Unveiling Variability in T Tauri Disk Inner Rims:
Radiative Simulations with IDEFIX

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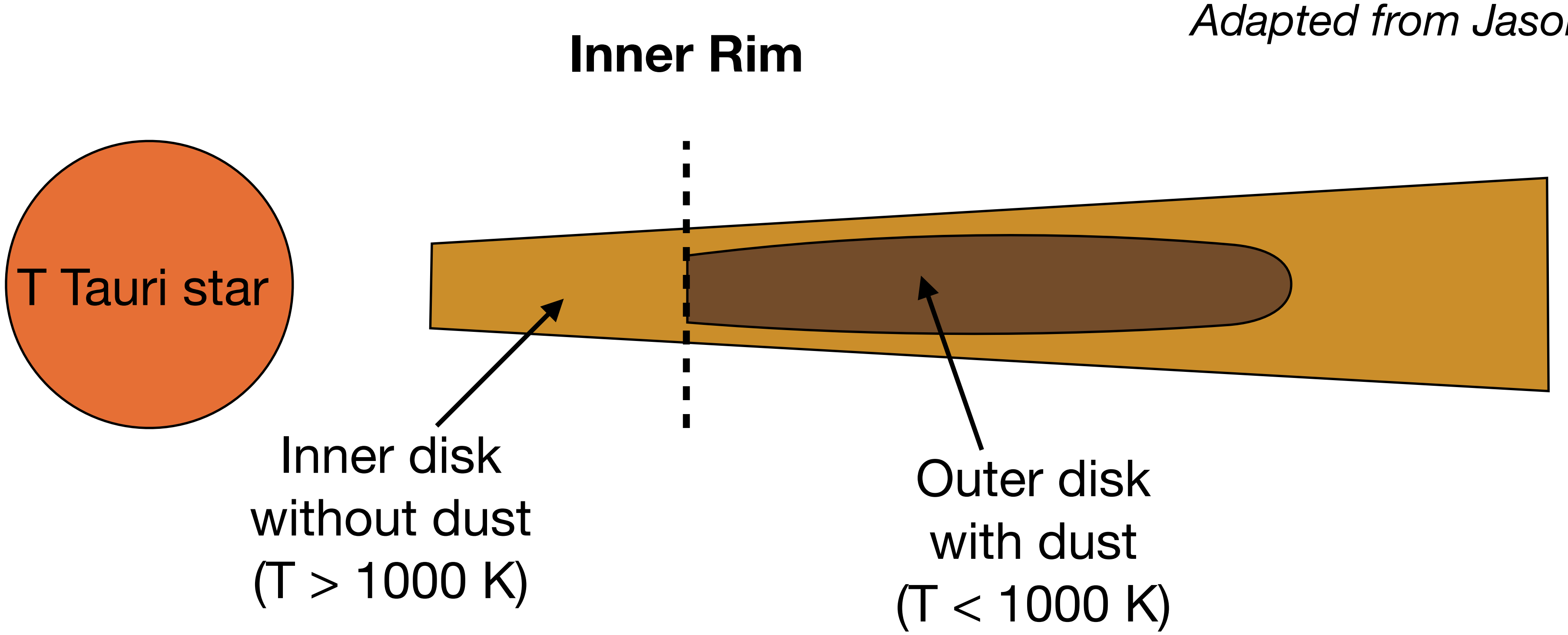
T Tauri disks and Inner Rim

T Tauri disks are made of gas and dust

Adapted from Jason Champion's PHD



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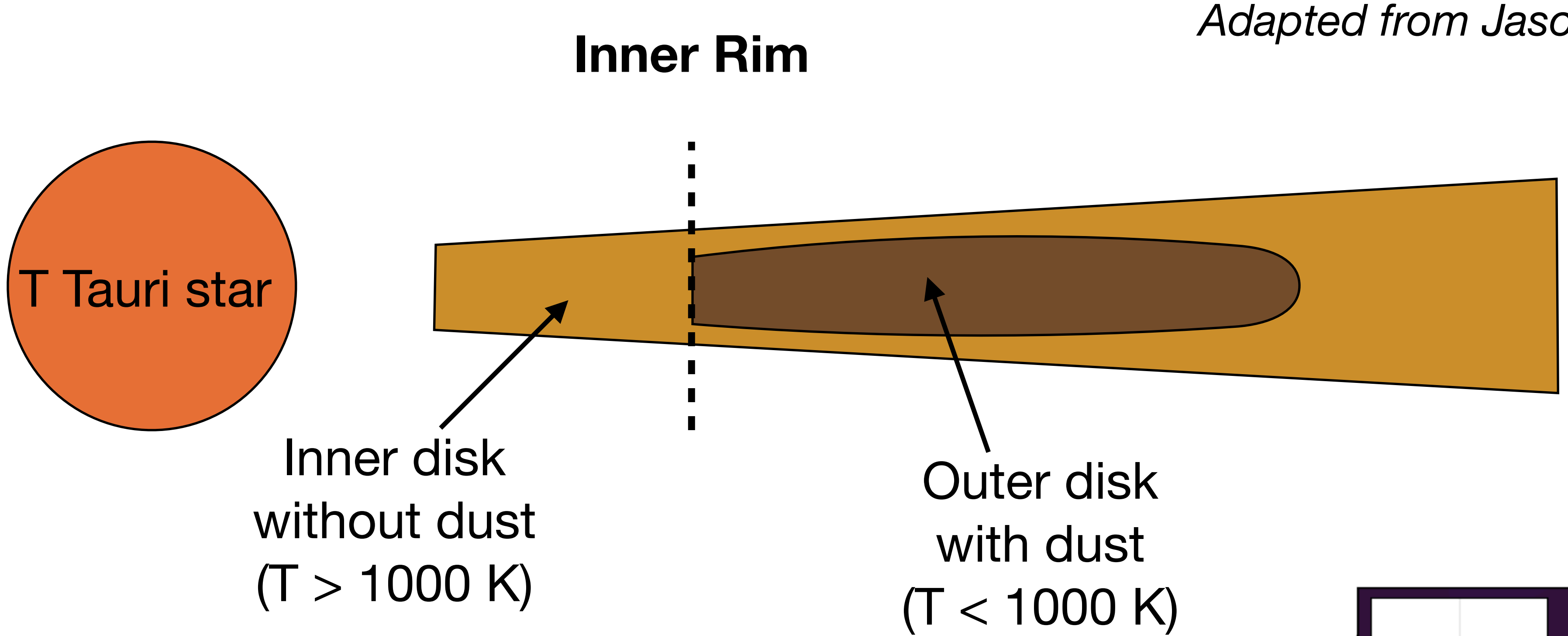
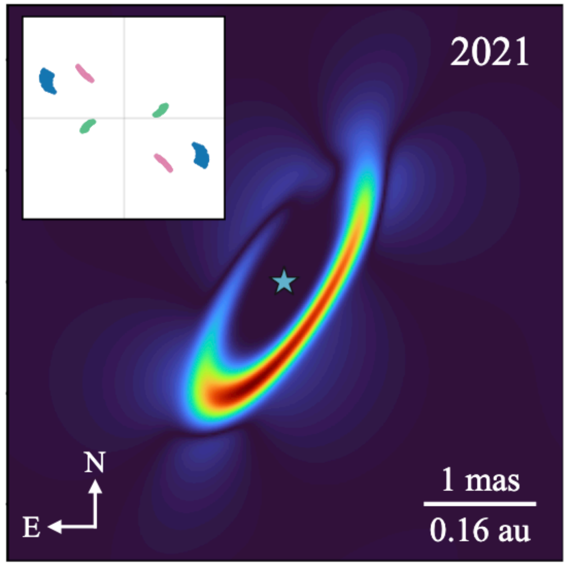


VLTI instrument GRAVITY can now resolve this inner rim !

Inner rim is located around 0.1 - 0.3 AU

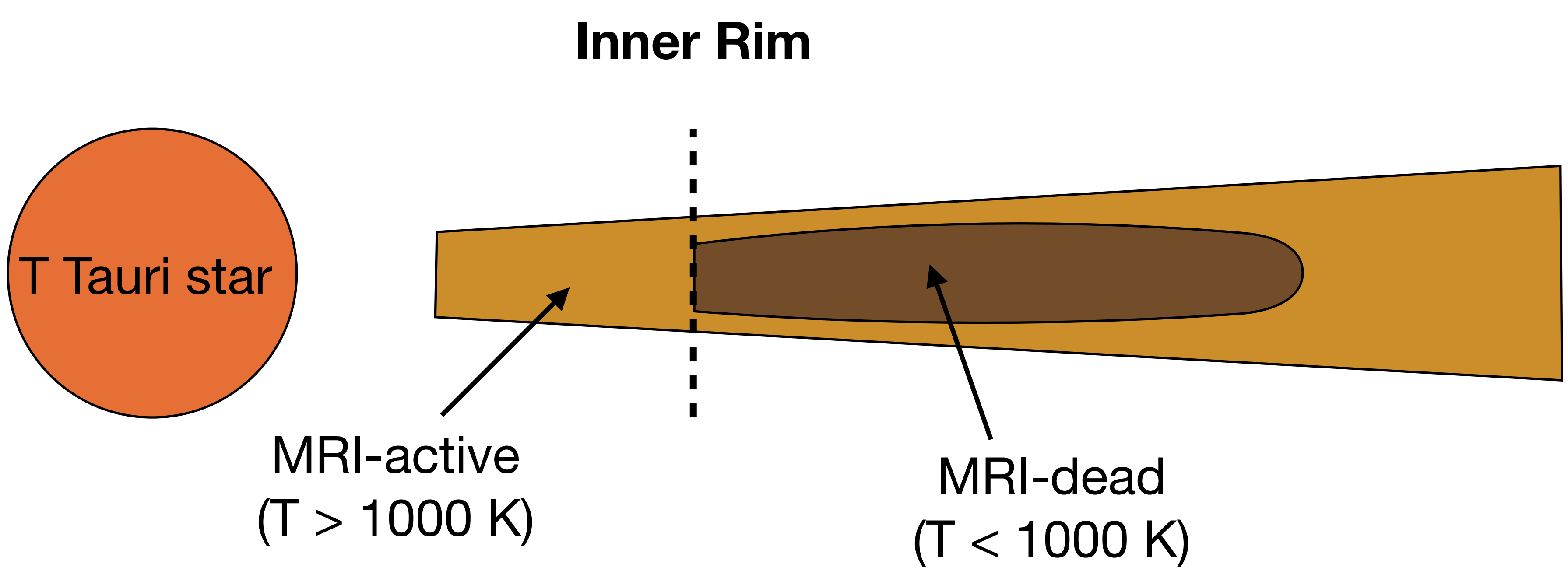
(Perraut et al. 2021)



Reconstruction of the inner rim from GRAVITY data
(Soulain et al. 2023)

MRI and Pressure Bumps

Inner rim close to radius where magneto-rotational instability (MRI) is triggered



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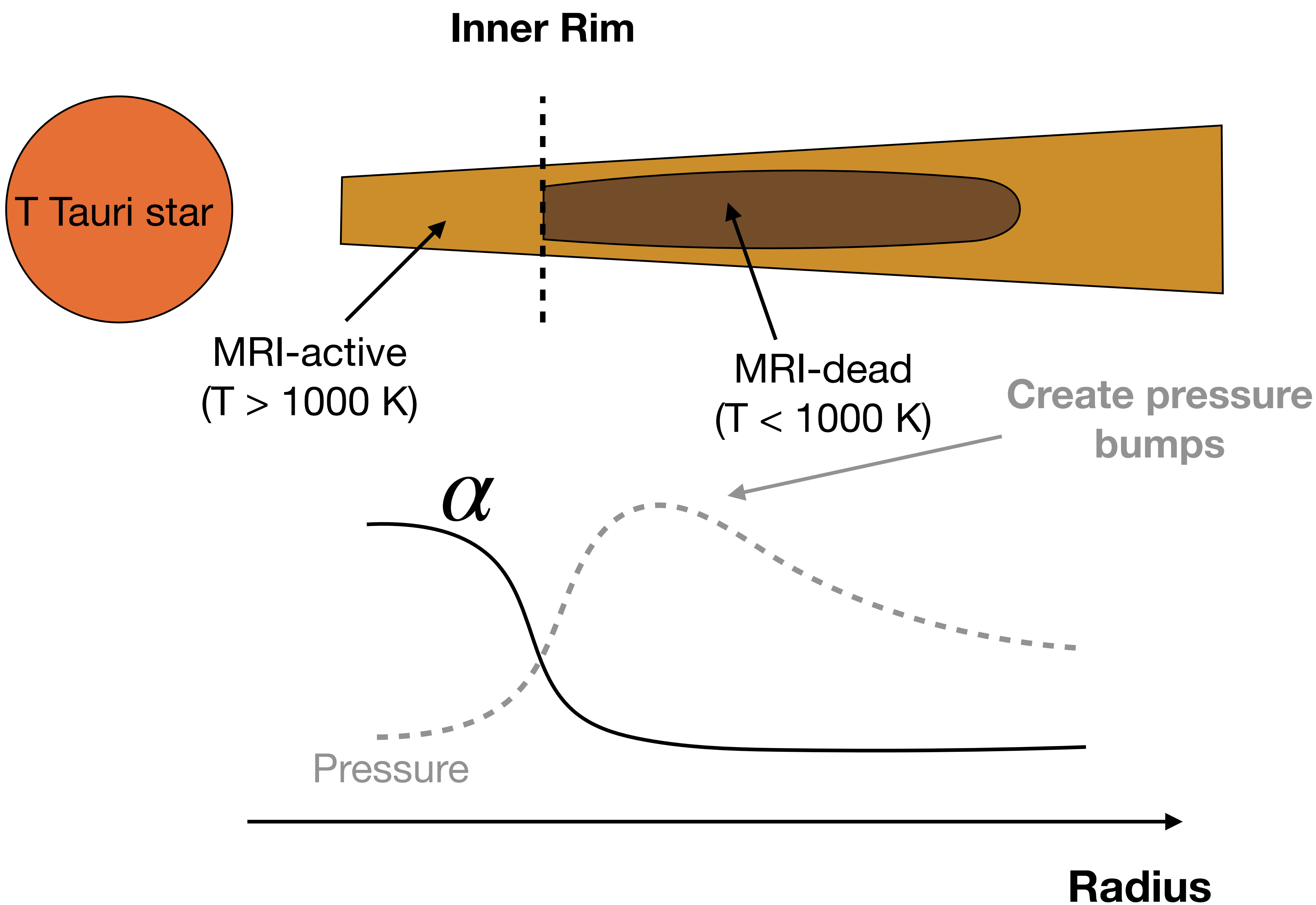
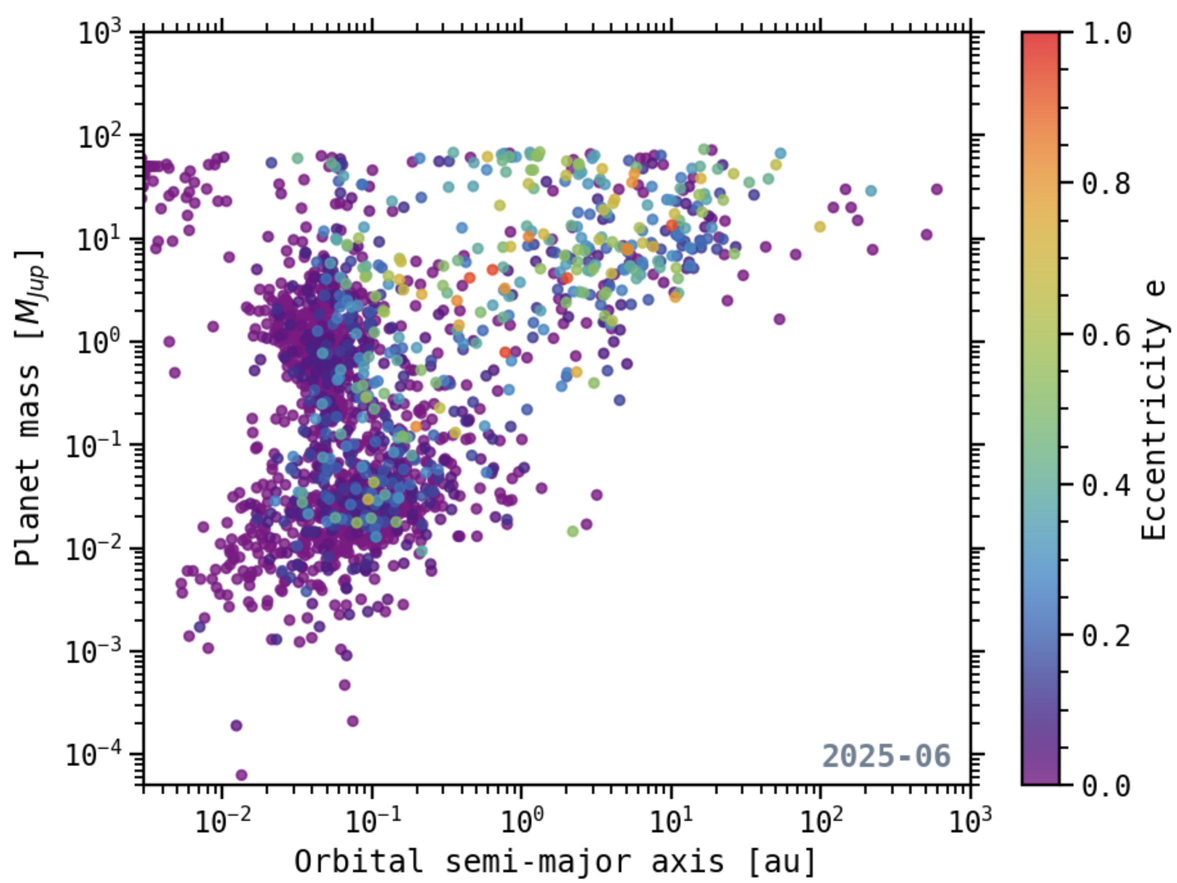


Inner Rim and Planets

Pressure bumps :

- **Trap dust** *(Kretke et al. 2007)*
- **Halt planet migration** *(Masset et al. 2006)*

Courtesy of G. Wafflard-Fernandez



Lots of planets detected around 0.1 AU !

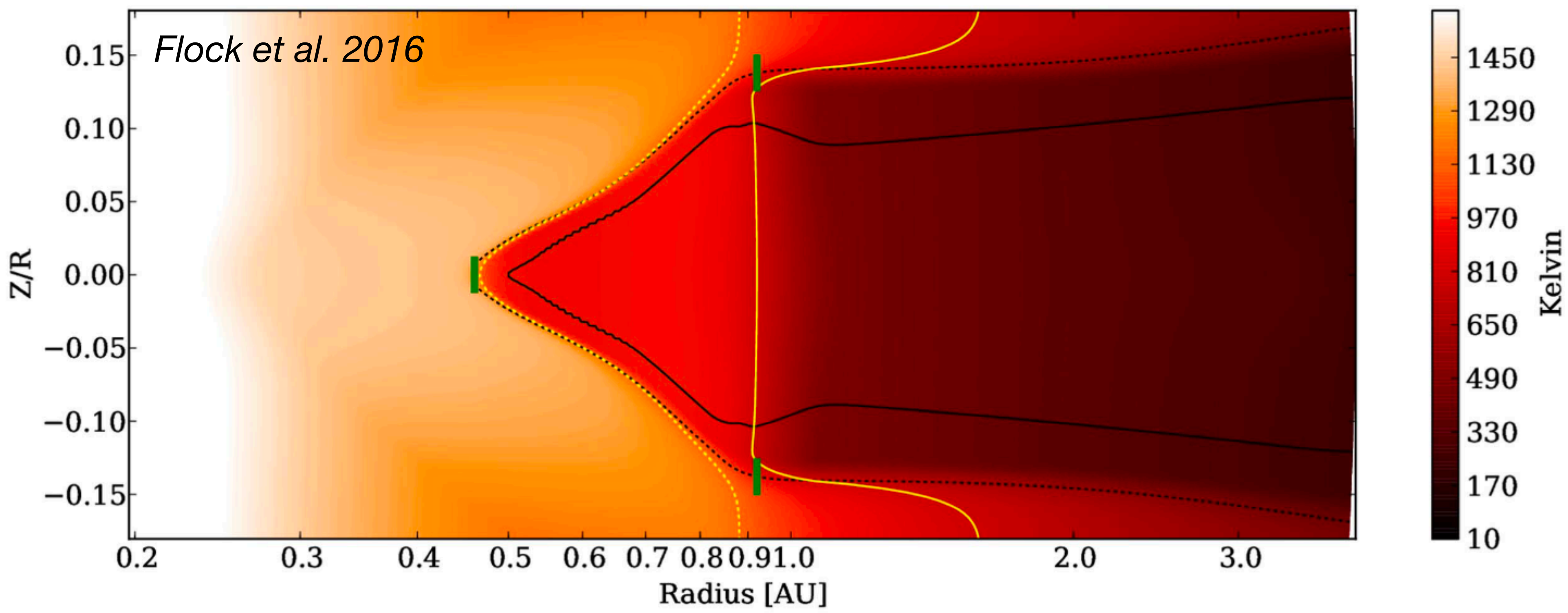
Inner rim likely plays a role

Inner Rim models

Semi-analytical models and simulations found that inner rim radius is stable over time

(Latter & Balbus 2012, Flock et al. 2016)

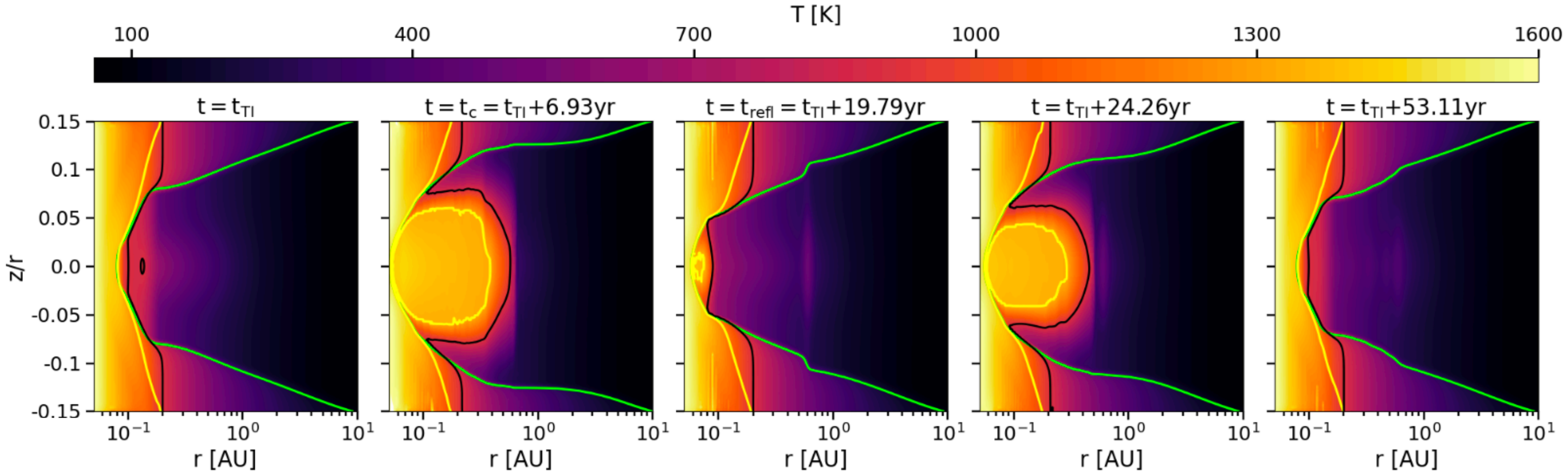
However, mostly focused on Herbig stars

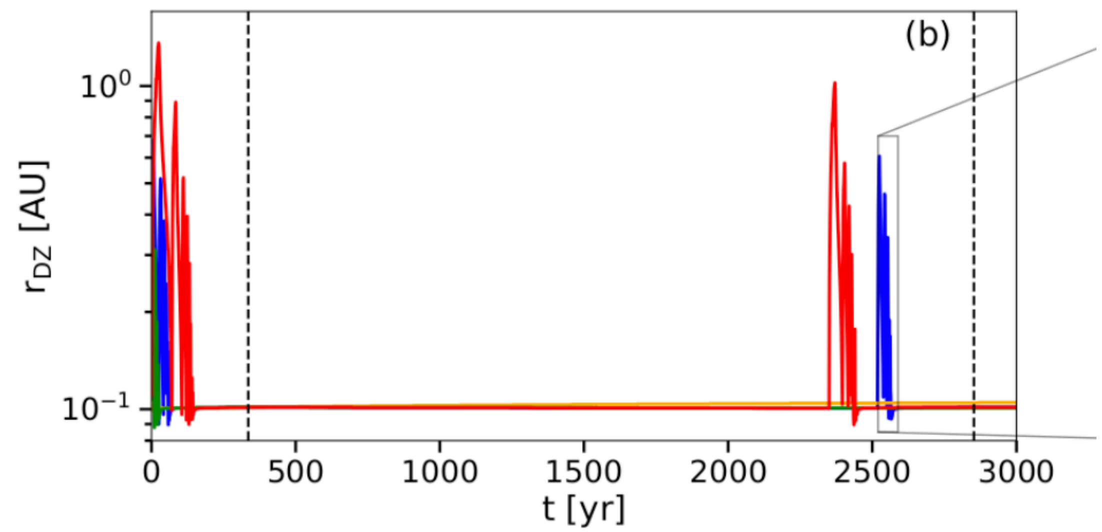


Inner Rim models

Recent work on T Tauri stars found unsteady behavior

(Cecil & Flock 2024)





Inner rim can increase by a factor of 10 over time.

(Cecil & Flock 2024)

First application of IDEFIX

Can we better understand the inner rim evolution ?

Radiative simulations with IDEFIX

We developed a radiative module in the MHD, finite-volume code, IDEFIX
(Lesur et al. 2023)

IDEFIX is a C++ code using the Kokkos Library for performance portability

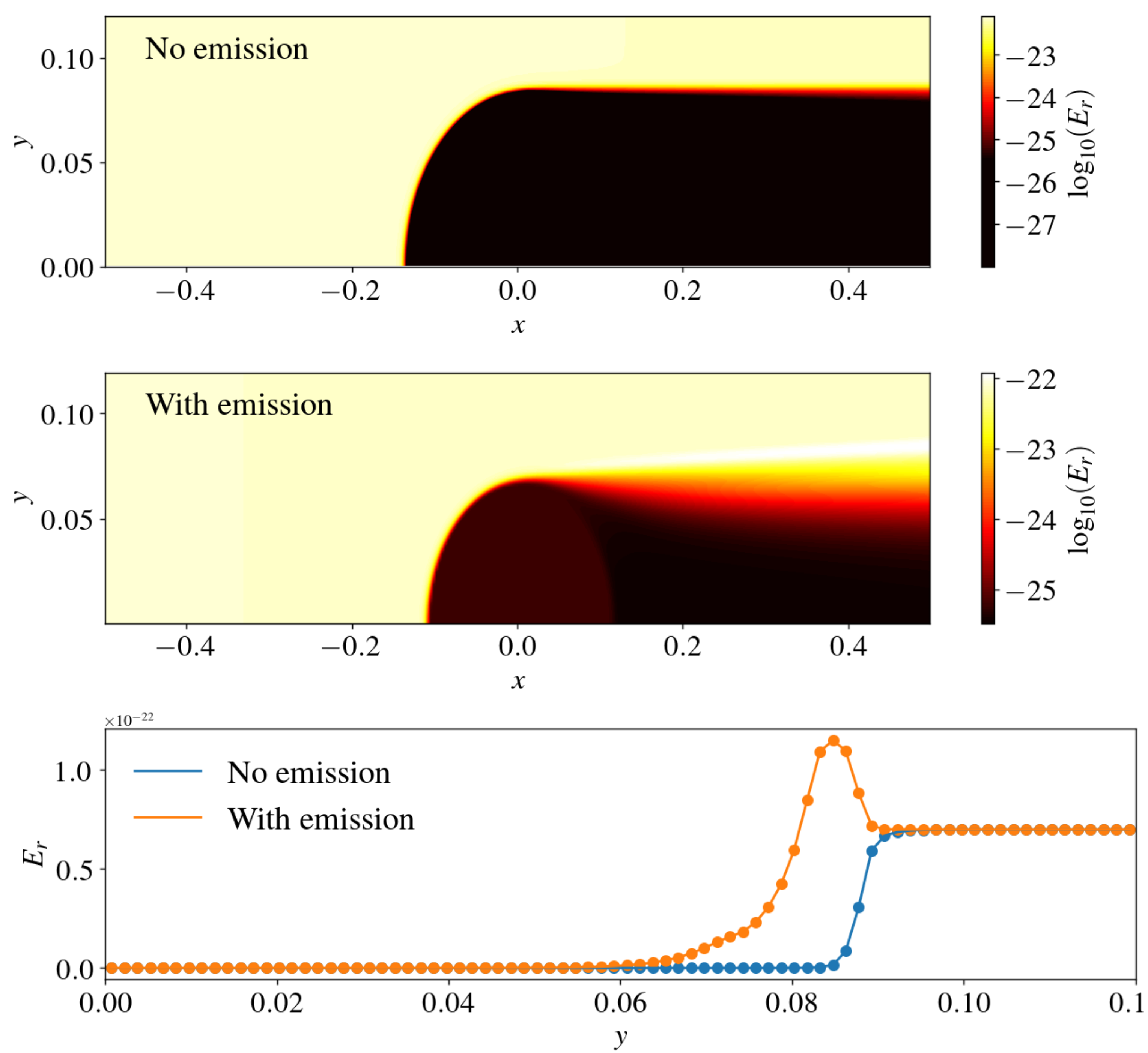
Radiative module uses :
(Largely follows Melon Fuksman et al. 2019, 2021)

- M1 approximation (able to handle shadows)
- Explicit for transport (reduced speed of light approximation)
- Semi-implicit for source terms *(same as in Commerçon et al. 2011)*
- Trivially multi-frequency

Radiative module performant on CPUs and GPUs
Radiative simulation only cost twice a non-radiative simulation
(~5e7 cells/s for a spherical 3D, MHD simulation with radiative transfer on Mi250)

Radiation transport

HLL with PLM, $N_x \times N_y = 140 \times 40$

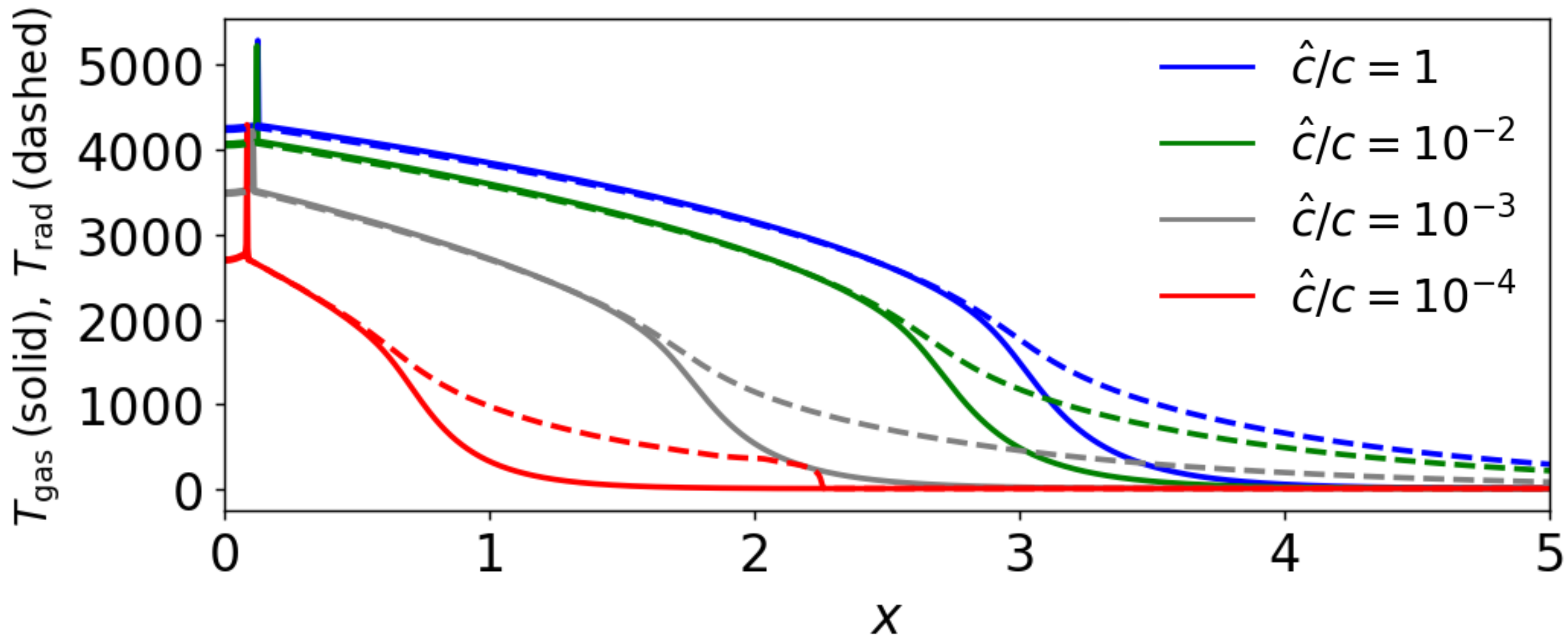


M1 scheme can well recover shadows

(Hayes & Norman 2003, González et al. 2007, Skinner et al. 2013)

Reduced speed of light

HLL with PLM, $N_x = 2048$



To avoid artifacts, we need $\hat{c} \gg \max(v_{\rm dyn}, v_{\rm diff})$

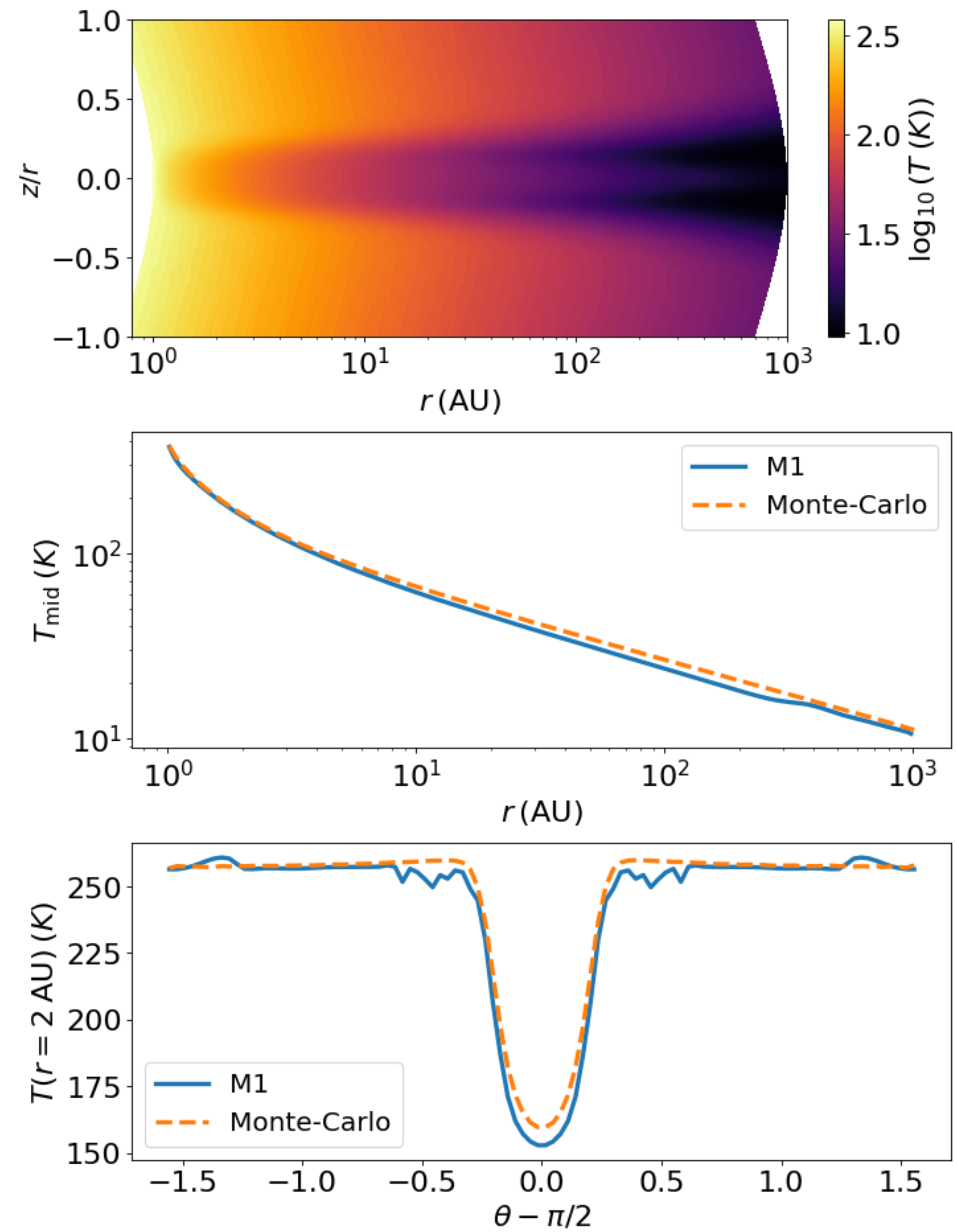
But $v_{\rm dyn}$ might not be trivial

$\hat{c}$ needs to be chosen with care for the problem at hand!

Stellar irradiation test

Test of stellar irradiation of a passive disk compares well with Monte-Carlo simulation

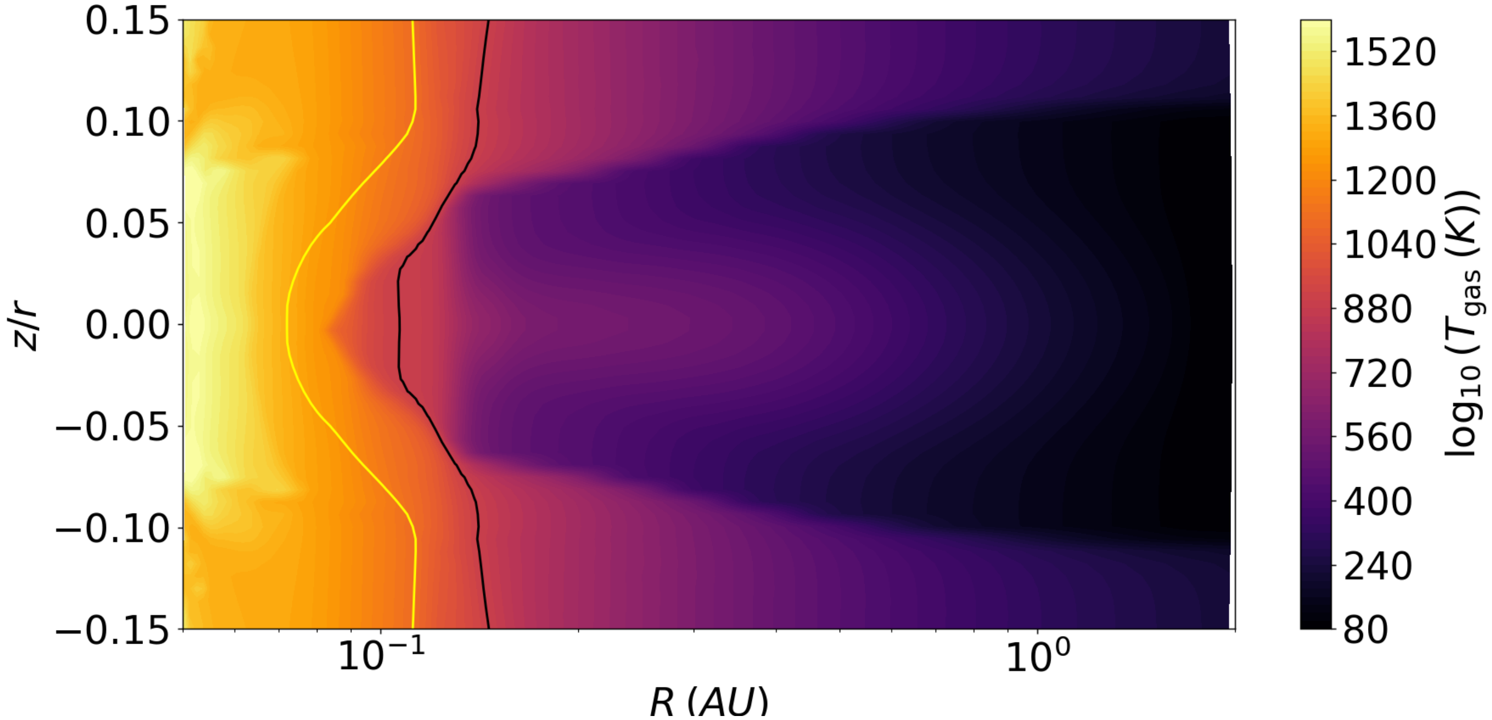
HLL with PLM, $N_r \times N_\theta = 240 \times 100$



Structure of the inner rim

2D viscous, radiative simulations of an active irradiated disk

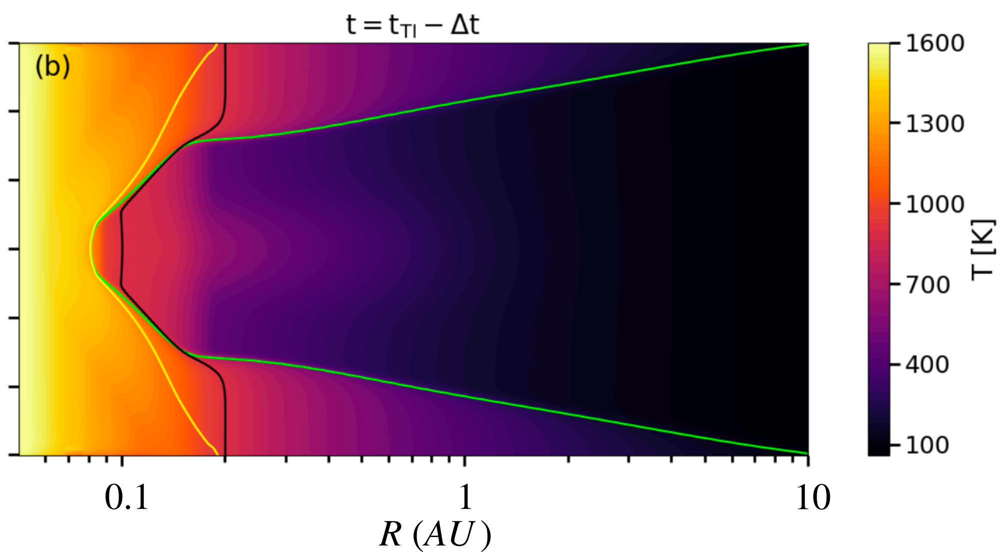
Scepi et al. 2025 in prep.



MRI activation is close to dust sublimation

Yellow line : dust sublimation
Black line : MRI activation

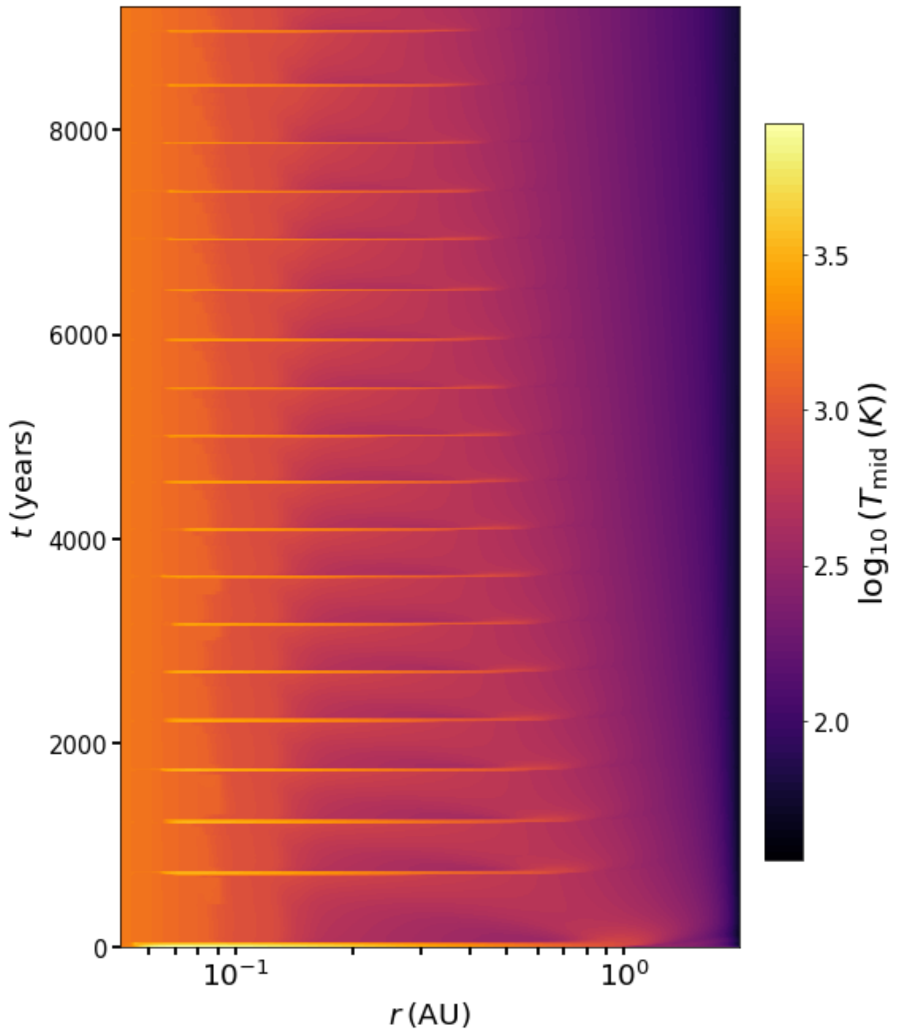
Cecil & Flock 2024



Temporal evolution

We do find recurrent eruptions that seem to last for long time scales

Scepi et al. 2025 in prep.



Dependence with α

$$\alpha = (\alpha_{\rm MRI} - \alpha_{\rm DZ})\frac{1}{2}[1 - \tanh(\frac{T_{\rm MRI} - T}{T_{\rm width}})] + \alpha_{\rm DZ}$$

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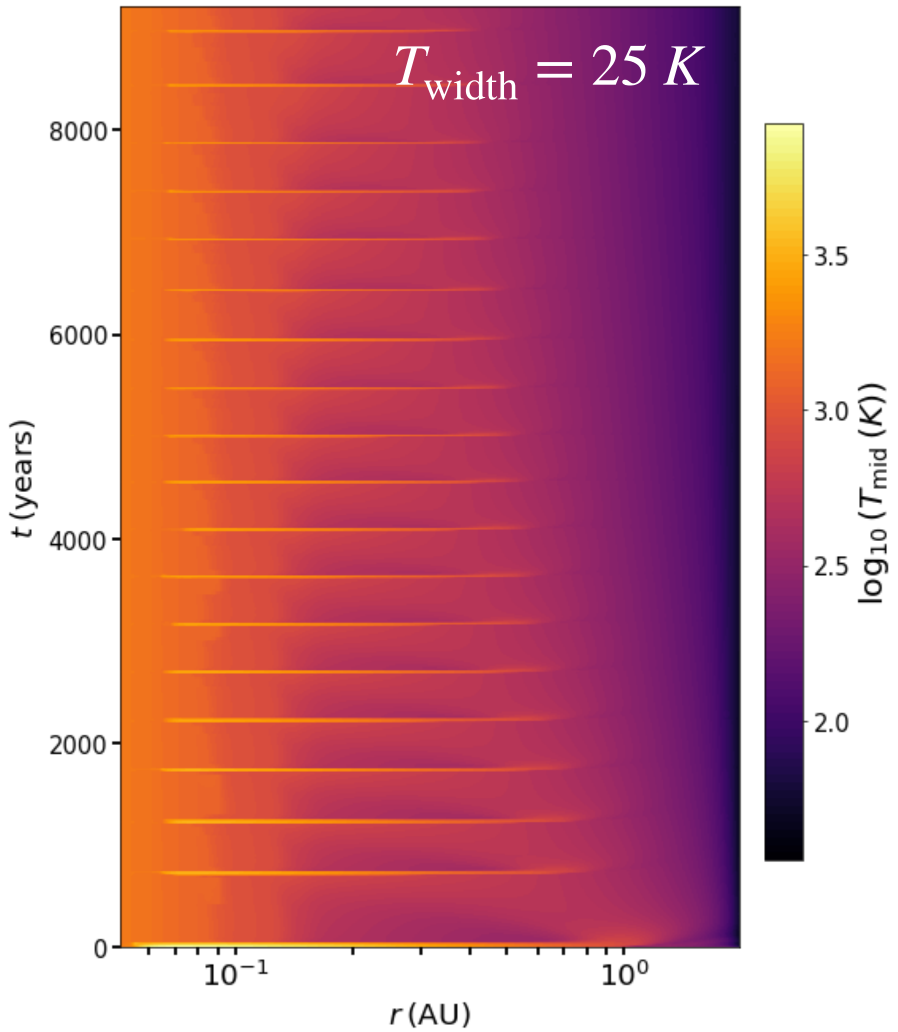

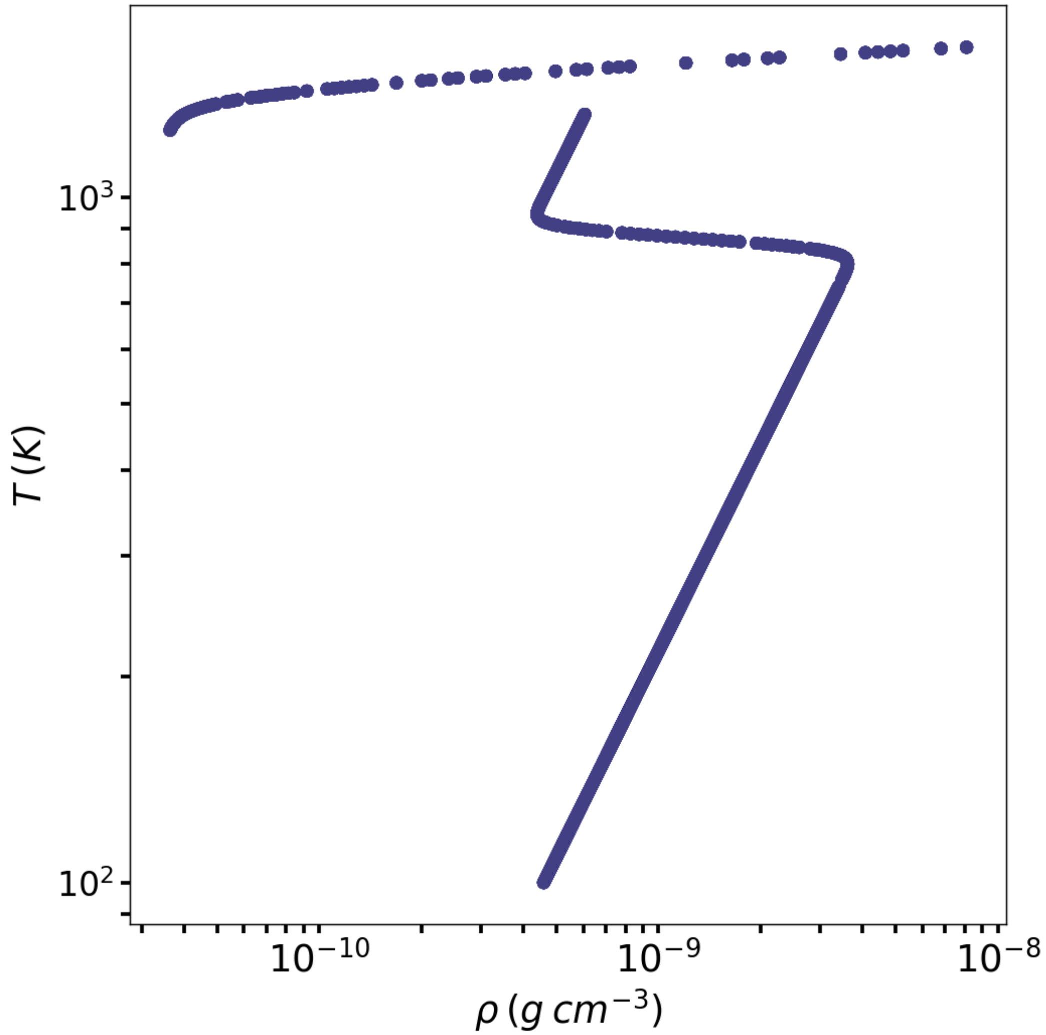

S-curve shows possible hysteresis cycle

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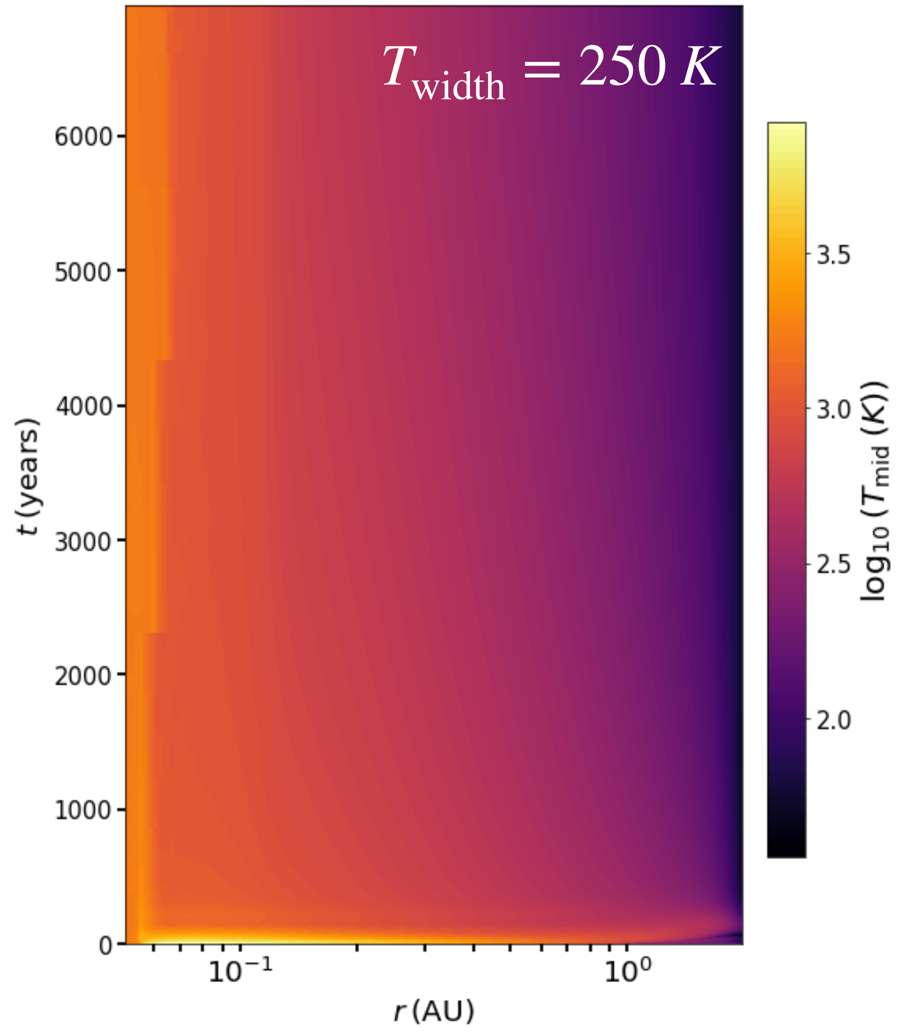

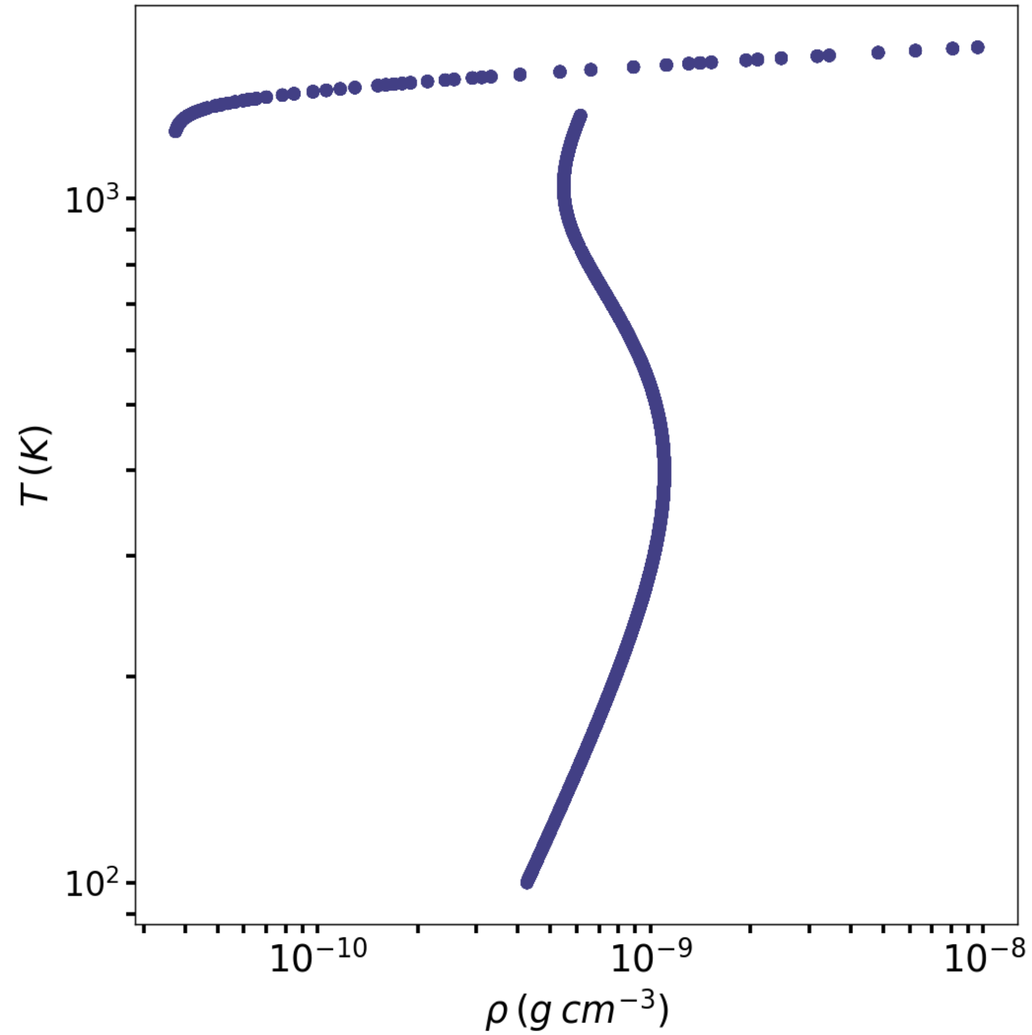

Eruptions are highly dependent on the α-prescription

Need to check that in 3D with MRI

Conclusion

New radiative module in IDEFIX is ready (on all major architectures) !

Will be made public after first scientific applications

Still need to better understand the mechanisms driving the T Tauri variability !

Going to 3D radiative, non ideal MHD simulations of T Tauri disks !