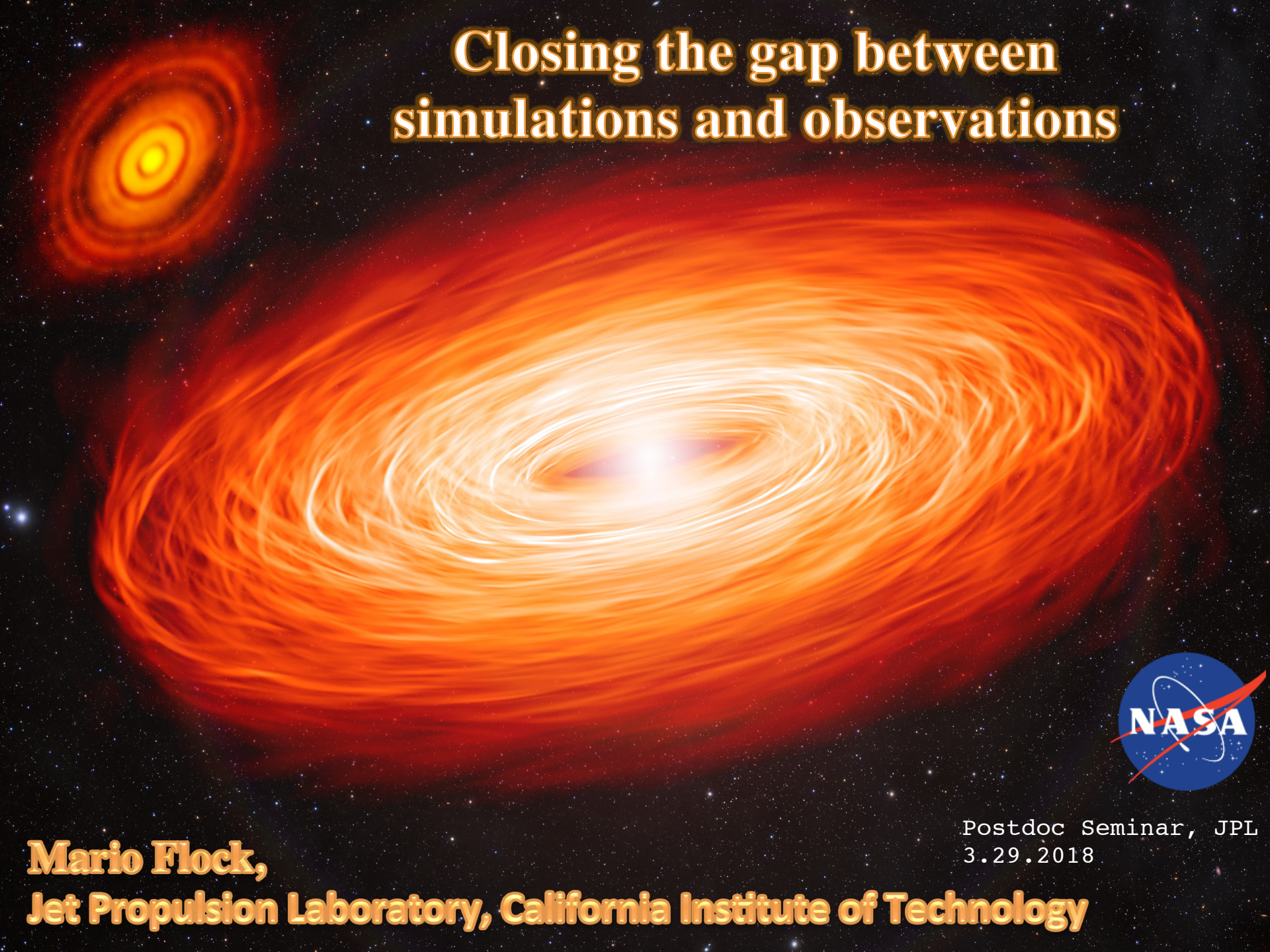
Closing the gap between simulations and observations



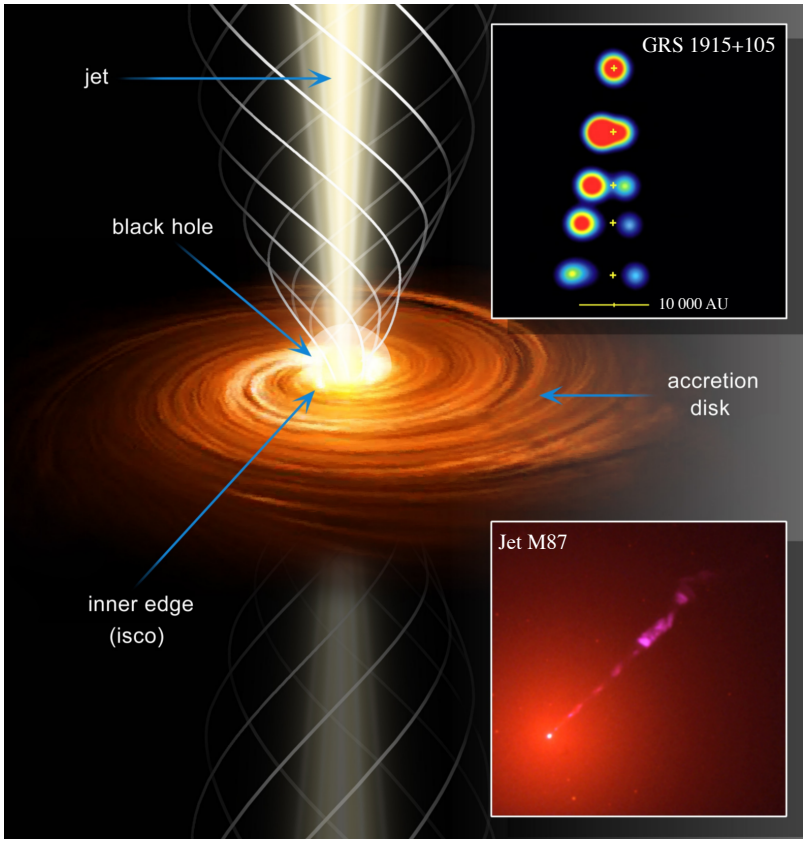
Postdoc Seminar, JPL
3.29.2018

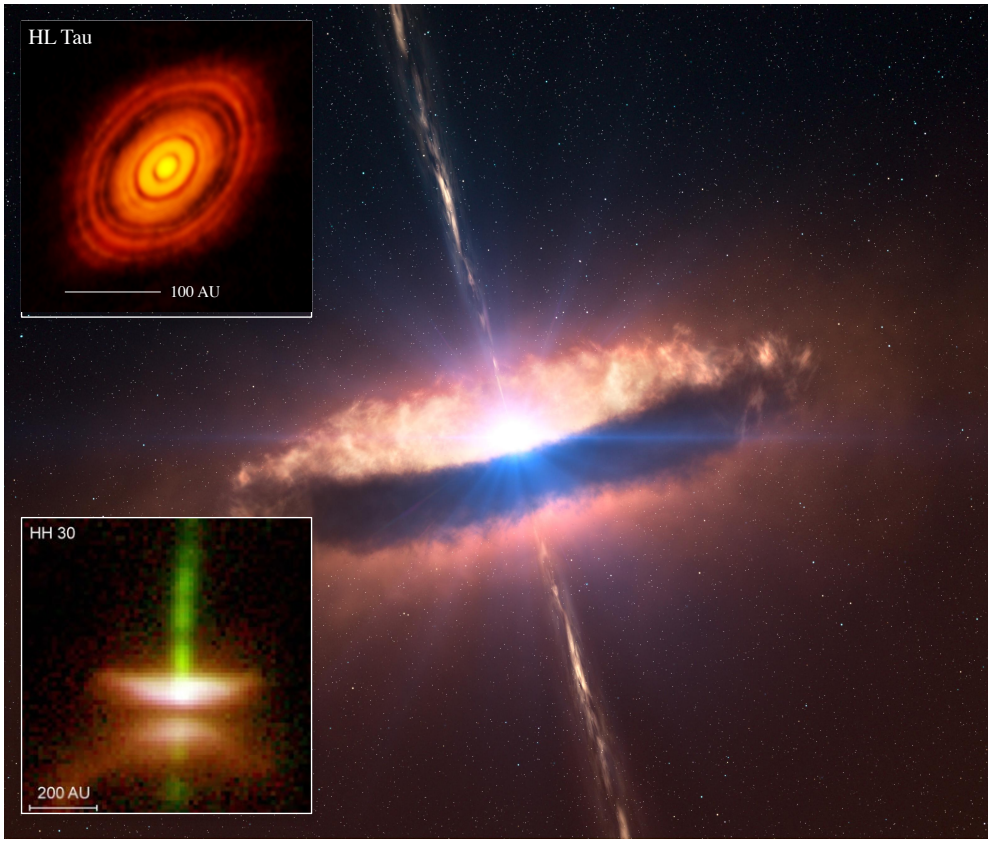
Mario Flock,
Jet Propulsion Laboratory, California Institute of Technology

Accretion disks are fundamental

They appear around a huge range of objects

From supermassive black holes to young giant planets





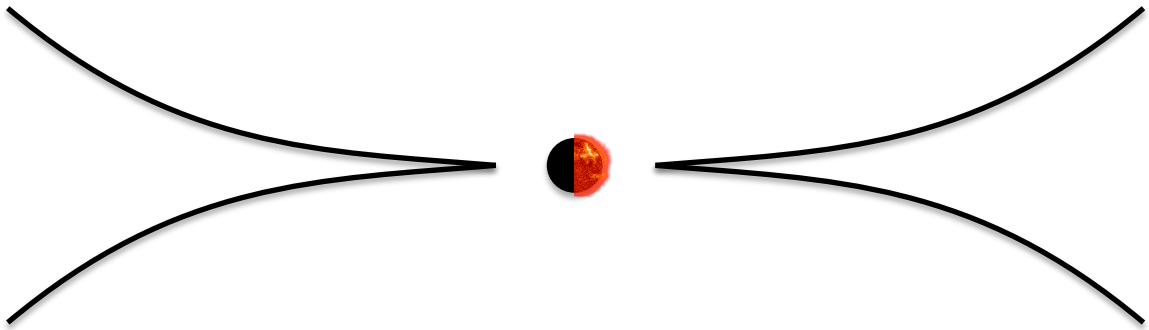
Credit: J.A. Biretta et al., Hubble Heritage Team (STScI /AURA), NASA, ALMA Partnership 2015

Introduction

Accretion disks

Challenges

- **Which process allows accretion?**



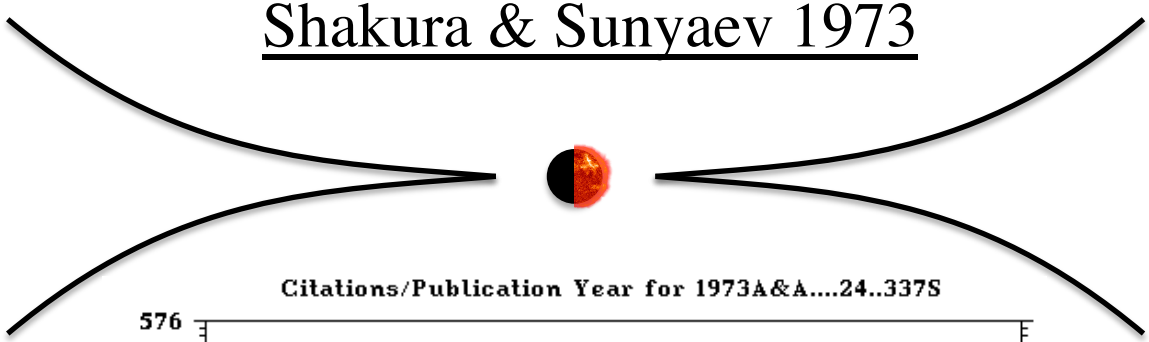
Introduction

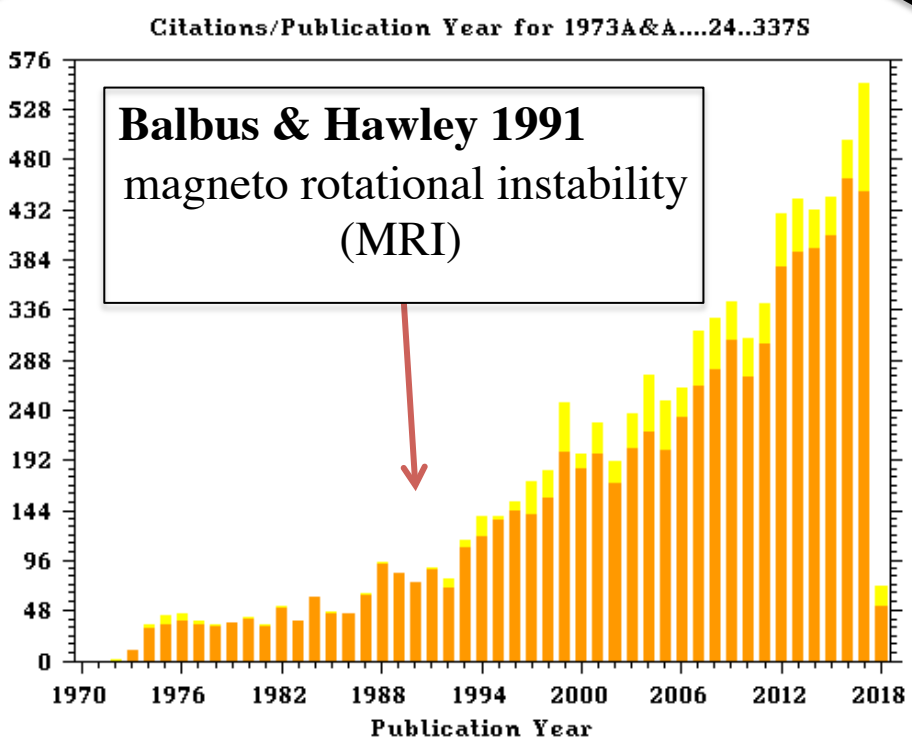
Accretion disks

Challenges

- **Which process allows accretion?**

Shakura & Sunyaev 1973



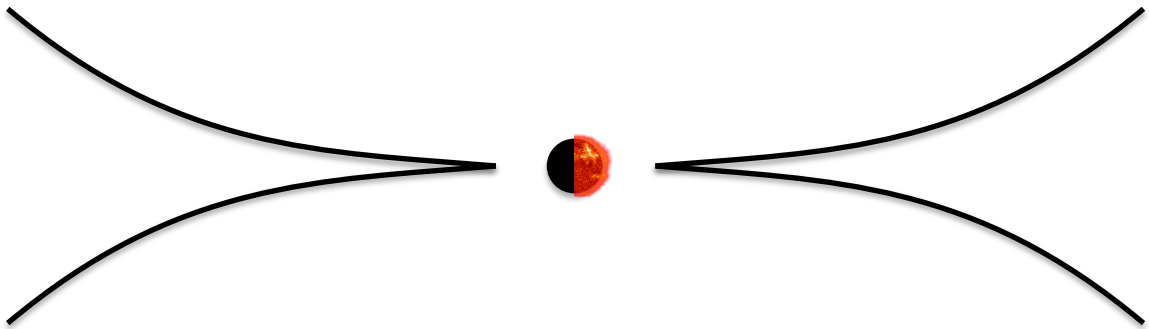


Introduction

Accretion disks

Challenges

- Which process allows accretion?
- **Which role have the magnetic fields?**



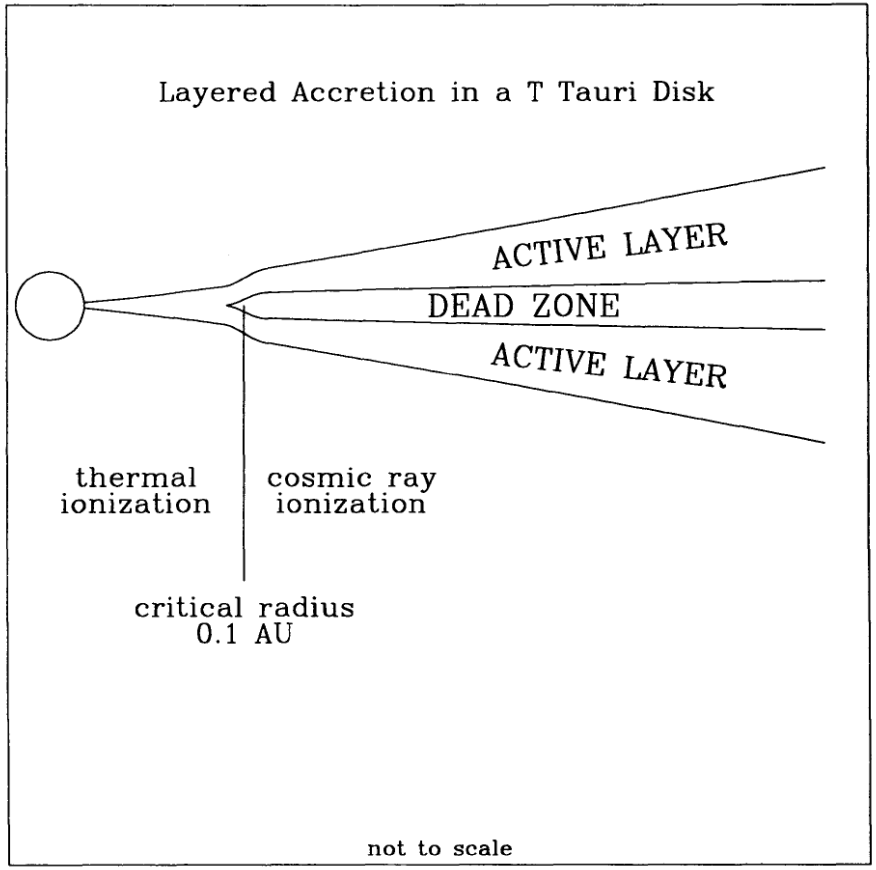
Introduction

Magnetic fields are crucial for the **jet**, the **wind** and the **turbulence** in the disk.

X-ray binary - AGN - Dwarf nova –T Tauri - Giant planet

High ionization ⟷ **Low ionization**

MRI
Balbus & Hawley 1991
Pessah et al. 2009



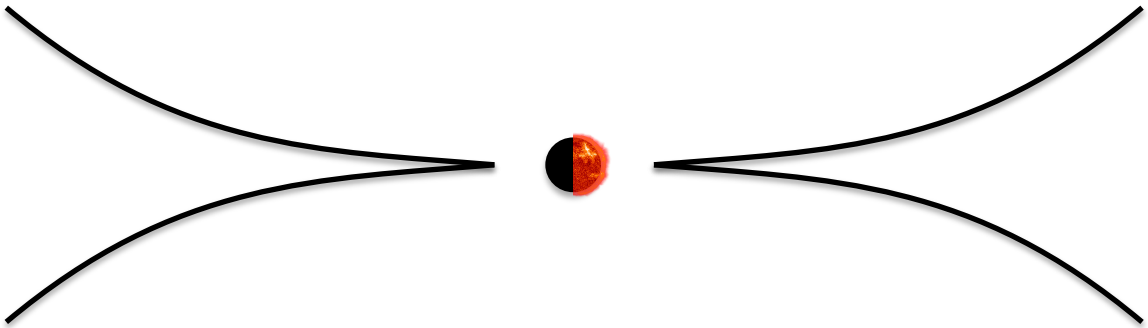
layered MRI
Gammie 1996
Wardle 1999

Gammie 1996, ApJ

Introduction

Overview

- **Magnetic fields determine the evolution of accretion disks.**
  Non-ideal MHD simulations allow us
  to model a wide range of accretion disks



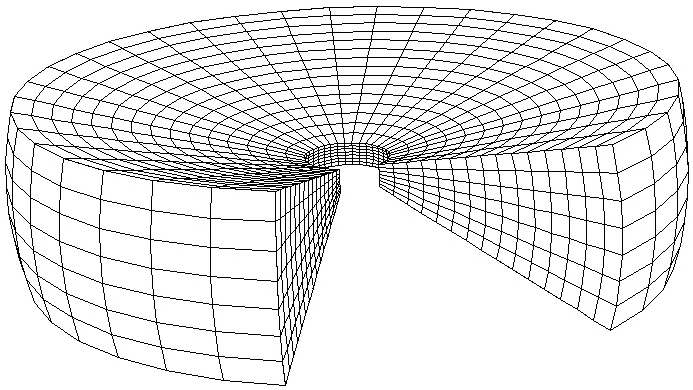
How do we model these systems?

Introduction

Active code development with the PLUTO code

- MHD scheme Flock et al. 2010
- Orbital advection method Mignone, Flock et al. 2012
- Radiation transfer Flock et al. 2013

- Sec. order (space + time)
- Spherical domain (r,ϑ,ϕ)
- CT-MHD scheme
- HLLD Riemann solver



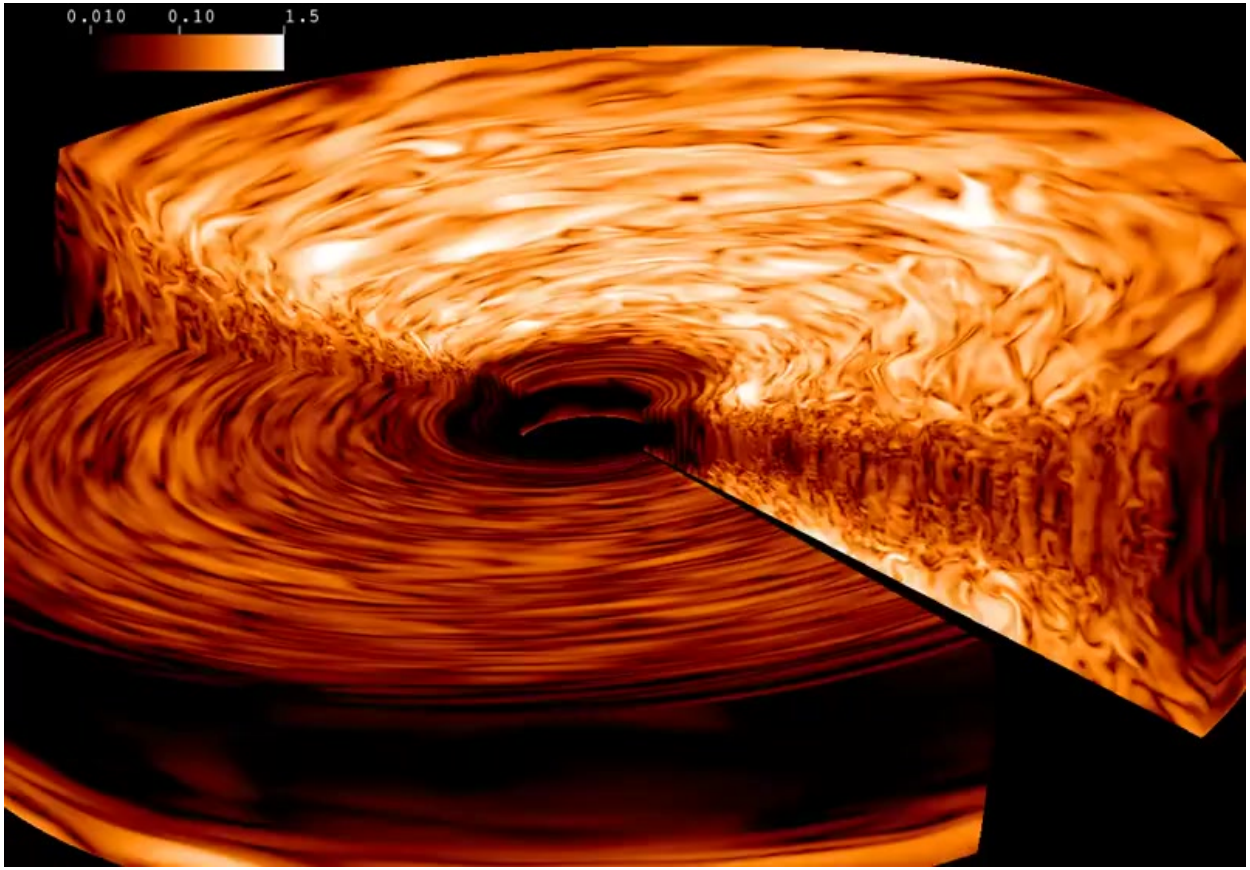
Collaborators:

A. Mignone, **Torino**, S. Fromang, **CEA-Saclay**,
M. Gonzalez, **Paris 7**, B. Commercon, **ENS-Lyon**

Theoretical models

First global 3D MHD models with a new Finite Volume scheme

- Fully stratified,
- 2π domain
- 384x192x768
- Initial B_ϕ (β=25)



RMS velocity [Mach]

Flock et al. 2011 ApJ, PhD

- 10 M CPU/h
  BlueGene/P
- MPG
  Public-eye award

Collaborators:
Th. Henning, H. Klahr, N. Dzyurkevich **MPIA,** N. Turner **JPL**

Theoretical models

Magnetized accretion disk properties

Flock et al. 2012 ApJ

$$\alpha_{MRI} = 0.01 \quad - \quad 0.0001$$

High ionization ⟷ **Low ionization**

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

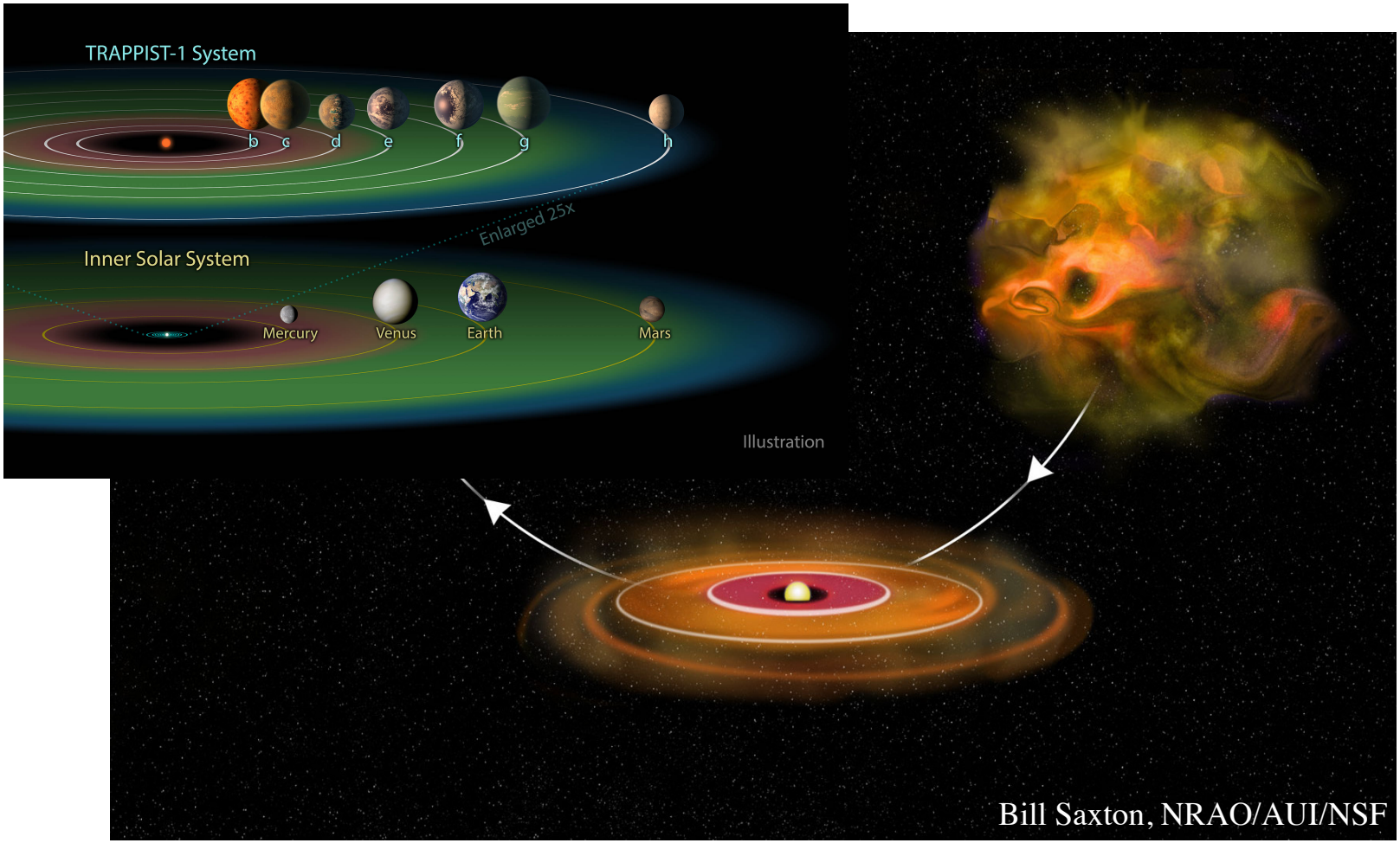
Global 3D MHD models enable us to study detailed dynamics at different ionization levels in accretion disks

Collaborators:

Th. Henning, H. Klahr, N. Dzyurkevich **MPIA,** N. Turner **JPL**

Introduction

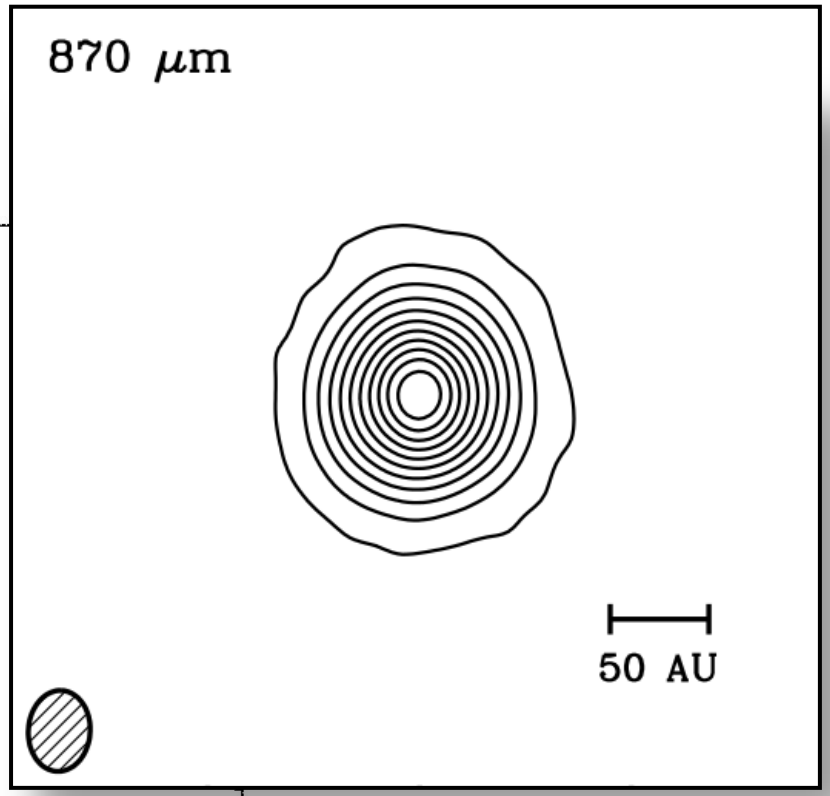
Planet formation



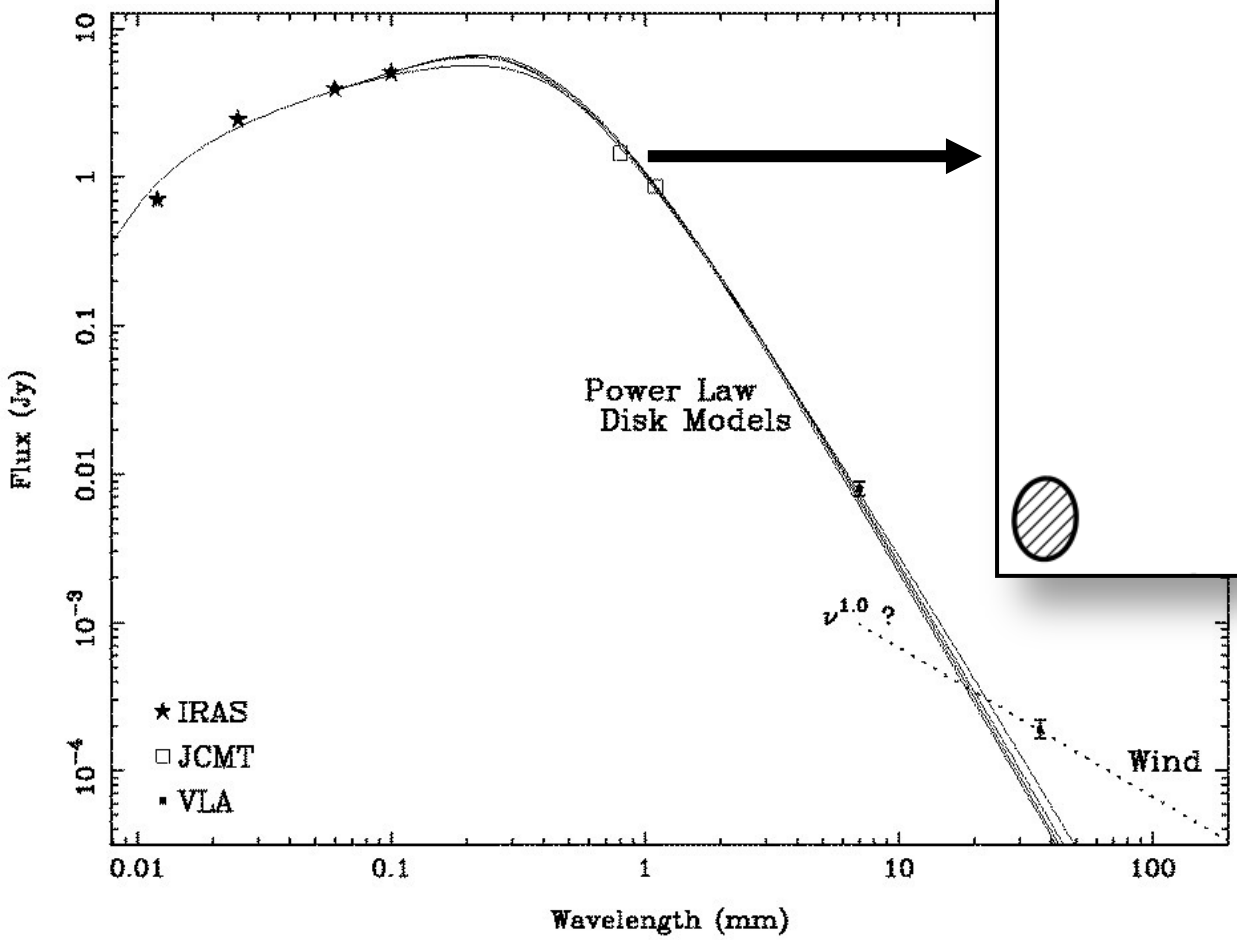
Introduction

Protoplanetary disk observations

Andrews et al. 2012, SMA



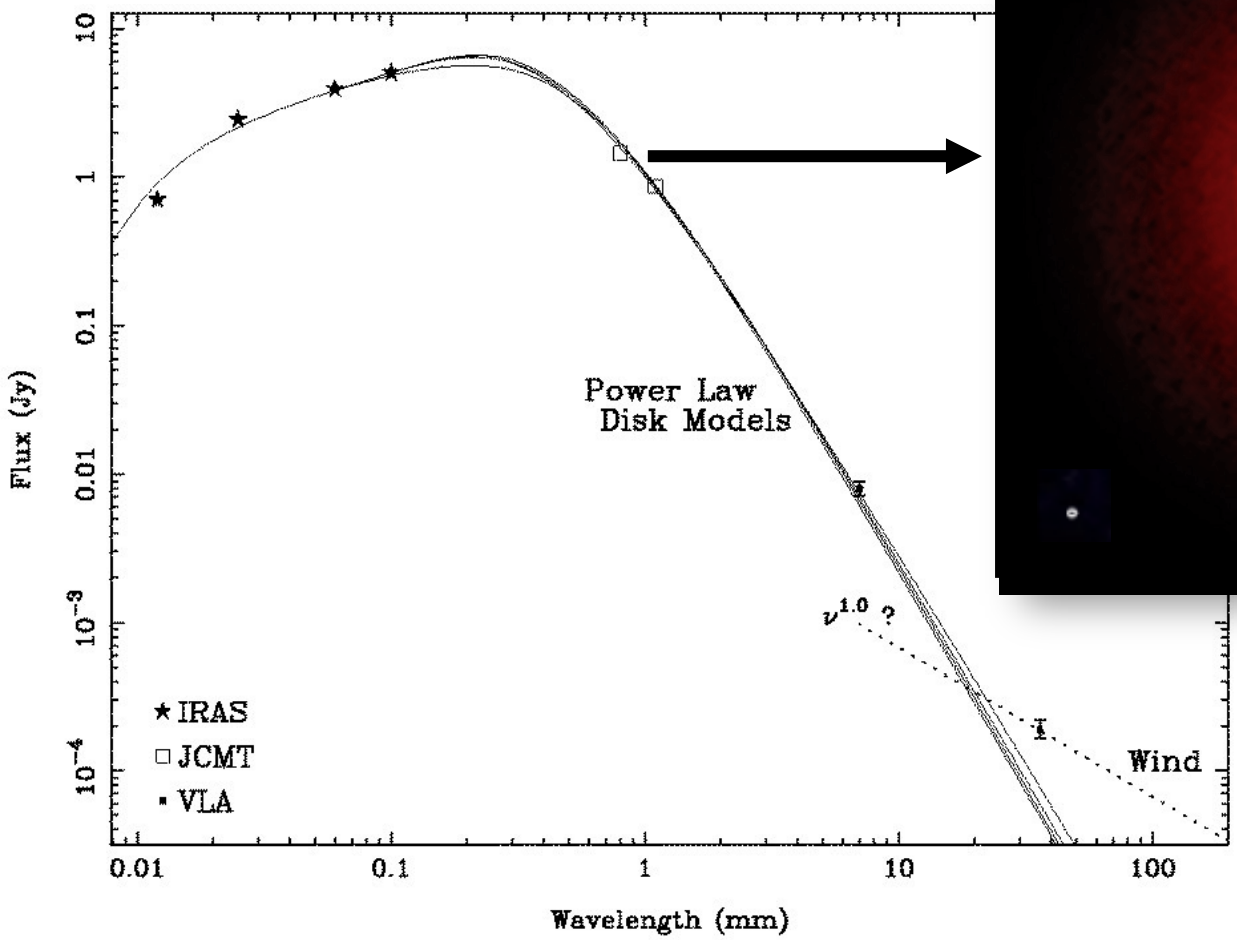
Wilner et al. 2000



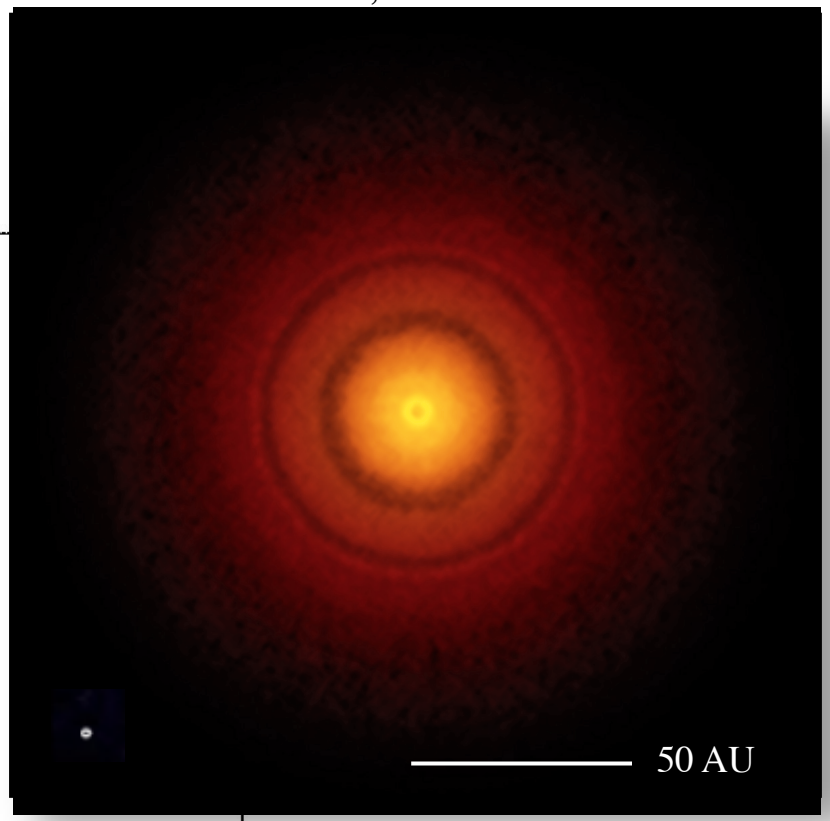
Introduction

Protoplanetary disk observations

Wilner et al. 2000



Andrews et al. 2012, SMA

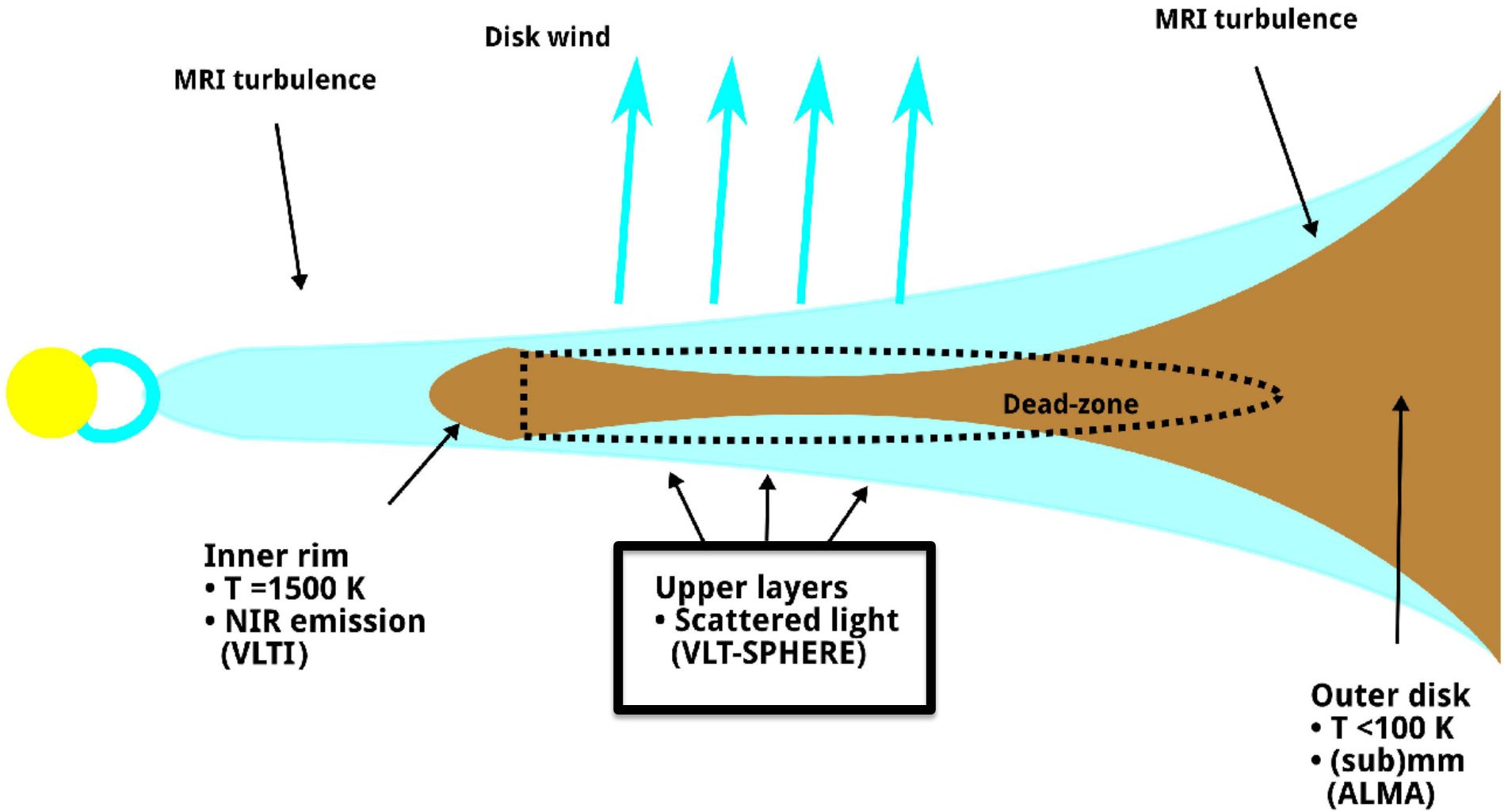


Andrews et al. 2016

Atacama Large Millimeter Array

Introduction

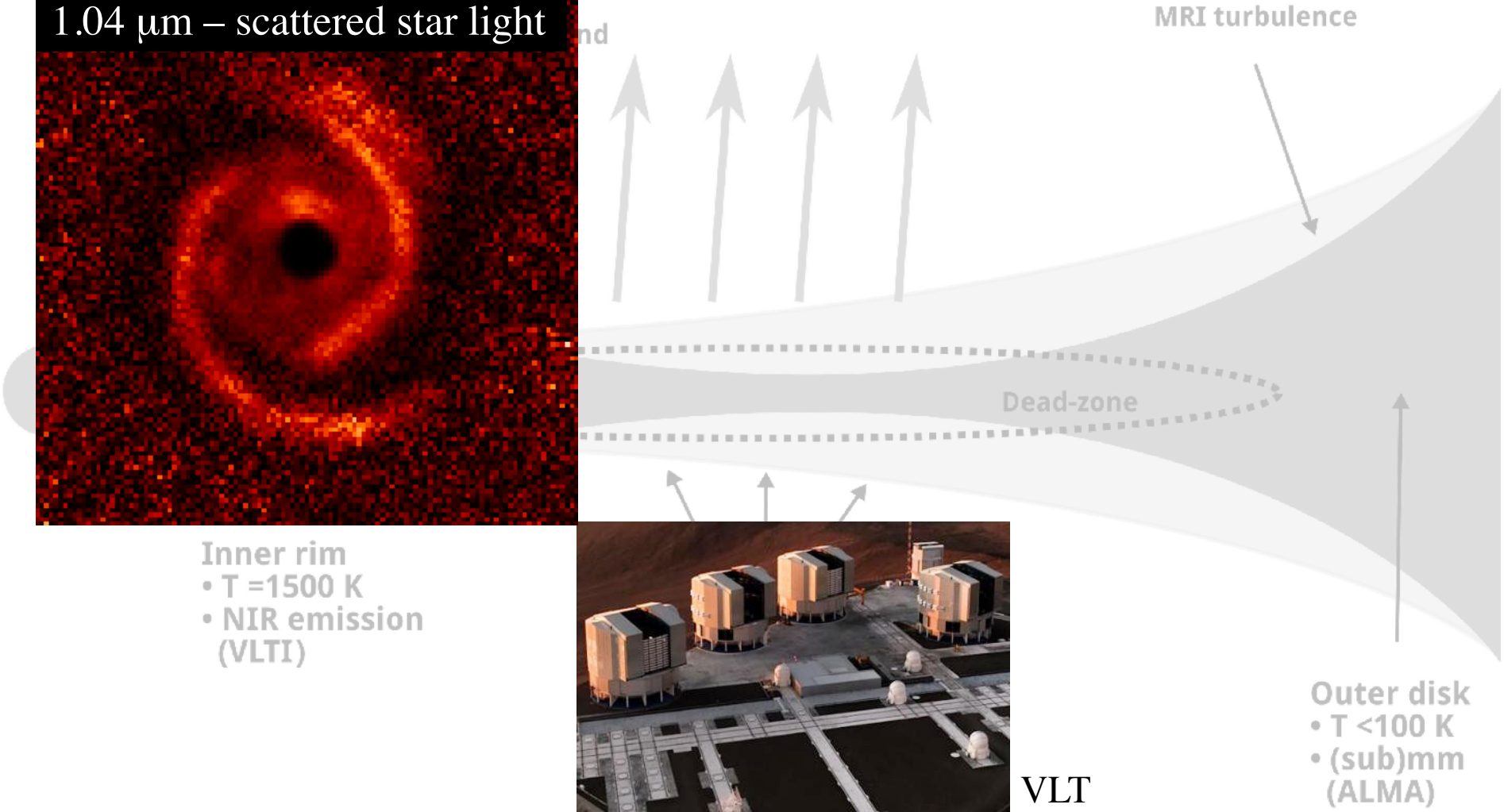
Protoplanetary disk



Introduction

Protoplanetary disk

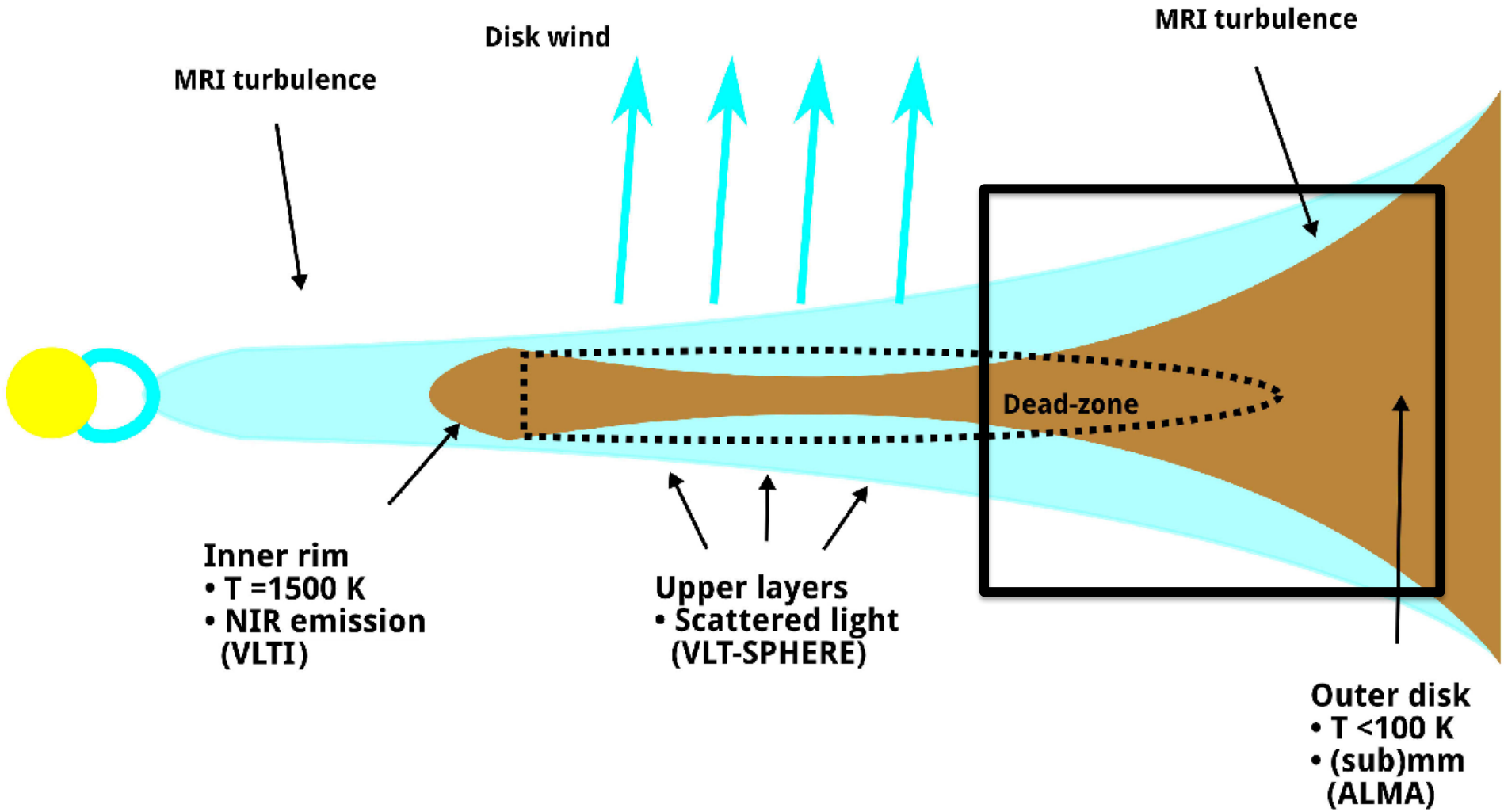
MWC 758 - Benisty et al. 2015



VLT
(Credit: ESO)

Introduction

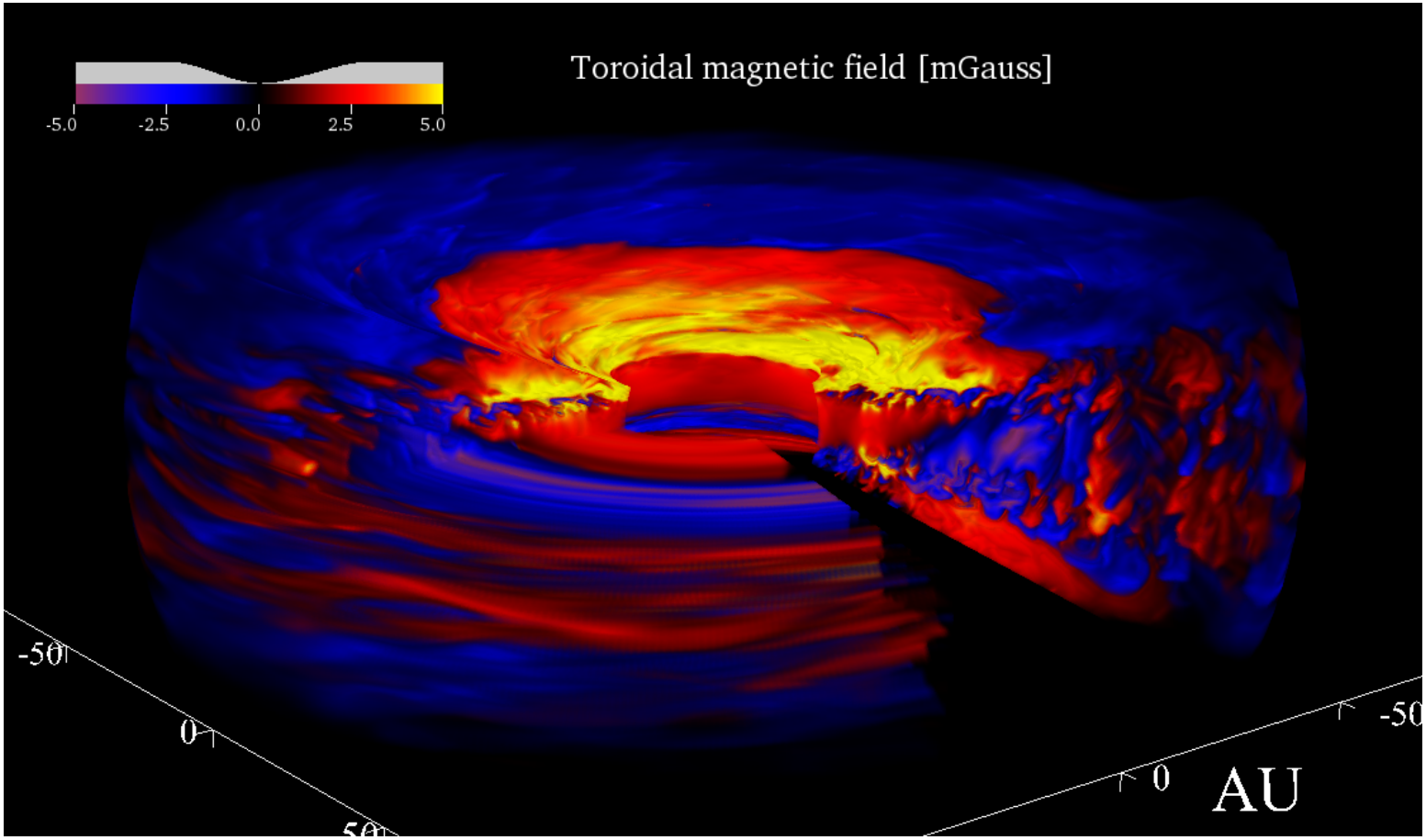
Protoplanetary disk



Connection to observations

outer disk > 10 AU

Flock et al. 2015 A&A
Ruge, Flock et al. 2016 A&A

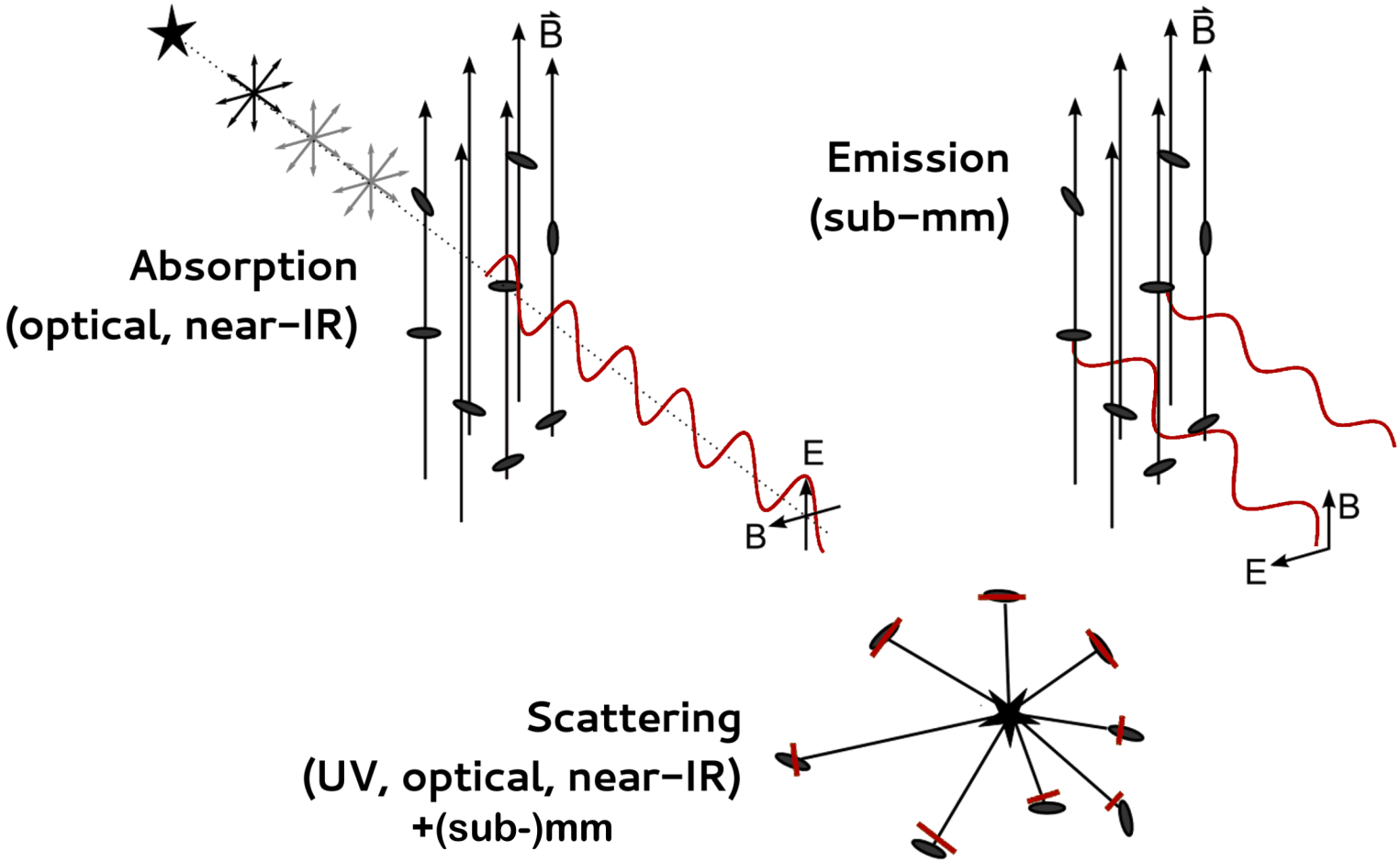


- vertical magnetic field
- resistivity profile (dust chemistry)
- temperature profile from RT

Collaborators:
J.-P. Ruge **Kiel university, Germany,** N. Dzyurkevich, **CSUN, et al.**

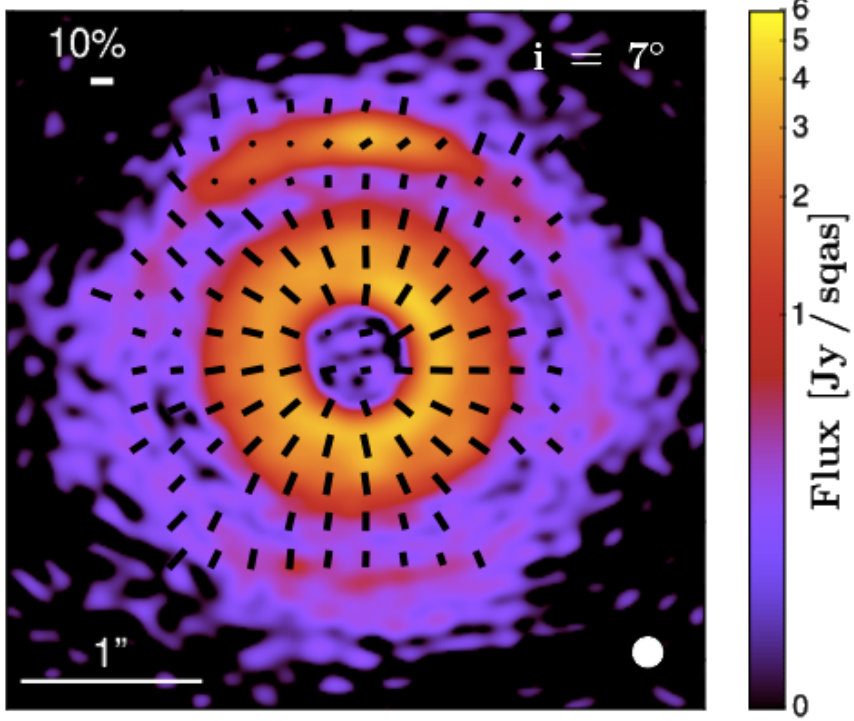
Connection to observations

Polarization



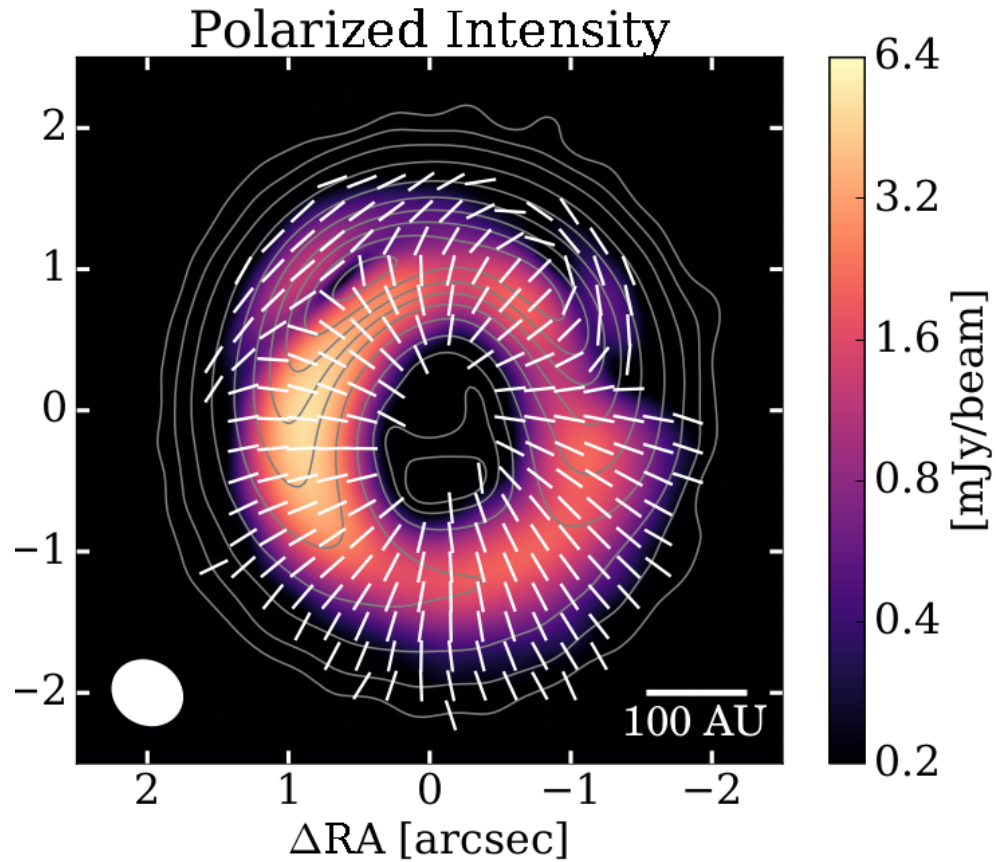
Connection to observations

polarized continuum emission



Model prediction: Bertrang, Flock et al. 2016

ALMA, HD 142527: Kataoka et al. 2016



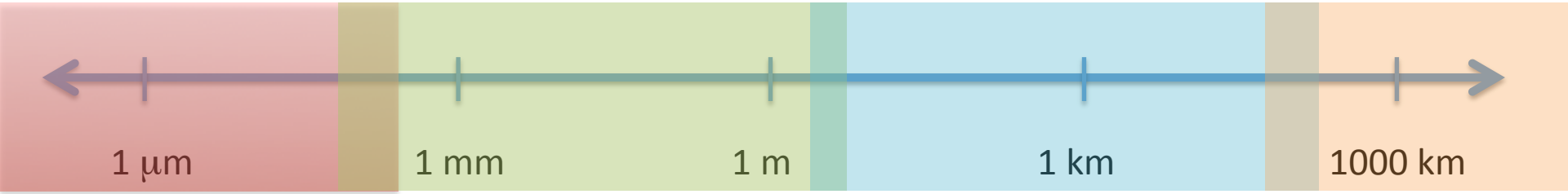
Dust grains aligned by the toroidal magnetic field can explain radial polarization pattern

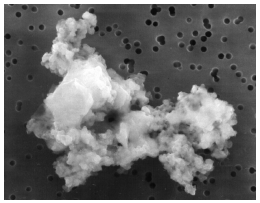
Collaborators:
Gesa Bertrang, **Universidad de Chile**
Sebastian Wolf, **Kiel university, Germany**

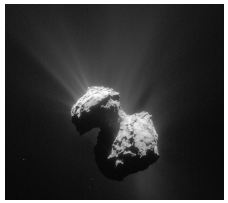
Grain evolution (Testi et al. 2014)

Pebbles

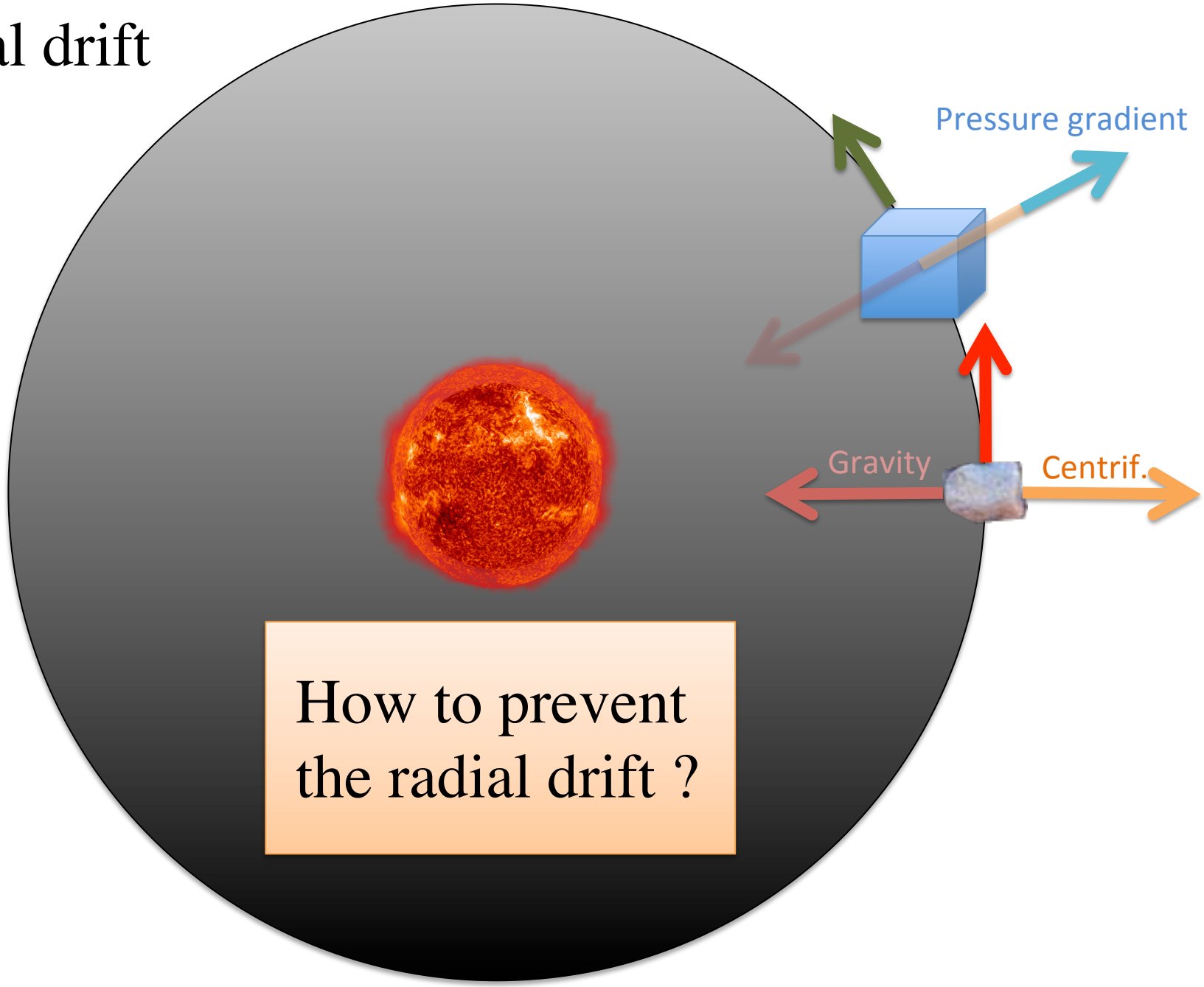
- Fastest inward migration - ‘radial drift’
- Difficult to grow
- Seen by continuum emission (mm,cm)





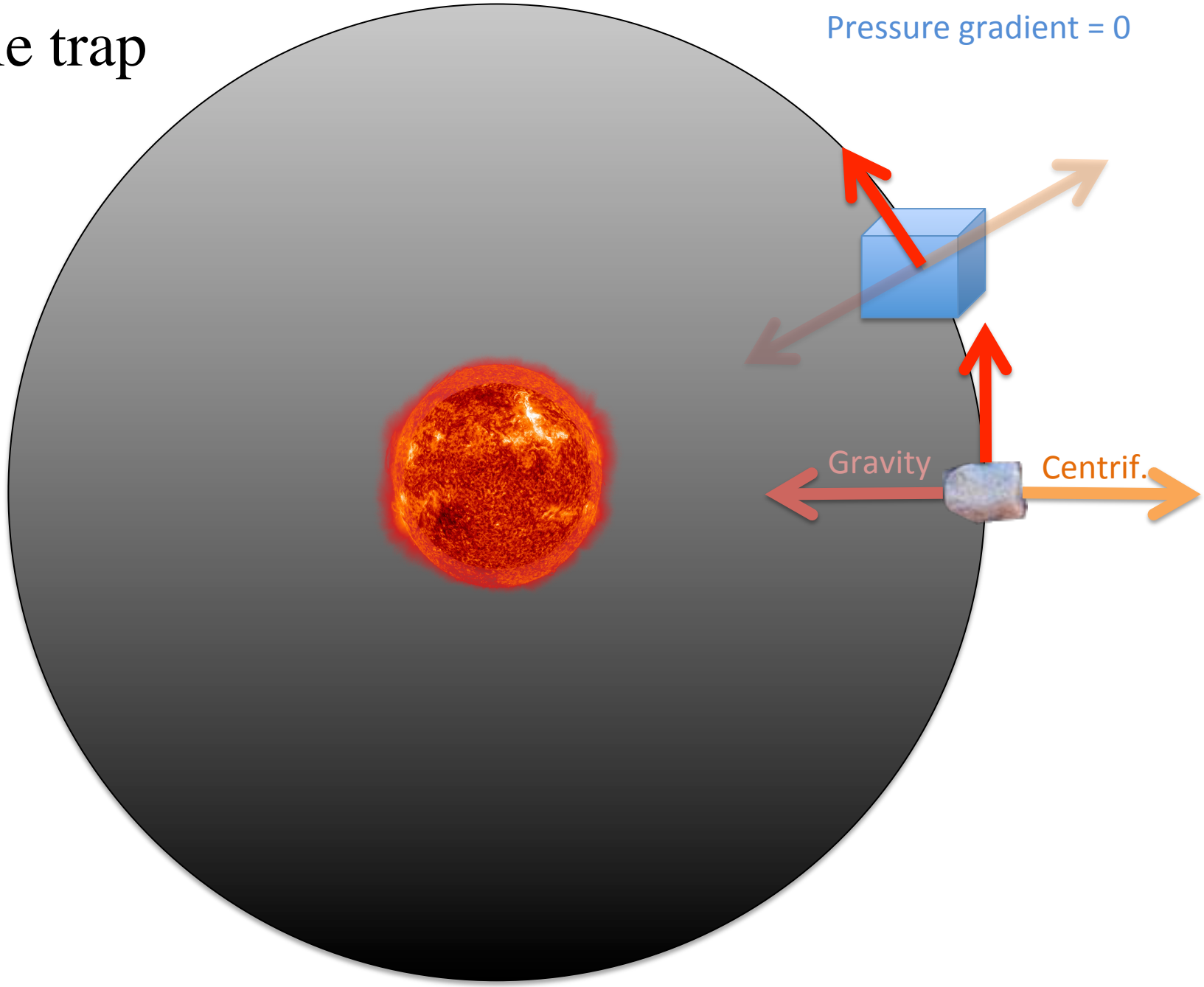


Radial drift

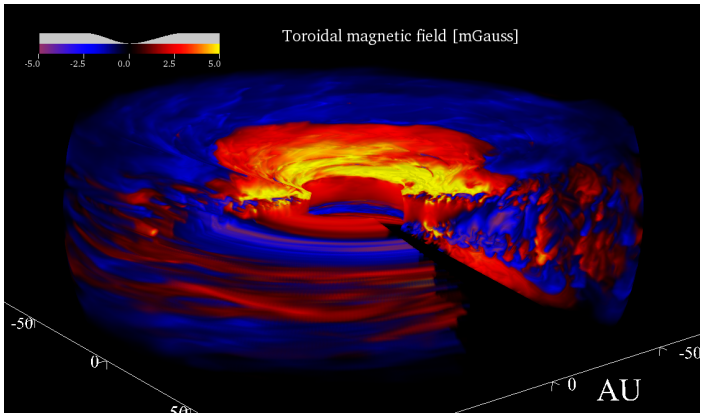


How to prevent the radial drift ?

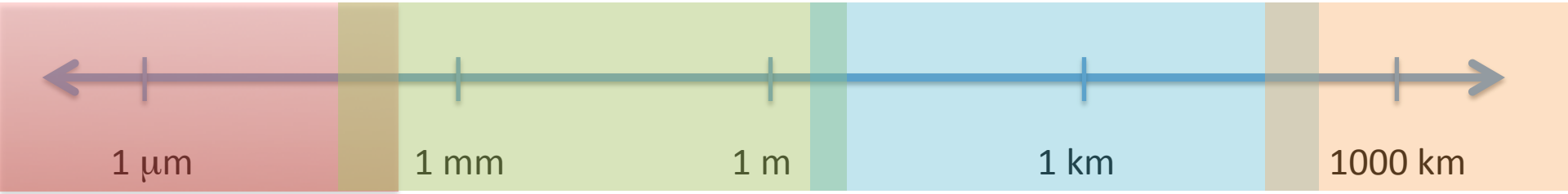
Pebble trap

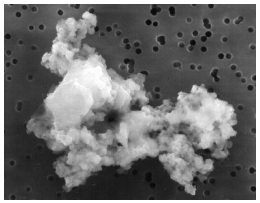


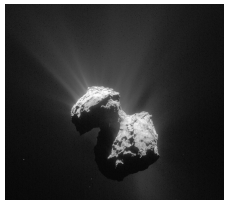
Grain evolution (Testi et al. 2014)

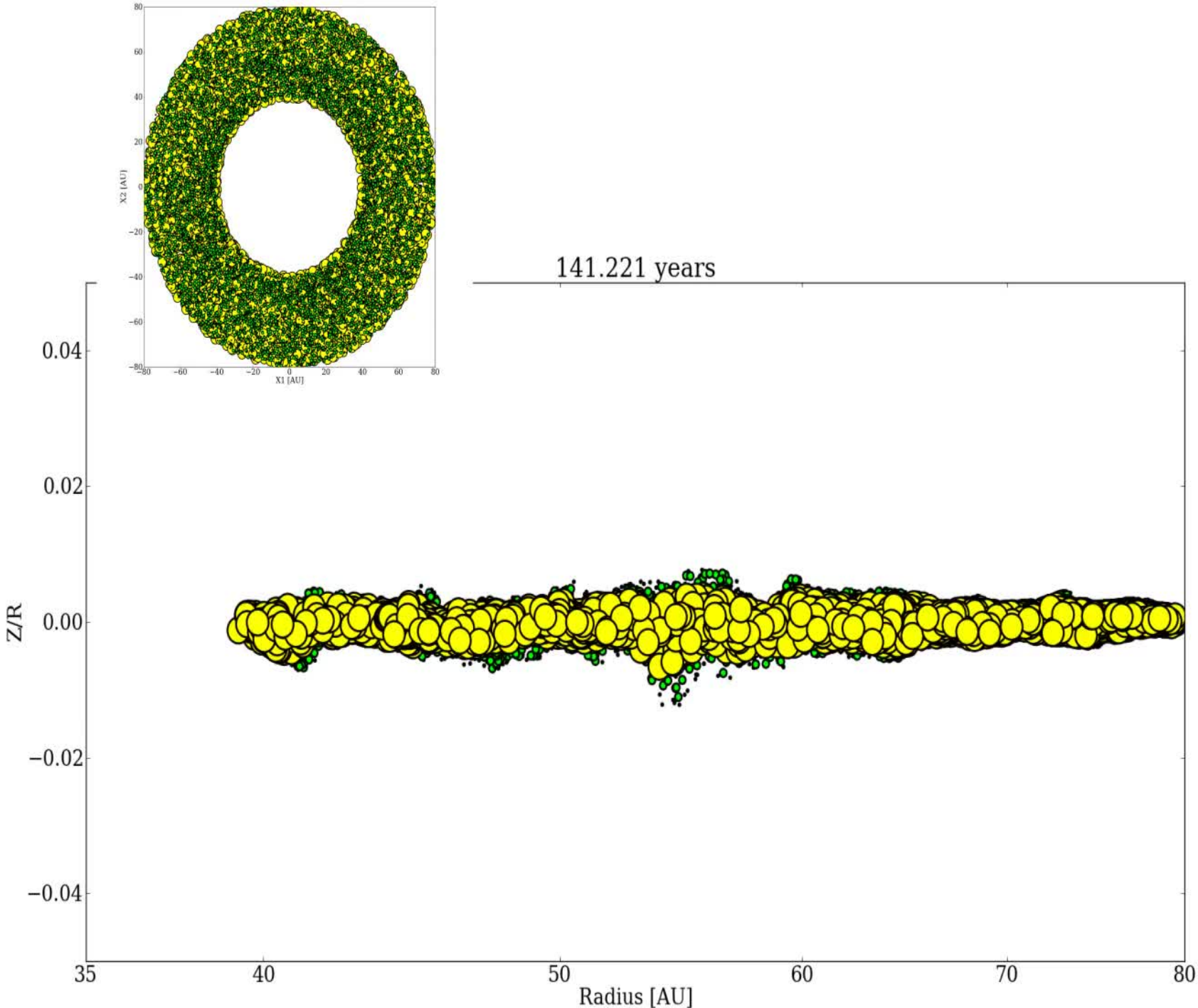


Pebbles





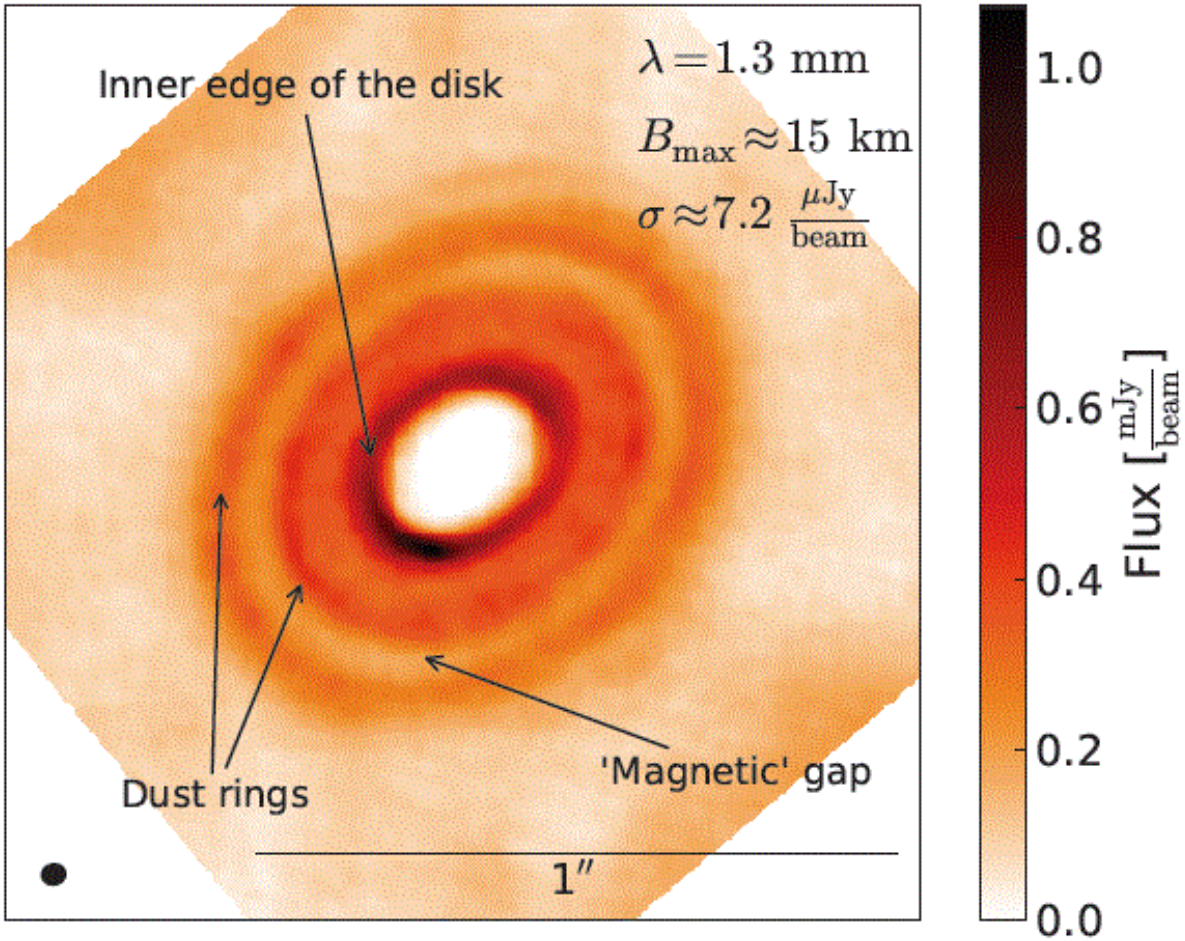



141.221 years
Z/R
0.04
0.02
0.00
−0.02
−0.04
35
40
50
60
70
80
Radius [AU]
X2 [AU]
X1 [AU]

Connection to observations

Stokes I – total intensity

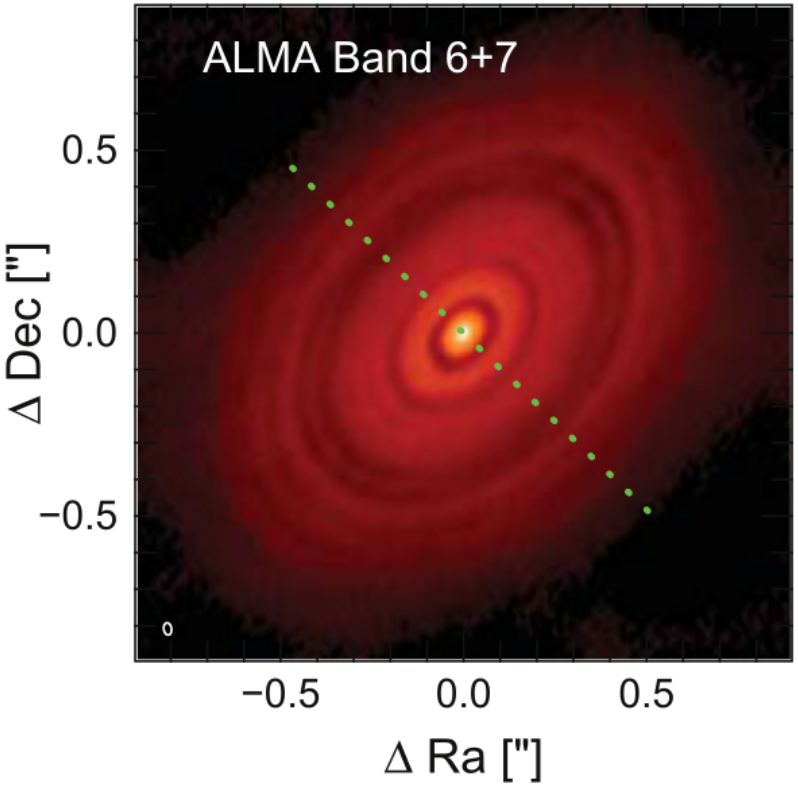
Flock et al. 2015 A&A
Ruge, Flock et al. 2016 A&A

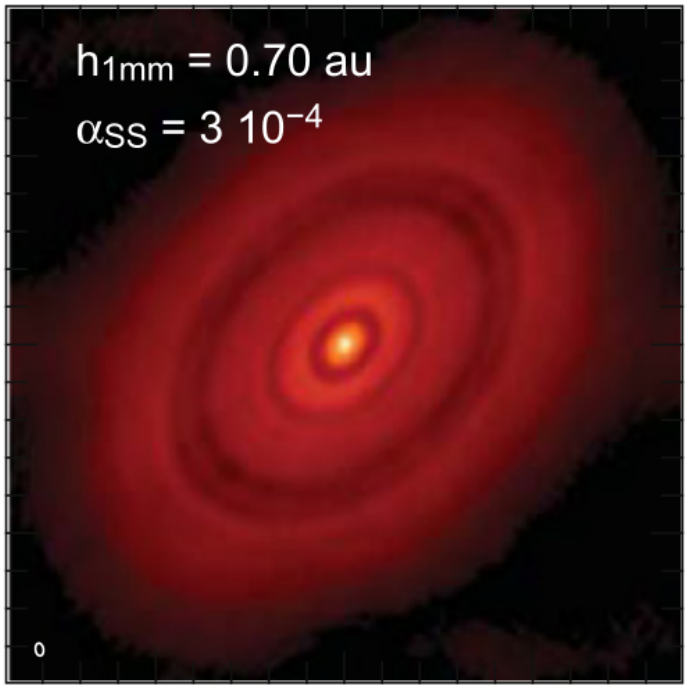


Magnetic field effects at ionization transition zones can cause gaps and rings

Connection to observations

vertical settling of the dust



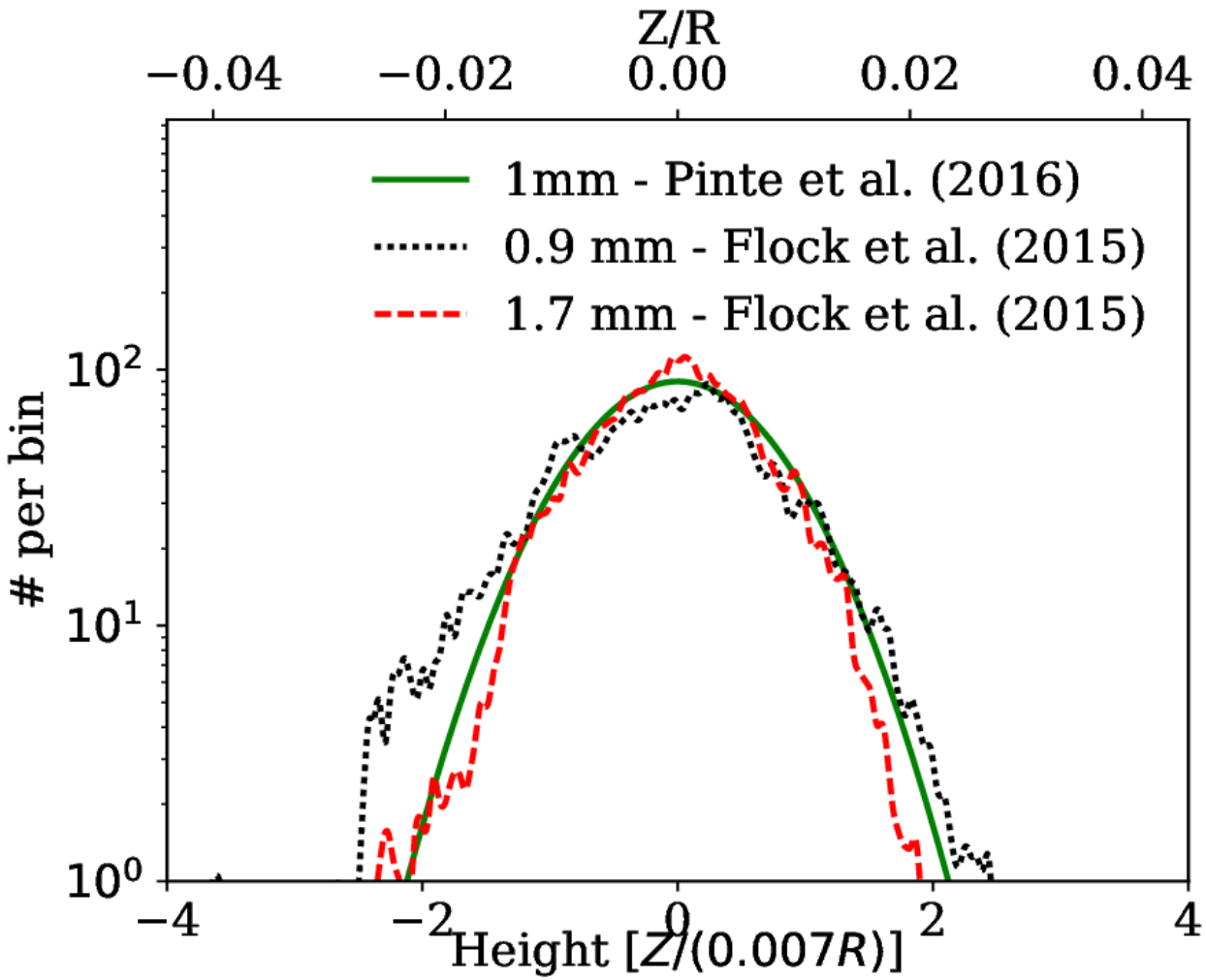


Pinte et al. 2016: mm dust grains should be strongly settled

H/R 0.007

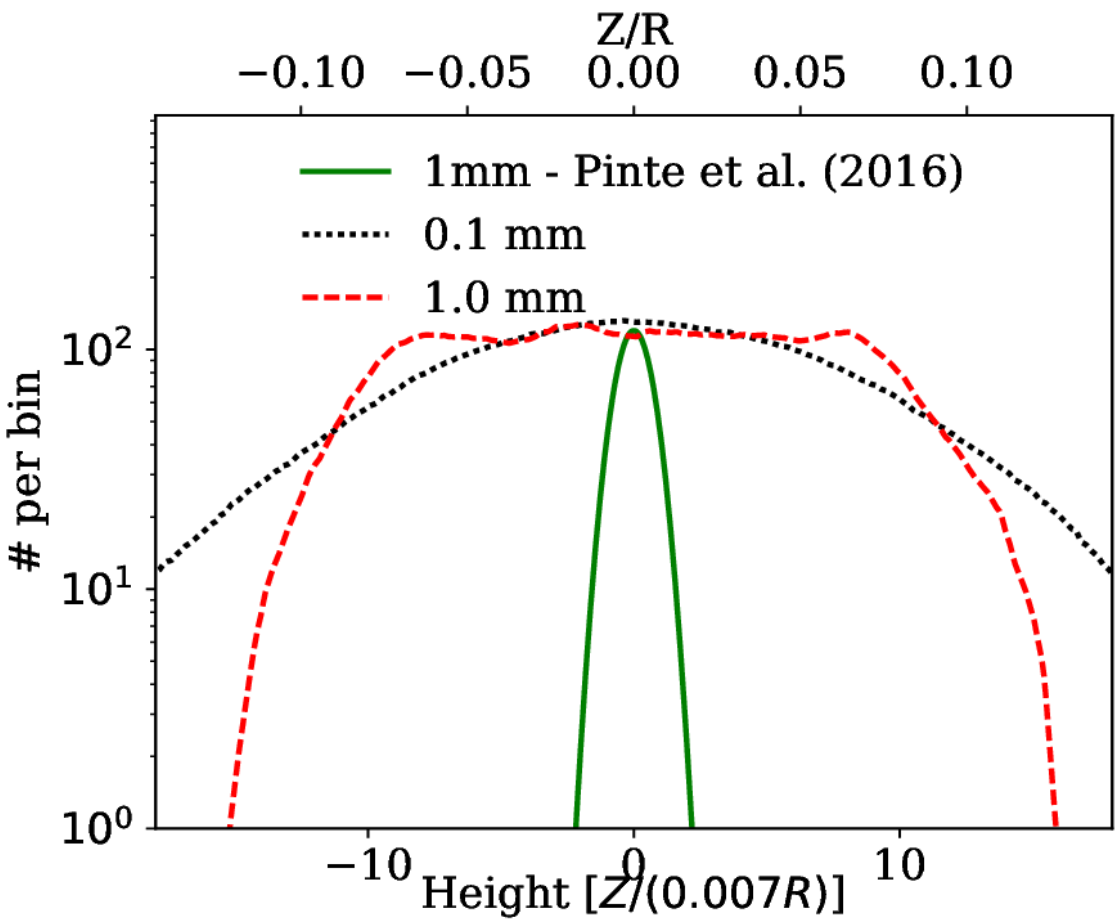
Connection to observations

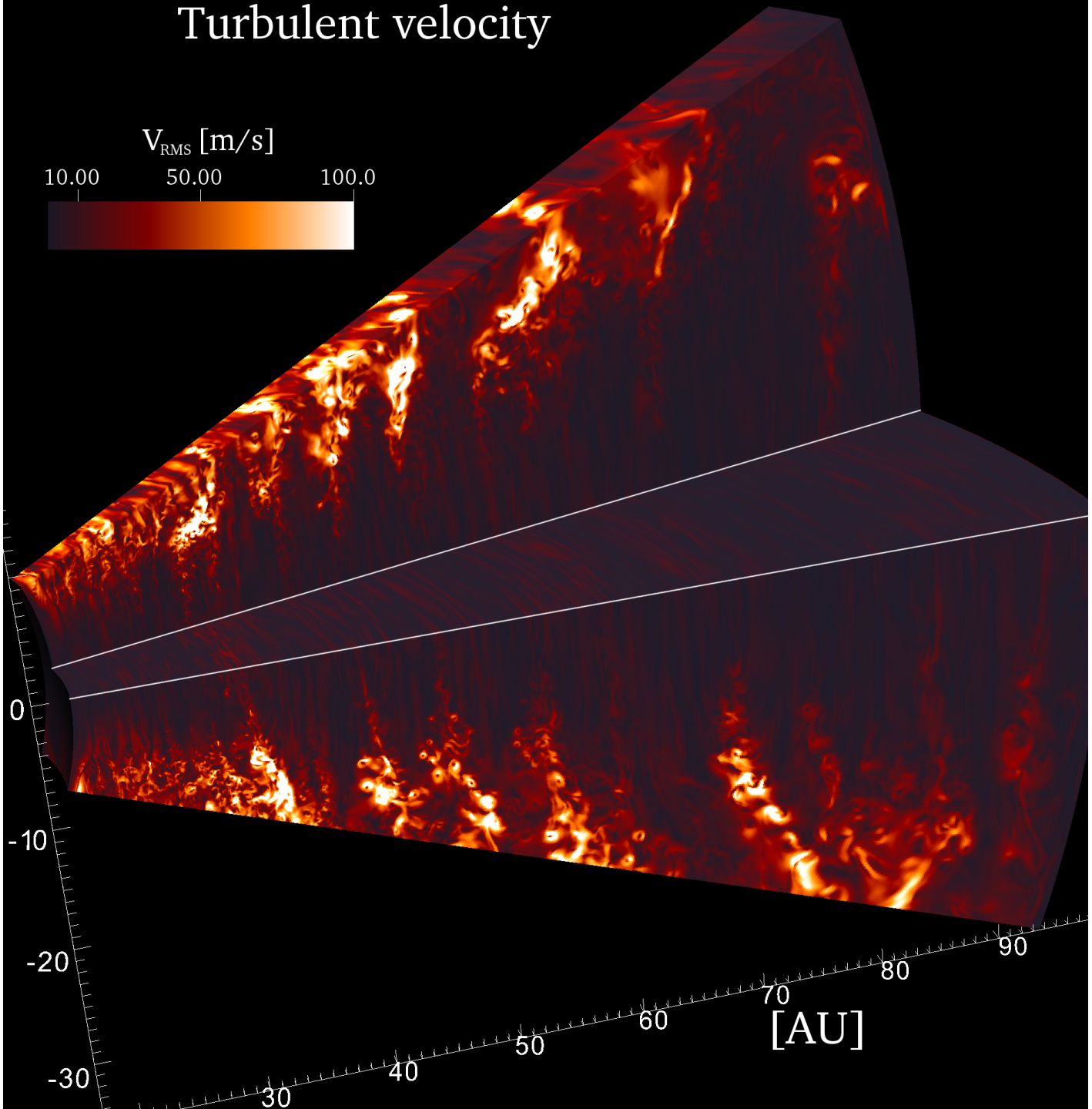
Vertical settling in dust rings of magnetized disks matches perfectly



Connection to observations

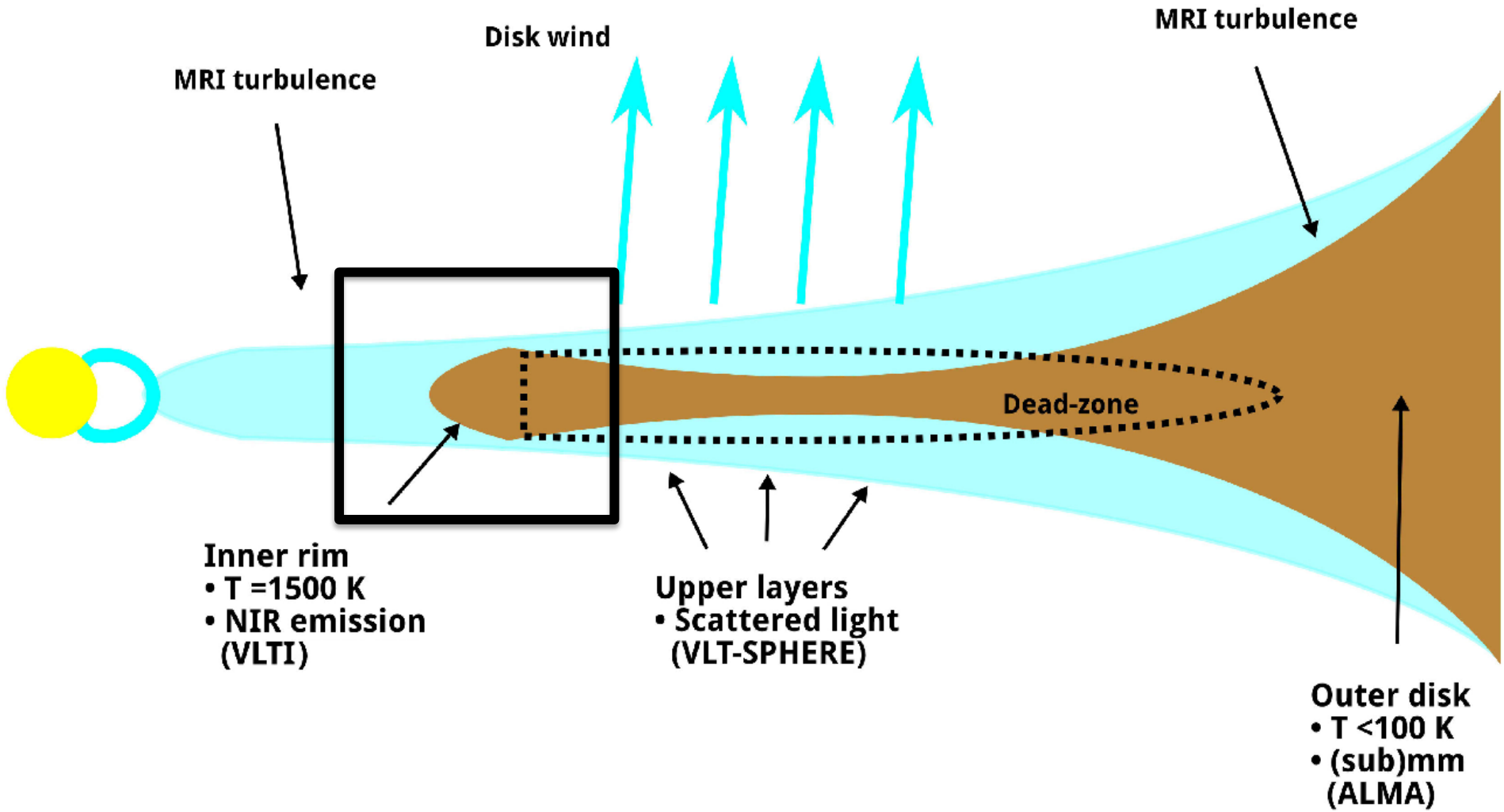
In contrast: pure hydrodynamical model (Flock et al. 2017)




Turbulent velocity
V_RMS [m/s]
10.00
50.00
100.0
0
-10
-20
-30
30
40
50
60
70
80
90
[AU]

Connection to observations

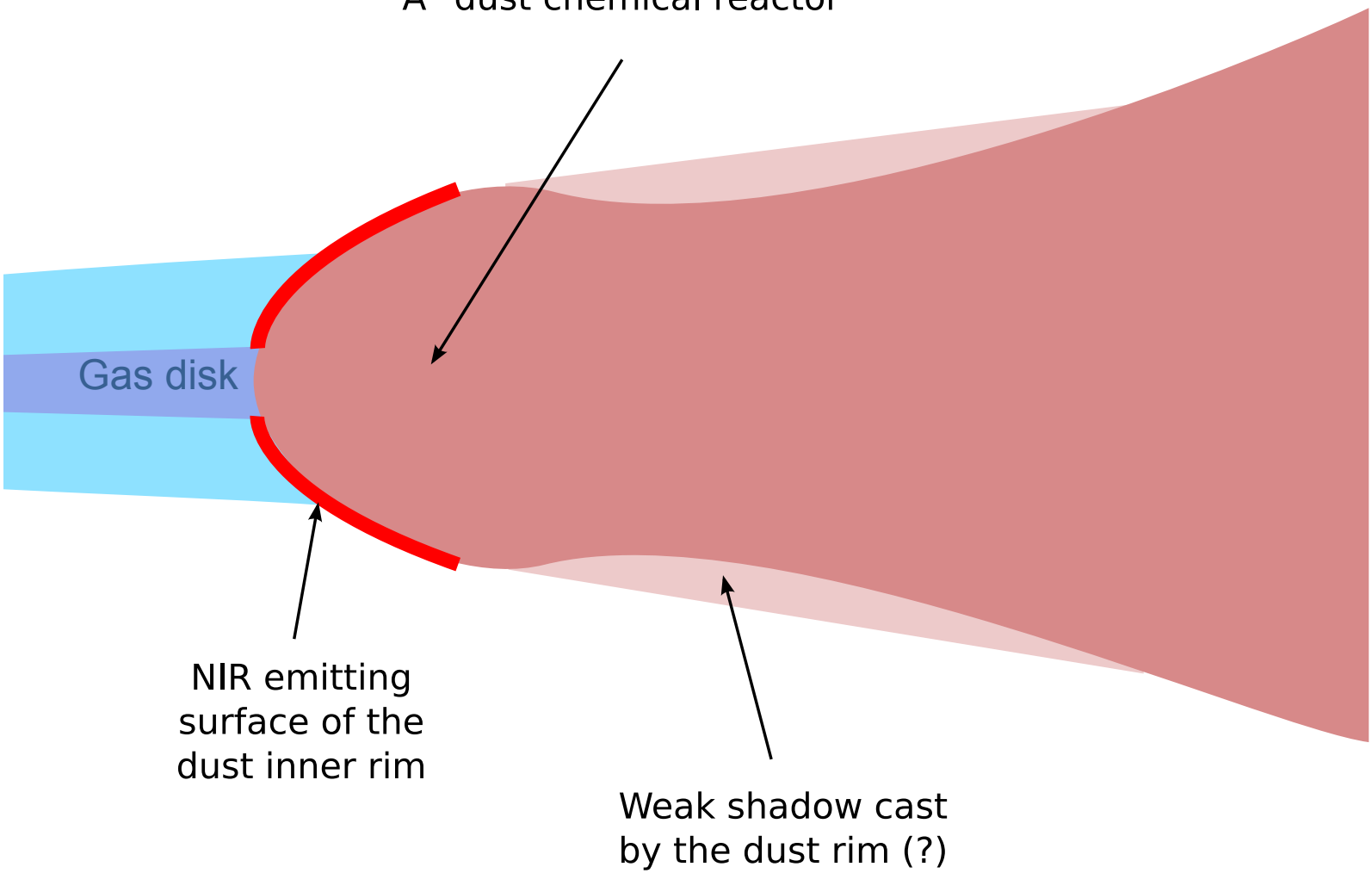
protoplanetary disk



Inner disk models

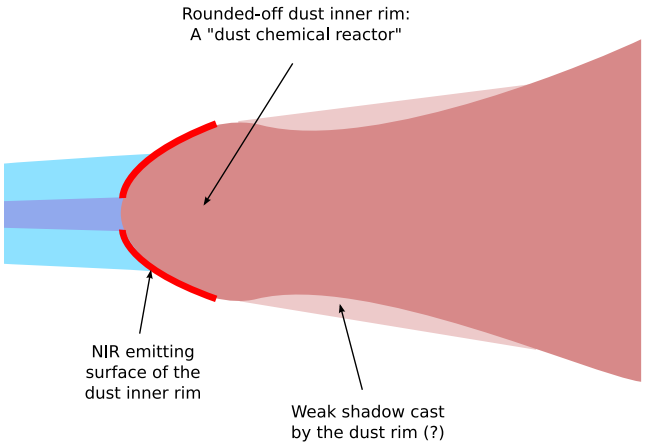
Inner disk < 10 AU

Review:
Dullemond et al. 2010



Inner disk models

Inner disk < 10 AU



Study the the inner rim with RHD simulations

Flock et al. 2016

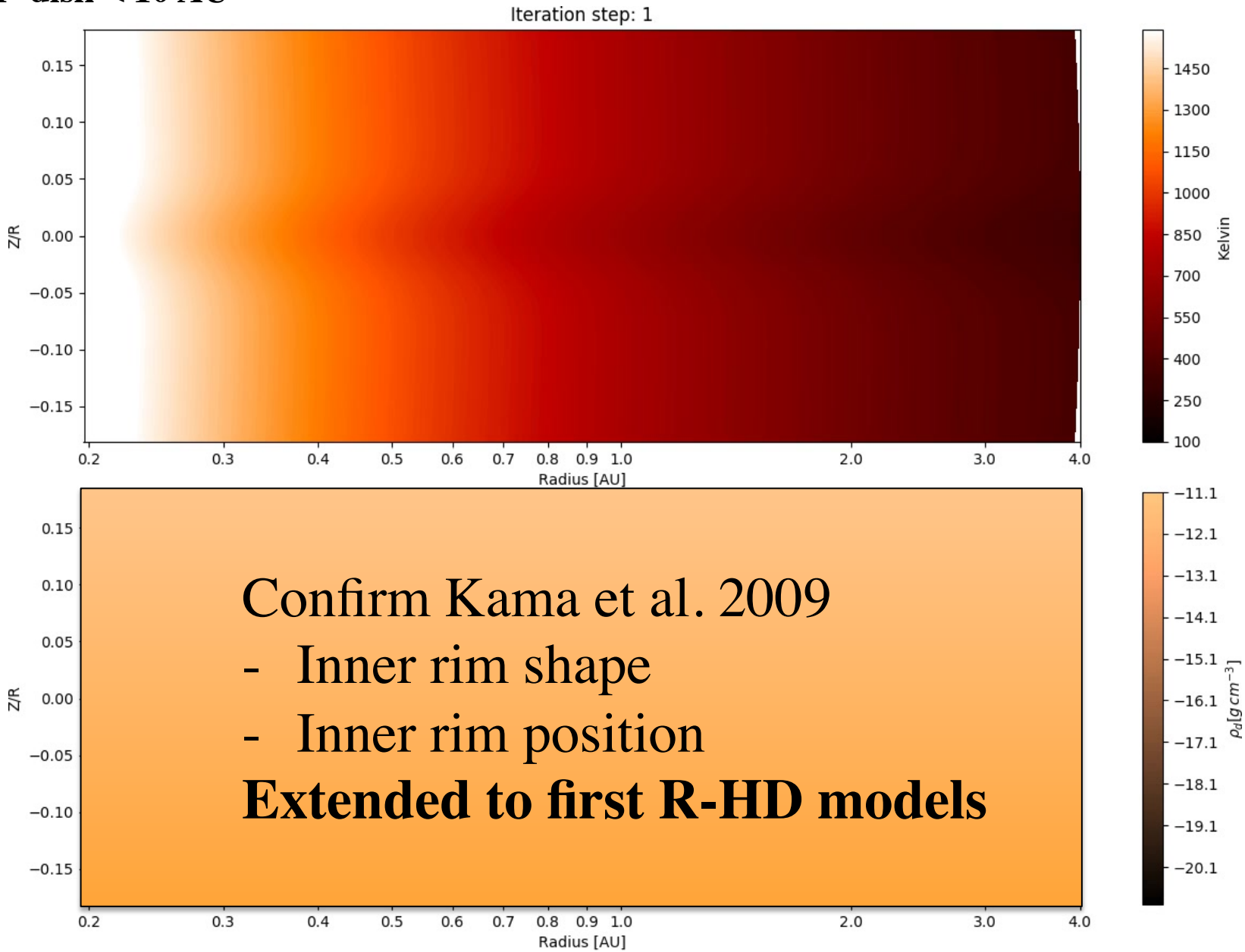
- **Herbig star**
  + Dust sublimation(T) + viscosity(T)

- **rim structure**
- **stability of the rim**
- **observational constraints**

Inner disk models

Radiation hydrostatic model

Inner disk < 10 AU



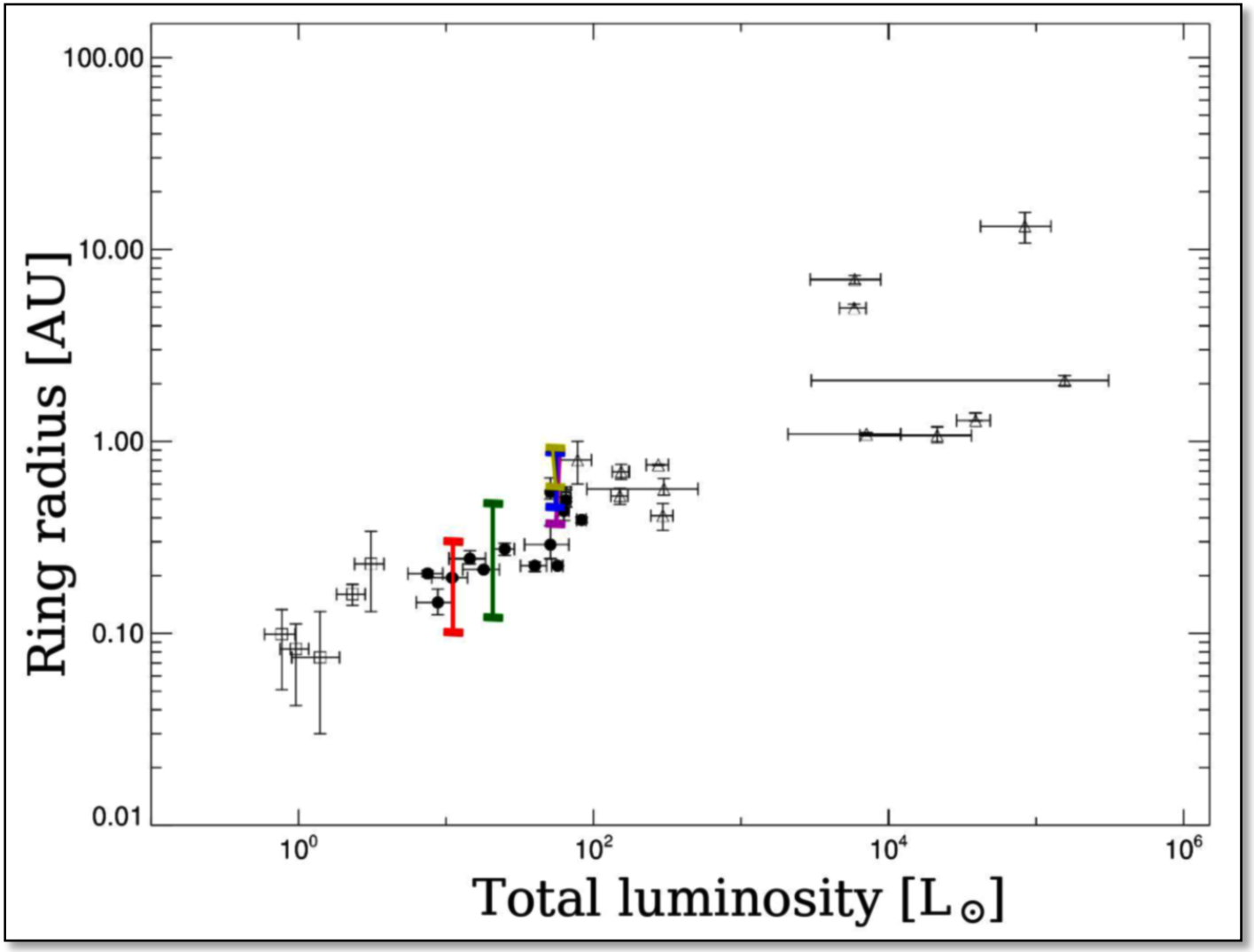
Confirm Kama et al. 2009

- Inner rim shape
- Inner rim position

Extended to first R-HD models

Connection to observations

Inner disk < 10 AU



Inner disk models

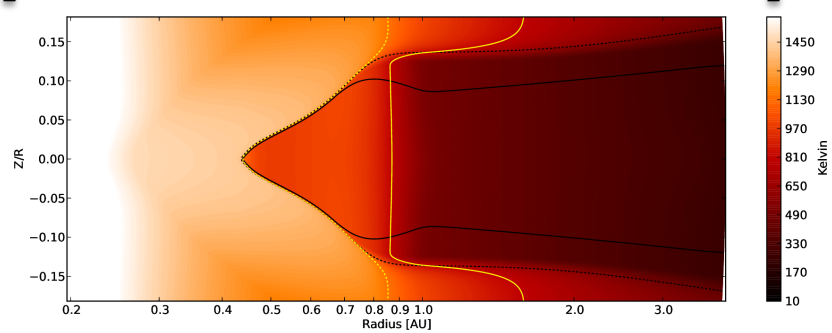
Inner disk < 10 AU

- Radiation transfer + irradiation
- Initial B_z + zero-net flux field

- Dust sublimation and deposition (T)
- Ohmic resistivity (T)

3D Radiation non-ideal MHD simulations

Initial conditions



Collaborators:

Sebastien Fromang, **CEA Saclay, France** Neal Turner**, JPL, USA**

Myriam Benisty, **IPAG, France**

Inner disk models

Inner disk < 10 AU

- Radiat
- Initial

position (T)

s

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

$$\frac{\partial \rho \boldsymbol{v}}{\partial t} + \nabla \times [\rho \boldsymbol{v}\boldsymbol{v}^T - \boldsymbol{B}\boldsymbol{B}^T] + \nabla P_t = -\rho \nabla \Phi,$$

$$\frac{\partial E}{\partial t} + \nabla \times [(E + P_t)\boldsymbol{v} - (\boldsymbol{v} \times \boldsymbol{B})\boldsymbol{B}]$$
$$= -\rho \boldsymbol{v} \times \nabla \Phi - \nabla \times F_* - \kappa_P \rho c (a_R T^4 - E_R)$$
$$- \nabla \times [(\eta \times \boldsymbol{J}) \times \boldsymbol{B}],$$

$$\frac{\partial E_R}{\partial t} - \nabla \frac{c\lambda}{\kappa_R \rho} \nabla E_R = \kappa_P \rho c (a_R T^4 - E_R),$$

$$\frac{\partial \boldsymbol{B}}{\partial t} - \nabla \times (\boldsymbol{v} \times \boldsymbol{B}) = -\nabla \times (\eta \times \boldsymbol{J}),$$

Collaborators:

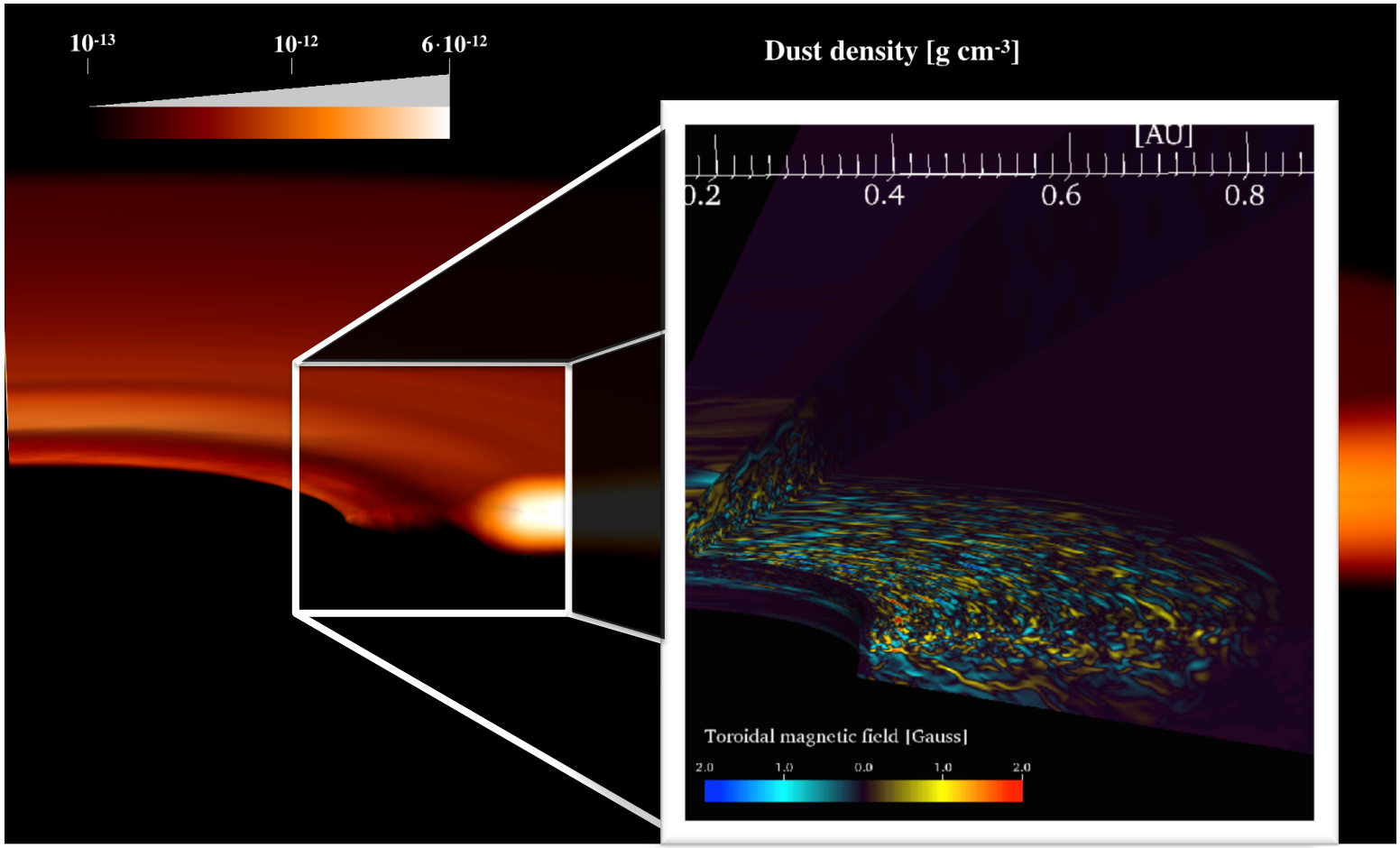
Sebastien Fromang, **CEA Saclay, France** Neal Turner**, JPL, USA**

Myriam Benisty, **IPAG, France**

Inner disk models

Inner disk < 10 AU

Flock et al. 2017, ApJ



Collaborators:

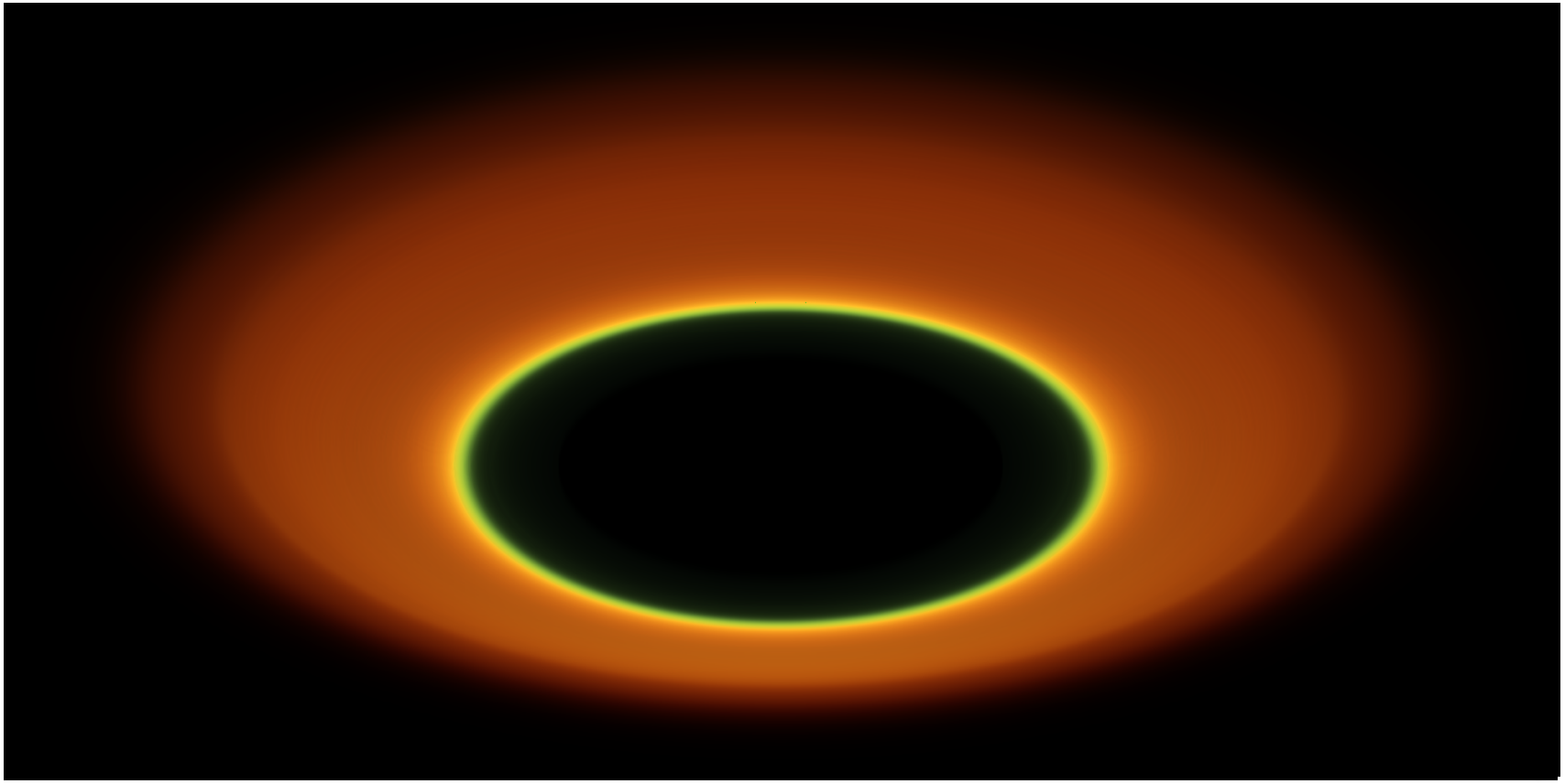
Sebastien Fromang, **CEA Saclay, France** Neal Turner**, JPL, USA**

Myriam Benisty, **IPAG, France**

Connection to observations

Synthetic image

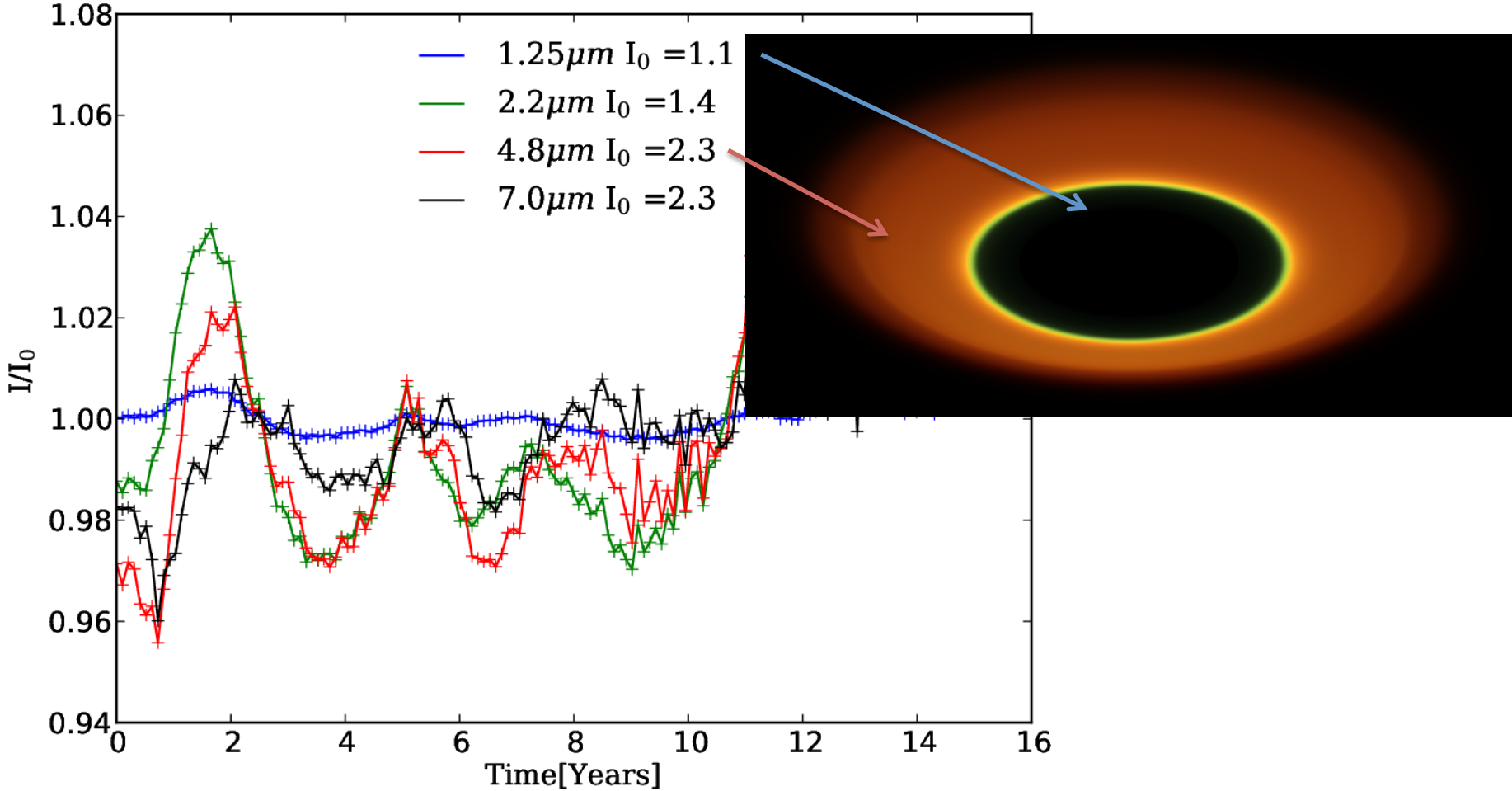
$i = 60^0$ 1.25 - 2.2 - 4.8 micron (B-G-R)



2 AU

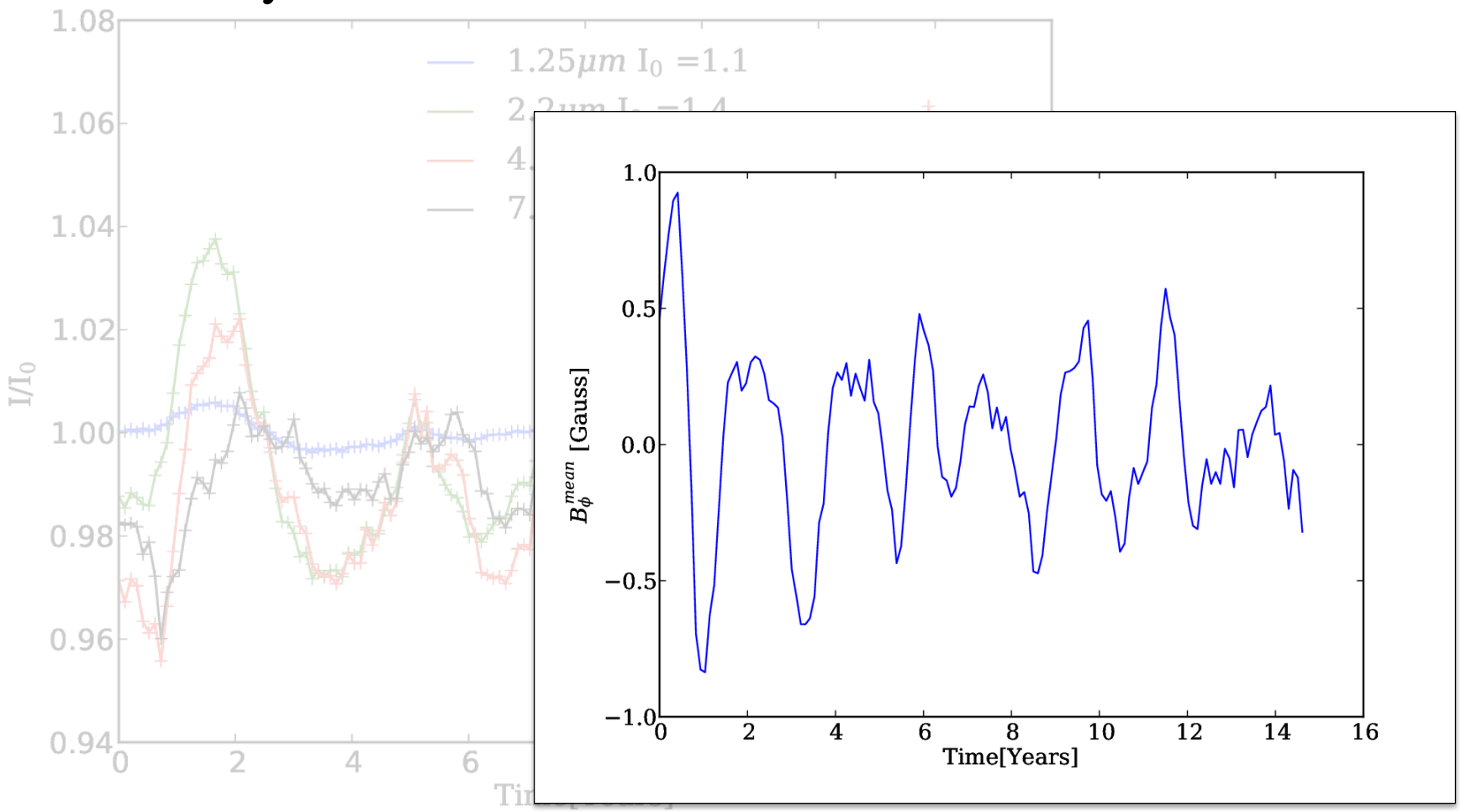
Connection to observations

Light-curve observations are a great tool to obtain constraints on the disk dynamics



Connection to observations

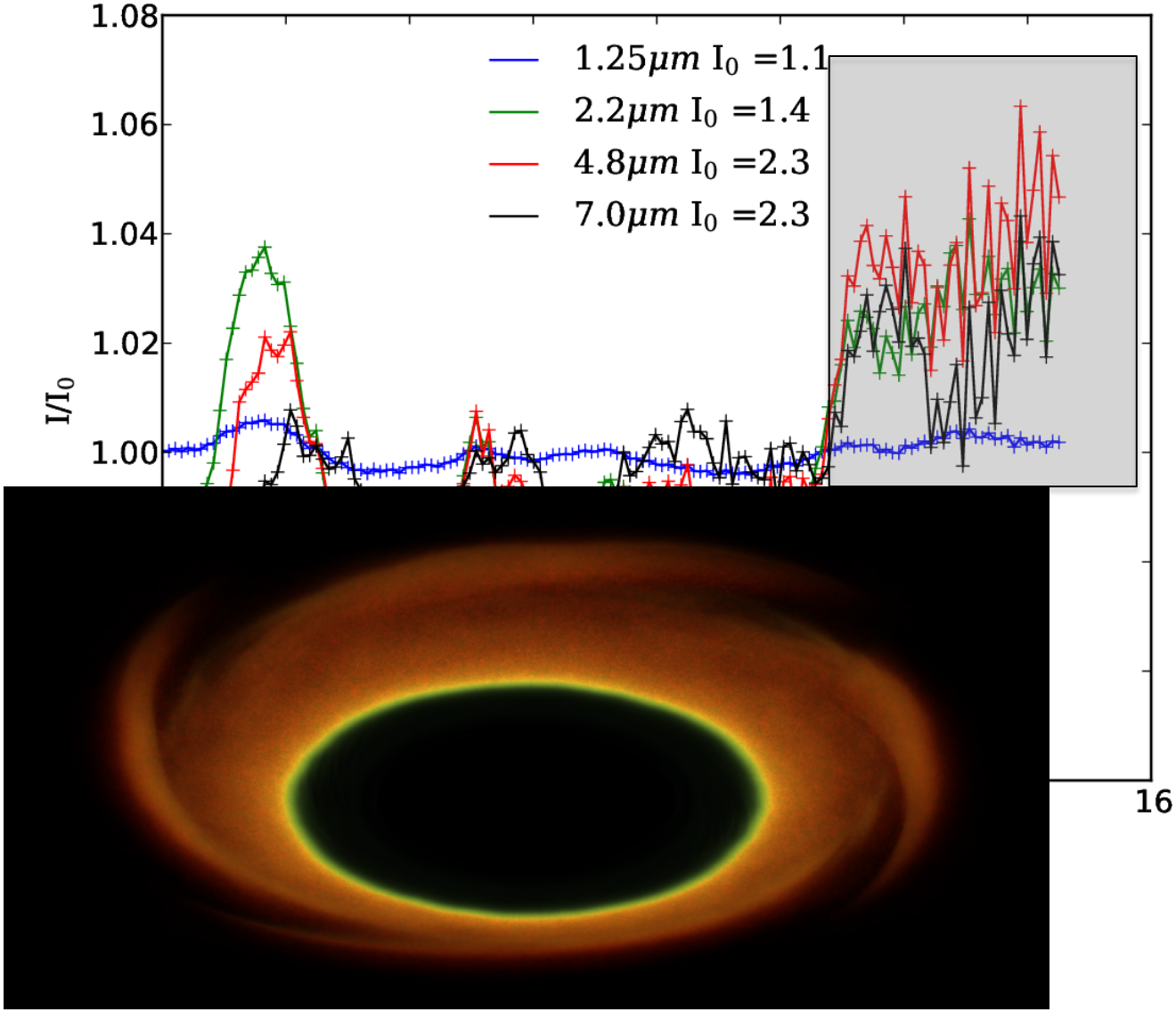
Light-curve observations are a great tool to obtain constraints on the disk dynamics



Variability caused by MRI activity at the rim.

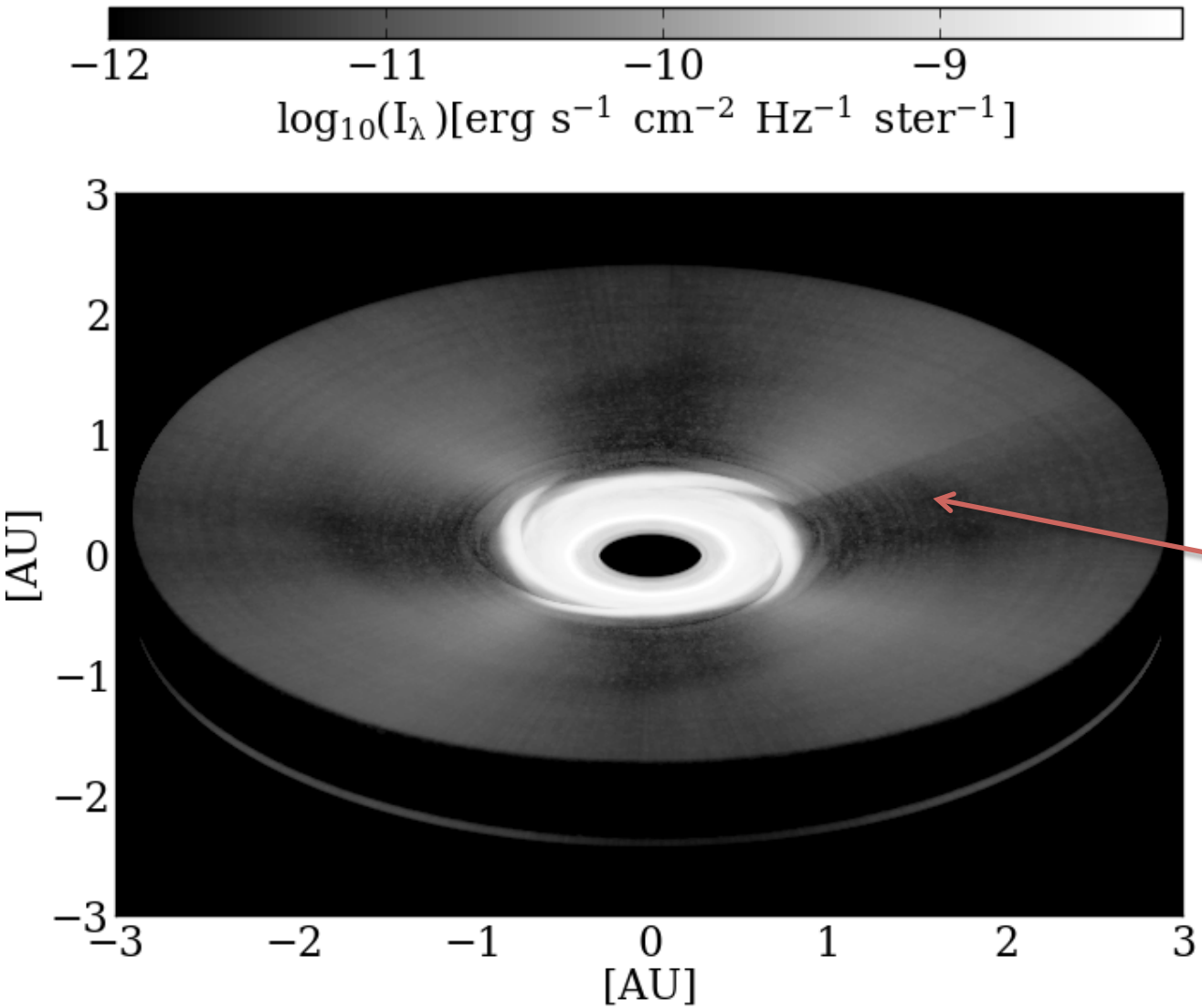
Connection to observations

Light-curve observations are a great tool to obtain constraints on the disk dynamics



Connection to observations

Shadowing



Inner rim can cast shadows
Reported by
Min et al. 2017
Stolker et al. 2017
HD 135344B
Pohl et al. 2017
HD 169142

Summary

3D global MHD models are a powerful tool to understand accretion disk physics

Spatial resolved multi-wavelength observations of nearby protoplanetary disks are a great opportunity to challenge, test and improve our models

3D global non-ideal MHD simulations with gas and dust match well observational constraints

Outlook

Radiation non-ideal MHD simulations of gas and dust

NIR, MIR (VLTI, MATISSE, ELT, JWST)

- **Disk surface structure**
- Dust opacity and properties

Radio emission (VLA,ALMA)

- **Dust structures in the disk midplane**
- **Polarization**
- Magnetization measurements

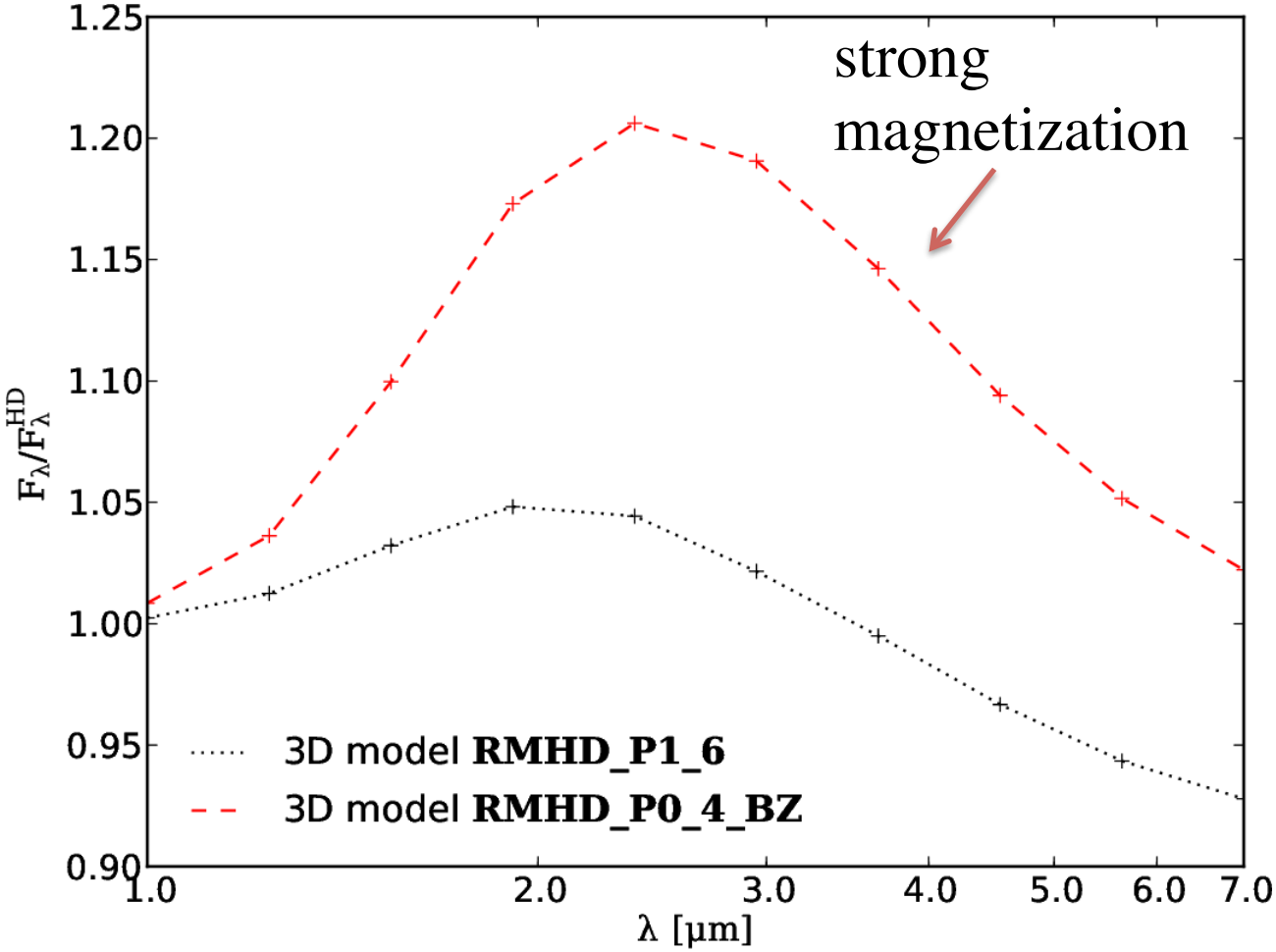
Dust concentration zones

- **Dust growth and evolution**
- Planet formation models
- Exoplanet occurance rate

Part III Connection to observations

Inner disk < 10 AU

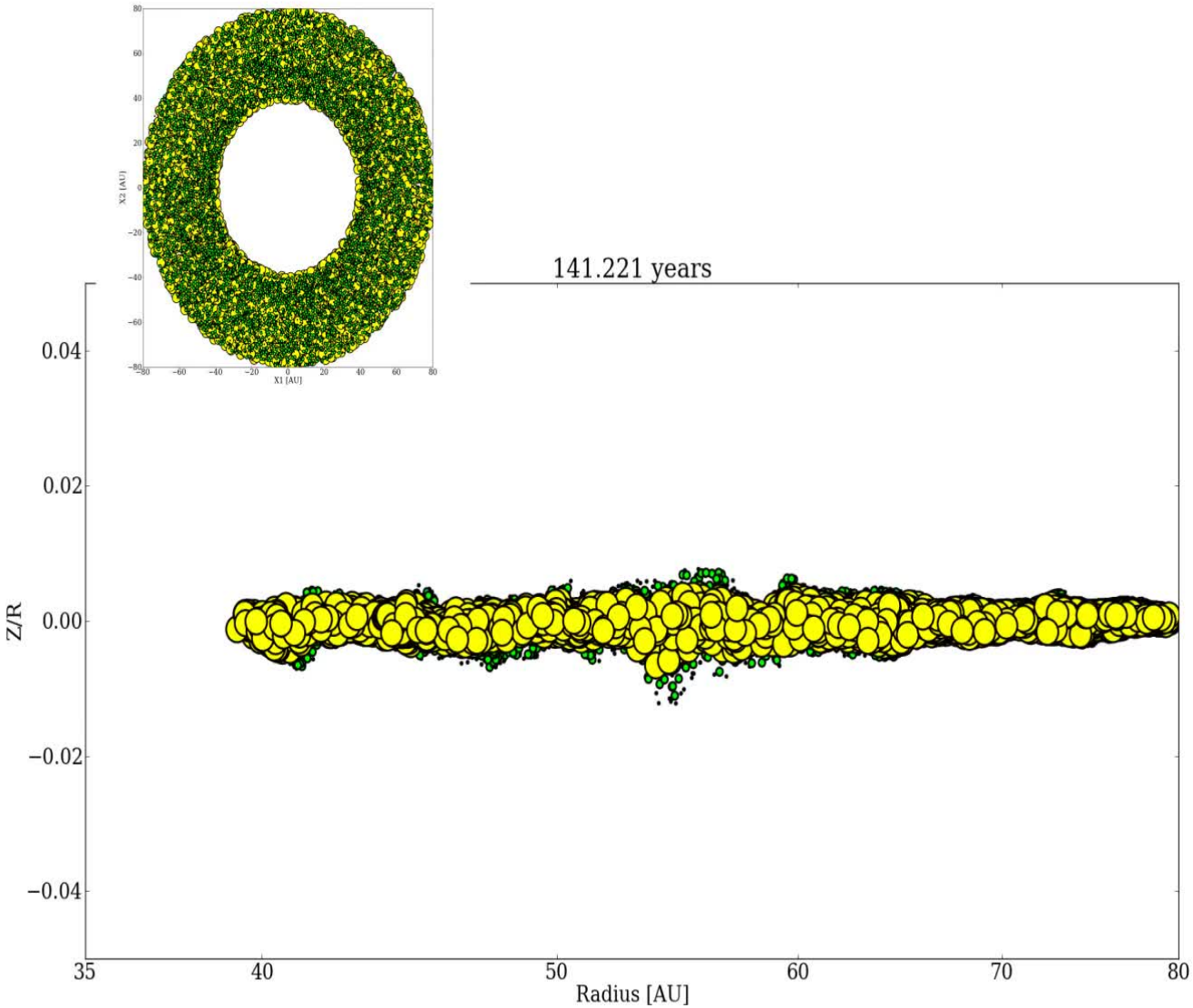
Intensity $^{MHD}/_{HD}$



Part III Connection to observations

Outer disk > 10 AU

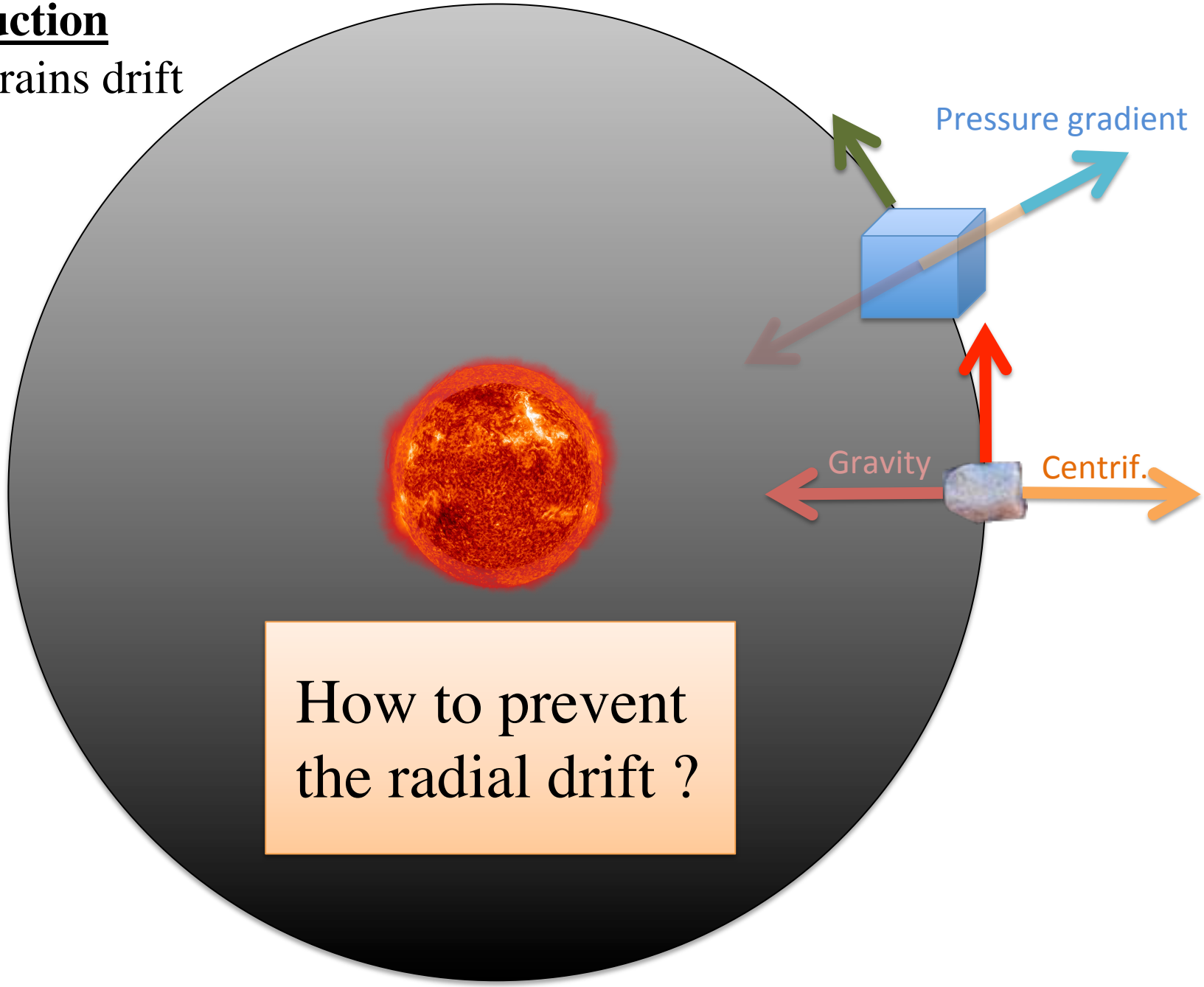
Flock et al. 2015 A&A
Ruge, Flock et al. 2016 A&A



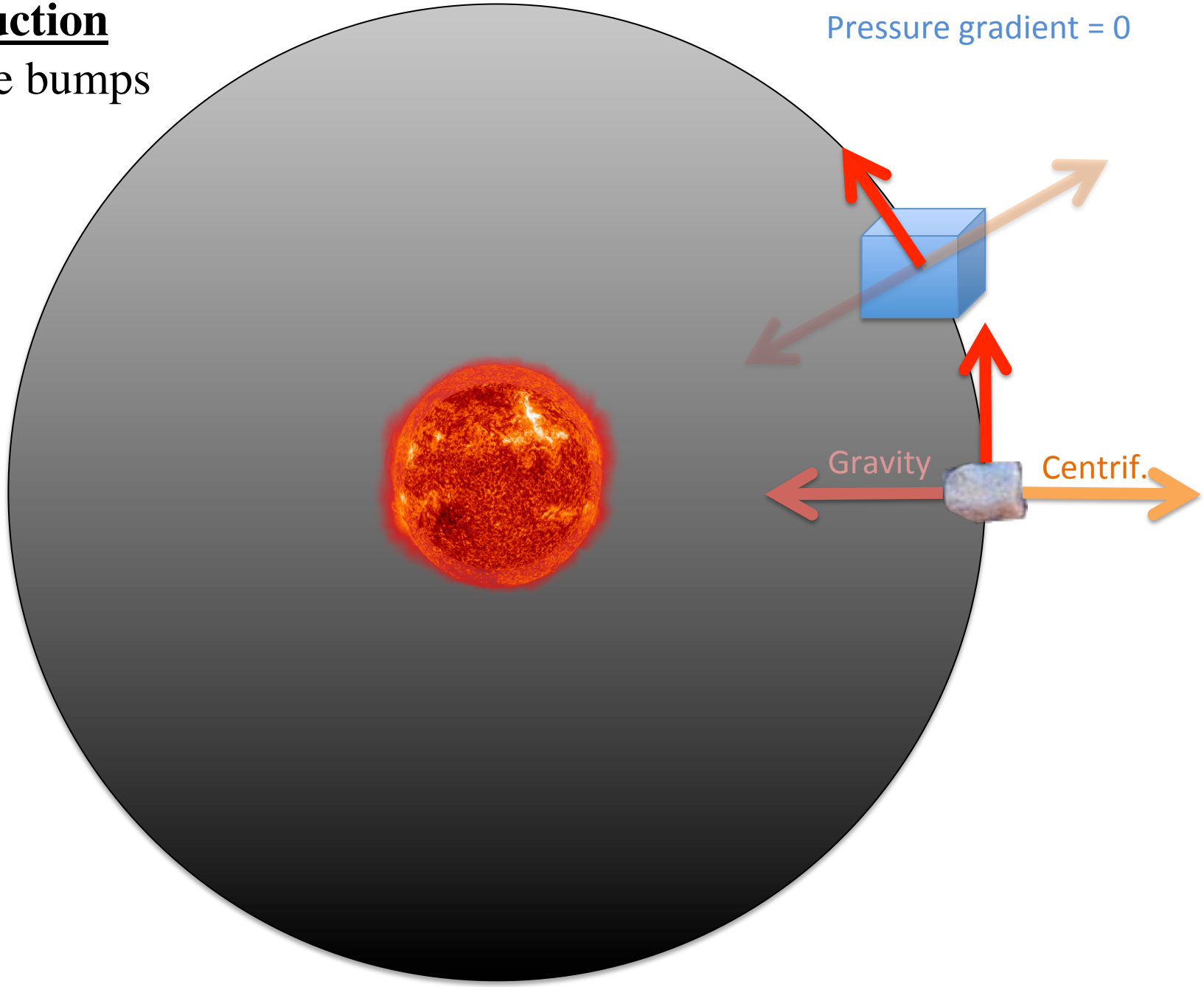
dust grain motion 0.05 - 0.5 - 5 mm

Introduction

Large grains drift



How to prevent the radial drift ?

Introduction

Pressure bumps