OUTFLOWS FROM BLACK HOLE ACCRETION

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THE BOTTOM LINE:

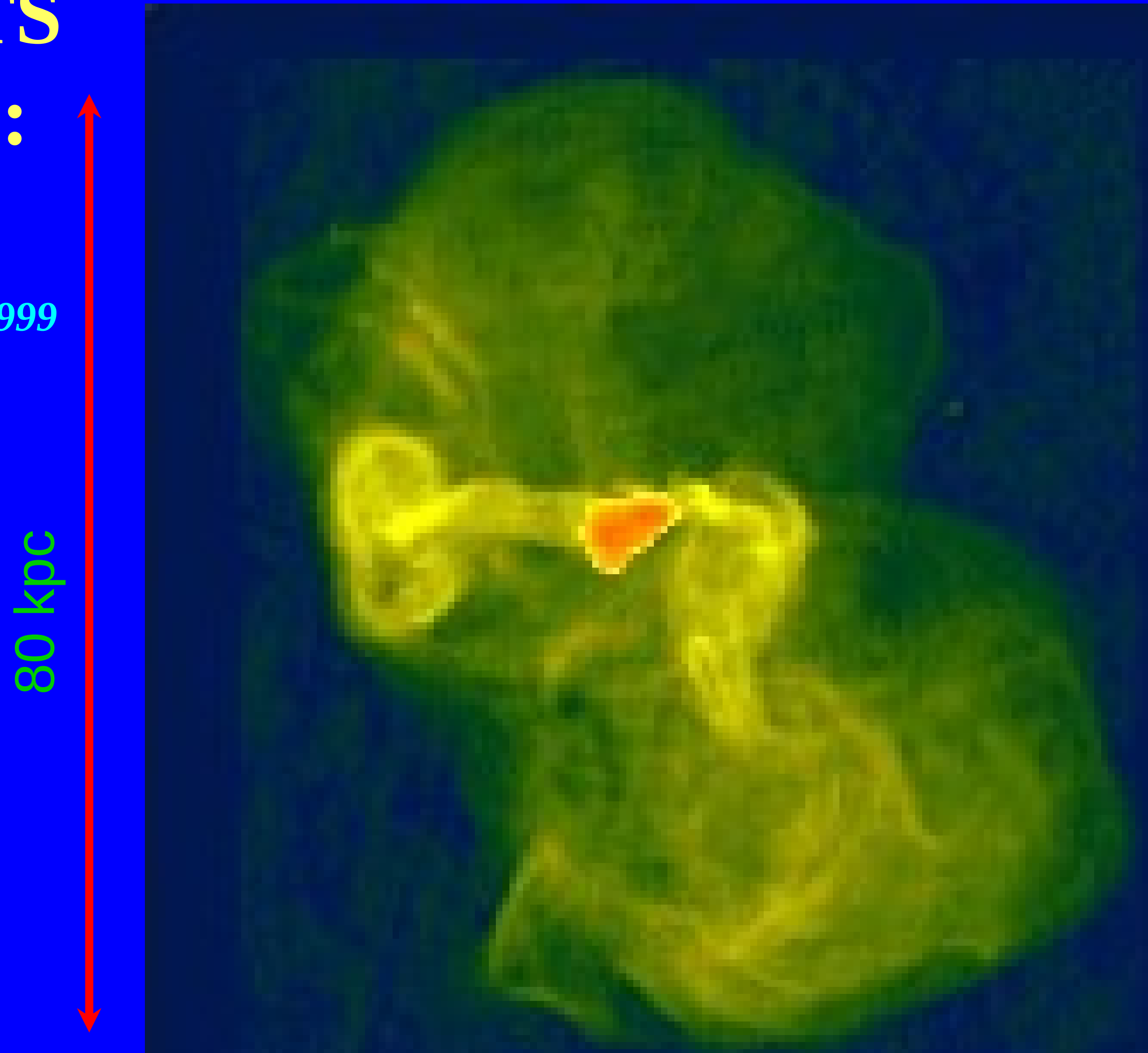
THE EXISTENCE OF OUTFLOWS FROM ACCRETING BLACK HOLES IS GENERIC

BUT THE DETAILS ARE DIVERSE AND SPECIFIC

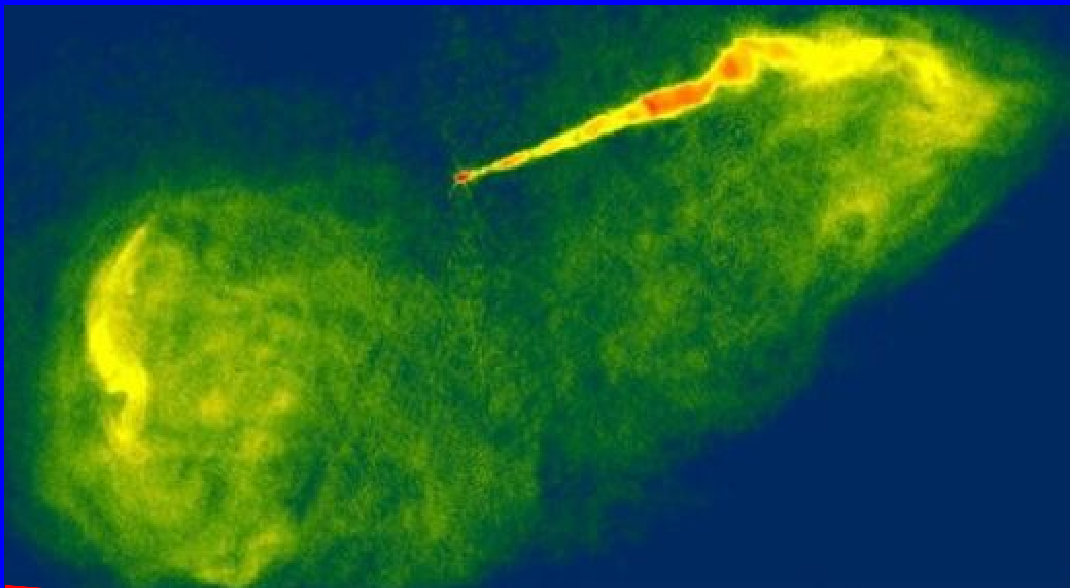
RADIO JETS & HALOES: M87

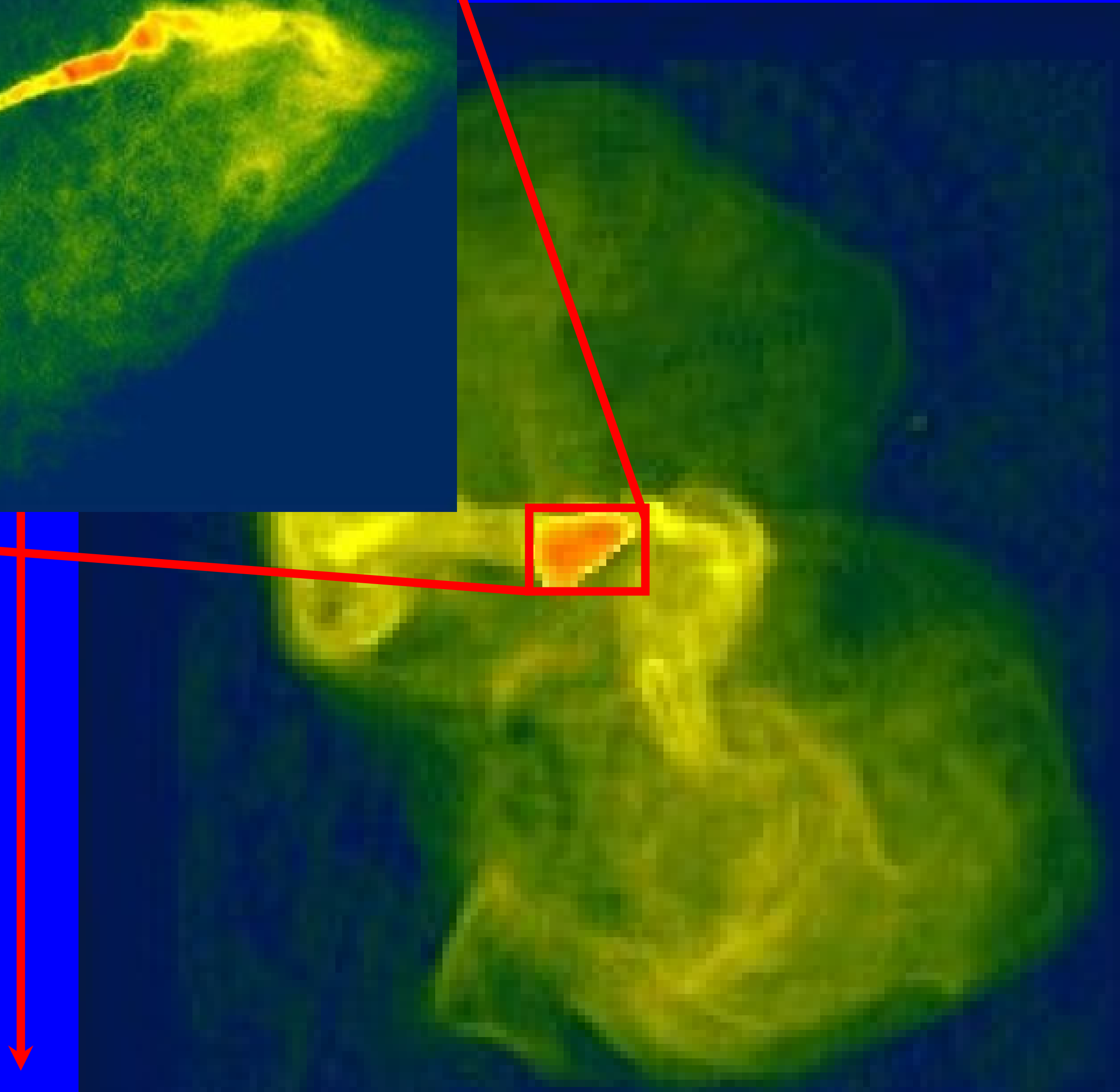
Owen, Eilek & Kassim 1999

VLA, 327 MHz



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





VLA, 327
MHz

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

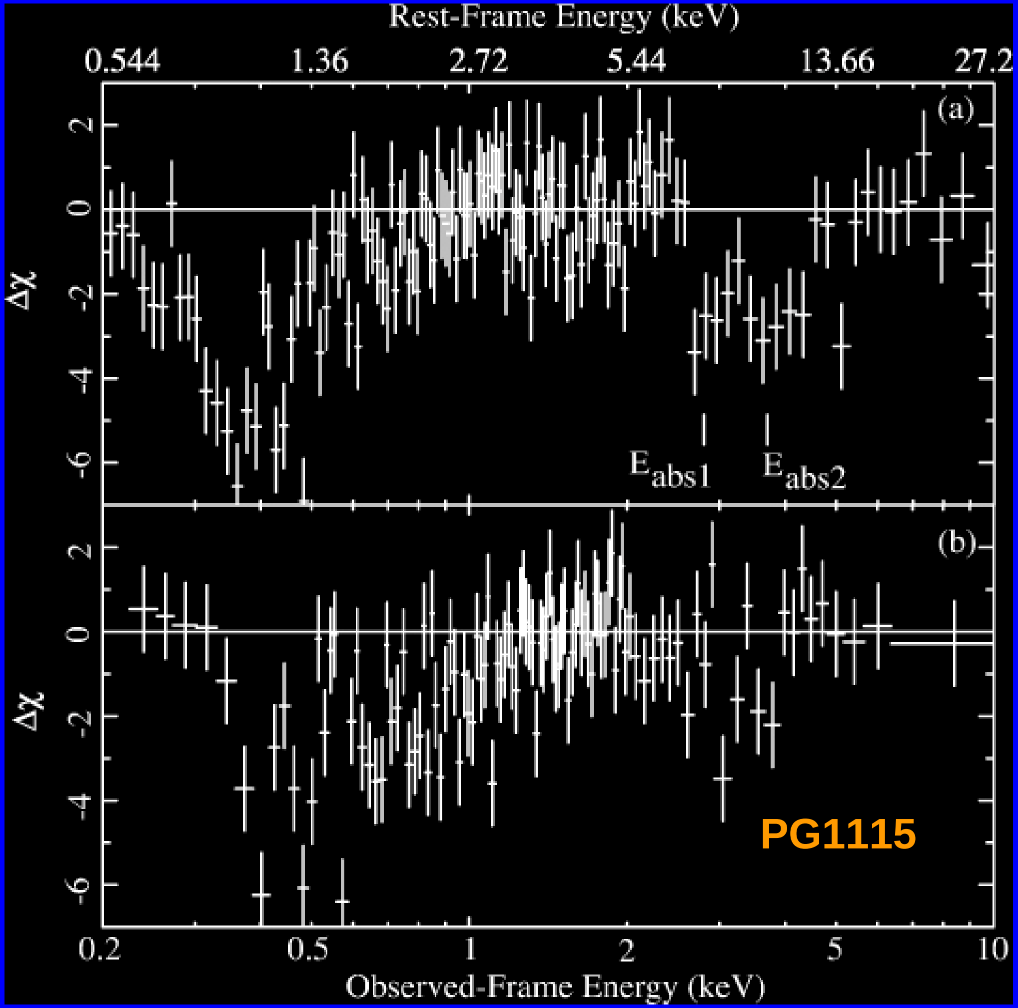
BAL Outflows in X-ray Absorption

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

$v \sim 0.2\ c$

$\Omega \sim 4\pi/10$

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



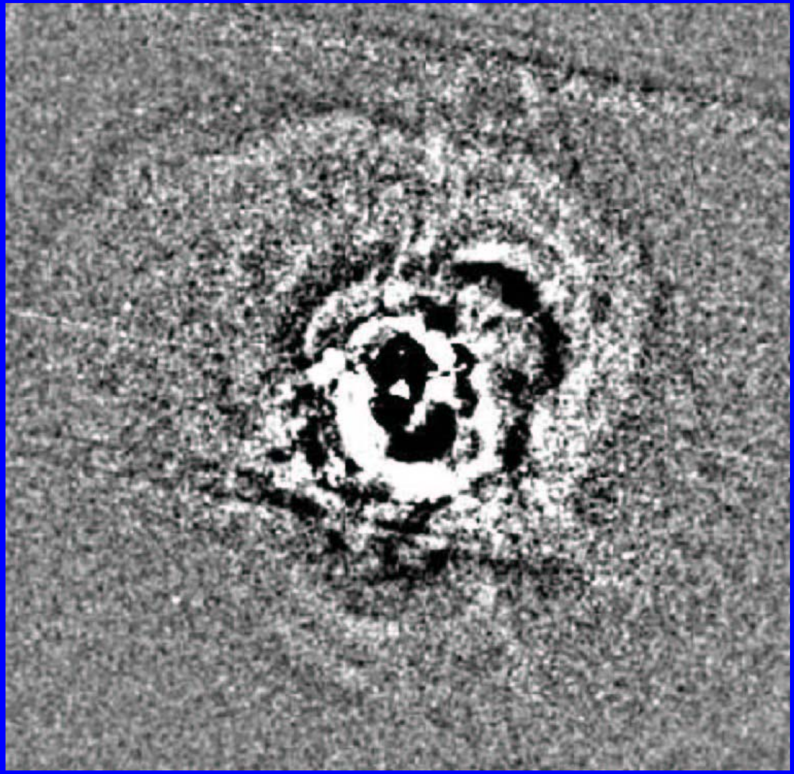
Chartas et al. 2003

Sound Waves in the Intracluster Medium

Perseus cluster

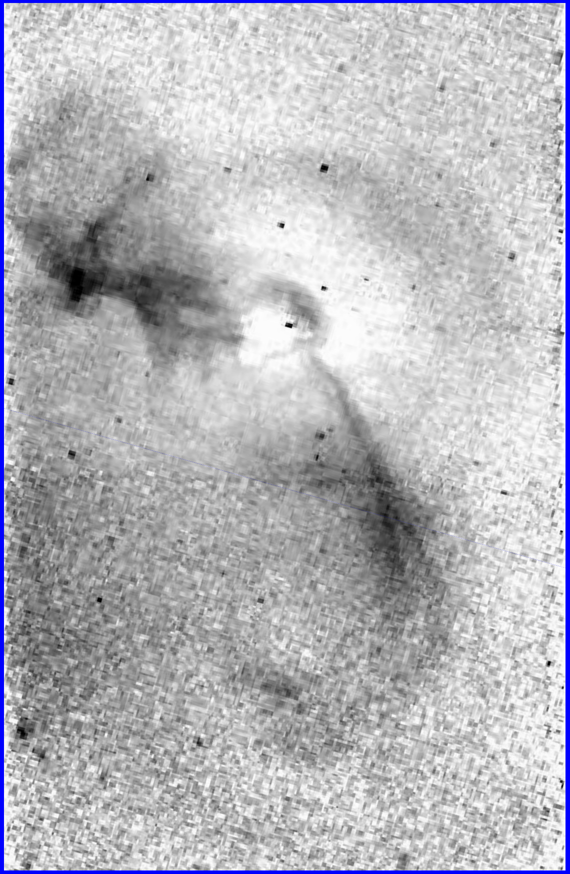
Unsharp masked Chandra image

131 kpc



Fabian et al. 2003

M87 + Virgo cluster

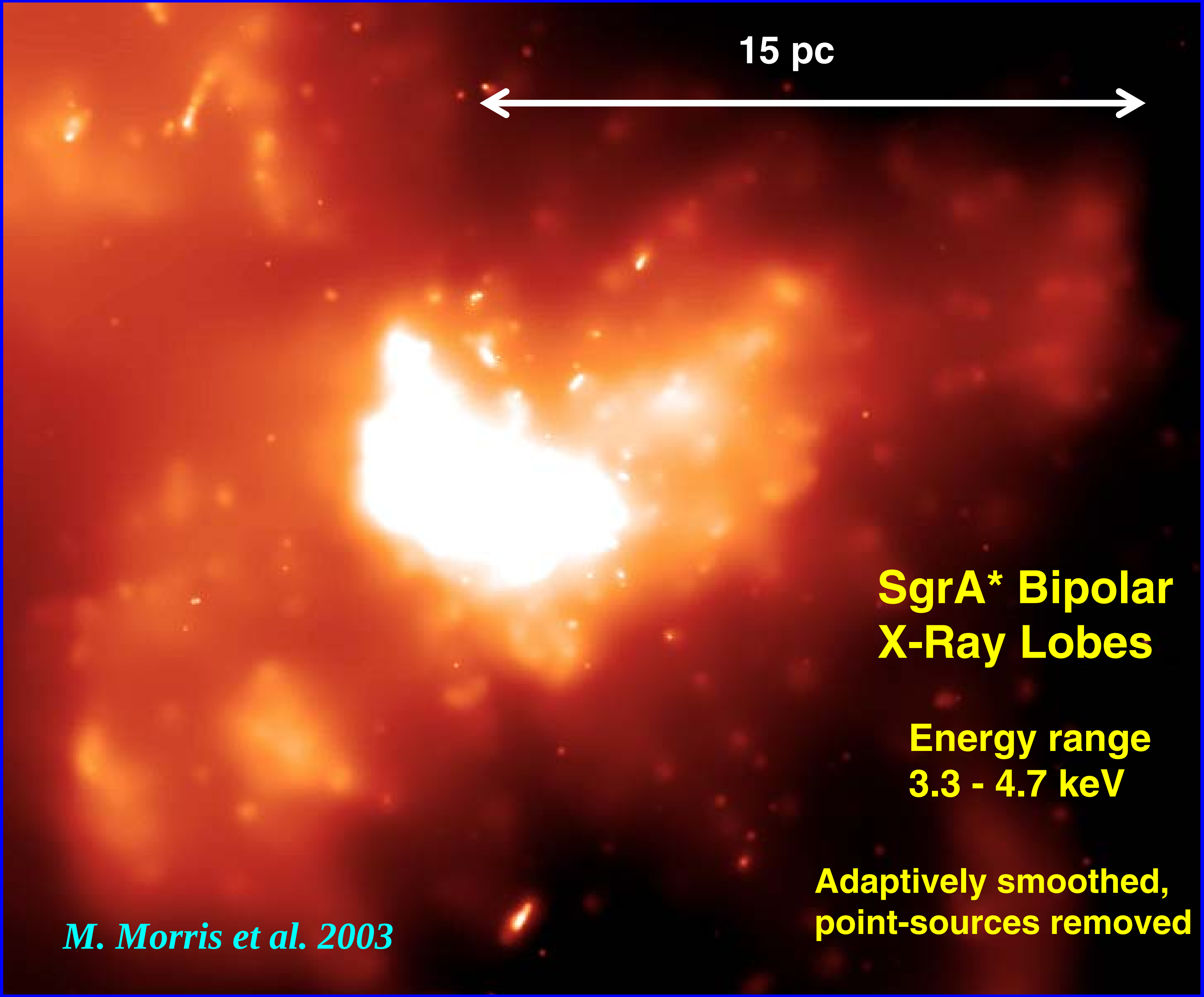


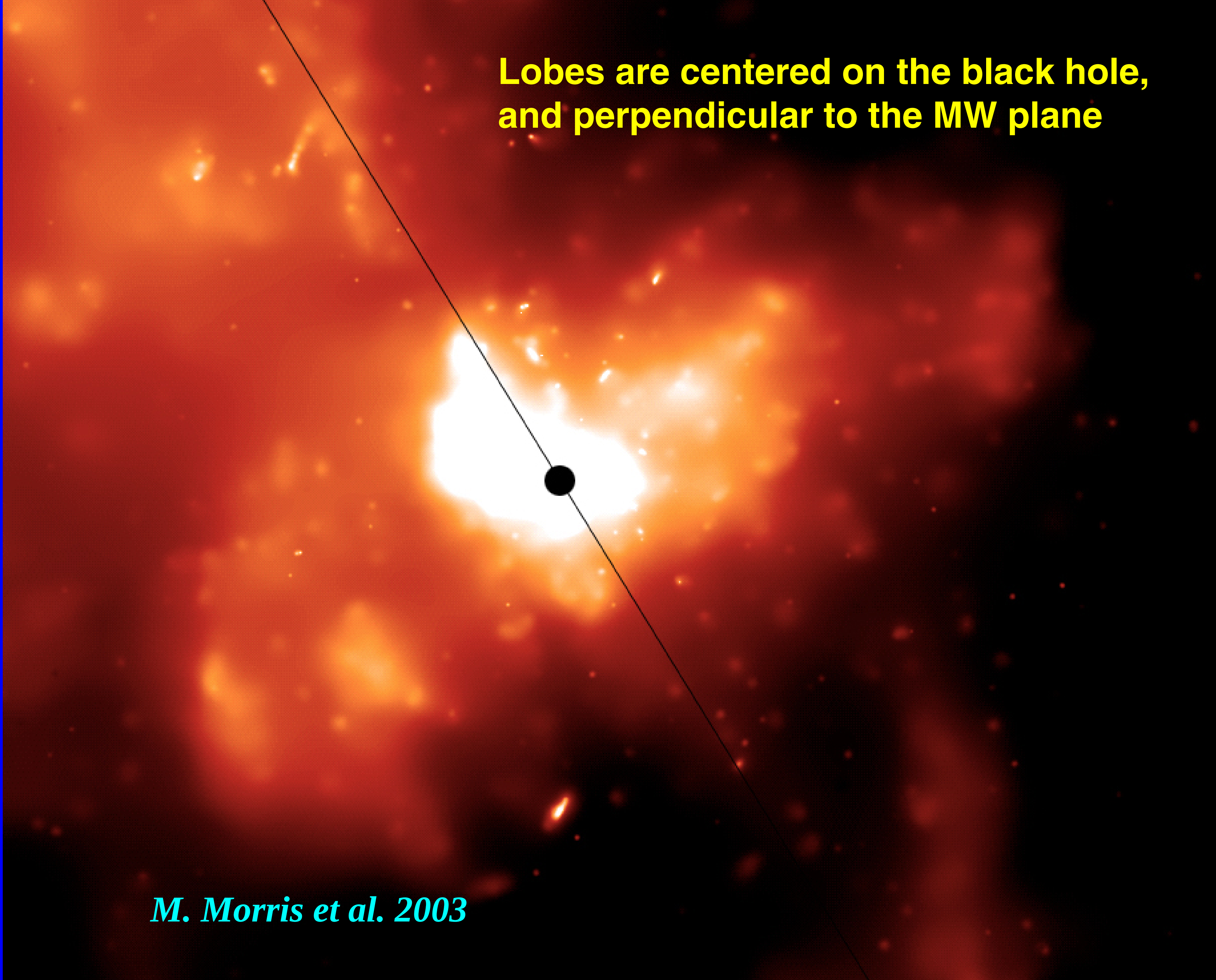
Forman et al. 2004

THE CLUSTER ENTROPY PROBLEM

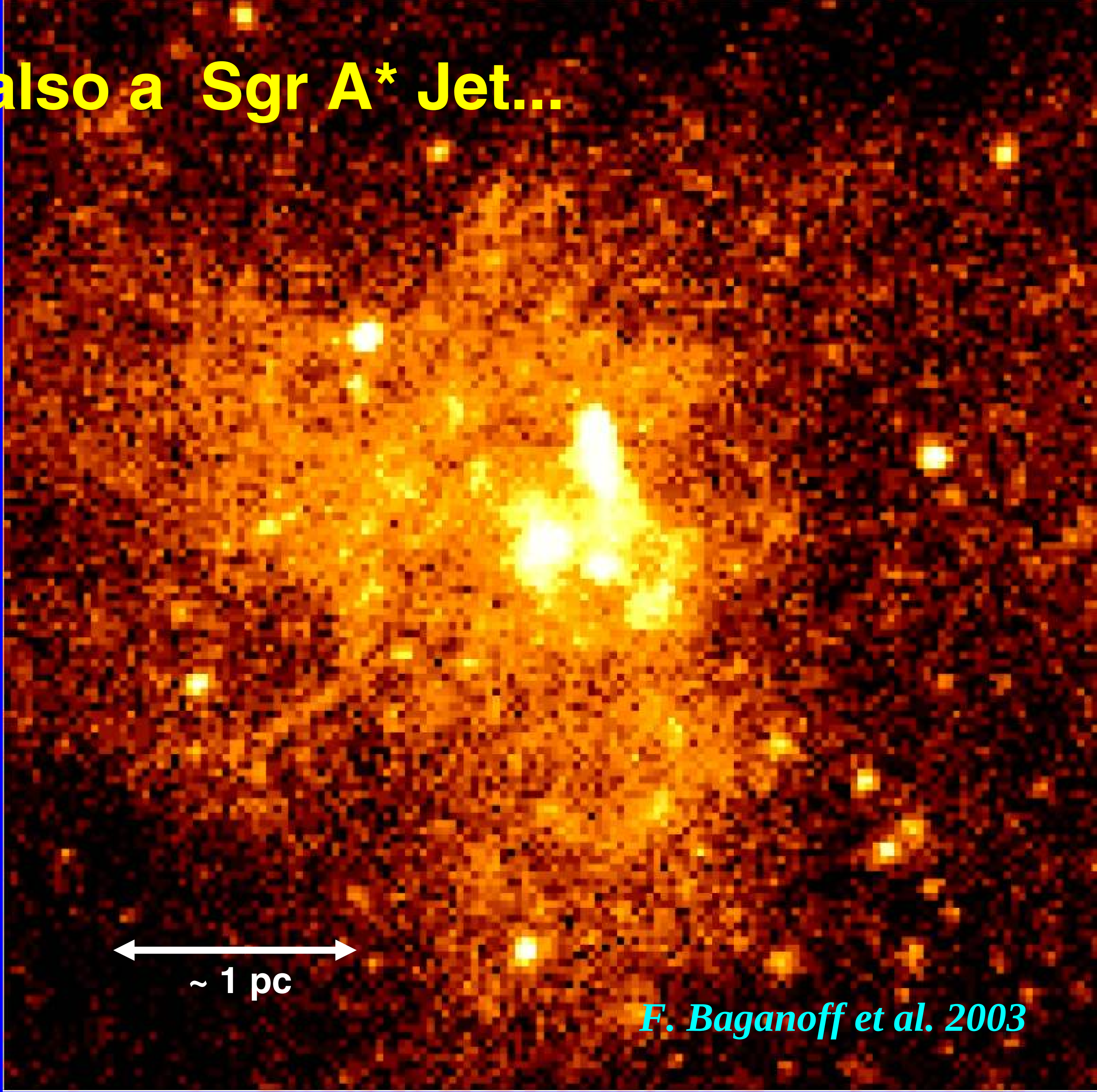
- **Hierarchical clustering** → $L_X \propto T^2$
- **Observed:** $L_X \propto T^3$ → **entropy "floor"**
- **Need ~ 1 keV/baryon EXTRA during cluster assembly**
  - **mixing/conduction not enough**
- **Supernova heating inadequate (?)**

→ **AGN HEATING?**


15 pc
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...



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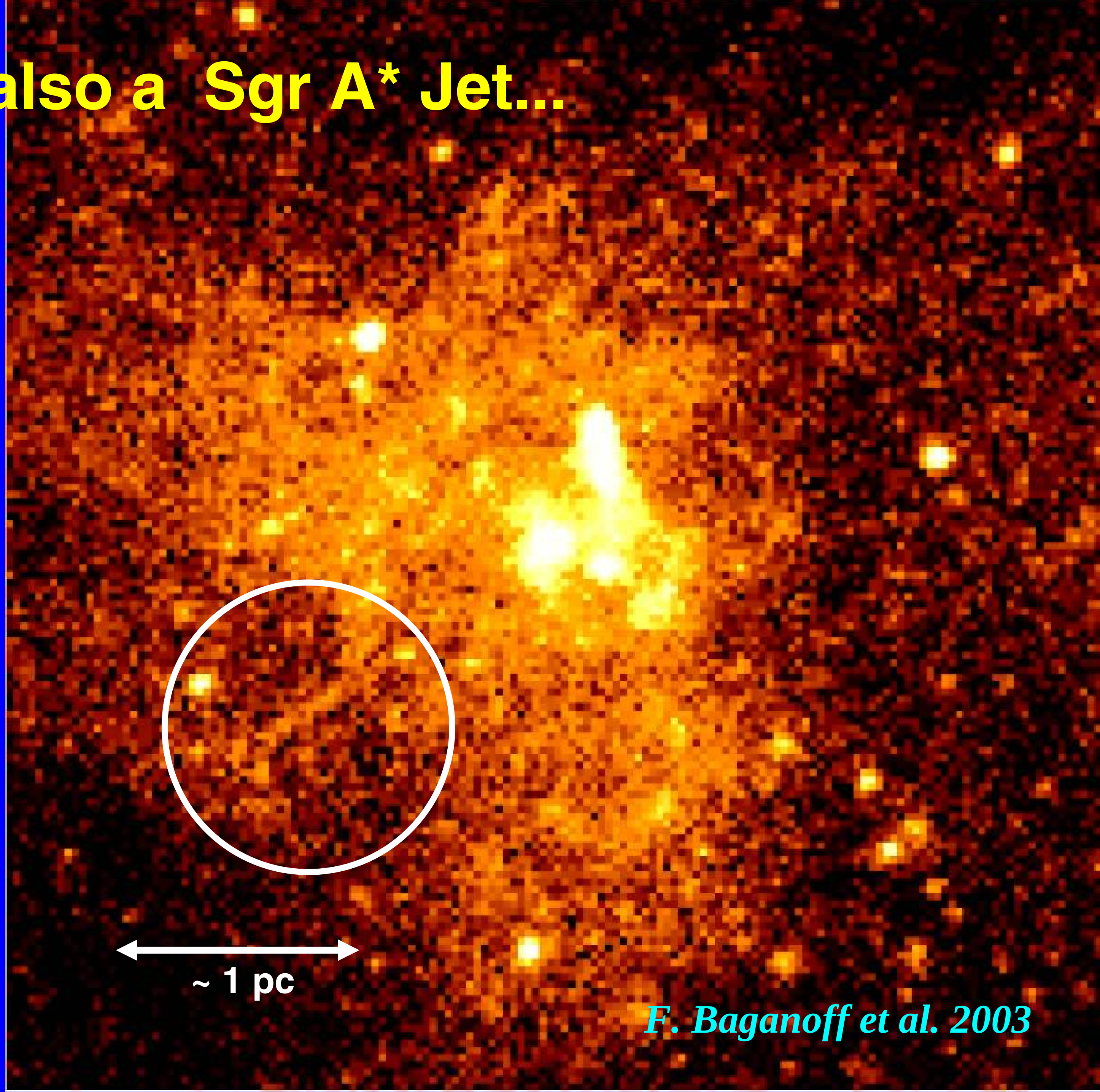
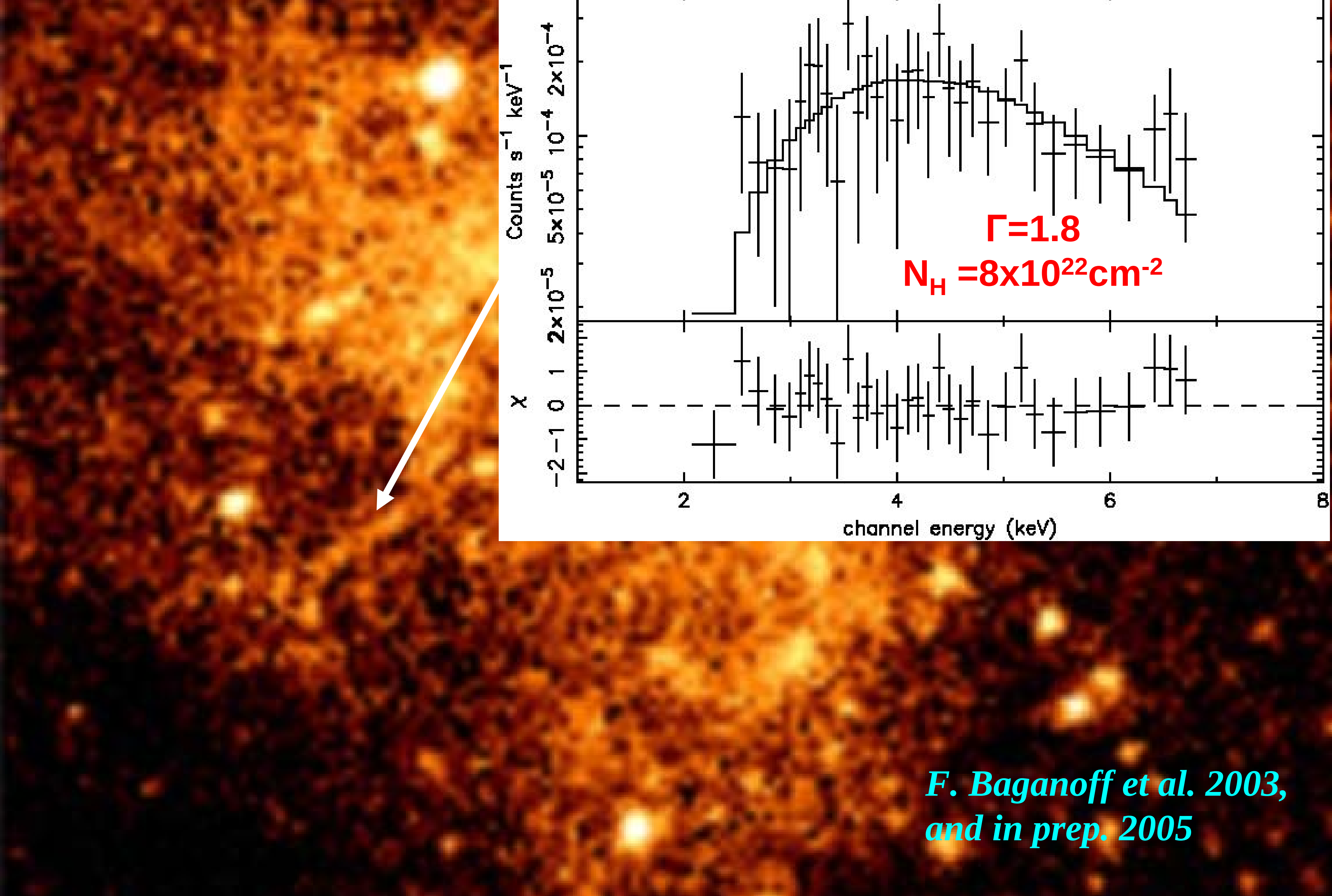




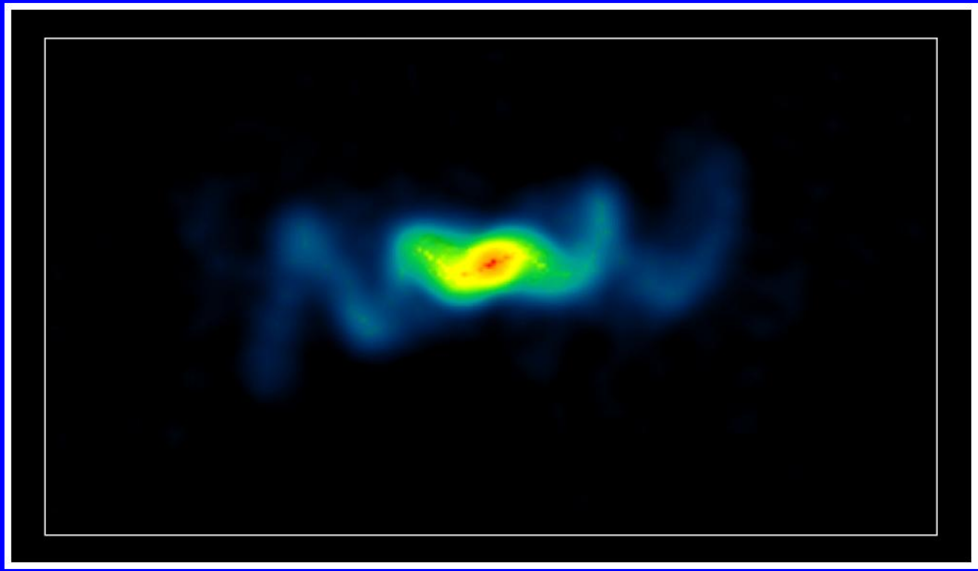
F. Baganoff et al. 2003, and in prep. 2005

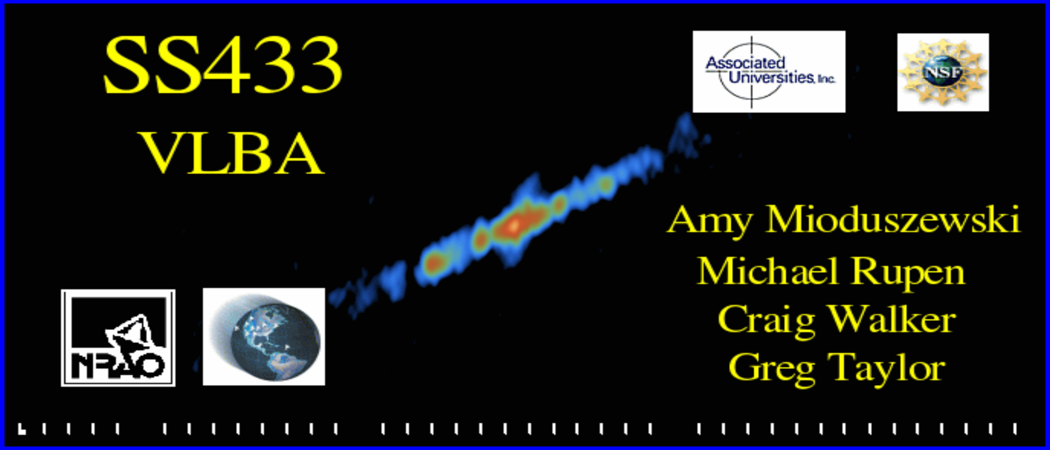
...with a hard nonthermal spectrum

SS433: Super-Eddington accretion + precessing jets

VLA, 5GHz

Blundell & Bowler 2004





Mioduszewski et al. 2004

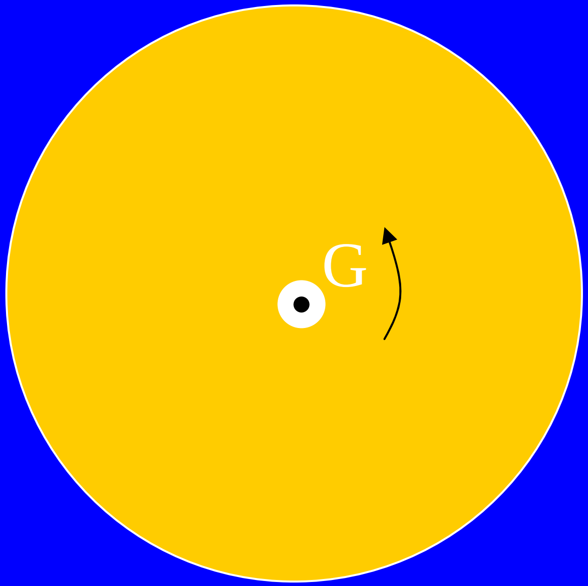
WHY ARE BLACK HOLES

SUCH FUSSY EATERS?

[CLUE: it's not just accreting black holes.... (cf. WDs, NSs, protostars)]

The culprit: Excess angular momentum, which must be transported outward... by internal torques, or winds

TORQUE TRANSPORTS ENERGY



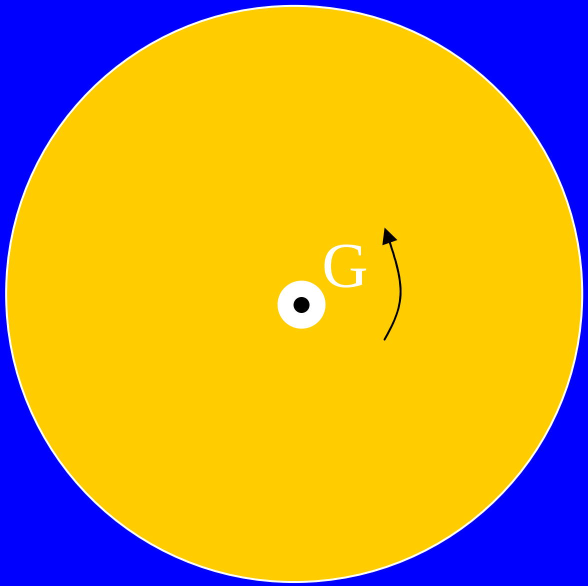
Angular Momentum Flux:

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

Energy Flux:

$G\Omega$ outward

IN A THIN ACCRETION DISK:



Local rate of energy release:

$$\dot{M}\ \frac{GM}{2\,R}$$

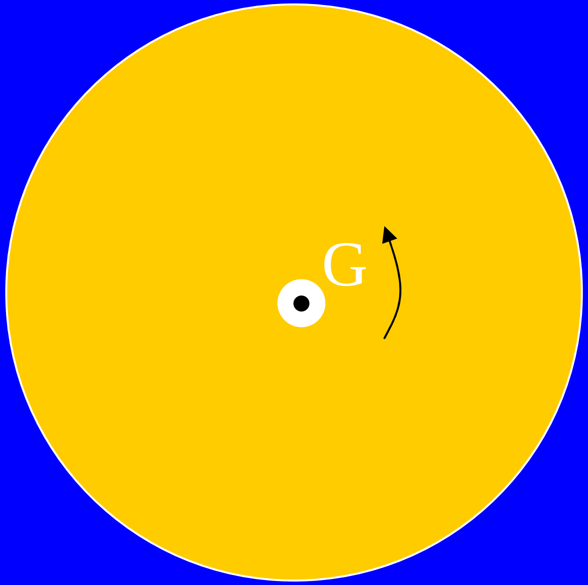
Local rate of dissipation:

$$3\times\left(\dot{M}\,\frac{GM}{2R}\right)$$

2/3 of energy dissipated at R transported from <R by viscous torque

IN A RADIATIVELY INEFFICIENT ACCRETION FLOW (RIAF):

Energy Transport:



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

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

Bernoulli Function

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

RIAFs are ***EXPLOSIVE***

1 g of gas accreting at r ~ m

can liberate 1 kg of gas at r ~ 1000 m

- **Torque a "conveyor belt" for liberated energy**
- **Flow must lose energy OR limit accretion**
  - **Mass loss or circulation**
  - **Small fraction of supplied mass reaches BH**

ADIOS = **ADIABATIC INFLOW-OUTFLOW SOLUTION** **(Blandford & Begelman 99)**

Adiabatic accretion occurs in 3 limits:

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  - gas highly opaque, radiates but photons can't escape

$$\dot{M} > \dot{M}_{Eddington}$$

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- **Low accretion rate**

If:
- **Dissipated energy goes mainly into protons**
- **Protons-electron thermal coupling weak**
  - gas is tenuous, falls into BH before radiating

$$\dot{M} < \alpha^2 \dot{M}_{Eddington}; \quad \alpha < 1$$

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- **Everything in-between?**
  - Coronae are common

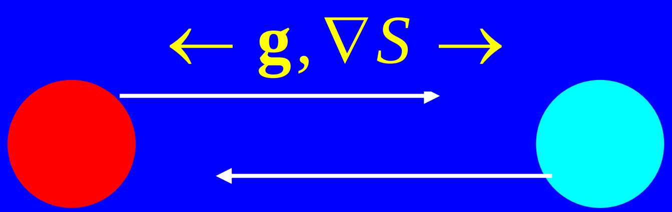
Energy argument is *generic*…

PHYSICALLY, WHAT DRIVES THE OUTFLOW or CIRCULATION?

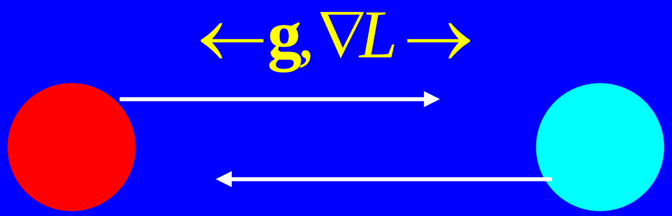
- **Candidate mechanisms:**
  - magnetic torques, flares
  - radiation pressure
  - radiative heating
- **Convection = "minimal" mechanism**
  - all else being equal, adiabatic flows must be convectively unstable

CONVECTION IN ACCRETION DISKS

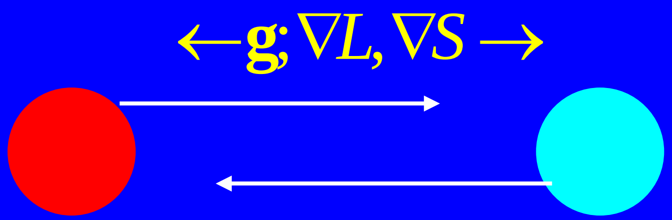
- **Entropy Gradient**
  - Schwarzschild Criterion



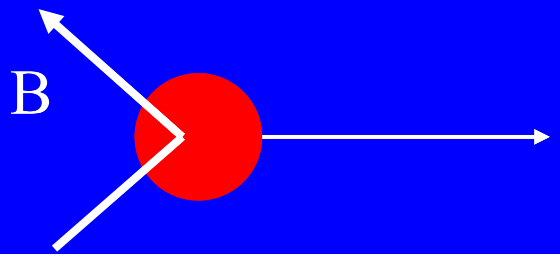
- **Ang. Mom. Gradient**
  - Rayleigh Criterion



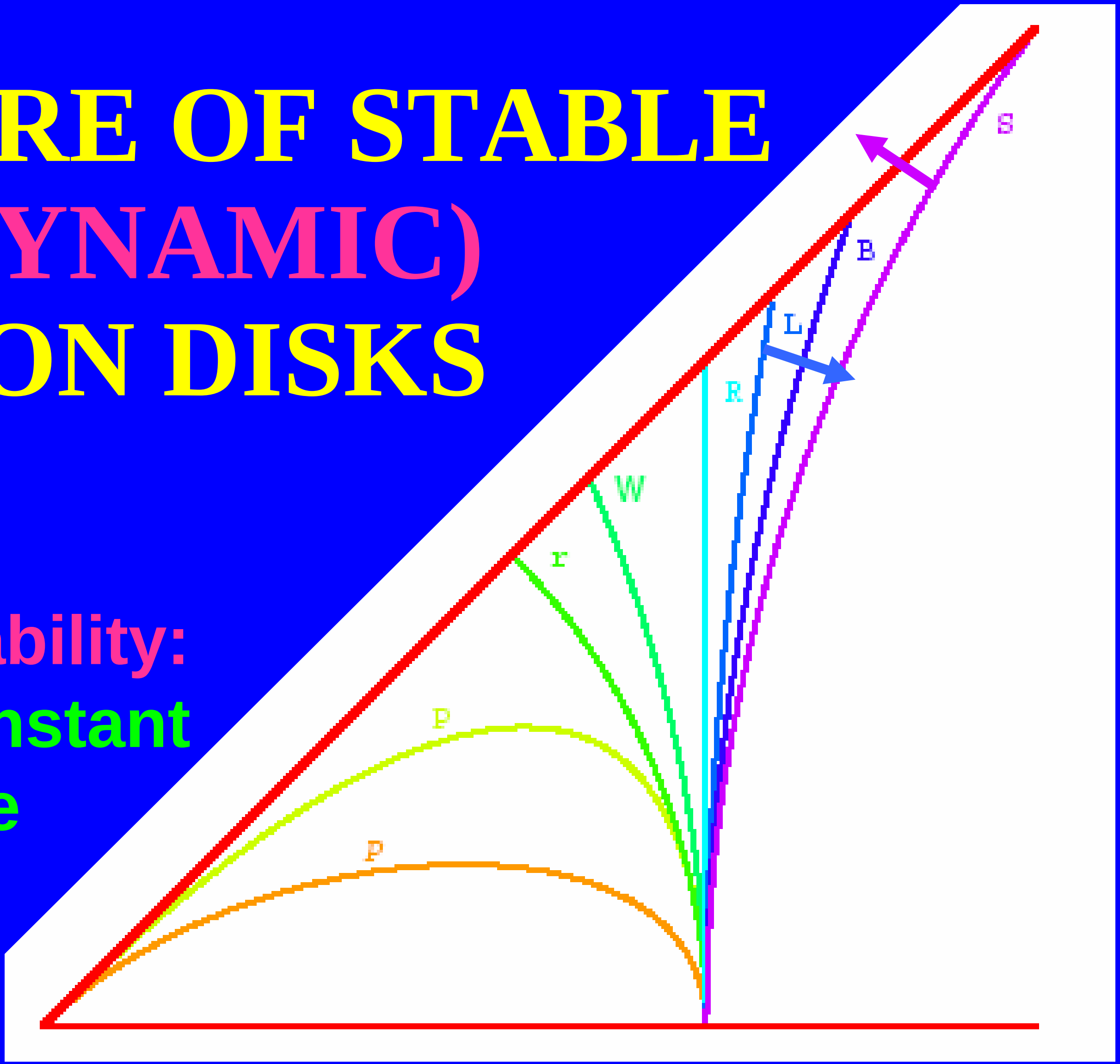
- **Both Gradients**
  - Høiland Criterion



- **MHD**
  - MRI, magnetic buoyancy



STRUCTURE OF STABLE (HYDRODYNAMIC) ACCRETION DISKS



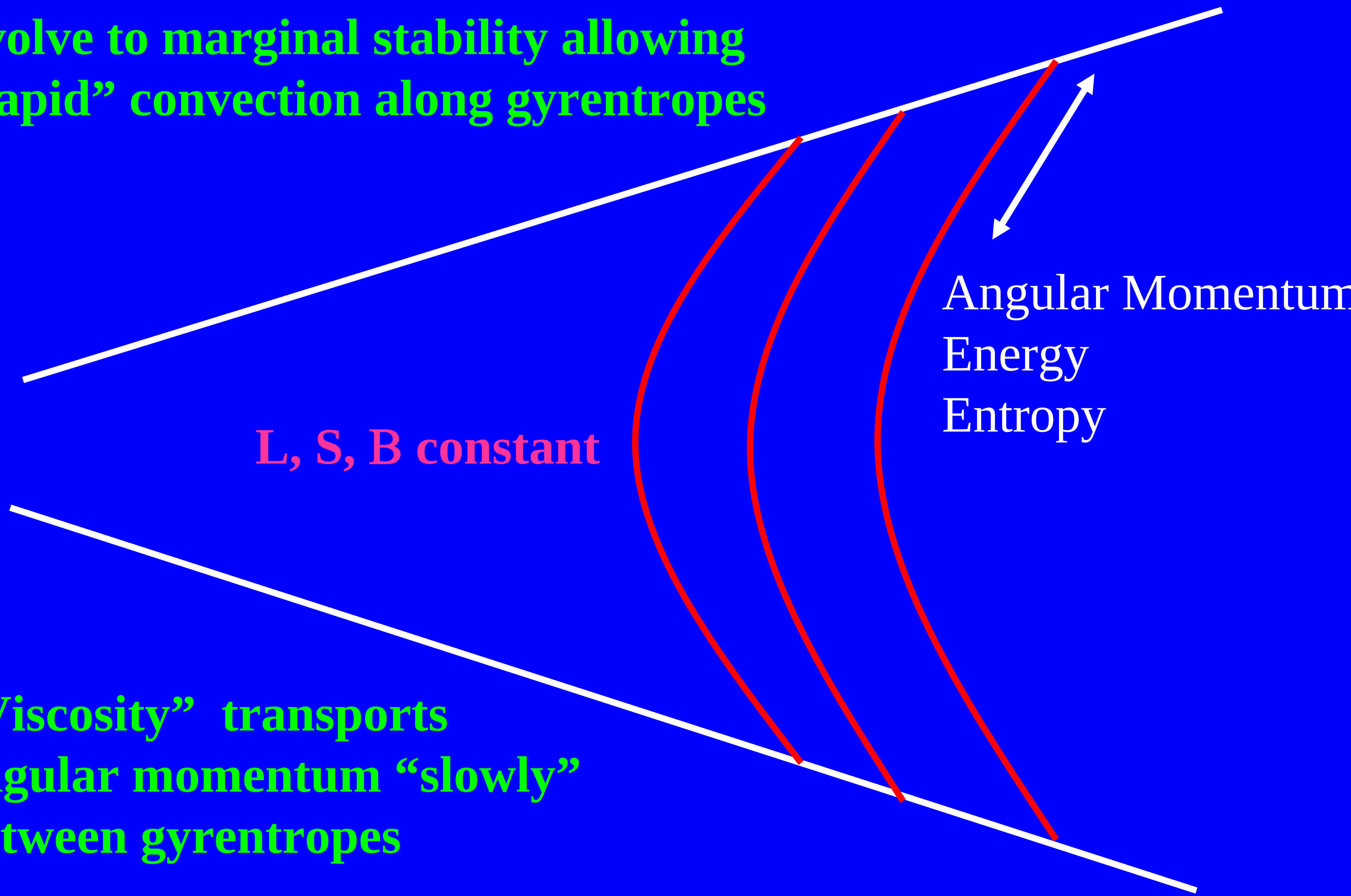
At marginal stability:

Surfaces of constant *S*, *L*, *B* coincide

Flow is "***GYRENTROPIC***"

“GYRENTROPIC HYPOTHESIS”

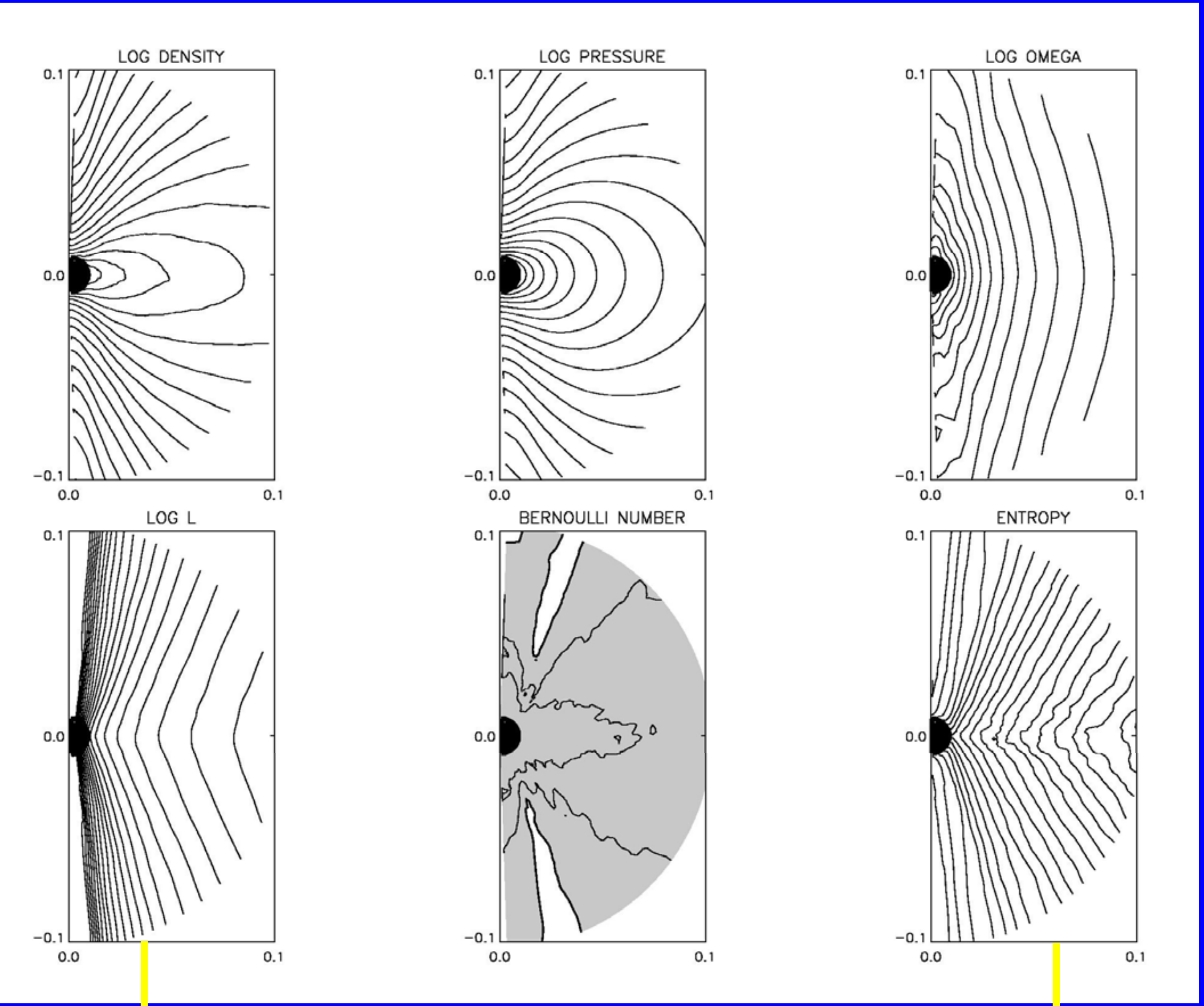
Evolve to marginal stability allowing “rapid” convection along gyrentropes



“Viscosity” transports angular momentum “slowly” between gyrentropes

2-D, adiabatic α-model

(time average)

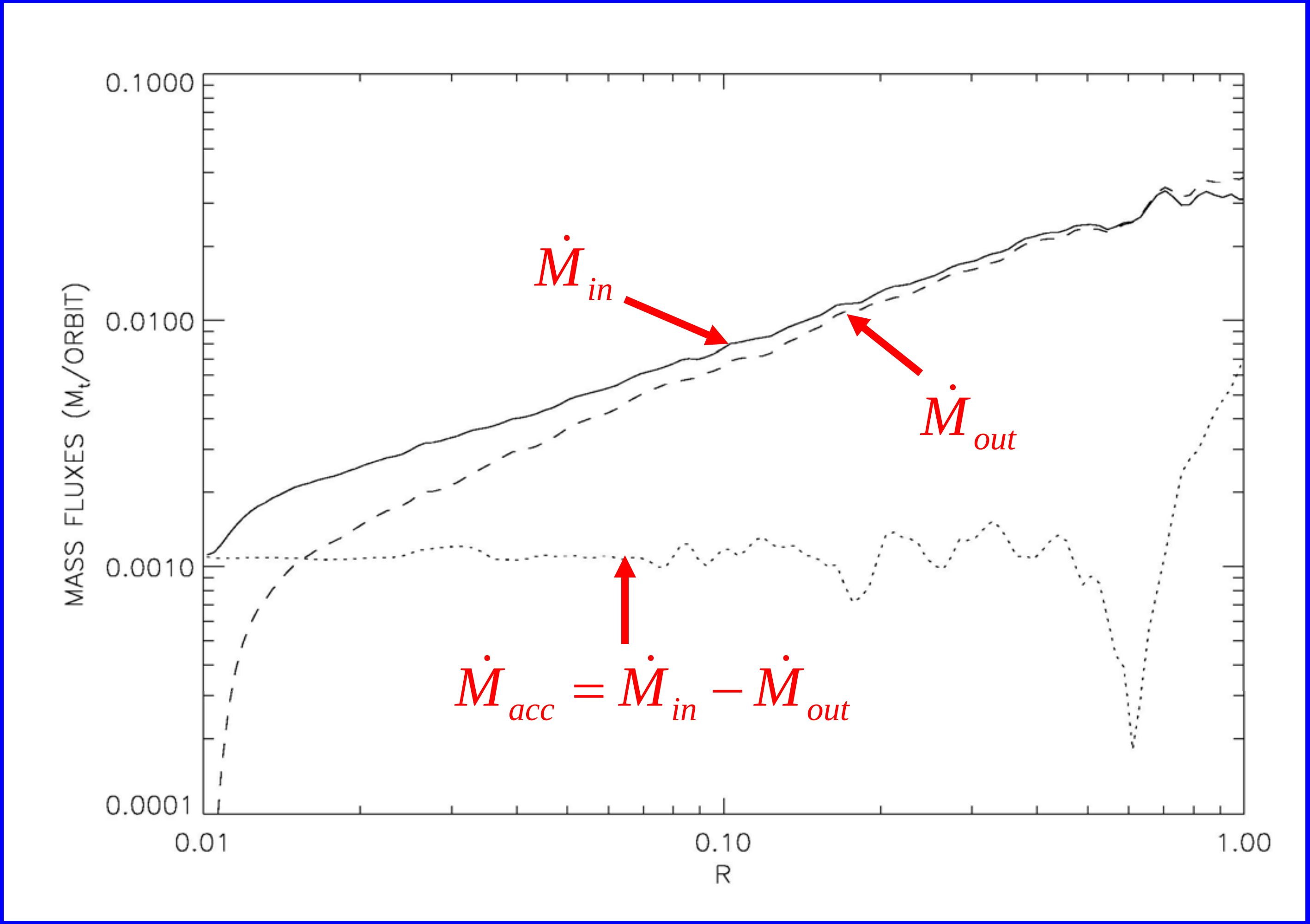


Similar L, S contours

→ **GYRENTROPIC**

SPB 99

2-D, adiabatic α-model: ADIOS



Stone, Pringle & Begelman 99

SELF-SIMILAR DISK-WIND MODEL

Disk: Viscous flow with B < 0

Entropy increases at disk-wind interface

Wind: Inviscid outflow with B < 0

Jet: Evacuated cone

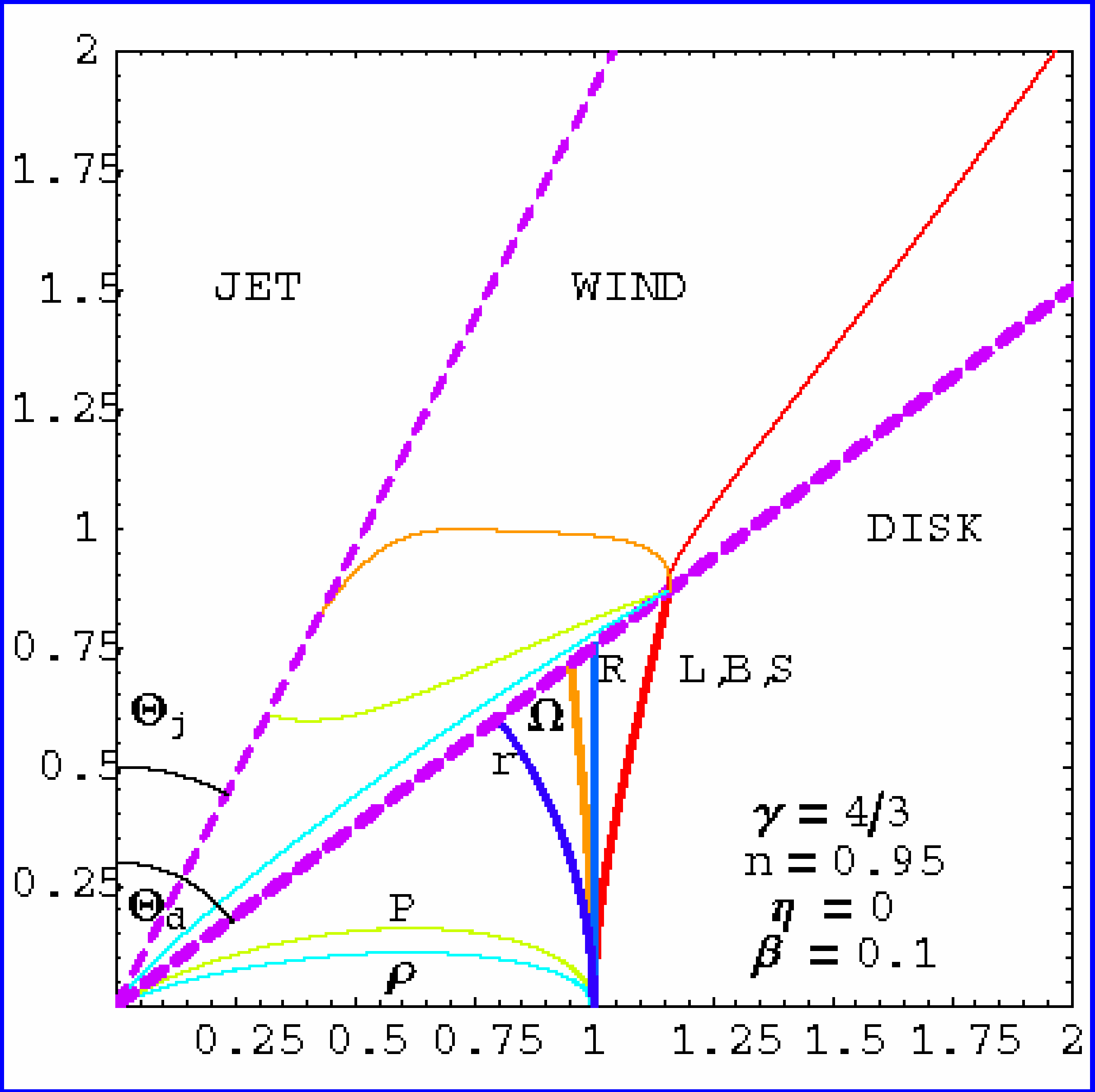
$dM/dt \sim r^{0.95}$

$P \sim r^{-1.55}$

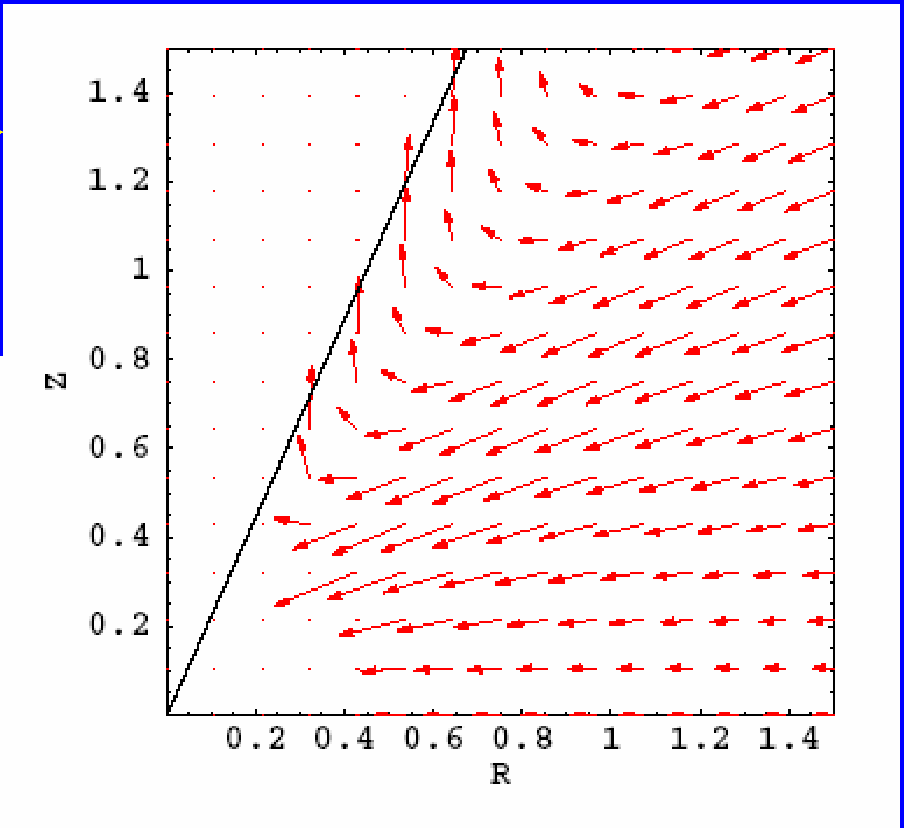
$\rho \sim r^{-0.55}$

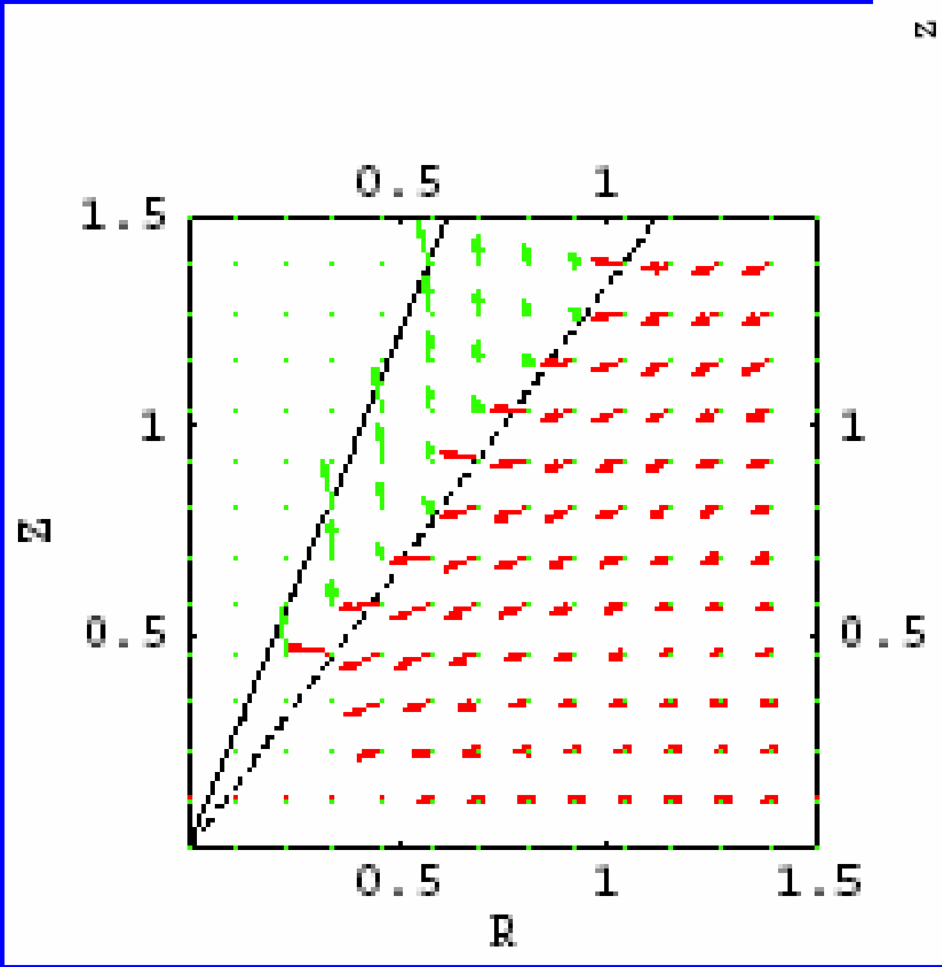
$V \sim r^{-0.5}$

Blandford & Begelman 2004



Convection drives meridional circulation...

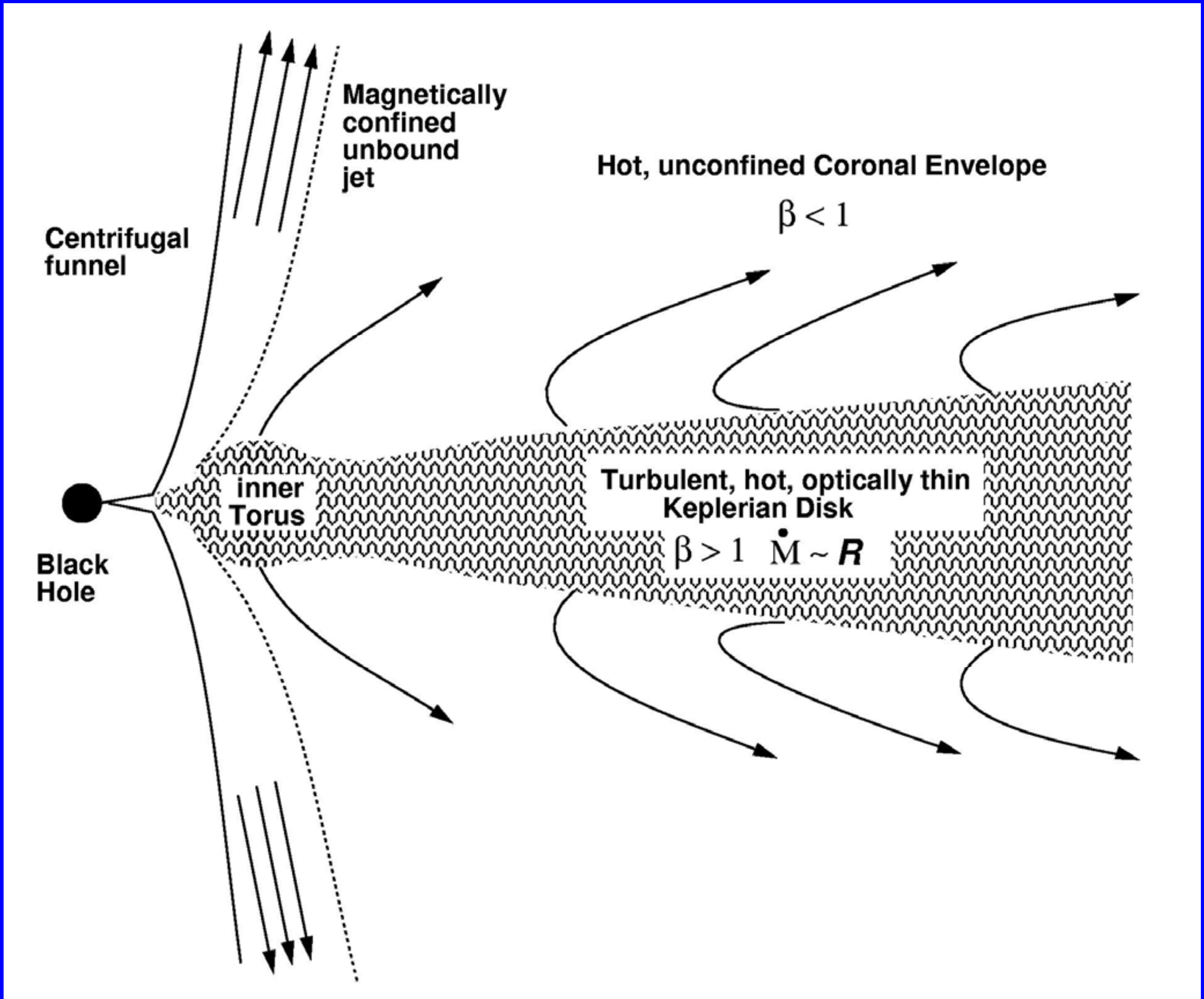




...which matches onto thermal wind

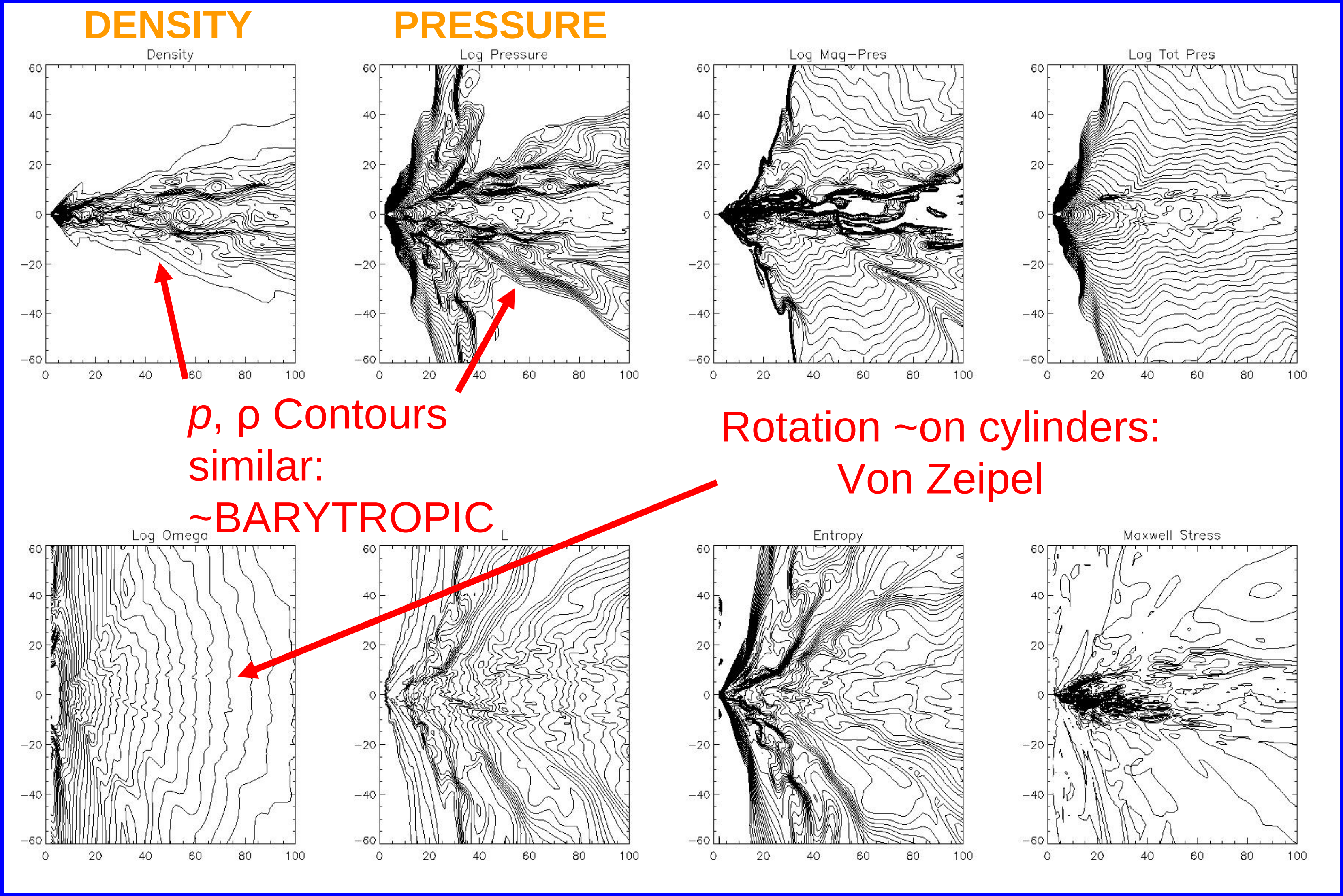
Blandford & Begelman 2004

ADIOS behavior also in MHD...



Hawley & Balbus 02

...but there are differences



Hawley, Balbus & Stone 01

3-D, adiabatic MHD model

What's Different About MHD?

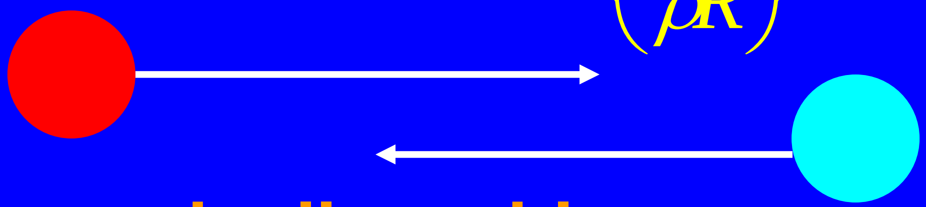
- **No marginal stability:** **always** **unstable to MRI**

  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)**

Magnetic Høiland Criterion

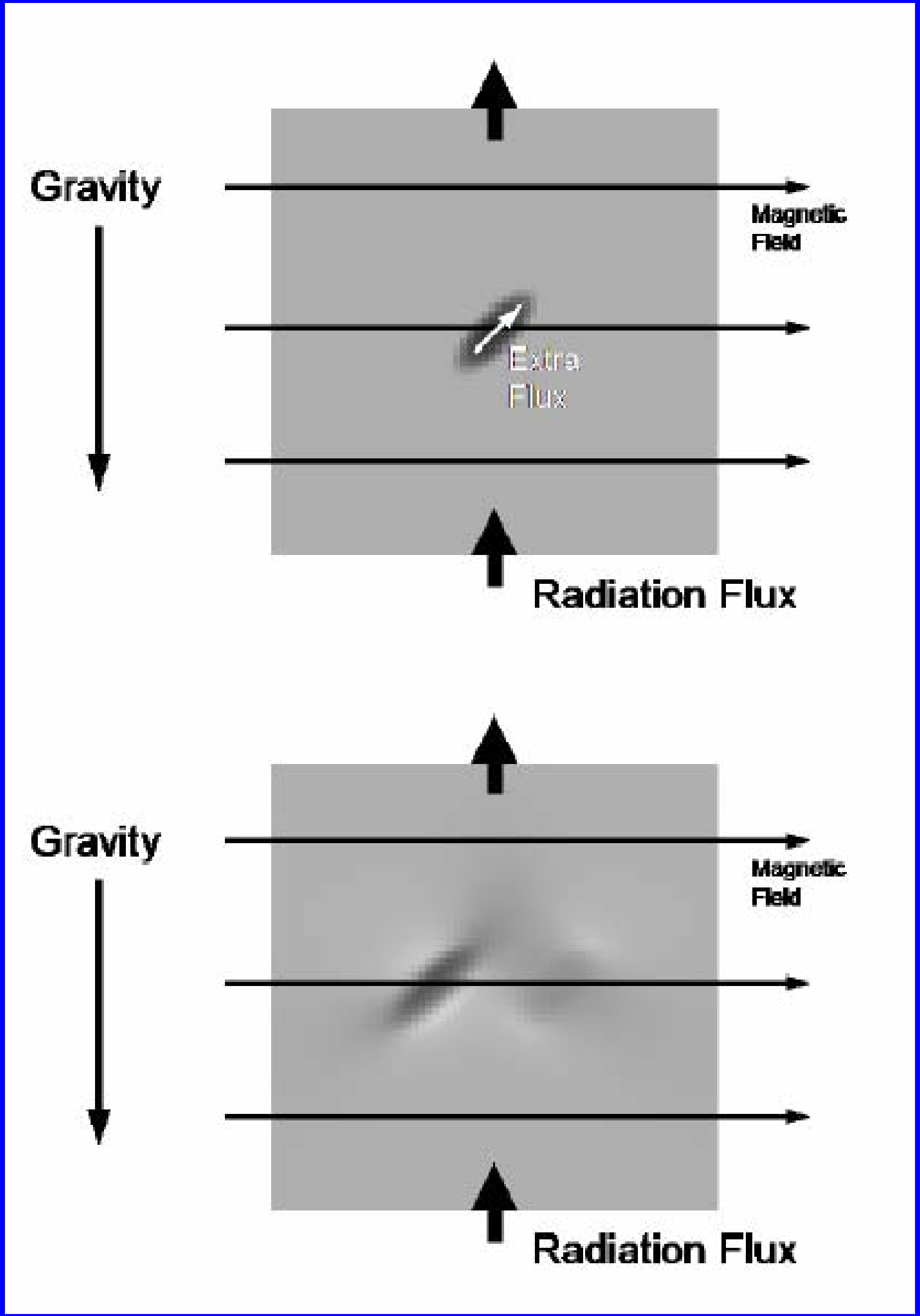
- 3 quantities to conserve

$$\leftarrow \mathbf{g};\ \nabla L,\ \nabla S,\ \nabla\left(\frac{B_\phi}{\rho R}\right) \rightarrow$$



- No unique marginally stable state
  - special case: "Campogyrentropic"
- Modest B_φ can make flow rotate on ~ cylinders
- Does magnetic convection power the outflows?

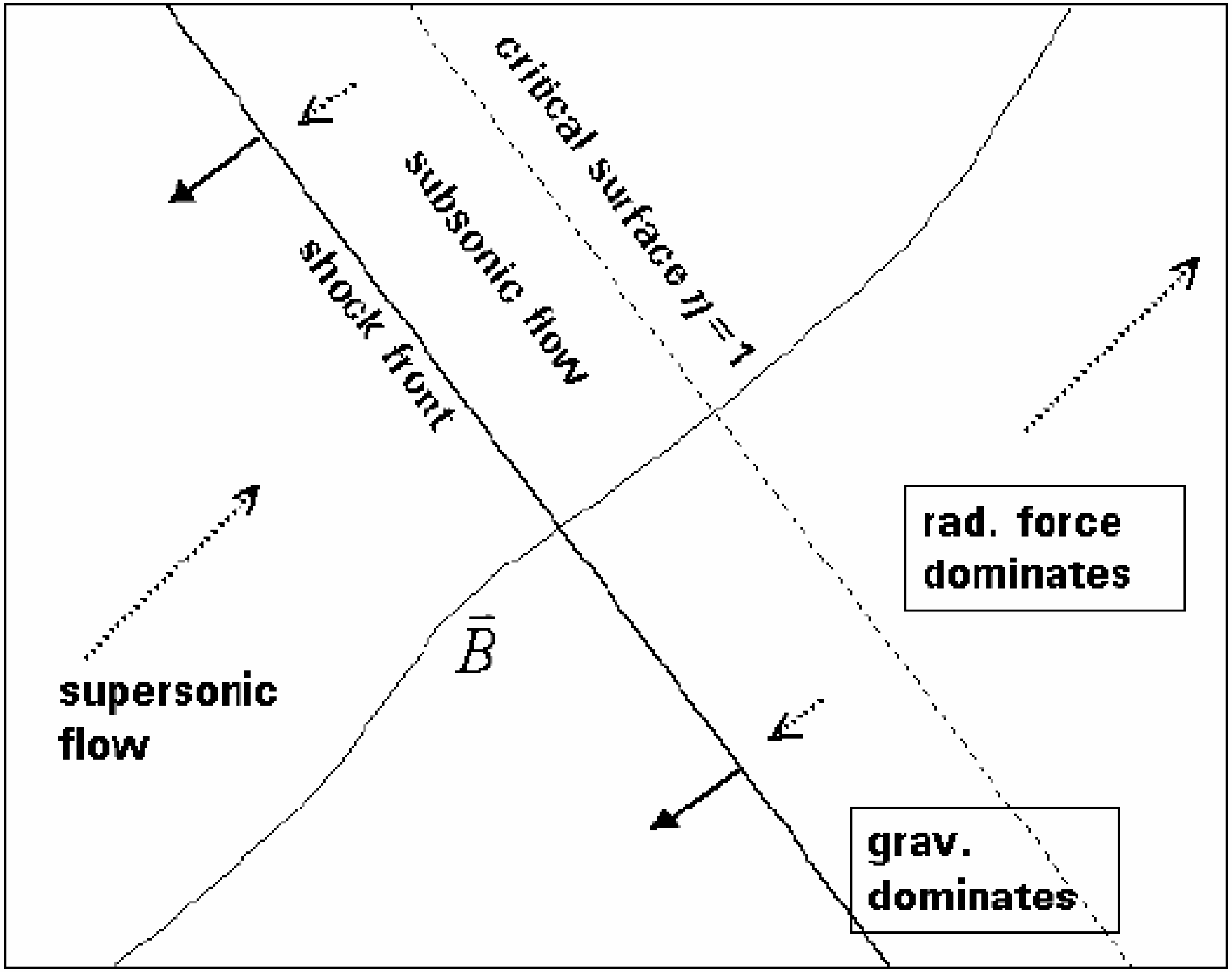
PHOTON BUBBLE INSTABILITY...



N. Turner et al. 2004

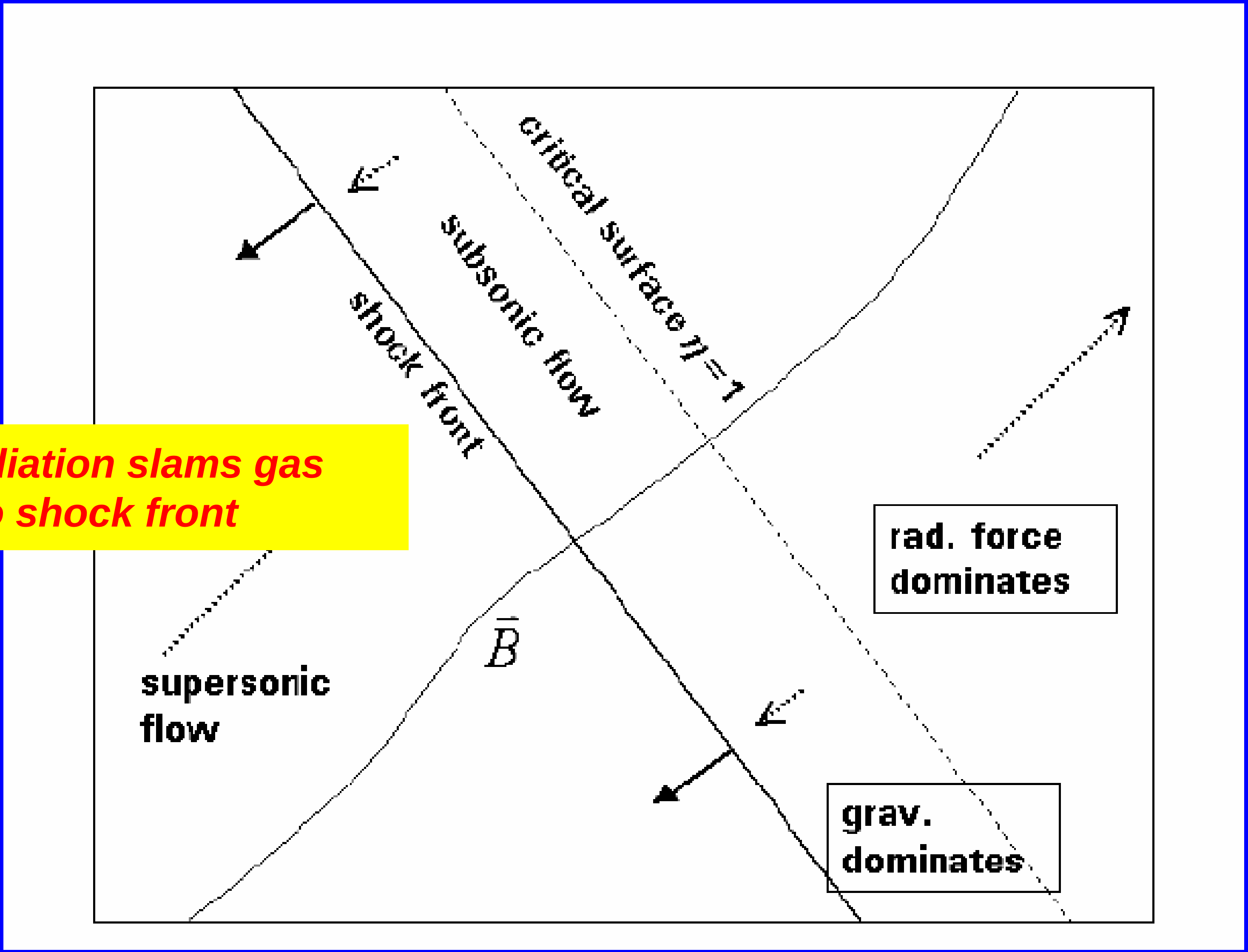
Nonlinear Evolution:

PHOTON BUBBLE SHOCK TRAINS



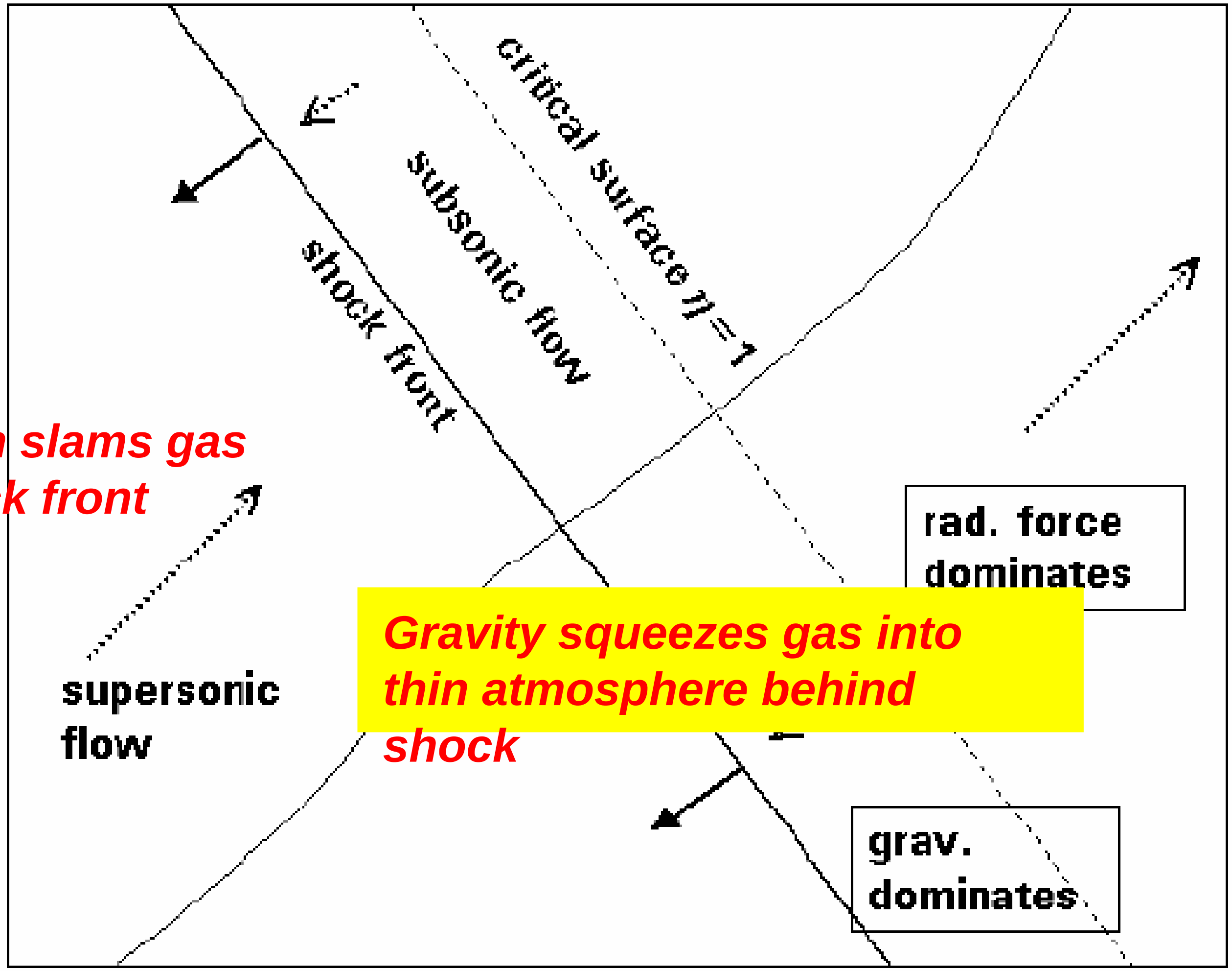
(Begelman 2001)

PHOTON BUBBLE SHOCK TRAINS



Radiation slams gas into shock front

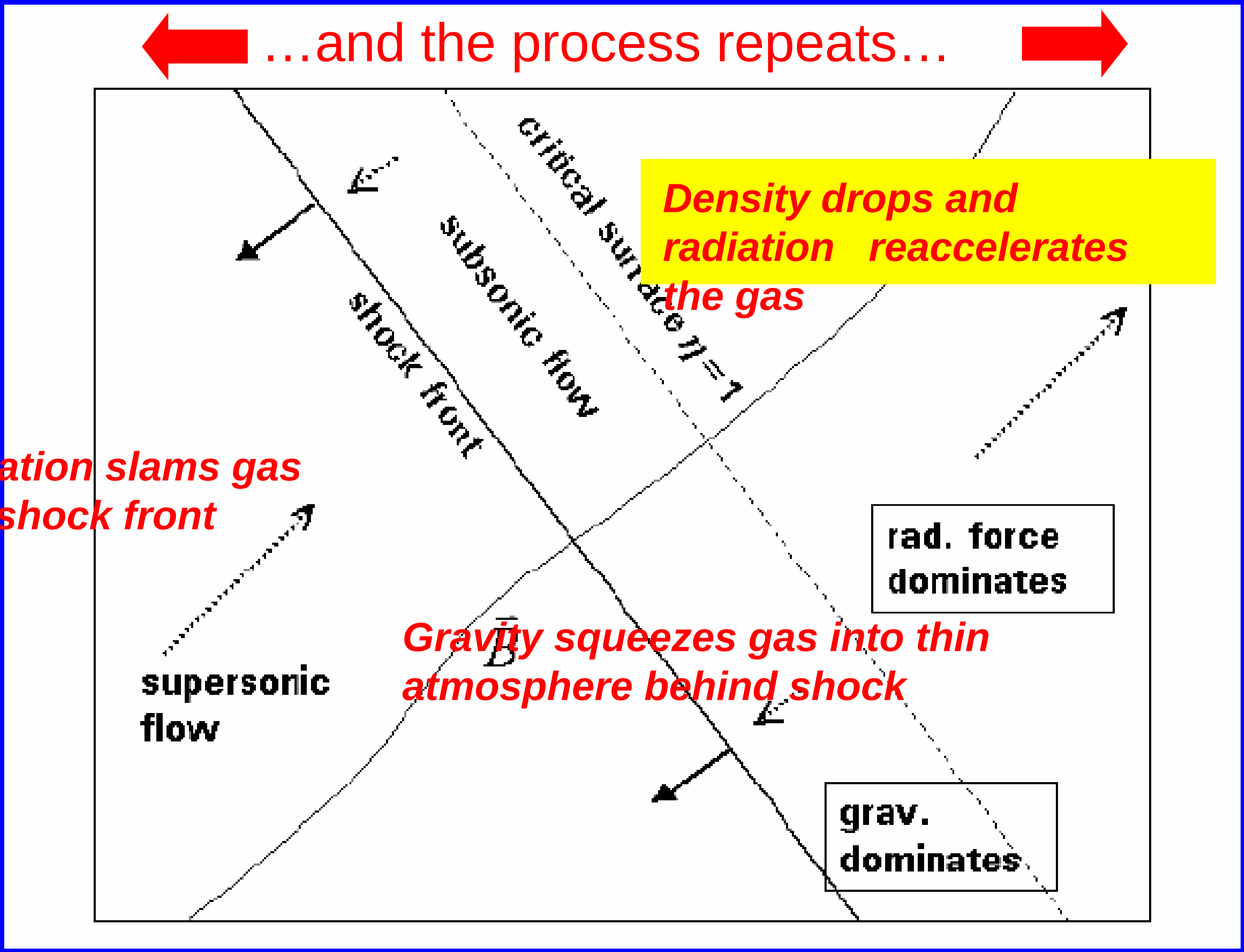
PHOTON BUBBLE SHOCK TRAINS



Radiation slams gas into shock front

Gravity squeezes gas into thin atmosphere behind shock

PHOTON BUBBLE SHOCK TRAINS



Density drops and radiation reaccelerates the gas

Radiation slams gas into shock front

Gravity squeezes gas into thin atmosphere behind shock

SUPER-EDDINGTON ACCRETION DISKS?

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

$L > L_E$ possible without blowing disk apart

Max. luminosity :

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

Near the top of the atmosphere…

- Optical depth must fall

⇨Weakens density-dependence of flux

⇨Drives strong wind if super-Eddington

…but…

- Energetics marginal for dispersing the disk (and regulating L to $\sim L_E$)
  - Requires effective radiation trapping
  - magnetically dominated corona may retain and recycle escaping gas

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