Magnetically-Dominated Accretion Flows (MDAFs) in Sgr A?: An Initial Assessment*

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Outline

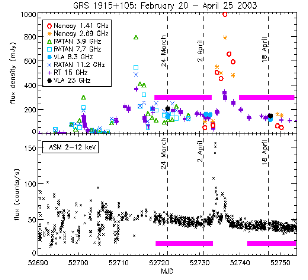
- The need for considering magnetically-dominated accretion flows (MDAFs) in low/hard states: the plateau state of GRS 1915+105 as an example
- General properties of MDAFs
- ADAFs & MDAFs in Sgr A*?
  - – In the quiescent state
  - – In the flaring state

The Need for MDAFs in Low-Hard Accreting Black Hole Systems: GRS 1915+105 in the Plateau State

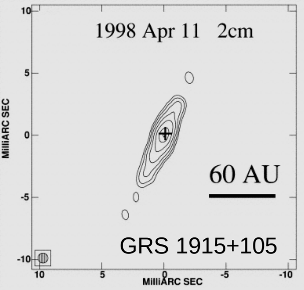
(Towards a Unified Model of Accretion and Jet Production in Black Hole Systems)

Microquasar GRS 1915+105's Plateau State

(high), flaring, plateau



Ribo *et al*. (2004)

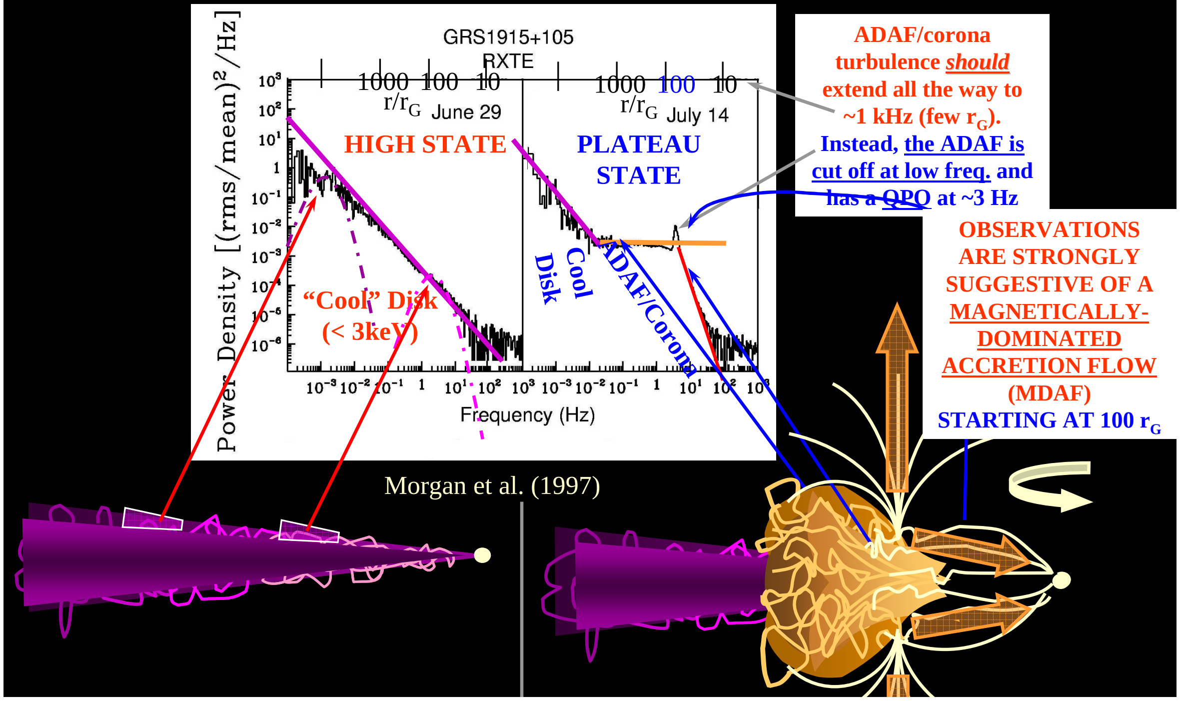


Dhawan *et al*. (2000)

- Plateau state characterized by
  - steady, optically thick, strong (>100 mJy) radio emission and low/hard X-ray emission
  - VLA images showing a steady, sub-relativistic jet (0.1-0.3 c)
  - staying in this state for weeks ($> 10^9$ dynamical times)
  - Equivalent to an LLAGN ~~state~~ but with a ~14 $M_\odot$ black hole in a binary system
  - NOTE: Sgr A* has a much lower $\mathrm{Mdot}/\mathrm{Mdot}_{\mathrm{Edd}}$ ($10^{-7} – 10^{-4}$ *vs.* <~0.1)

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

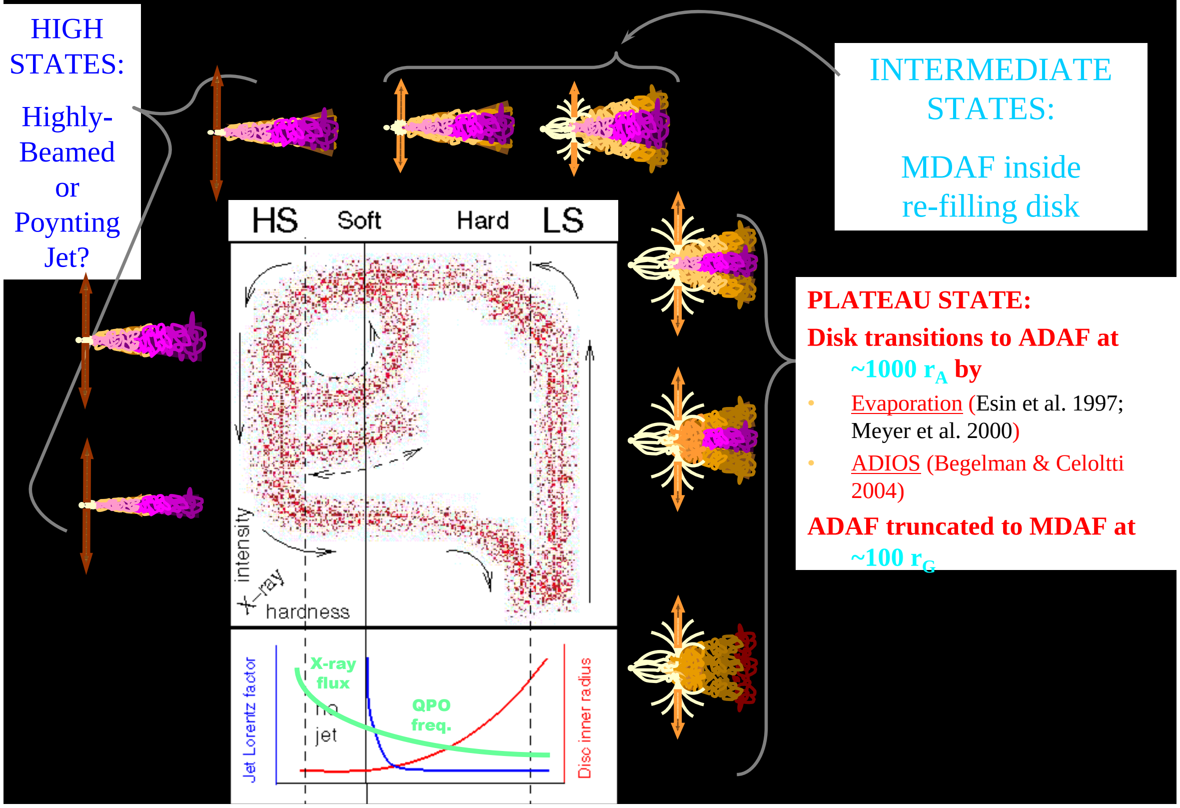


Morgan et al. (1997)

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

MDAFs and the Fender, Belloni, & Gallo Model



HIGH STATES:

Highly-Beamed or Poynting Jet?

INTERMEDIATE STATES:

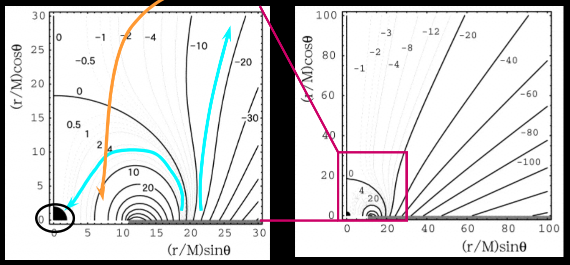
MDAF inside re-filling disk

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

What is an MDAF?



Tomimatsu & Takahashi (2001);
Uzdensky (2004)

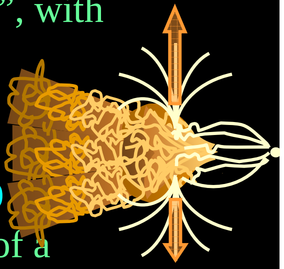
Magnetically-dominated accretion flow (MDAF)

Closely related to a "black hole magnetosphere"

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

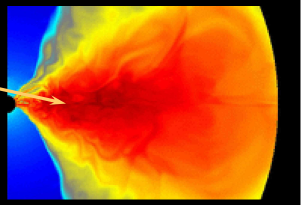
The **MRI is turned off** in the MDAF region

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



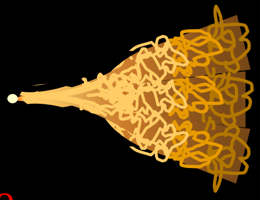
- Best thought of as an "*accretion disk* magnetosphere", with
  - Field lines stretching inward toward the black hole, channeling the inner accretion flow
  - Field lines stretching outward, creating an MHD wind/jet
  - All rotating at the inner disk Keplerian rate $\Omega_K(r_{in}) = \Omega_K(r_{tr})$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

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



McKinney & Gammie (2004)

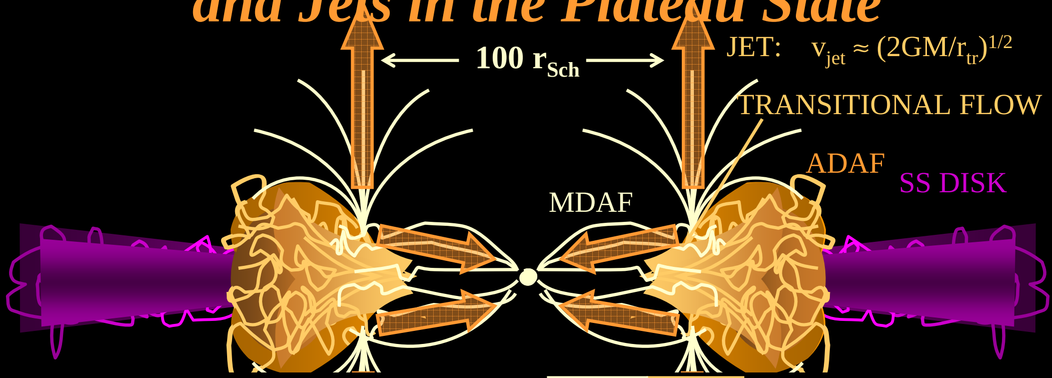
- The ADAF solution *assumes* a 2-Temperature flow
  - Hot ions ($T_i \approx T_{virial} \le 5 \times 10^{12}$ K) support the thick flow
  - Electrons remain around $10^{10\text{-}11}$ K, radiating copiously
- But, if this doesn't happen, and the ADAF remains a ***1-T*** flow ($T_i = T_e = T \le 10^{10\text{-}11}$ K), it will collapse when
  - $T_{virial} > 10^{10\text{-}11}$ K
  - Or $r < GM\mu / \mathscr{R} T_e$ = 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

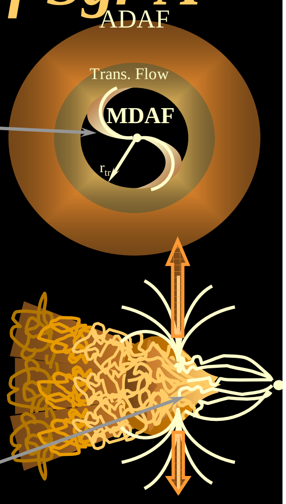
A Complete Theoretical Model for Accretion and Jets in the Plateau State



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

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	$\propto r^{1/2}$	$\propto r^{0}$	$\propto r^{-1}$	$\propto r^{-9/10}$
v_r	$\propto r^{-1/2}$	$\propto r^{-1}$	$\propto r^{-1/2}$	$\propto r^{-2/5}$
$B_r B_\phi / 4\pi p \equiv \alpha$	$\propto r^{-2}$	$\propto r^{-3/2}$	$\propto r^{0}$	$\propto r^{0}$

MDAF as the Quiescent State of Sgr A*



- The inner accretion flow is in a nearly-radial in-spiral
  - In an MDAF, angular momentum is transferred outward to transition radius along stiff field lines
  - Inflow slips along field lines on near-geodesic paths
- It is likely broken up into several “spokes” or filaments (rotating hot spots or “hot tubes or channels”)
- The entire (magnetically-dominated) inflow is in solid-body rotation at the transition radius orbital / Alfvén frequency

$$\nu_A = V_A/2\pi r_{tr} = (GM/r_{tr}^3)^{1/2}/2\pi = 0.65\ \mathrm{d}^{-1}\ m_{6.6}^{-1}\ [r_{tr}/100r_G]^{-3/2}$$

- The velocity of any jet would be low, roughly the escape speed at the outer MDAF radius (inner ADAF radius)

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

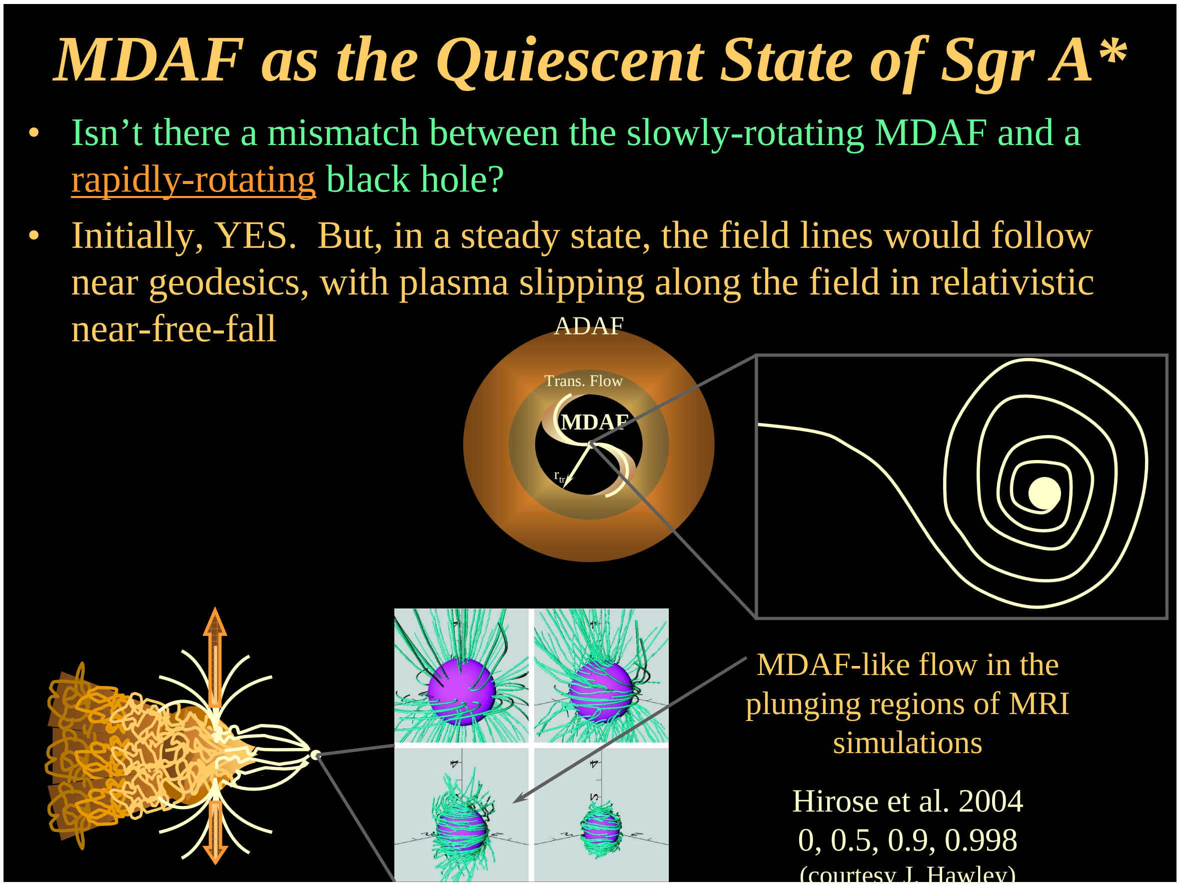
- Because MDAF inflow is cool (10^{10} K plasma), most of the dissipation takes place in the outer ADAF:

  Therefore, the radiative efficiency of the inflow is very low, at least an order of magnitude less than an equivalent ADAF

$$L_{MDAF} \approx L_{ADAF}\,(r_{eff}/r_{tr}) = 10^{36}\ \mathrm{erg\ s^{-1}}\ [\dot{M} / 10^{-5.5}\ M_\odot\ \mathrm{yr}^{-1}]^2\ [r_{tr}/100r_G]^{-1}$$

- An MDAF could dramatically change the predicted geometry and polarization properties of the inner ~100 r_G

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

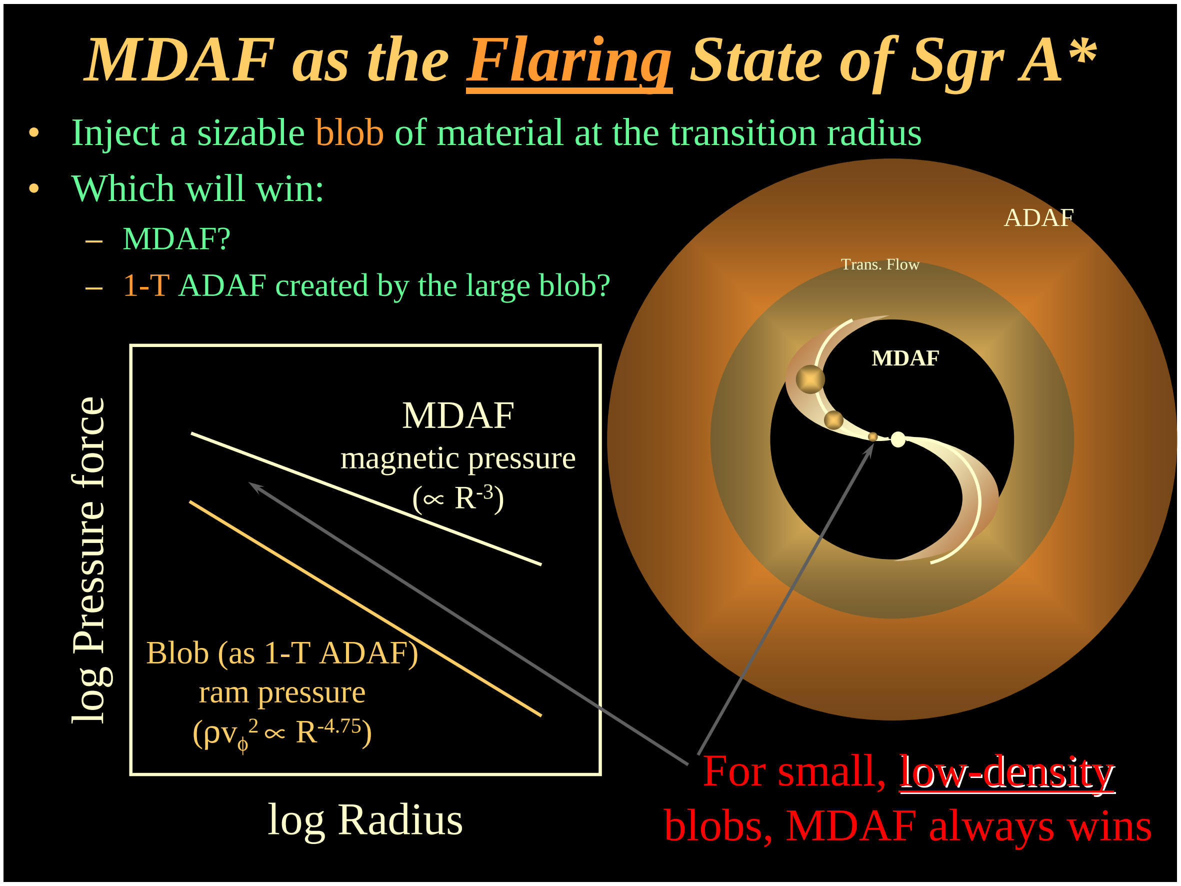


*MDAF as the Quiescent State of Sgr A**

- Isn’t there a mismatch between the slowly-rotating MDAF and a rapidly-rotating black hole?
- Initially, YES. But, in a steady state, the field lines would follow near geodesics, with plasma slipping along the field in relativistic near-free-fall

MDAF-like flow in the plunging regions of MRI simulations

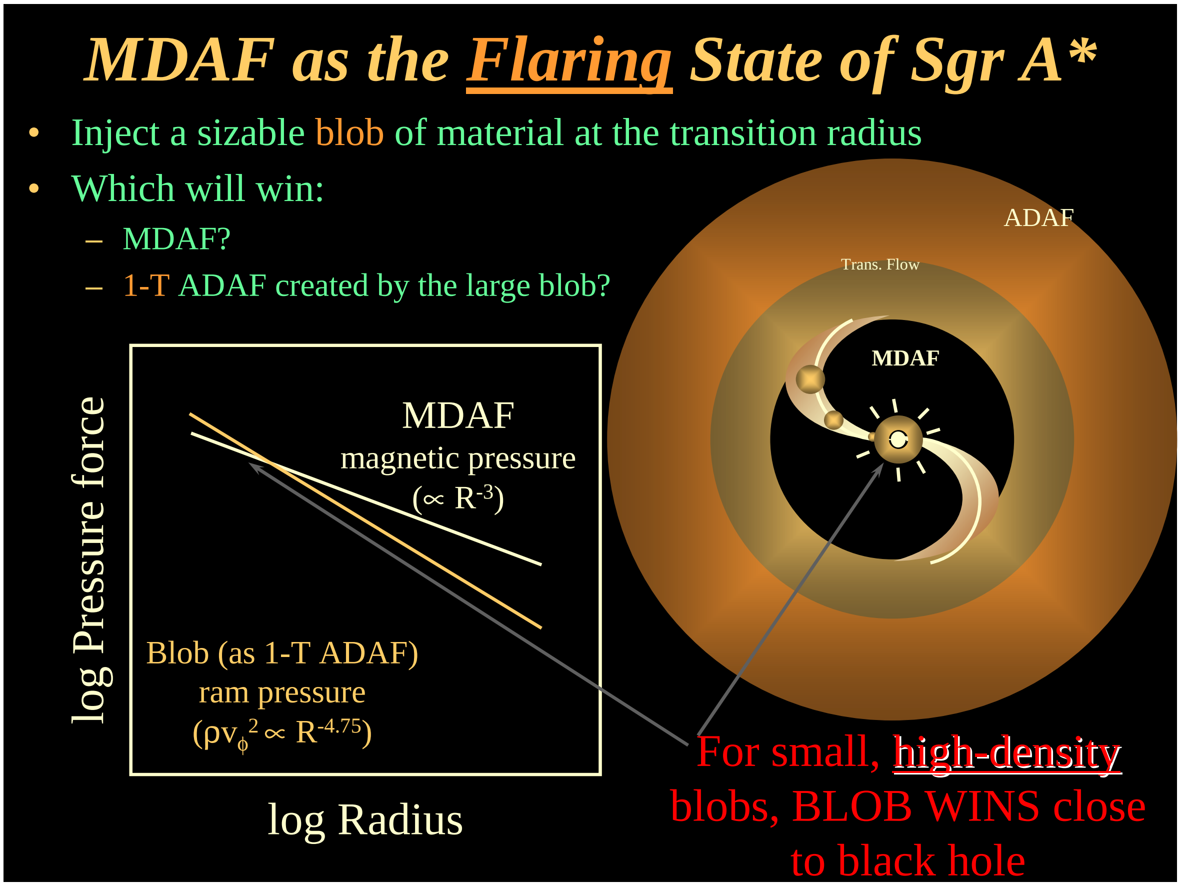
Hirose et al. 2004
0, 0.5, 0.9, 0.998
(courtesy J. Hawley)



*MDAF as the Flaring State of Sgr A**

- Inject a sizable blob of material at the transition radius
- Which will win:
  - MDAF?
  - 1-T ADAF created by the large blob?

For small, low-density blobs, MDAF always wins



MDAF as the Flaring State of Sgr A*

- Inject a sizable blob of material at the transition radius
- Which will win:
  - MDAF?
  - 1-T ADAF created by the large blob?

MDAF
magnetic pressure
(∝ R^{-3})

Blob (as 1-T ADAF)
ram pressure
($\rho v_\phi^2 \propto R^{-4.75}$)

log Pressure force

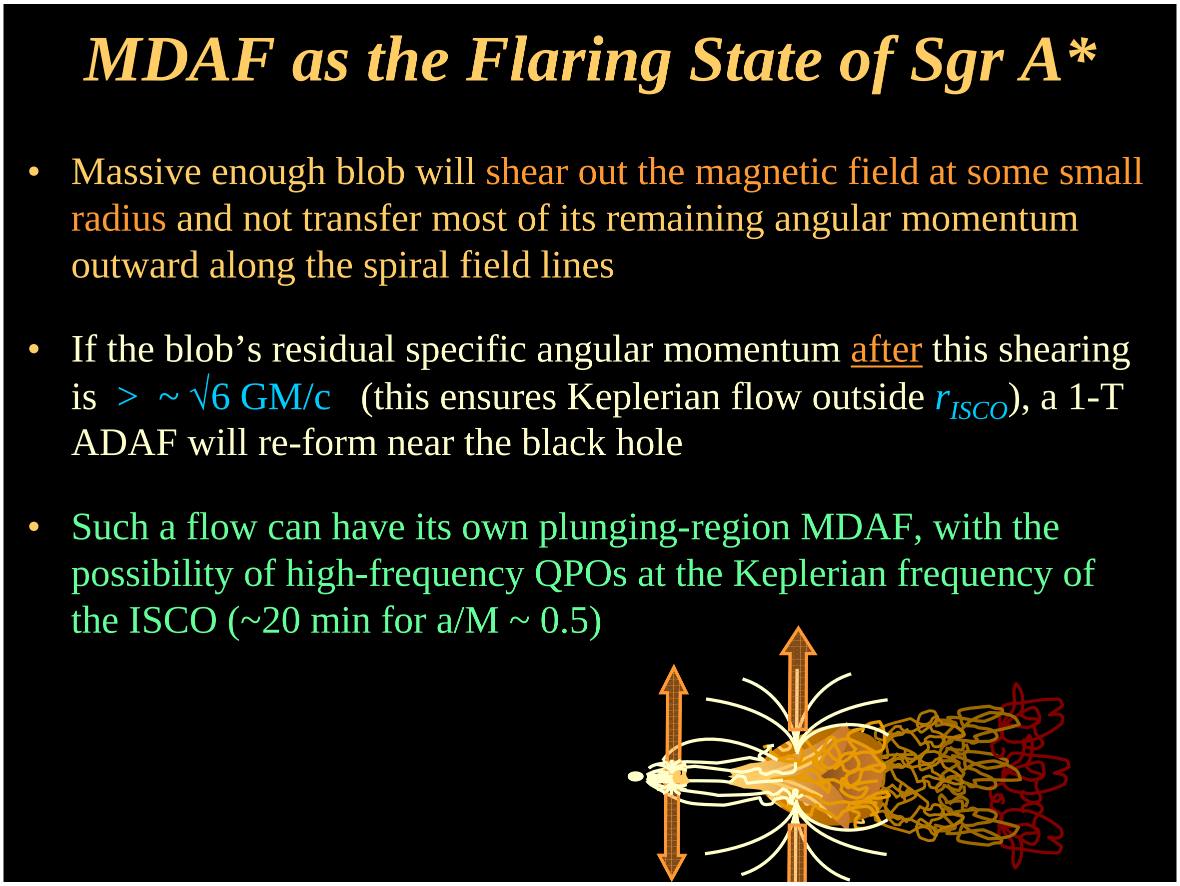
log Radius

ADAF

Trans. Flow

MDAF

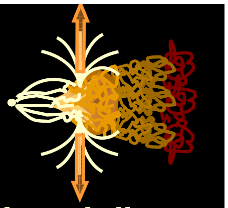
For small, high-density blobs, BLOB WINS close to black hole



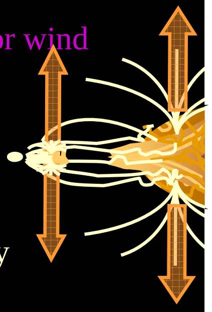
MDAF as the Flaring State of Sgr A*

- Massive enough blob will shear out the magnetic field at some small radius and not transfer most of its remaining angular momentum outward along the spiral field lines
- If the blob's residual specific angular momentum after this shearing is $> \sim \sqrt{6}\, GM/c$ (this ensures Keplerian flow outside r_{ISCO}), a 1-T ADAF will re-form near the black hole
- Such a flow can have its own plunging-region MDAF, with the possibility of high-frequency QPOs at the Keplerian frequency of the ISCO (~20 min for a/M ~ 0.5)

Summary



- IF a large (~100 r_G) MDAF/magnetosphere exists in the Sgr A* quiescent state, it would
  - Be 10-40 times less efficient than an ADAF with the same Mdot and allow 3-6 times higher accretion rates (not a big deal)
  - Drastically change the predicted polarization characteristics in the inner 100 r_G and, therefore, the derived accretion rate
  - Predict a <u>low-frequency QPO</u> (P ~ 1 day) in the quiescent state
  - Provide a means of calculating the properties of any MHD jet or wind ejected



- IF a temporary small (< r_{ISCO}) MDAF/magnetosphere forms in the flaring state, it would
  - Occur inside a small 1-T ADAF, with $\beta > \sim 1$ (<u>not</u> magnetically dominated)
  - Explain any observed high frequency QPOs (~20 min) in the flaring state
  - Possibly eject a weak relativistic jet

Epilogue: Unanswered Questions

- Can an MDAF really form inside an ADAF? Inside a thin disk?
- If so, what is the primary mechanism? What controls the radius at which the transition takes place? 2-T → 1-T ADAF collapse? (NEEDED: MRI simulations with optically thin cooling)
- What is the structure and nature of the magnetic field in an MDAF? Does β really remain << 1? Somewhat < 1? Of order 1? Do the field lines really follow approximate geodesics?
- How does an MDAF respond to an overload of accreting matter from outside?
- Do the numbers work out for Sgr A*? That is, is the amount of material accreted during a flare sufficient to temporarily disrupt the inner part of the MDAF?
- What are the implications for jet formation and the radiated spectrum?