Magnetically-Dominated Jet and Accretion Flows

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Outline

- Helical Kink Instabilities in Propagating Poynting-Flux-Dominated Jets (compare with Denise Gabuzda's talk)
  - Simulations of non-relativistic jets
  - Predictions for ultra-relativistic jets

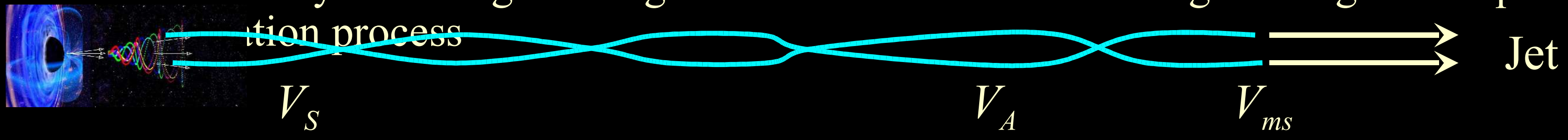
- Magnetically-Dominated Accretion Flows Around Black Holes (MDAFs) (compare with John Hawley's talk)
  - Microquasars: GRS 1915+105 in the low/hard & high/soft states
  - GRBs in hyper-critical accretion

Propagation of (non-Relativistic) Poynting-Flux-Dominated Jets: Development of Helical Kinks

(Nakamura & Meier 2004)

Poynting-Flux-Dominated Jets

- If jets are MHD-accelerated, they will
  - Be magnetically dominated, $B^2/8\pi \gg p_{gas}$ (B is magnetic induction)
  - Have a more complex set of characteristic speeds:
    - Slow mode: $V_S = c_{sound}\, V_A/V_{ms} \approx c_{sound} = (p_{gas}/\rho)^{1/2}$
    - Alfvén speed: $V_A = B/(4\pi\, \rho)^{1/2}$ (ρ is density)
    - Fast (magnetosonic) mode: $V_{ms} = (c_{sound}{}^2 + V_A{}^2)^{1/2}$
  - Be driven by a rotating/twisting “torsional Alfvén wave” and go through a complex tion process



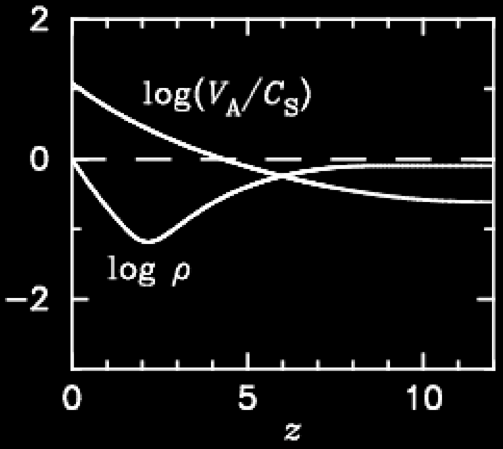
Sub-slow region	$v_{jet} < V_S$	near the central BH engine
Sub-Alfvénic region	$V_S < v_{jet} < V_A$	“Poynting-flux-dominated”
Trans-Alfvénic region	$V_A < v_{jet} < V_{ms}$	far from the hole
Super-fast region	$V_{ms} < v_{jet}$	
Super-modified-fast region	$V_{ms} < v_{\theta,jet}$	kinetic-energy-dominated & collimated

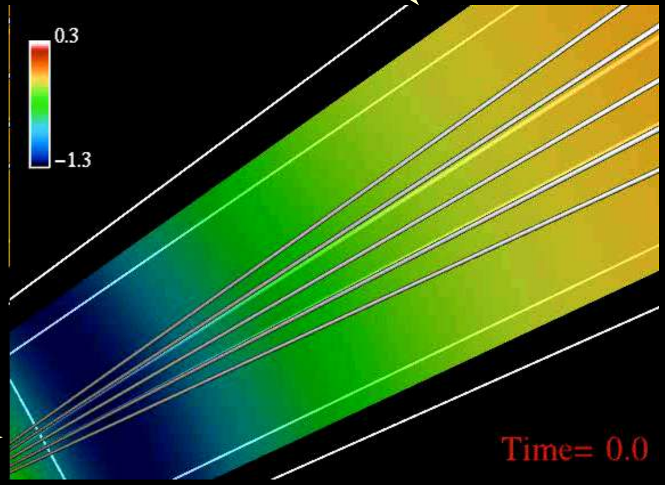
- Some theoretical models of jet acceleration (Vlahakis & Konigl 2004) predict that the sub-Alfvénic / Poynting-flux-dominated region in AGN will lie in the range 0.1 – 10 pc — precisely the region imaged by VLBI

3D Simulations of PFD Jets

(Nakamura et al. 2001; Nakamura & Meier 2004)

- Models of PFD jets have been built (*e.g.*: Li *et al.* 1992; Lovelace *et al.* 2001; Li *et al.* 2002; Vlahakis & Konigl 2002, 2003), but no full numerical simulations have produced highly *relativistic* jets yet
- We have performed 3-D *non-relativistic* simulations that show *current-driven instabilities*

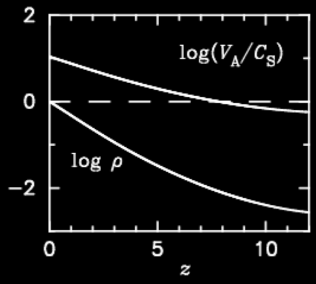


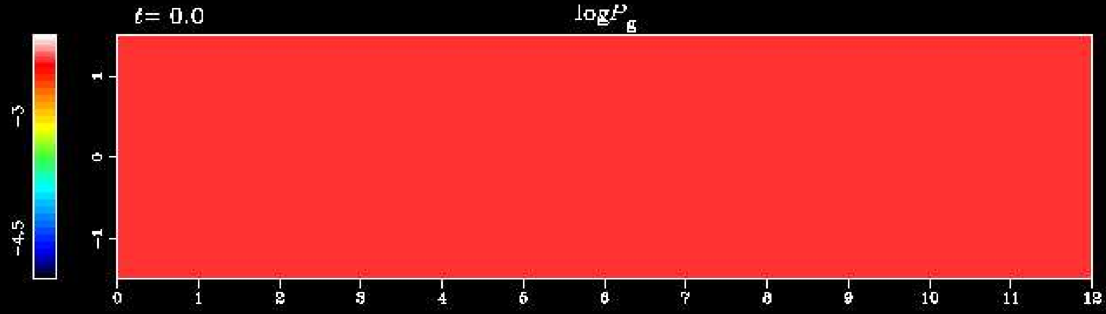


Helical kink develops in field

Magnetic field rotated at base

- Most well-known C-D instability is the $m = 0$ sausage pinch (in a uniform pressure medium)

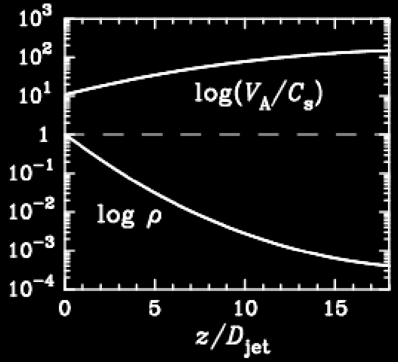


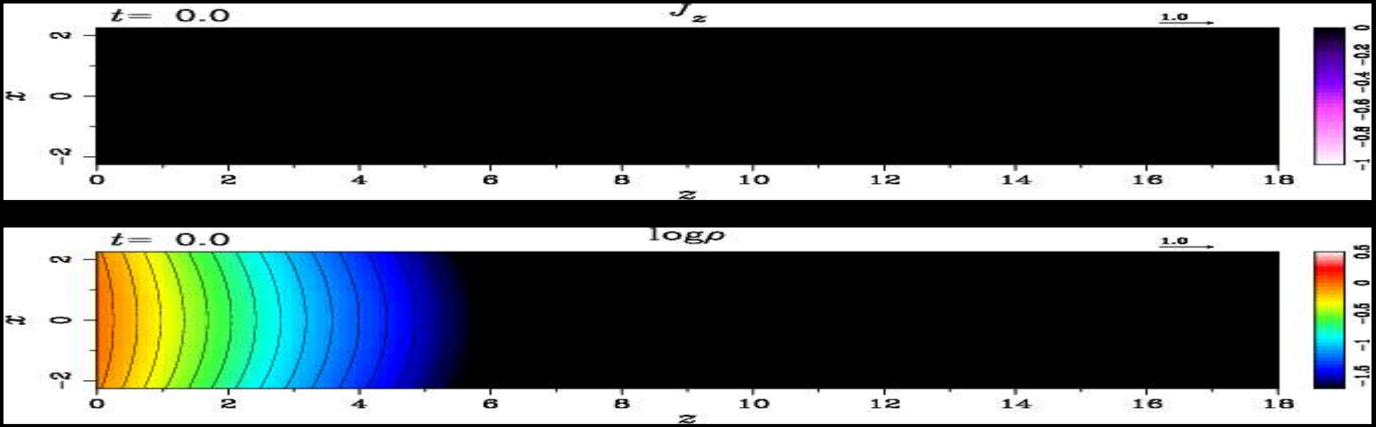


Results of 3D Numerical Simulations of

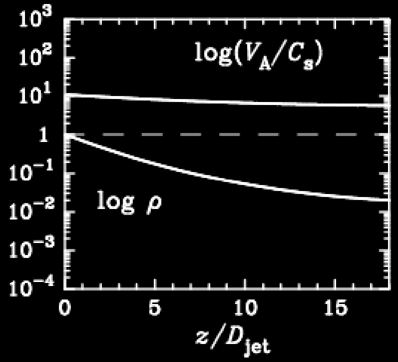
Poynting-Flux-Dominated Jets

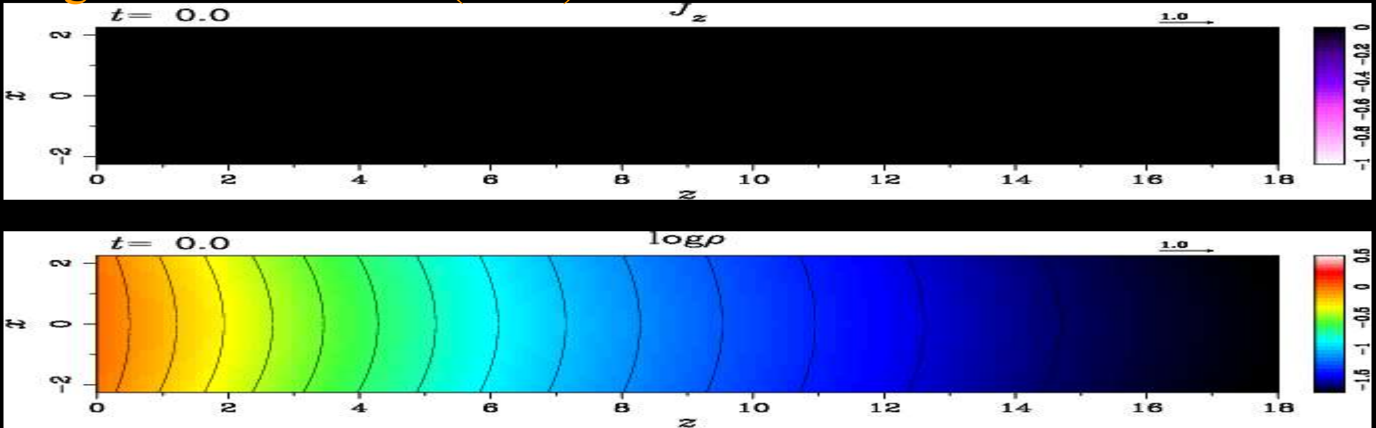
- Jet is more stable if density gradient is very steep ($\propto z^{-3}$) and jet is mildly PFD (60%)





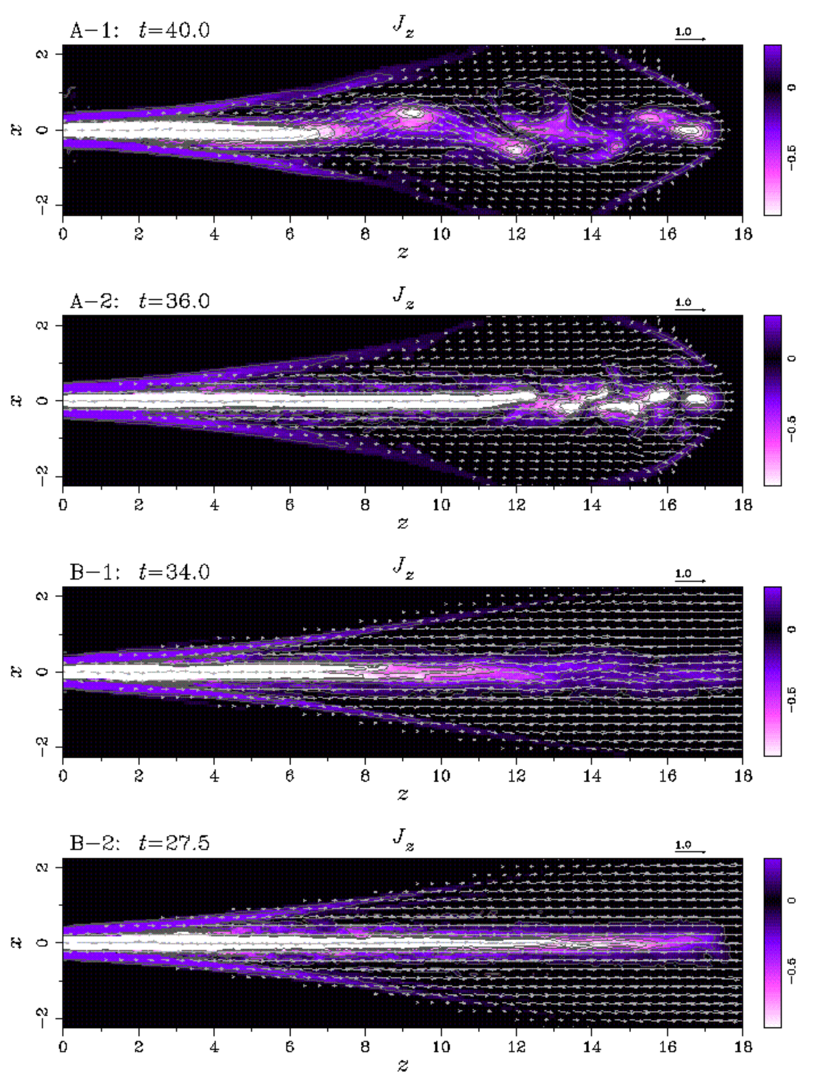
- Jet is more ***un***stable to $m = 1$ helical kink if density gradient is shallow ($\propto z^{-2}$) and jet is highly Poynting-flux dominated (90%)



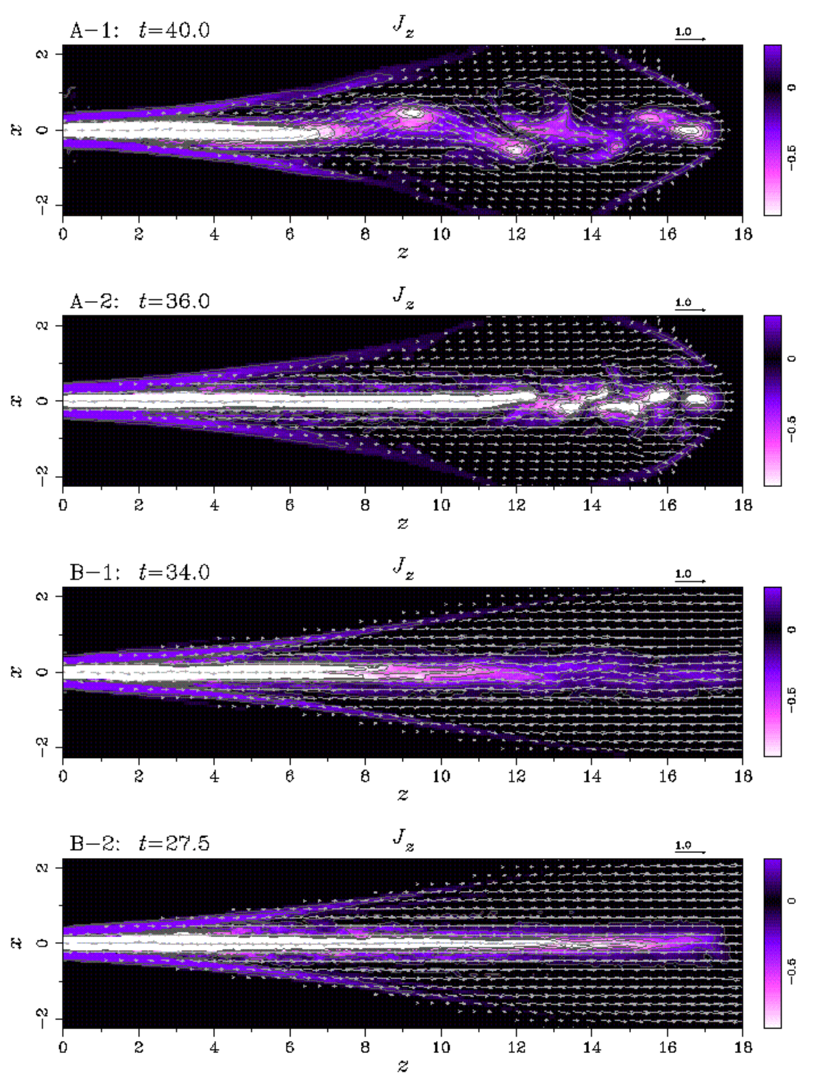


Results (continued)

- The helical kink (m=1) or screw mode is, by far, the dominant unstable mode in a decreasing density atmosphere
- The fastest growing longitudinal wavelengths are around two (2) jet diameters
- All jets that we simulated (60-90% Poynting dominated) eventually became kink unstable
- A steeper density gradient makes the jet more stable
- A greater relative amount of Poynting flux (twist) causes the kink to appear earlier in the flow
- This CD instability is driven by a Lorentz force imbalance in the nearly force-free jet; it can be partially stabilized by plasma rotation
- The large scale kinks saturate and do not become turbulent
- The kinks advect with the overall jet propagation speed



Results (continued)



- The twist stability threshold can be *raised* by rapid rotation of the plasma (plasma inertia provides centrifugal "force" perpendicular to the jet, balancing magnetic pinch forces)

$$0 = \frac{\rho_m v_\phi^2}{r} - \frac{1}{4\pi}\frac{B_\phi^2}{r} - \frac{1}{8\pi}\frac{d\left(B_z^2 + B_\phi^2\right)}{dr}$$

- Highly-magnetized, rapidly-rotating ultra-relativistic jets may be self-stabilizing due to the inertia of the rotating magnetic field itself

$$0 = \frac{\rho_T v_\phi^2}{r} - \frac{1}{4\pi}\frac{B_\phi^2}{r} - \frac{1}{8\pi}\frac{dB_\phi^2}{dr} - \cancelto{0}{\frac{1}{8\pi\Gamma_\phi^2}\frac{dB_z^2}{dr}}$$

$$\rho_T \equiv \Gamma_\phi \rho_m + \frac{B_z^2}{2\pi c^2}$$

$$\Rightarrow \frac{B_Z}{B_\phi} : 1 \quad \Rightarrow \boxed{\frac{B'_Z}{B'_\phi} : \frac{1}{\Gamma_Z}}$$

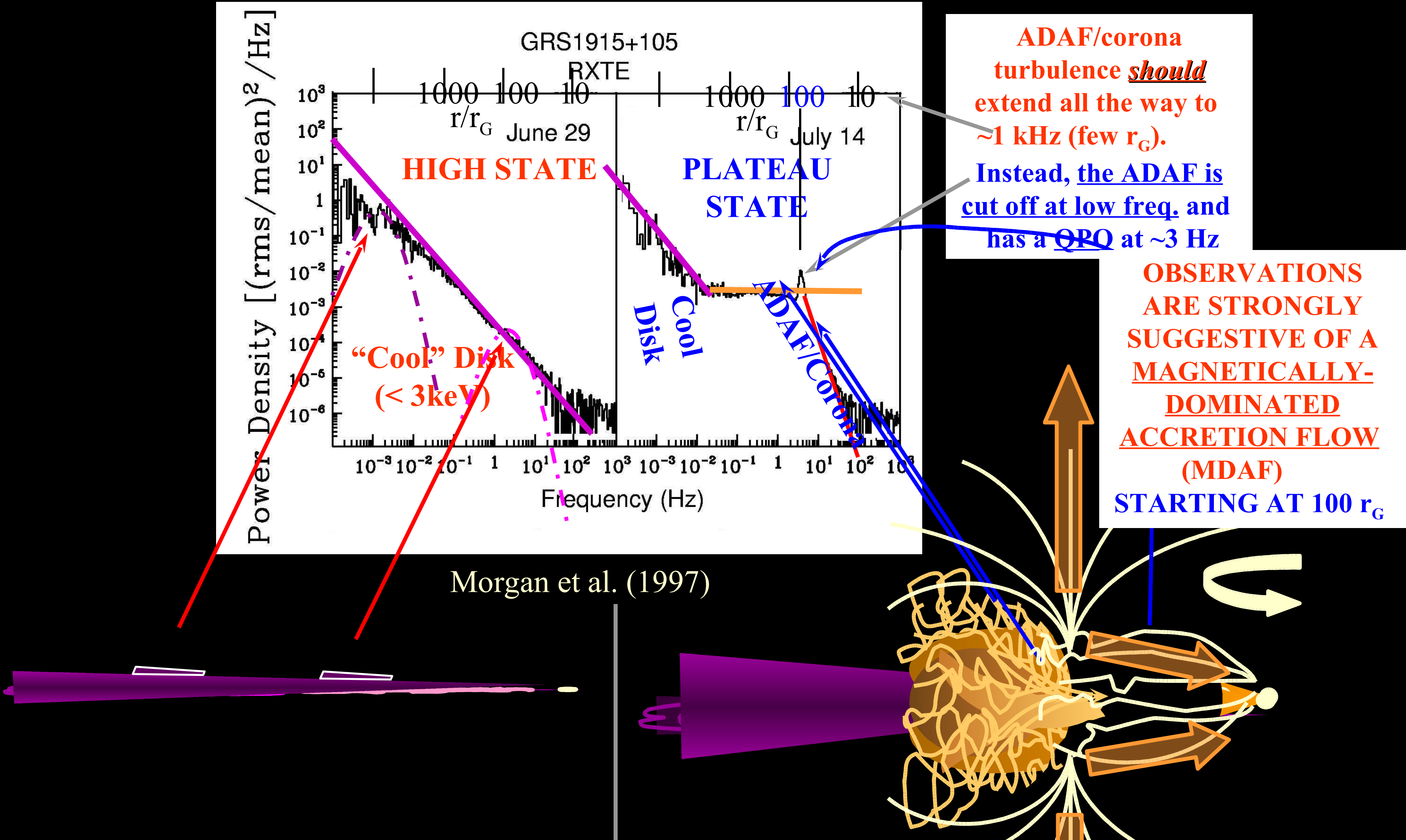
- We (N & M 2006) are developing a relativistic MHD code to test URPFD jet stability

Magnetically-Dominated Accretion Flows (MDAFs): How Black Holes Make Jets

(Meier 2005)

Power Spectrum Changes with Accretion State In Microquasars Like 1915+105

Gives important clues to the magnetic field structure and how a jet may form



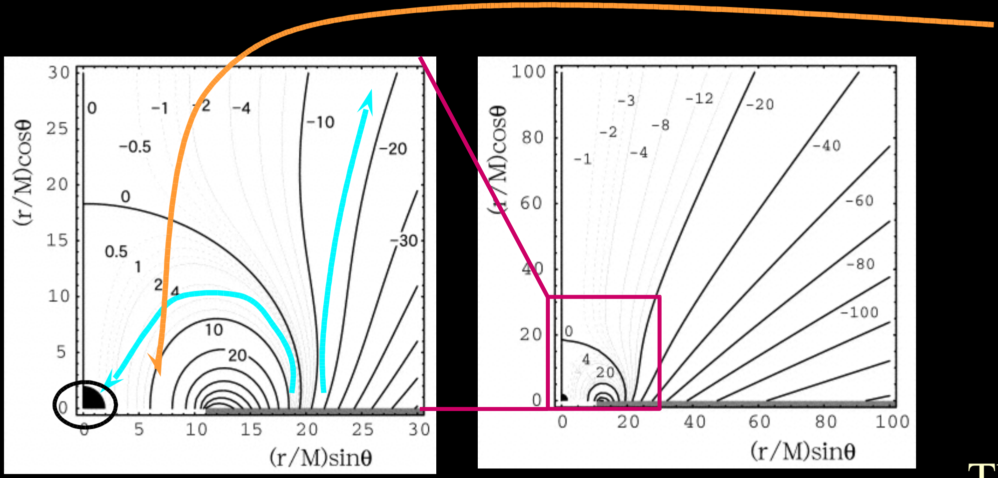
Morgan et al. (1997)

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?



Tomimatsu & Takahashi (2001);
Uzdensky (2004)

Magnetically-dominated accretion flow
(MDAF)

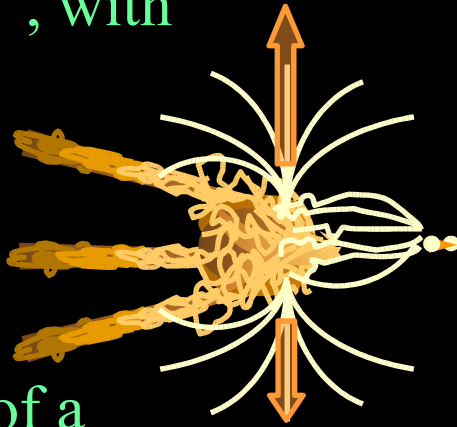
Closely related to a "black hole magnetosphere"

Laminar, ***<u>NON-turbulent</u>*** accretion flow **along strong magnetic field lines**

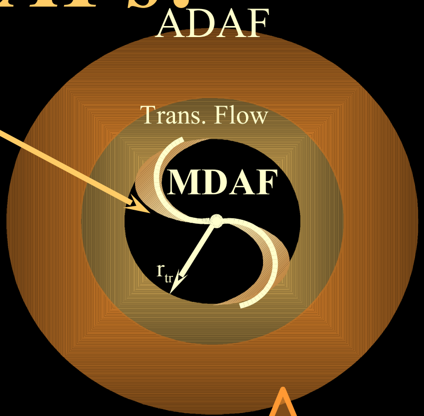
The **MRI is turned off** in the MDAF region

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

- Best thought of as an "*<u>accretion disk</u>* magnetosphere", with
  - Field lines stretching <u>inward toward the black hole</u>, <u>channeling the inner accretion flow</u>
  - Field lines stretching <u>outward</u>, <u>creating an MHD wind/jet</u>
  - 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 <u>any reasonable accretion flow</u>

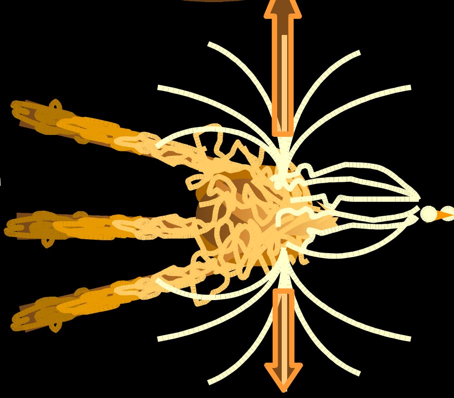


What are the Properties of MDAFs?



- 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

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



- 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
- This is a natural configuration for driving a steady jet at the inner ADAF escape speed (Meier 2001)

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

- The velocity of this jet also should increase as the MDAF radius decreases, and will be relativistic for small MDAFs

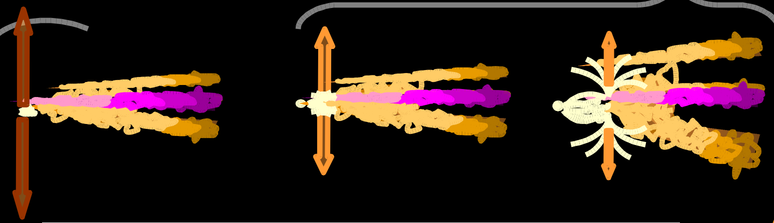
Uchida et al. (1999); Nakamura (2001)

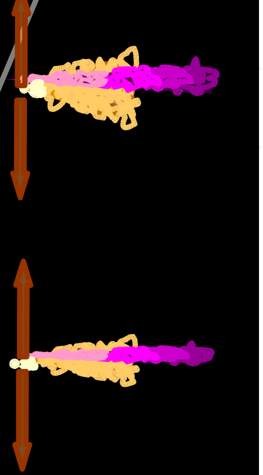
MDAFs and the Fender, Belloni, & Gallo Model

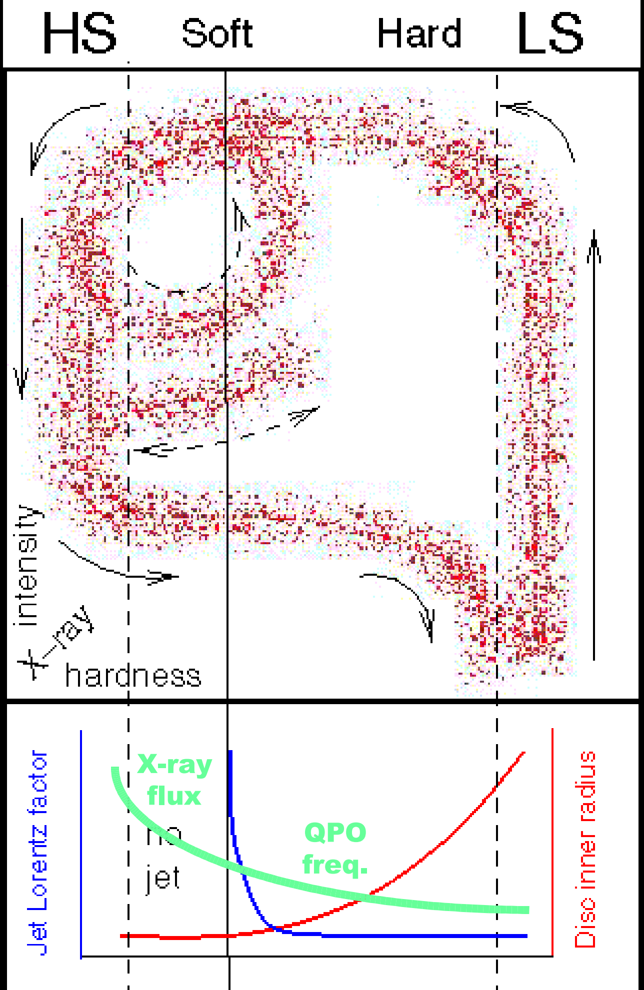
HIGH STATES:

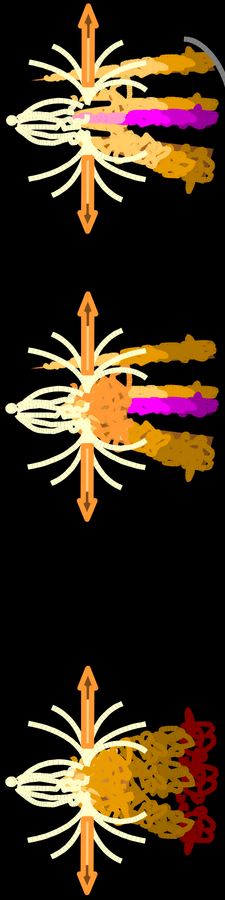
No Jet?

Highly-Beamed or Poynting Jet?









INTERMEDIATE STATES / **QUASARs**:

MDAF inside re-filling disk

PLATEAU STATE / BL LACs:

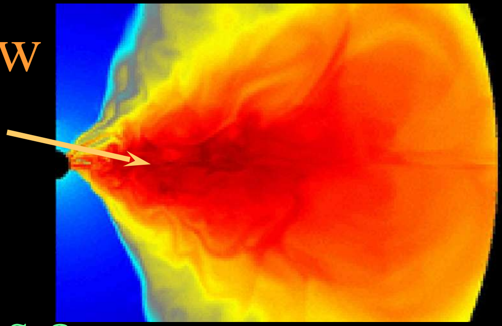
Disk transitions to ADAF at ~1000 r_A by

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

ADAF truncated to MDAF at ~100 r_G

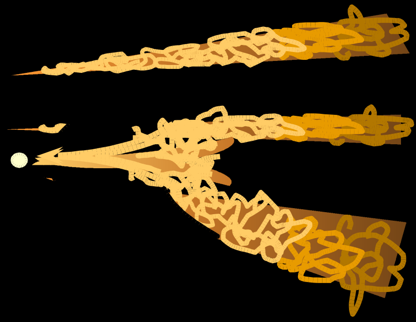
What would cause an ADAF to be cut off at ~100 r_G?

- 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 $10^{10\text{-}11}$ K, radiating copiously



McKinney & Gammie (2004)

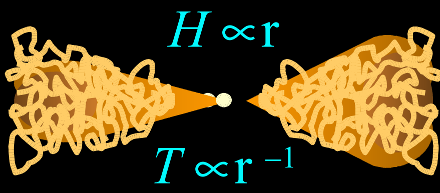
- But, if this doesn't happen, and the ADAF remains a ***1-T*** flow ($T_i = T_e = T \leq 10^{10\text{-}11}$ K), it will collapse when
  - $T_{virial} > T_e \approx 10^{10\text{-}11}$ K
  - Or $r < GM\mu / \mathcal{R} T_e \approx 60 - 600\ r_G$



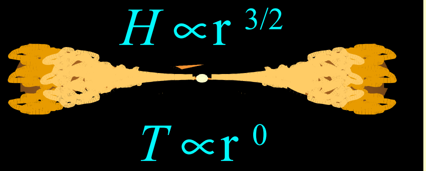
- Relation to MRI simulations: This collapse
  - Would ***not*** have been seen in most simulations, as they have no thermal cooling to $p_{gas} << GM\rho / r$
  - ***Has*** been seen by Machida & Matsumoto (2005) in Bremsstrahlung-cooled MRI disks

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

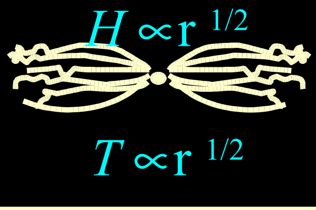
What causes Global Field to form from chaos?



- 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)
  - $y = 4\,\tau_{es}\, kT_e / m_e c^2 \approx 1$ is a good simple energy equation for T_e

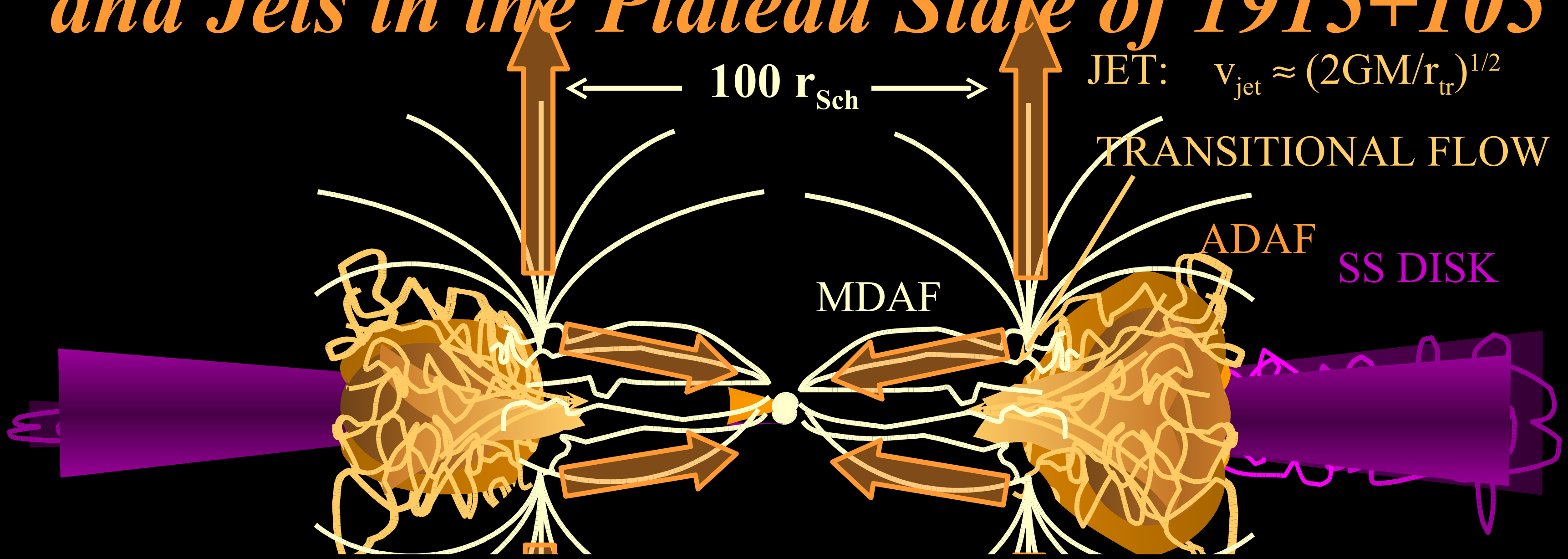


- New accretion solution #1: "Magnetic-Advection or "transitional flow" ($\alpha \rightarrow 1$)
  - Still turbulent, but now inflow time < largest eddy turnover time
  - Tangled field is advected inward and *stretched*:
    - $B_r \propto r^{-1} H^{-1} \propto r^{-5/2}$; $B_\phi \propto v_r^{-1} H^{-1} \propto r^{-1/2}$
  - 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 $B_r \propto r^{-3/2}$; $B_\phi \propto r^{-1}$; $\alpha \propto r^{-2}$

A Complete Theoretical Model for Accretion and Jets in the Plateau State of 1915+105



$\leftarrow$ **100 r_{Sch}** $\rightarrow$

JET: $v_{jet} \approx (2GM/r_{tr})^{1/2}$

TRANSITIONAL FLOW

ADAF

SS DISK

MDAF

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

The Key Assertions of the Theoretical MDAF Model

- Microquasars & AGN:
  - The two-temperature, ion-pressure-supported torus model of the hard state 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 following microquasar features:
    - The power fluctuation spectrum (BW-limited noise; QPOs)
    - The presence of a slow jet in the low/hard/plateau state
    - Increase in jet speed to relativistic values in the very high/unstable states
- GRBs:
  - In the inner region of the hyper-critical accretion flow, neutrino cooling can be more important than advection
  - May lead to a magnetically-dominant flow / magnetosphere and jet
  - To create a relativistic jet, must occur very near BH (inside ergosphere ?)

Summary and Conclusions

- **Jets accelerated by strong magnetic fields**
  - **Can be helically-kink unstable in the Poynting-Flux-Dominated regime**
  - **But, may be self-stabilizing if ultra-relativistic (stay tuned)**
- **MDAFs**
  - **Provide a natural synthesis of BH accretion, magnetosphere, and MHD jet-production theories to produce a complete picture of accretion and jet-production in black hole systems**
  - For microquasars they naturally explain
    - BW-limited noise, QPOs, & jets in the plateau state
    - Increase in jet speed and QPO frequency with spectral softening (*a la* Fender et al. model)
  - **May be important in GRB engines, but <u>only where neutrino cooling dominates advection</u>**