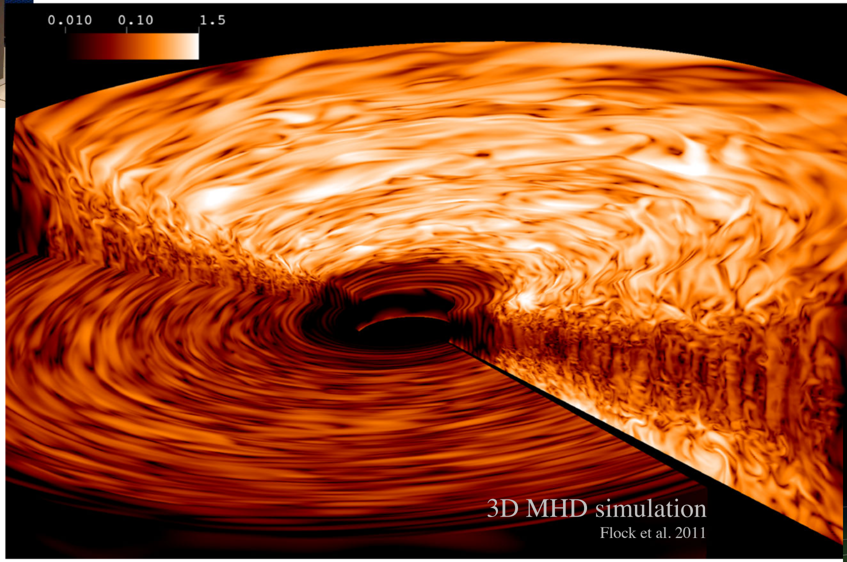
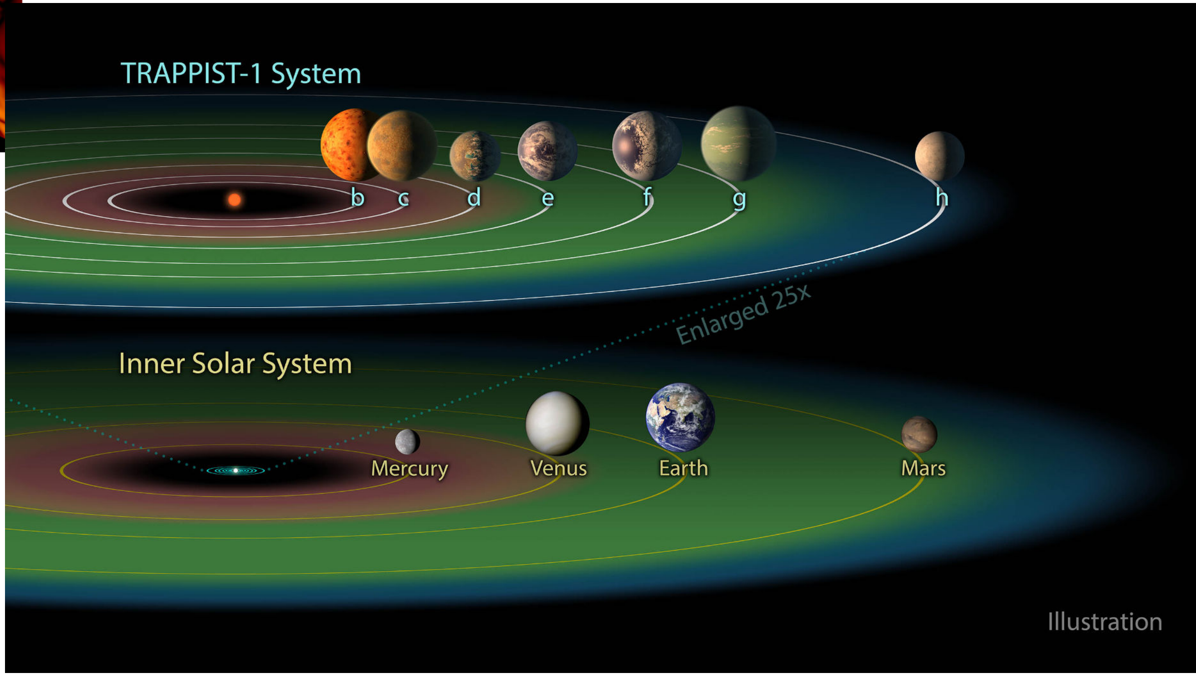
Planet formation

The role of gas and dust dynamics in the evolution of protoplanetary disks


Pleiades, NASA



3D MHD simulation
Flock et al. 2011

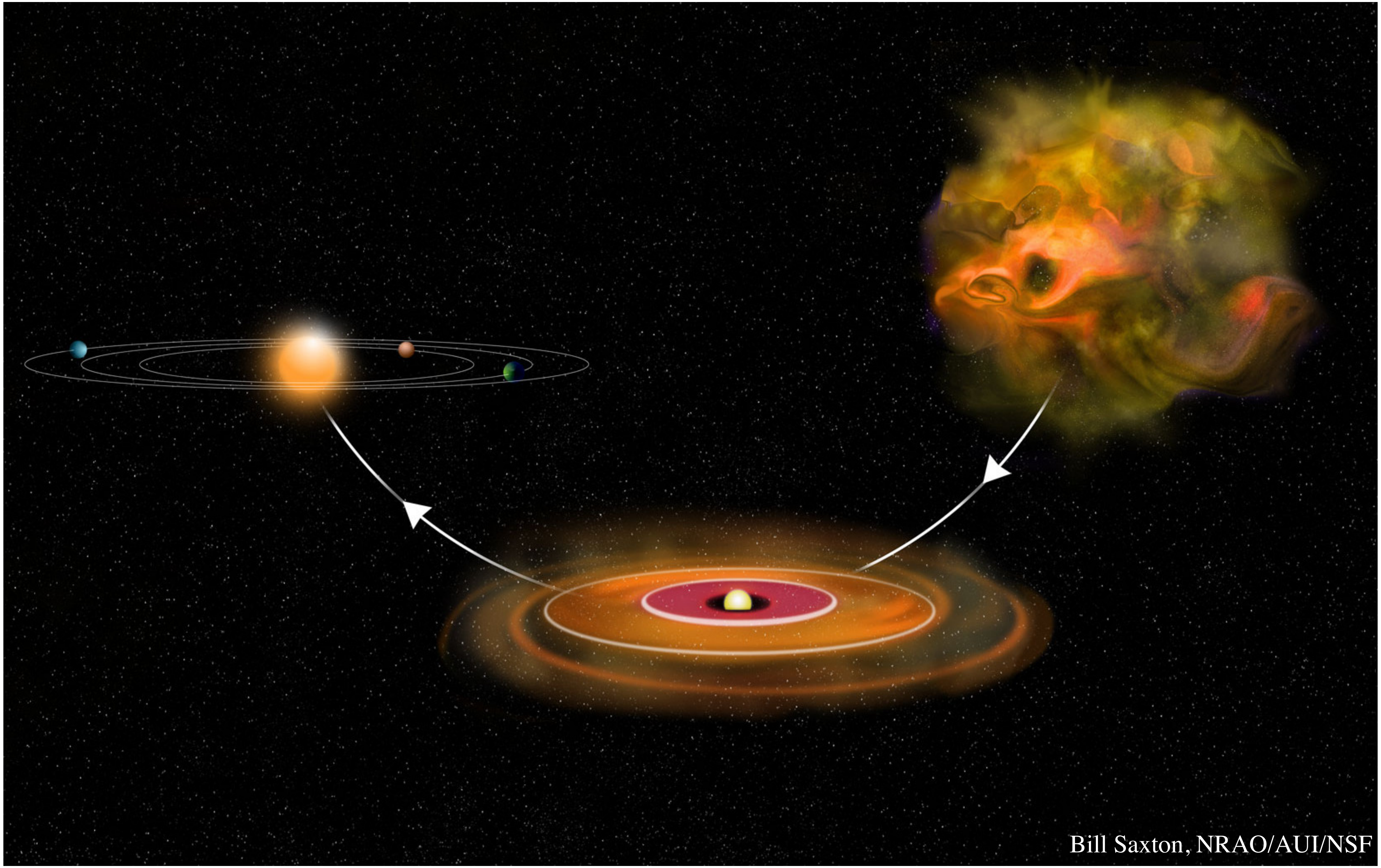


Mario Flock
University of Zürich, 24.9.2021

Kant-Laplace Nebular Hypothesis (1755-1795)

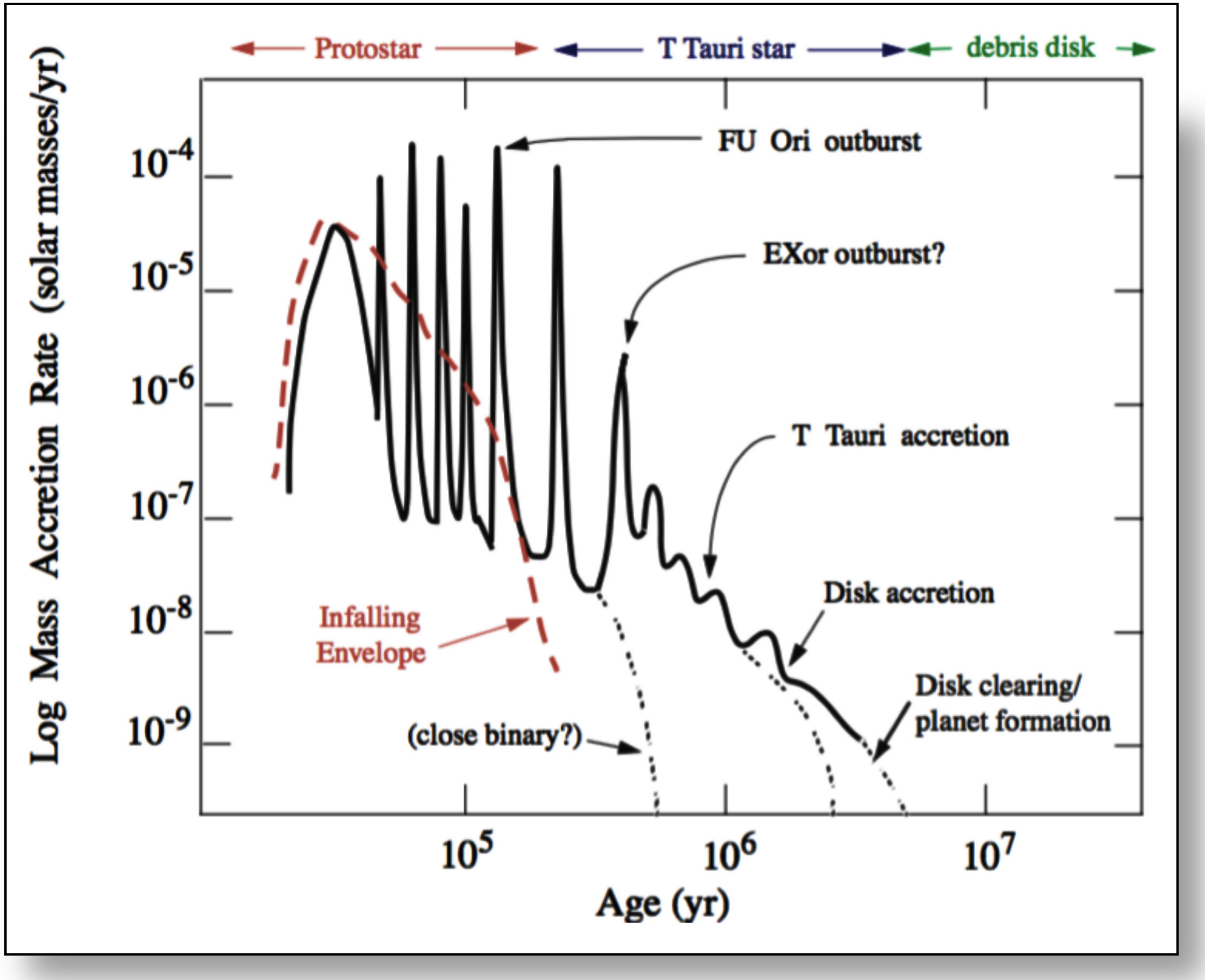
- Formation of a disk around a contracting nebular
- Early ideas of protoplanetary disk

Introduction



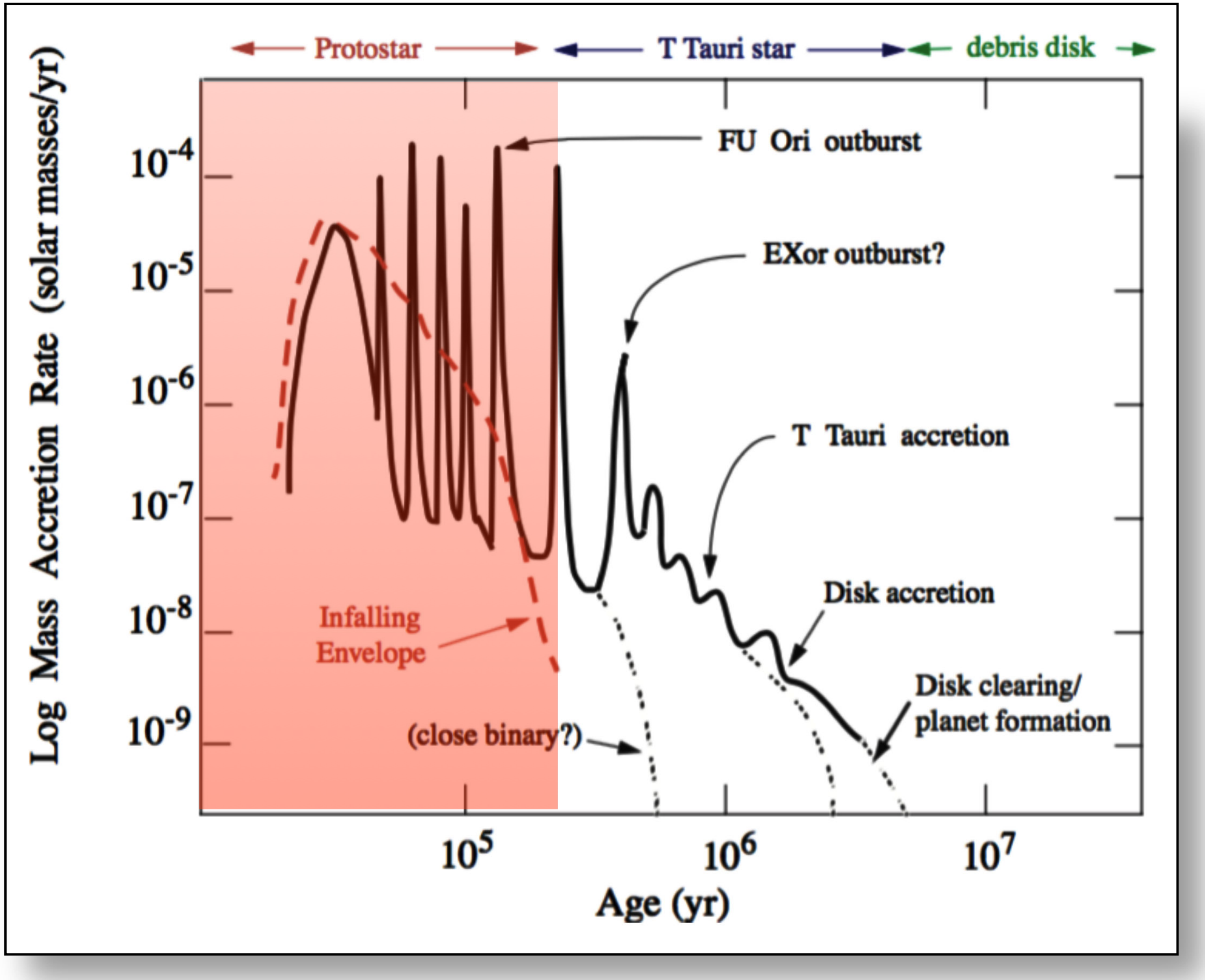
Bill Saxton, NRAO/AUI/NSF

Planets form in disks



Hartman 2017 KITP

Planets form in disks



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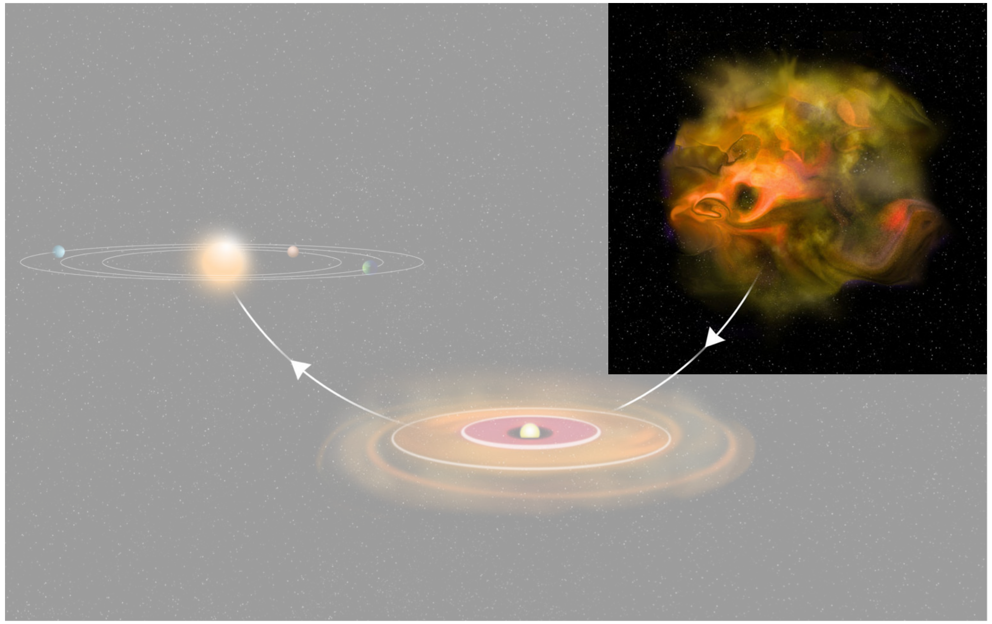

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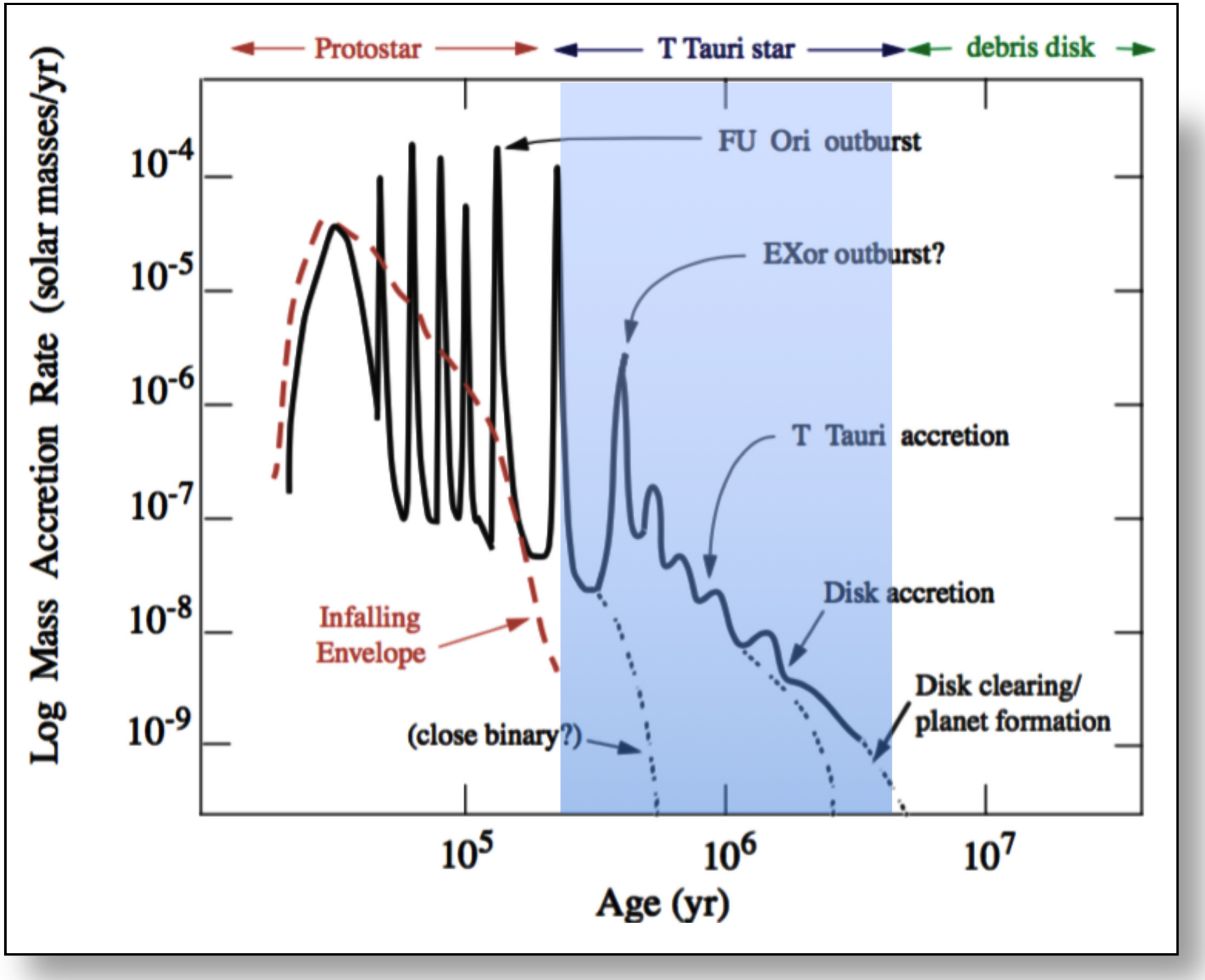

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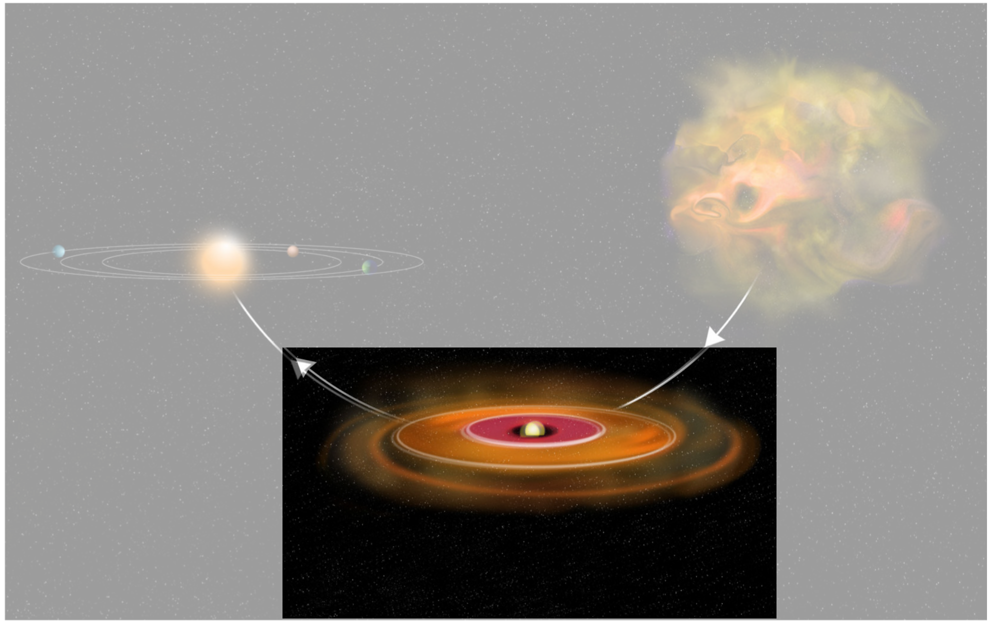

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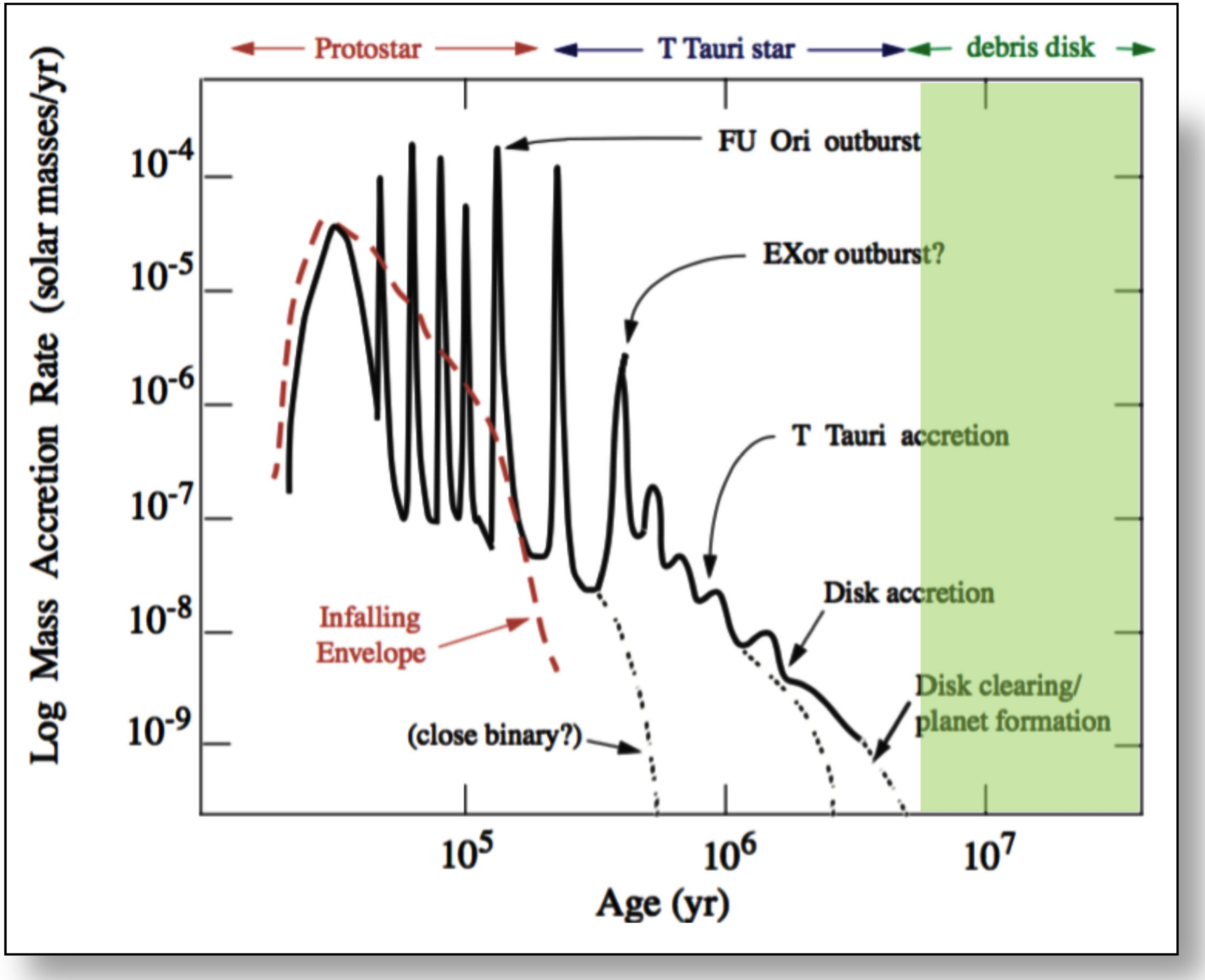

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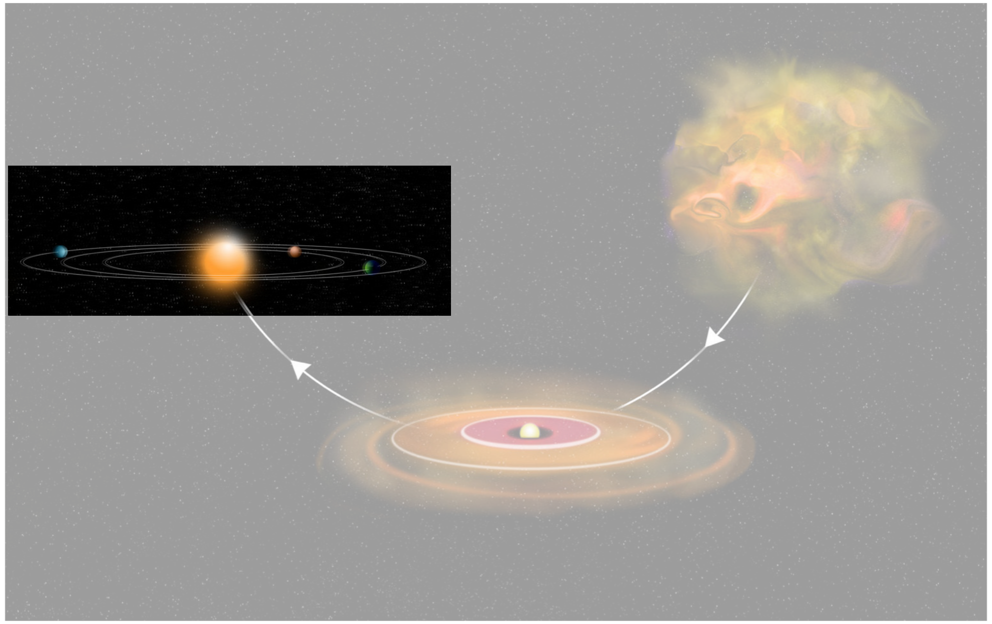

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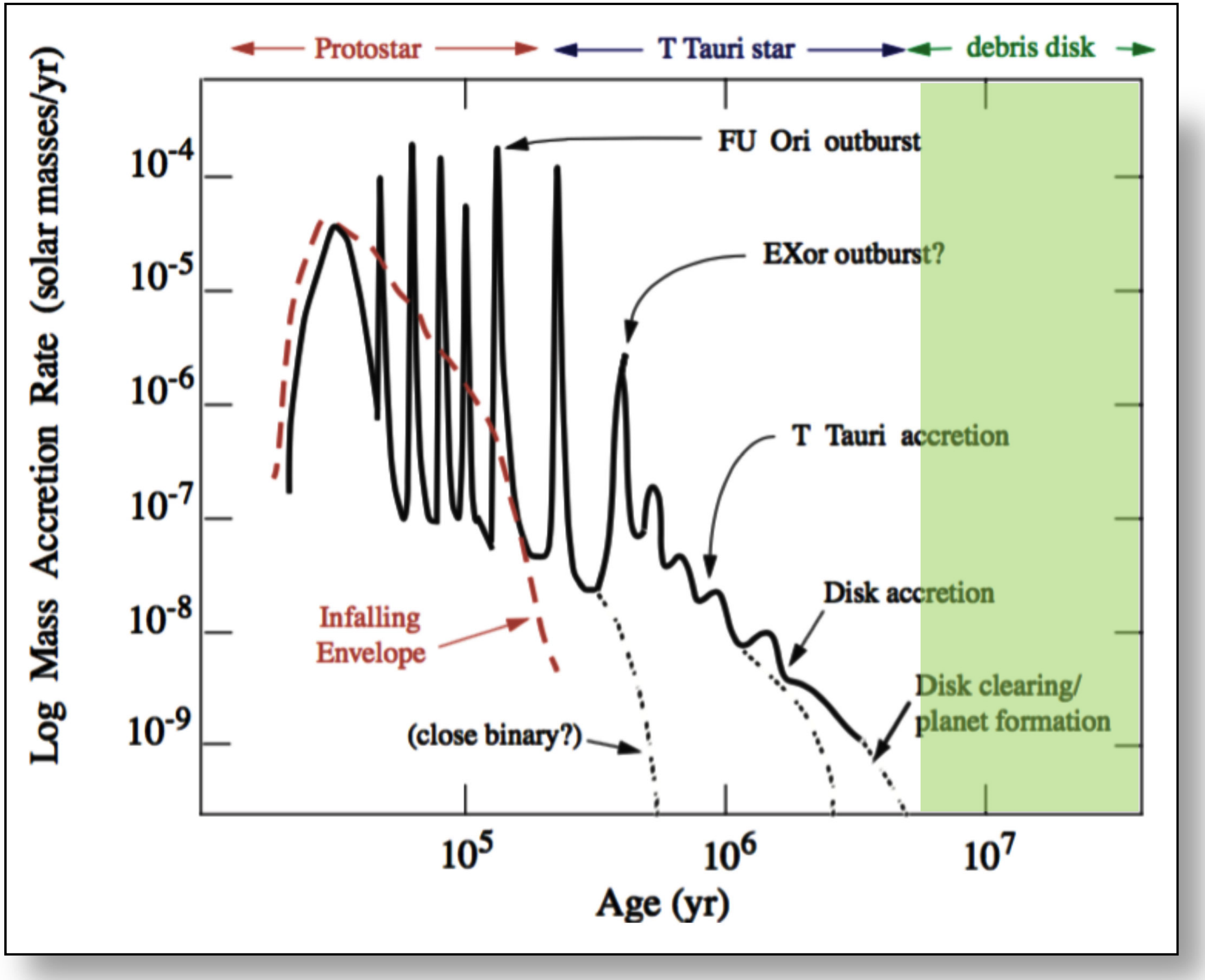
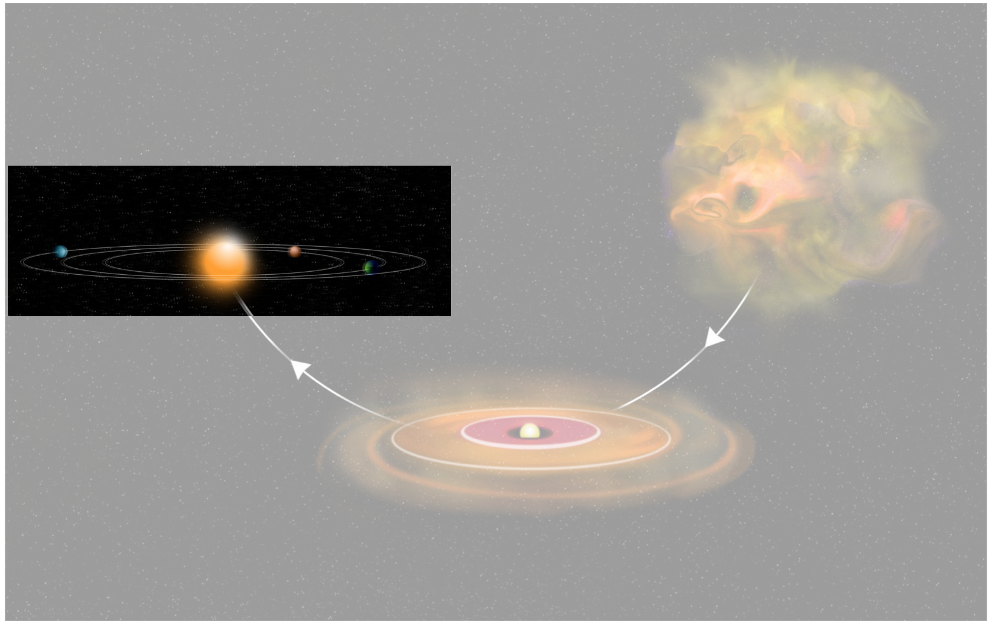


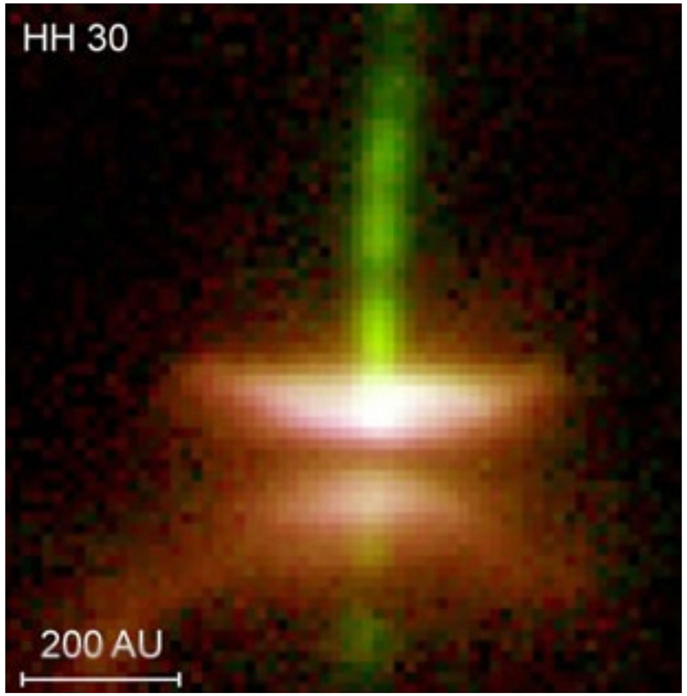
Hartman 2017 KITP

Review chapter and book
PROTOSTARS & PLANETS VI



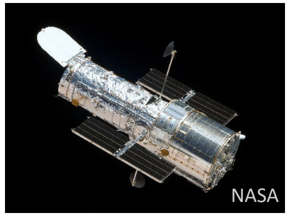
Advanced observations

Optical (~0.5 μm)

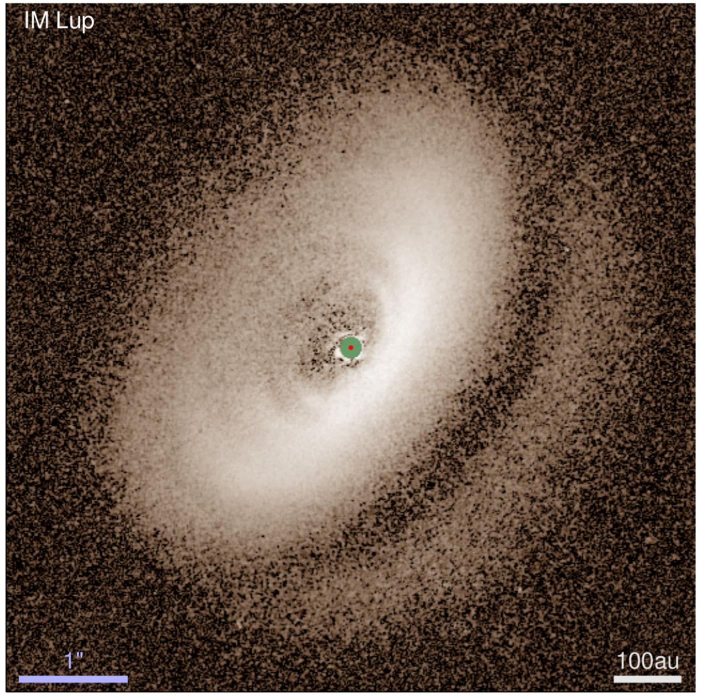


Burrows et al. 1996

Hubble Space Telescope



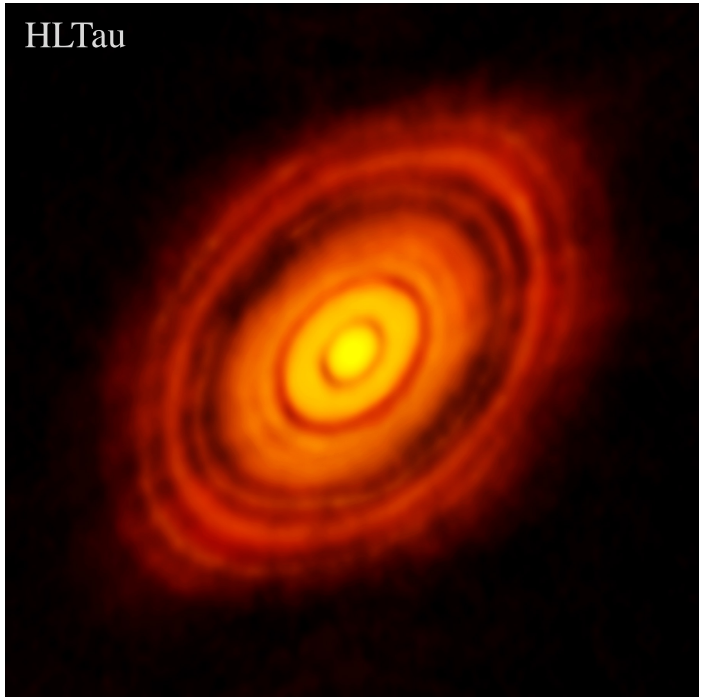
Near Infrared (~ 2μm)



Avenhaus et al. 2018

VLT-SPHERE

Radio (~ mm)



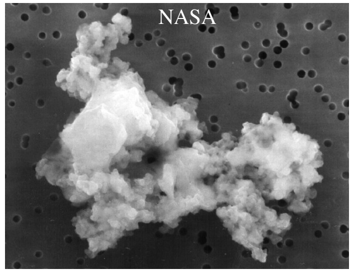
Partnership et al. 2015

ALMA

Planet formation

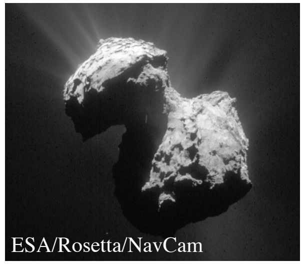
Protoplanetary disks

dust evolution


interplanetary dust particle

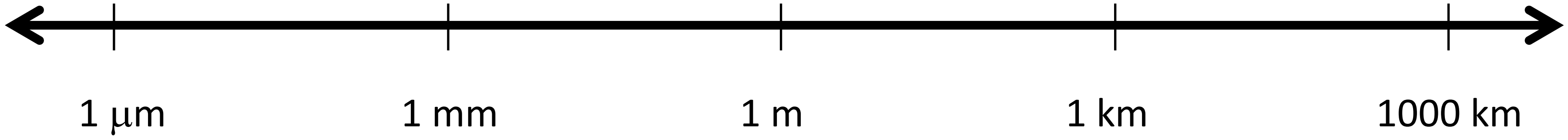
NASA


dust pebbles


planetesimals

ESA/Rosetta/NavCam

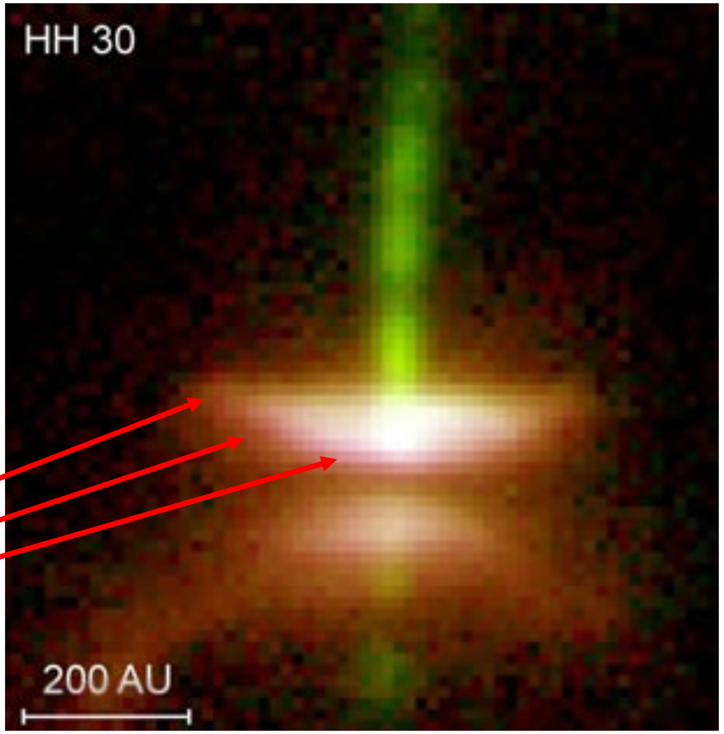

rocky planets



Planet formation

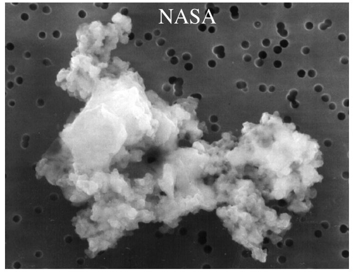
Protoplanetary disks

dust evolution



Small grains reveal the gas disk structure

interplanetary dust particle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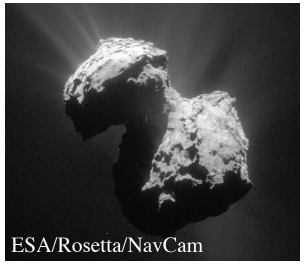
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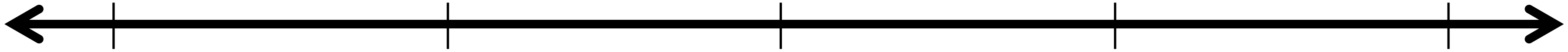
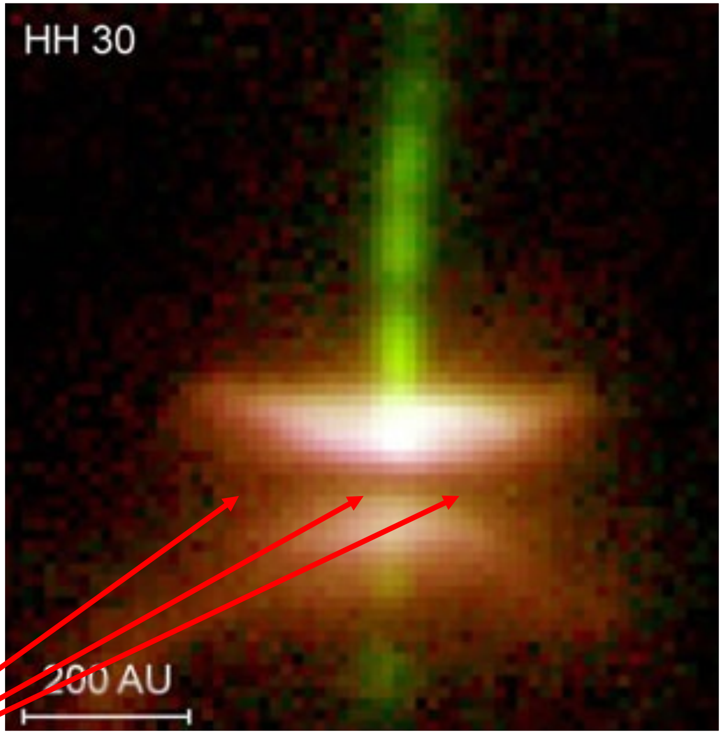


1 μm 1 mm 1 m 1 km 1000 km

Planet formation

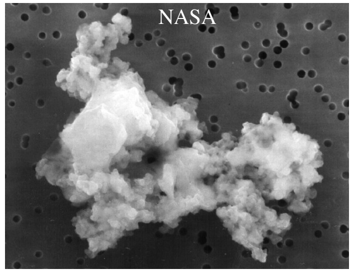
Protoplanetary disks

dust evolution



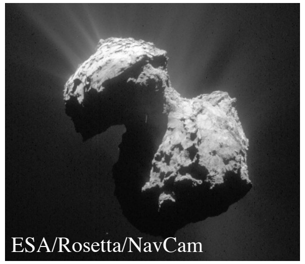
Pebbles are settled

interplanetary dust particle

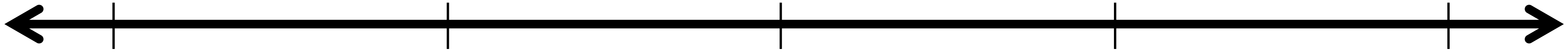


dust pebbles

planetesimals



rocky planets

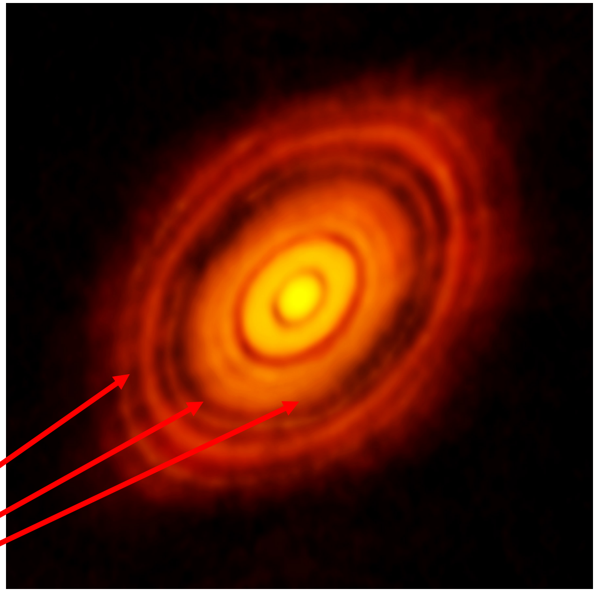


1 µm 1 mm 1 m 1 km 1000 km

Planet formation

Protoplanetary disks

dust evolution



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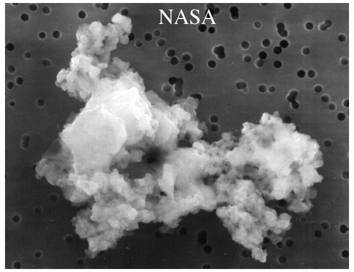
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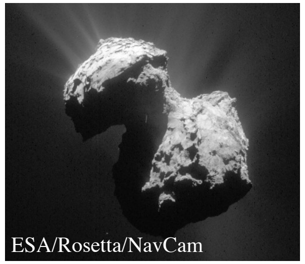
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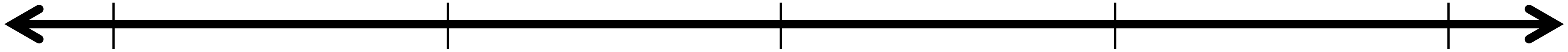


1 µm

1 mm

1 m

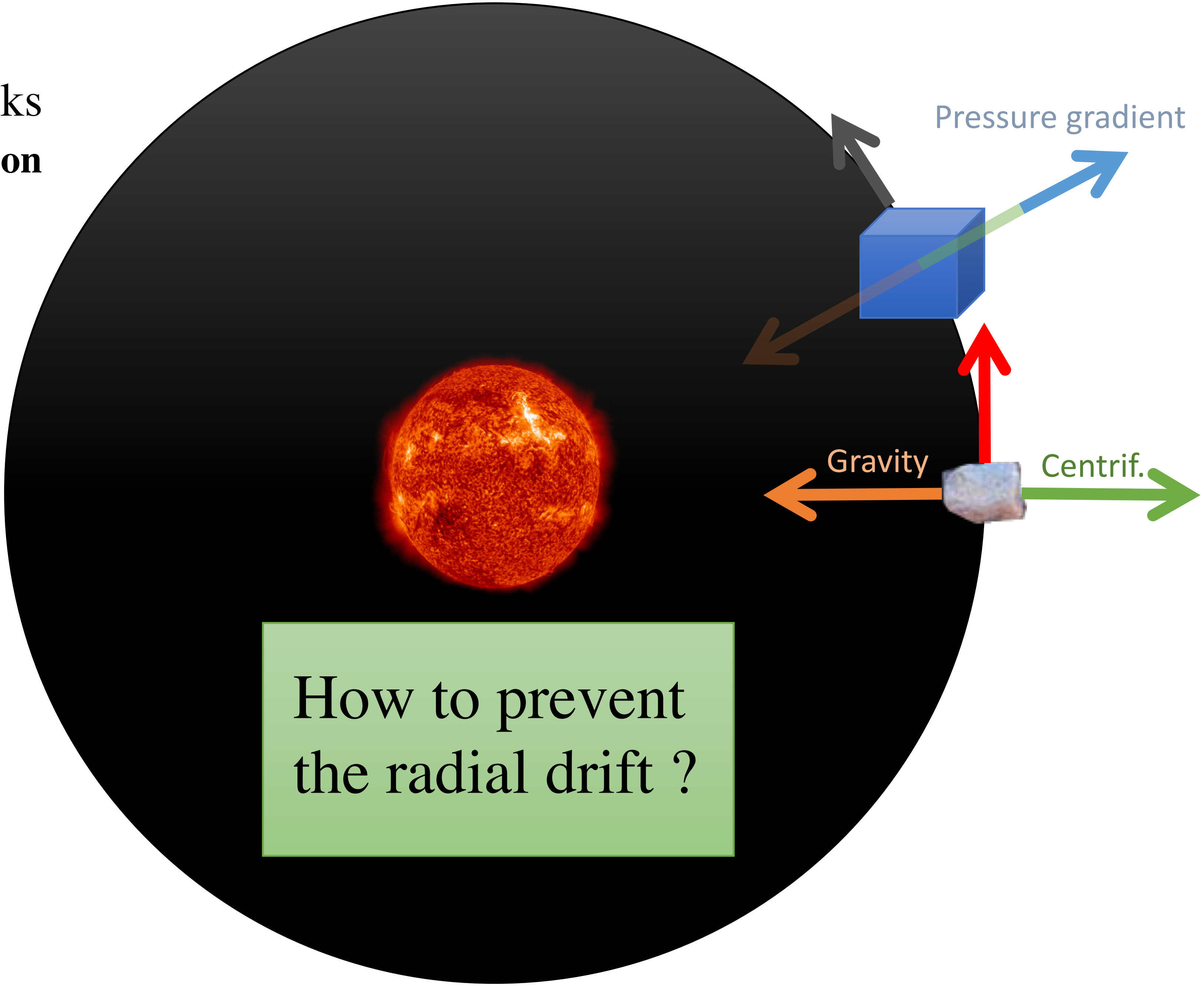
1 km

1000 km

Planet formation

Protoplanetary disks

└── **dust evolution**

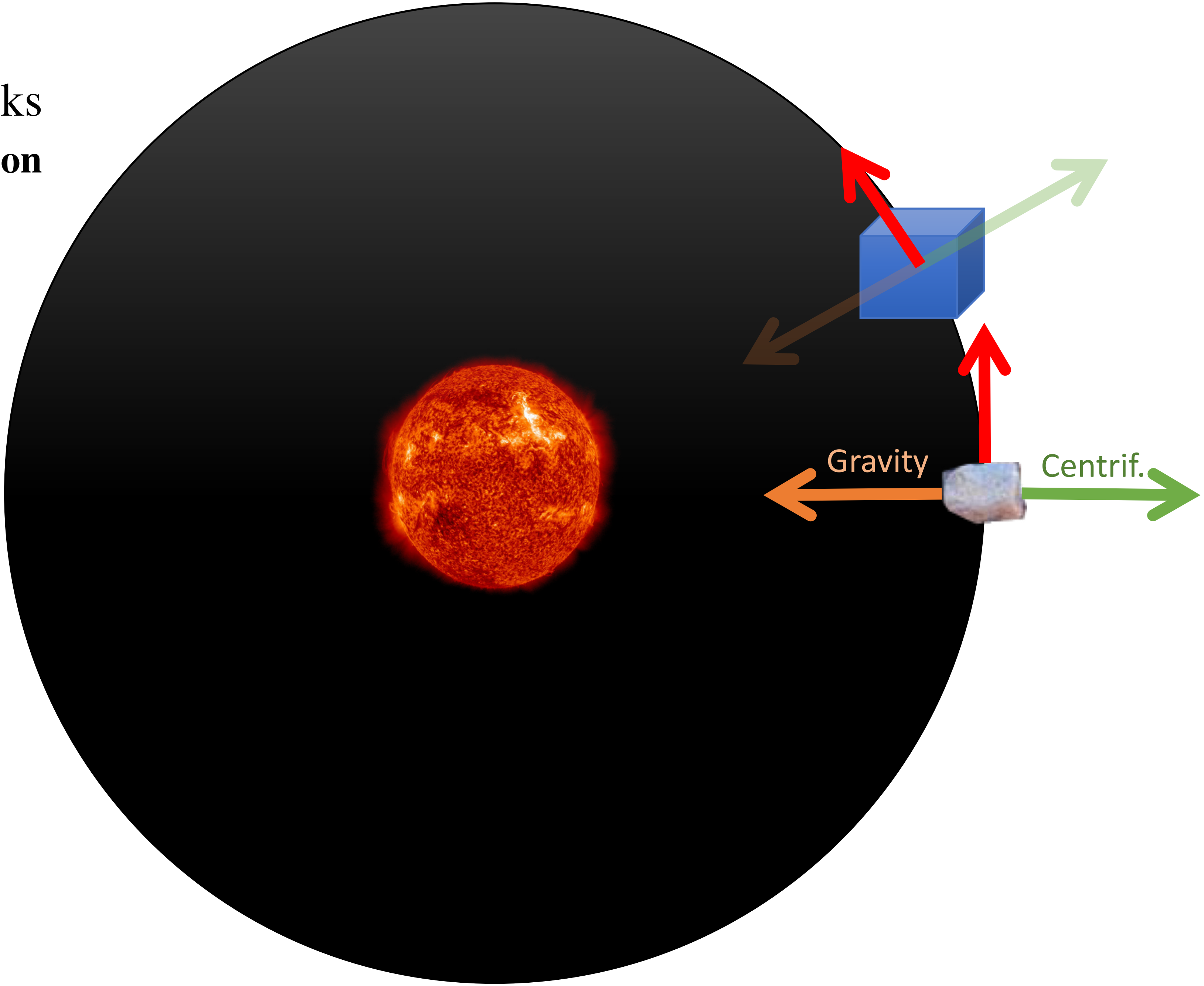


How to prevent the radial drift ?

Planet formation

Protoplanetary disks

└── **dust evolution**



Possible solution:

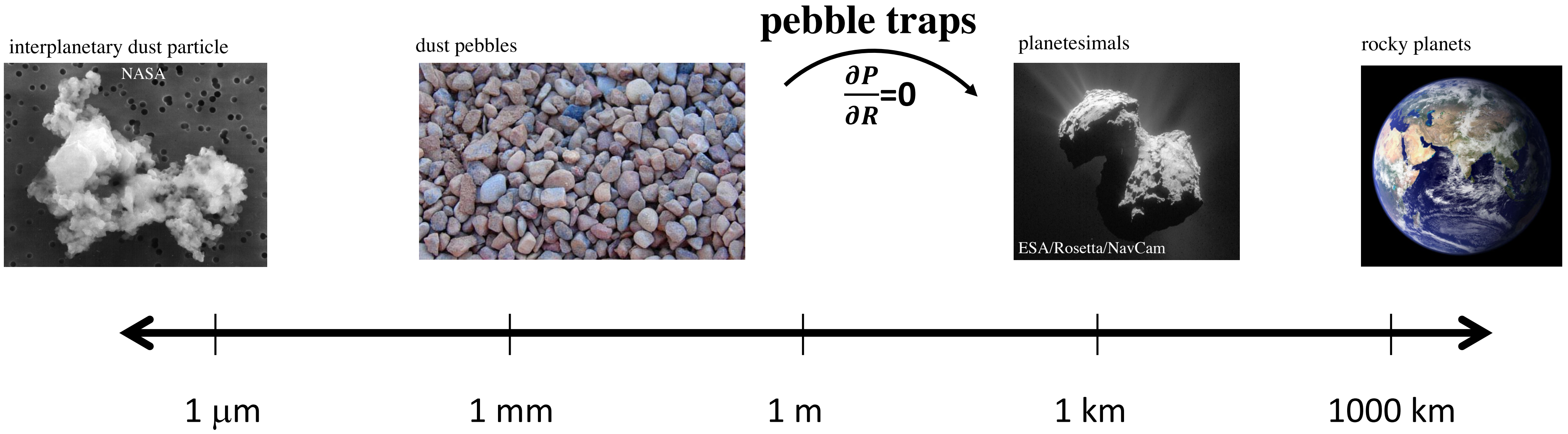
Pebble trap

at $\frac{\partial P}{\partial R}=0$

Planet formation

Protoplanetary disks

dust evolution



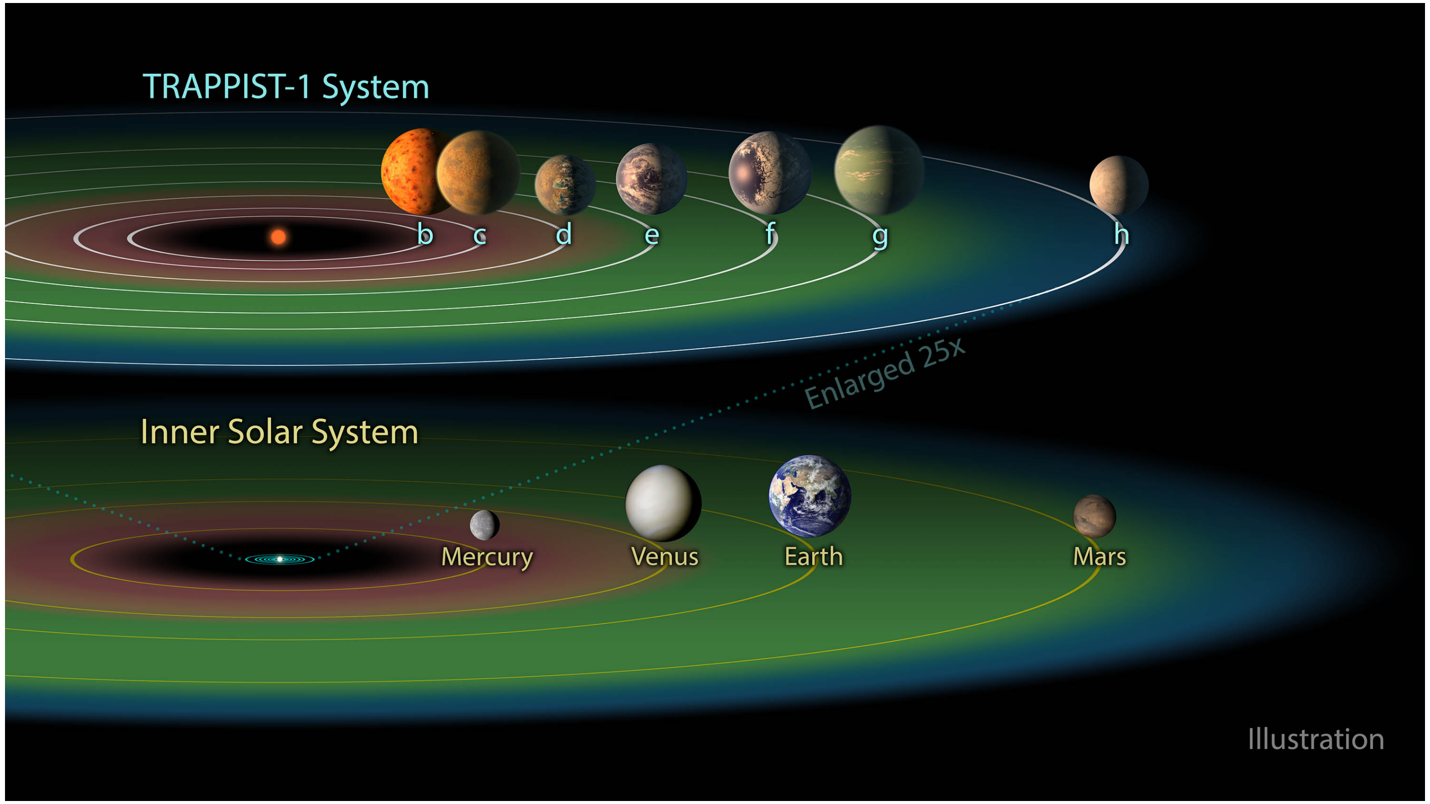
pebble traps

$$\frac{\partial P}{\partial R}=0$$

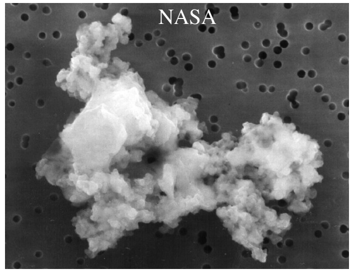
Planet formation

Protoplanetary disks

dust evolution



interplanetary dust particle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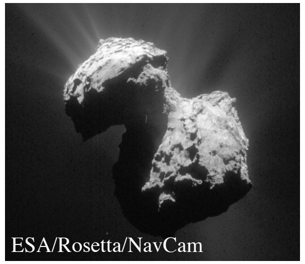
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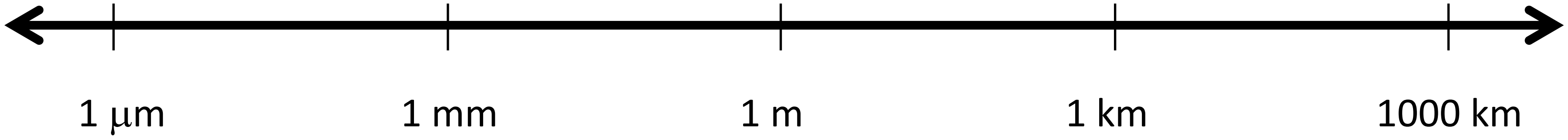
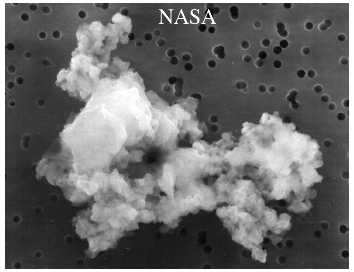


Planet formation

Protoplanetary disks

Theoretical models of accretion disks are crucial to understand the gas and dust evolution

interplanetary dust particle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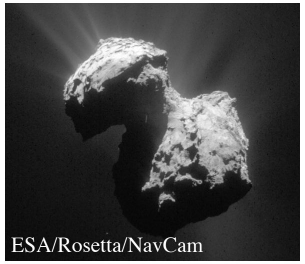
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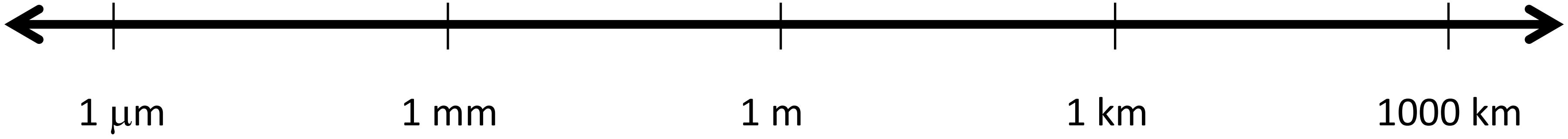

How to enable gas accretion?

Von Weizsäcker 1948
Lüst 1952

Planet formation

Protoplanetary disks

gas evolution

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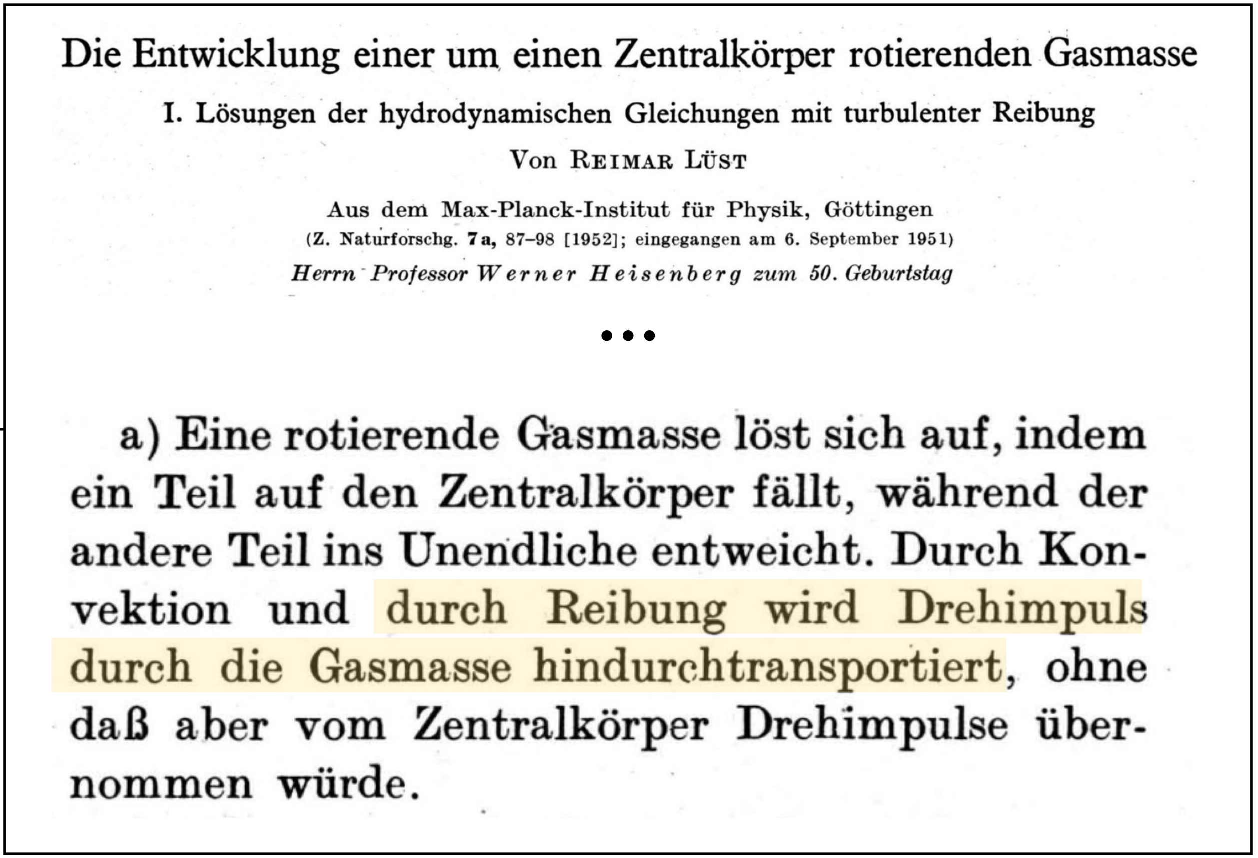

Die Entwicklung einer um einen Zentralkörper rotierenden Gasmasse

I. Lösungen der hydrodynamischen Gleichungen mit turbulenter Reibung

Von Reimar Lüst

Aus dem Max-Planck-Institut für Physik, Göttingen

(Z. Naturforschg. **7a**, 87–98 [1952]; eingegangen am 6. September 1951)

Herrn Professor Werner Heisenberg zum 50. Geburtstag

…

a) Eine rotierende Gasmasse löst sich auf, indem ein Teil auf den Zentralkörper fällt, während der andere Teil ins Unendliche entweicht. Durch Konvektion und durch Reibung wird Drehimpuls durch die Gasmasse hindurchtransportiert, ohne daß aber vom Zentralkörper Drehimpulse übernommen würde.

Planet formation

Protoplanetary disks

gas evolution

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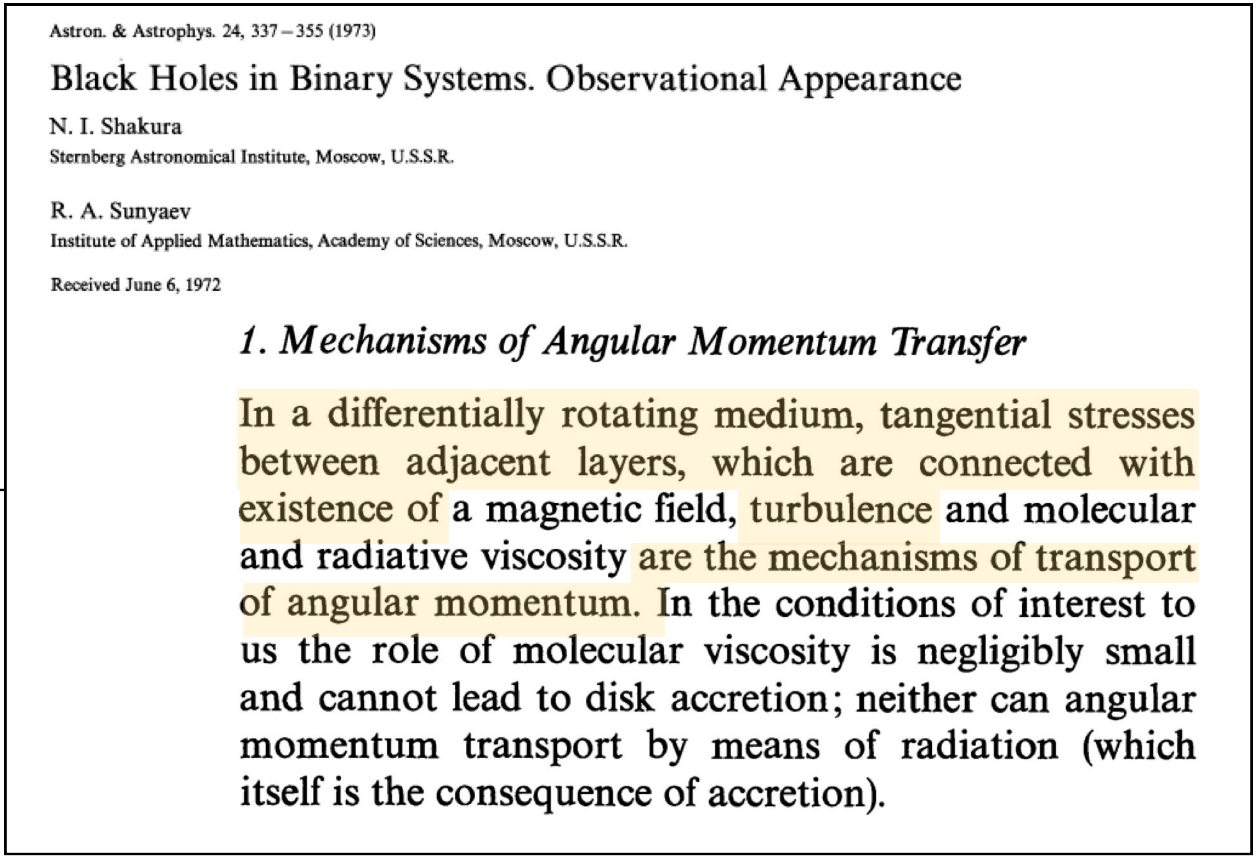
Lüst 1952

Shakura & Sunyaev 1973



Astron. & Astrophys. 24, 337 – 355 (1973)

Black Holes in Binary Systems. Observational Appearance

N. I. Shakura
Sternberg Astronomical Institute, Moscow, U.S.S.R.

R. A. Sunyaev
Institute of Applied Mathematics, Academy of Sciences, Moscow, U.S.S.R.

Received June 6, 1972

1. Mechanisms of Angular Momentum Transfer

In a differentially rotating medium, tangential stresses between adjacent layers, which are connected with existence of a magnetic field, turbulence and molecular and radiative viscosity are the mechanisms of transport of angular momentum. In the conditions of interest to us the role of molecular viscosity is negligibly small and cannot lead to disk accretion; neither can angular momentum transport by means of radiation (which itself is the consequence of accretion).

Planet formation

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gas evolution

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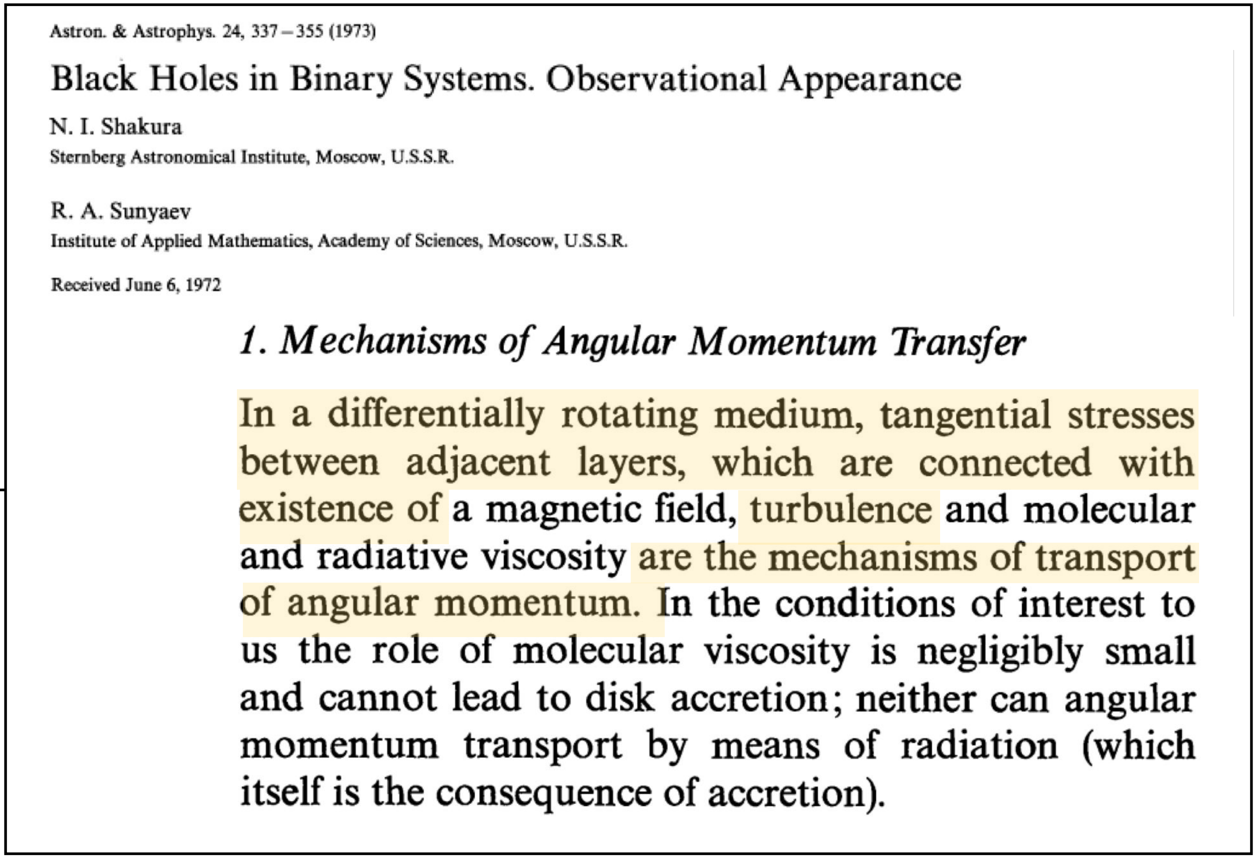
$$\alpha = \frac{\rho v'_{\phi} v'_{r}}{P} - \frac{B_{\phi} B_{r}}{P}$$



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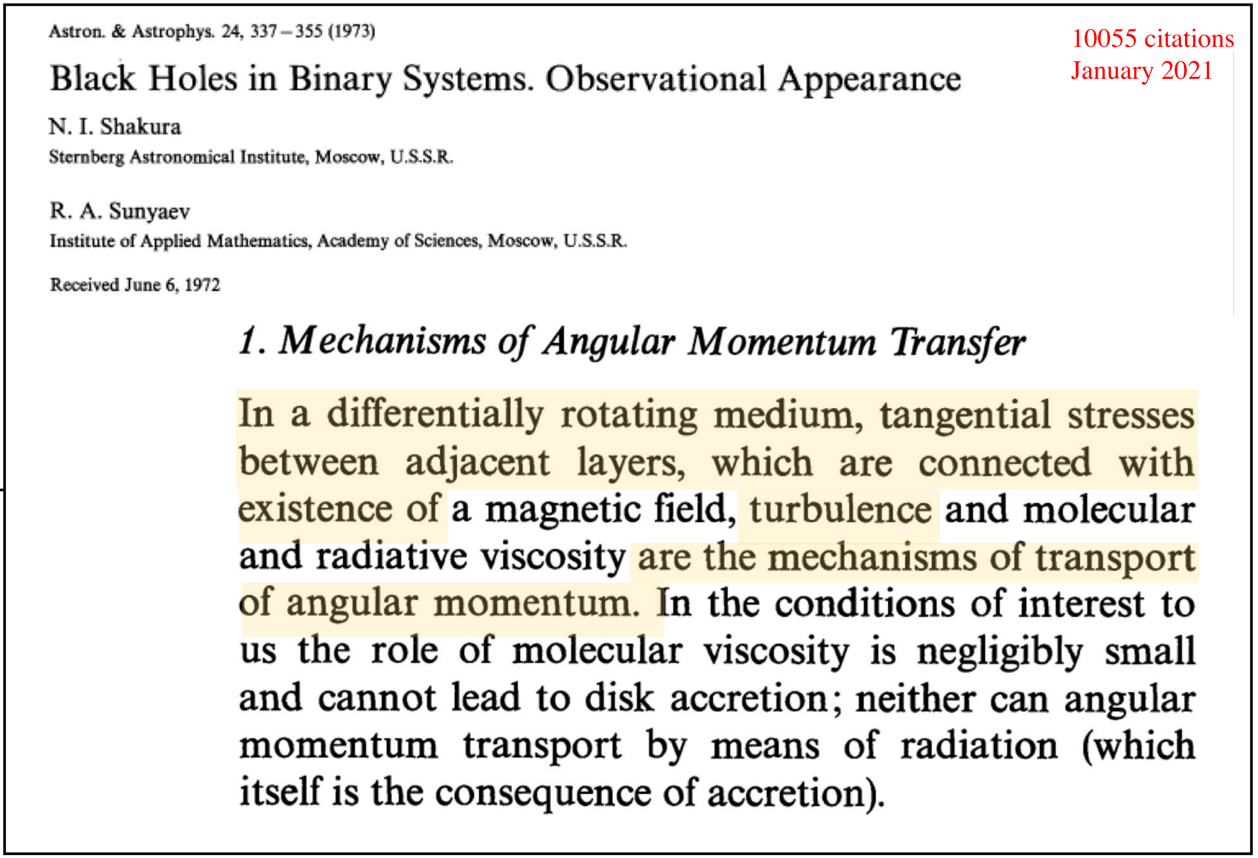

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10055 citations
January 2021

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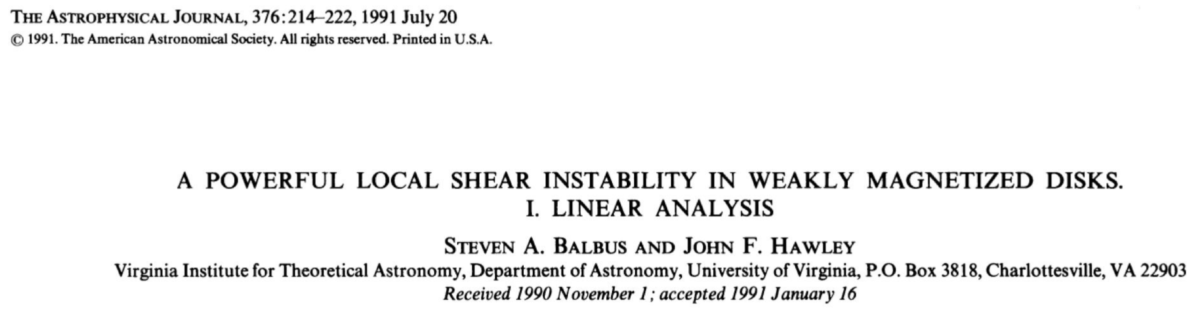

THE ASTROPHYSICAL JOURNAL, 376:214–222, 1991 July 20
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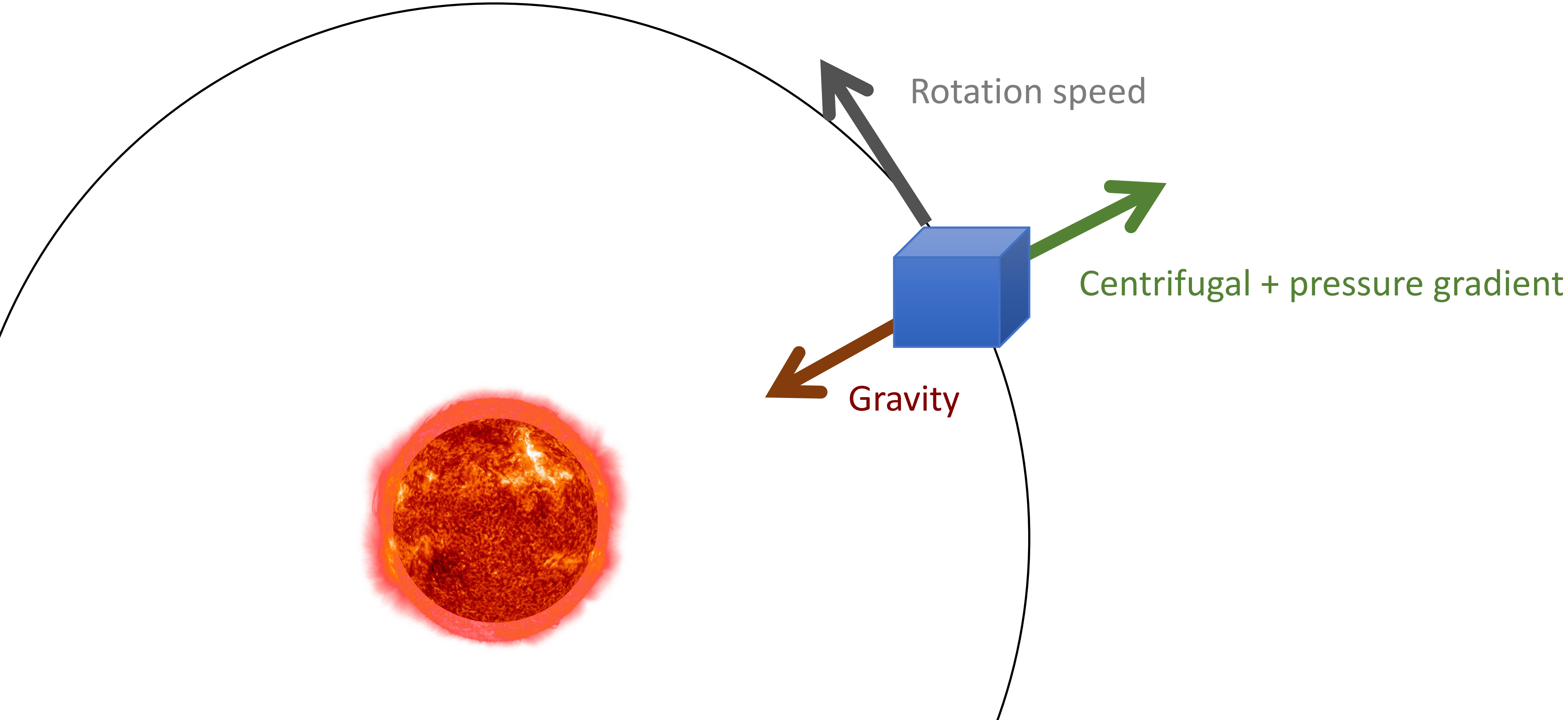
A POWERFUL LOCAL SHEAR INSTABILITY IN WEAKLY MAGNETIZED DISKS.
I. LINEAR ANALYSIS

STEVEN A. BALBUS AND JOHN F. HAWLEY
Virginia Institute for Theoretical Astronomy, Department of Astronomy, University of Virginia, P.O. Box 3818, Charlottesville, VA 22903
Received 1990 November 1; accepted 1991 January 16

The magneto-rotational instability (MRI) generates turbulence

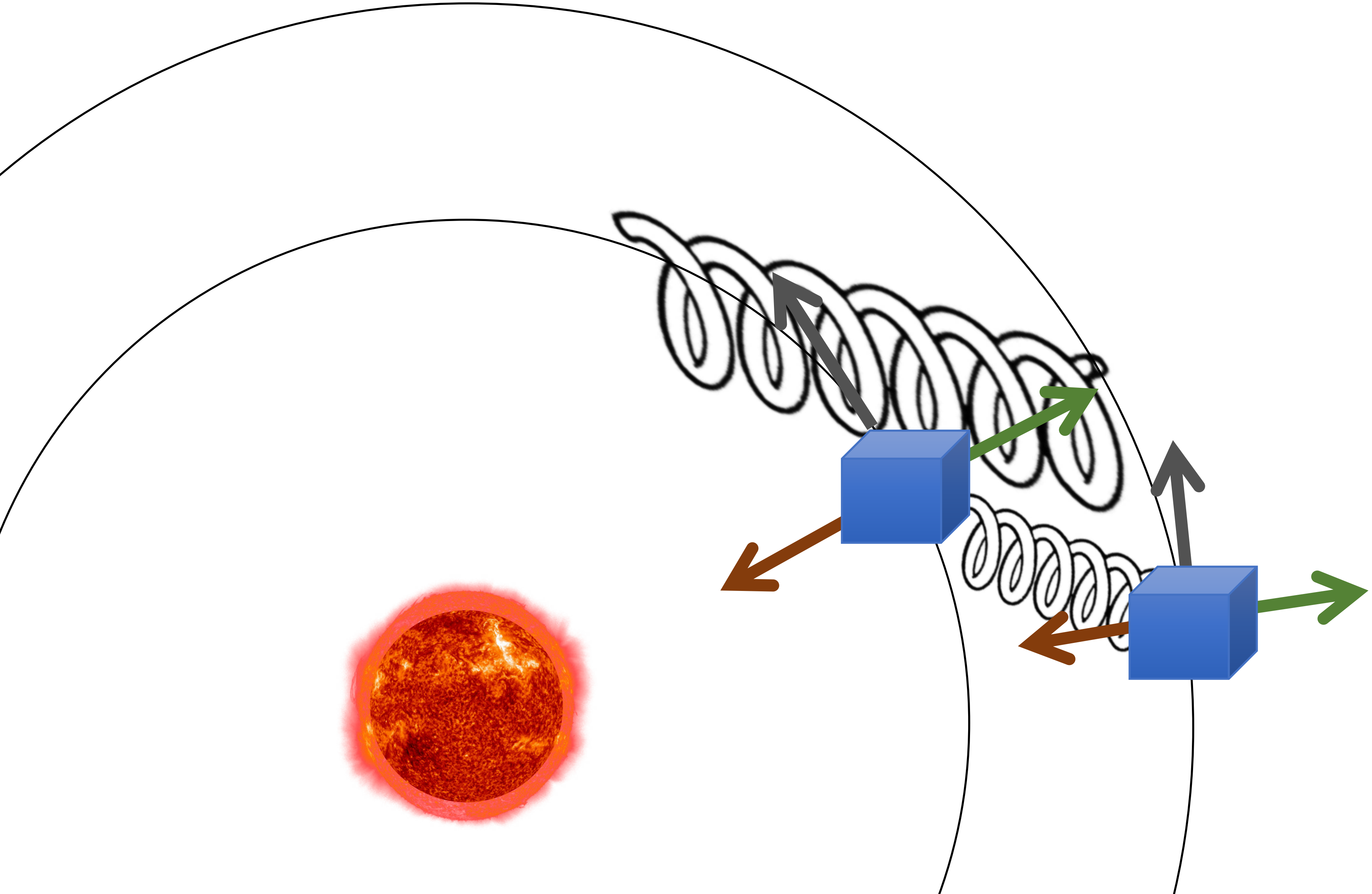
Planet formation

└ **MRI**



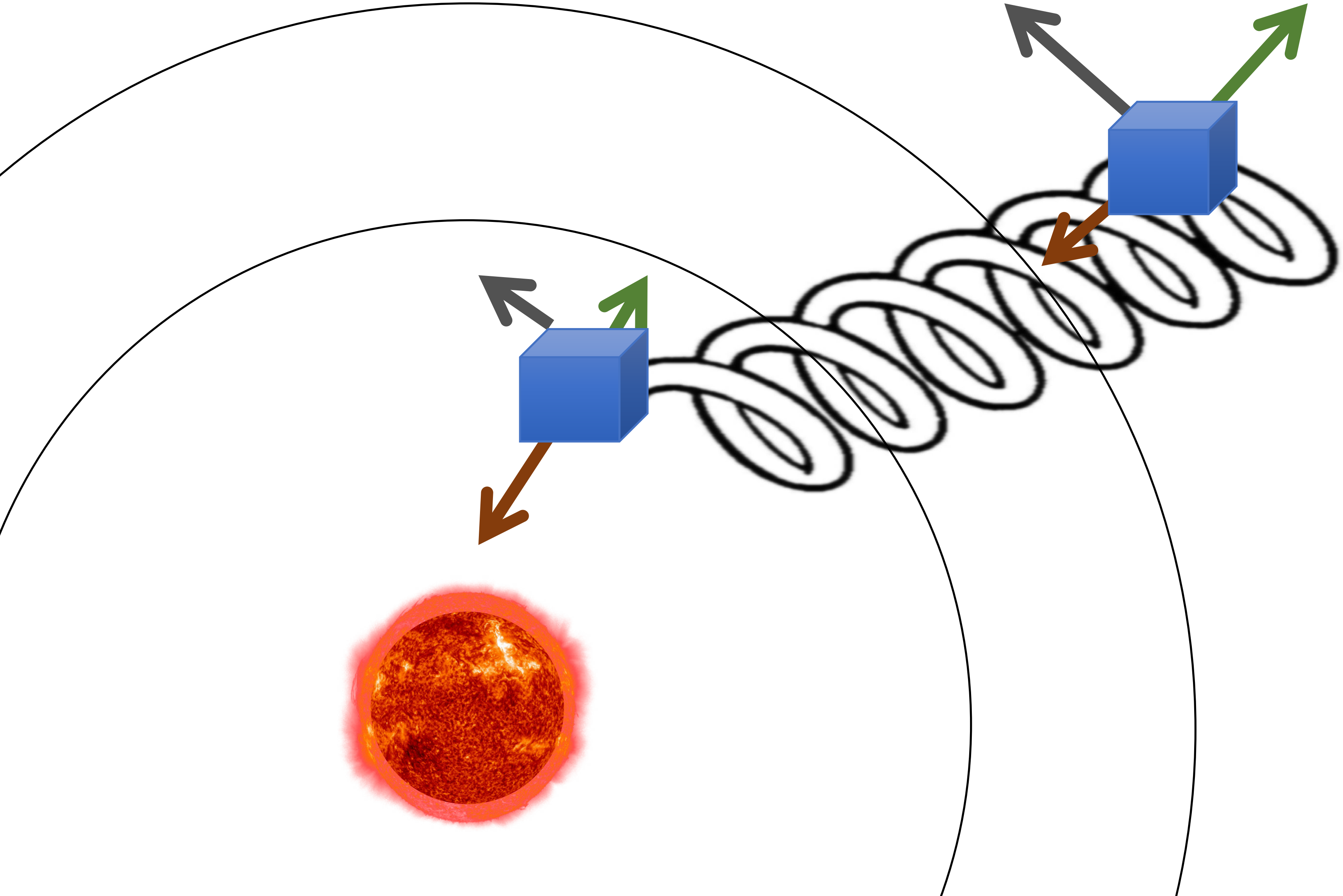
Planet formation

└ MRI



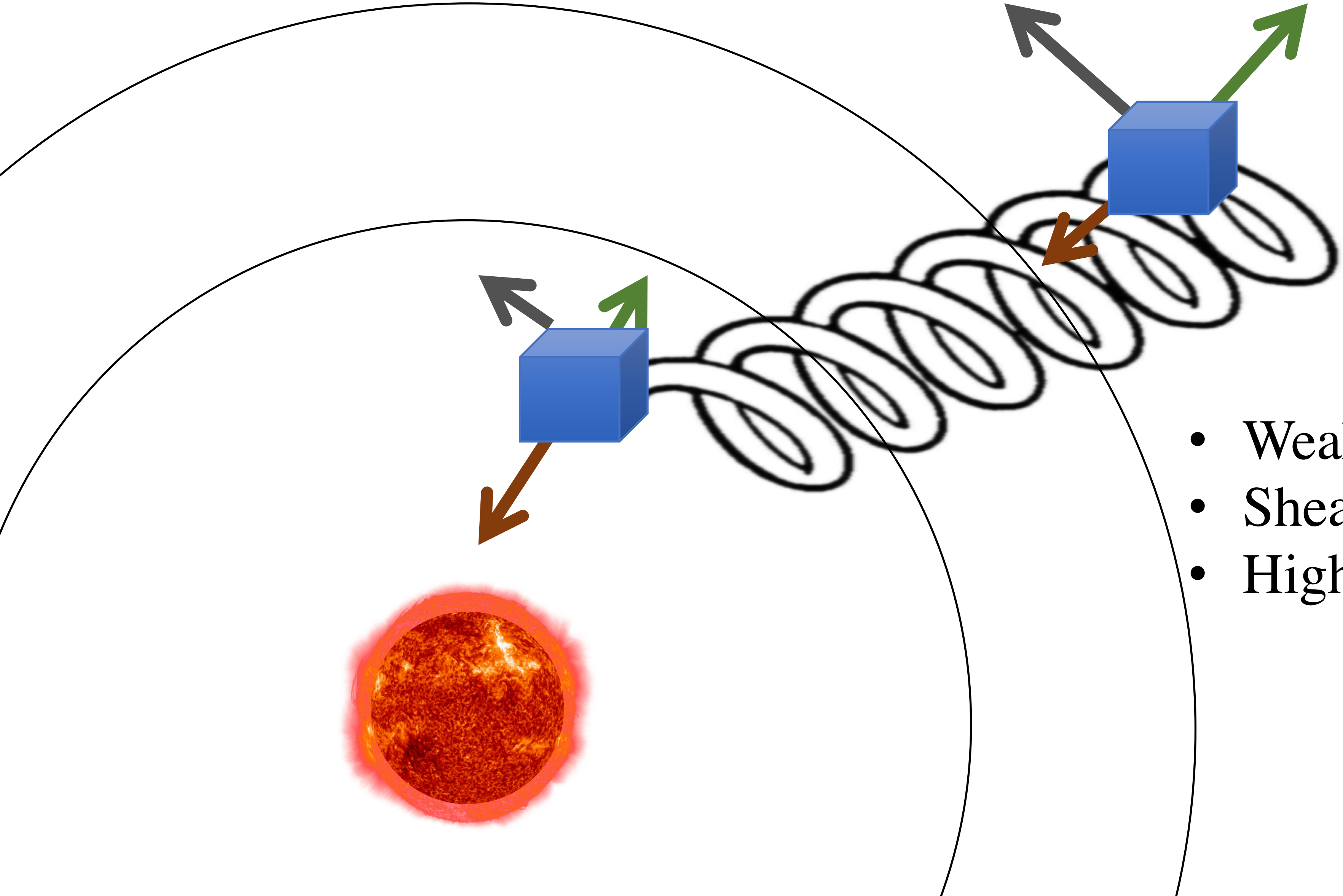
Planet formation

└ **MRI**



Planet formation

└ MRI



- Weak magnetic field (β >10)
- Shear
- High enough ionization

Planet formation

Protoplanetary disks

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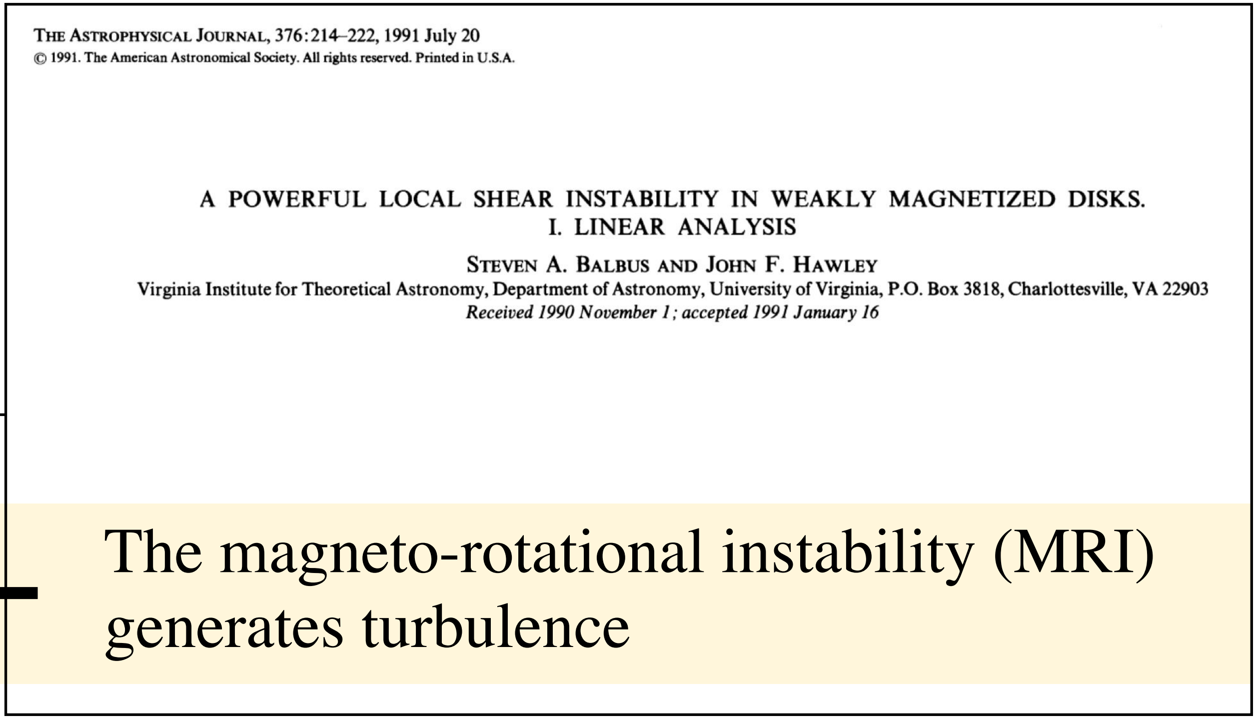

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←

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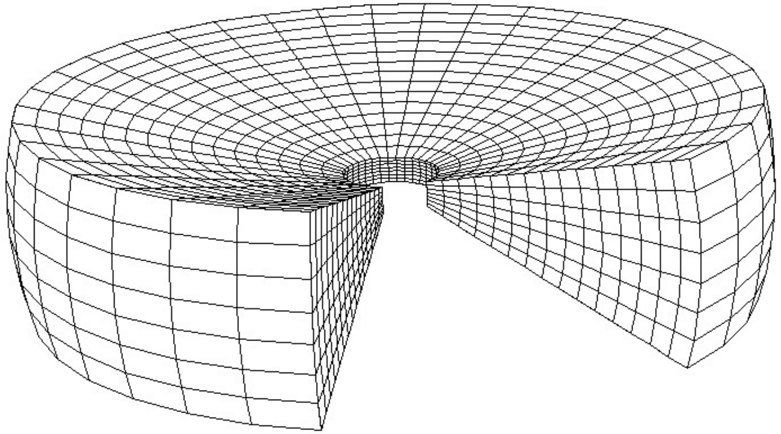
Planet formation

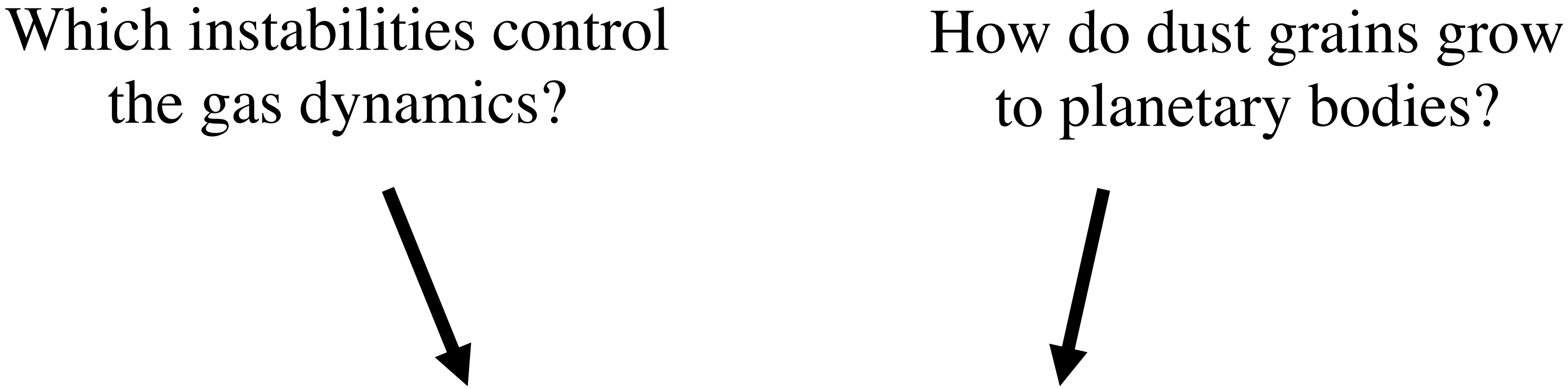
Which instabilities control the gas dynamics?

How do dust grains grow to planetary bodies?

Global 3D MHD simulations



Planet formation



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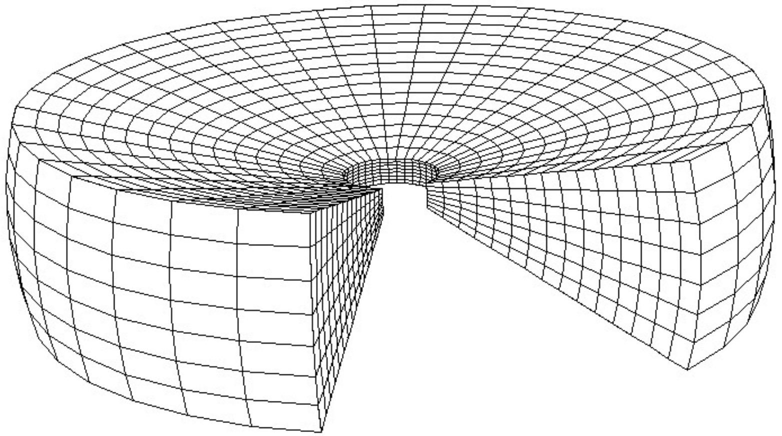
How do dust grains grow to planetary bodies?

Global 3D MHD simulations



+ Many scales and physics
+ Less boundary effects

- Computationally expensive
- Difficult to perform
(only few groups Princeton, Tokyo, Santa Barbara)

Research

-The non-linear dynamics in disks

-Dust concentration at the transition regions

Research

Flock et al. 2010 A&A

First finite volume method for global 3D simulations of magnetized disks

Research

Flock et al. 2010 A&A

First finite volume method for global 3D simulations of magnetized disks

Ideal MHD equations

$$\frac{\partial \rho}{\partial t} + \nabla \cdot [\rho \boldsymbol{v}] = 0,$$

$$\frac{\partial \rho \boldsymbol{v}}{\partial t} + \nabla \cdot \left[\rho \boldsymbol{v}\boldsymbol{v}^T - \boldsymbol{B}\boldsymbol{B}^T\right] + \nabla P_{\mathrm{t}} = -\rho \nabla \Phi,$$

$$\frac{\partial B}{\partial t} + \nabla \times (\boldsymbol{v} \times \boldsymbol{B}) = 0,$$

Closure $P = c_s^2 \rho$

Research

Flock et al. 2010 A&A

First finite volume method for global 3D simulations of magnetized disks

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Closure $P = c_s^2 \rho$

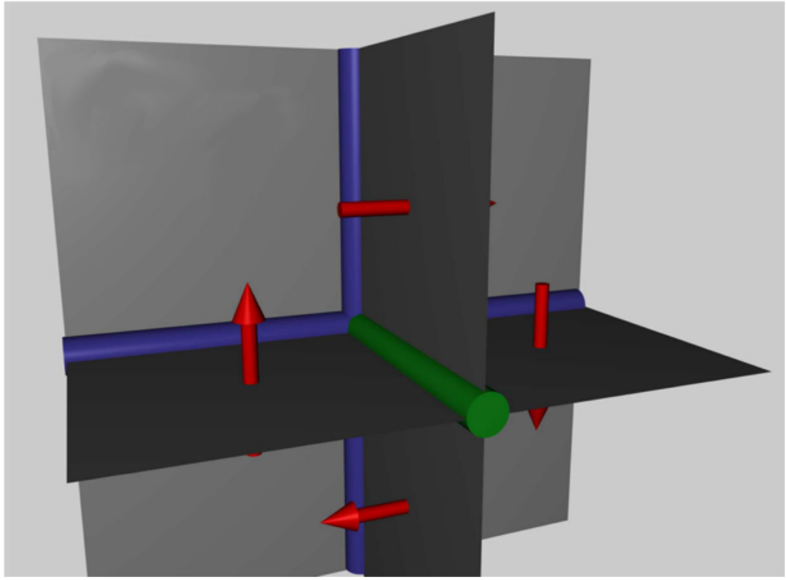
$\nabla \cdot B = 0$ is difficult to sustain

Research

Flock et al. 2010 A&A

First finite volume method for global 3D simulations of magnetized disks

Grid cell and interface



$\nabla \cdot B = 0$ with hybrid scheme: update magnetic field at cell interface

Ideal MHD equations

$$\frac{\partial \rho}{\partial t} + \nabla \cdot [\rho \boldsymbol{v}] = 0,$$

$$\frac{\partial \rho \boldsymbol{v}}{\partial t} + \nabla \cdot \left[\rho \boldsymbol{v}\boldsymbol{v}^T - \boldsymbol{B}\boldsymbol{B}^T\right] + \nabla P_{\mathrm{t}} = -\rho \nabla \Phi,$$

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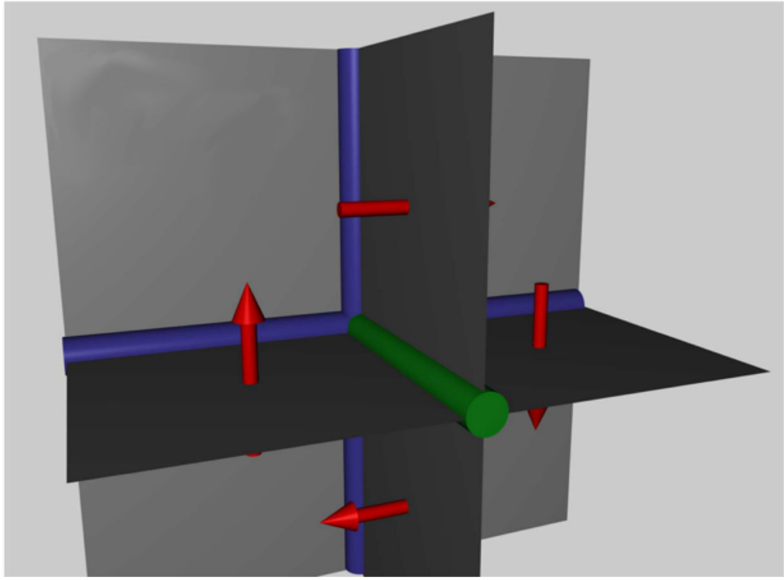
Research

Flock et al. 2010 A&A

First finite volume method for global 3D simulations of magnetized disks

Grid cell and interface



Ideal MHD equations

$$\frac{\partial \rho}{\partial t} + \nabla \cdot [\rho \boldsymbol{v}] = 0,$$

$$\frac{\partial \rho \boldsymbol{v}}{\partial t} + \nabla \cdot \left[\rho \boldsymbol{v}\boldsymbol{v}^T - \boldsymbol{B}\boldsymbol{B}^T\right] + \nabla P_{\mathrm{t}} = -\rho \nabla \Phi,$$

$$\frac{\partial B}{\partial t} + \nabla \times (\boldsymbol{v} \times \boldsymbol{B}) = 0,$$

Closure $P = c_s^2 \rho$

- Conservation of mass, momentum energy and $\nabla \cdot B = 0$ at machine accuracy
- Second order in time and space
- Shock capturing (Riemann problem at cell interface)

PLUTO code (Mignone et al. 2007)

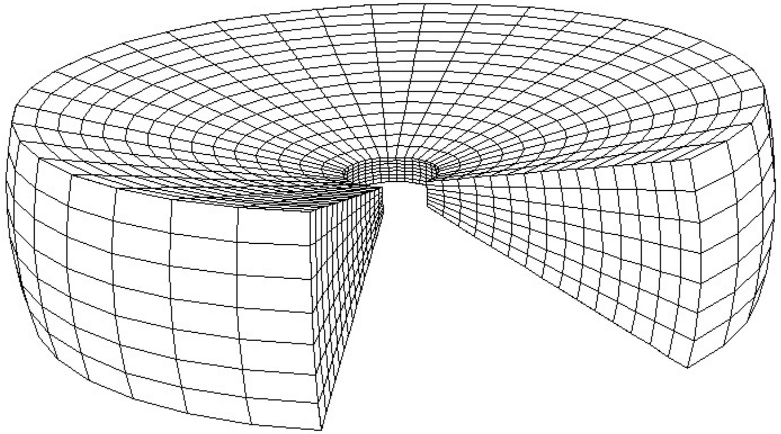
Research

Flock et al. 2011 ApJ

Detail and long-term study of the MRI in the non-linear regime

Accretion disk setup

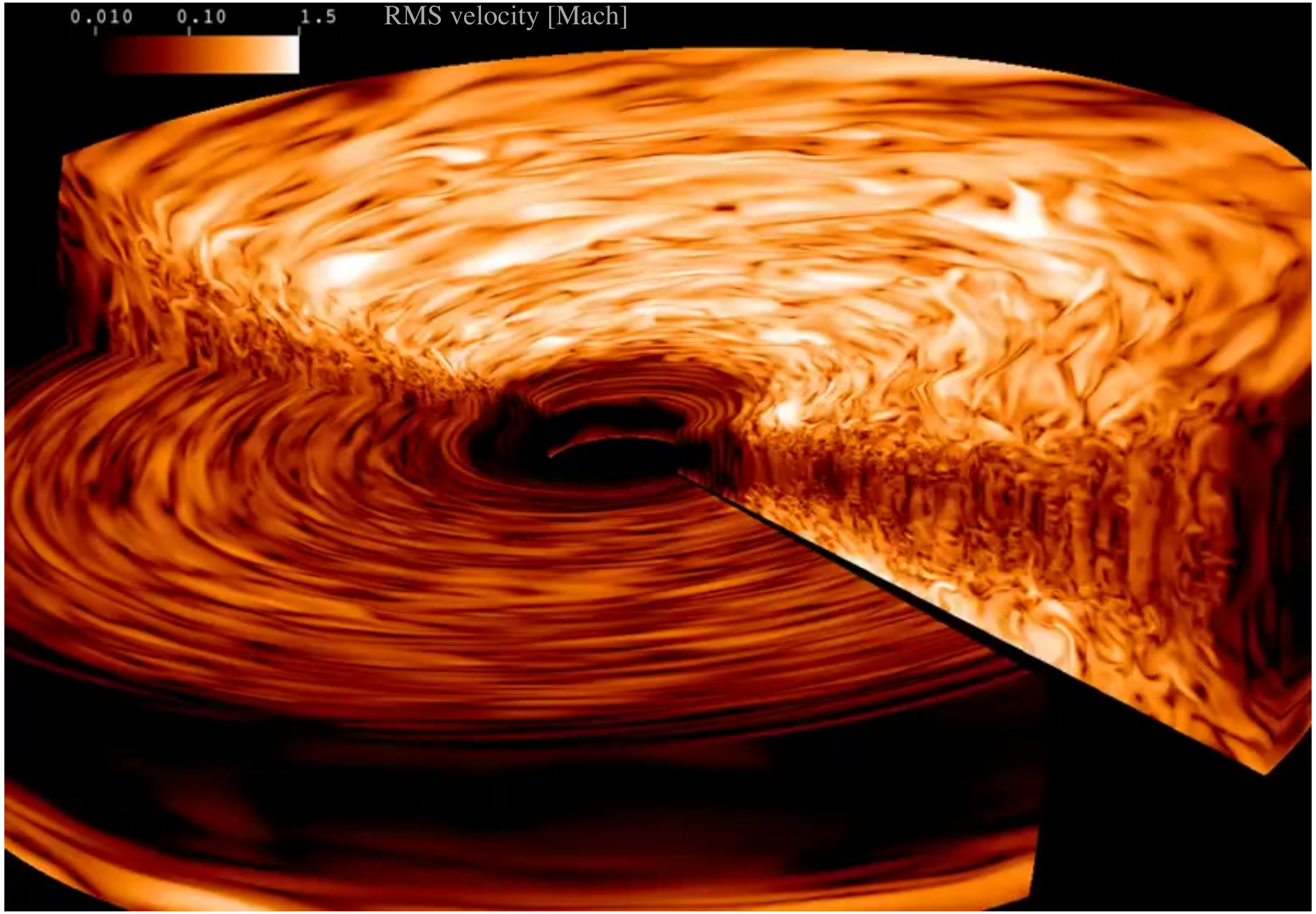
- radial and vertical density stratification
- toroidal magnetic field (β=25)
- outflow boundary condition
- spherical geometry



Research

Flock et al. 2011 ApJ

Detail and long-term study of the MRI in the non-linear regime



R/θ/Φ
384x192x768
10 M CPU h
on BlueGene/P

Similar model and resolution
by Zhu & Stone 2018

Research

Flock et al. 2011 ApJ

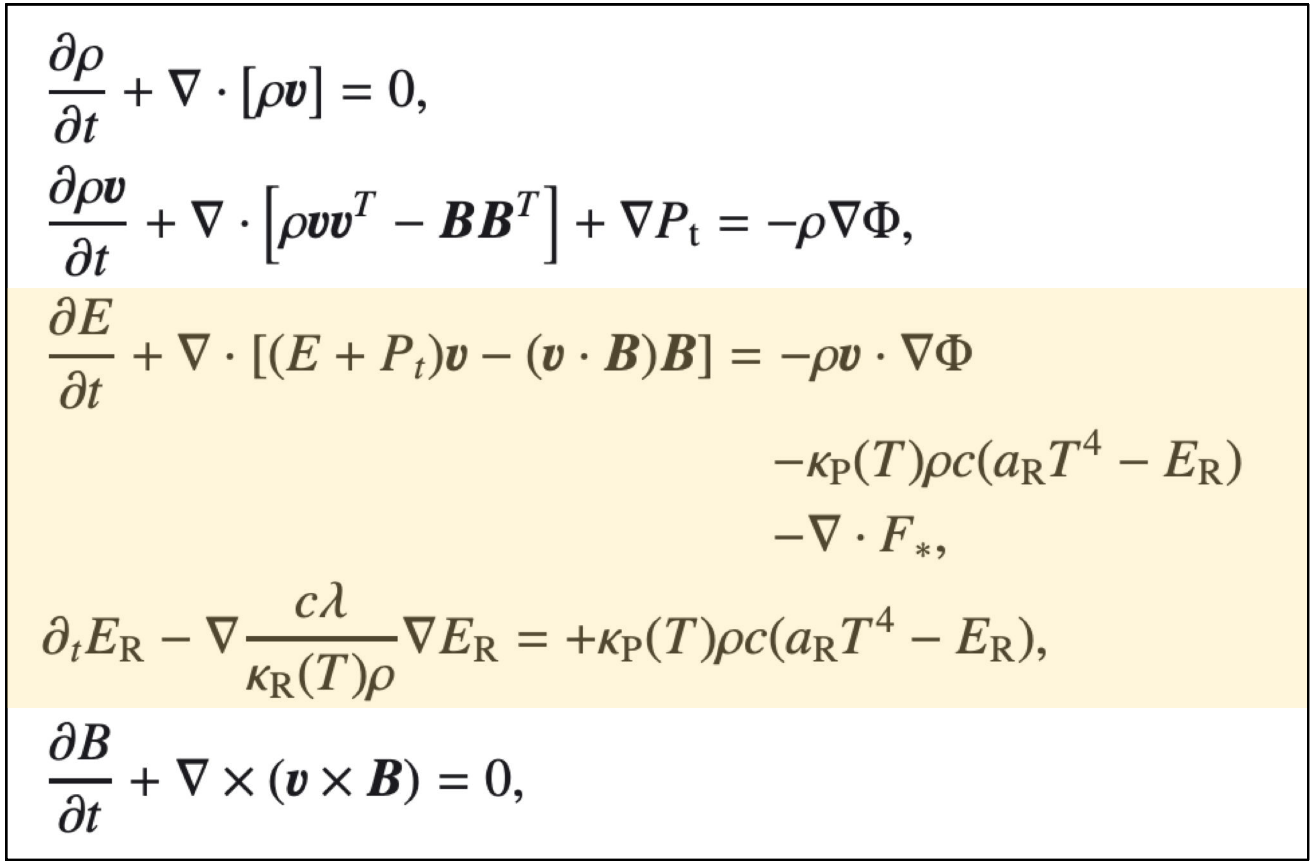
Detail and long-term study of the MRI in the non-linear regime

- Steady state α value of 0.1 to 0.01
- Strong vertical gradient of turbulent activity

Research

Flock et al. 2013 A&A

Radiation magneto-hydrodynamical equations



$$\frac{\partial \rho}{\partial t} + \nabla \cdot [\rho \boldsymbol{v}] = 0,$$

$$\frac{\partial \rho \boldsymbol{v}}{\partial t} + \nabla \cdot \left[\rho \boldsymbol{v}\boldsymbol{v}^T - \boldsymbol{B}\boldsymbol{B}^T\right] + \nabla P_{\mathrm{t}} = -\rho \nabla \Phi,$$

$$\begin{aligned}\frac{\partial E}{\partial t} + \nabla \cdot [(E + P_t)\boldsymbol{v} - (\boldsymbol{v} \cdot \boldsymbol{B})\boldsymbol{B}] = {} & -\rho \boldsymbol{v} \cdot \nabla \Phi \\ & -\kappa_{\mathrm{P}}(T)\rho c(a_{\mathrm{R}}T^4 - E_{\mathrm{R}}) \\ & -\nabla \cdot F_*,\end{aligned}$$

$$\partial_t E_{\mathrm{R}} - \nabla \frac{c\lambda}{\kappa_{\mathrm{R}}(T)\rho} \nabla E_{\mathrm{R}} = +\kappa_{\mathrm{P}}(T)\rho c(a_{\mathrm{R}}T^4 - E_{\mathrm{R}}),$$

$$\frac{\partial B}{\partial t} + \nabla \times (\boldsymbol{v} \times \boldsymbol{B}) = 0,$$

Research

Flock et al. 2013 A&A

Radiation magneto-hydrodynamical equations

$$\frac{\partial \rho}{\partial t} + \nabla \cdot [\rho \boldsymbol{v}] = 0,$$

$$\frac{\partial \rho \boldsymbol{v}}{\partial t} + \nabla \cdot \left[\rho \boldsymbol{v}\boldsymbol{v}^T - \boldsymbol{B}\boldsymbol{B}^T\right] + \nabla P_{\mathrm{t}} = -\rho \nabla \Phi,$$

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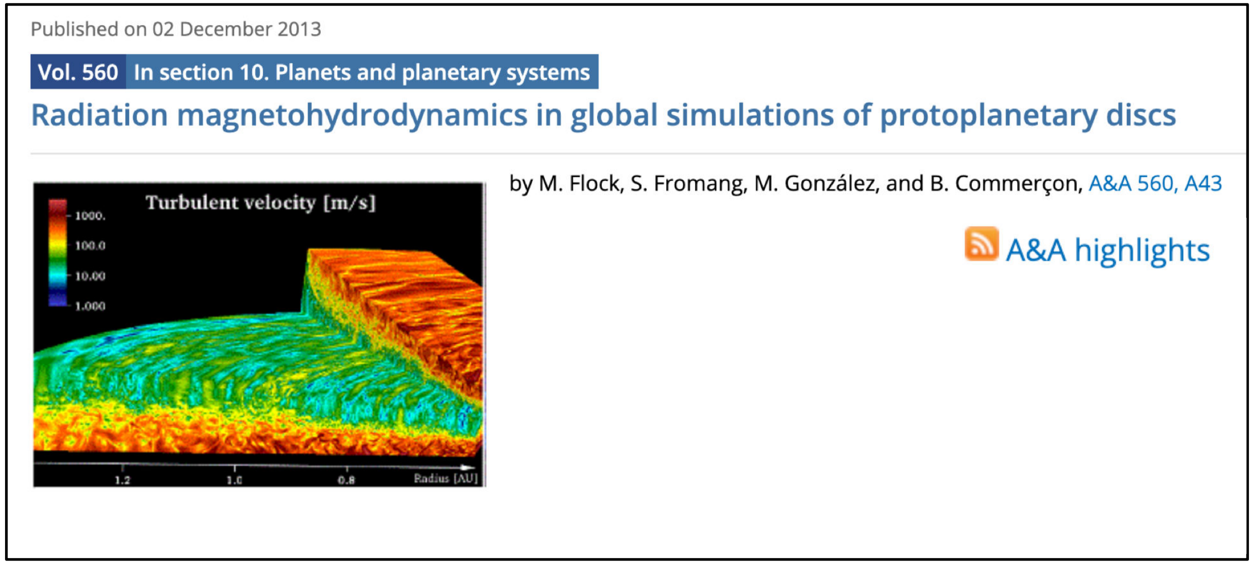
$$\frac{\partial B}{\partial t} + \nabla \times (\boldsymbol{v} \times \boldsymbol{B}) = 0,$$

Flux-limited diffusion + irradiation
- implicit time integration
- BICGStab to solve the matrix inversion

Research

Flock et al. 2013 A&A

3D radiation magneto-hydrodynamical simulations + irradiation



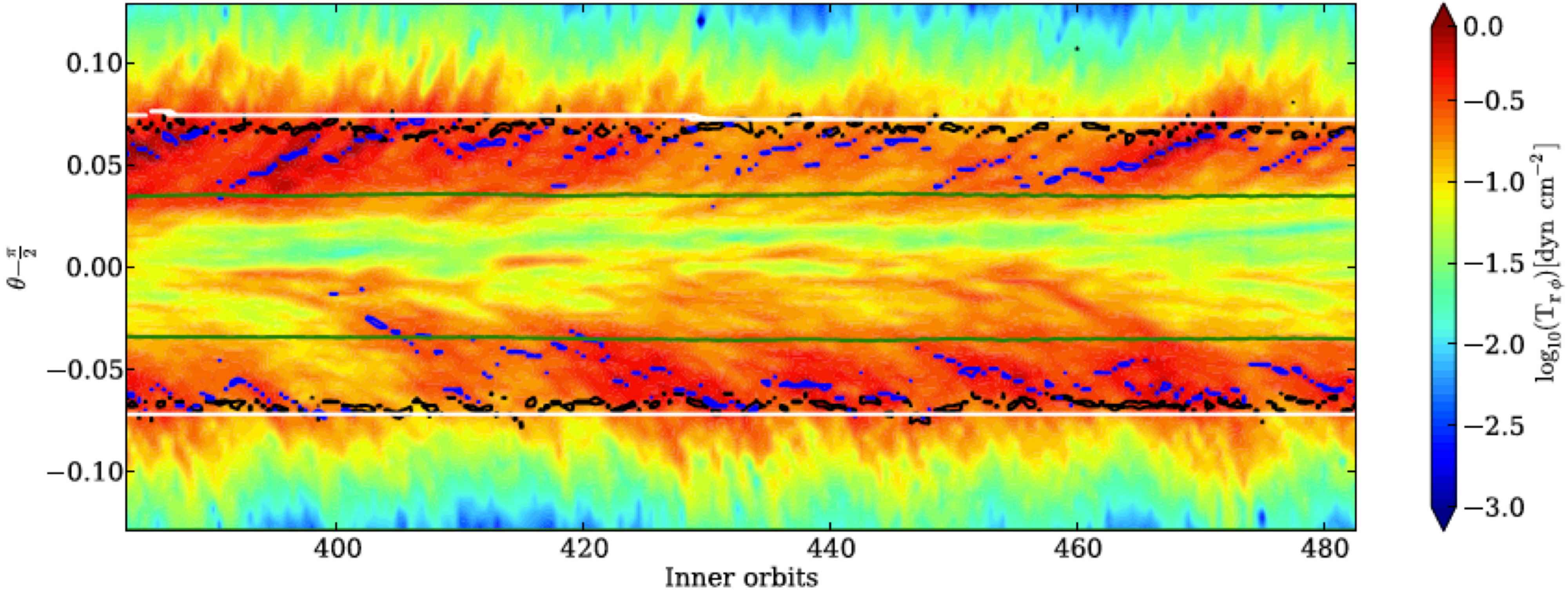
Published on 02 December 2013

Vol. 560 In section 10. Planets and planetary systems

Radiation magnetohydrodynamics in global simulations of protoplanetary discs

by M. Flock, S. Fromang, M. González, and B. Commerçon, A&A 560, A43

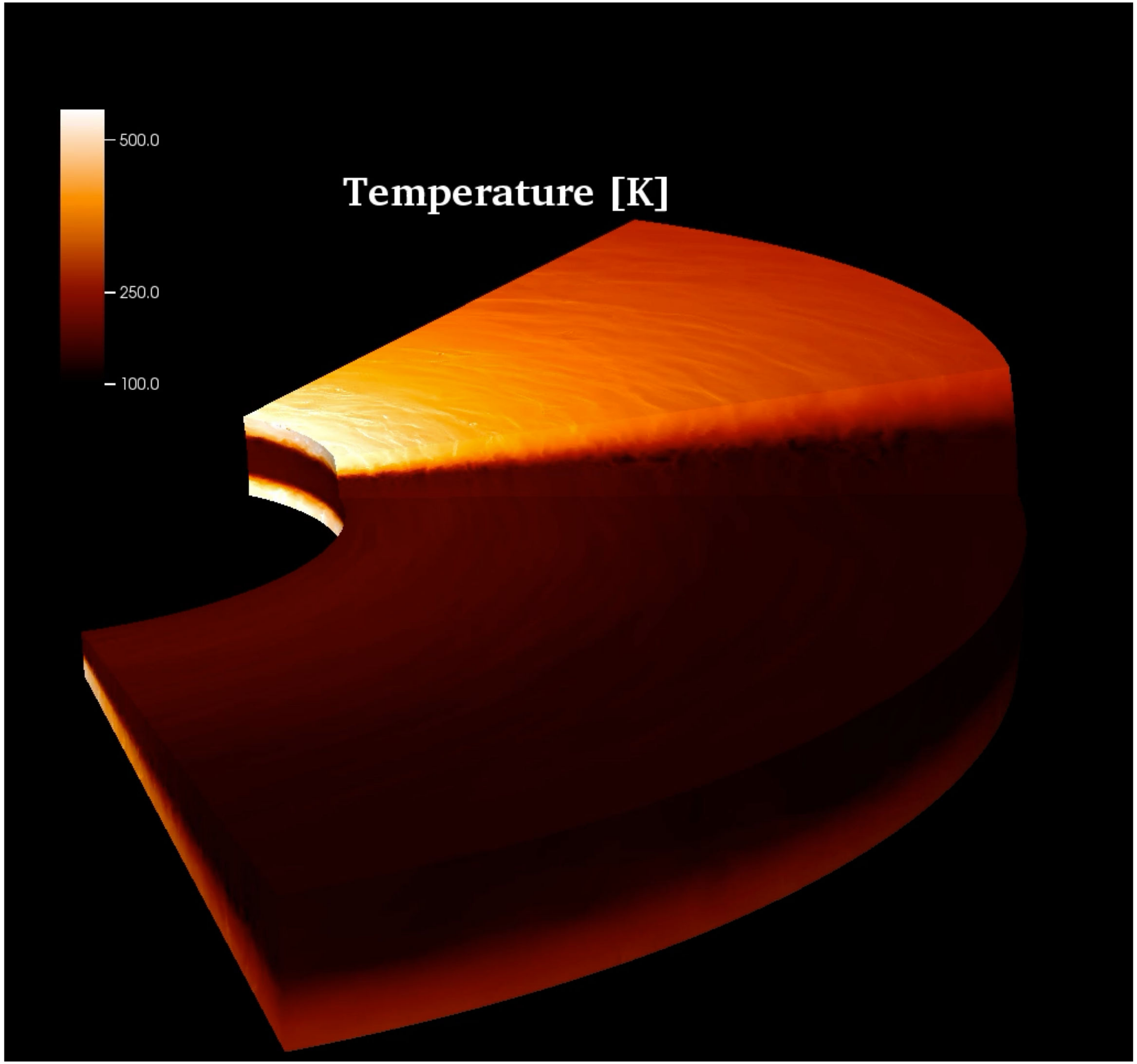
A&A highlights



Research

Flock et al. 2013 A&A

- **New turbulence level**
- **Realistic temperature profile**
- **Enables to compare with observations**

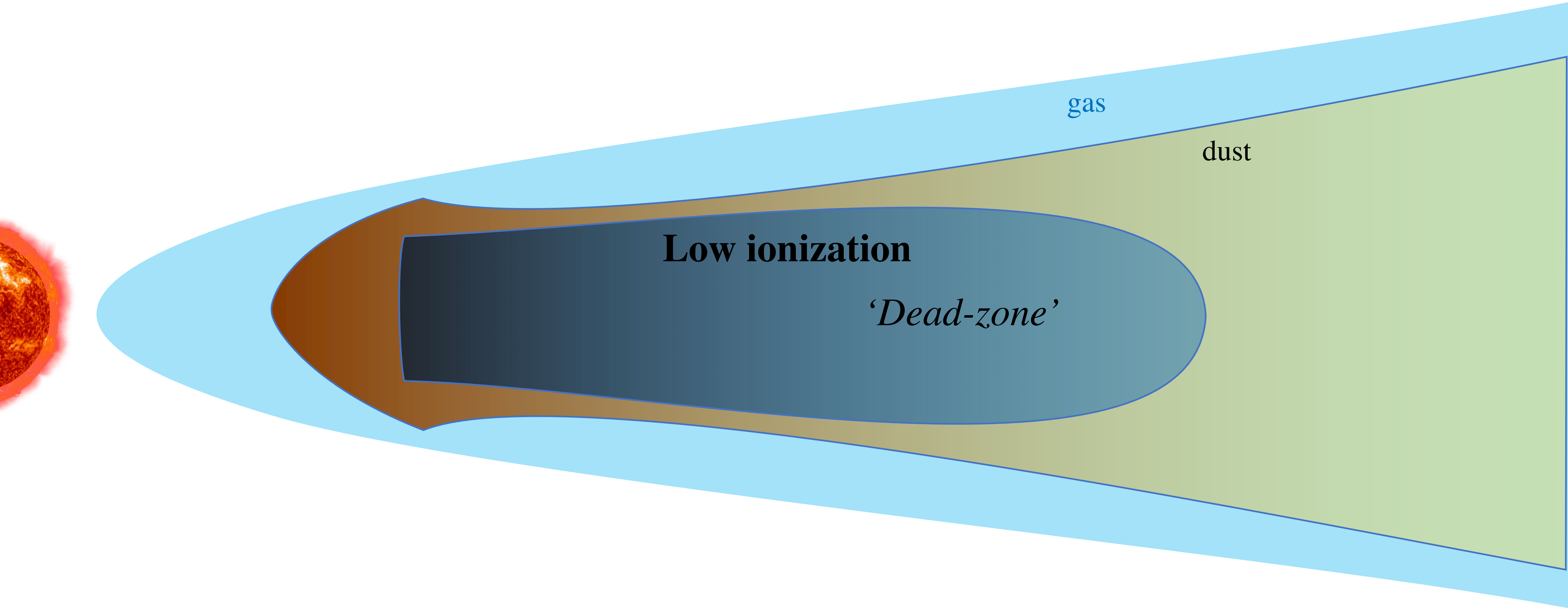


Research

-The non-linear dynamics in disks

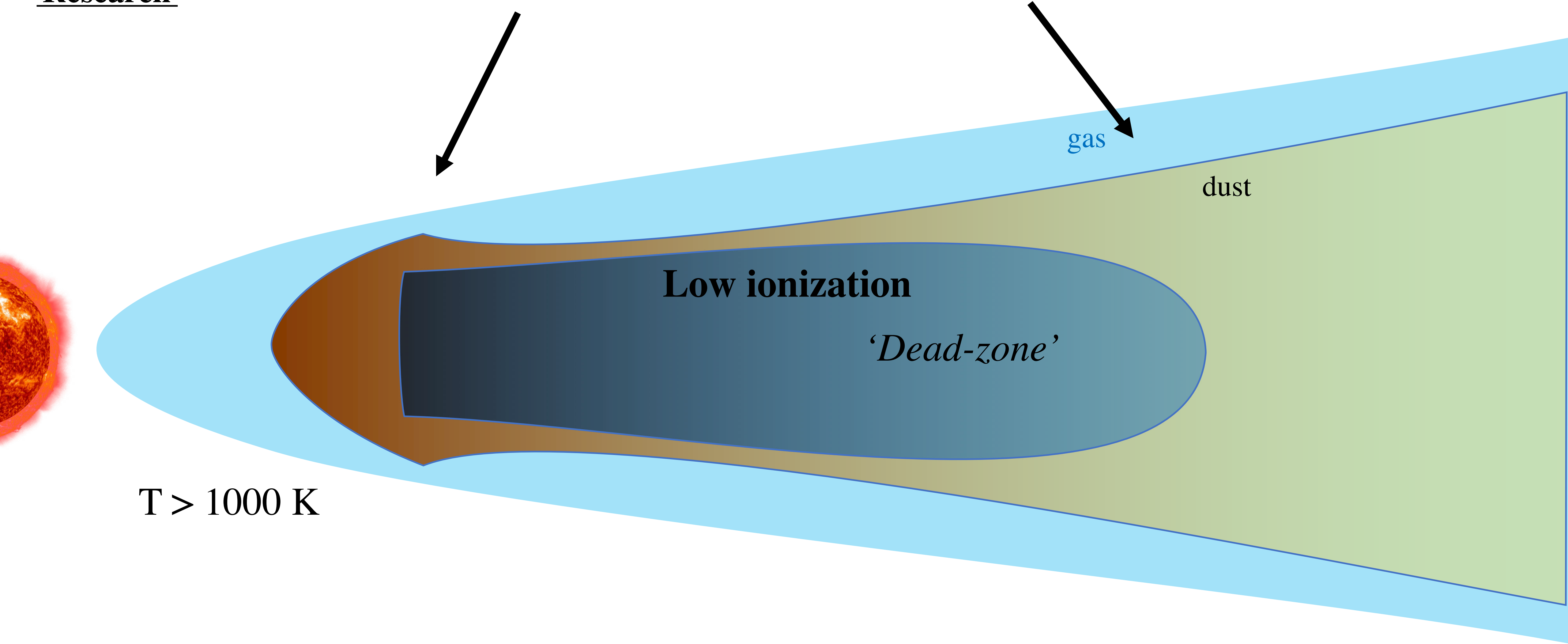
-**Dust concentration at the transition regions**

Research



Research

Ionization transition regions



gas

dust

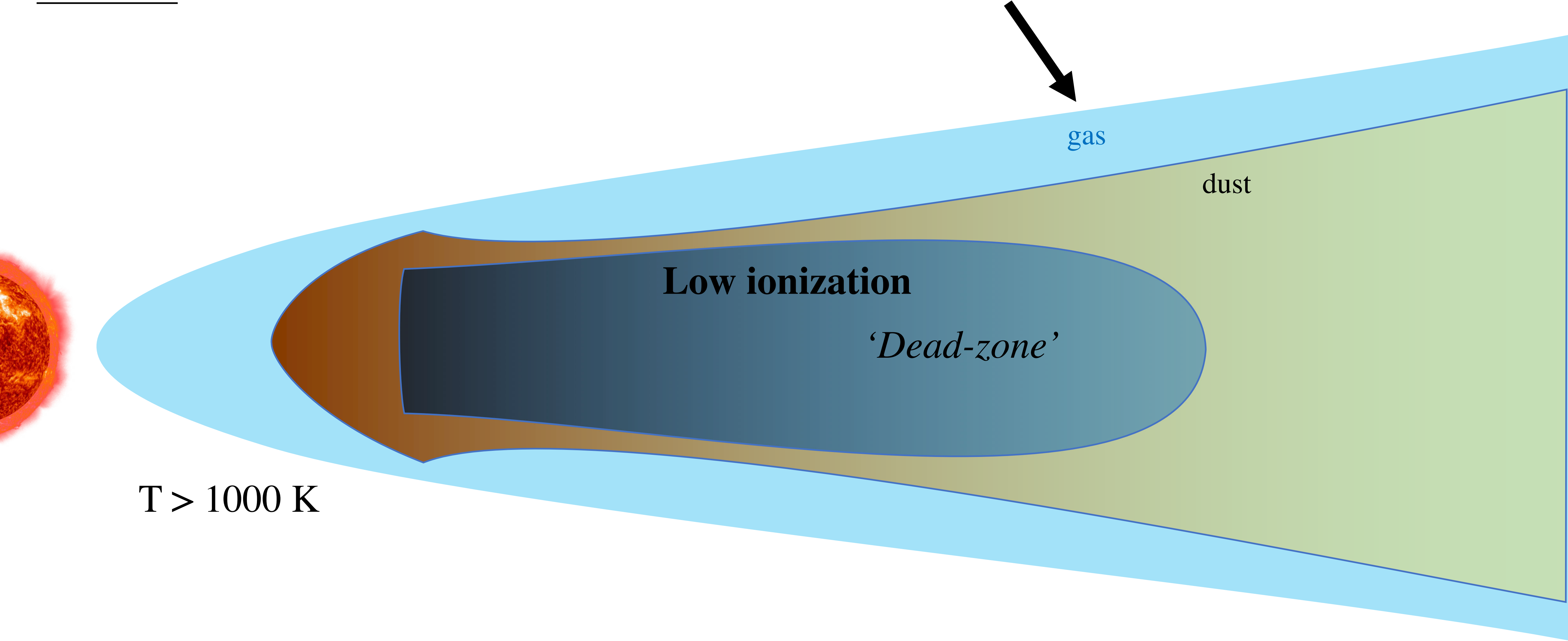
Low ionization

‘Dead-zone’

T > 1000 K

FUV, Cosmic Ray ionization

Ionization transition regions



gas

dust

Low ionization

'Dead-zone'

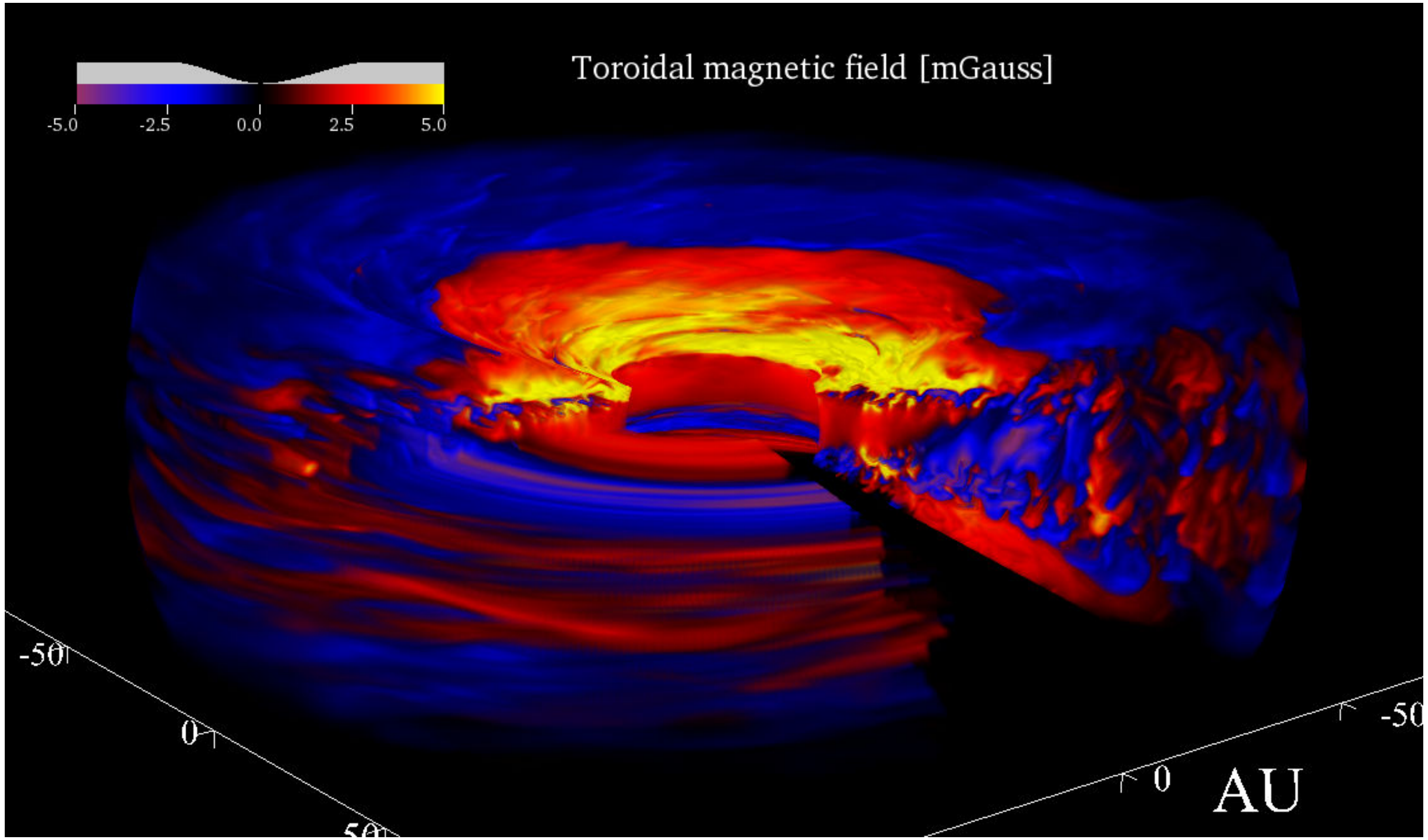
T > 1000 K

FUV, Cosmic Ray ionization

Research

Flock et al. 2015 A&A

Global 3D non-ideal MHD simulations

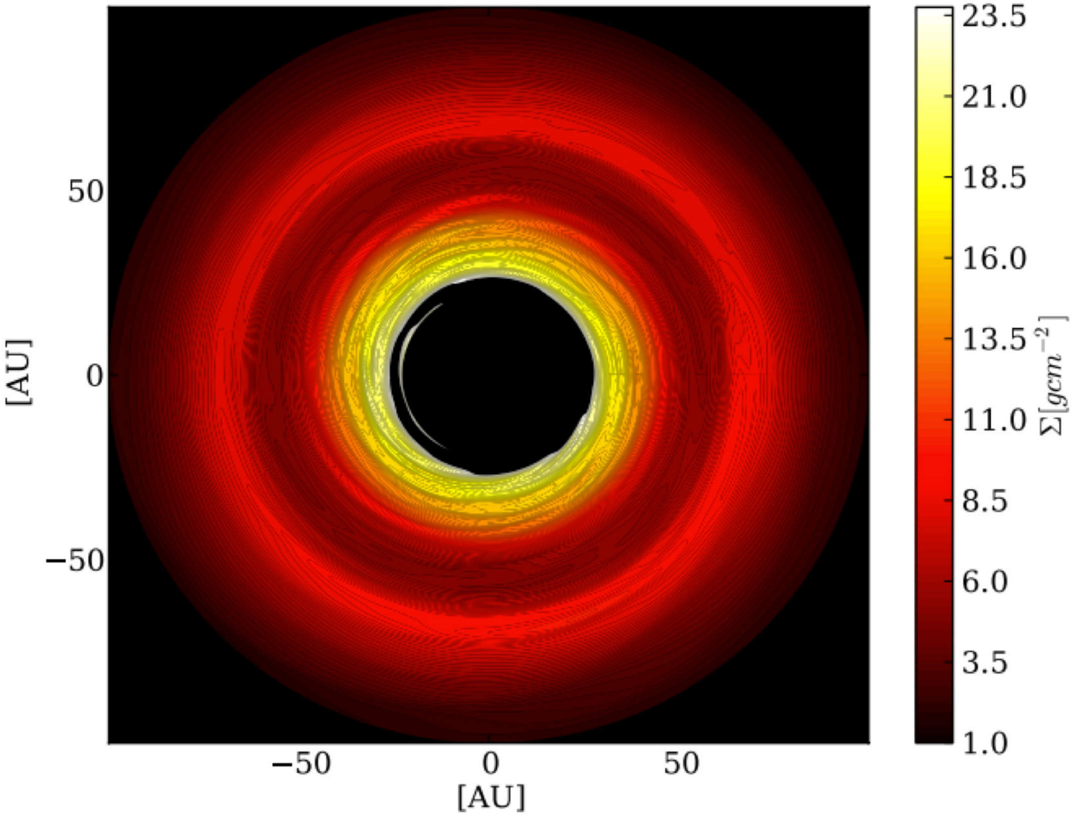


Research

Flock et al. 2015 A&A

Global 3D non-ideal MHD simulations

Surface density

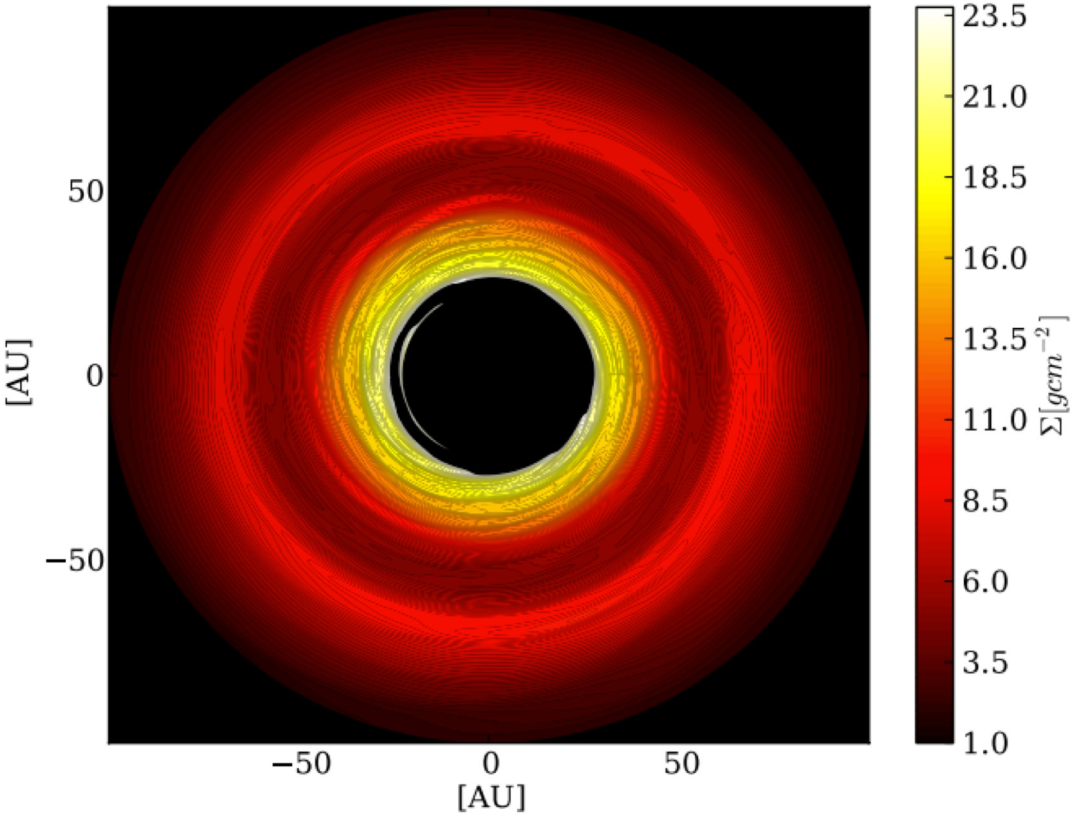


Research

Flock et al. 2015 A&A

Global 3D non-ideal MHD simulations

Surface density

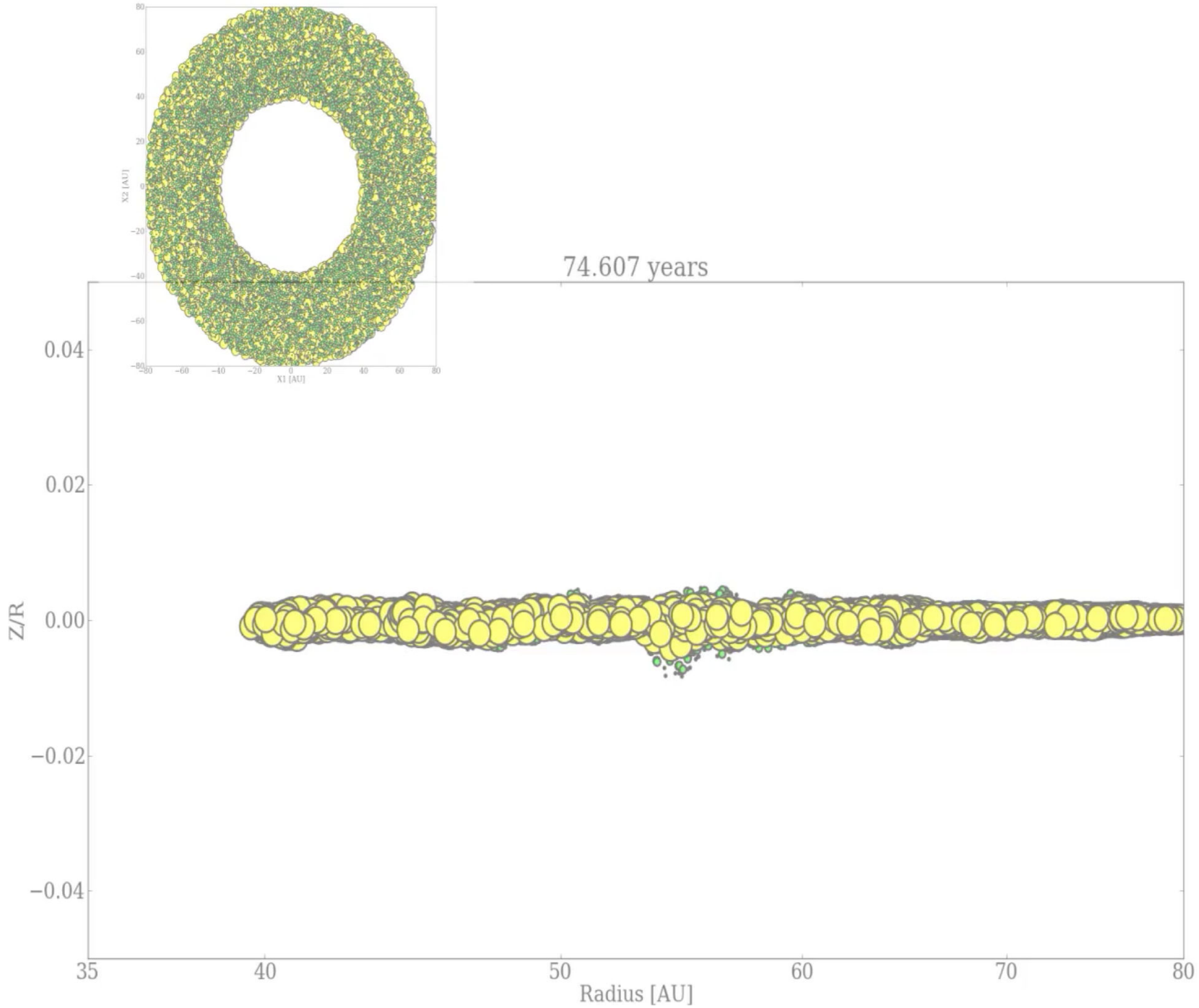


$\frac{\partial P}{\partial R}=0$ ⇨ **concentration of grains**

Research

Ruge, Flock et al. 2016 A&A

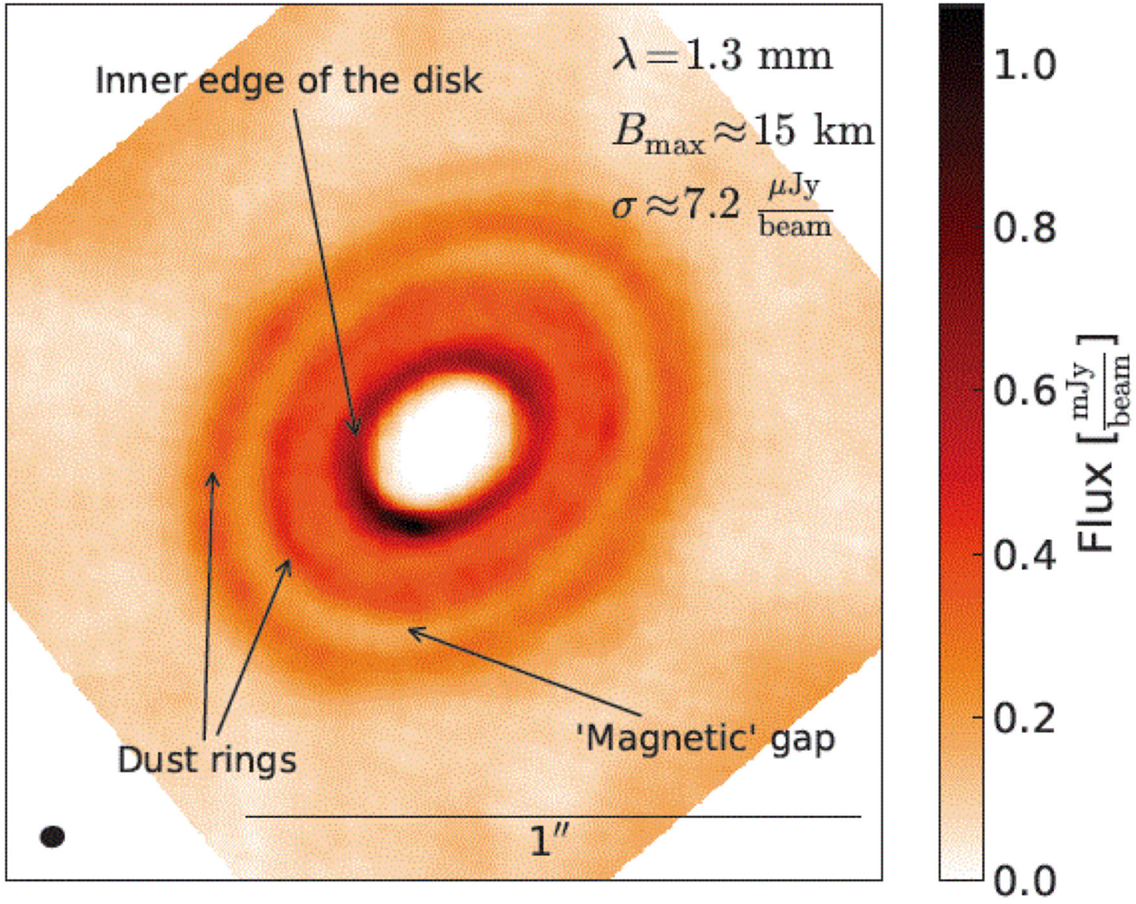
Gas and dust global 3D MHD simulations



Research

Ruge, Flock et al. 2016 A&A

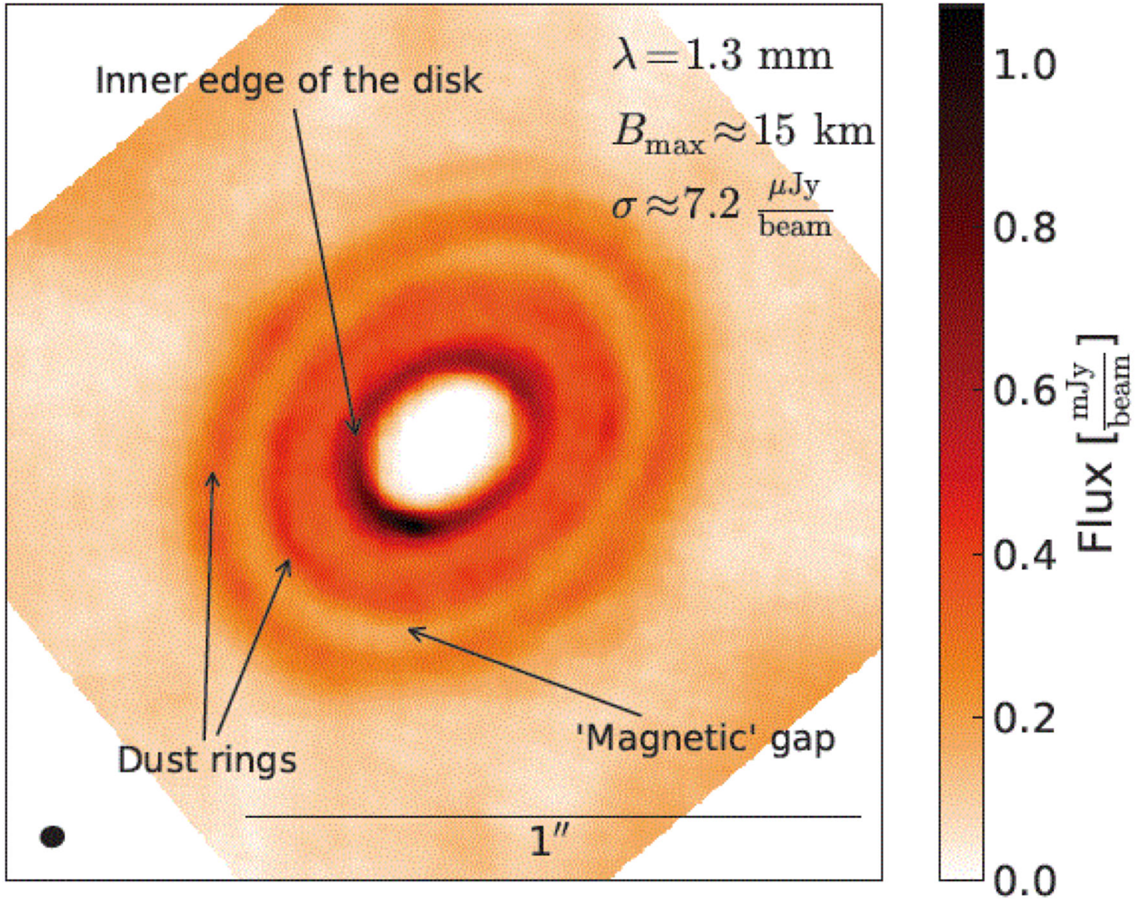
Synthetic ALMA observation of the global model

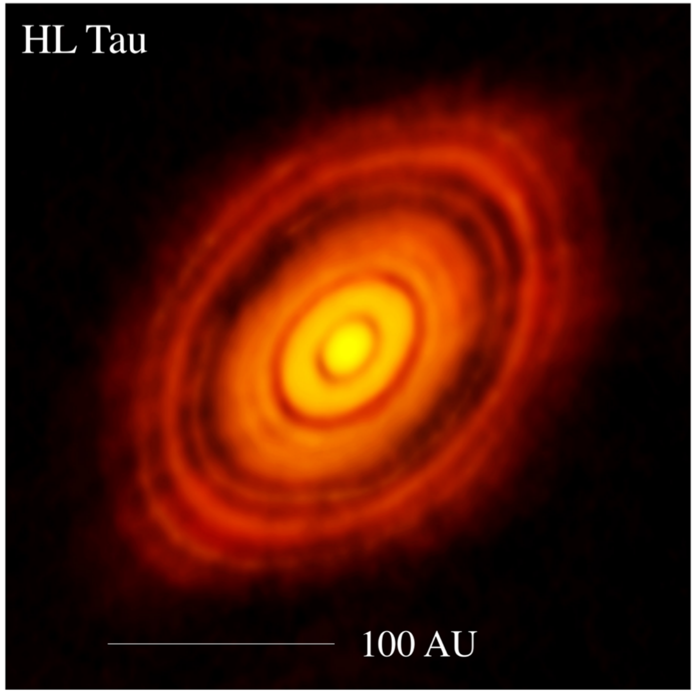


Research

Ruge, Flock et al. 2016 A&A

Synthetic ALMA observation of the global model



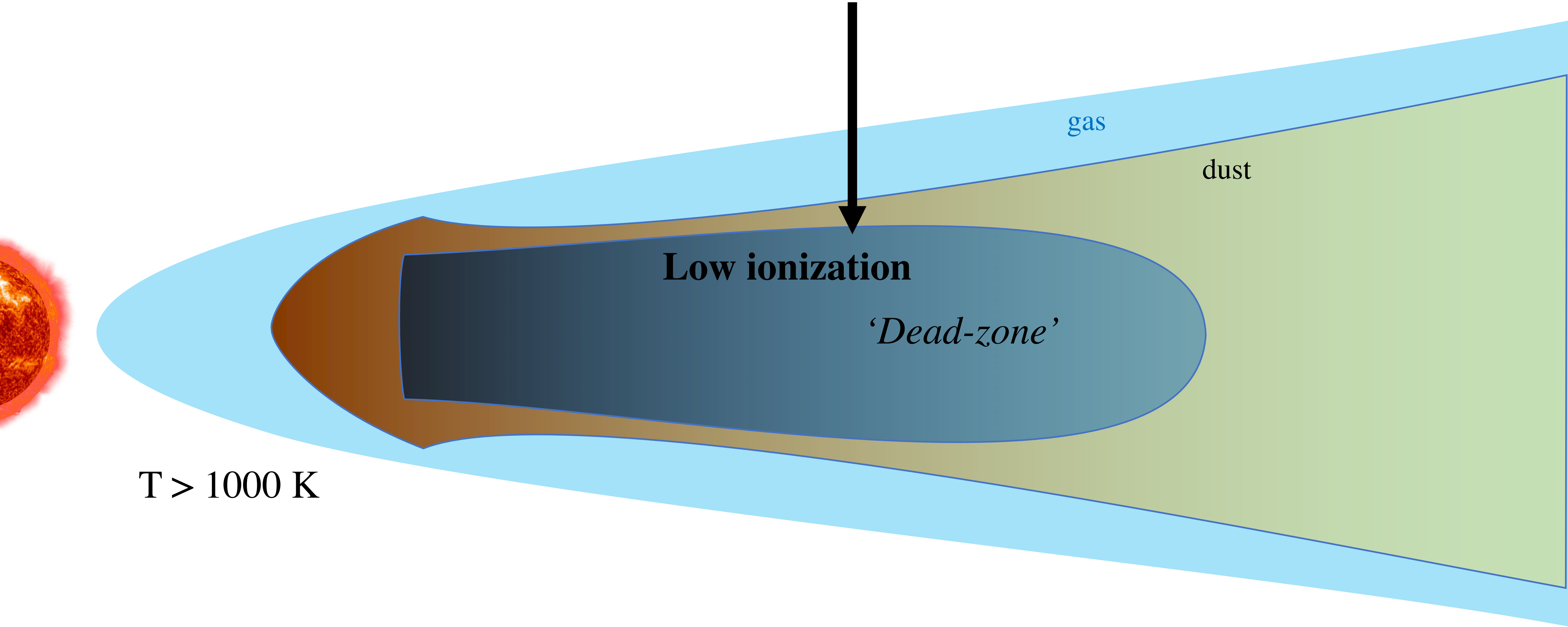


Partnership et al. 2015 ApJL

Magnetic effects can cause dust concentrations and ring formation

Research

‘Dead-zone’ regions



FUV, Cosmic Ray ionization

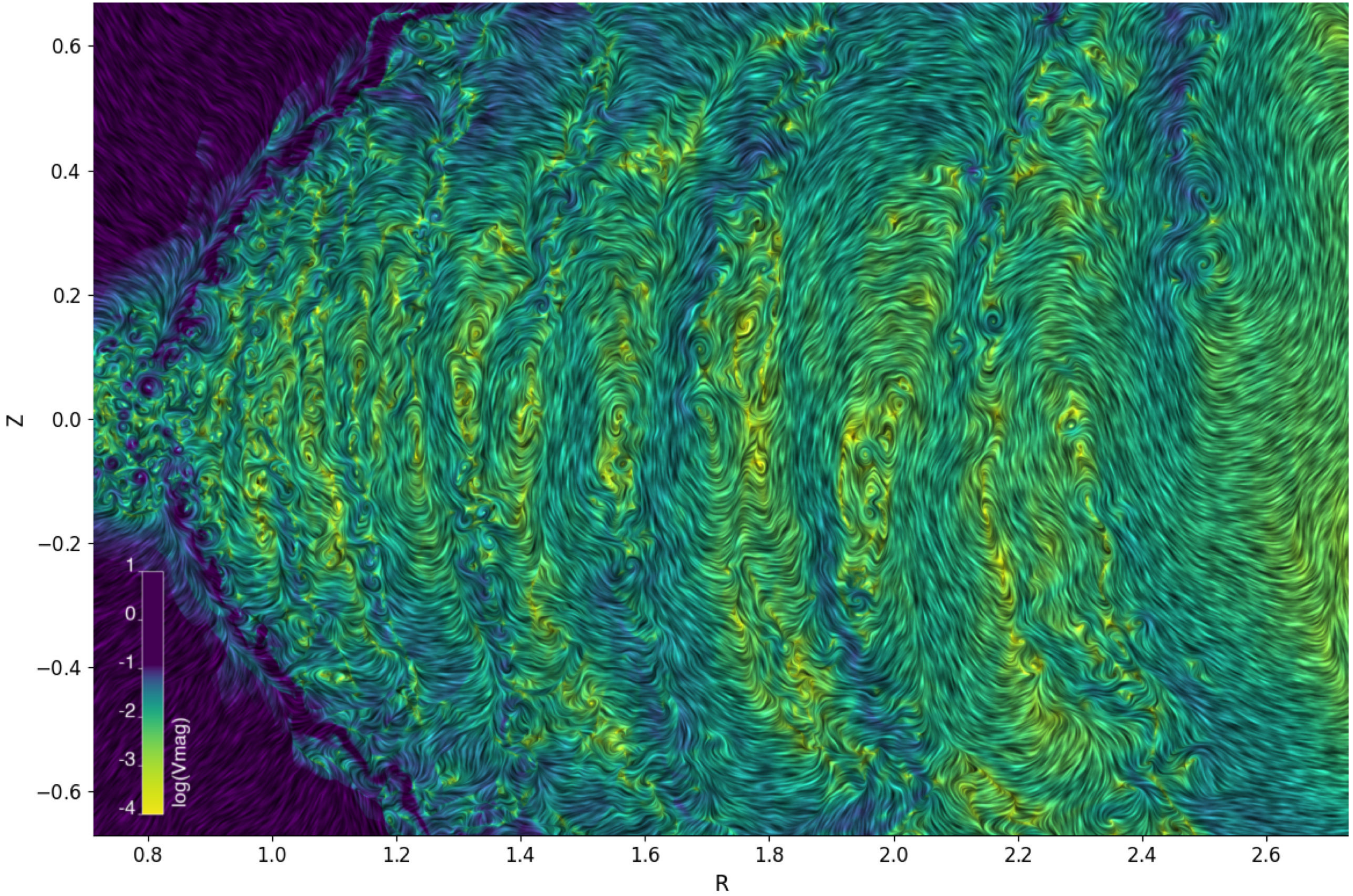
Research

Flock et al. 2020 ApJ

Flores-Rivera, Flock et al. 2020 A&A

Vertical shear instability in low ionized disks

High-resolution 2D hydrodynamical simulations

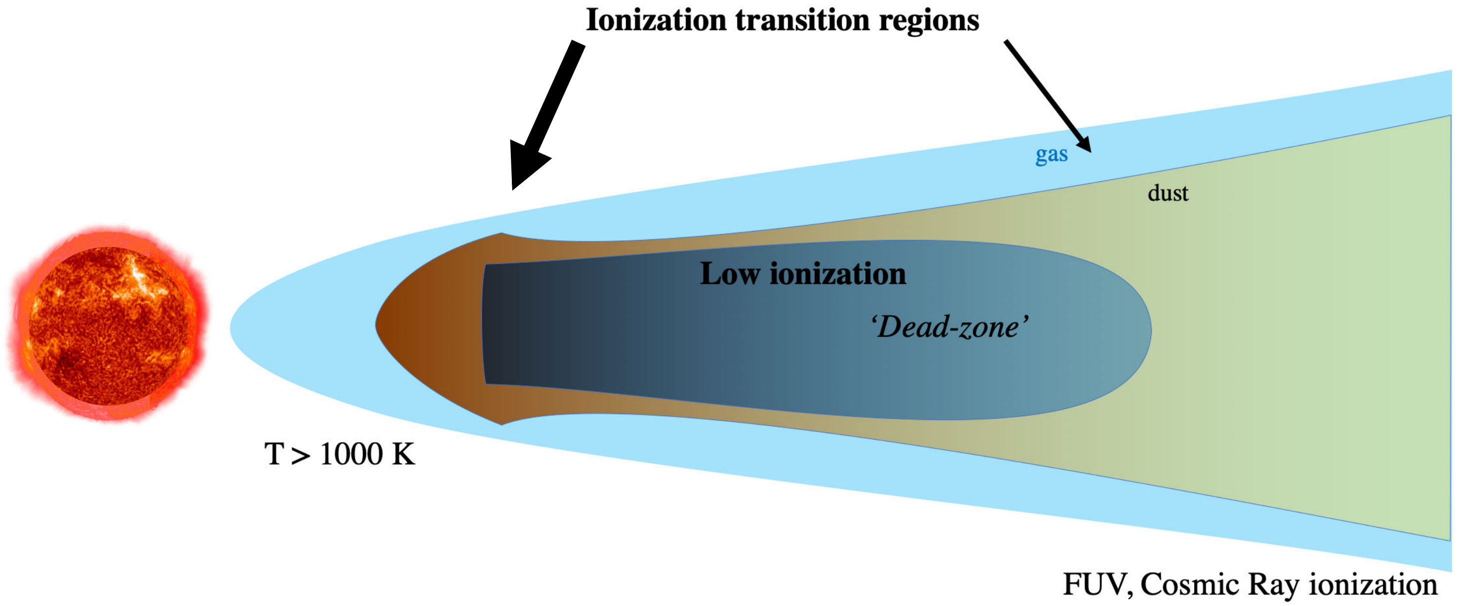


Line integral convolution (LIC)

Research

Flock et al. 2016 ApJ
Flock et al. 2017 ApJ
Flock et al. 2019 A&A

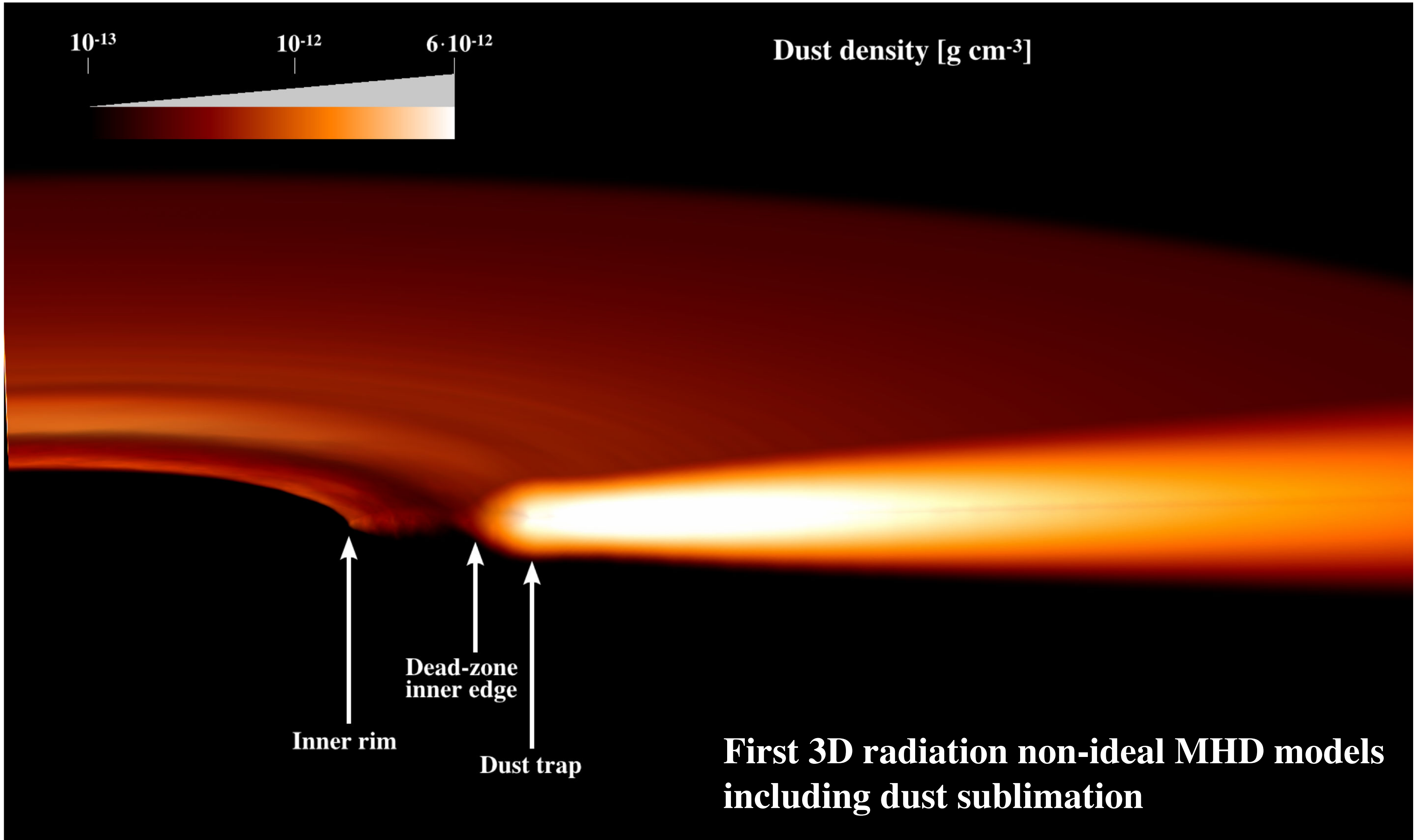
The inner disk as birthplaces of planets



Research

Flock et al. 2016 ApJ
Flock et al. 2017 ApJ
Flock et al. 2019 A&A

The inner disk as birthplaces of planets



First 3D radiation non-ideal MHD models including dust sublimation

Research

Flock et al. 2016 ApJ
Flock et al. 2017 ApJ
Flock et al. 2019 A&A

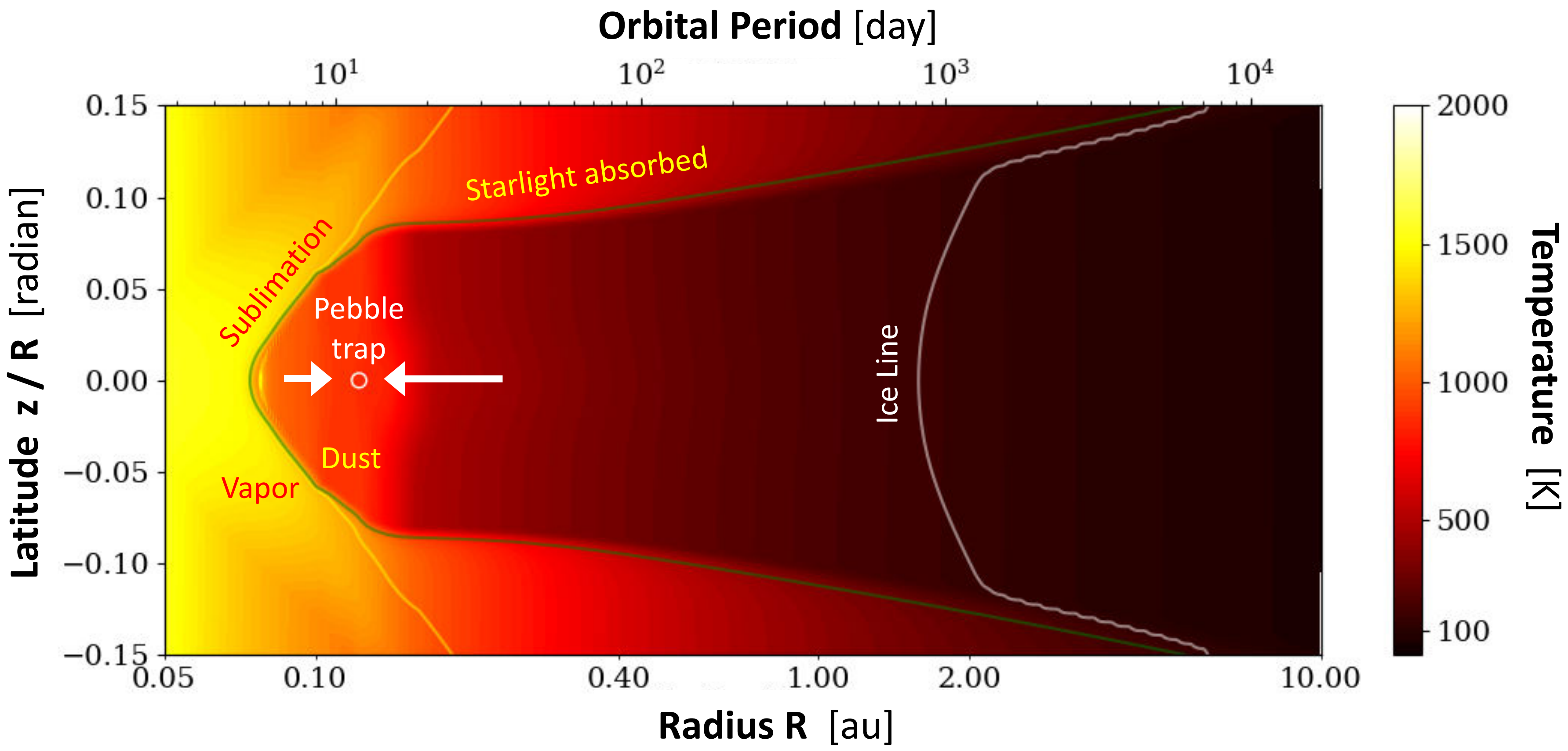
The inner disk as birthplaces of planets

- Global 2D radiation hydrodynamical simulations including dust sublimation
- Dust density fully linked to radiation transfer
- Axisymmetric solution
- Search for pebble traps

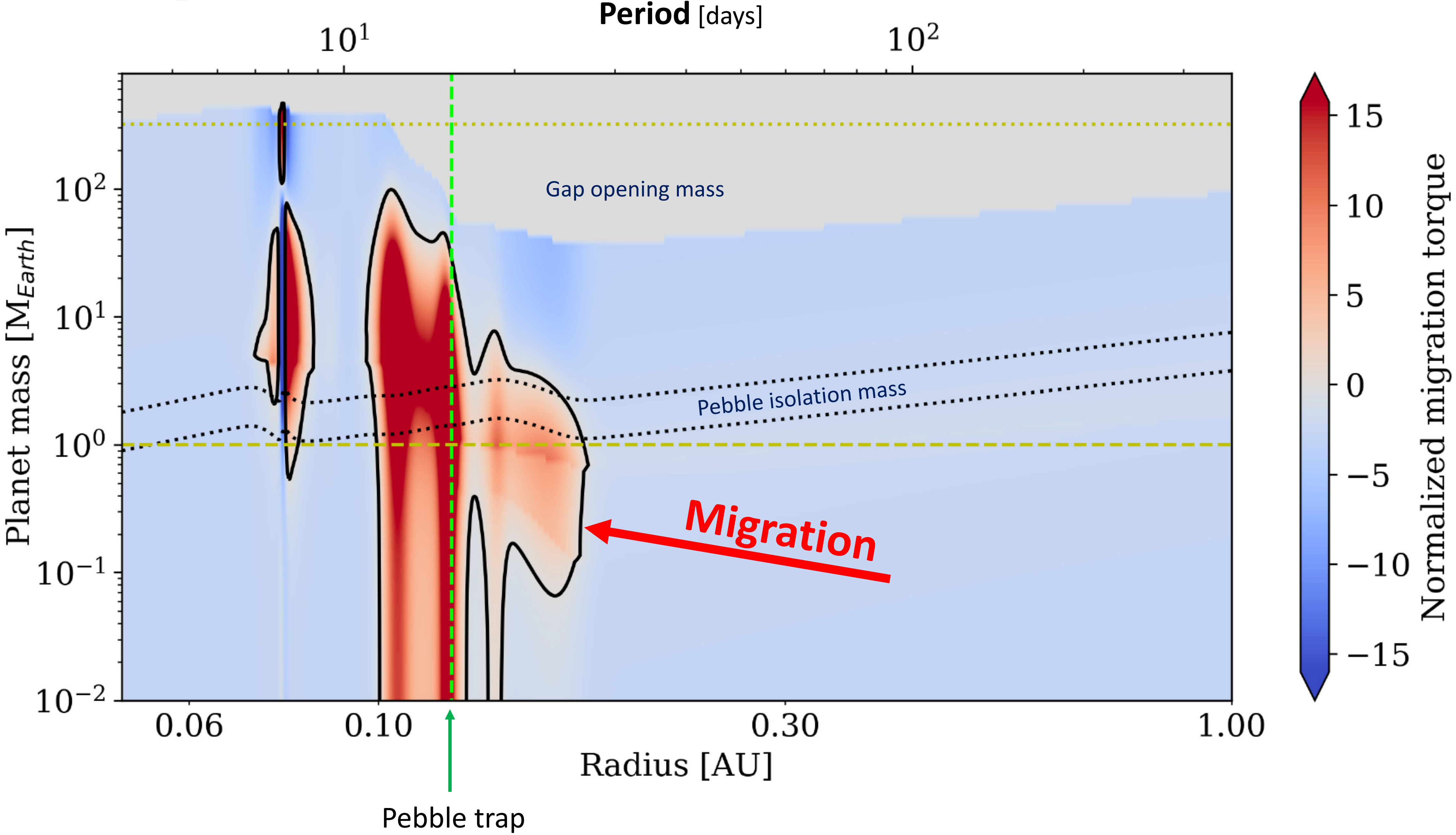
Research

Flock et al. 2016 ApJ
Flock et al. 2017 ApJ
Flock et al. 2019 A&A

The inner disk as birthplaces of planets



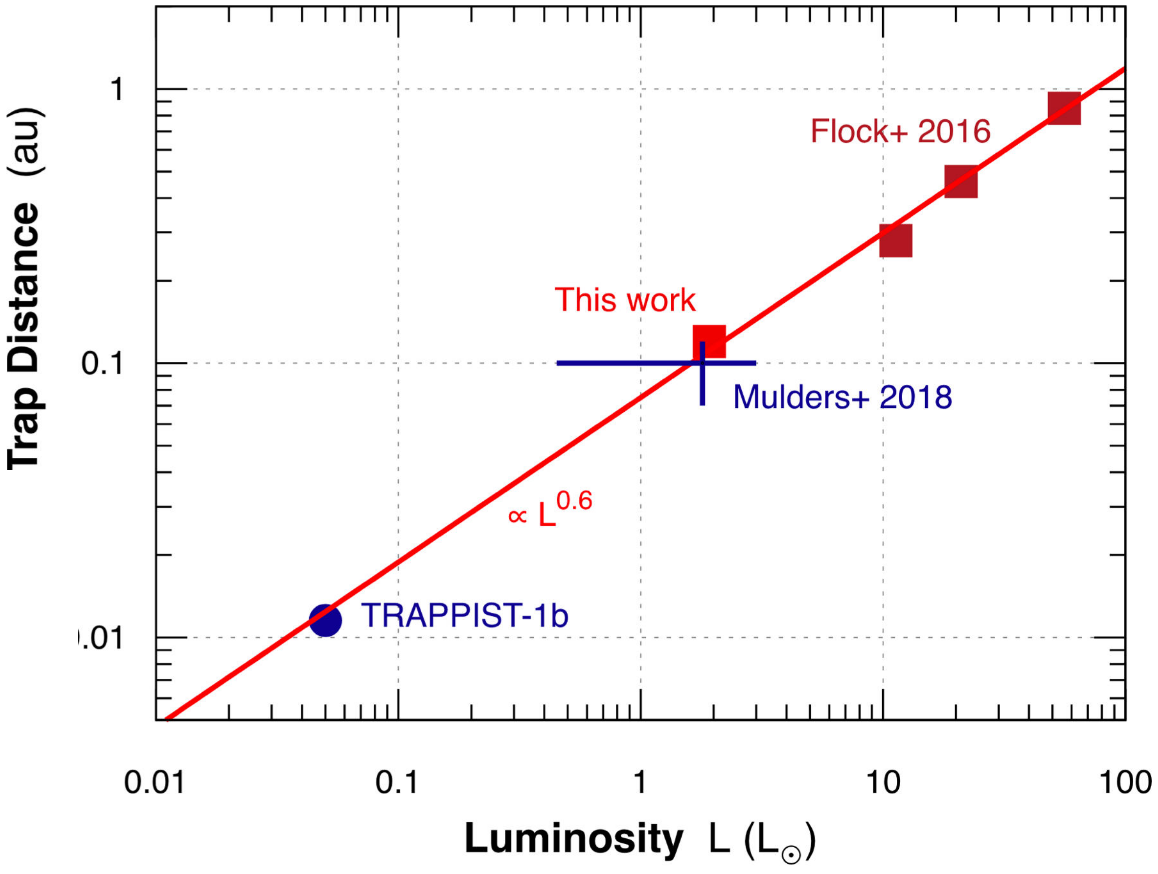
Migration map



Research

Flock et al. 2019 A&A

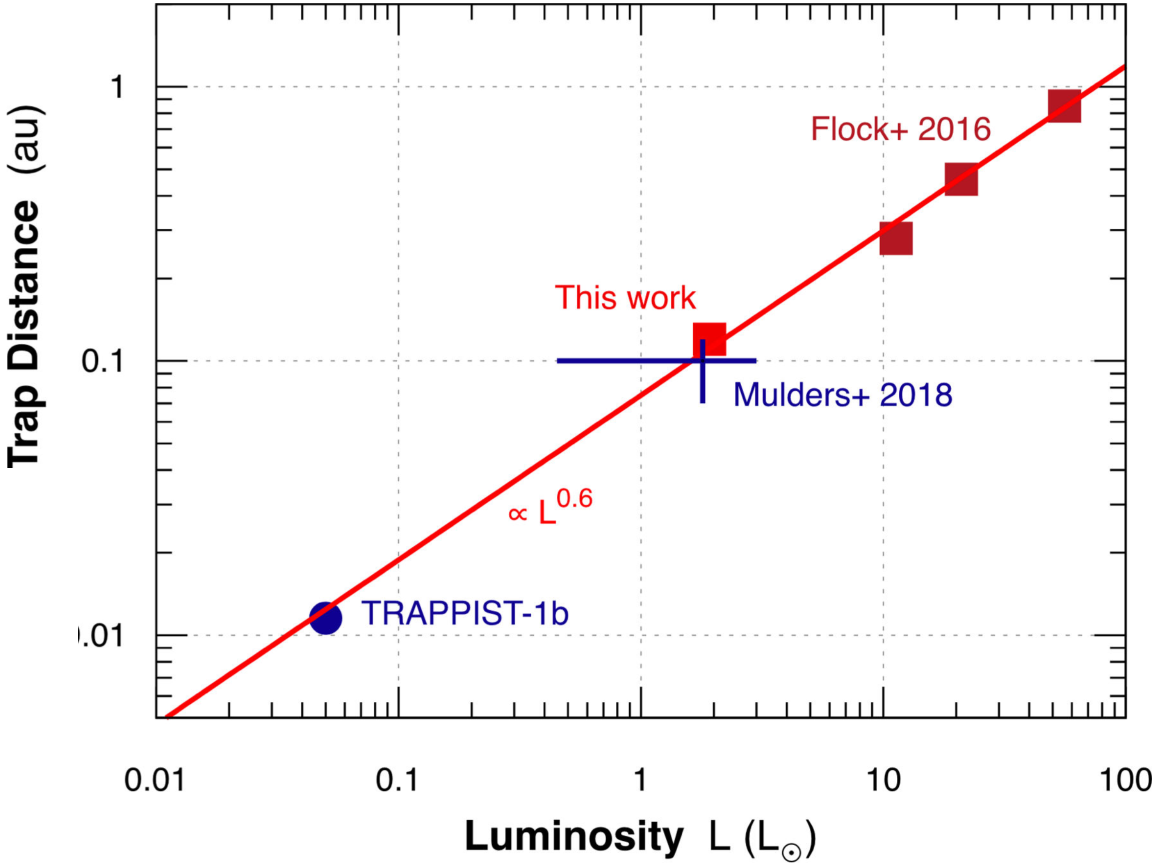
The inner disk as birthplaces of planets

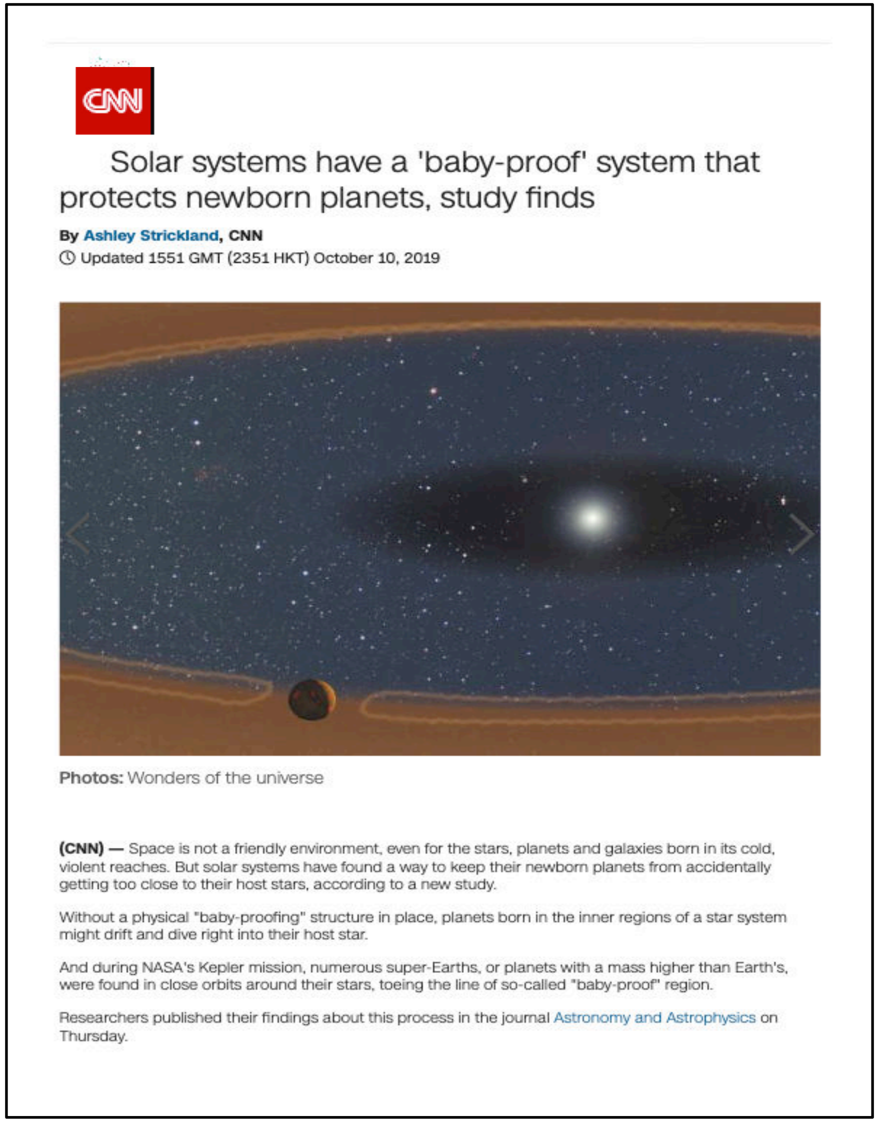


Research

Flock et al. 2019 A&A

The inner disk as birthplaces of planets





Solar systems have a 'baby-proof' system that protects newborn planets, study finds

By Ashley Strickland, CNN

Updated 1551 GMT (2351 HKT) October 10, 2019

Photos: Wonders of the universe

(CNN) — Space is not a friendly environment, even for the stars, planets and galaxies born in its cold, violent reaches. But solar systems have found a way to keep their newborn planets from accidentally getting too close to their host stars, according to a new study.

Without a physical "baby-proofing" structure in place, planets born in the inner regions of a star system might drift and dive right into their host star.

And during NASA's Kepler mission, numerous super-Earths, or planets with a mass higher than Earth's, were found in close orbits around their stars, toeing the line of so-called "baby-proof" region.

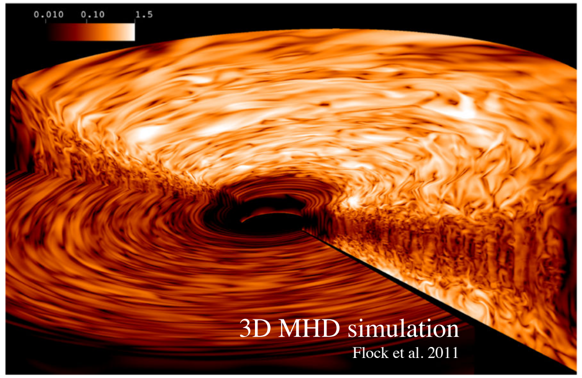
Researchers published their findings about this process in the journal Astronomy and Astrophysics on Thursday.

Summary

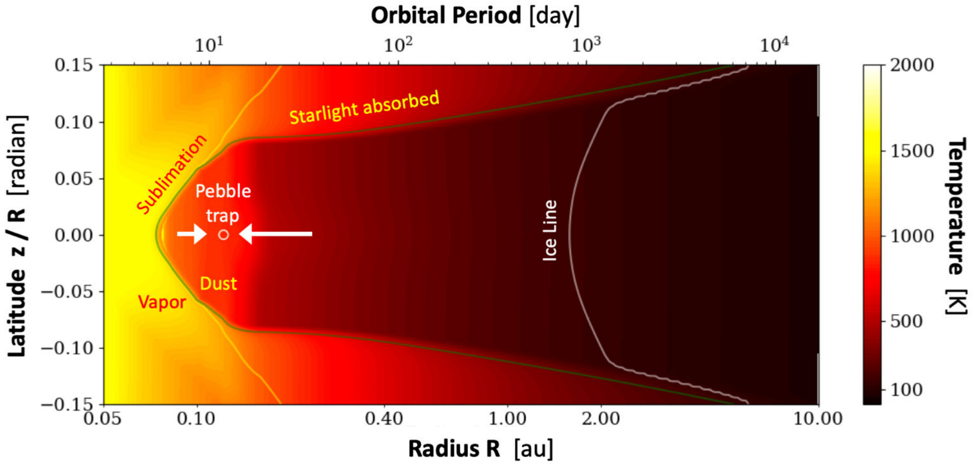
Planet formation in circumstellar disks

- Turbulence and ionization transition zones set the birthplace of proto-planets


Pleiades, NASA



3D MHD simulation
Flock et al. 2011



- Advanced observations to see planet formation in action