PHD advisor: Sébastien FROMANG (CEA)
& Henrik LATTER (DAMTP, Cambridge)

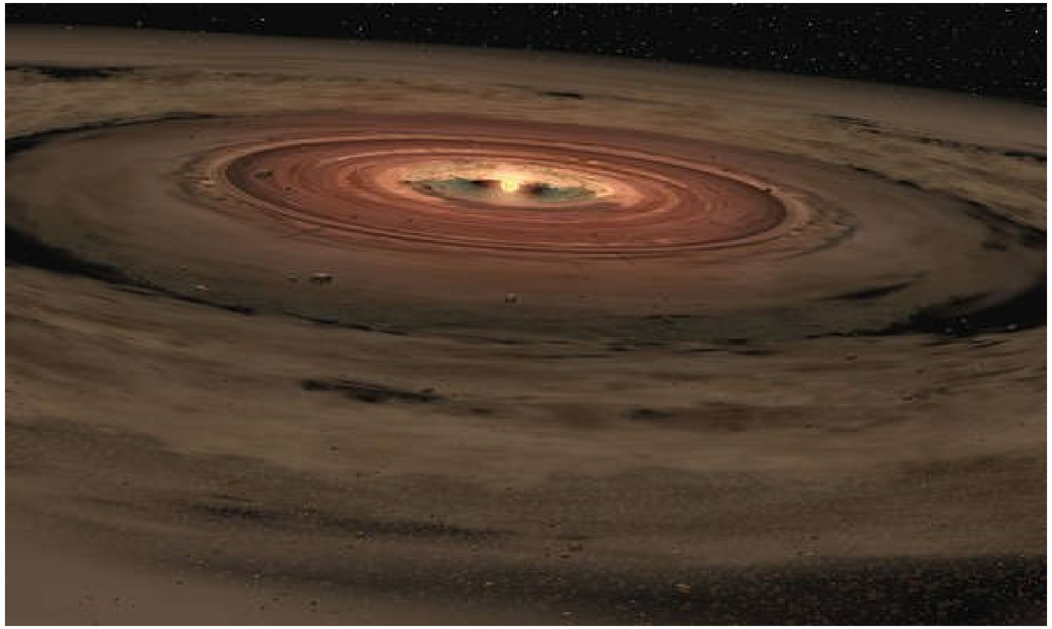
DEAD ZONE

the INNER EDGE DYNAMICS

FAURE Julien

GENERAL INTRODUCTION

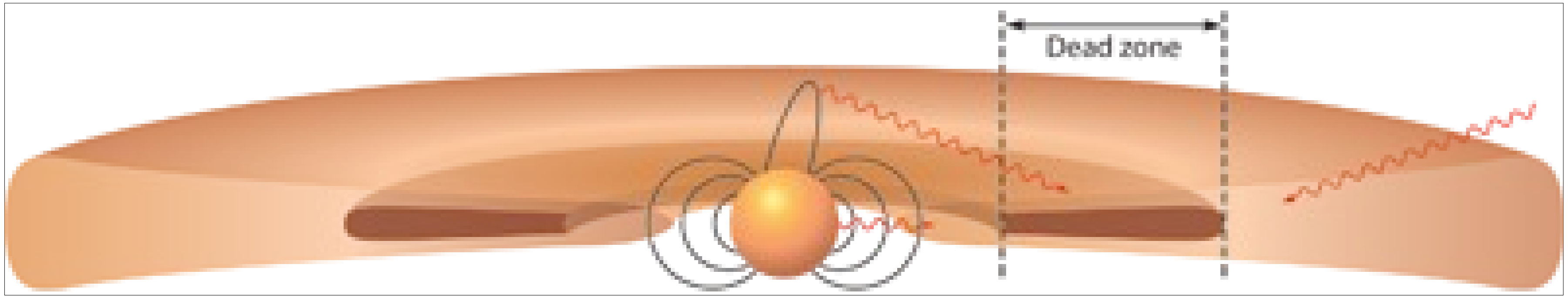
PROTO-PLANETARY DISKS



ACCRETION AND TURBULENCE

Picture credit: Artist’s impression of a protoplanetary disk around the brown dwarf OTS44. Nasa

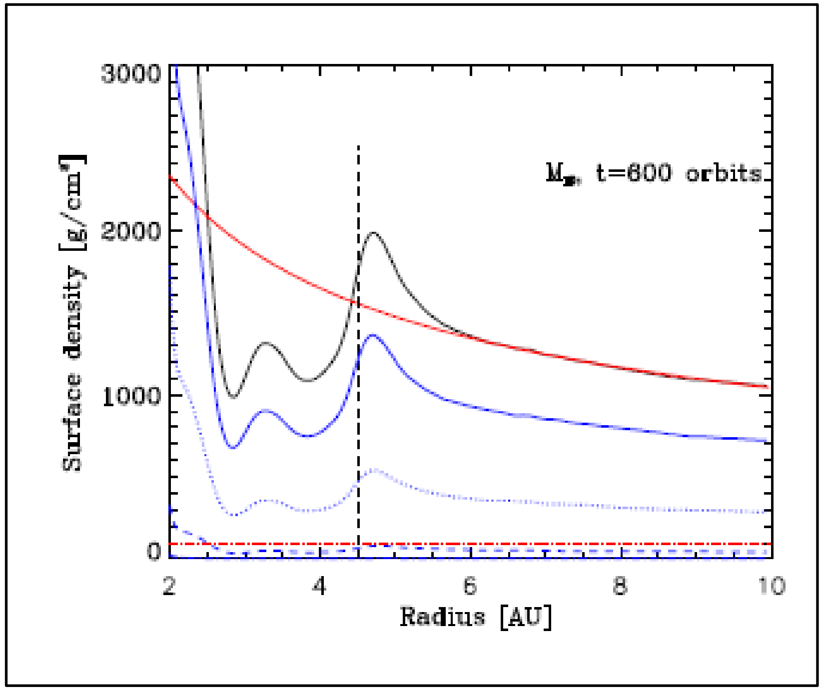
TURBULENCE, MRI AND DEAD ZONE



TO PLANET FORMATION

Picture credit: www.lanl.org

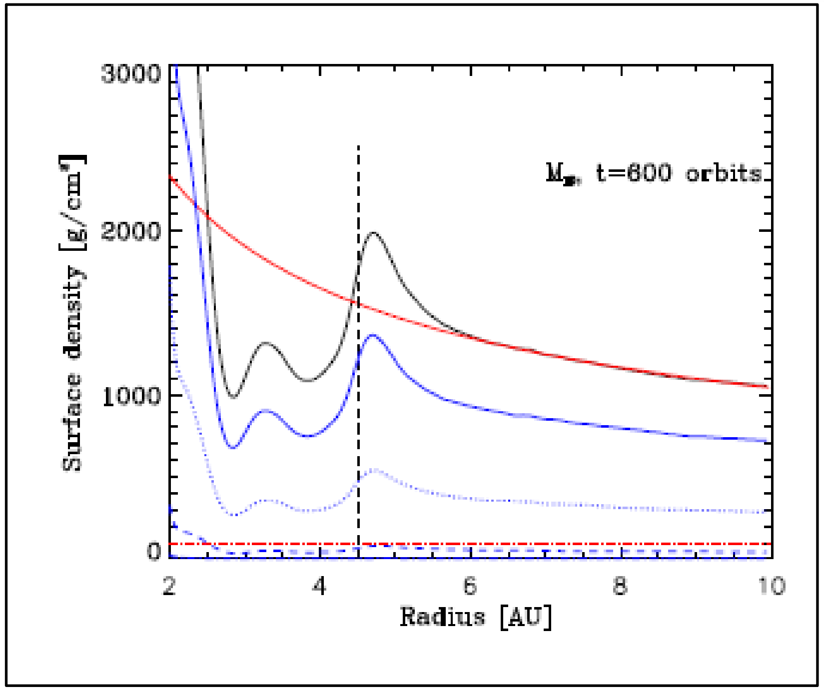
MOST RECENT STUDIES

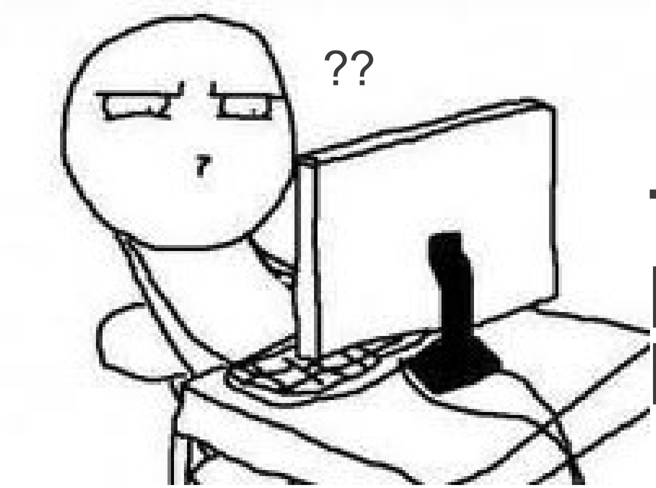


FIND « PRESSURE BUMPS » AND VORTICES

Picture credit: Dzyurkevich et. Al (2010) ; Lyra & MacLow (2012)

MOST RECENT STUDIES





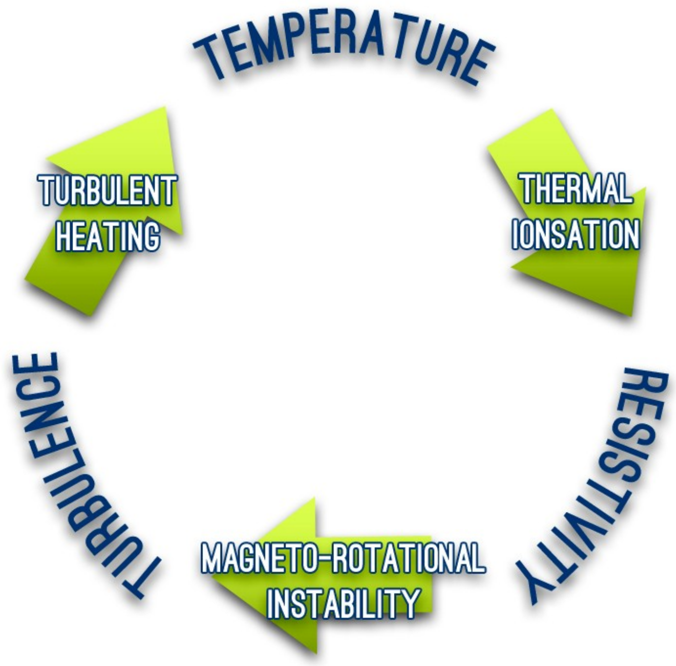
THERMAL FLOW PROPERTIES in

LOCALLY ISOTHERMAL SIMULATIONS

FIND « PRESSURE BUMPS » AND VORTICES

Picture credit: Dzyurkevich et. Al (2010) ; Lyra & MacLow (2012)

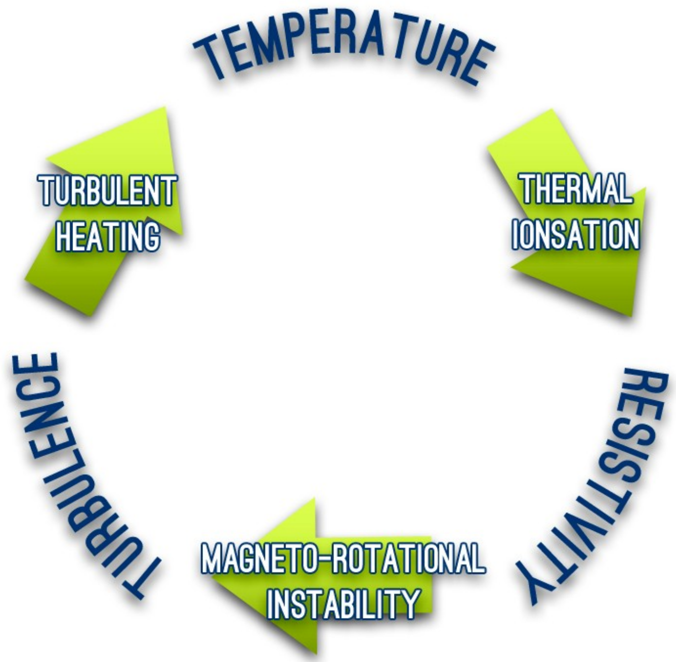
COMPLEXE INTERPLAY



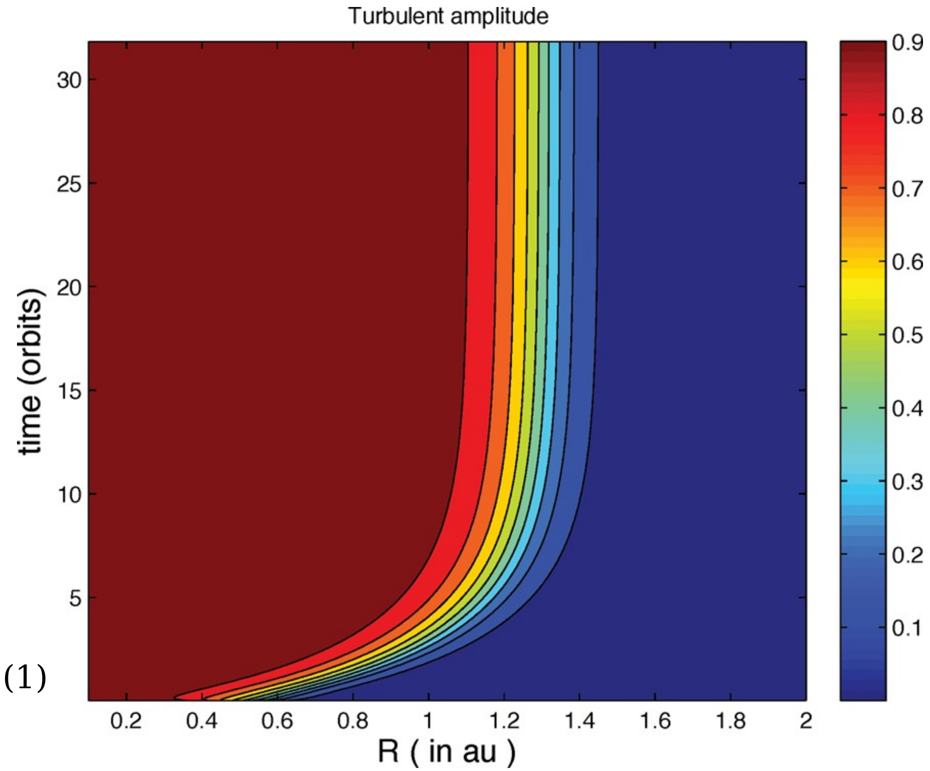
IMPACT ON THE INNER EDGE ?

Picture credit:

COMPLEXE INTERPLAY



INNER EDGE DYNAMICS

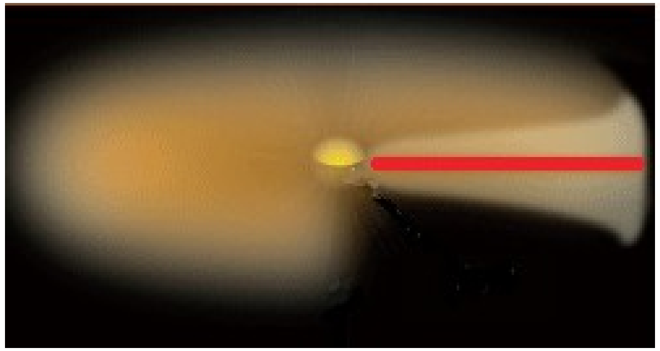


(1)

Picture credit: (1) Latter & Balbus (2012)

METHOD

NUMERICAL TOOL

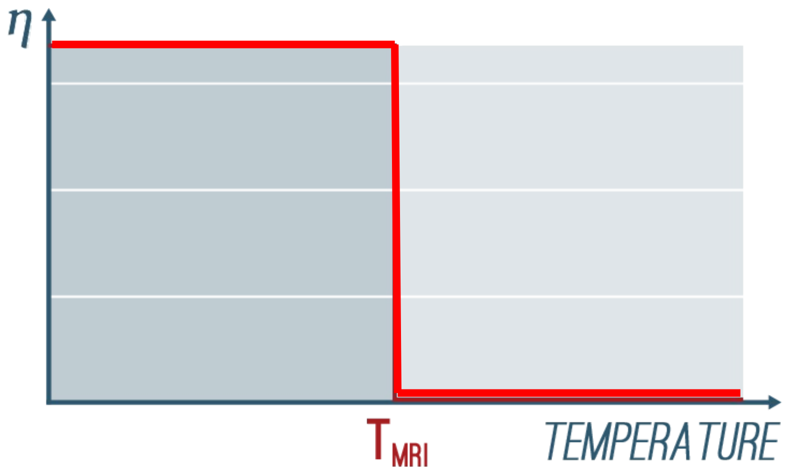


NON ISOTHERMAL MHD SIMULATIONS

- non AMR version of RAMSES
- no vertical stratification
- toroïdal magnetic field
- No dust

THERMODYNAMICAL PROCESSES

- Heating = local dissipation of turbulent fluctuations
- Cooling: $-\sigma\rho\left(T^4 - T_0^4\right)$



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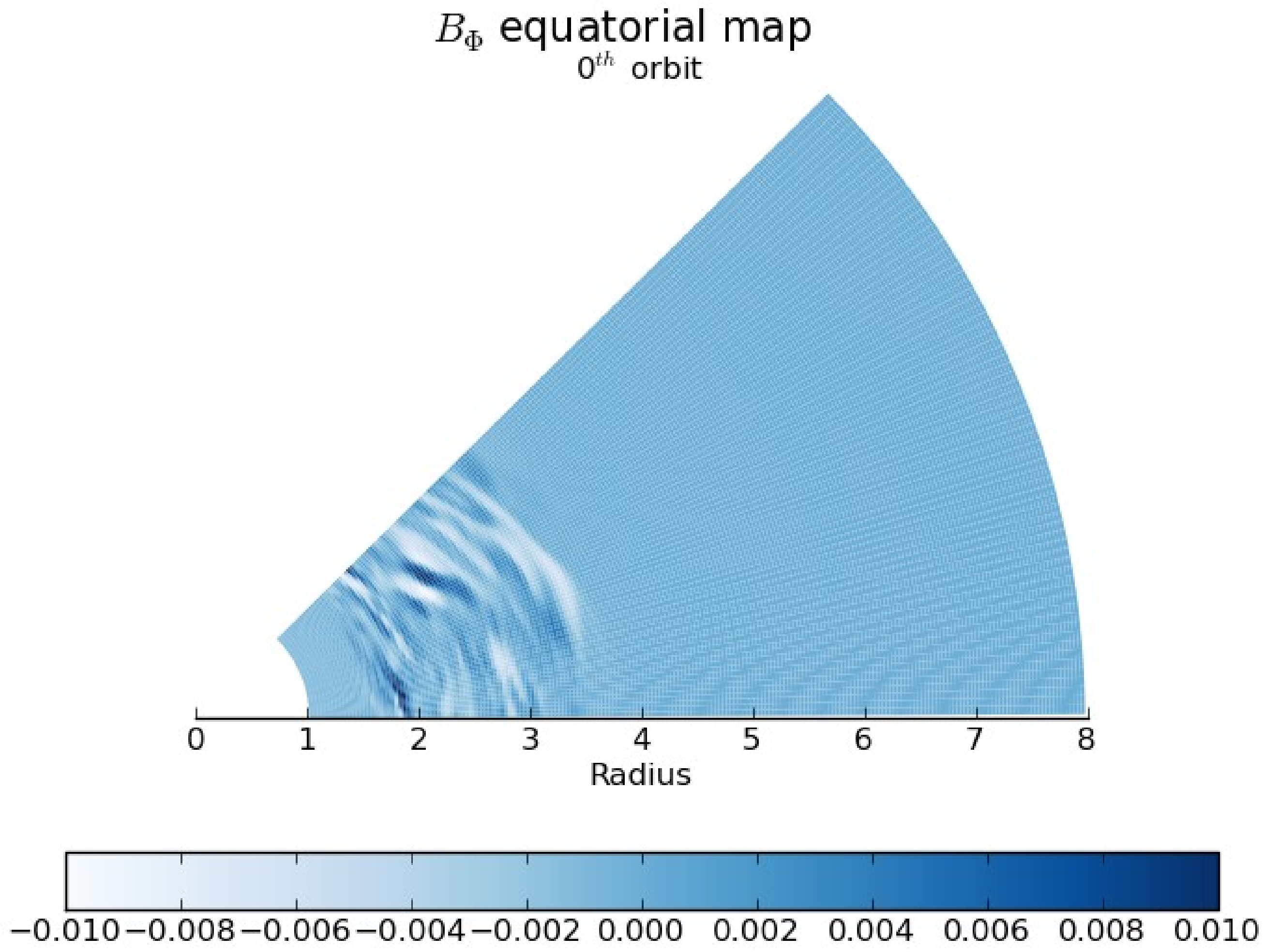
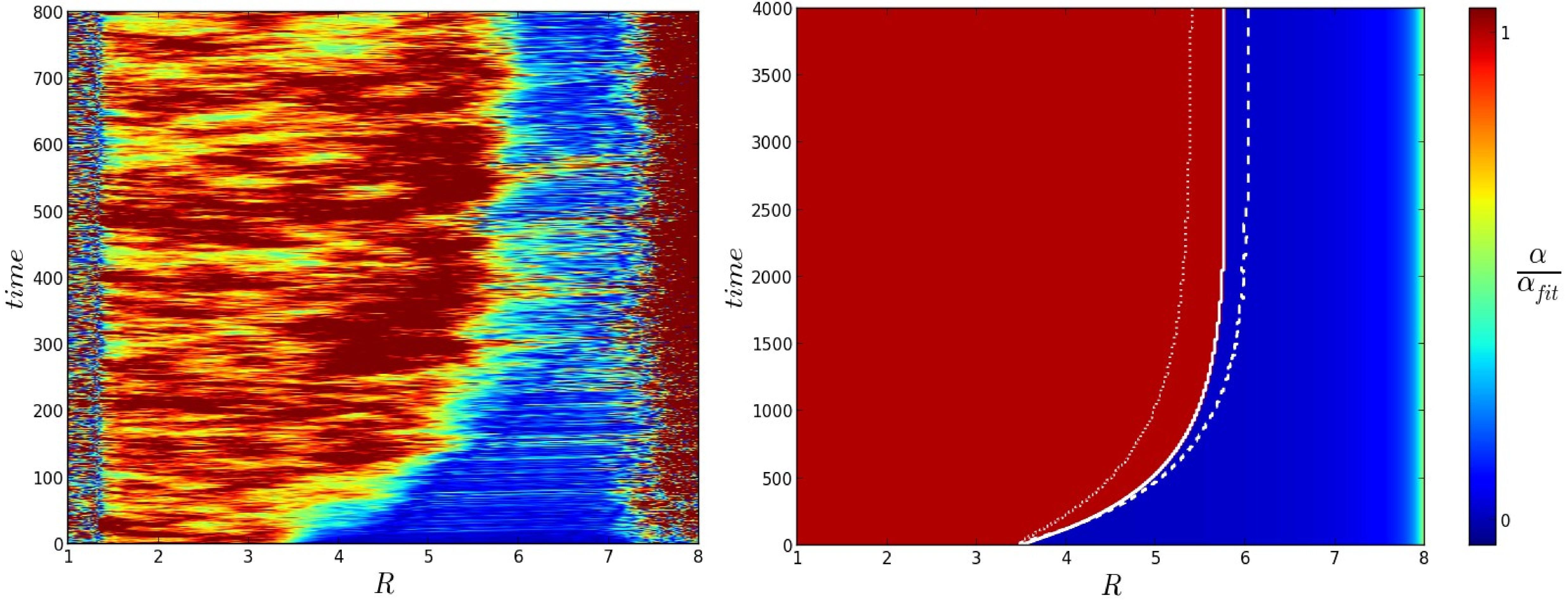
MAIN RESULT


B_Φ equatorial map
0^{th} orbit
0
1
2
3
4
5
6
7
8
Radius
−0.010
−0.008
−0.006
−0.004
−0.002
0.000
0.002
0.004
0.006
0.008
0.010

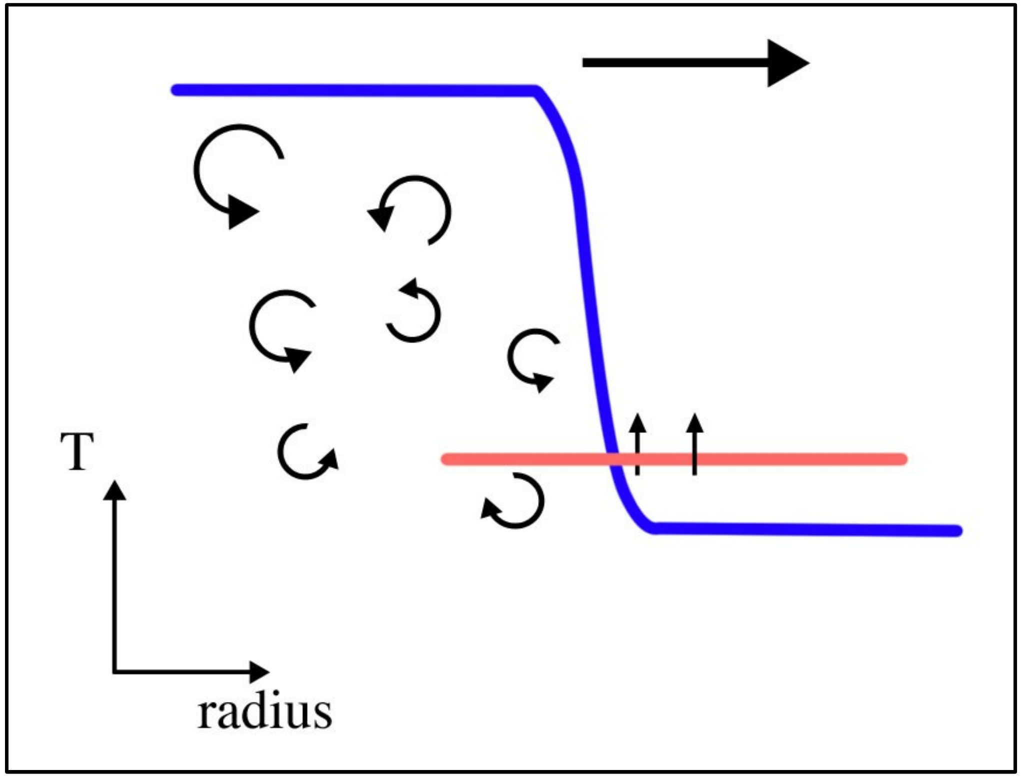
PHYSICAL INVESTIGATIONS

COMPARISON WITH THE MEAN FIELD MODEL



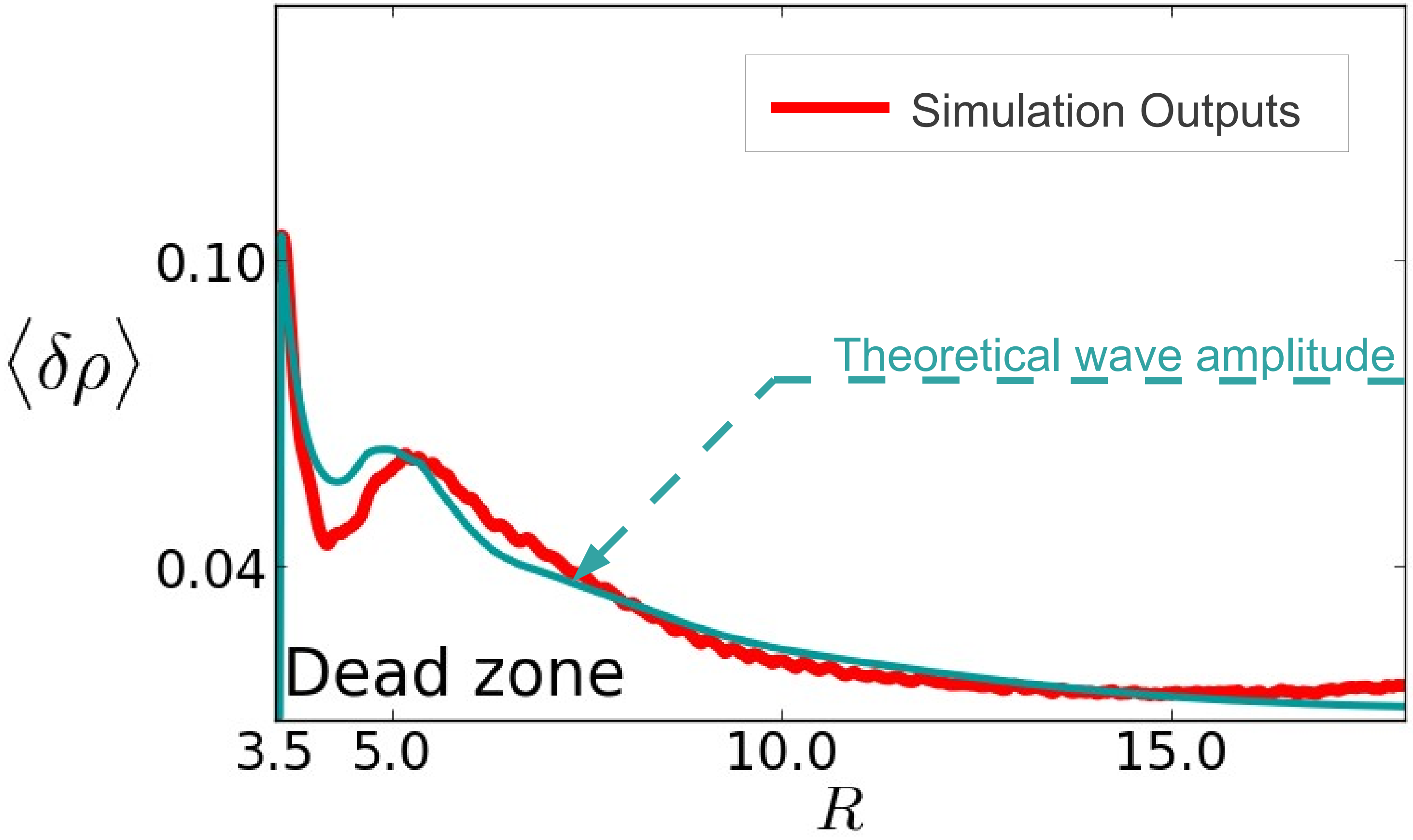
Picture credit:

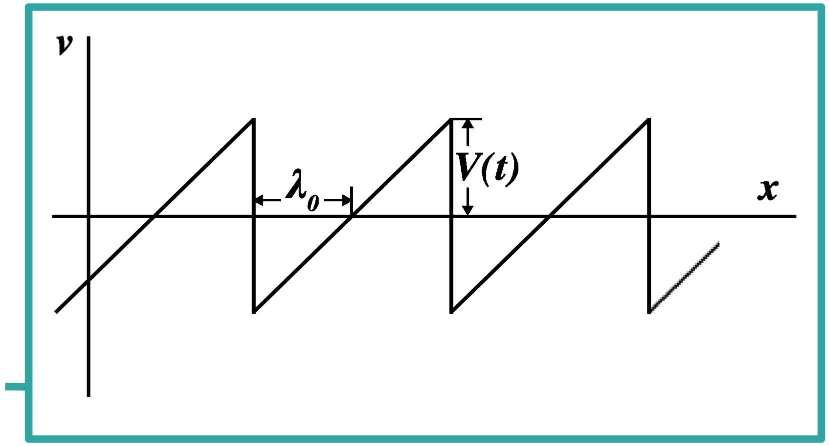
PROPAGATION PROCESS...



Picture credit: Latter & Balbus (2012)

DENSITY WAVES HEAT THE GAS

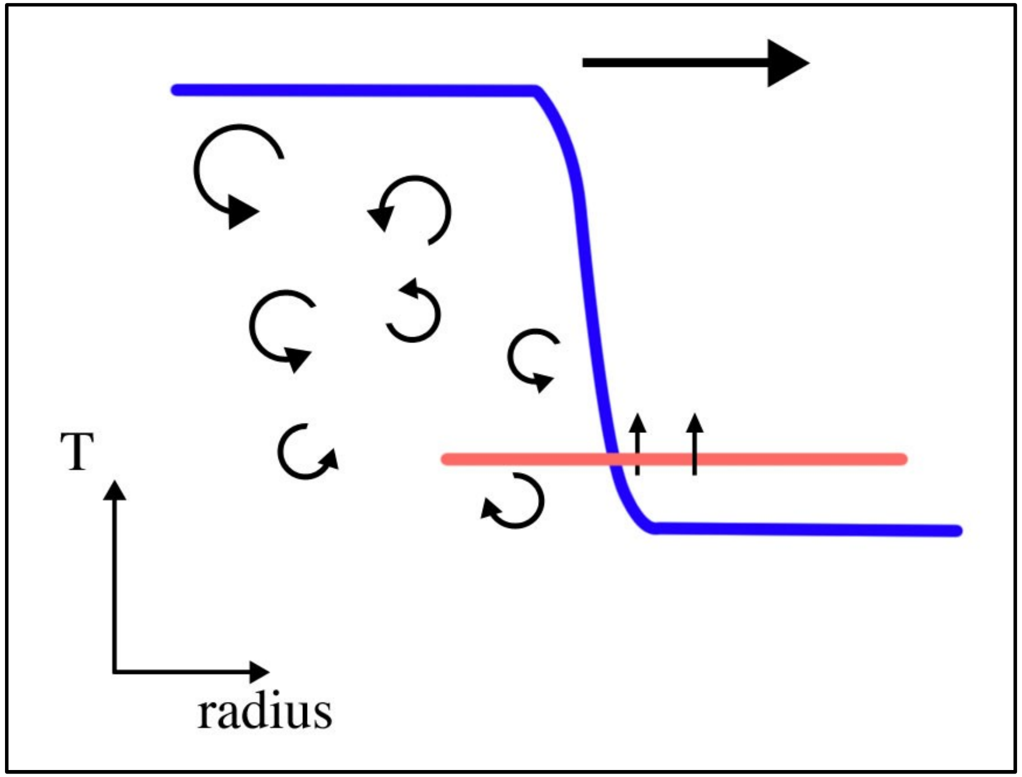




Fluid Mechanics
Landau and Lifshitz (1987)

Picture credit:

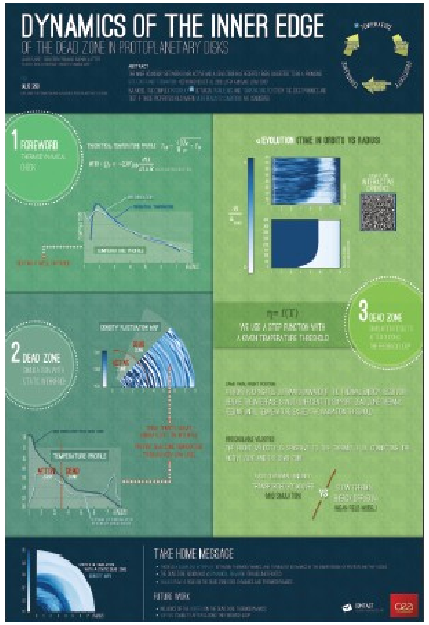
PROPAGATION PROCESS...



5 TIME FASTER !

Picture credit: Latter & Balbus (2012)

« Best student Poster » prize
@ IAUS 299 (June 2013)
« Exploring the Formation and Evolution
of Planetary Systems »



SCIENTIFIC PRODUCTIONS

Astronomy & Astrophysics manuscript no. main
May 17, 2013

Thermodynamics of the dead-zone inner edge in protoplanetary disks

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Accepted/ Received/ in original form

ABSTRACT

Context. In protoplanetary disks, the inner boundary between the MRI active and inactive regions could be a promising site for planet formation, due to the trapping of solids at the boundary itself or in vortices generated by the Rossby wave instability. Activity at this radius will also control the thermodynamic structure of much of the dead-zone (including features such as the ice line). At the interface the disk thermodynamics and the turbulent dynamics are intimately entwined, because of the importance of turbulent dissipation and thermal ionisation. Numerical models of the boundary, however, have neglected the thermodynamics, and thus miss a key element in its behaviour.
Aims. The aim of this paper is to numerically investigate the interplay of thermodynamics and dynamics in the inner regions of protoplanetary disks by properly accounting for turbulent heating and the dependence of the resistivity on the local temperature.
Methods. Using the Godunov code RAMSES, we have performed a series of 3D global numerical simulations of protoplanetary disks in the cylindrical limit including turbulent heating and a simple prescription for radiative cooling.
Results. We find that waves excited at the dead/active interface significantly heat the dead zone, and we subsequently provide a simple theoretical framework to estimate the wave heating and consequent temperature profile. In addition, our simulations reveal that the dead zone inner edge can propagate outward into the dead zone, stalling a critical radius that can be estimated from a mean field model. The engine driving the propagation is in fact density wave heating close to the interface. A pressure maximum appears at the interface in all simulations; we note the apearance of the Rossby wave instability in simulations with extended azimuth.
Conclusions. Our simulations illustrate the complex interplay between thermodynamics and turbulent dynamics in the inner regions of protoplanetary disks. They also reveal how important activity at the dead-zone interface is for dead-zone thermodynamics.

Key words. Protoplanetary disk - Dead zone - thermodynamic - planet formation

1. Introduction

Current models of protoplanetary (PP) disks are predicated on the idea that significant regions of the disk are too poorly ionised to sustain MRI turbulence. PP disks are thought to comprise a turbulent body of plasma (the 'active zone') enveloping a region of cold quiescent gas, in which accretion is effectively absent (the 'dead zone') (Gammie 1996, Armitage 2011). Such models posit a critical inner radius (~ 1 au), within which the disk is fully turbulent and beyond which the disk exhibits a characteristic layered structure for some range of radii (1 – 10 au), where turbulence is active only in the surface layers (but see Bai & Stone 2013 for a complication of this picture).

The inner boundary between the MRI-active and dead regions is crucial for several key processes. Because there is a mismatch in accretion across the boundary, a pressure maximum will naturally form at this location which: (a) may halt the inward spiral of centimetre to metre-sized planetesimals and aid in their coagulation (Kretke et al. 2009), and (b) excite a large-scale vortex instability ('Rossby wave instability') (Lovelace et al. 1999), that may promote dust accumulation and hence planet formation (Barge & Sommeria 1995; Lyra et al. 2009; Meheut et al. 2012). On the other hand, the inner dead zone interface will control the global radial profiles of the disk's thermodynamic variables within much of the dead zone — temperature and entropy most importantly. Not only will it impact on global disk structure and key disk features (such as the ice line), the interface will control the preconditions for dead-zone instabilities that feed on the disk's small adverse entropy gradient, such as the subcritical baroclinic instability and double diffusive instability (Lesur & Papaloizou 2010; Latter et al. 2010).

Most studies of the interface have been limited to isothermality. This is a problematic assumption because of the pervasive interpenetration of dynamics and thermodynamics in this region. Temperature depends on the turbulence via the dissipation of its kinetic and magnetic fluctuations, but the MRI turbulence, in turn, depends on the temperature through the ionisation fraction, which is determined by thermal ionisation in the inner disk (Balbus

Send offprint requests to: J.Faure

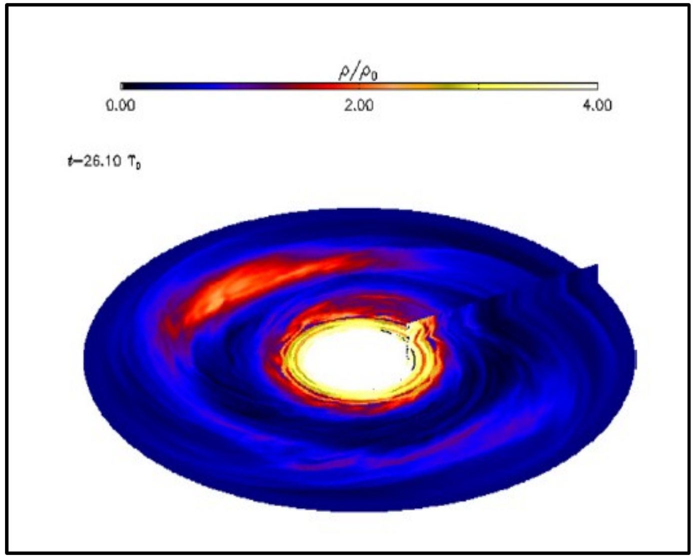
J. Faure et al. 2013
« Dynamics of the dead zone inner edge in PP disks »
(submitted to A&A)

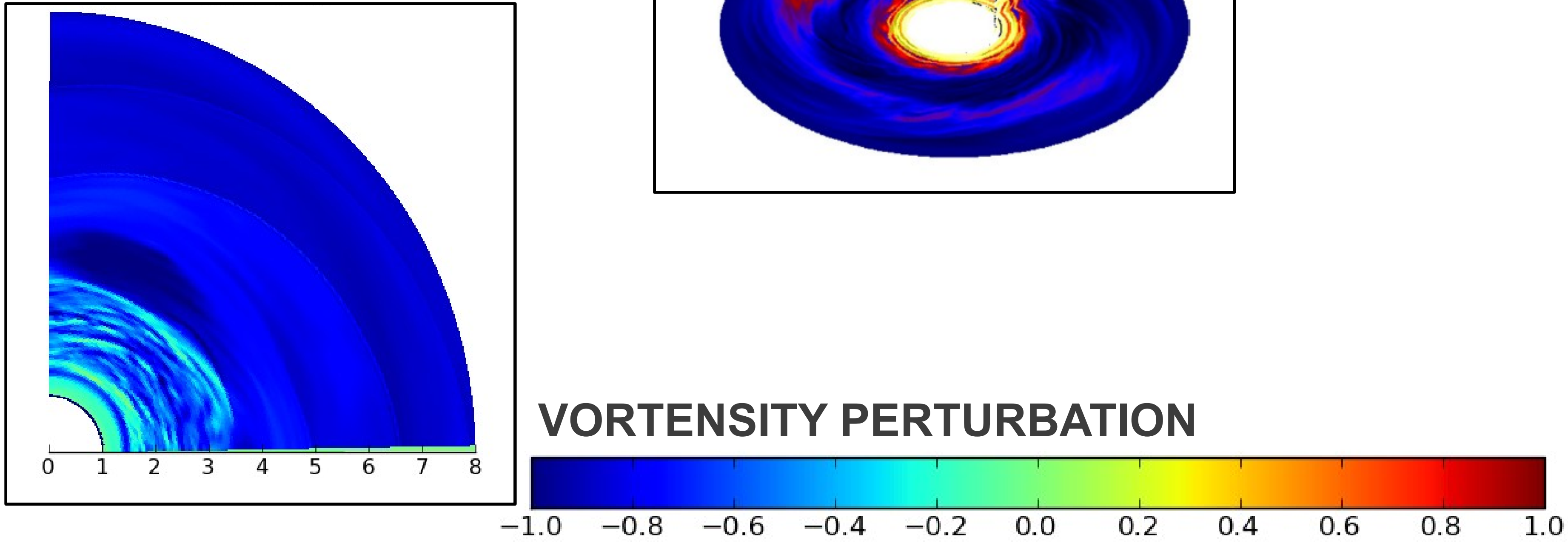
Picture credit:

FUTURE WORK

VORTEX FORMATION

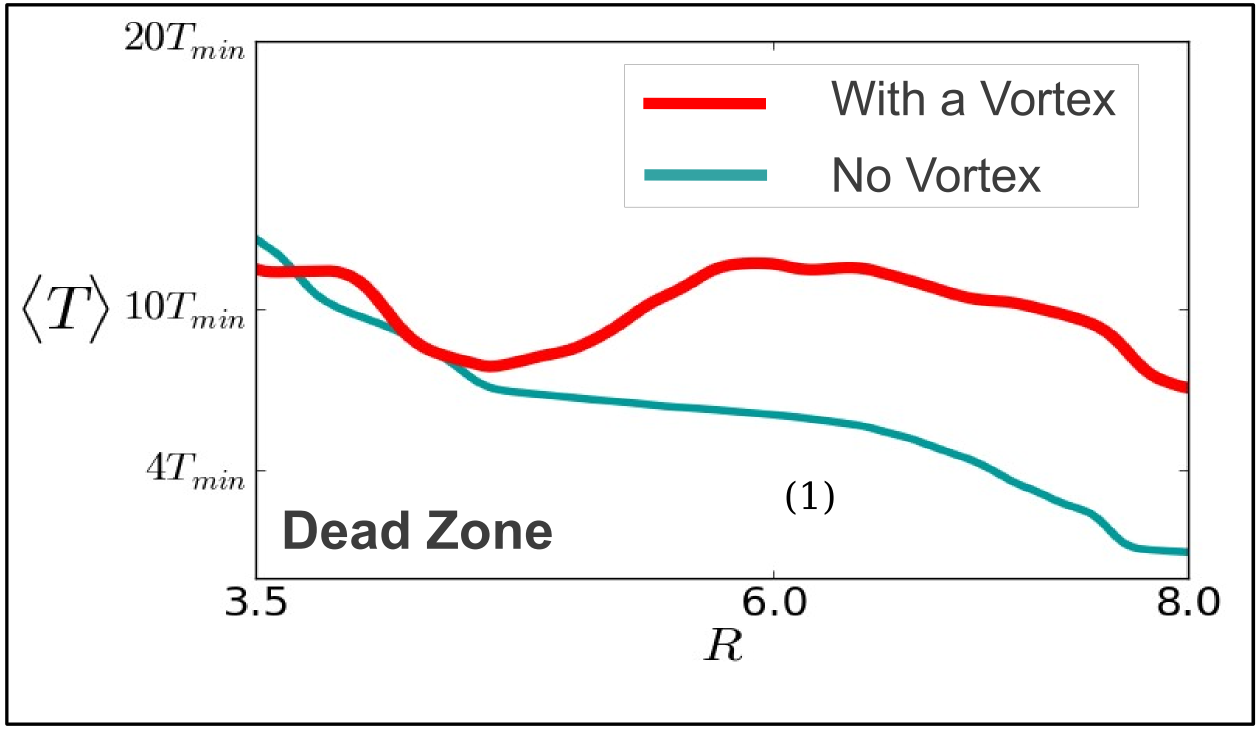
Lyra et. al (2012)



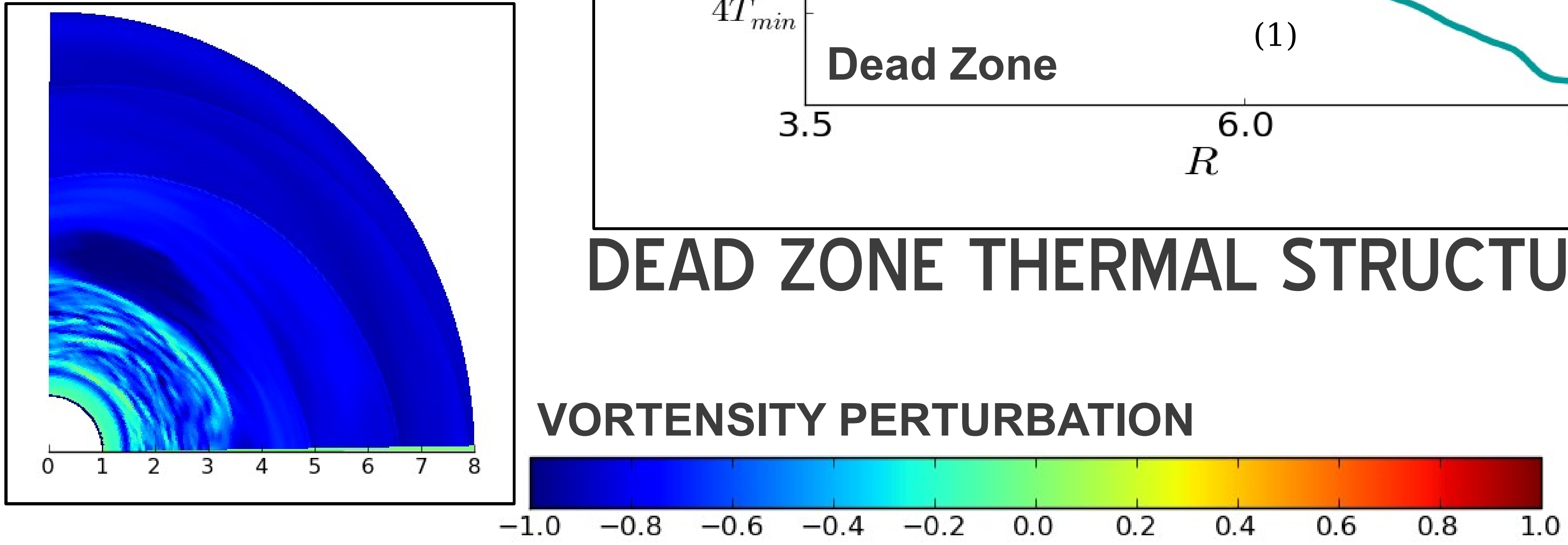


Picture credit:

VORTEX FORMATION



DEAD ZONE THERMAL STRUCTURE



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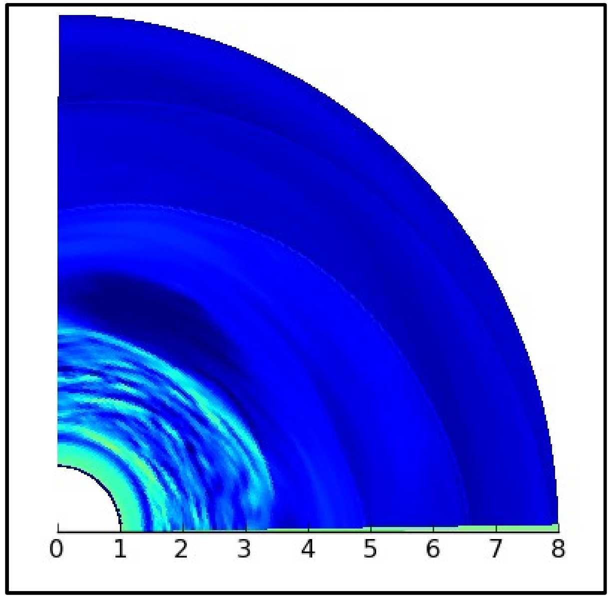
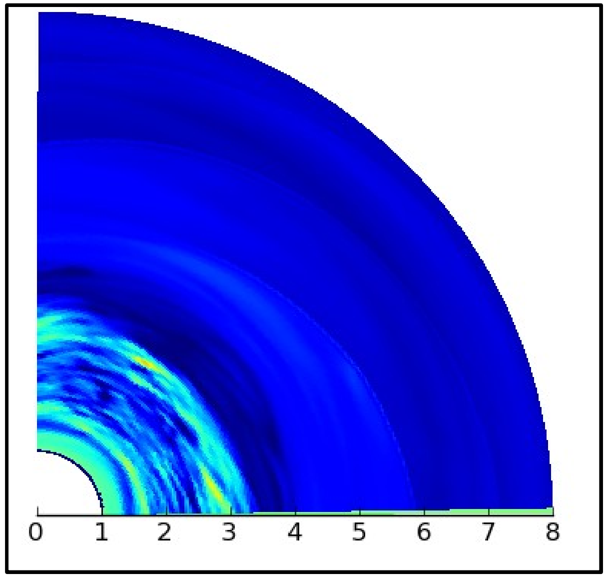
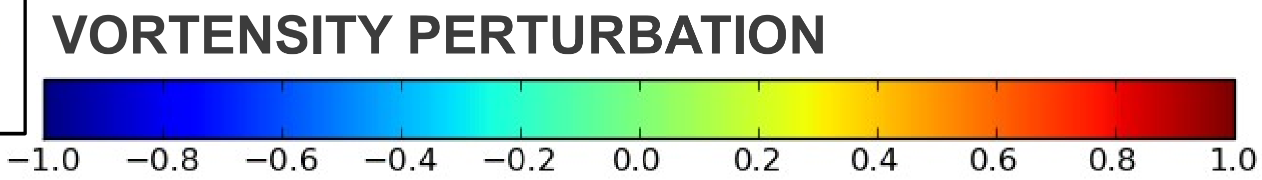
VORTEX FORMATION



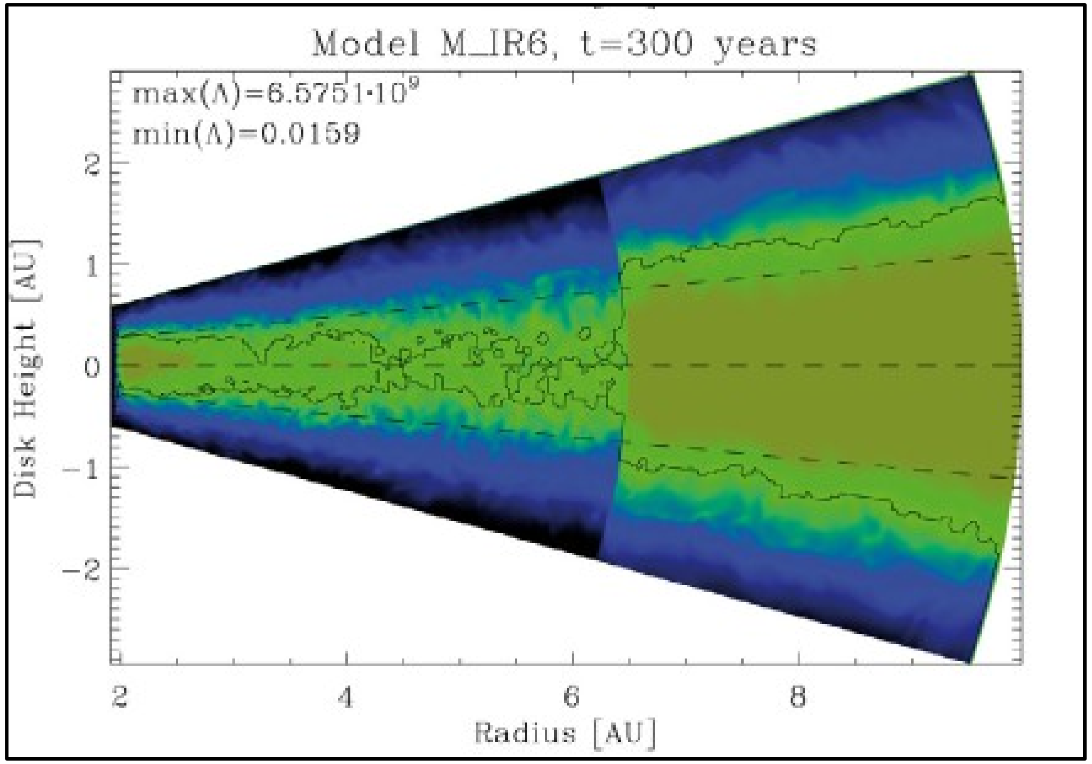


WHEN THE FRONT HAS REACHED ITS FINAL POSITION



Picture credit:

VERTICAL STRATIFICATION



- Global **stratified** MHD simulations
  - More realistic cooling function σ(z)

- Global **stratified + radiative** MHD simulations
  - Mario FLOCK CEA Saclay FLD method in PLUTO code (Flock et. al 2013)

Picture credit: Dzyurkevich et. al (2010)

CONCLUSIONS

The Active/Dead interface exhibits a dynamical behavior

Waves play a crutial role on the dead zone dynamics and thermodynamics

Vortex formation ?

THANK YOU

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