Hydrodynamical Instabilities in protoplanetary disks: a synthesis.

Wladimir Lyra

California State University

Jet Propulsion Laboratory

Funding

Exoplanet Research Program
XRP - 2018

NRAO 2017

XRP - 2016

HST Cycle 24, 2016

Computational Facilities

Ringberg, Jul 10th, 2019

Publications of the Astronomical Society of the Pacific

INVITED REVIEW

The Initial Conditions for Planet Formation: Turbulence Driven by Hydrodynamical Instabilities in Disks around Young Stars

Wladimir Lyra[1,2] and Orkan M. Umurhan[3,4]

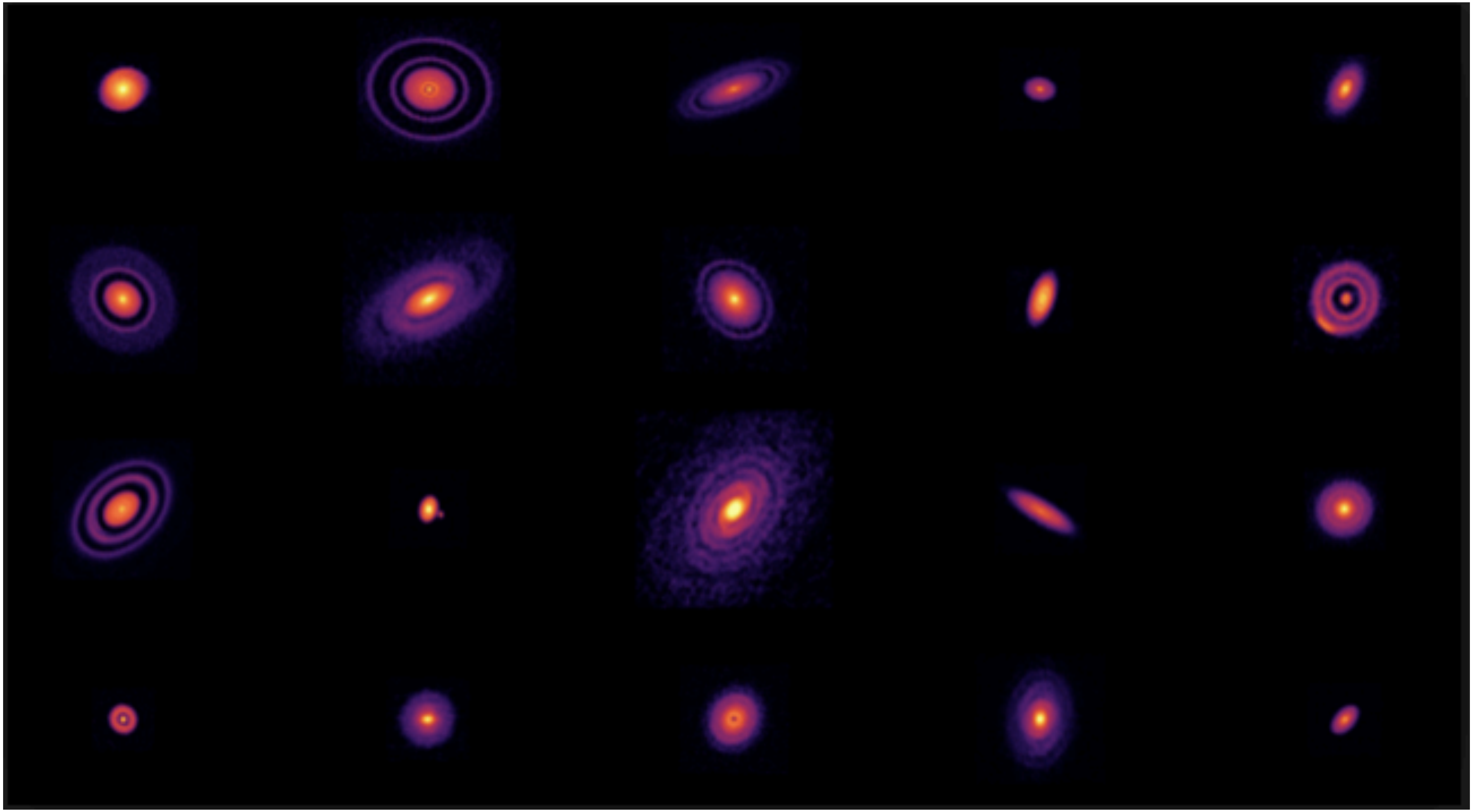
Published 2019 June 12 •

Publications of the Astronomical Society of the Pacific, Volume 131, Number 1001

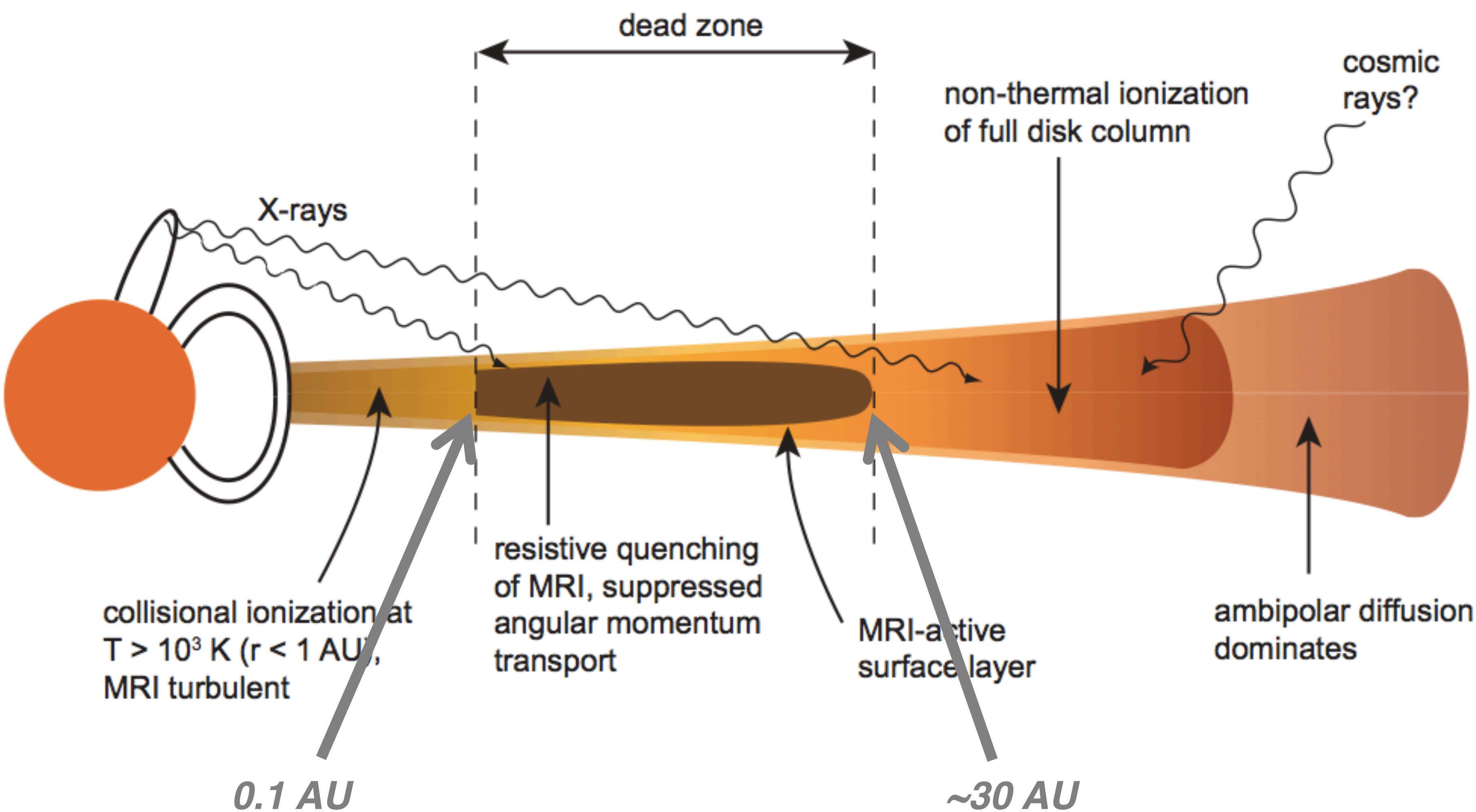
+ Article information

Abstract

This review examines recent theoretical developments in our understanding of turbulence in cold, non-magnetically active, planetesimal-forming regions of protoplanetary disks that we refer to throughout as "Ohmic zones." We give a brief background introduction to the subject of disk turbulence followed by a terse pedagogical review of the phenomenology of hydrodynamic turbulence. The equations governing the dynamics of cold astrophysical disks are given and basic

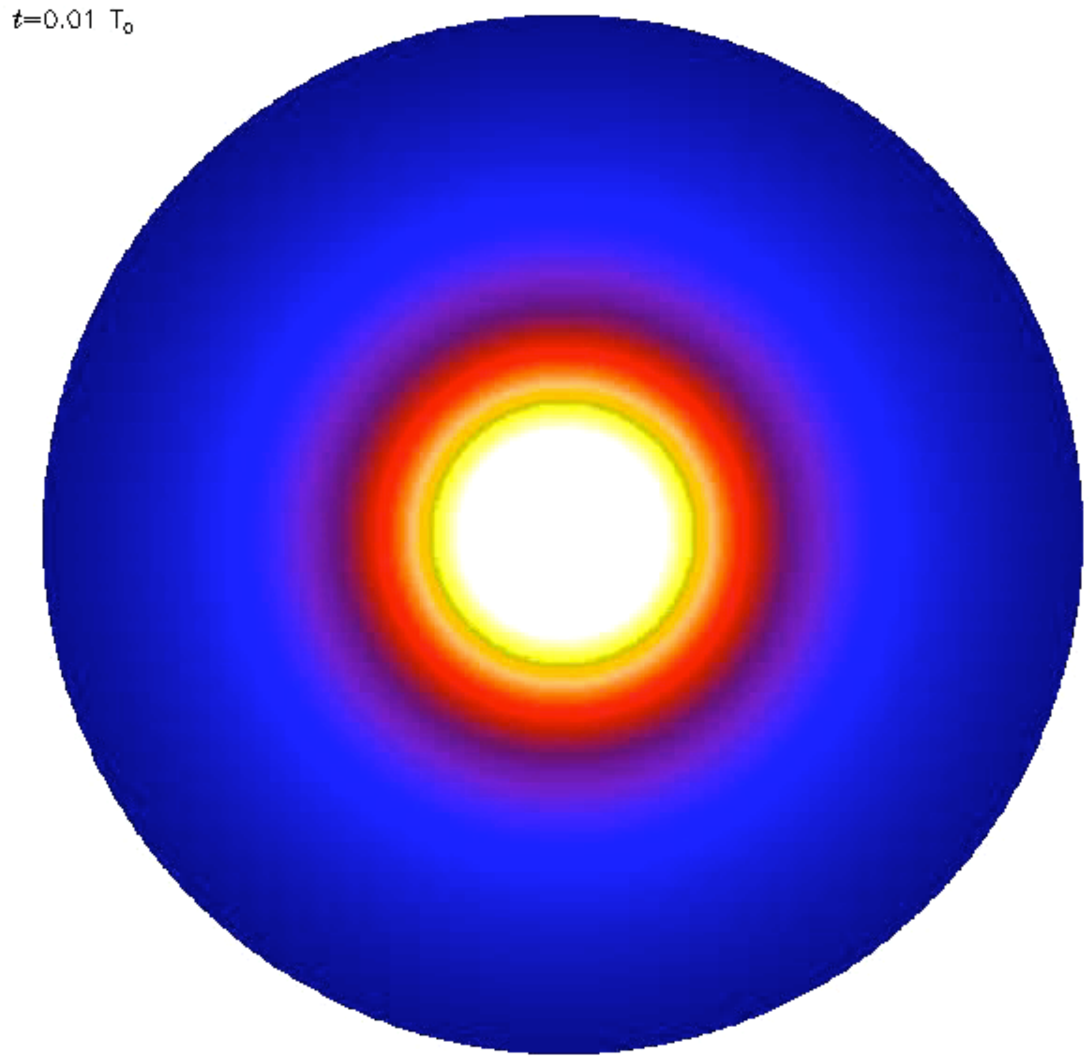


Dead zones



dead zone
cosmic
rays?
non-thermal ionization
of full disk column
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

Rossby wave instability



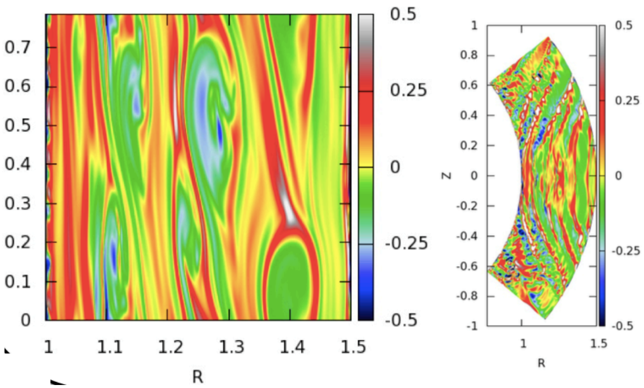
Magnetized inner disk + resistive outer disk

Lyra & Mac Low (2012)

Lovelace+ '99, Li+ '00, Tagger '01, Varniere & Tagger '06, de Val Borro+ 07,
Lyra+ 08, Lyra+ '09, Meheut+ '10, Meheut+ '12, Lin & Papaloizou 2012, Lin 2013, Faure et al. (2014), see also Mario's talk

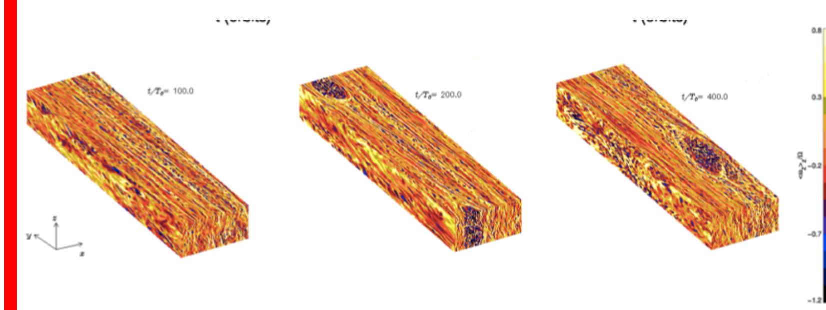
Hydrodynamical Instabilities

Vertical Shear Instability



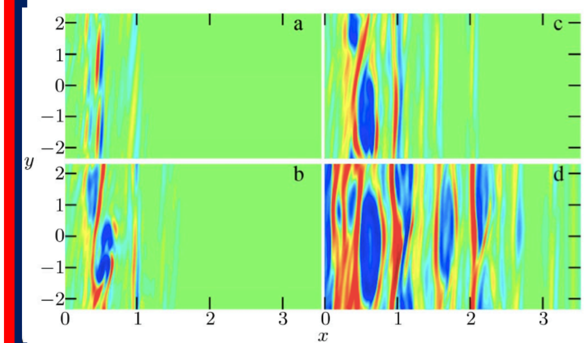
Nelson et al. 2013, Lin & Youdin 2015, Umurhan et al. 2016

Convective Overstability



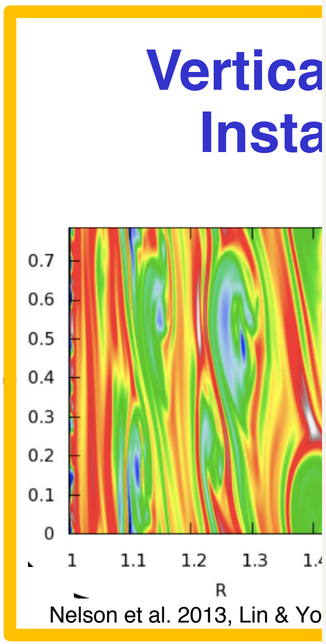
Klahr 2003, Petersen et al. 2007, Lesur & Papaloizou 2010, Lyra & Klahr 2011, Klahr & Hubbard 2014, Lyra 2014

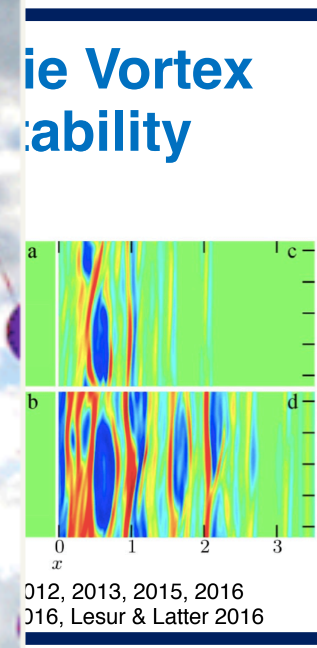
Zombie Vortex Instability



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

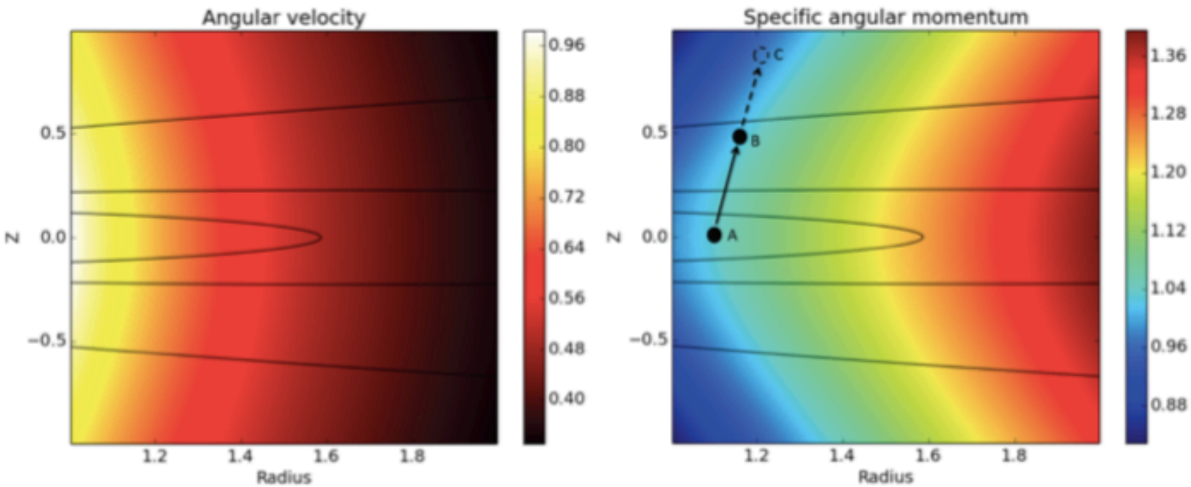
Hydrodynamical Instabilities



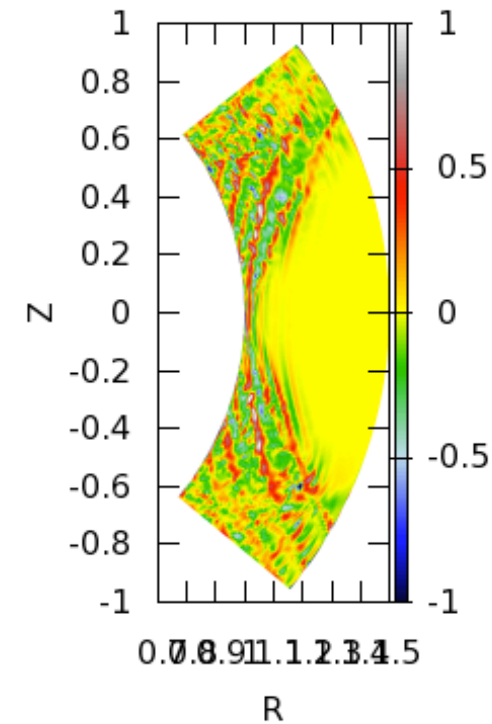


Vertical shear instability

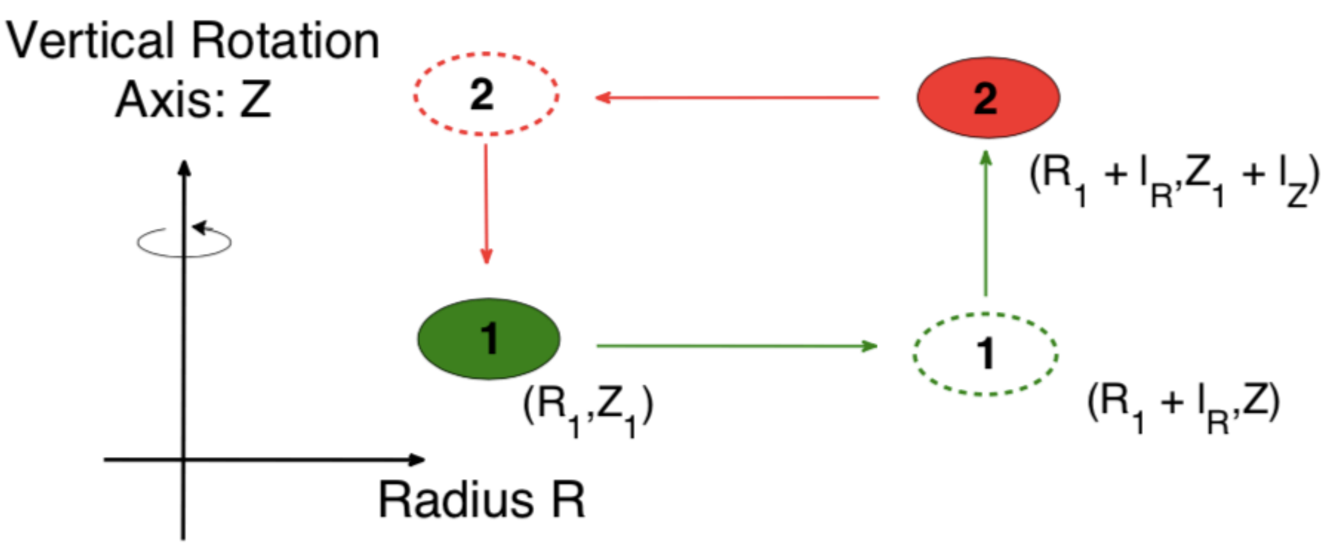
Angular velocity not constant in cylinders: unstable



Fromang & Lesur (2017)



Nelson et al. (2013)



(see also Glen's talk)

Vertical shear instability

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

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

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

Halvor Solberg

Solberg-Hoiland Criteria

$$N_z^2 > 0,$$

$$\kappa_{\mathrm{eq}}^2 + N_R^2 > 0,$$

$$-\frac{\partial p}{\partial z}\left(\frac{\partial s}{\partial z}\frac{\partial L^2}{\partial r} - \frac{\partial s}{\partial r}\frac{\partial L^2}{\partial z}\right) > 0.$$

Buoyancy stabilizes!

The most unstable mode is ***isothermal***

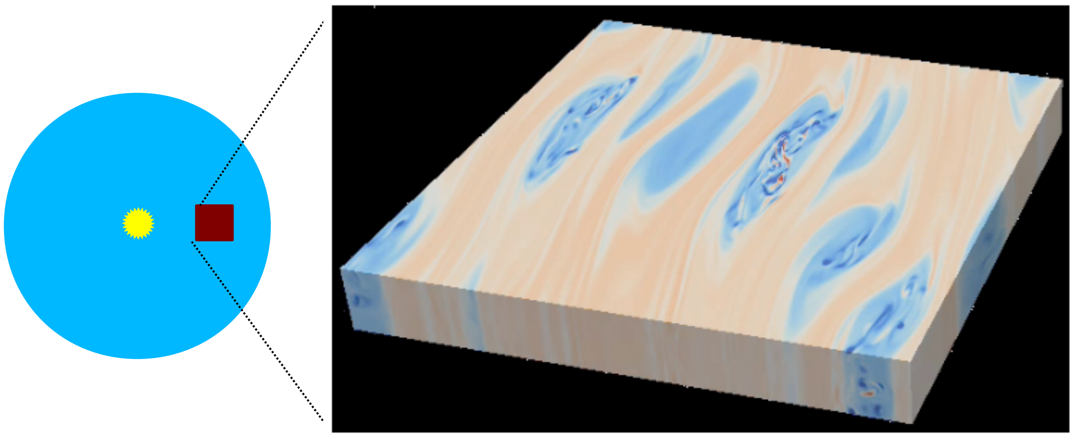
Einar Hoiland

$d\Omega/dz \;!= 0 \quad => \quad dL^2/dz < 0$

$ds/dz=0$

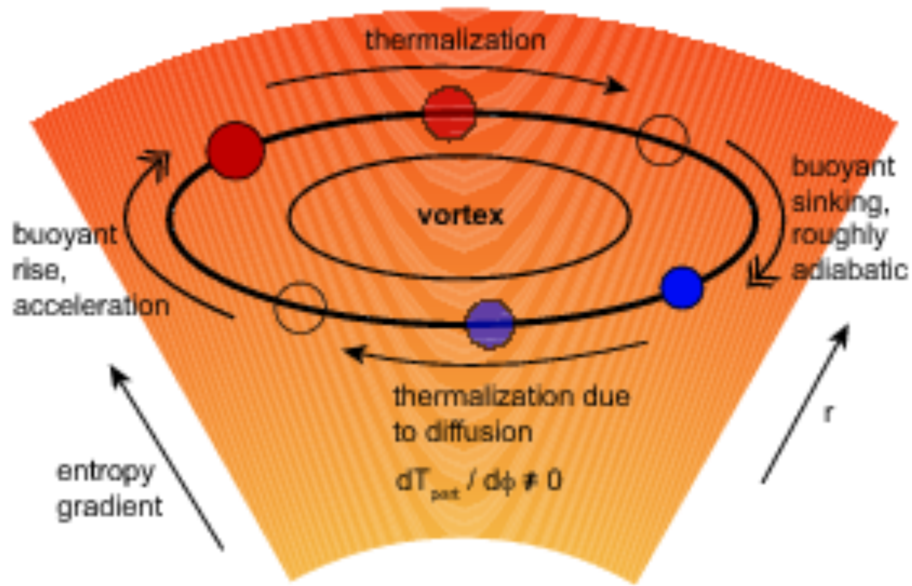
3rd criterion violated

Convective Overstability (née "Subcritic Baroclinic Instability")



Lesur & Papaloizou (2010)

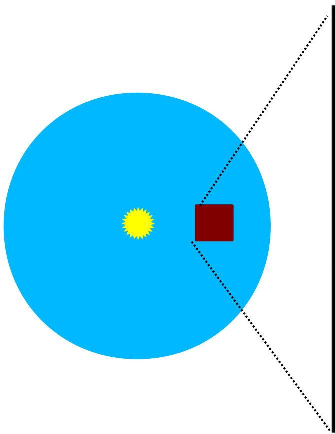
Sketch of the
Subcritic Baroclinic Instability

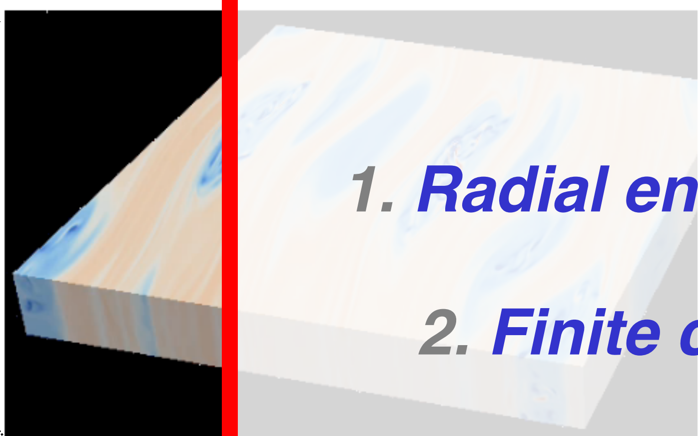


Armitage (2010)

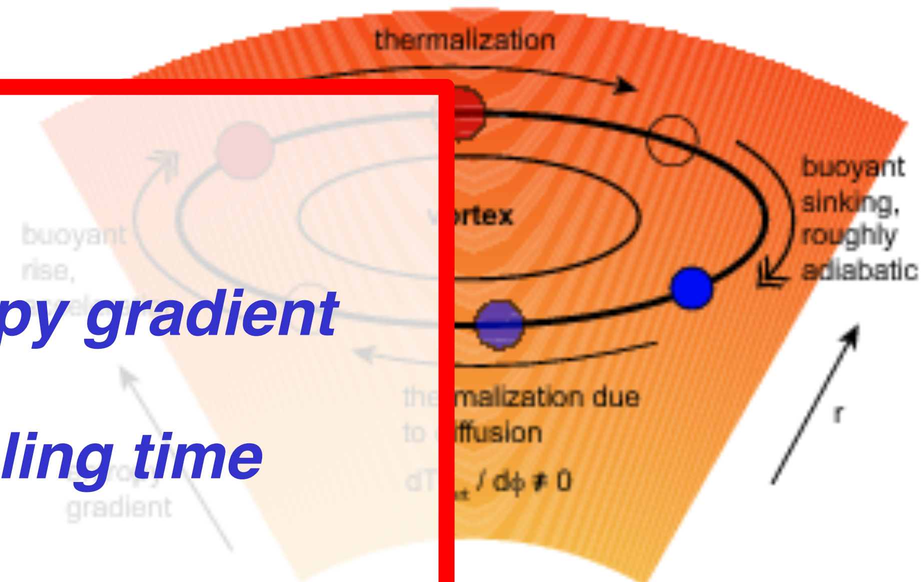
Convective Overstability (née "Subcritic Baroclinic Instability")

Sketch of the
Subcritic Baroclinic Instability





Lesur & Papaloizou (2010)



Armitage (2010)

1. ***Radial entropy gradient***

2. ***Finite cooling time***

Convective Overstability

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

Cooling destabilizes!

$$\frac{\partial \rho}{\partial t} + (\boldsymbol{u} \cdot \boldsymbol{\nabla})\rho = -\rho \boldsymbol{\nabla} \cdot \boldsymbol{u},$$

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

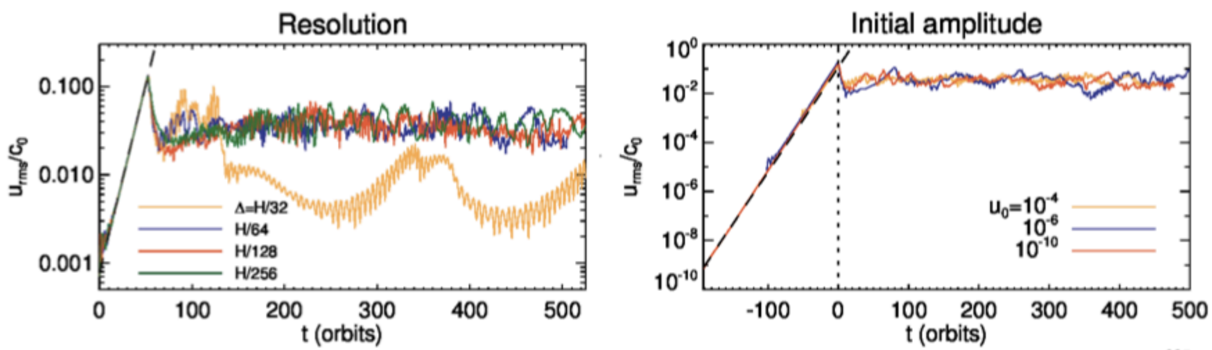
$$\frac{\partial p}{\partial t} + (\boldsymbol{u} \cdot \boldsymbol{\nabla}) p = -\gamma p \boldsymbol{\nabla} \cdot \boldsymbol{u} - \frac{p}{T}\frac{(T - T_0)}{\tau},$$

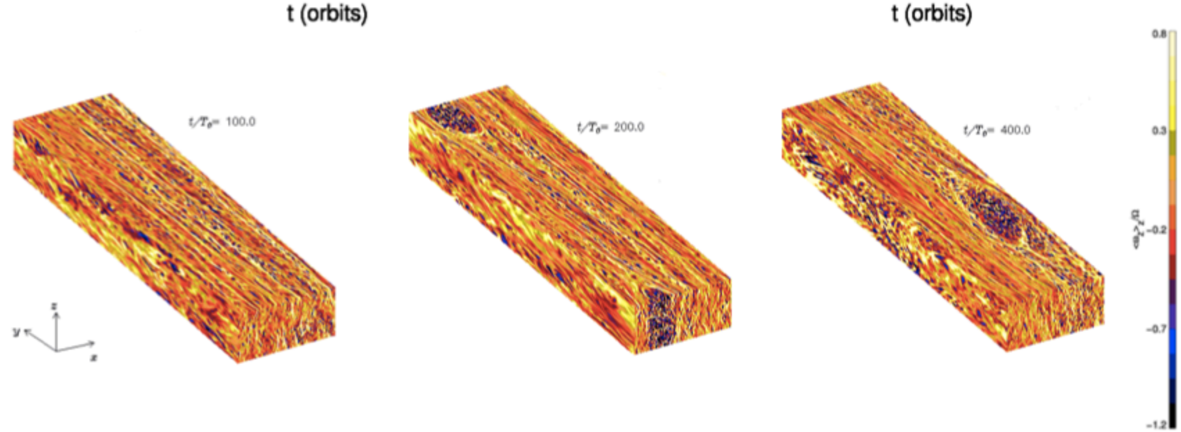
$$\tau_{\max} = \frac{1}{\gamma \Omega};$$

Cooling time of maximum growth

$$\sigma_{\max} = -\frac{N^2}{4\Omega}.$$

Growth rate



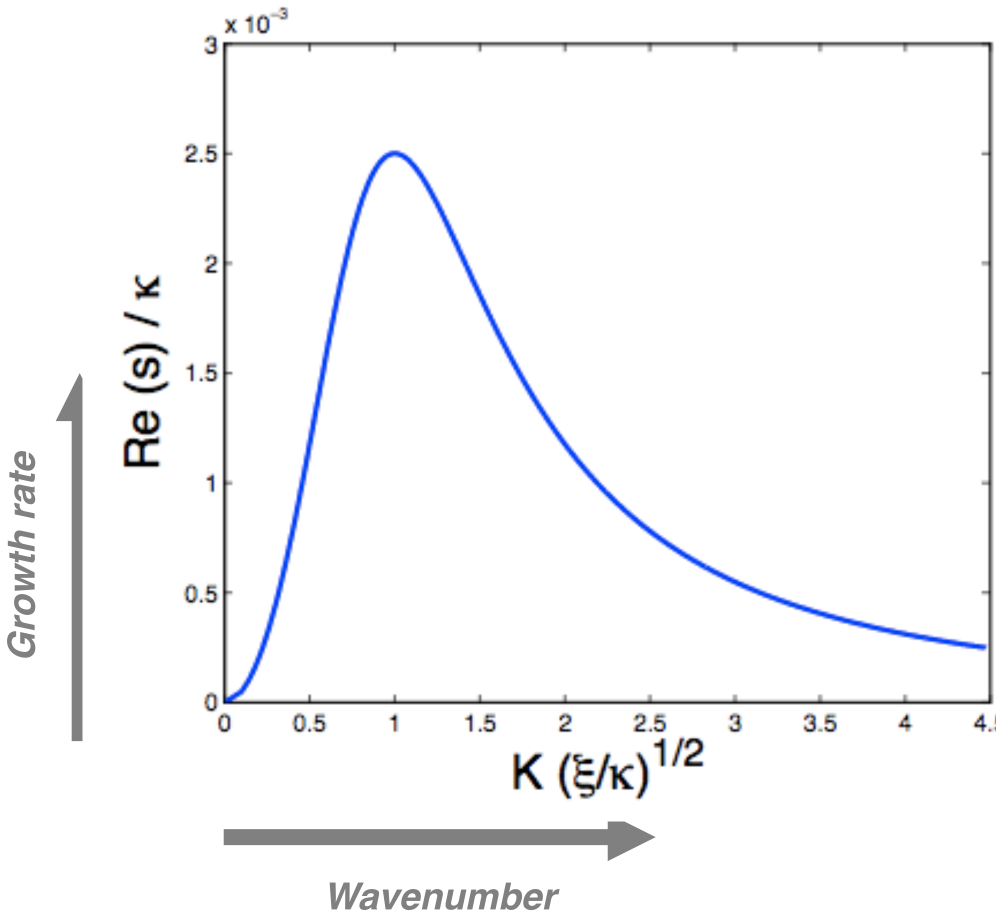


Lyra (2014)

Convective Overstability

Cooling renders the 2nd Solberg-Hoiland criterion irrelevant

$$\kappa_{eq}^2 + N_R^2 > 0,$$



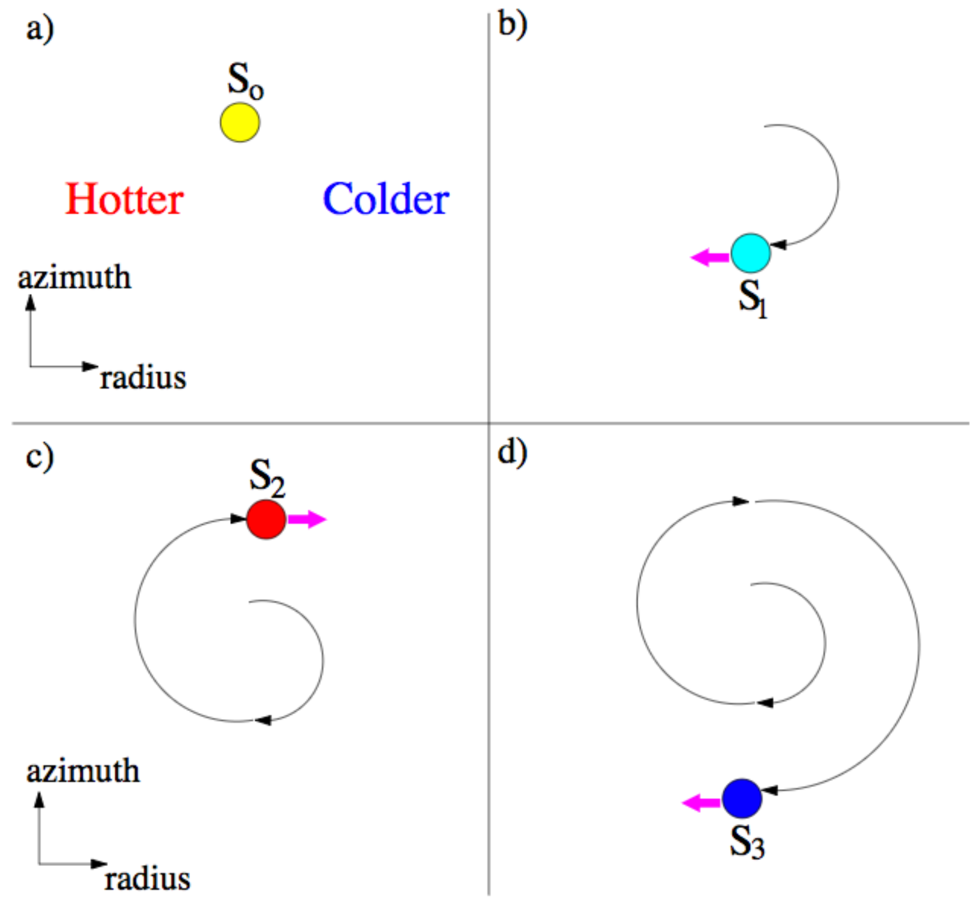
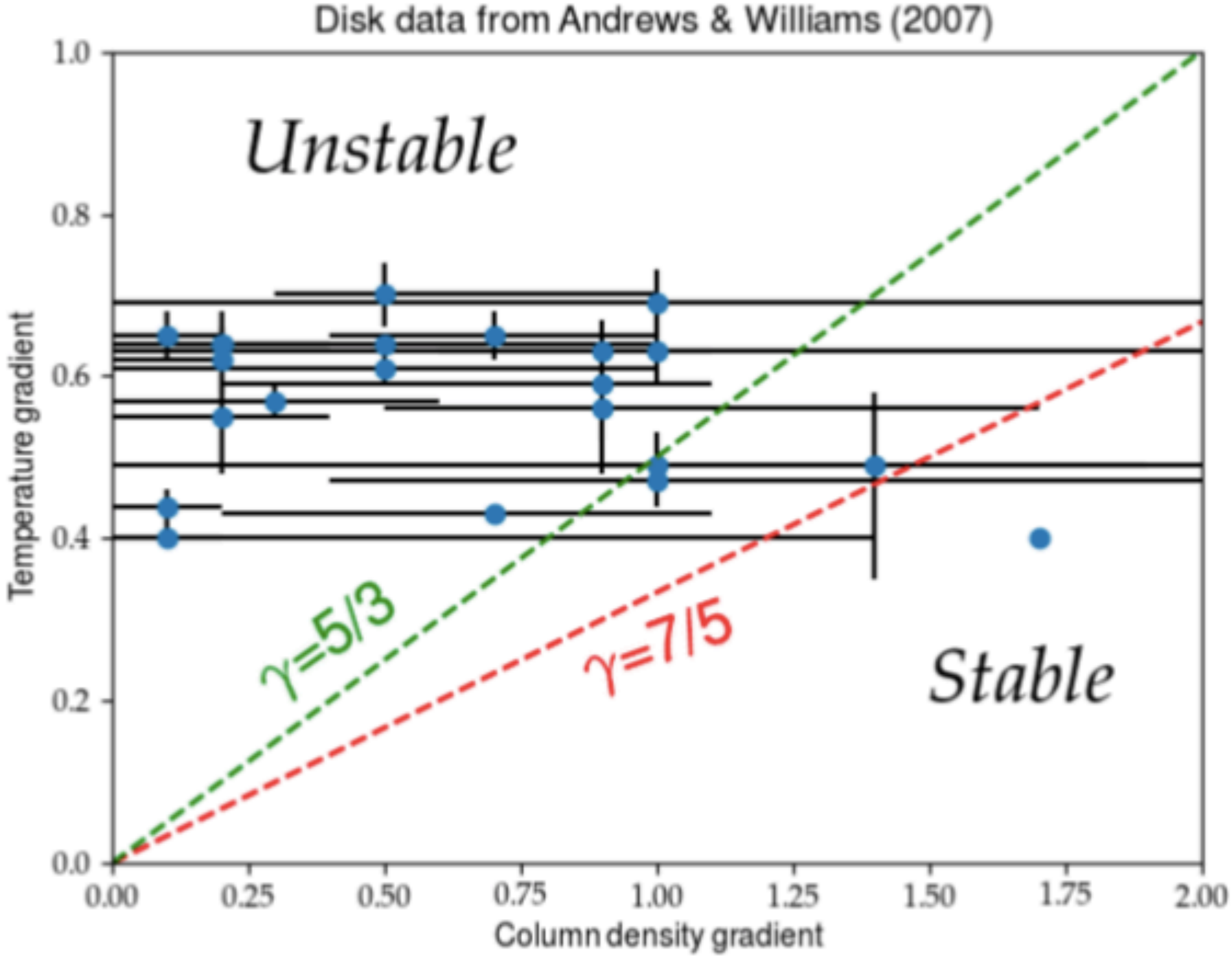


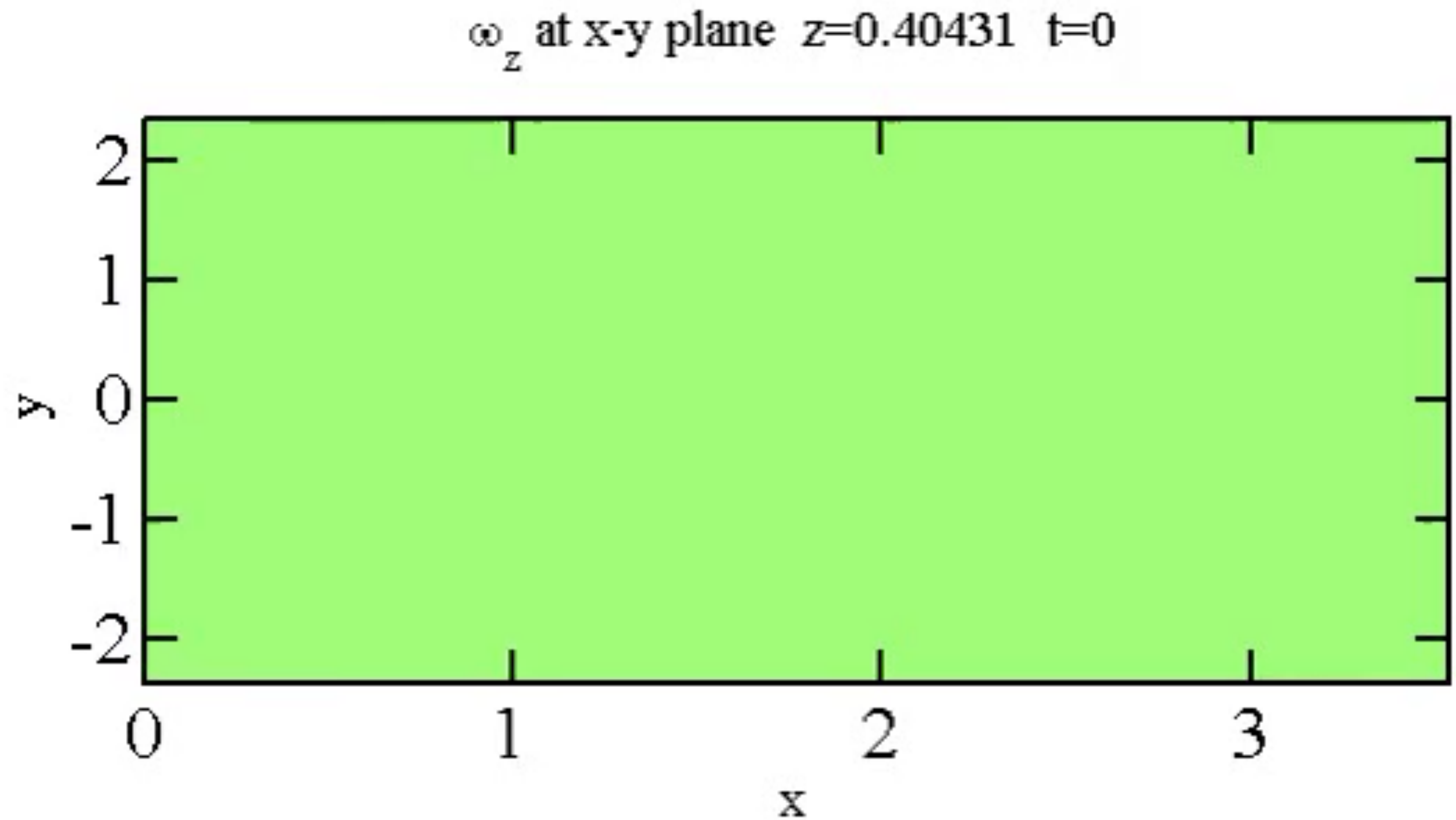
Figure 2. Four panels indicating the convective overstability mechanism. In panel (a) a fluid blob is embedded in a radial entropy gradient. In panel (b) it undergoes half an epicycle and returns to its original radius with a smaller entropy than when it begun $S_1 < S_0$. It hence feels a buoyancy acceleration 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)

Prevalence of Convective Overstability in actual disks

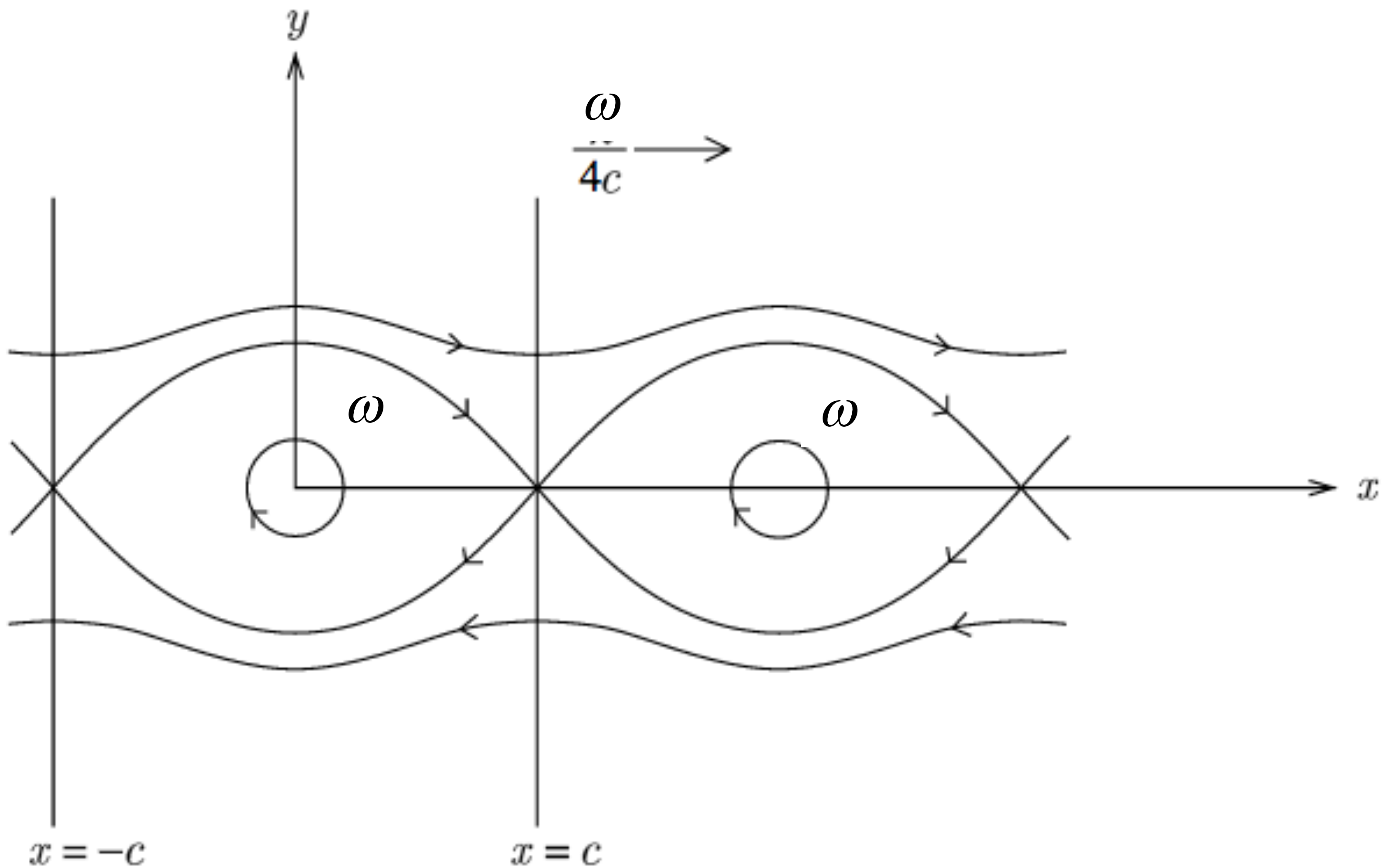


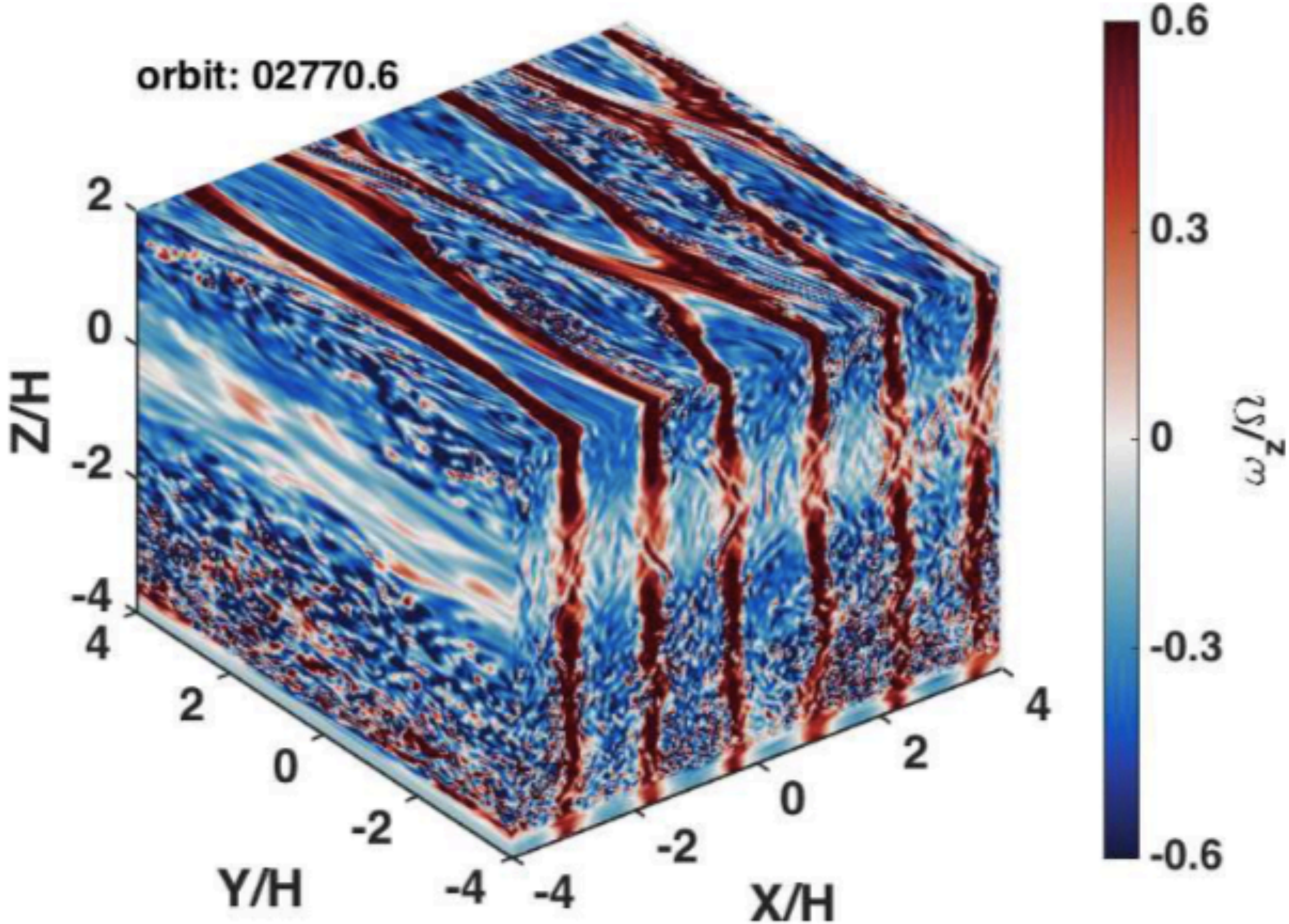
Zombie Vortex Instability



Cascade of baroclinic critical layers

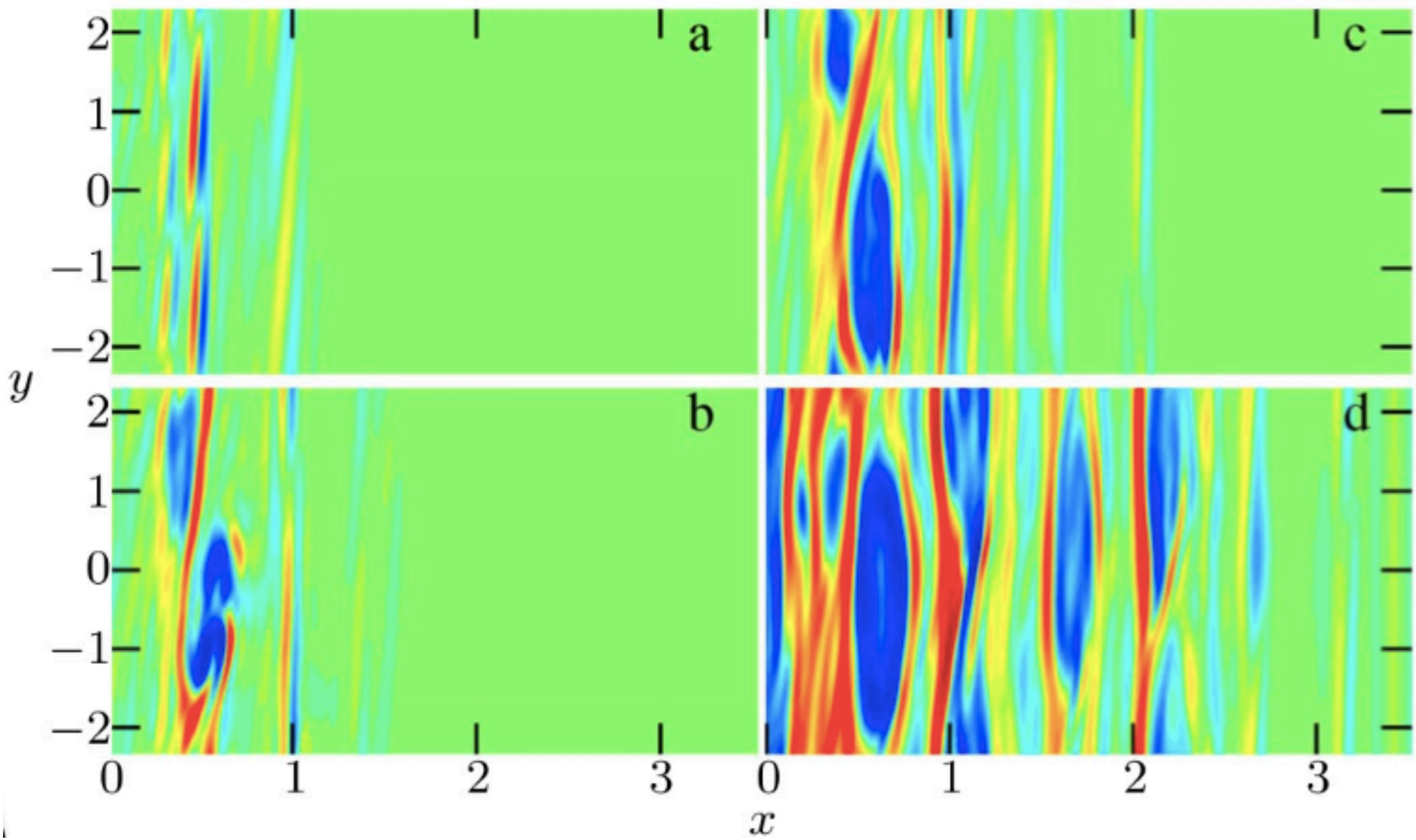
Marcus et al. (2015, 2016)


y
ω
4c
ω
ω
x
x = −c
x = c



Barranco et al. (2018)

Zombie Vortex Instability



Cascade of baroclinic critical layers

Marcus et al. (2015, 2016)

Zombie Vortex Instability

Reproduced with hyperviscosity,
But not with Laplacian viscosity
(needs 2048^3, Re ~ 10^7)

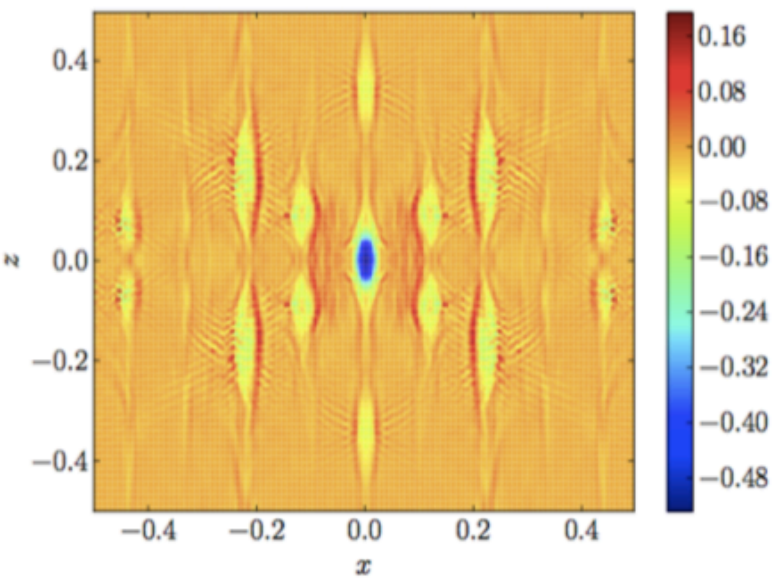


Figure 1. Vertical vorticity ω_z in a $x-z$ cut of our fiducial simulation with $\mathrm{Re}_6 = \mathrm{Pe}_6 = 5\times10^5$ at $t = 500$. Similarly to Marcus et al. 2013, we observe the formation and replication of anticyclonic vortices on a fixed lattice.

The critical layer should have width $\sim 10^{-4}H$. Buoyancy (near-adiabatic conditions) needs to be maintained over long times at that length.

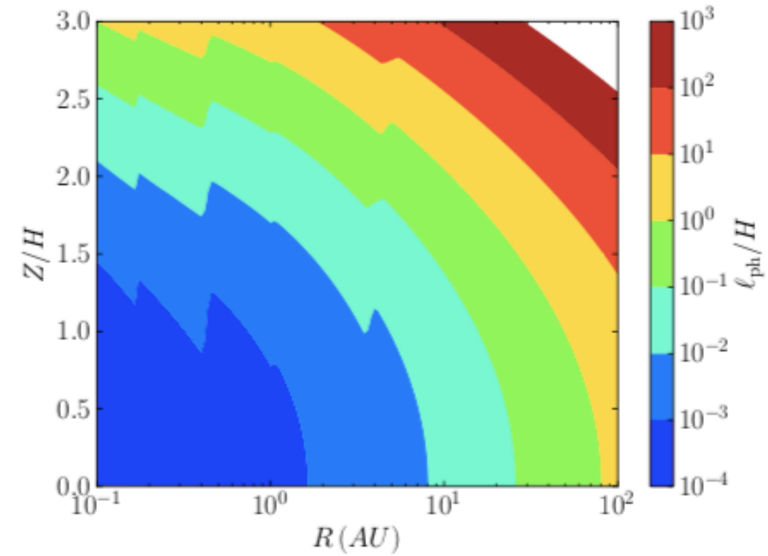


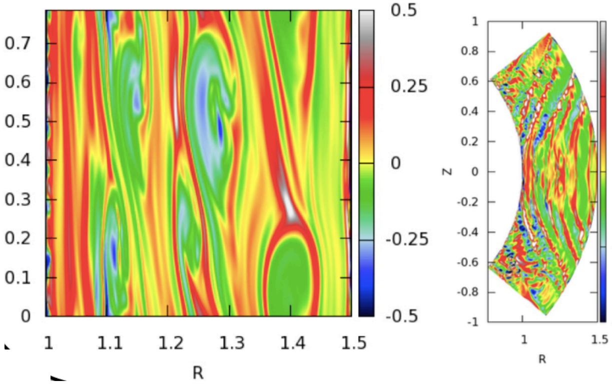
Figure 5. Photon mean free path ℓ_{ph} compared to the disc scale height H in a $0.01 M_\odot$ disk model. Shortest mean free paths are found close to the midplane in the innermost parts of the disc.

Only in the very inner disk,
that may be MRI-unstable anyway

Lesur & Latter (2016)

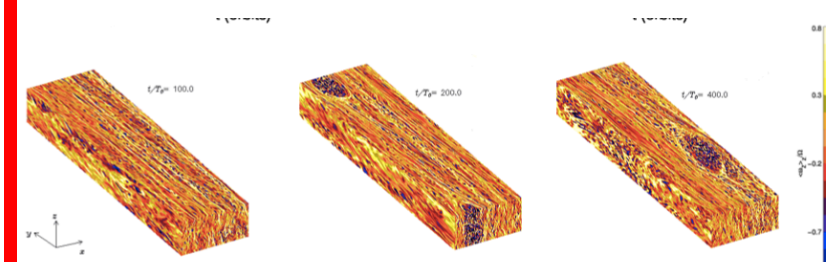
Hydrodynamical Instabilities

Vertical Shear Instability



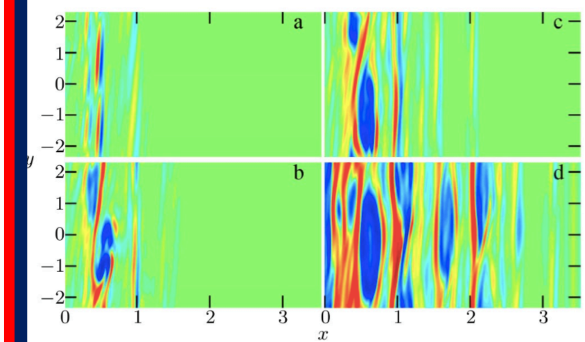
Nelson et al. 2013, Lin & Youdin 2015, Umurhan et al. 2016

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

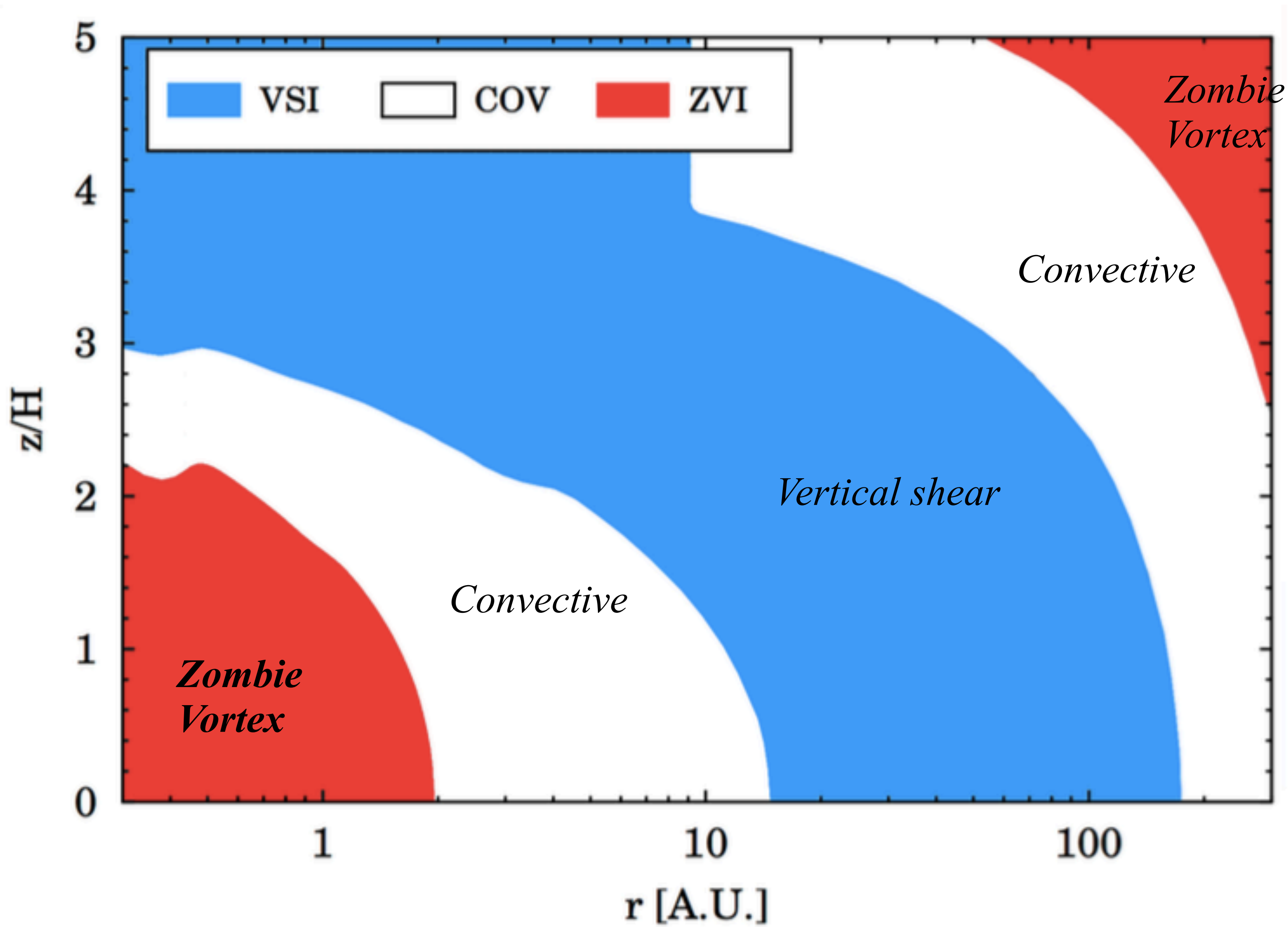
$\Omega\tau << 1$
($\kappa < 1$ cm^2/g)

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

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

Opacity

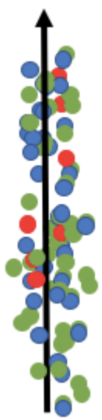
Synthesis



Malygin et al. 2017, Lyra & Umurhan 2019, Pfeil & Klahr 2019

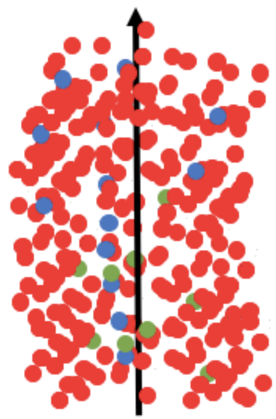
MHD regimes

Ideal MHD



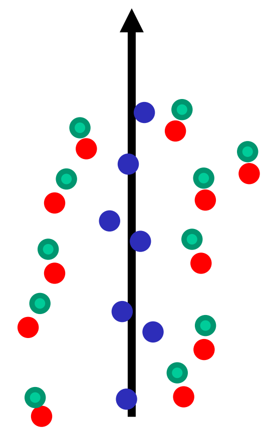
Field coupled to ions and electrons. Drags neutrals.

Ohmic



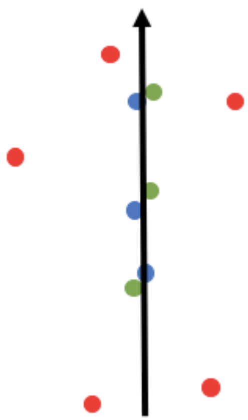
Neutrals dominate. Decouple ions and electrons.

Hall

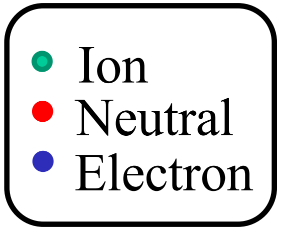


Neutrals can drag ions, But not electrons.

Ambipolar Diffusion

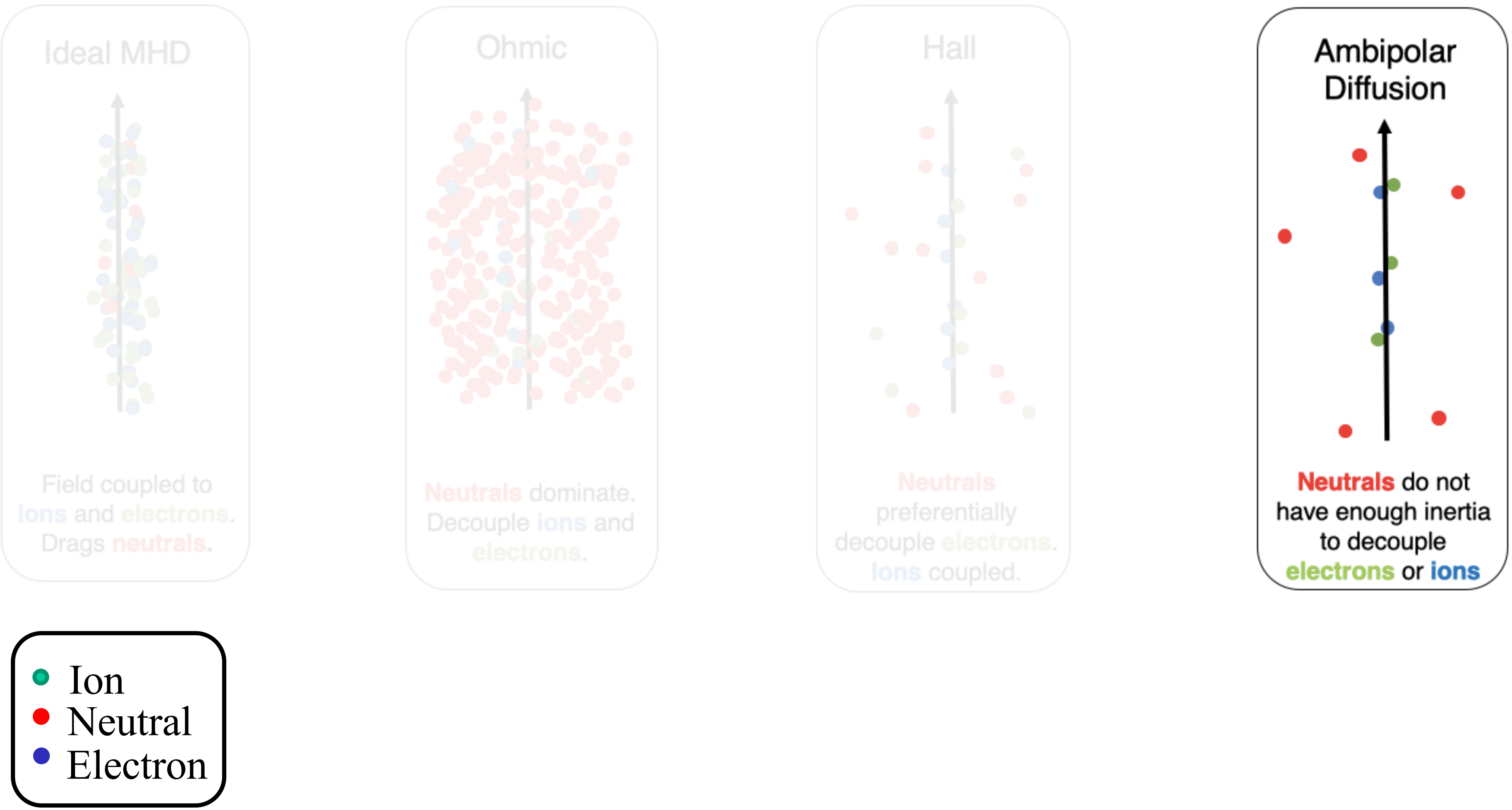


Neutrals do not have enough inertia to decouple electrons or ions



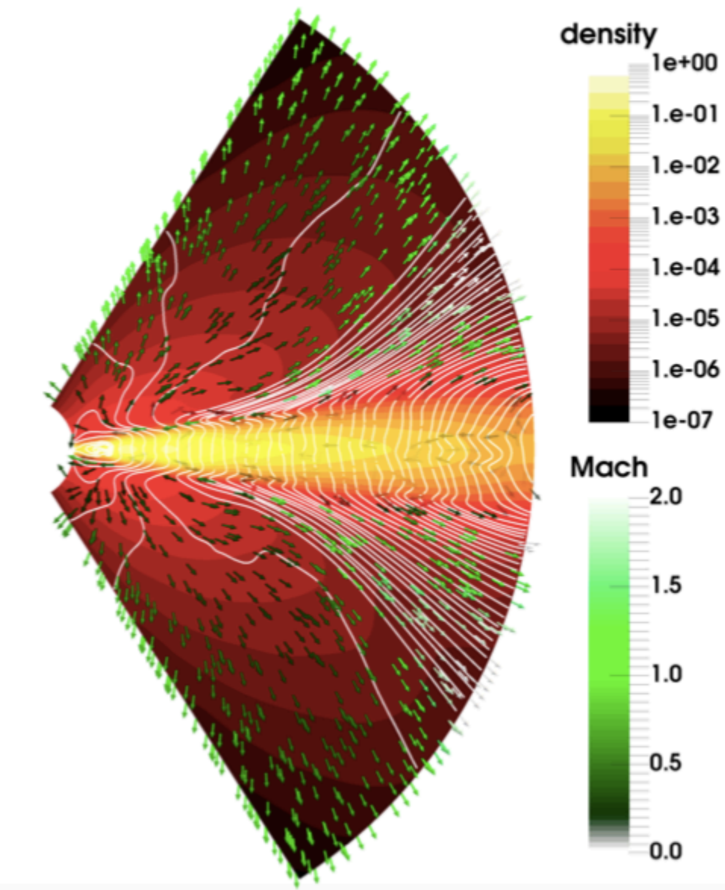
Wardle 1999, Wardle 2007

MHD regimes

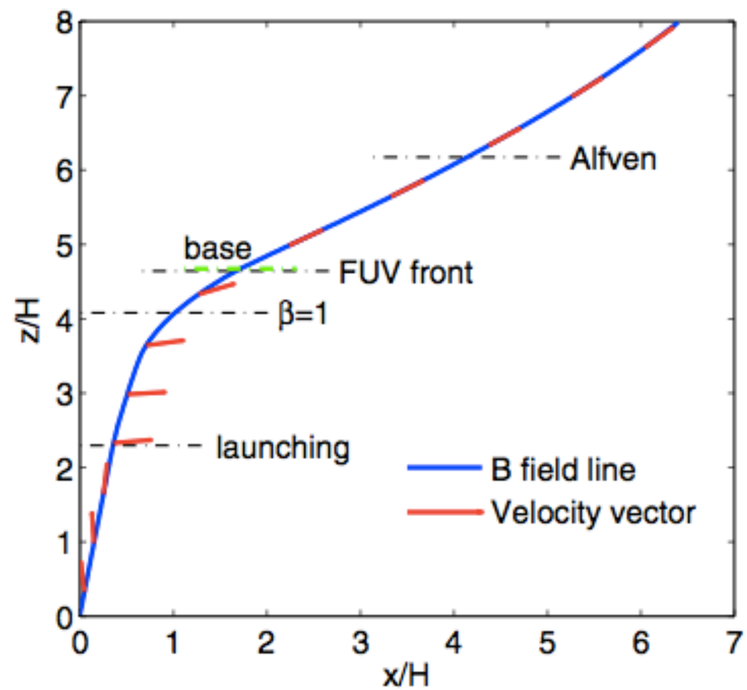


Wardle 1999, Wardle 2007, Bai & Stone 2011

Magnetocentrifugal wind

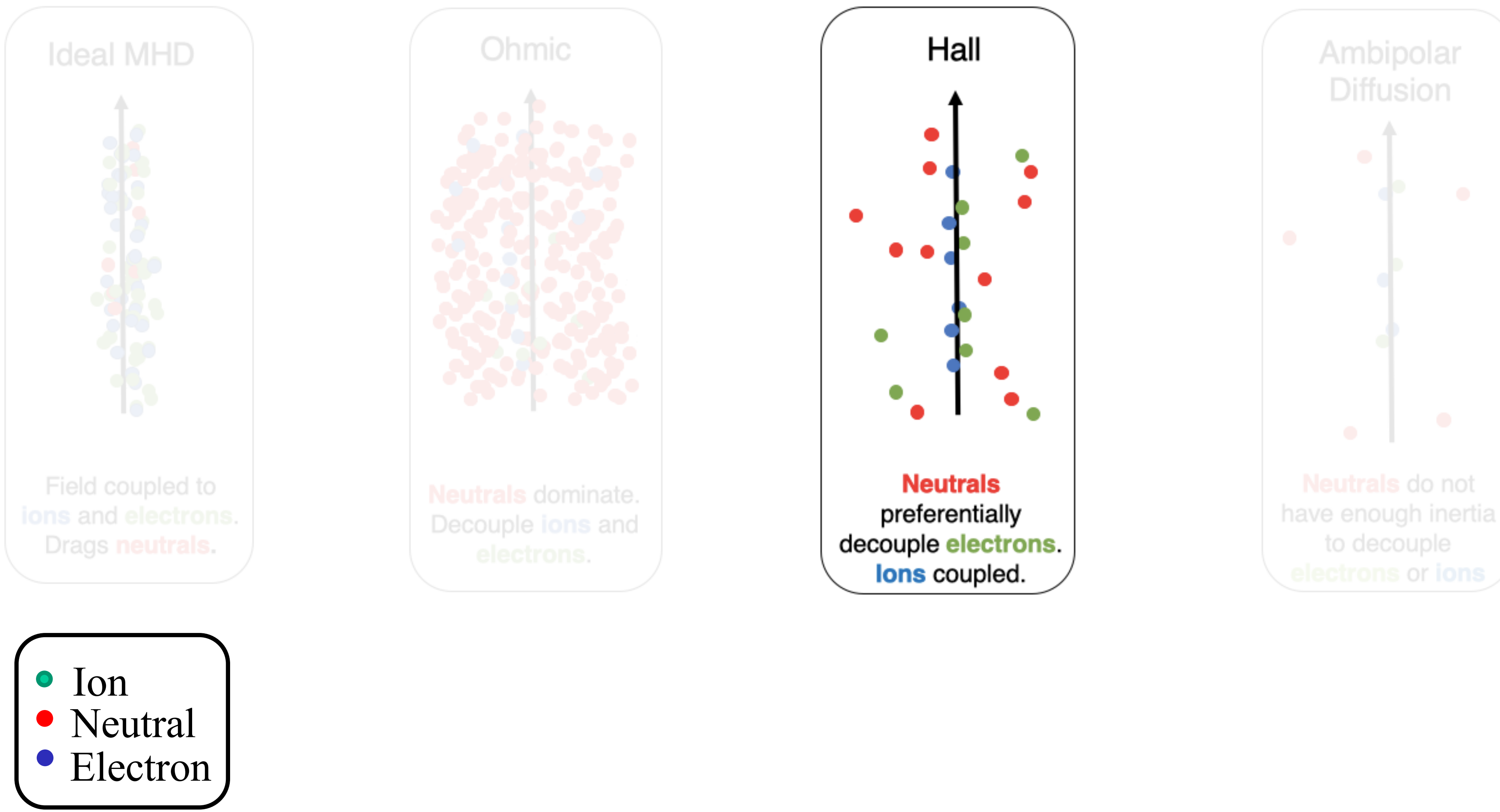


Bhétune et al. (2017)



Bai & Stone (2013)

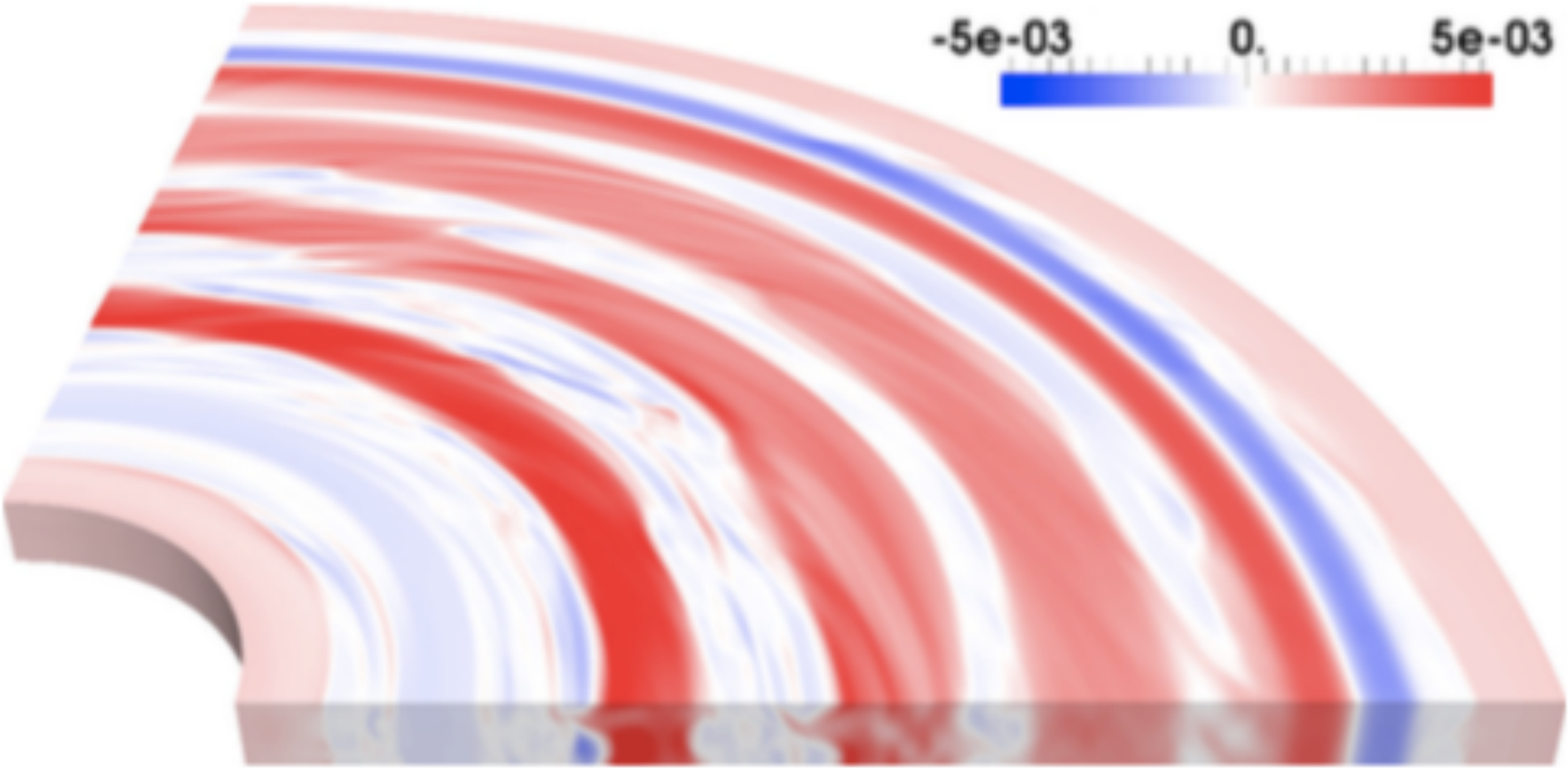
MHD regimes



Wardle 1999, Wardle 2007, Kunz et al 2008

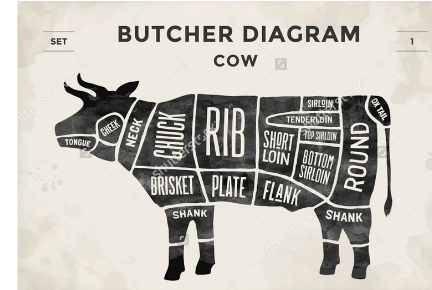
Hall MHD

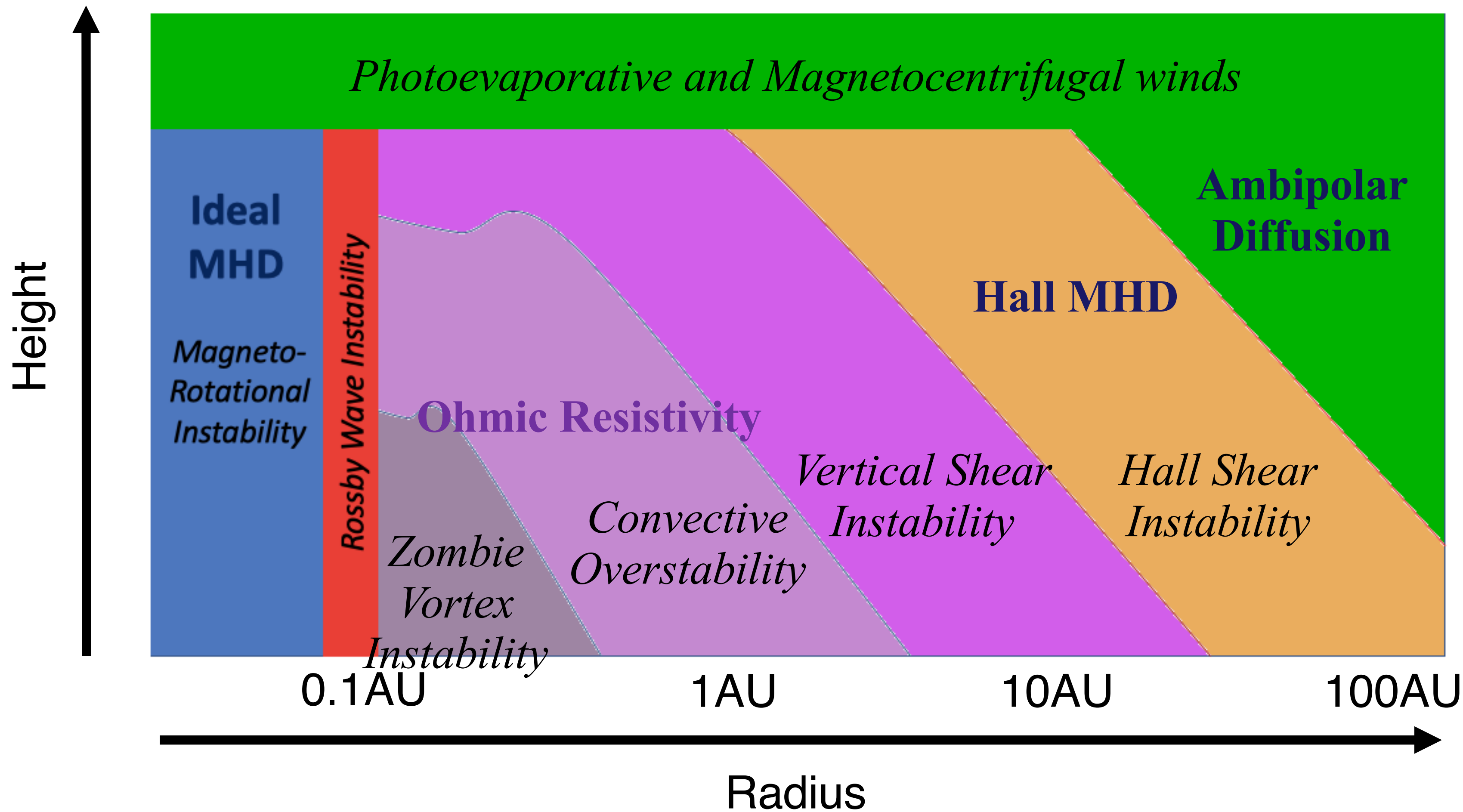
Self-organization



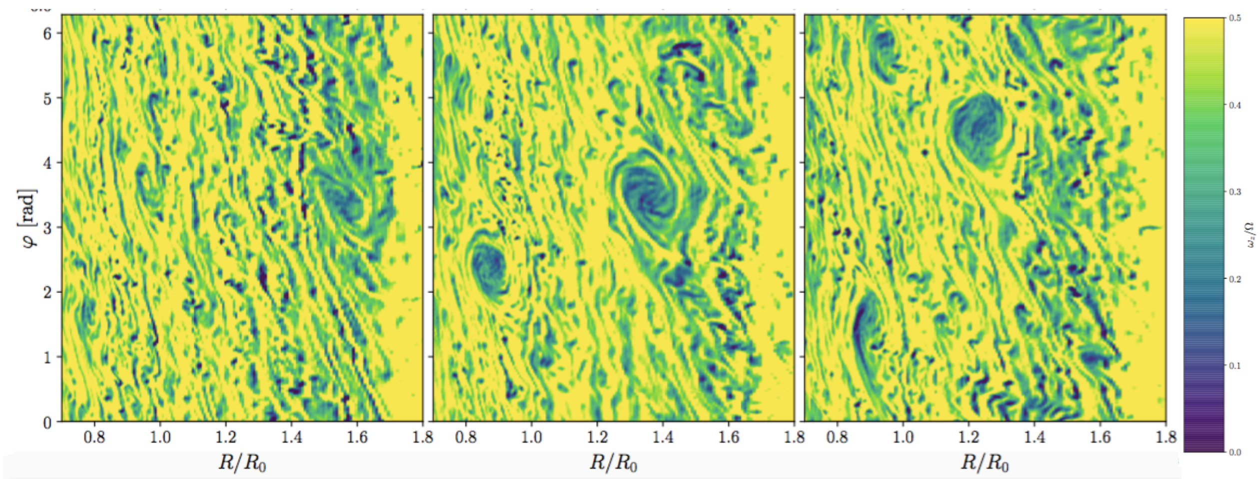
Bethune et al. (2016)

A butcher diagram for disk instabilities and structure



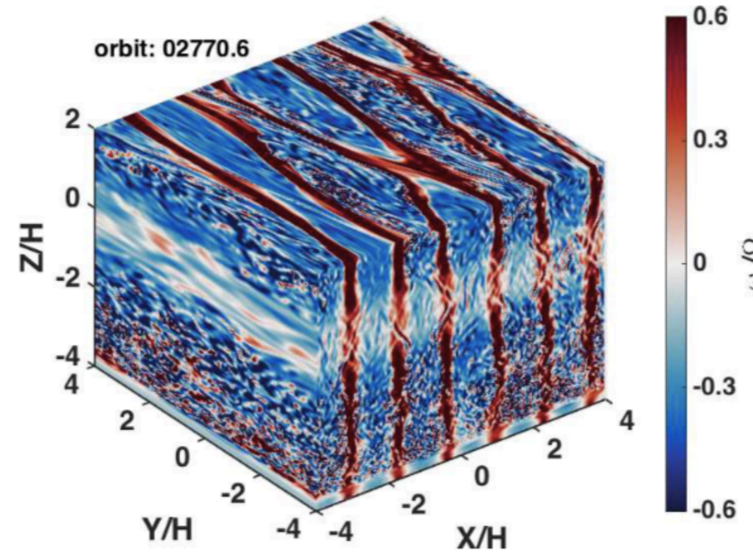


Saturation – vortices and α between 10^{-4} and 10^{-3}



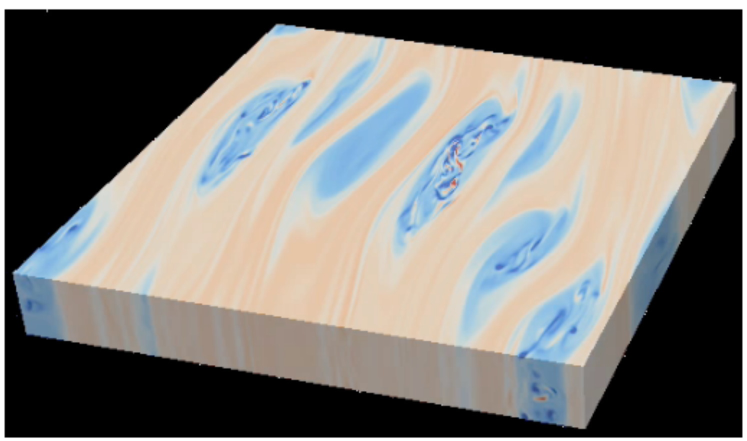
Manger & Klahr (2018)

VSI saturates into vortices



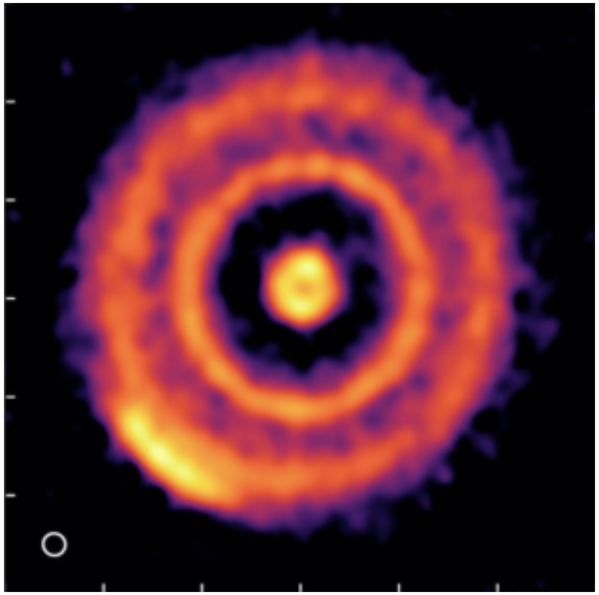
ZVI saturates into vortices

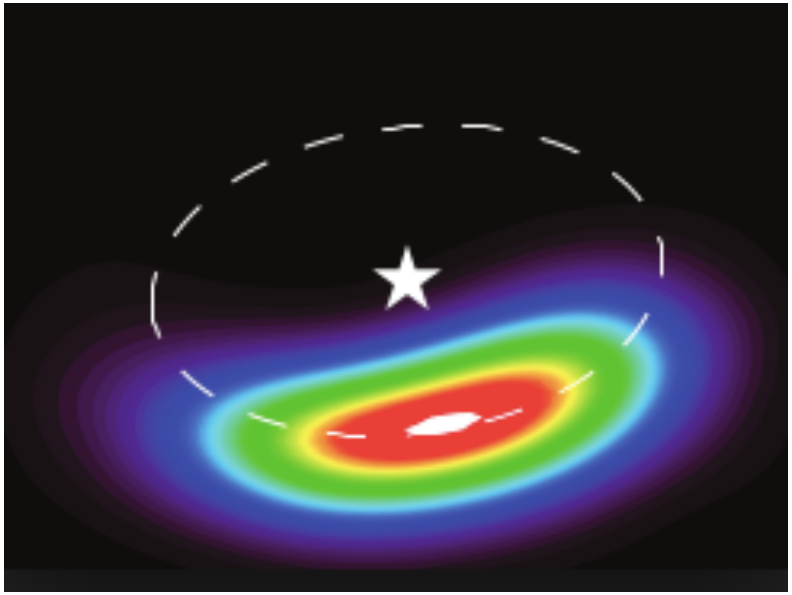
Barranco et al. (2019)

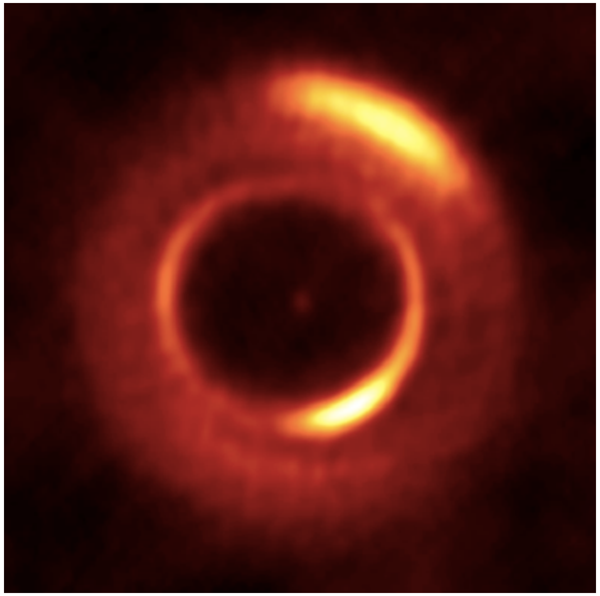


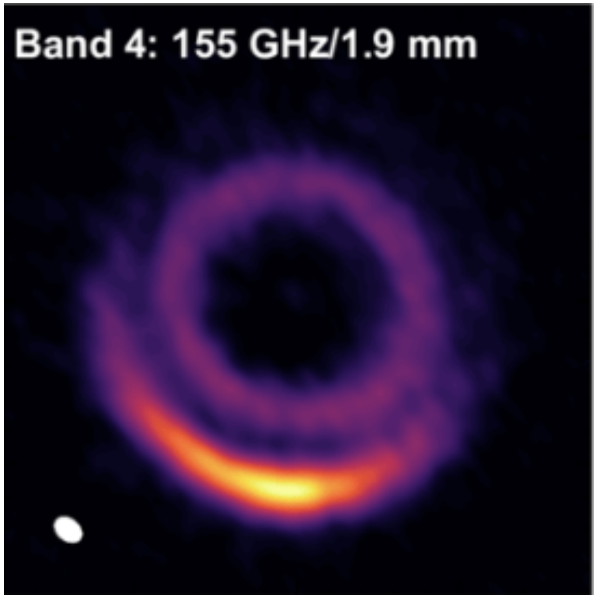
COV saturates into vortices

Lesur & Papaloizou (2010)



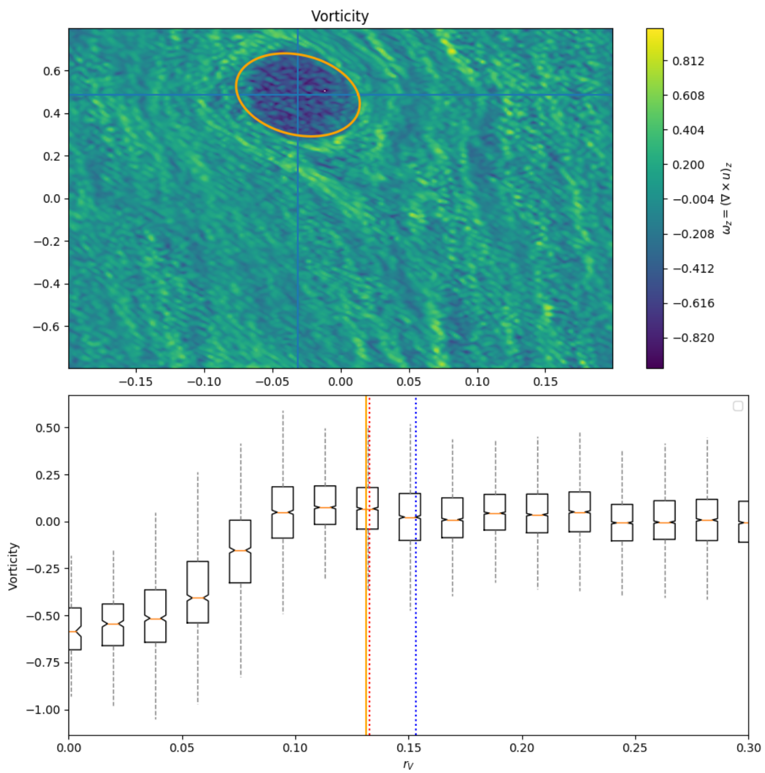




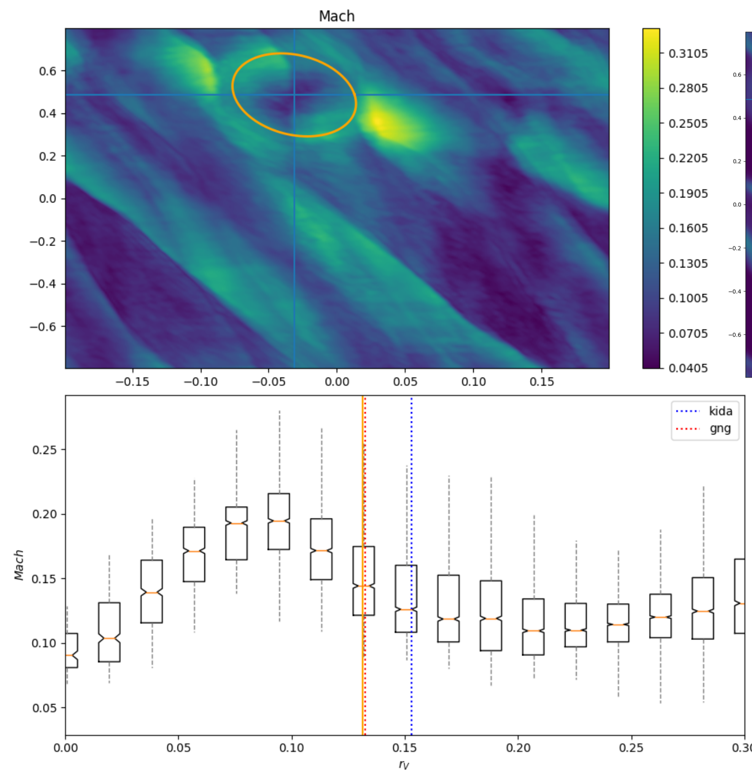

Band 4: 155 GHz/1.9 mm

What sets the size of a vortex?
Not shocks….

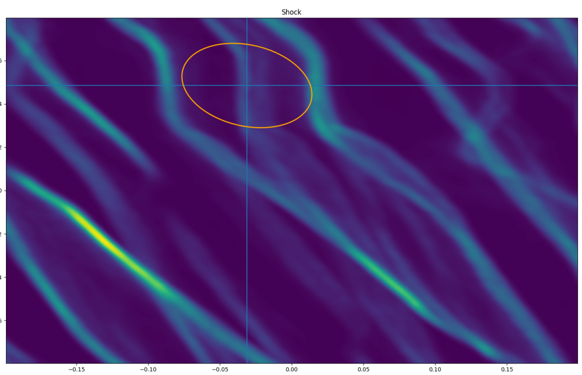
Vorticity



Mach number



Shocks



Valdelllon & Lyra (in prep)

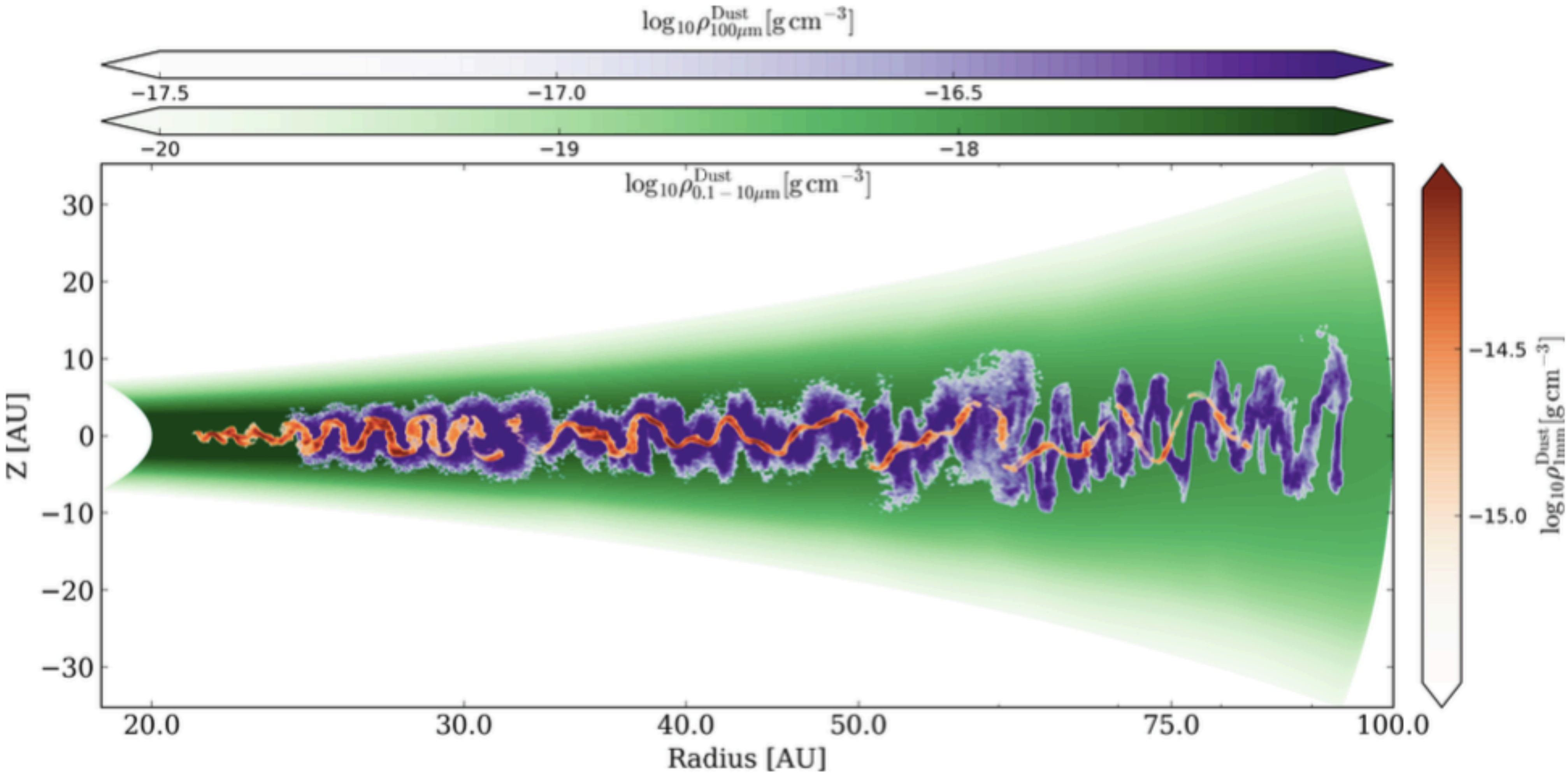
TABLE 2
HYDRODYNAMICAL INSTABILITIES SUMMARY CHARACTERISTICS.

Instability	Violation of Rayleigh criterion	Mechanism Type	Linear growth rate	Length scale of linear growth	Opacity κ (cm^2/g)	Thermal time ($\Omega\tau$)	α
Vertical Shear	$d\Omega/dz \neq 0$	Angular momentum exchange between adjacent elements.	$\sqrt{m}\lvert q\rvert h\Omega/4$	$\pi\lvert q\rvert hH$	< 1	$\ll 1$	$10^{-4} - 10^{-3}$
Convective	$N_R^2 < 0$	Buoyant amplification of epicyclic oscillations.	$\lvert N^2\rvert/4\Omega$	$\sqrt{\chi/\Omega}$	$1 - 50$	~ 1	$10^{-4} - 10^{-3}$
Zombie Vortex	$N_z^2 > 0$	Resonance between Rossby and buoyancy frequency.	–	–	> 50	$\gg 1$	$10^{-4} - 10^{-3}$

Outstanding issues

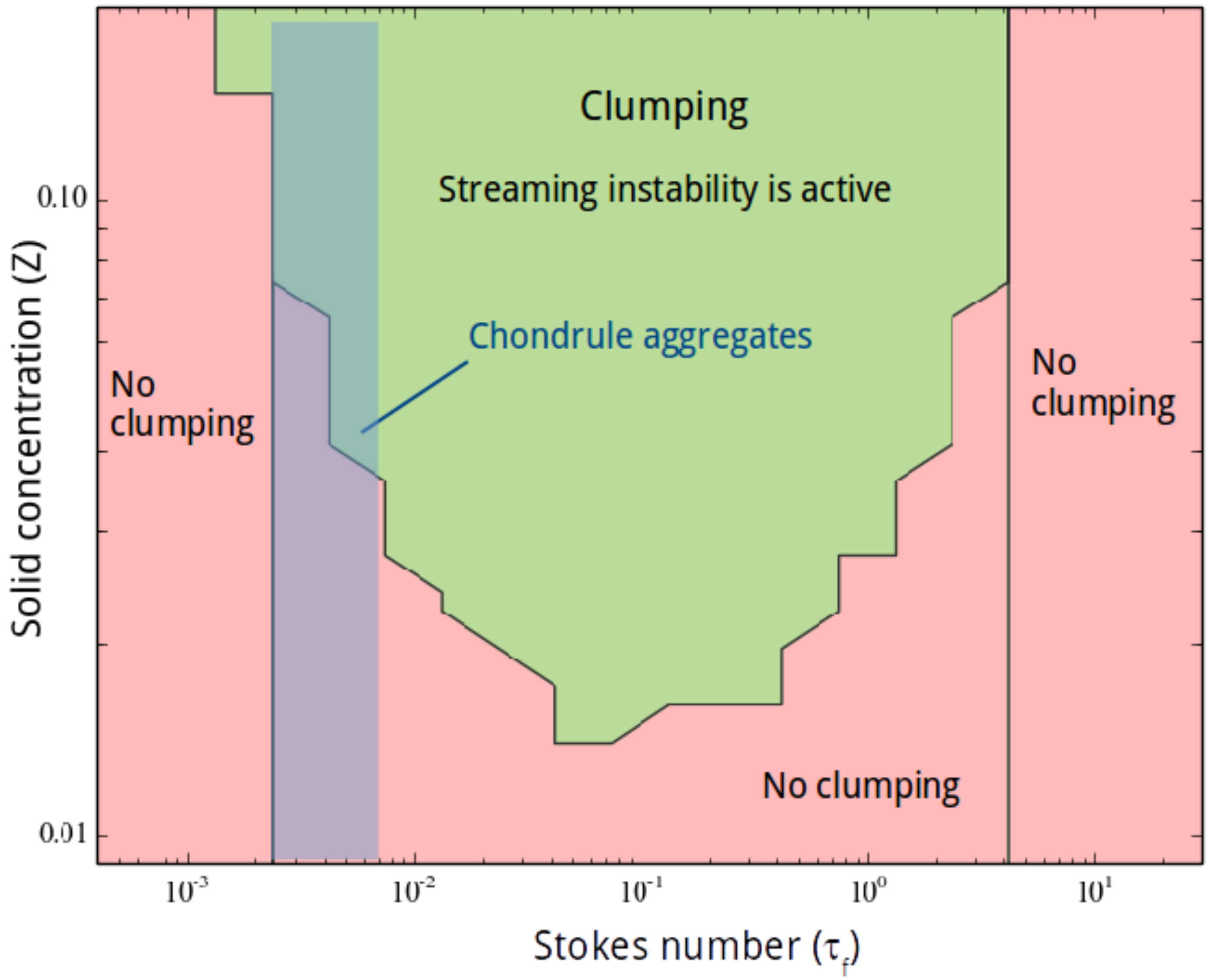
	ZVI	COV	VSI
Global model	✗	✗	✓
Vertical Stratification	✓	✗	✓
Boundaries with other instabilities	✗	✗	✗
Interaction with dust	✗	✓	✓
Observational Validation/Rule out	✗	✗	✗
Planet Forming Properties	✗	✗	✗

Dust in Vertical-Shear turbulence

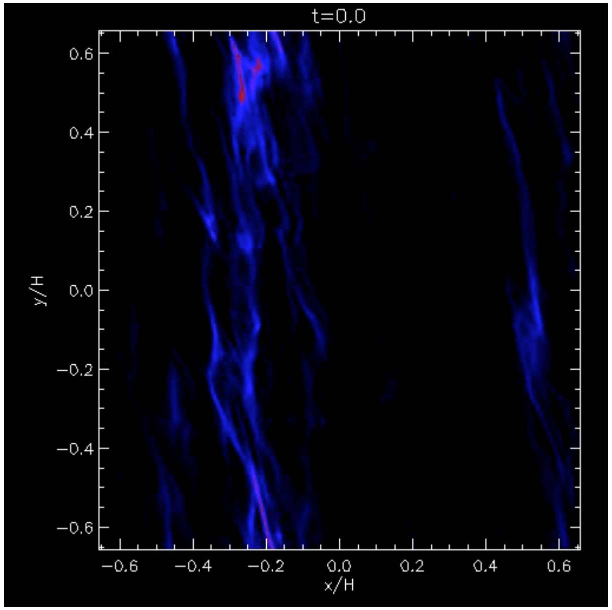


Flock et al. (2017); see also Anders' talk.

Synergy with streaming instability?



Carrera et al. (2015)



Johansen et al. (2007)

Conclusions

- Three dynamical instabilities in the Ohmic dead zone
  - Vertical Shear Instability
    - *Vertical violation of Solberg-Hoiland criterion*
  - Convective Overstability
    - *Amplification of epicyclic motion by buoyancy*
  - Zombie Vortex Instability
    - *Resonance between epicyclic and buyoancy frequency*

- Different regimes of opacity, operate in different regions
- Saturate into vortices, $\alpha \sim 10^{-4} - 10^{-3}$

- Issues:
  - Are they responsible for the observed crescents?
  - Overlap unclear
  - Global model of COV needed
  - Relevance of ZVI unclear/unlikely.
  - Planet formation properties / Synergy with streaming instability