Galactic nuclei: inside from the outside

or

Dynamics of magnetized spherical accretion flows

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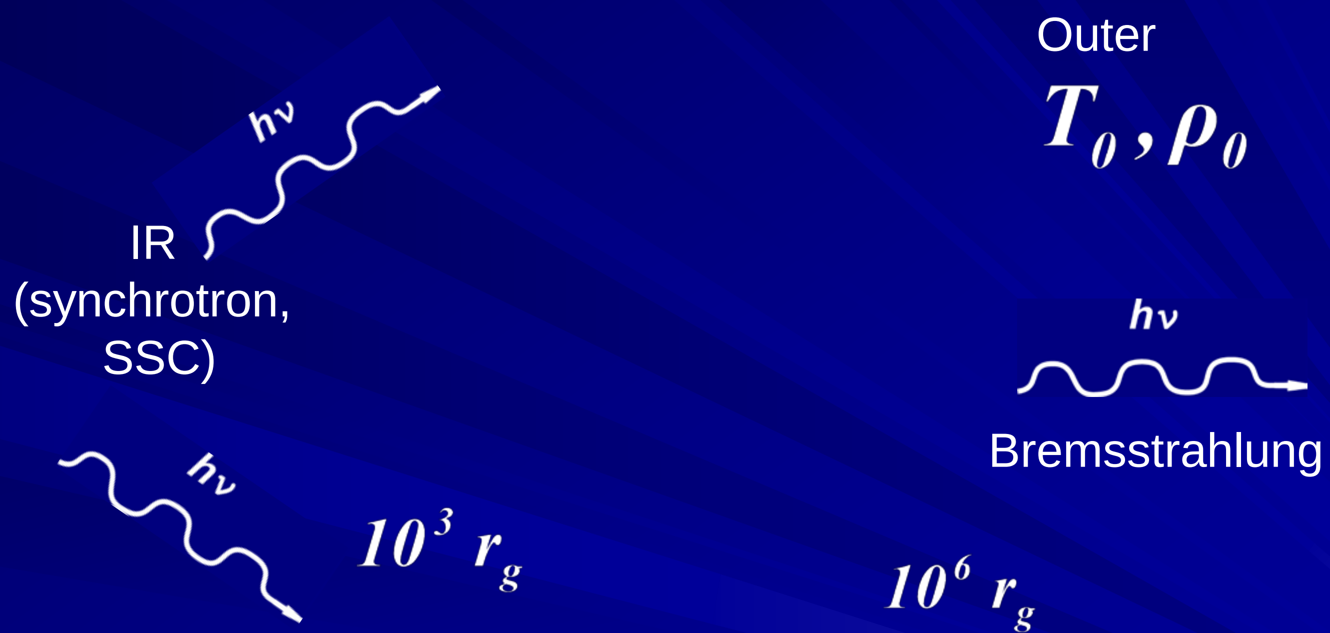
Thanks to **Ramesh Narayan**

HuangShan, China
1-7 July 2007

How accretion without cooling works

Bondi (1952) (ideal, radial, **NO** magnetic field) => Bondi accretion rate.



Sgr A*:

$$T_\infty \approx 1.5\cdot 10^7\ K,\ \rho_{e\infty} \approx 26\,cm^{-3},\ M_{BH} \approx 3.6\cdot 10^6\ M_\otimes \Rightarrow \boxed{\dot{M} \approx 4\cdot 10^{-6}\ M_\otimes year^{-1}}$$

Baganoff, 2003 Ghez 2005

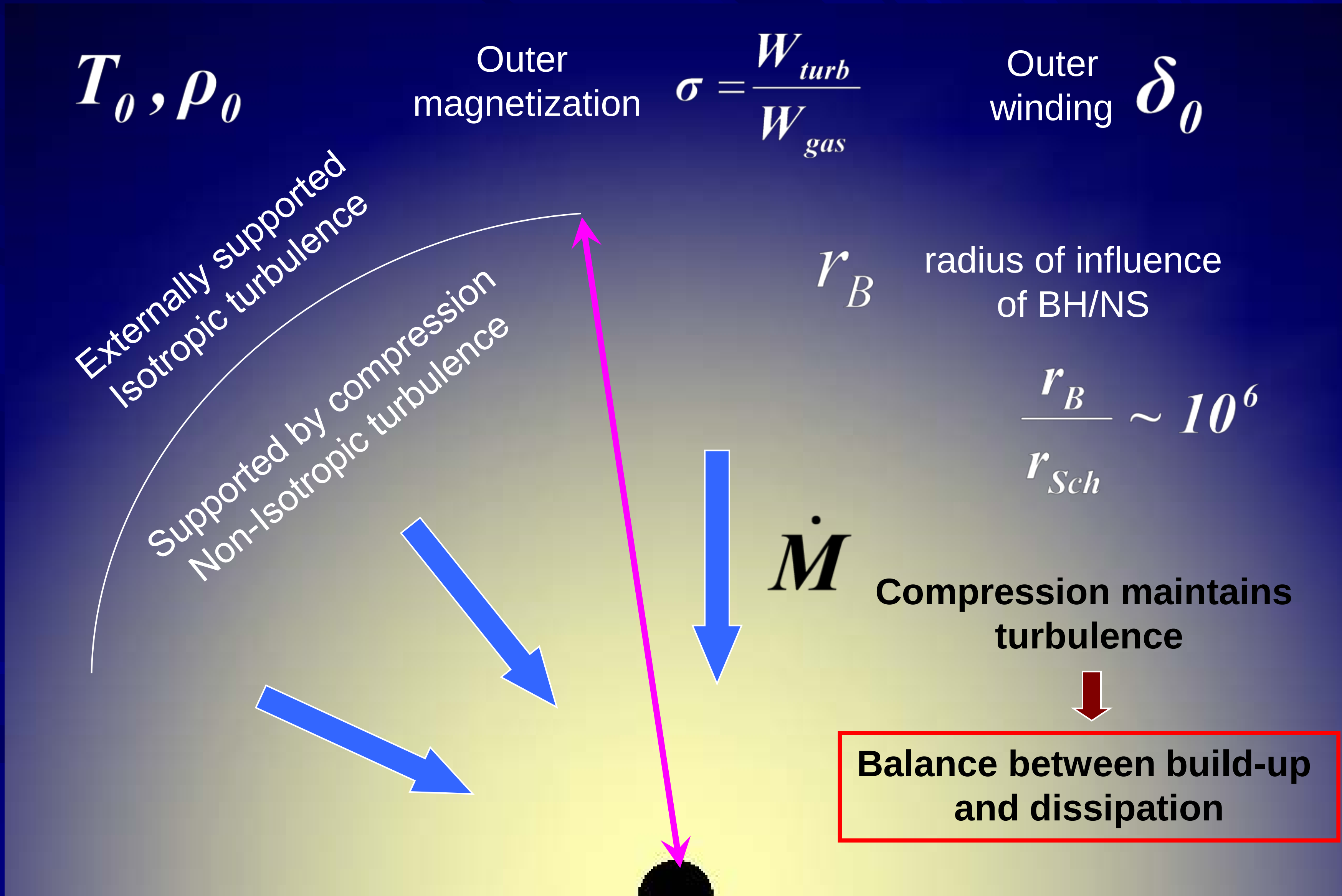
What about magnetic field?

Realistic radial accretion

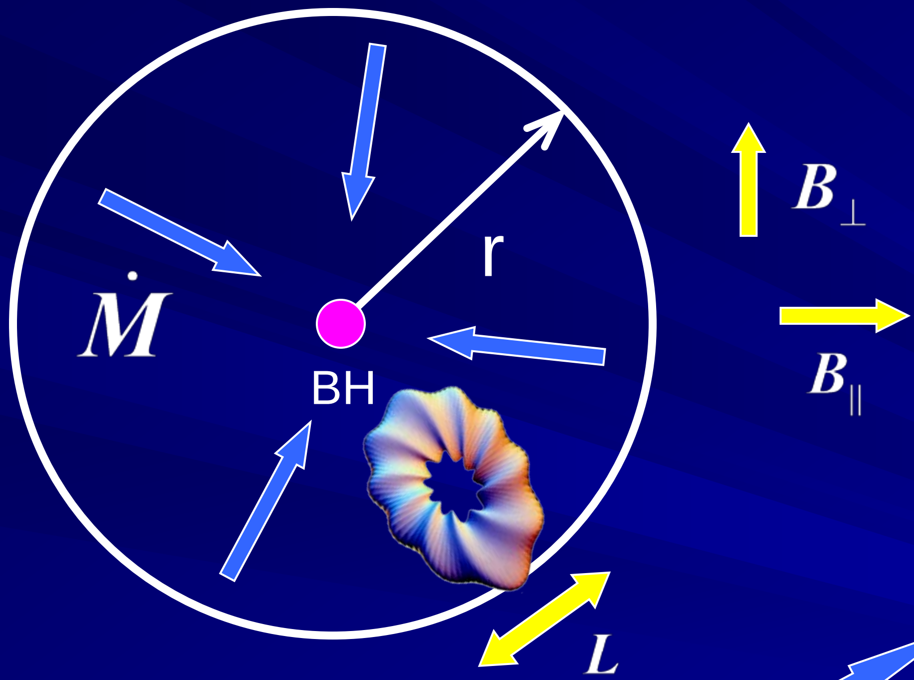
$10^6\ r_g$

Magnetically arrested flow?

Basic Scheme



What do we need to describe the flow?



- v = regular (V_{in}) + isotropic turbulent (u) velocities
- ρ – density
- T – temperature
- $B_\perp$ – perpendicular magnetic field
- $B_\parallel$ – radial magnetic field
- L – perpendicular length scale
- δ – magnetic helicity

8 functions of radius
8 equations needed

For random quantity
its characteristic value is considered,
usually $\sqrt{< Q^2 >_{angle}}$

How to include dissipation?

Magnetic field inhibits accretion (Schwartzman, 1971),

but **how much is the effect**?

No dissipation → No matter inflow

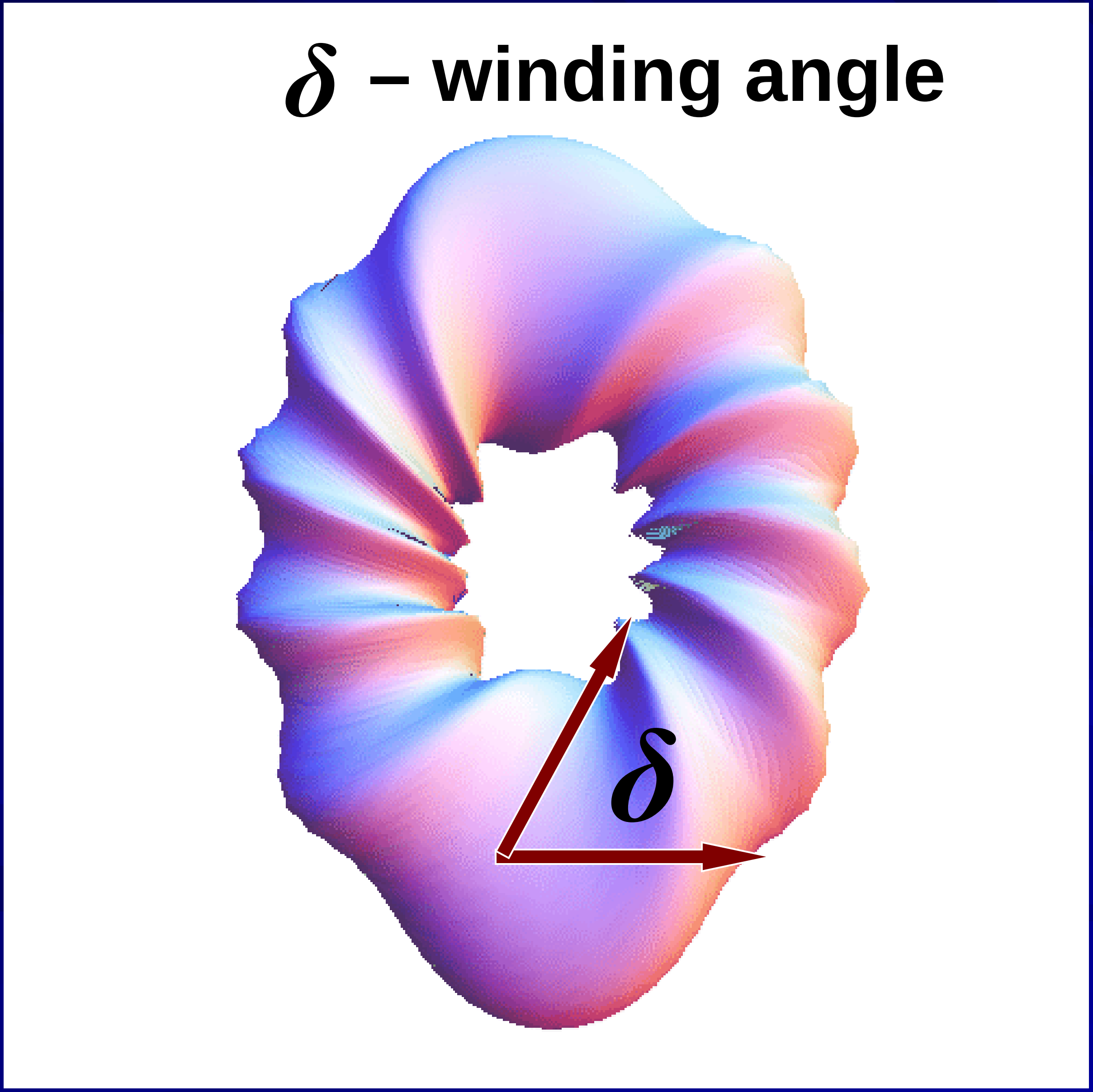
No theory available → Use other (simple) numerical simulations

The better we correspond to the experiment, the more reliable the result is.

Dissipation of hydrodynamic turbulence	Dissipation of MHD turbulence	Dynamo action
Sreenivasan, 1995	Biskamp, 2003	Shchekochihin,2004

+ phenomenological magnetic helicity conservation

Flux tubes



Self-part of magnetic helicity

$$\boxed{H = \pm N \cdot \Phi^2}$$

Biskamp, 2000

Energy decay

$$\frac{dW}{dt} = -\eta_M \int \vec{j}^{\,2} d^3x$$

Magnetic helicity decay

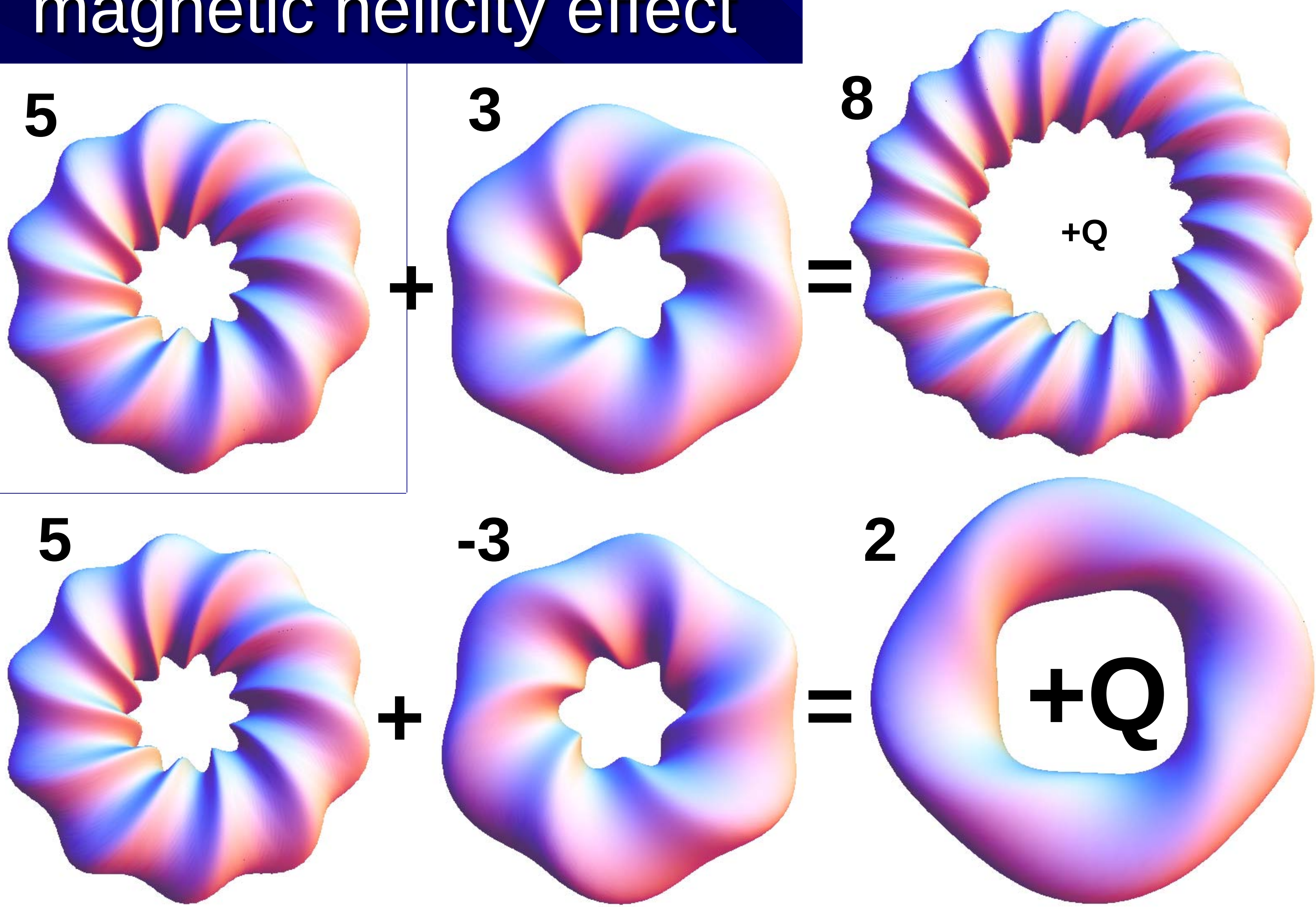
$$\frac{dH}{dt} = -\eta_M \int \vec{j} \cdot \vec{B} d^3x$$

In current sheets $j \rightarrow \infty$

$$\boxed{\frac{dH}{H} \sim \frac{\eta_M}{\eta_{turb}} \frac{dW}{W} << \frac{dW}{W}}$$

Biskamp, 2003

Interactions of flux tubes magnetic helicity effect



Equations

1D (radial) equations on $V_{in}, \rho, T, B_\perp^2, B_\parallel^2, u^2, L, \delta$

$\rho V_{in} r^2 = const$ $\dot{M}$ mass flux (+1)

momentum and energy fluxes (+2)

Angular averaged ideal MHD

$$V_{in}V'_{in} + \frac{r_g c^2}{2(r-r_g)^2} + \frac{R}{\mu}\frac{(\rho T)'}{\rho} + \frac{(\rho u^2)'}{3\rho} + \frac{(r^2 B_\perp^2)'}{4\pi\rho r^2} - \frac{(r^4 B_\parallel^2)'}{8\pi\rho r^4} = 0$$

$$V_{in}w'_{in} + w + \frac{r_g c^2}{2(r-r_g)^2} + 4V_{A\perp}V_{A\perp}' = 0$$

$L = const\ (at\ r >> r_B)$, $L = \gamma r\ (at\ r << r_B)$ and

$$L = \gamma r\left(\exp\left(-\frac{2r}{r_B}\right) + \left(1-\exp\left(-\frac{r}{r_B}\right)\right)\right)$$

Magnetic helicity conservation

$$\tan\delta = \tan\delta_\infty \frac{L^2 V_{A\parallel\infty}^2 + 2V_{A\perp\infty}^2}{L_\infty^2 V_{A\parallel}^2 + 2V_{A\perp}^2}$$

length scale and winding angle (+2)

$$(B_\parallel^2)' = -4\frac{B_\parallel^2}{r} + \frac{c_{BB}B_\parallel^2 V_{A\parallel}\exp(-\tan\delta) - c_{Bu}(B_\parallel^2 + 2B_\perp^2)u}{V_{in}L} - \frac{\rho c_{11}}{V_{in}L_\infty}\left(\frac{\beta R T_\infty}{\mu}\right)^{3/2}$$

$$(B_\perp^2)' = -2B_\perp^2\frac{(V_{in}r)'}{V_{in}r} + \frac{c_{BB}B_\perp^2 V_{A\perp}\exp(-\tan\delta) - c_{Bu}(B_\parallel^2 + 2B_\perp^2)u}{V_{in}L} - \frac{\rho c_{22}}{V_{in}L_\infty}\left(\frac{\beta R T_\infty}{\mu}\right)^{3/2}$$

$$(u^2)' = -\frac{2}{3}\frac{2u^2}{r} + \frac{c_{uu}u^3 - c_{uB}(V_{A\parallel}^3 + 2V_{A\perp}^3)\exp(-\tan\delta)}{V_{in}L} - \frac{c_{00}}{V_{in}L_\infty}\left(\frac{\beta R T_\infty}{\mu}\right)^{3/2}$$

- ➢Small external isotropic energy input
- ➢Freezing-in amplification of turbulence
- ➢Empiric energy dissipation
- ➢Correspondence to simulations

evolution of turbulence (+3),

$$(\ldots)' \Leftrightarrow \frac{d(\ldots)}{dr}$$

$\boxed{\text{Search for maximum } \dot{M}}$

Evolution of turbulence

$$\frac{\partial \overline{B}}{\partial t} = \nabla \times (\overline{V} \times \overline{B}) + \nu_M \Delta \overline{B}$$

$$< (\dots \cdot \overline{B}) >_{average\ over\ angle}$$

$B_k \sim k^{-5/3}$ + numerical simulations

$$\frac{dB^2}{dr} = freezing' in + dynamo + dissipation$$

Similar procedure for random velocity

Radial/perpendicular splitting

$$(B_\parallel^2)' = -4\frac{B_\parallel^2}{r} + \frac{c_{BB} B_\parallel^2 V_{A\parallel} exp(-\tan\delta) - c_{Bu}(B_\parallel^2 + 2B_\perp^2)u}{V_{in} L} - \frac{\rho c_{11}}{V_{in} L_\infty}\left(\frac{\beta R T_\infty}{\mu}\right)^{3/2}$$

$$(B_\perp^2)' = -2B_\parallel^2 \frac{(V_{in} r)'}{V_{in} r} + \frac{c_{BB} B_\perp^2 V_{A\perp} exp(-\tan\delta) - c_{Bu}(B_\parallel^2 + 2B_\perp^2)u}{V_{in} L} - \frac{\rho c_{22}}{V_{in} L_\infty}\left(\frac{\beta R T_\infty}{\mu}\right)^{3/2}$$

$$(u^2)' = -\frac{2}{3}\frac{2u^2}{r} + \frac{c_{uu} u^3 - c_{uB}(V_{A\parallel}^3 + 2V_{A\perp}^3) exp(-\tan\delta)}{V_{in} L} - \frac{c_{00}}{V_{in} L_\infty}\left(\frac{\beta R T_\infty}{\mu}\right)^{3/2}$$

Why averaged MHD?

Numerical simulations are resource-intensive

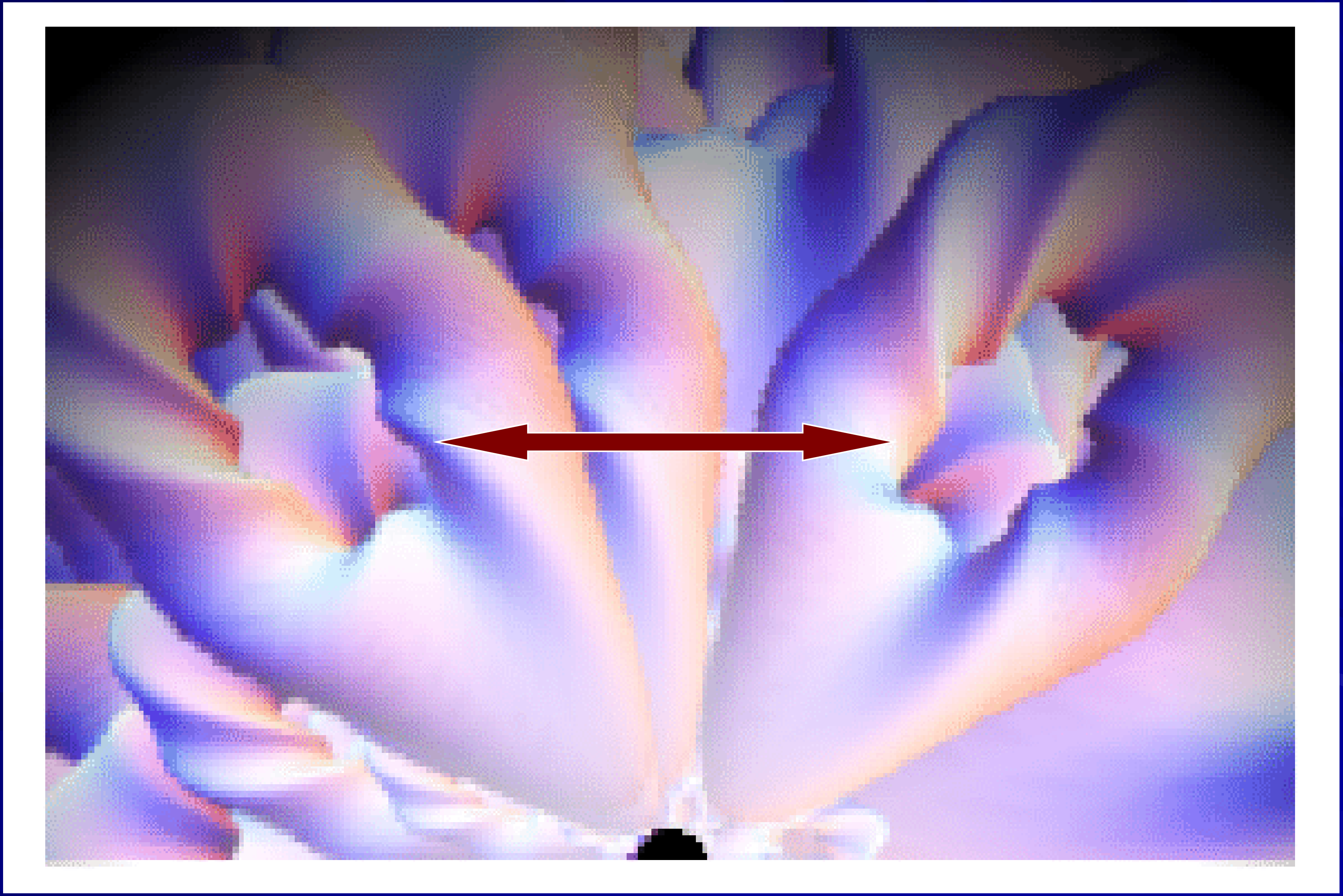
Need Re>500

But who gives a supercomputer…
to a grad student?

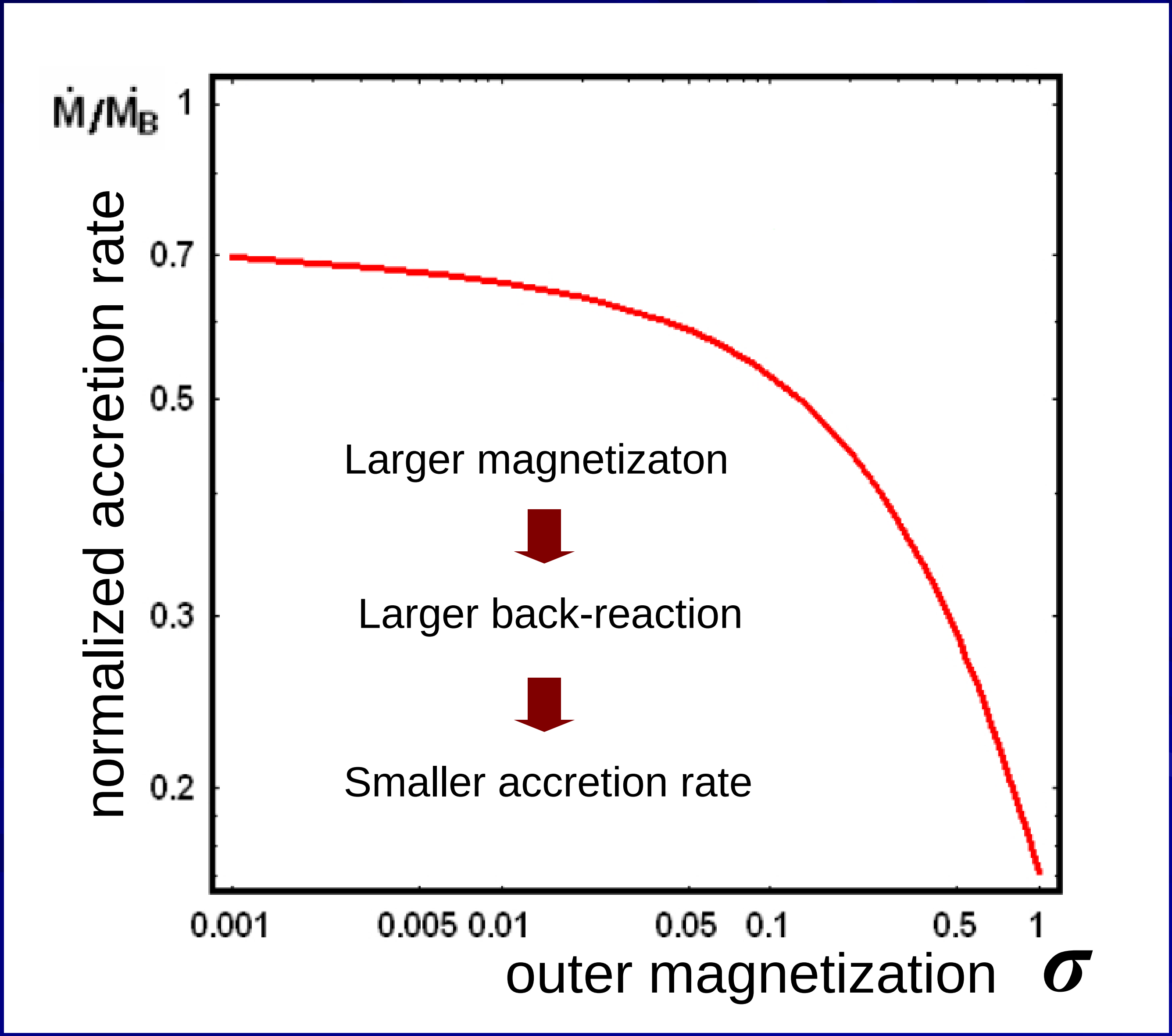
Instead in my approach

☺

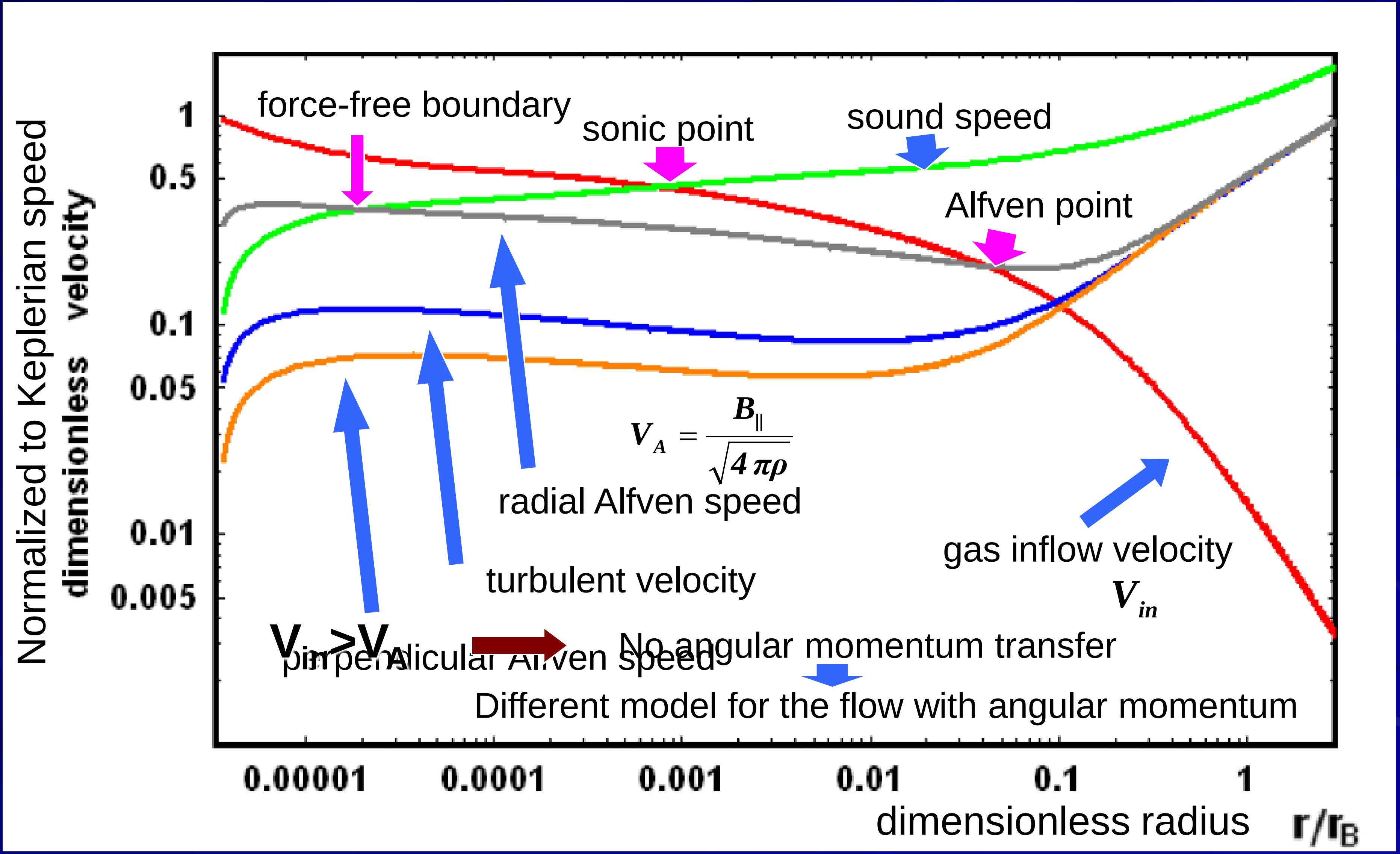
Flux tube accretion, perpendicular diffusion



Results. Accretion rate

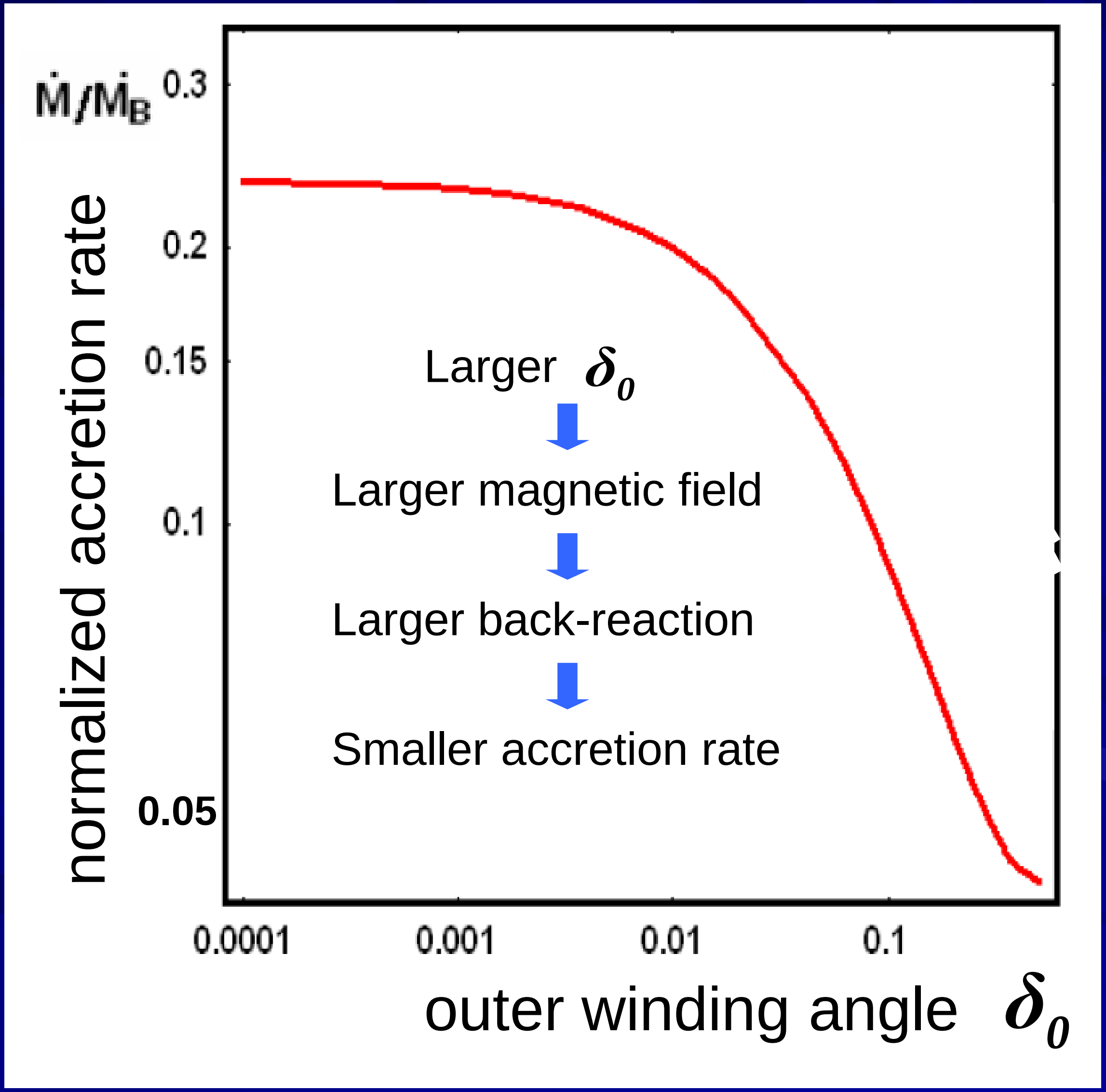


Results. Velocities

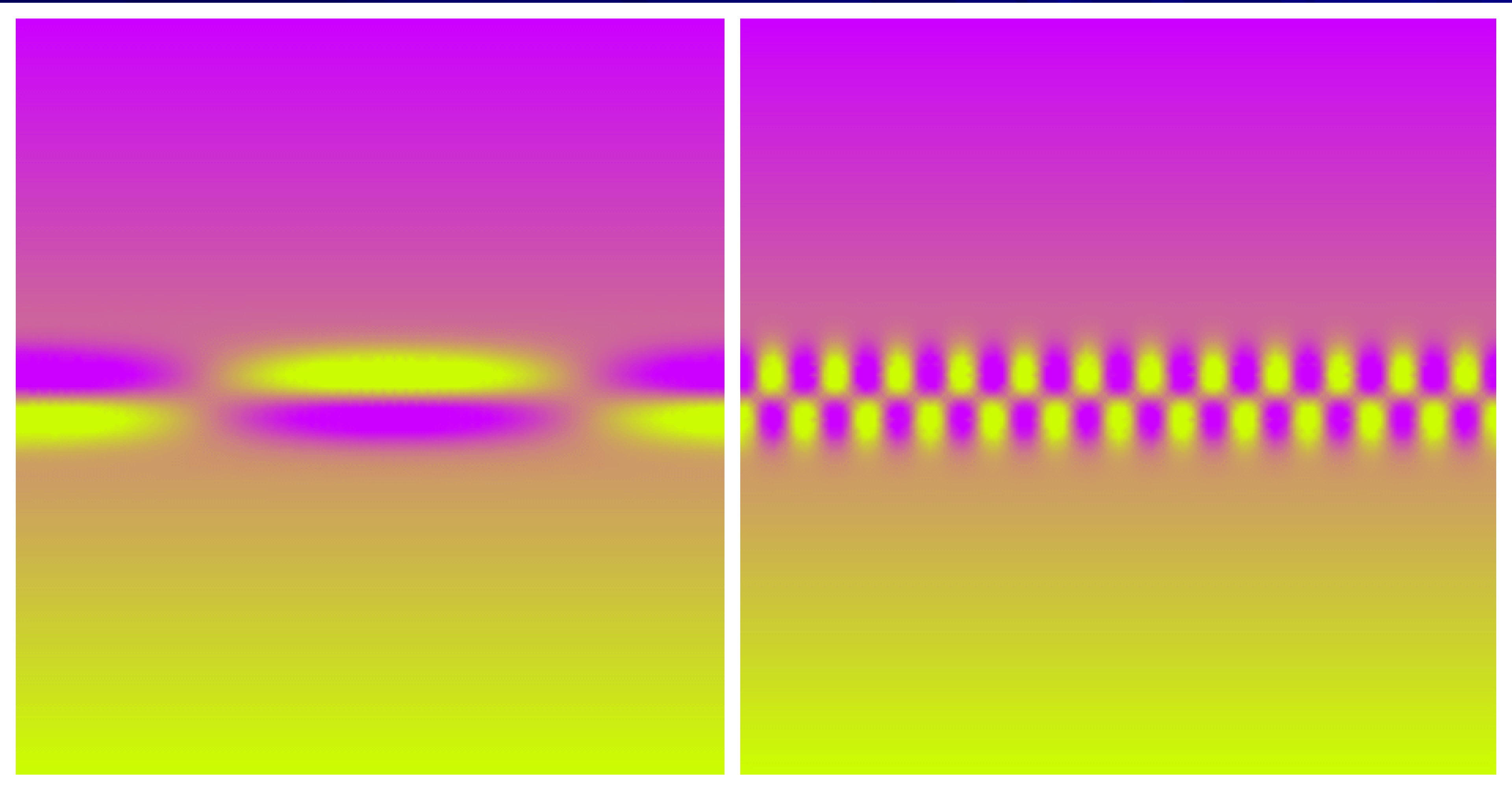


Accretion rate vs. winding angle

No angular momentum

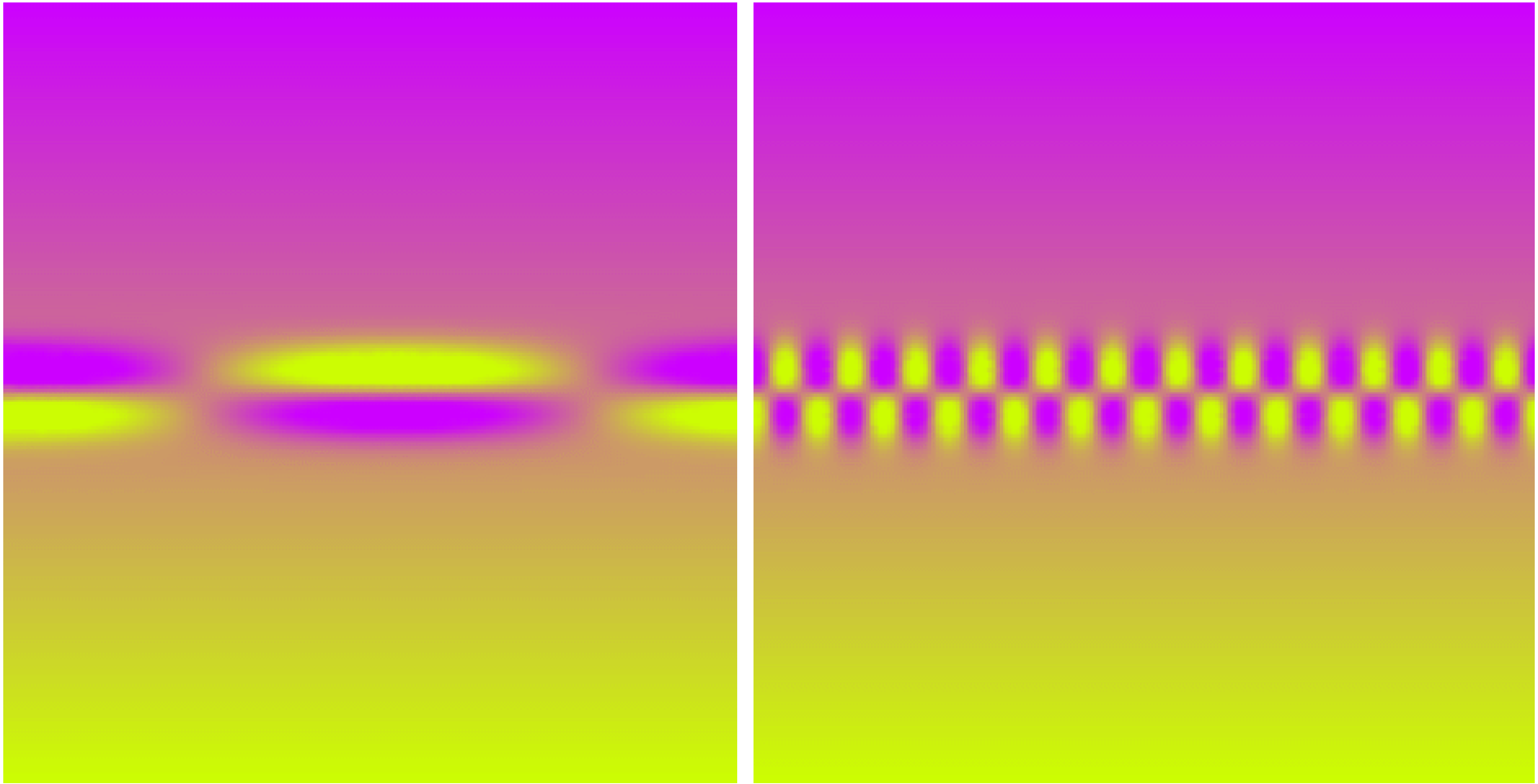


Convection, no diffusion.



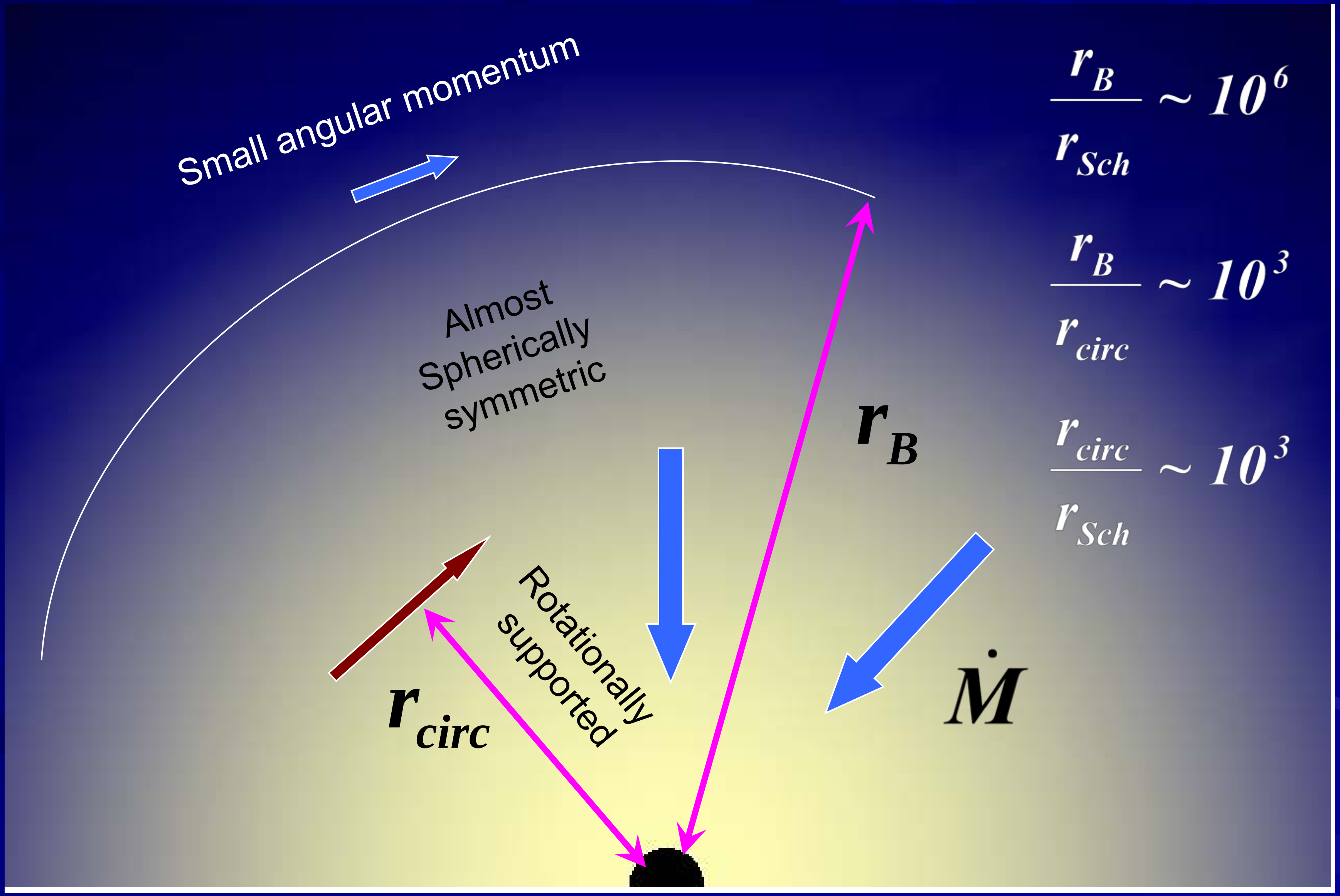
Effectiveness is almost independent on scale

Convection, diffusion is on.



Only large scale perturbations survive

Case with angular momentum



Conclusions

- Averaged MHD approach (approximately) works
  isotropic case corresponds to simulations

- Accretion rate is much lower, than without magnetic field
  2-5 times without angular momentum $\boxed{10^{-6}\ M_{\otimes}\, year^{-1}}$ Sgr A*
  another 4 times lower with high magnetic helicity
  (preliminary) about $\boxed{10^{-7}\ M_{\otimes}\, year^{-1}}$ for $R_{circ} = (1 \div 5) \cdot 10^{3}\ R_{Sch}$

- Subequipartition magnetic field

- Convection and diffusion should be accounted for together
  only large scale approach works

More results soon