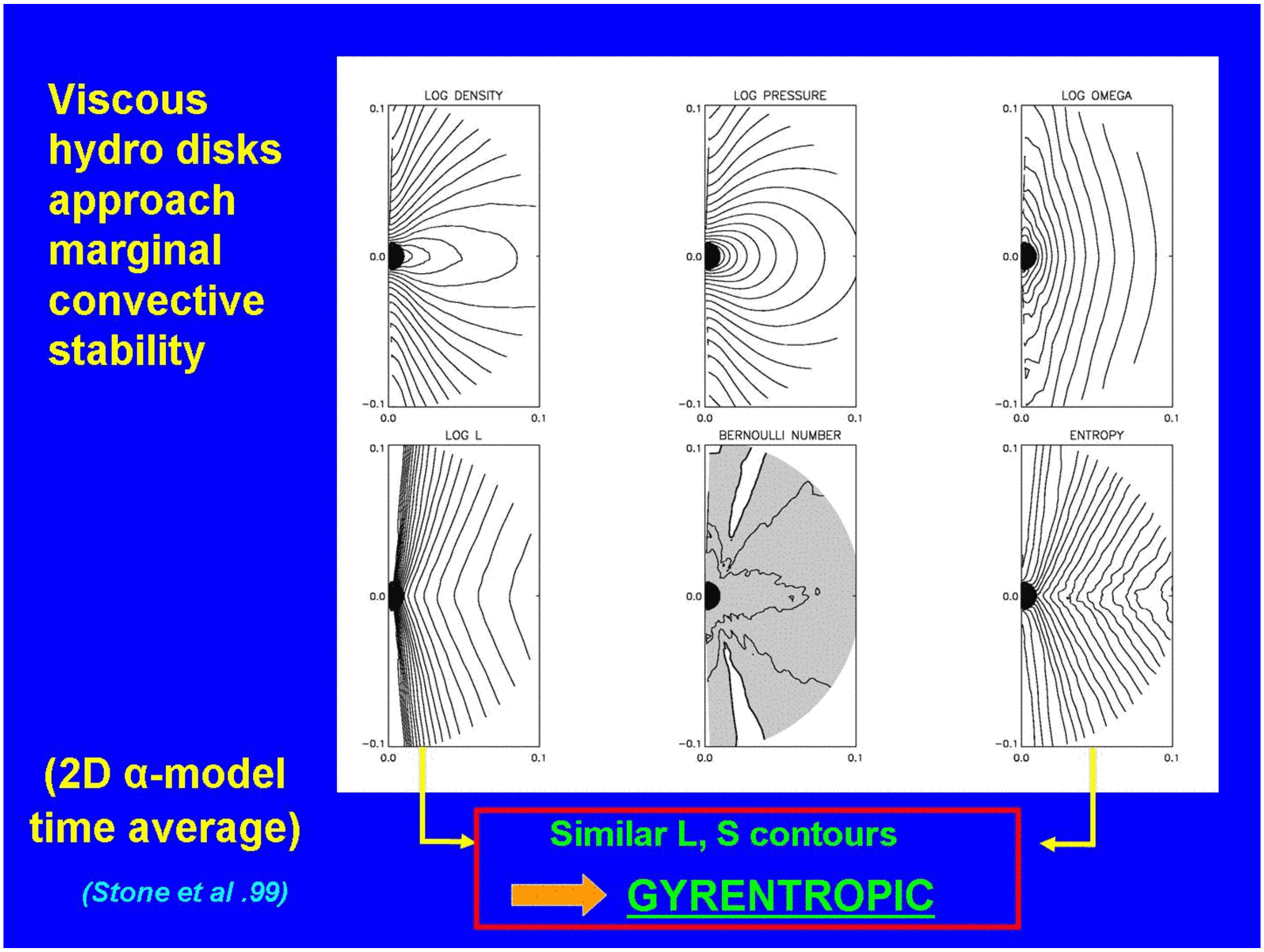


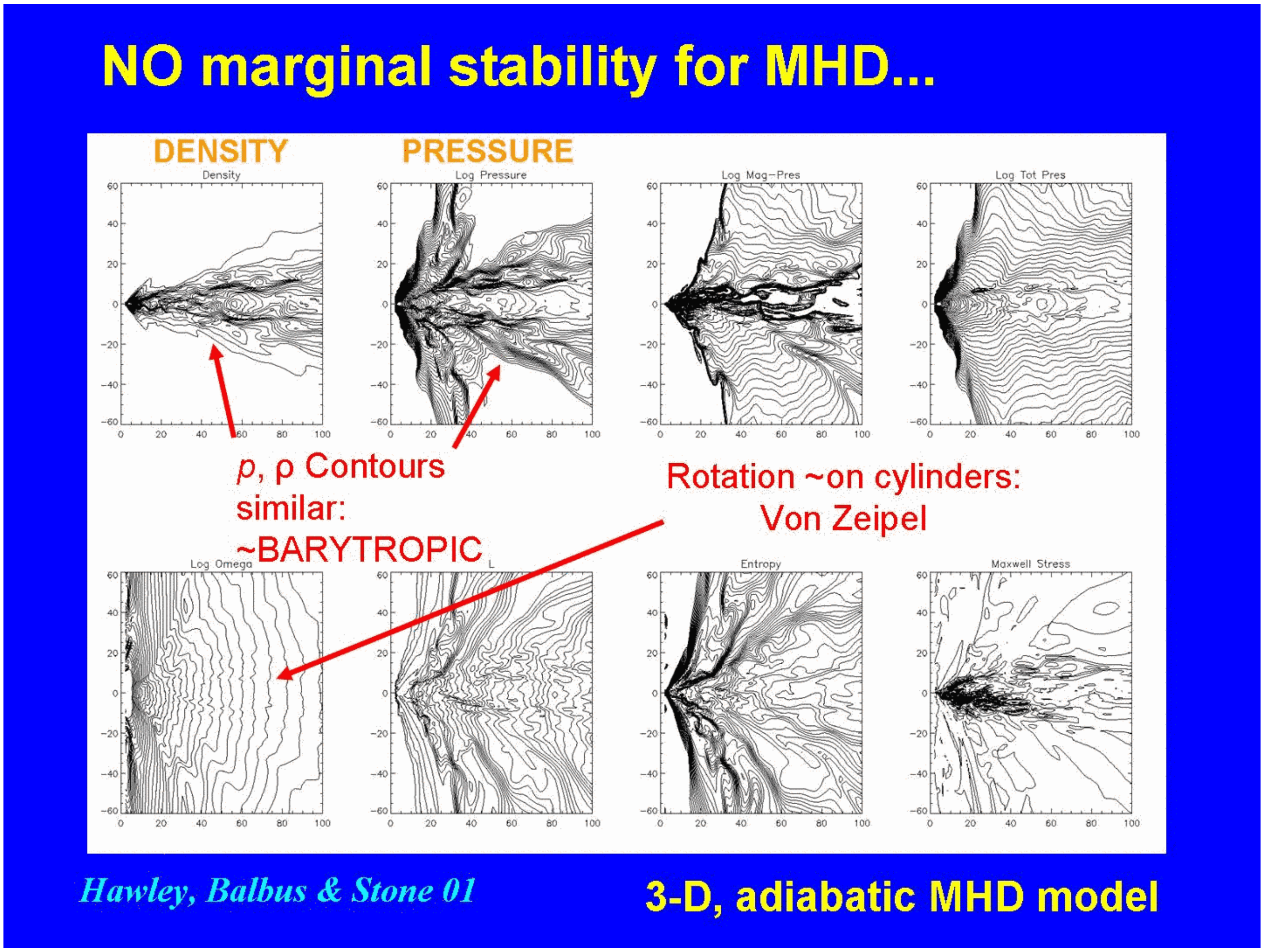
Viscous hydro disks approach marginal convective stability

(2D α-model time average)

(Stone et al .99)

Similar L, S contours

→ GYRENTROPIC



NO marginal stability for MHD...

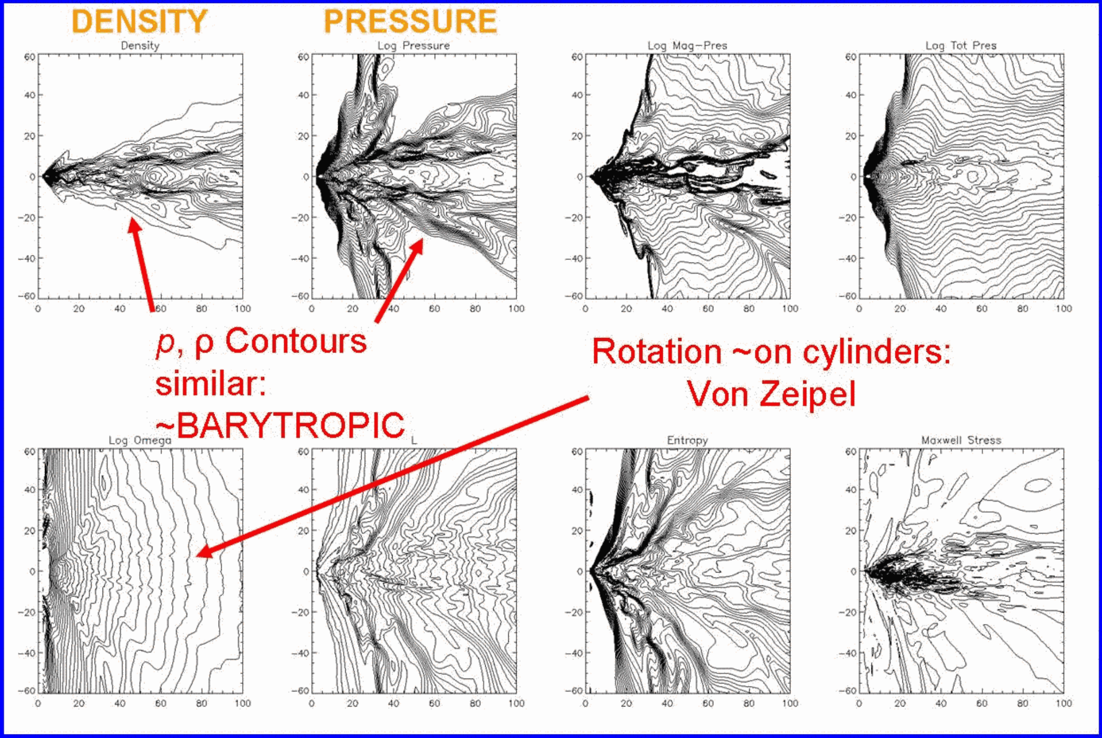
p, ρ Contours similar: ~BARYTROPIC

Rotation ~on cylinders: Von Zeipel

Hawley, Balbus & Stone 01

3-D, adiabatic MHD model

...yet disks look organized. WHY???



p, ρ Contours similar: ~BARYTROPIC

Rotation ~on cylinders: Von Zeipel

Hawley, Balbus & Stone 01

3-D, adiabatic MHD model

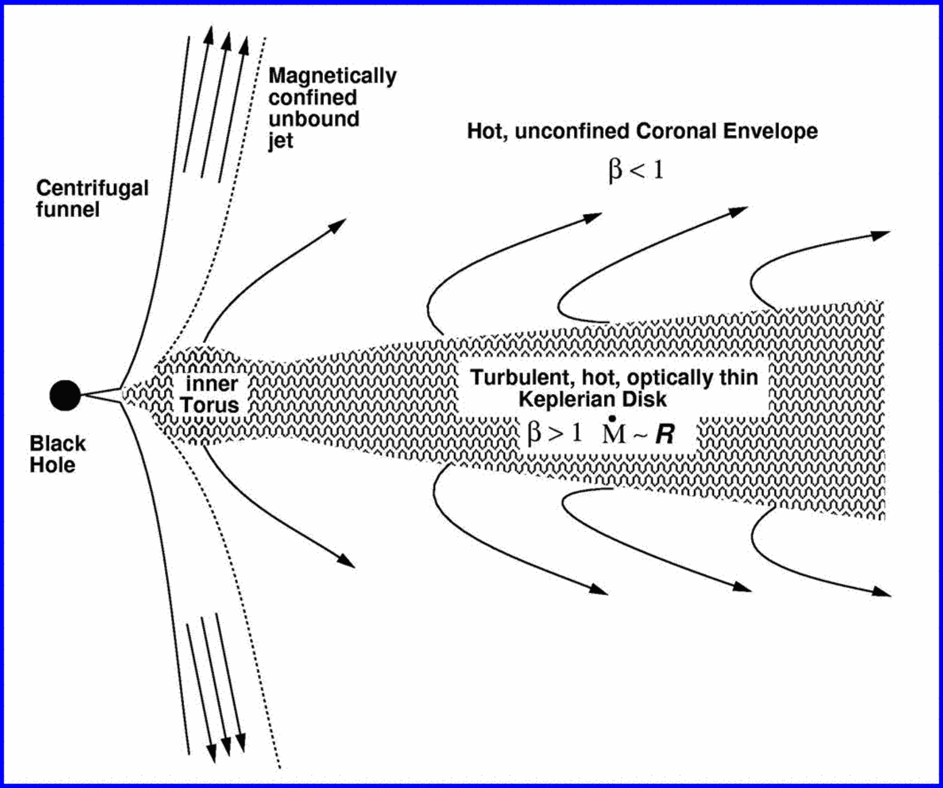
What's the organizing principle for MHD disks?

- **No marginal stability:** always unstable to MRI

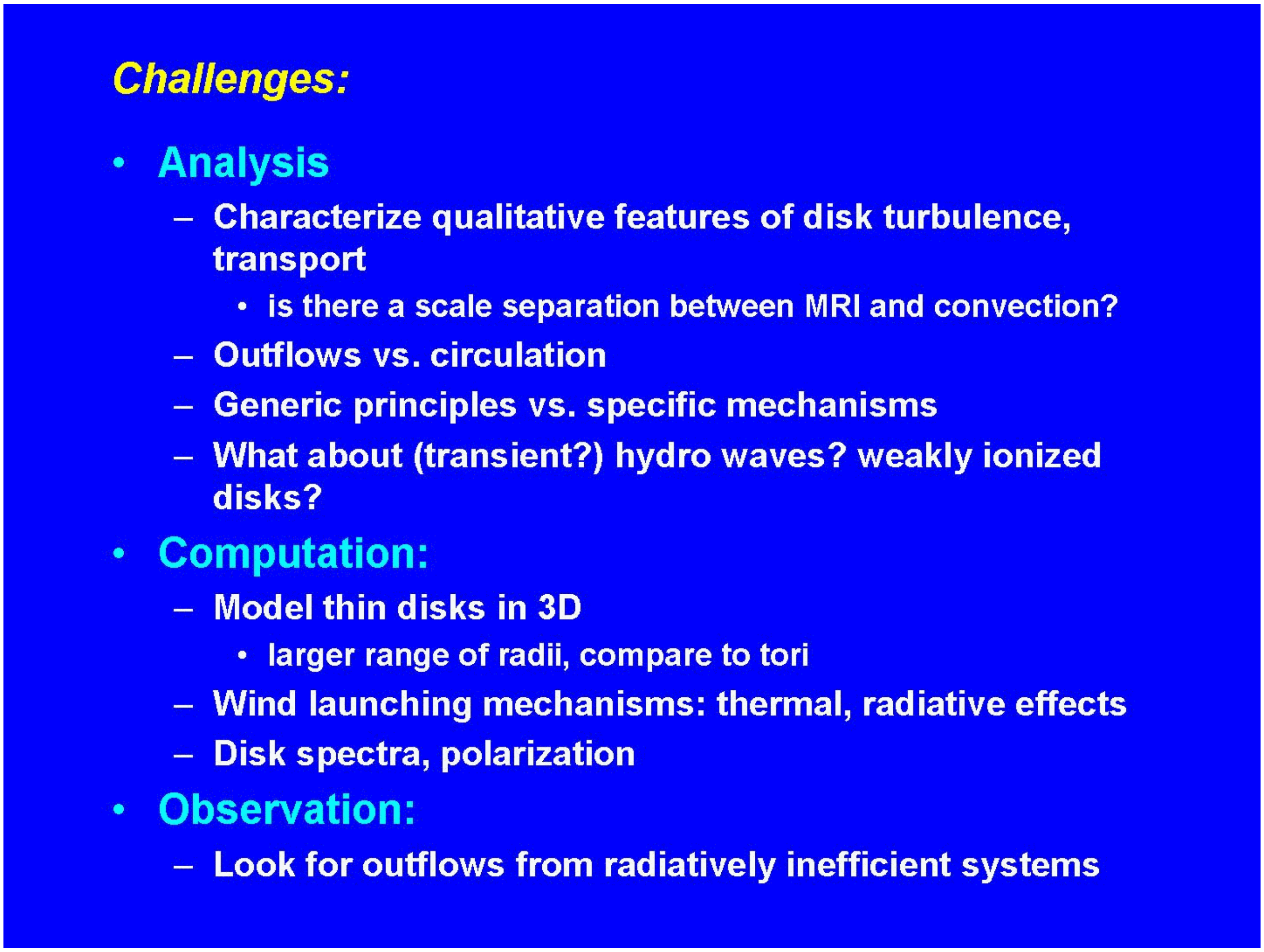
  So why is there any systematic structure? ("looks like" marginal stability)
- **Clue 1:** MRI most effective on small scales, convection works best on large scales.
- **Clue 2:** MRI "winds up" B_φ more than B_{pol}, buoyancy of B_φ can affect disk structure
- **Result?** MRI dominates on small scales, but magnetic buoyancy governs overall disk structure…maybe (similar to hydro case, but different details)

Approaches:

- **Analysis:**
  - Stability: convective, MRI
  - Self-similar disk-wind models
  - Thermal properties: coronae, radiation mechanisms, electron-ion coupling
- **Computation:**
  - 2- and 3D shearing box and vertically stratified models
  - Global evolution of tori and thick disks
- **Observation:**
  - Galactic nuclei: Evidence of radiatively inefficient accretion, outflows
  - Microquasars: disk instabilities, disk-jet coupling

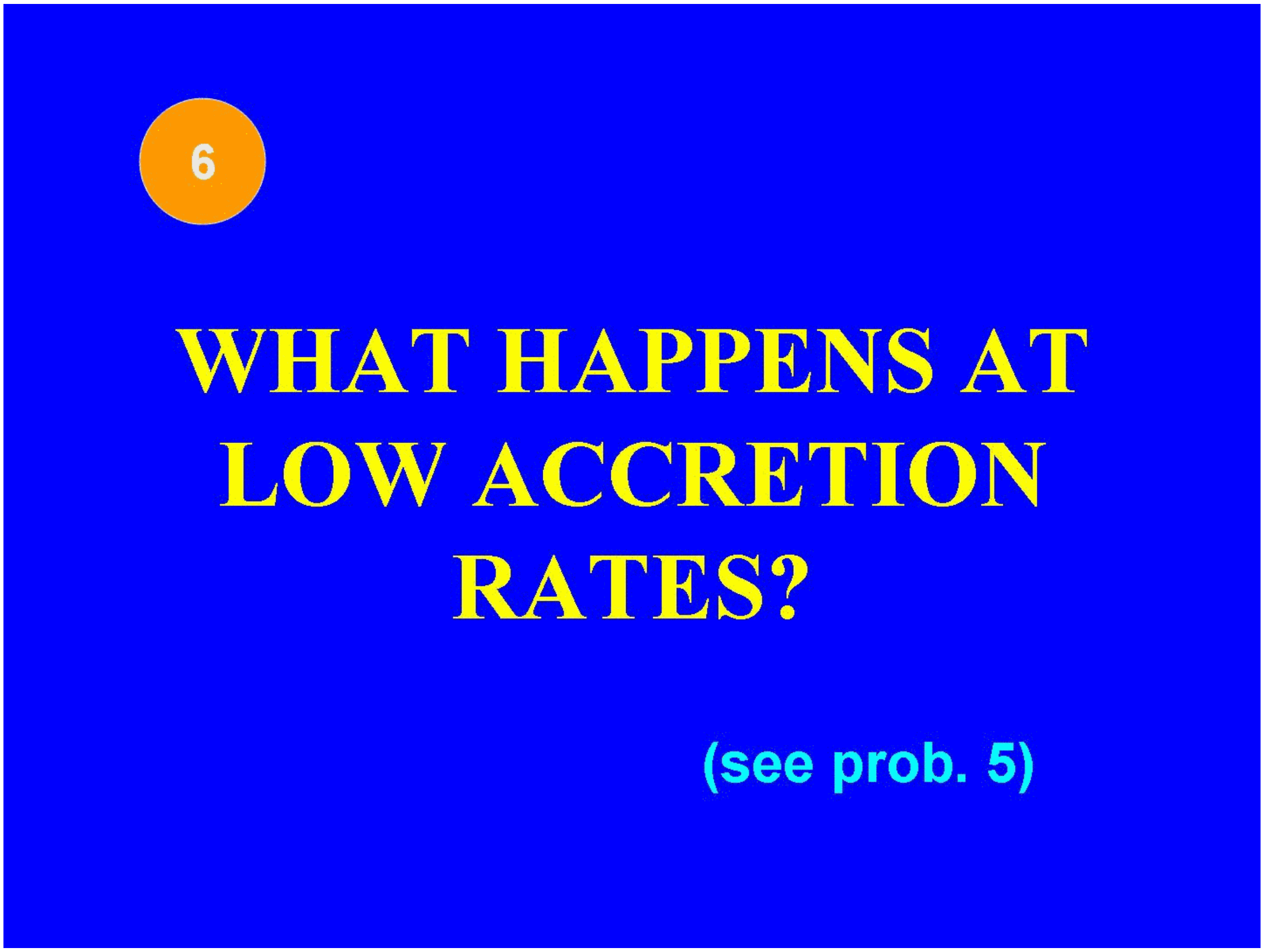


Hawley & Balbus 02



Challenges:

- Analysis
  - Characterize qualitative features of disk turbulence, transport
    - is there a scale separation between MRI and convection?
  - Outflows vs. circulation
  - Generic principles vs. specific mechanisms
  - What about (transient?) hydro waves? weakly ionized disks?
- Computation:
  - Model thin disks in 3D
    - larger range of radii, compare to tori
  - Wind launching mechanisms: thermal, radiative effects
  - Disk spectra, polarization
- Observation:
  - Look for outflows from radiatively inefficient systems



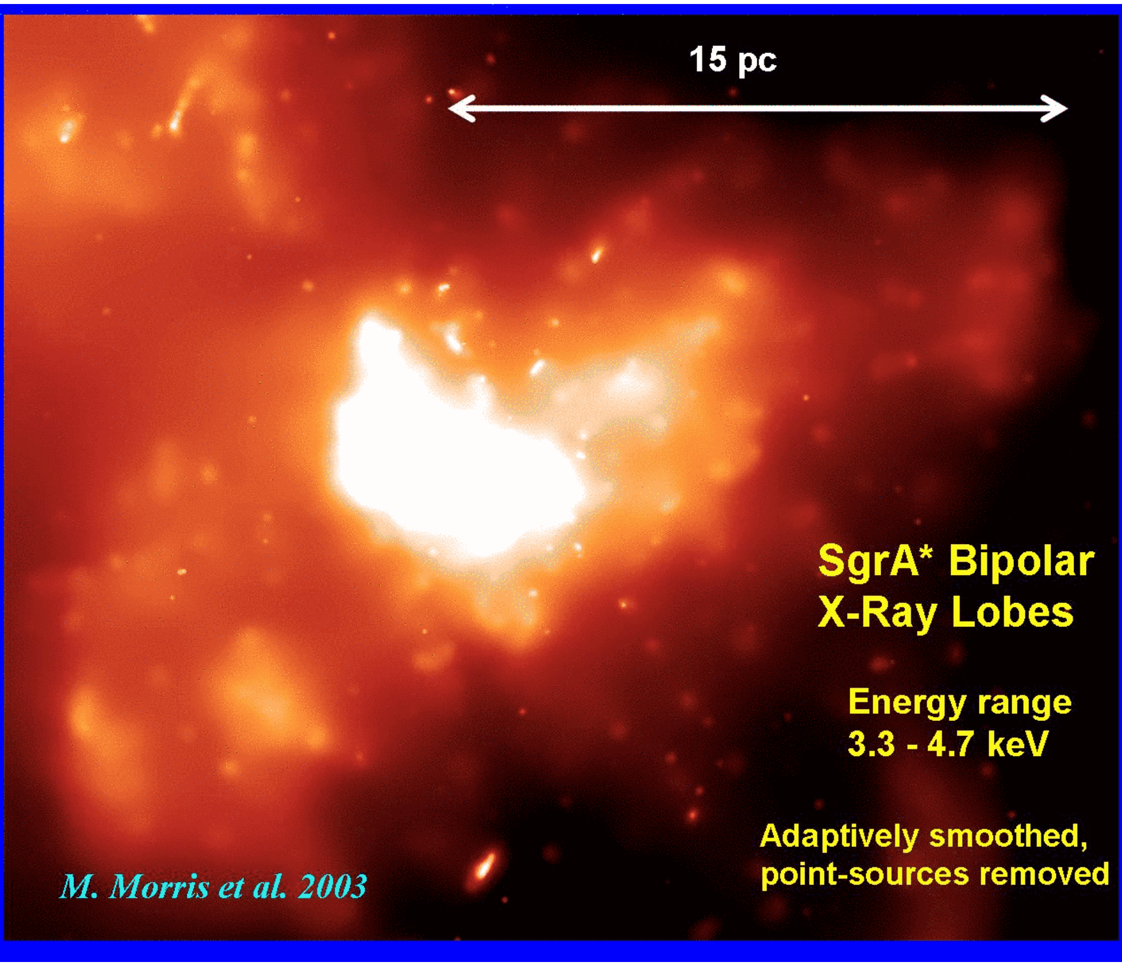
6

WHAT HAPPENS AT LOW ACCRETION RATES?

(see prob. 5)

What we know:

- "Stealth accretion" is common
  - Galactic Center, many gal. nuclei
- Requires weak thermal coupling between electrons and ions
  - Some proposals about this but is it solved?
  - Does Coulomb scattering set the rate?
- Distinguish between true radiative inefficiency and $\dot{m}_{accreted} \ll \dot{m}_{supplied}$

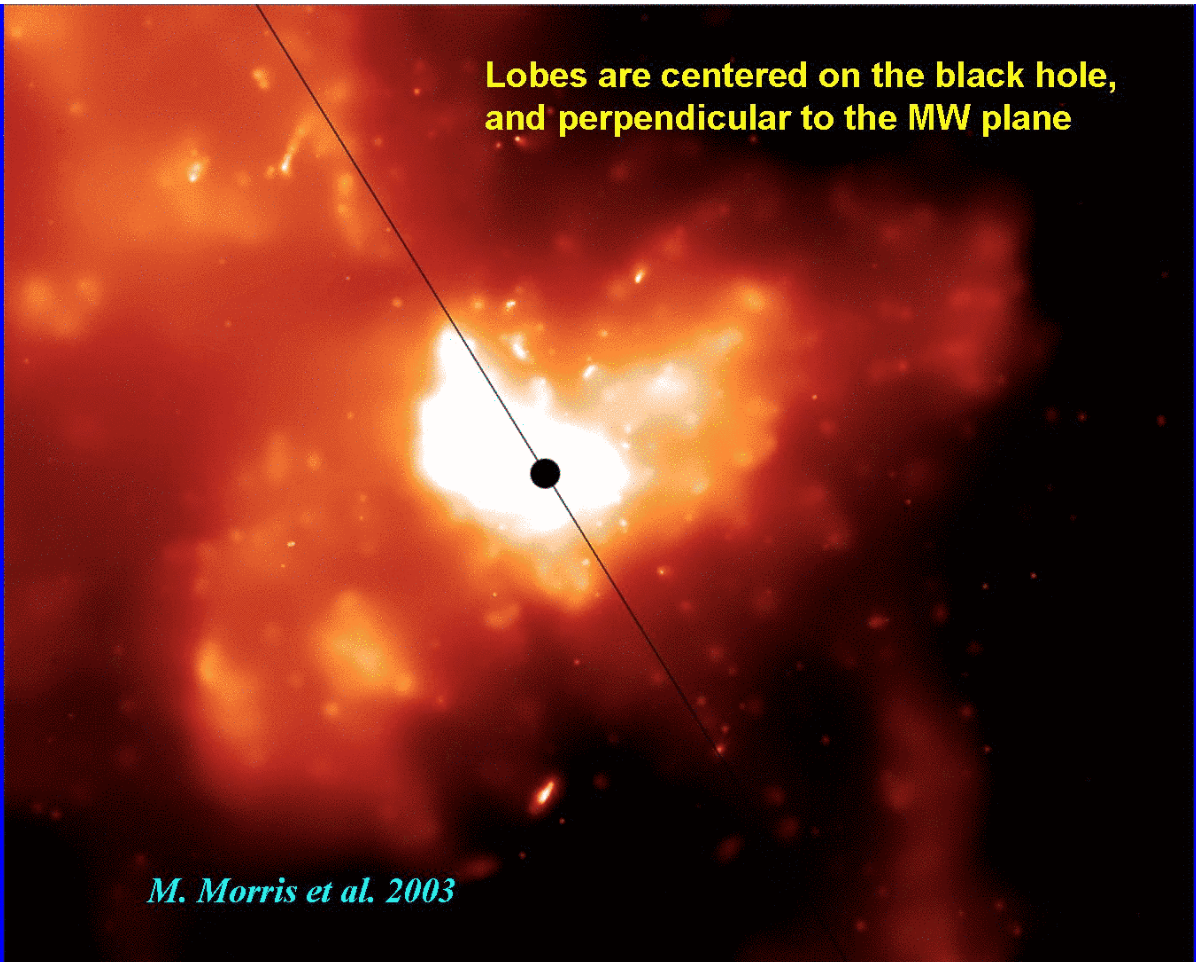


SgrA* Bipolar X-Ray Lobes

Energy range
3.3 - 4.7 keV

Adaptively smoothed, point-sources removed

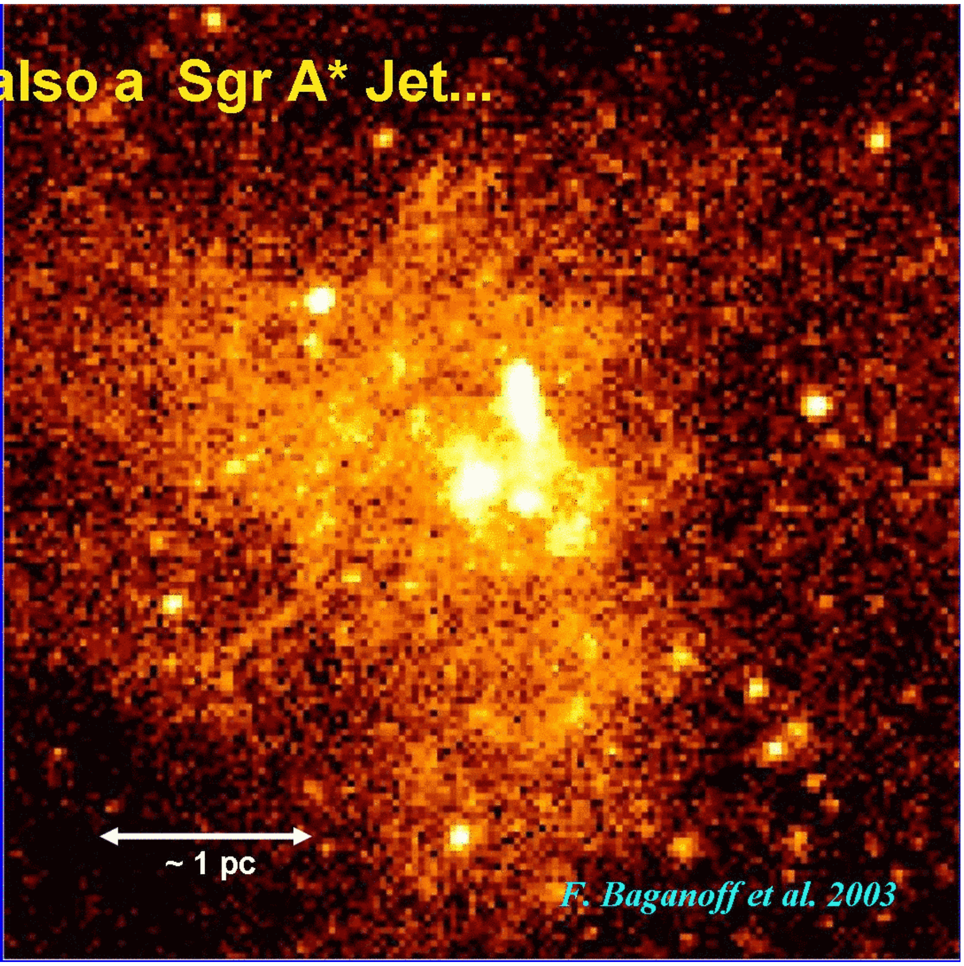
M. Morris et al. 2003



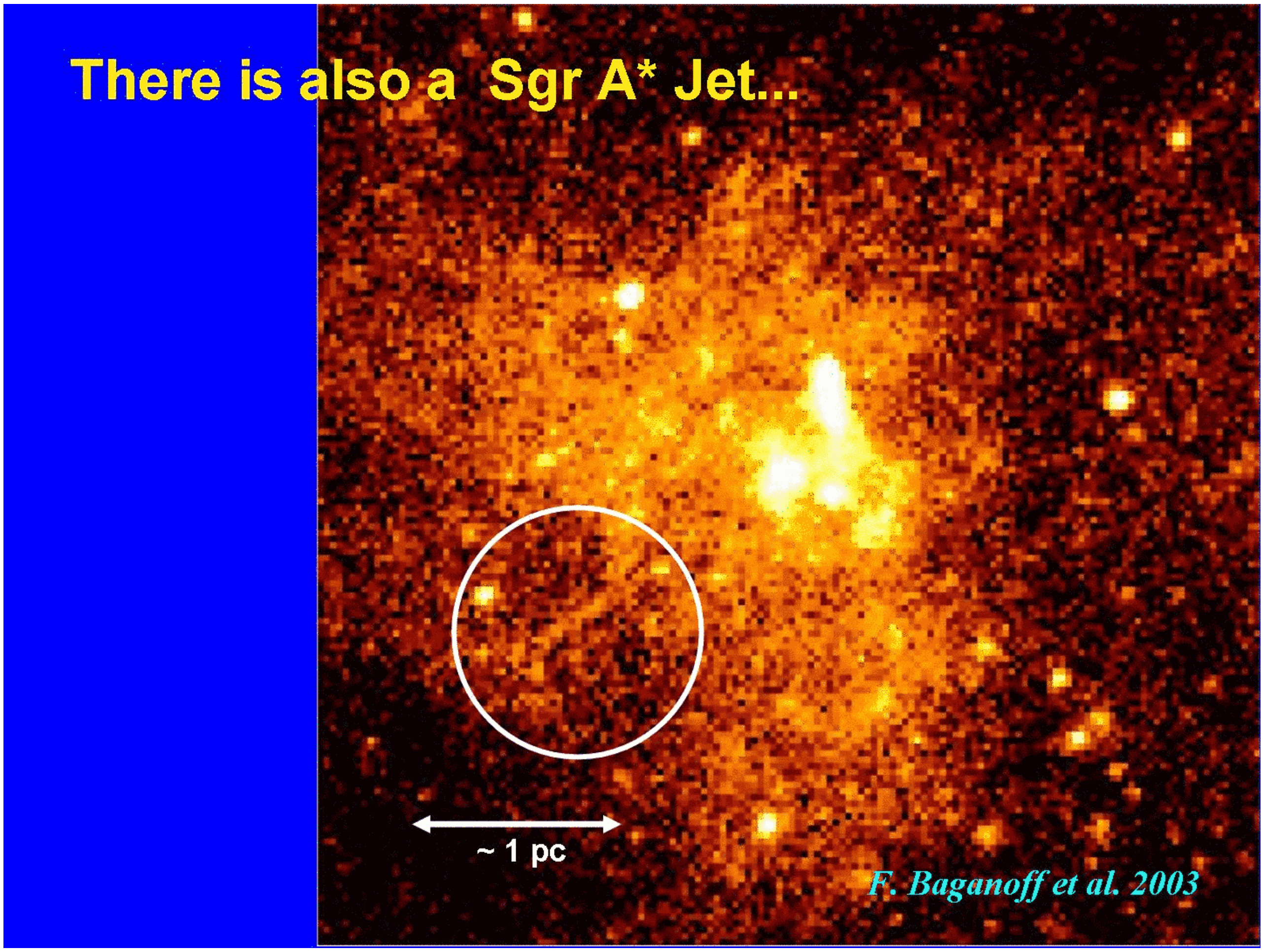
Lobes are centered on the black hole, and perpendicular to the MW plane

M. Morris et al. 2003

There is also a Sgr A* Jet...



F. Baganoff et al. 2003



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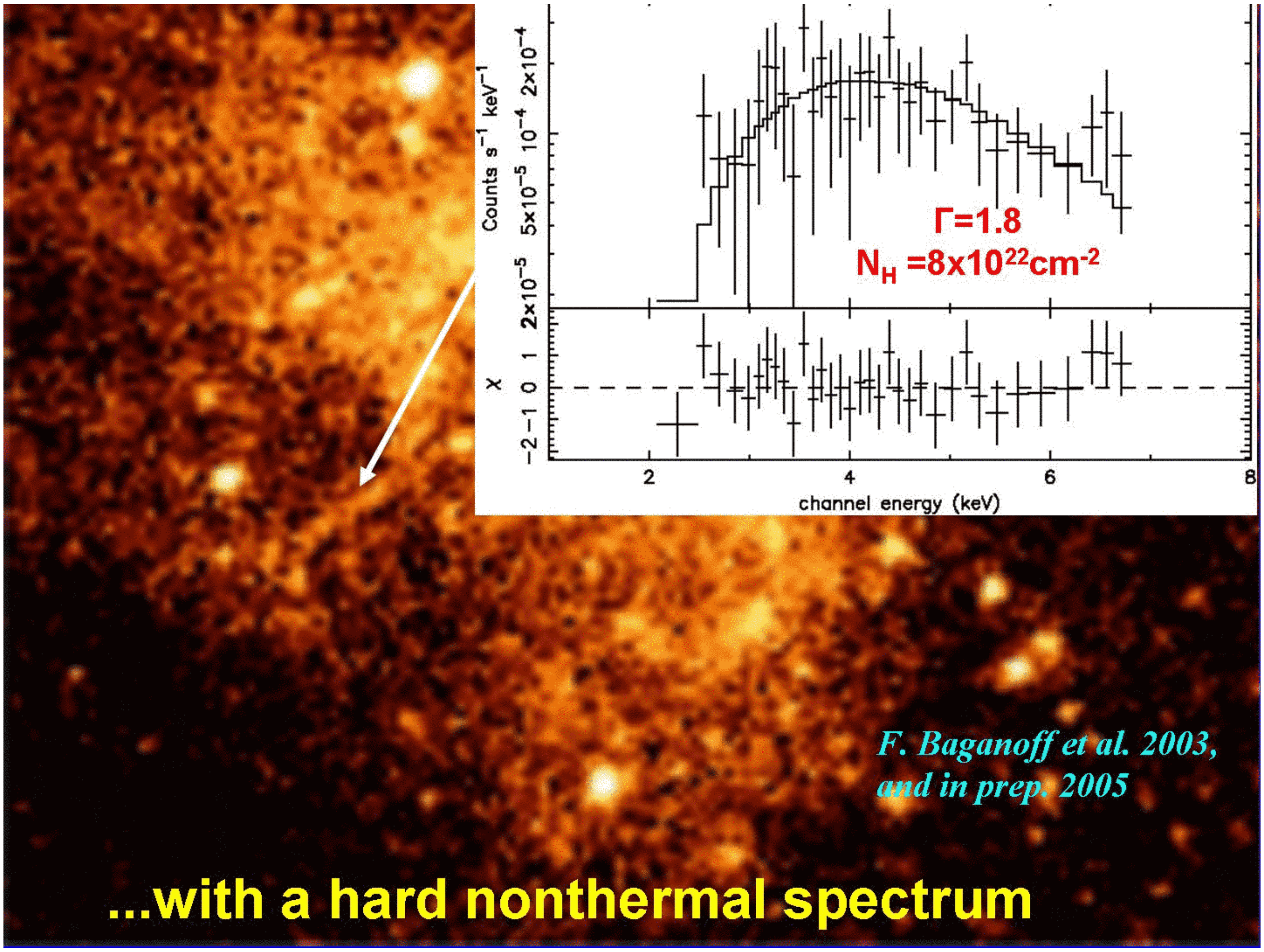
F. Baganoff et al. 2003



F. Baganoff et al. 2003,
and in prep. 2005

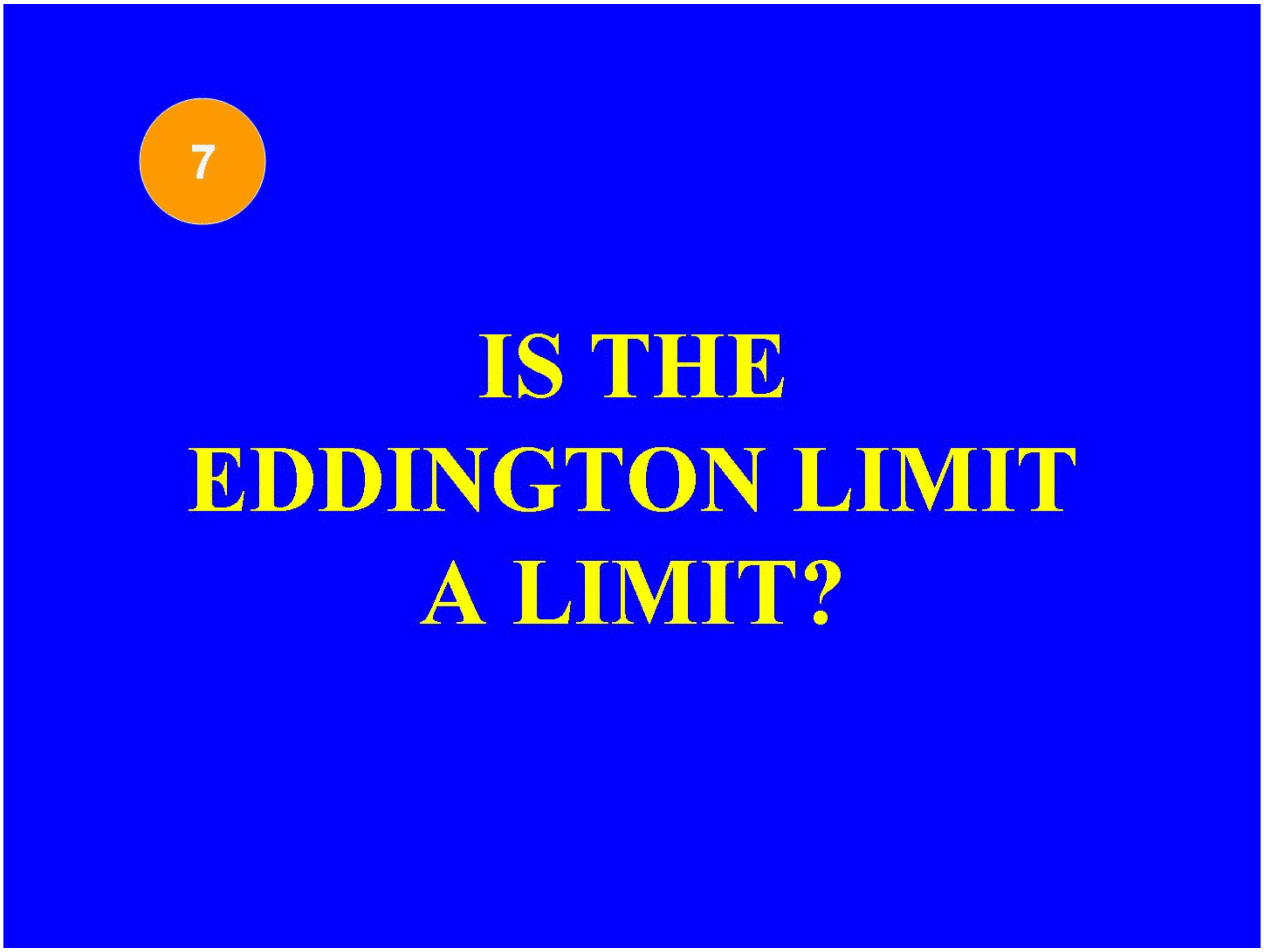
...with a hard nonthermal spectrum

Approaches:

- **Analysis:**
  - Physics of two-temperature plasmas
    - Include nonlocal radiative effects
    - Include effects of mass loss
  - Radiative/nonradiative disk transition
- **Observation:**
  - Galactic nuclei: Evidence of radiatively inefficient accretion, outflows

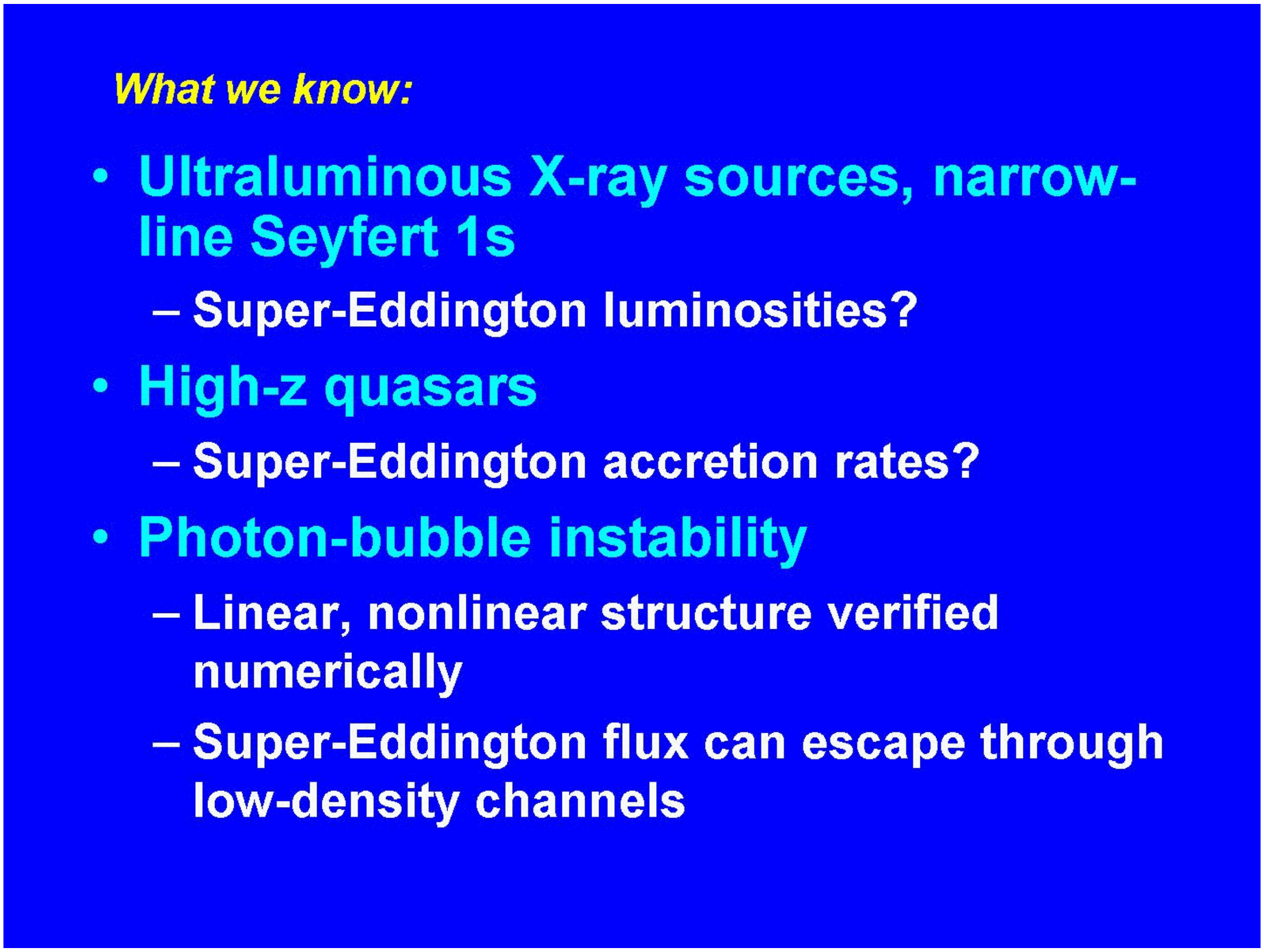
Challenges:

- **Analysis**
  - Why luminosities so low?
    - accretion rate suppressed by ADIOS (radiative efficiency could be >1/2 but $\dot{M}_{accreted} << \dot{M}_{supplied}$)
    - very low radiative efficiencies (electrons not heated)
  - Nonthermal processes, reconnection theory
- **Computation:**
  - Particle simulations of plasma processes
- **Observation:**
  - Look for evidence of accretion rates, densities (e.g., Faraday rotation, circular polarization)



7

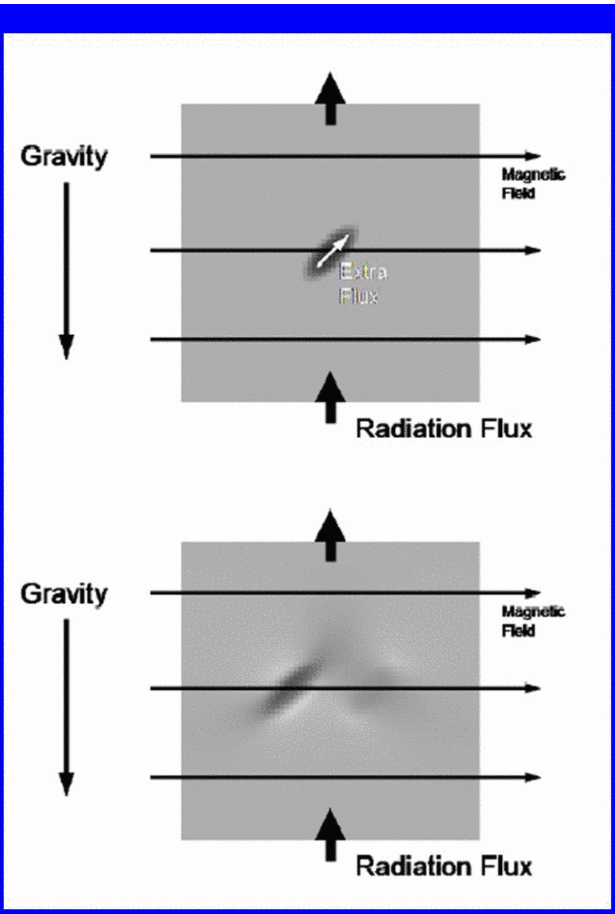
IS THE EDDINGTON LIMIT A LIMIT?



What we know:

- Ultraluminous X-ray sources, narrow-line Seyfert 1s
  - Super-Eddington luminosities?
- High-z quasars
  - Super-Eddington accretion rates?
- Photon-bubble instability
  - Linear, nonlinear structure verified numerically
  - Super-Eddington flux can escape through low-density channels

PHOTON BUBBLE INSTABILITY...



N. Turner et al. 2004

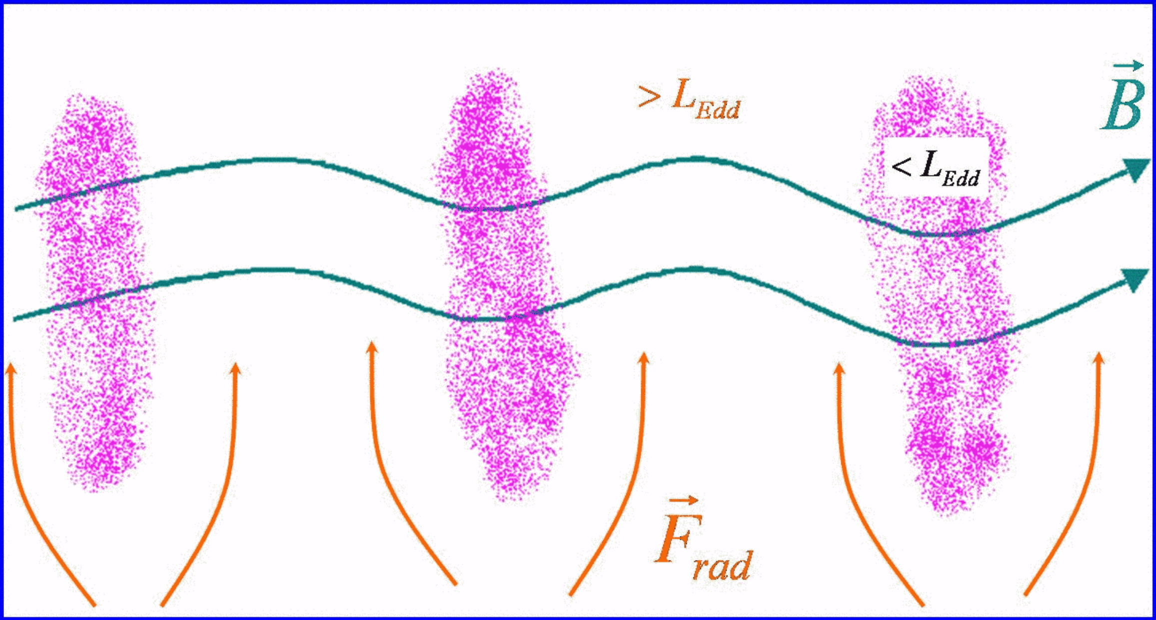
SUPER-EDDINGTON ACCRETION DISKS?

Photon bubbles $\Rightarrow$ porous disk $\Rightarrow$

$L > L_E$ possible without blowing disk apart

Max. luminosity:

$$\frac{L}{L_E} \sim 40 \left(\frac{\alpha}{0.01}\right)\left(\frac{m}{10}\right)^{1/5}\left(\frac{\xi}{0.1}\right)^{4/5}$$



Magnetic tension holds disk together

Approaches:

- **Analysis:**
  - Linear stability analyses
  - Models of nonlinear wave trains
  - Estimate density contrasts, luminosities in different circumstances (disks, massive stars, GRB outflows)
- **Computation:**
  - 2D, 3D RHD with flux-limited diffusion
  - Atmospheres but without shear, MRI
- **Observation:**
  - Spectral signatures of porous atmospheres
  - Estimates of L/L_{Edd} from colors, variability

Challenges:

- **Analysis:**
  - – Model nonlinear buoyant modes
    - Relevant when gas pressure is weaker, wave speed set by radiative diffusion
  - – Radiation-driven winds (inevitable at top of atmosphere)
- **Computation:**
  - – Get beyond flux-limited diffusion!!
  - – Does MRI/turbulence kill photon bubbles?
  - – Simulate whole atmosphere including wind
  - – Role of global (non-magnetic?) modes
- **Observation:**
  - – Get dynamical masses of ULXs!

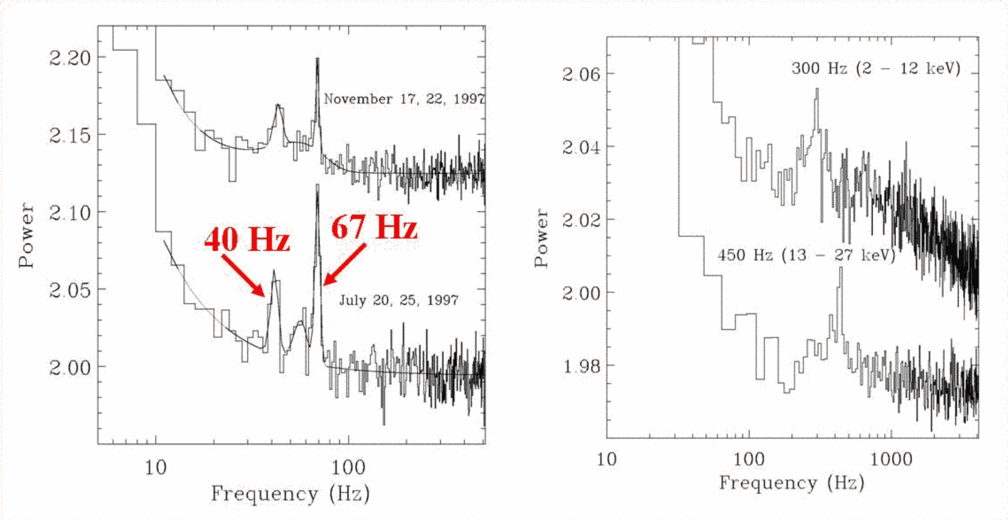
8

HOW CLOSE ARE WE TO MAPPING SPACETIMES USING DISKS?

What we know:

- Broad, variable iron lines
  - Line profiles susggest emission from inner accretion disk
  - Illumination by corona
- Fast QPOs with stable (?) frequencies
  - Resonances?
- Potential to determine black hole spins

QPOs in 2 MICROQUASARS



GRS 1915+105

GRO J1655-40

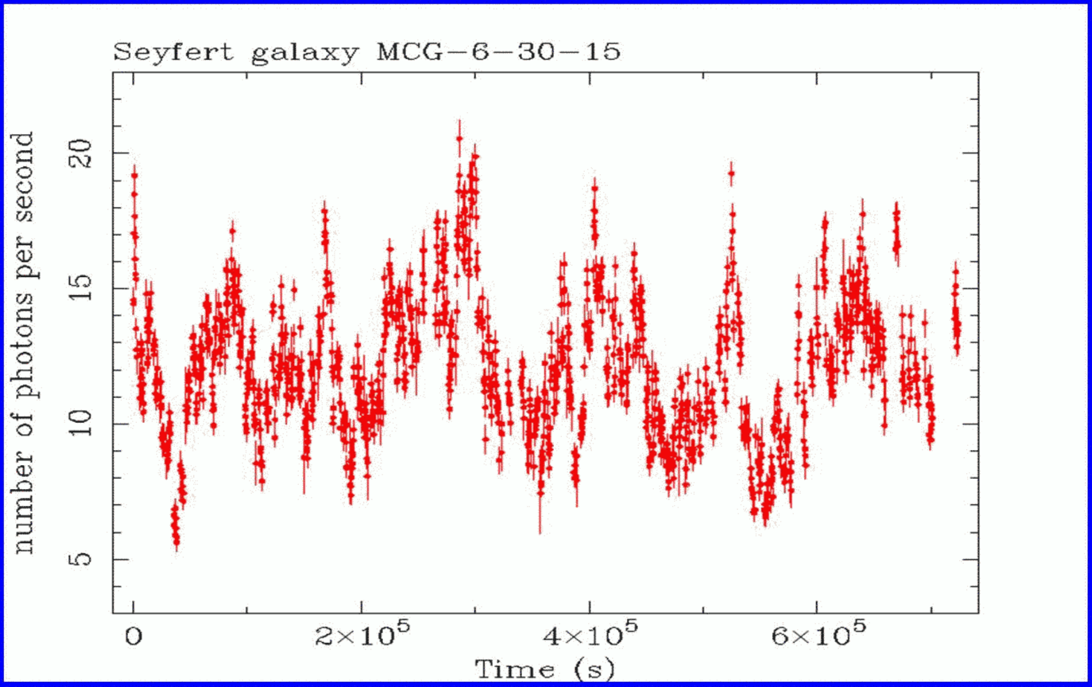
Archival RXTE data: Strohmayer 2001

QUASI-PERIODIC OSCILLATIONS

- Rich spectrum of modes: coherence up to Q ~20
- Highest frequency QPOs must come from close to horizon - tied to marginally stable orbit?
- Origins of modes still unclear
  - – Period of circular orbits
  - – Precessional modes
    - dragging of inertial frames by BH spin
    - Precession of periastron
  - – Pulsational modes: “diskoseismology”
    - Disk acts as resonant cavity under influence of GR effects
  - – Bending modes
- Redundant probes of spacetime structure

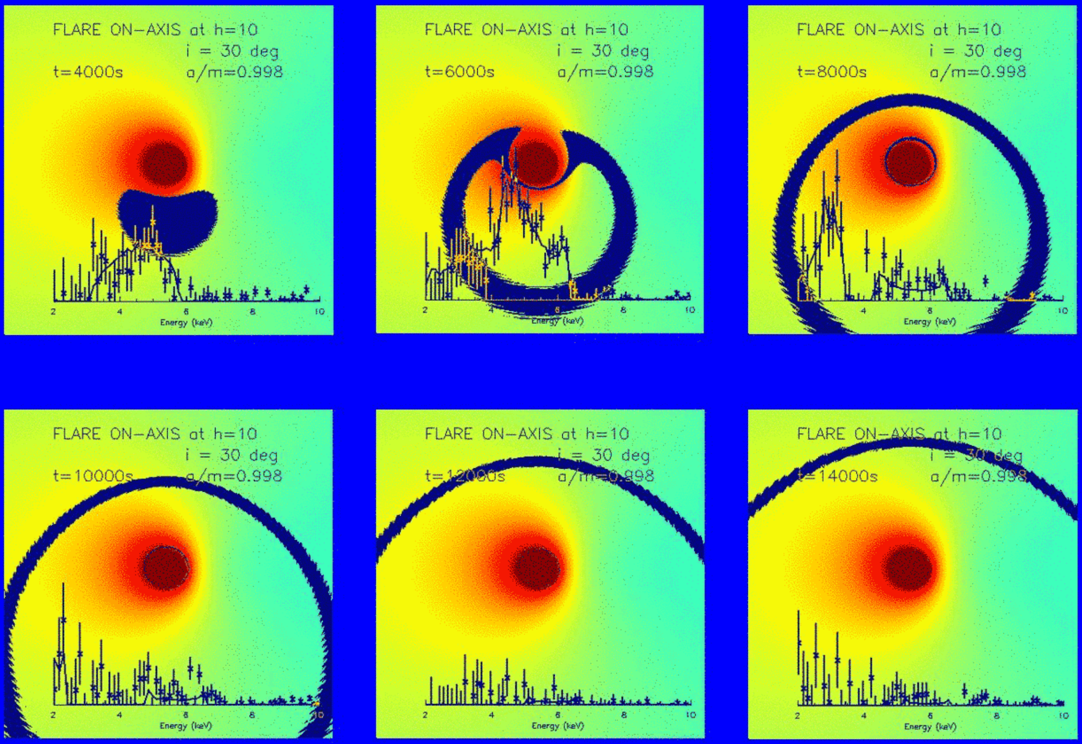
… all depend on metric in different ways

Reverberation mapping...



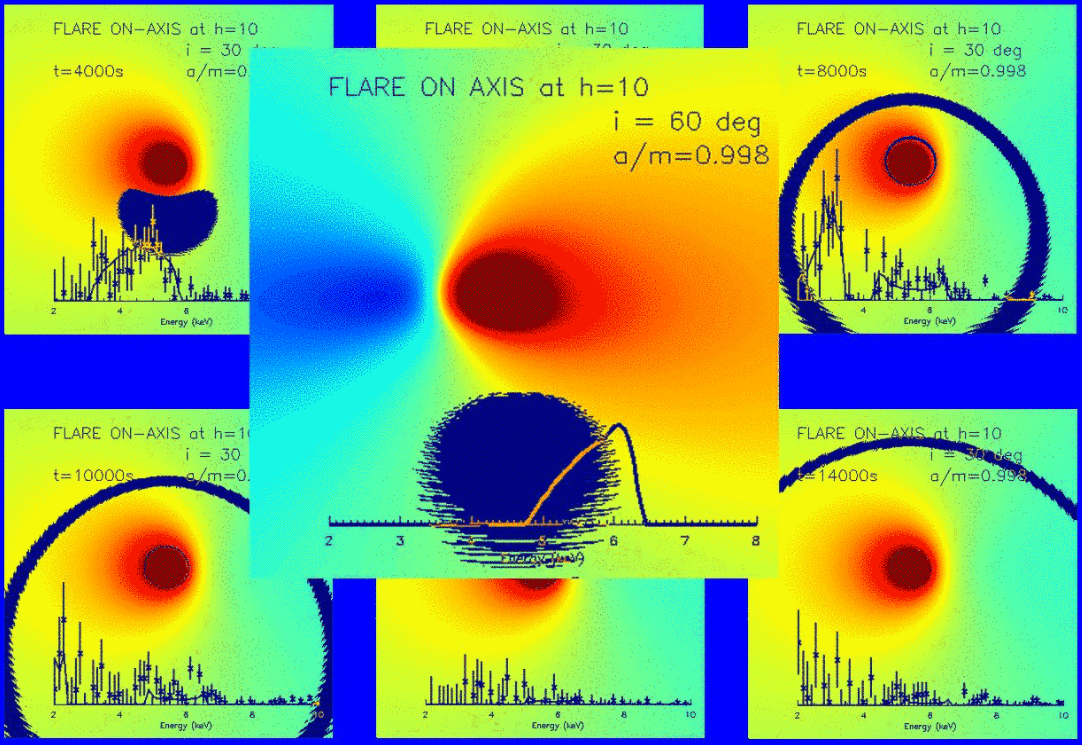
Lee, Fabian, Reynolds et al. (2000); Reynolds (2000)

Iron line variability arises from the finite time it takes the X-ray echo to sweep across the disk



(C. Reynolds, A. Young)

Iron line variability arises from the finite time it takes the X-ray echo to sweep across the disk



(C. Reynolds, A. Young)

Approaches:

- **Analysis:**
  - Relativistic ray-tracing
  - Dynamical models of QPO (instabilities, orbiting blobs)
  - Reflection models of iron lines – different coronal geometries
- **Computation:**
  - Simulations of reverberation
  - Diskoseismology
- **Observation:**
  - QPO power-density spectra
  - Broad iron lines in different spectral states

Challenges:

- **Analysis:**
  - Radiation physics: what modulates QPOs?
  - Coronal physics: illumination source
  - Disk physics: ionization state of iron, scattering atmosphere
- **Computation:**
  - Reverberation inverse problem
  - Model QPOs
- **Observation:**
  - Mass scaling: compare AGNs and microquasars

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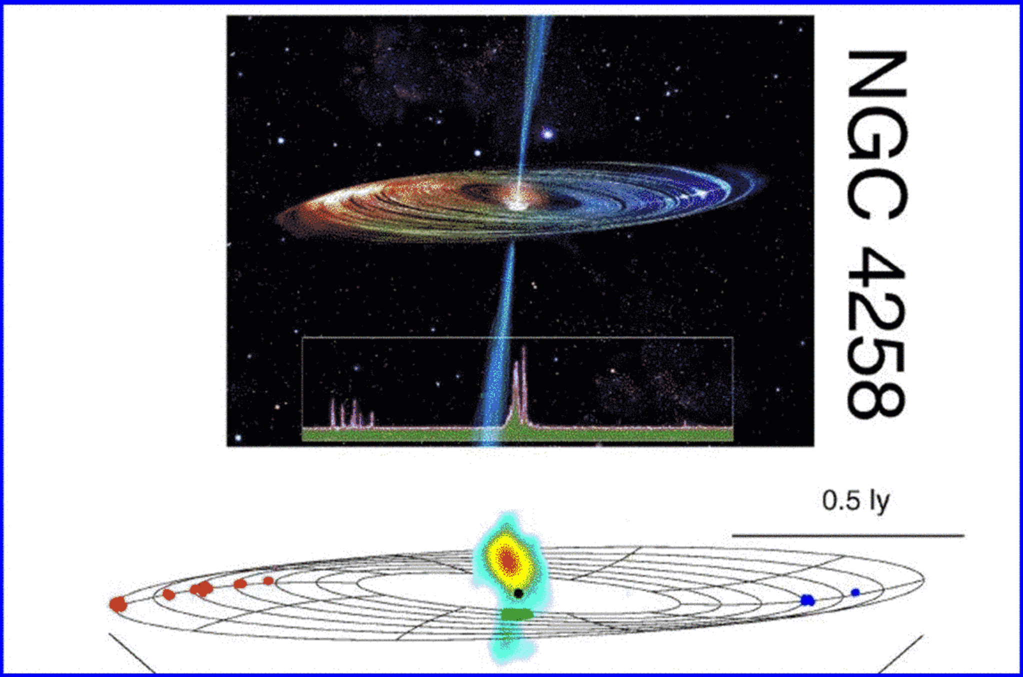
ARE DISKS REALLY FLAT AND CIRCULAR?

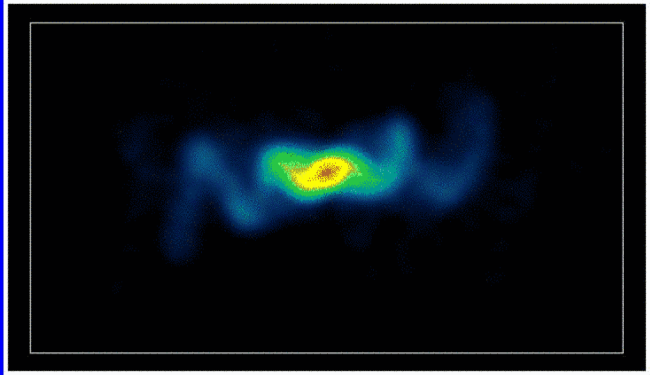
What we know:

- Warped disk in NGC 4258 (from masers)
- Precession in SS433, Her X-1, etc.
- Warping instability
  - Driven by radiation pressure, mass loss
- Bardeen-Petterson effect
  - Driven by Lense-Thirring effect
- May be difficult to warp disks

NGC 4258: 36 million solar masses

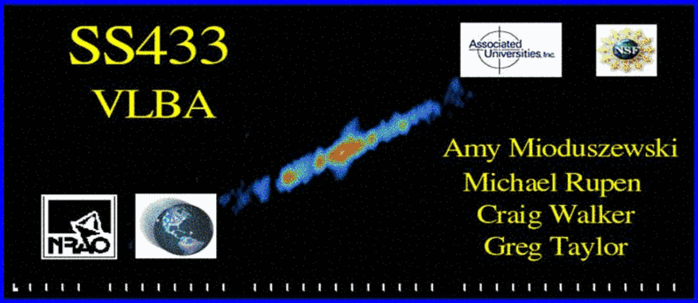


SS433: Super-Eddington accretion + precessing jets

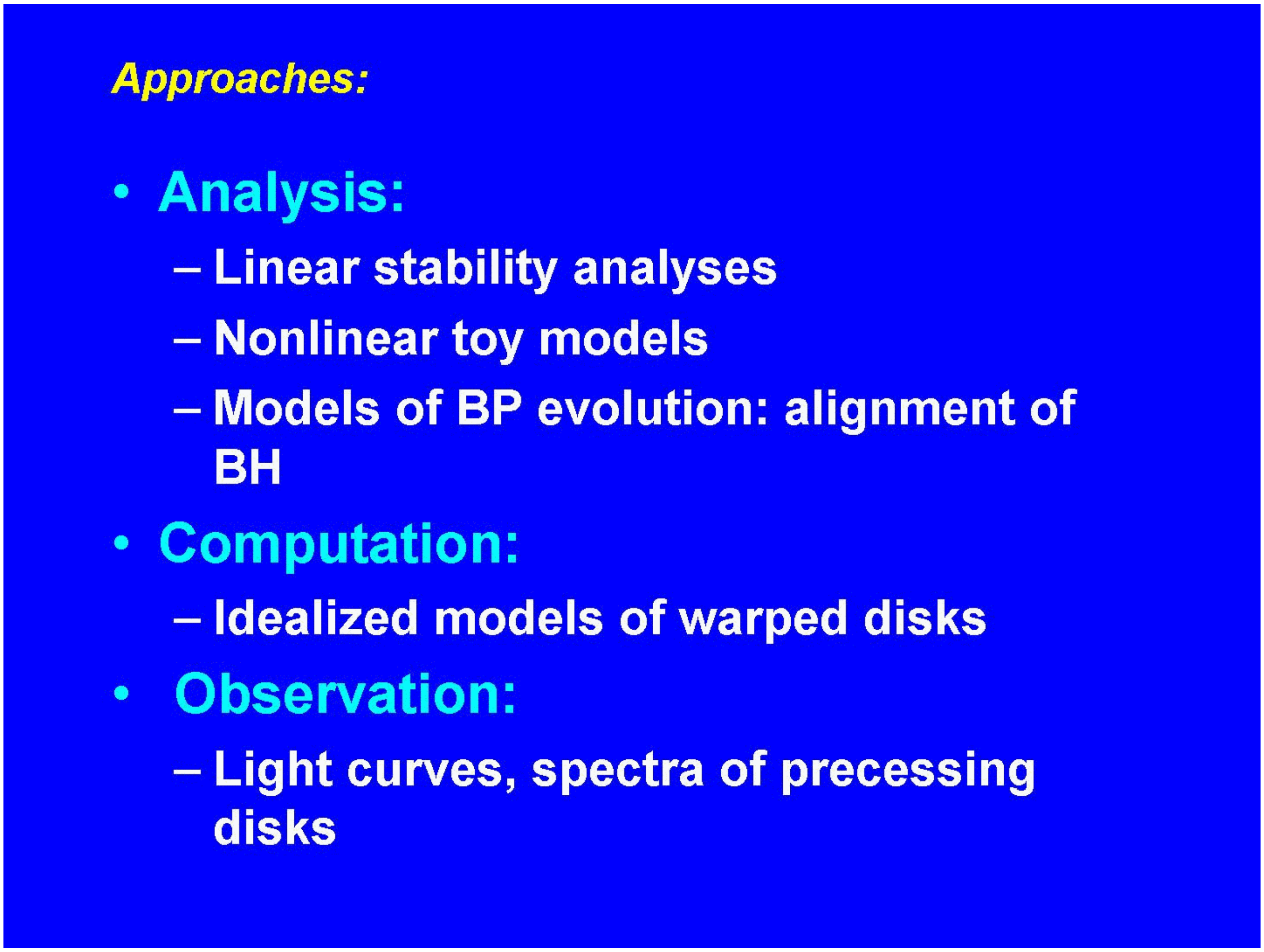


VLA, 5GHz

Blundell & Bowler 2004

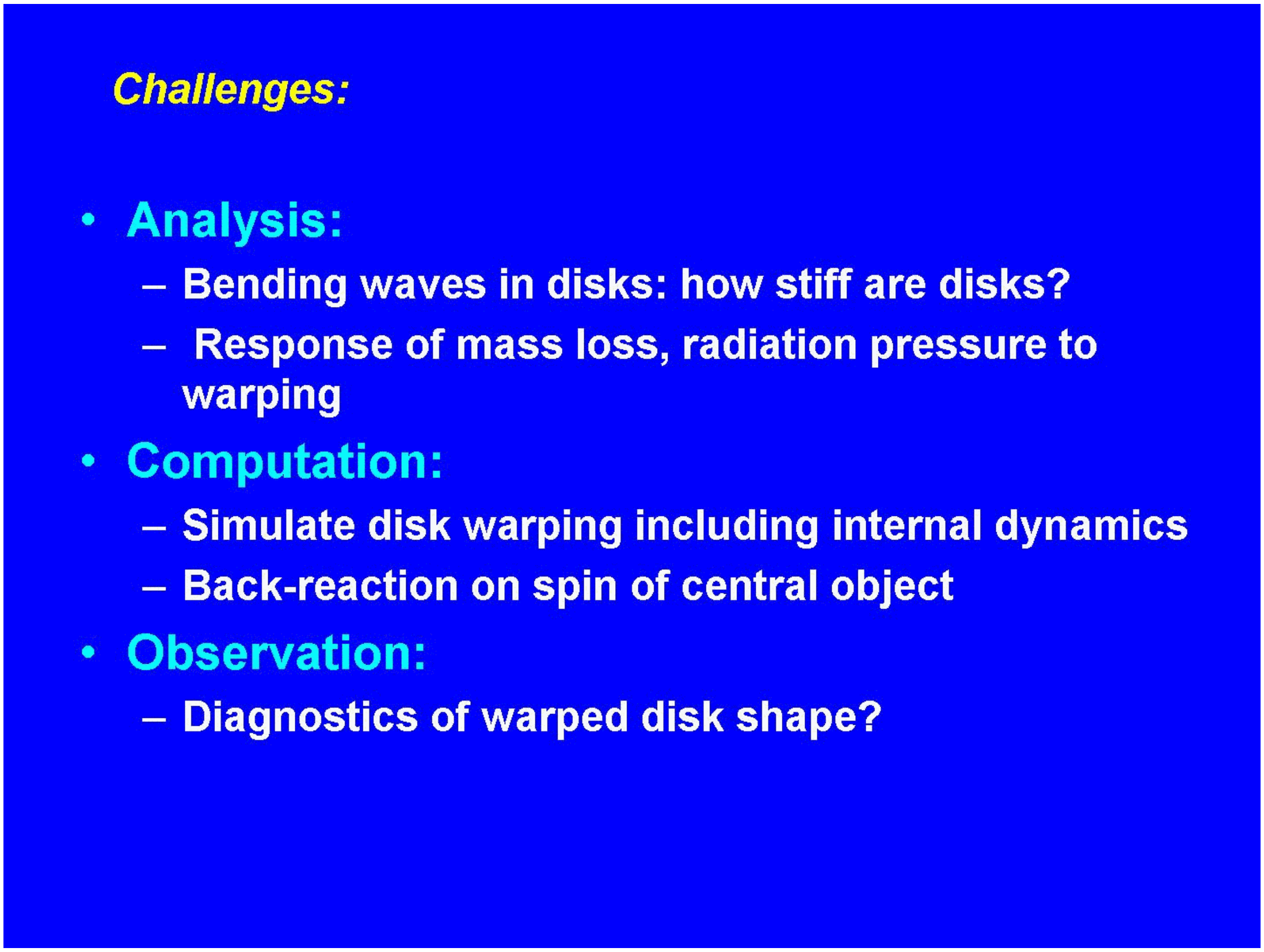


Mioduszewski et al. 2004



Approaches:

- Analysis:
  - Linear stability analyses
  - Nonlinear toy models
  - Models of BP evolution: alignment of BH
- Computation:
  - Idealized models of warped disks
- Observation:
  - Light curves, spectra of precessing disks



Challenges:

- Analysis:
  - Bending waves in disks: how stiff are disks?
  - Response of mass loss, radiation pressure to warping
- Computation:
  - Simulate disk warping including internal dynamics
  - Back-reaction on spin of central object
- Observation:
  - Diagnostics of warped disk shape?

HOW DO DISKS INTERACT WITH MAGNETOSPHERES?

What we know:

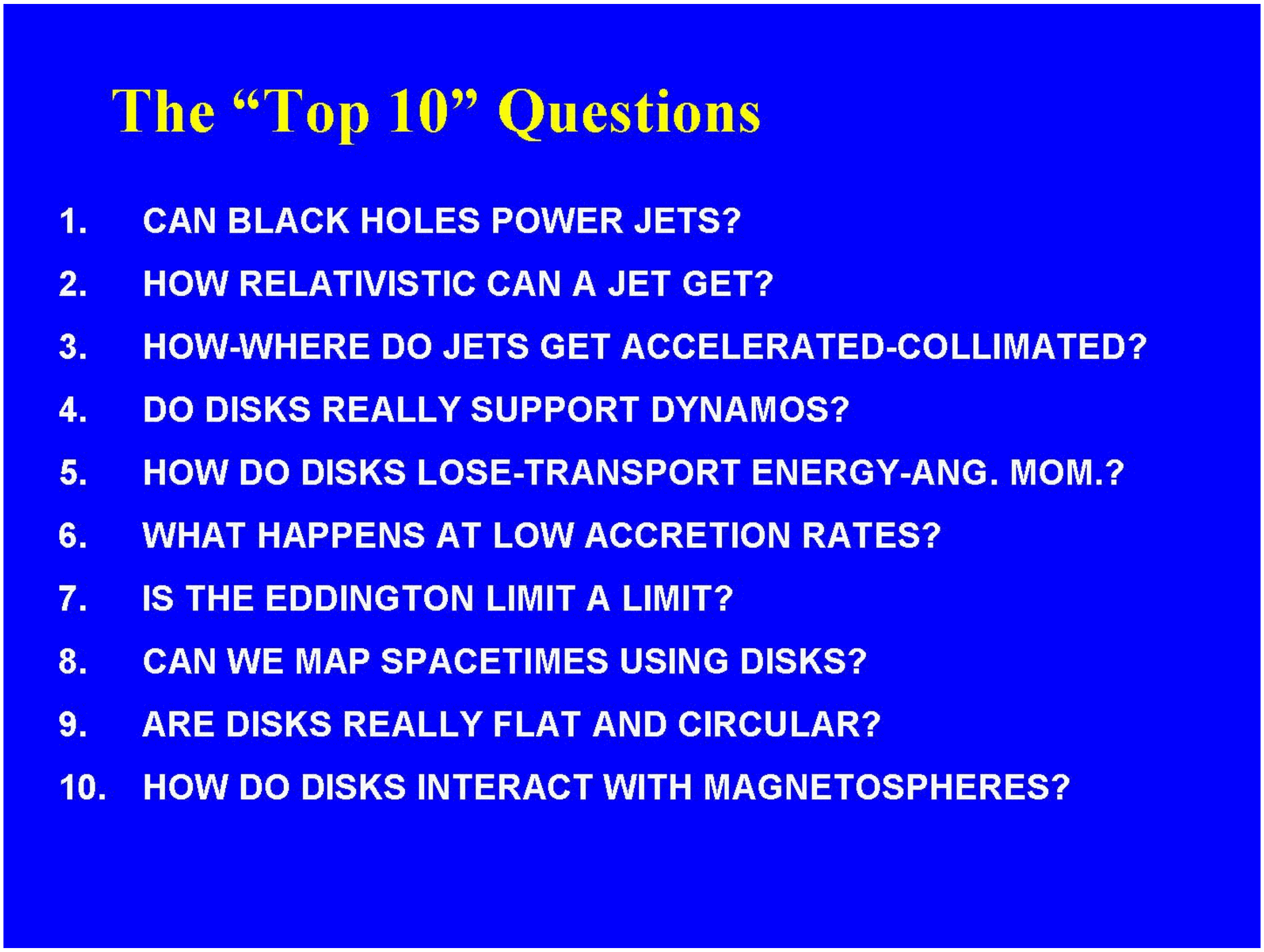
- Propeller effect
  - – Spindown of protostars?
- Hot spots, accretion columns
  - – X-ray pulsars
  - – magnetic CVs

Approaches:

- Analysis:
  - Dipole embedded in diamagnetic disk
  - Aligned disk/rotator
  - Estimate magnetosphere radius
- Computation:
  - 3D simulation of oblique rotator, more complex models of hotspots
- Observation:
  - X-ray pulsars, magnetic CVs
  - Emission from accretion columns

Challenges:

- Analysis:
  - Add reconnection and radiation physics (eg, photon bubbles in accretion columns?)
- Computation:
  - More microphysics, realistic reconnection



The “Top 10” Questions

1. CAN BLACK HOLES POWER JETS?
2. HOW RELATIVISTIC CAN A JET GET?
3. HOW-WHERE DO JETS GET ACCELERATED-COLLIMATED?
4. DO DISKS REALLY SUPPORT DYNAMOS?
5. HOW DO DISKS LOSE-TRANSPORT ENERGY-ANG. MOM.?
6. WHAT HAPPENS AT LOW ACCRETION RATES?
7. IS THE EDDINGTON LIMIT A LIMIT?
8. CAN WE MAP SPACETIMES USING DISKS?
9. ARE DISKS REALLY FLAT AND CIRCULAR?
10. HOW DO DISKS INTERACT WITH MAGNETOSPHERES?