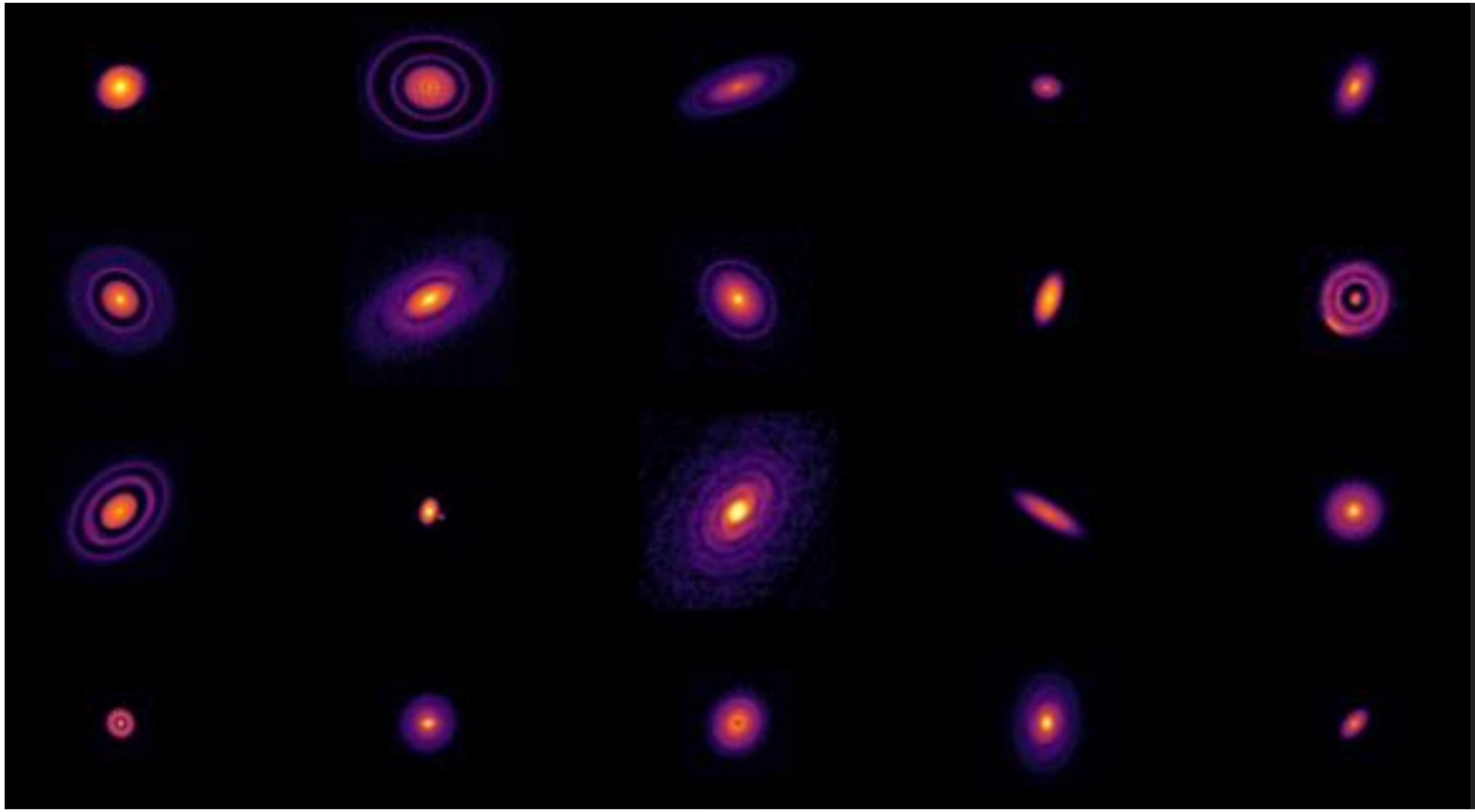
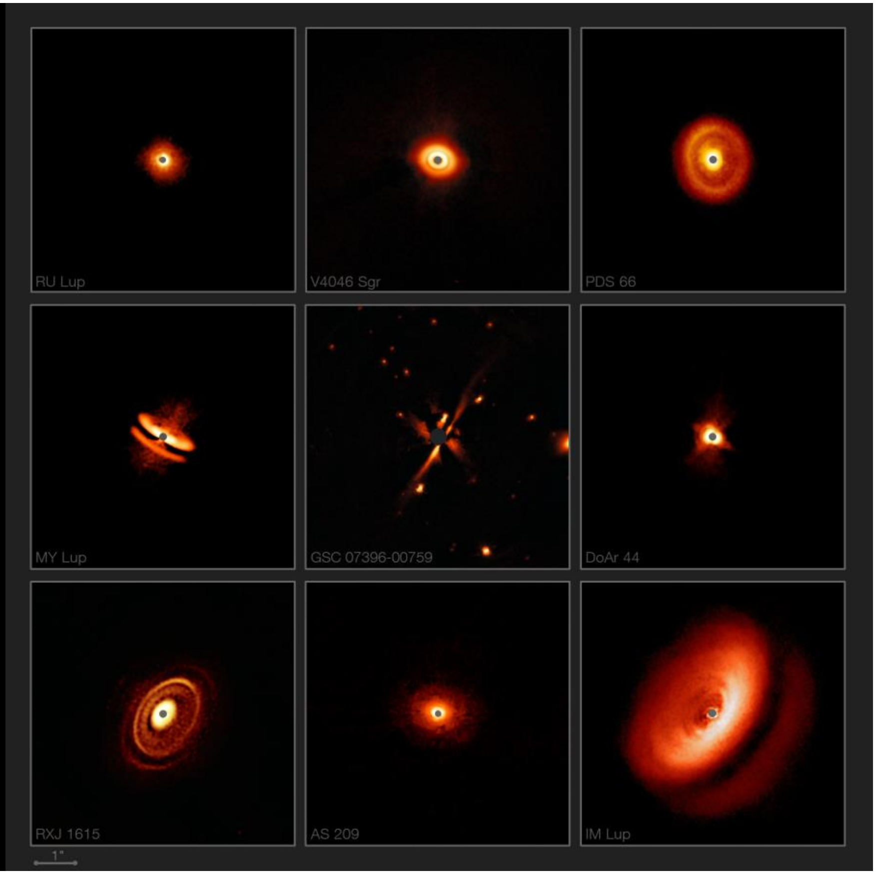
Dust dynamics in the inner regions of protoplanetary disks



ALMA / ESO / NAOJ / NRAO / S. Andrews et al / AUI / NSF / S. Dagnello.



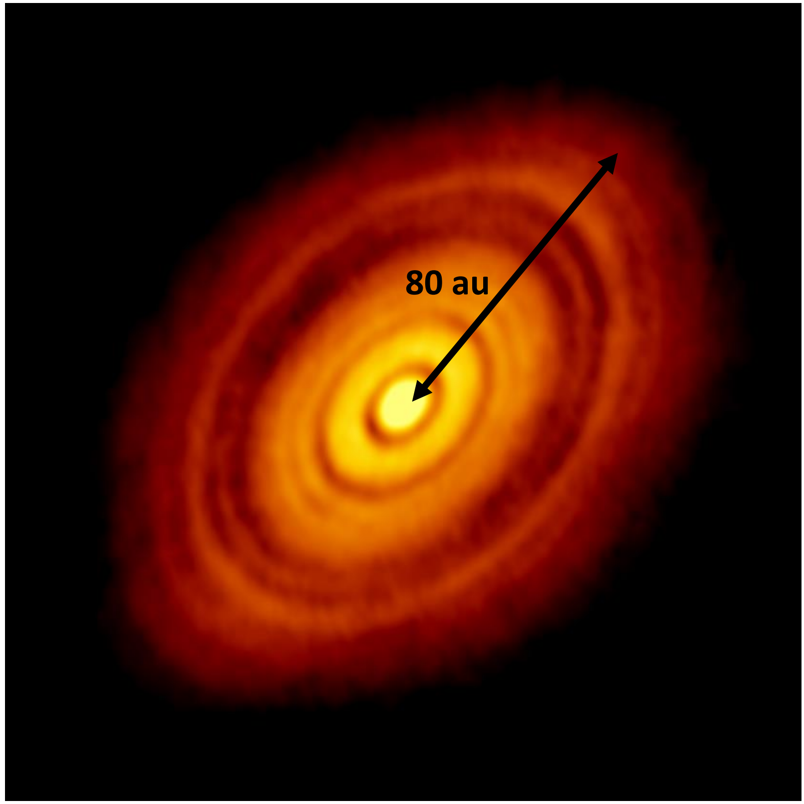
ESO/H. Avenhaus et al./E. Sissa et al./DARTT-S and SHINE collaborations

UNIVERSITY OF CAMBRIDGE

Thomas Jannaud, *Henrik Latter, Matthew Roberts*

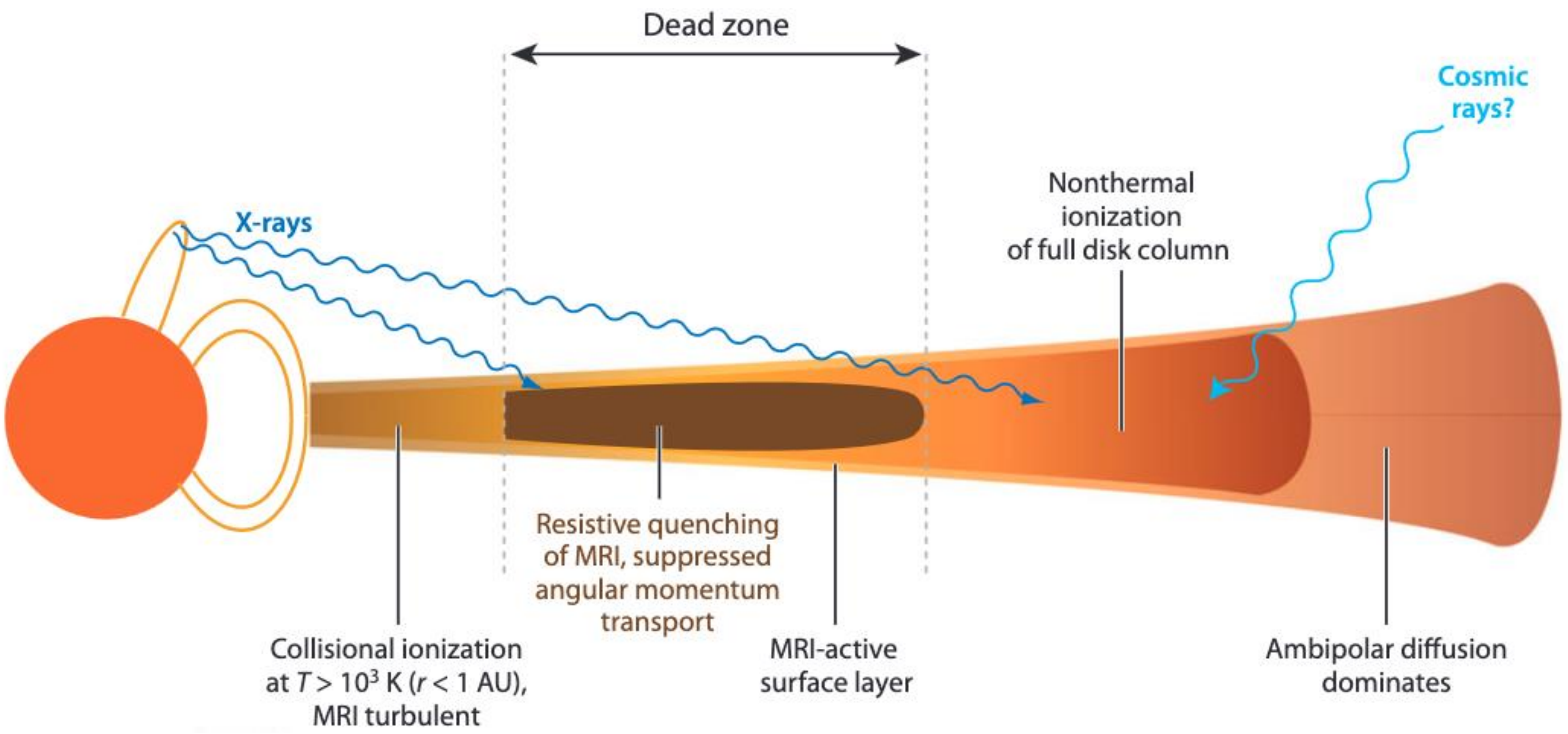
UKI Discs

Inner regions

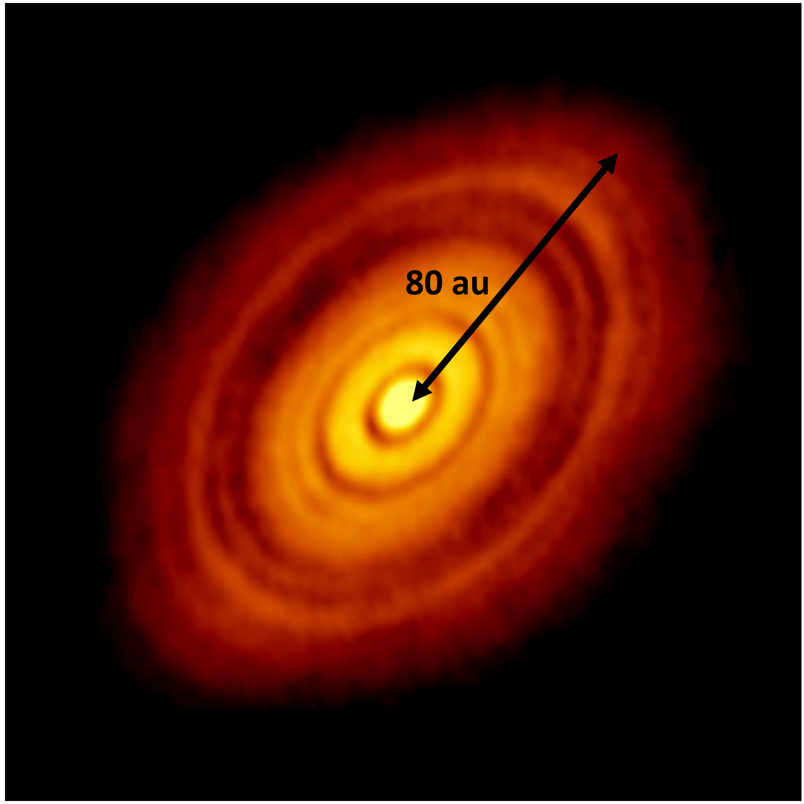


ALMA+(2014)

Inner regions

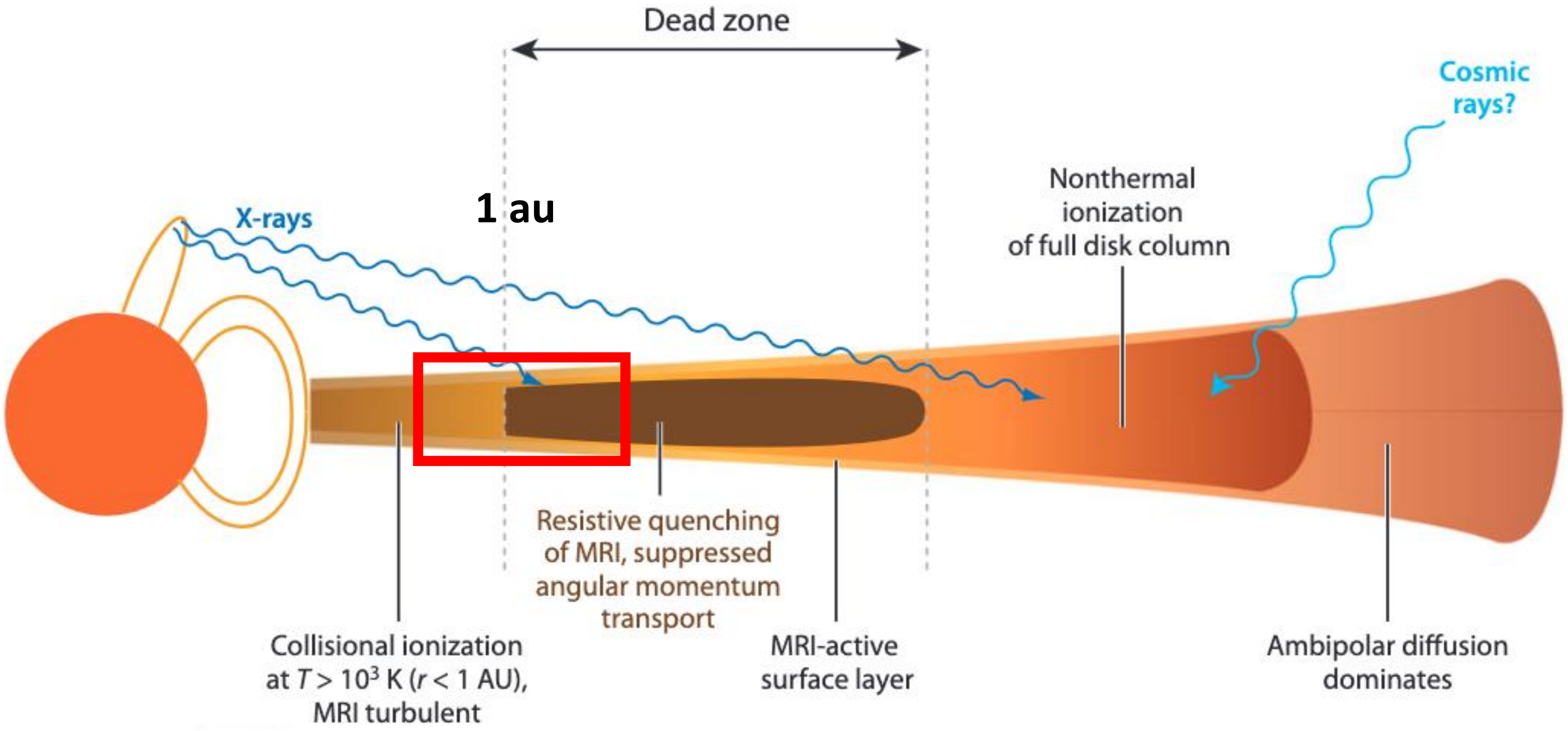


Adapted from Armitage(2011)

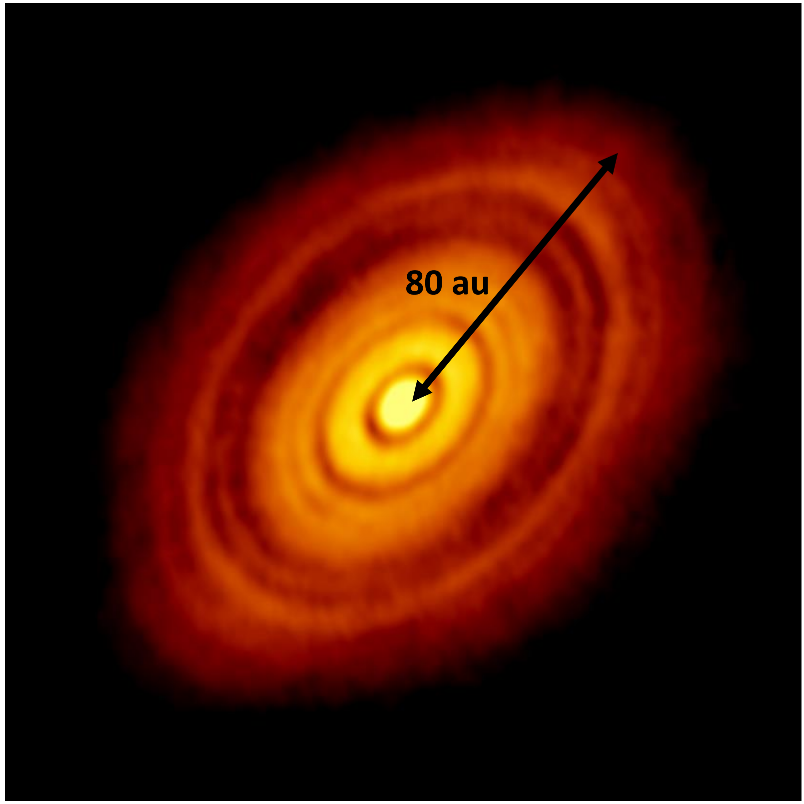


ALMA+(2014)

Inner regions



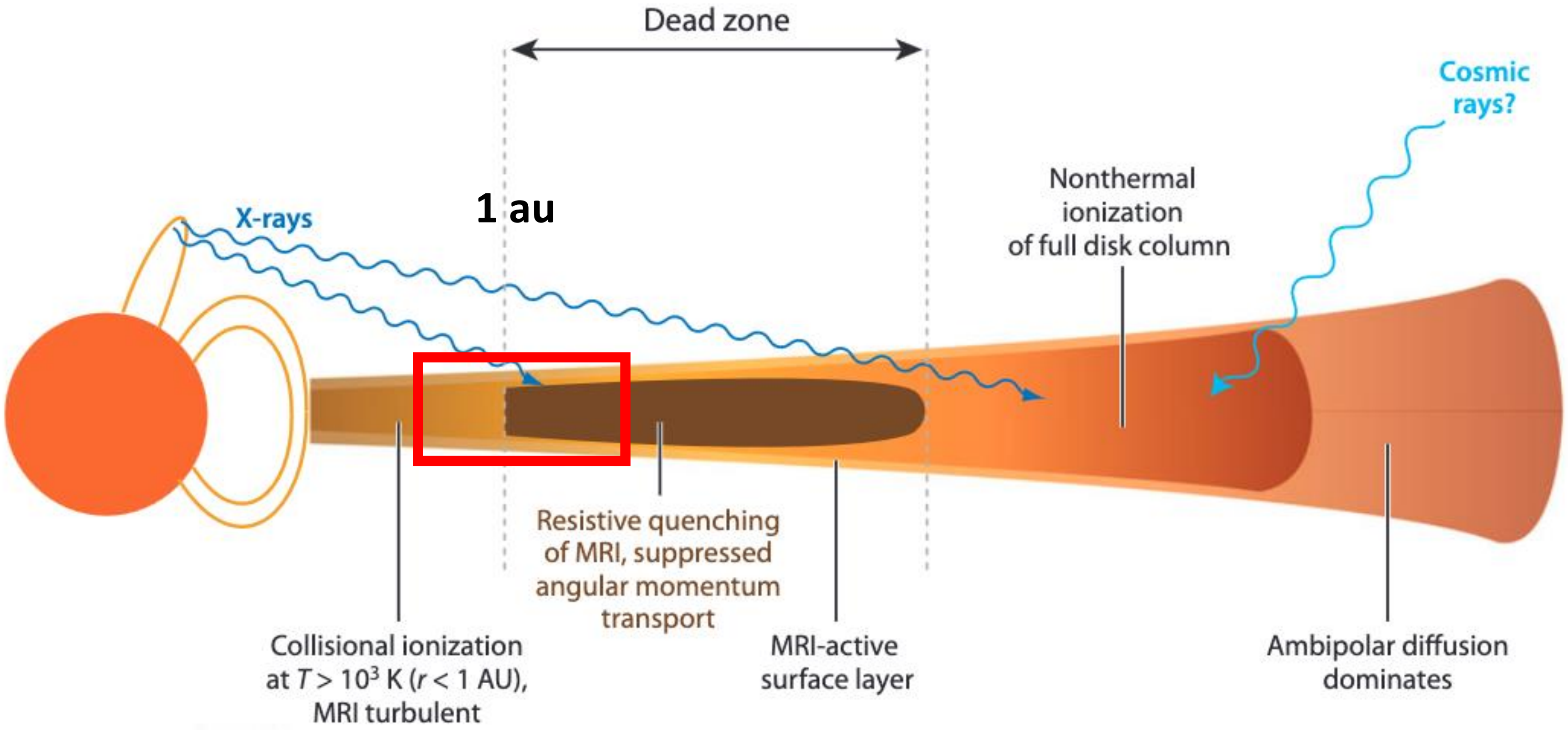
Adapted from Armitage(2011)



ALMA+(2014)

Ideal MHD

$$\frac{\partial \vec{B}}{\partial t} = \vec{\nabla}[\vec{v} x \vec{B}]$$

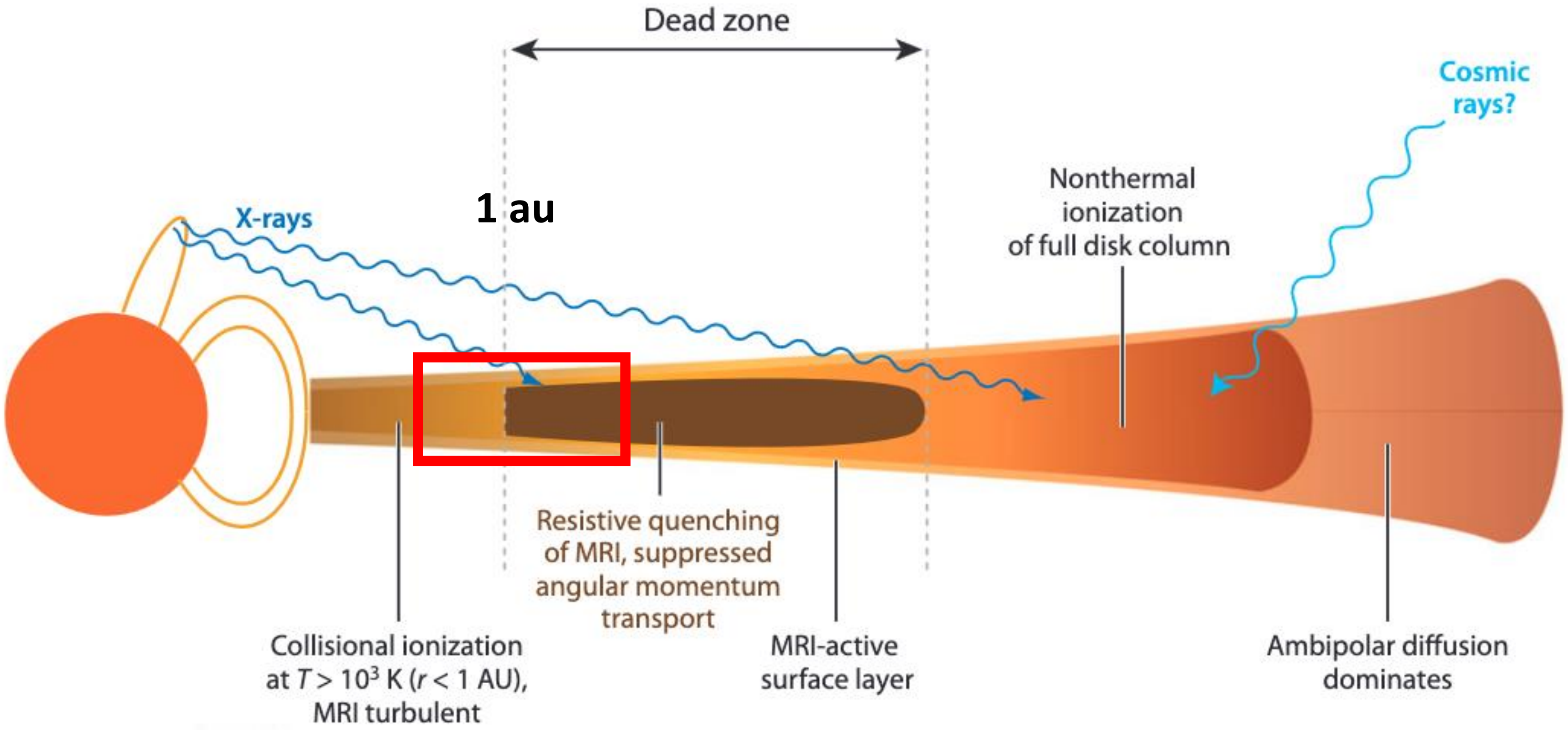


Adapted from Armitage(2011)

Non-ideal MHD

$$\frac{\partial \vec{B}}{\partial t} = \vec{\nabla}\left[\vec{v}x\vec{B} + \eta_O \vec{\nabla}x\vec{B} - \eta_H \frac{\vec{J}x\vec{B}}{B} + \eta_A \frac{(\vec{J}x\vec{B})x\vec{B}}{B^2}\right]$$

Ohmic diffusion | Hall effect | Ambipolar diffusion

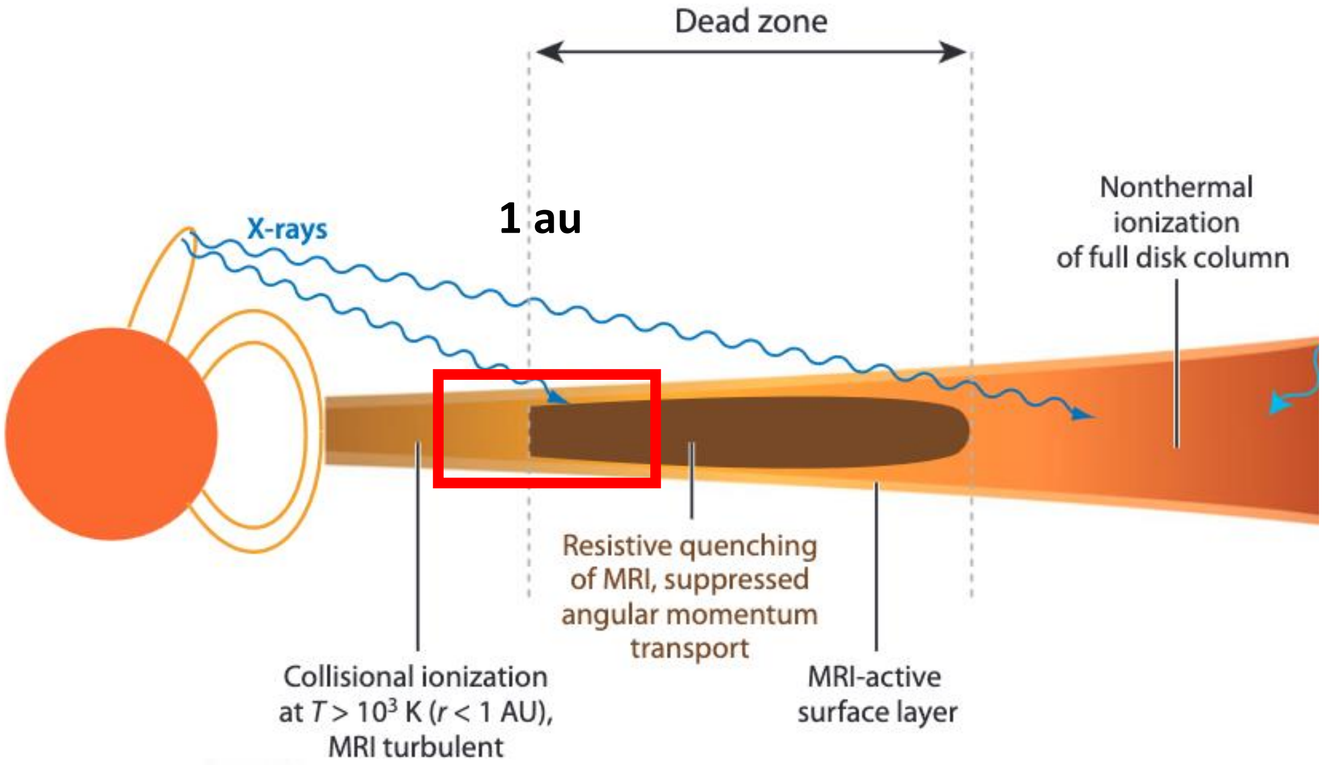


Adapted from Armitage(2011)

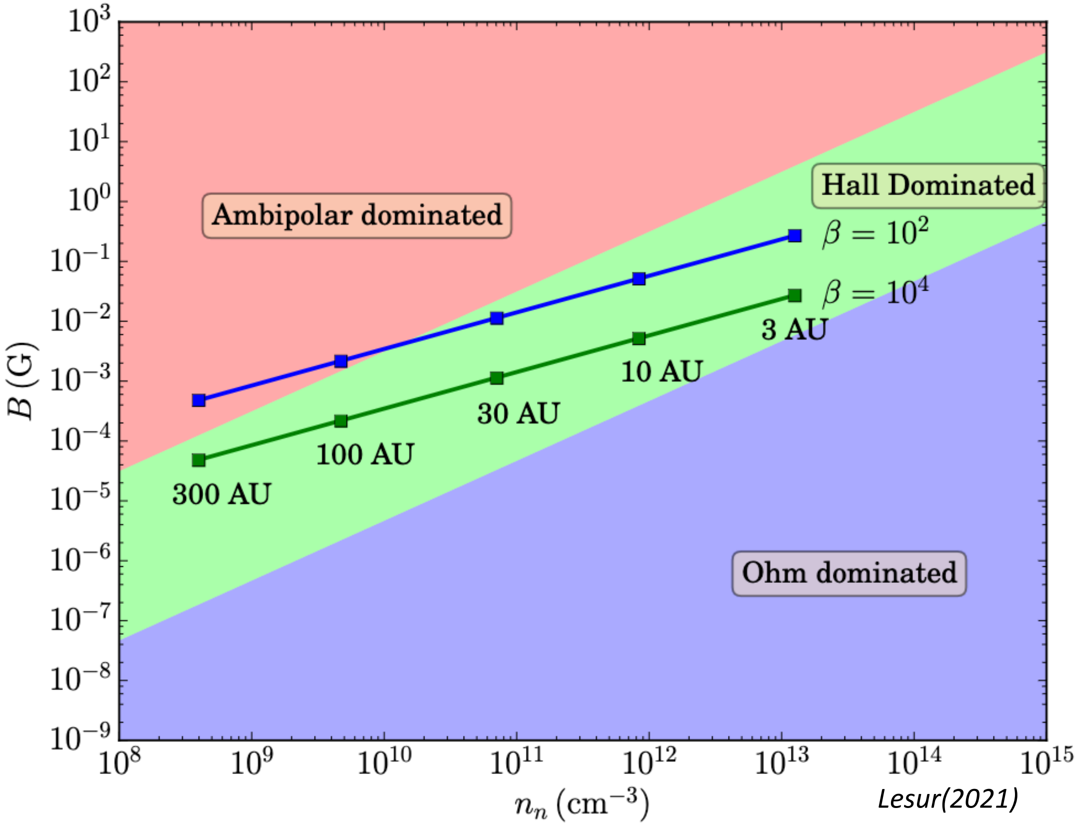
Non-ideal MHD

$$\frac{\partial \vec{B}}{\partial t} = \vec{\nabla}\left[\vec{v}\times\vec{B} + \eta_O \vec{\nabla}\times\vec{B} - \eta_H \frac{\vec{J}\times\vec{B}}{B} + \eta_A \frac{(\vec{J}\times\vec{B})\times\vec{B}}{B^2}\right]$$

Ohmic diffusion — Hall effect — Ambipolar diffusion



Adapted from Armitage(2011)



Lesur(2021)

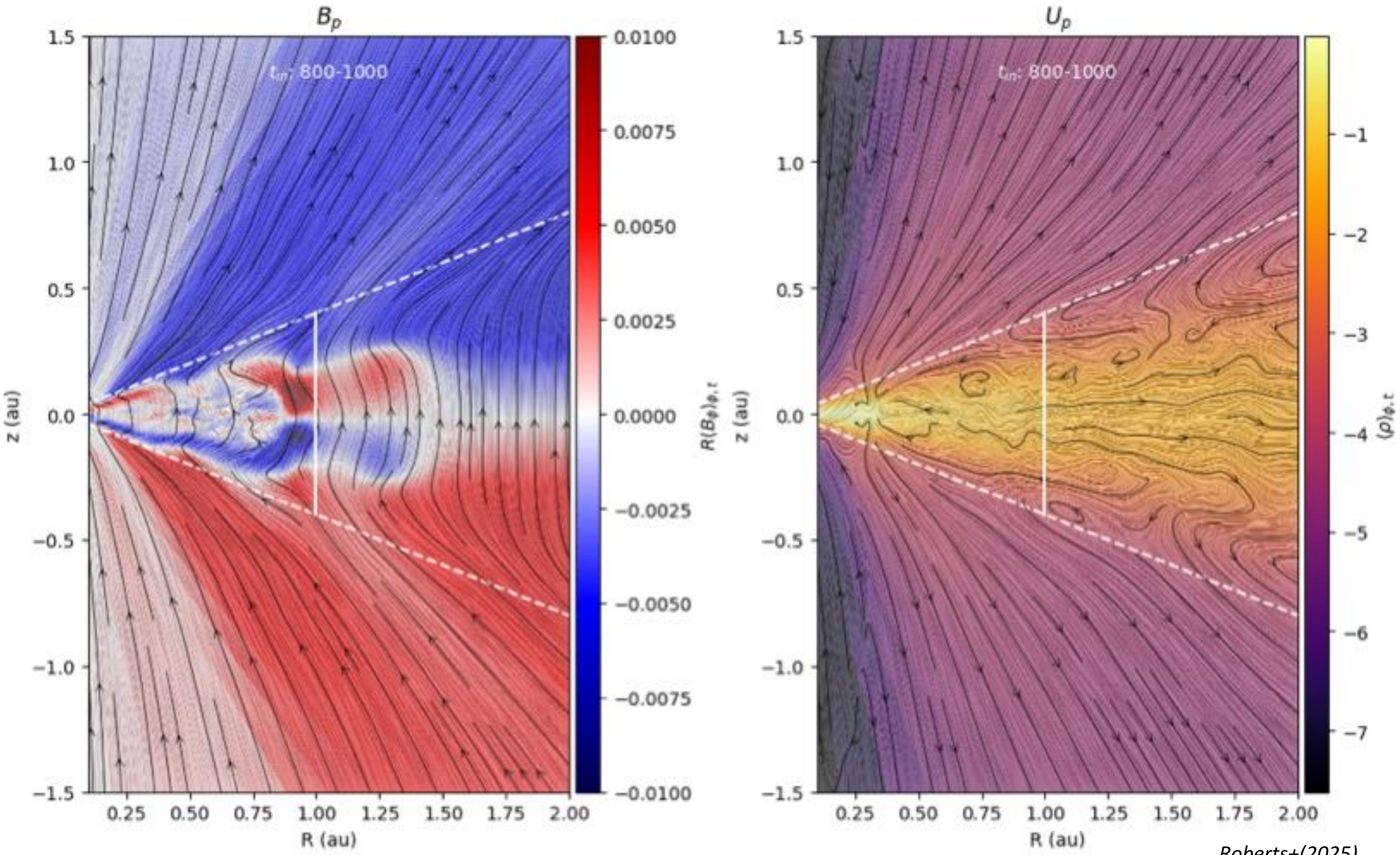
Non-ideal MHD

Matthew Roberts

- Full 3D global numerical simulations of a protoplanetary disk
- Centered around the dead/active zone interface
- Includes ohmic and ambipolar diffusion
- Performed on the GPU-accelerated Godunov code Idefix (Lesur+2023)

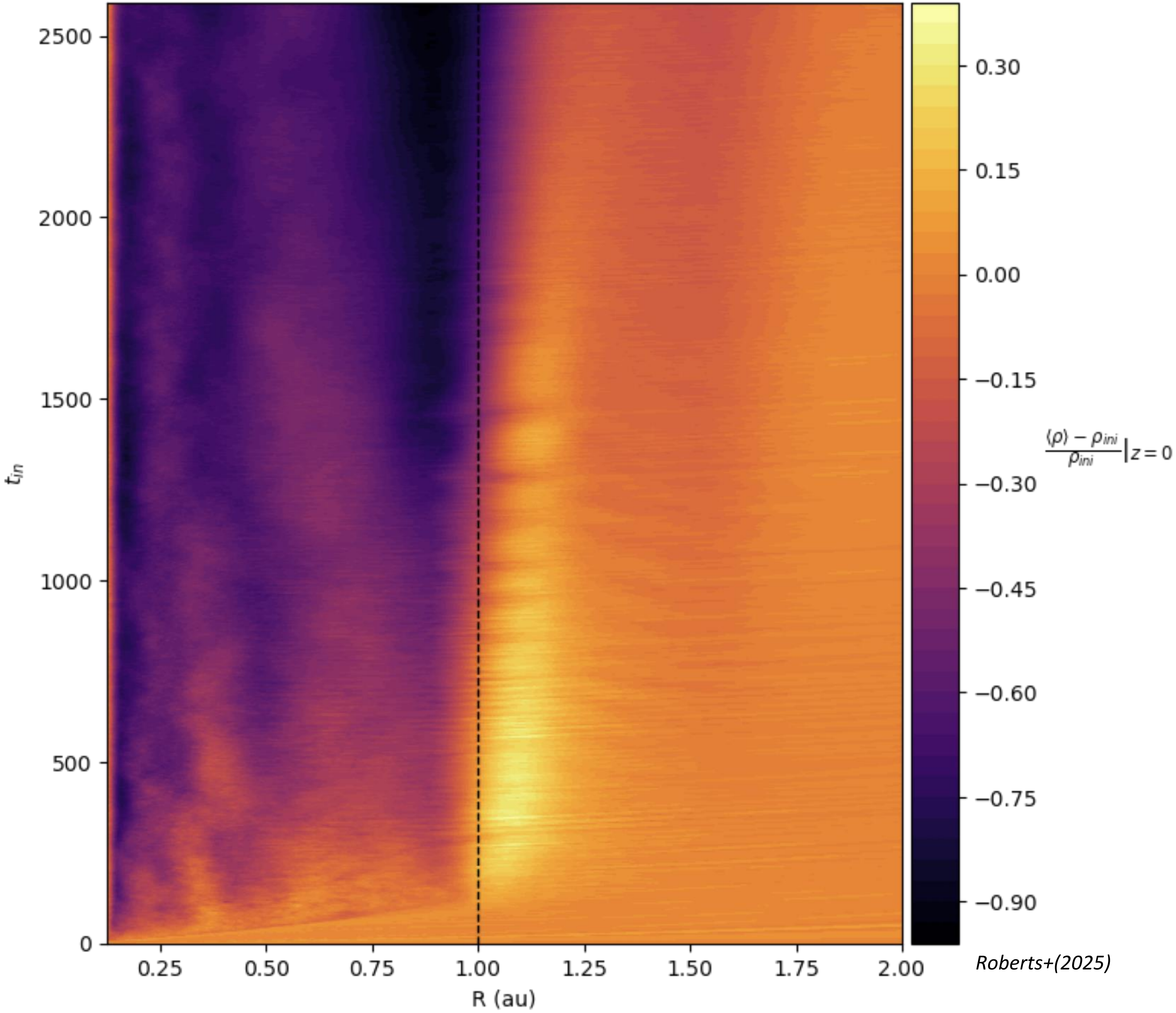
Non-ideal MHD

Matthew Roberts



Roberts+(2025)

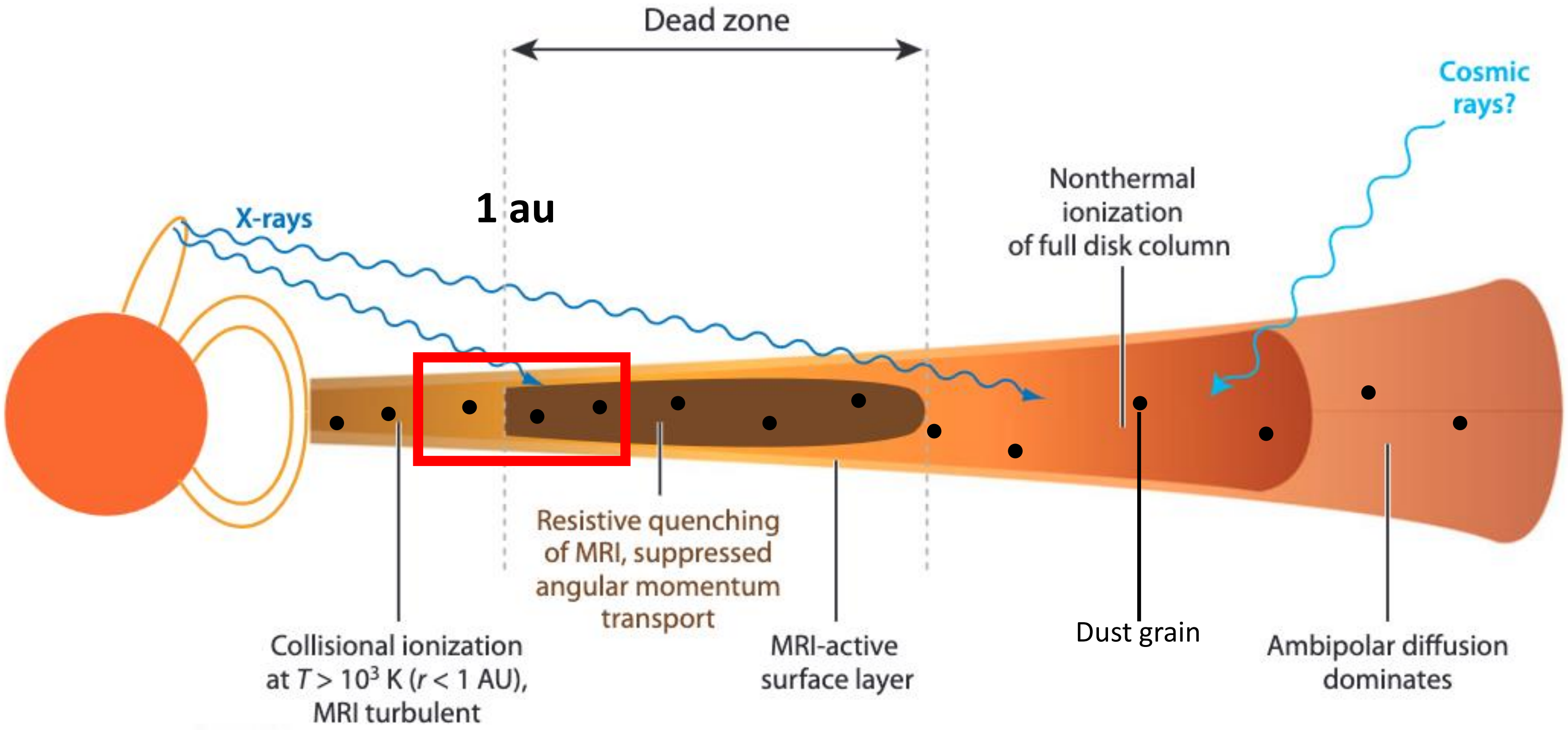
Matthew Roberts



Roberts+(2025)

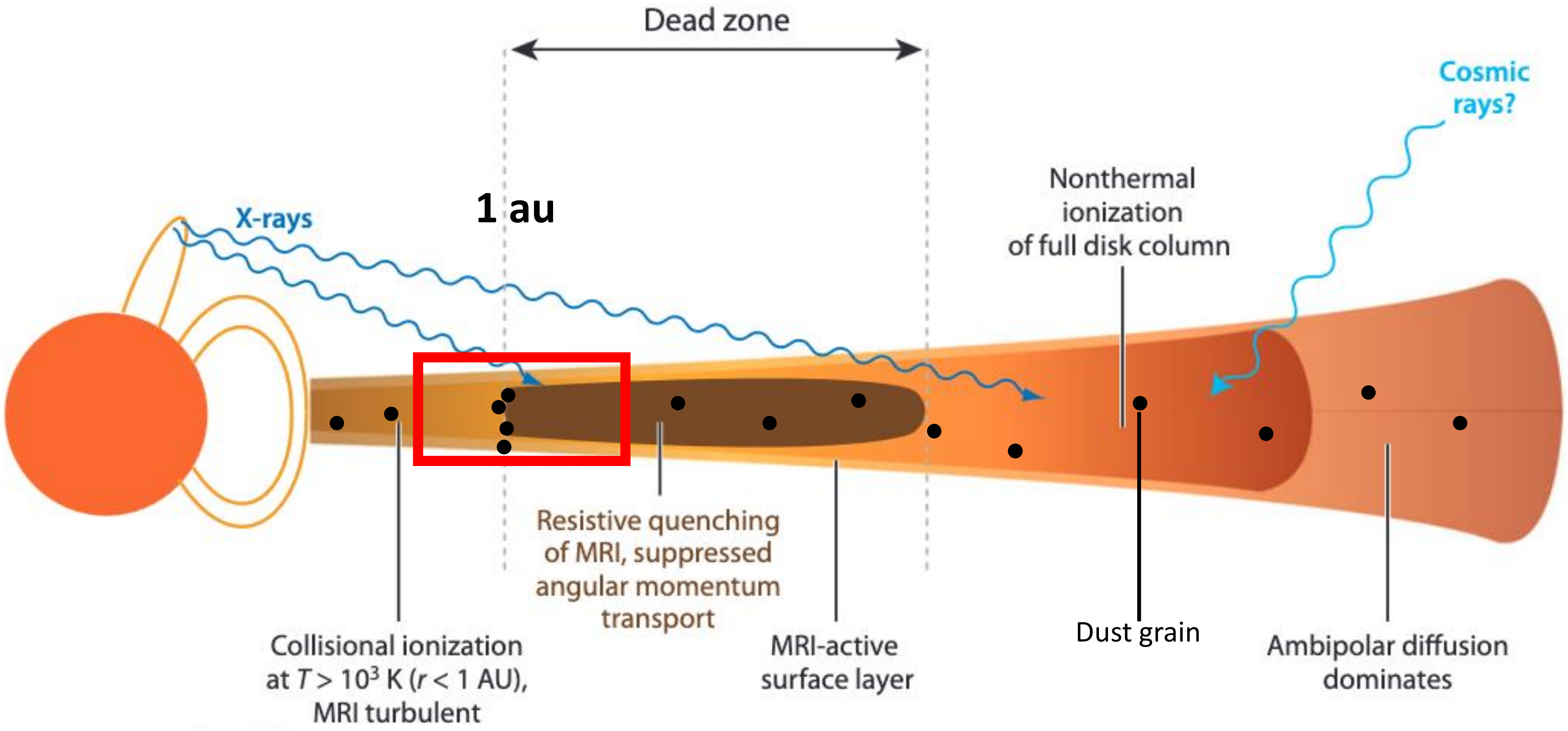
Planet formation via core-accretion

- Disks intially filled with sub-mm dust grains



Adapted from Armitage(2011)

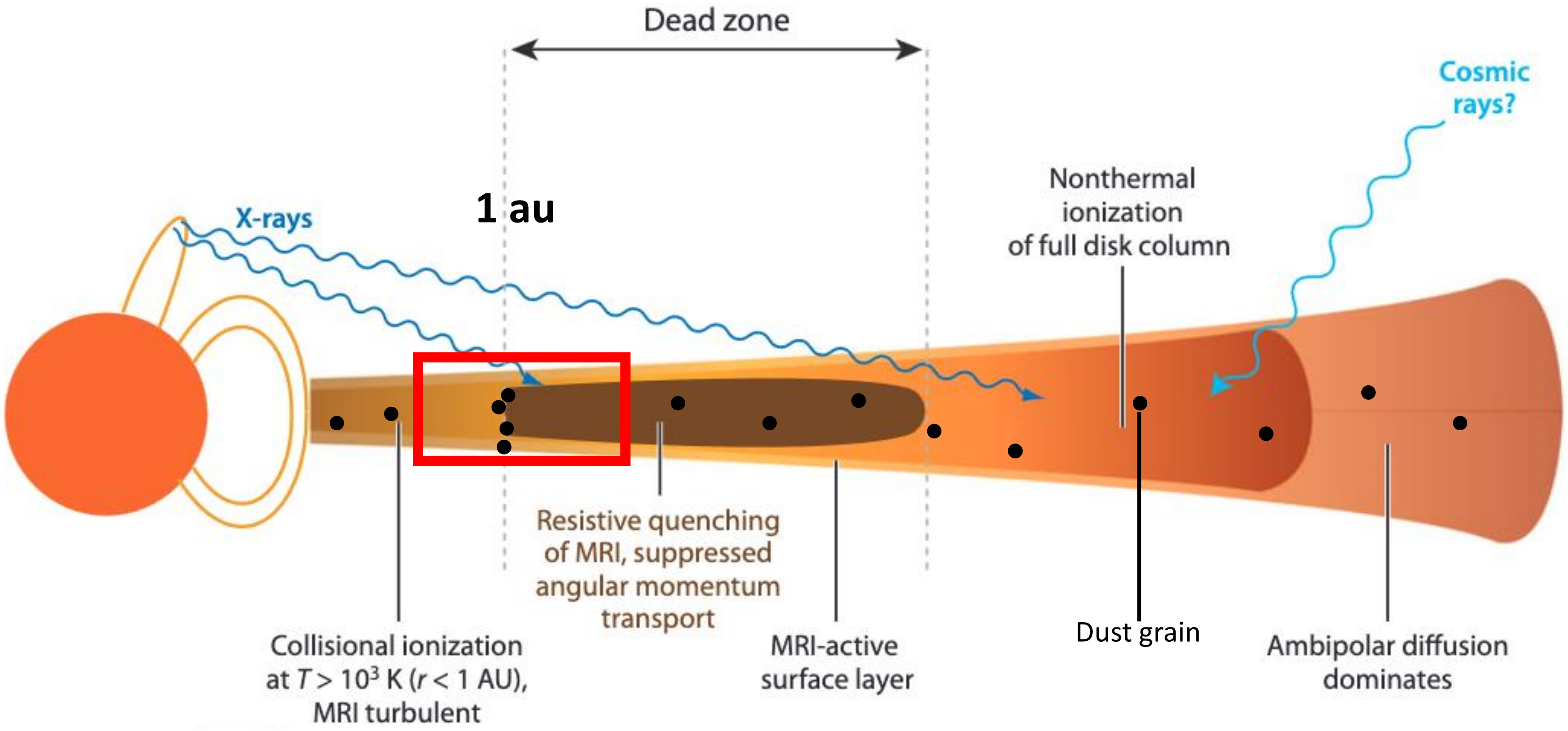
Planet formation via core-accretion



Adapted from Armitage(2011)

- Disks intially filled with sub-mm dust grains
- Dust accumulates at the inner/dead zone interface

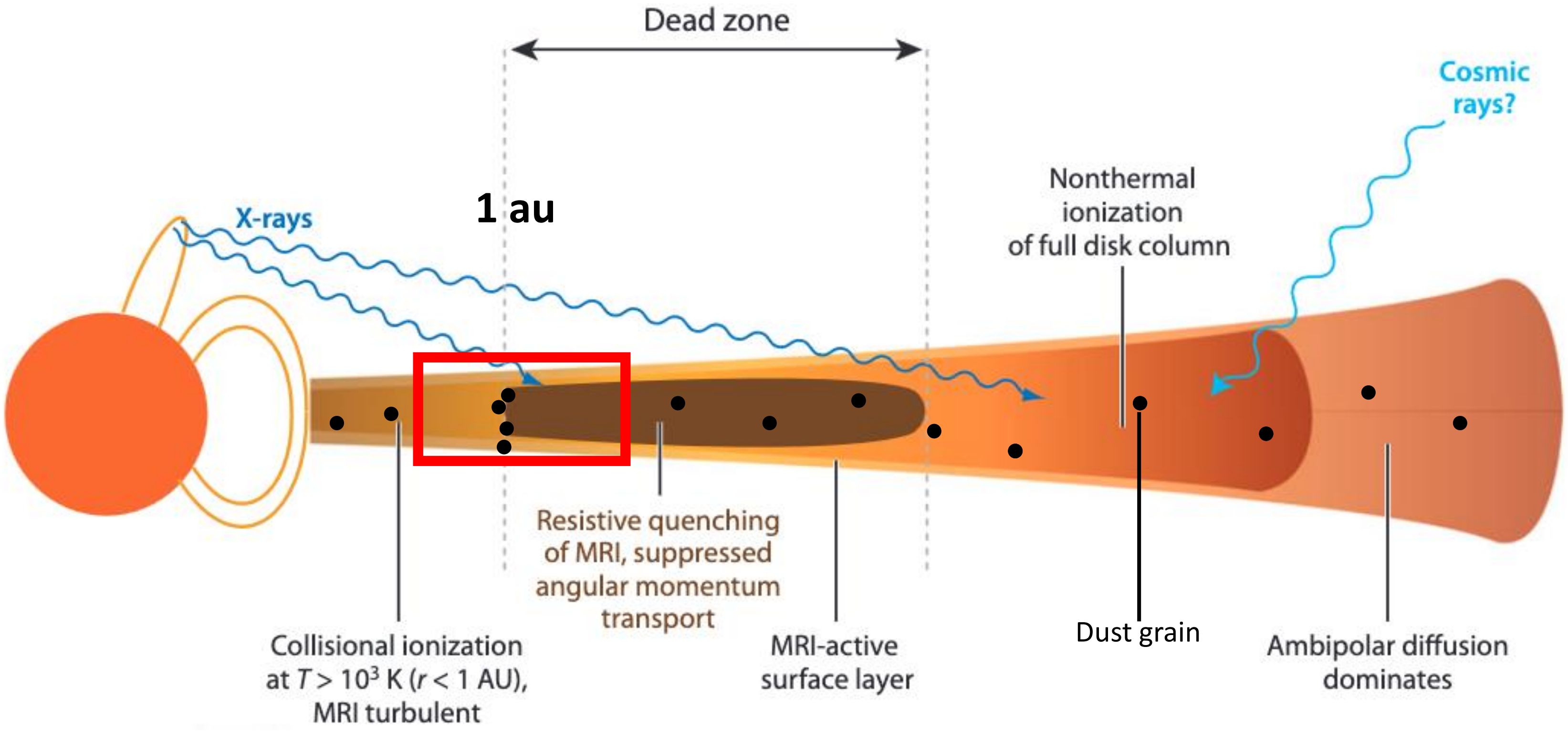
Planet formation via core-accretion



Adapted from Armitage(2011)

- Disks intially filled with sub-mm dust grains
- Dust accumulates at the inner/dead zone interface
- Agglomeration of the accumulated dust to form a planetesimal

Planet formation via core-accretion



Adapted from Armitage(2011)

- Disks intially filled with sub-mm dust grains
- Dust accumulates at the inner/dead zone interface
- Agglomeration of the accumulated dust to form a planetesimal
- Assembly of planetesimals to form planets

Simulations with dust as a pressure-less fluid

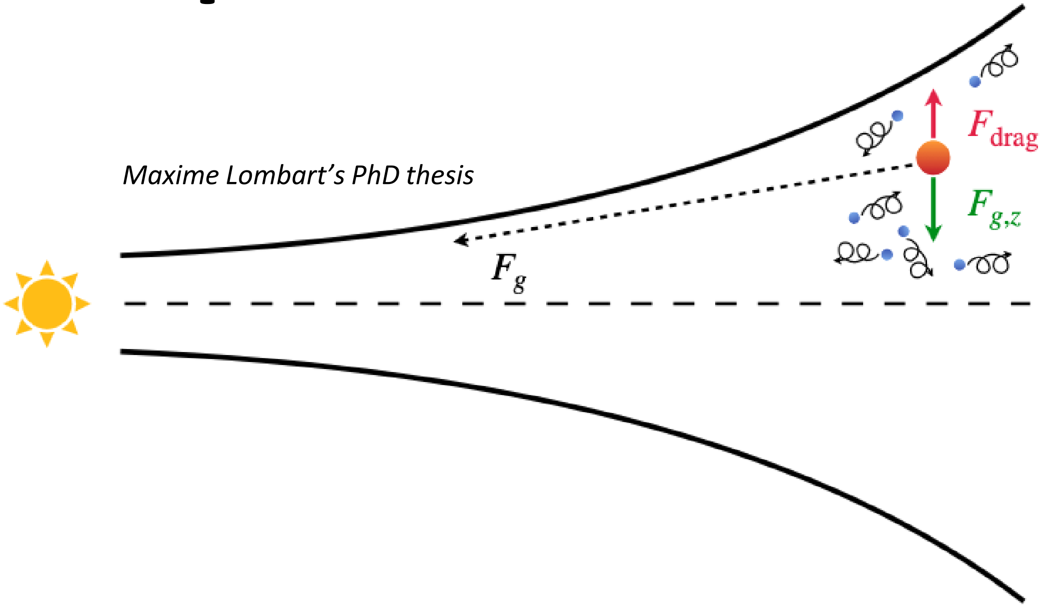
$$\frac{\partial(\rho_d)}{\partial t} + \vec{\nabla} \cdot (\rho_d \vec{v}_d) = 0$$

$$\frac{\partial(\rho_d \vec{v}_d)}{\partial t} + \vec{\nabla} \cdot (\rho_d \vec{v}_d \otimes \vec{v}_d) = \rho_d(\vec{g} + \vec{\gamma}_{g \to d})$$

Gravity

Gas drag

Maxime Lombart's PhD thesis

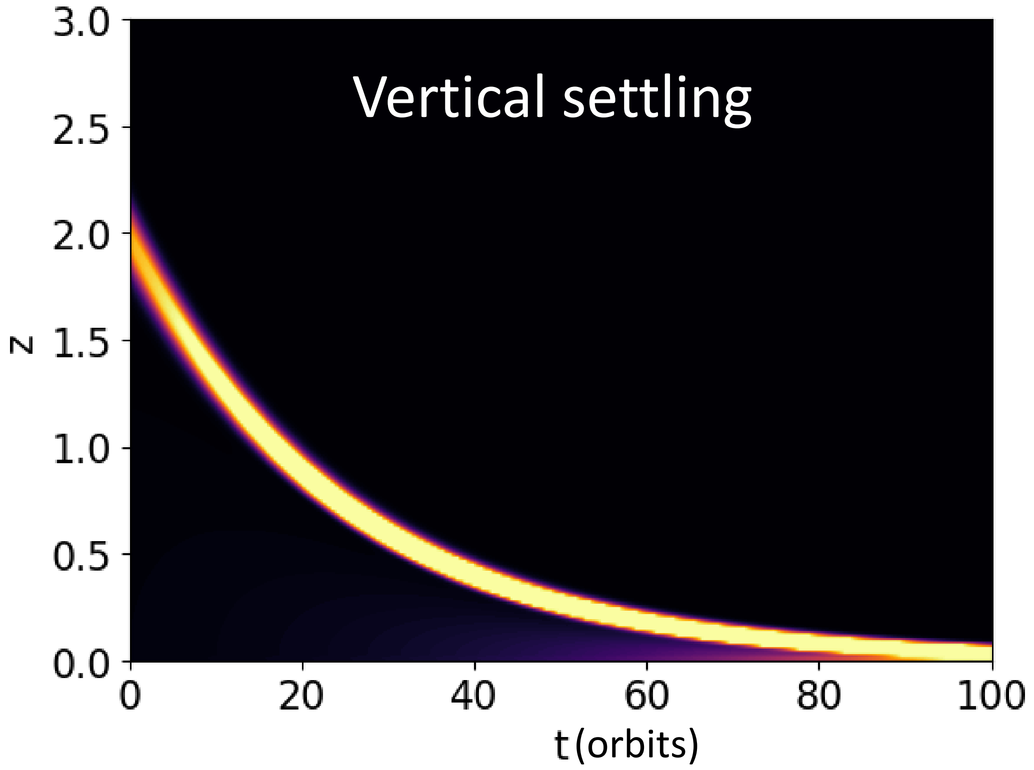


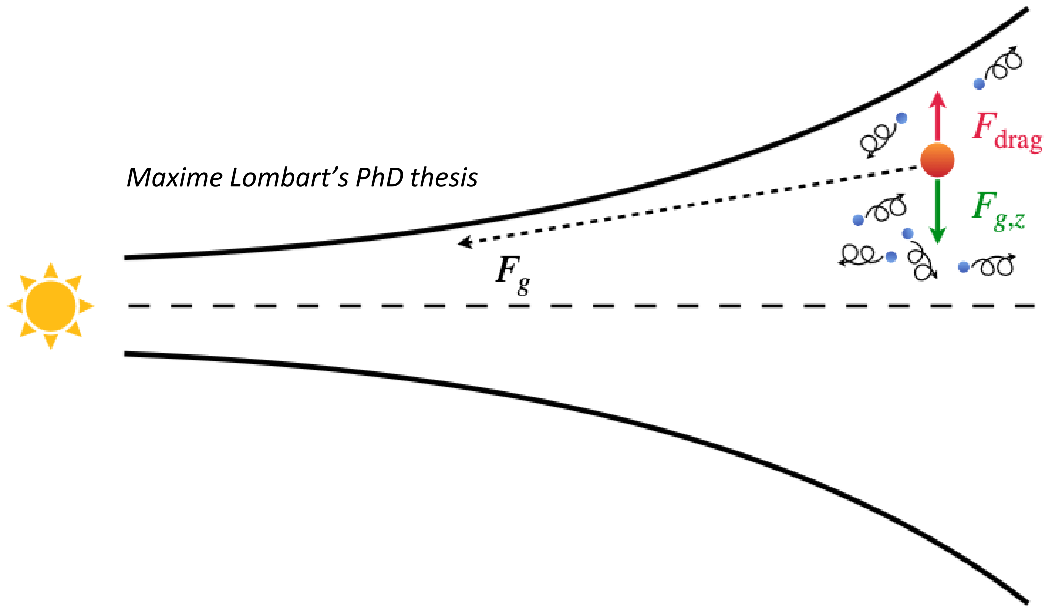
Tests: Inviscid disk

$$\frac{\partial(\rho_d)}{\partial t} + \vec{\nabla} \cdot (\rho_d \vec{v}_d) = 0$$

$$\frac{\partial(\rho_d \vec{v}_d)}{\partial t} + \vec{\nabla} \cdot (\rho_d \vec{v}_d \otimes \vec{v}_d) = \rho_d(\vec{g} + \vec{\gamma}_{g \to d})$$

Gravity ($\vec{g}$)   Gas drag ($\vec{\gamma}_{g \to d}$)





Tests: Inviscid disk

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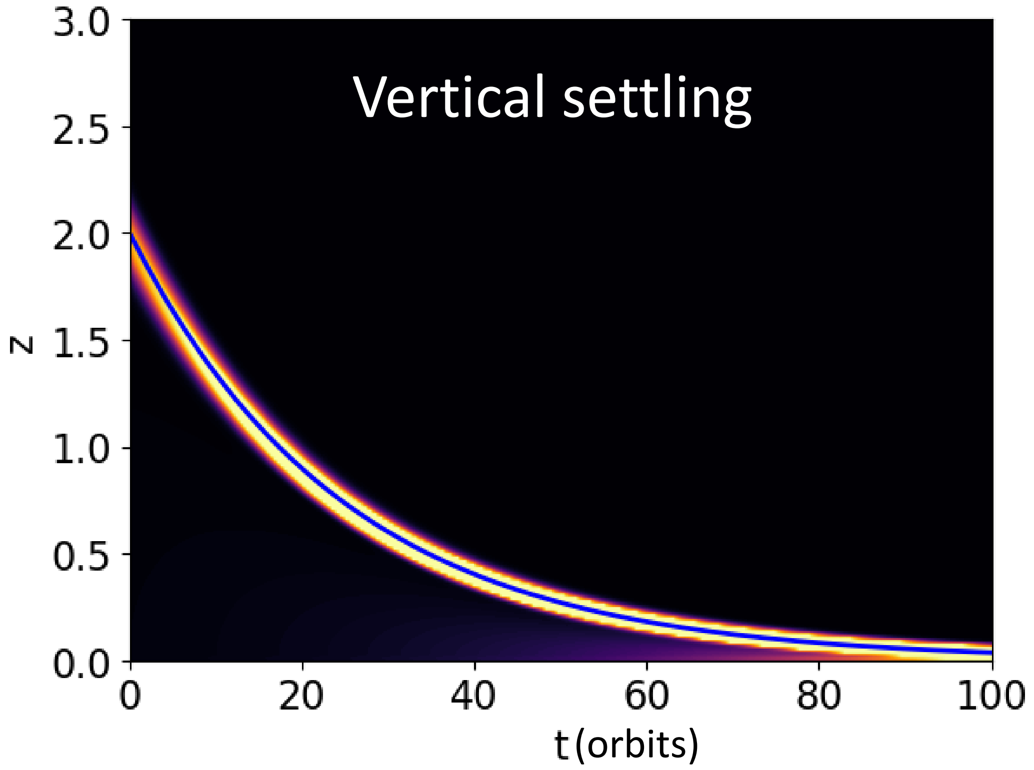
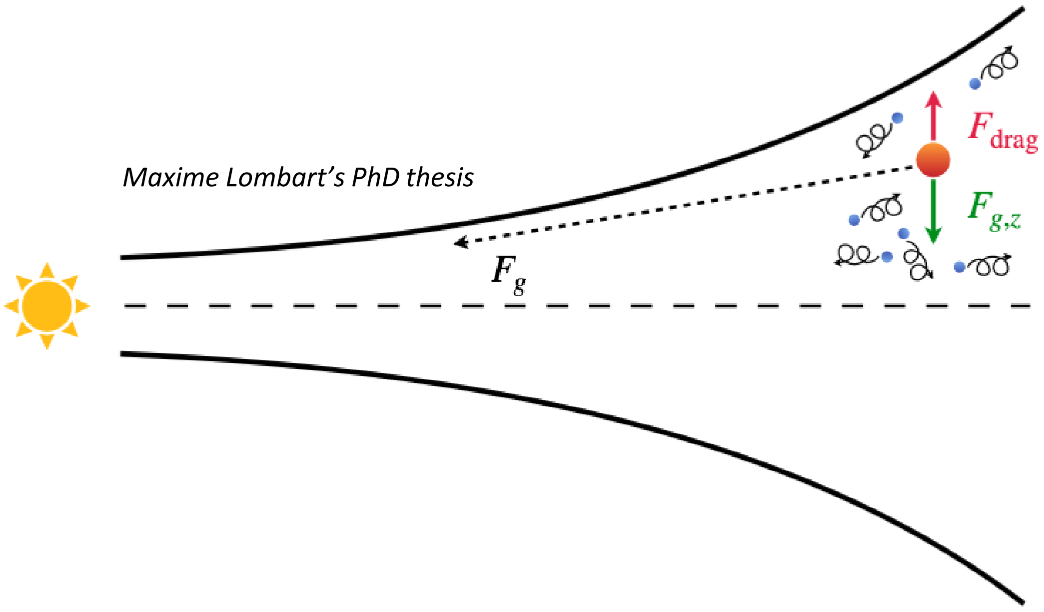
Gravity

Gas drag



Maxime Lombart's PhD thesis

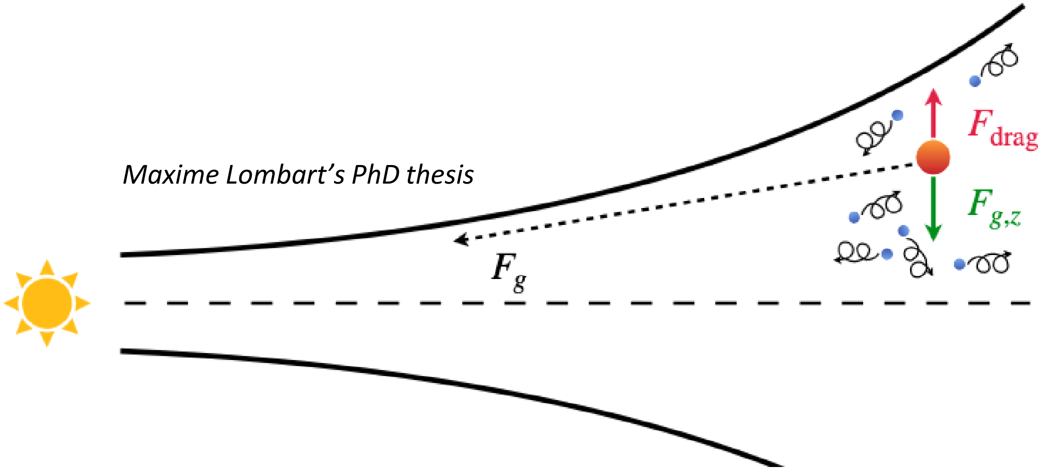


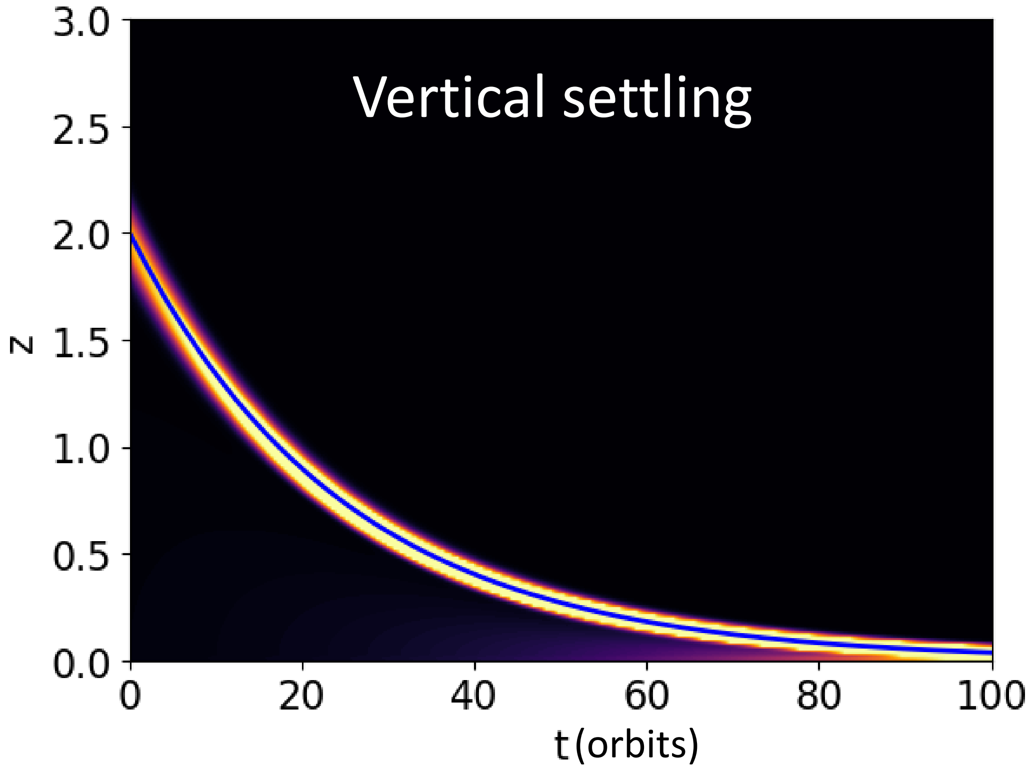
Tests: Inviscid disk

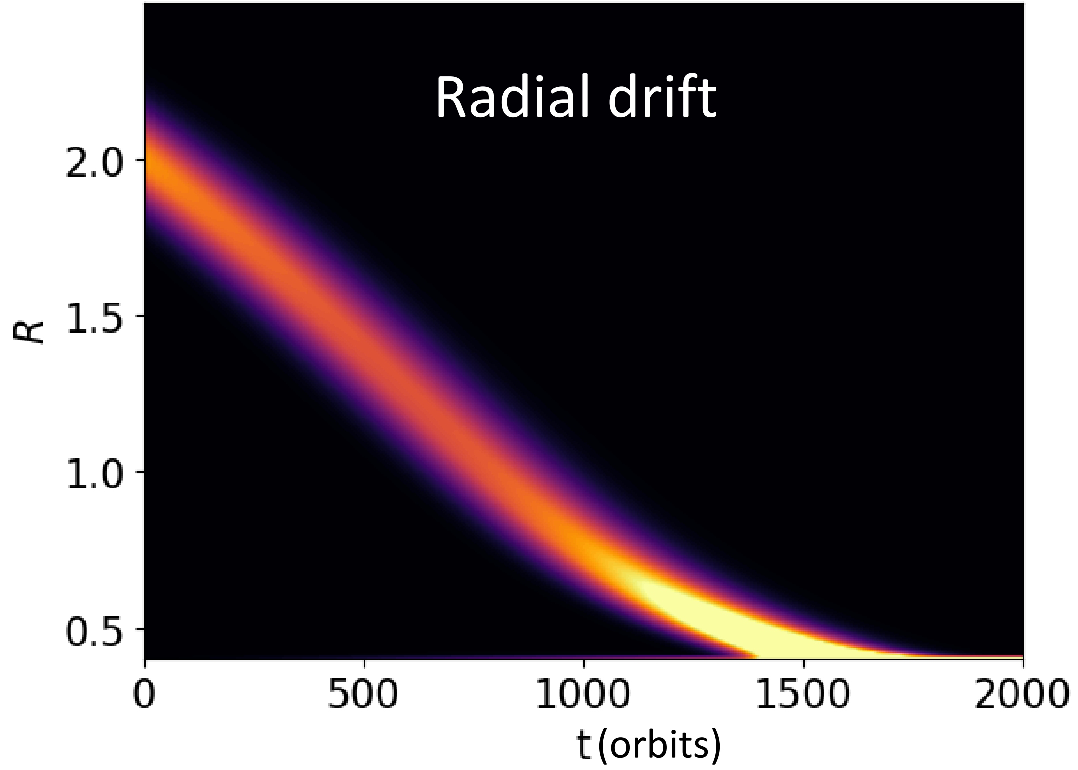
$$\frac{\partial(\rho_d)}{\partial t} + \vec{\nabla}\cdot(\rho_d \vec{v}_d) = 0$$

$$\frac{\partial(\rho_d \vec{v}_d)}{\partial t} + \vec{\nabla}\cdot(\rho_d \vec{v}_d \otimes \vec{v}_d) = \rho_d(\vec{g} + \vec{\gamma}_{g\to d})$$

Gravity   Gas drag







Tests: Inviscid disk

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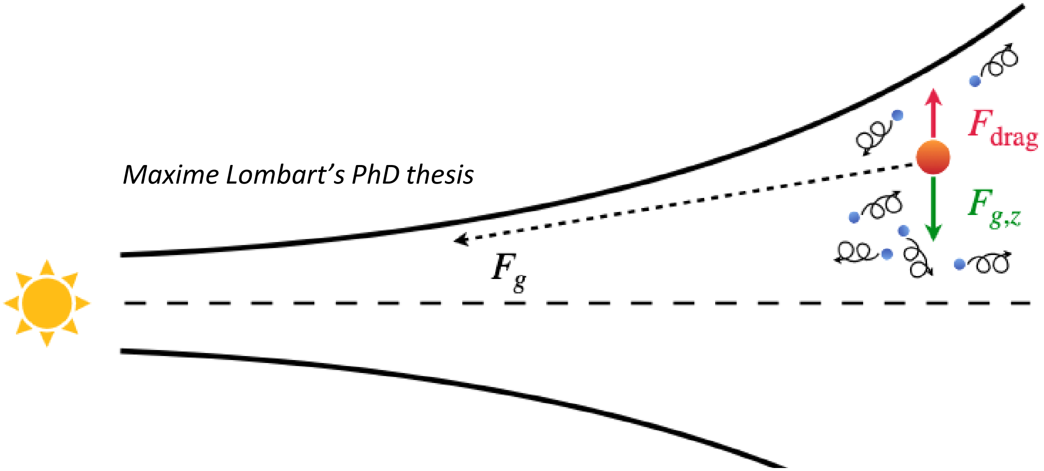
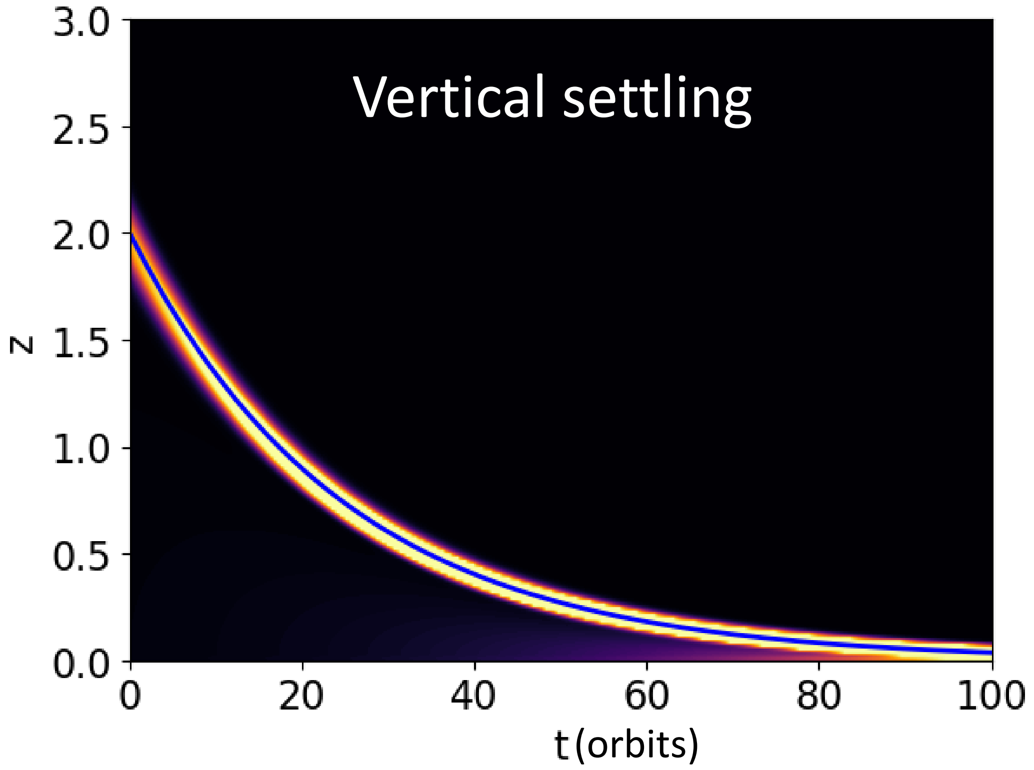
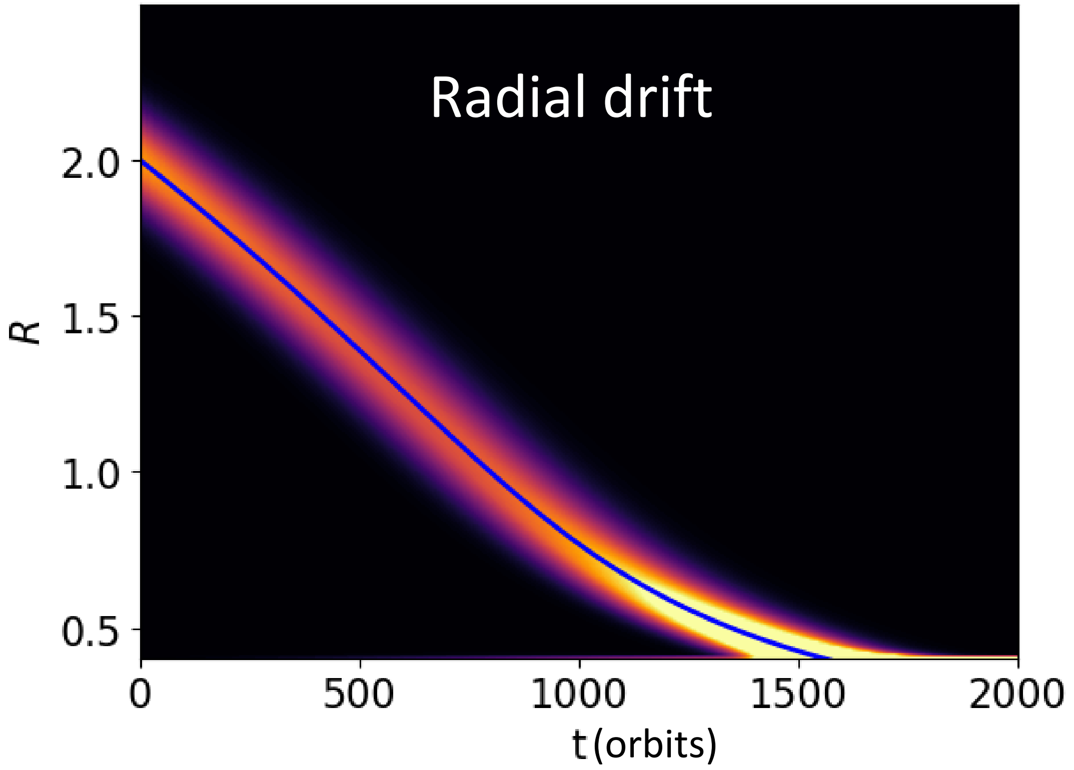
Gravity Gas drag

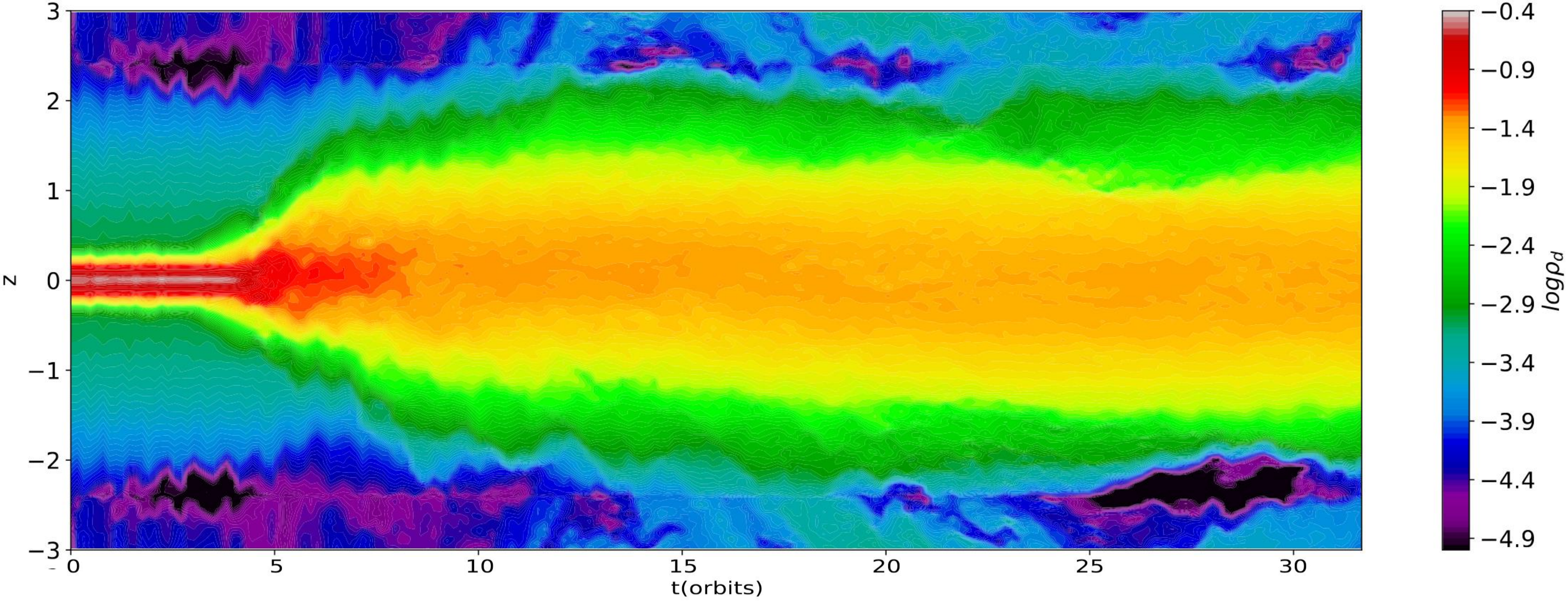
Maxime Lombart's PhD thesis





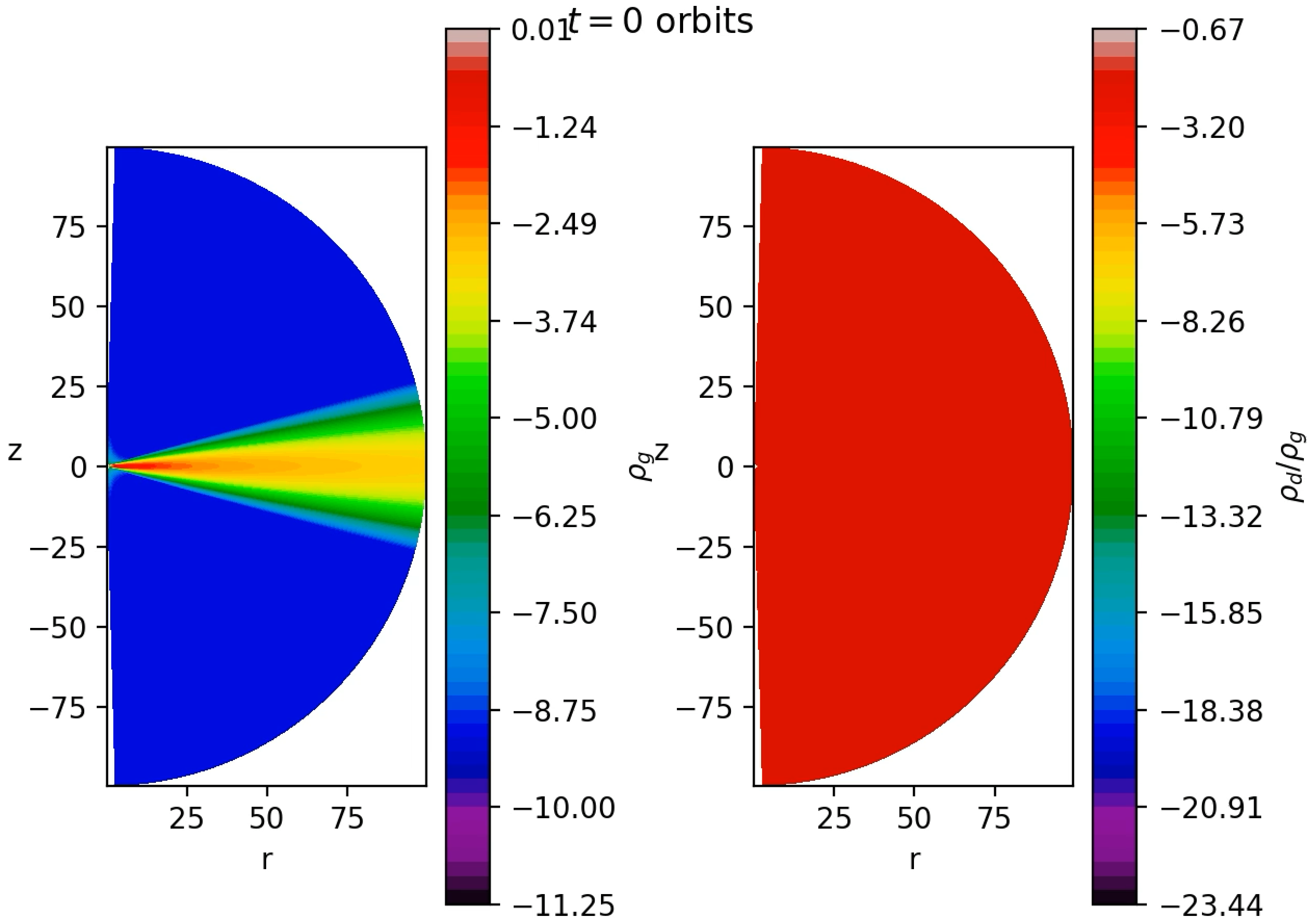


Tests: Turbulent disk (ideal MHD)



Successful comparisons to Fromang & Papaloizou(2006), Okuzumi & Hirose (2011), Zhu, Stone & Bai (2015)…

Tests: Turbulent disk (ambipolar diffusion)



Comparisons to Riols & Lesur (2020)