# Hydrodynamical Instabilities in the Ohmic dead zone in circumstellar disks and dwarf novae

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***Collaborators***

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**Colin McNally (QMUL)**
**Mordecai Mac Low (AMNH)**
**Nikolai Piskunov (Uppsala)**
**Natalie Raettig (MPIA)**
**Orkan Umurhan (NASA Ames)**
**Neal Turner (JPL)**

KITP, Feb 28th, 2017

# Outline

- The MRI active and dead zones
    - Rossby wave instability

- Hydrodynamical instabilities
    - Convective overstability
    - Zombie vortex instability
    - Vertical shear instability

- Secondary mechanisms
    - Elliptic and Magneto-Elliptic Instability

- Applications to dwarf novae

# Protoplanetary Disks

**PP disk fact sheet**

Density: $10^{13} – 10^{15}$ cm$^{-3}$
(Air ~ $10^{21}$ cm$^{-3}$)

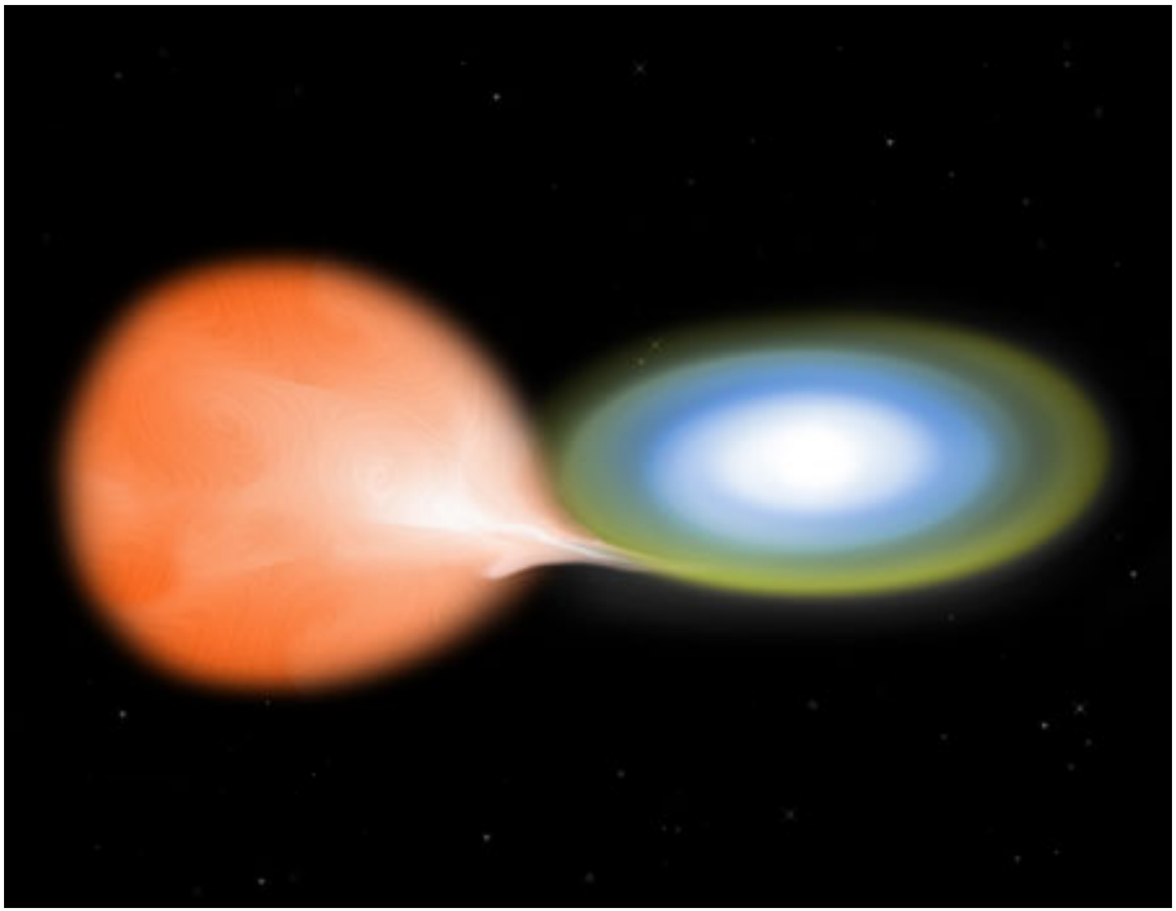
Temperature: 10-1000 K

Scale: 0.1-100AU
(1 AU ~ 1.5 x $10^{13}$ cm)

Mass: $10^{-3} – 10^{-1}$ $M_{sun}$
(1 $M_{sun}$ ~ 2 x $10^{33}$ g)

Timescales :
Dynamical: 0.01 – 1000 yr
Lifetime ~ 1-10 Myr

# Dwarf Novae Disks



**DN disk fact sheet**

Density: $10^{17} – 10^{19}$ cm$^{-3}$
(Air ~ $10^{21}$ cm$^{-3}$)

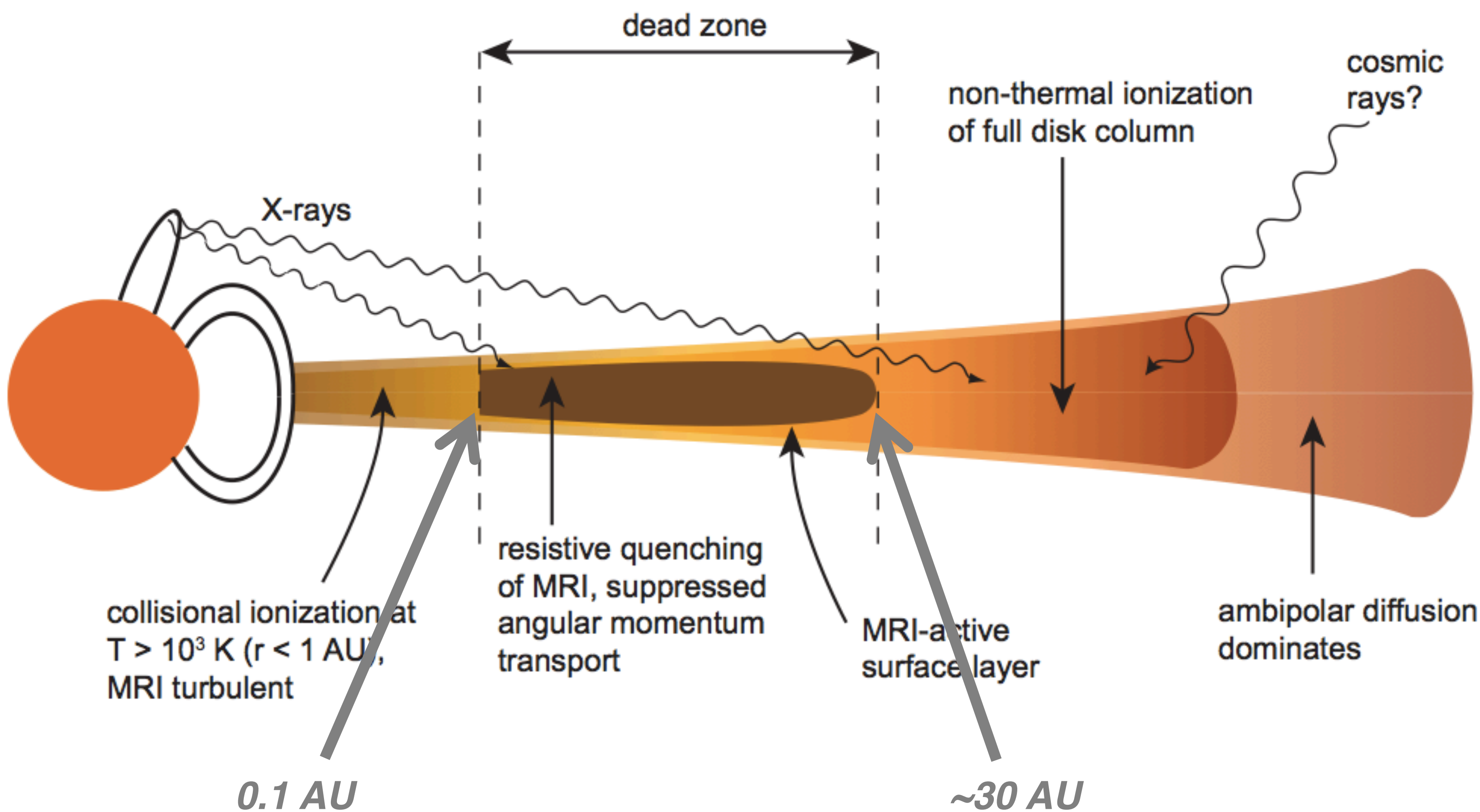
Temperature: $10^{3}$-$10^{5}$ K

Scale: $10^{9}$ -$10^{11}$ cm
(1 AU ~ 1.5 x $10^{13}$ cm)

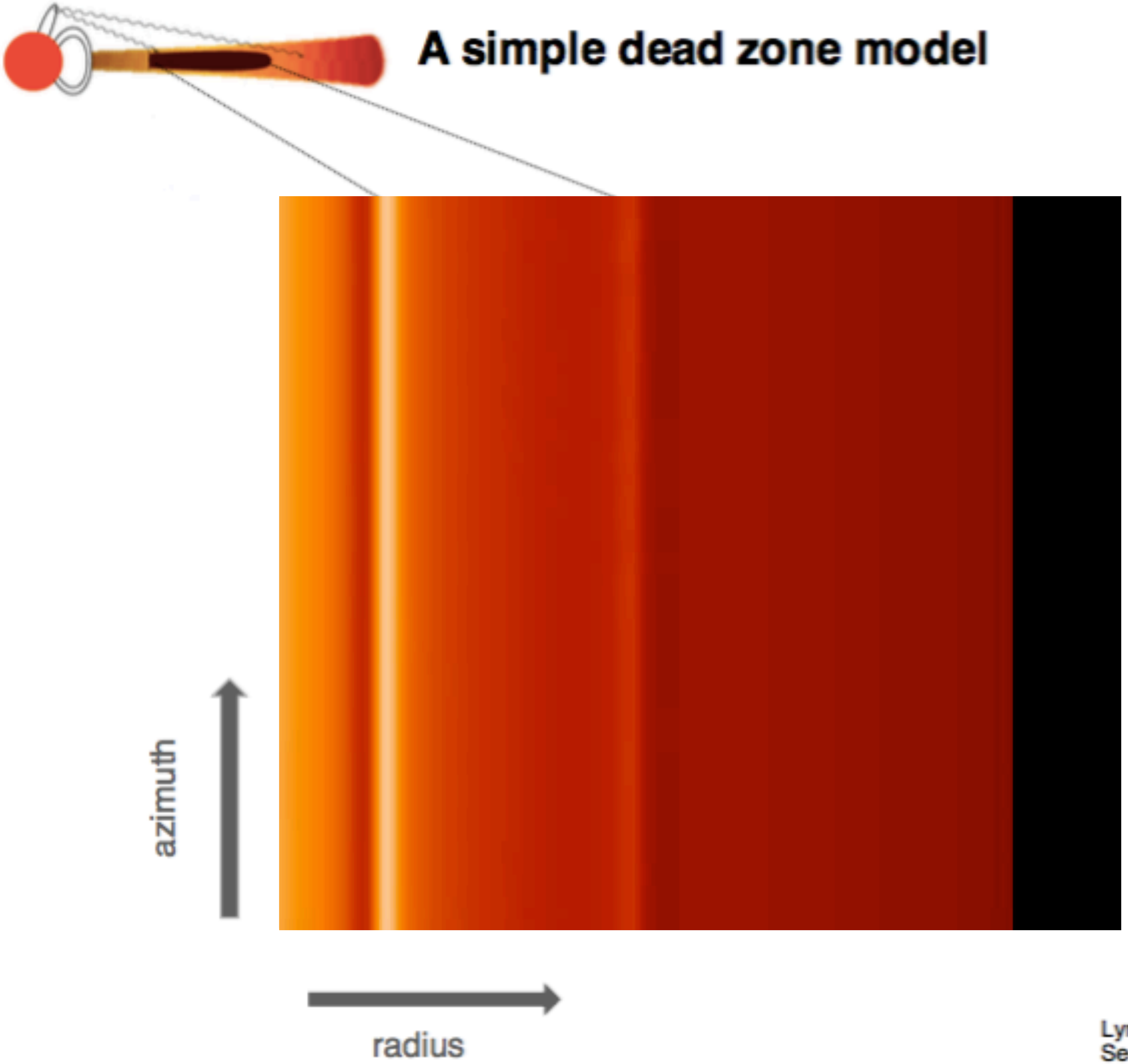
Mass: $10^{-9} – 10^{-8}$ $M_{sun}$
(1 $M_{sun}$ ~ 2 x $10^{33}$ g)

Timescales :
Dynamical ~ hours
Viscous time ~ weeks - months

# Dead zones


dead zone
non-thermal ionization
of full disk column
cosmic
rays?
X-rays
resistive quenching
of MRI, suppressed
angular momentum
transport
collisional ionization at
T > 10³ K (r < 1 AU),
MRI turbulent
MRI-active
surface layer
ambipolar diffusion
dominates
0.1 AU
~30 AU

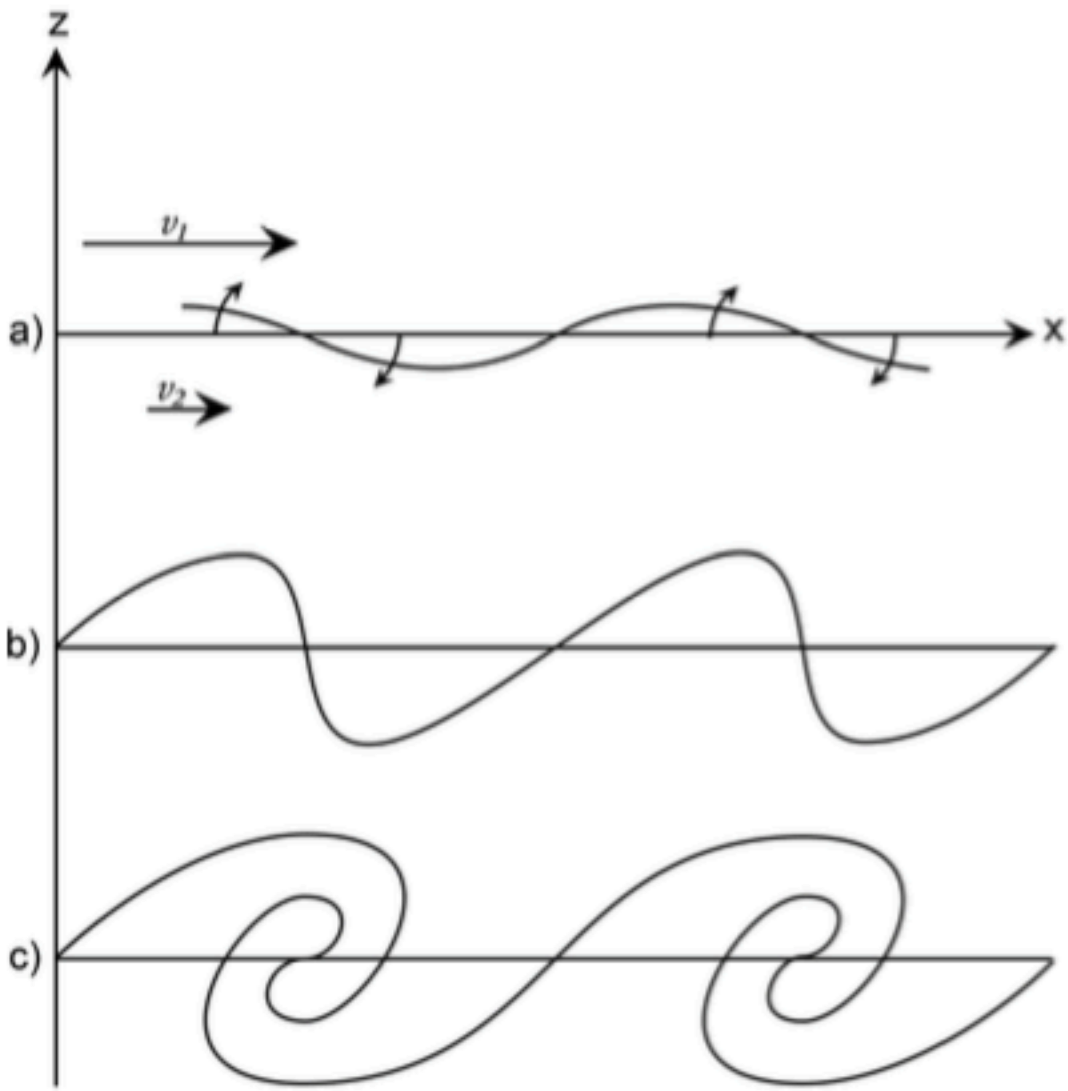
# A simple dead zone model




Lyra et al. (2008b, 2009a);
See also Varniere & Tagger (2006)

# Rossby wave instability

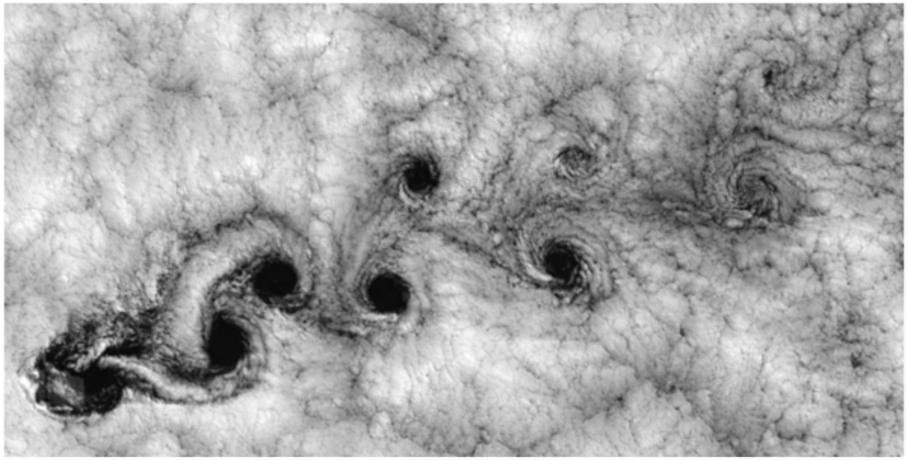
(or… Kelvin-Helmholtz in differentially rotating disks)




# Vortices – an ubiquitous fluid mechanics phenomenon



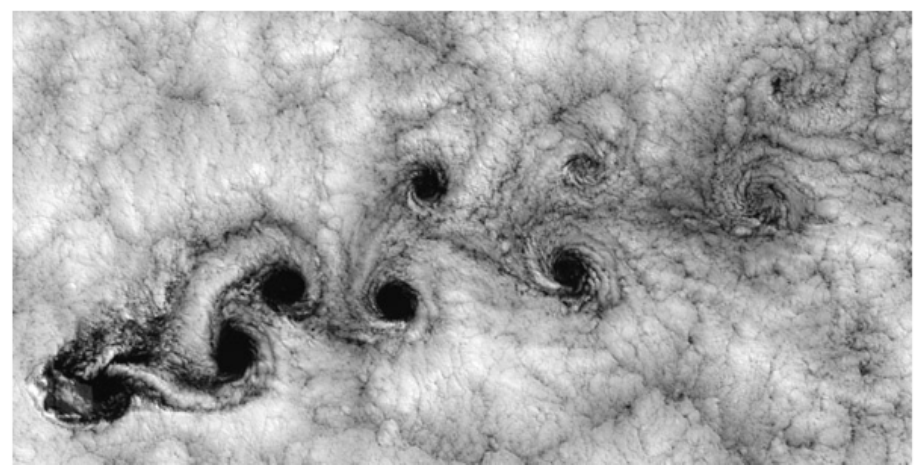




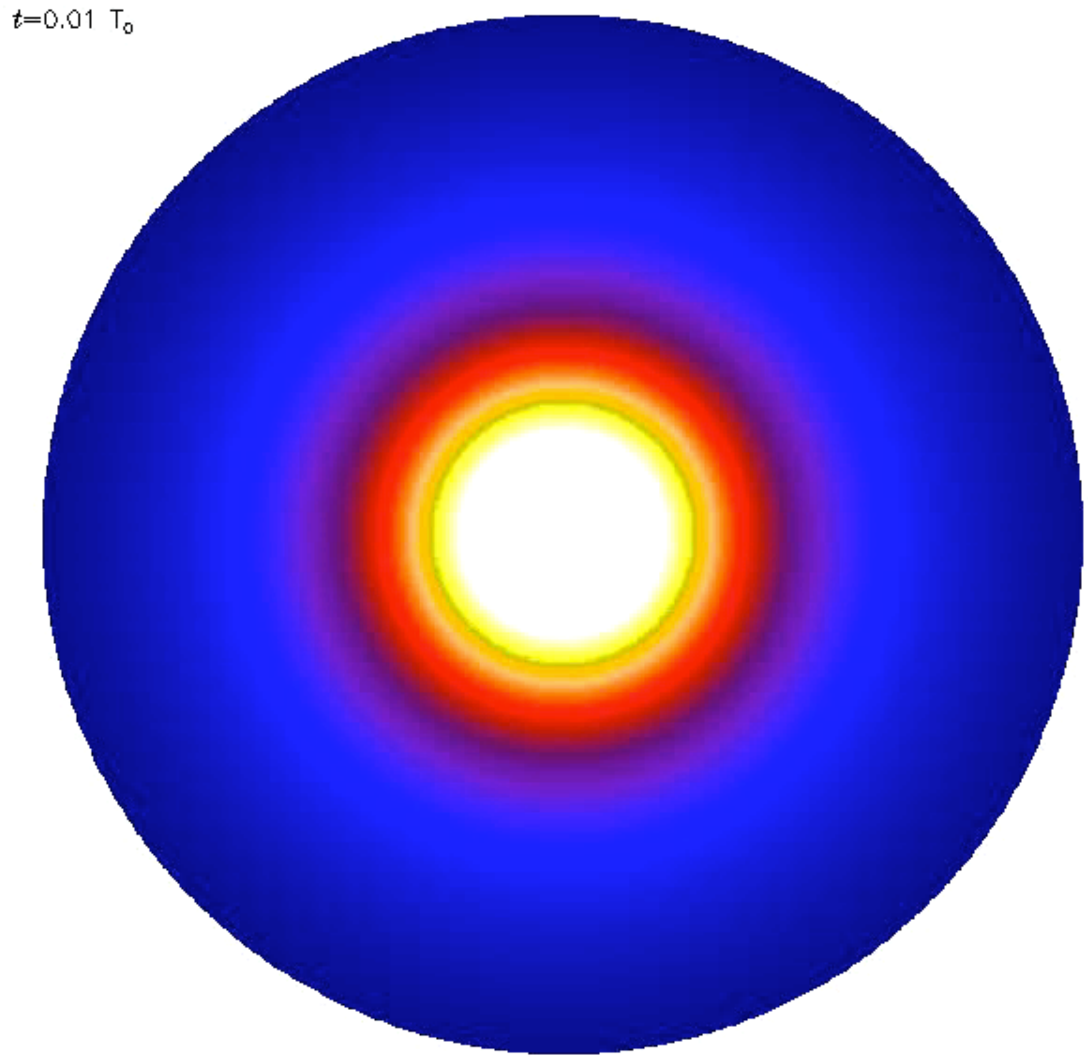
# Vortices – an ubiquitous fluid mechanics phenomenon



## Von Kármán *vortex street*

# Inner (0.1 AU) active/dead zone boundary




Magnetized inner disk + resistive outer disk

Lyra & Mac Low (2012)

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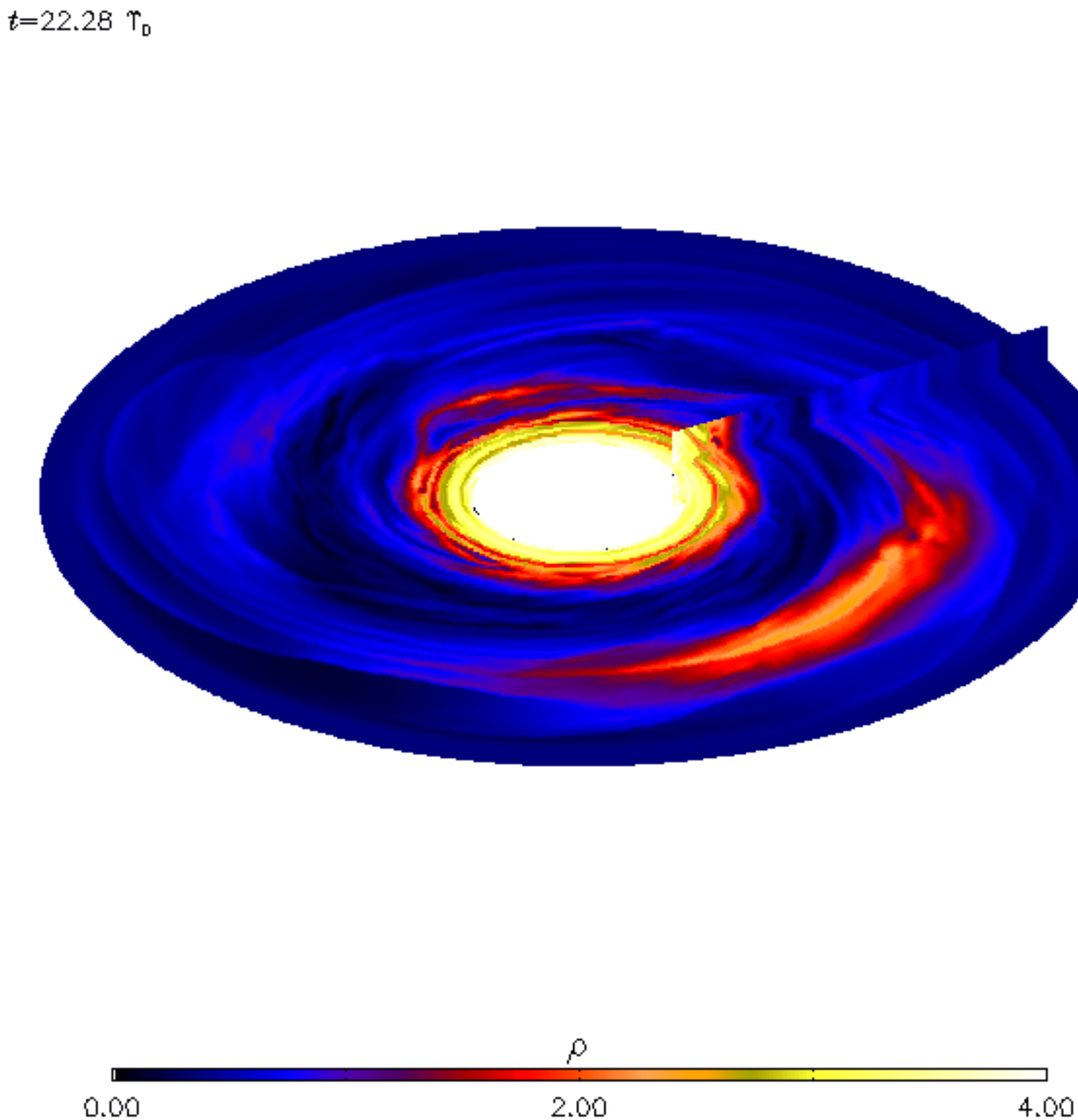


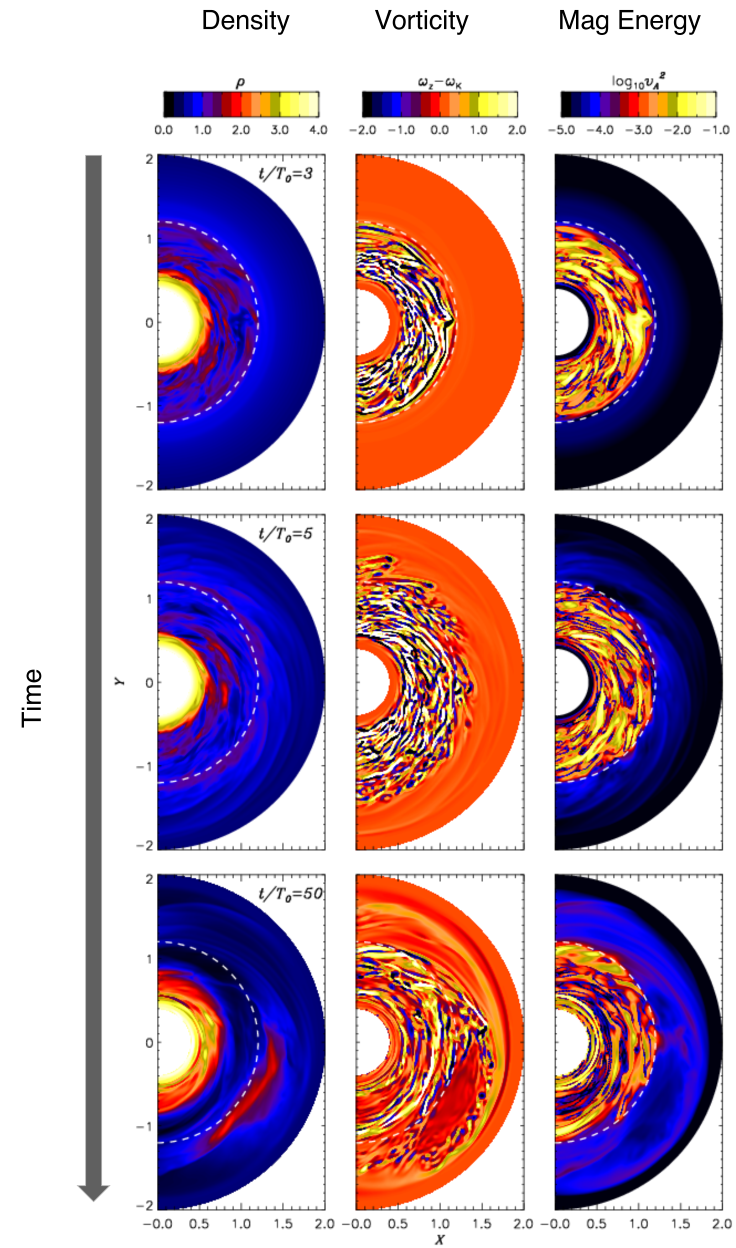


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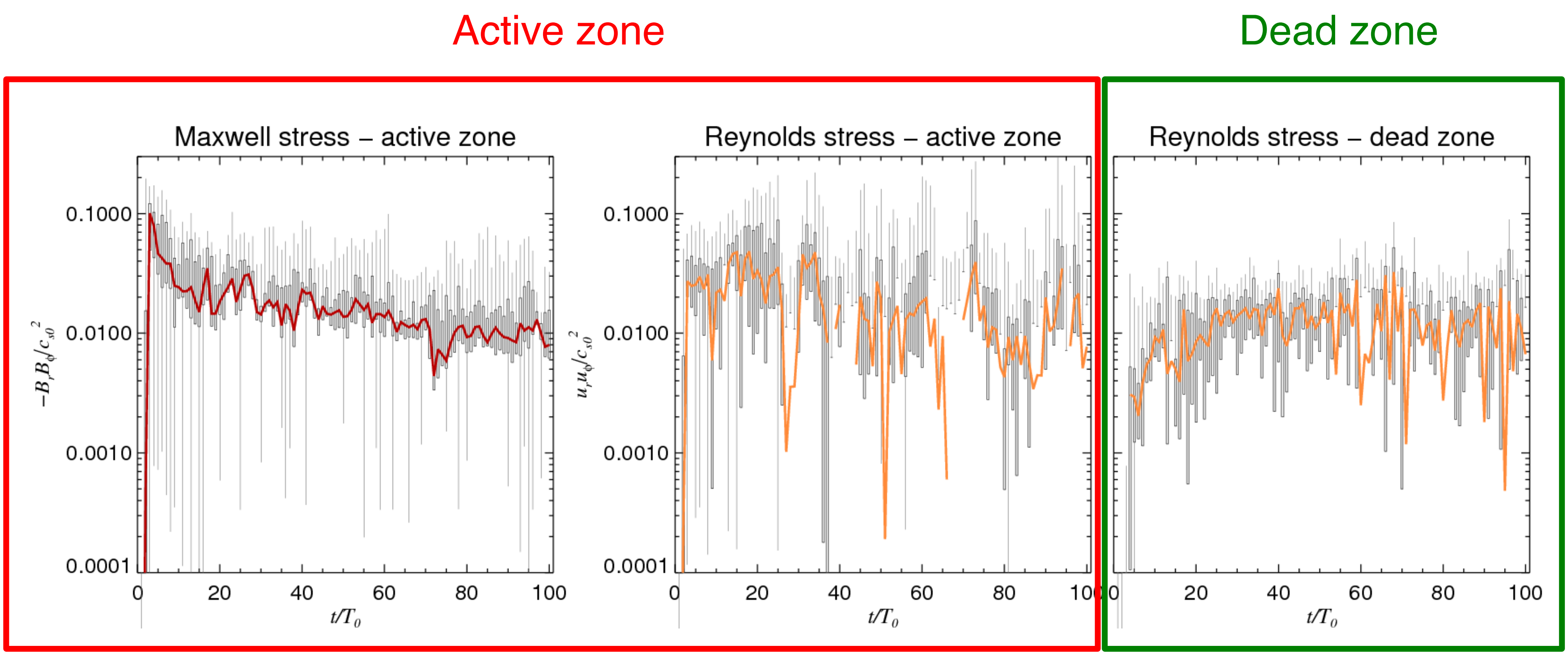
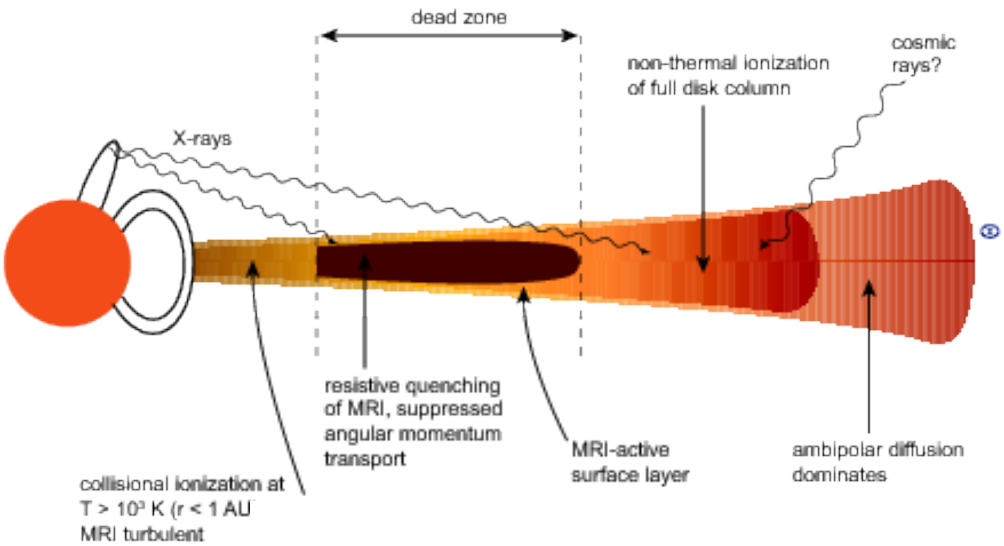



$\alpha \sim 10^{-3} - 10^{-2}$

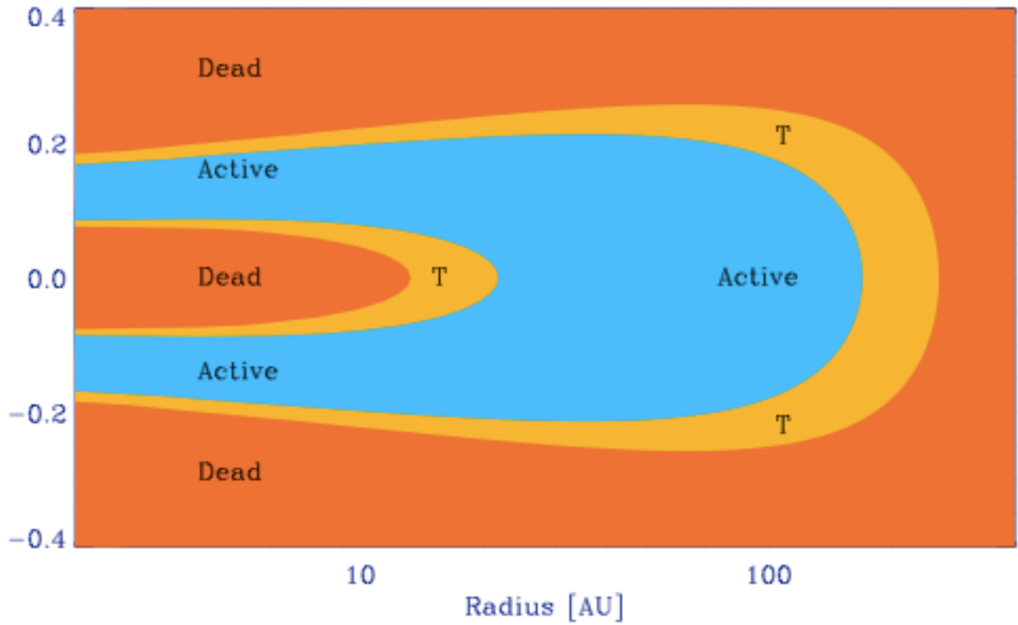
Significant angular momentum transport

Lyra & Mac Low (2012)

# Outer Dead/Active zone transition KHI




Armitage (2010)



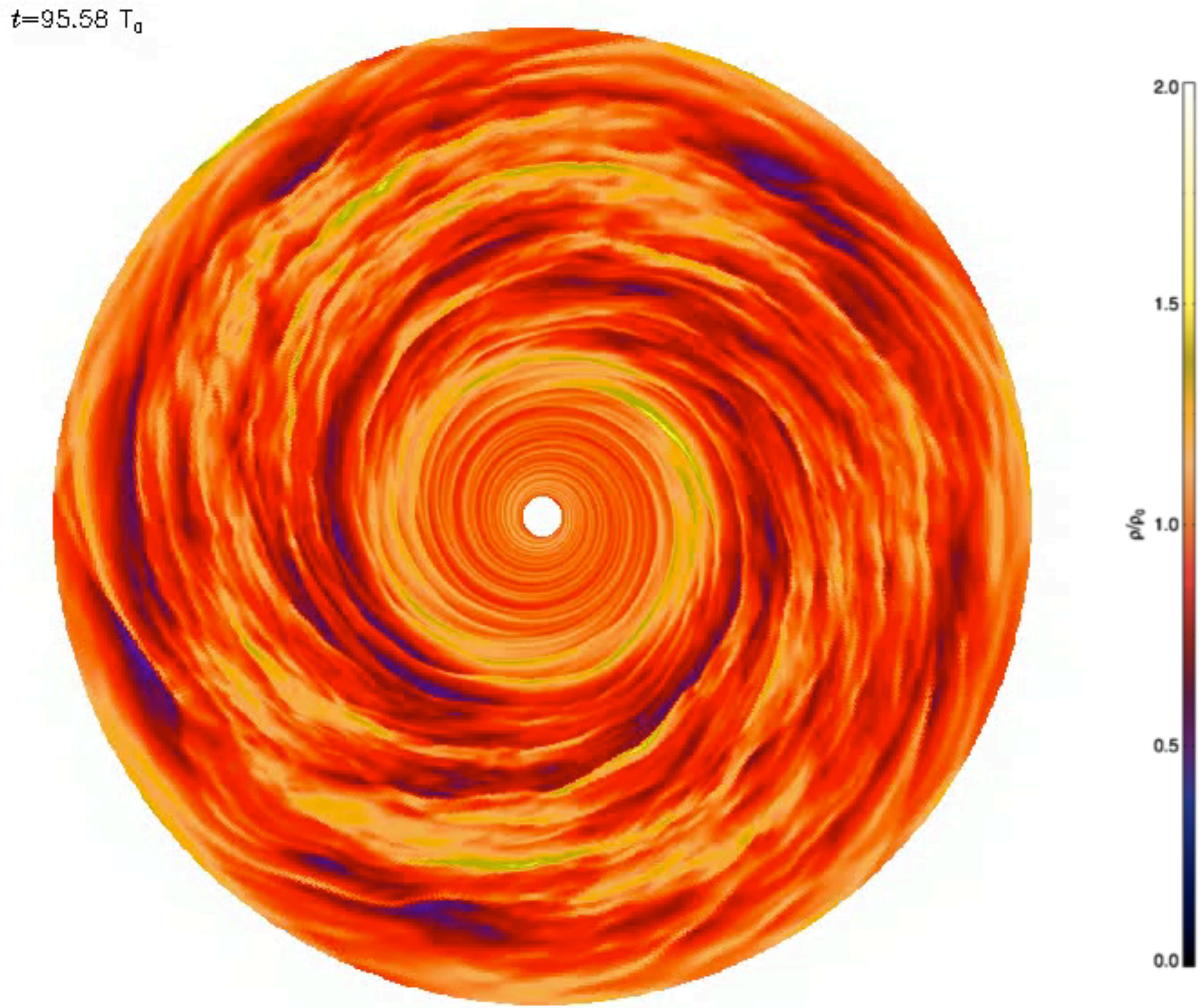

Dzyurkevitch et al (2013)

The **outer** dead zone transition in ionization supposed

**TOO SMOOTH**

to generate an KH-unstable bump.

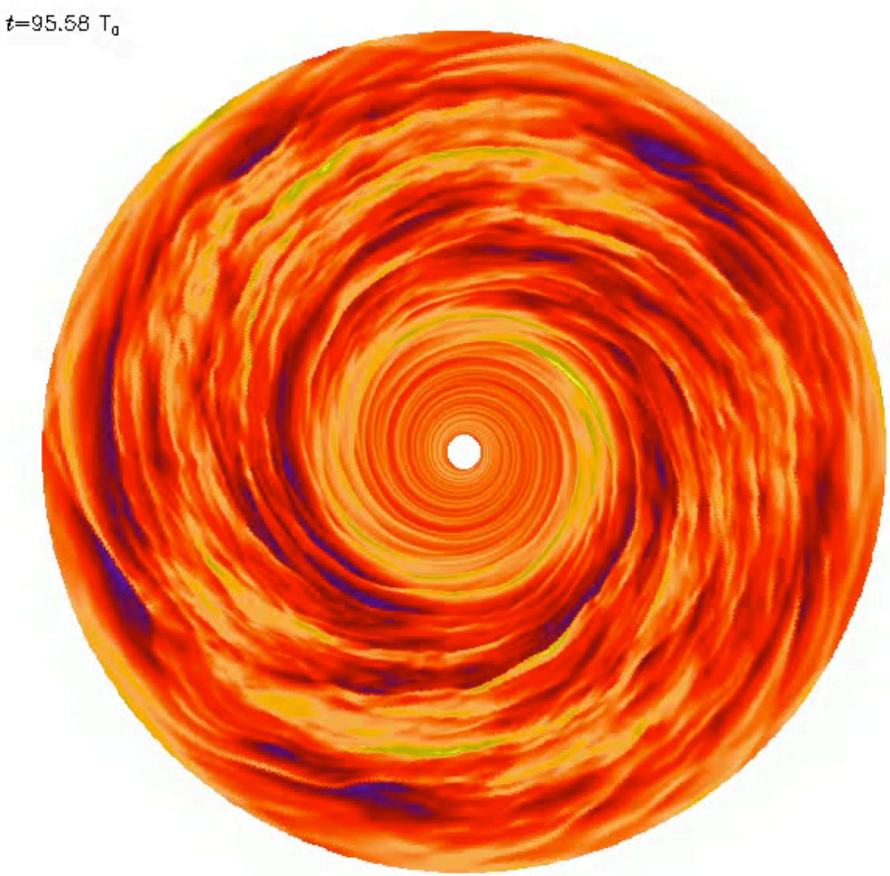
# Outer Dead/Active zone transition: 3D MHD

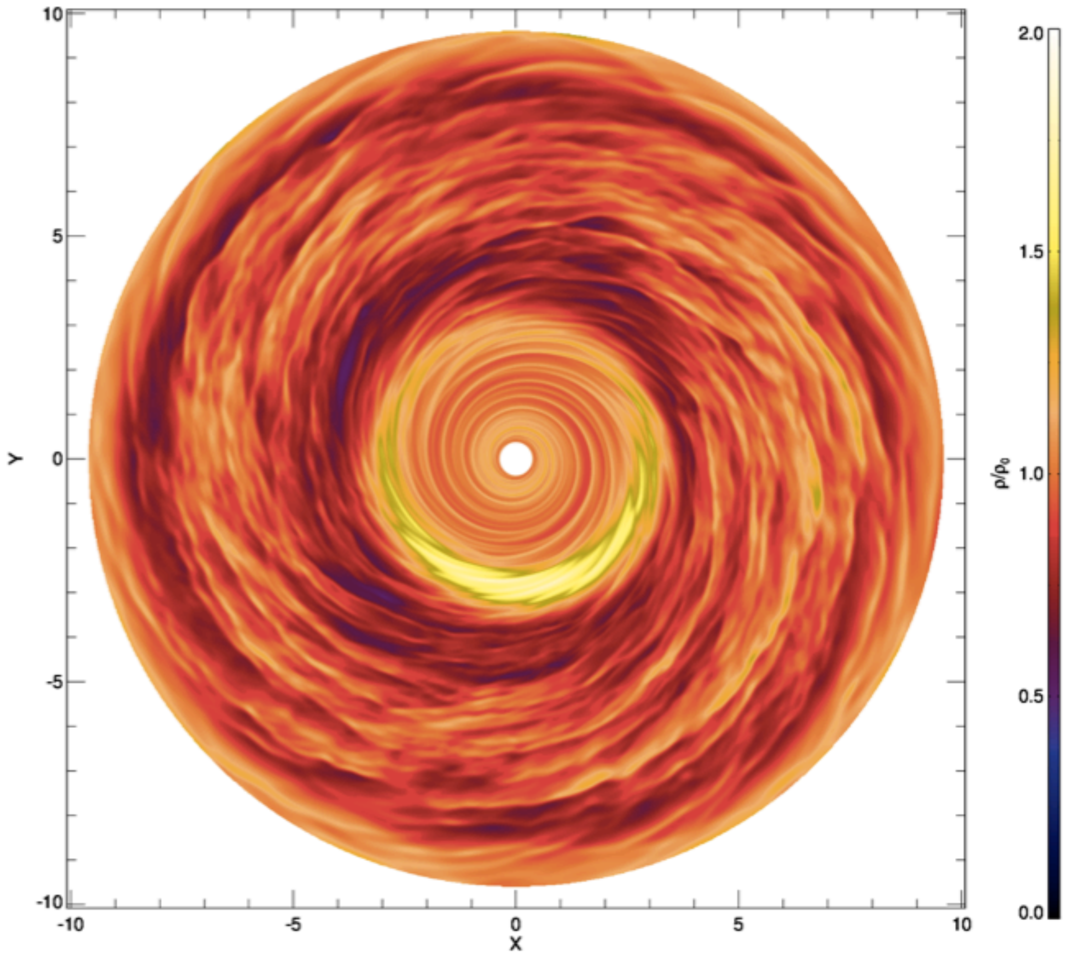



Resistive inner disk + magnetized outer disk

Lyra, Turner, & McNally (2015)

# Outer Dead/Active zone transition KHI

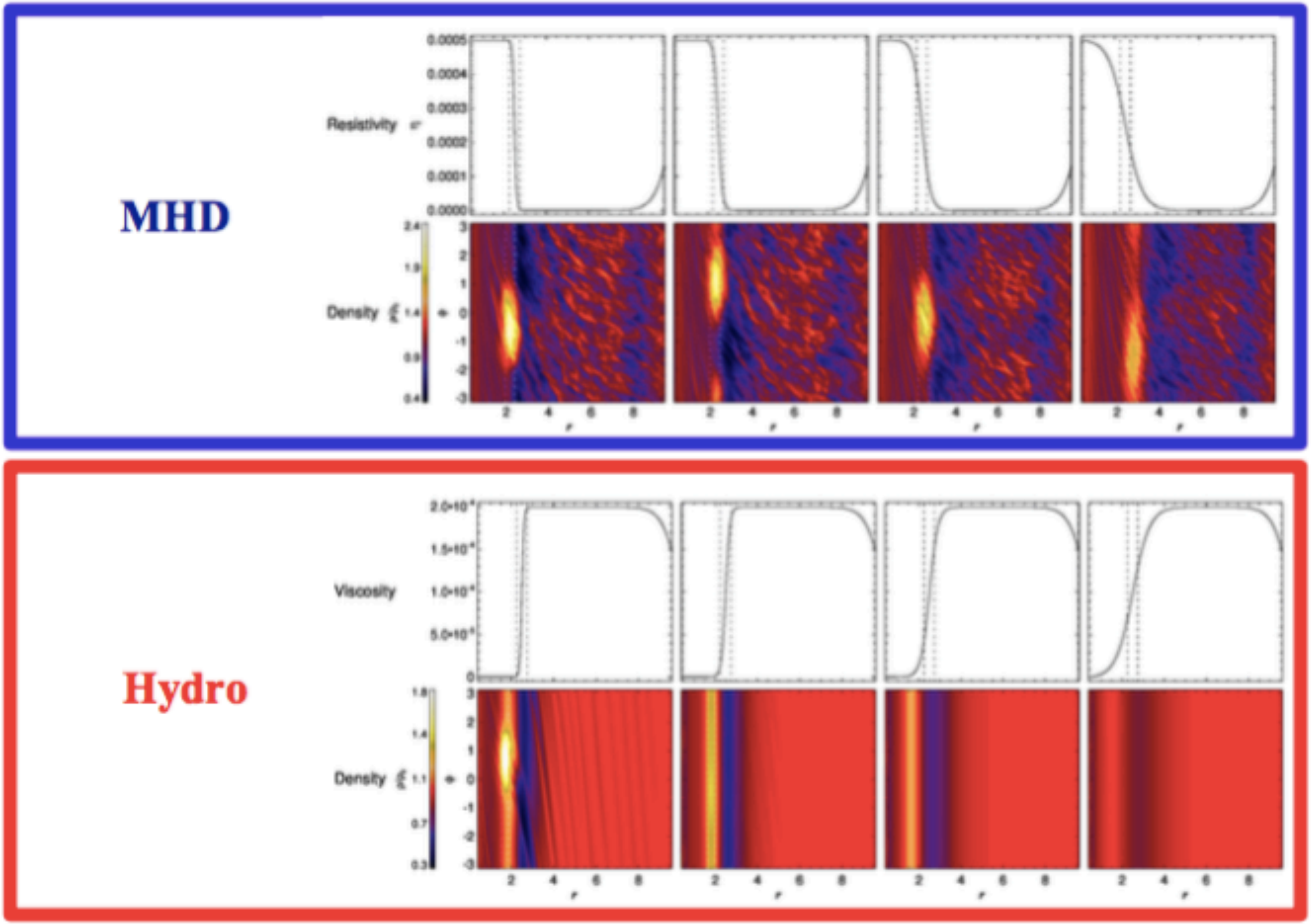



Resistive inner disk + magnetized outer disk

Lyra, Turner, & McNally (2015)

# Outer Dead/Active zone transition RWI




Lyra, Turner, & McNally (2015)

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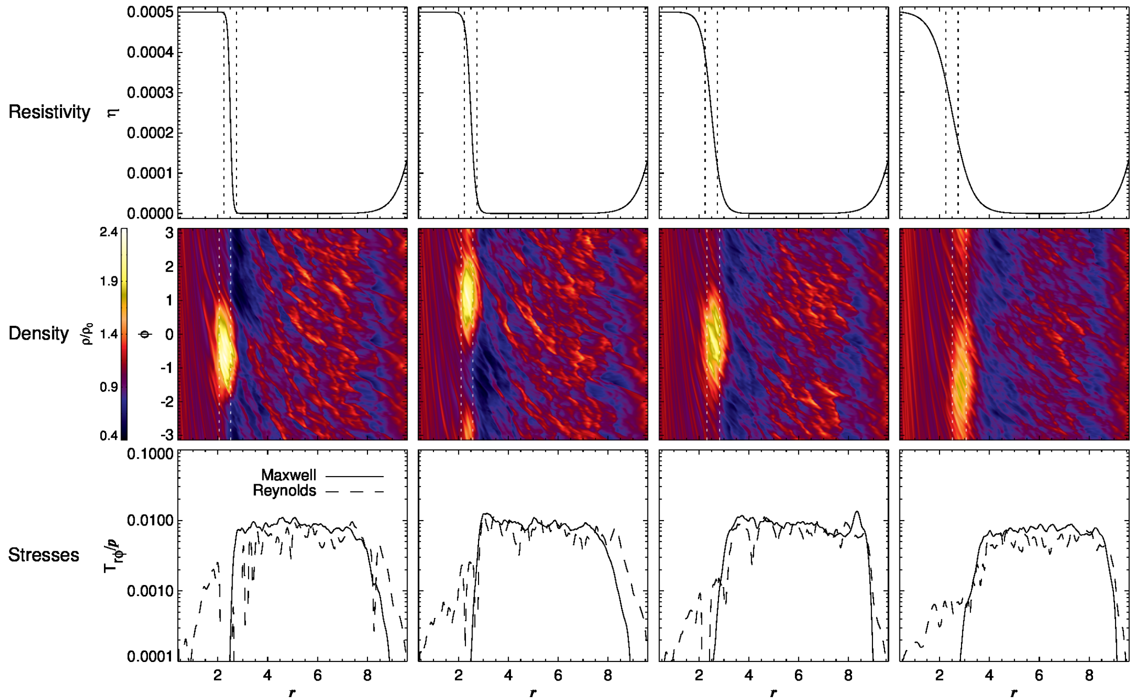



Lyra, Turner, & McNally (2015)

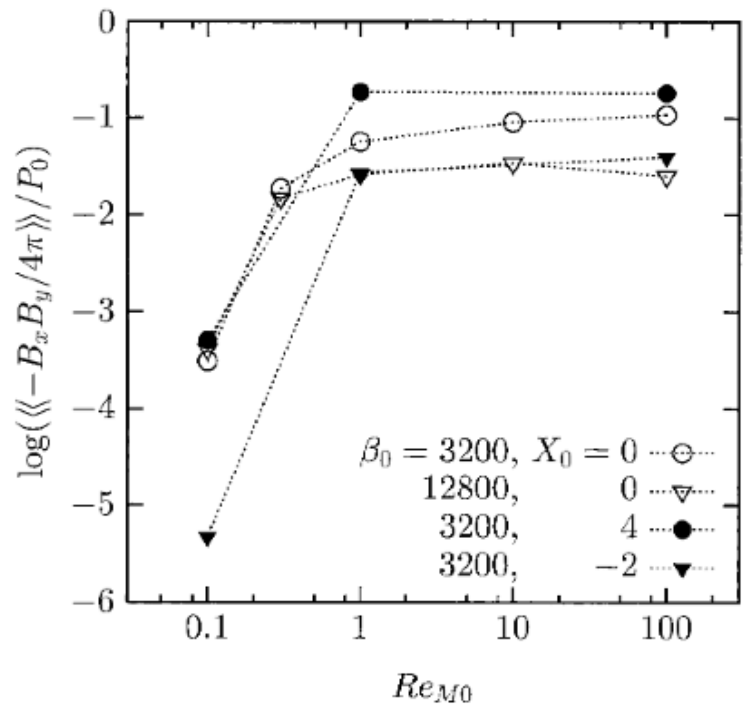
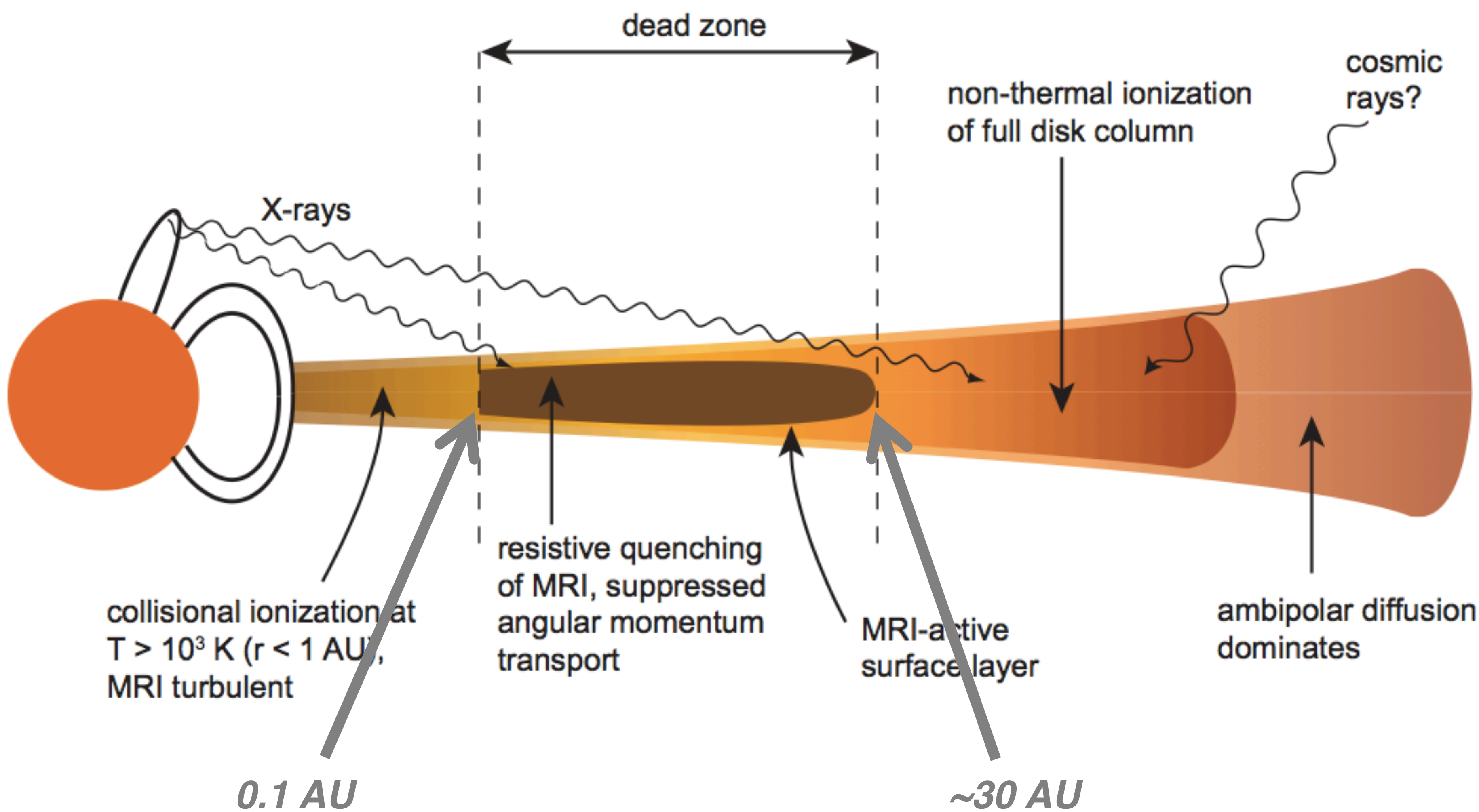



FIG. 9.—Saturation level of the Maxwell stress as a function of the magnetic Reynolds number $Re_{M0}$. Open circles and triangles denote the models without Hall term ($X_0 = 0$) for $\beta_0 = 3200$ and 12,800, respectively. The models including the Hall term are shown by filled circles ($X_0 = 4$) and triangles ($X_0 = -2$).

Sano and Stone (2002)

# Dead zones



dead zone
non-thermal ionization
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MRI turbulent
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0.1 AU
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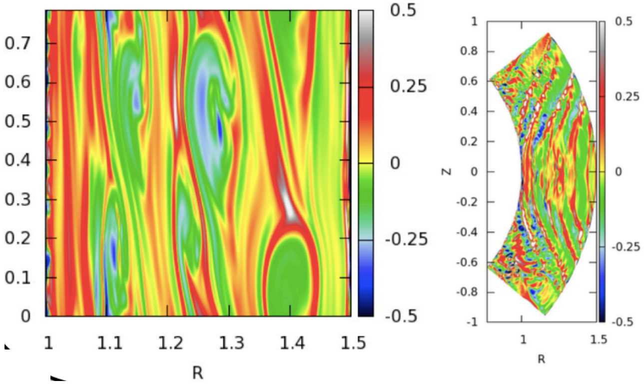
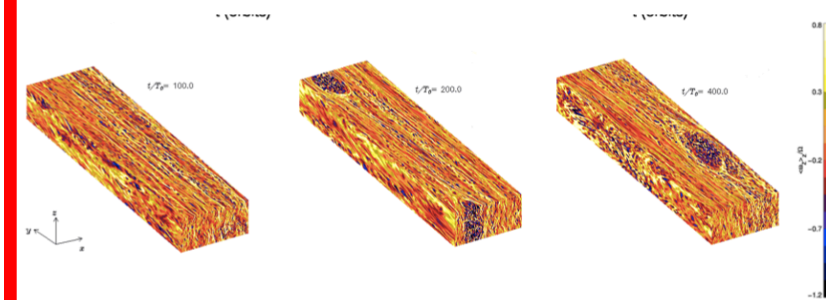
# Thermal Instabilities

## Vertical Shear Instability



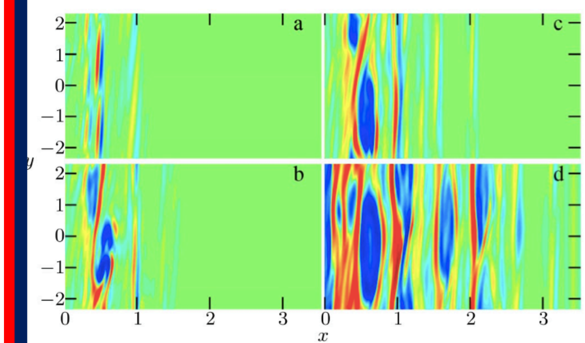

Nelson et al. 2013, Lin & Youdin 2015, Umurhan et al. 2016

## Convective Overstability



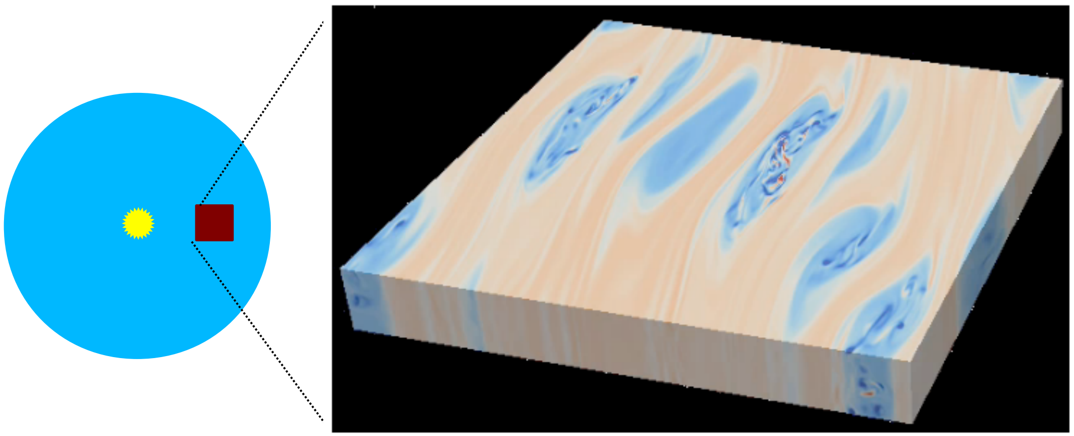
Klahr 2003, Lesur & Papaloizou 2010, Lyra & Klahr 2011, Lyra 2014

## Zombie Vortex Instability



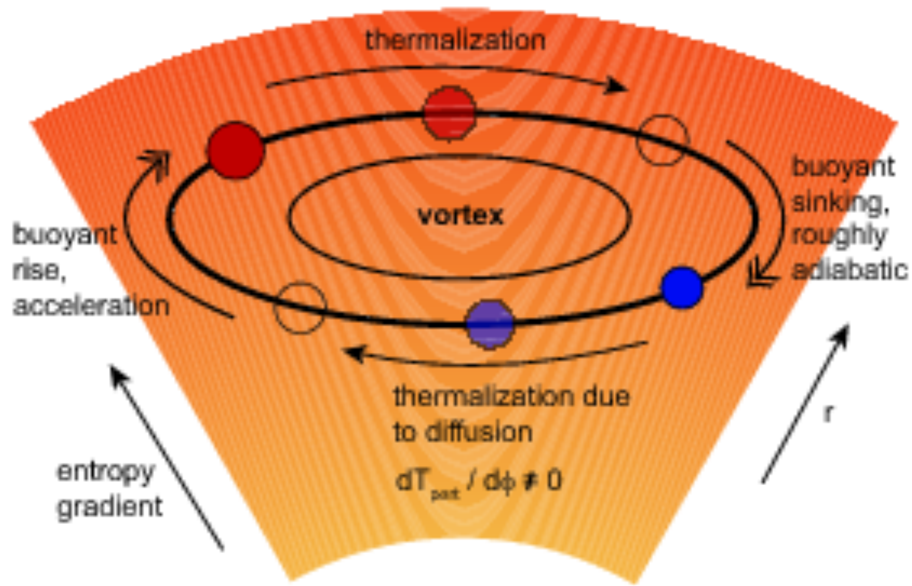

Marcus et al. 2012, 2013, 2015, 2016
Umurhan et al 2016, Lesur & Latter 2016

# Convective Overstability (née "Subcritic Baroclinic Instability")



Lesur & Papaloizou (2010)

## Sketch of the Subcritic Baroclinic Instability




Armitage (2010)

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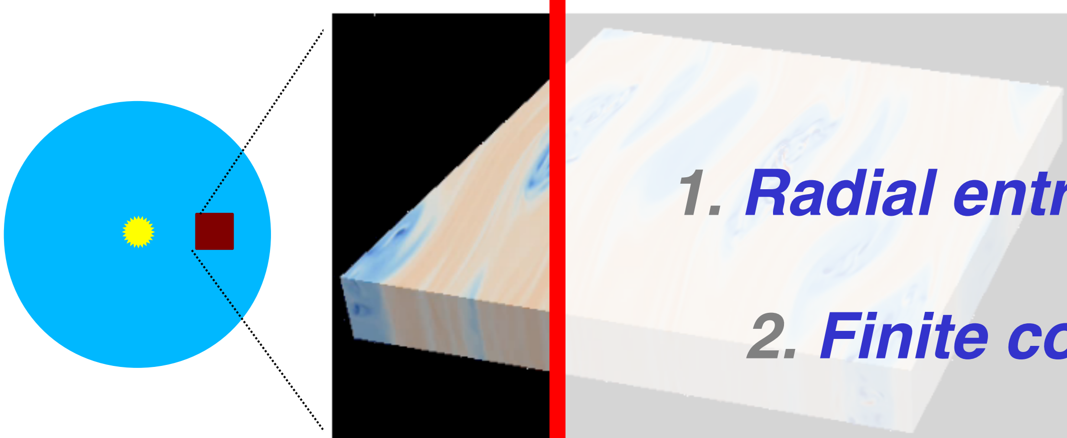

Lesur & Papaloizou (2010)

Sketch of the
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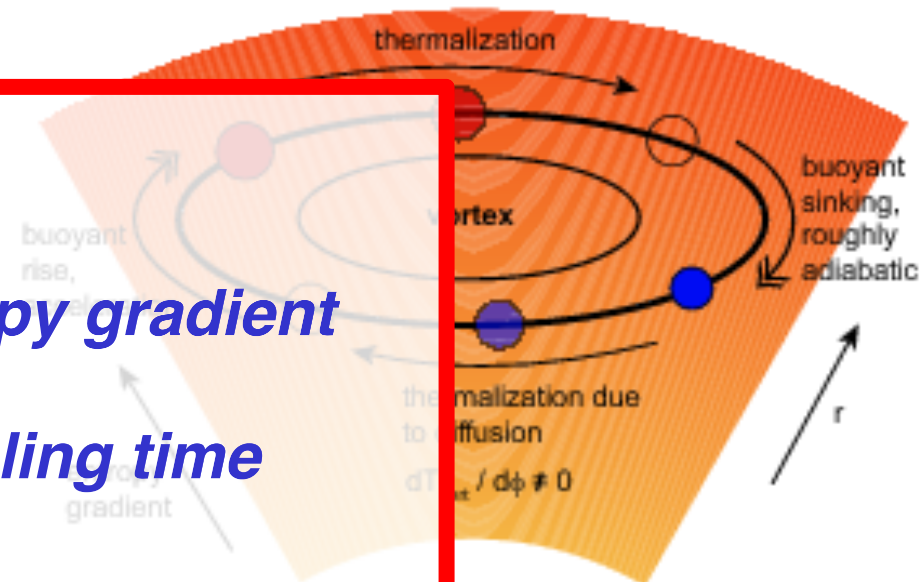


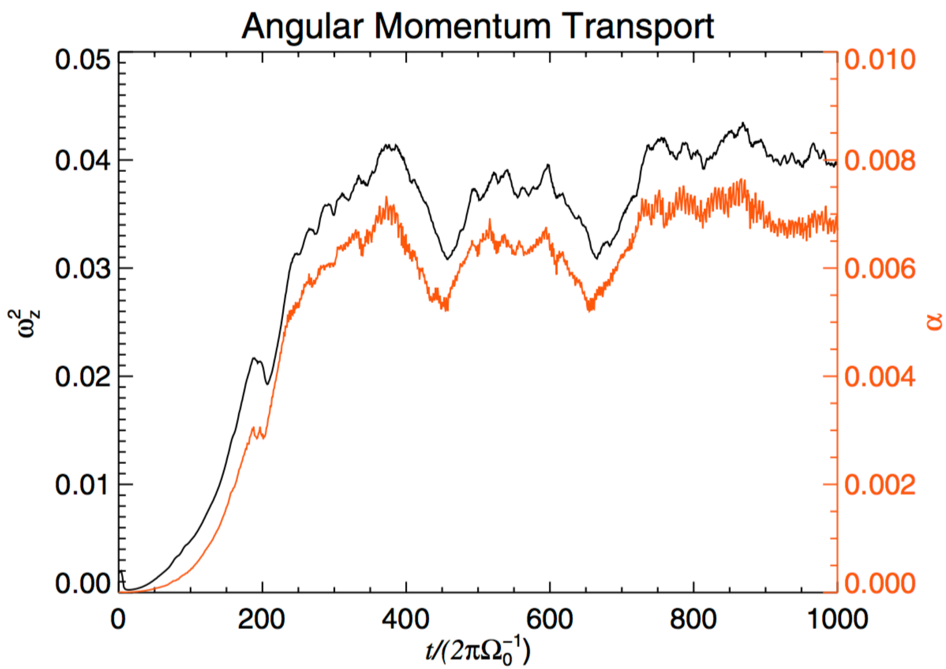

Armitage (2010)

1. ***Radial entropy gradient***

2. ***Finite cooling time***

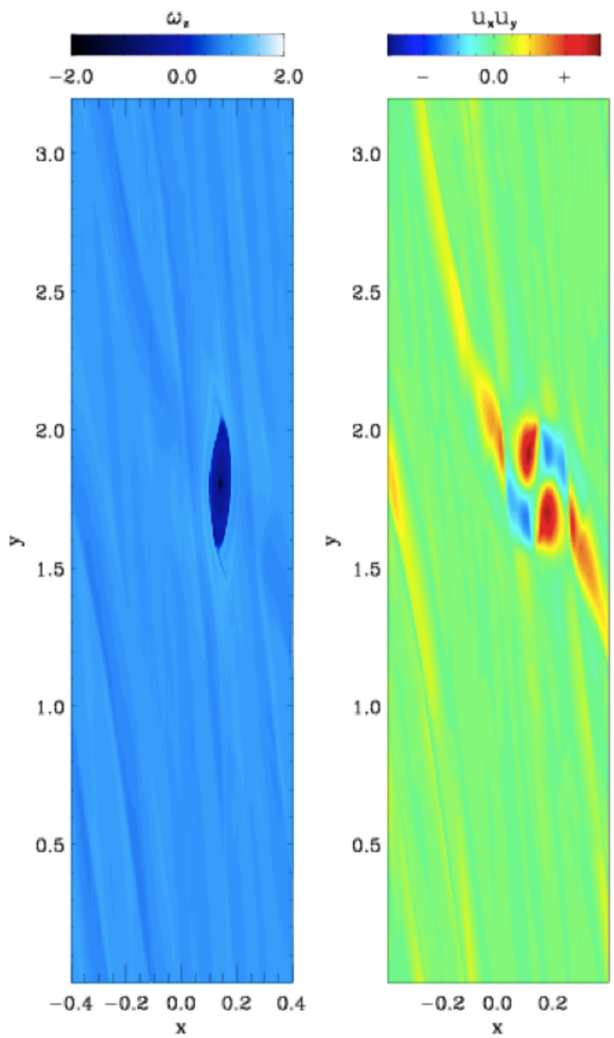
# Subcritic baroclinic instability and Accretion

$\alpha \sim 0.005$




Lyra & Klahr (2011)

Raettig, Lyra, & Klahr (2013)




The angular momentum is carried by **waves** excited by the vortex

(see also Heinemann & Papaloizou 2008, 2009)

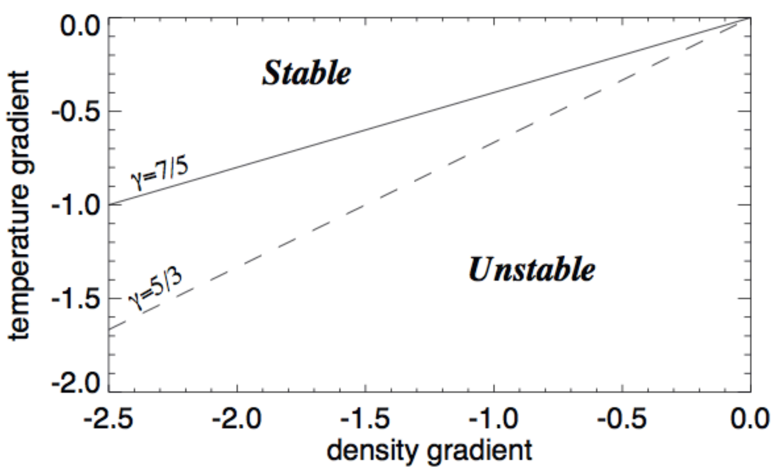
# Convective Overstability

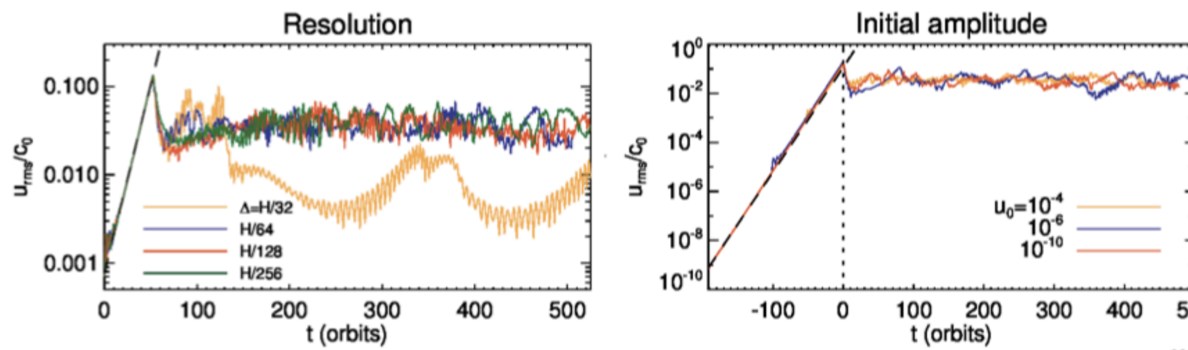
Klahr & Hubbard (2014), Lyra (2014), Latter (2015)

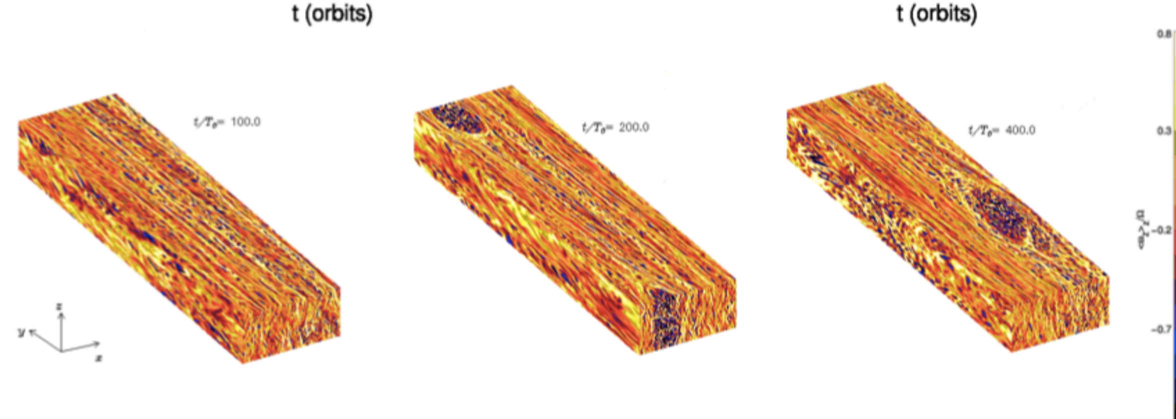
$$\frac{\partial \rho}{\partial t} + (\boldsymbol{u}\cdot\boldsymbol{\nabla})\,\rho = -\rho\boldsymbol{\nabla}\cdot\boldsymbol{u},$$
$$\frac{\partial \boldsymbol{u}}{\partial t} + (\boldsymbol{u}\cdot\boldsymbol{\nabla})\,\boldsymbol{u} = -\frac{1}{\rho}\boldsymbol{\nabla} p + \boldsymbol{g},$$
$$\frac{\partial p}{\partial t} + (\boldsymbol{u}\cdot\boldsymbol{\nabla})\,p = -\gamma p\boldsymbol{\nabla}\cdot\boldsymbol{u} - \frac{p}{T}\frac{(T-T_0)}{\tau},$$

$$\bar{\omega}^3 + i\varsigma\bar{\omega}^2 - \bar{\omega}\mu^2(\kappa^2+N^2) - i\varsigma\kappa^2\mu^2 = 0,$$
$$\varsigma = 1/\gamma\tau \qquad \mu^2 = k_z^2/k^2.$$

$$\tau_{\rm max} = \frac{1}{\gamma}\left|\frac{k}{k_z}\right|\frac{1}{\sqrt{\kappa^2+N^2}} \qquad \sigma_{\rm max} = -\frac{1}{4}\left|\frac{k_z}{k}\right|\frac{N^2}{\sqrt{\kappa^2+N^2}}$$



Lyra (2014)

# Convective Overstability

Klahr & Hubbard (2014), Lyra (2014), Latter (2015)

$$\frac{\partial \rho}{\partial t} + (\boldsymbol{u}\cdot\boldsymbol{\nabla})\,\rho = -\rho\boldsymbol{\nabla}\cdot\boldsymbol{u},$$
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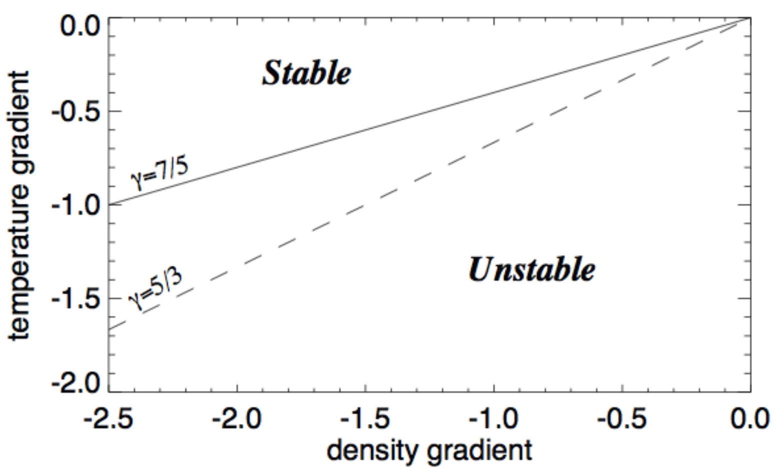
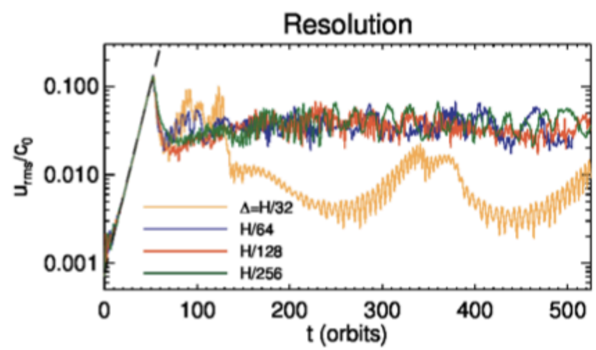
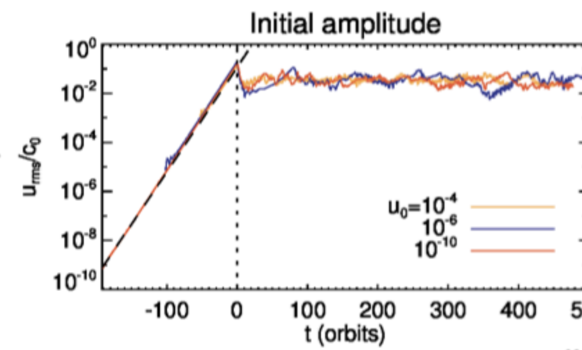
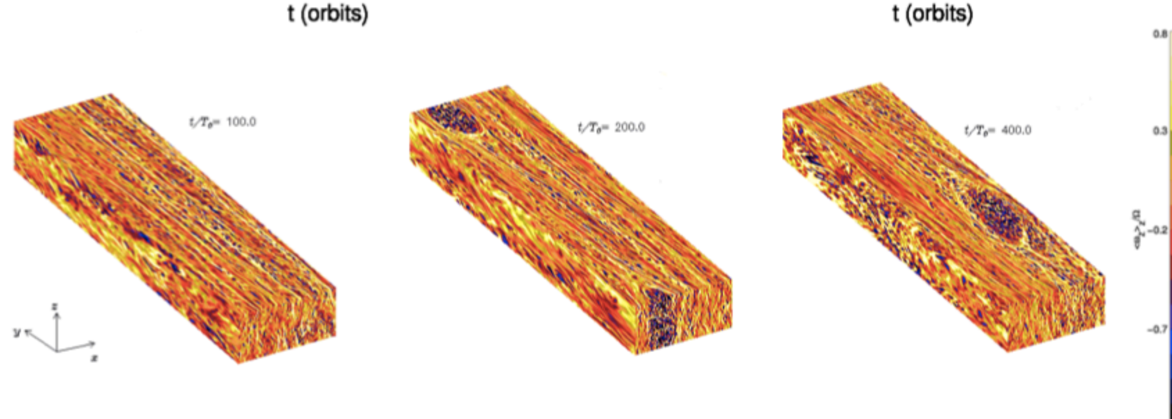
$$\frac{\partial p}{\partial t} + (\boldsymbol{u}\cdot\boldsymbol{\nabla})\,p = -\gamma p\boldsymbol{\nabla}\cdot\boldsymbol{u} - \frac{p}{T}\frac{(T-T_0)}{\tau},$$

$$\tau_{\rm max} = \frac{1}{\gamma\Omega};$$
$$\sigma_{\rm max} = -\frac{N^2}{4\Omega}.$$



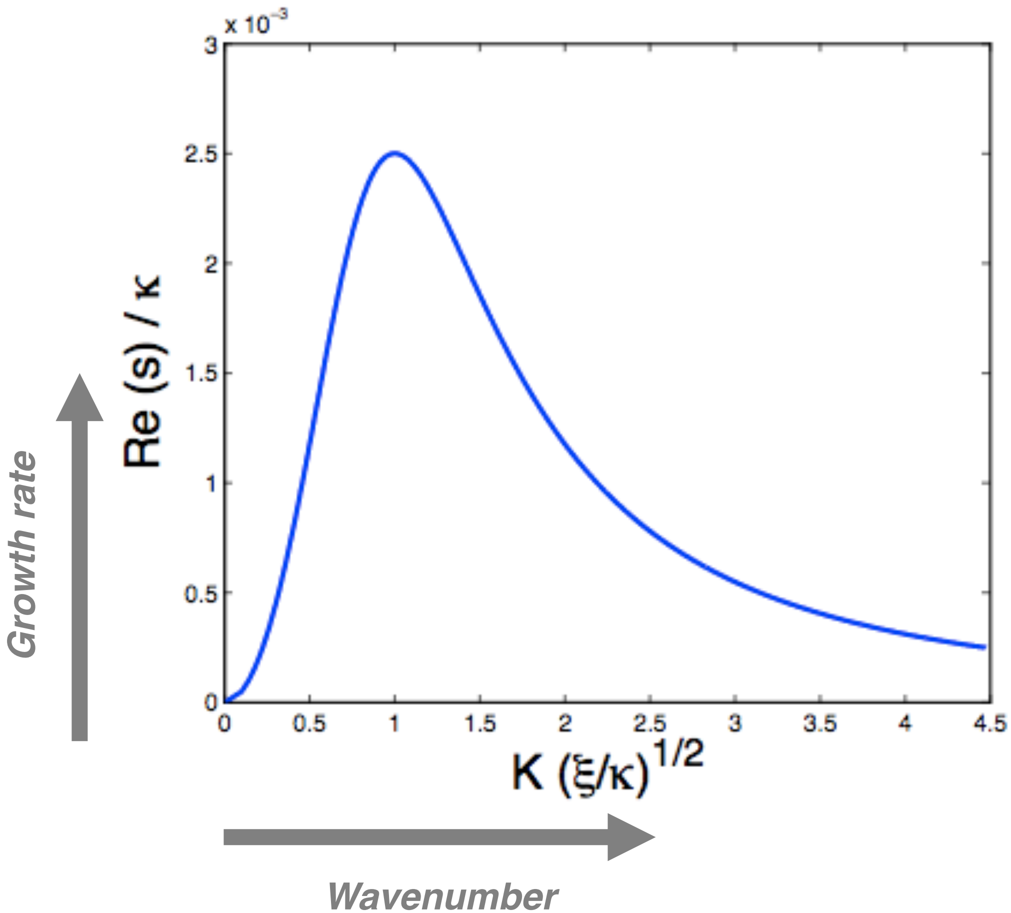



Lyra (2014)

# Convective Overstability



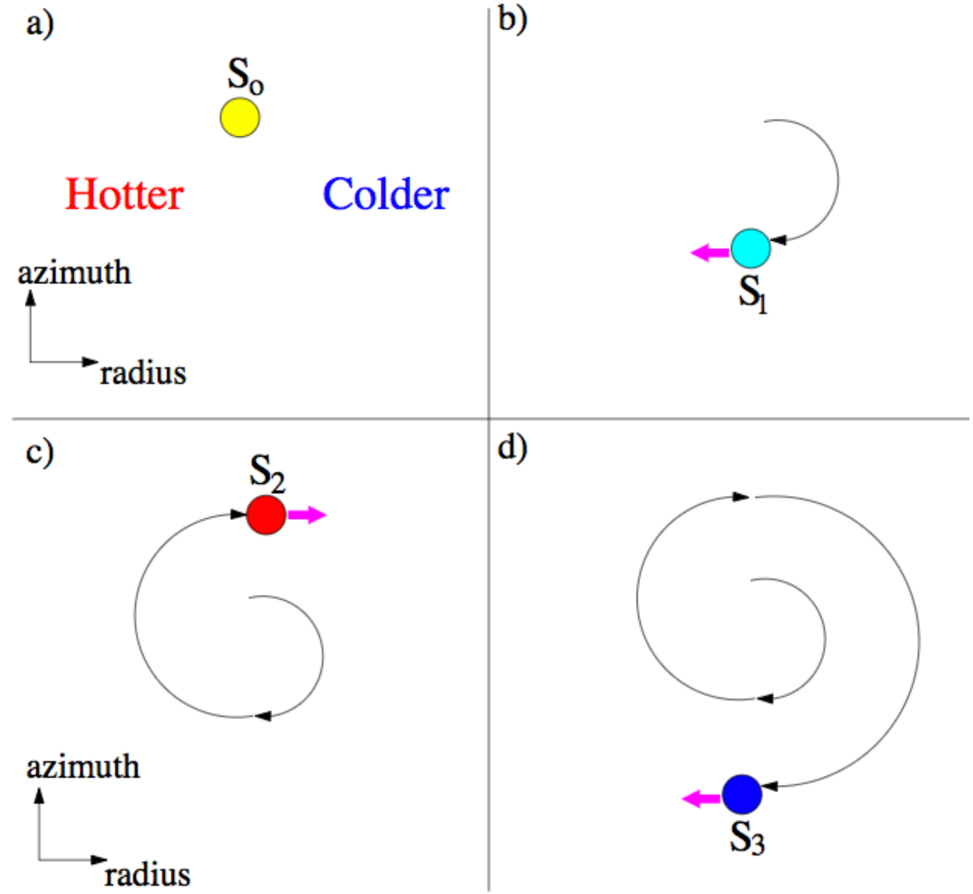
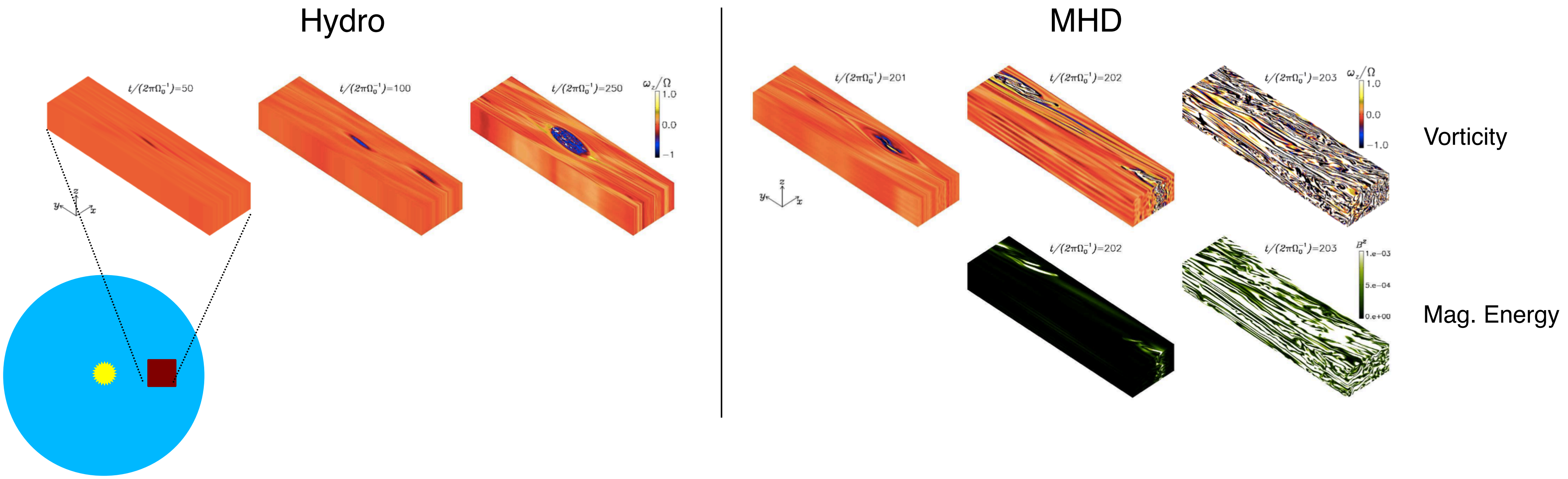




**Figure 2.** Four panels indicating the convective overstability mechanism. In panel (a) a fluid blob is embedded in a radial entropy gradient. In panel (b) it undergoes half an epicycle and returns to its original radius with a smaller entropy than when it begun $S_1 < S_0$. It hence feels a buoyancy acceleration inwards and the epicycle is amplified. The process occurs in reverse once the epicycle is complete, shown in panel (c), where now $S_2 > S_0$. The oscillations hence grow larger and larger.

Latter (2015)

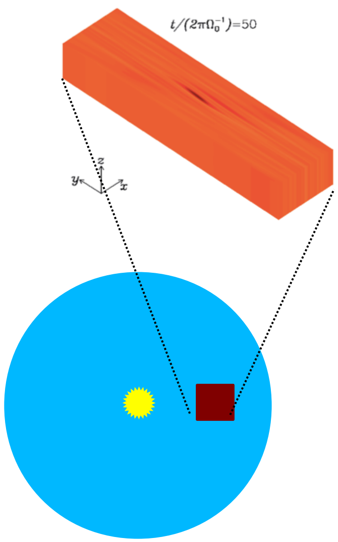
# COV/SBI and MRI

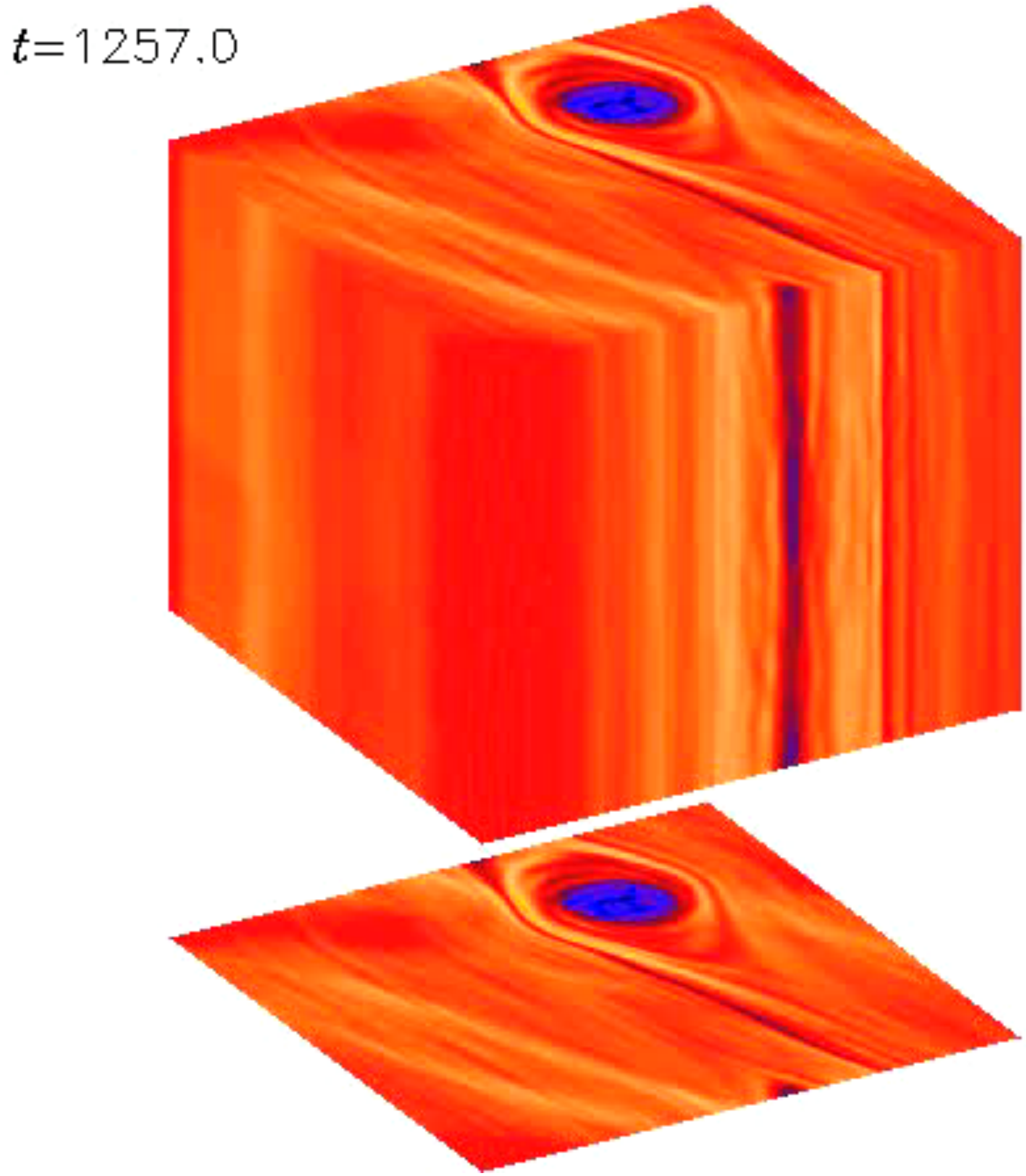
What happens when the disk is magnetized?

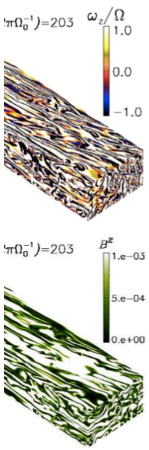



Lyra & Klahr (2011)

# COV/SBI and MRI



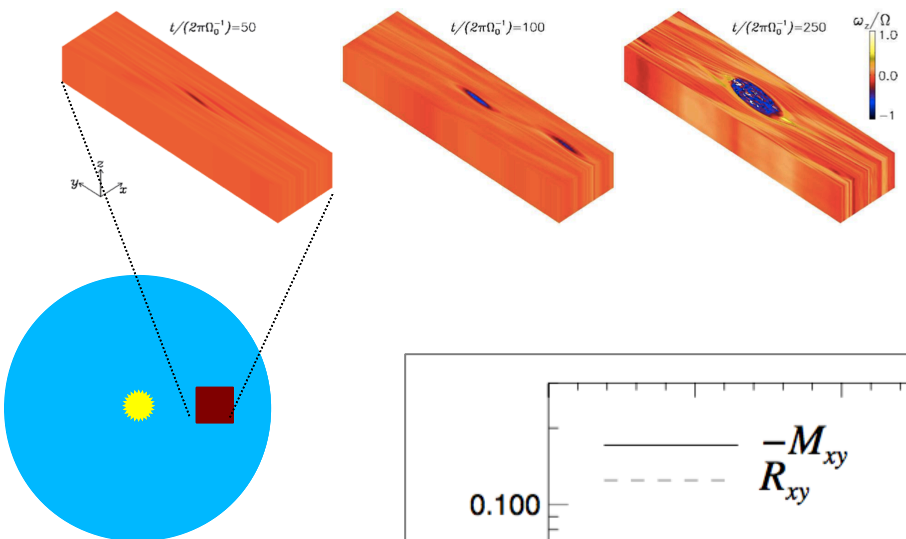




Vorticity

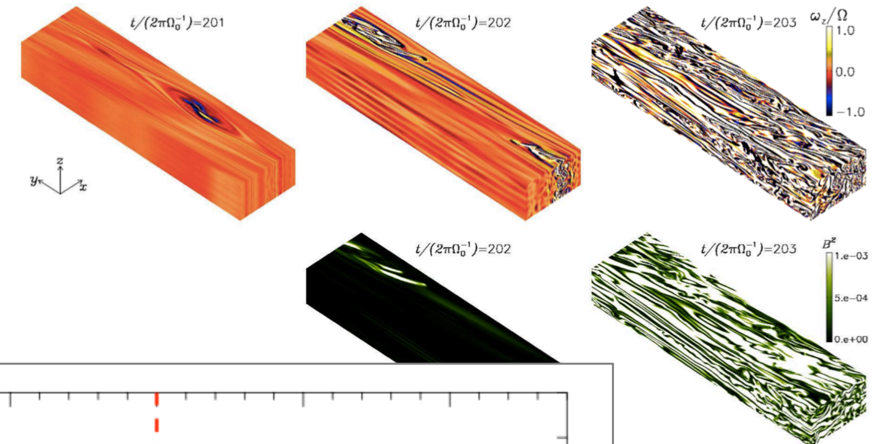
Mag. Energy

# COV/SBI and MRI

Hydro




MHD




Vorticity

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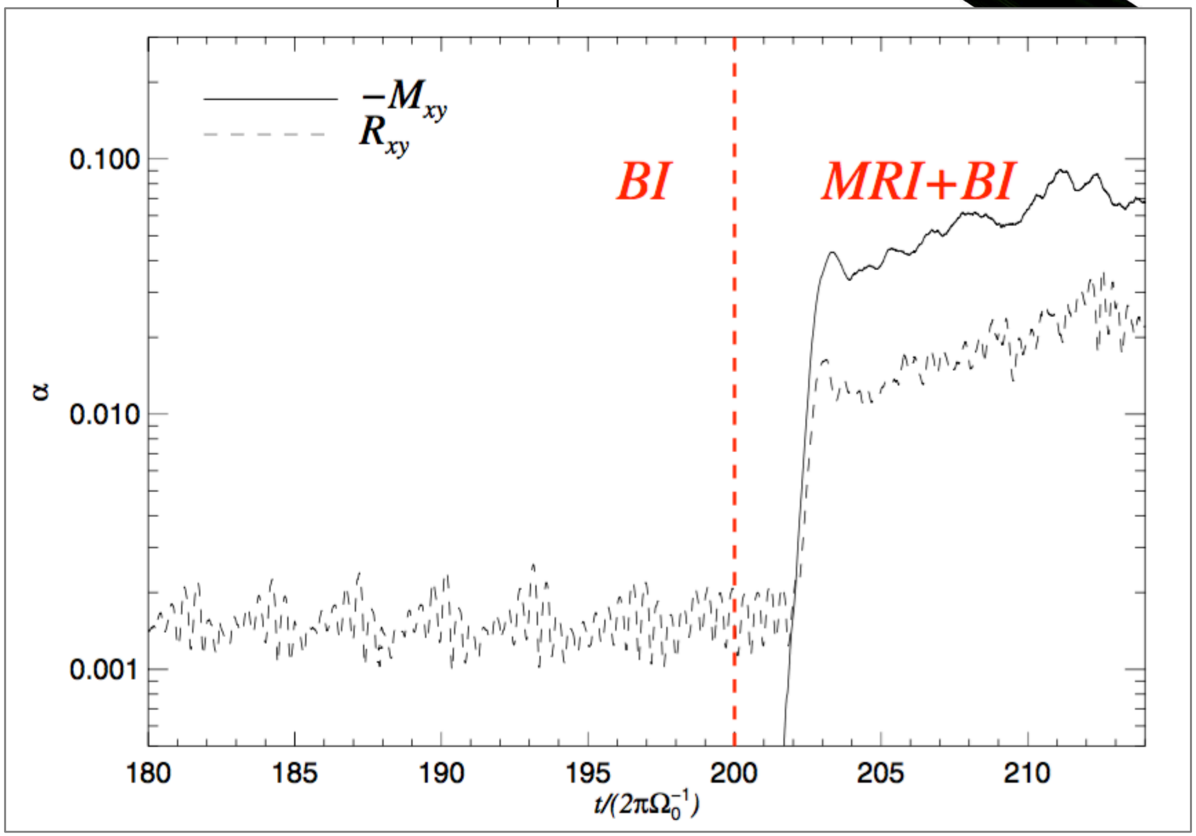
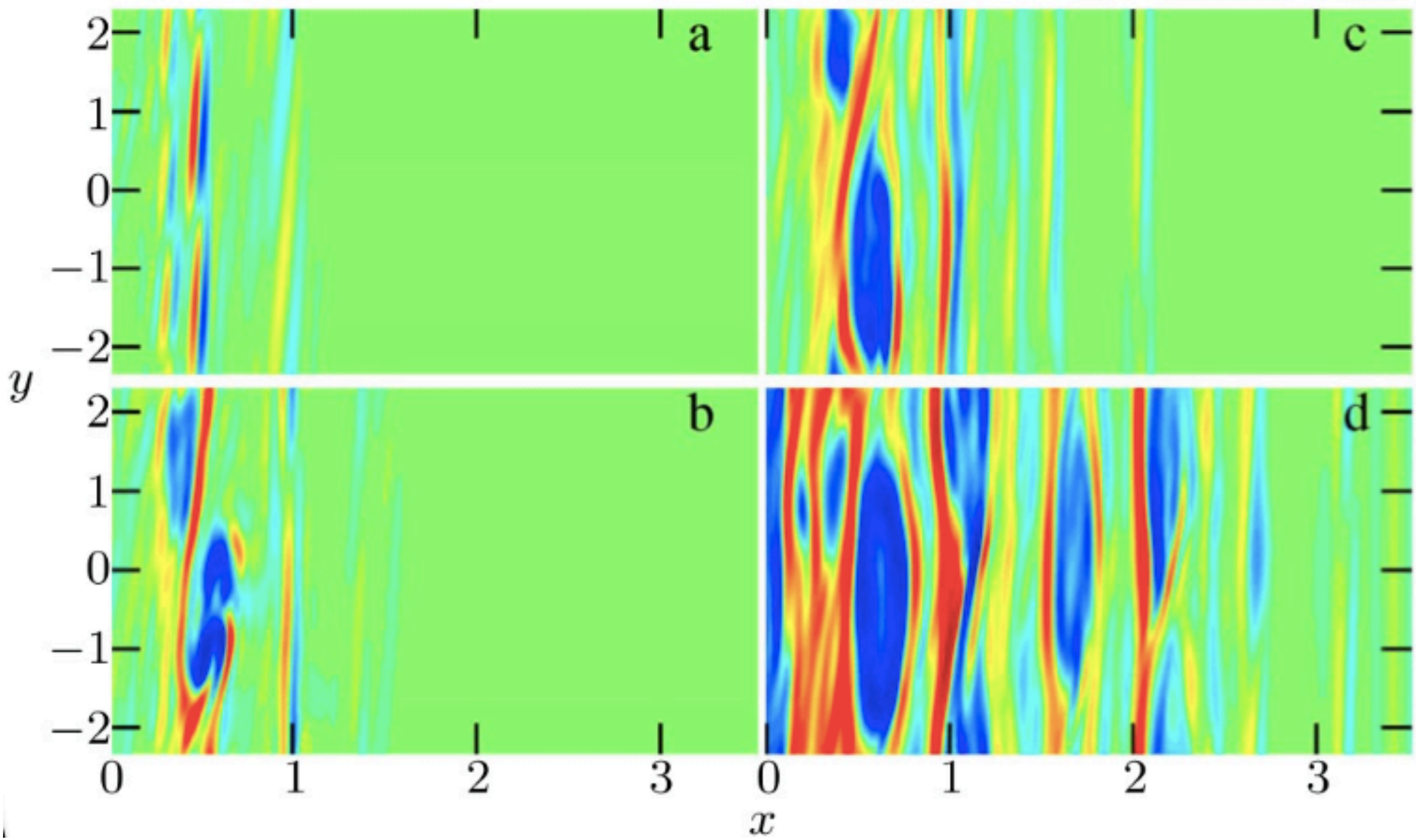



Lyra & Klahr (2011)

# Zombie Vortex Instability




Cascade of baroclinic critical layers

Marcus et al. (2015, 2016)

“Because the vortices arise from these dead zones, and because new generations of giant vortices march across these dead zones, we affectionately refer to them as ‘zombie vortices,’” said Marcus.

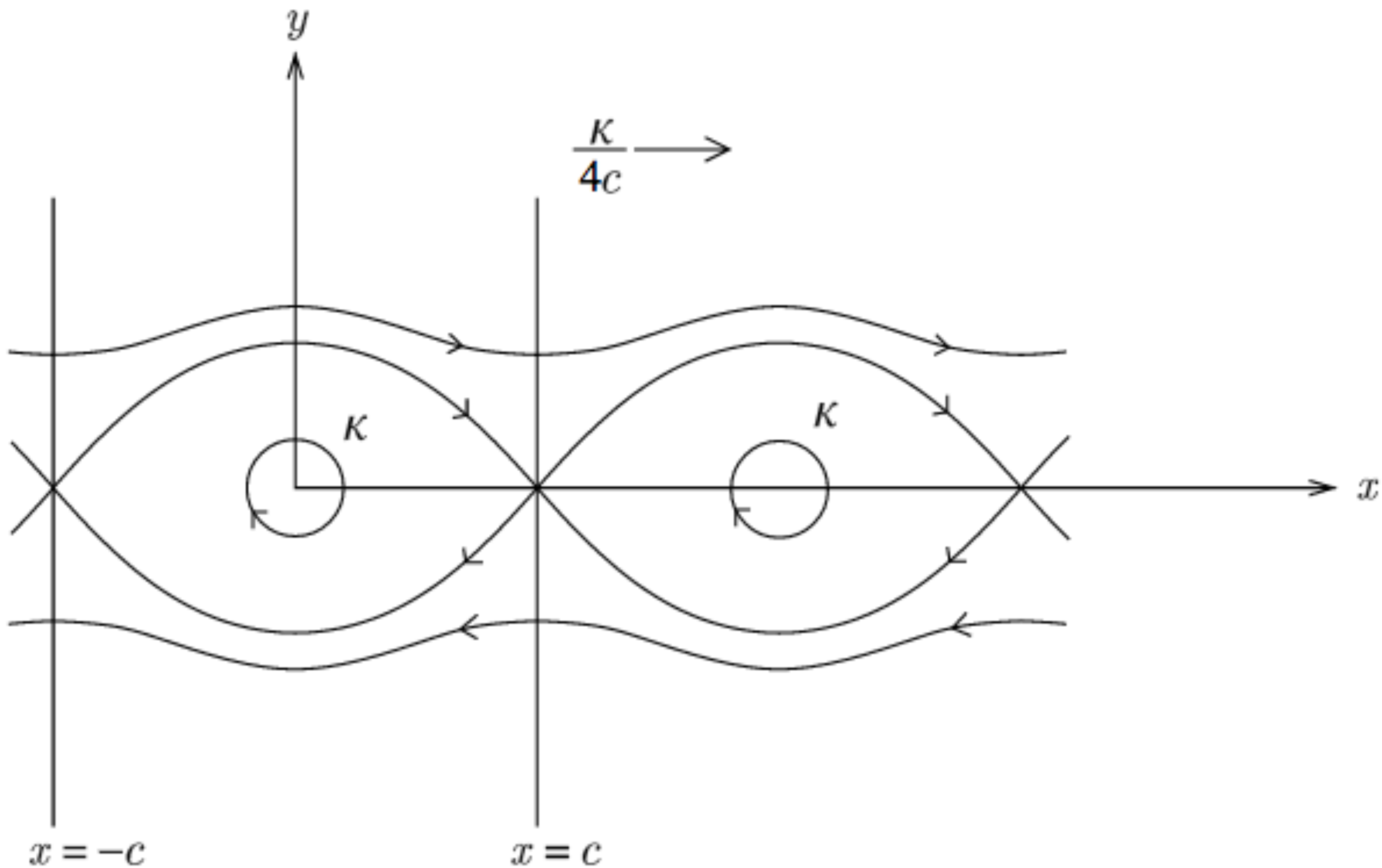



Figure 1. Notation and cat's-eye streamlines.

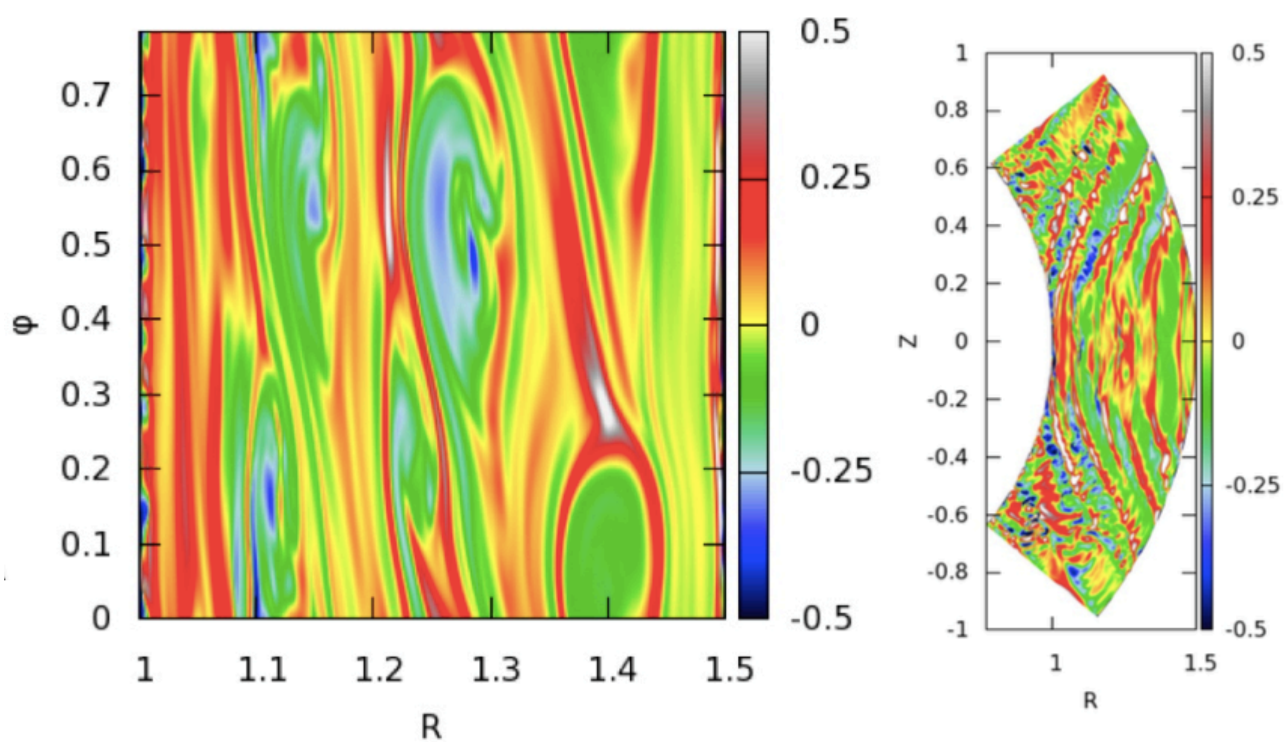
# Vertical shear instability

$$\rho_{\rm mid} = \rho_0 \left(\frac{R}{R_0}\right)^p,$$

$$c_s^2 = c_0^2 \left(\frac{R}{R_0}\right)^q,$$

$$\Omega = \Omega_K \left[1 + \frac{1}{2}\left(\frac{H}{R}\right)^2 \left(p + q + \frac{q}{2}\frac{Z^2}{H^2}\right)\right]$$

$d\Omega / dz$ != 0 ; $\kappa_z^2 < 0$ => Rayleigh unstable




Nelson et al. (2013)

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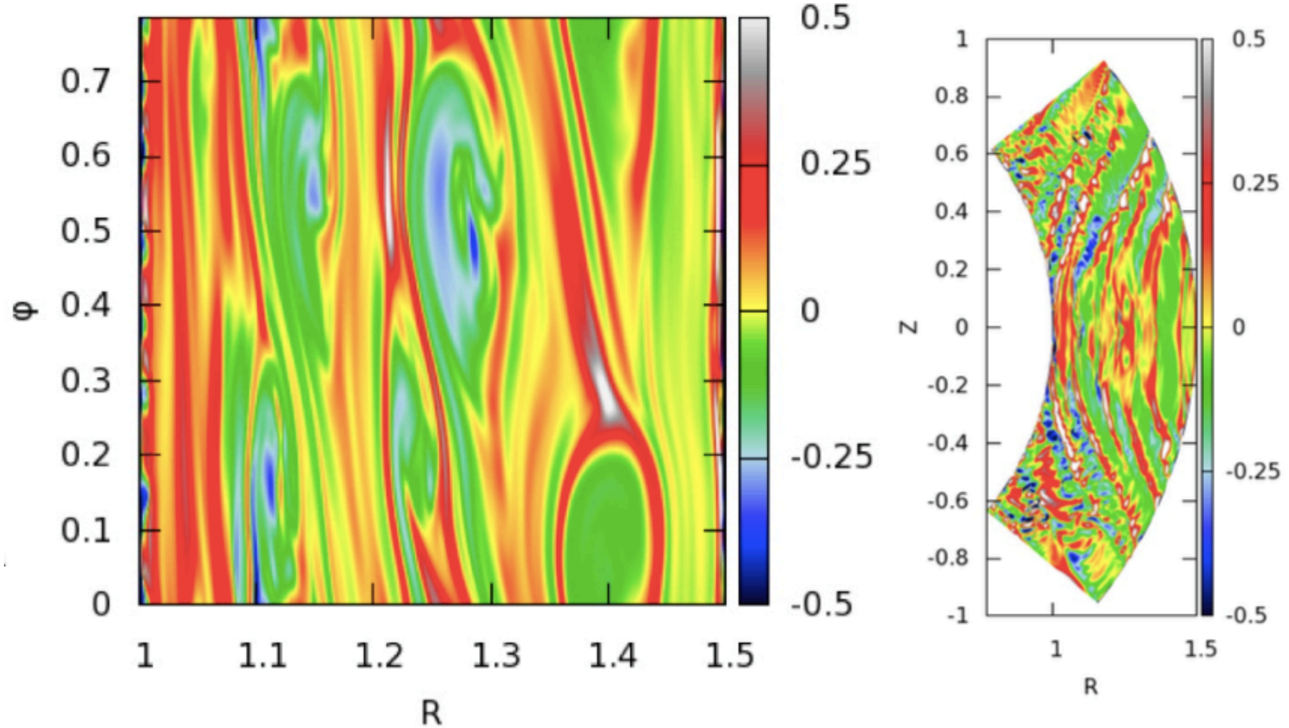
Solberg-Hoiland stability criterion

$\kappa^2 + N^2 > 0$




Nelson et al. (2013)

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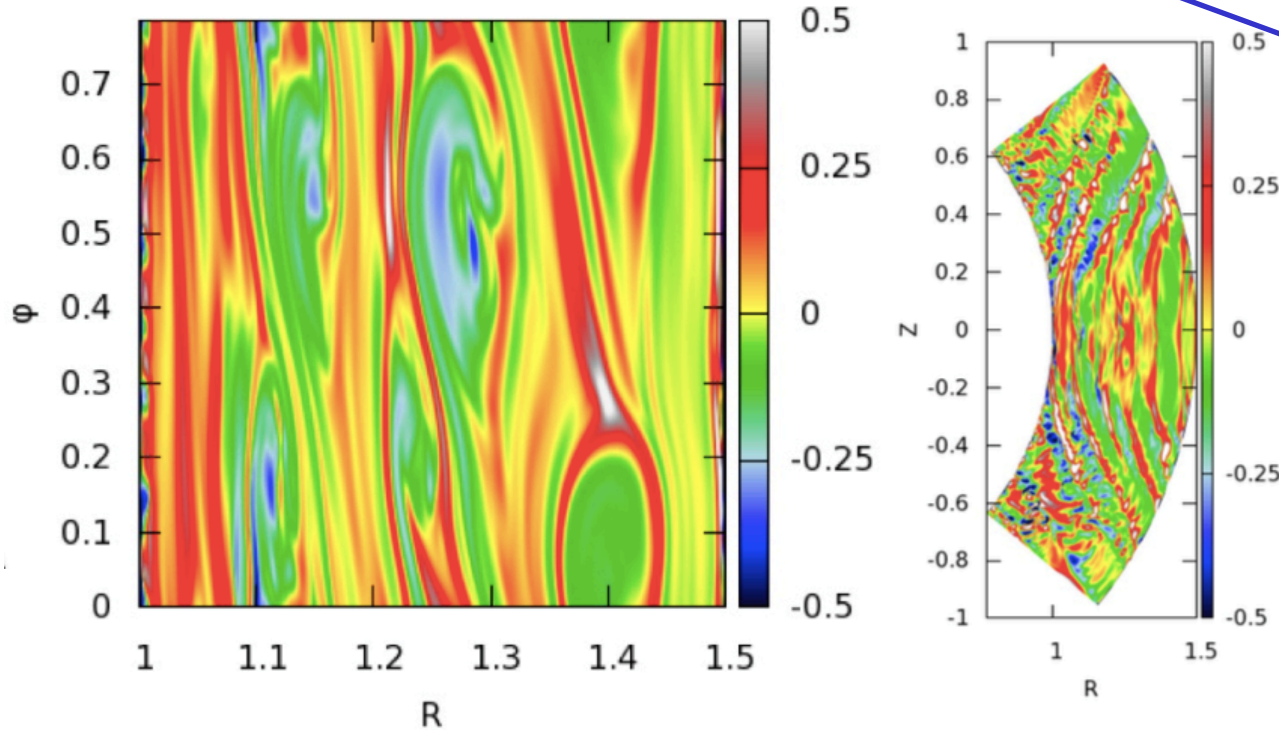
Solberg-Hoiland stability criterion

$\kappa^2 + N^2 > 0$

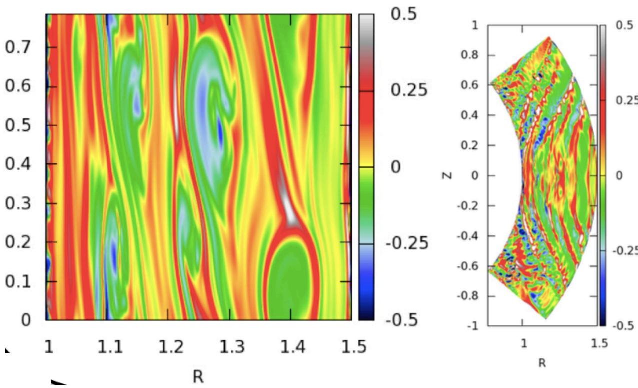
*Buoyancy stabilizes!*




Nelson et al. (2013)

# Thermal Instabilities

## Vertical Shear Instability

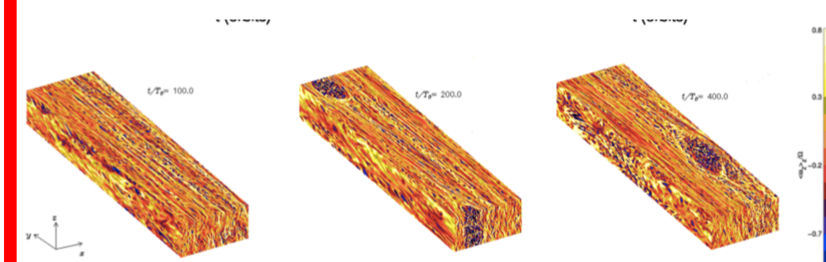



Nelson et al. 2013, Lin & Youdin 2015, Umurhan et al. 2016

$\alpha \sim 10^{-4} - 10^{-3}$

$\Omega\tau << 1$
$(\kappa < 1\ \mathrm{cm^2/g})$

## Convective Overstability

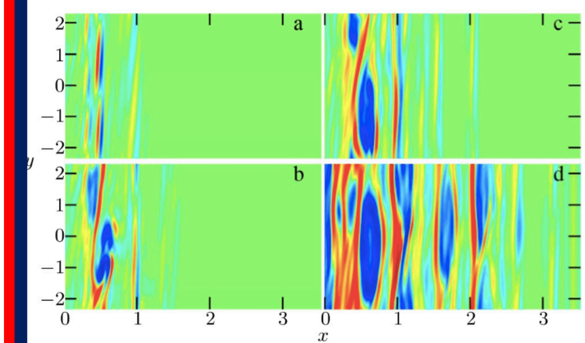


Klahr 2003, Lesur & Papaloizou 2010, Lyra & Klahr 2011, Lyra 2014

$\alpha \sim 10^{-4} - 10^{-3}$

$\Omega\tau \sim 1$
$(\kappa \sim 1\text{–}50\ \mathrm{cm^2/g})$

## Zombie Vortex Instability

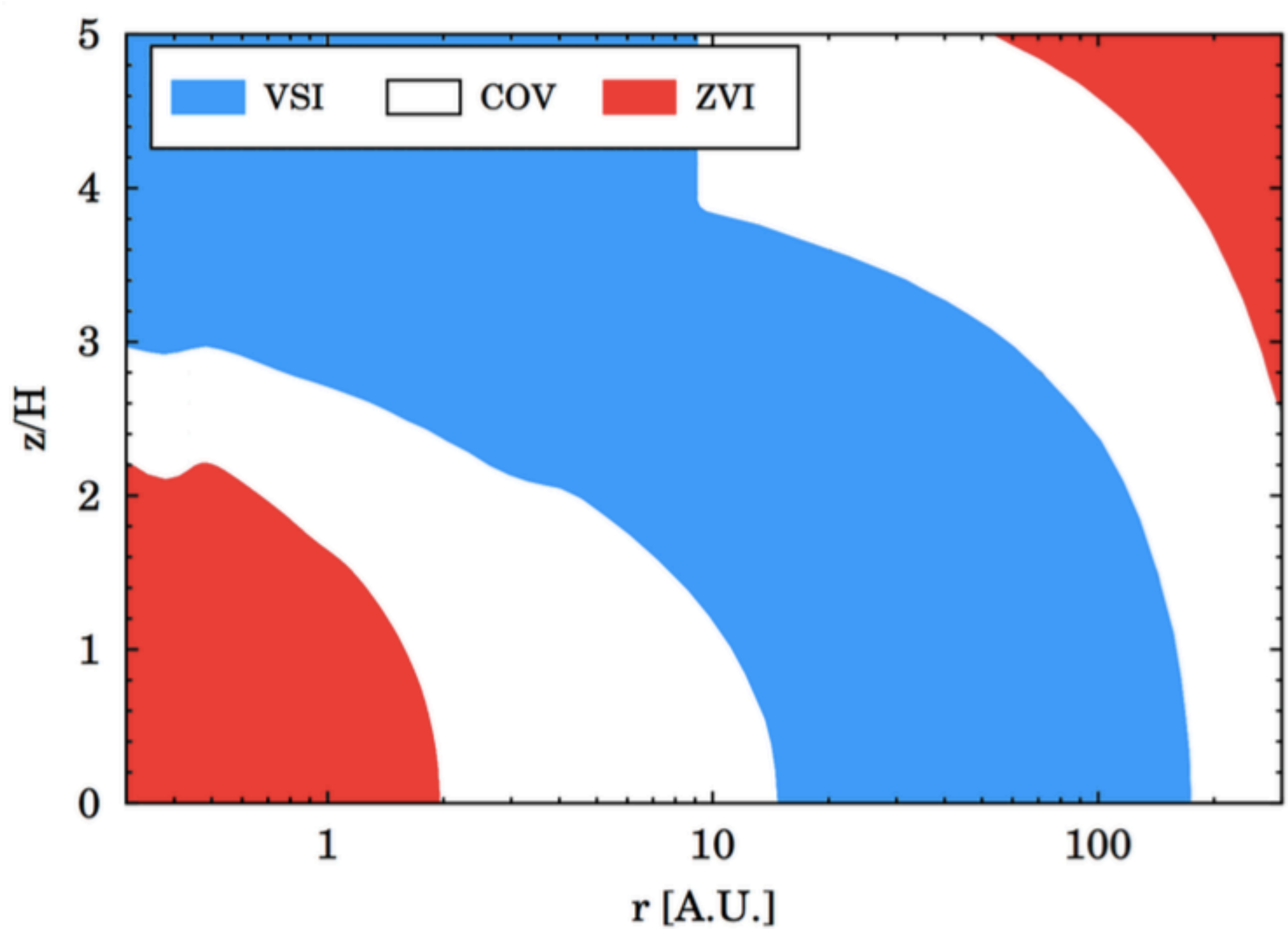



Marcus et al. 2012, 2013, 2015, 2016
Umurhan et al 2016, Lesur & Latter 2016

$\alpha <\sim 10^{-3}$

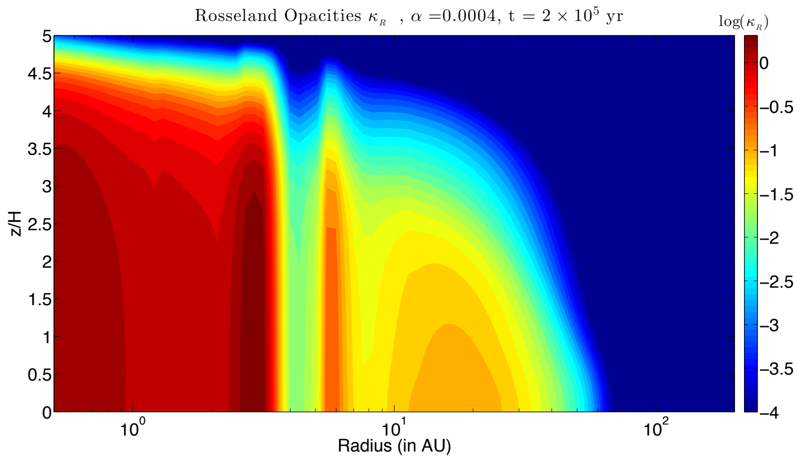
$\Omega\tau >> 1$
$(\kappa > 50\ \mathrm{cm^2/g})$

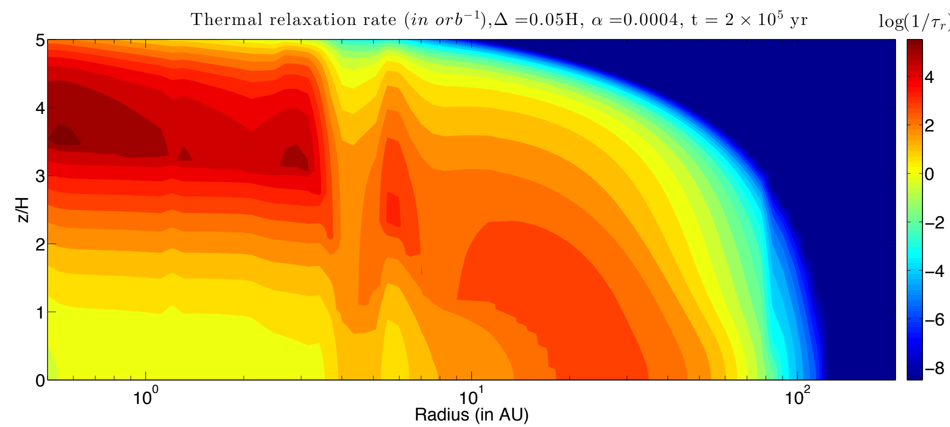
# Synthesis

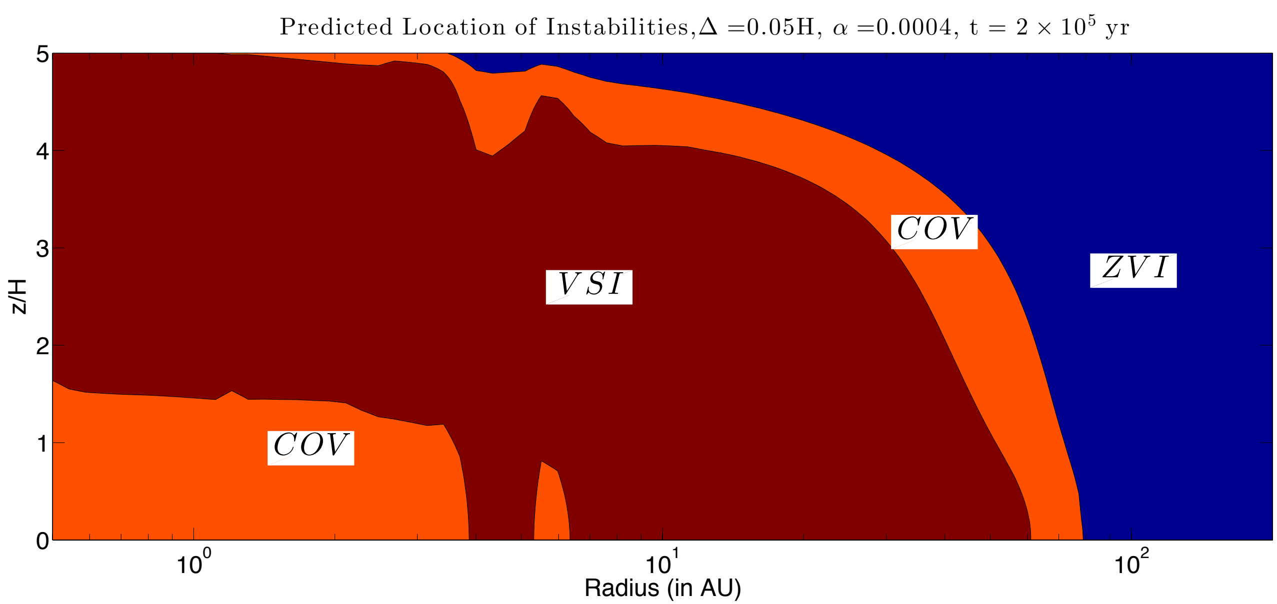



Malygin 2016

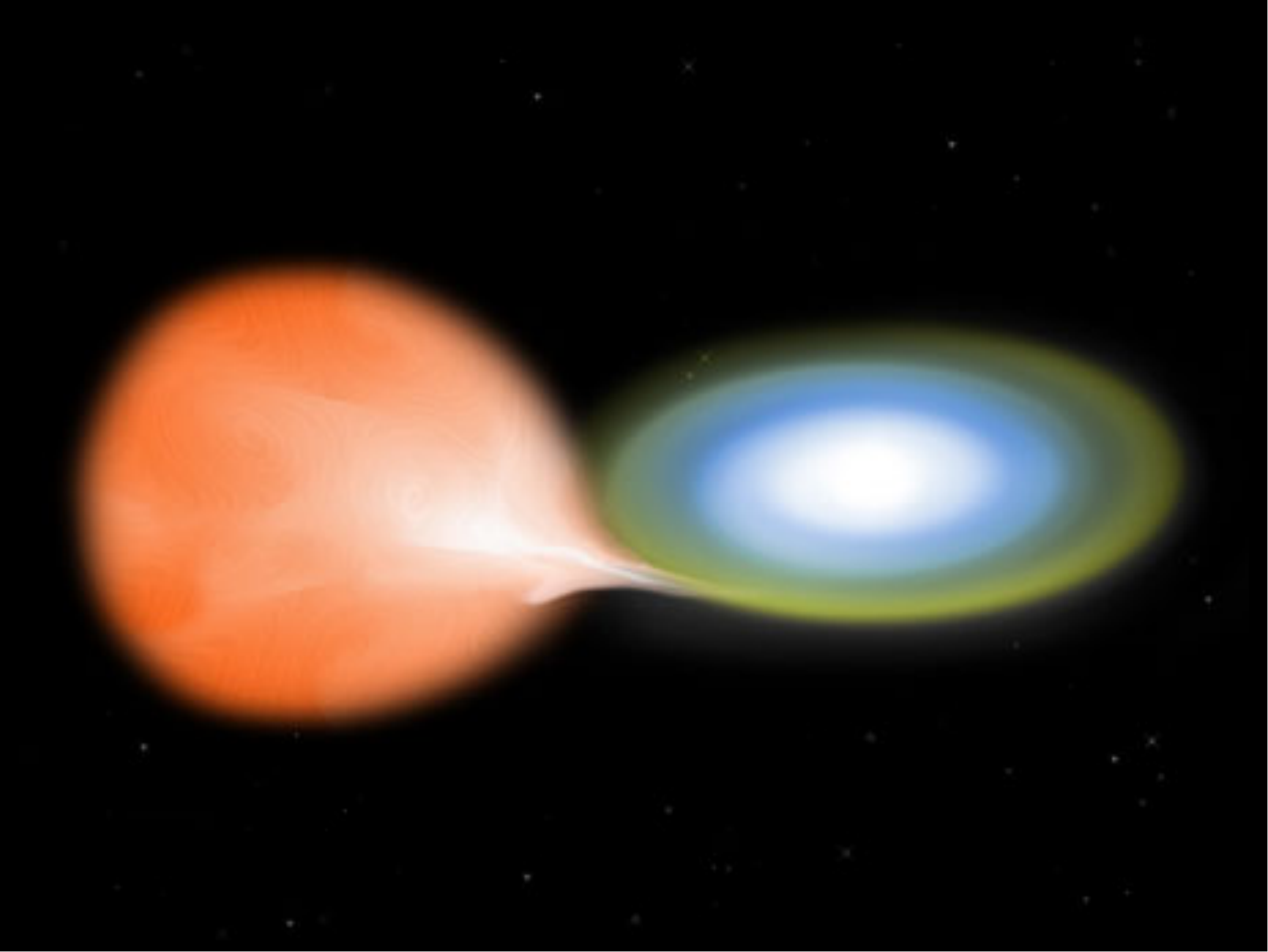
# Synthesis



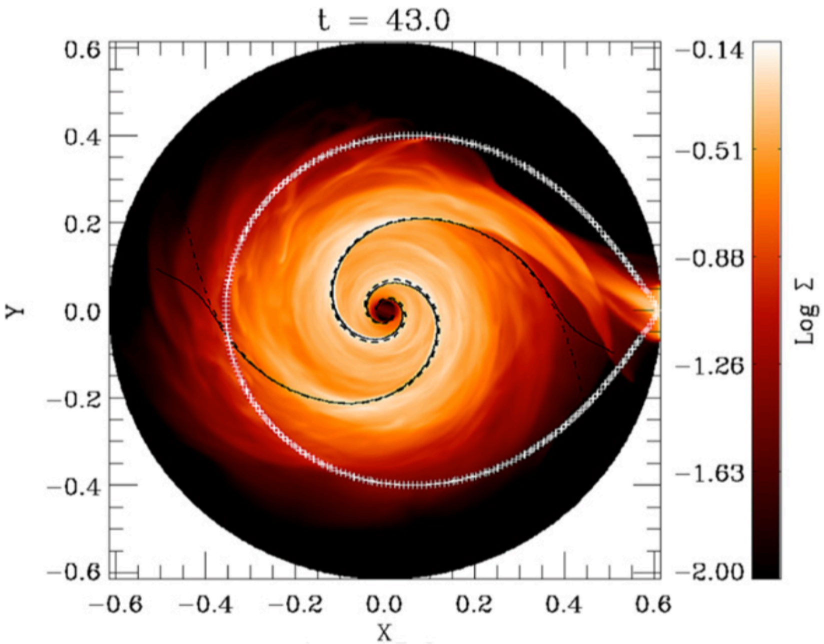




Cuzzi, Estrada, & Umurhan, in prep



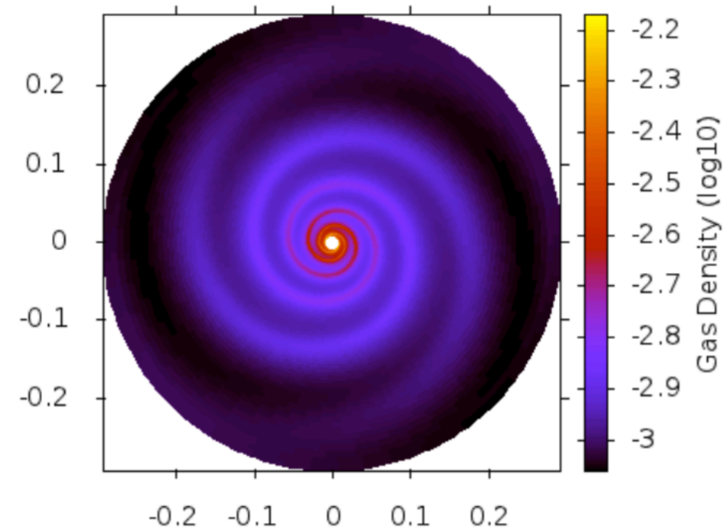
# Tidal deformation

Dwarf novae

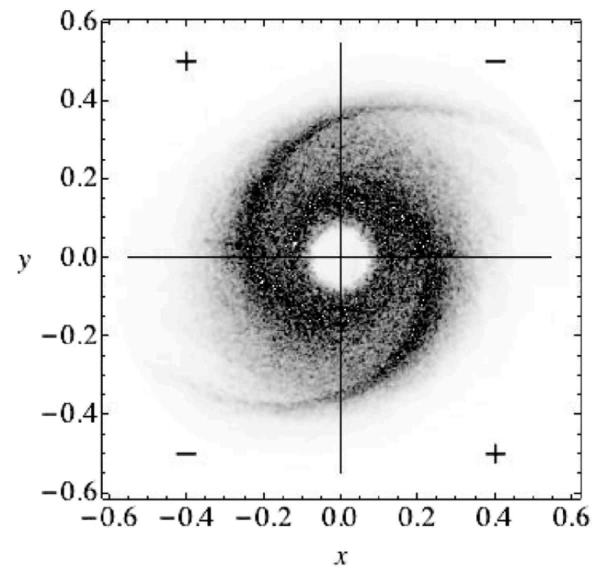



Ju, Stone and Zhu (2016)

Circumplanetary

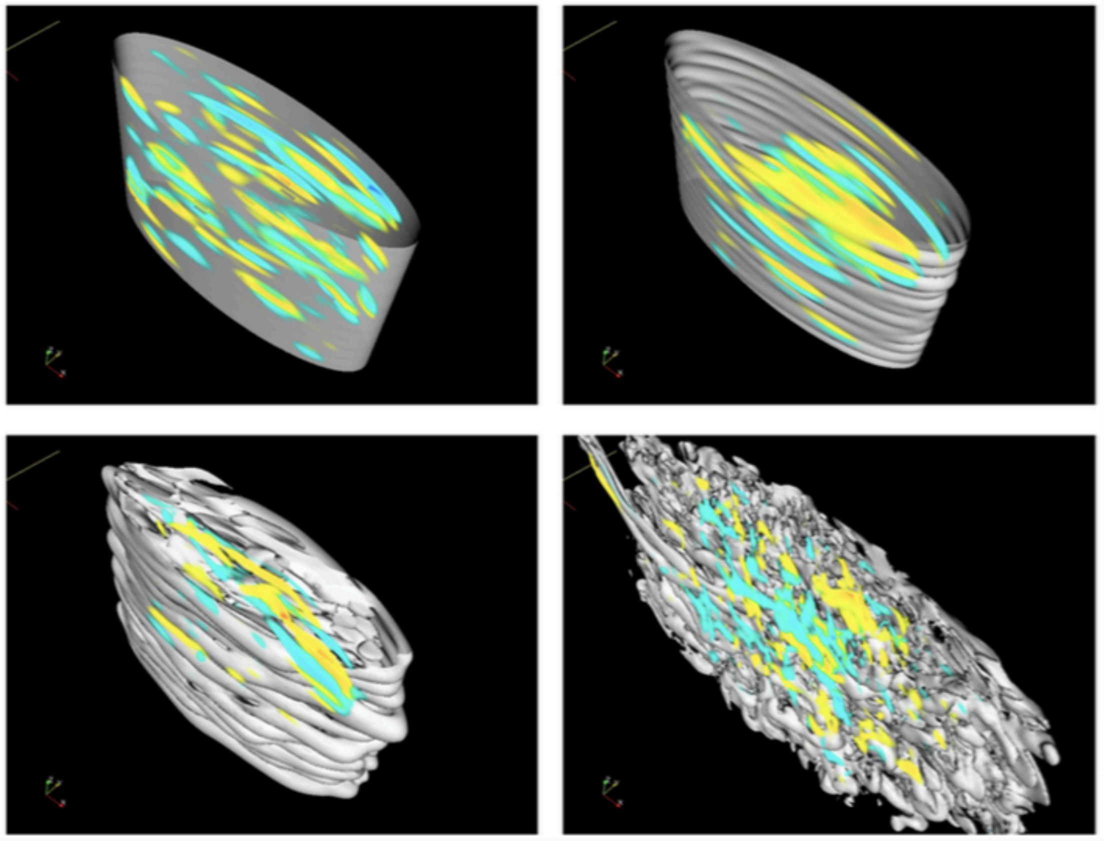


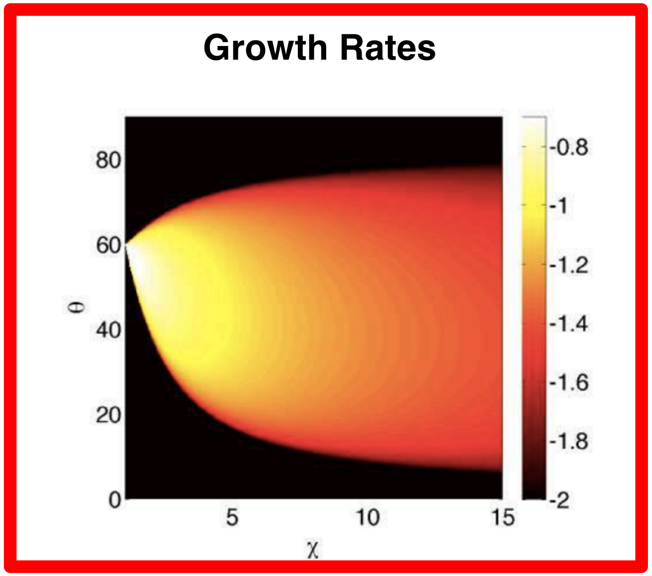

Rivier et al. (2012)




Martin & Lubow (2011)

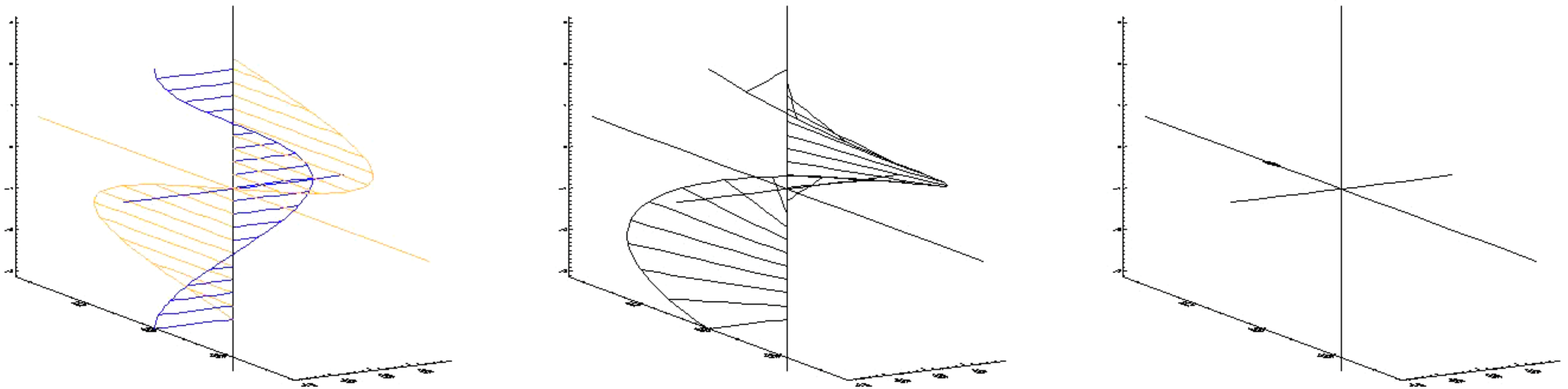
# Elliptic Instability



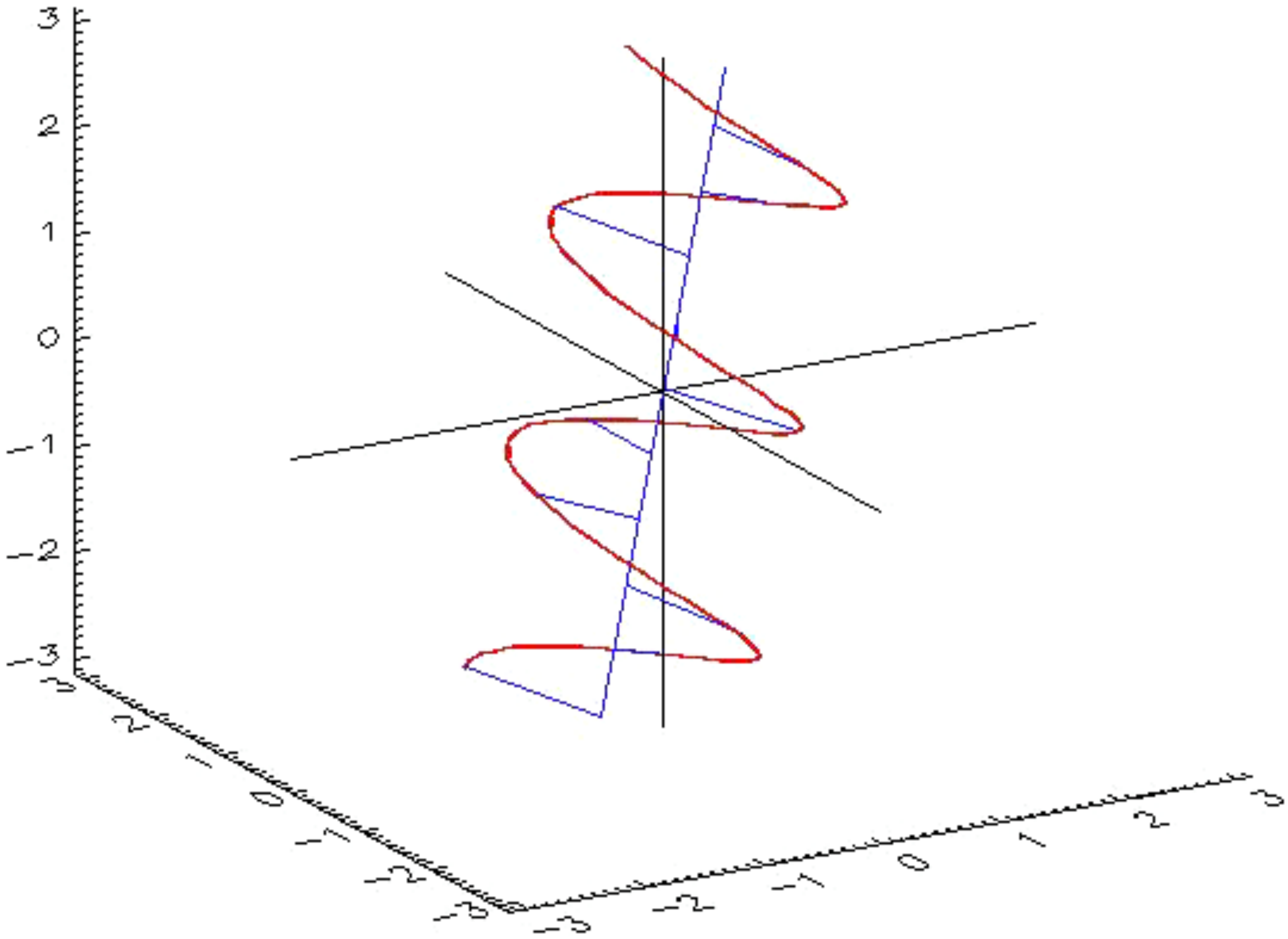



Bayly 1984, Lesur & Papaloizou 2009

# Fluid in rigid rotation supports a spectrum of oscillations

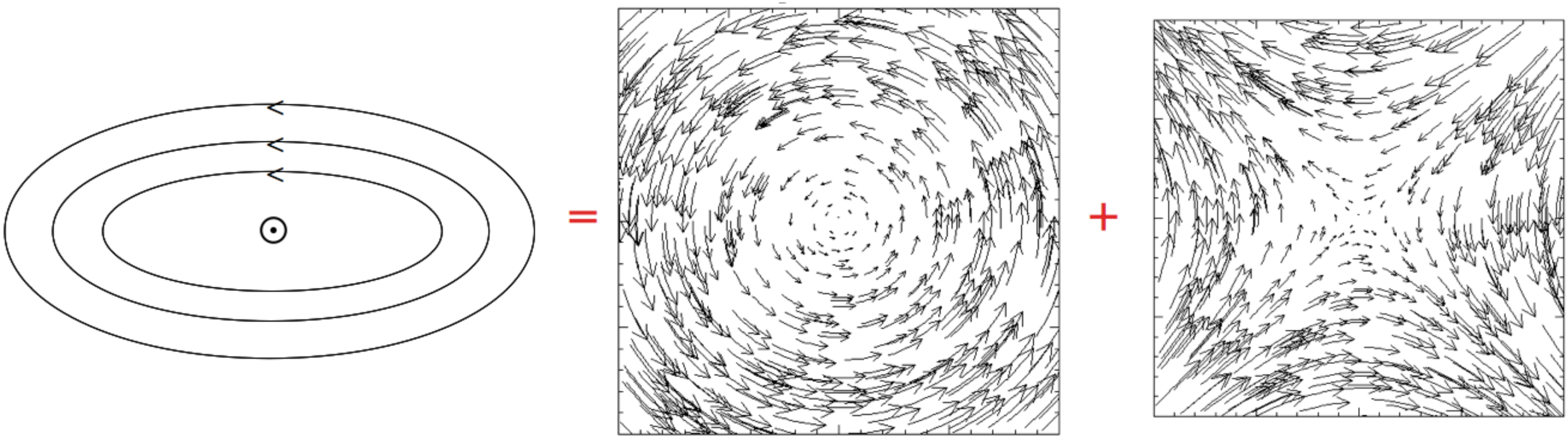


## Fluid in rigid rotation supports a spectrum of oscillations



# Introducing ellipticity: Strain

Rigid rotation | Strain field

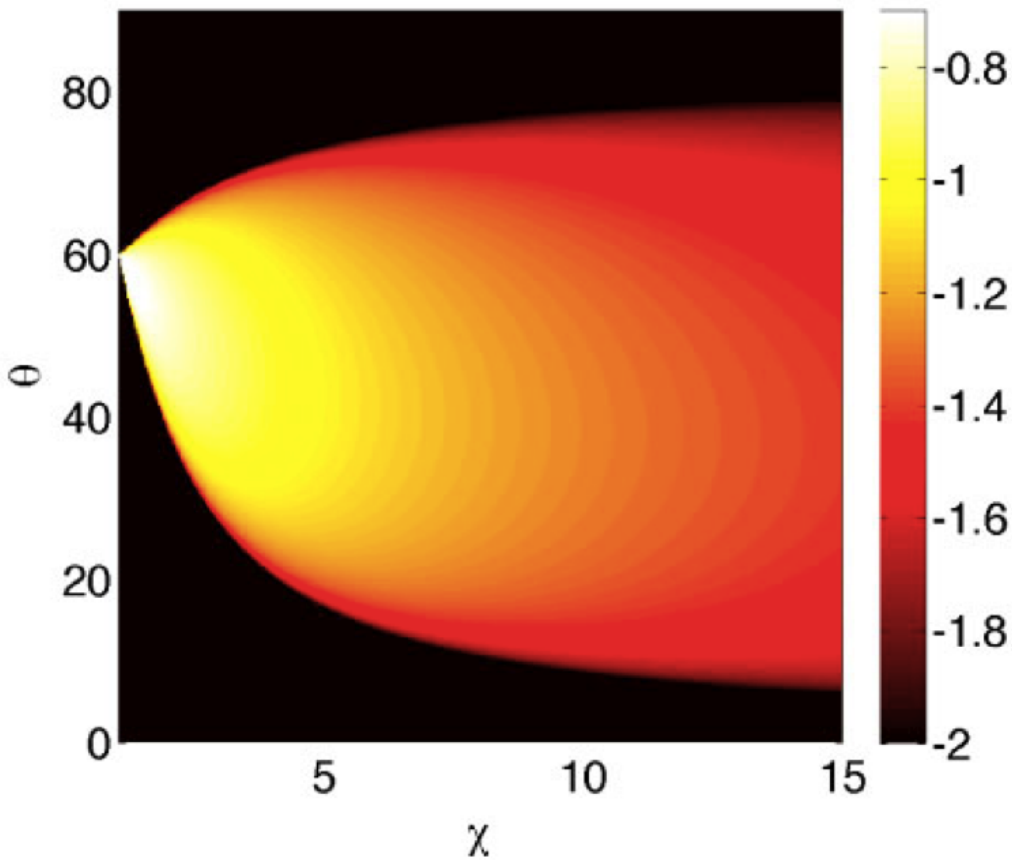


$$U=[-(1-\epsilon)y,(1-\epsilon)x] = [-y,x] + -\epsilon[y,x]$$

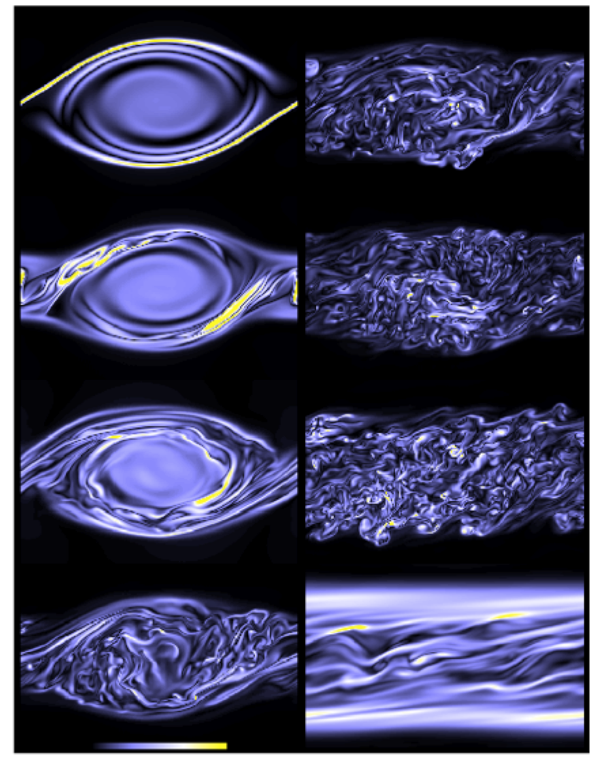
Rigid rotation is stable.

Strain is ***not*** necessarily so.

# Elliptic Instability




Lesur & Papaloizou (2009)
After Bayly (1986)

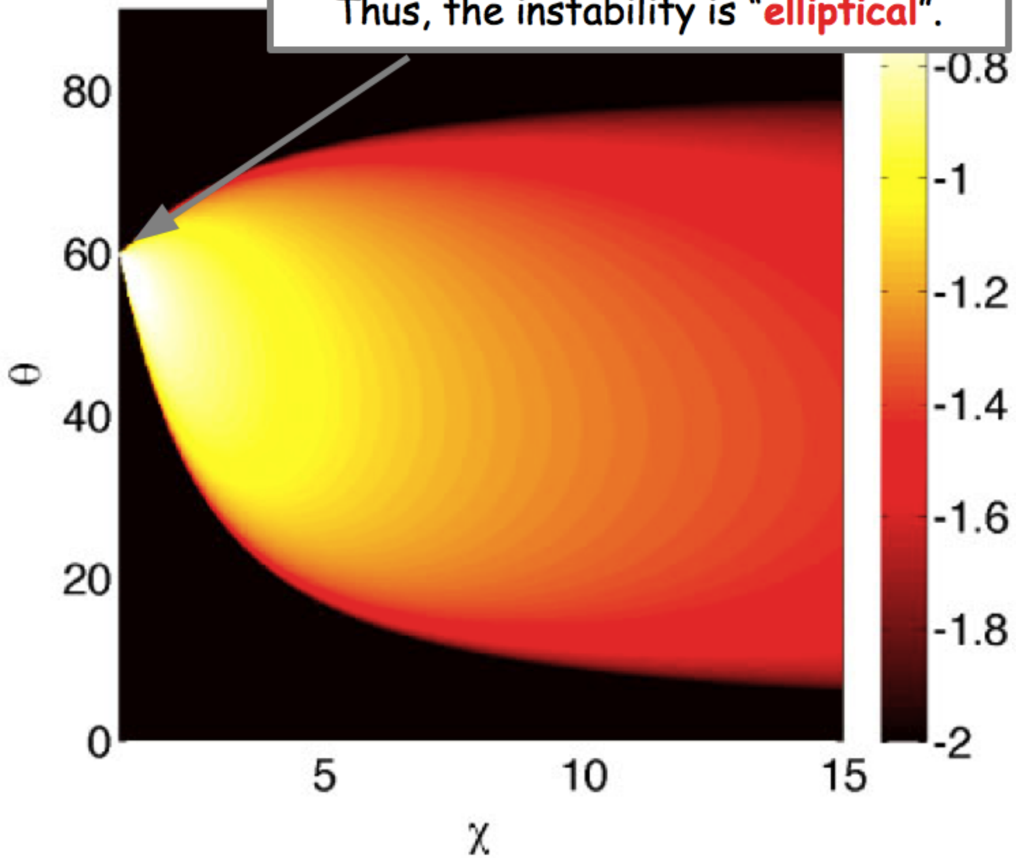


Vortex coherence is destroyed.
Energy cascades forward and dissipates.
The flow relaminarizes.

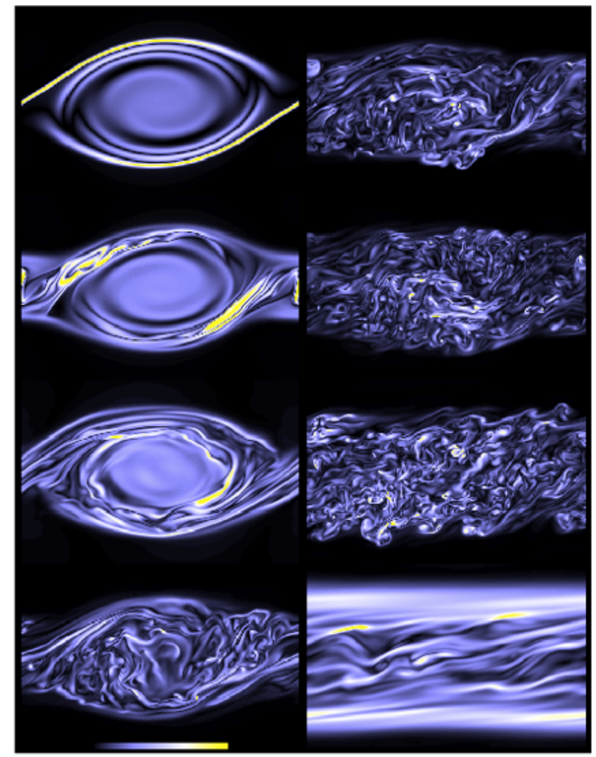
McWilliams (2010)

# Elliptic Instability

No instability for circular streamlines.
Thus, the instability is "**elliptical**".



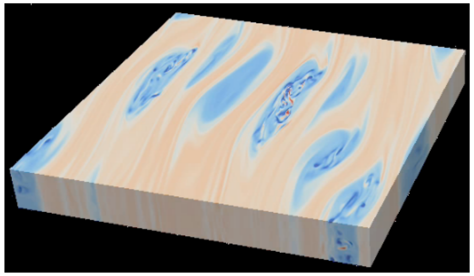

Lesur & Papaloizou (2009)
After Bayly (1986)



Vortex coherence is destroyed
Energy cascades forward and dissipates
The flow relaminarizes

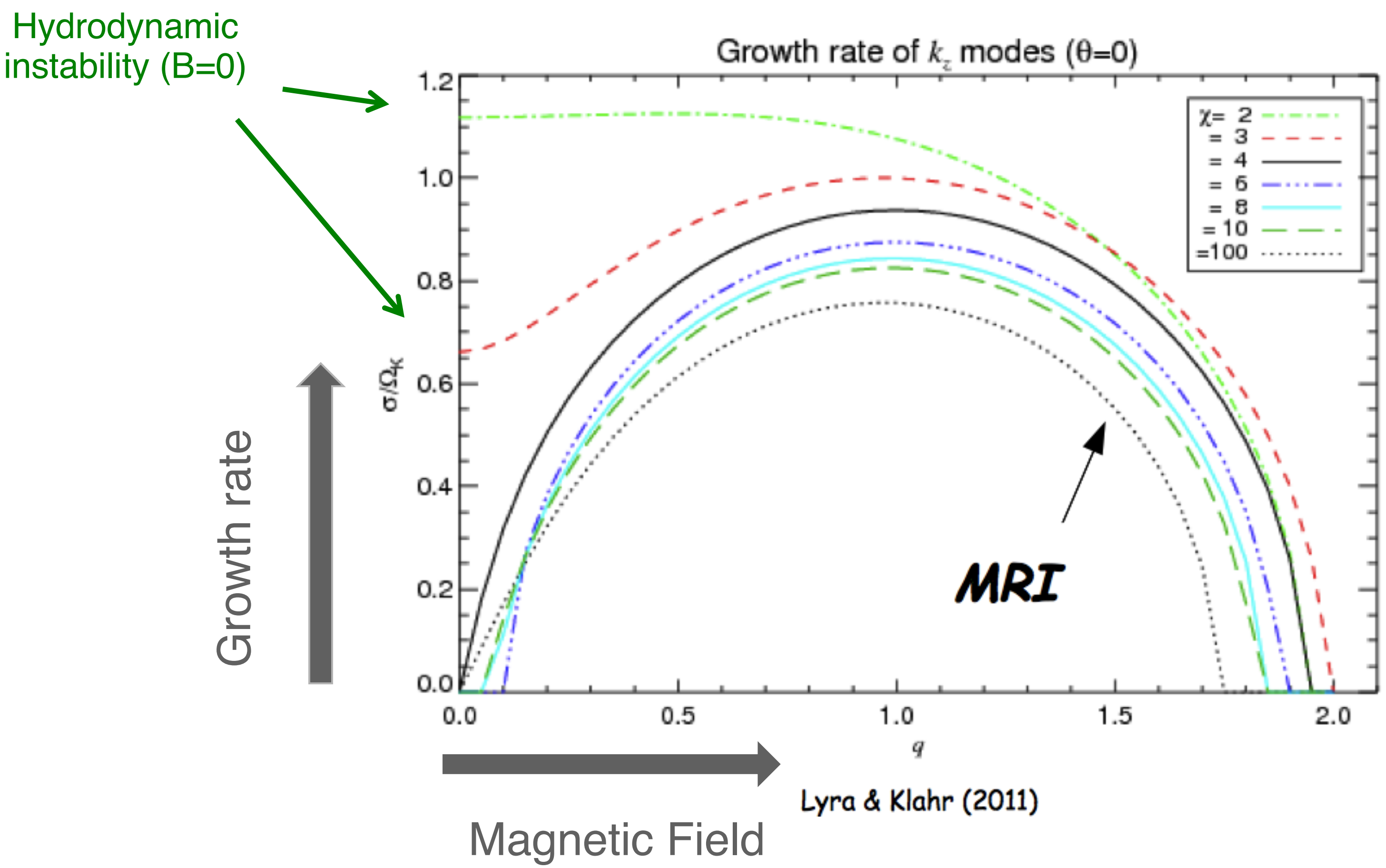
McWilliams (2010)

# Magneto-Elliptic Instability



Lesur & Papaloizou (2010)

See also
Pierrehumbert 1986
Bayly 1986
Kerswell 2002
Lesur & Papaloizou 2009
Lesur & Papaloizou 2010
Lyra & Klahr 2011
Lyra 2013

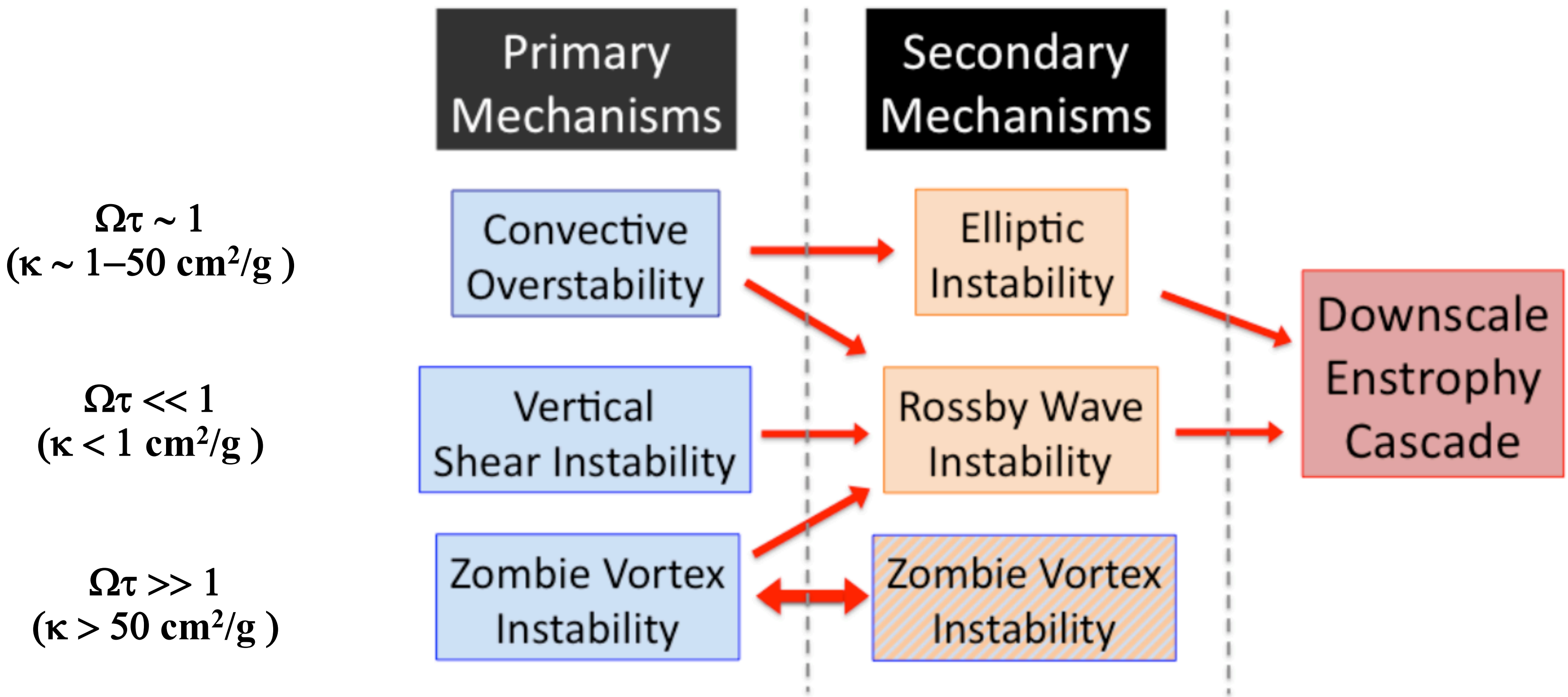



Lyra & Klahr (2011)

**Infinitely elongated vortices** are equivalent to **shear flows**.

They are subject to an MRI-like instability when magnetized.

# Conclusion




Umurhan (2016)