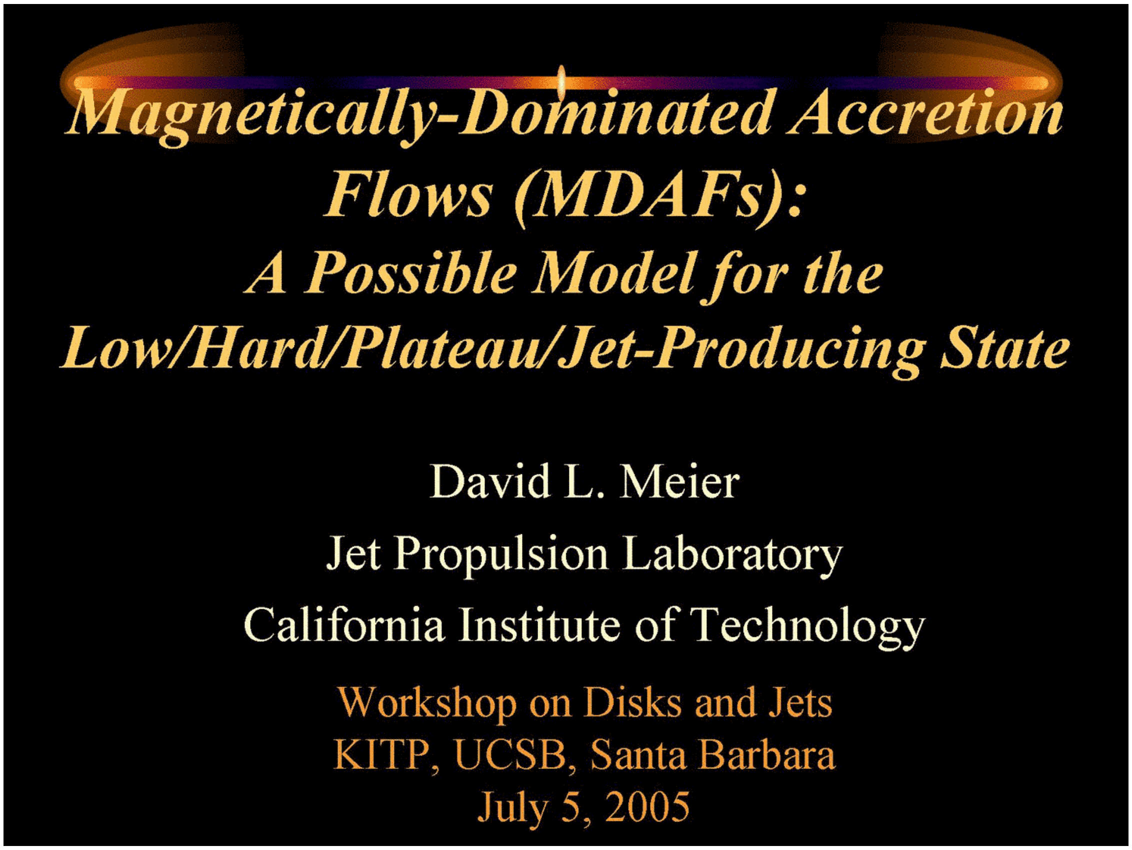

Magnetically-Dominated Accretion Flows (MDAFs):
A Possible Model for the Low/Hard/Plateau/Jet-Producing State

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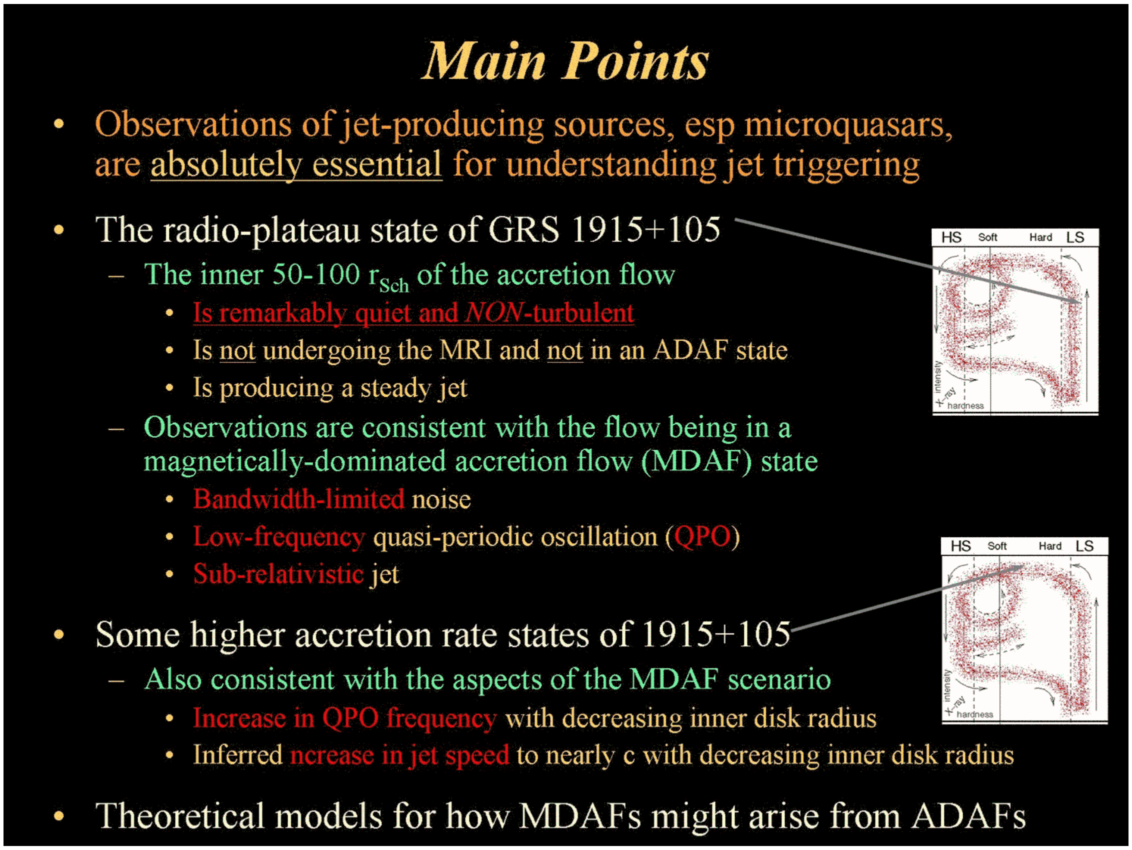
Workshop on Disks and Jets
KITP, UCSB, Santa Barbara
July 5, 2005

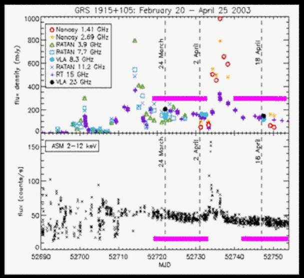


Main Points

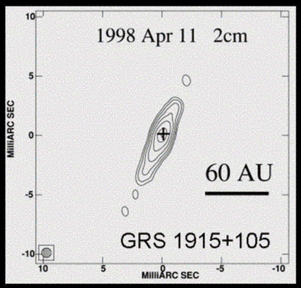
- Observations of jet-producing sources, esp microquasars, are absolutely essential for understanding jet triggering
- The radio-plateau state of GRS 1915+105
  - The inner 50-100 r_{Sch} of the accretion flow
    - Is remarkably quiet and *NON*-turbulent
    - Is not undergoing the MRI and not in an ADAF state
    - Is producing a steady jet
  - Observations are consistent with the flow being in a magnetically-dominated accretion flow (MDAF) state
    - Bandwidth-limited noise
    - Low-frequency quasi-periodic oscillation (QPO)
    - Sub-relativistic jet
- Some higher accretion rate states of 1915+105
  - Also consistent with the aspects of the MDAF scenario
    - Increase in QPO frequency with decreasing inner disk radius
    - Inferred ncrease in jet speed to nearly c with decreasing inner disk radius
- Theoretical models for how MDAFs might arise from ADAFs

Observational Evidence that
<u>Large</u> (~50-100 r_G = 25-50 r_S)
Magnetically – Dominated Accretion Flows
Exists in the Plateau State of 1915+105

The GRS 1915+105 Plateau State

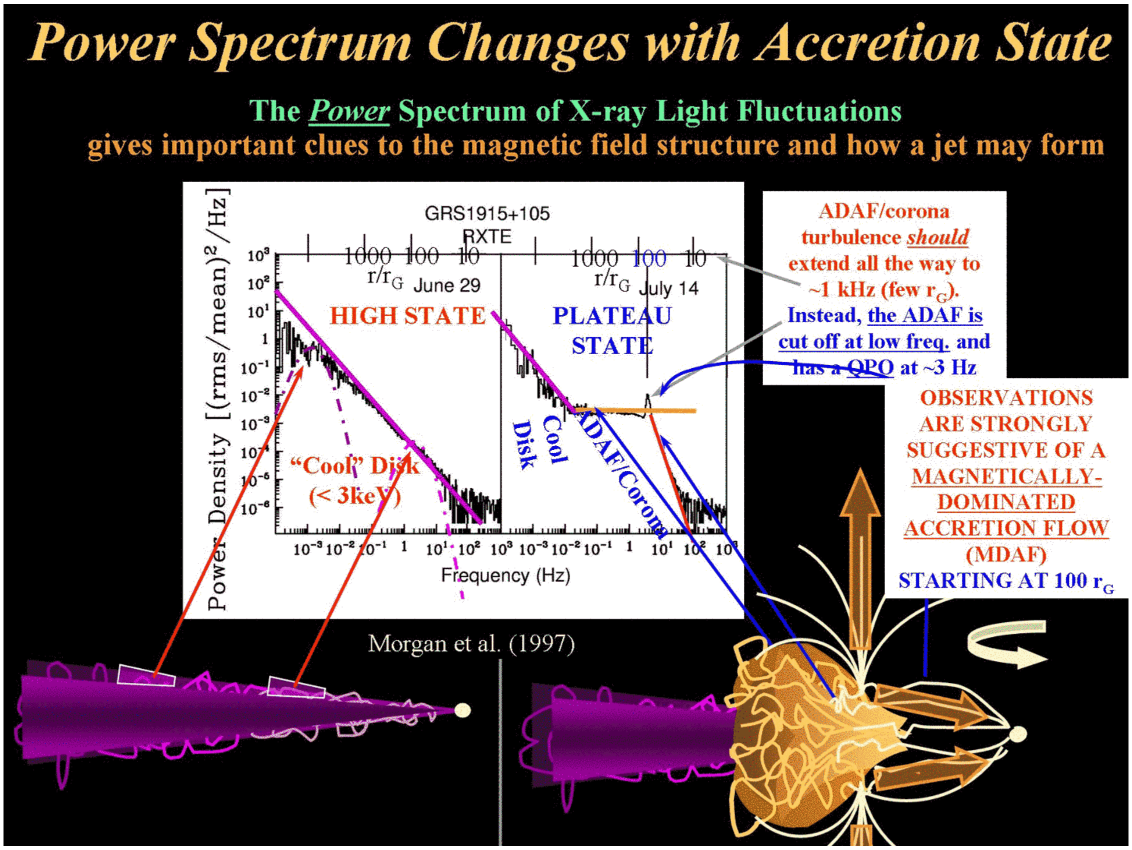


Ribo *et al.* (2004)



Dhawan *et al.* (2000)

- Characterized by
  - steady, optically thick, strong (>100 mJy) radio emission and low/hard X-ray emission
  - VLA images showing a <u>steady, sub-relativistic jet</u> (0.1-0.3 c)
  - staying in this state for <u>weeks</u> (> 10^9 dynamical times)



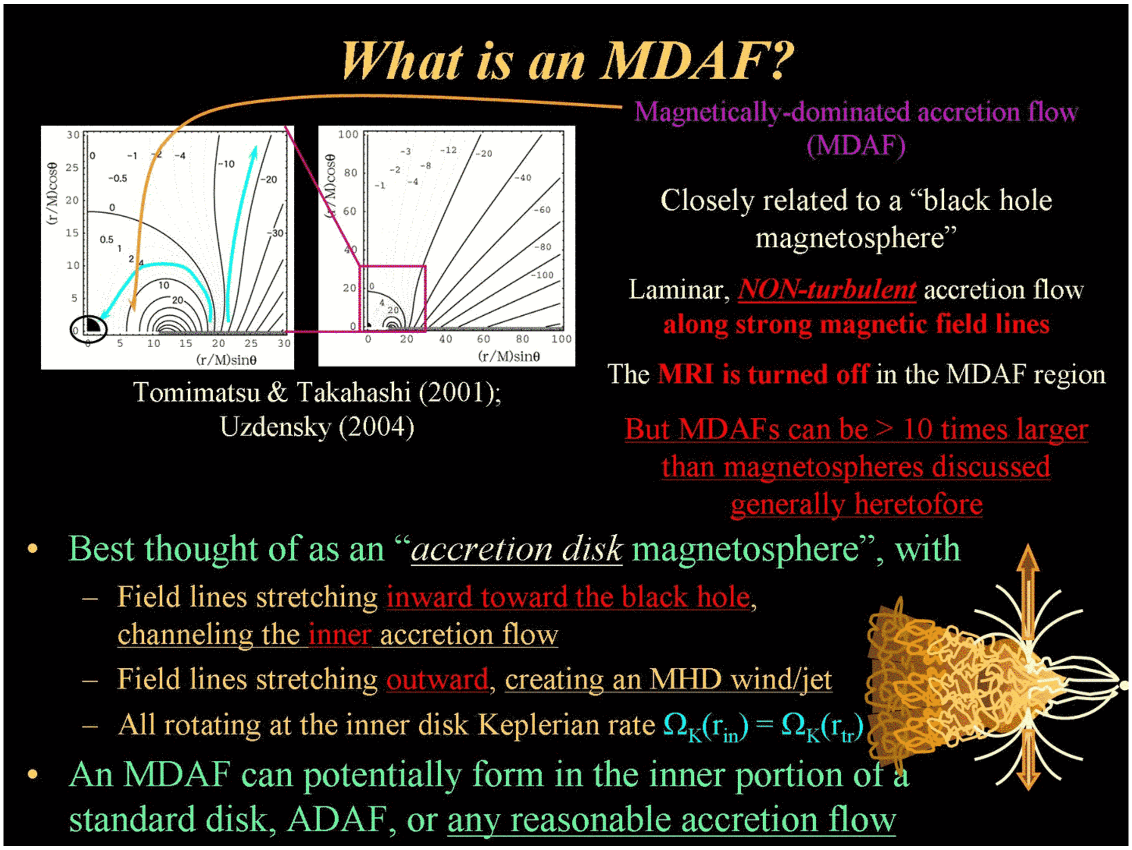
Power Spectrum Changes with Accretion State

The *Power* Spectrum of X-ray Light Fluctuations gives important clues to the magnetic field structure and how a jet may form

Morgan et al. (1997)

ADAF/corona turbulence *should* extend all the way to ~1 kHz (few r_G). Instead, the ADAF is cut off at low freq. and has a QPO at ~3 Hz

OBSERVATIONS ARE STRONGLY SUGGESTIVE OF A MAGNETICALLY-DOMINATED ACCRETION FLOW (MDAF) STARTING AT 100 r_G



What is an MDAF?

Magnetically-dominated accretion flow (MDAF)

Closely related to a "black hole magnetosphere"

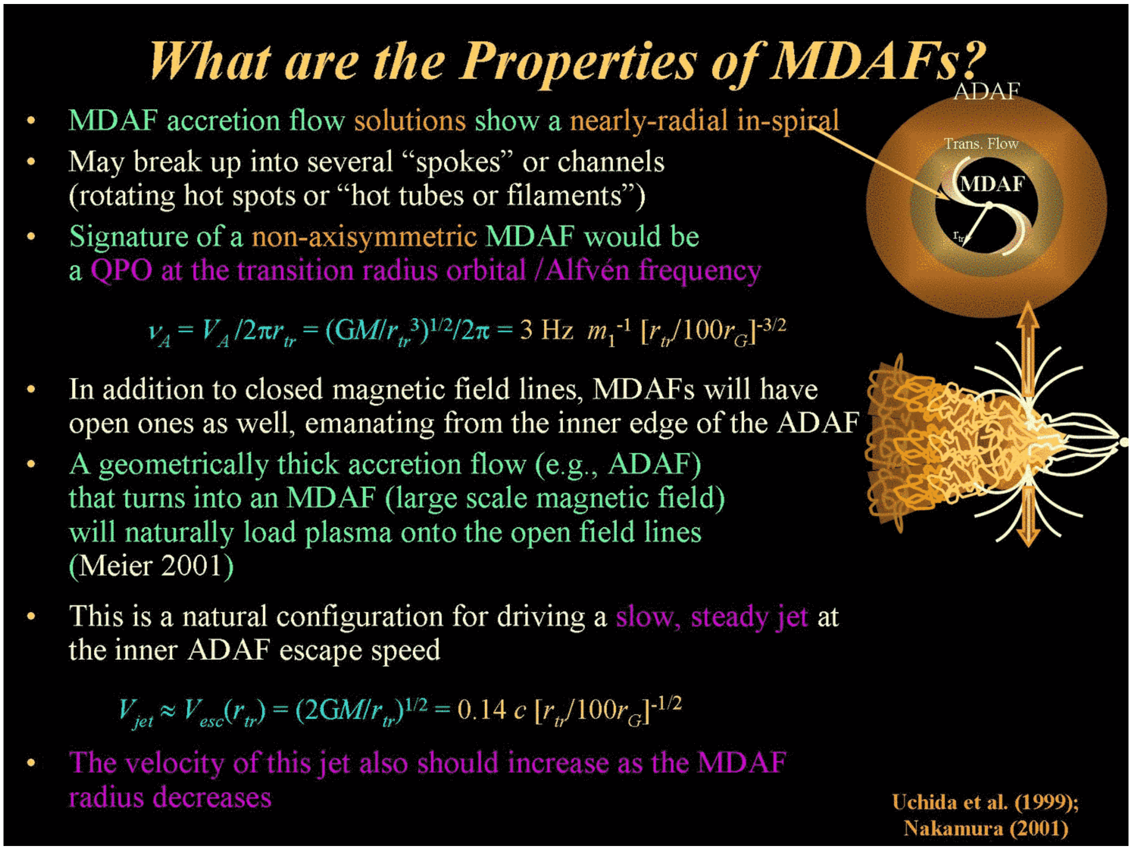
Laminar, ***NON-turbulent*** accretion flow **along strong magnetic field lines**

The **MRI is turned off** in the MDAF region

But MDAFs can be > 10 times larger than magnetospheres discussed generally heretofore

Tomimatsu & Takahashi (2001); Uzdensky (2004)

- Best thought of as an "*accretion disk* magnetosphere", with
  - Field lines stretching inward toward the black hole, channeling the inner accretion flow
  - Field lines stretching outward, creating an MHD wind/jet
  - All rotating at the inner disk Keplerian rate $\Omega_K(r_{in}) = \Omega_K(r_{tr})$
- An MDAF can potentially form in the inner portion of a standard disk, ADAF, or any reasonable accretion flow



What are the Properties of MDAFs?

- MDAF accretion flow solutions show a nearly-radial in-spiral
- May break up into several “spokes” or channels (rotating hot spots or “hot tubes or filaments”)
- Signature of a non-axisymmetric MDAF would be a QPO at the transition radius orbital /Alfvén frequency

$$\nu_A = V_A/2\pi r_{tr} = (GM/r_{tr}^{\ 3})^{1/2}/2\pi = 3\ \mathrm{Hz}\ \ m_1^{-1}\ [r_{tr}/100r_G]^{-3/2}$$

- In addition to closed magnetic field lines, MDAFs will have open ones as well, emanating from the inner edge of the ADAF
- A geometrically thick accretion flow (e.g., ADAF) that turns into an MDAF (large scale magnetic field) will naturally load plasma onto the open field lines (Meier 2001)
- This is a natural configuration for driving a slow, steady jet at the inner ADAF escape speed

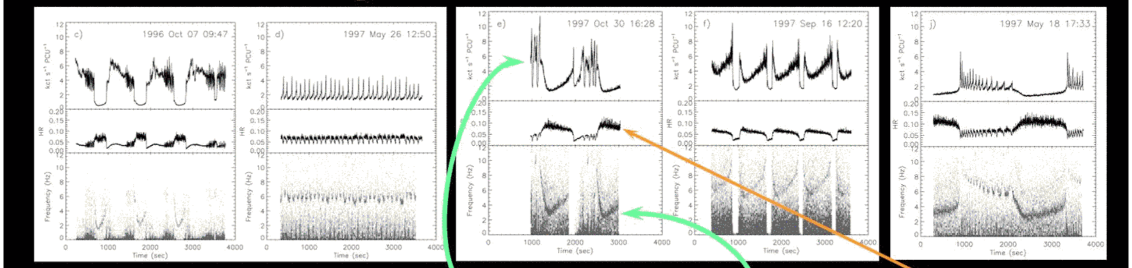
$$V_{jet} \approx V_{esc}(r_{tr}) = (2GM/r_{tr})^{1/2} = 0.14\ c\ [r_{tr}/100r_G]^{-1/2}$$

- The velocity of this jet also should increase as the MDAF radius decreases

Uchida et al. (1999); Nakamura (2001)

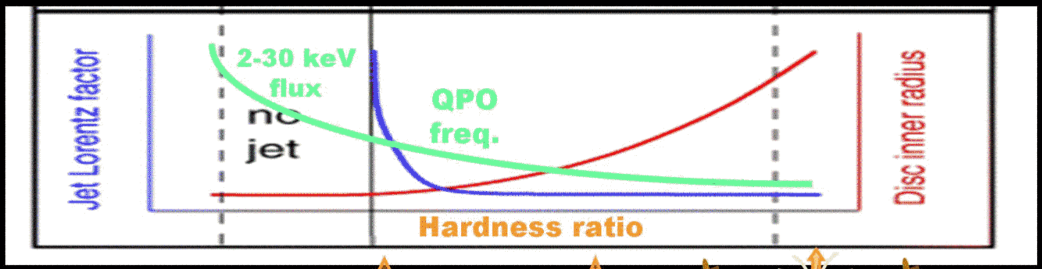
Observational Evidence that Magnetically – Dominated Accretion Flows May Exists in Higher Accretion States of 1915+105 as Well

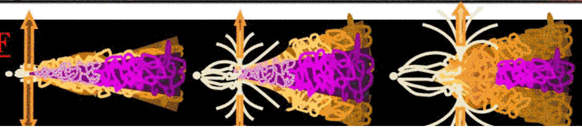
Frequency of 1915+105 LF QPO Also Changes with Hardness Ratio



Muno et al. (1999)

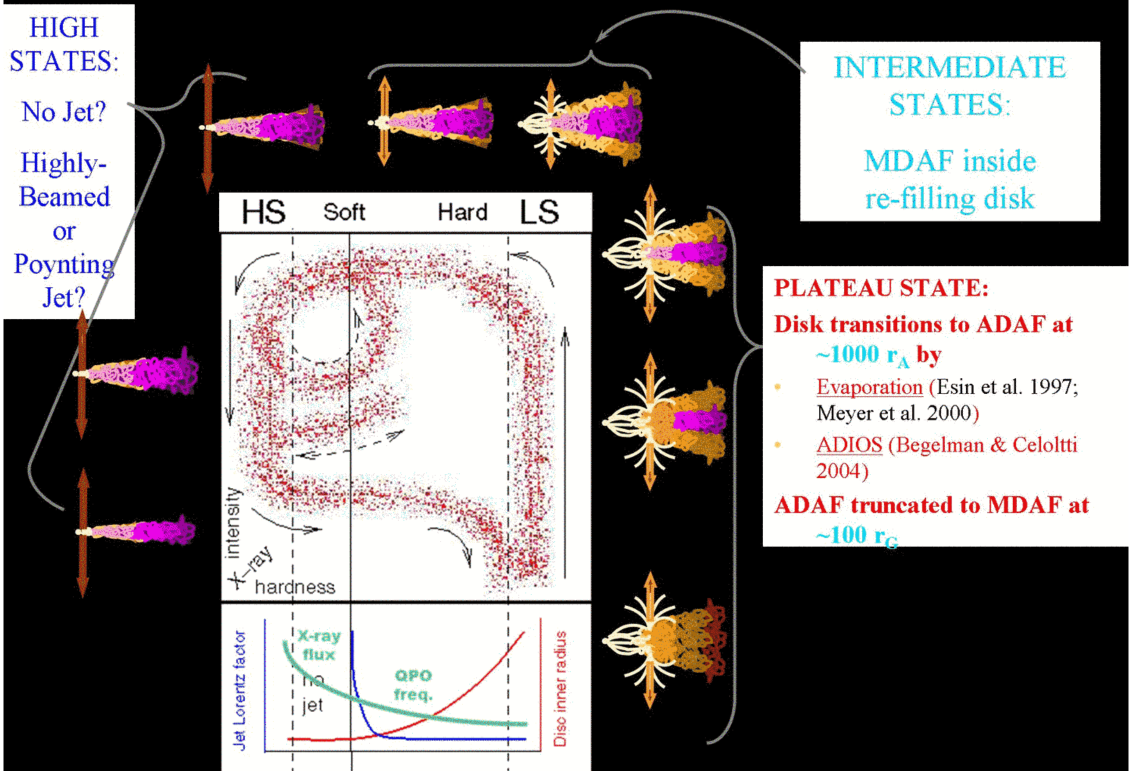
As X-ray flux drops, QPO frequency drops and spectrum hardens





All are consistent with an MDAF causing the "hole in the disk", the QPO (and the jet)

MDAFs and the Fender, Belloni, & Gallo Model



HIGH STATES:

No Jet?

Highly-Beamed or Poynting Jet?

INTERMEDIATE STATES:

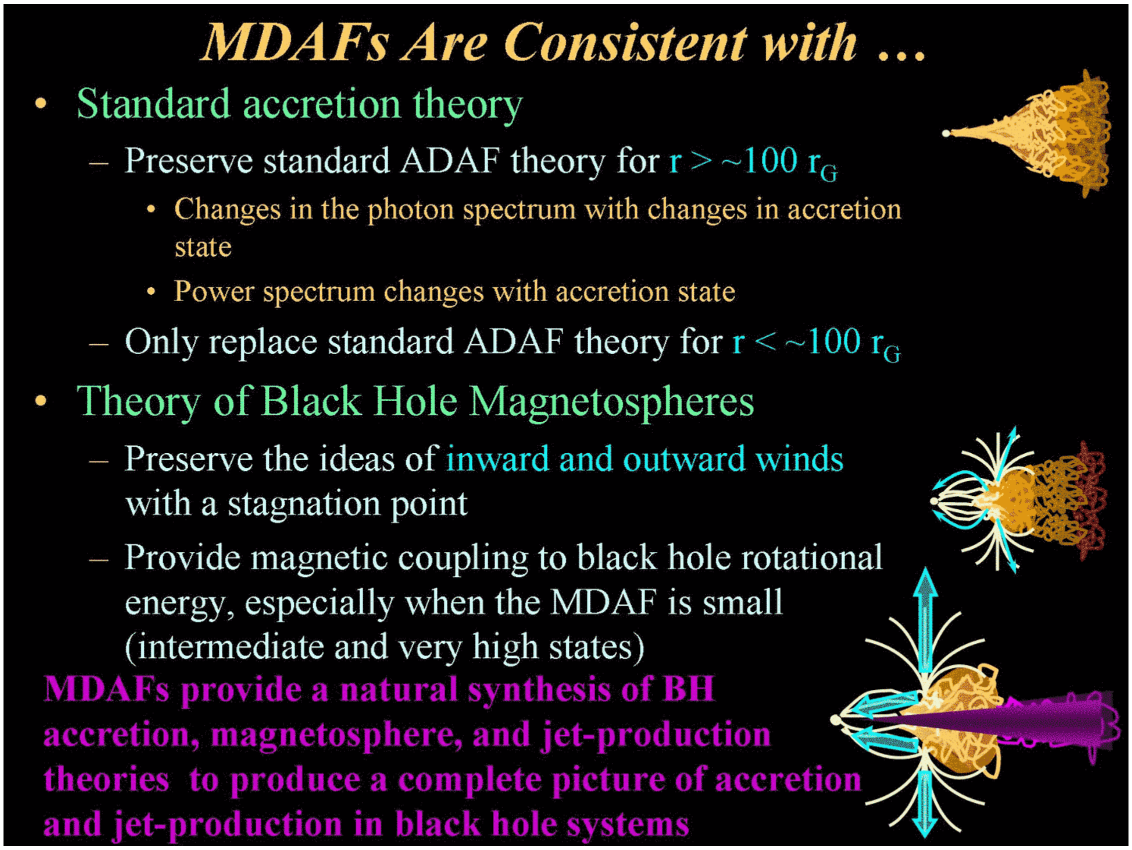
MDAF inside re-filling disk

PLATEAU STATE:

Disk transitions to ADAF at ~1000 r_A by

- Evaporation (Esin et al. 1997; Meyer et al. 2000)
- ADIOS (Begelman & Celoltti 2004)

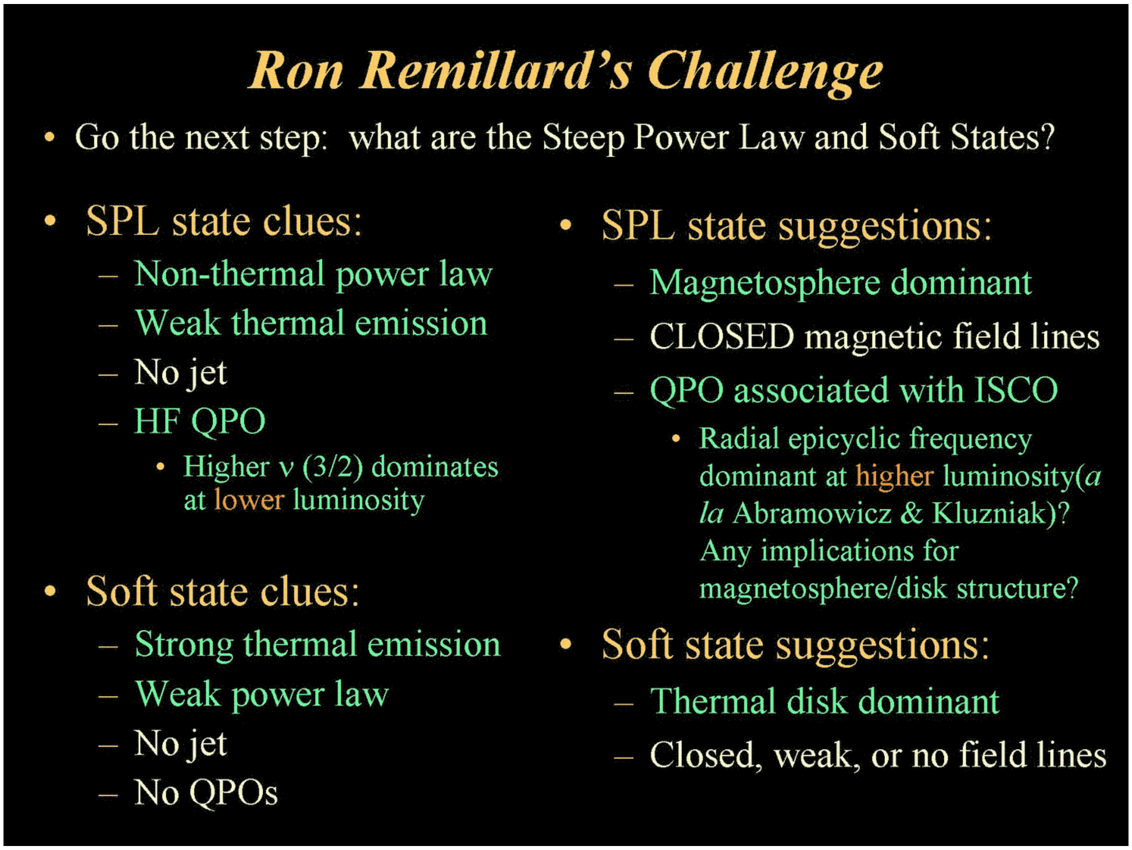
ADAF truncated to MDAF at ~100 r_G



MDAFs Are Consistent with …

- Standard accretion theory
  - Preserve standard ADAF theory for $r > \sim 100\ r_G$
    - Changes in the photon spectrum with changes in accretion state
    - Power spectrum changes with accretion state
  - Only replace standard ADAF theory for $r < \sim 100\ r_G$
- Theory of Black Hole Magnetospheres
  - Preserve the ideas of inward and outward winds with a stagnation point
  - Provide magnetic coupling to black hole rotational energy, especially when the MDAF is small (intermediate and very high states)

MDAFs provide a natural synthesis of BH accretion, magnetosphere, and jet-production theories to produce a complete picture of accretion and jet-production in black hole systems

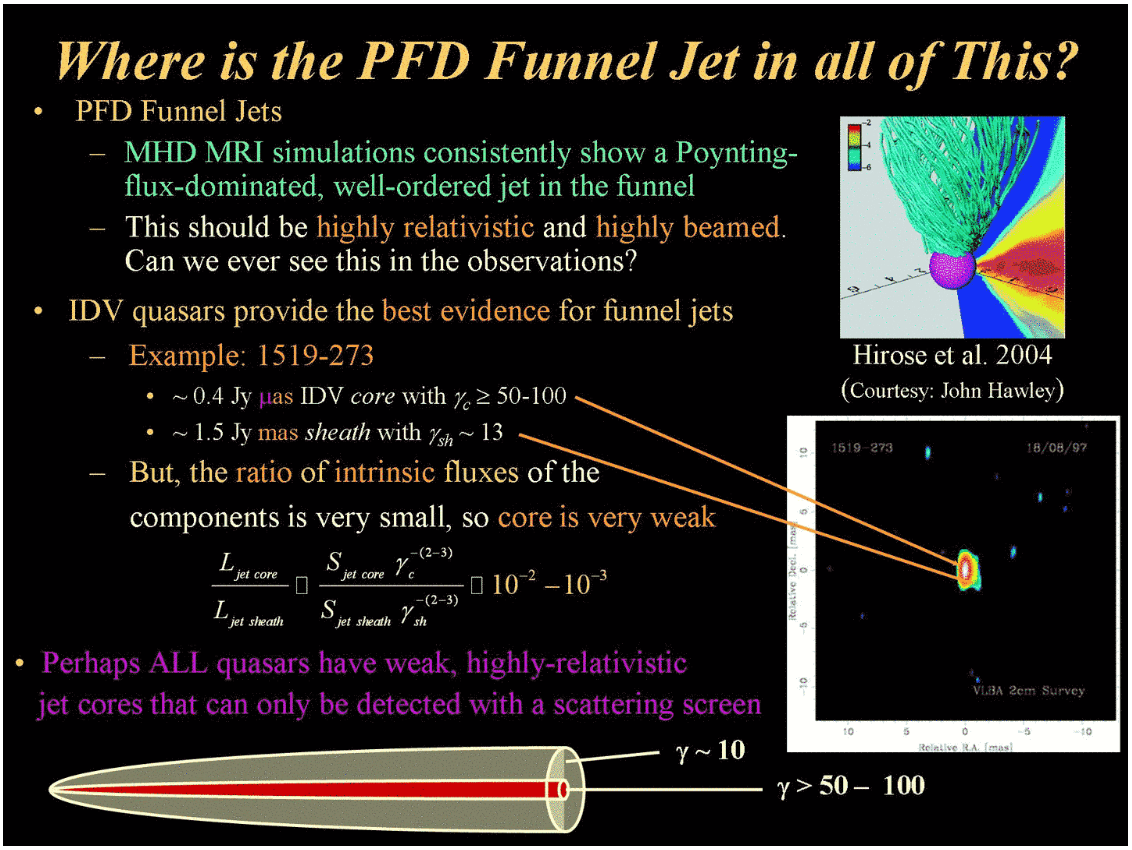


Ron Remillard’s Challenge

- Go the next step: what are the Steep Power Law and Soft States?

- SPL state clues:
  - Non-thermal power law
  - Weak thermal emission
  - No jet
  - HF QPO
    - Higher ν (3/2) dominates at lower luminosity
- Soft state clues:
  - Strong thermal emission
  - Weak power law
  - No jet
  - No QPOs

- SPL state suggestions:
  - Magnetosphere dominant
  - CLOSED magnetic field lines
  - QPO associated with ISCO
    - Radial epicyclic frequency dominant at higher luminosity(*a la* Abramowicz & Kluzniak)? Any implications for magnetosphere/disk structure?
- Soft state suggestions:
  - Thermal disk dominant
  - Closed, weak, or no field lines



Where is the PFD Funnel Jet in all of This?

- PFD Funnel Jets
  - MHD MRI simulations consistently show a Poynting-flux-dominated, well-ordered jet in the funnel
  - This should be highly relativistic and highly beamed. Can we ever see this in the observations?
- IDV quasars provide the best evidence for funnel jets
  - Example: 1519-273
    - ~ 0.4 Jy μas IDV *core* with $\gamma_c \geq$ 50-100
    - ~ 1.5 Jy mas *sheath* with $\gamma_{sh} \sim 13$
  - But, the ratio of intrinsic fluxes of the components is very small, so core is very weak

$$\frac{L_{jet\ core}}{L_{jet\ sheath}} \square \frac{S_{jet\ core}\ \gamma_c^{-(2-3)}}{S_{jet\ sheath}\ \gamma_{sh}^{-(2-3)}} \square 10^{-2} - 10^{-3}$$

- Perhaps ALL quasars have weak, highly-relativistic jet cores that can only be detected with a scattering screen

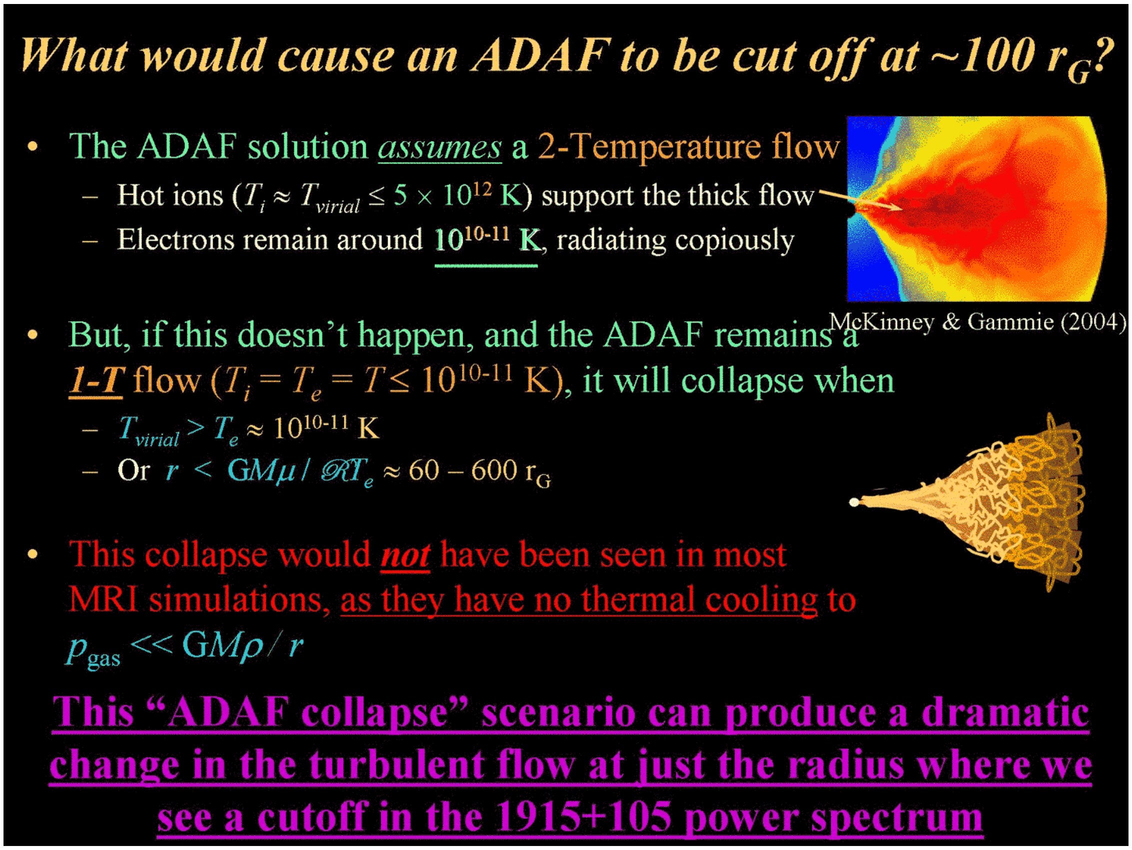
Hirose et al. 2004
(Courtesy: John Hawley)

γ ~ 10

γ > 50 – 100

Suggested Theoretical Model for Why A __Large__ MDAF May Exist in the Plateau State

(D.L.M. 2005)



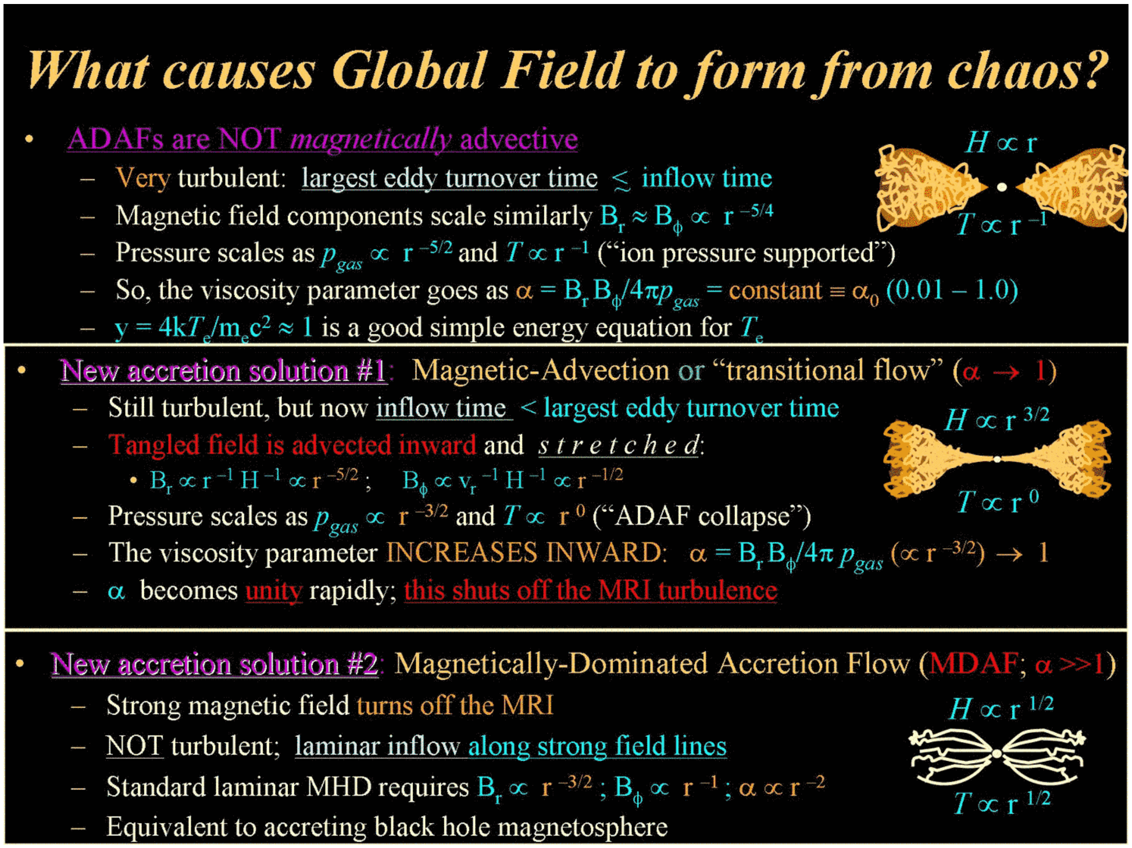
What would cause an ADAF to be cut off at ~100 r_G?

- The ADAF solution *assumes* a 2-Temperature flow
  - Hot ions ($T_i \approx T_{virial} \leq 5 \times 10^{12}$ K) support the thick flow
  - Electrons remain around **10^{10-11} K**, radiating copiously

McKinney & Gammie (2004)

- But, if this doesn't happen, and the ADAF remains a ***1-T*** flow ($T_i = T_e = T \leq 10^{10-11}$ K), it will collapse when
  - $T_{virial} > T_e \approx 10^{10-11}$ K
  - Or $r < GM\mu / \mathscr{R}T_e \approx 60 - 600\ r_G$
- This collapse would ***not*** have been seen in most MRI simulations, as they have no thermal cooling to $p_{gas} << GM\rho / r$

This "ADAF collapse" scenario can produce a dramatic change in the turbulent flow at just the radius where we see a cutoff in the 1915+105 power spectrum

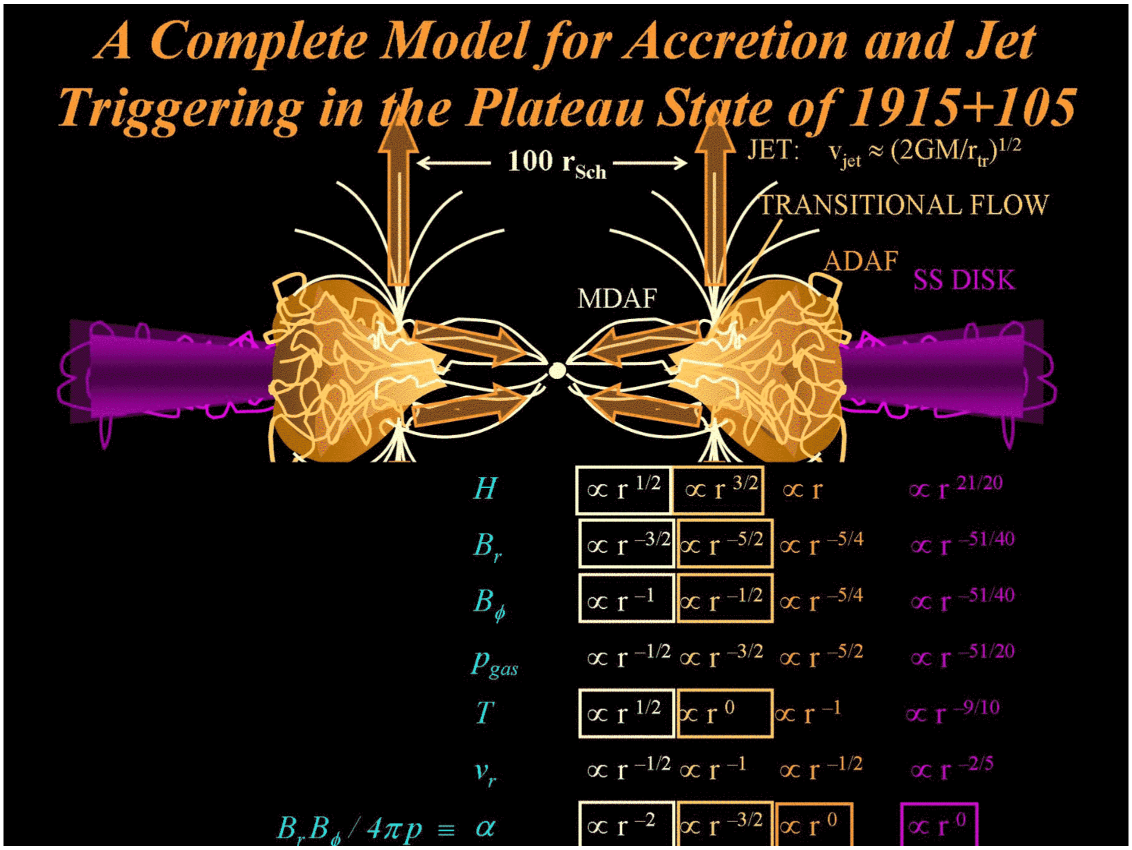


What causes Global Field to form from chaos?

- ADAFs are NOT *magnetically* advective
  - Very turbulent: largest eddy turnover time $\lesssim$ inflow time
  - Magnetic field components scale similarly $B_r \approx B_\phi \propto r^{-5/4}$
  - Pressure scales as $p_{gas} \propto r^{-5/2}$ and $T \propto r^{-1}$ ("ion pressure supported")
  - So, the viscosity parameter goes as $\alpha = B_r B_\phi / 4\pi p_{gas}$ = constant $\equiv \alpha_0$ (0.01 – 1.0)
  - $y = 4kT_e/m_e c^2 \approx 1$ is a good simple energy equation for T_e

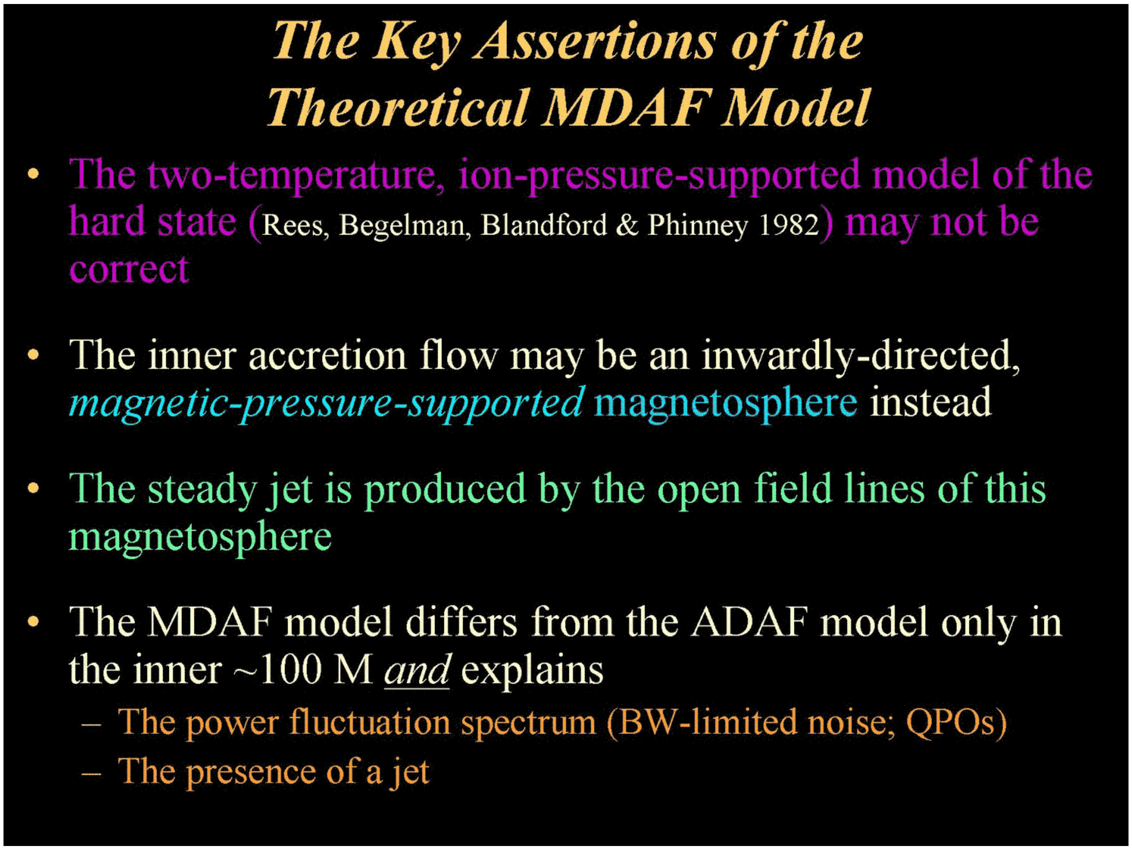
- New accretion solution #1: Magnetic-Advection or "transitional flow" ($\alpha \rightarrow 1$)
  - Still turbulent, but now inflow time < largest eddy turnover time
  - Tangled field is advected inward and *stretched*:
    - $B_r \propto r^{-1} H^{-1} \propto r^{-5/2}$; $B_\phi \propto v_r^{-1} H^{-1} \propto r^{-1/2}$
  - Pressure scales as $p_{gas} \propto r^{-3/2}$ and $T \propto r^0$ ("ADAF collapse")
  - The viscosity parameter INCREASES INWARD: $\alpha = B_r B_\phi / 4\pi\, p_{gas}$ ($\propto r^{-3/2}$) $\rightarrow 1$
  - α becomes unity rapidly; this shuts off the MRI turbulence

- New accretion solution #2: Magnetically-Dominated Accretion Flow (MDAF; $\alpha >> 1$)
  - Strong magnetic field turns off the MRI
  - NOT turbulent; laminar inflow along strong field lines
  - Standard laminar MHD requires $B_r \propto r^{-3/2}$; $B_\phi \propto r^{-1}$; $\alpha \propto r^{-2}$
  - Equivalent to accreting black hole magnetosphere



A Complete Model for Accretion and Jet Triggering in the Plateau State of 1915+105

H	$\boxed{\propto r^{1/2}}$	$\boxed{\propto r^{3/2}}$	$\propto r$	$\propto r^{21/20}$
B_r	$\boxed{\propto r^{-3/2}}$	$\boxed{\propto r^{-5/2}}$	$\propto r^{-5/4}$	$\propto r^{-51/40}$
B_ϕ	$\boxed{\propto r^{-1}}$	$\boxed{\propto r^{-1/2}}$	$\propto r^{-5/4}$	$\propto r^{-51/40}$
p_{gas}	$\propto r^{-1/2}$	$\propto r^{-3/2}$	$\propto r^{-5/2}$	$\propto r^{-51/20}$
T	$\boxed{\propto r^{1/2}}$	$\boxed{\propto r^{0}}$	$\propto r^{-1}$	$\propto r^{-9/10}$
v_r	$\propto r^{-1/2}$	$\propto r^{-1}$	$\propto r^{-1/2}$	$\propto r^{-2/5}$
$B_r B_\phi / 4\pi p \equiv \alpha$	$\boxed{\propto r^{-2}}$	$\boxed{\propto r^{-3/2}}$	$\boxed{\propto r^{0}}$	$\boxed{\propto r^{0}}$



The Key Assertions of the Theoretical MDAF Model

- The two-temperature, ion-pressure-supported model of the hard state (Rees, Begelman, Blandford & Phinney 1982) may not be correct
- The inner accretion flow may be an inwardly-directed, *magnetic-pressure-supported* magnetosphere instead
- The steady jet is produced by the open field lines of this magnetosphere
- The MDAF model differs from the ADAF model only in the inner ~100 M *and* explains
  - The power fluctuation spectrum (BW-limited noise; QPOs)
  - The presence of a jet

Power Spectra of Radially-Stratified, Inhomogeneously-Turbulent Disks

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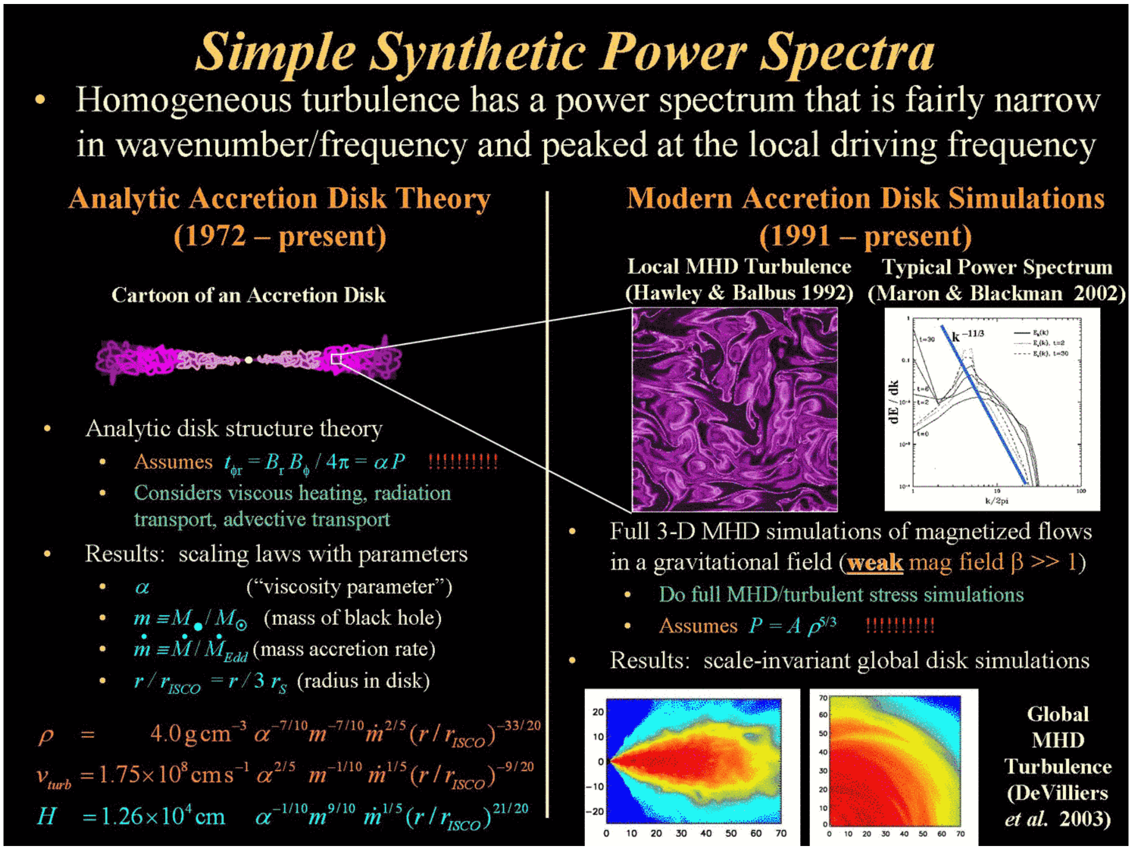


Simple Synthetic Power Spectra

- Homogeneous turbulence has a power spectrum that is fairly narrow in wavenumber/frequency and peaked at the local driving frequency

Analytic Accretion Disk Theory
(1972 – present)

Cartoon of an Accretion Disk

- Analytic disk structure theory
  - Assumes $t_{\phi r} = B_r B_\phi / 4\pi = \alpha P$!!!!!!!!!!
  - Considers viscous heating, radiation transport, advective transport
- Results: scaling laws with parameters
  - α ("viscosity parameter")
  - $m \equiv M_\bullet / M_\odot$ (mass of black hole)
  - $\dot{m} \equiv \dot{M} / \dot{M}_{Edd}$ (mass accretion rate)
  - $r / r_{ISCO} = r / 3\, r_S$ (radius in disk)

$$\rho = 4.0\,\mathrm{g\,cm^{-3}}\ \alpha^{-7/10} m^{-7/10} \dot{m}^{2/5} (r / r_{ISCO})^{-33/20}$$
$$v_{turb} = 1.75\times10^{8}\,\mathrm{cm\,s^{-1}}\ \alpha^{2/5}\ m^{-1/10}\ \dot{m}^{1/5} (r / r_{ISCO})^{-9/20}$$
$$H = 1.26\times10^{4}\,\mathrm{cm}\quad \alpha^{-1/10} m^{9/10}\ \dot{m}^{1/5} (r / r_{ISCO})^{21/20}$$

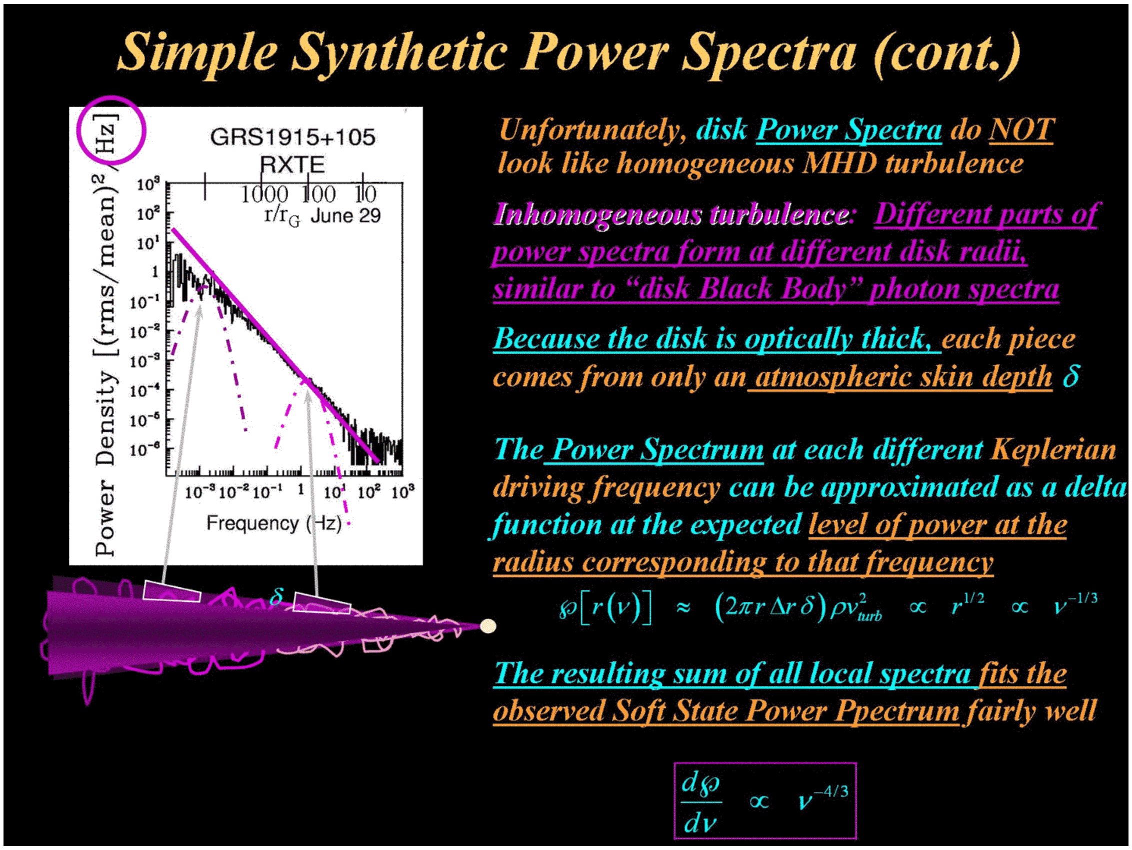
Modern Accretion Disk Simulations
(1991 – present)

Local MHD Turbulence (Hawley & Balbus 1992)

Typical Power Spectrum (Maron & Blackman 2002)

- Full 3-D MHD simulations of magnetized flows in a gravitational field (**weak** mag field β >> 1)
  - Do full MHD/turbulent stress simulations
  - Assumes $P = A\,\rho^{5/3}$!!!!!!!!!!
- Results: scale-invariant global disk simulations

Global MHD Turbulence (DeVilliers *et al.* 2003)



Simple Synthetic Power Spectra (cont.)

Unfortunately, disk Power Spectra do NOT look like homogeneous MHD turbulence

Inhomogeneous turbulence: Different parts of power spectra form at different disk radii, similar to "disk Black Body" photon spectra

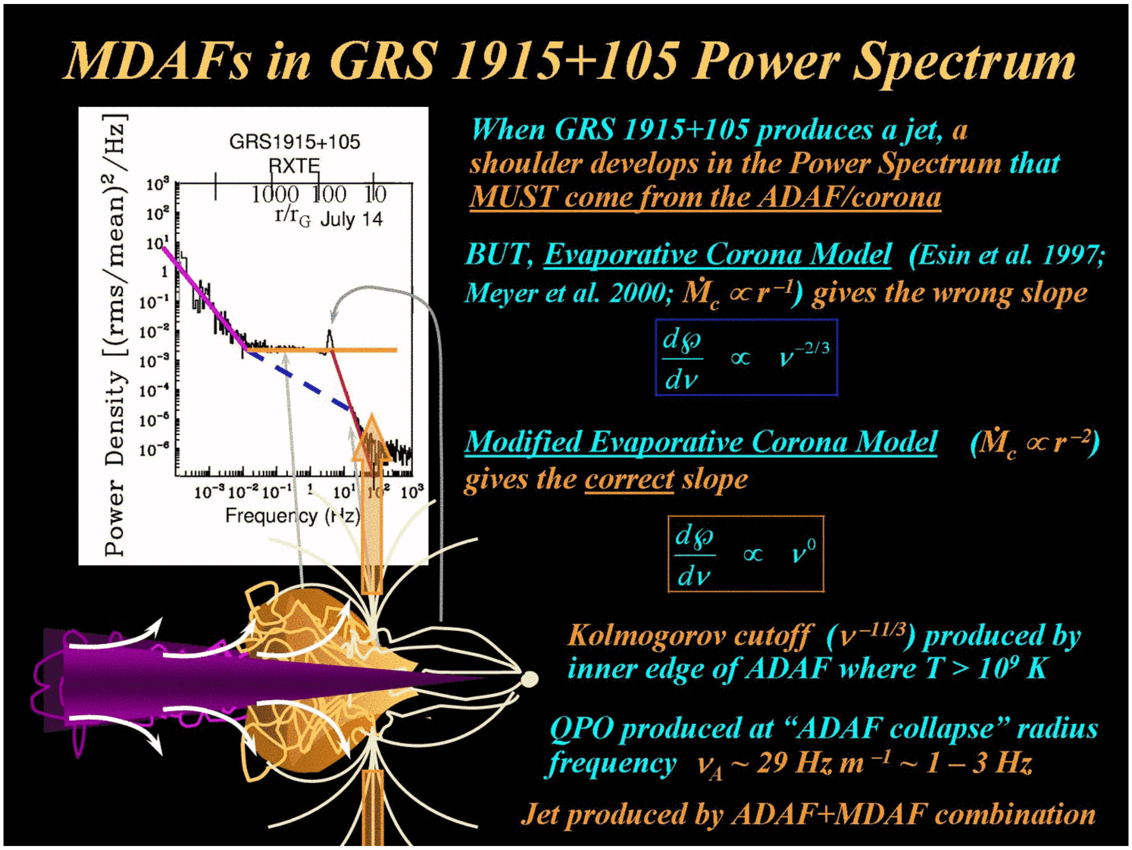
Because the disk is optically thick, each piece comes from only an atmospheric skin depth δ

The Power Spectrum at each different Keplerian driving frequency can be approximated as a delta function at the expected level of power at the radius corresponding to that frequency

$$\wp\left[r(\nu)\right] \approx (2\pi r\,\Delta r\,\delta)\,\rho v_{turb}^2 \propto r^{1/2} \propto \nu^{-1/3}$$

The resulting sum of all local spectra fits the observed Soft State Power Ppectrum fairly well

$$\boxed{\frac{d\wp}{d\nu} \propto \nu^{-4/3}}$$



MDAFs in GRS 1915+105 Power Spectrum

When GRS 1915+105 produces a jet, a shoulder develops in the Power Spectrum that MUST come from the ADAF/corona

BUT, Evaporative Corona Model (Esin et al. 1997; Meyer et al. 2000; $\dot{M}_c \propto r^{-1}$) gives the wrong slope

$$\boxed{\frac{d\wp}{d\nu} \propto \nu^{-2/3}}$$

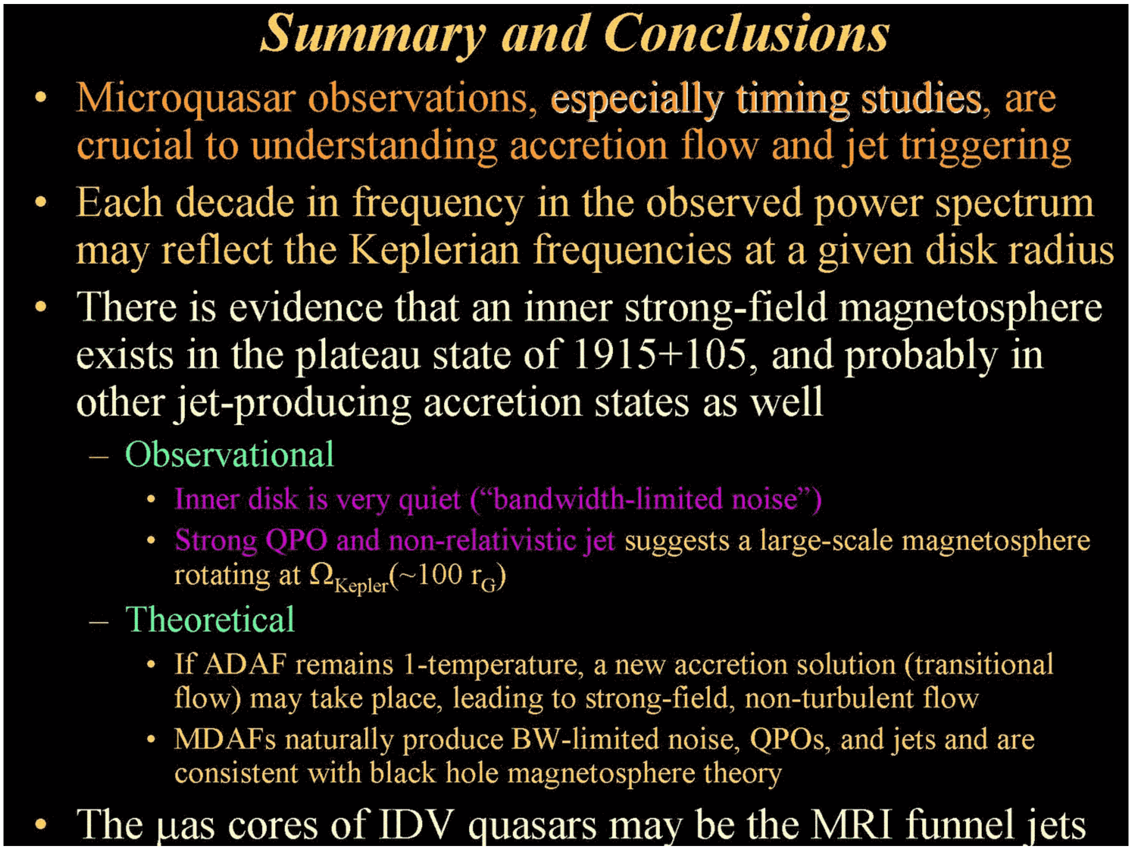
Modified Evaporative Corona Model ($\dot{M}_c \propto r^{-2}$) gives the correct slope

$$\boxed{\frac{d\wp}{d\nu} \propto \nu^{0}}$$

Kolmogorov cutoff ($\nu^{-11/3}$) produced by inner edge of ADAF where $T > 10^9$ K

QPO produced at "ADAF collapse" radius frequency $\nu_A \sim 29$ Hz $m^{-1} \sim 1 - 3$ Hz

Jet produced by ADAF+MDAF combination



Summary and Conclusions

- Microquasar observations, especially timing studies, are crucial to understanding accretion flow and jet triggering
- Each decade in frequency in the observed power spectrum may reflect the Keplerian frequencies at a given disk radius
- There is evidence that an inner strong-field magnetosphere exists in the plateau state of 1915+105, and probably in other jet-producing accretion states as well
  - Observational
    - Inner disk is very quiet (“bandwidth-limited noise”)
    - Strong QPO and non-relativistic jet suggests a large-scale magnetosphere rotating at $\Omega_{Kepler}(\sim 100\ r_G)$
  - Theoretical
    - If ADAF remains 1-temperature, a new accretion solution (transitional flow) may take place, leading to strong-field, non-turbulent flow
    - MDAFs naturally produce BW-limited noise, QPOs, and jets and are consistent with black hole magnetosphere theory
- The μas cores of IDV quasars may be the MRI funnel jets