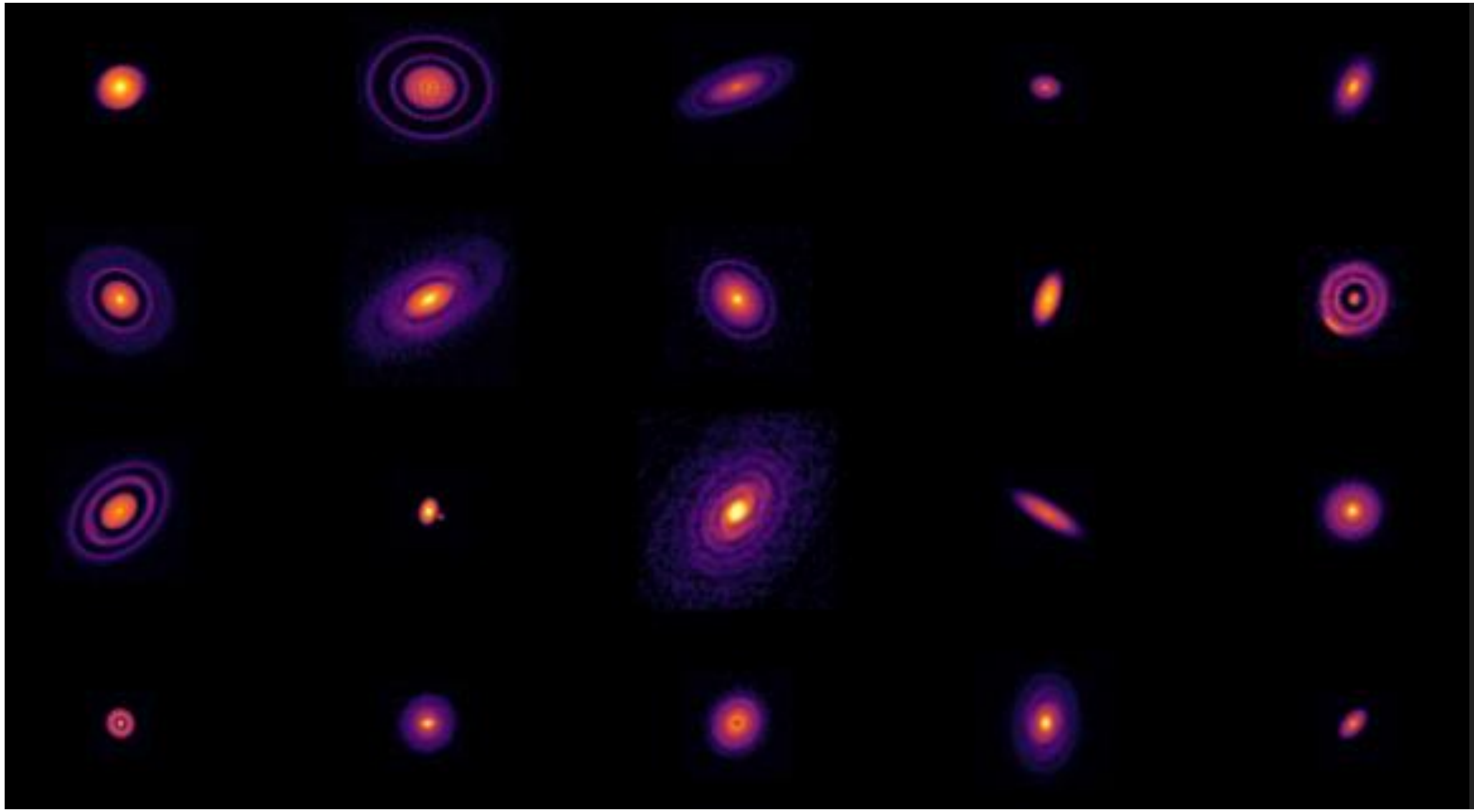
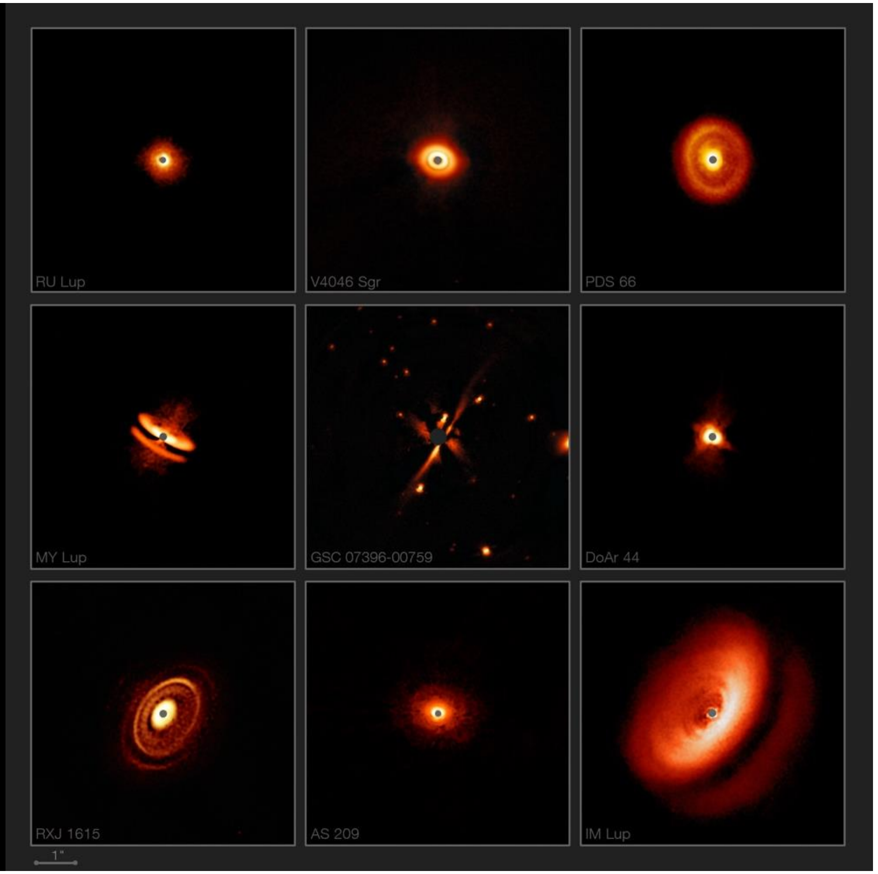
Magnetohydrodynamics and dust in the inner regions of protoplanetary disks



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



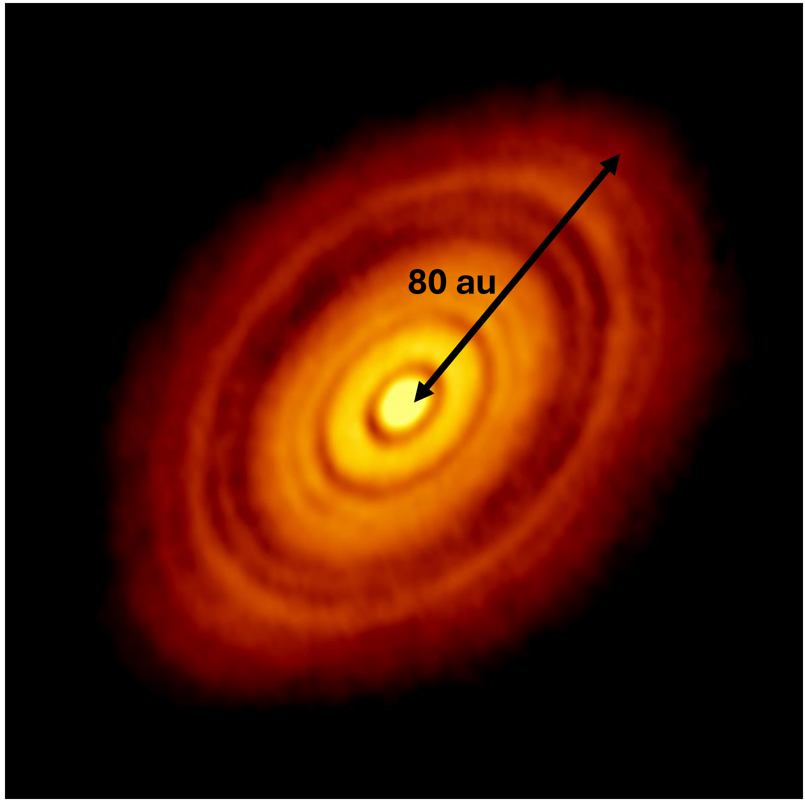
ESO/H. Avenhaus et al./E. Sissa et al./DARTT-S and SHINE collaborations.

UNIVERSITY OF CAMBRIDGE

Thomas Jannaud, *Henrik Latter, Matthew Roberts*

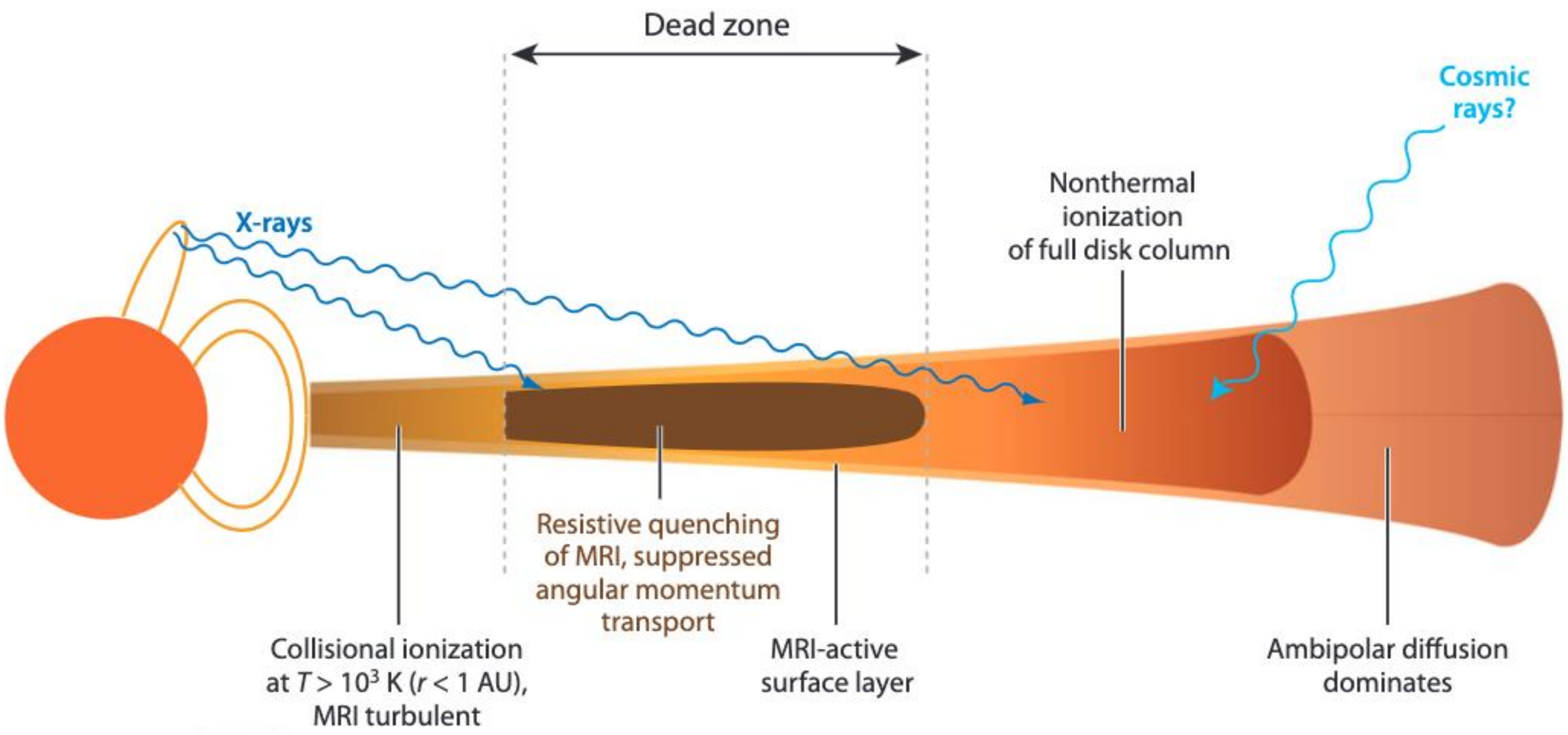
Idefix user days 2024

Inner regions

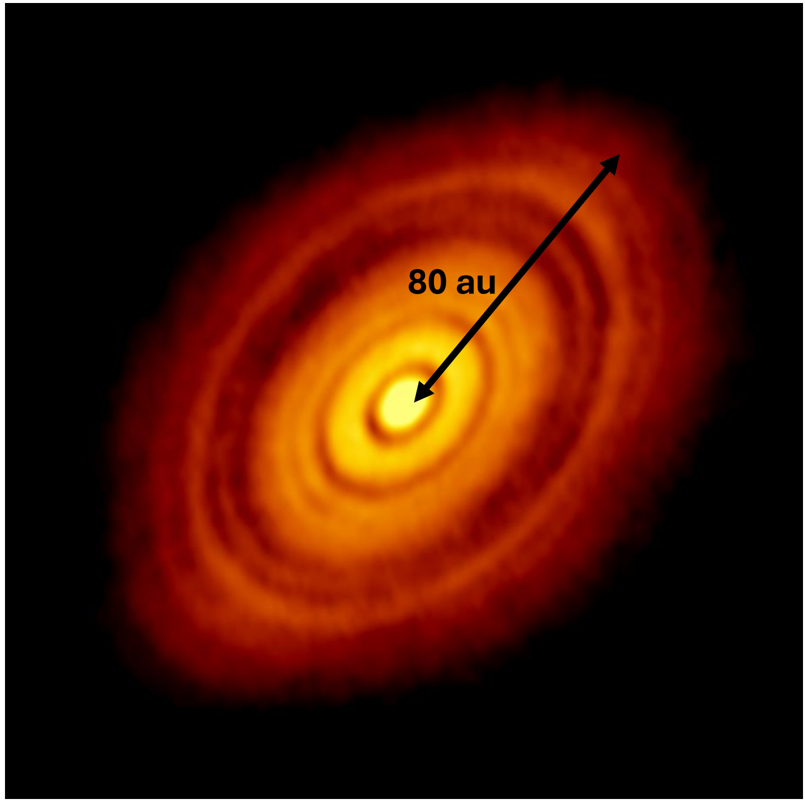


ALMA+(2014)

Inner regions



Adapted from Armitage(2011)



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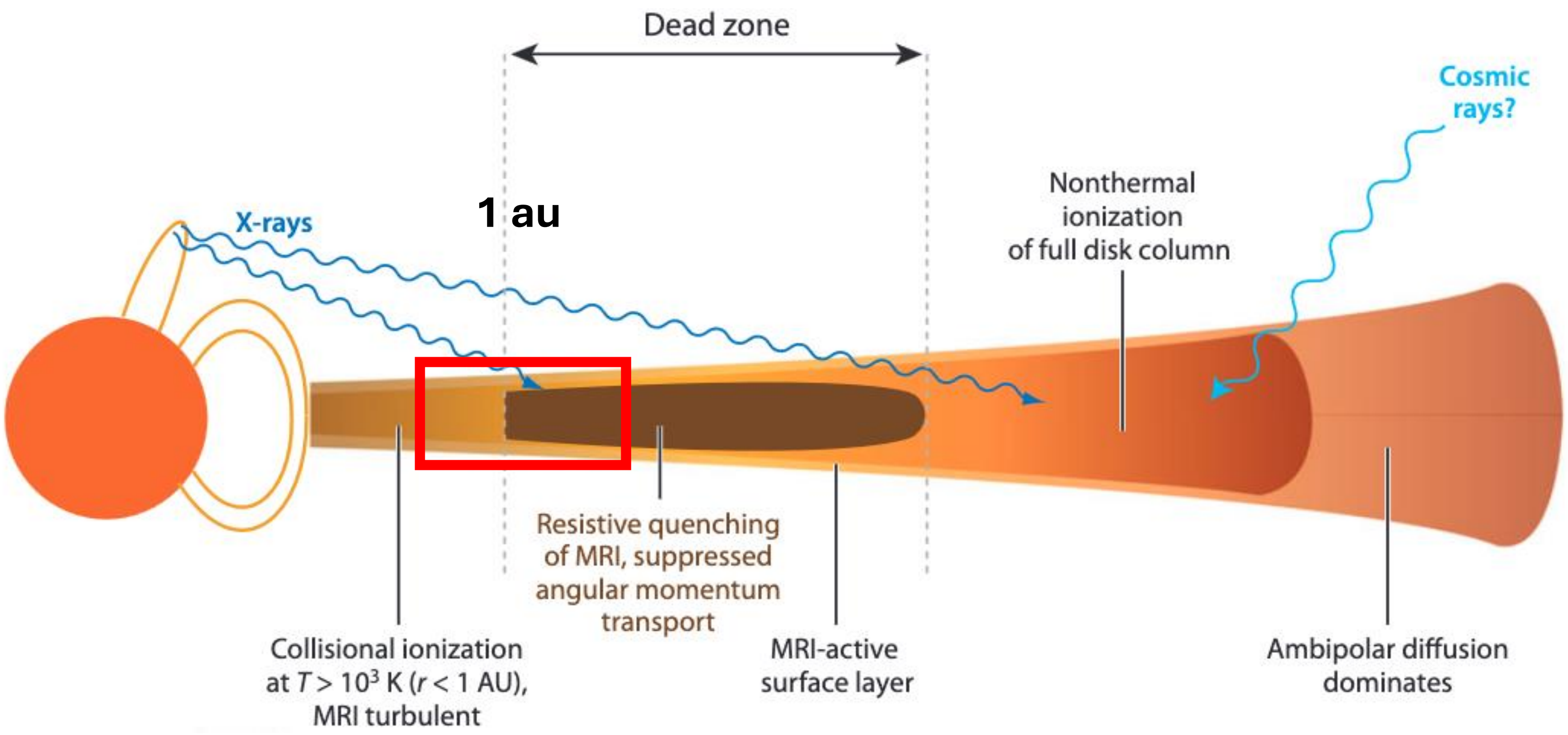

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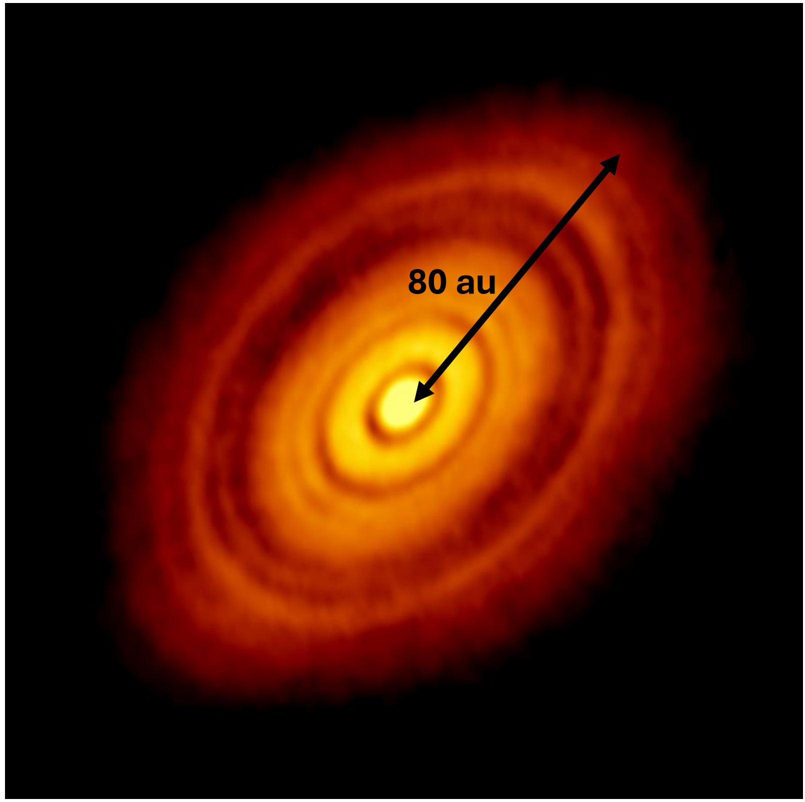
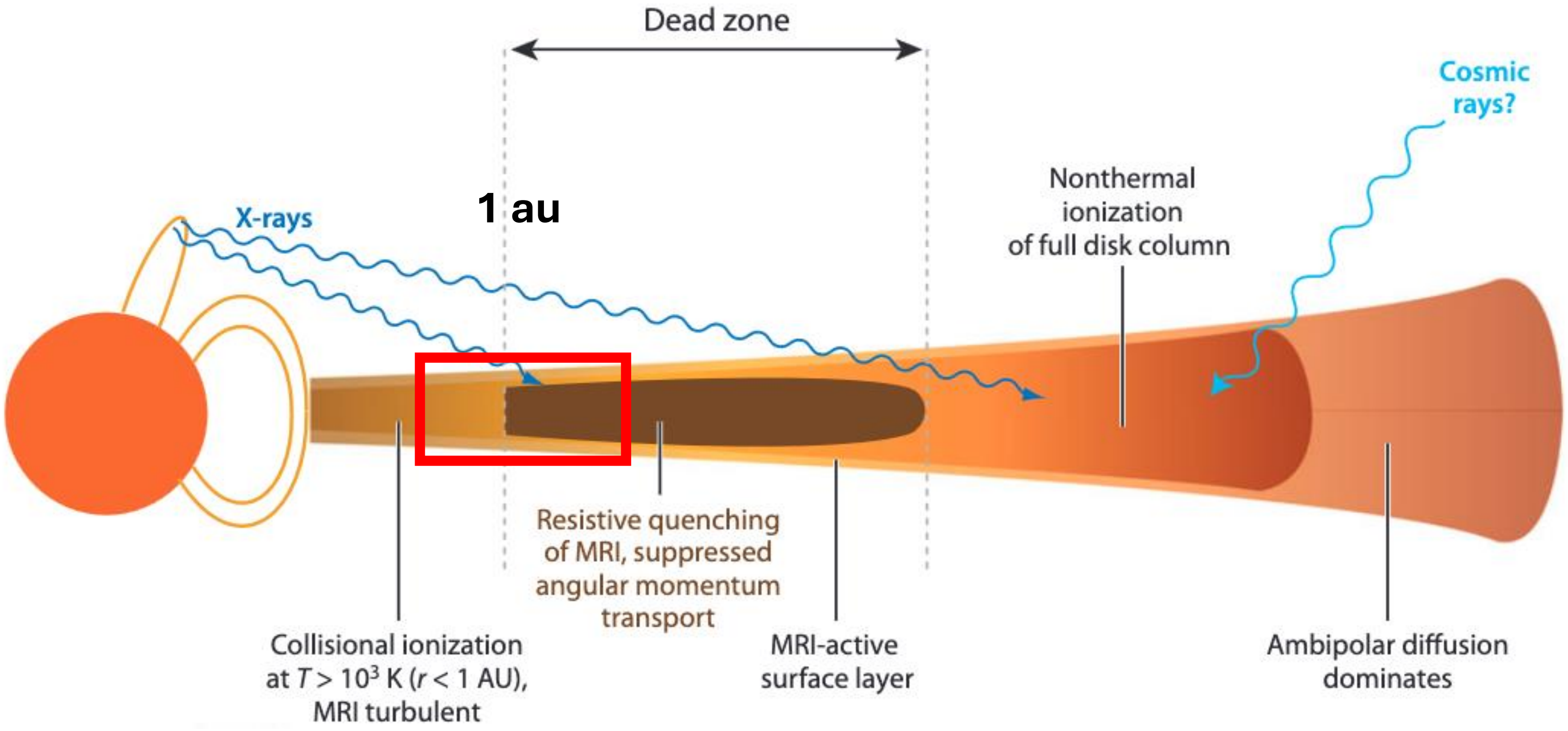


ALMA+(2014)

Ideal MHD

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



Adapted from Armitage(2011)

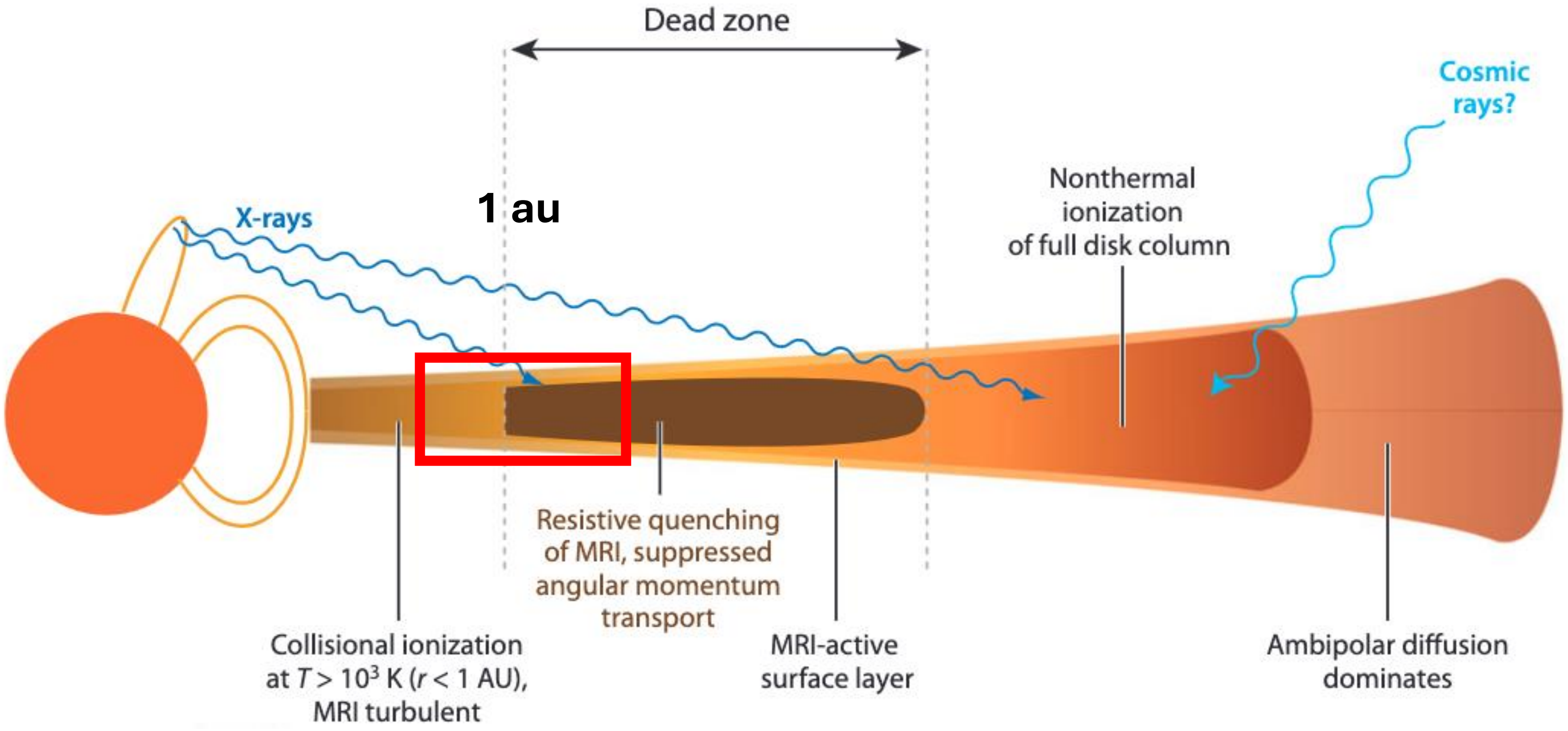
Non-ideal MHD

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

Ohmic diffusion

Hall effect

Ambipolar diffusion



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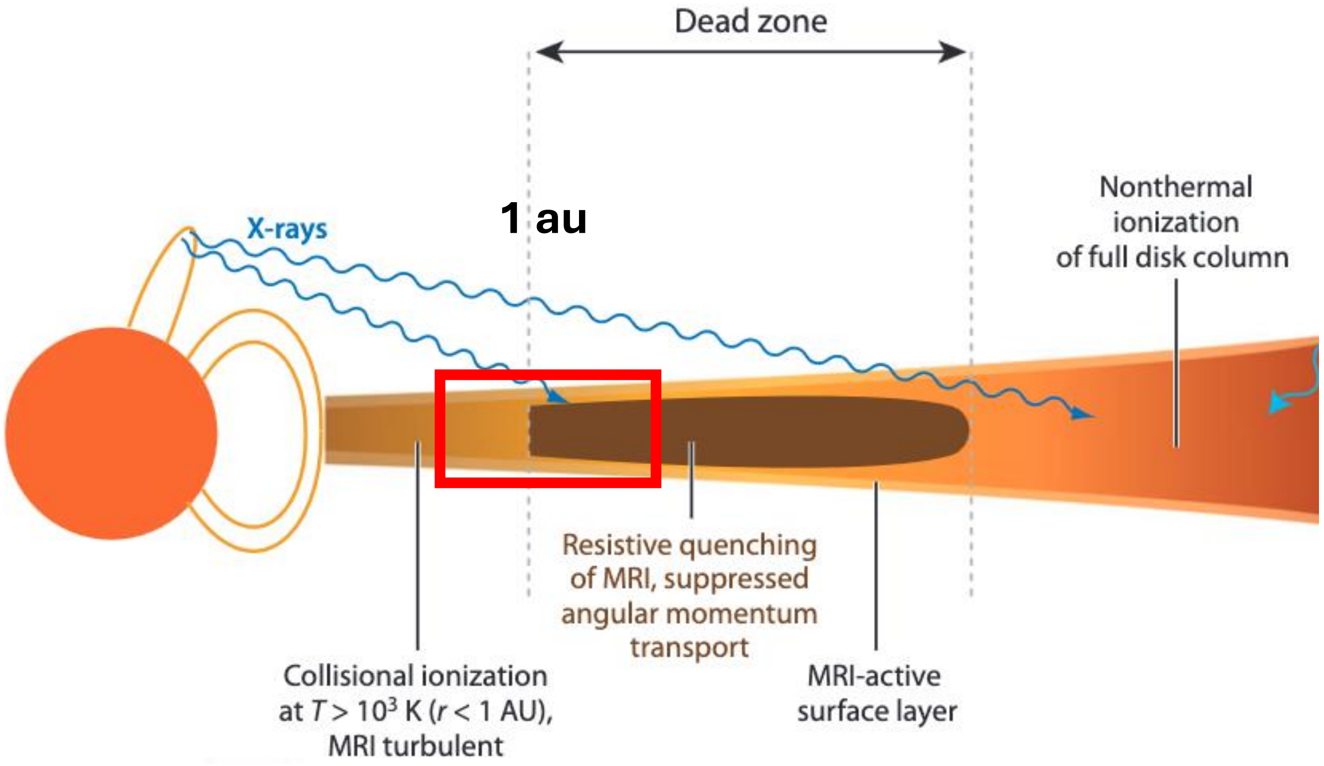
Ohmic diffusion | Hall effect | Ambipolar diffusion



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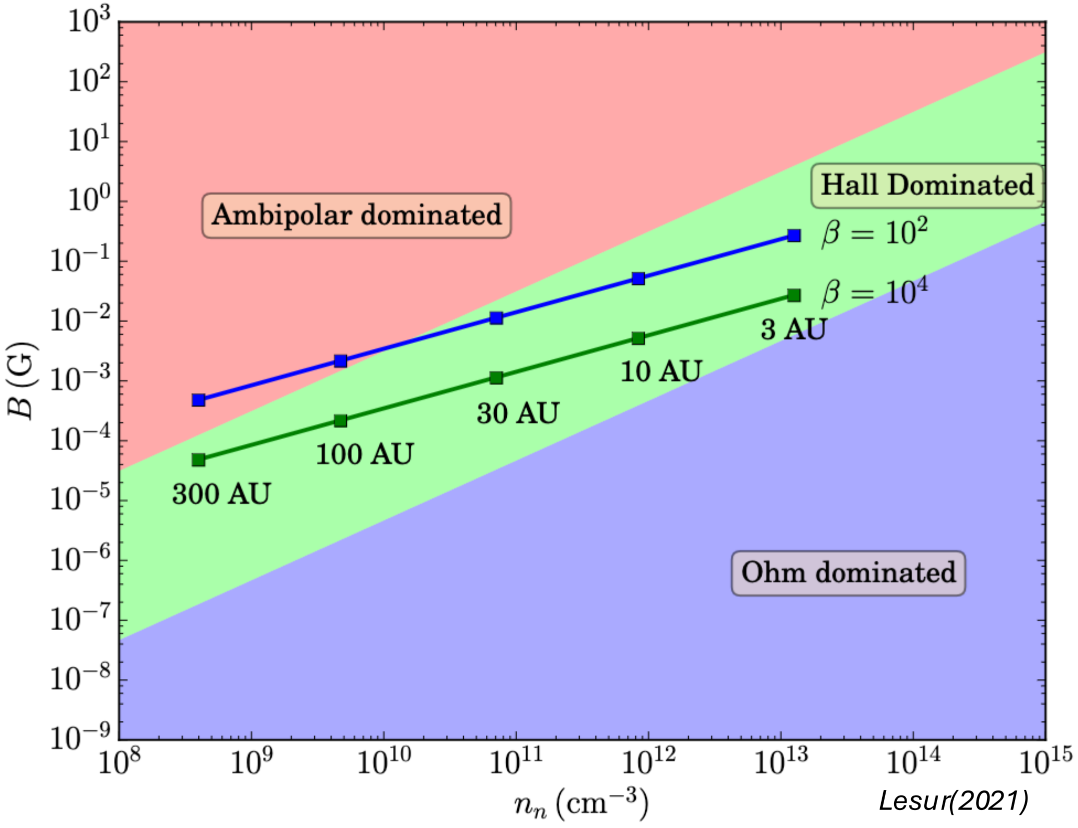


Lesur(2021)

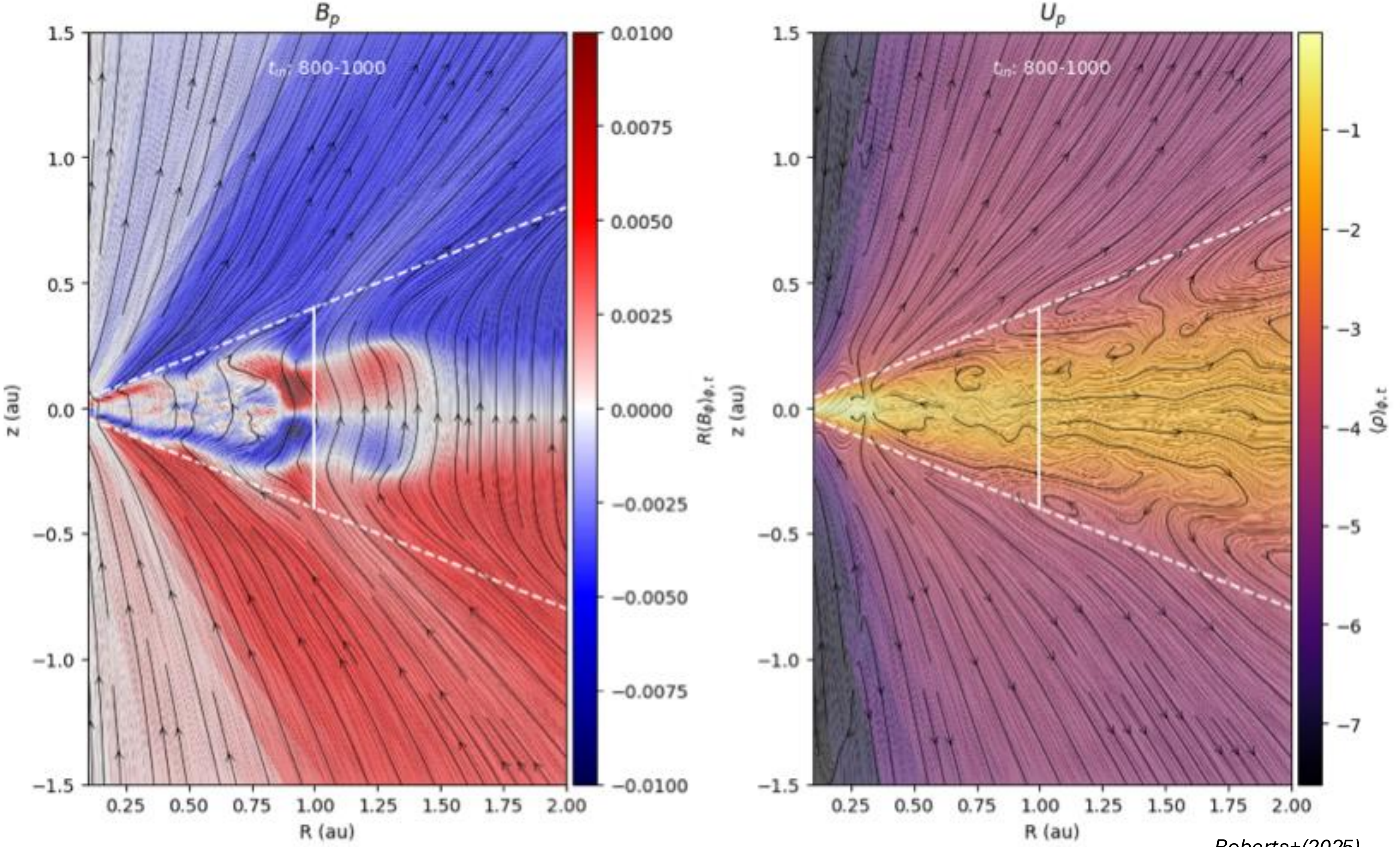
Non-ideal MHD


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)

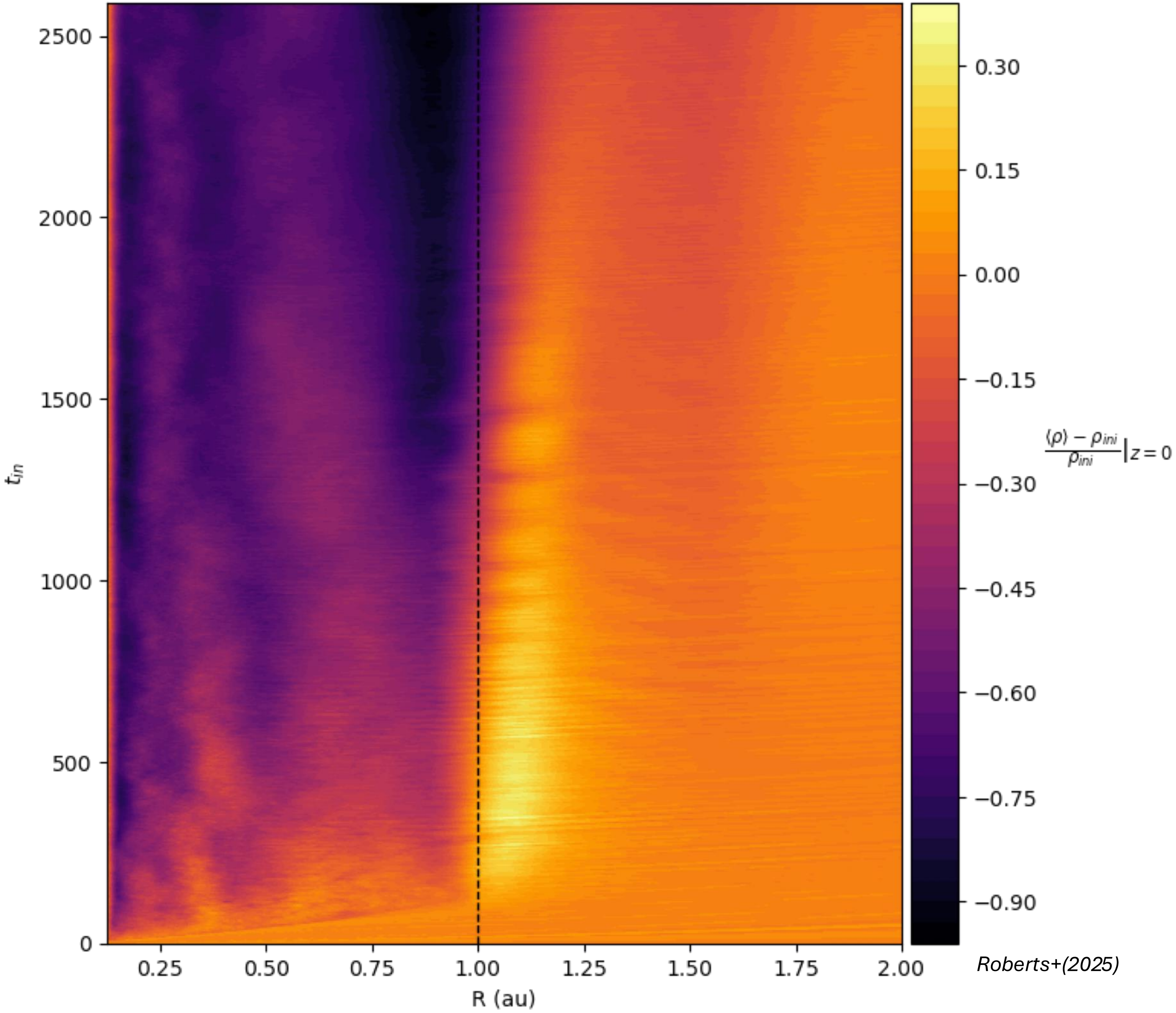
Non-ideal MHD

Matthew Roberts



Roberts+(2025)

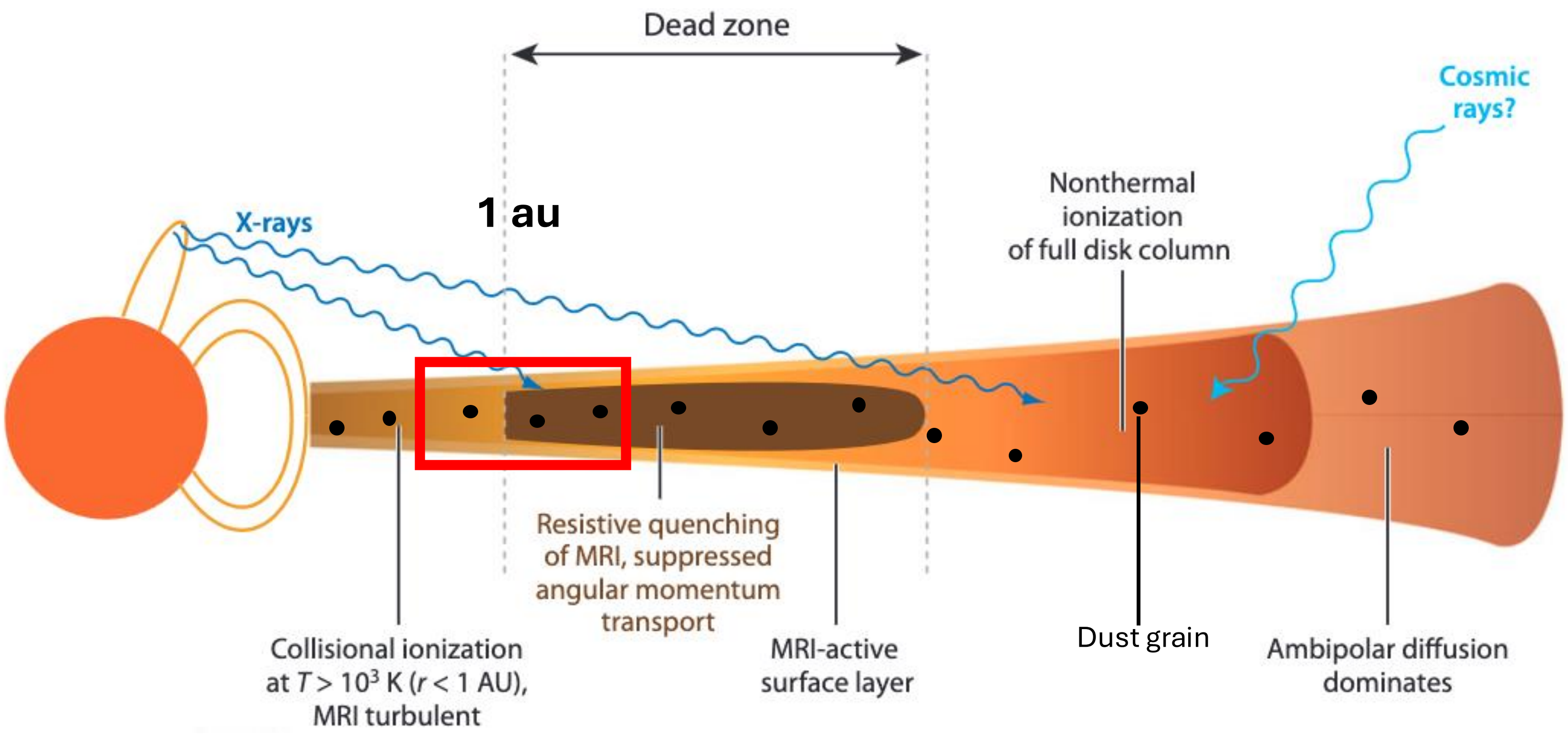
Matthew Roberts



Roberts+(2025)

Planet formation via core-accretion

- Disks intially filled with sub-mm dust grains



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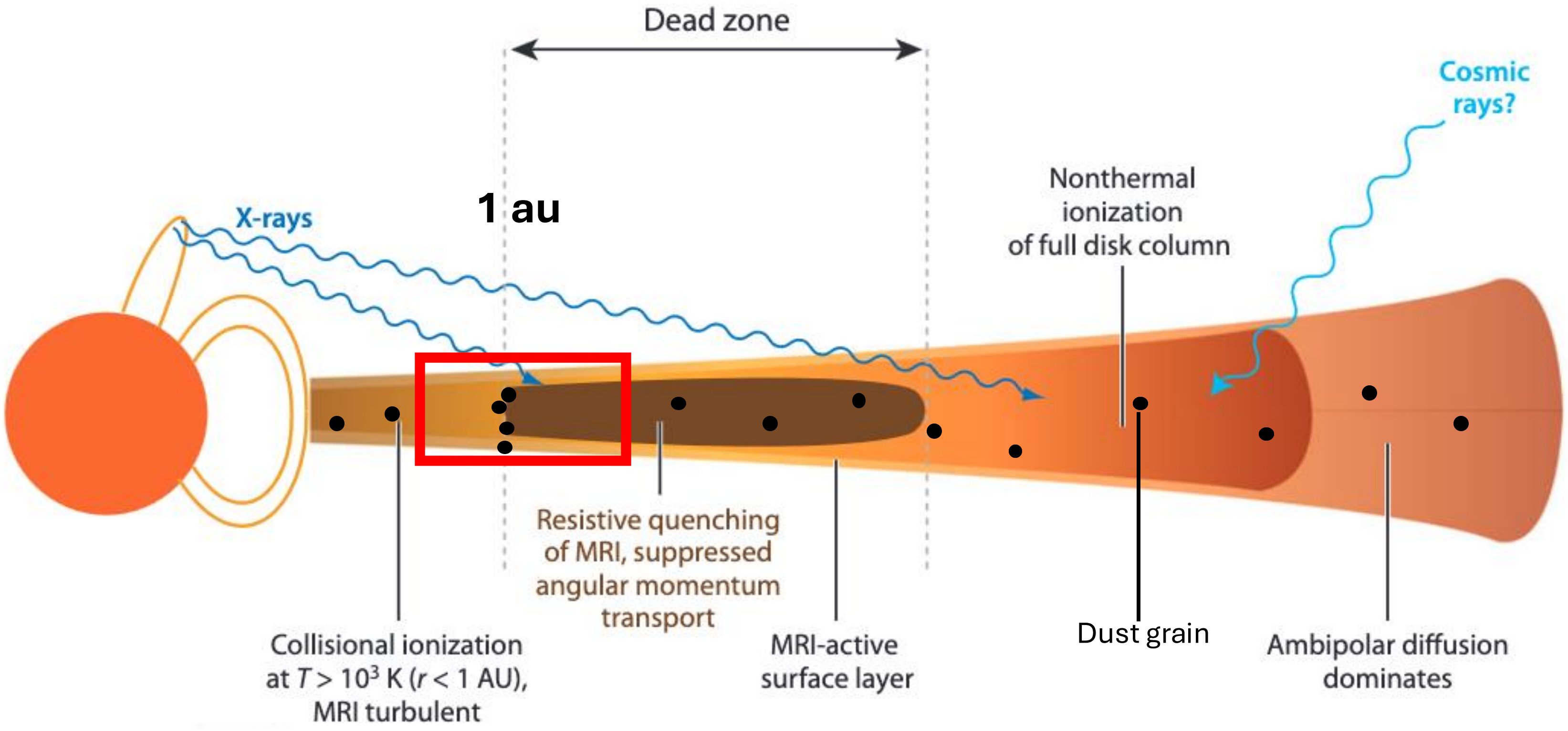
Planet formation via core-accretion



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- Disks intially filled with sub-mm dust grains
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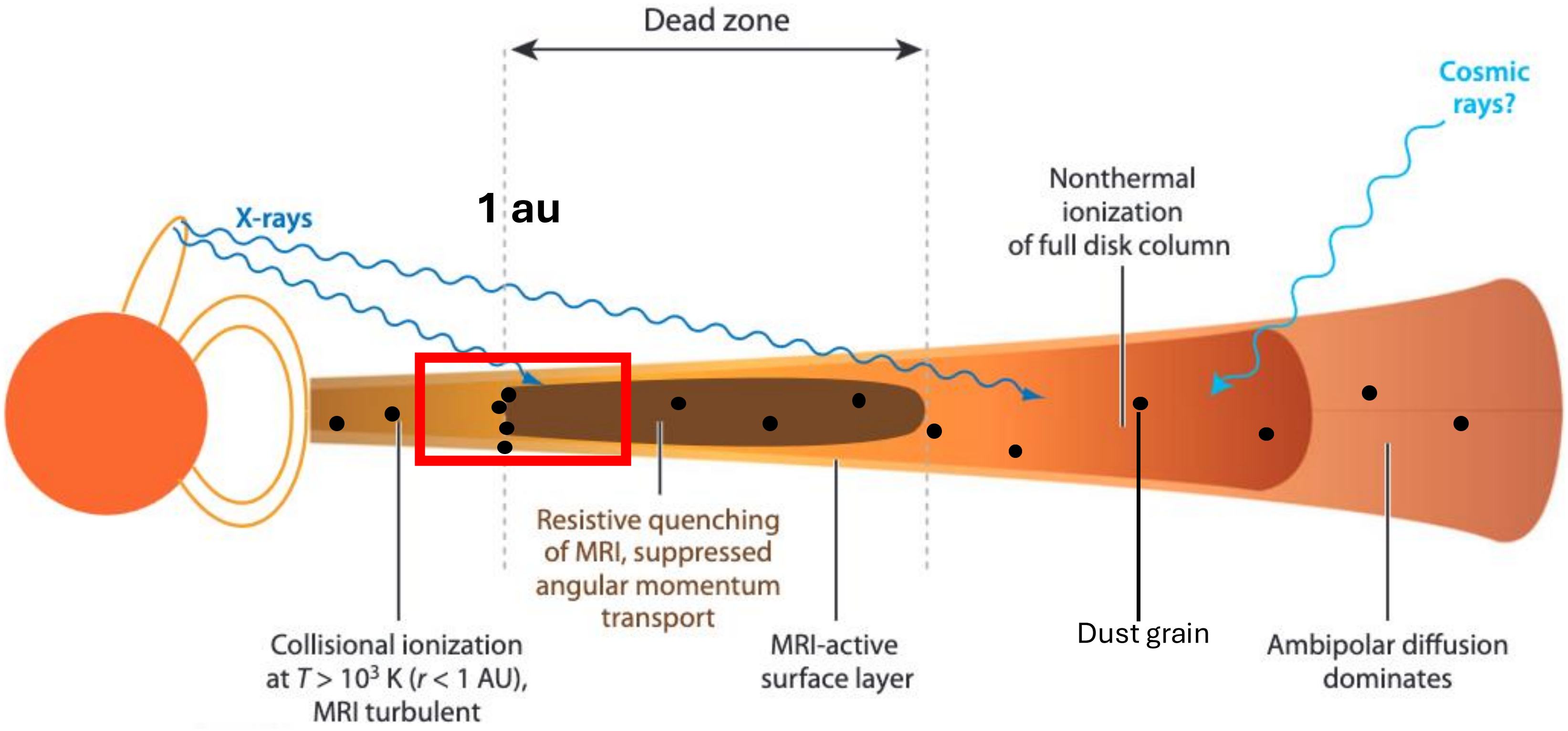
Planet formation via core-accretion



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- Disks intially filled with sub-mm dust grains
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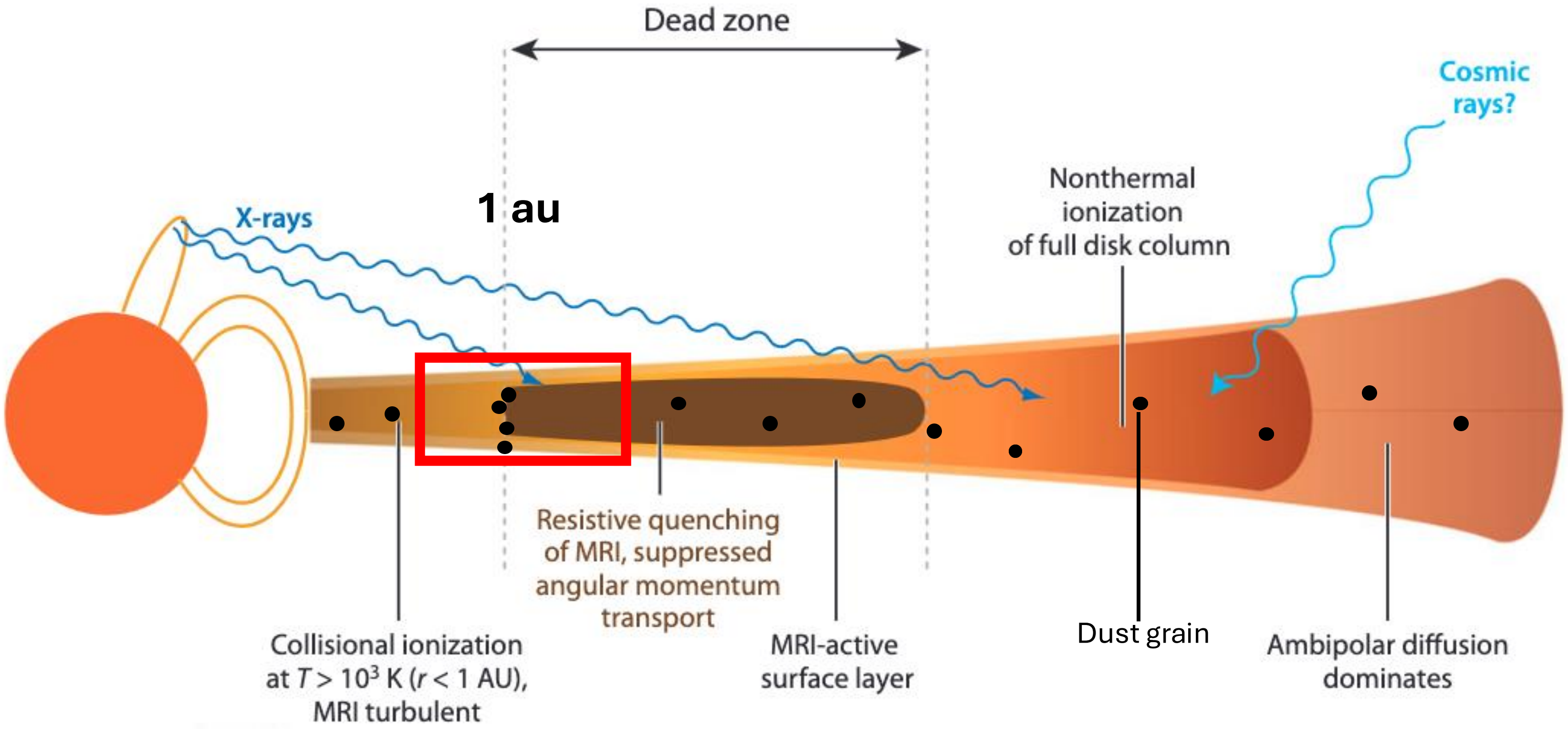


Adapted from Armitage(2011)

- 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 

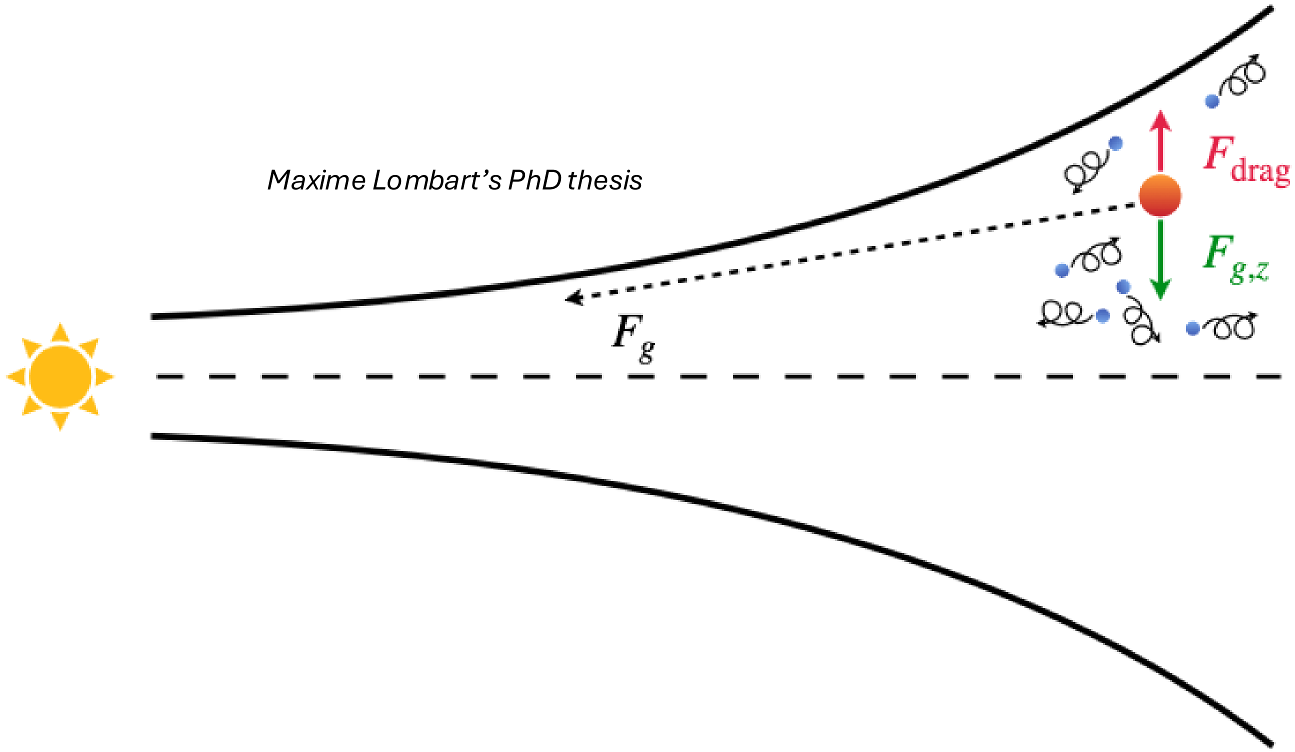
Dust simulations with Idefix

$$\frac{\partial(\rho_{d_i})}{\partial t} + \vec{\nabla}\cdot(\rho_{d_i}\vec{v}_{d_i}) = 0$$

$$\frac{\partial(\rho_{d_i}\vec{v}_{d_i})}{\partial t} + \vec{\nabla}\cdot(\rho_{d_i}\vec{v}_{d_i}\otimes\vec{v}_{d_i}) = \rho_{d_i}\vec{g} + \vec{f}_{g\rightarrow d_i}$$

For each dust species i

Maxime Lombart's PhD thesis



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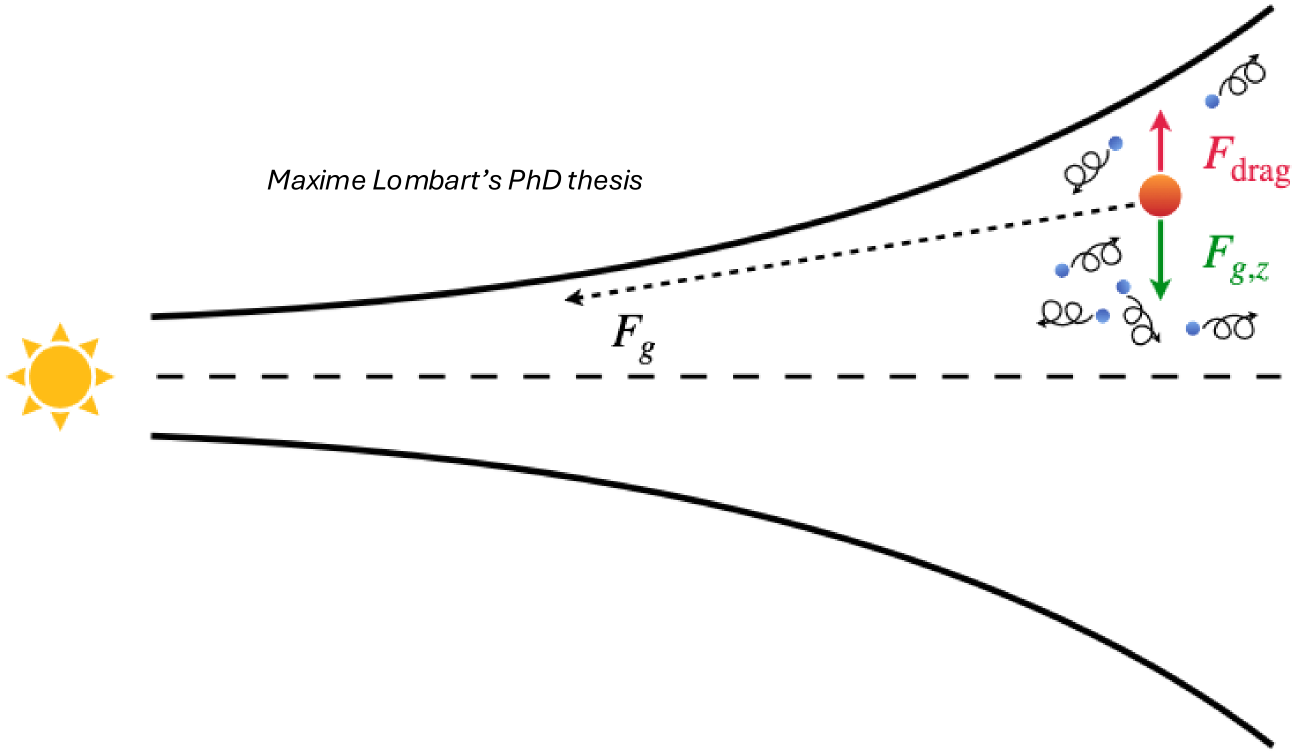

If we put dust in an inviscid gas disk at equilibrium, we expect it to:

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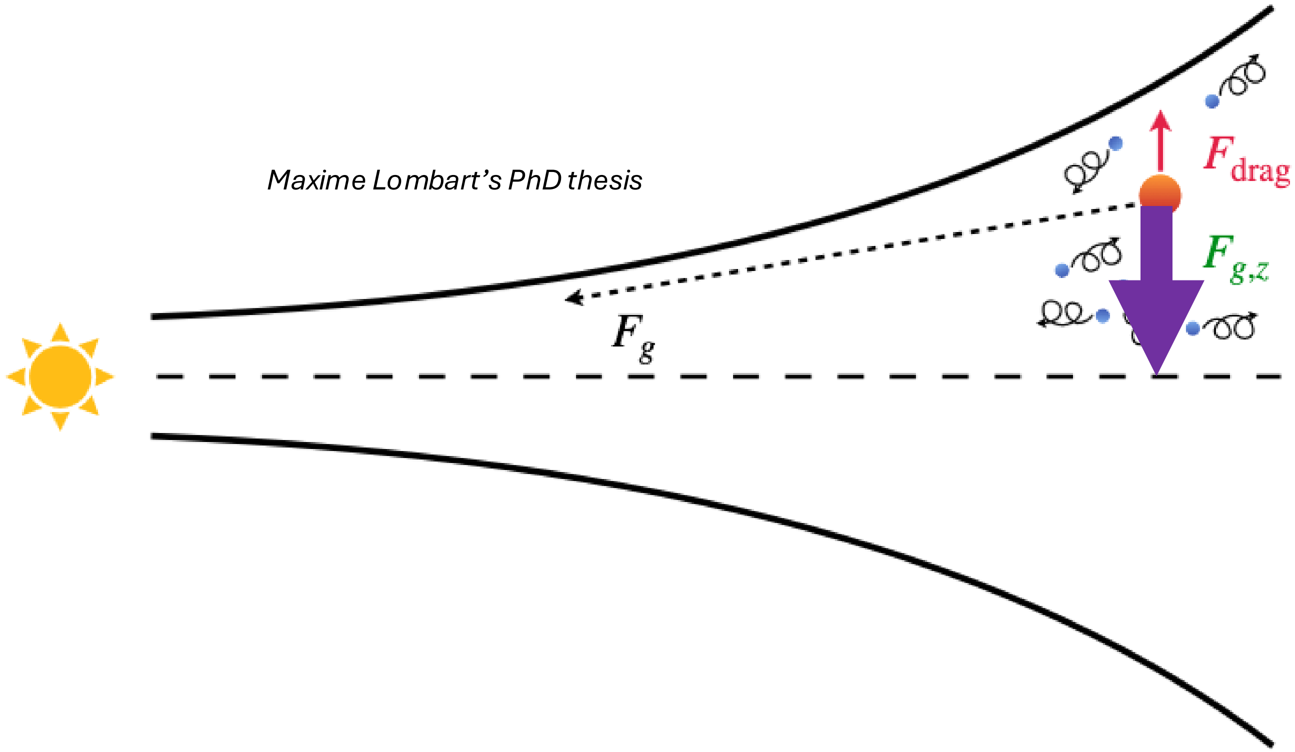

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- Quickly settle vertically towards the midplane

Dust simulations with Idefix

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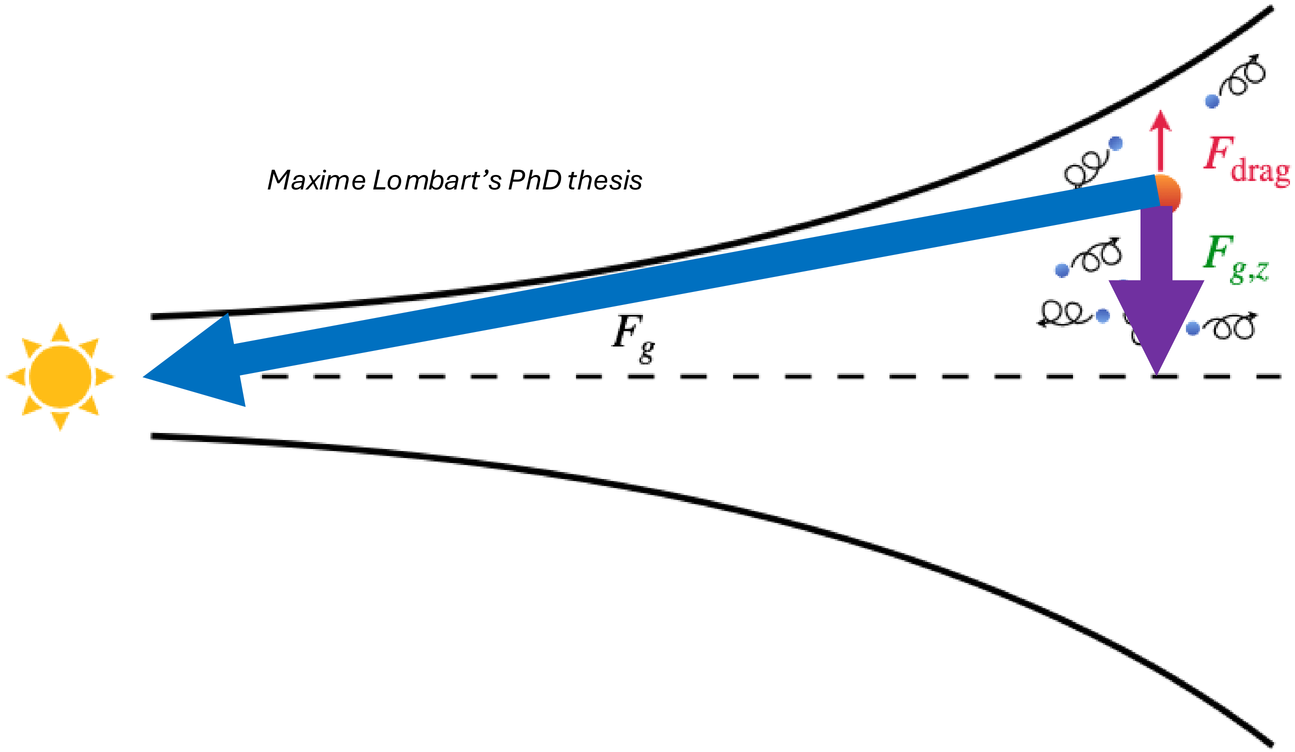

If we put dust in an inviscid gas disk at equilibrium, we expect it to:

- Quickly settle vertically towards the midplane
- Slowly drift radially towards the star

How to test radial drift in Idefix

- Take the FargoPlanet test setup (the one with cool movies in Gaylor’s presentation)

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- Take the FargoPlanet test setup (the one with cool movies in Gaylor's presentation)
- Remove the planet 
- Control the initial profiles of the sound speed c_s and gas density ρ
  - $c_s^2(r) = c_0^2 r^q$
  - $\rho(r) = \rho_0 r^p$

How to test radial drift in Idefix

- Take the FargoPlanet test setup (the one with cool movies in Gaylor's presentation)
- Remove the planet 
- Control the initial profiles of the sound speed c_s and gas density ρ
  - $c_s^2(r) = c_0^2 r^q$
  - $\rho(r) = \rho_0 r^p$
- Control the drag force, either tau or size

Where $\vec{f}_{g\to d_i} = \gamma_i \rho_{d_i} \rho (\vec{v}_g - \vec{v}_{d_i}) = \frac{\rho_i}{t_i}(\vec{v}_g - \vec{v}_{d_i}) = \frac{c_s \rho_{d_i} \rho}{\beta_i}(\vec{v}_g - \vec{v}_{d_i})$

$$\gamma_i = \frac{1}{\rho t_i}$$

$$t_i = \frac{\beta_i}{\rho c_s}$$

Four possible drag laws: **gamma** fixes γ_i, **tau** fixes t_i, **size** fixes β_i and **userdef** is whatever you like

fixed drag parameter

fixed stopping time

Epstein or Stokes drag law with fixed:
- Dust density ρ_s
- Dust size a

Epstein: $\beta_i = (\rho_s a)_i$

Parameter normalization and Stokes number

- Stokes number $\tau_i = t_i \Omega_K$ is the adimensioned stopping time

- Sets the dust radial drift speed:
  - $v_r = \frac{dr}{dt} = \frac{-\eta V_K}{\tau_i + 1/\tau_i}$ where $\eta = -(p+q) r c_S^2$

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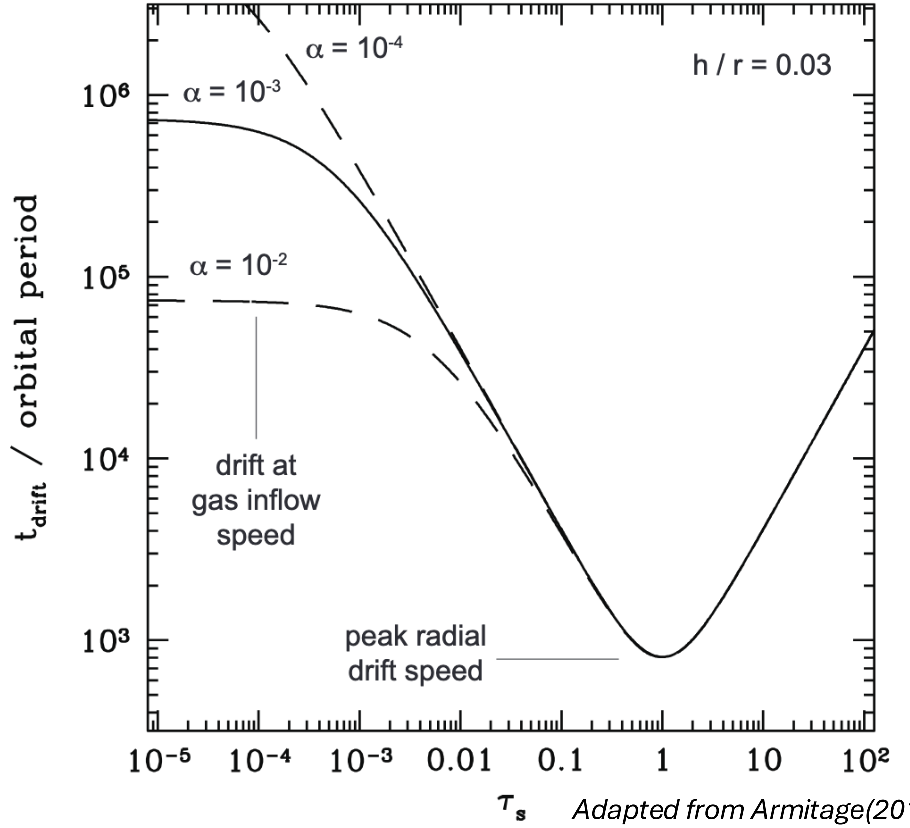

Adapted from Armitage(2011)

Parameter normalization and Stokes number

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- Sets the dust radial drift speed:
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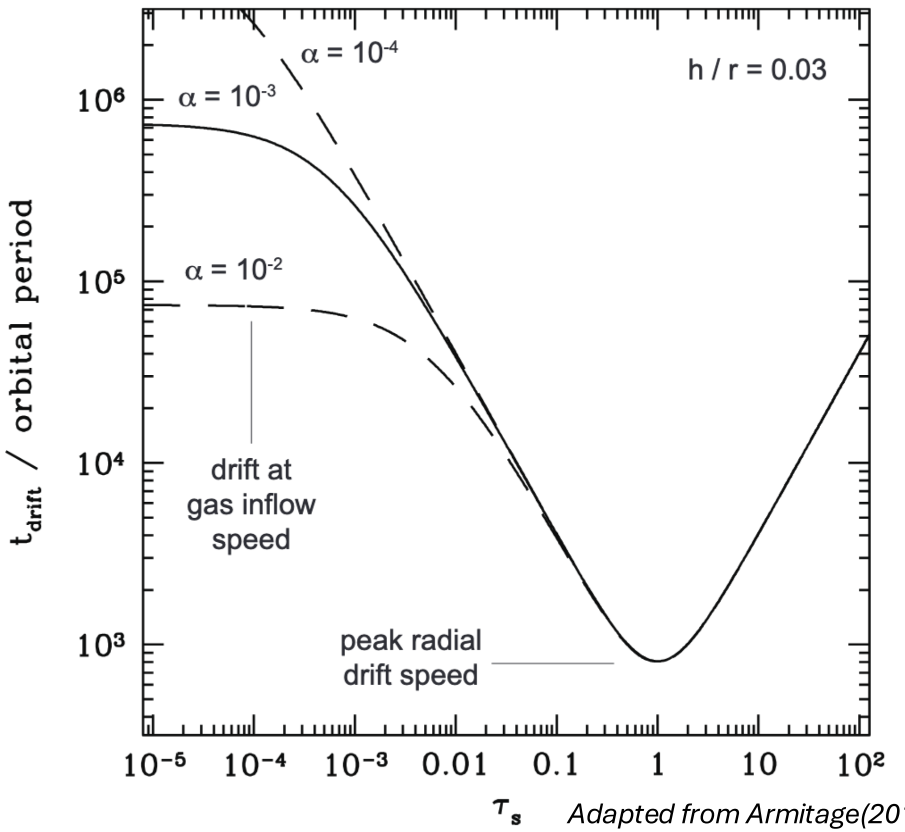
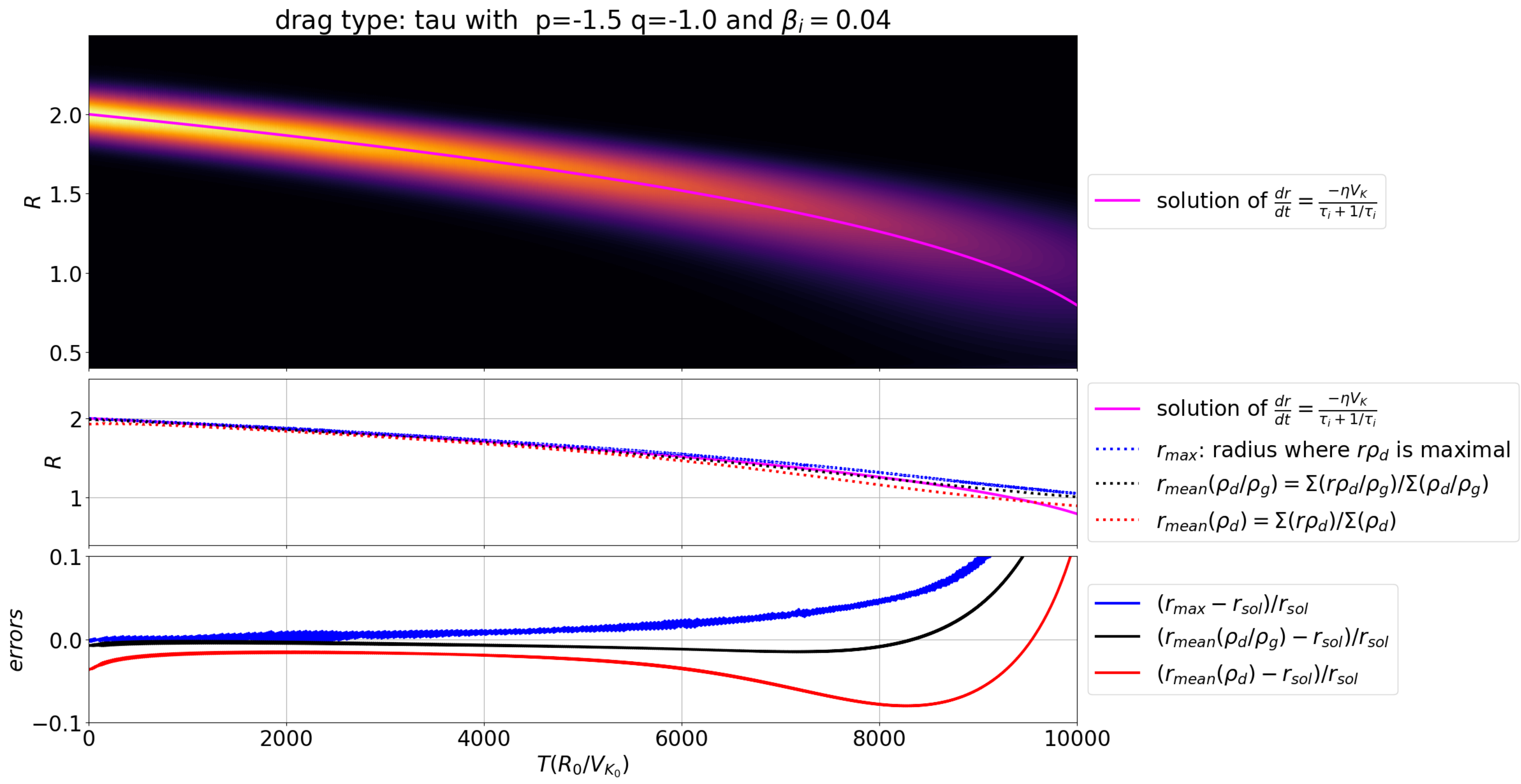
- Let us call β_i the Idefix drag input parameter
- For a tau drag law $\tau_i(r) = \beta_i \Omega_K = \beta_i \Omega_0 (r/r_0)^{-3/2}$
- For a size drag law $\tau_i(r) = \beta_i \frac{\Omega_K}{\rho c_s} = \beta_i \frac{\Omega_0}{\rho_0 c_0} (r/r_0)^{-\frac{3+2p+q}{2}}$



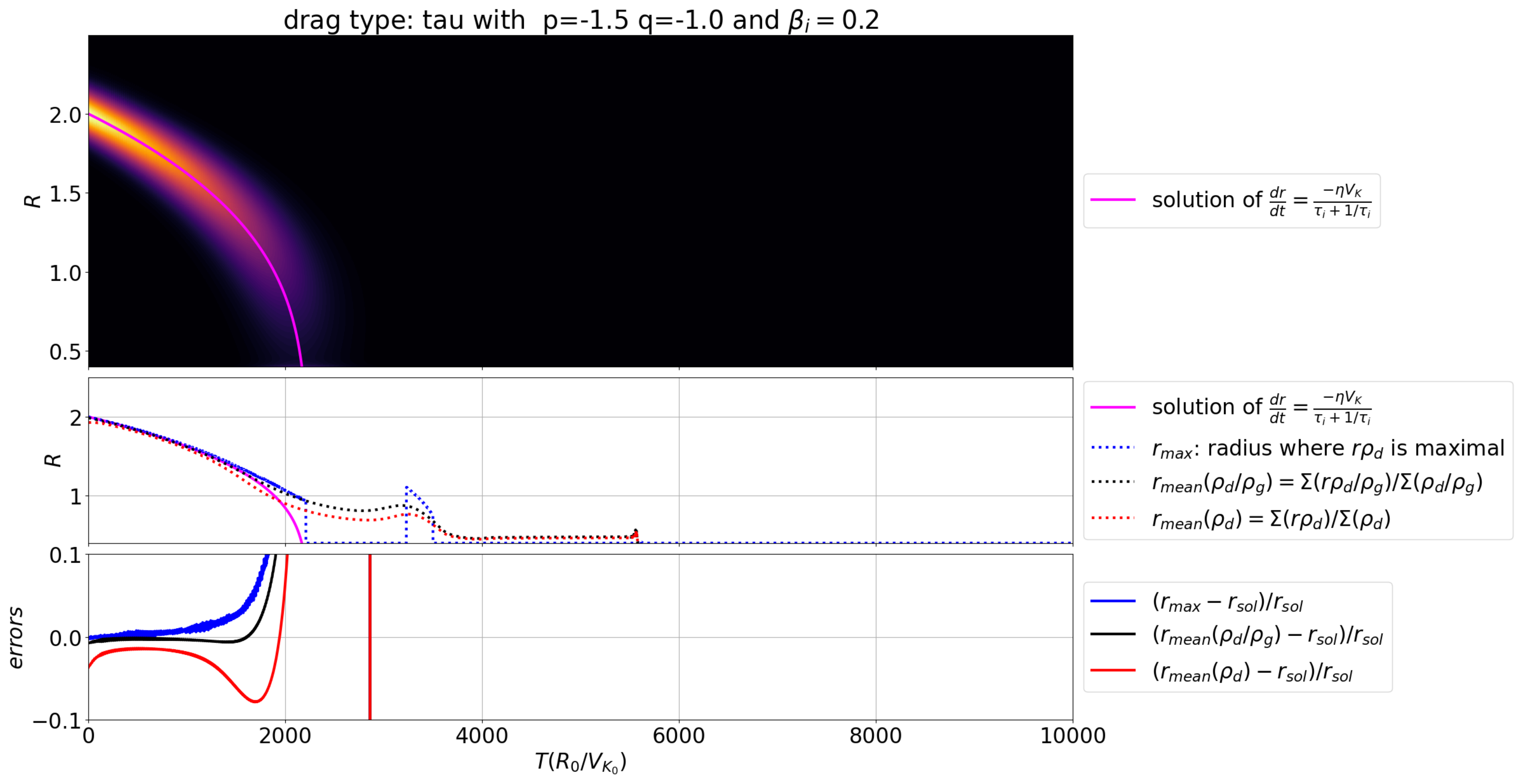
Adapted from Armitage(2011)

Radial drift test setup

- Put dust mostly in a ring in the outer disk
- Run and see the radial drift
- See how well it fits with what is expected:
  - $v_r = \frac{dr}{dt} = \frac{-\eta V_K}{\tau_i + 1/\tau_i}$ where $\eta = -(p+q) r c_S^2$
- Try different profiles of gas density (p) and sound speed (q)
- Try different drag laws (tau and size) and different input parameters β_i



drag type: tau with p=-1.5 q=-1.0 and $\beta_i = 0.04$
R
2.0
1.5
1.0
0.5
solution of $\frac{dr}{dt} = \frac{-\eta V_K}{\tau_i + 1/\tau_i}$
R
2
1
solution of $\frac{dr}{dt} = \frac{-\eta V_K}{\tau_i + 1/\tau_i}$
r_{max}: radius where $r\rho_d$ is maximal
$r_{mean}(\rho_d/\rho_g) = \Sigma(r\rho_d/\rho_g)/\Sigma(\rho_d/\rho_g)$
$r_{mean}(\rho_d) = \Sigma(r\rho_d)/\Sigma(\rho_d)$
errors
0.1
0.0
−0.1
$(r_{max} - r_{sol})/r_{sol}$
$(r_{mean}(\rho_d/\rho_g) - r_{sol})/r_{sol}$
$(r_{mean}(\rho_d) - r_{sol})/r_{sol}$
0
2000
4000
6000
8000
10000
$T(R_0/V_{K_0})$



drag type: tau with p=-1.5 q=-1.0 and $\beta_i = 0.2$
R
errors
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r_{max}: radius where $r\rho_d$ is maximal
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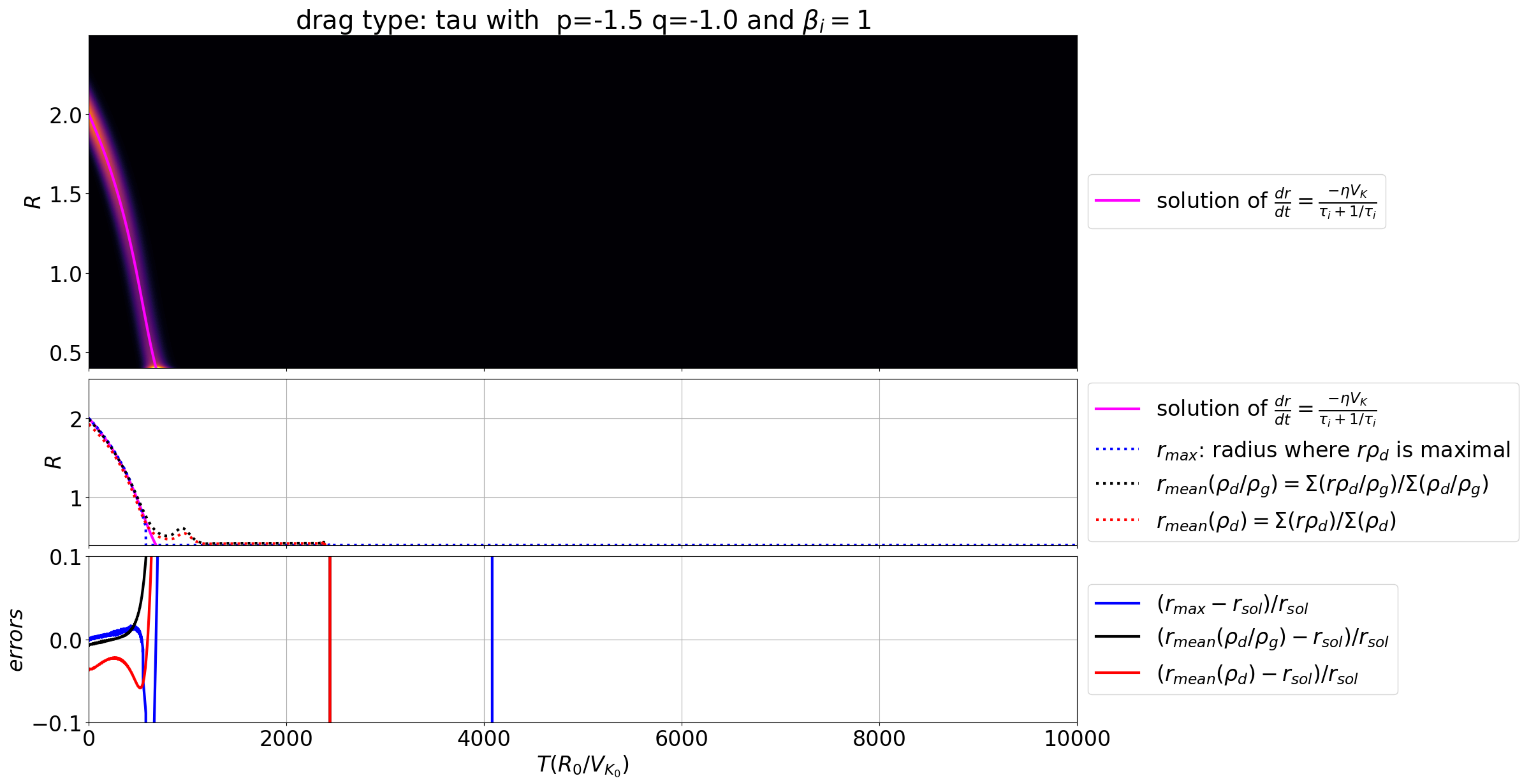

drag type: tau with p=-1.5 q=-1.0 and $\beta_i = 1$
R
2.0
1.5
1.0
0.5
solution of $\frac{dr}{dt} = \frac{-\eta V_K}{\tau_i + 1/\tau_i}$
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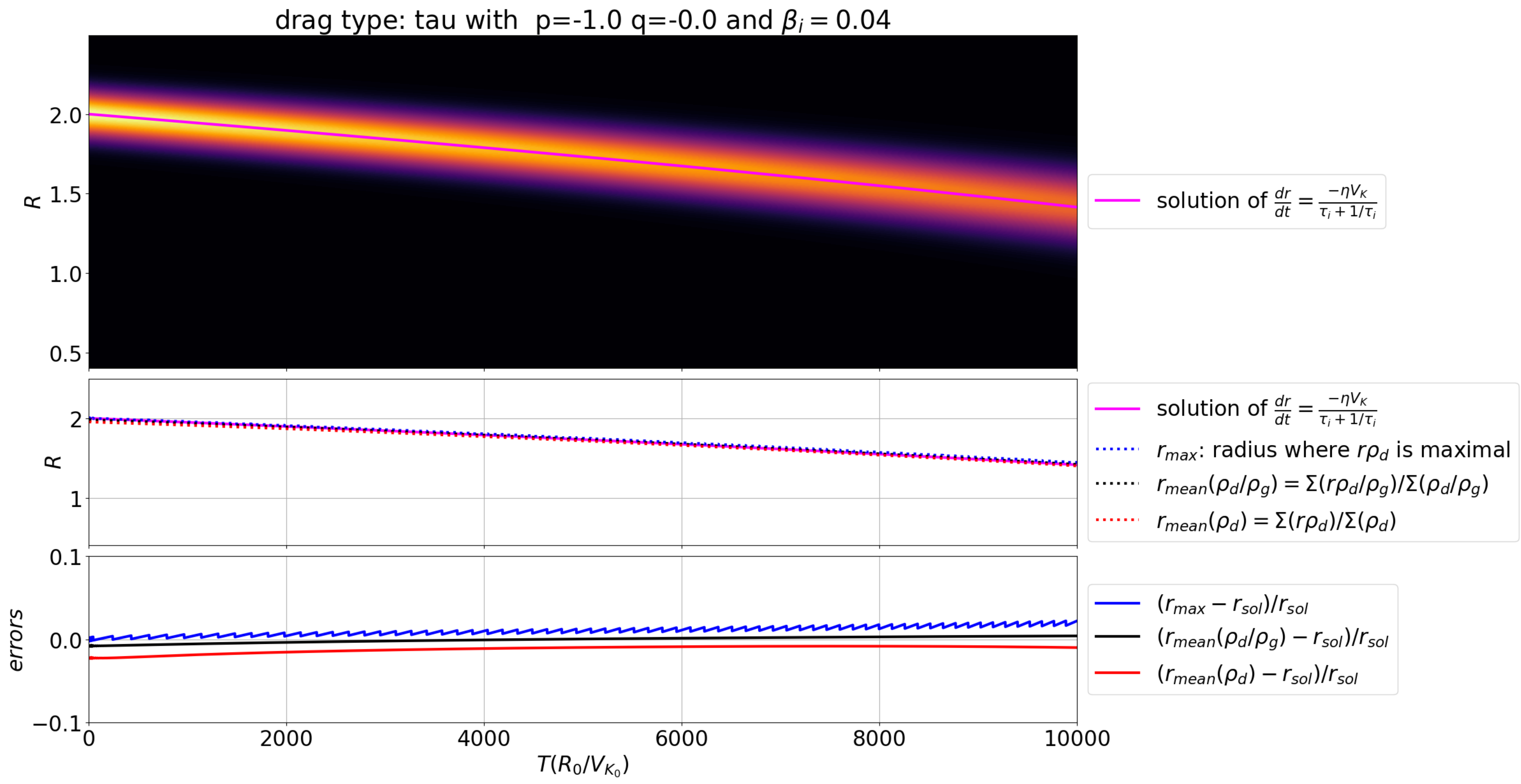
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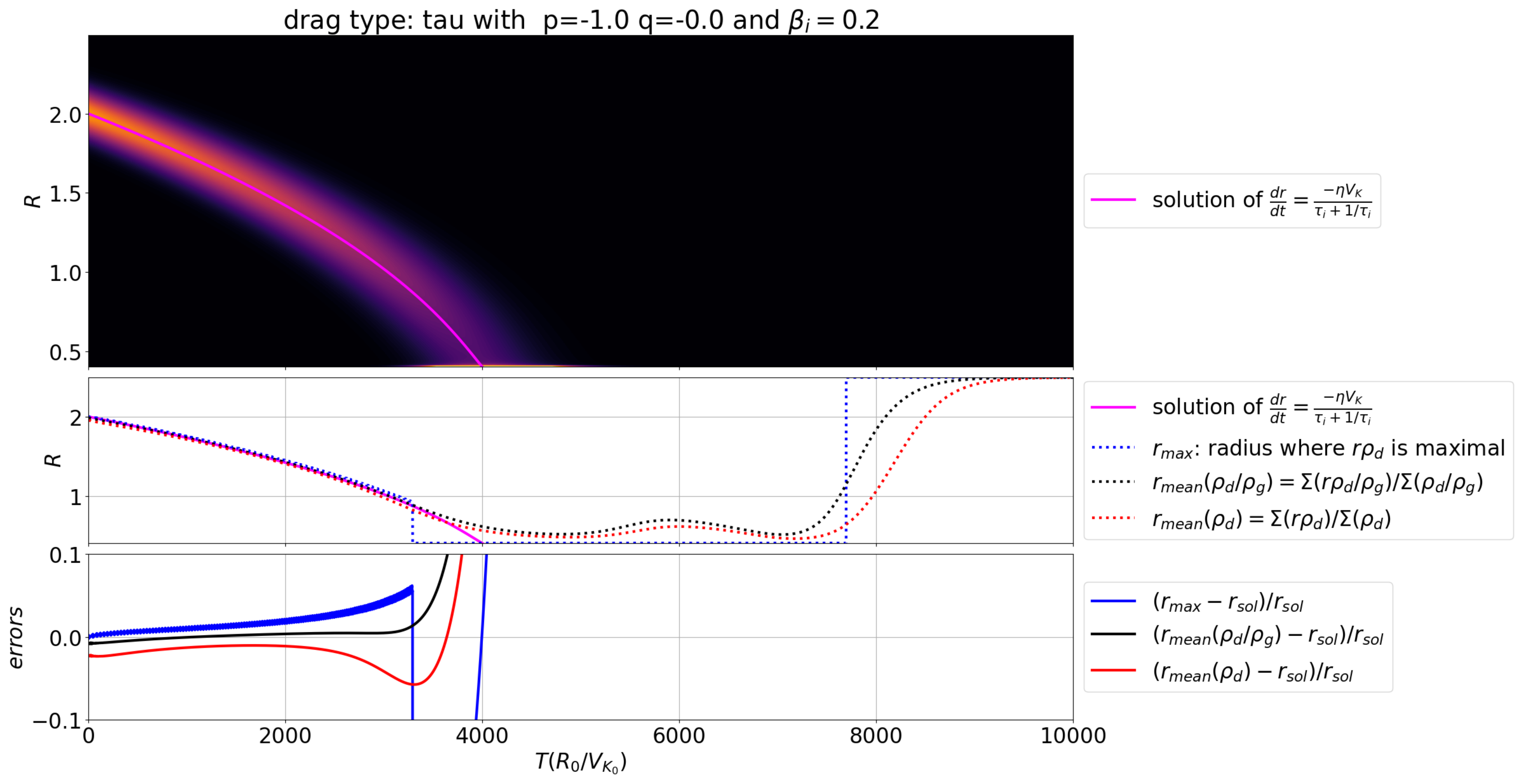

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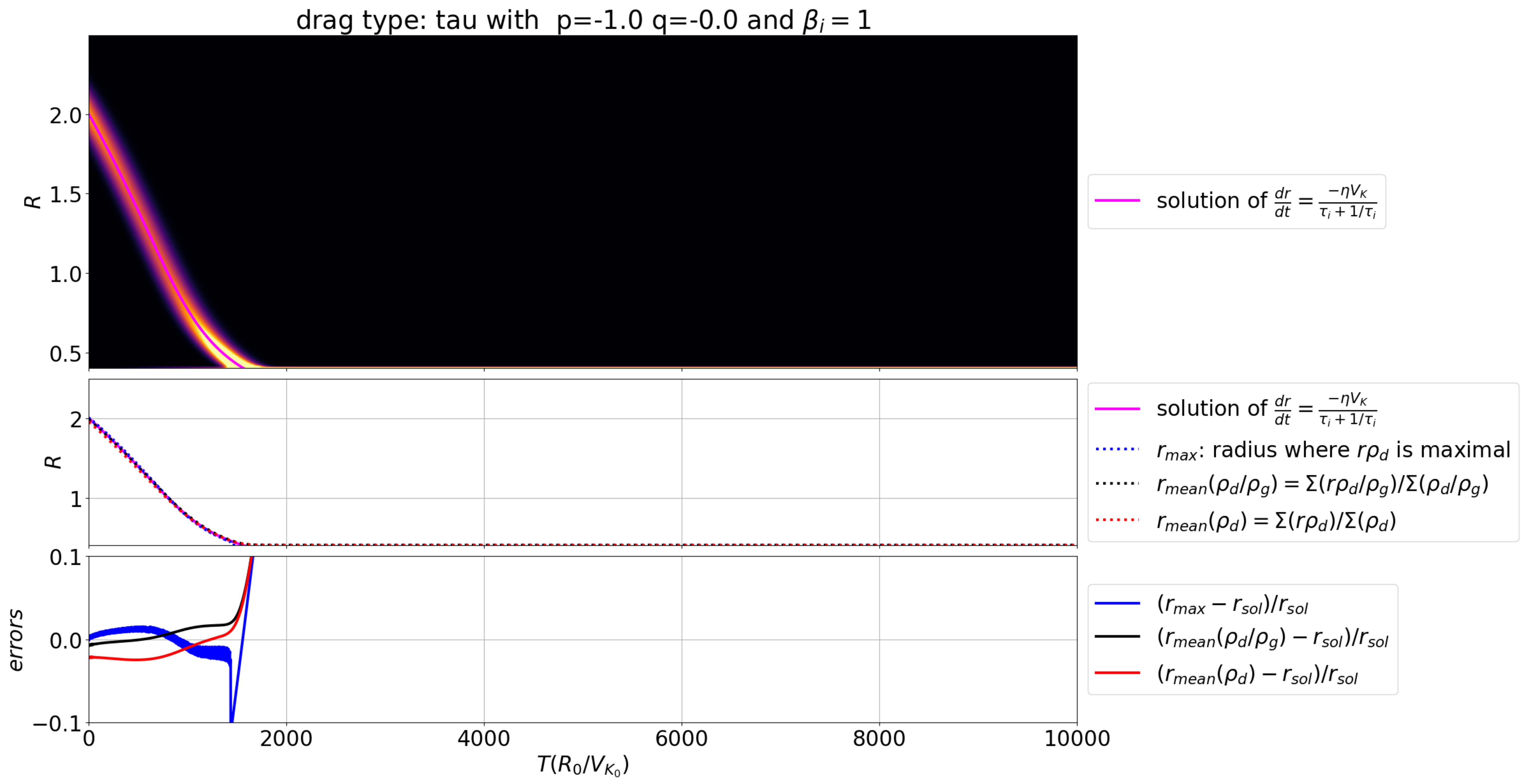

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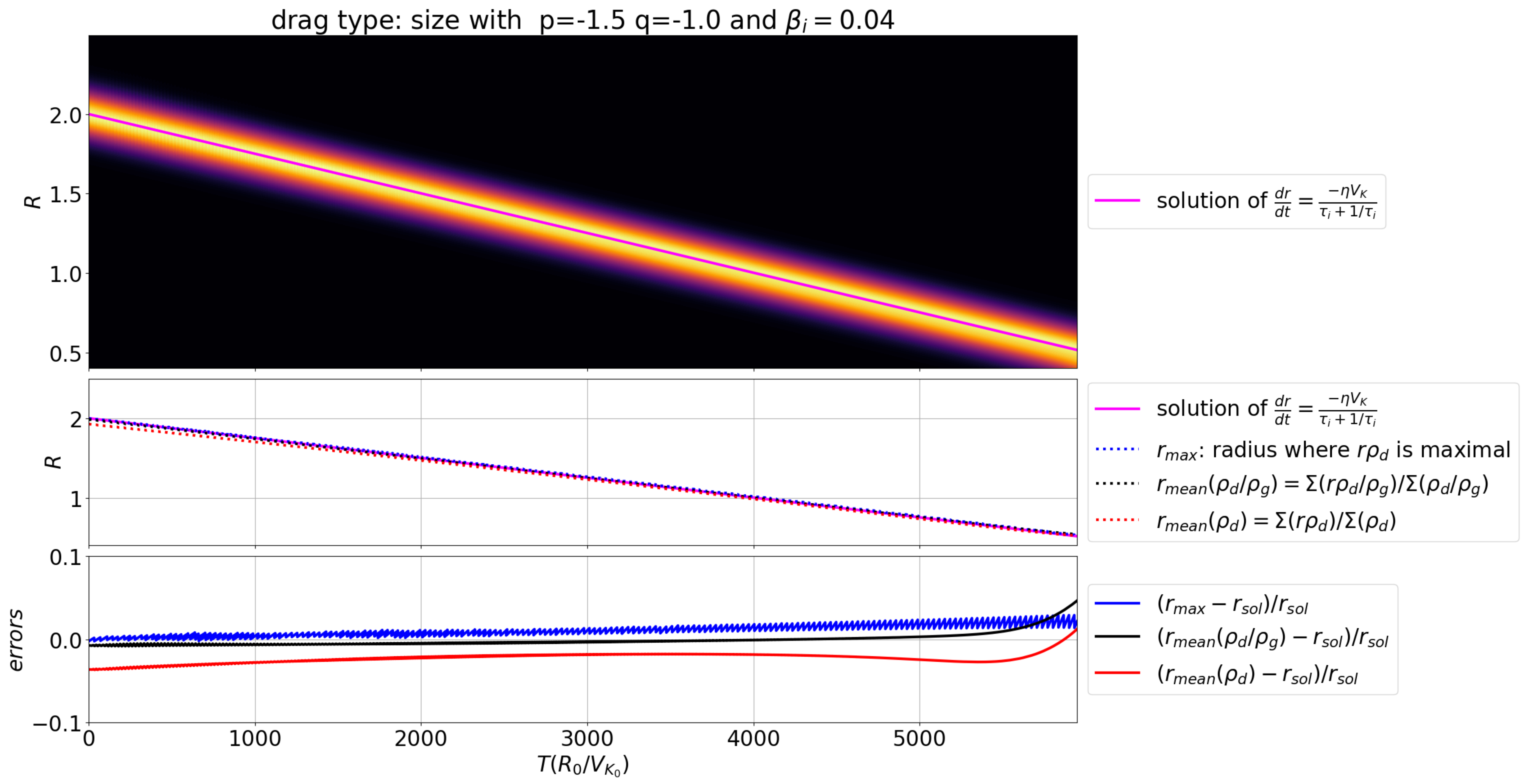

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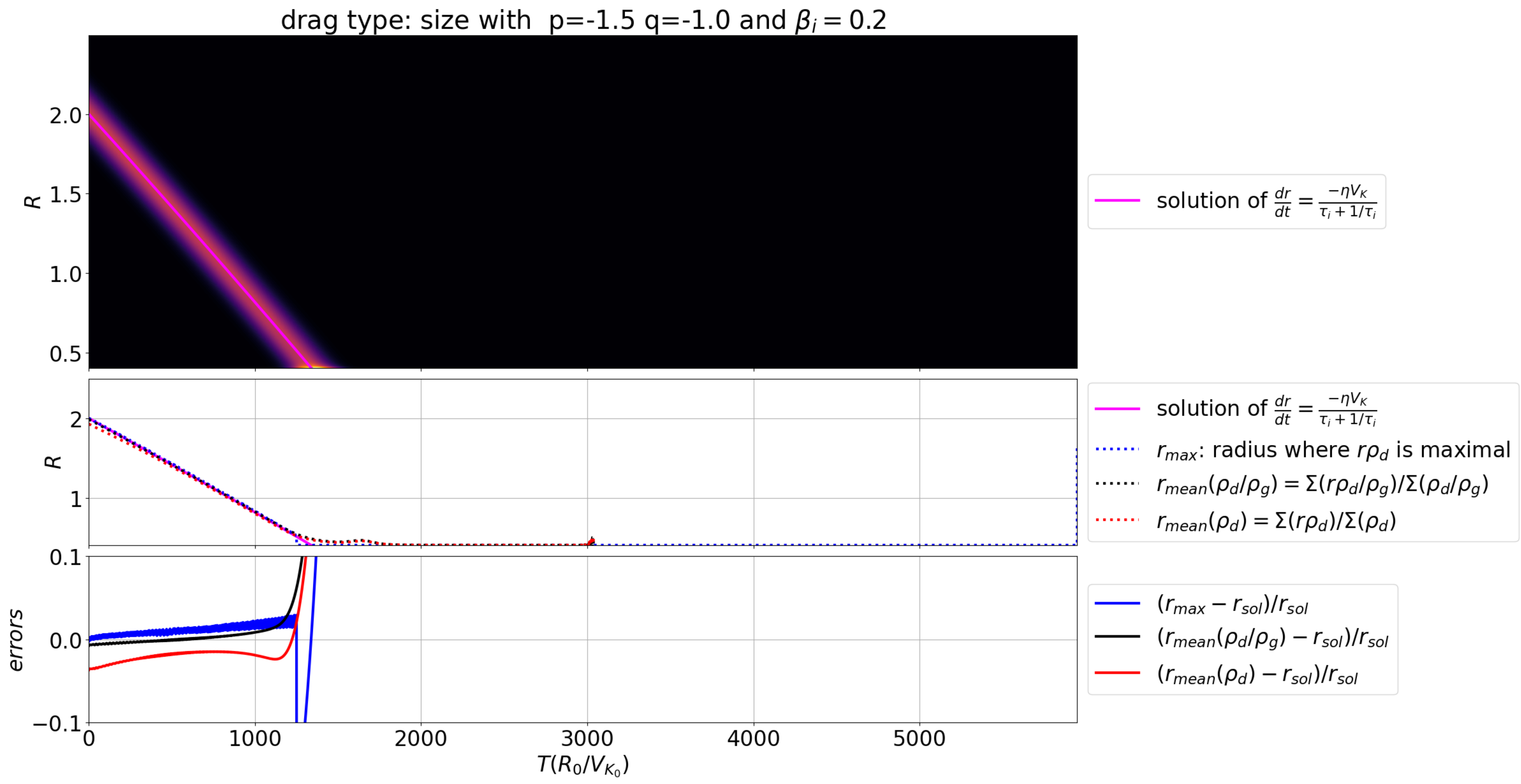

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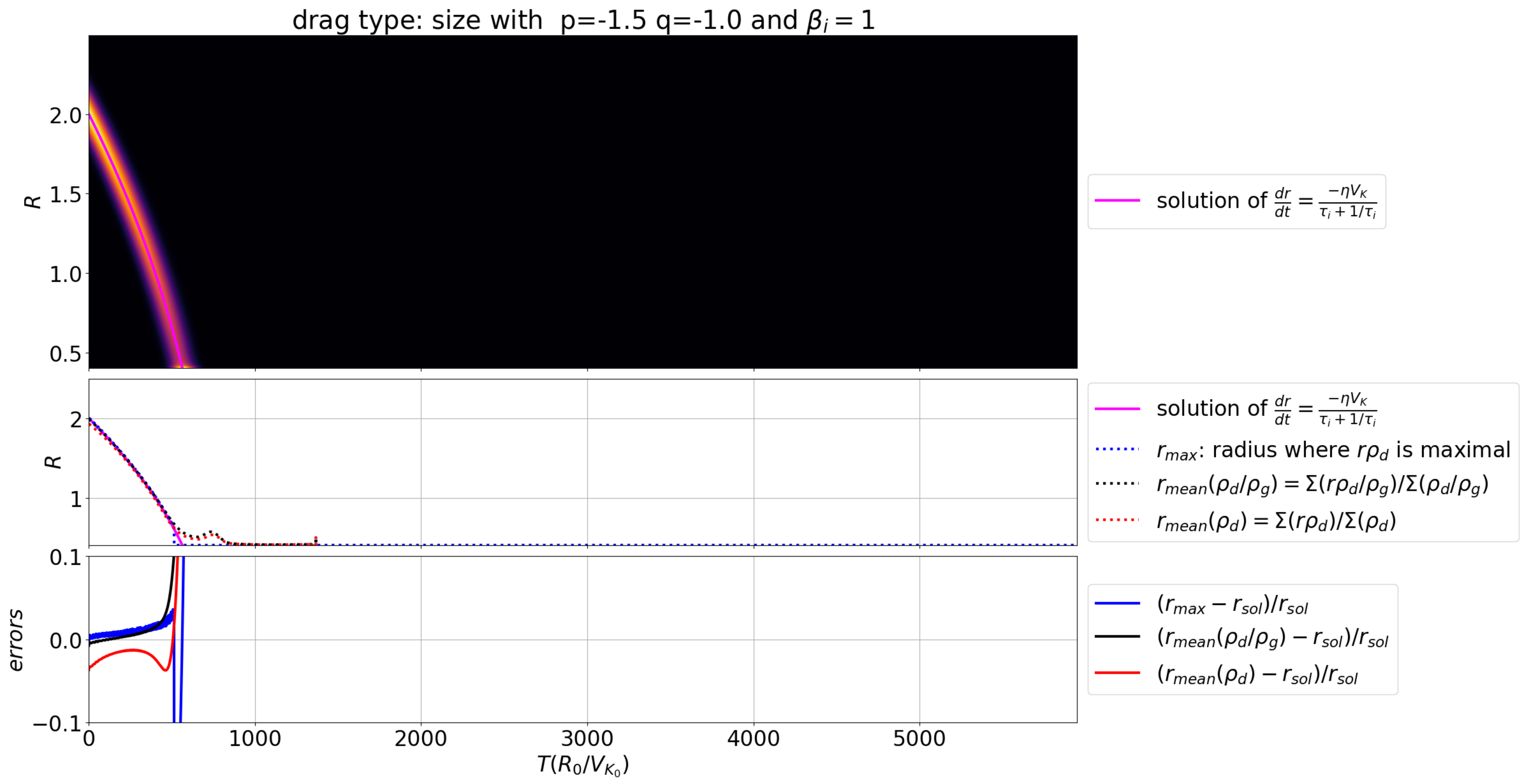
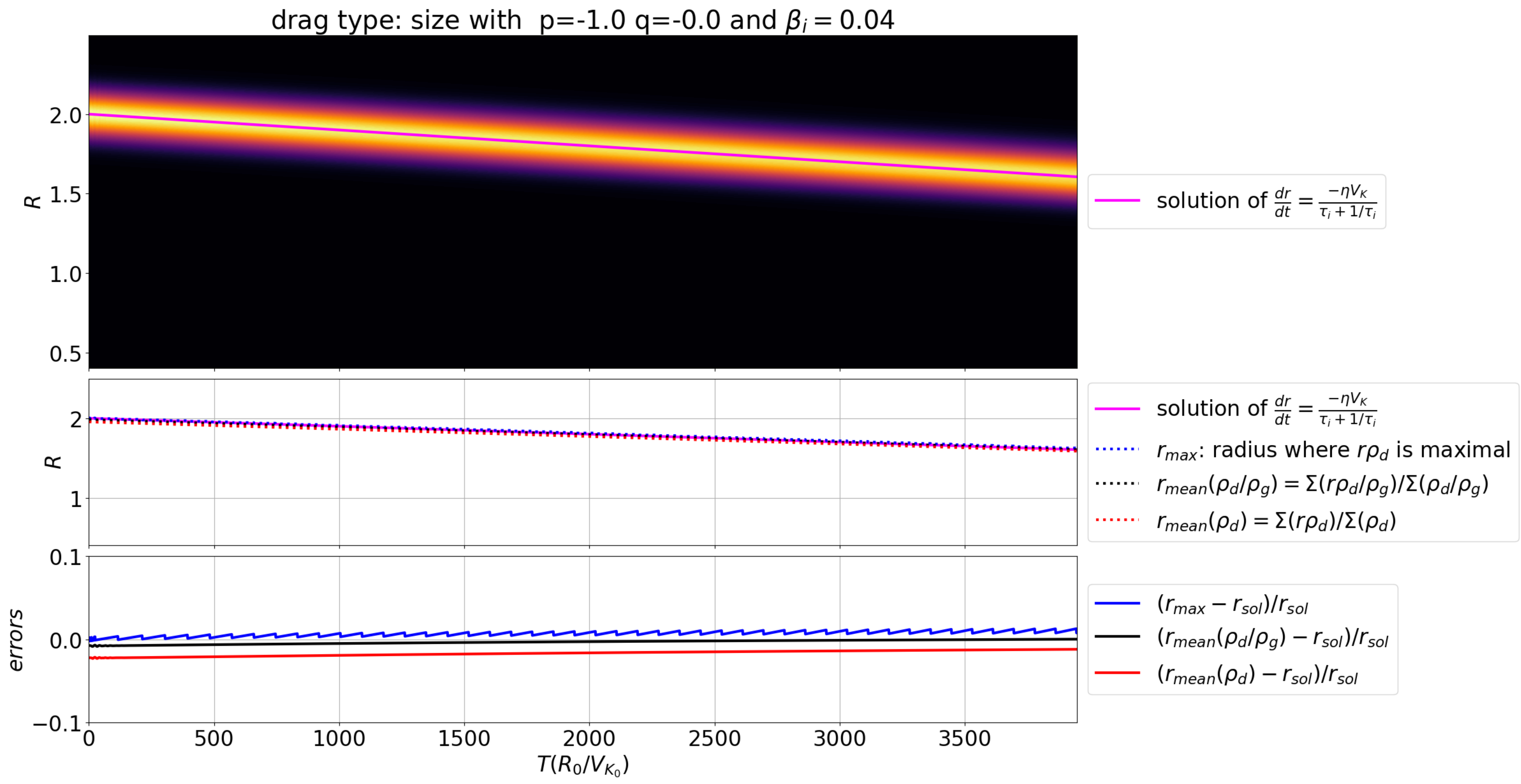
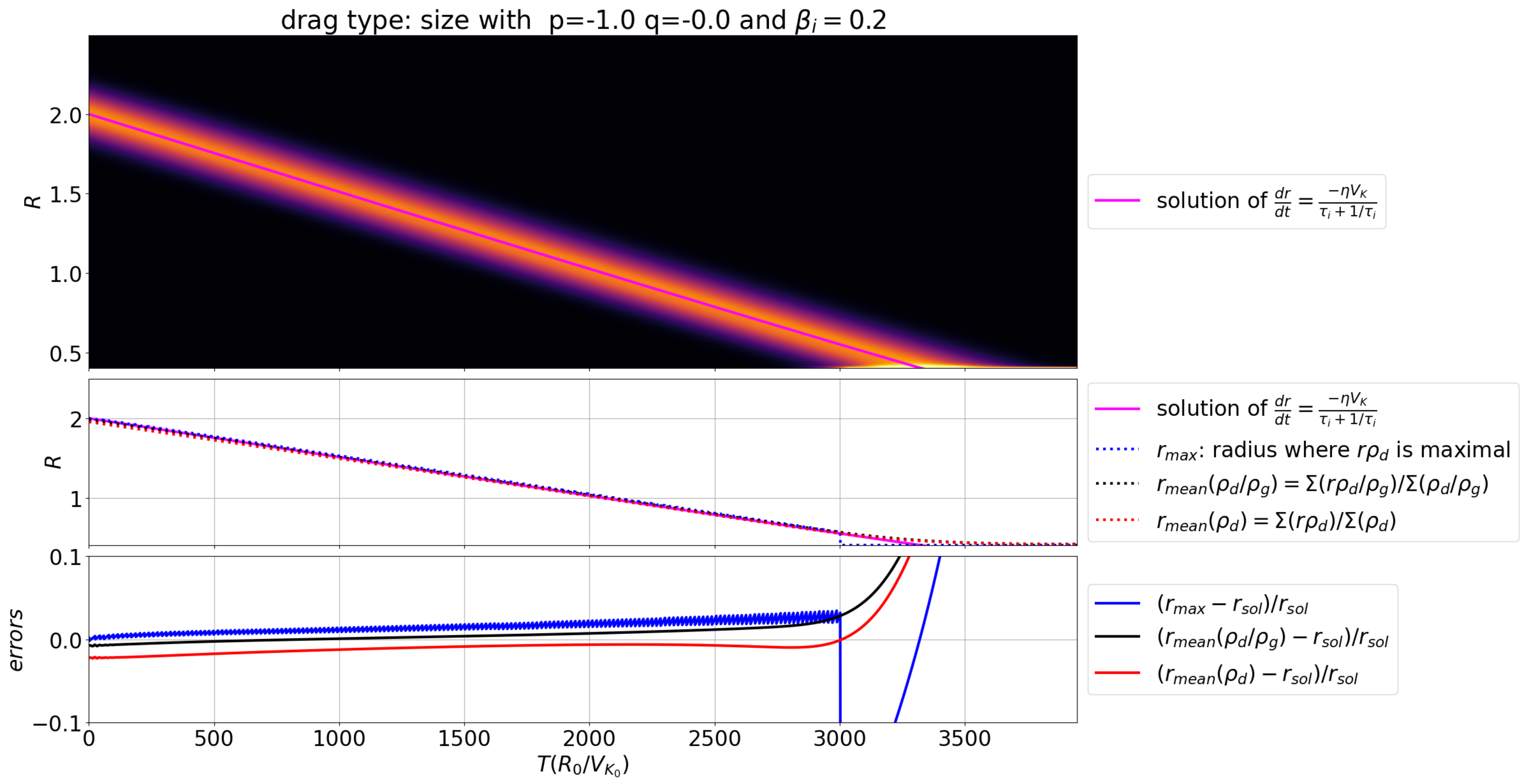
$(r_{mean}(\rho_d/\rho_g) - r_{sol})/r_{sol}$
$(r_{mean}(\rho_d) - r_{sol})/r_{sol}$



drag type: size with p=-1.5 q=-1.0 and $\beta_i = 1$
R
2.0
1.5
1.0
0.5
solution of $\frac{dr}{dt} = \frac{-\eta V_K}{\tau_i + 1/\tau_i}$
R
2
1
solution of $\frac{dr}{dt} = \frac{-\eta V_K}{\tau_i + 1/\tau_i}$
r_{max}: radius where $r\rho_d$ is maximal
$r_{mean}(\rho_d/\rho_g) = \Sigma(r\rho_d/\rho_g)/\Sigma(\rho_d/\rho_g)$
$r_{mean}(\rho_d) = \Sigma(r\rho_d)/\Sigma(\rho_d)$
errors
0.1
0.0
−0.1
$(r_{max} - r_{sol})/r_{sol}$
$(r_{mean}(\rho_d/\rho_g) - r_{sol})/r_{sol}$
$(r_{mean}(\rho_d) - r_{sol})/r_{sol}$
0
1000
2000
3000
4000
5000
$T(R_0/V_{K_0})$



drag type: size with p=-1.0 q=-0.0 and $\beta_i = 0.04$
R
2.0
1.5
1.0
0.5
solution of $\frac{dr}{dt} = \frac{-\eta V_K}{\tau_i + 1/\tau_i}$
2
1
solution of $\frac{dr}{dt} = \frac{-\eta V_K}{\tau_i + 1/\tau_i}$
r_{max}: radius where $r\rho_d$ is maximal
$r_{mean}(\rho_d/\rho_g) = \Sigma(r\rho_d/\rho_g)/\Sigma(\rho_d/\rho_g)$
$r_{mean}(\rho_d) = \Sigma(r\rho_d)/\Sigma(\rho_d)$
$errors$
0.1
0.0
−0.1
$(r_{max} - r_{sol})/r_{sol}$
$(r_{mean}(\rho_d/\rho_g) - r_{sol})/r_{sol}$
$(r_{mean}(\rho_d) - r_{sol})/r_{sol}$
0
500
1000
1500
2000
2500
3000
3500
$T(R_0/V_{K_0})$



drag type: size with p=-1.0 q=-0.0 and $\beta_i = 0.2$
R
2.0
1.5
1.0
0.5
solution of $\frac{dr}{dt} = \frac{-\eta V_K}{\tau_i + 1/\tau_i}$
R
2
1
solution of $\frac{dr}{dt} = \frac{-\eta V_K}{\tau_i + 1/\tau_i}$
r_{max}: radius where $r\rho_d$ is maximal
$r_{mean}(\rho_d/\rho_g) = \Sigma(r\rho_d/\rho_g)/\Sigma(\rho_d/\rho_g)$
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errors
0.1
0.0
−0.1
$(r_{max} - r_{sol})/r_{sol}$
$(r_{mean}(\rho_d/\rho_g) - r_{sol})/r_{sol}$
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0
500
1000
1500
2000
2500
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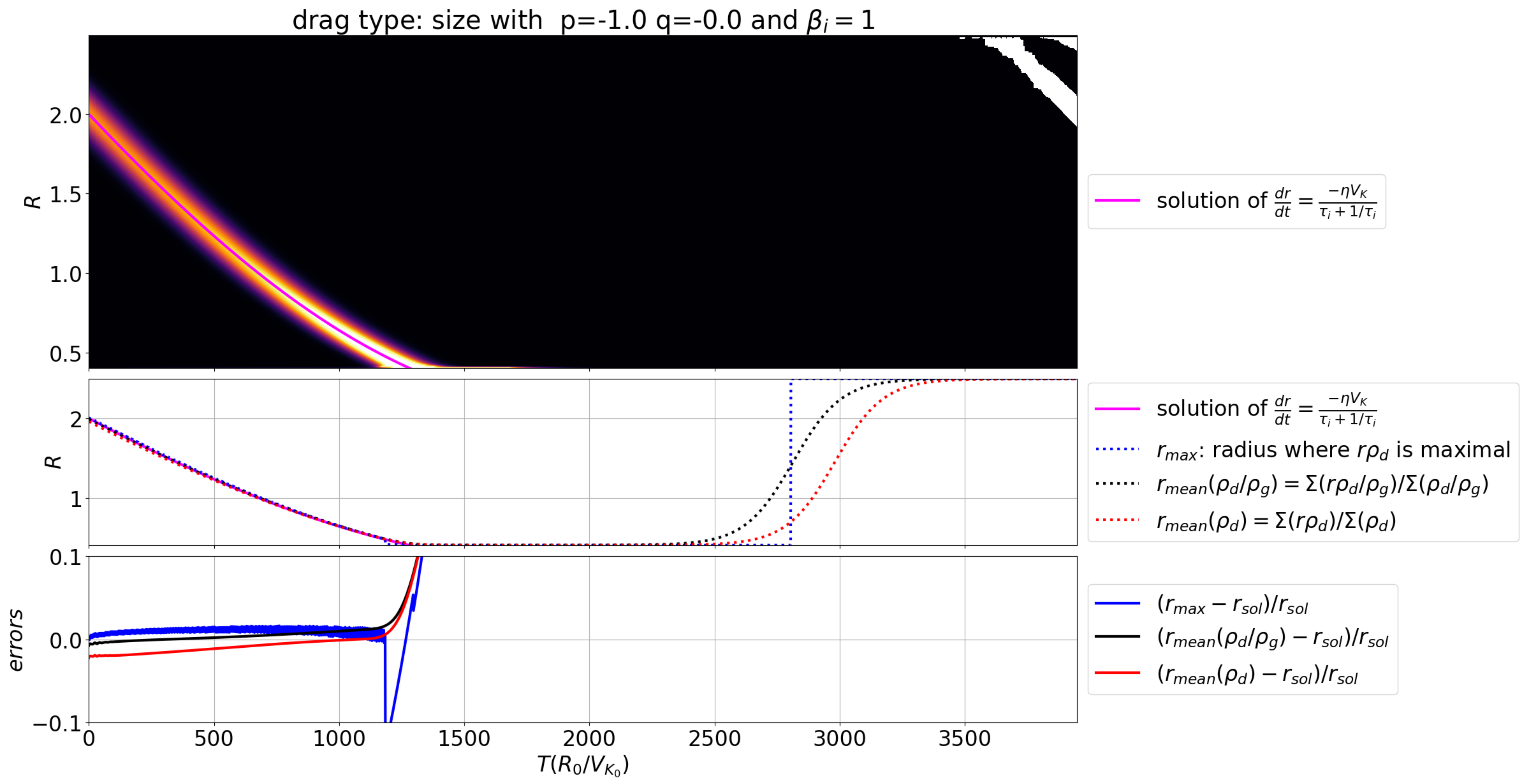
3500
$T(R_0/V_{K_0})$



drag type: size with p=-1.0 q=-0.0 and $\beta_i = 1$
R
2.0
1.5
1.0
0.5
solution of $\frac{dr}{dt} = \frac{-\eta V_K}{\tau_i + 1/\tau_i}$
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0.1
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0
500
1000
1500
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$(r_{max} - r_{sol})/r_{sol}$
$(r_{mean}(\rho_d/\rho_g) - r_{sol})/r_{sol}$
$(r_{mean}(\rho_d) - r_{sol})/r_{sol}$

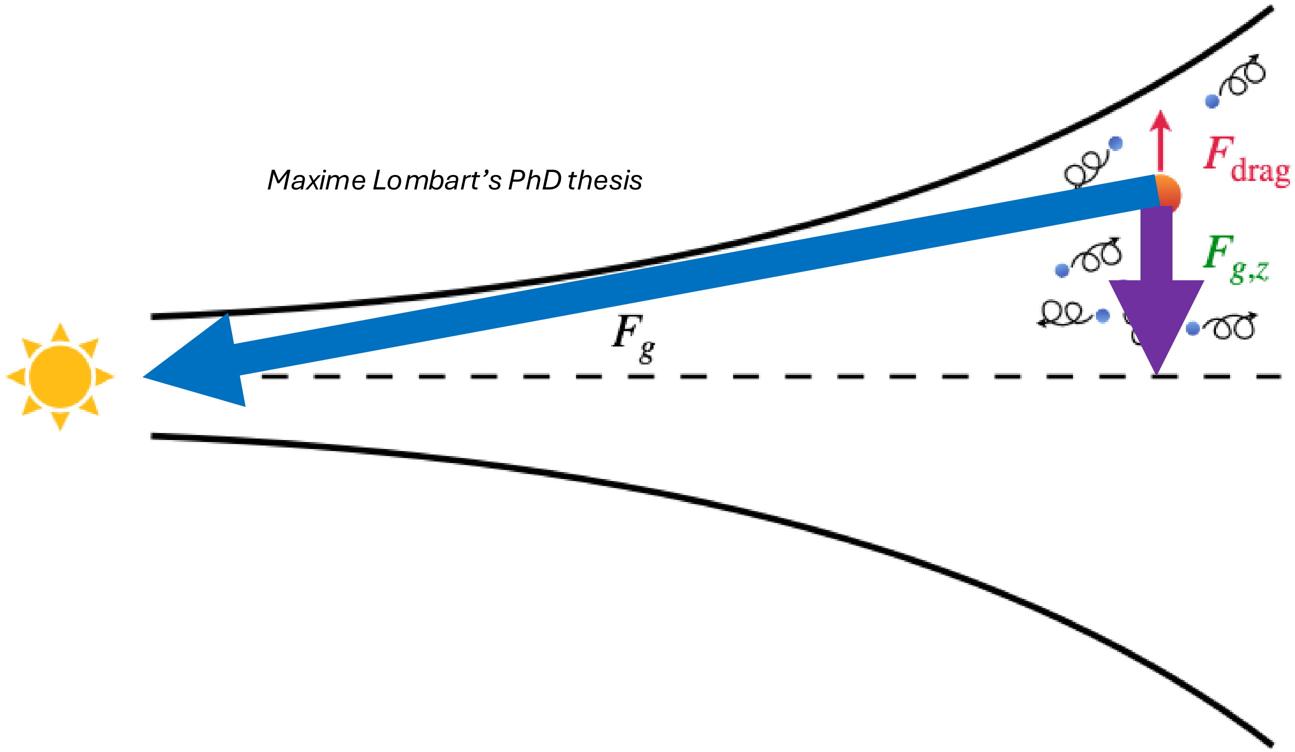
Dust simulations with Idefix

$$\frac{\partial(\rho_{d_i})}{\partial t} + \vec{\nabla}\cdot(\rho_{d_i}\vec{v}_{d_i}) = 0$$

$$\frac{\partial(\rho_{d_i}\vec{v}_{d_i})}{\partial t} + \vec{\nabla}\cdot(\rho_{d_i}\vec{v}_{d_i}\otimes\vec{v}_{d_i}) = \rho_{d_i}\vec{g} + \vec{f}_{g\to d_i}$$

For each dust species i

Maxime Lombart's PhD thesis



If we put dust in an inviscid gas disk at equilibrium, we expect it to:

- Quickly settle vertically towards the midplane
- Slowly drift radially towards the star

Vertical settling setup

- 1D Inviscid shearing box, with dust initially far above the midplane
- Vertical stratification: $\vec{g} = -z\Omega_0^2\vec{e}_z$ and $\rho = \rho_0 e^{-\frac{z^2}{2H}}$

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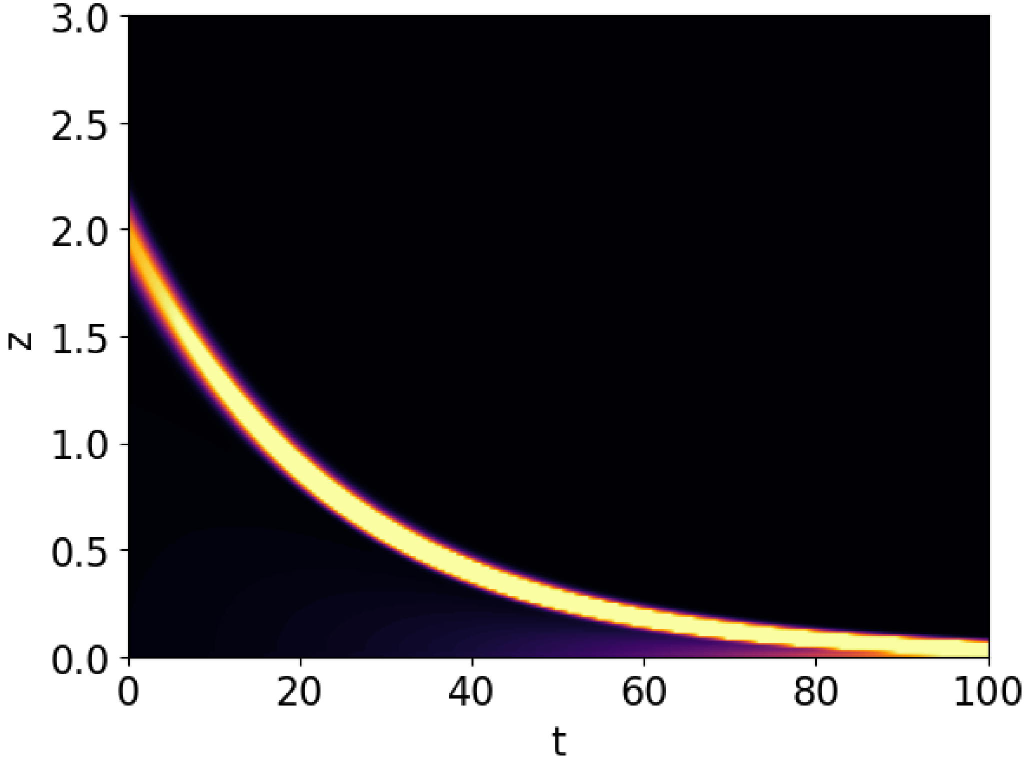

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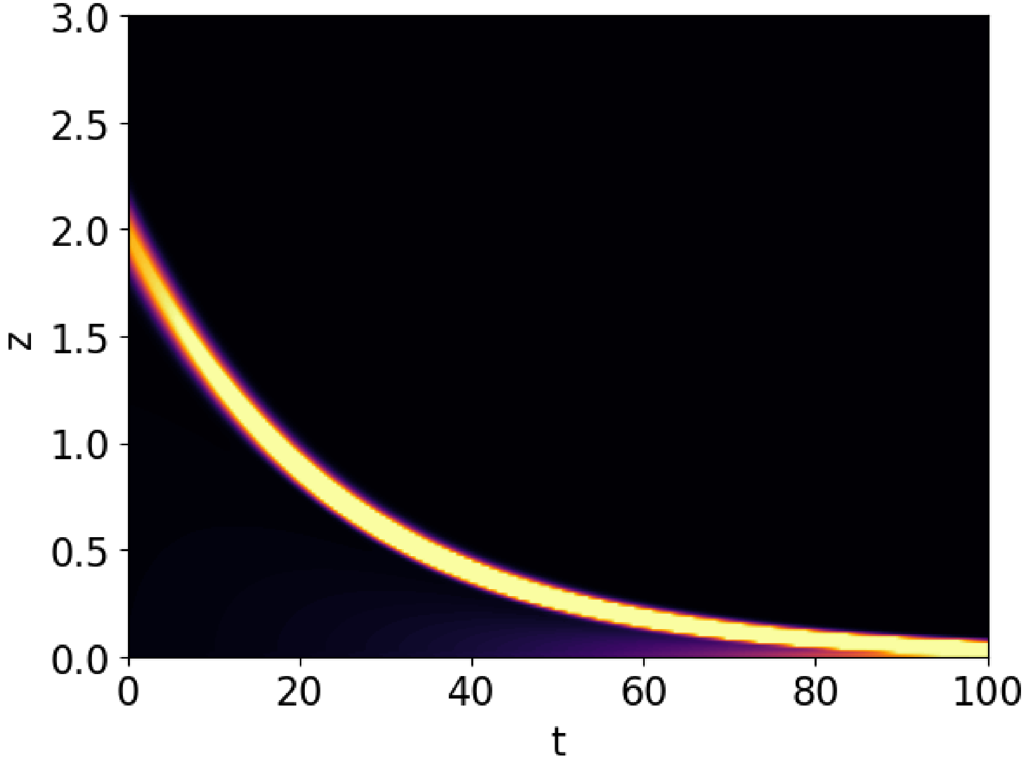
- Dust motion equation $\frac{d^2z}{dt^2} + \frac{1}{t_d}\frac{dz}{dt} + \Omega^2 z = 0$ admits an analytic solution for the tau drag



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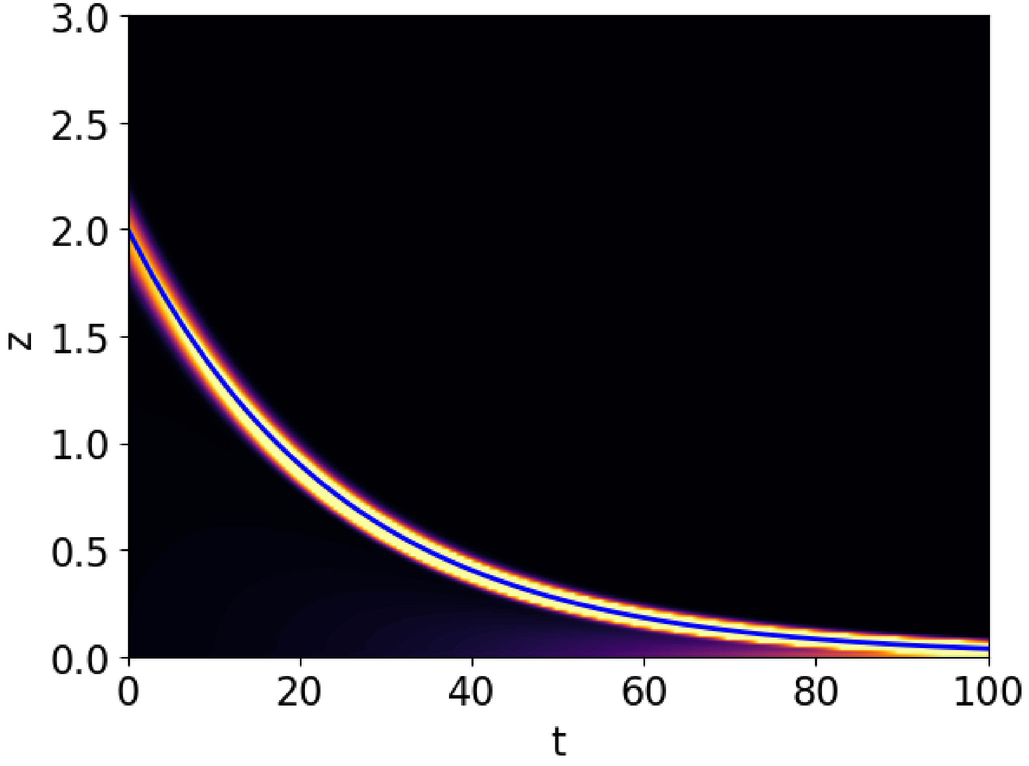
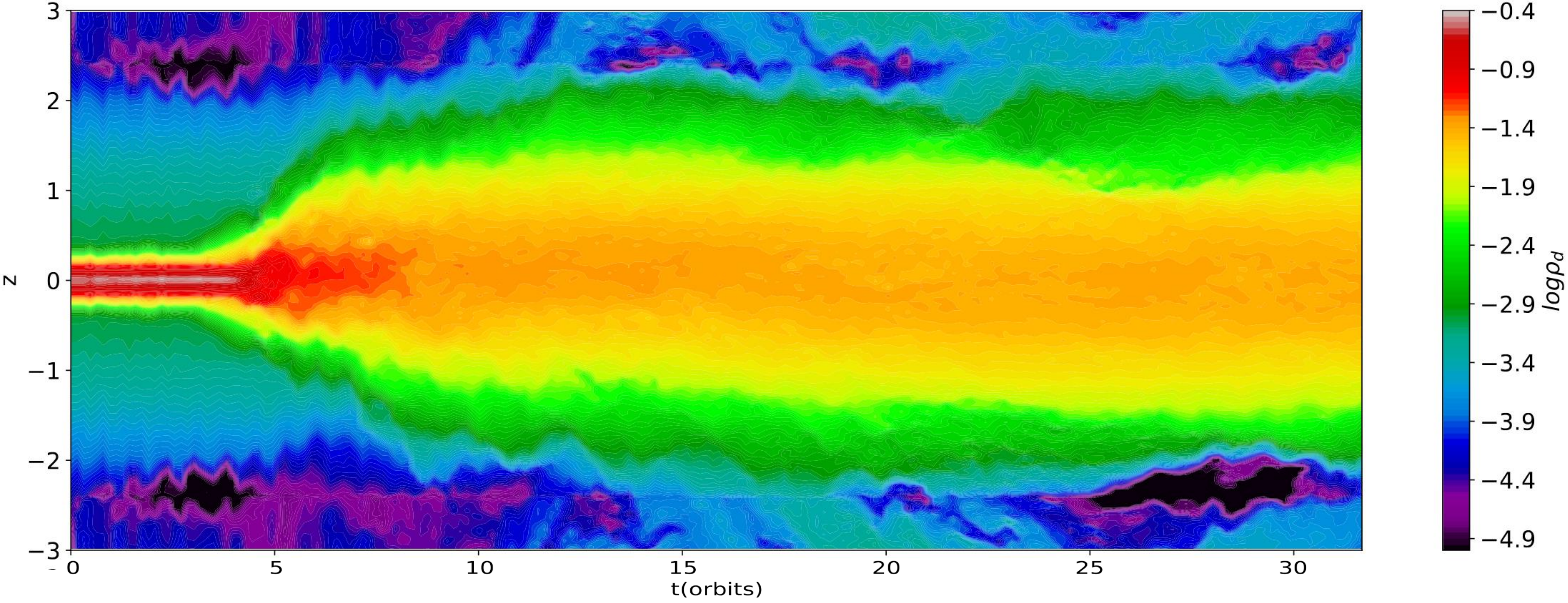


Settling in a MRI turbulent disk (ideal MHD)



Comparisons to Fromang & Papaloizou(2006), Okuzumi & Hirose (2011), Zhu, Stone & Bai (2015)...

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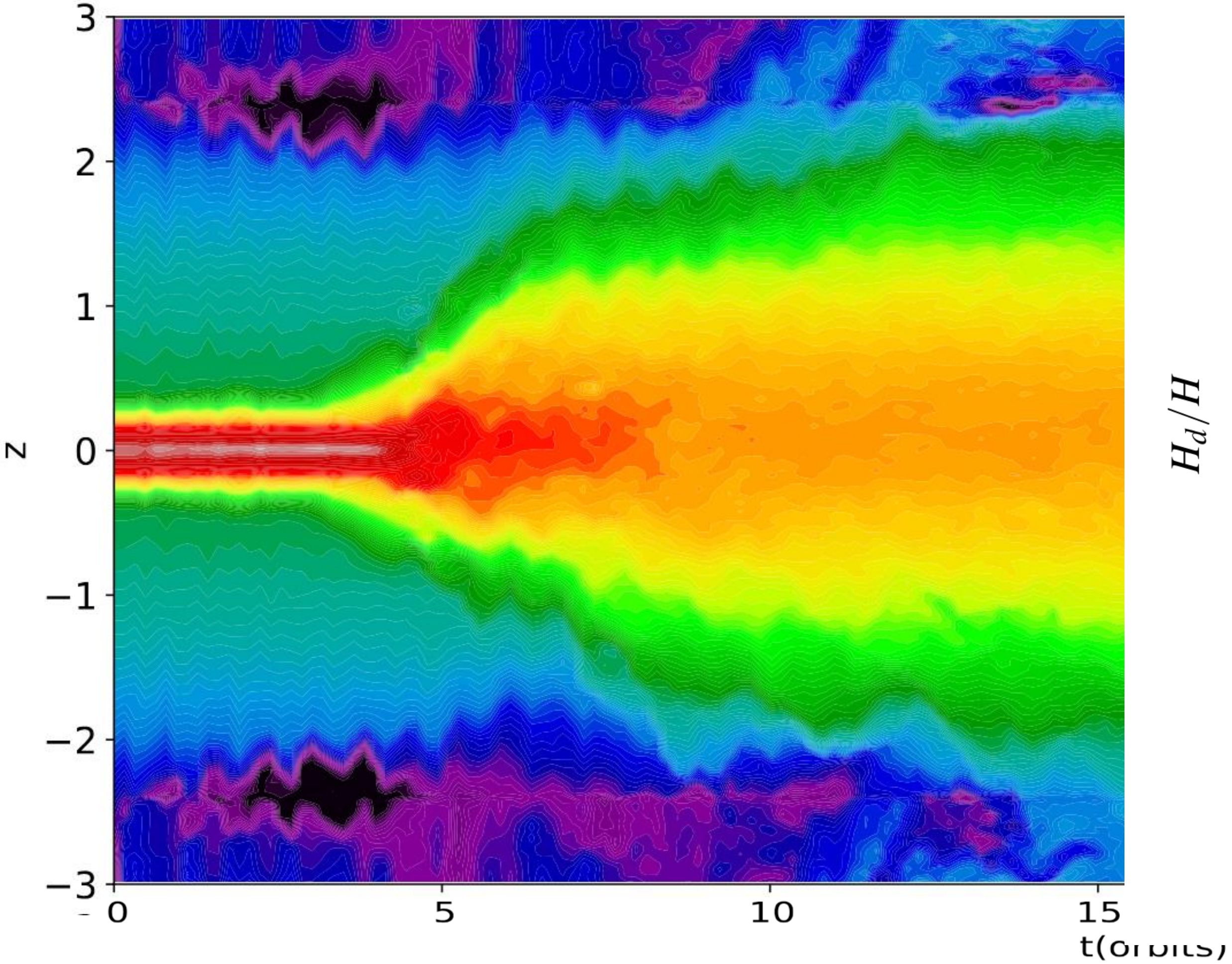
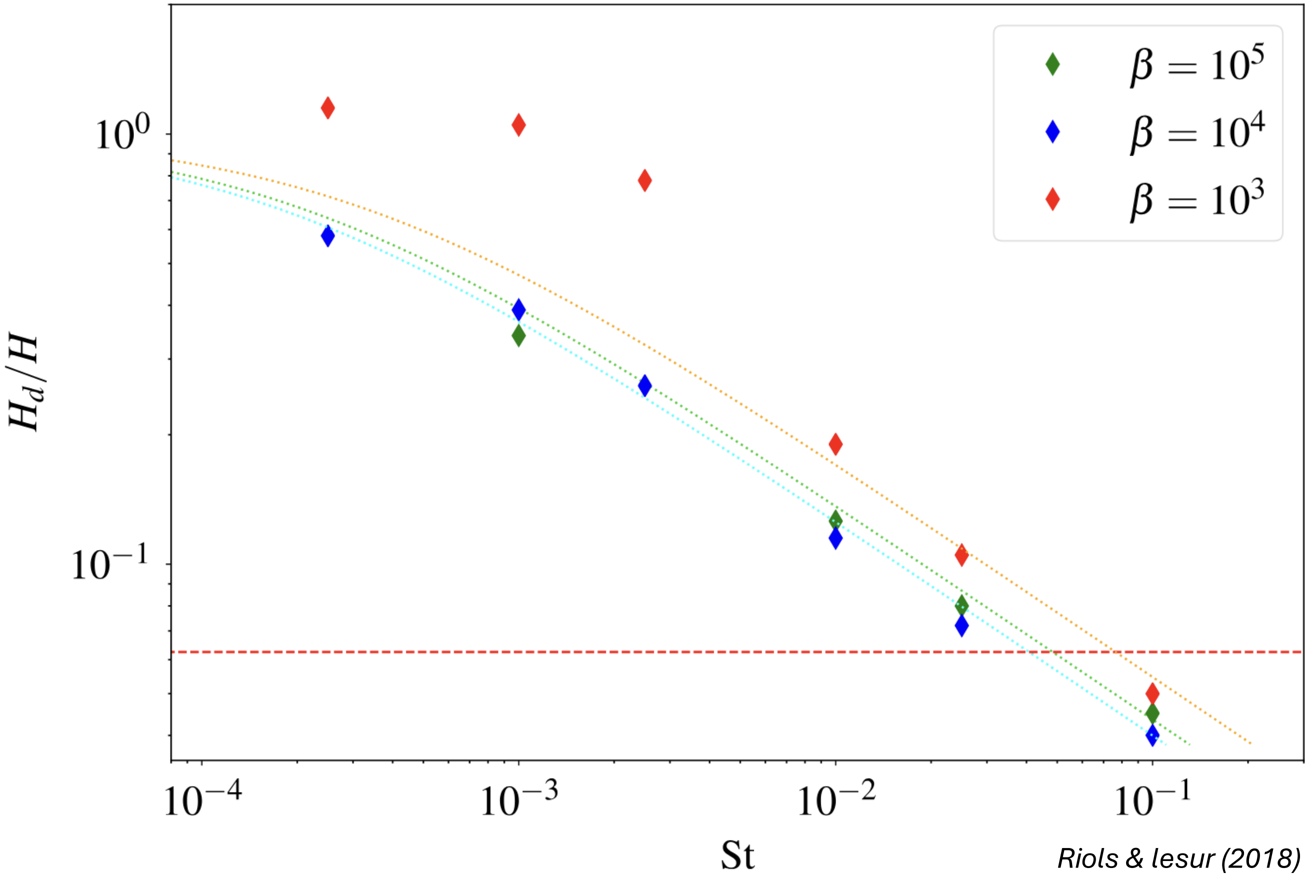




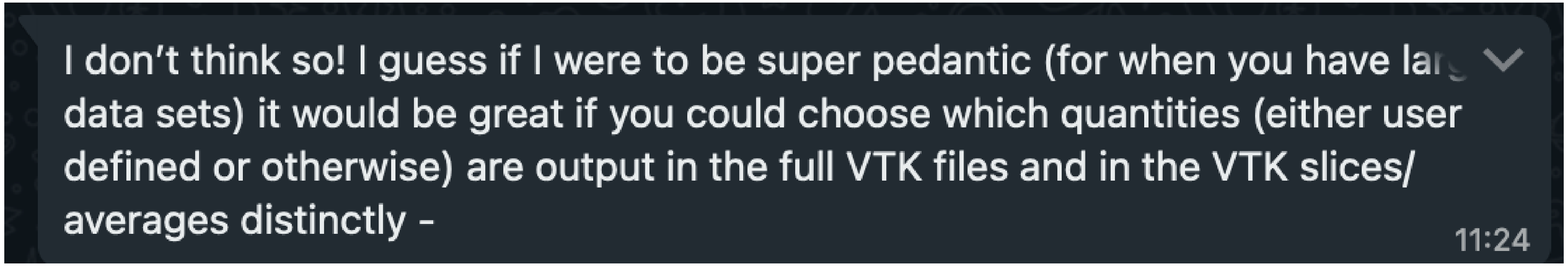
Comparisons to Fromang & Papaloizou(2006), Okuzumi & Hirose (2011), Zhu, Stone & Bai (2015)...

Perspectives with Idefix

- Writing on the convergence of ideal MRI zero net flux simulations
  - How useful is the MRI quality factor ?
  - Can such simulations converge ?
- Put dust in simulations with active and dead zone of PPDs
  - How much is retained in vortices at the interface ?
  - How much is entrained onto the star or falls onto the star ?
- Longer term perspectives

Complaints about Idefix

- Overall very happy with the code
- Very useful test setups
  - ➢ Maybe not enough with dust
  - ➢ Could use more guidance to know what test is useful for what



Matthew Roberts

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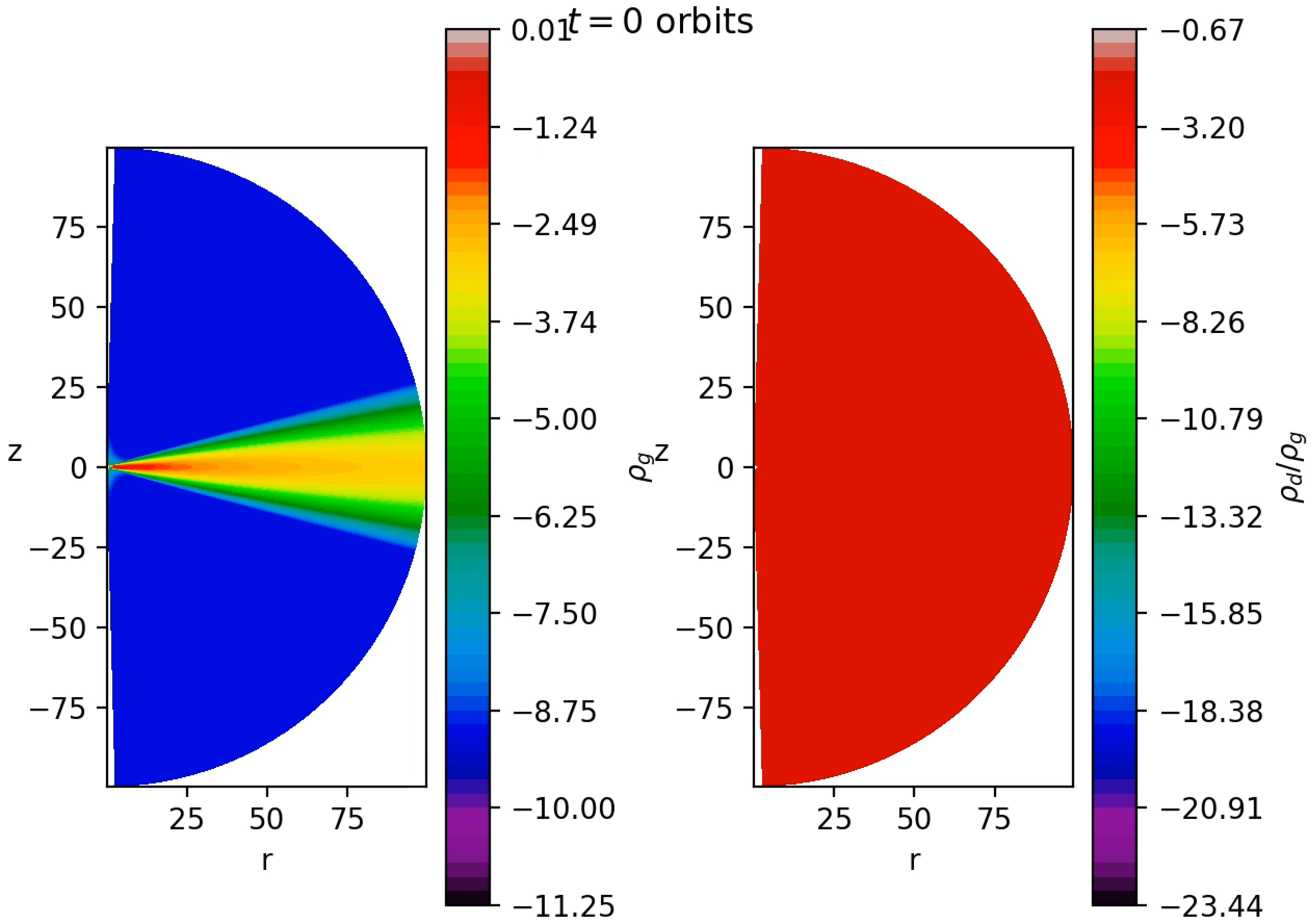

Riols & Lesur (2020)-like