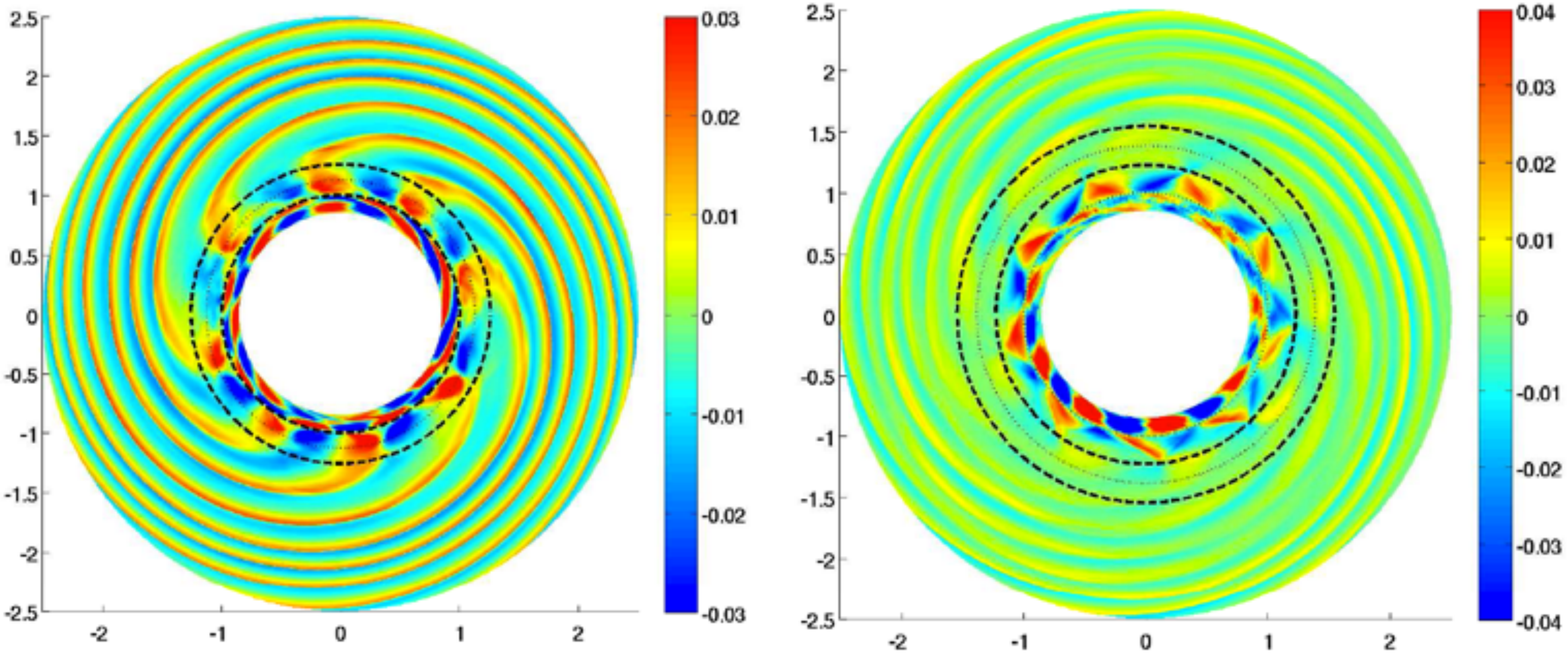
A New Picture of Accretion Disk Boundary Layers



Mikhail (Mike) Belyaev

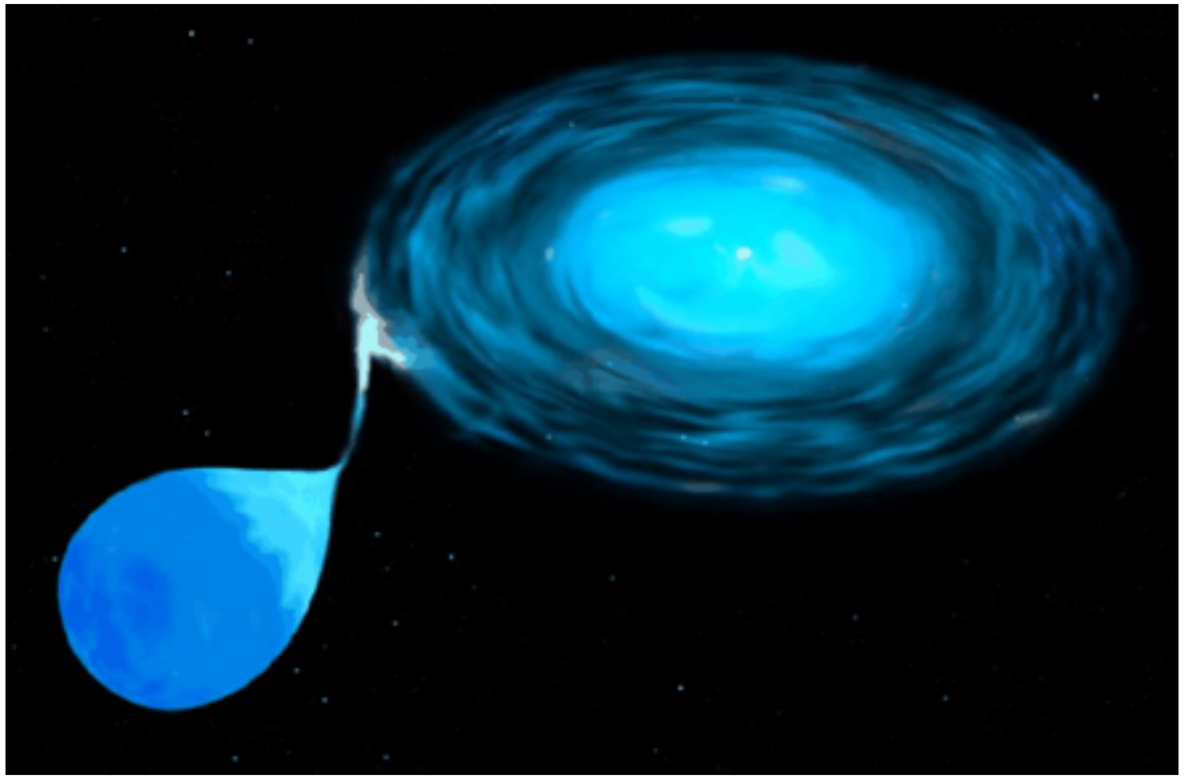
UC Berkeley (TAC)

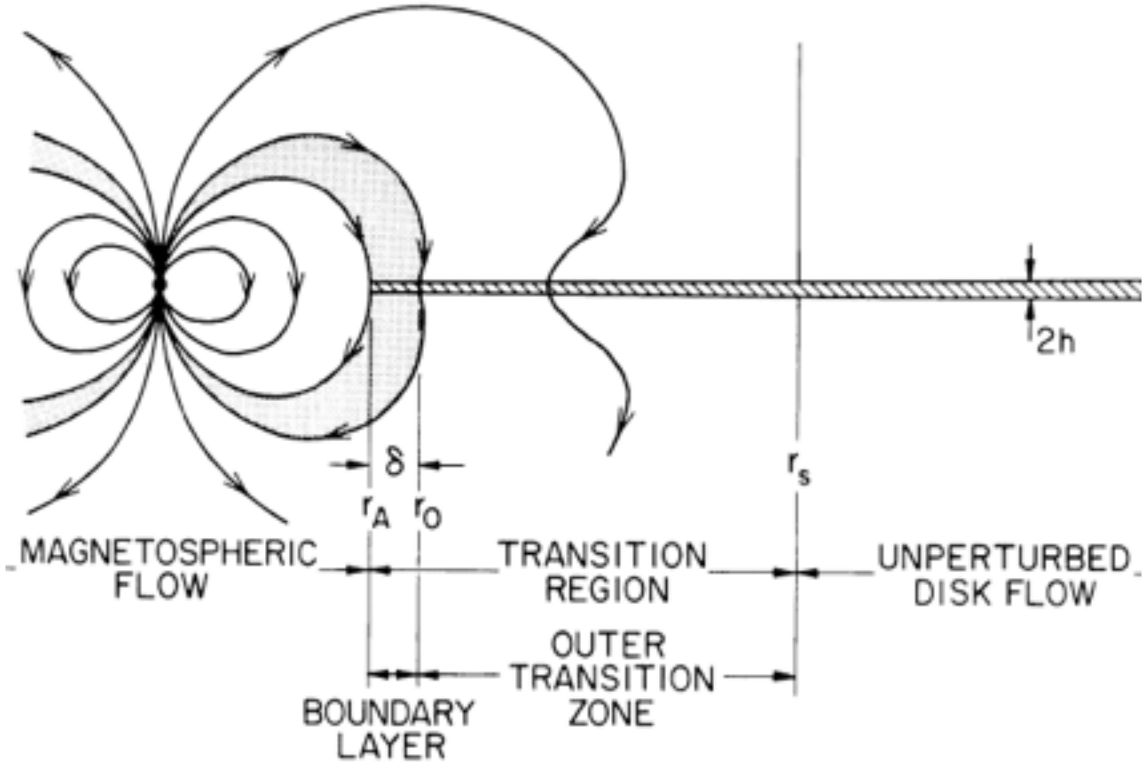
Disk Boundary Layer

Accretion via a disk onto a WD, NS, protostar...

Case 1: accretion proceeds all the way to the surface of the central object.

Case 2: accretion is disrupted by magnetic field before the disk reaches the surface.



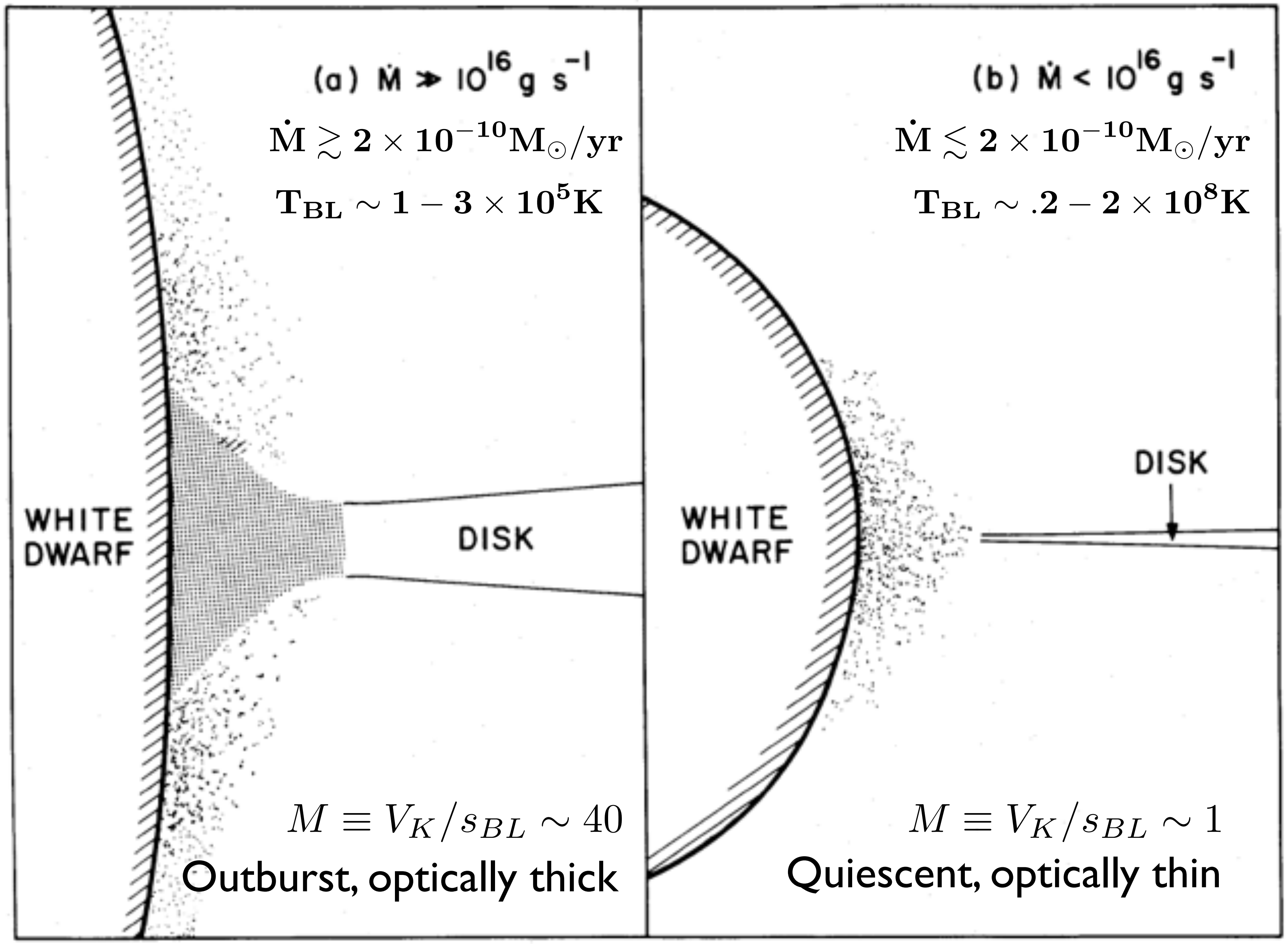


Boundary Layer in Cataclysmic Variables

$L_{BL} \approx \frac{\dot{M} R_*^2}{2}(\Omega_K(R_*) - \Omega_*)^2$ up to 50% of accretion energy released in BL.

$L_{BL} \lesssim L_{disk}, \text{ if } \Omega_* \lesssim \Omega_K(R_*)$

Patterson & Raymond (1985)



$\dot{\mathrm{M}} \gtrsim 2 \times 10^{-10} \mathrm{M}_\odot/\mathrm{yr}$

$\mathrm{T_{BL}} \sim 1 - 3 \times 10^5 \mathrm{K}$

$M \equiv V_K/s_{BL} \sim 40$

Outburst, optically thick

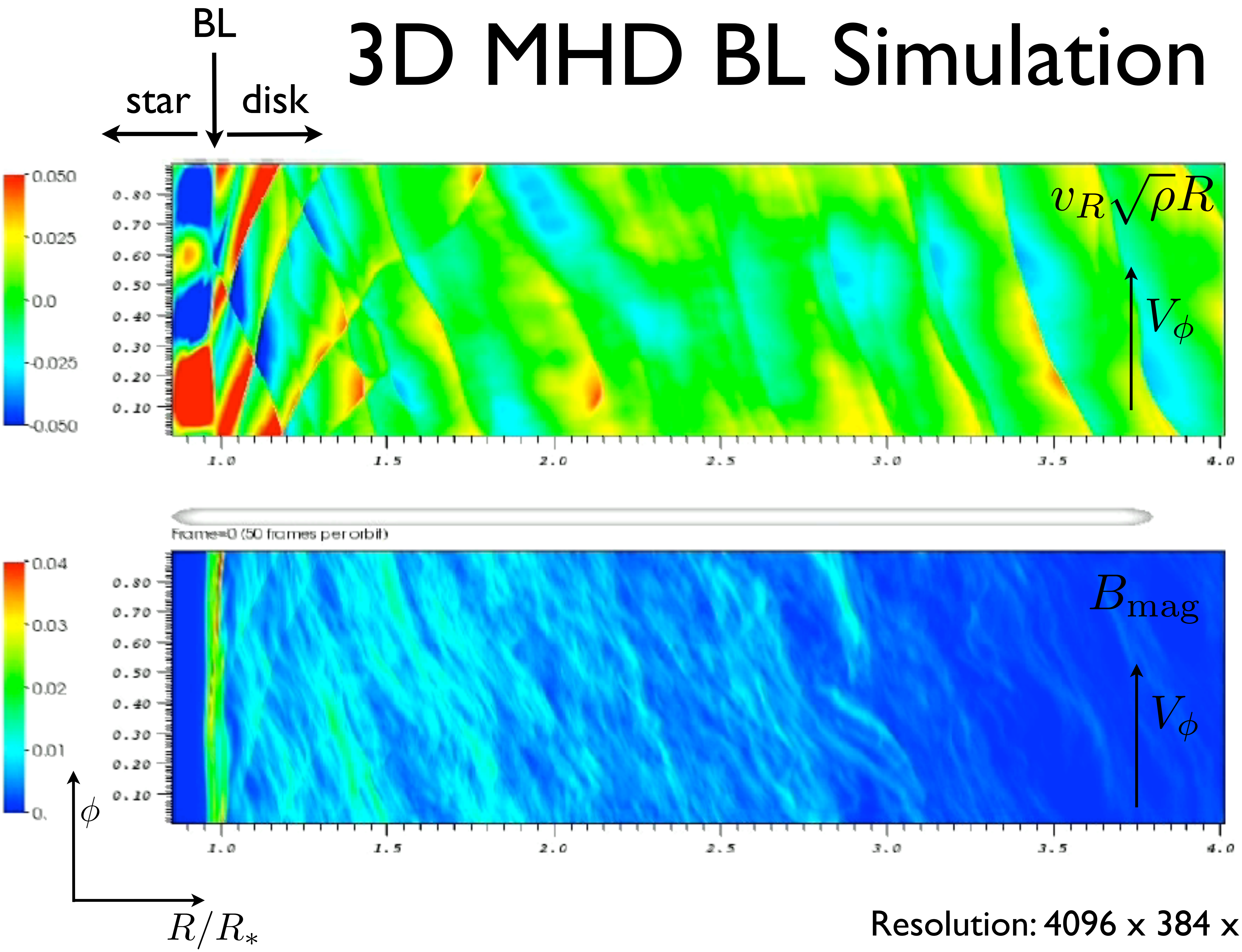
$\dot{\mathrm{M}} \lesssim 2 \times 10^{-10} \mathrm{M}_\odot/\mathrm{yr}$

$\mathrm{T_{BL}} \sim .2 - 2 \times 10^8 \mathrm{K}$

$M \equiv V_K/s_{BL} \sim 1$

Quiescent, optically thin

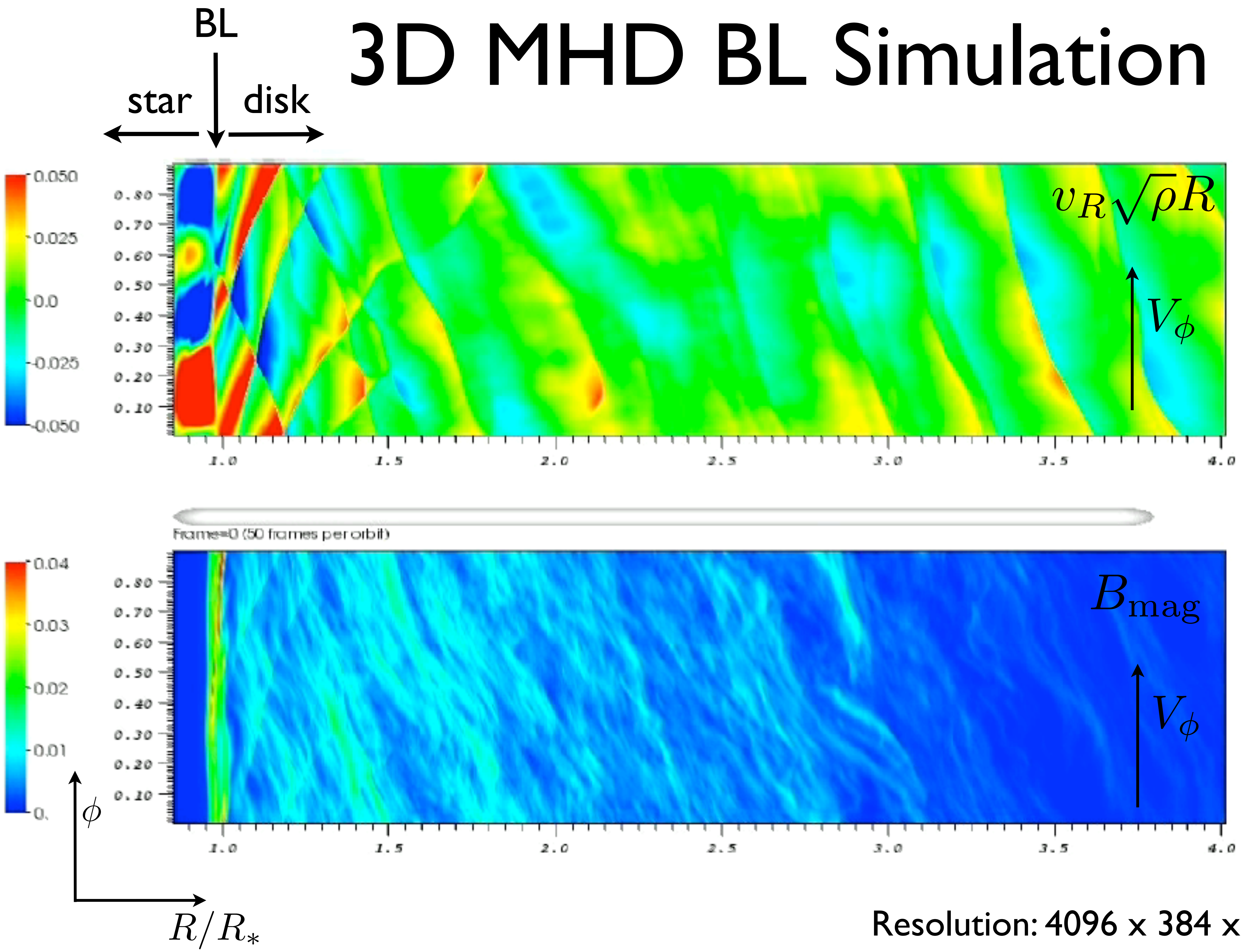
3D MHD BL Simulation



Resolution: 4096 x 384 x 128

Both variables have been vertically averaged along z.

3D MHD BL Simulation

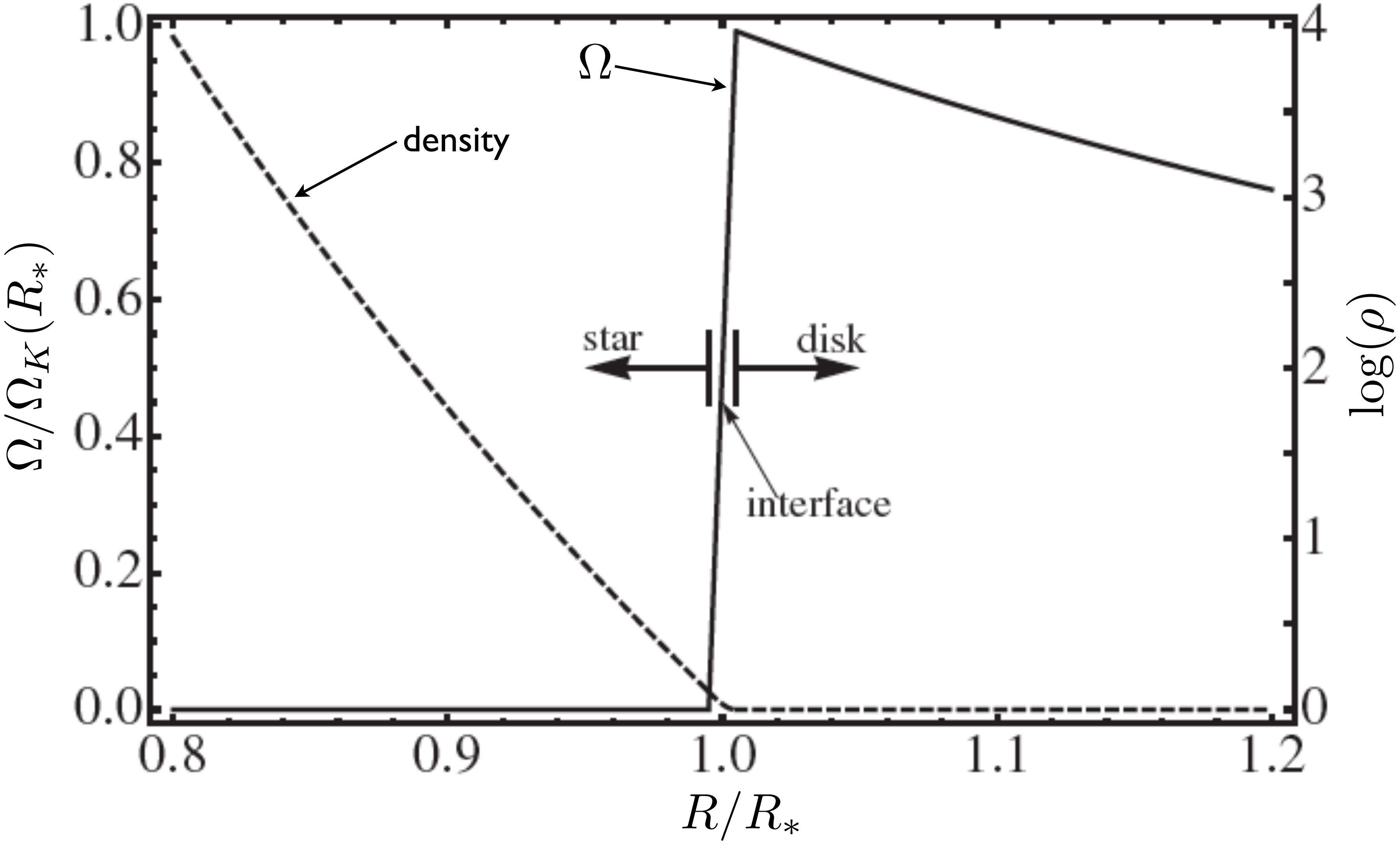


Resolution: 4096 x 384 x 128

Both variables have been vertically averaged along z.

Disk +BL + Star

Zoom-in of initial conditions around $R = R_*$



initial density profile

$$\rho(R) = \begin{cases} \exp\left[-\frac{\int^{\varpi} dR' g(R')}{s^2}\right], & \text{star} \\ 1, & \text{disk} \end{cases}$$

fixed potential

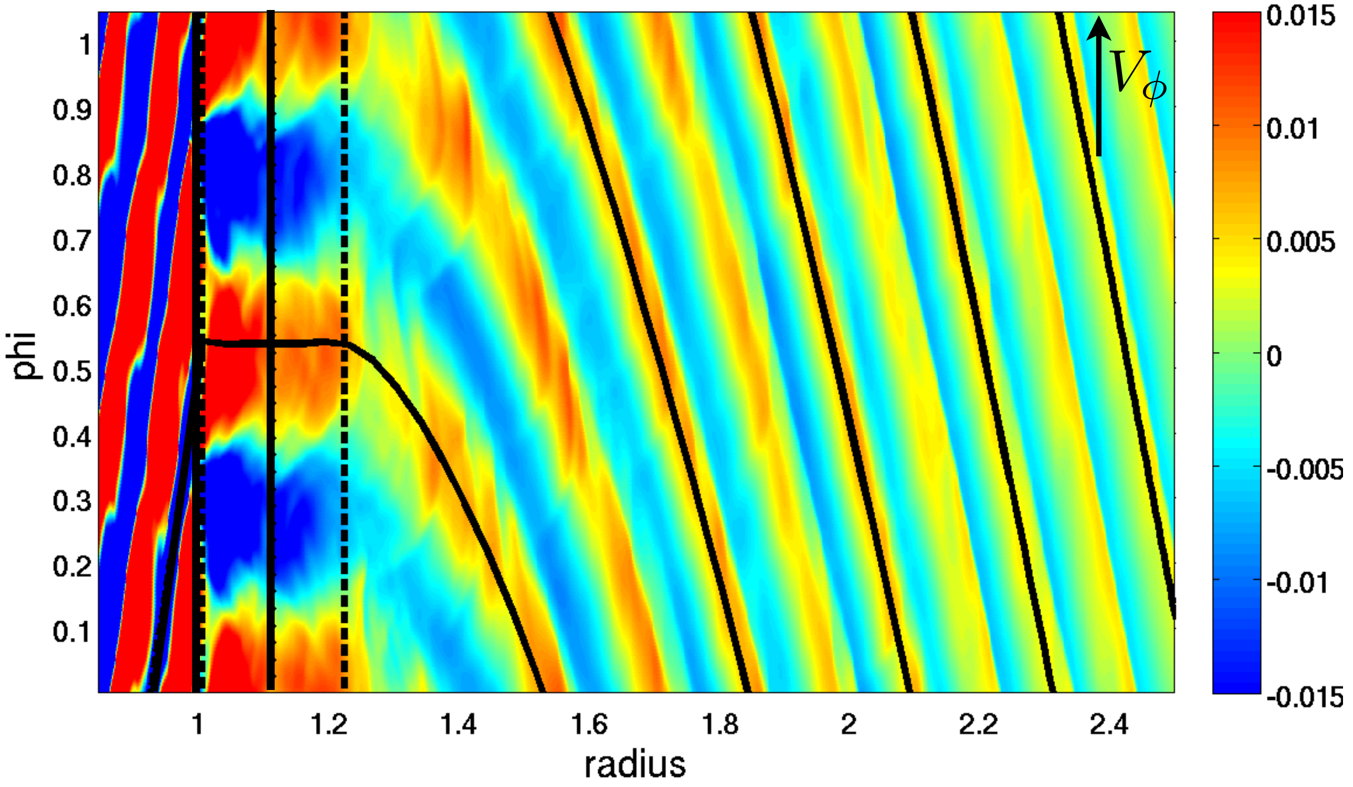
$$\Phi(R) = -1/R$$

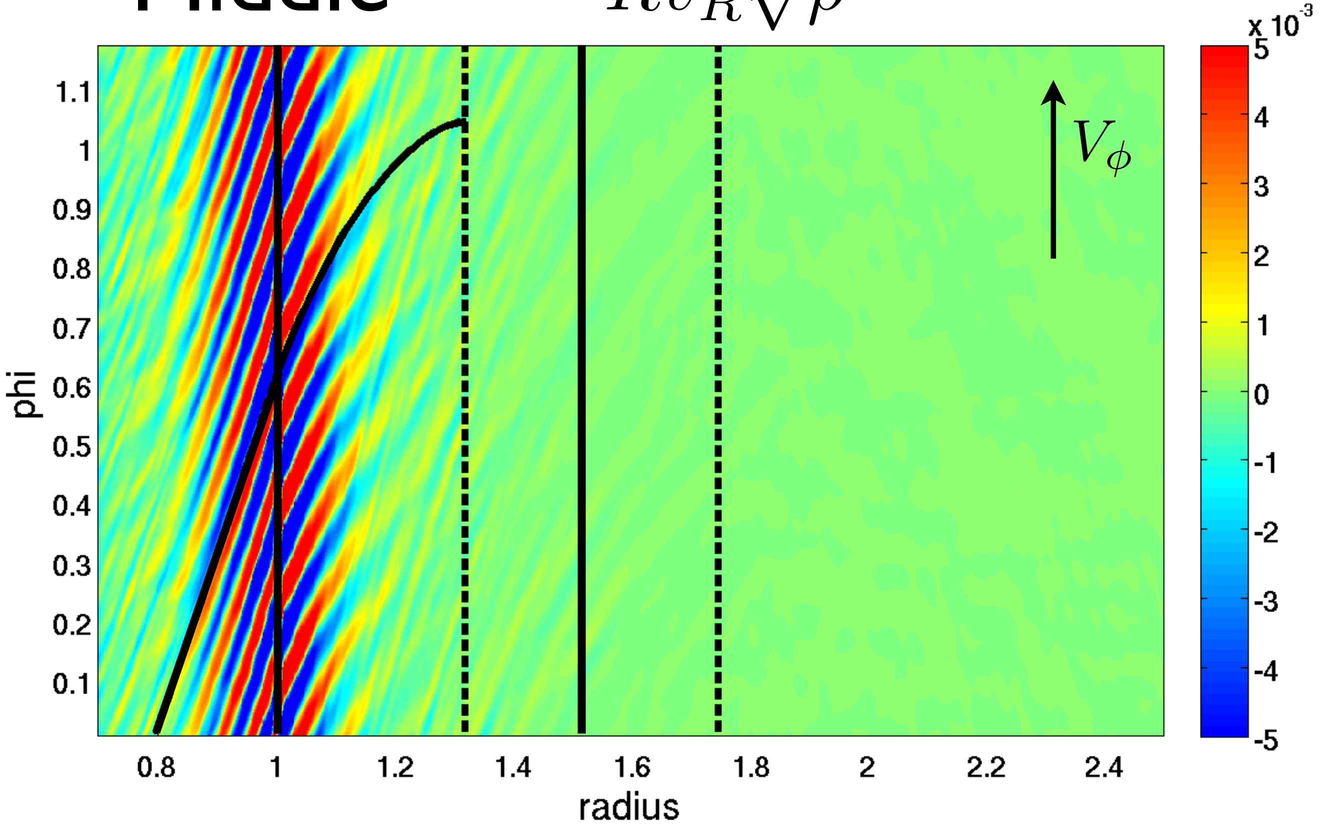
isothermal EOS

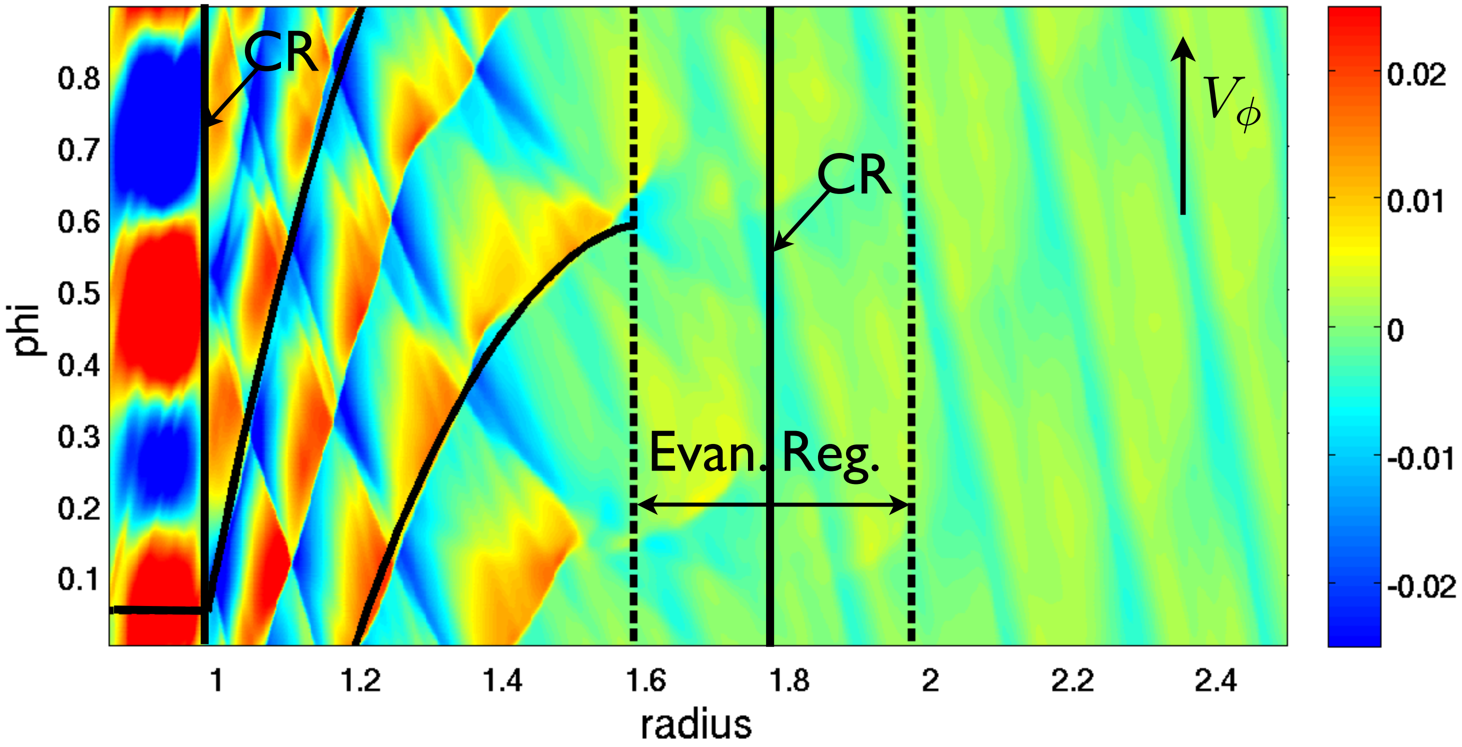
$$P = \rho s^2$$

$$M \equiv \Omega_K(R_*) R_*/s \sim 10$$

Three Wave Branches


Upper $Rv_R\sqrt{\rho}$


Middle $Rv_R\sqrt{\rho}$


Lower $Rv_R\sqrt{\rho}$

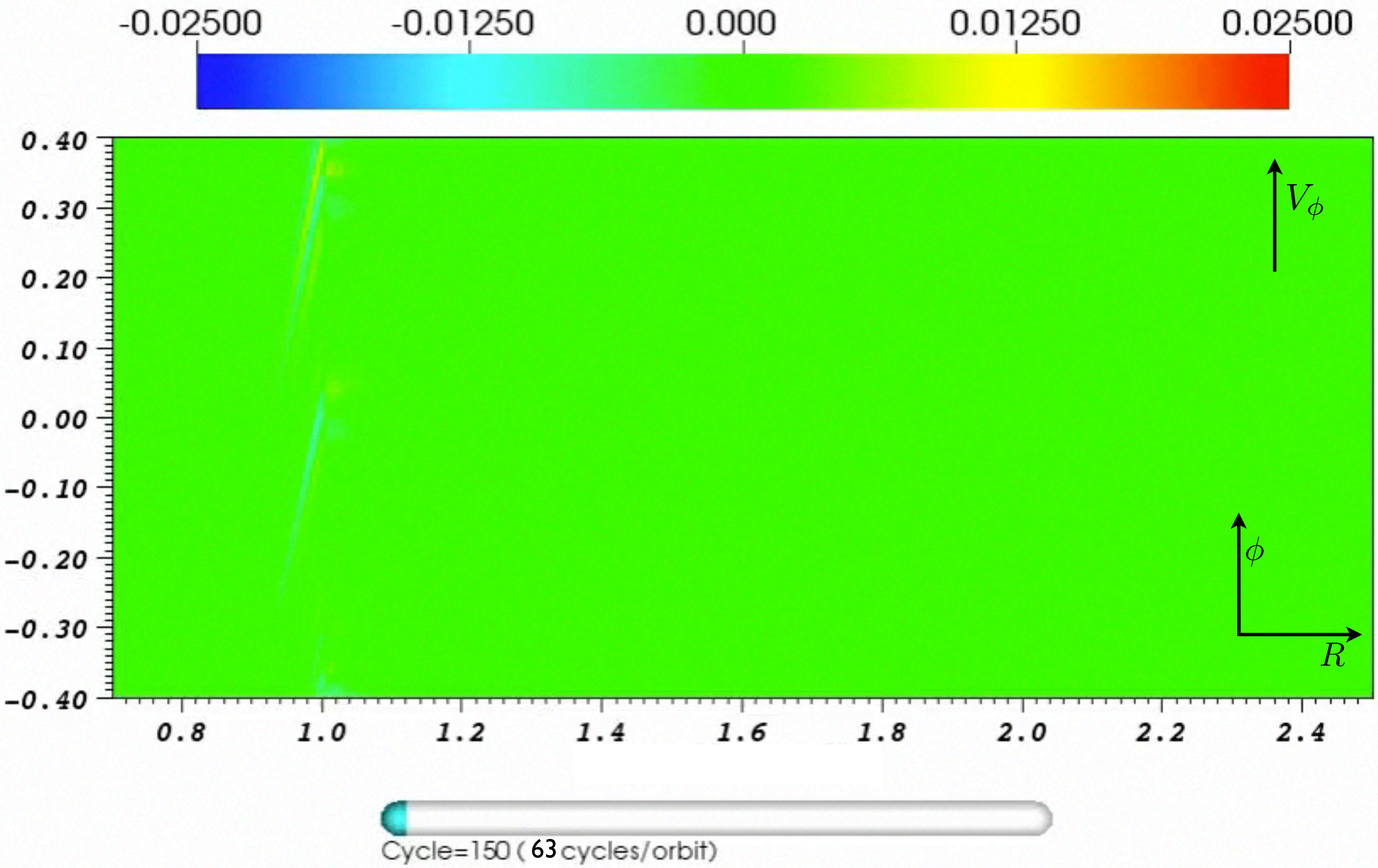
Wave branches characterized by:

Upper: Sound wave in disk propagating in the direction of the flow.

Lower: Gravitosonic wave in star propagating against direction of the flow.

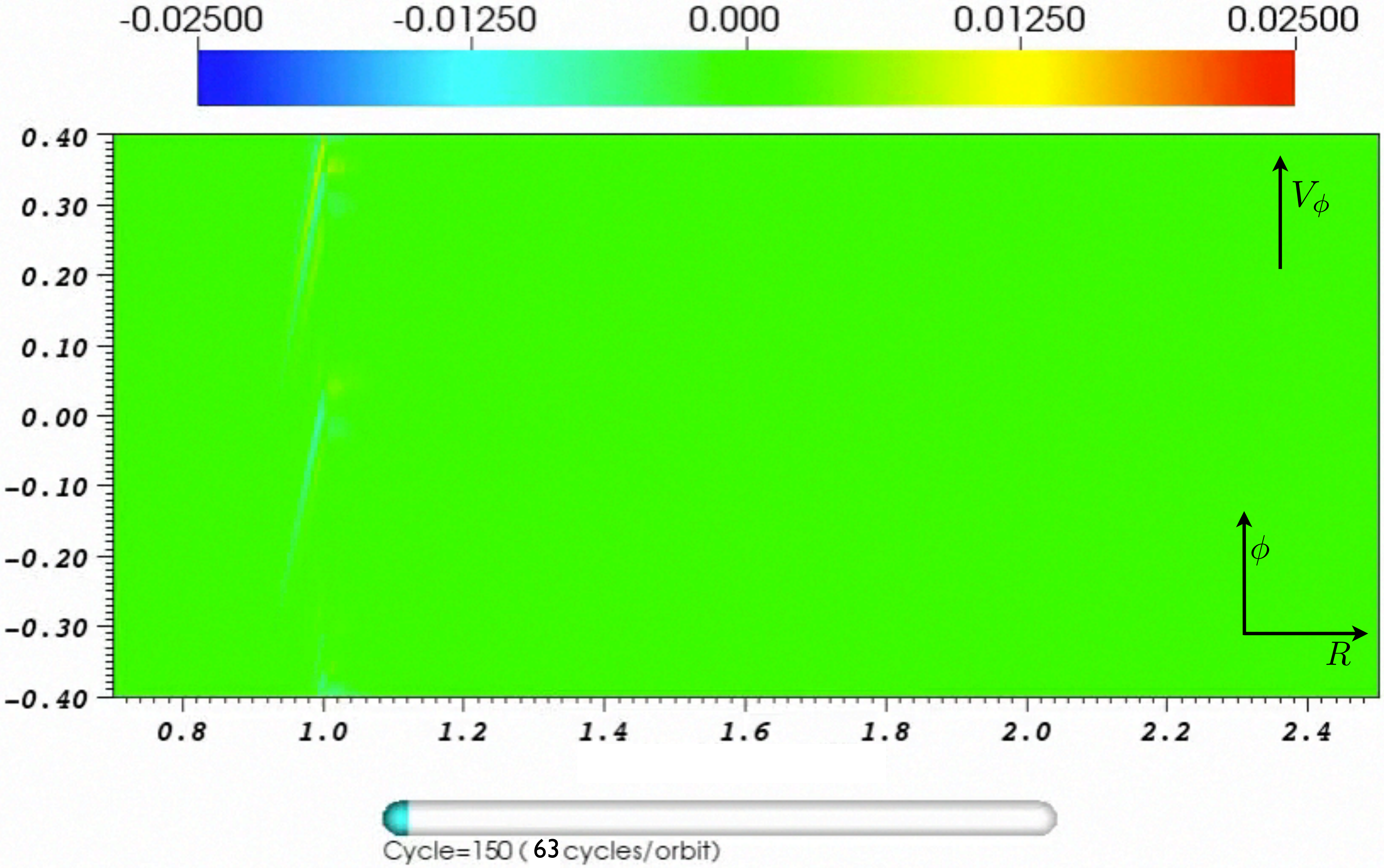
Middle: $\frac{k_{R,disk}(R_*)}{k_\phi} \approx \frac{k_{R,star}}{k_\phi}$

V_R 2D hydro



$R^2 \Sigma \delta V_R^2 \approx \mathrm{const}$ in the absence of dissipation for waves.

V_R 2D hydro



$R^2\Sigma\delta V_R^2 \approx \text{const}$ in the absence of dissipation for waves.

The Role of Mach Number

- KH regime (M << 1) 2 modes: $\frac{\omega}{k_y} = \pm i \frac{\Delta V}{2}$
- Acoustic mode regime (M >> 1) 3 modes: $\frac{\omega}{k_y} = \pm\,(M-1)\,s,\ \ \frac{\omega}{k_y} = 0$

Finite width of shear layer ***very important***

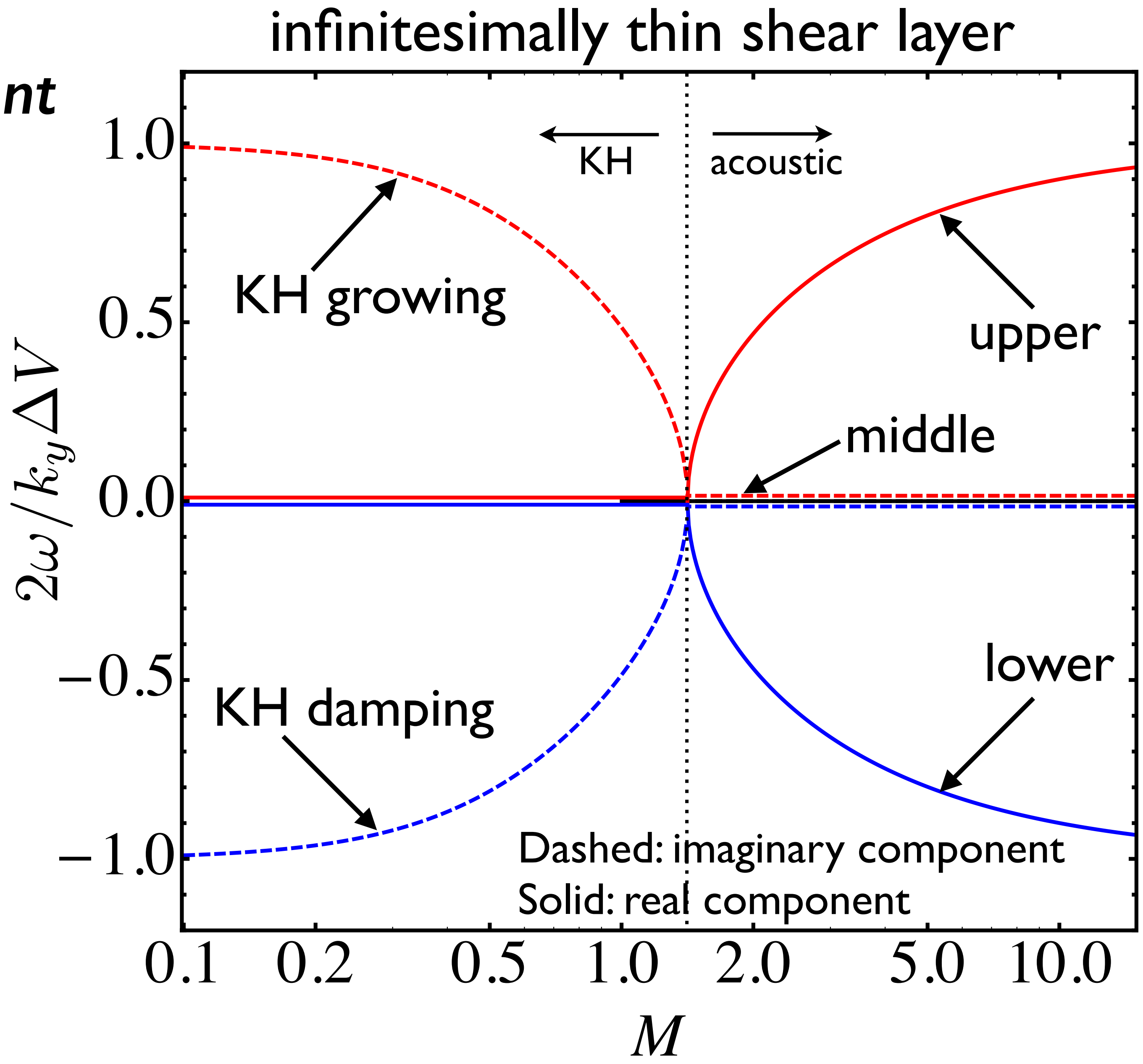
Shear instability: fastest growing mode

$$\mathrm{Im}[\omega_{max}] \sim \Delta V/\delta,\ \ k_y\delta \sim 1$$

True of both KH and acoustic regime

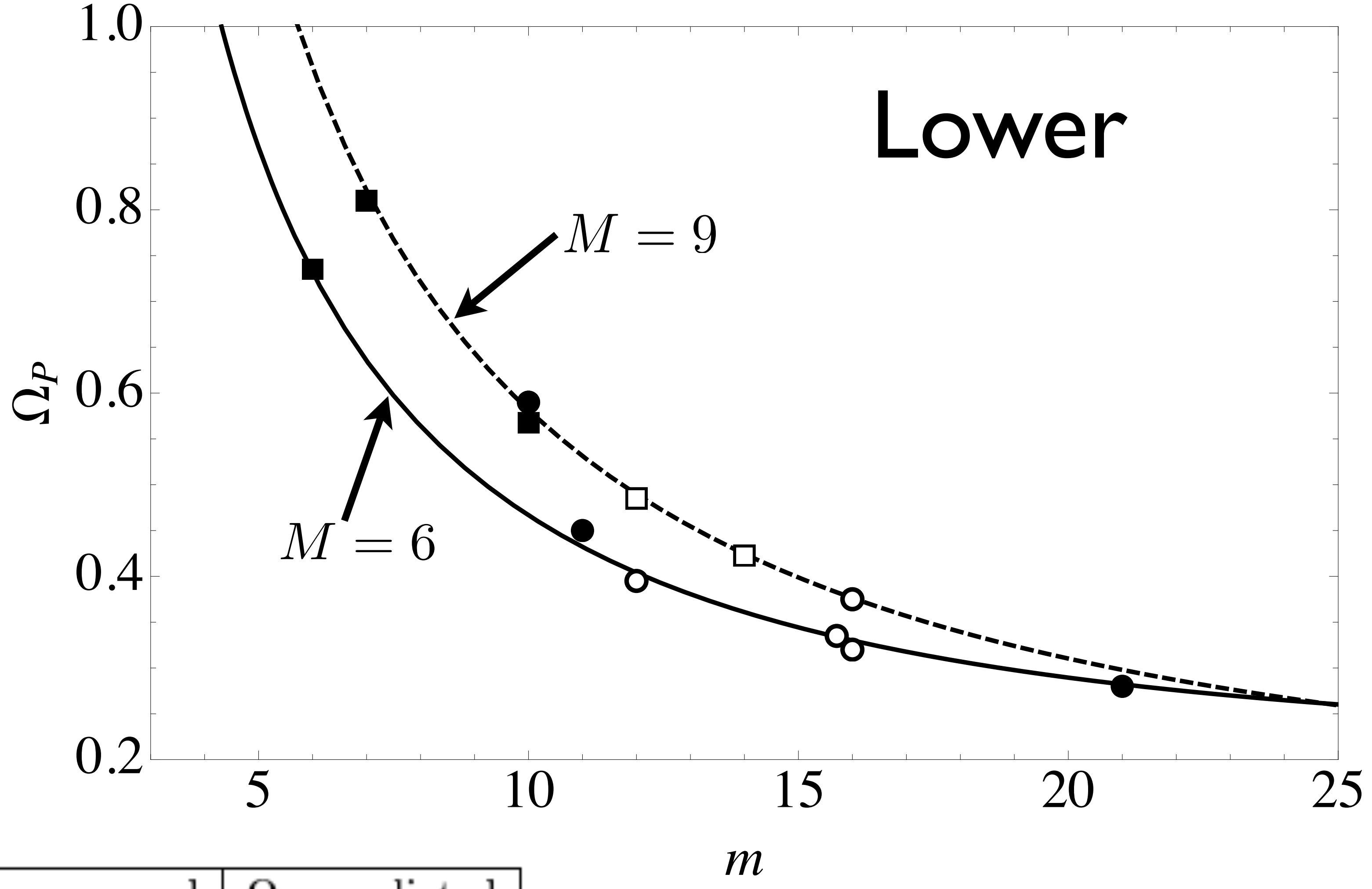
Acoustic regime

$$\mathrm{Im}[\omega] = 0, \quad k_y\delta \gg 1$$



infinitesimally thin shear layer

Comparison of Theory to Simulations



Lower

Upper

label	time	m	Ω_P measured	Ω_P predicted
2D6a	20	≈ 40	.84	.831
2D6b	20	≈ 40	.835	.831
2D6c	20	≈ 40	.835	.831
3D9a	100	≈ 10	.83	.850
3D9d	60	12	.85	.861
2D9a	30	≈ 29	.87	.884
2D9a	280	11	.815	.856
2D9b	30	≈ 24	.87	.881
2D9c	30	≈ 32	.88	.885

Middle

label	time	m	Ω_P measured	Ω_P predicted
3D6a	10	≈ 42	.535	.502
3D6d	10	≈ 36	.53	.503
3D9e	20	≈ 28	.57	.515

Standard BL Picture

azimuthal momentum equation

$$\dot{M}\Omega R^2 + 2\pi R^3 \nu \Sigma \frac{d\Omega}{dR} = \dot{J},$$

constant accretion rate

$$\dot{M} = -2\pi R v_R \Sigma,$$

alpha viscosity

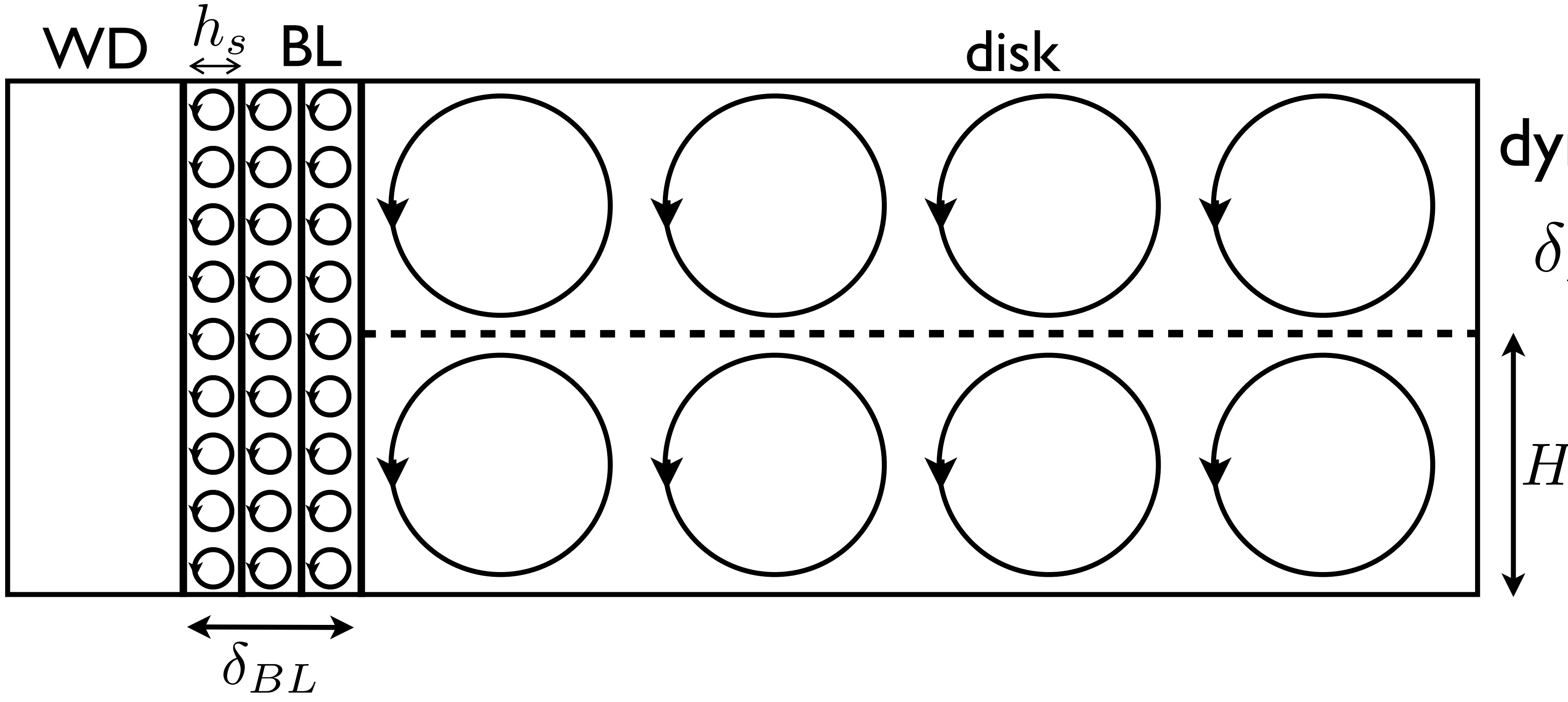
$$\nu = \alpha s \min(H, h_s)$$

radial momentum equation

$$v_R \frac{dv_R}{dR} = \left(\Omega^2 - \Omega_K^2\right) R - \frac{1}{\Sigma}\frac{dP}{dR},$$

disk scale height & star pressure scale height

$$H \equiv \frac{s}{\Omega_K R} R, \qquad h_s \sim \left(\frac{s}{\Omega_K R}\right)^2 R$$



dynamical boundary layer width

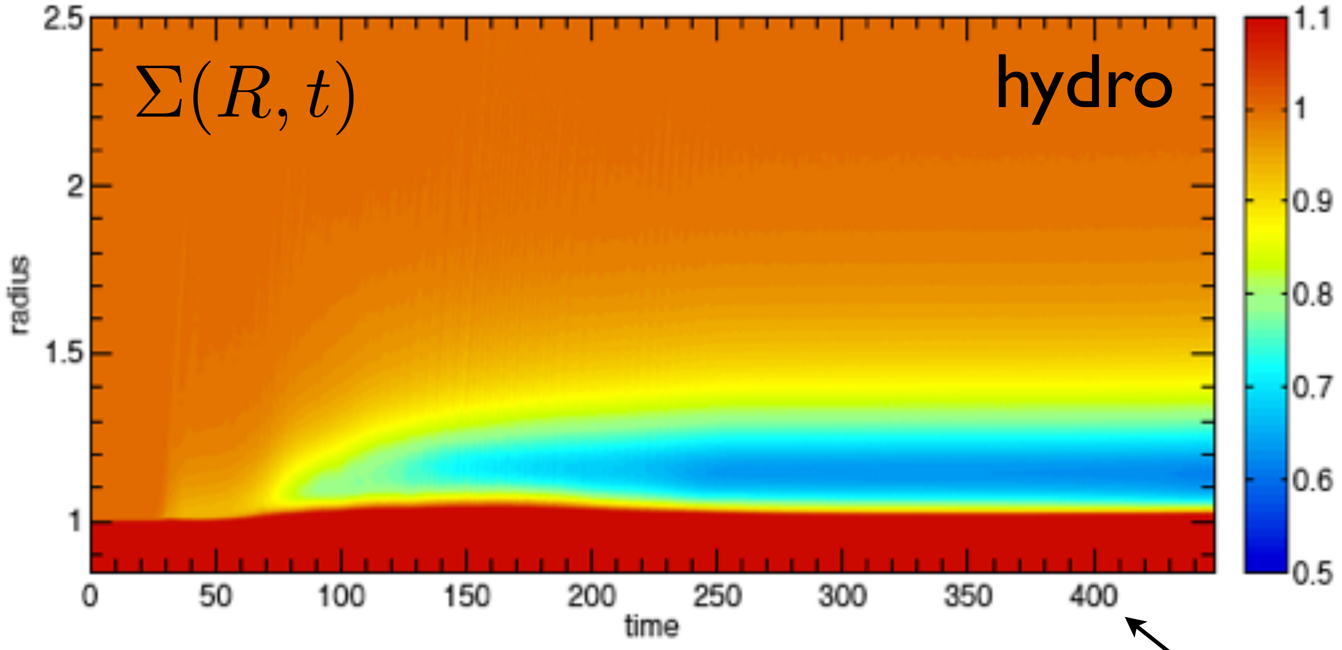
$$\delta_{BL} = n_{HS} h_s = n_{HS} M_*^{-2} R_*$$

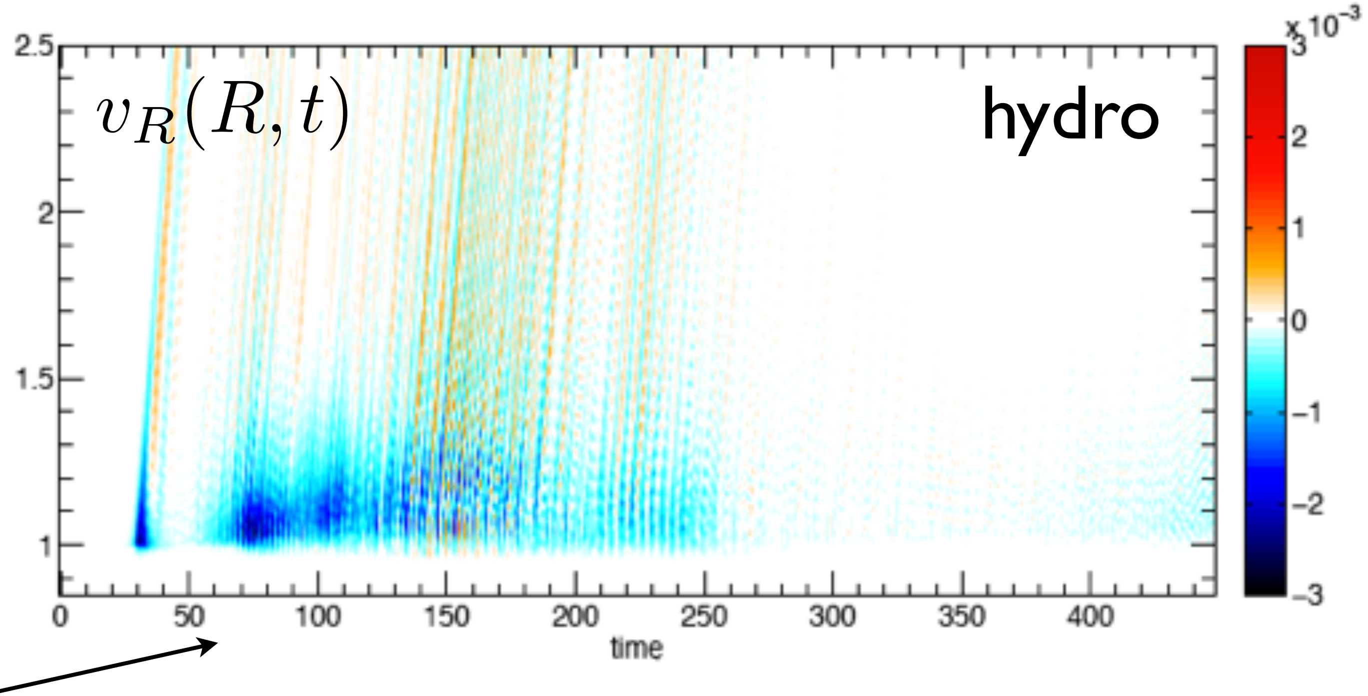
Mach number

$$M \equiv \frac{\Omega_K R}{s} \sim 40$$

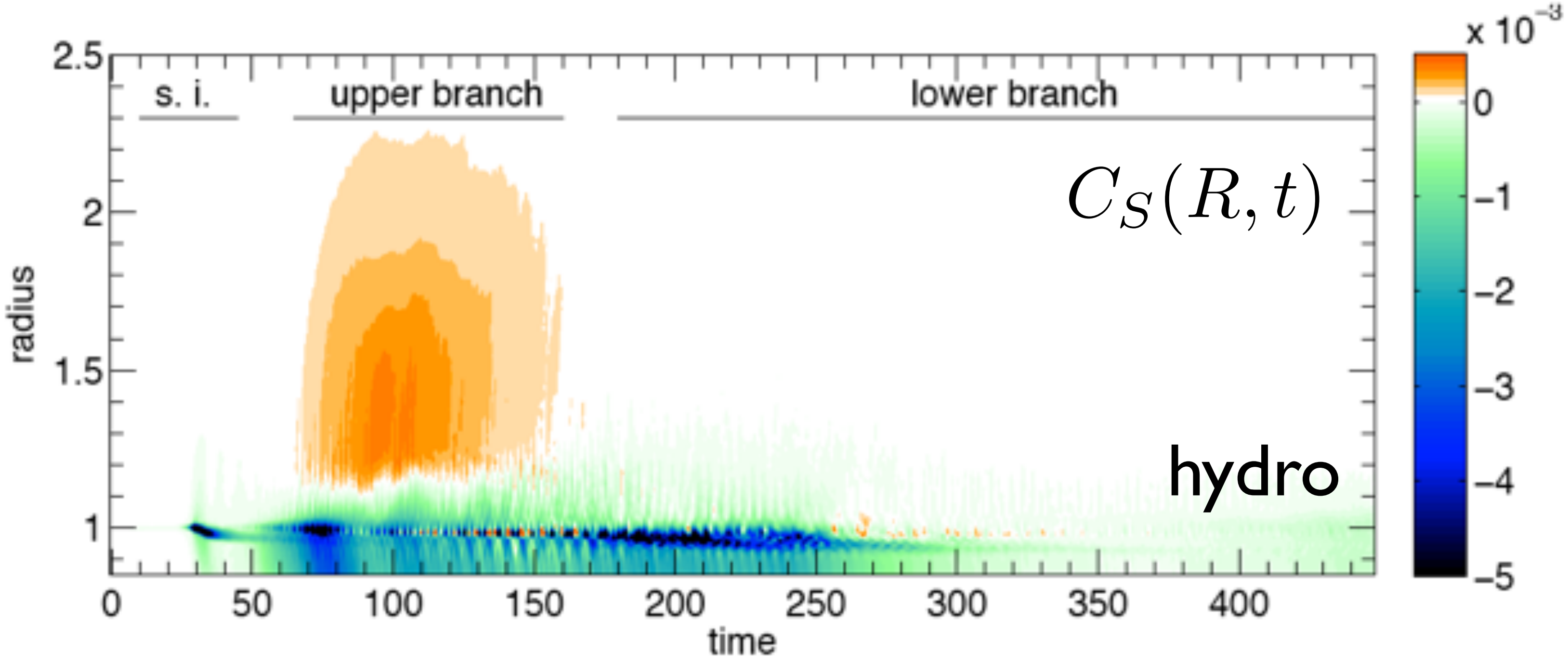
What is the mechanism of ang. mom. transport in the boundary layer?
Not MRI turbulence since BL is (linearly) stable to MRI ($d\Omega/dR > 0$).

New BL Picture: Waves Transport AM





At $t \approx 75$ density gap opened in inner disk. Simultaneously, accretion onto the star.



Stress angular momentum current

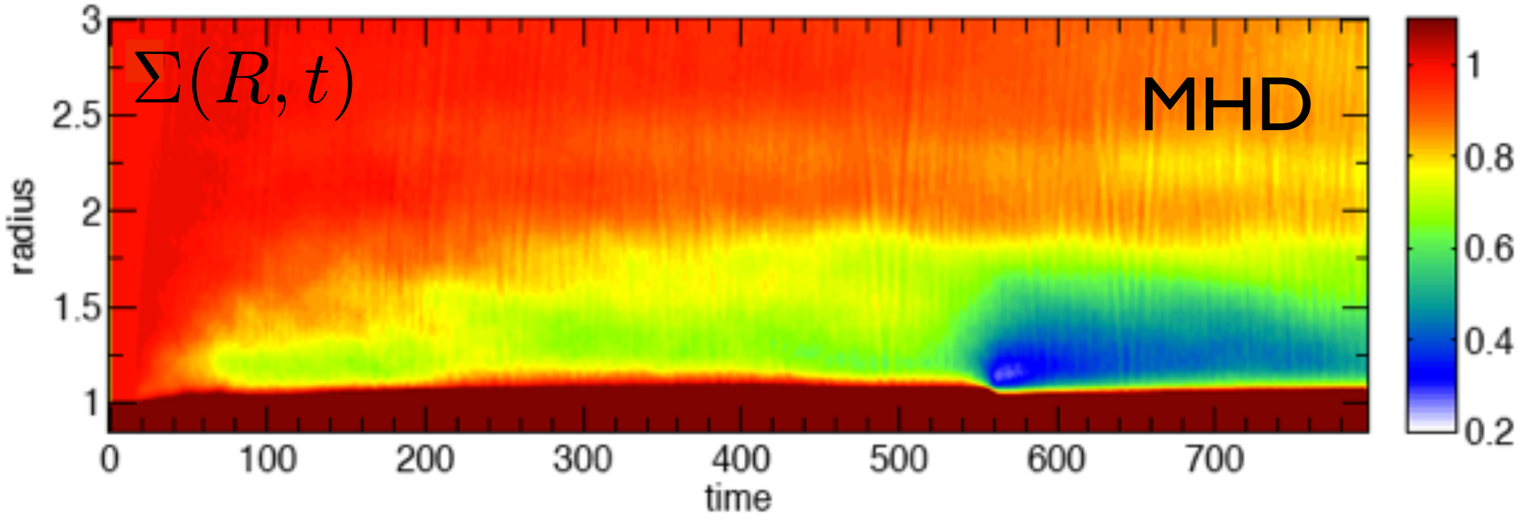
$$C_S \equiv 2\pi R^2 \Sigma \langle \delta v_\phi v_R \rangle$$

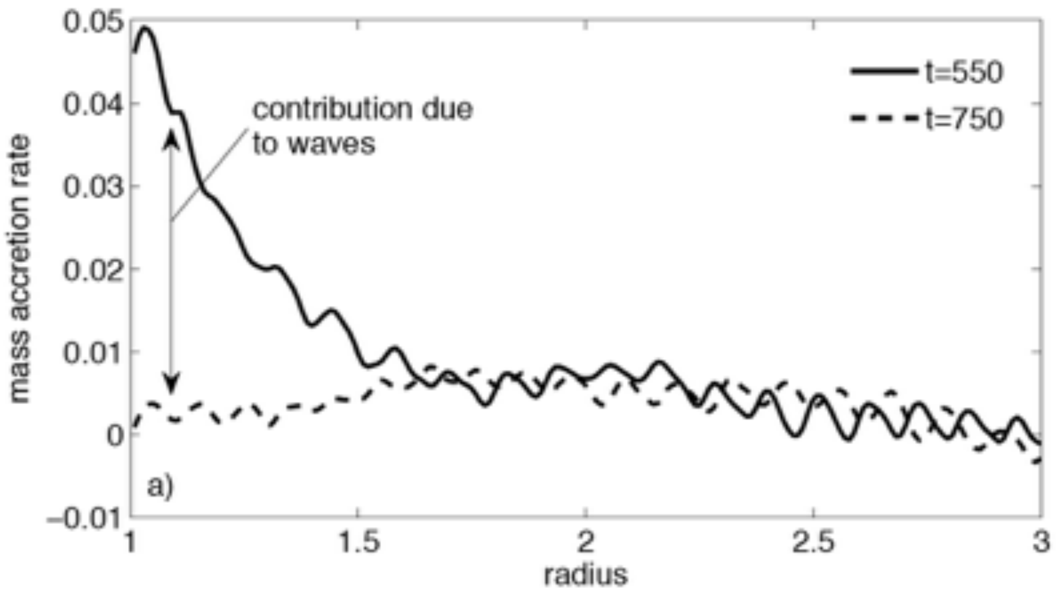
Mass accretion rate

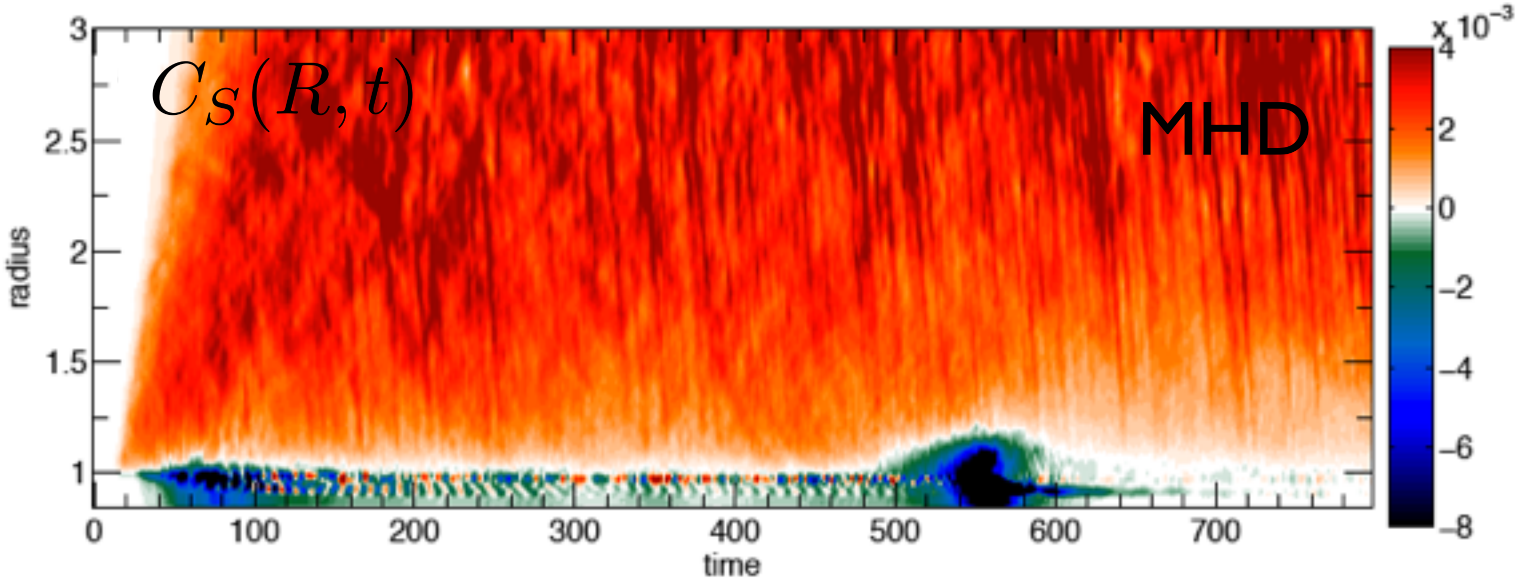
$$\dot{M} = \left(\frac{dl}{dR}\right)^{-1} \frac{\partial C_S}{\partial R}$$

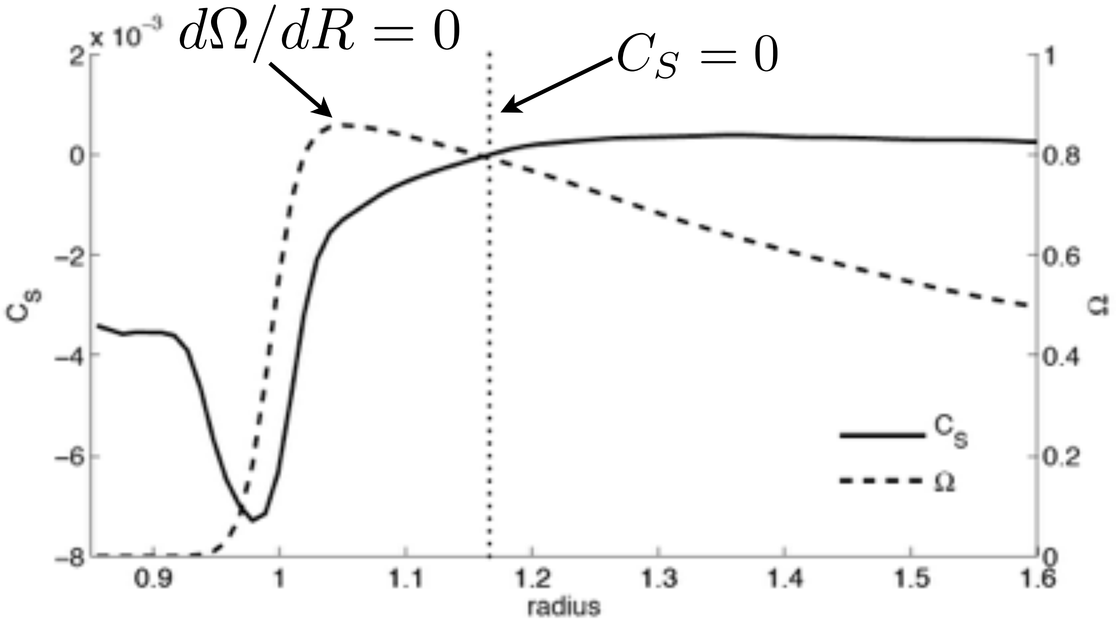
Angular momentum is radiated away from the BL into both the star and the disk.

Angular Momentum Transport: MHD









- A.M.T by waves in inner disk and star, MRI throughout disk.
- Gap formation and BL widening due to magnetosonic modes.
- Possible stochastic re-excitation of modes on viscous timescale

Comparison: waves vs. anomalous viscosity

Waves:

- Travel long distances before dissipating - Nonlocal heating.
- C_S changes sign at the corotation radius of the mode.
- C_S depends on amplitude, wavenumber, and wave branch of excited mode. Modes are potentially stochastically excited.

Anomalous Turbulent Viscosity: $\nu_{\rm turb} \equiv \alpha s H, \quad \alpha \approx {\rm constant}$

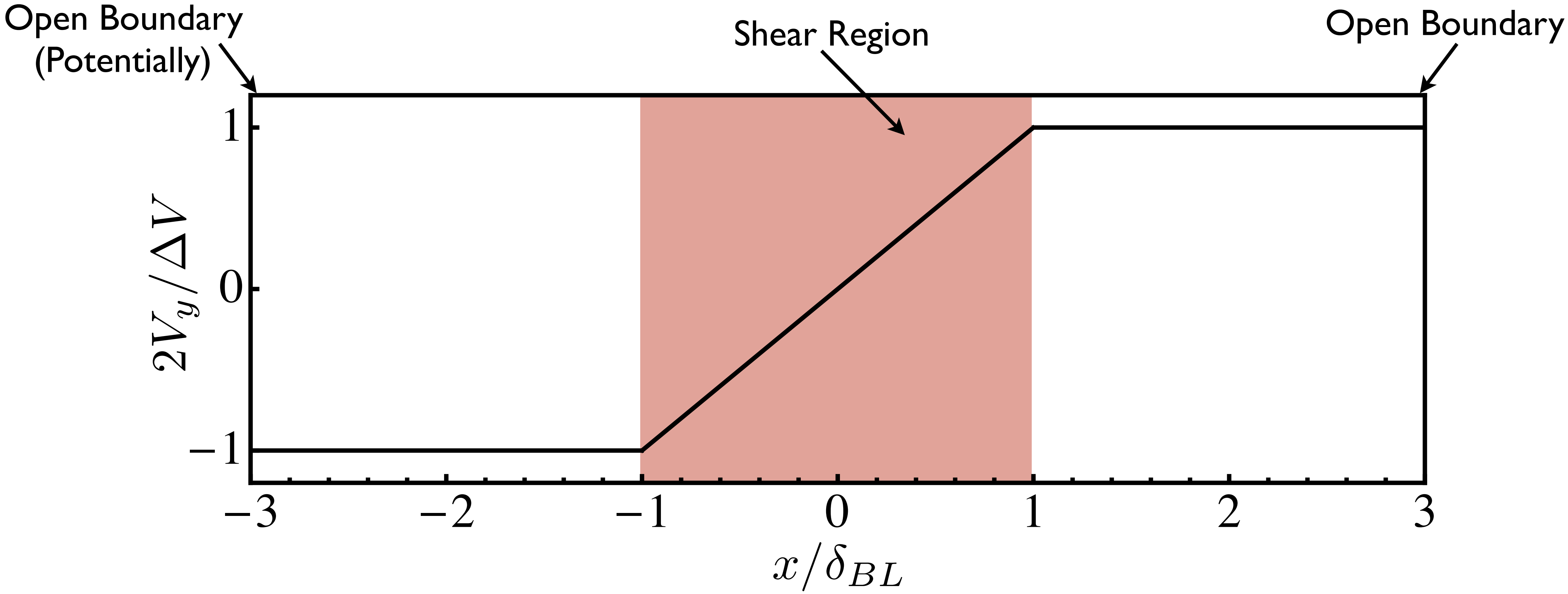
- Local dissipation and heating: $Q_d = \frac{1}{2}\Sigma \nu_{\rm turb}(R d\Omega/dR)^2$
- C_S changes sign where $d\Omega/dR = 0 : C_S = -2\pi R^3 \Sigma \nu_{\rm turb} d\Omega/dR$
- Turbulent viscosity is typically quasi steady state.

Conclusion

Waves Transport Angular Momentum in the Boundary Layer

Acoustic Instability is like the “MRI” of the boundary layer.

BL Model #1: Compressible Shear Layer



Velocity profile

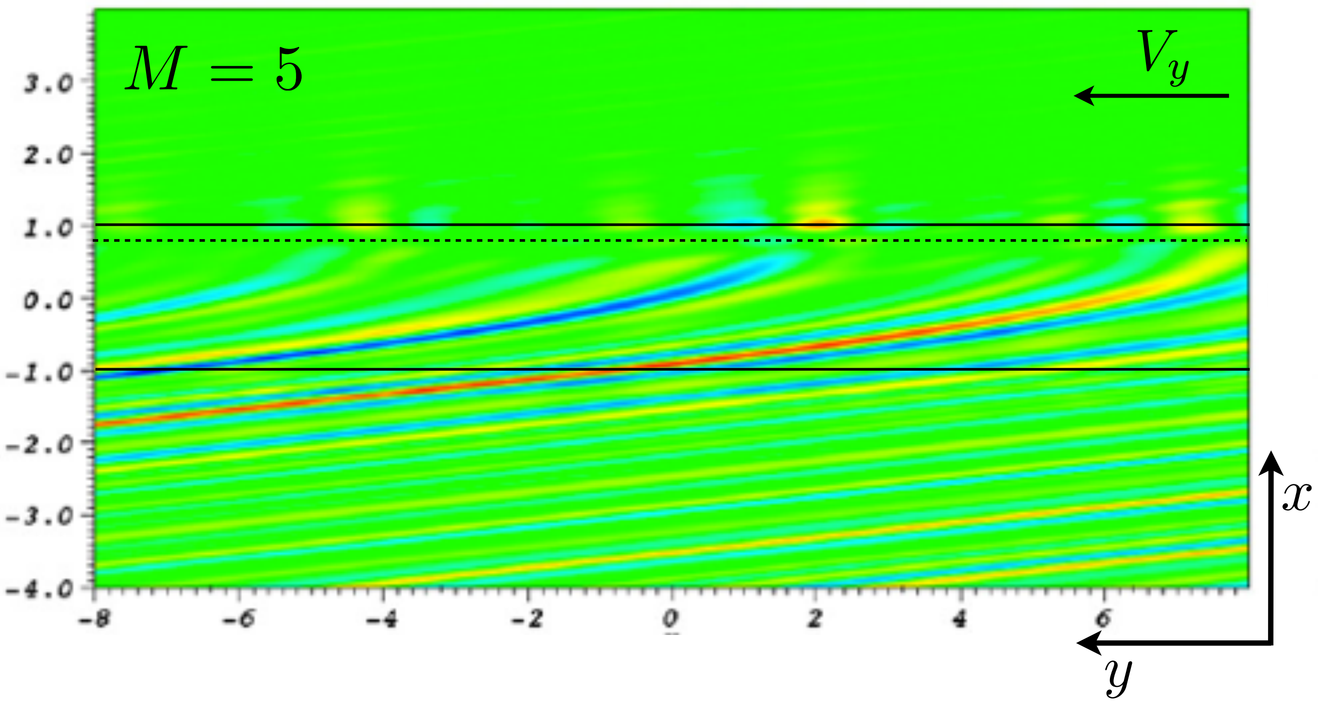
$$V_y(x) = \begin{cases} \Delta V/2, & x > \delta_{BL} \\ \Delta V x/2\delta_{BL}, & -\delta_{BL} \leq x \leq \delta_{BL} \\ -\Delta V/2 & x < \delta_{BL} \end{cases}$$

Mach number

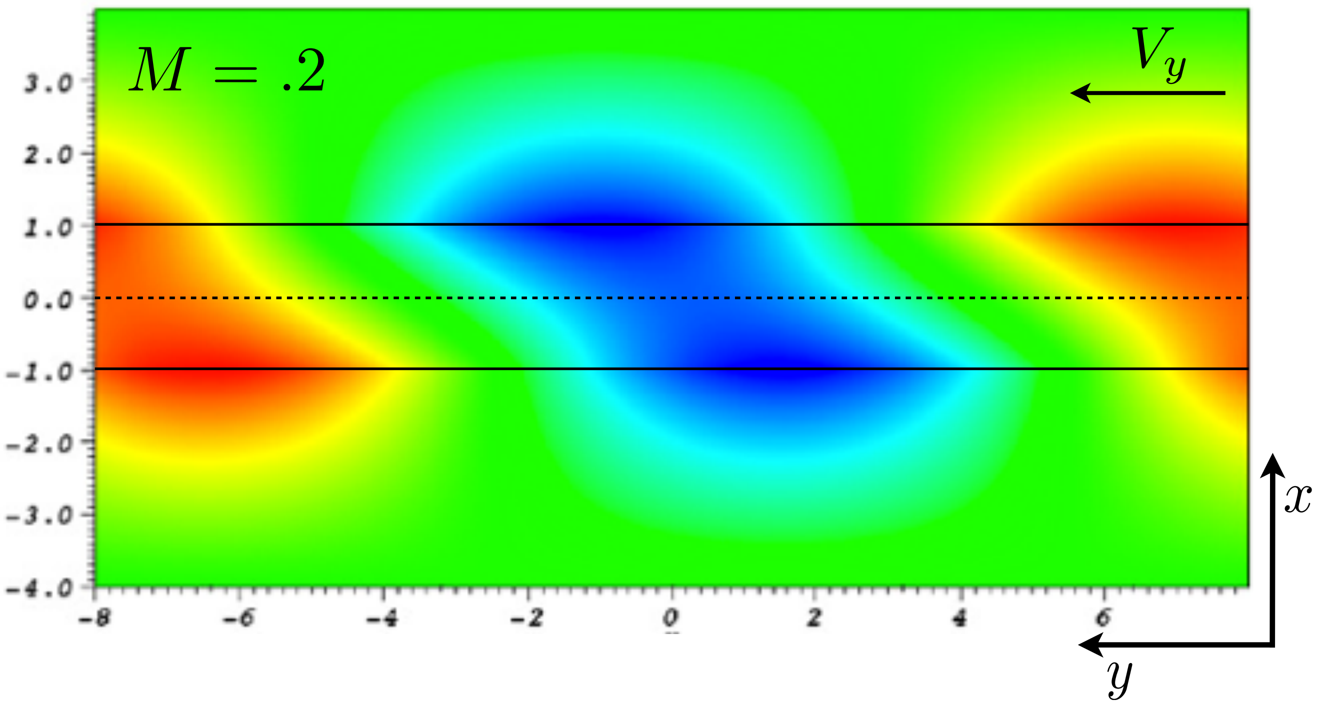
$$M \equiv \Delta V/2s$$

Shear Instability for Linear Velocity Profile

Plot of δV_x for radiation mechanism



Plot of δV_x for KH instability



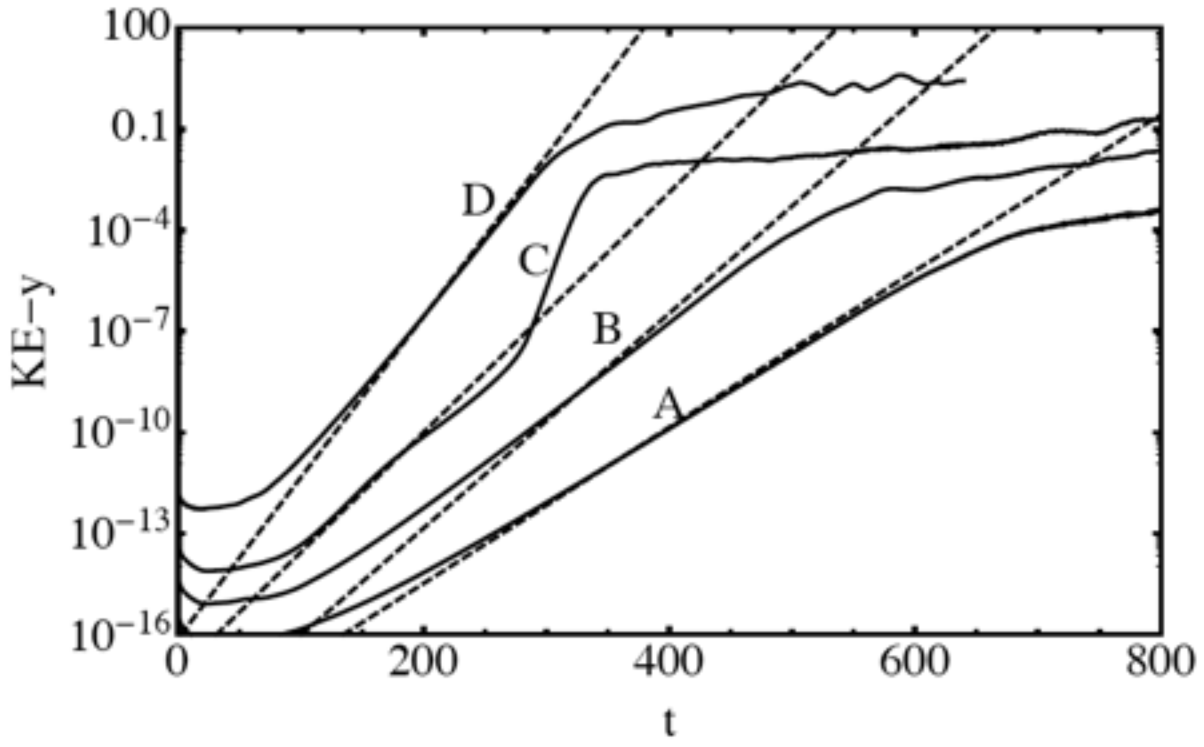
growth rate estimate

$$\mathrm{Im}[\omega] \approx \epsilon \frac{s}{\delta_{BL}} = \frac{\epsilon M}{n_{HS}} \Omega_K(R_*)$$

$$\delta_{BL} \approx n_{HS} \frac{P}{dP/dR} = n_{HS} M^{-2} R_*$$

$$\epsilon \sim .2, \;\; n_{HS} \sim 6, \;\; M \sim 10 - 100$$

$$\mathrm{Im}[\omega] \sim .3\Omega_K(R_*) - 3\Omega_K(R_*)$$



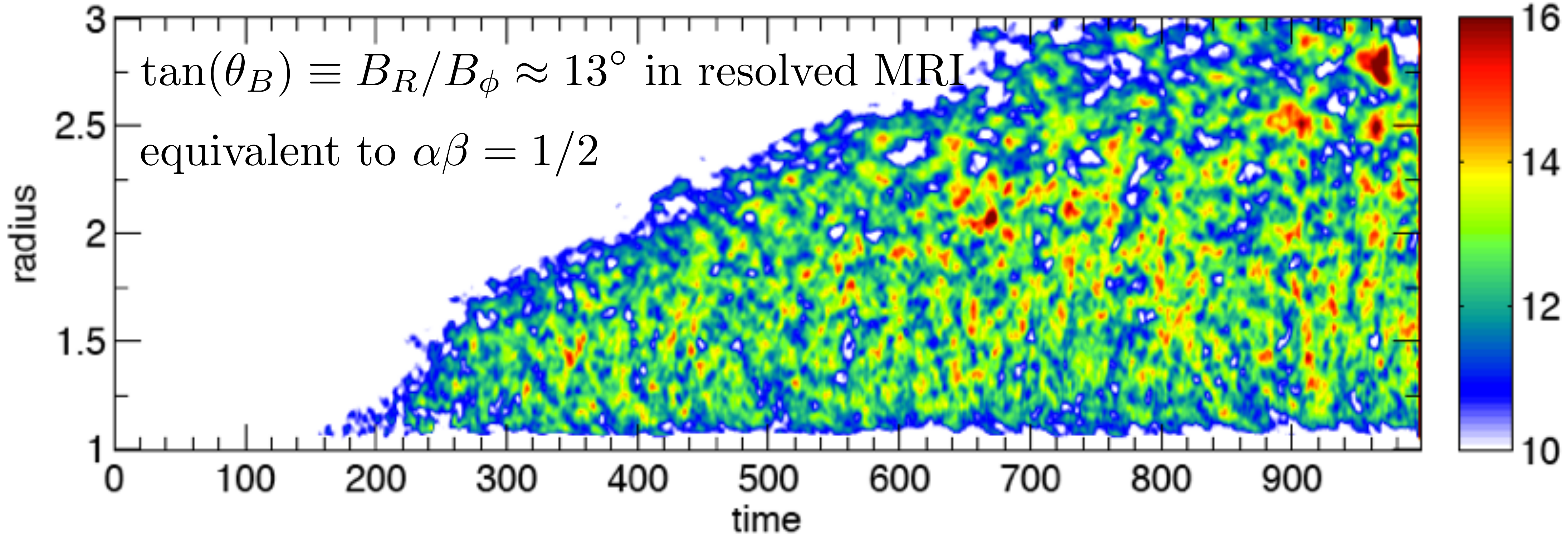
BL Model #2(MHD): Disk + BL + Star

Initial Field: $\mathbf{B} = 0 \text{ for } R > R_*$

$$\mathbf{B}(R \geq R_*, z) = \begin{cases} \frac{B_0}{R}\hat{\boldsymbol{z}}, & \text{NVF} \\ B_0\hat{\boldsymbol{\phi}}, & \text{NAF} \\ \frac{B_0}{R}\sin\left[\frac{2\pi}{\lambda_R}(R - R_*)\right]\hat{\boldsymbol{z}}, & \text{ZNF} \end{cases}$$

Stability: Disk is MRI unstable $\frac{d\Omega}{dR} < 0.$ BL is MRI stable $\frac{d\Omega}{dR} > 0\,.$

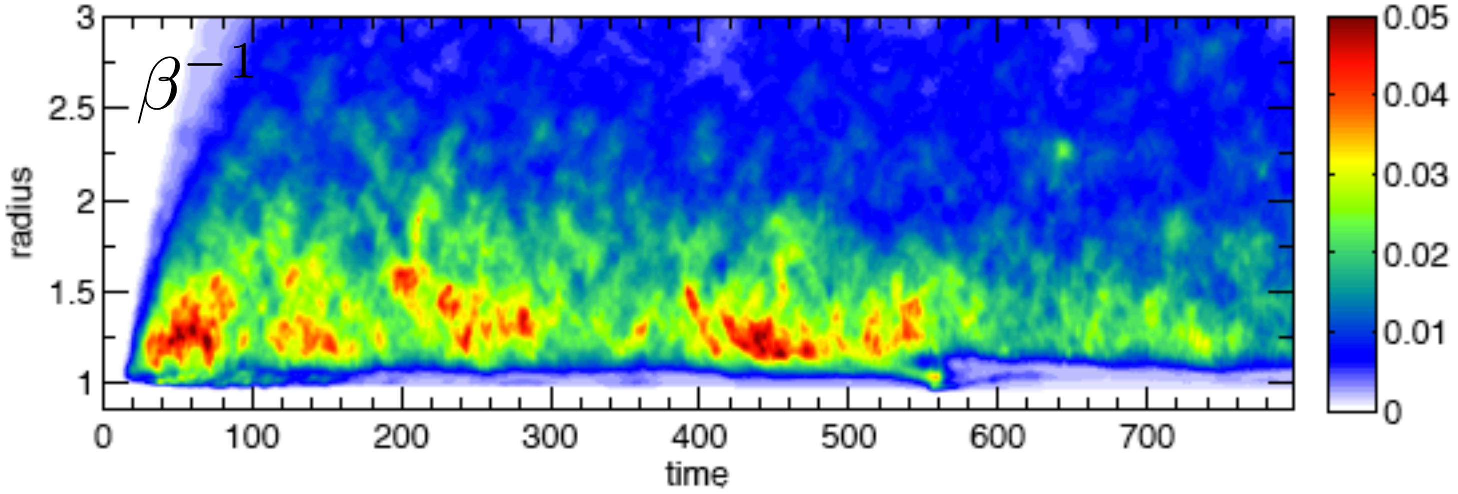
Convergence for MRI in disk (NAF geometry):

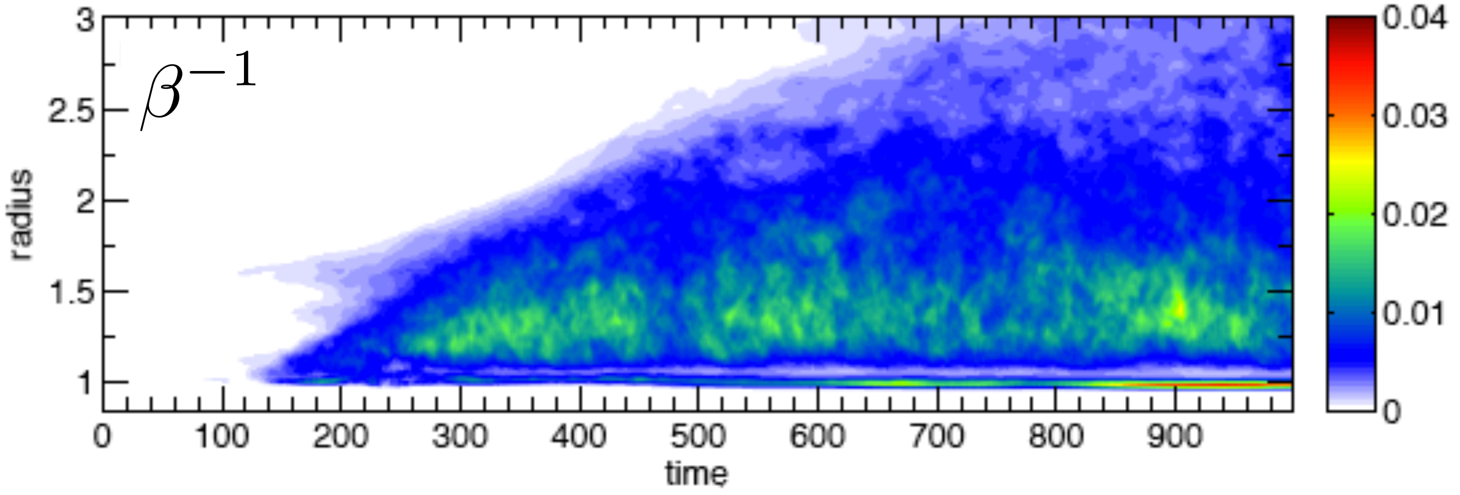


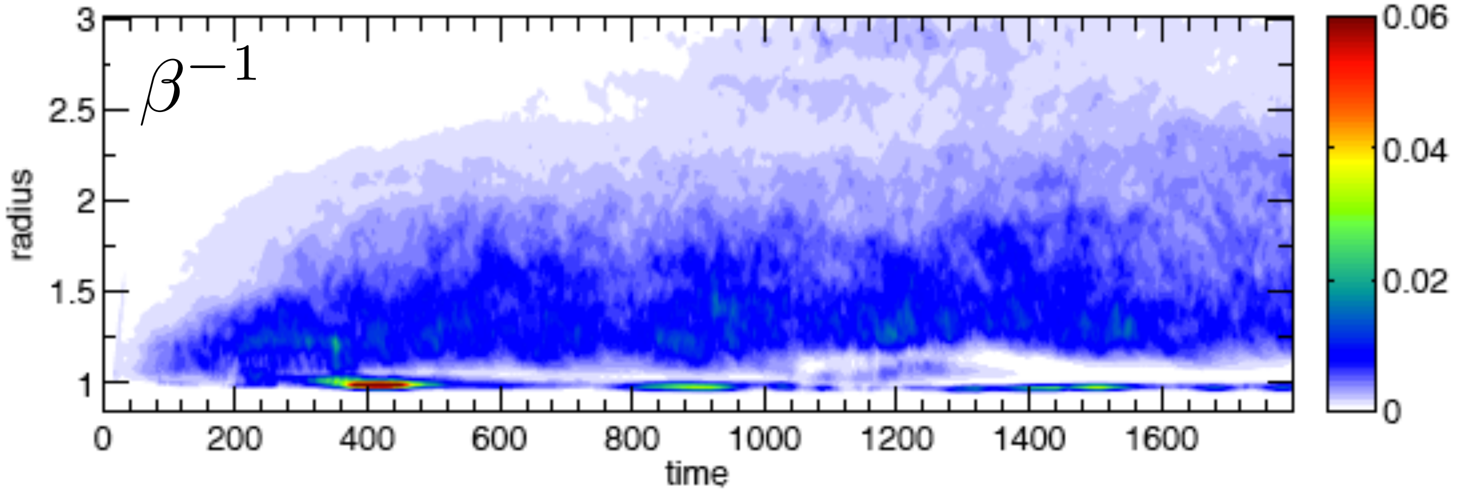
$\tan(\theta_B) \equiv B_R/B_\phi \approx 13^\circ$ in resolved MRI

equivalent to $\alpha\beta = 1/2$

The Role of β


NVF


NAF


ZNF

One expects acoustic modes to be modified by terms $\mathcal{O}\left(\beta^{-1}\right)$ in the MHD case.

$$\beta \equiv \frac{\rho s^2}{B^2/2\mu}$$

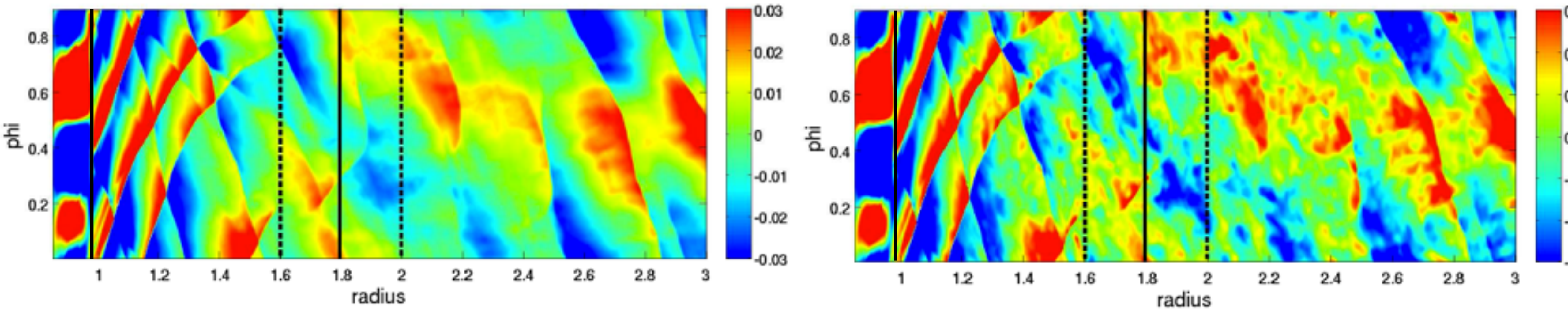
$$\begin{aligned} v_{\rm ms} &= \sqrt{s^2 + v_A^2} \\ &= s\sqrt{1 + \frac{2}{\gamma}\beta^{-1}} \end{aligned}$$

Since $\beta^{-1} \lesssim .05$, acoustic modes are not significantly modified by introduction of B field.

$$\beta_{BL}^{-1}/\beta_{disk}^{-1} \sim 1 - 5$$

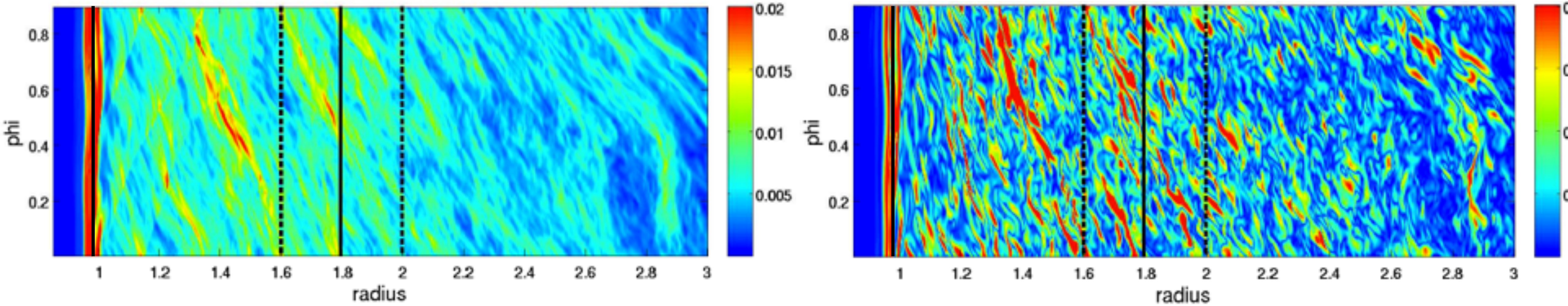
Magnetosonic Modes in the MHD Context

ZNF simulation - lower branch



v_R vertical average

v_R slice



B_{mag} vertical average

B_{mag} slice

- Magnetosonic modes resemble acoustic modes due to $\beta^{-1} \lesssim .05.$
- Amplification of B field in BL partly due to accretion and frozen-in flux law.

Astrophysical Implications

Hidden boundary layer problem in CVs:

$L_{BL}/L_{disk} \sim 1 \text{ in quiescence } \dot{M} \sim 10^{-12} - 10^{-10}$ (Pandel et al. 2005, Sion et al. 2005)

$L_{BL}/L_{disk} \ll 1 \text{ in outburst } \dot{M} \sim 10^{-9} - 10^{-8}$ (very little EUV or soft X-ray flux)

Two nearby systems UGem and VW Hyi have BL observed in outburst, but temperatures that are too low by factors of 2-3 according to models.

Why low BL temperature? **Solution:** waves carry energy away from BL!

DNOs/QPOs?

Very simplified model, but can generate regular periodicity.

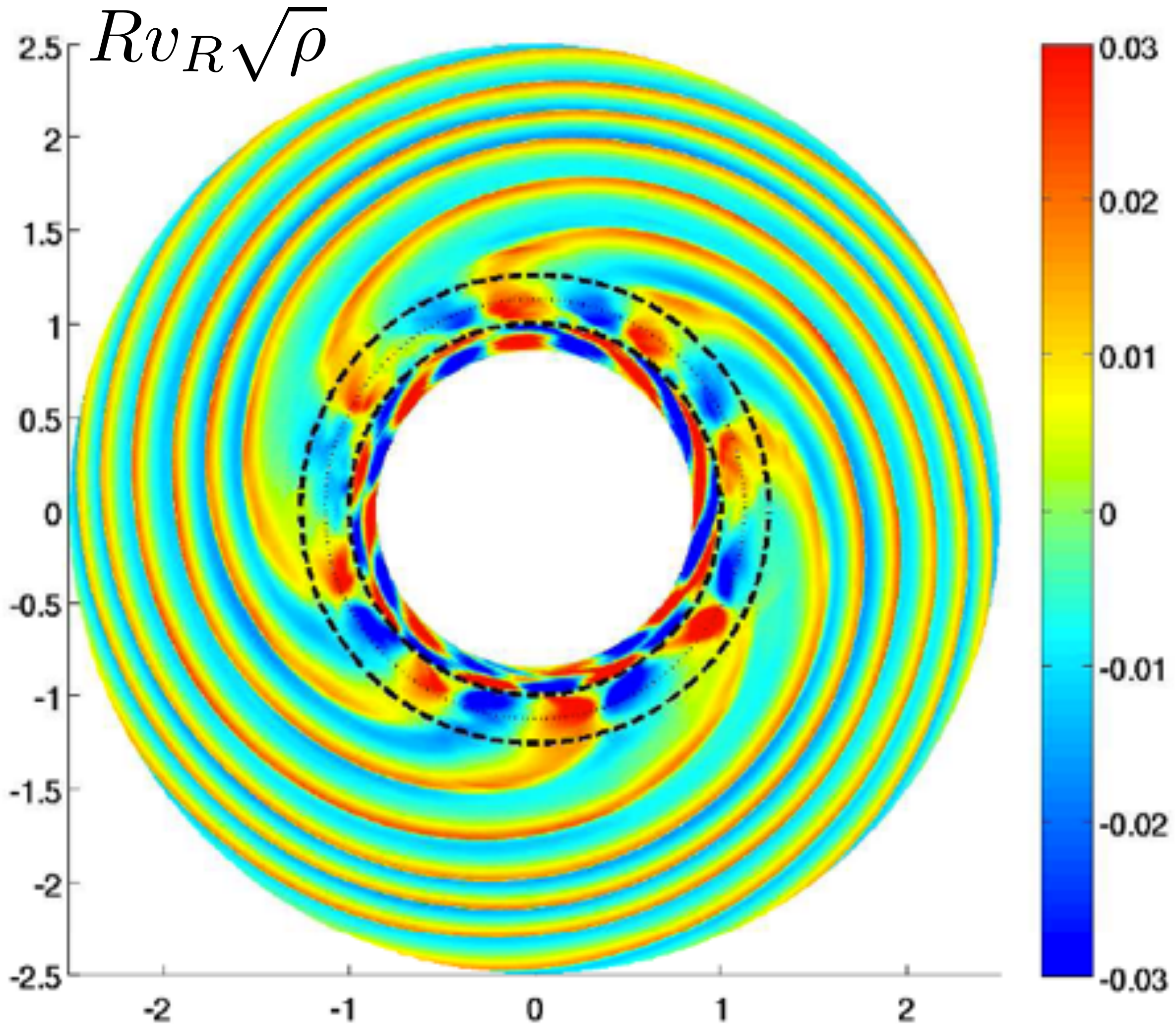
Even in black holes could transition from accretion disk to radiatively inefficient accretion flow share some properties with a BL?

Future Prospects

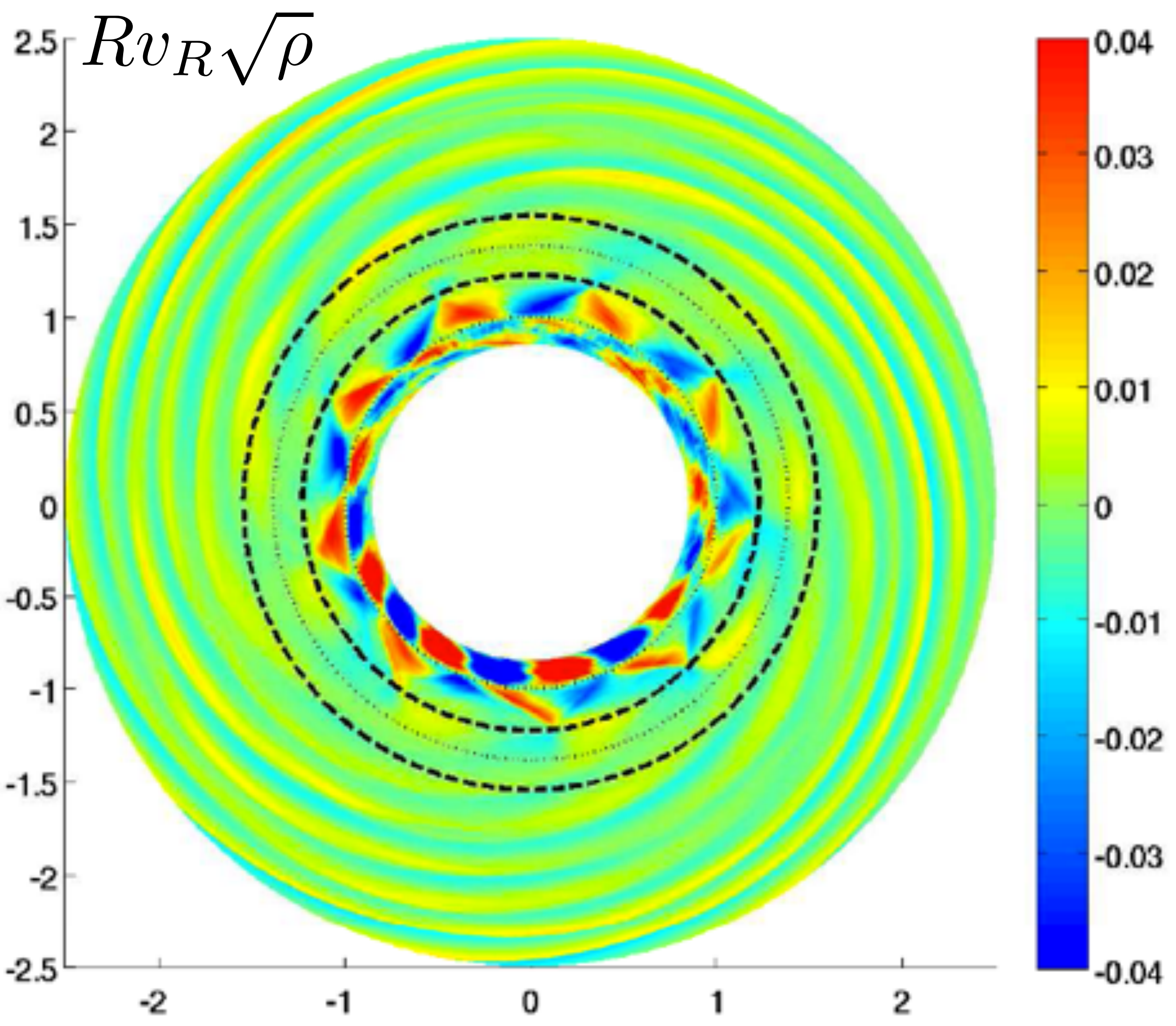
- **Realistic E.O.S. + cooling or radiative transfer**
  - Excited gravity modes.
  - Connection to DNOs/QPOs.
- **Field Amplification (stratified MHD)**
  - Does the field amplify to equipartition in the BL?
  - In global simulations is there some global dynamo process going on that amplifies fields? What limits field growth?
- **Meridional Spreading Layer**
  - Differential rotation in meridional direction leading to possible Kelvin-Helmholtz and baroclinic instabilities.
  - Possible pinch (Tayler-Spruit) or Parker magnetic instabilities.

Acoustic Modes in Global Simulations

Upper Branch



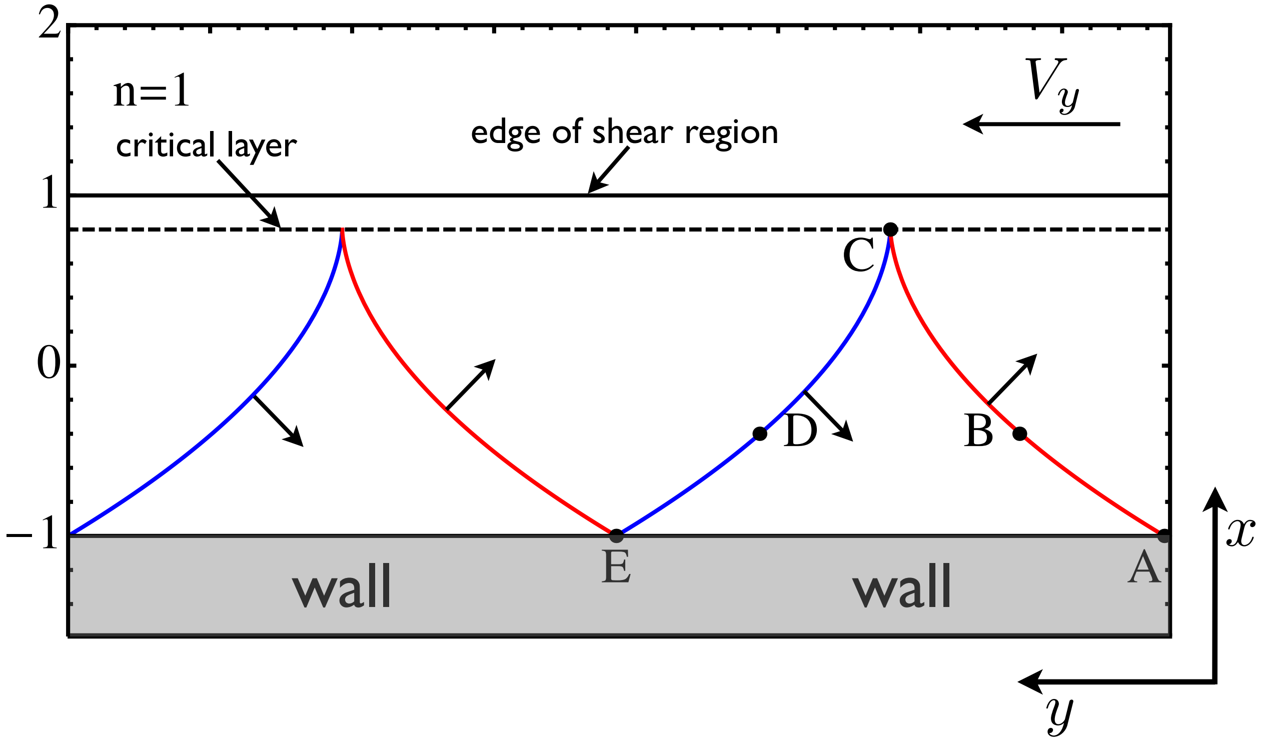
Lower Branch



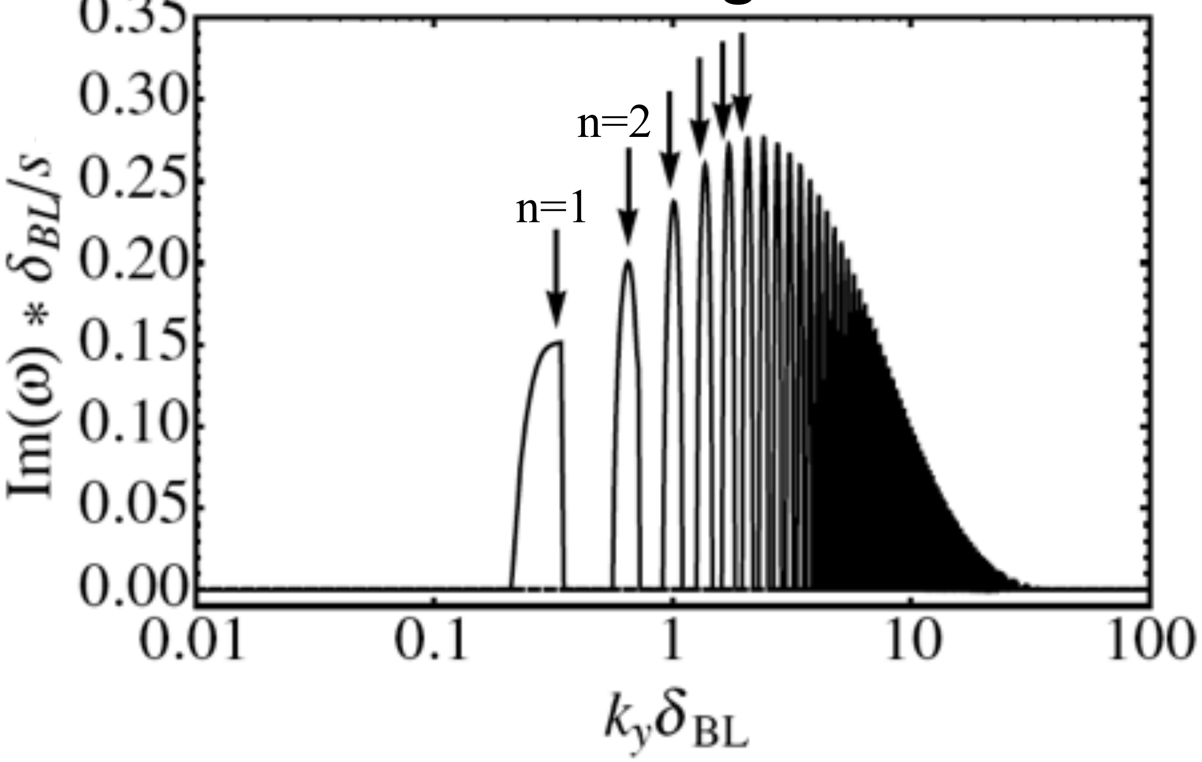
In hydro and MHD simulations, of an isothermal BL, acoustic modes are <u>always</u> present. Dimensionality, azimuthal extent of the simulation domain, Mach number, magnetic field, and stratification only modify the details.

Instability: const. density, reflecting wall

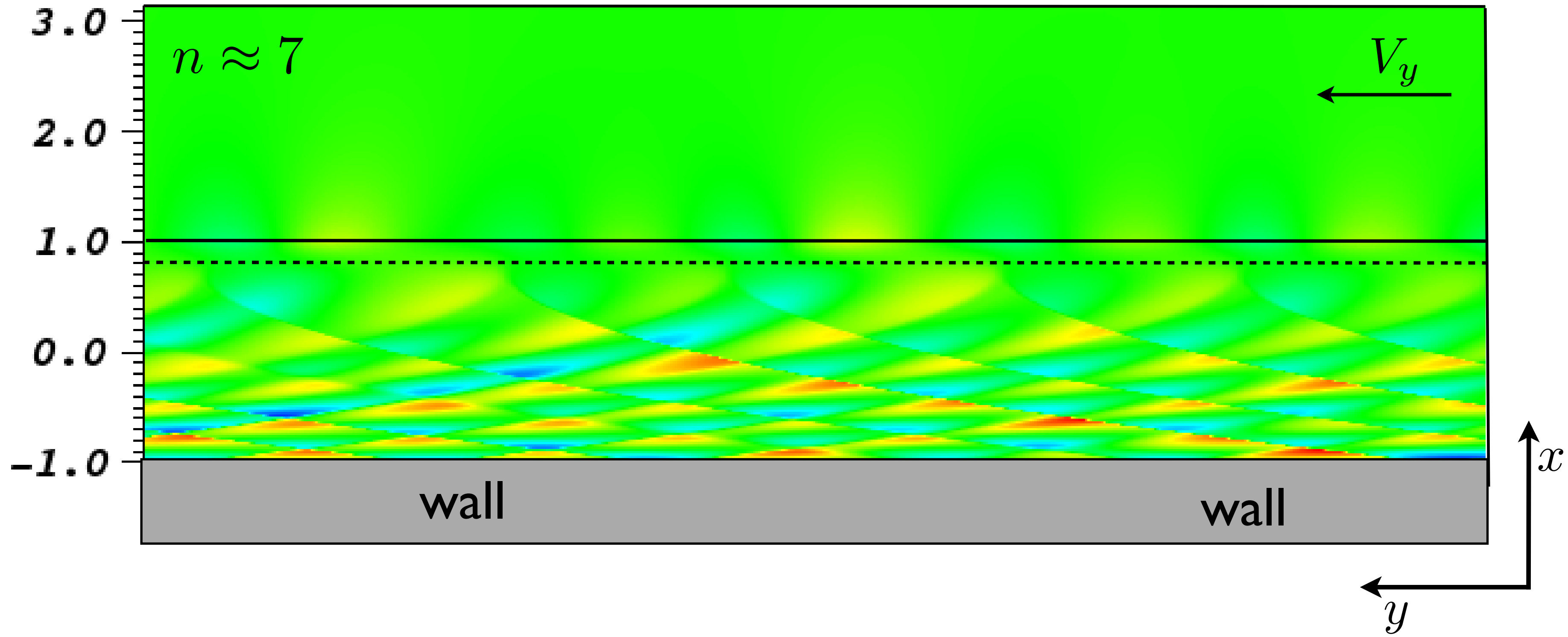
$M = 5$



Dimensionless growth rate

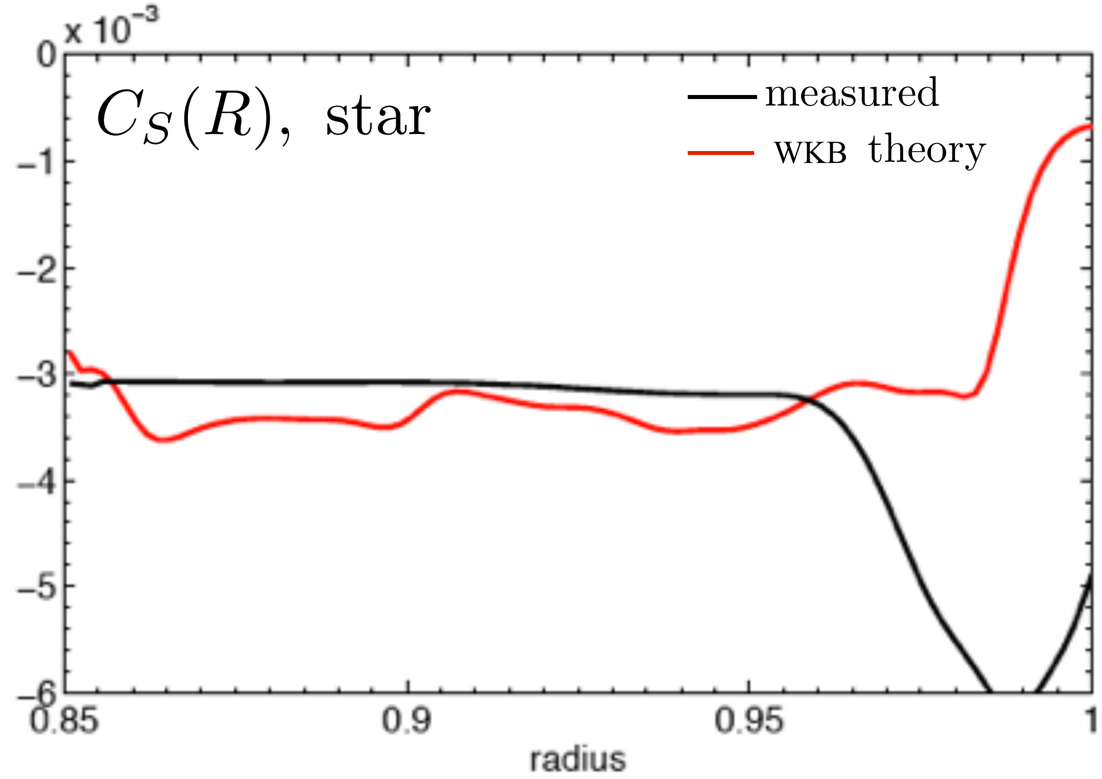


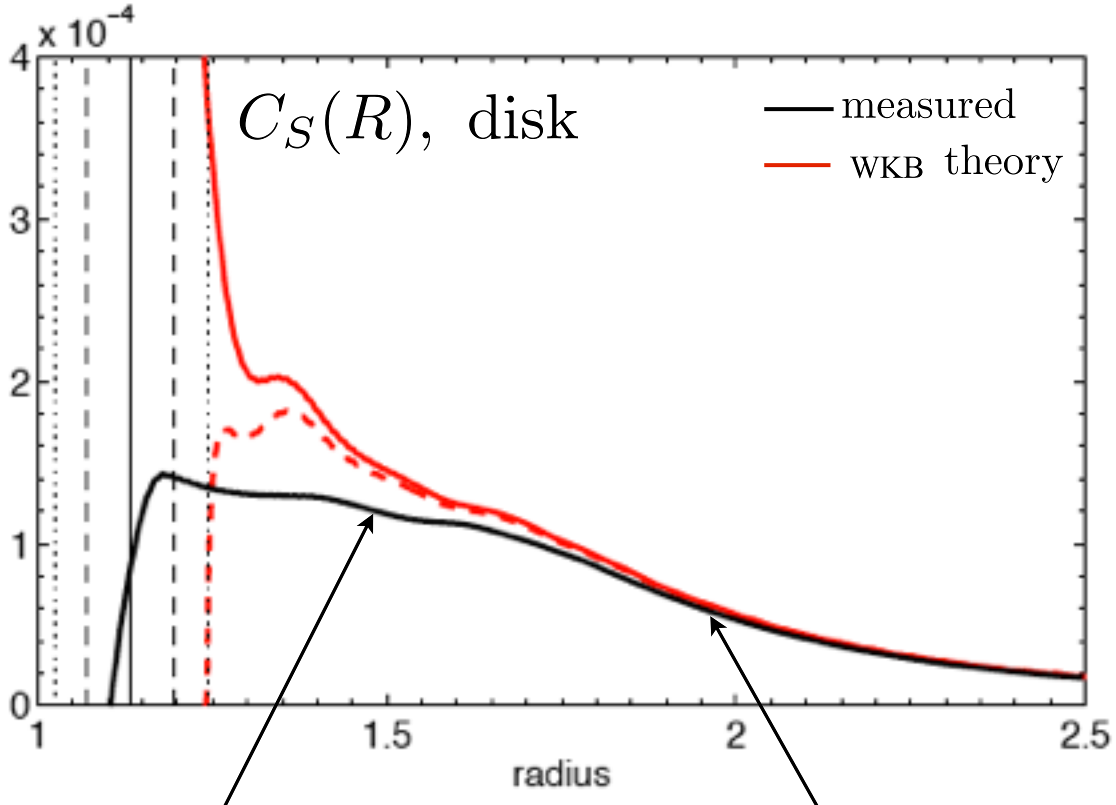
Plot of δV_x from Athena simulation



Accretion by Wave Excitation and Dissipation

Stress angular momentum current when upper mode is dominant. The wave is generated at corotation in the BL and dissipates in the disk after shocking.



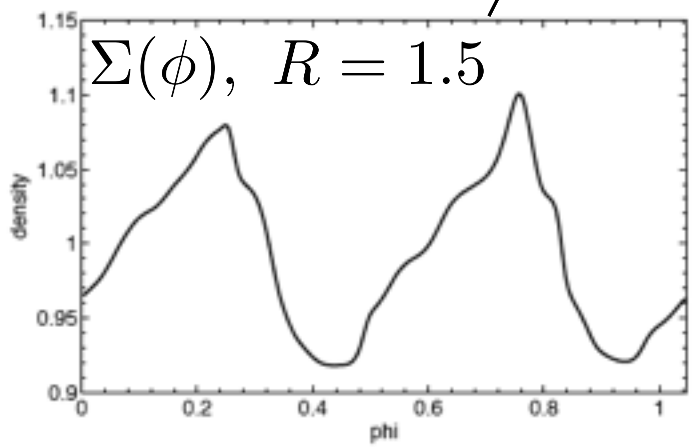


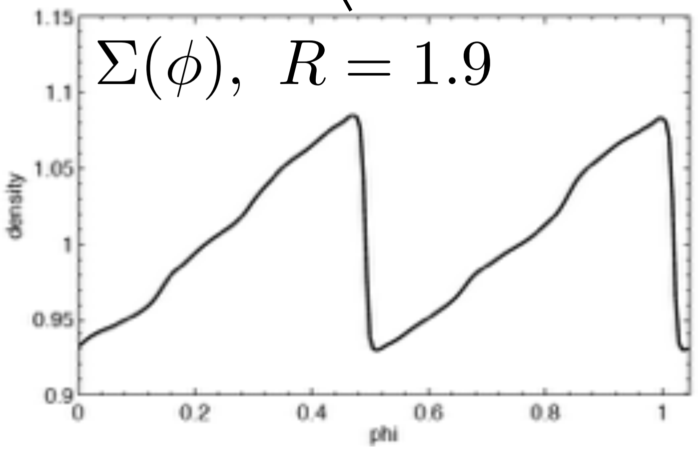
Mass accretion rate

$$\dot{M} = \left(\frac{dl}{dR}\right)^{-1} \frac{\partial C_S}{\partial R}$$

specific angular momentum

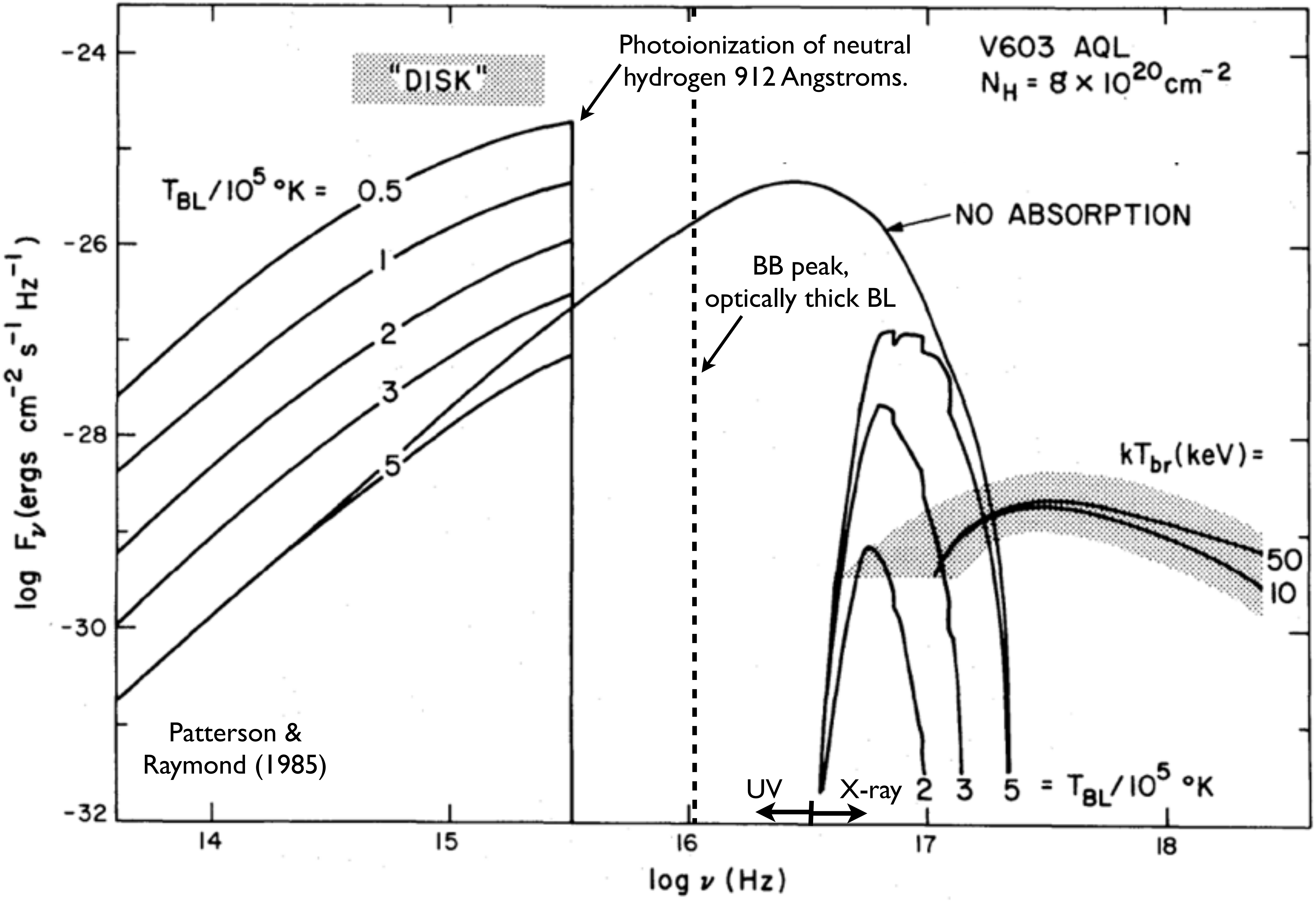
$$l = \Omega R^2$$





Shock density profiles at two different radii. The sound wave steepens and shocks as it travels into the disk.

Observing CV Boundary Layer



Photoionization of neutral hydrogen 912 Angstroms.

BB peak, optically thick BL

UV

X-ray

Patterson & Raymond (1985)