Protoplanetary disks dynamics

An account of 5-yrs of ERC funded research (PETADISK project)

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PETADISK Team

J. Faure *(Paris, France)*, **M. Flock** *(JPL & Caltech, USA)*, **M. Joos** *(Paris, France)* & **H. Méheut** *(Obs. Nice, France), and many external collaborators!*

Outline

I. Angular momentum transport in accretion disks

II. Properties (local simulations)

III. Consequences (global simulations)

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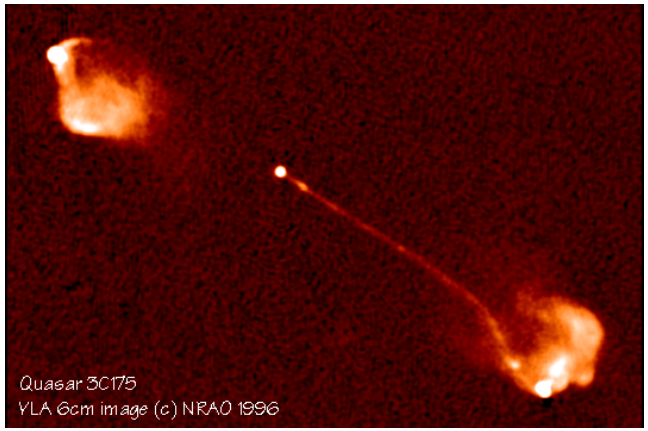
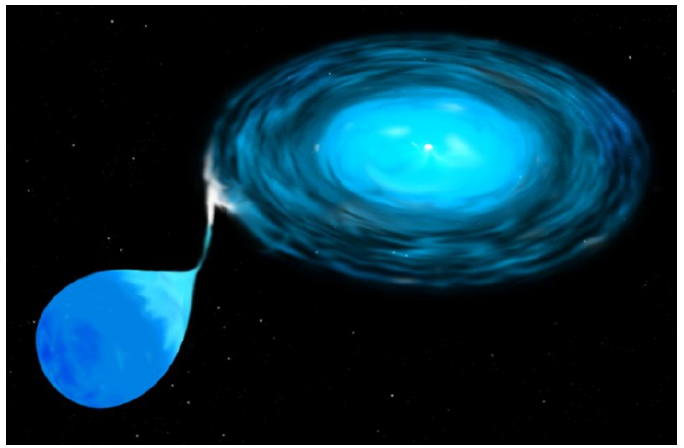
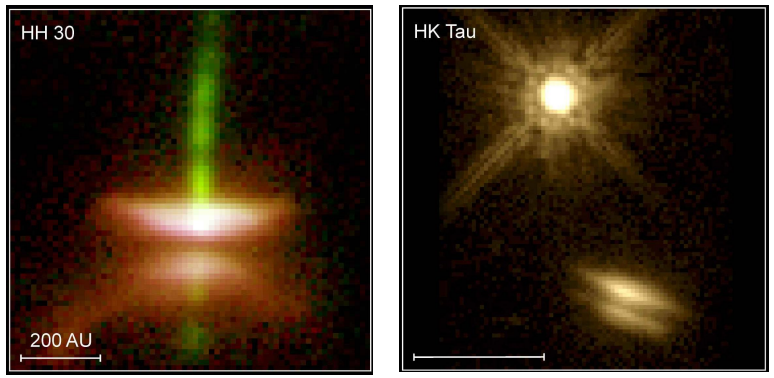
Accretion disks in the universe



In Active Galaxy Nuclei



In binary star system



In star forming regions =>
protoplanetary disks (PP disks)

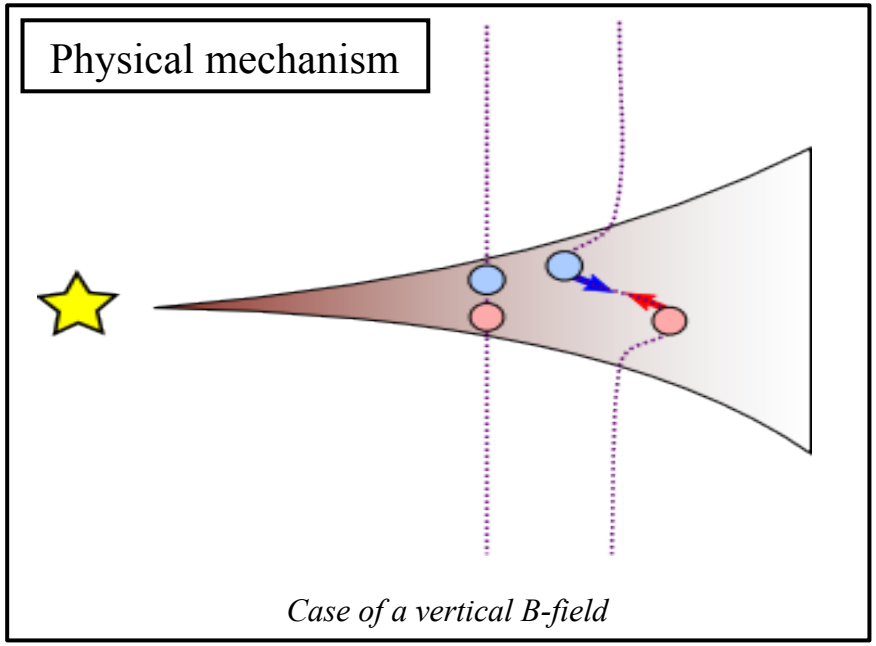
Observations: accretion of mass from disk to central object.

The magnetorotational instability (known as the « MRI »)

Balbus & Hawley (1991)

See also *Velikhov (1959)* and *Chandrasekhar (1960)*

The MRI



A MHD instability that destabilizes a rotating shear flow

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MRI => MHD turbulence => protoplanetary disk structure & planet formation

Numerical simulations needed to constrain MHD turbulence, angular momentum transport, PP disk properties and planet formation model

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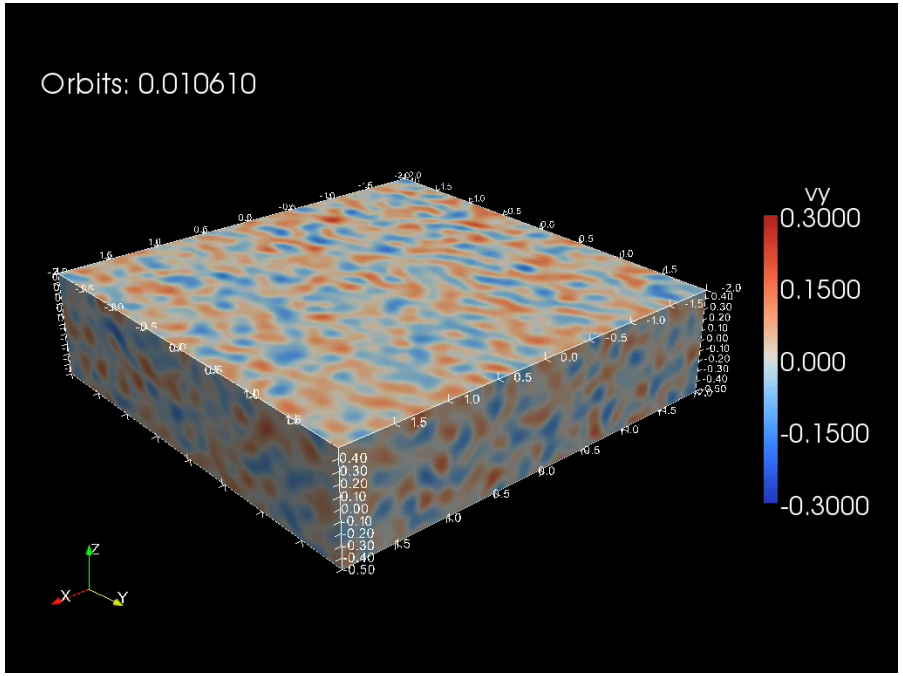
The PETADISK project (2011-2016)

Methods

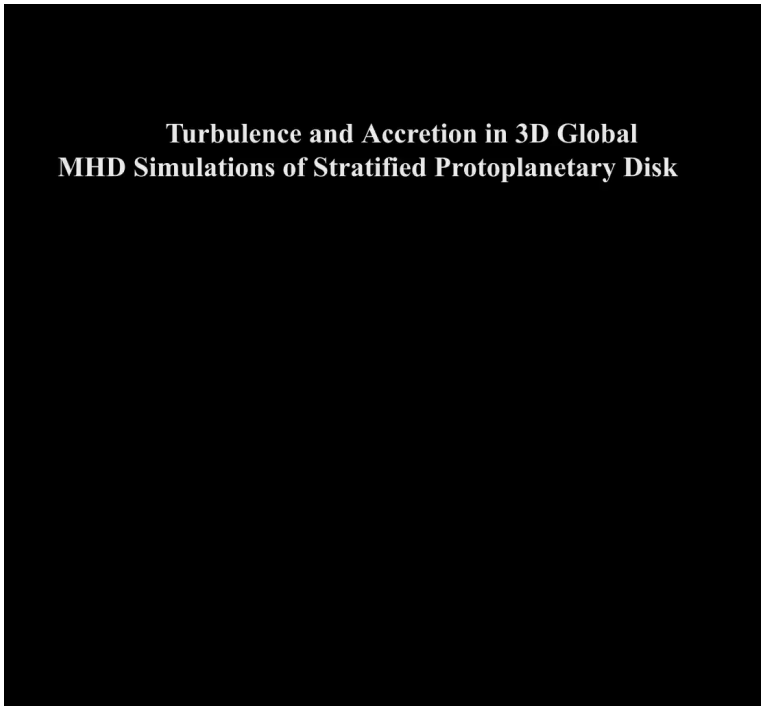
How does the MRI shape the environment in which planets form?

Local (« idealized ») simulations



Credit: G. Lesur

Global (« realistic ») simulations

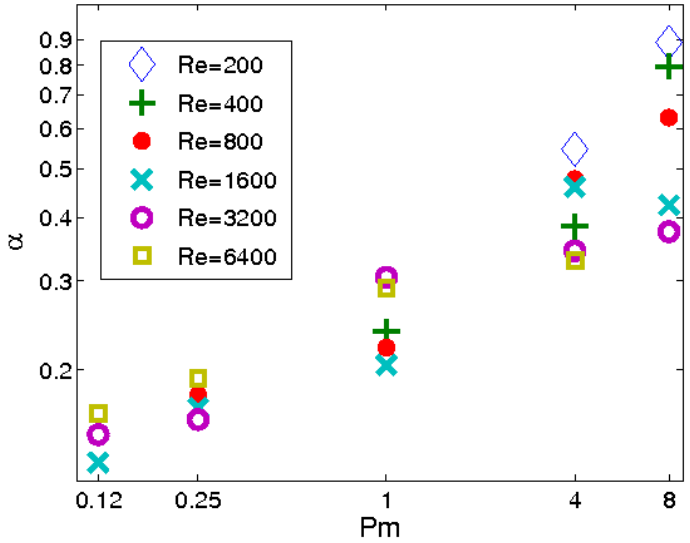


Credit: M. Flock

The situation in 2010

Local simulations

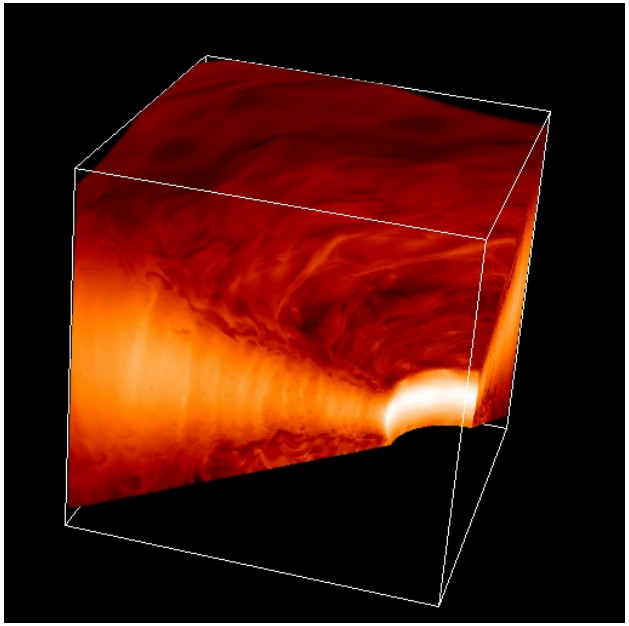
Sensitivity of MRI-induced turbulence to Ohmic dissipation



Lesur & Longaretti (2007), **Fromang** *et al. (2007), Longaretti & Lesur (2010)*

Global simulations

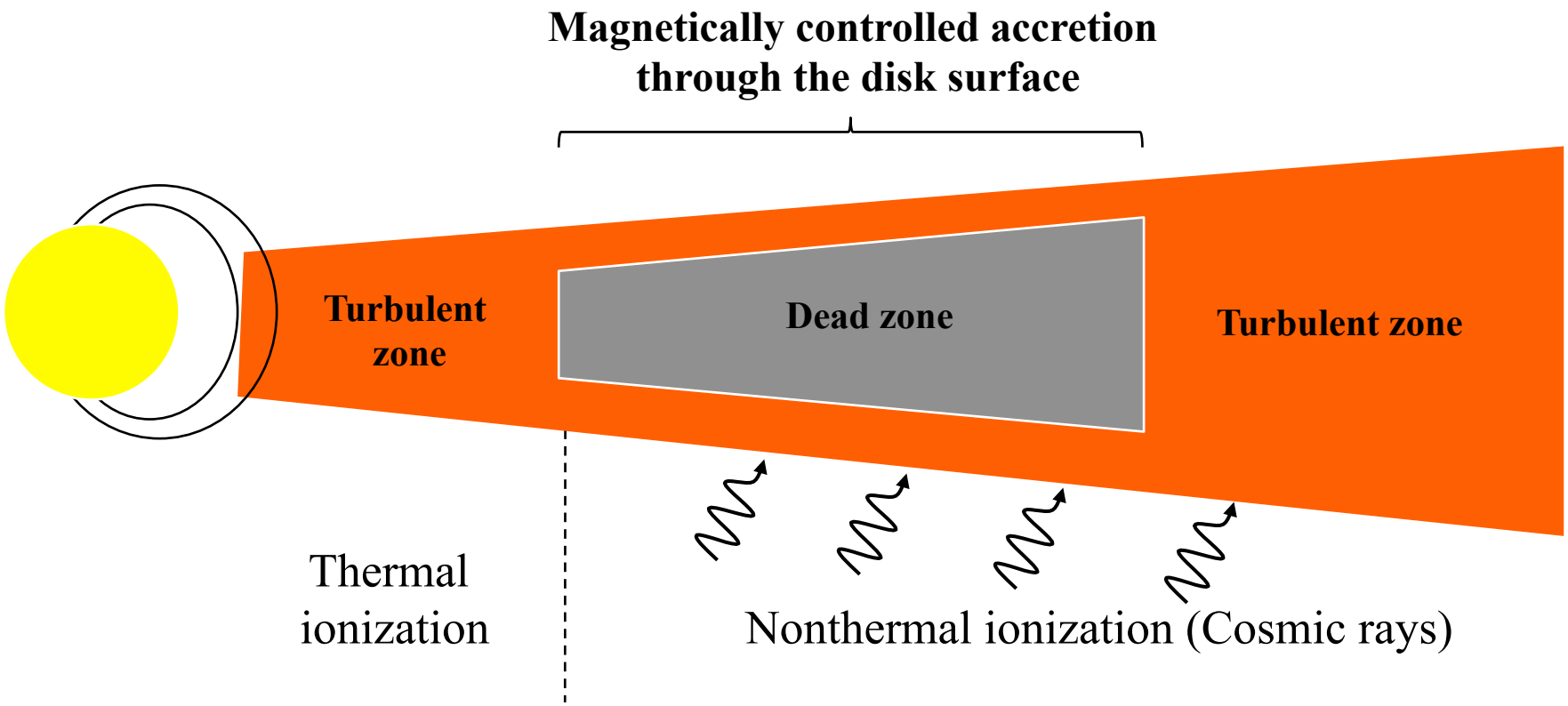
Global simulations of PP disks using isothermal equation of state



Fromang *& Nelson (2006, 2009),* **Flock** *et al. (2010)*

The dead zone paradigm

Gammie (1996), Fleming & Stone (2003) & many others…



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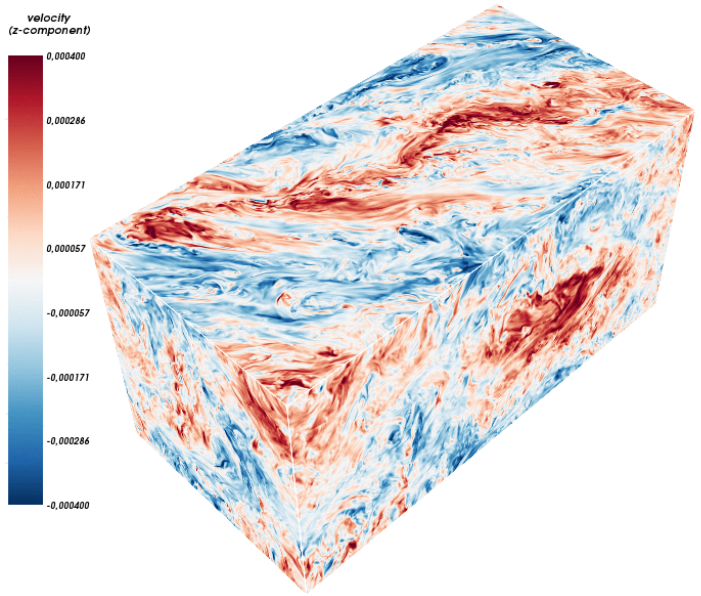
Asymptotic convergence (Pm=ν/η<<1)

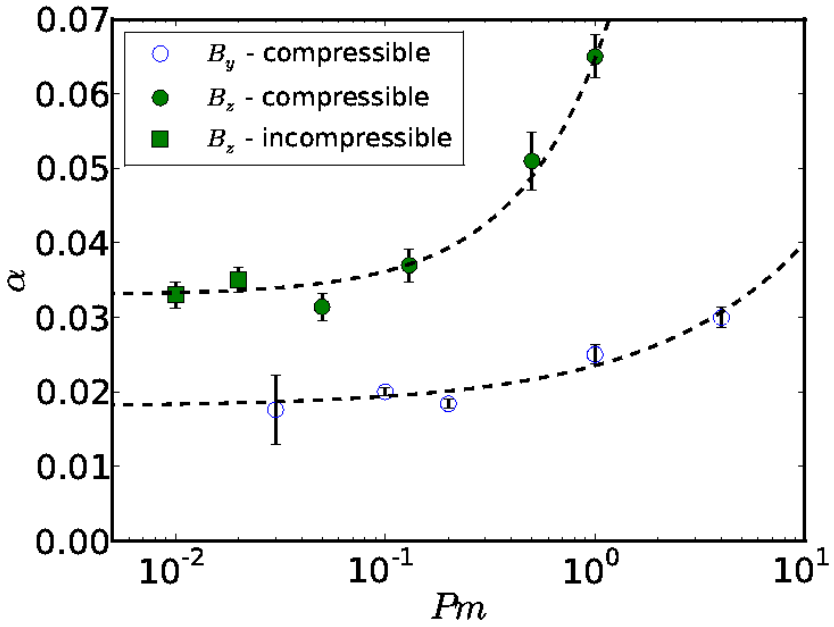
Méheut, Fromang, Lesur, Joos & Longaretti (2015)

TURING Grand challenge



Credit: M. Joos

- TURING Grand challenge
- $(N_x,N_y,N_z)=(800,1600,800)$
- ~2000 years of single core computation - more than 10^5 cores

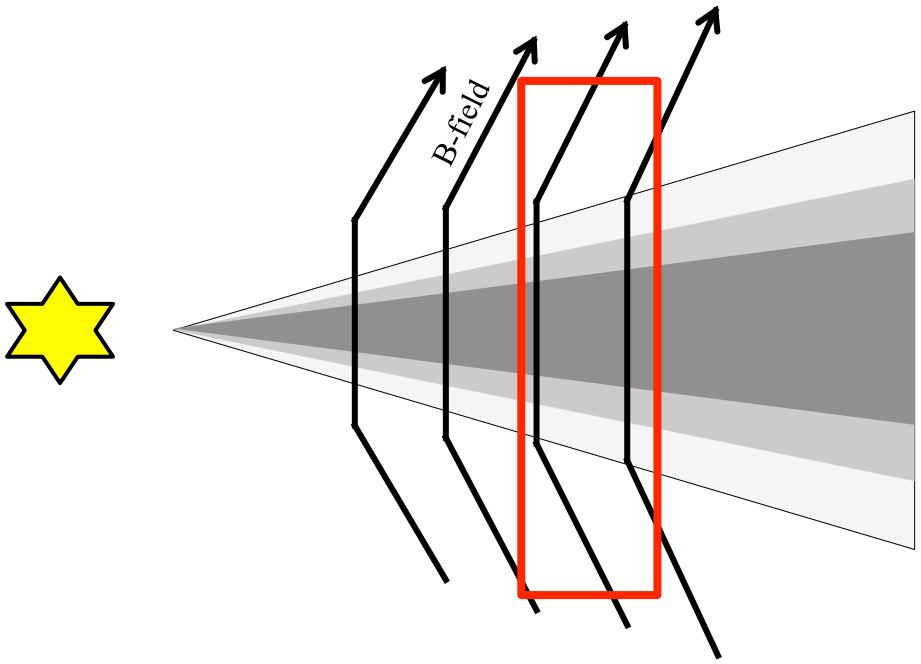


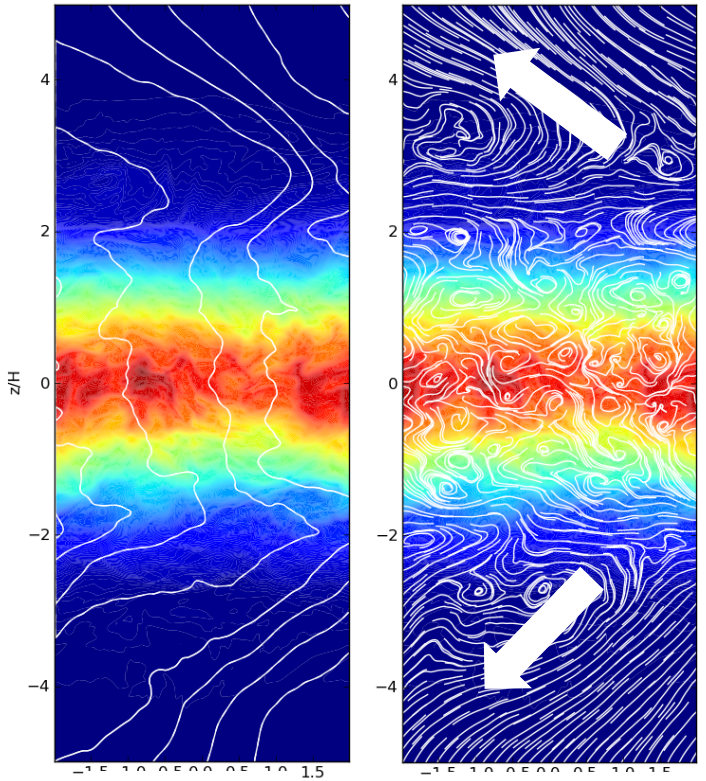
Convergence to finite α values

But MHD is complex and can reveal surprises…

Realistic disk structure: density stratification

Suzuki et al. (2010), ***Fromang****, Latter, Lesur & Ogilvie (2013), Moll (2013), Lesur et al. (2013) and Bai & Stone (2013)*





Field lines Streamlines

Two ingredients:

- Vertical density stratification
- Vertical magnetic field

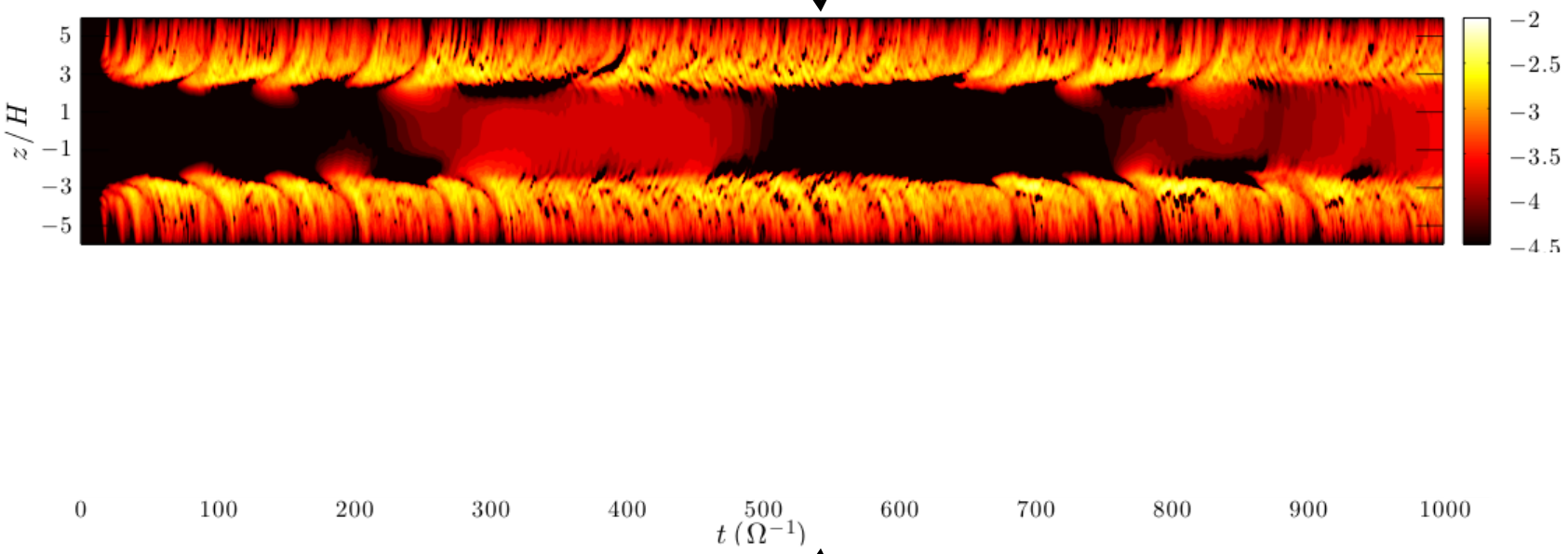
Main results

•Strong outflows develops (but numerical artefacts prevents definite conclusions)

Realistic disk structure: Hall dissipation

*Lesur, Kunz & **Fromang** (2014)*

Ohmic dissipation alone @ 1AU
Stress tensor spacetime diagram: α=2.5 10^{-3}



Ohmic dissipation + Hall effect (@ 1 AU)
Stress tensor spacetime diagram: α=4.5 10^{-1}

• Large stress & azimuthal field in the Hall dominated region
• Flow laminar in the disk midplane, powerful outflows

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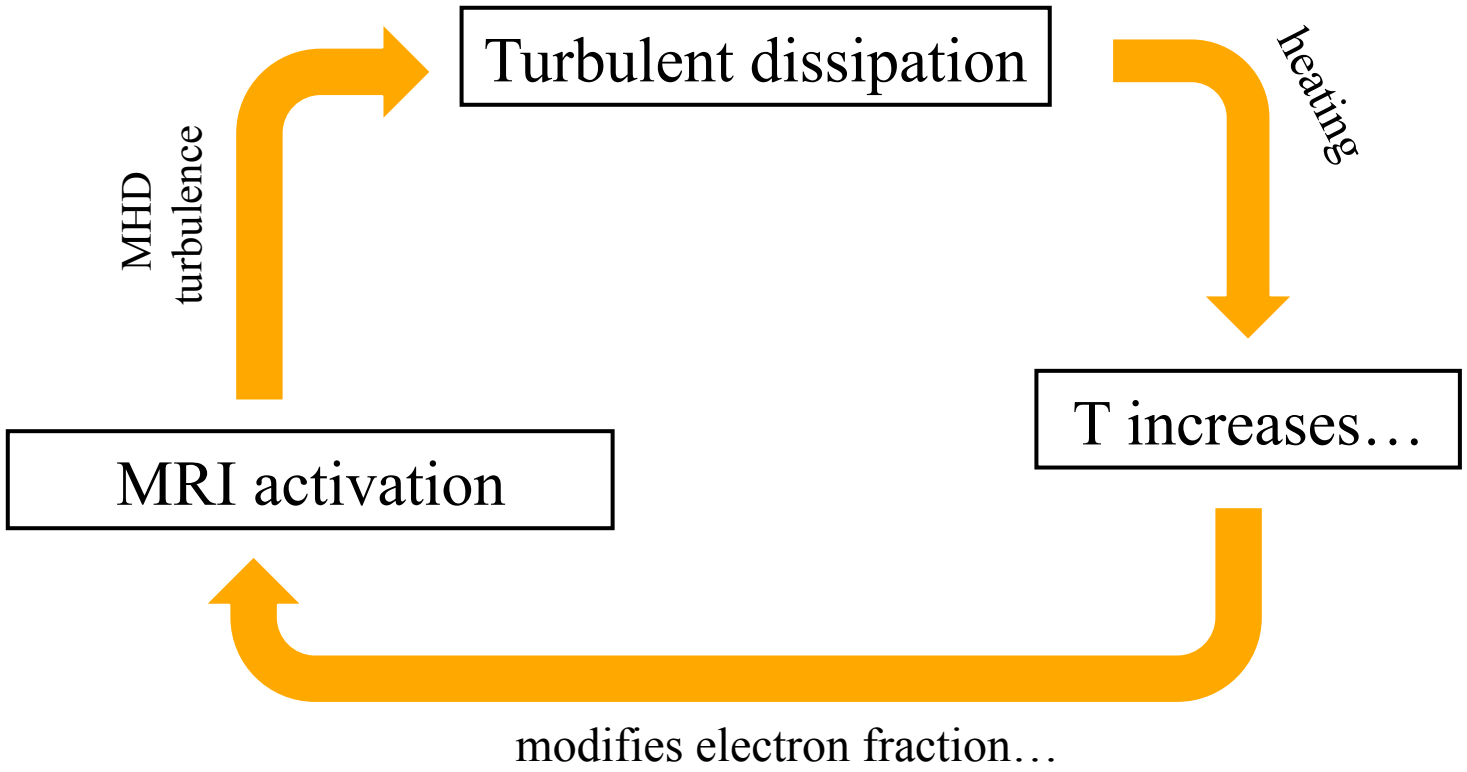
MRI ⇔ thermodynamics

MRI-mediated MHD turbulence (dynamics) and PP disk temperature structure are linked to one another

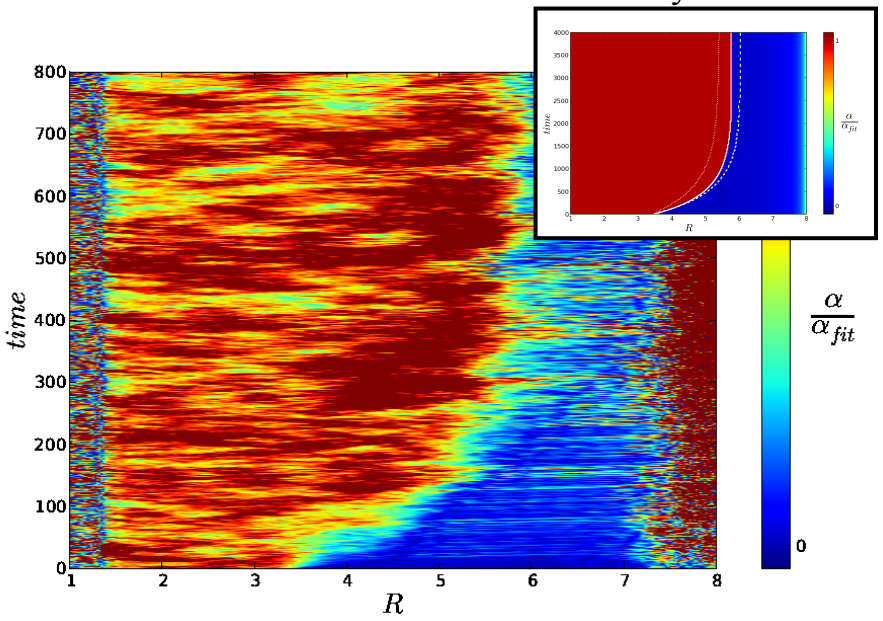


Coupling thermal effects & disk dynamics

***Faure**, **Fromang** & Latter (2014), **Faure, Fromang**, Latter & **Méheut** (2015)*

- Global disk simulation (code: RAMSES)
- Simplified treatment of heating/cooling processes
- Resitivity: η= η(T)

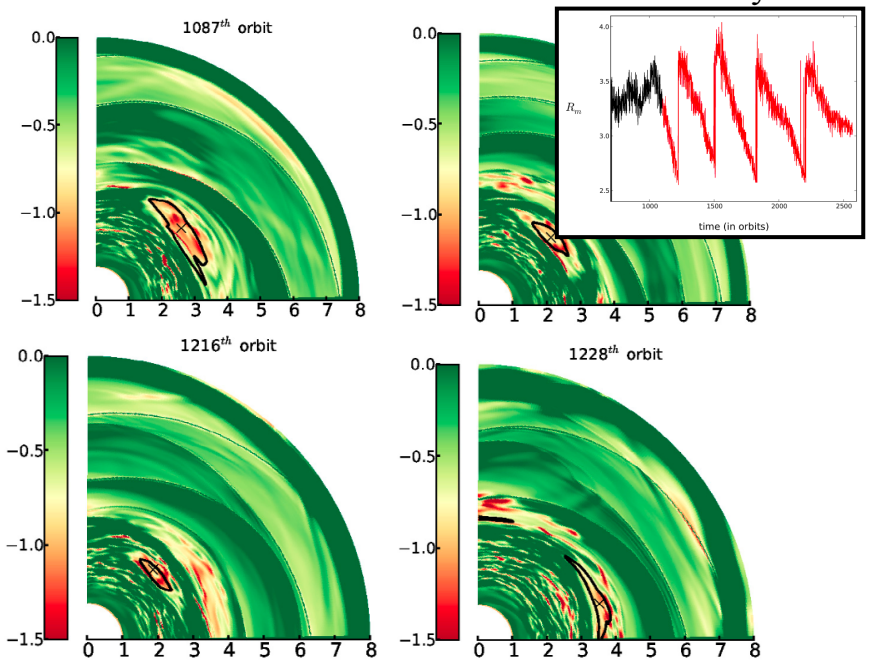
Toy model



Main result

• Dynamic behavior of the dead/active interface – agreement with simplified models

Vortex cycle



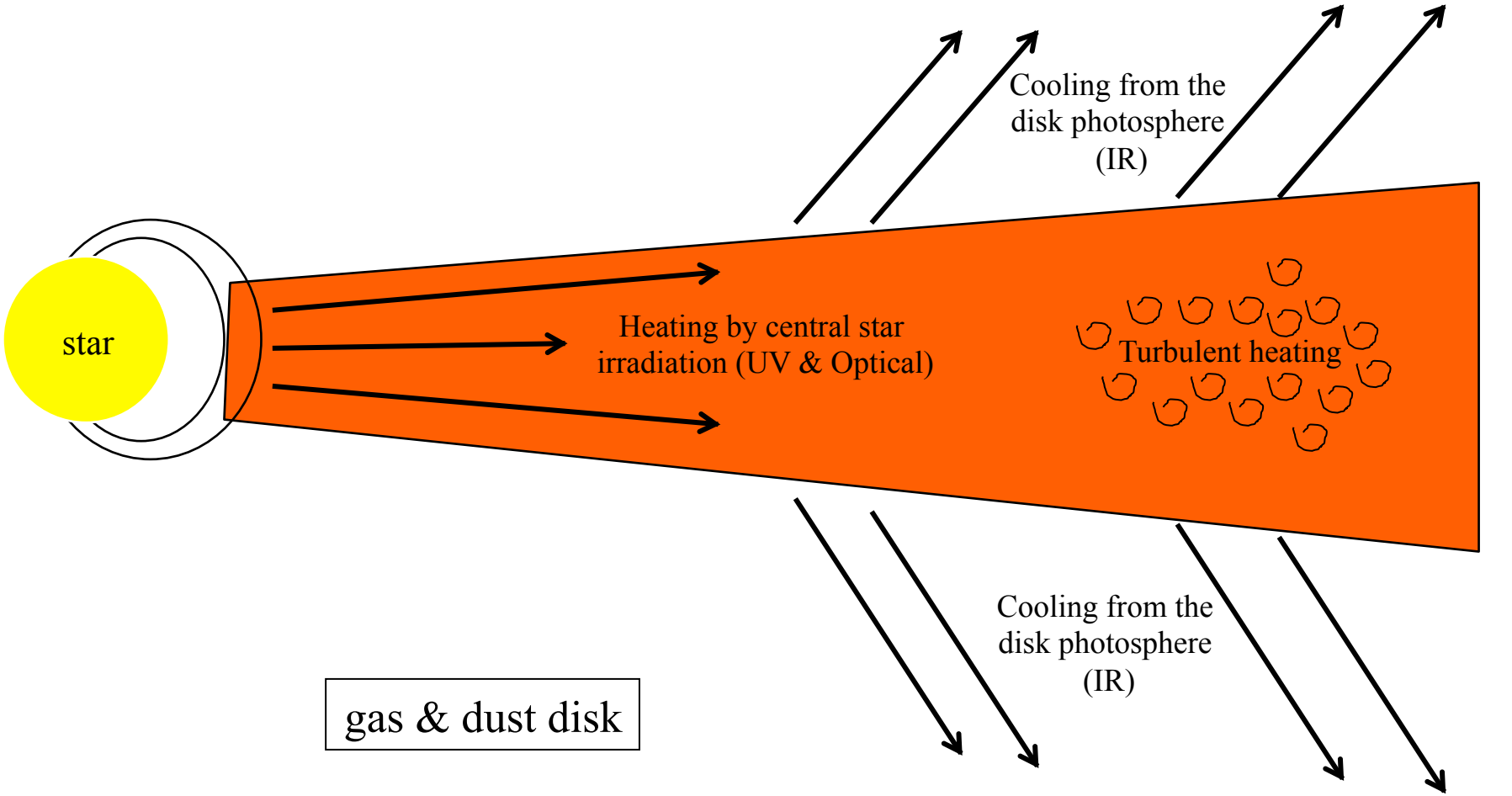
Main result

• Cycle of formation-migration-destruction of a vortex at the dead/active interface

Radiative-MHD in accretion disks

Flock*, *Fromang*, *Gonzalez & Commercon (2013)

Ray-tracing (irradiation by central star) + Flux Limited Diffusion (infrared radiation by dust particles)



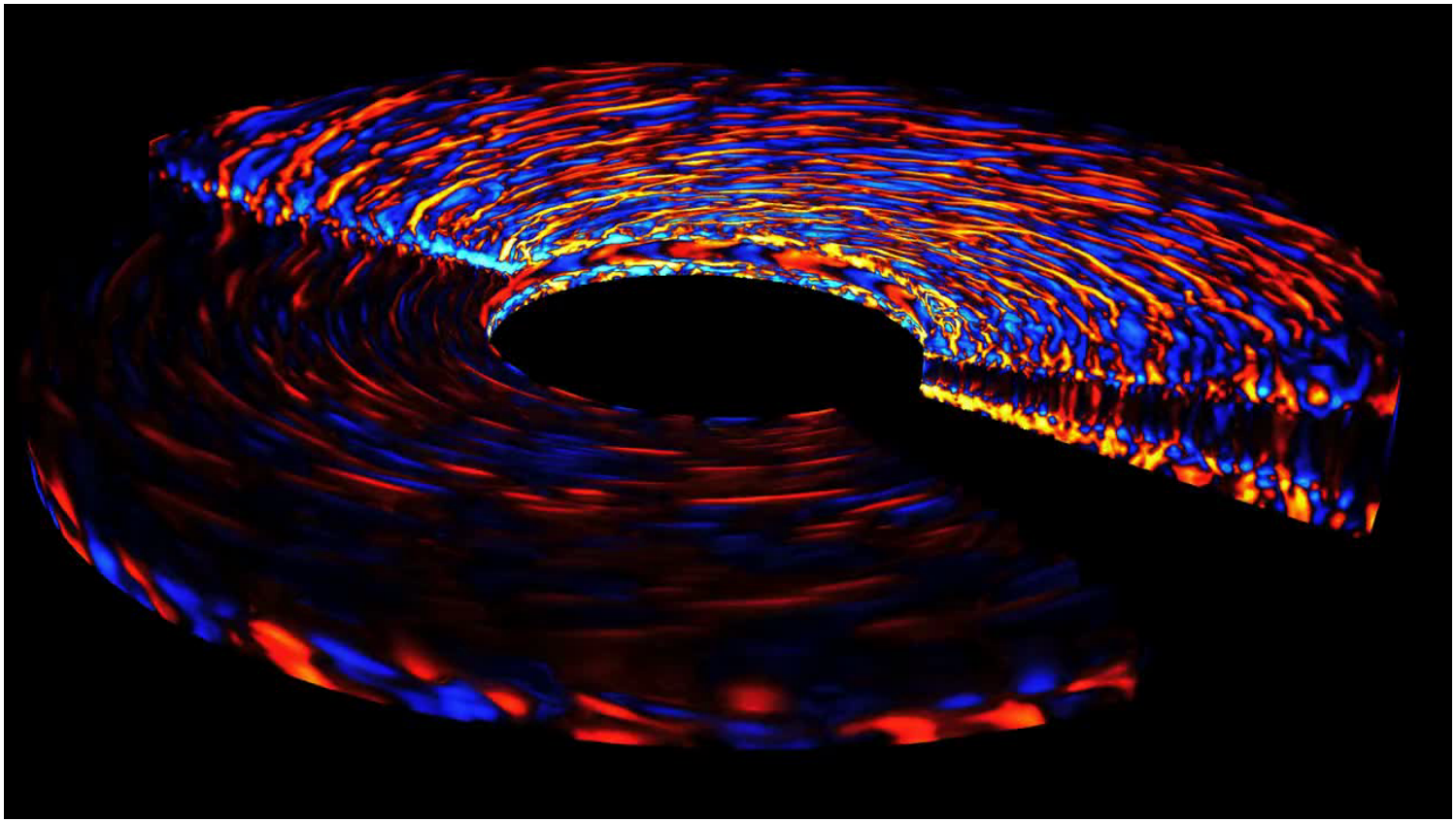
Implemented in the PLUTO code

Global radiative MHD simulations of accretion disks

***Flock**, **Fromang**, Gonzalez & Commercon (2013)*

First GLOBAL radiative-MHD simulations of protoplanetary disks

Temperature fluctuations

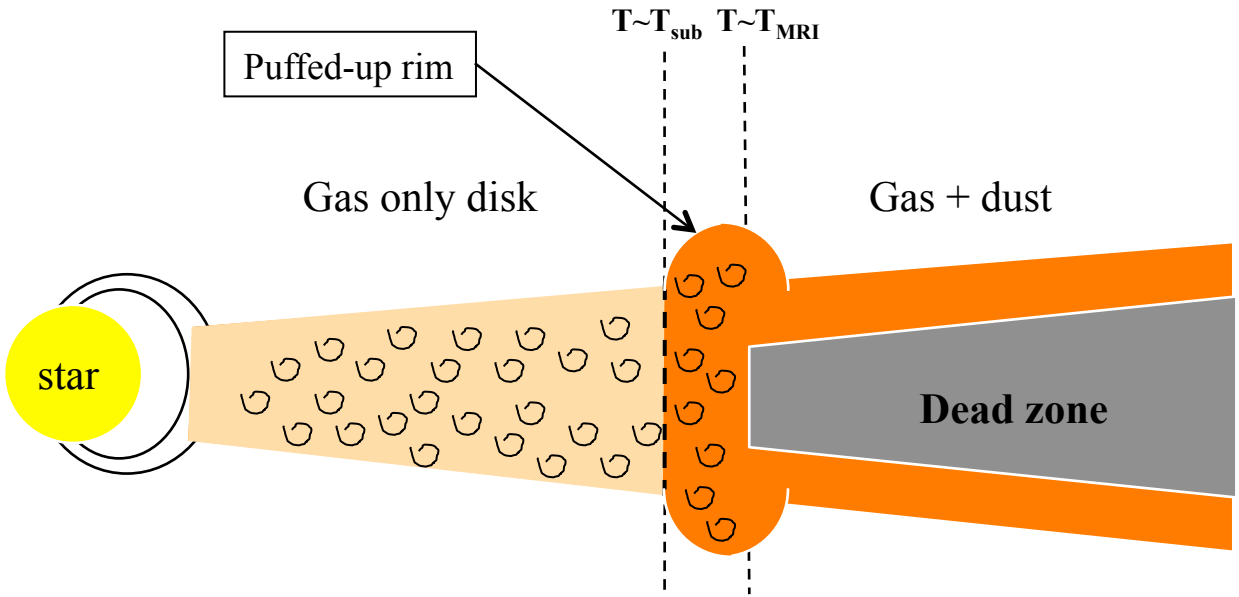


Credit: D. Pomarède, B.Thooris & M.Flock

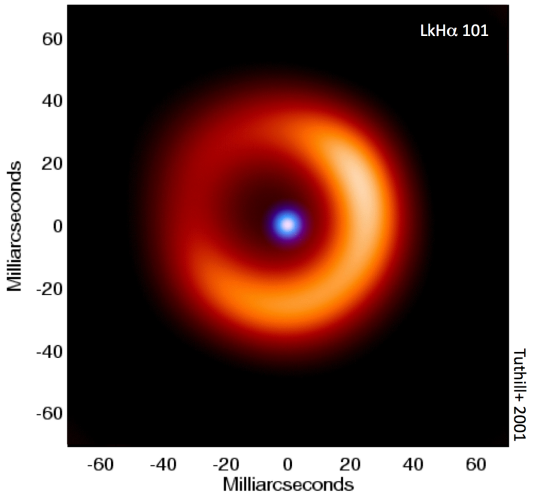
https://vimeo.com/134087074

Inner PP disk structure

***Flock**, **Fromang**, Turner & Benisty (2016)*



Mid-IR interferometric observations



Use the radiative MHD module

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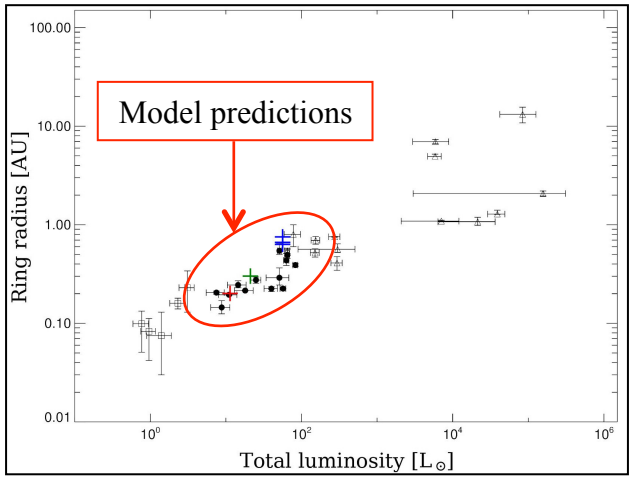
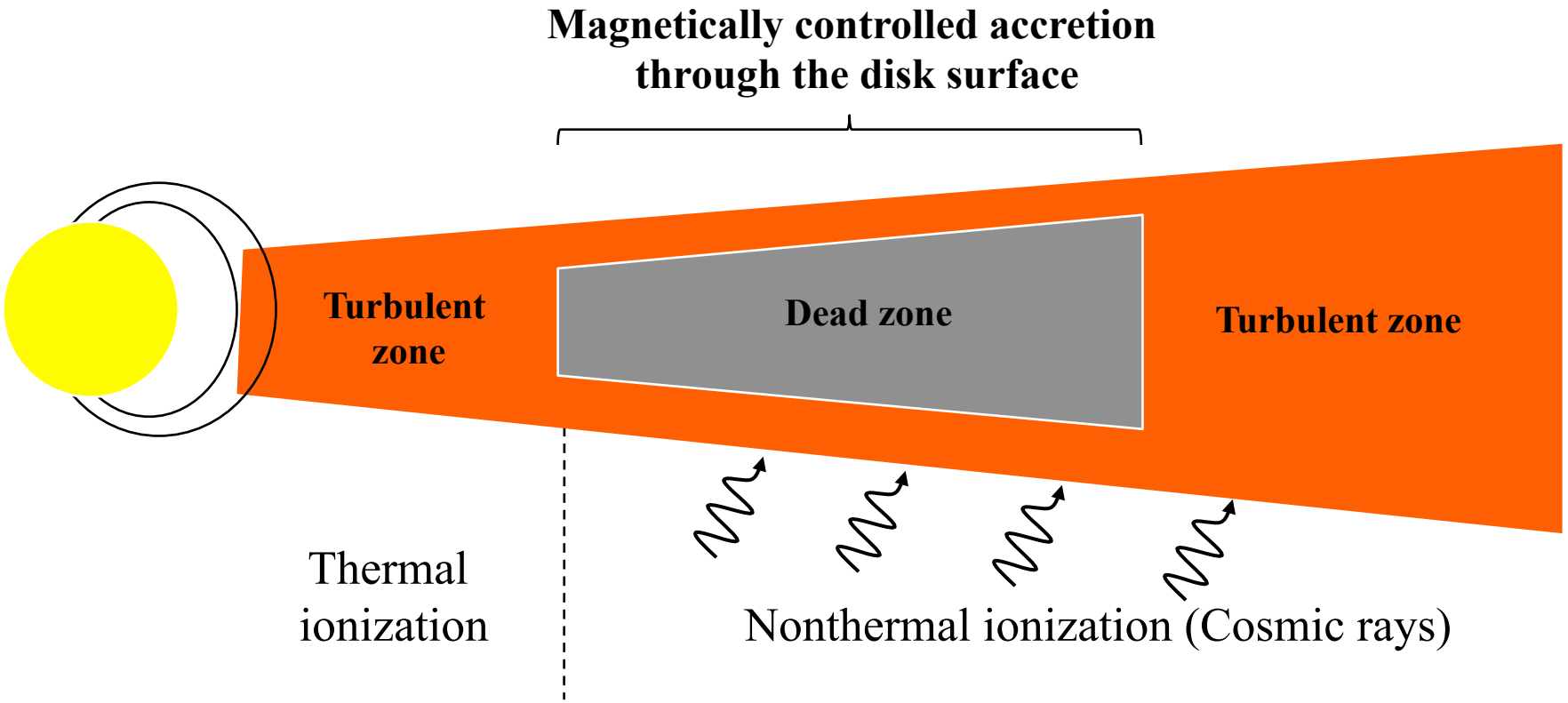
2D steady state simulations of PP inner disks

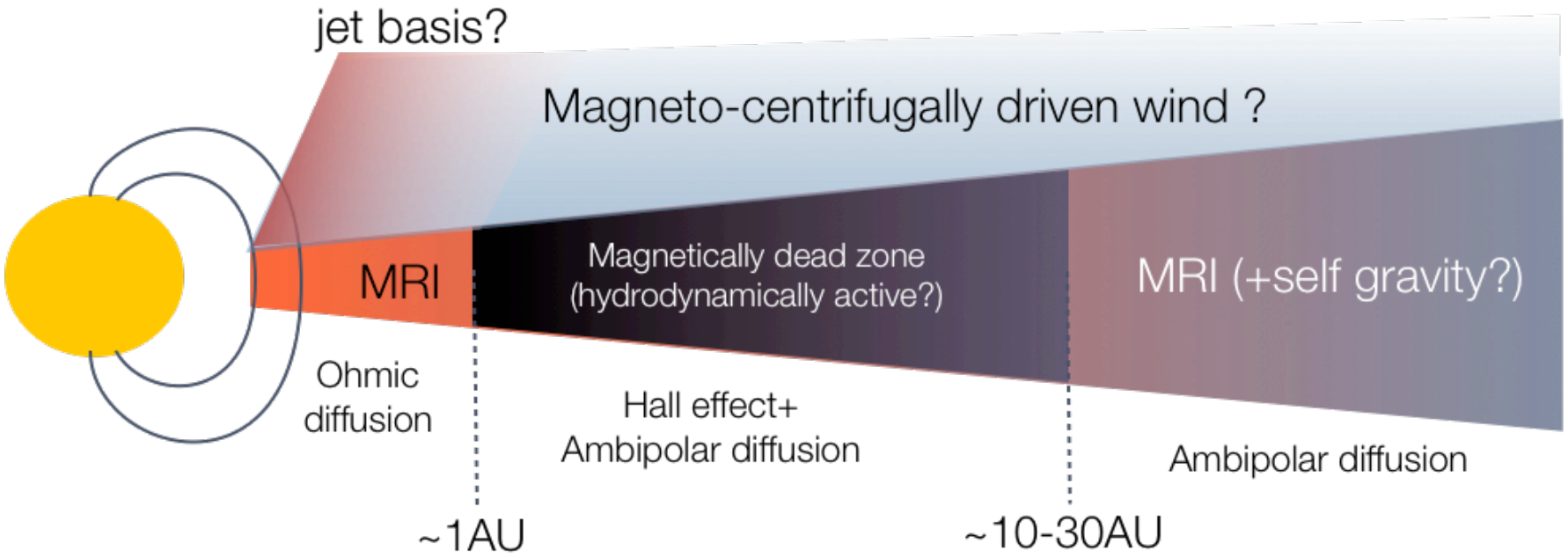


Conclusions

PP disk structure (2010)



PP disk structure (2016)



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Open questions

- Interplay between turbulence and jets/winds?
- Hall effect in stratified & large scale disks?
- Observational signatures of the MRI?

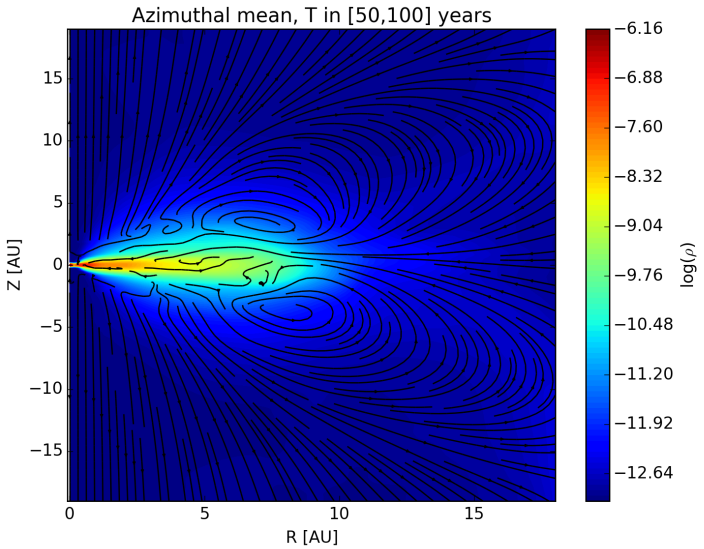
The future: 2016-?…

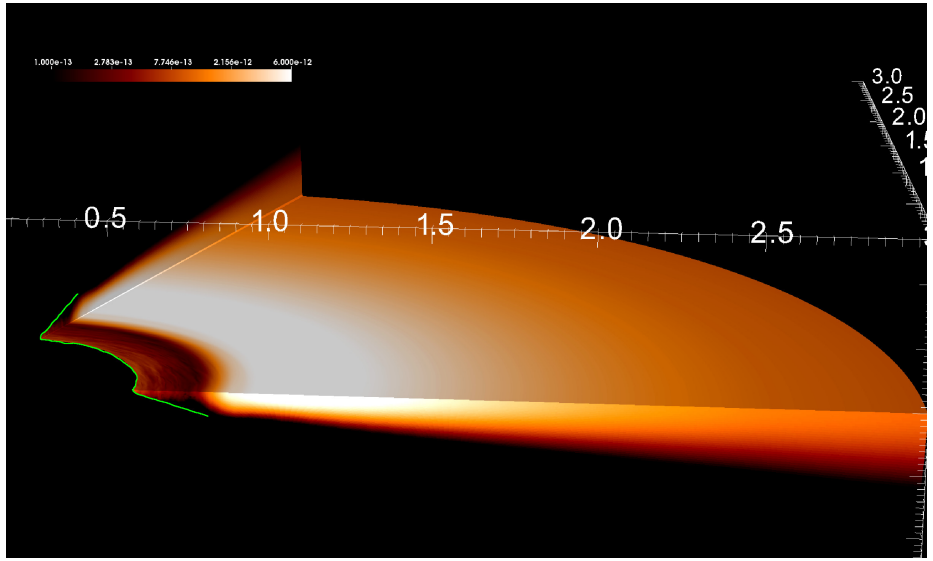
Interaction MHD turbulence vs. disk winds (coll. **H.Méheut**)

Observational constraints – PP disk inner parts (coll. **M.Flock**)

Global disk simulations with RAMSES (using the AMR technique)

3D simulations of PP disk inner parts (using radiative MHD simulations)





Merci de votre attention…