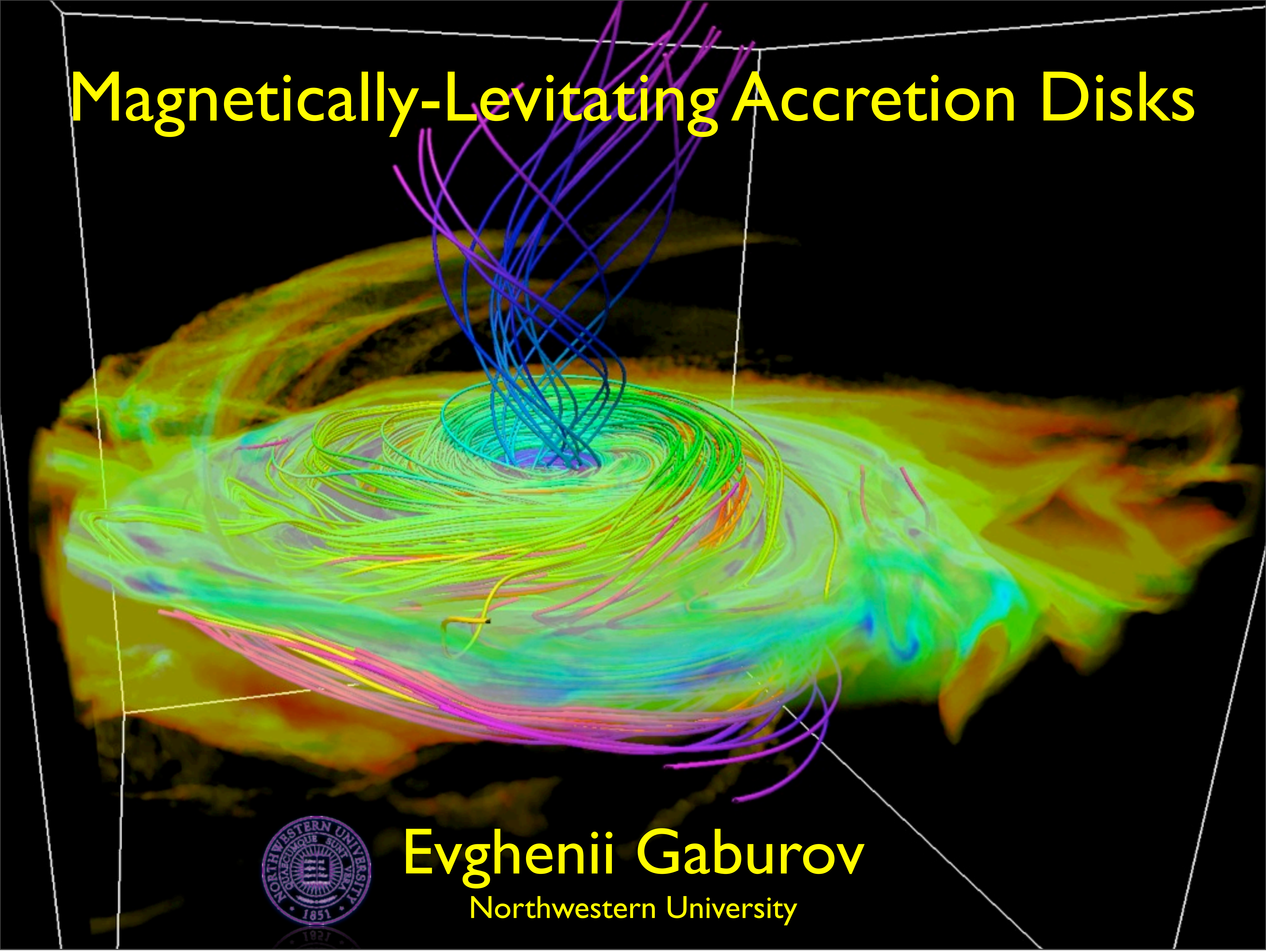

Magnetically-Levitating Accretion Disks

Evghenii Gaburov

Northwestern University

Magnetised ISM
Strong galactic *B*-field

Crocker et al 2010, Nature

Magnetically levitating disks

Shibata et al 1990,
Pariev et al 2003,
Begelman & Pringle 2007

B-field is an extra source of pressure

JR Maglev

Levitating frog, Geim 1998, Ig Nobel prize 2000
(also won Nobel prize 2010 for graphene)

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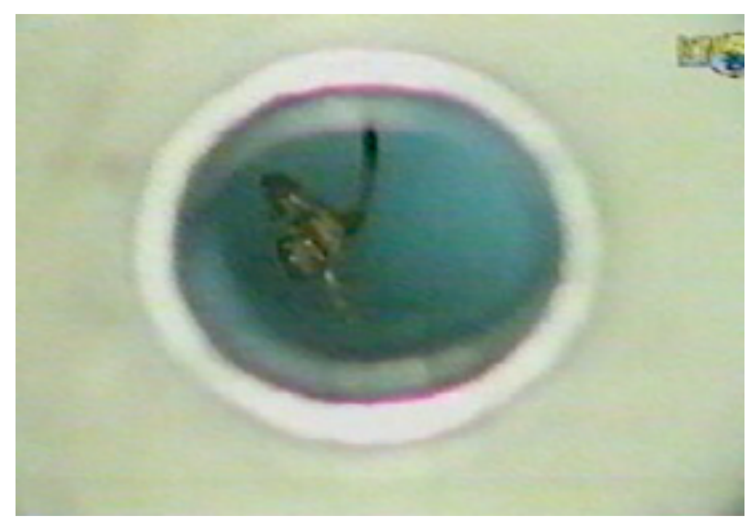
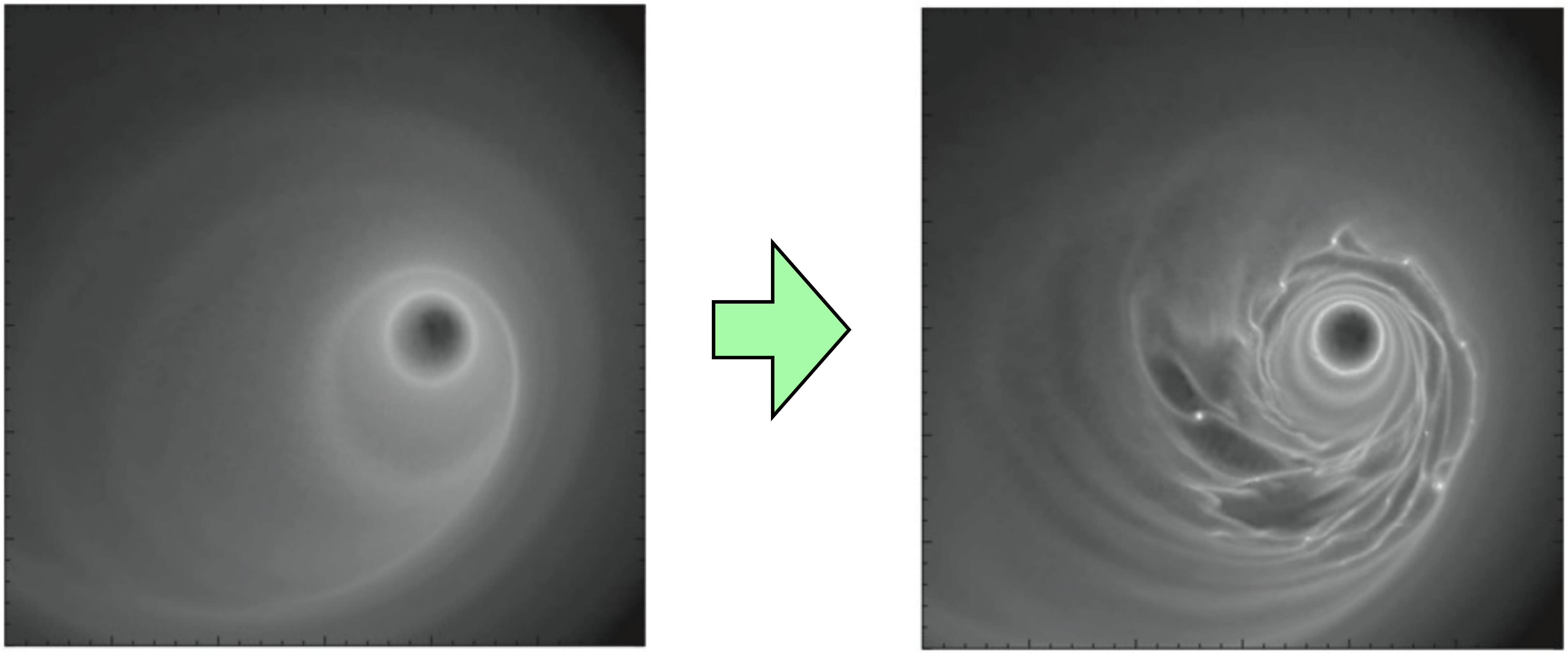


Levitating frog, Geim 1998, Ig Nobel prize 2000
(also won Nobel prize 2010 for graphene)

Disks around SMBH tend to fragment for $r > 10^{-2}$ pc

e.g. Goodman 2003

Alexander et al 2008

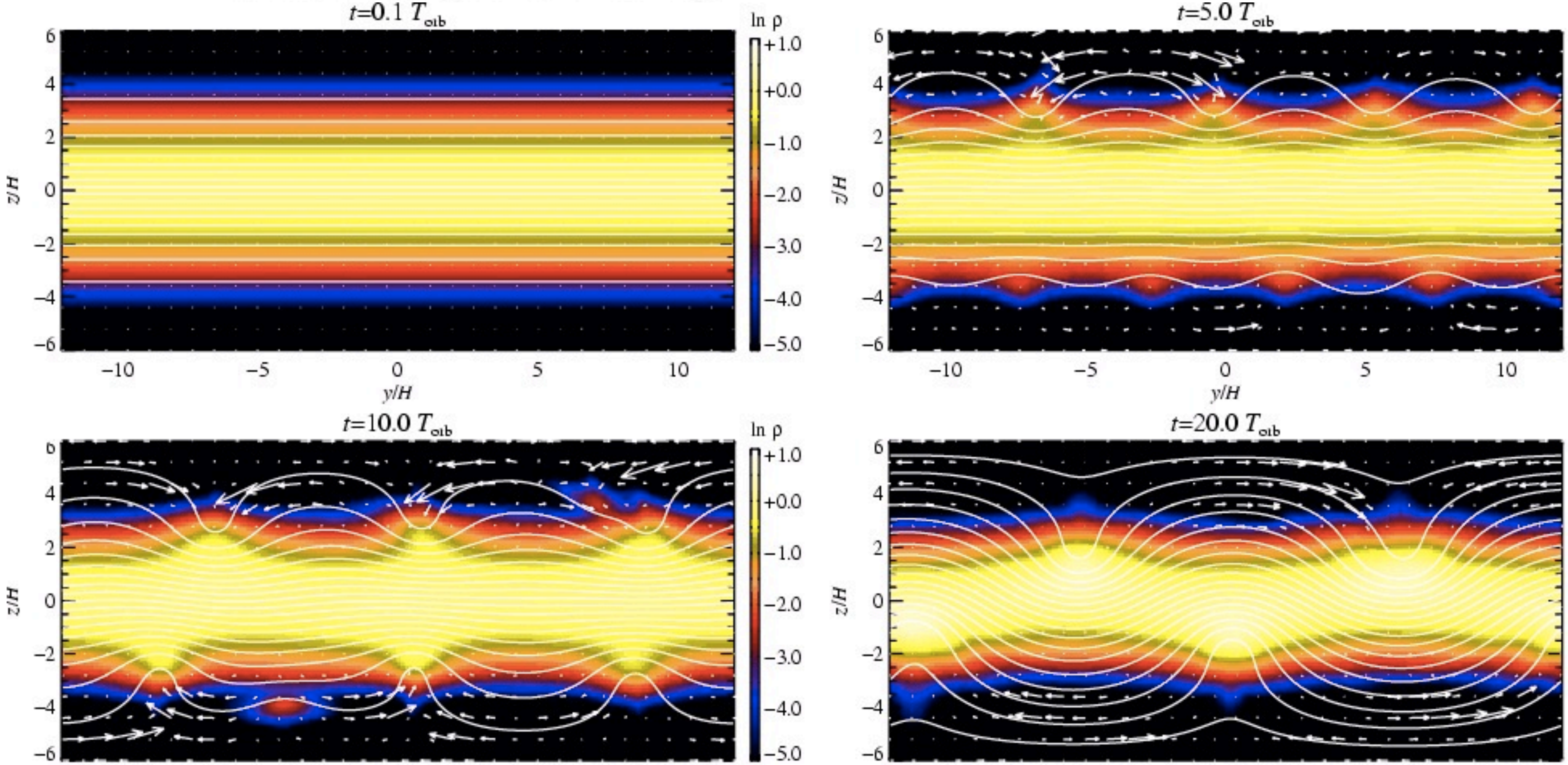


Observations shows ~pc size disks

Miyoshi et al 1995, Nature (NGC 4258)
Jaffe et al 2004, Nature (NGC 1068)

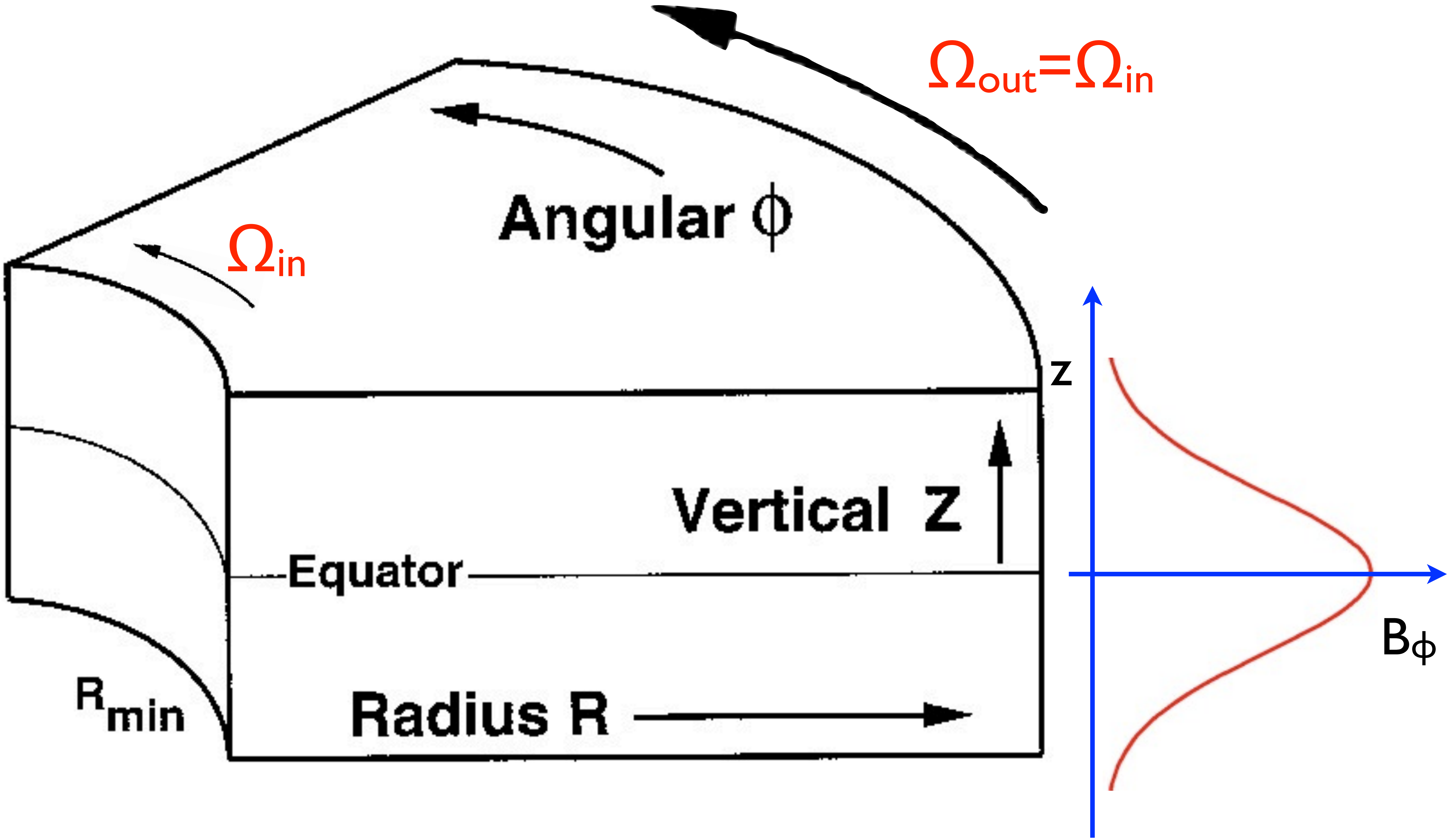
Parker instability

- Stratification with $P_{mag} = P_{gas}$ is unstable to magnetic buoyancy (Parker 1966)



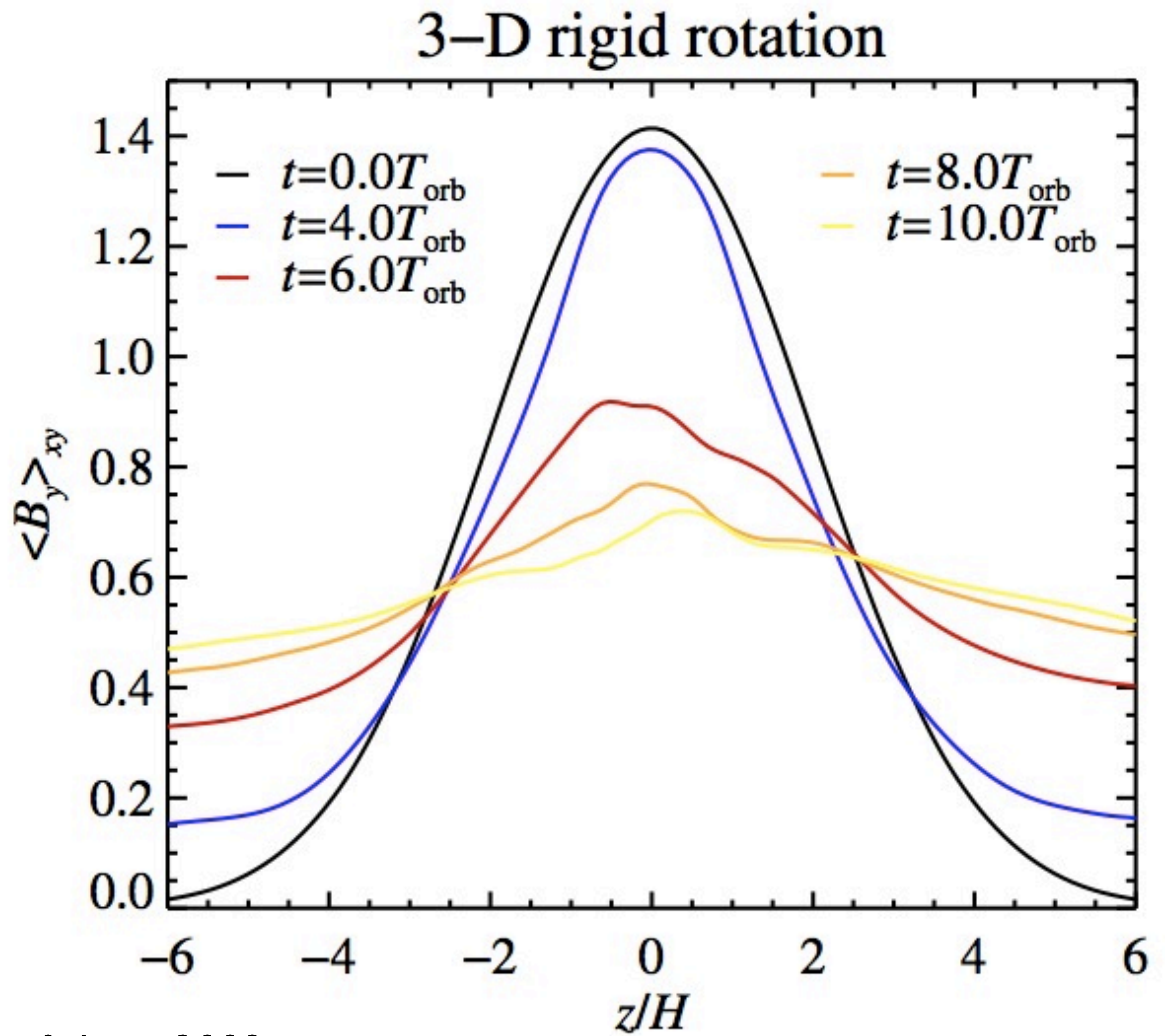
\

Rigid rotation



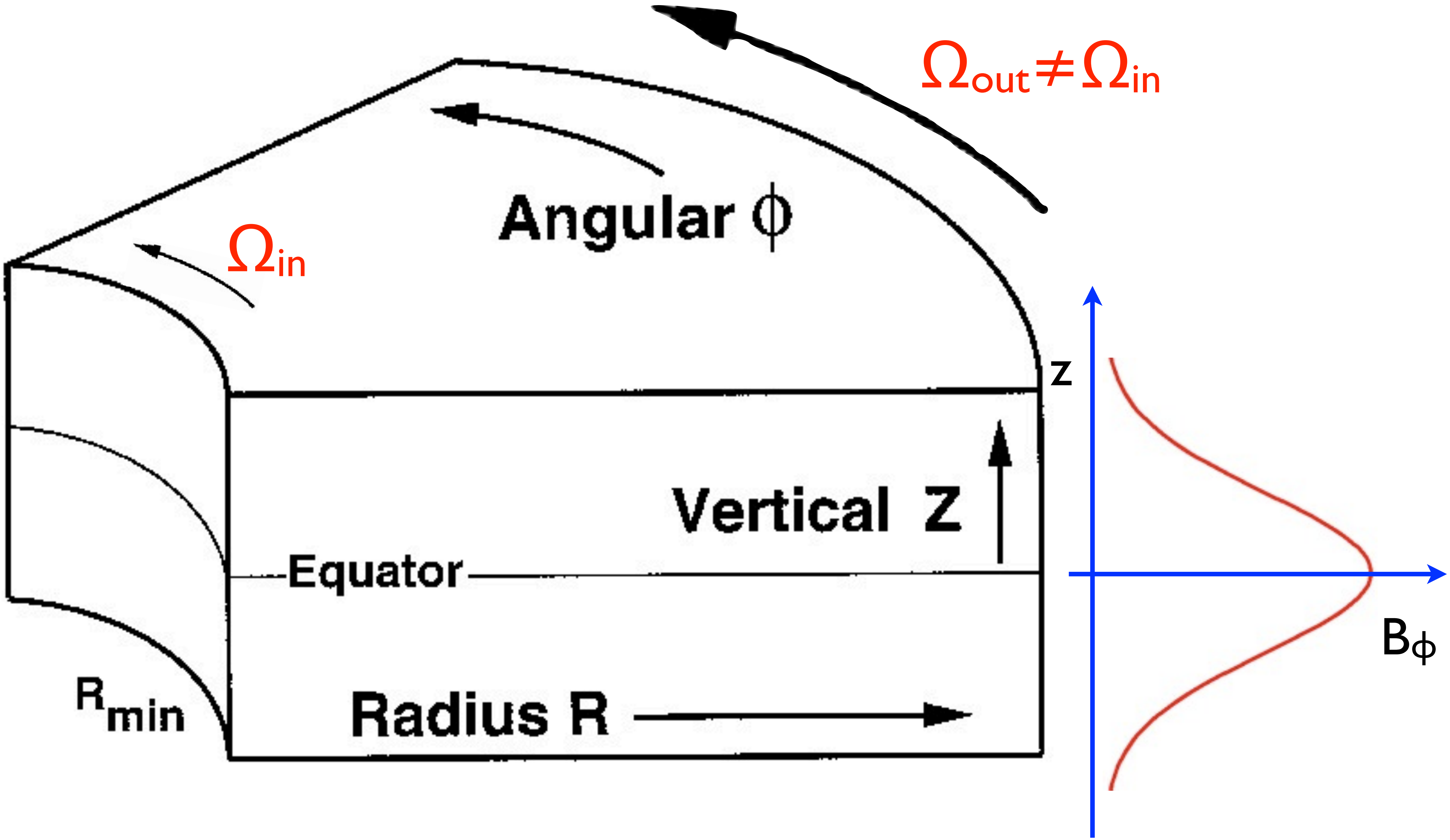
$\Omega(R)$ = const

Rigid rotation + Parker instability



Johansen & Levin 2008

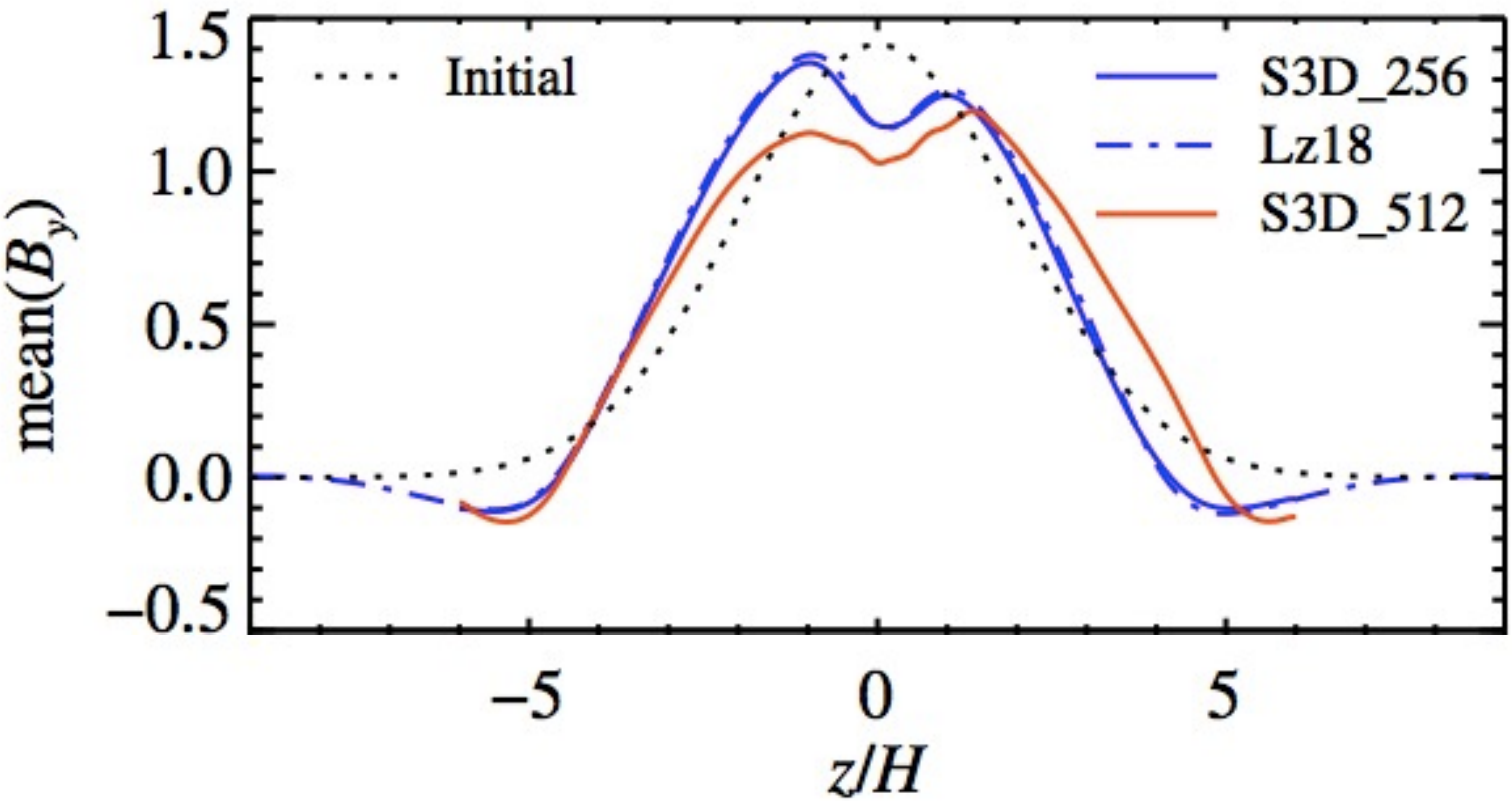
Keplerian shear



$\Omega(R) = \Omega_{Kepler}(R)$

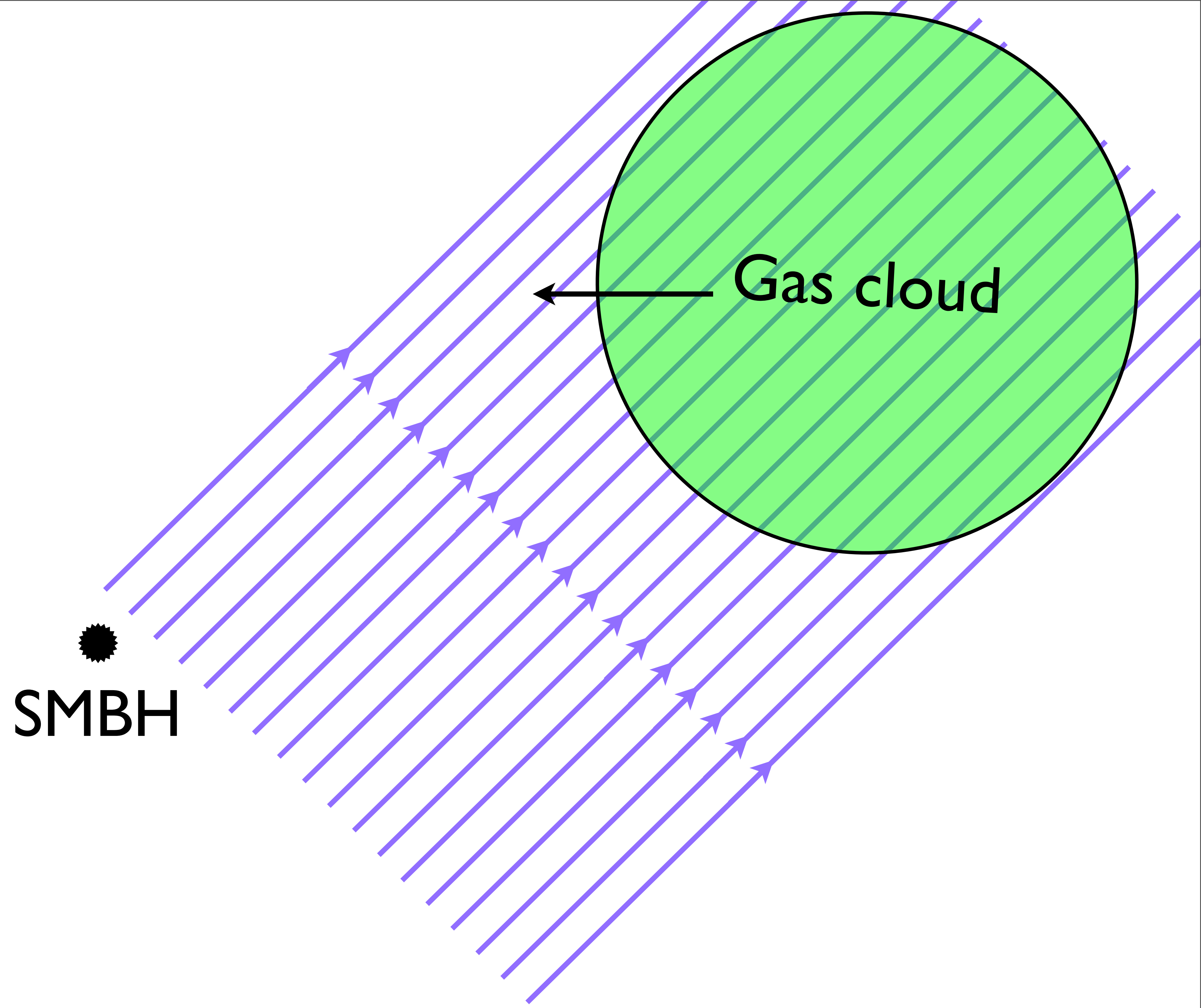
Keplerian shear + Parker instability

Unexpected physics



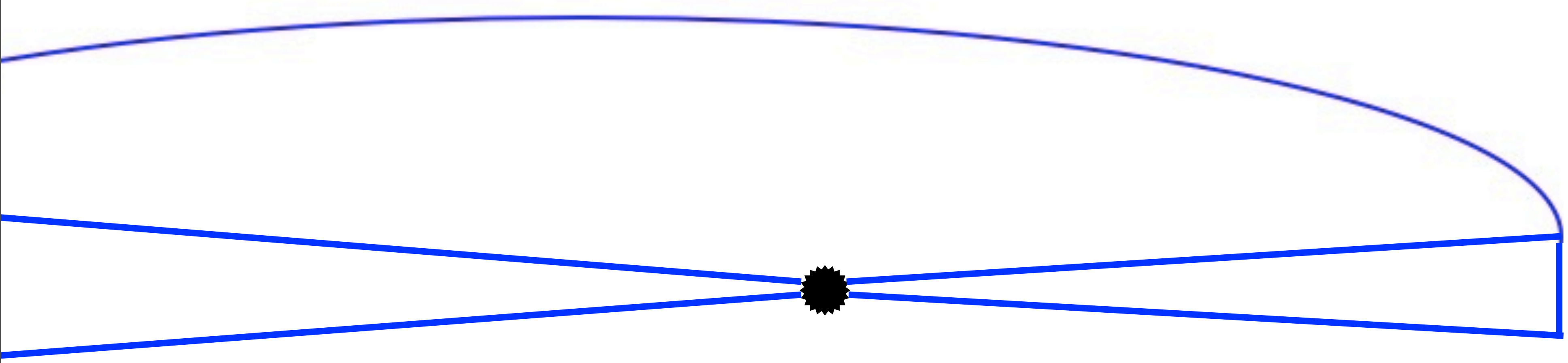
Johansen & Levin 2008

Can magnetically-levitating disks be formed ?



$$\beta_{\mathrm{cl},0} = \frac{P_{\mathrm{gas}}}{P_{\mathrm{mag}}} = 1$$

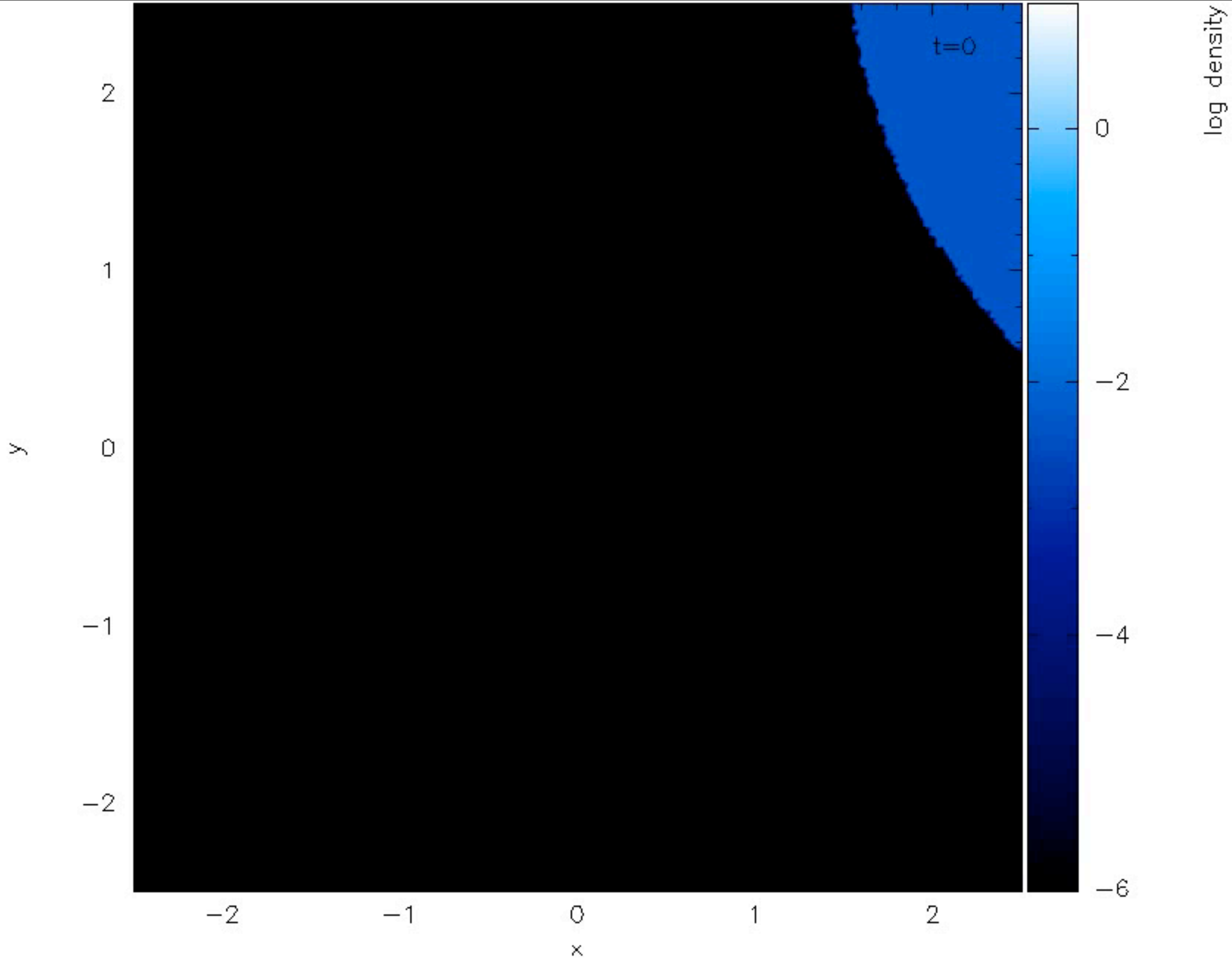
Accretion disk is formed



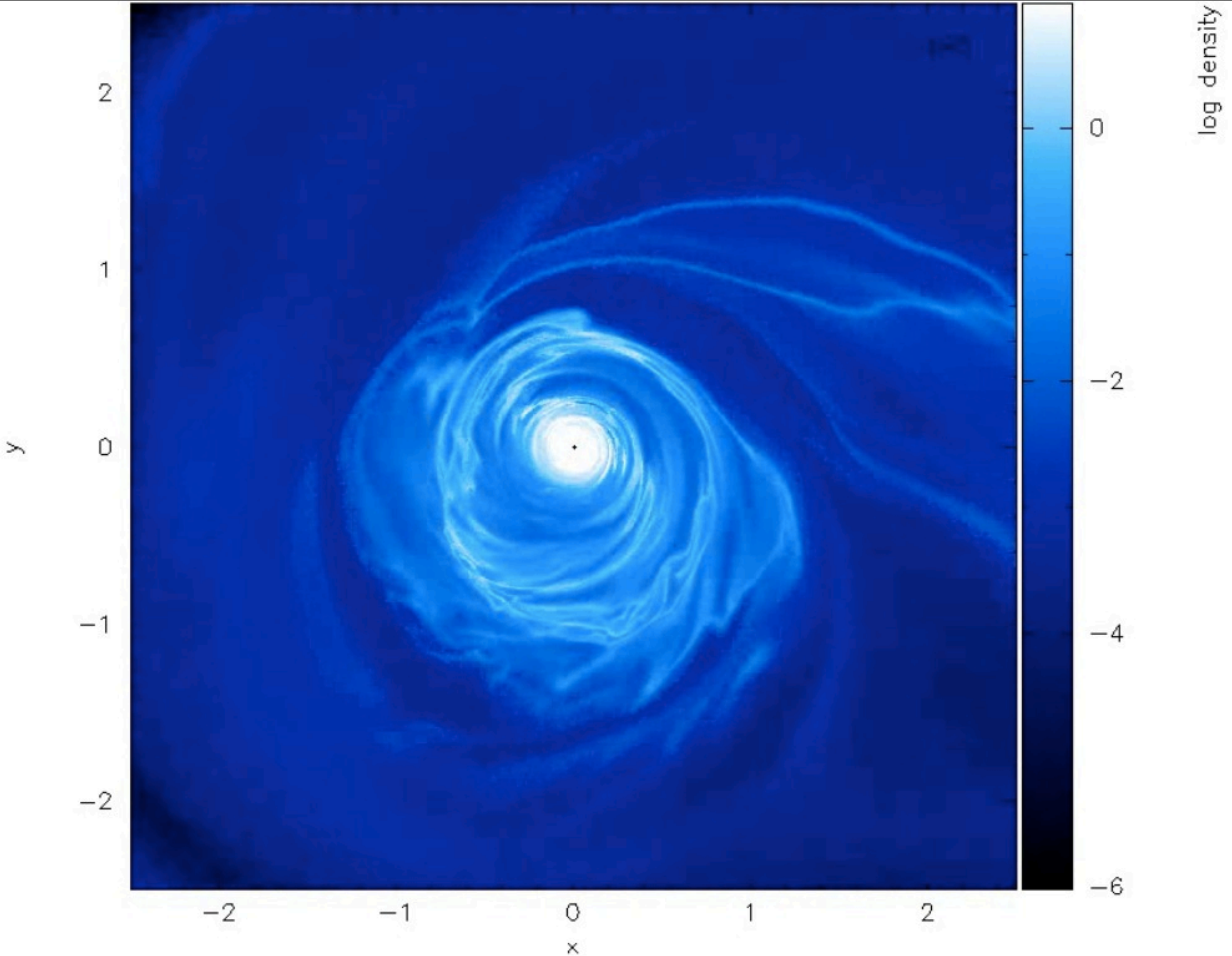
Gas/magnetic pressure supported disk

Magneto-Rotational Instability/Large scale field

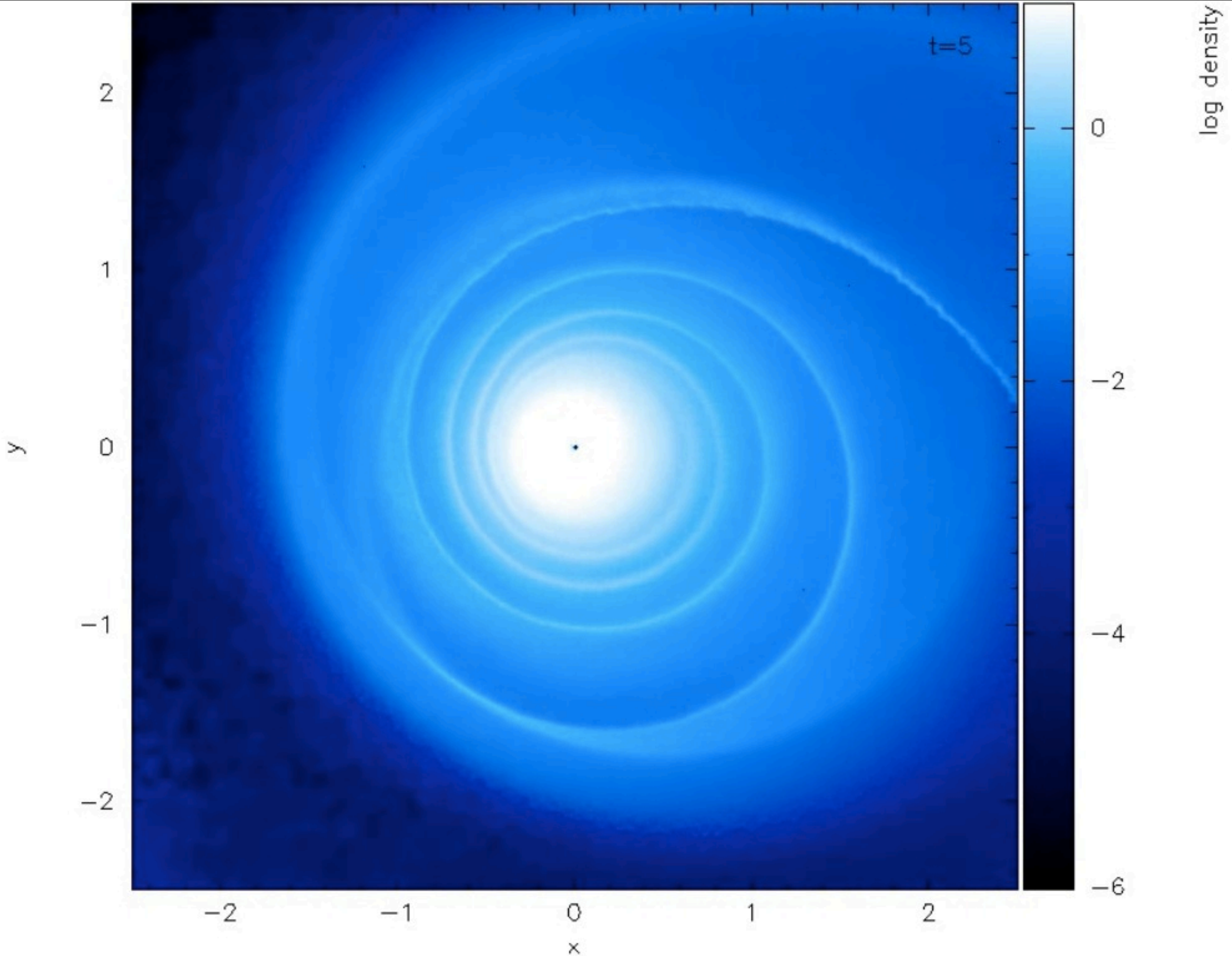
Prone/stable to fragmentation

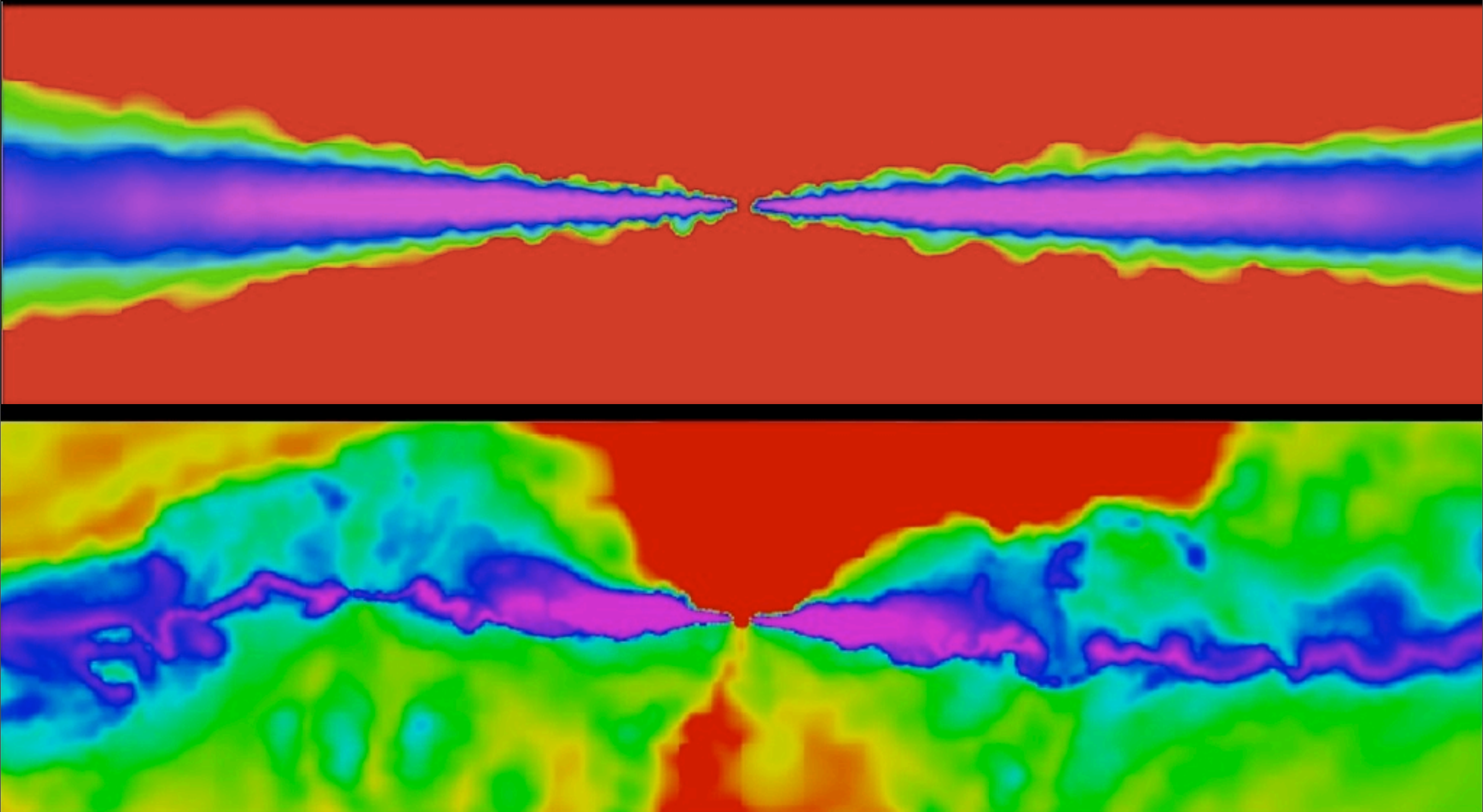


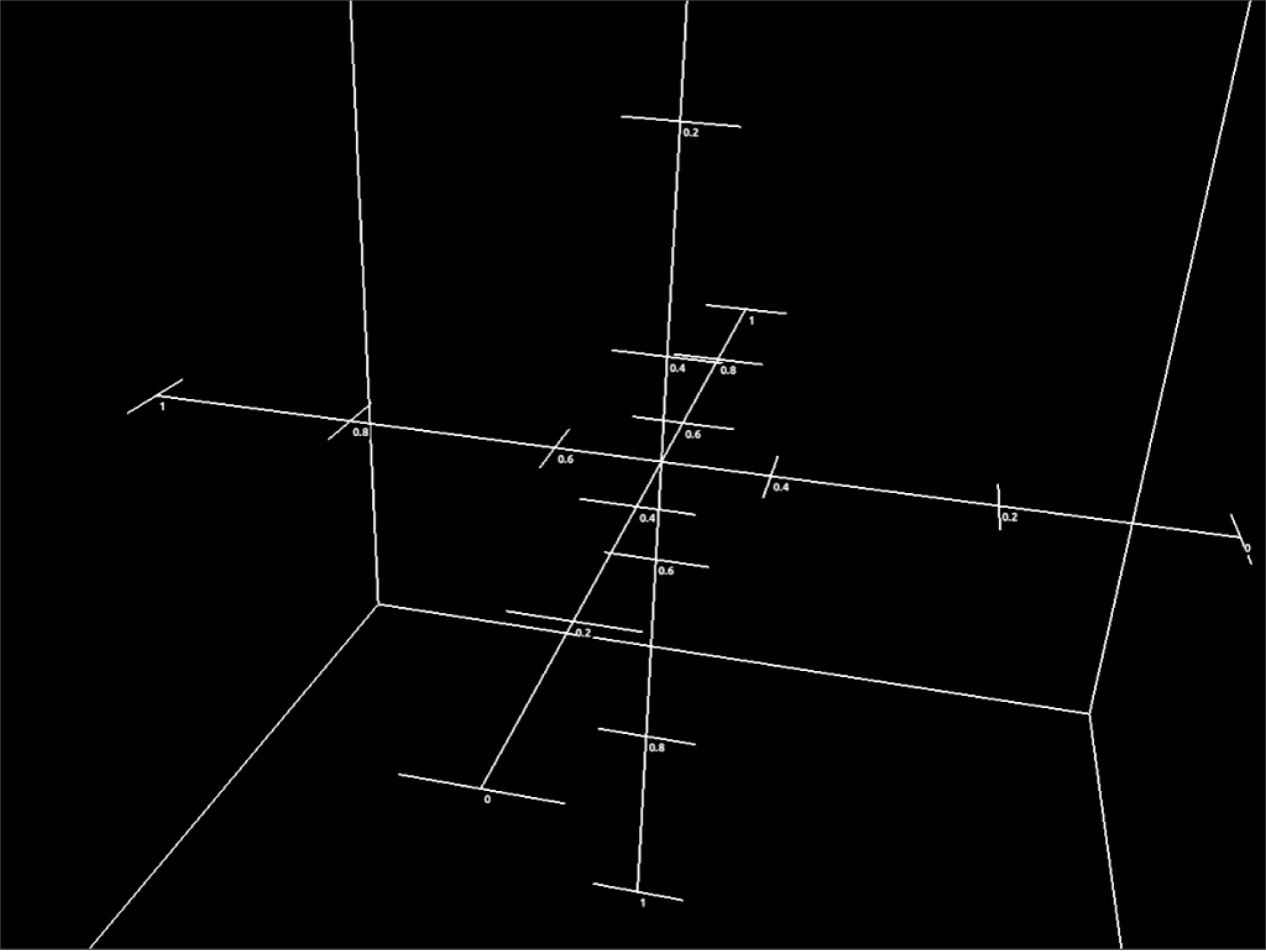
t=0
2
1
0
−1
−2
y
−2
−1
0
1
2
x
0
−2
−4
−6
log density

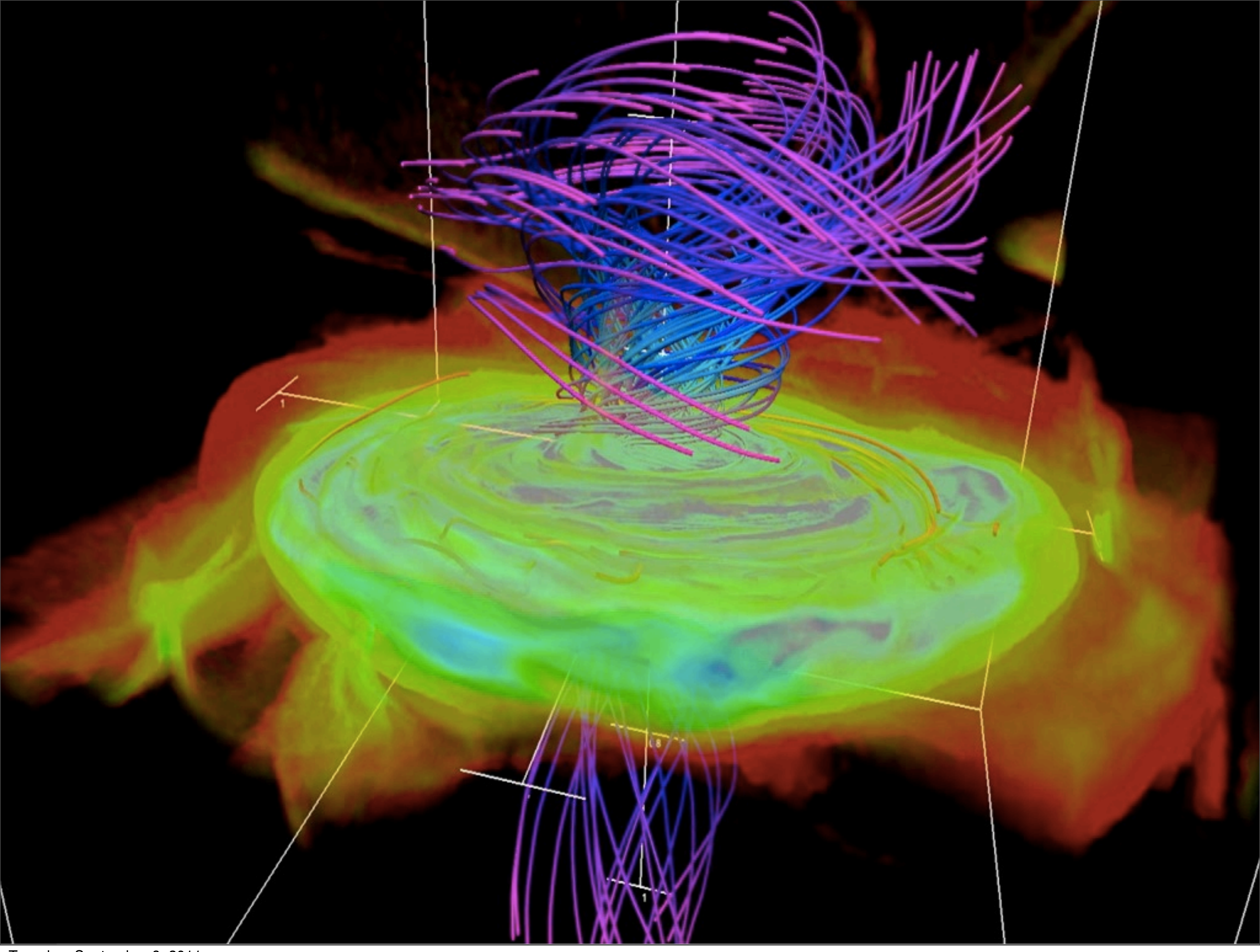


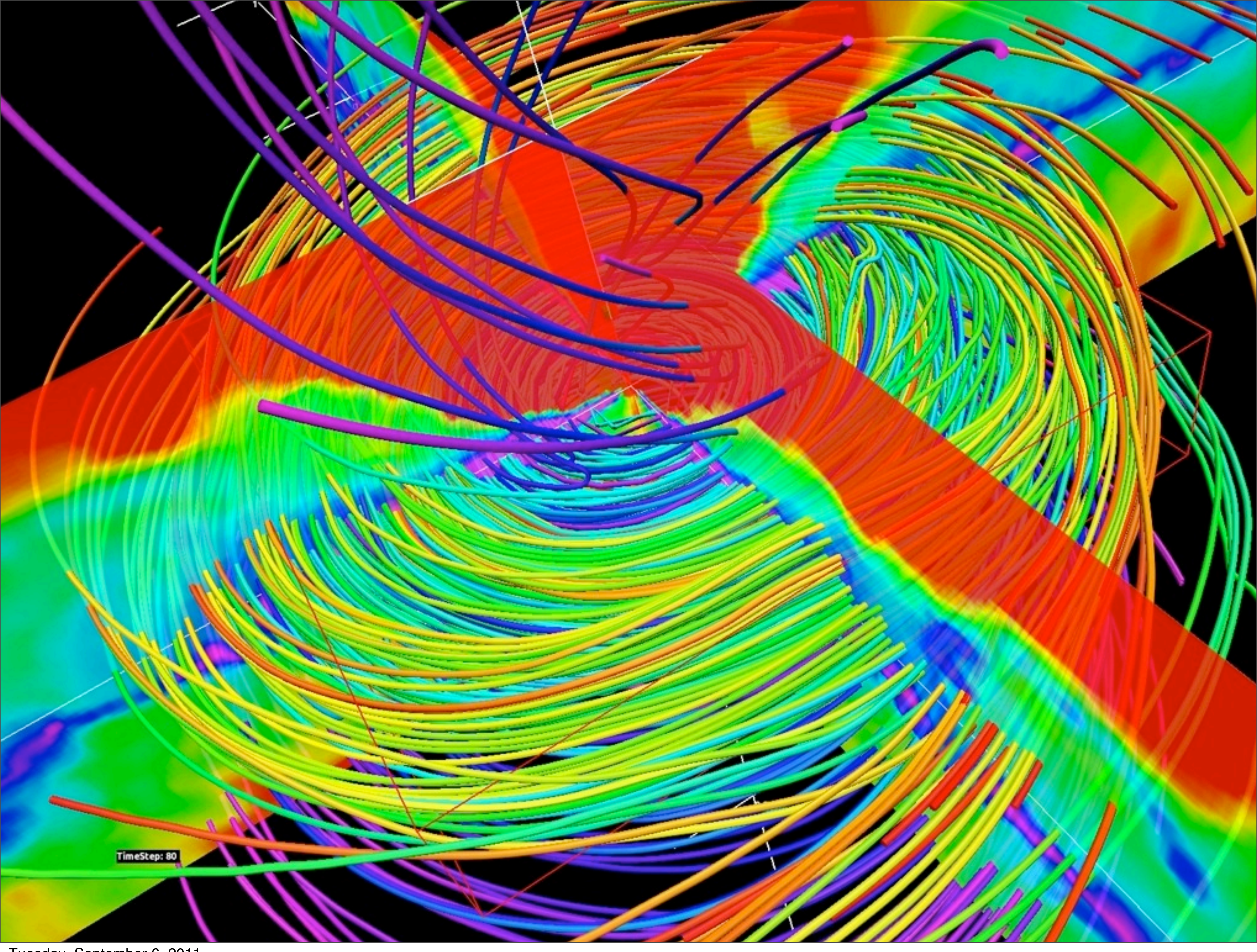
log density
0
−2
−4
−6
y
2
1
0
−1
−2
x
−2
−1
0
1
2


t=5
log density
0
−2
−4
−6
y
2
1
0
−1
−2
x
−2
−1
0
1
2

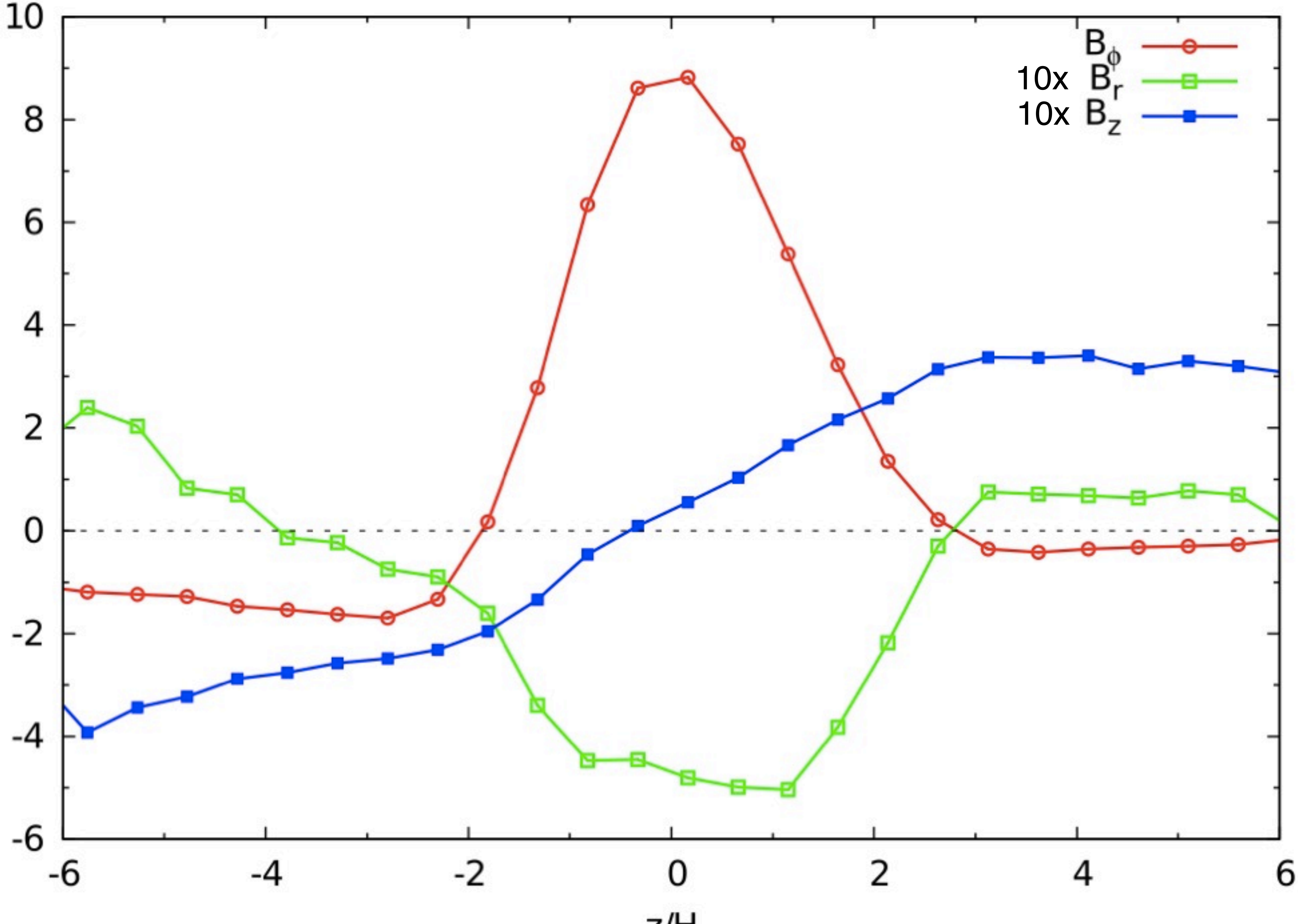



0.2
1
0.4
0.8
1
0.8
0.6
0.6
0.4
0.4
0.2
0
0.6
0.2
0.8
0
1

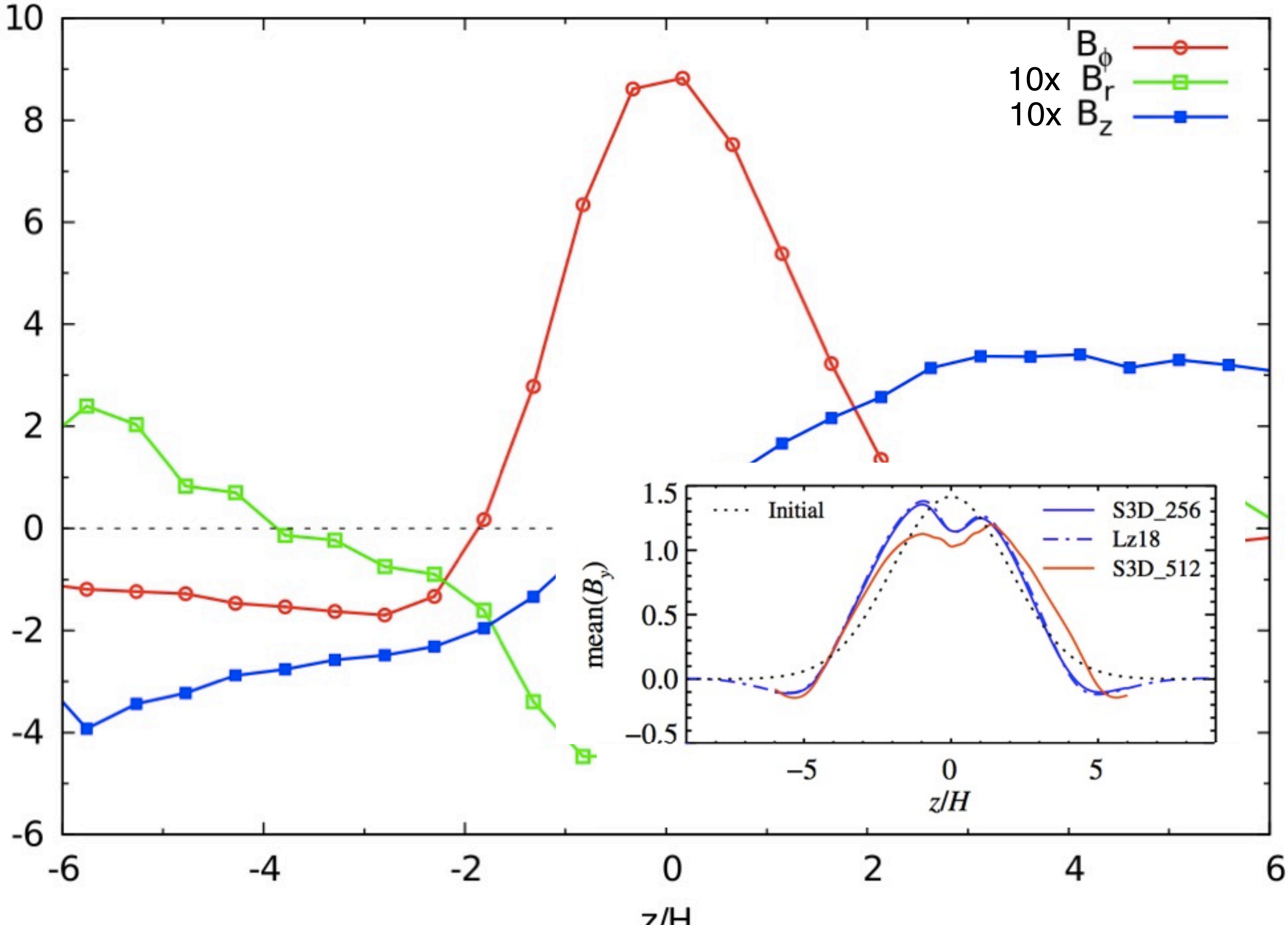



TimeStep: 80

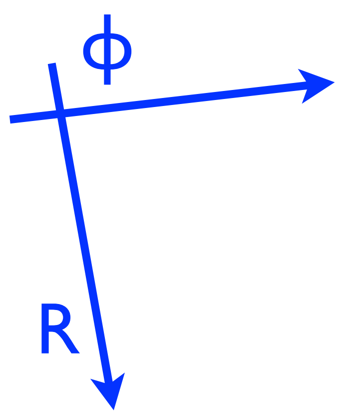
Azimuthal field confinement



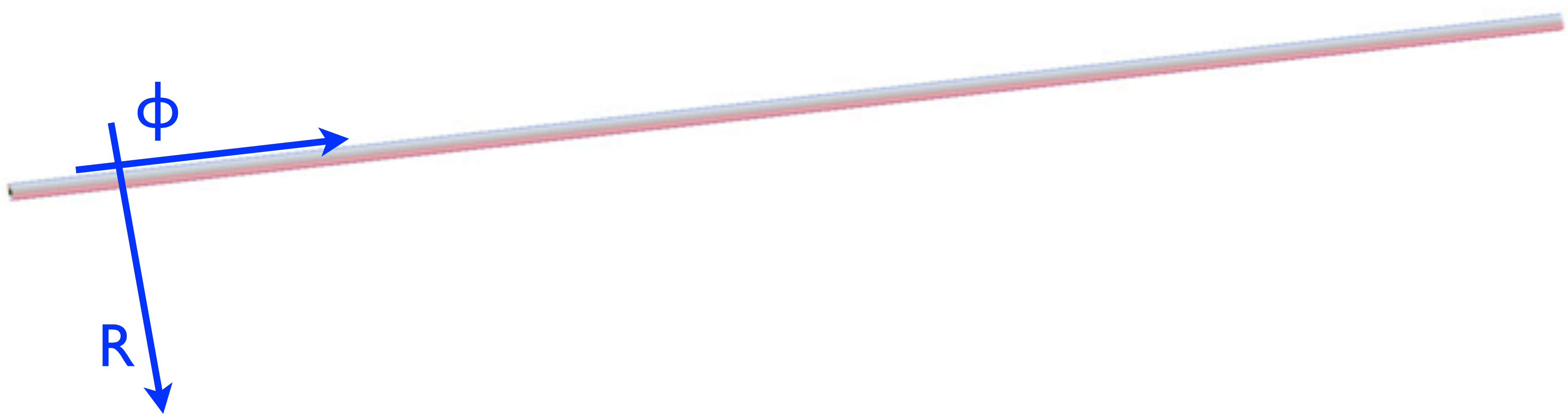
Azimuthal field confinement



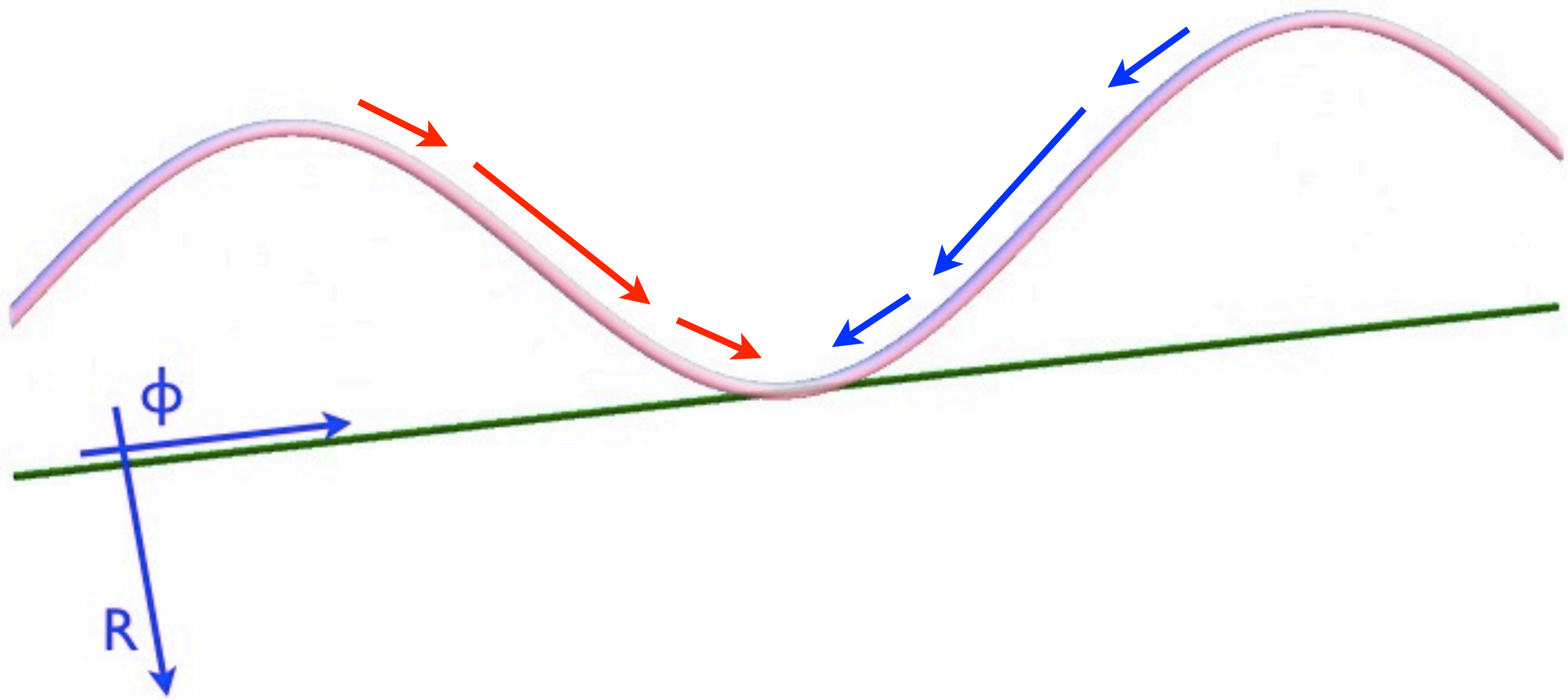
Parker instability



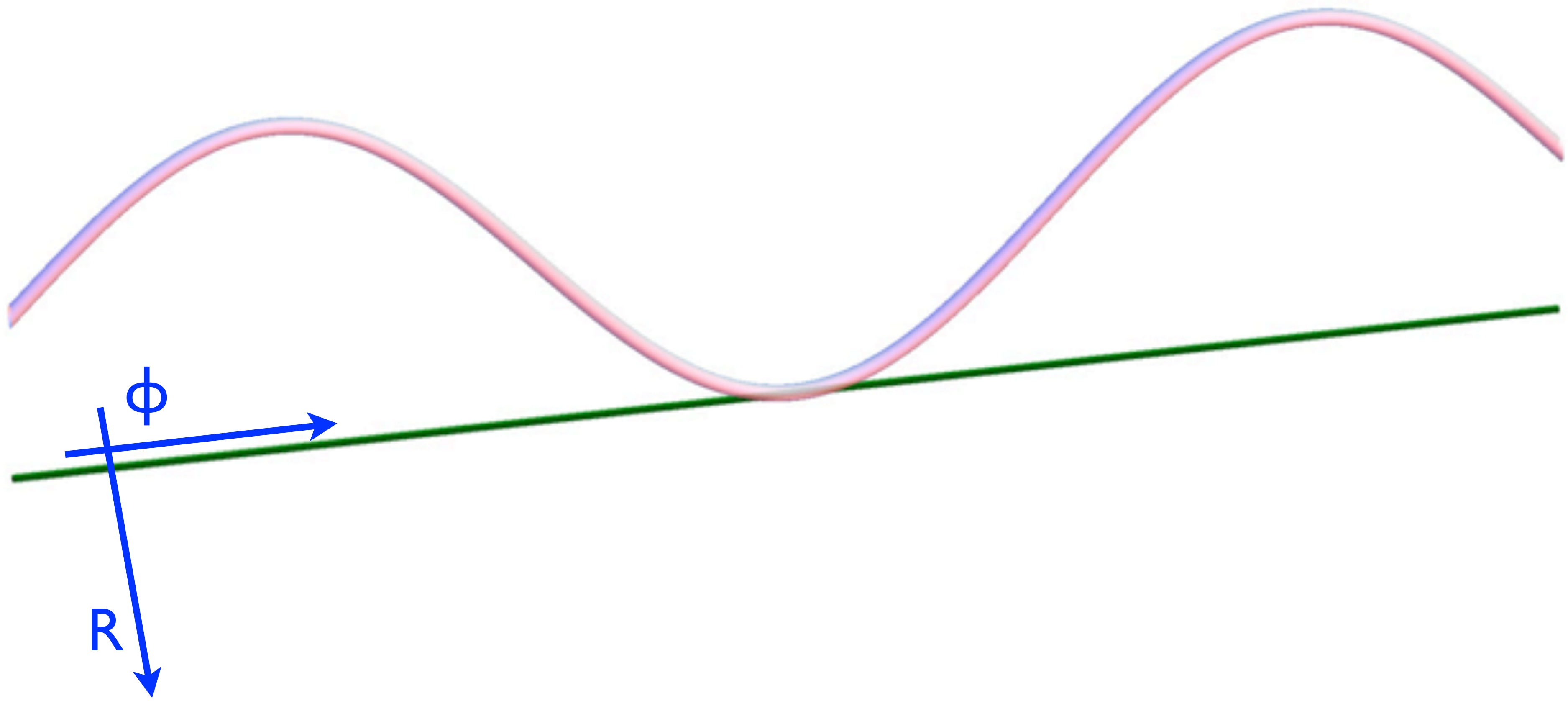
Parker instability



Fluid slides downwards

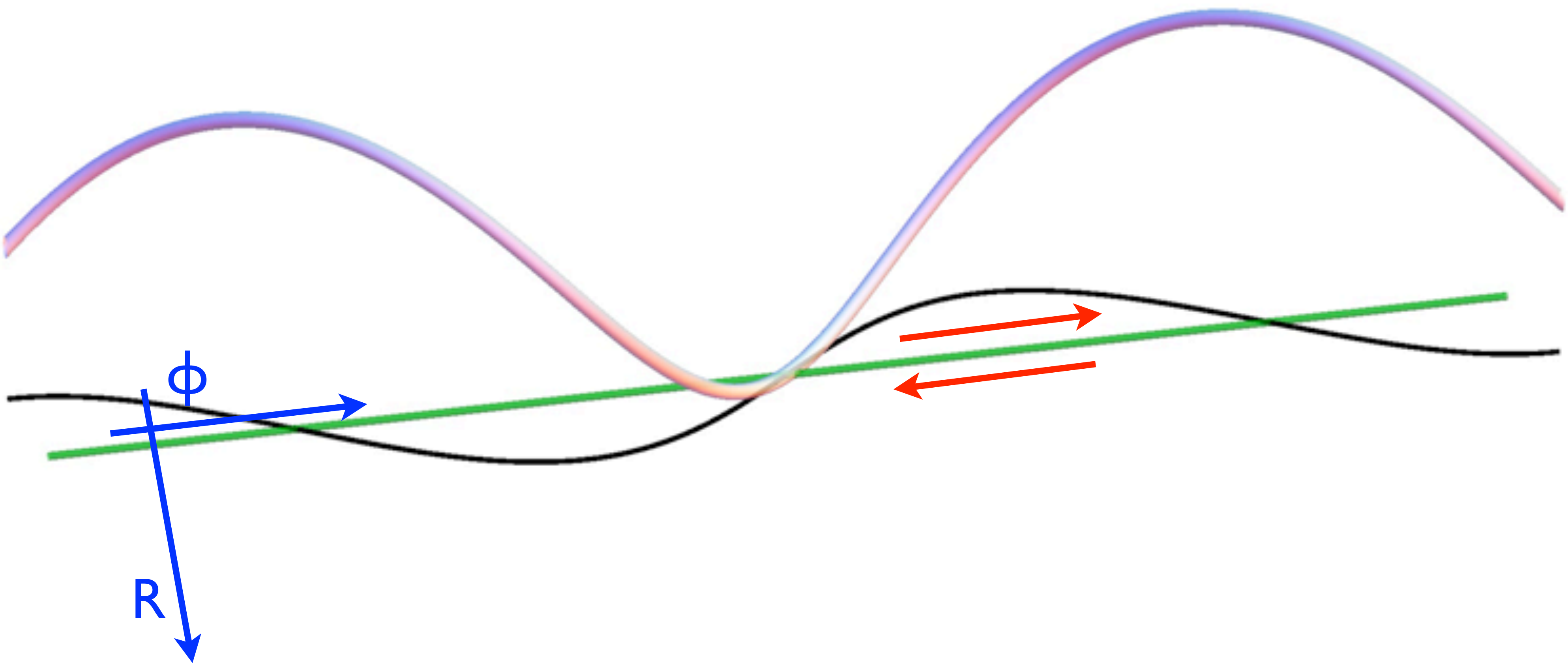


Coriolis force

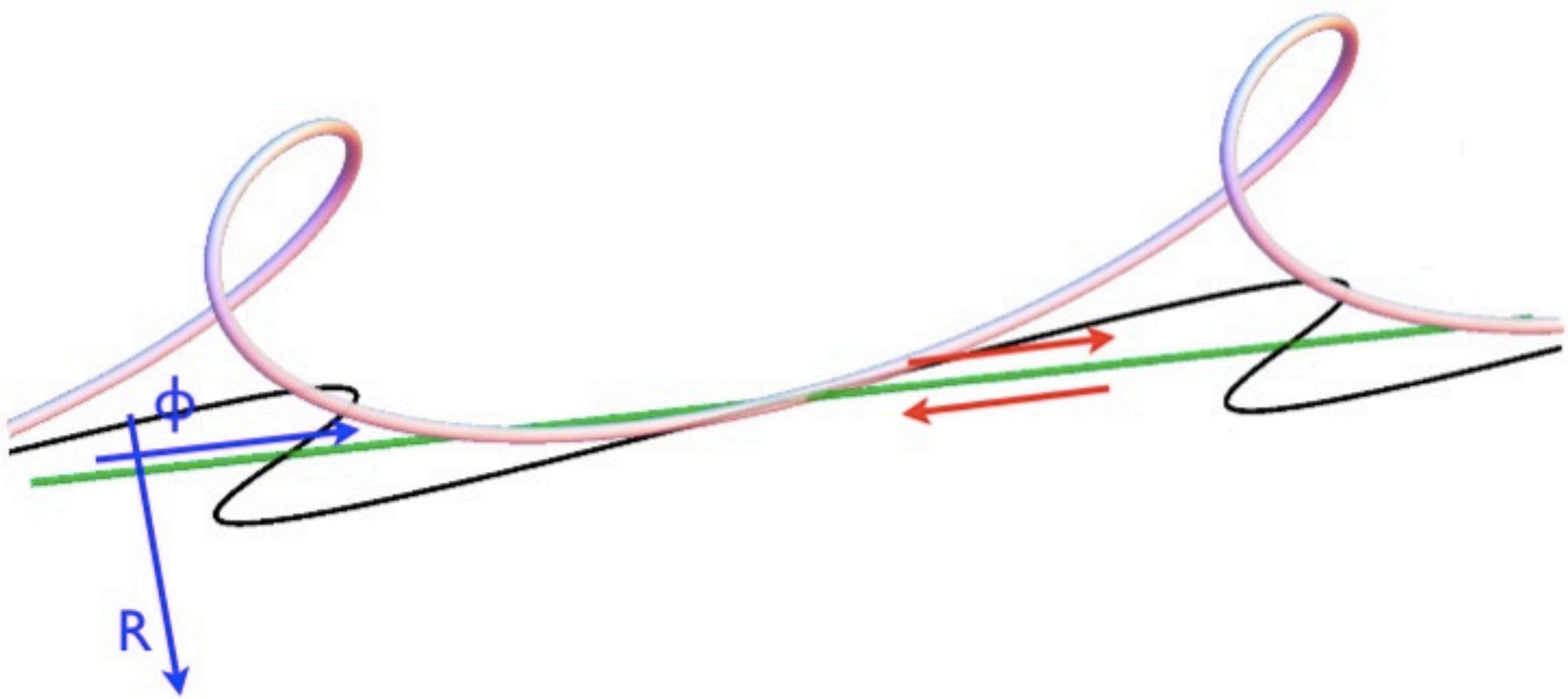


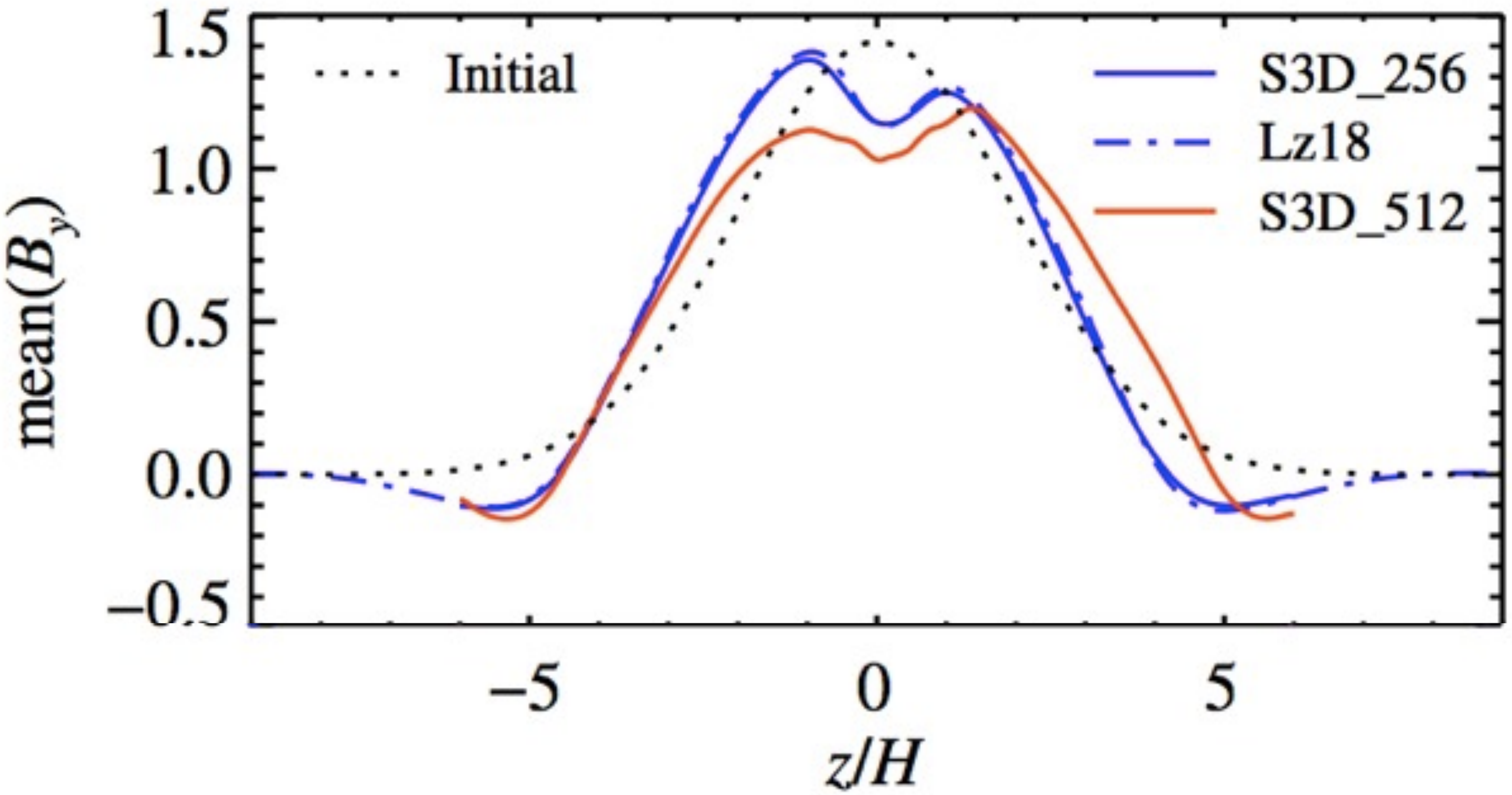
Keplerian shear

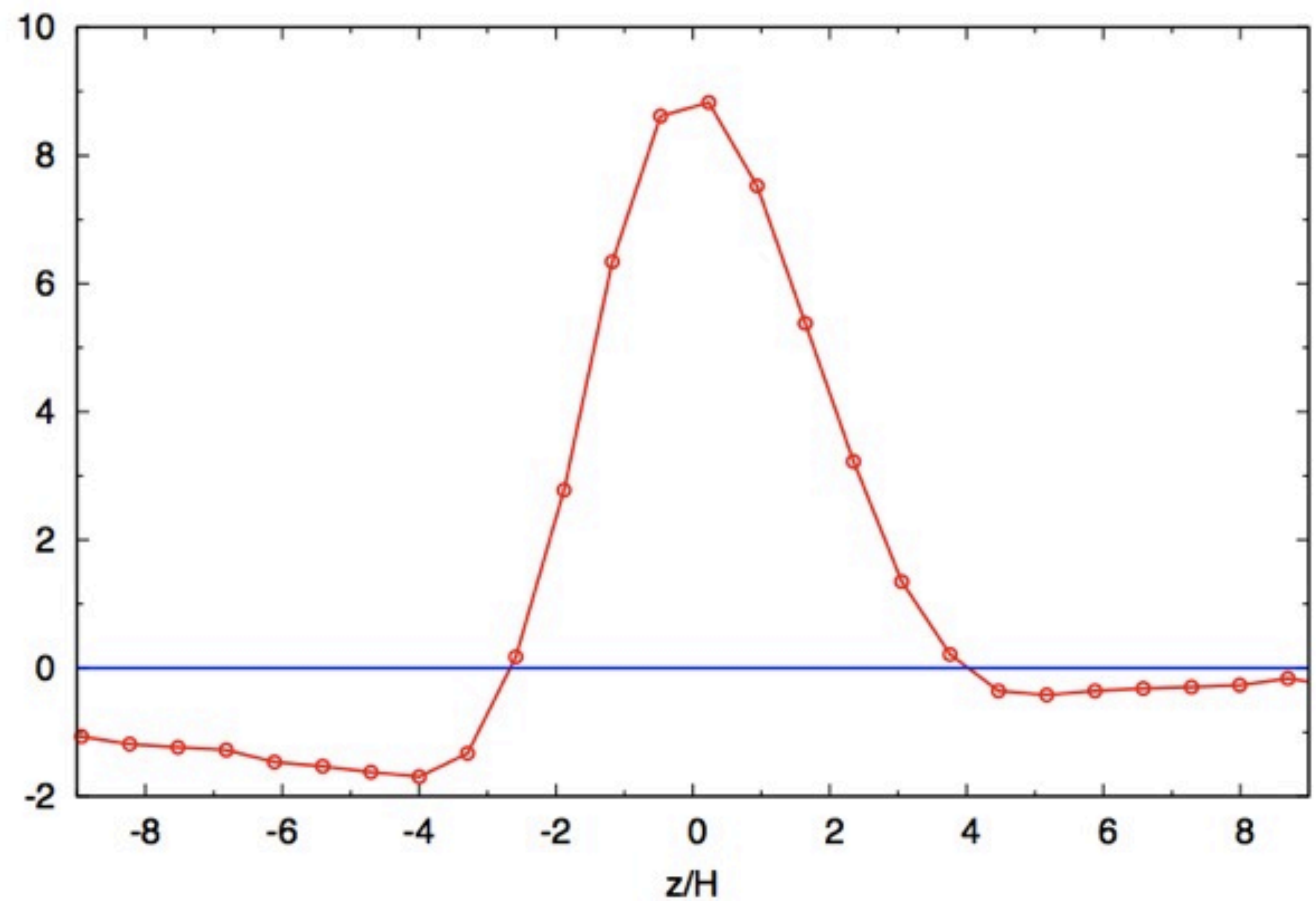
Keplerian shear

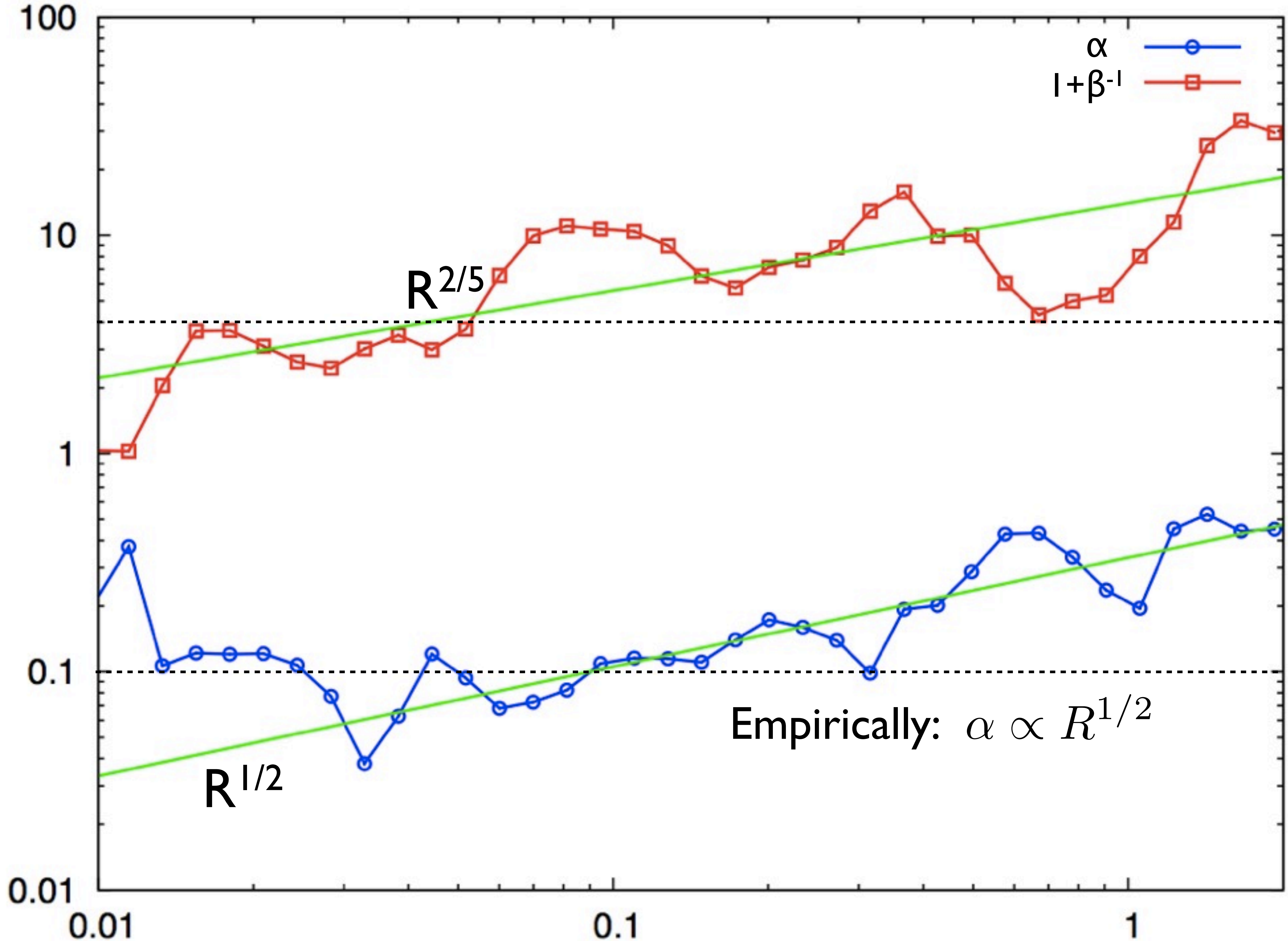


Keplerian shear




Initial
S3D_256
Lz18
S3D_512
mean(B_y)
z/H


z/H



100
10
1
0.1
0.01
0.01
0.1
1
α
1+β-1
R2/5
R1/2
Empirically: $\alpha \propto R^{1/2}$

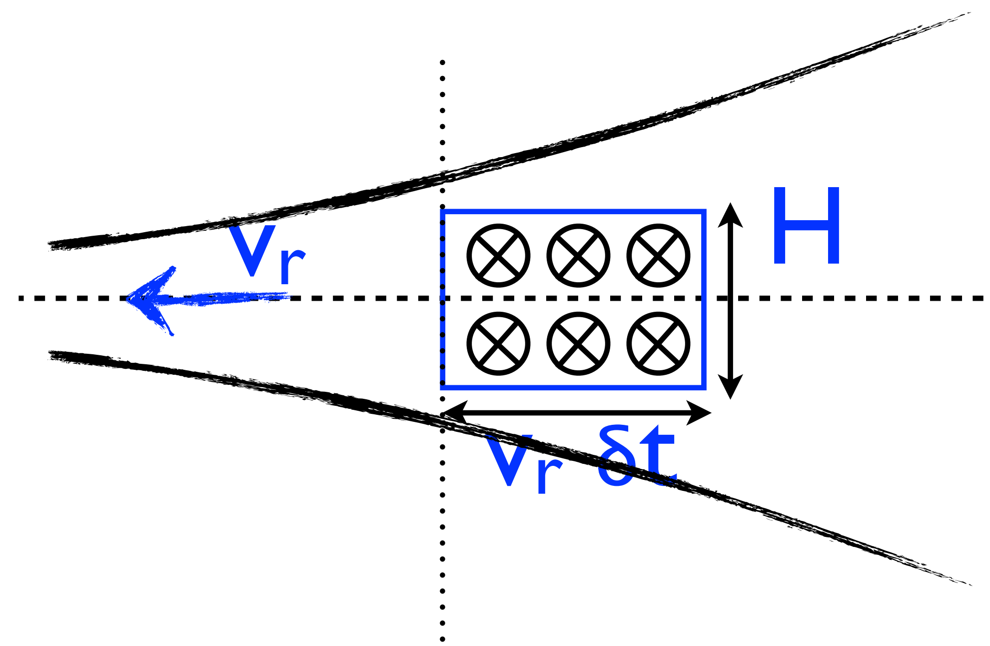
Field confinement ➡ new accretion disk model

$$\delta M = 2\pi R\, \rho\, H\, v_r \delta t$$

$$\delta \Phi = \quad B_\phi\, H\, v_r \delta t$$

Flux confinement +
Frozen-in condition:

$$\frac{\delta M}{\delta \Phi} = \text{const}$$



Assuming $\beta = P_{gas}/P_{mag} \ll 1$

$$\Sigma \propto R^{-11/10}\, \alpha^{-3/5}$$

$$H \propto R^{13/10}\, \alpha^{-1/5}$$

$$B_\varphi = \alpha^{-1} B_R \propto R^{-7/5}\, \alpha^{-2/5}$$

$$\alpha = -\langle B_r\, B_\phi \rangle / P_{tot} \sim 0.2$$

Independent
of thermal structure

Stability to fragmentation

Toomre 1964

$$Q = \frac{c_s \Omega}{\pi G \Sigma} < 1 \quad \Rightarrow \quad \rho_{\rm disk} \gtrsim \frac{M_{\rm BH}}{R^3}$$

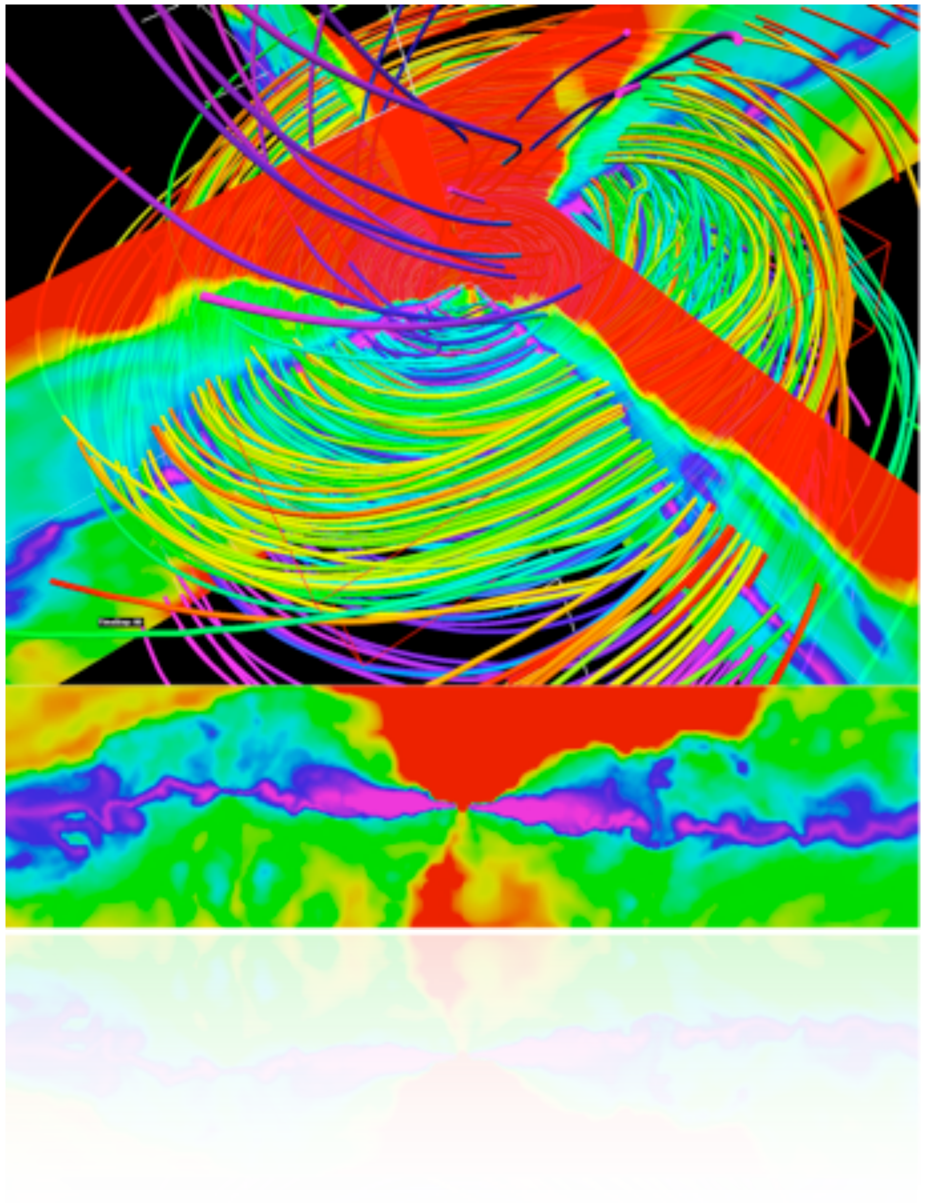
$\rho_{\rm MLAD} \sim \Sigma / H \propto R^{-24/10}\, \alpha^{-2/5}$

$$R_{\rm frag} \sim 10\, \frac{M_8^{1/3}}{\zeta_{10}^2}\, {\rm pc} \qquad \zeta \propto \frac{M}{\Phi}$$ mass-to-flux ratio

Stable to fragmentation at ~pc

$$\frac{M_{\rm disk}}{M} \approx 0.331\, \frac{r^{9/10}}{\zeta_{10}} \qquad \frac{H}{R} \approx 0.149\, \frac{r^{3/10}}{\zeta_{10}}$$

$$r = \frac{R}{R_{\rm frag}}$$



Main features of
Magnetically-Levitating Accretion Disks

Long-lived large scale field

Magnetically supported disks

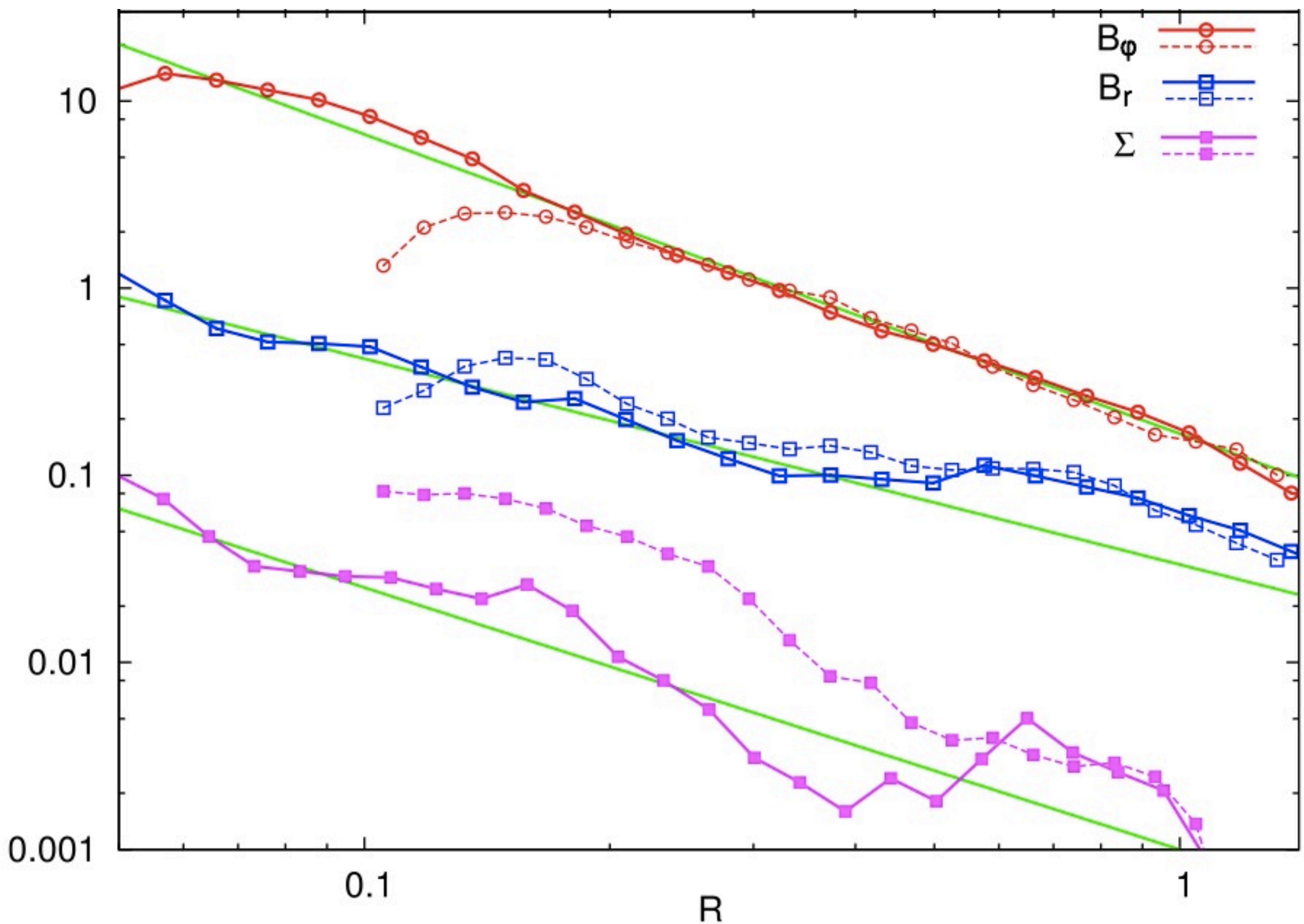
Clumpy & filamentary density

High accretion rates

Common outcome of a collision between magnetised gas cloud and supermassive black hole

Accretion rate

R	$\dot{M}$	$\alpha_{\rm acc}$	α
0.05	0.035	0.06	0.03
0.1	0.066	0.09	0.14
0.2	0.070	0.22	0.18
0.4	0.085	0.37	0.31
0.8	0.045	0.33	0.23



10
1
0.1
0.01
0.001
0.1
1
R
B_φ
B_r
Σ

Fragmentation

Toomre 1964

$$Q = \frac{\Omega^2 H}{\pi G \Sigma} < 1 \quad \Rightarrow \quad \rho_{\rm disk} \gtrsim \frac{M_{\rm BH}}{R^3}$$

$\rho_{MLAD} \sim \Sigma / H \propto R^{-24/10} \alpha^{-2/5}$

$$R_{\rm frag} \approx 2.09 \left(\frac{M_6\, \alpha_{0.1}^2\, \epsilon_{0.1}^2}{\zeta_{10}^6\, l_{\rm E}^2} \right)^{\frac{1}{3}} \text{pc}$$

$$\zeta = \frac{M}{\Phi} 3\pi \sqrt{\frac{G}{5}}$$

Stable to fragmentation at ~pc

$$\frac{M_{\rm disk}}{M} \approx 0.331 \frac{r^{9/10}}{\zeta_{10}} \qquad \frac{H}{R} \approx 0.149 \frac{r^{3/10}}{\zeta_{10}}$$

$$r = \frac{R}{R_{\rm frag}}$$