Computational Planet Formation: What Do We Need From the Next Generation of Models?

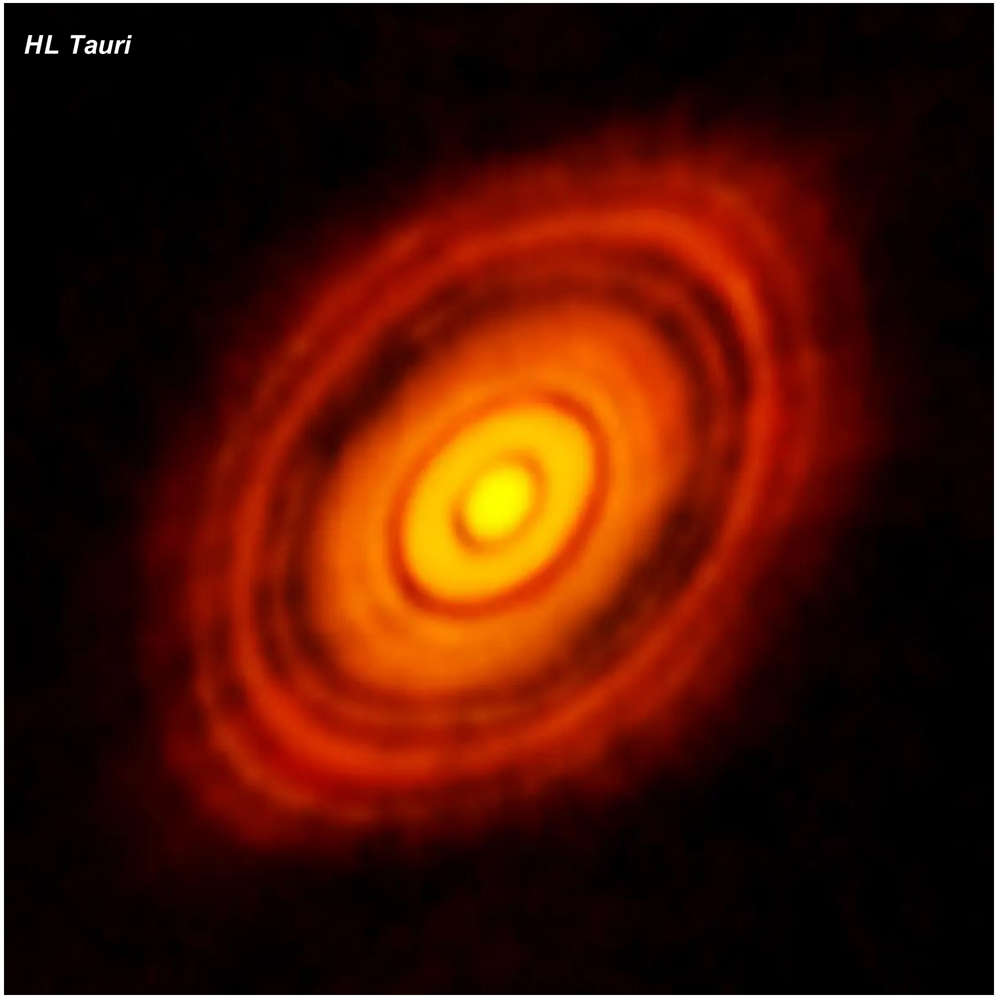
Wladimir Lyra

New Mexico State University

Challenges and Innovations in Computational Astrophysics VI
Indian Institute of Science Education and Research (IISER) - Mohali, India
Sept 29th, 2025

Observational Evidence

The Atacama Large (sub-)Millimeter Array (ALMA)
has been returning high-resolution images of circumstellar disks, resolving structure



The ALMA Partnership et al. (2015)

Instruments

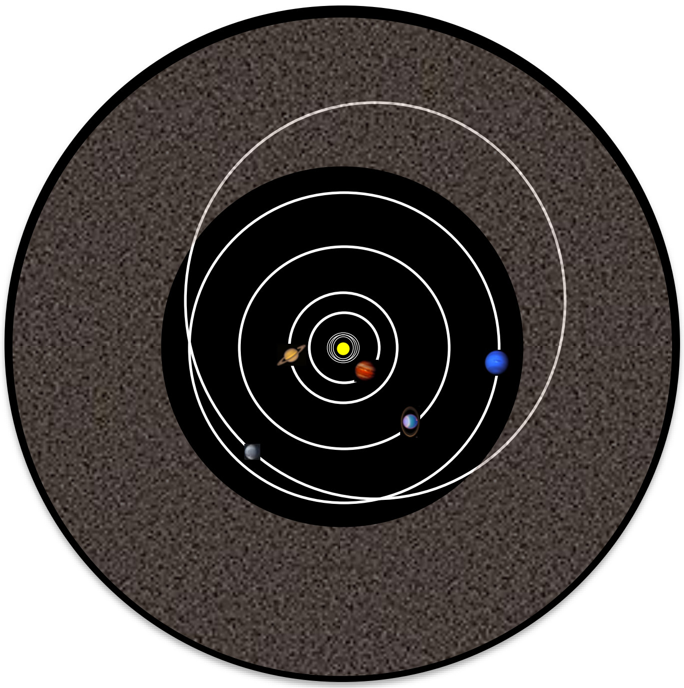
Atacama Large (sub-)Millimeter Array
ALMA

Very Large Array
VLA

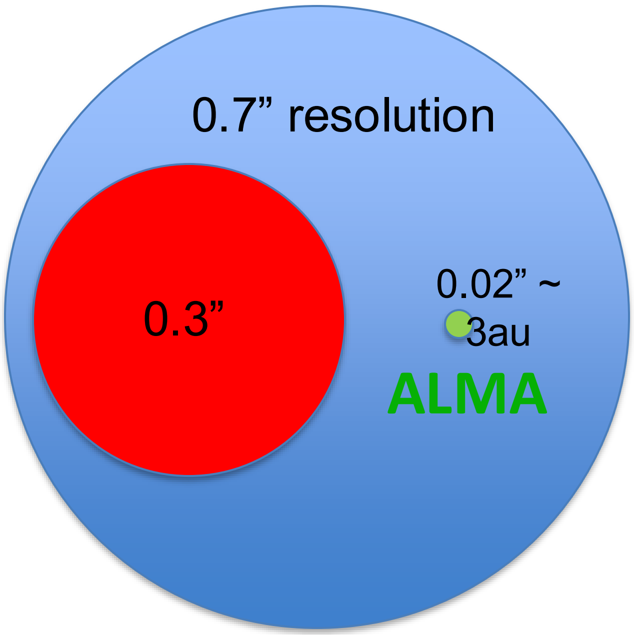
Subaru

VLT

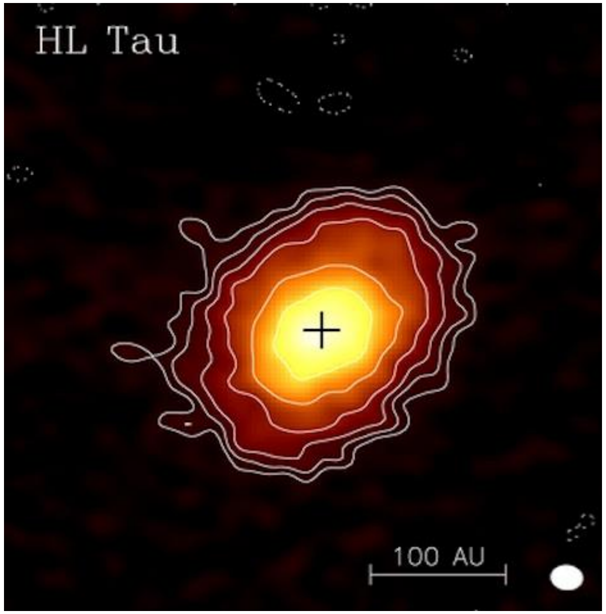
The ALMA Re~~v~~solution



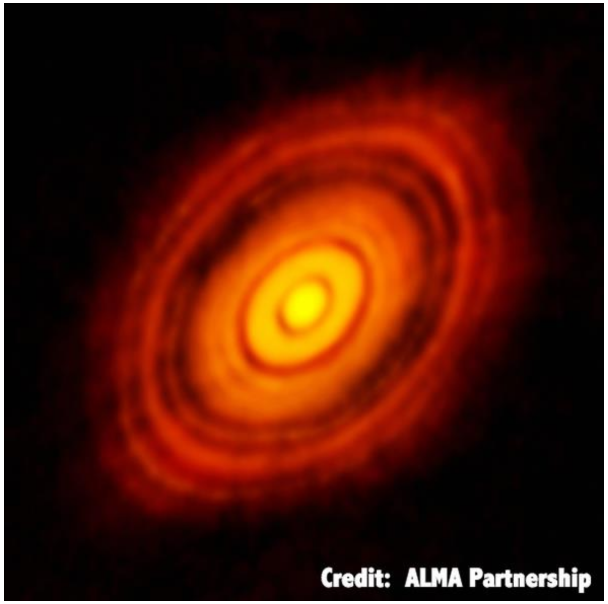
At 140 pc



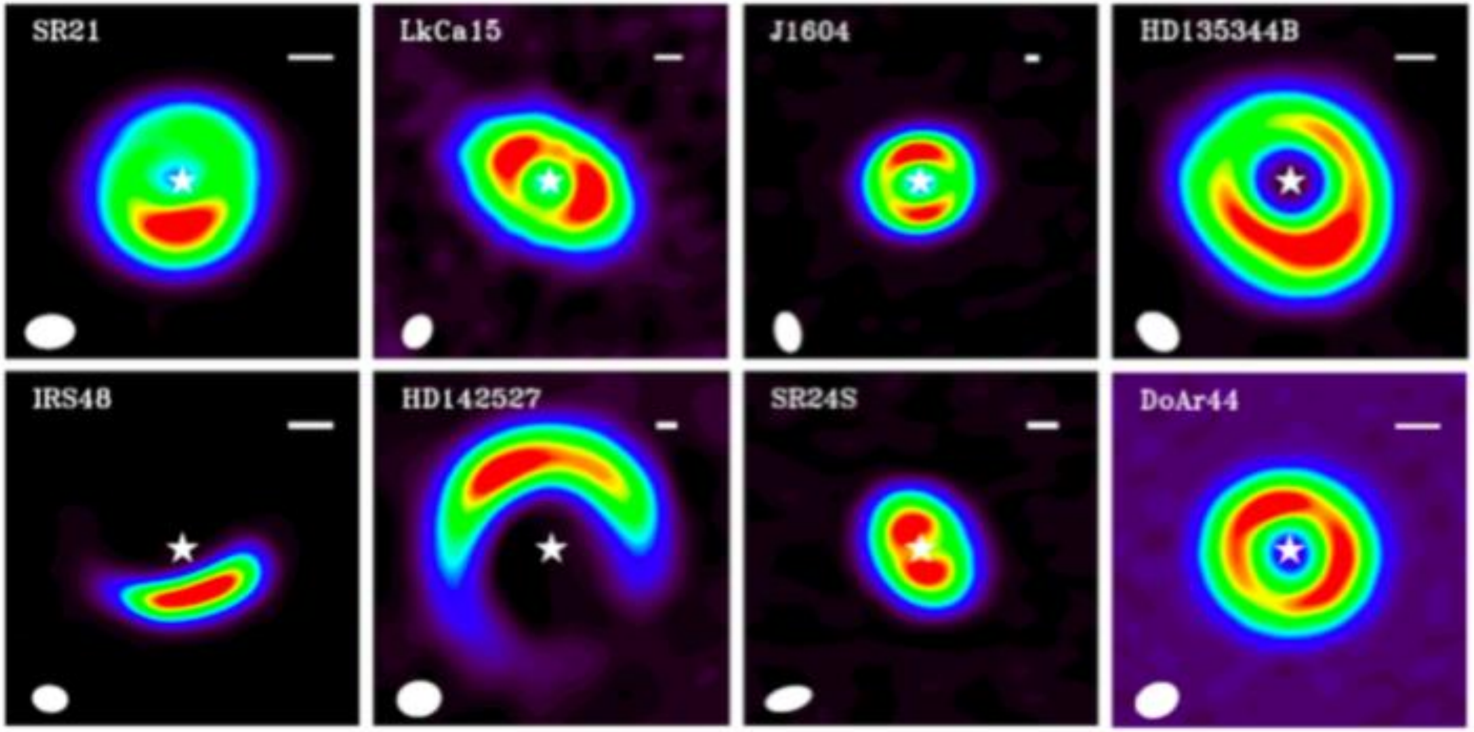
Before ALMA



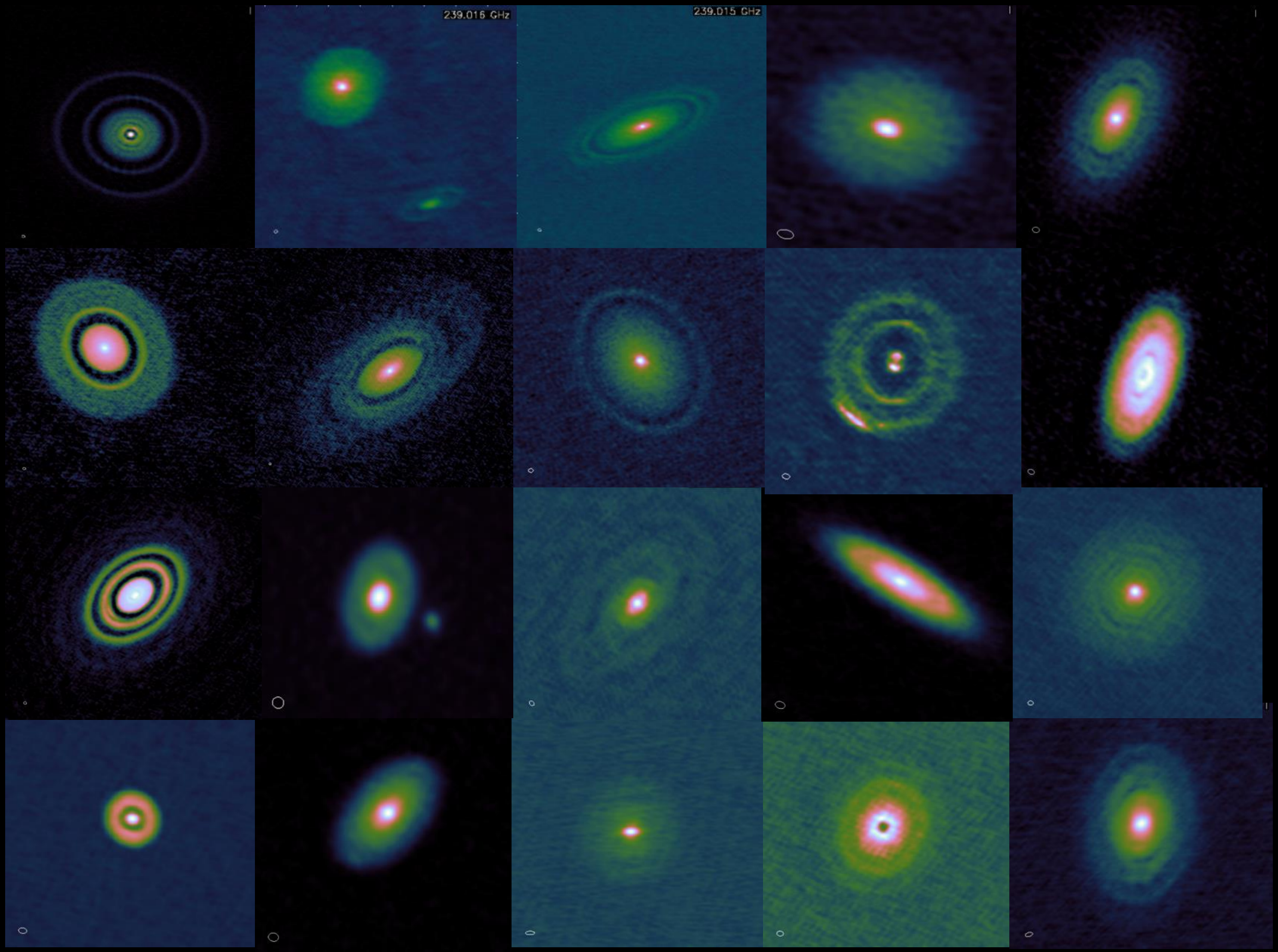
ALMA



ALMA Cycle 0 (2012)



ALMA Disk Substructure in High-Angular Resolution (DSHARP) Survey (2018)



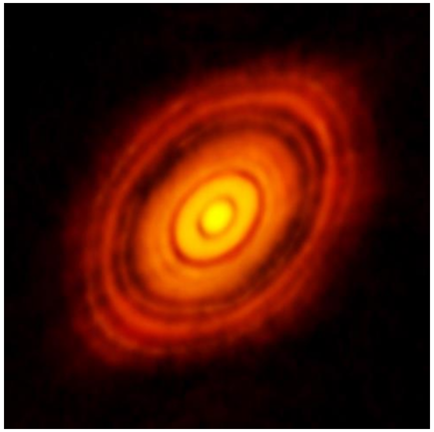
W. Lyra

PI: Sean Andrews

Observational Evidence

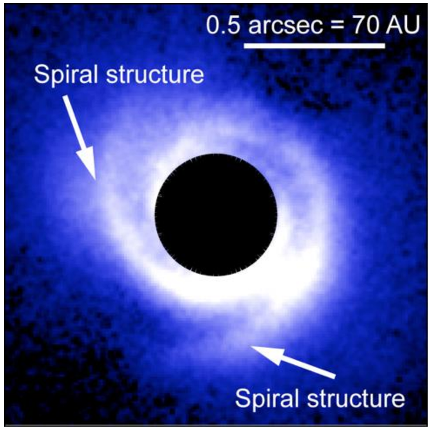
Structure: gaps, spirals, and vortices

HL Tau



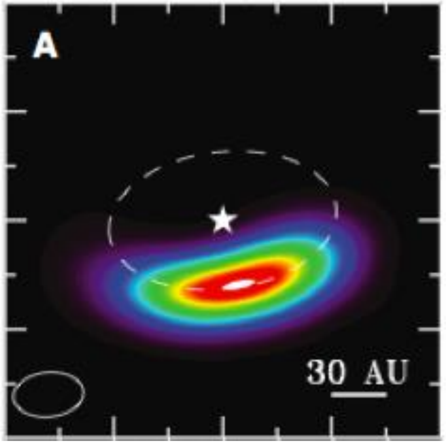
The ALMA Partnership et al. (2015)

SAO 206462



Muto et al. (2012)

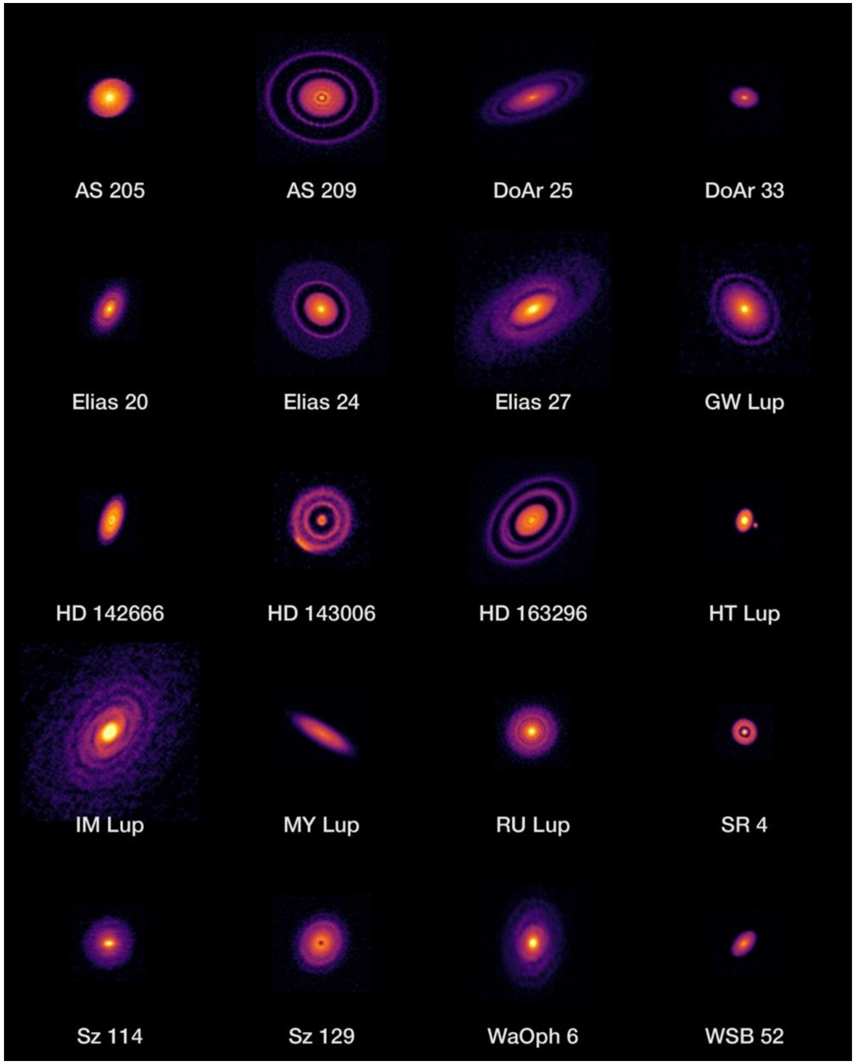
Oph IRS 48



van der Marel et al. (2013)

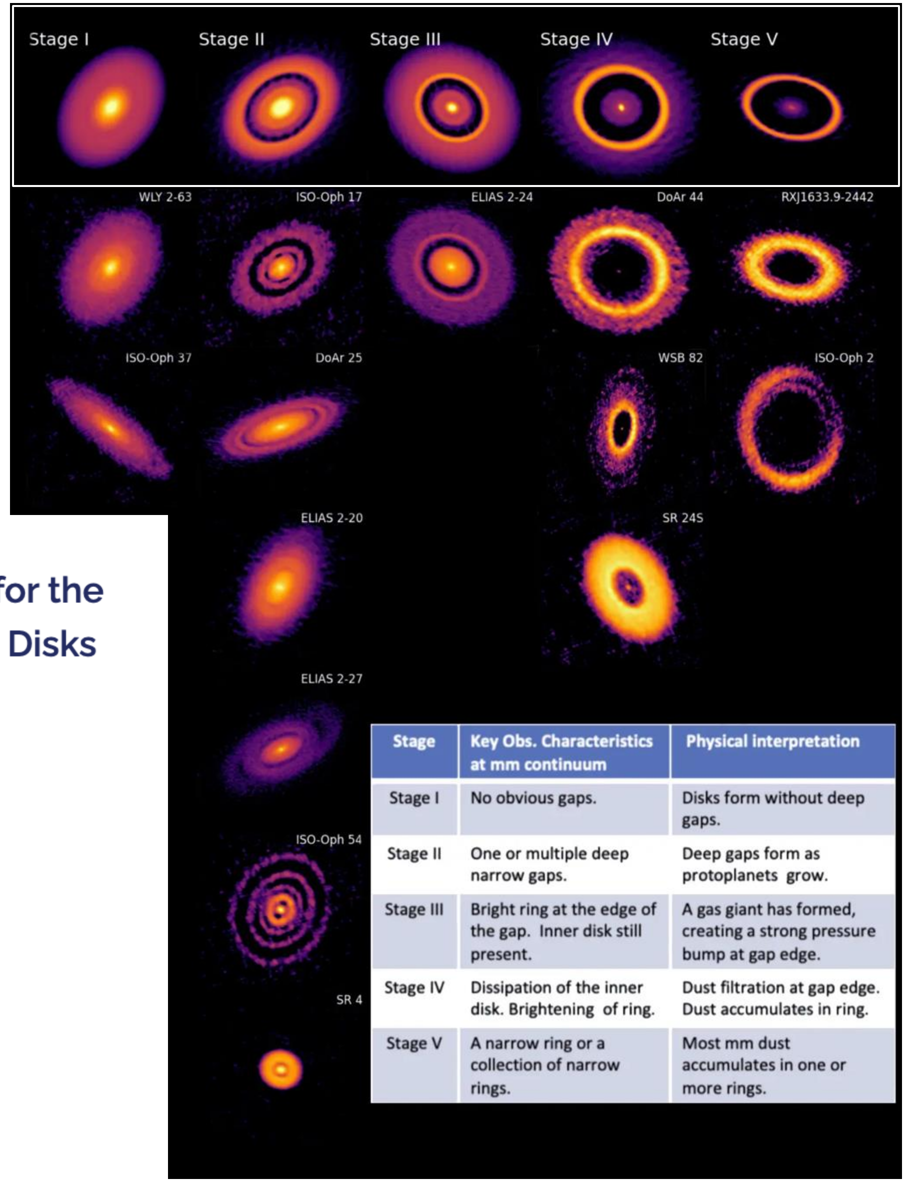
Observational Evidence

The Ophiucus Disk Survey Employing ALMA (ODISEA)



ODISEA (2018); PI: Lucas Cieza

Time series of planet formation?



Stage	Key Obs. Characteristics at mm continuum	Physical interpretation
Stage I	No obvious gaps.	Disks form without deep gaps.
Stage II	One or multiple deep narrow gaps.	Deep gaps form as protoplanets grow.
Stage III	Bright ring at the edge of the gap. Inner disk still present.	A gas giant has formed, creating a strong pressure bump at gap edge.
Stage IV	Dissipation of the inner disk. Brightening of ring.	Dust filtration at gap edge. Dust accumulates in ring.
Stage V	A narrow ring or a collection of narrow rings.	Most mm dust accumulates in one or more rings.

Press Releases

ALMA Inspires New Models for the Evolution of Planet-Forming Disks

6 May, 2025 / Read time: **7 minutes**

Orcajo et al. (2025)

Observational Evidence

Polarization maps: dust properties and magnetic fields

nature astronomy

Explore content | About the journal | Publish with us

nature > nature astronomy > articles > article

Article | Open access | Published: 05 February 2025

Observationally derived magnetic field strength and 3D components in the HD 142527 disk

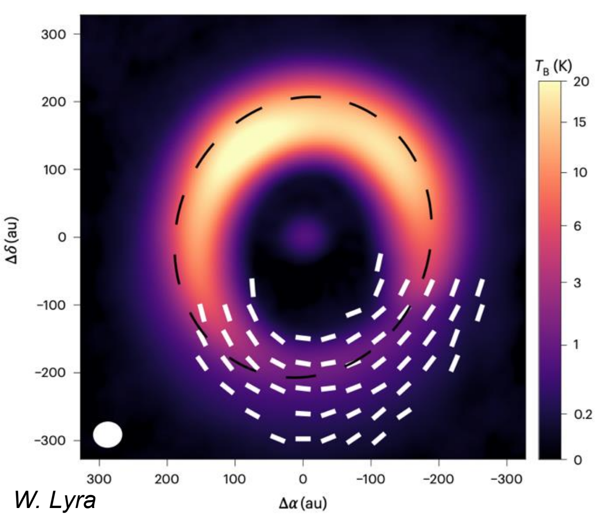
Satoshi Ohashi, Takayuki Muto, Yusuke Tsukamoto, Akimasa Kataoka, Takashi Tsukagoshi, Munetake Momose, Misato Fukagawa & Nami Sakai

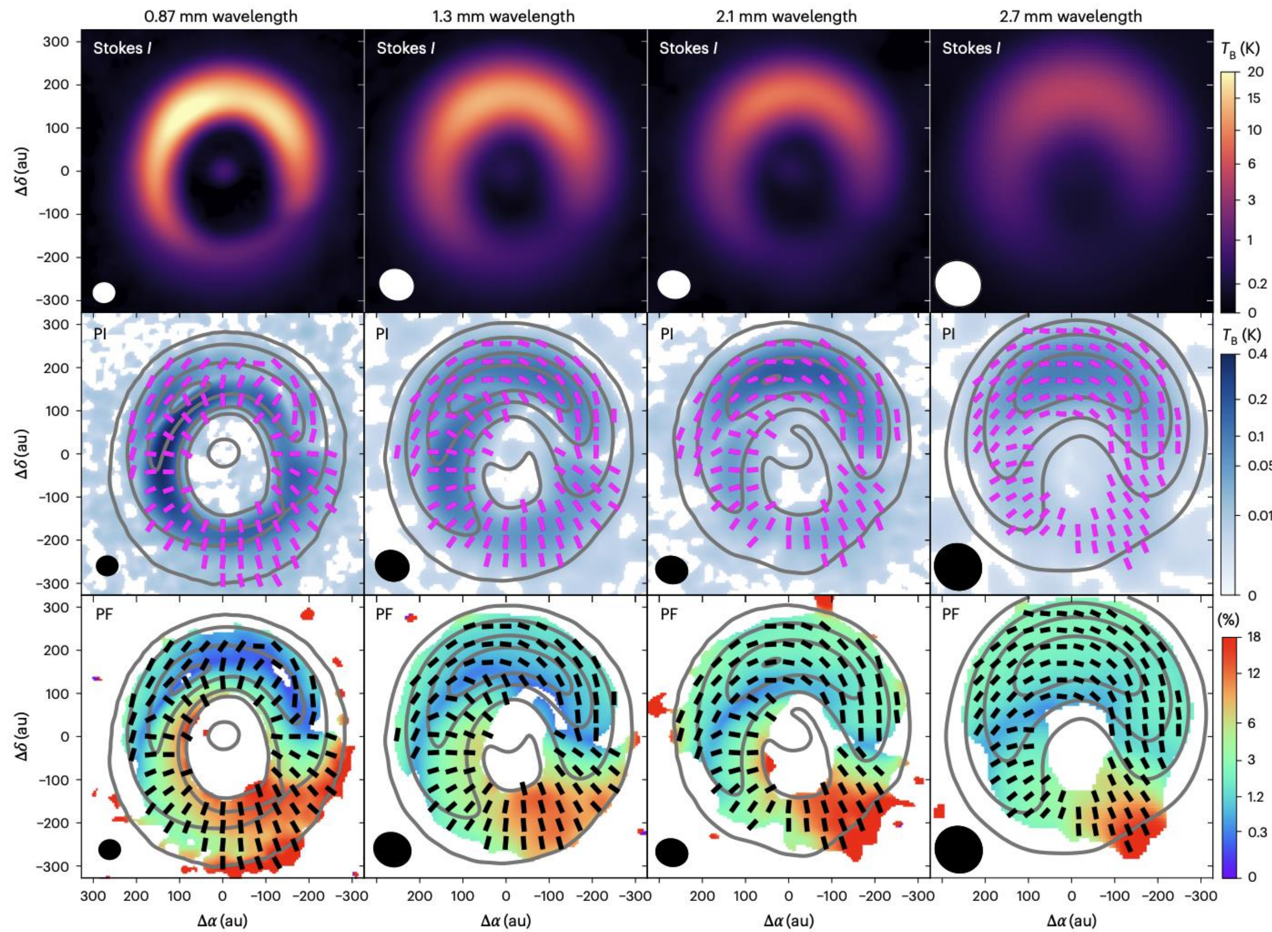
Field geometry
$|B_r| : |B_\varphi| : |B_z| \sim 0.26 : 1.0 : 0.23$

Field strength
$|\mathbf{B}| \sim 0.3$ mG

Plasma beta
$\beta \sim 2.0 \times 10^2$

Ambipolar Elsasser number
Am ~ 0.4



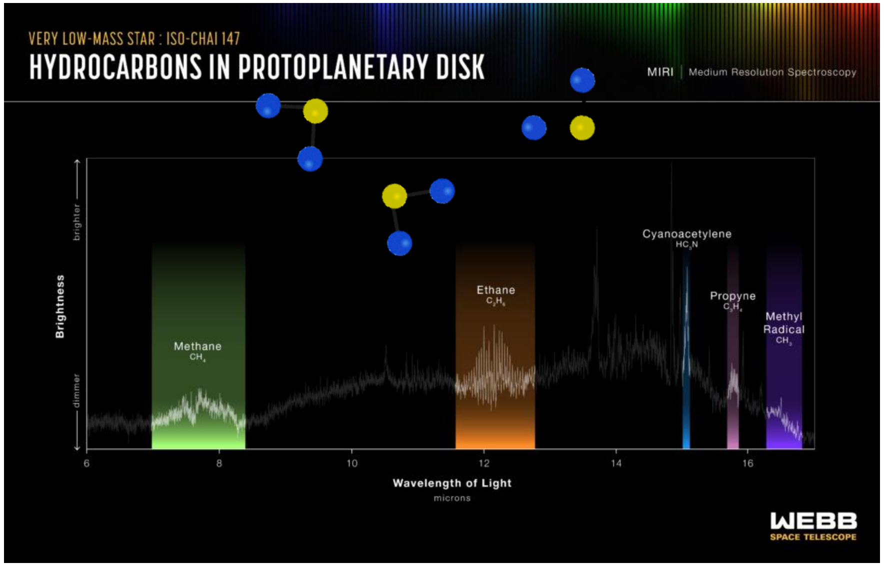


W. Lyra

Ohashi et al (2025)

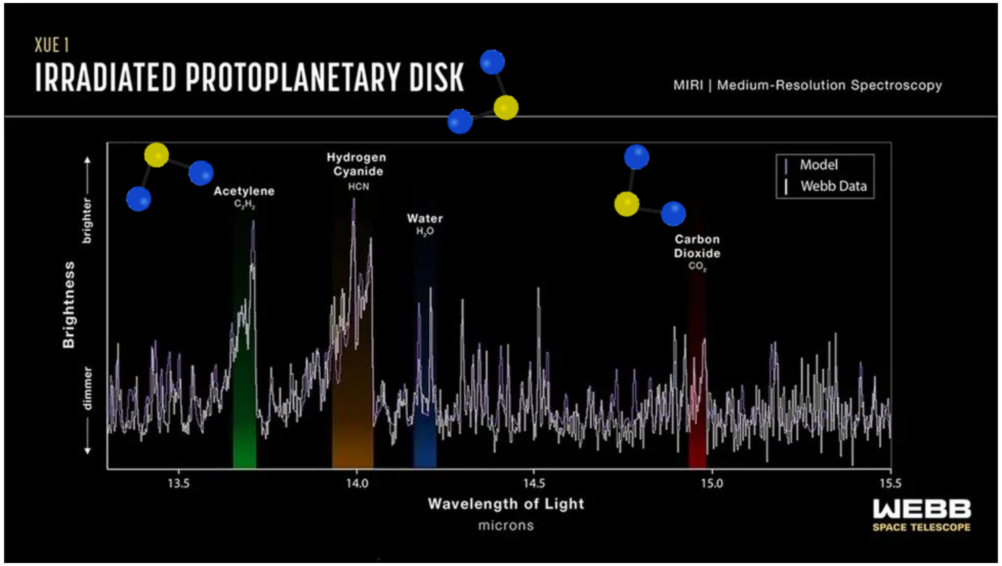
Observational Evidence

The JWST Mid-Infrared Survey (MINDS)



Arabavi et al. (2024, 2025)
PI Thomas Henning

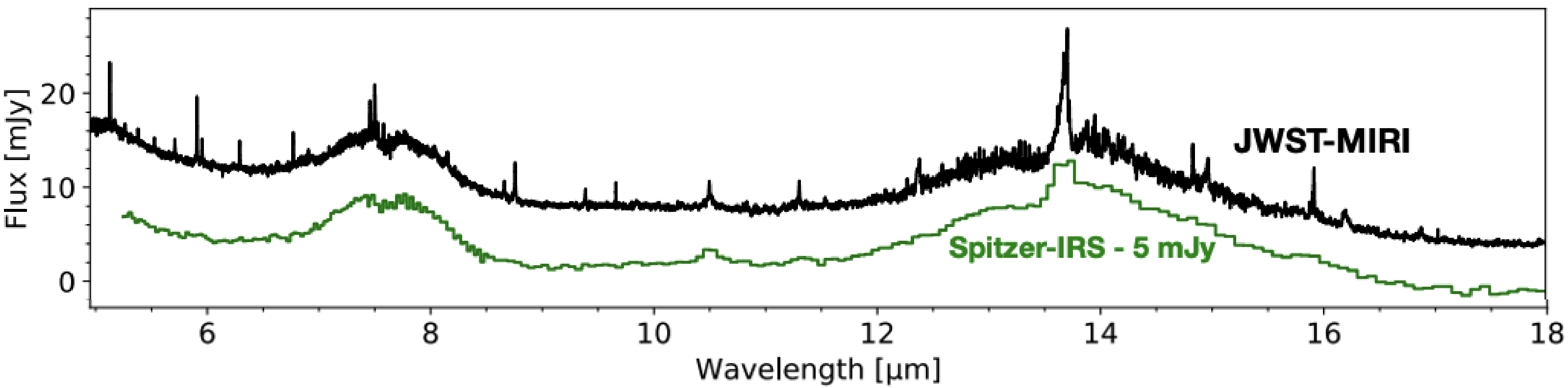
The Extreme UV Environments JWST program (XUE)

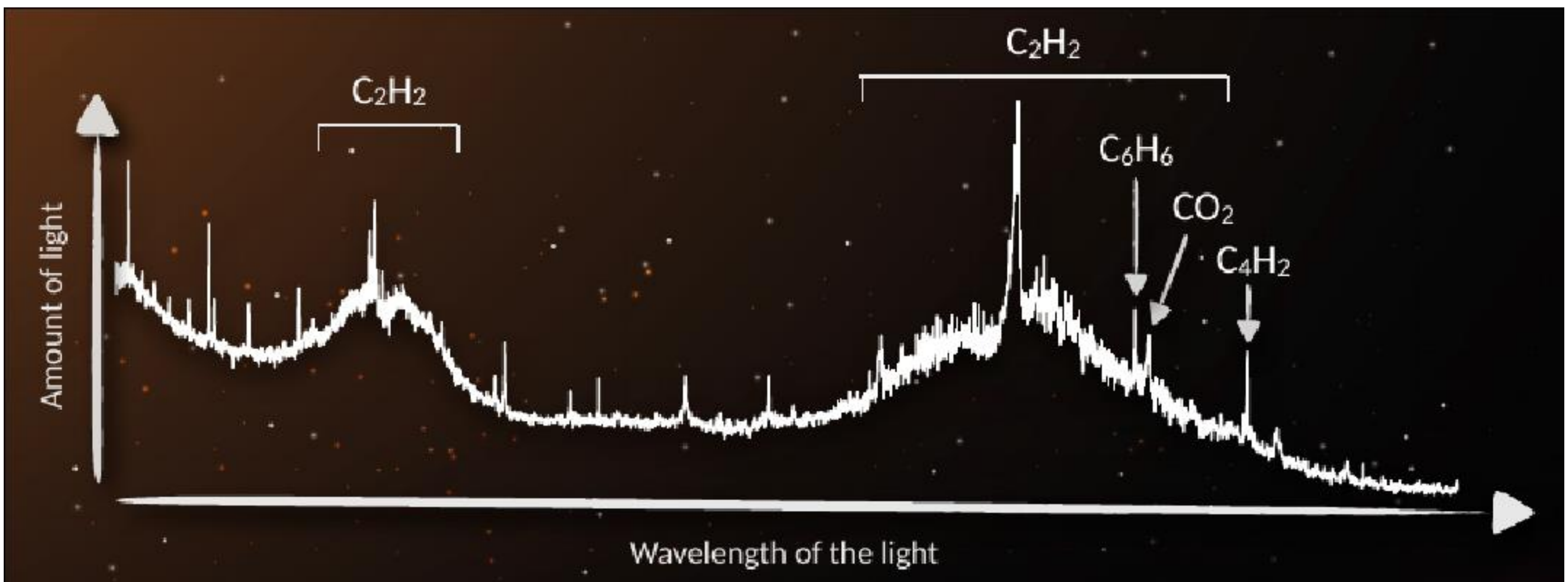


Ramirez-Tannus et al. (2023)
PI Maria Ramirez-Tannus & Arjan Bik

Observational Evidence

JWST *vs* Spitzer

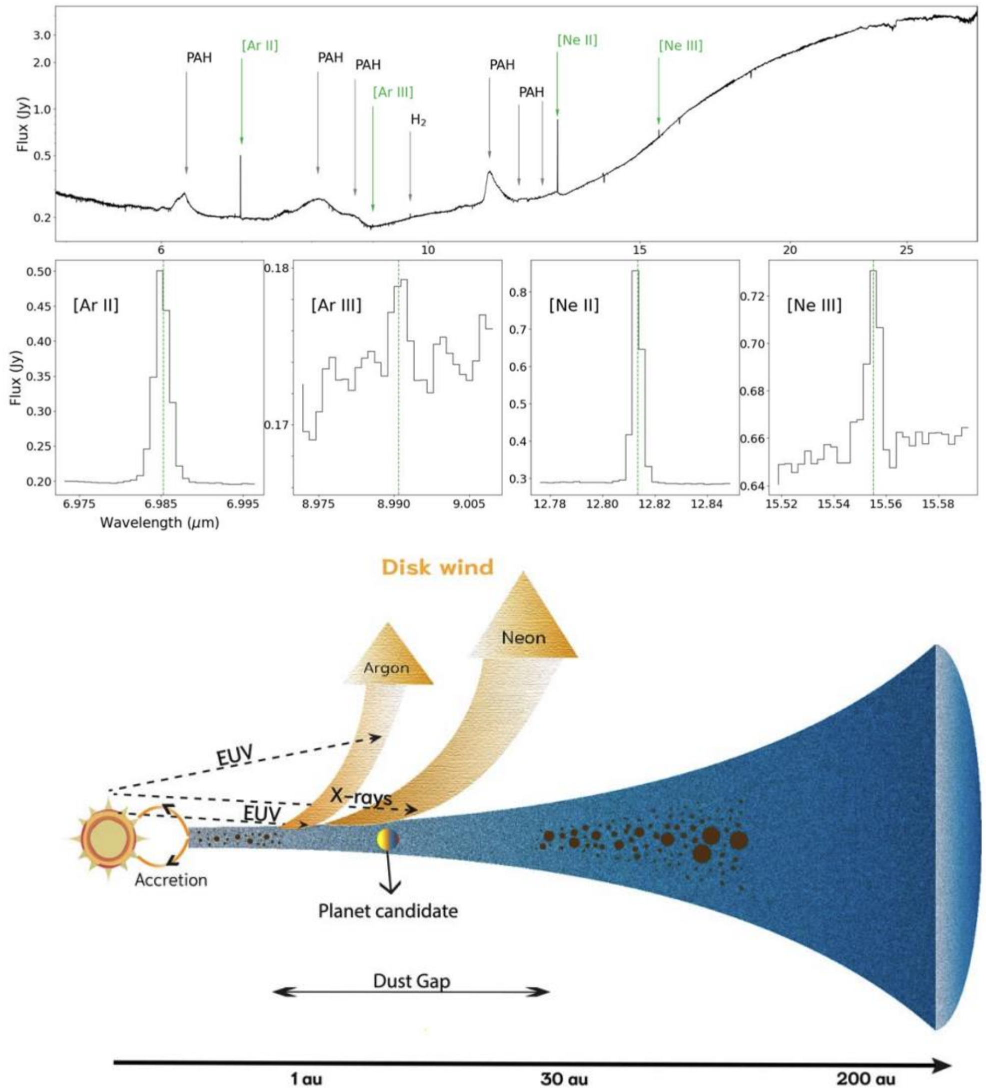




Tabone et al. (2023); MINDS PI Thomas Henning

Observational Evidence

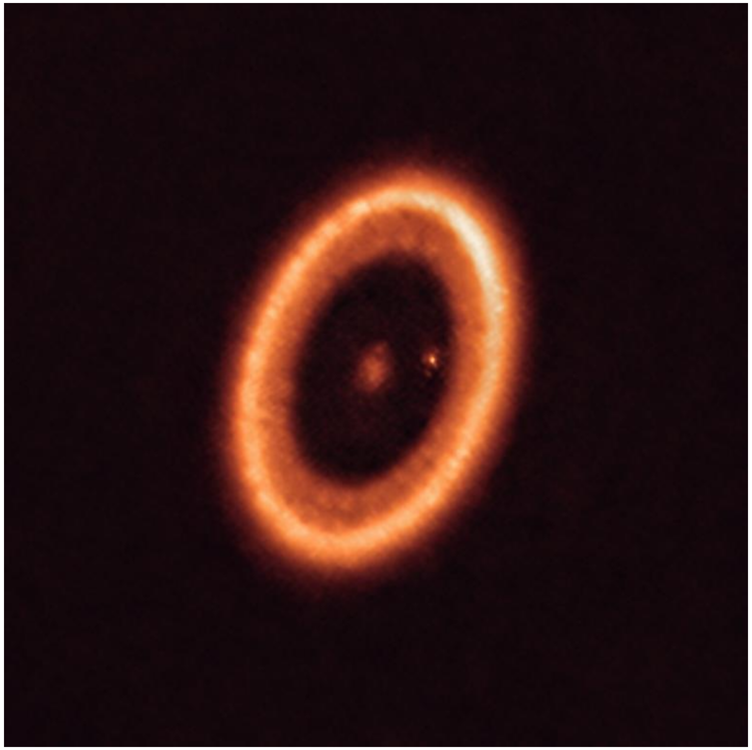
JWST: disk spectra (chemistry, ice/gas tracers)



Bajaj et al (2024)

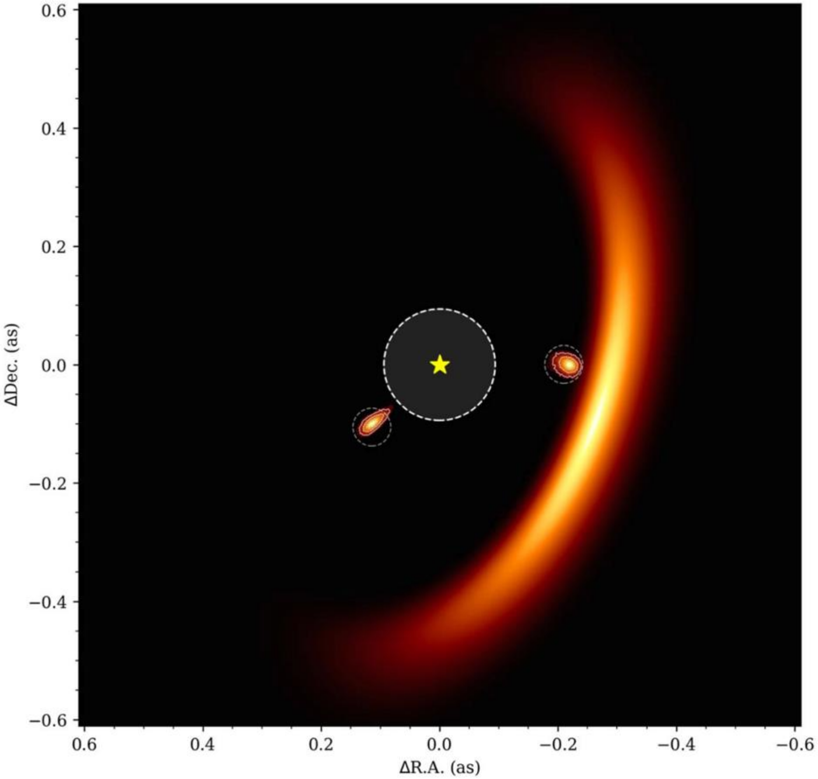
Detection of Circumplanetary Disk

ALMA



Keppler et al. (2018); Isella et al. (2019); Benisty et al. (2021)
Balsalobre-Ruza et al. (2023)

JWST Interferometry



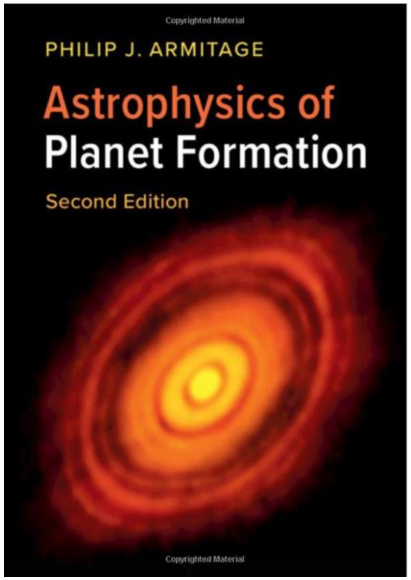
Blakely et al. (2025)

Observations demand models that are:

- 3D,
- High-resolution,
- Multiscale
- Multiphysics (+chemistry)

Reading Material

- PP7 Chapter 13 - Hydro-, Magnetohydro-, and Dust-Gas Dynamics of Protoplanetary Disks, Lesur et al. 2022.
- The Initial Conditions for Planet Formation: Turbulence Driven by Hydrodynamical Instabilities in Disks around Young Stars, Lyra & Umurhan 2019, PASP, 131, 1001.
- Astrophysics of Planet Formation, 2nd edition 2020, Armitage, Cambridge University Press.




Publications of the Astronomical Society of the Pacific, 131:072001 (34pp), 2019 July
https://doi.org/10.1088/1538-3873/aaf5ff

The Initial Conditions for Planet Formation: Turbulence Driven by Hydrodynamical Instabilities in Disks around Young Stars

Wladimir Lyra[1,2] and Orkan M. Umurhan[3,4]
[1] California State University, Northridge. Department of Physics and Astronomy 18111 Nordhoff Street, Northridge, CA 91330; wlyra@csun.edu
[2] Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA, 91109; wlyra@jpl.nasa.gov
[3] NASA Ames Research Center, Space Sciences Division, Planetary Sciences Branch, Moffatt Field, CA 94035; orkan.m.umurhan@nasa.gov
[4] SETI, Carl Sagan Center, 190 Bernardo Way, Mountain View, CA 94043
Received 2018 April 27; accepted 2018 October 25; published 2019 June 12

Abstract

This review examines recent theoretical developments in our understanding of turbulence in cold, non-magnetically active, planetesimal-forming regions of protoplanetary disks that we refer to throughout as "Ohmic zones." We give a brief background introduction to the subject of disk turbulence followed by a terse pedagogical review of the phenomenology of hydrodynamic turbulence. The equations governing the dynamics of cold astrophysical disks are given and basic flow states are described. We discuss the Solberg–Høiland conditions required for stability, and the three recently identified turbulence-generating mechanisms that are possibly active in protoplanetary disk Ohmic zones: (i) the vertical shear instability, (ii) the convective overstability, and (iii) the zombie vortex instability. We summarize the properties of these processes, identify their limitations, and discuss where and under what conditions these processes are active in protoplanetary disk Ohmic zones.

Key words: turbulence – protoplanetary disks – hydrodynamics – instabilities – accretion – accretion disks – magnetohydrodynamics (MHD)

Online material: color figures

1. Introduction

Planet formation is simultaneously one of the oldest and one of the newest concerns of human inquiry. "How did the Earth come to be?" is a question that almost invariably appears in the cosmogonies of the ancients. They did not always have a clear idea of what "Earth" meant, but this is a question that, in one form or another, virtually every society in recorded history has at some point asked itself. Particularly interesting are the ideas of Leucippus (480–420? B.C.E.) who, according to testimonial, is to have said (Diels & Kranz 1961)

> *The worlds come into being as follows: many bodies of all sorts and shapes move from the infinite into a great void; they come together there and produce a single whirl, in which, colliding with one another and revolving in all manner of ways, they begin to separate like to like.*
>
> (Diogenes Laertius IX, 31)[5]

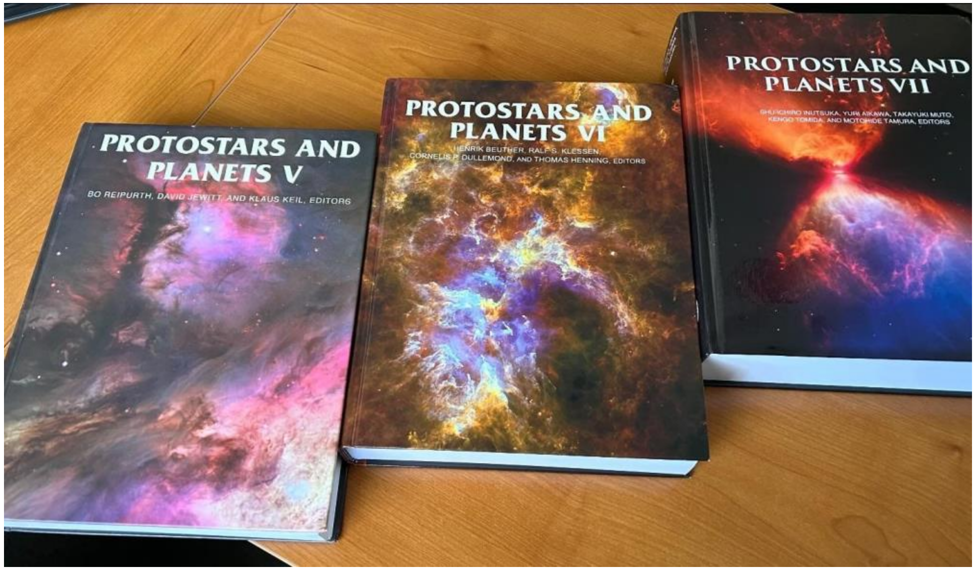
This vision strikes surprisingly modern, and not without foundation within the modern theory of planet formation. Substitute "many bodies of all sorts and shapes" with gas and dust, then "single whirl" with protoplanetary disk, and finally "revolving in all manner of ways" with turbulence, and it could have figured in the introduction of a paper in the latest issue of a major astronomy journal. This attests not to clairvoyance of the ancient Greeks, but to the antiquity of the question. Given the huge sample space, some of the educated guesses of the time are bound to contain some truth.

By the 18th century, Newtonian gravity and the orbits of the planets were understood in enough detail to realize that the low inclinations of the orbits implied that the easiest way to attain that configuration was if the planets have formed in a disk that orbited the proto-Sun (Kant 1755). Because Jupiter and Saturn are gas giant planets, this disk must have been a disk of gas. Early mathematical considerations by Laplace (1796) applied Newton's theory of universal gravitation and laws of motion to a slowly rotating spherical cloud, implying that it should collapse under its own weight. Due to conservation of angular momentum, the gas settles into a flat disk orbiting the condensing proto-Sun in the center. In this *solar nebula*, planets are taking shape.

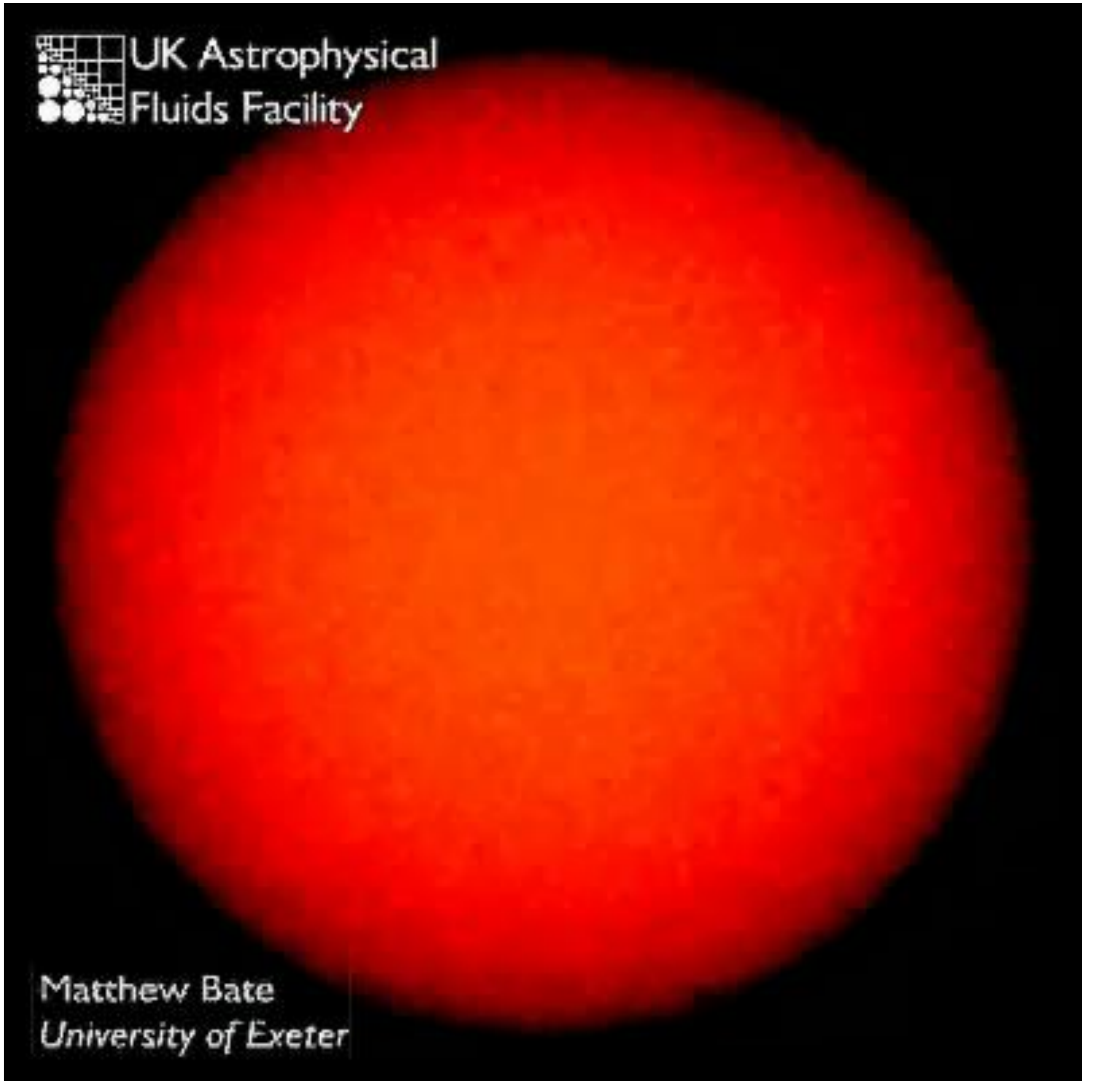
C. F. von Weizsäcker extended these fundamental notions, and pointed out that eddies in the forming solar nebula ought to

[5] Scholars of the Classical period note that nothing but third-person accounts survive of Leucippus' words.

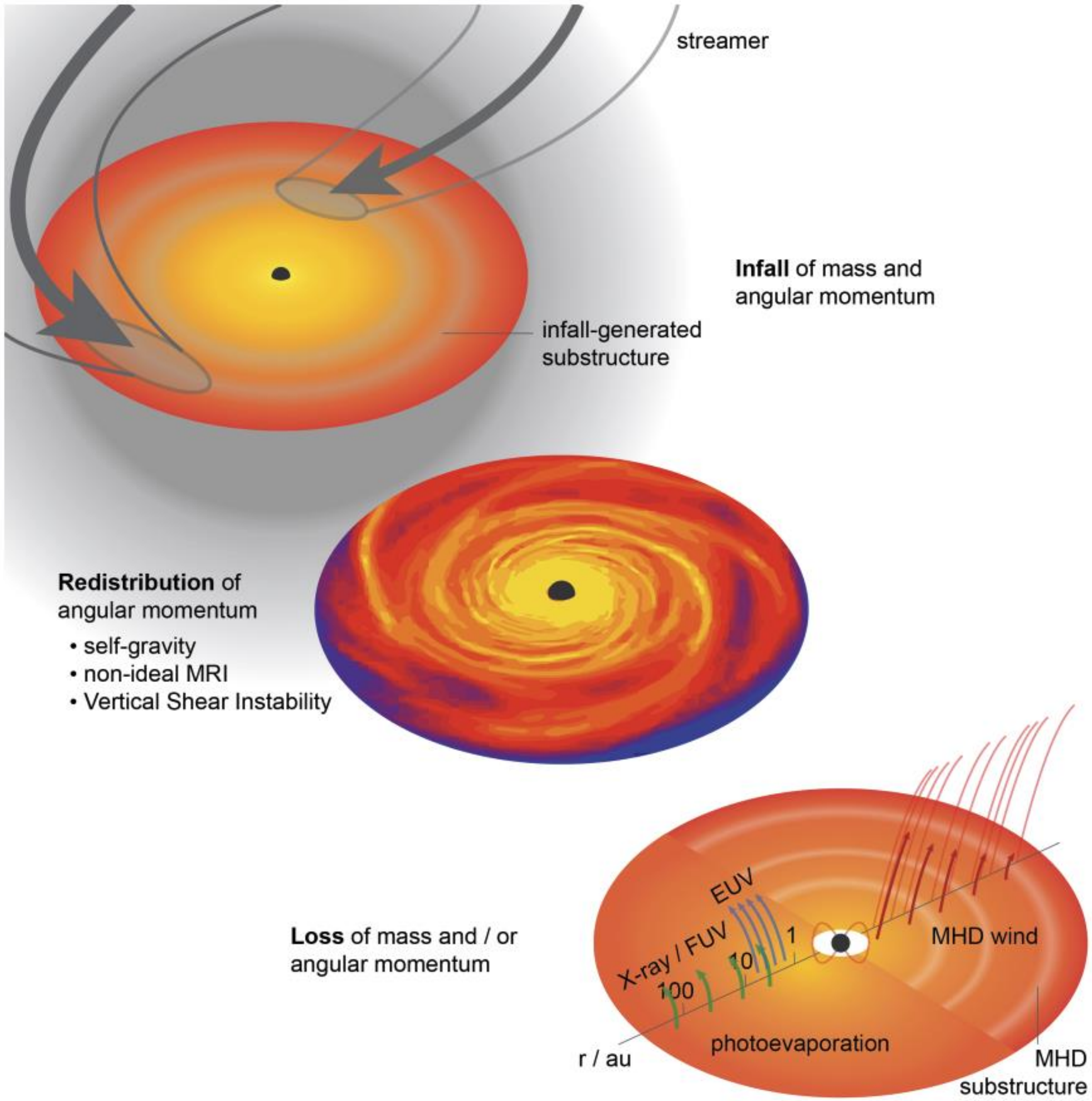
1



Square One: Star Formation

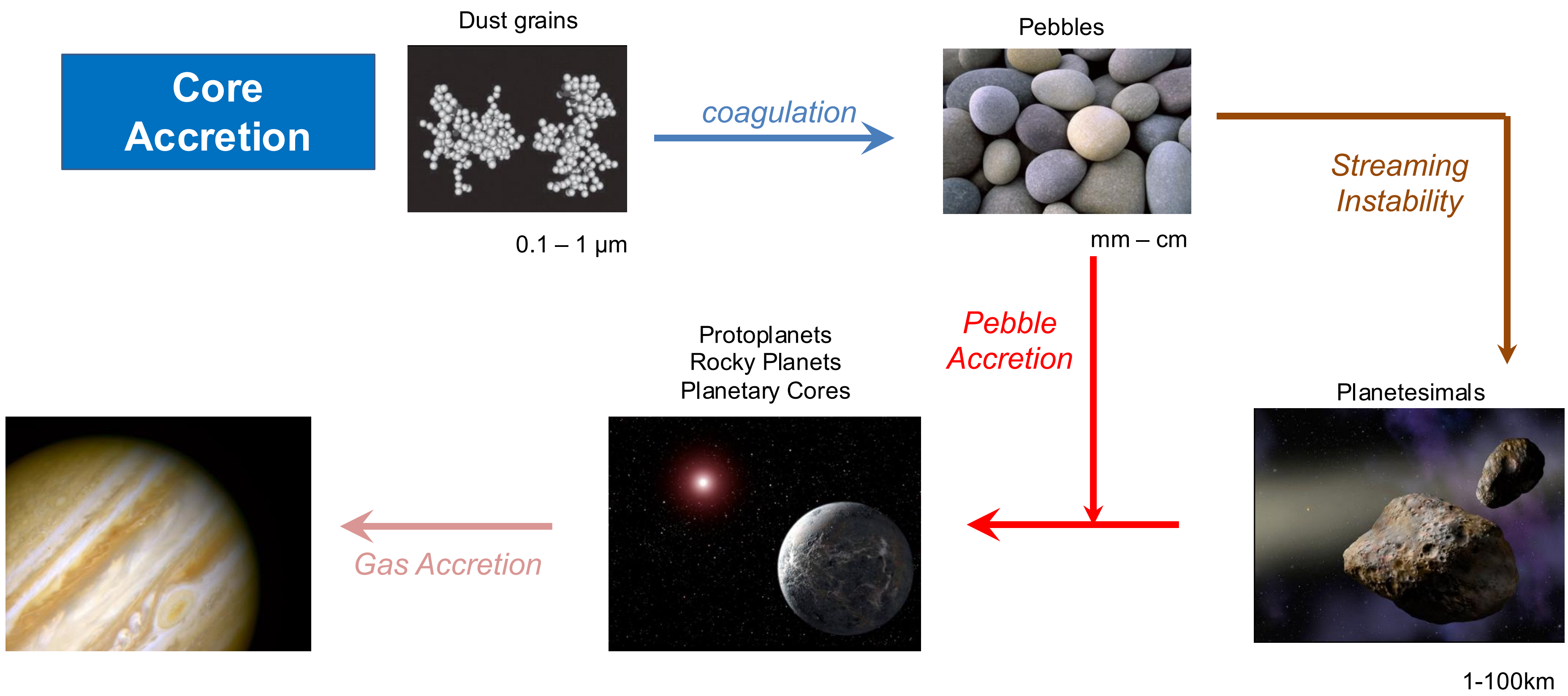


Disk evolution

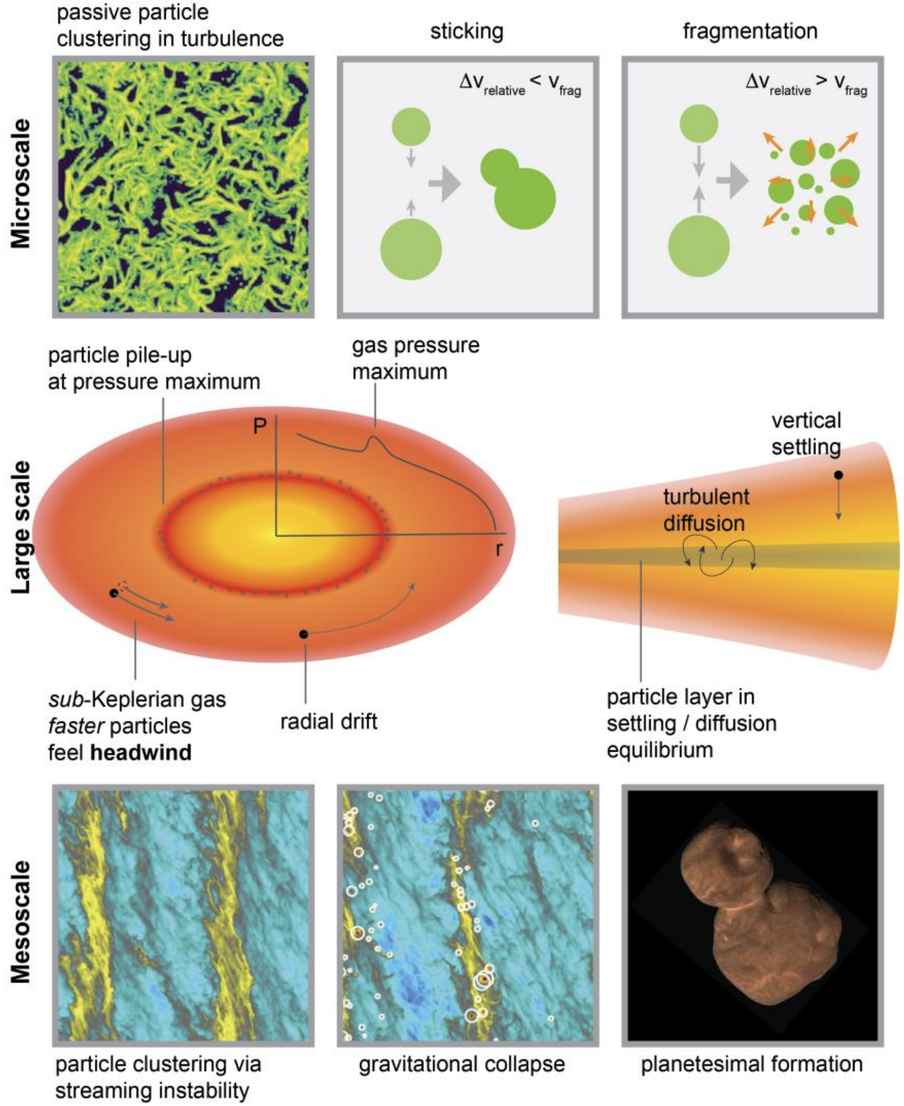


Armitage (2024)

Planet Formation via Core Accretion

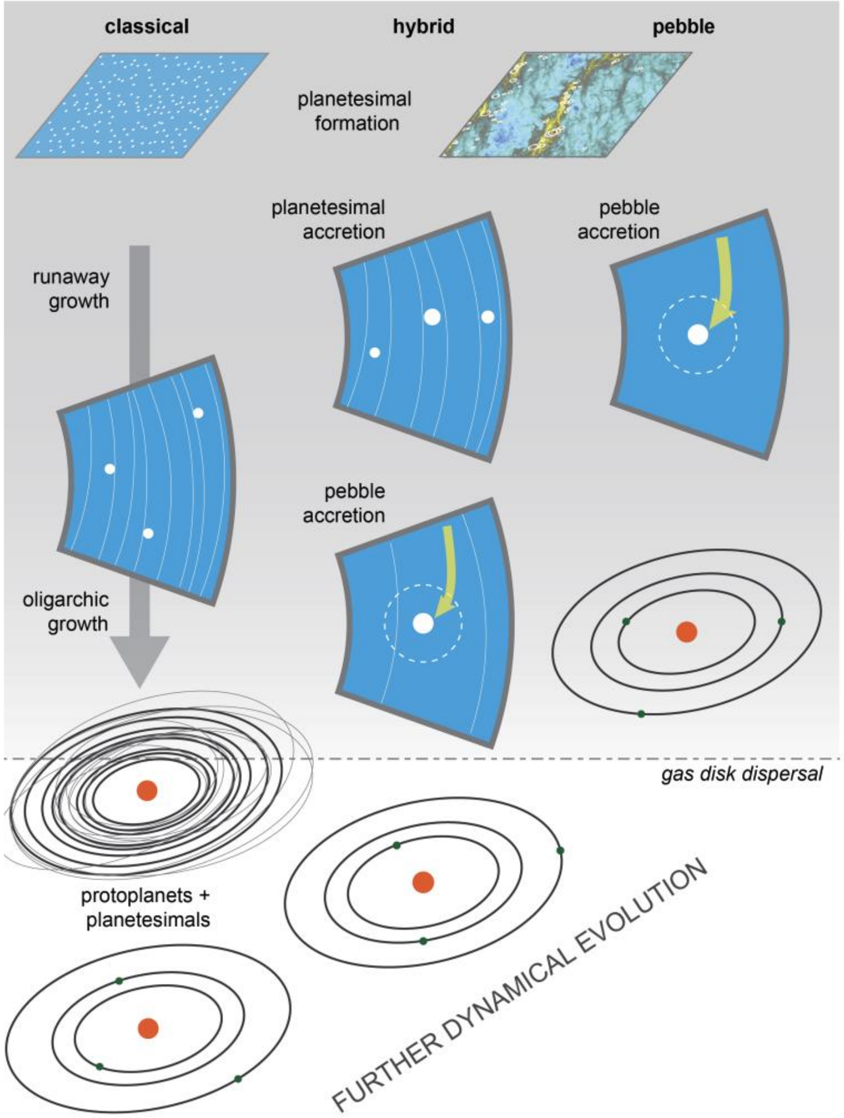


Dust growth and planet formation



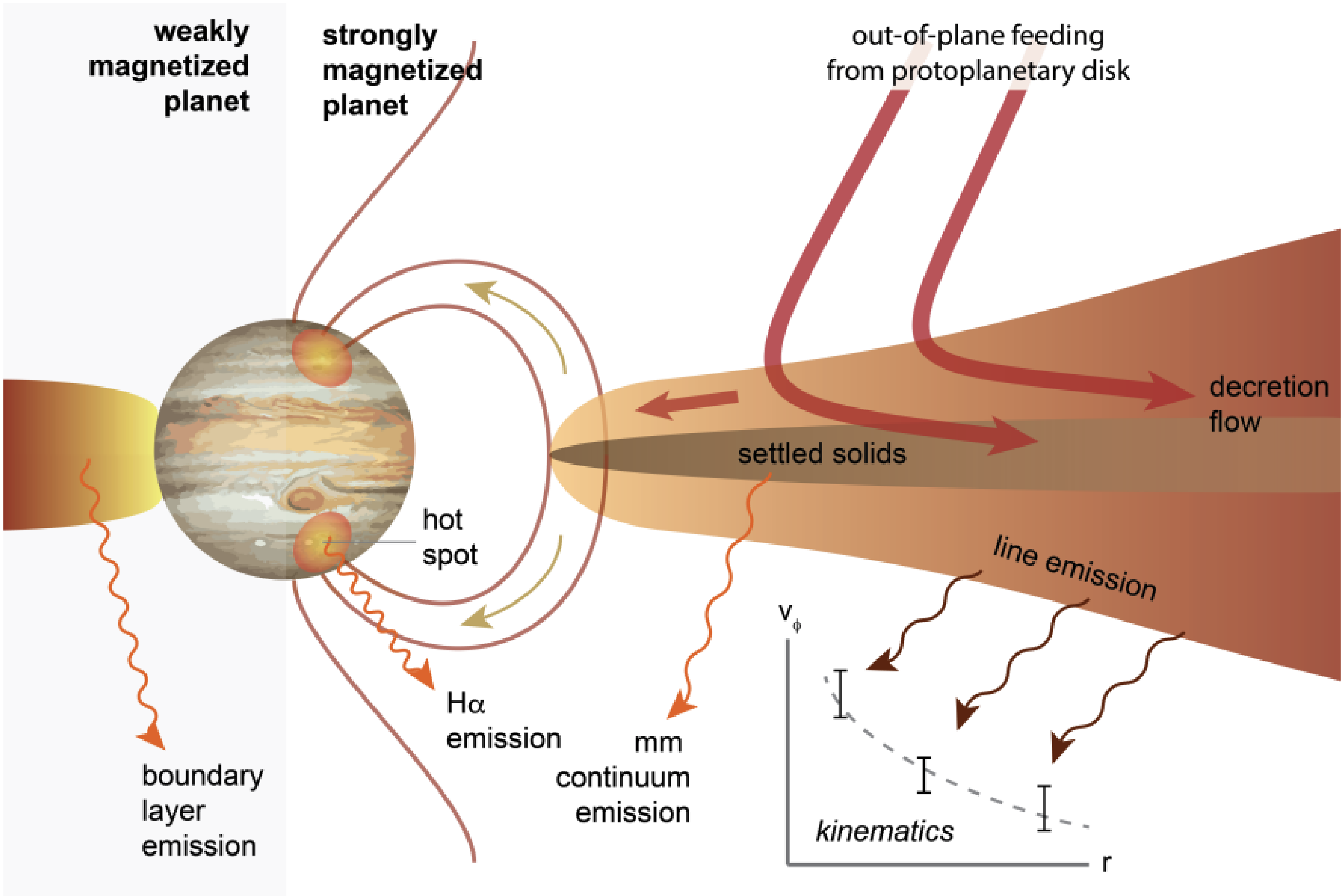
Armitage (2024)

Planetary Growth



Armitage (2024)

Circumplanetary disks



Armitage (2024)

Simulations

Global hydro & MHD models
Magneto-Rotational Instability

Resolution
384 x 192 x 768

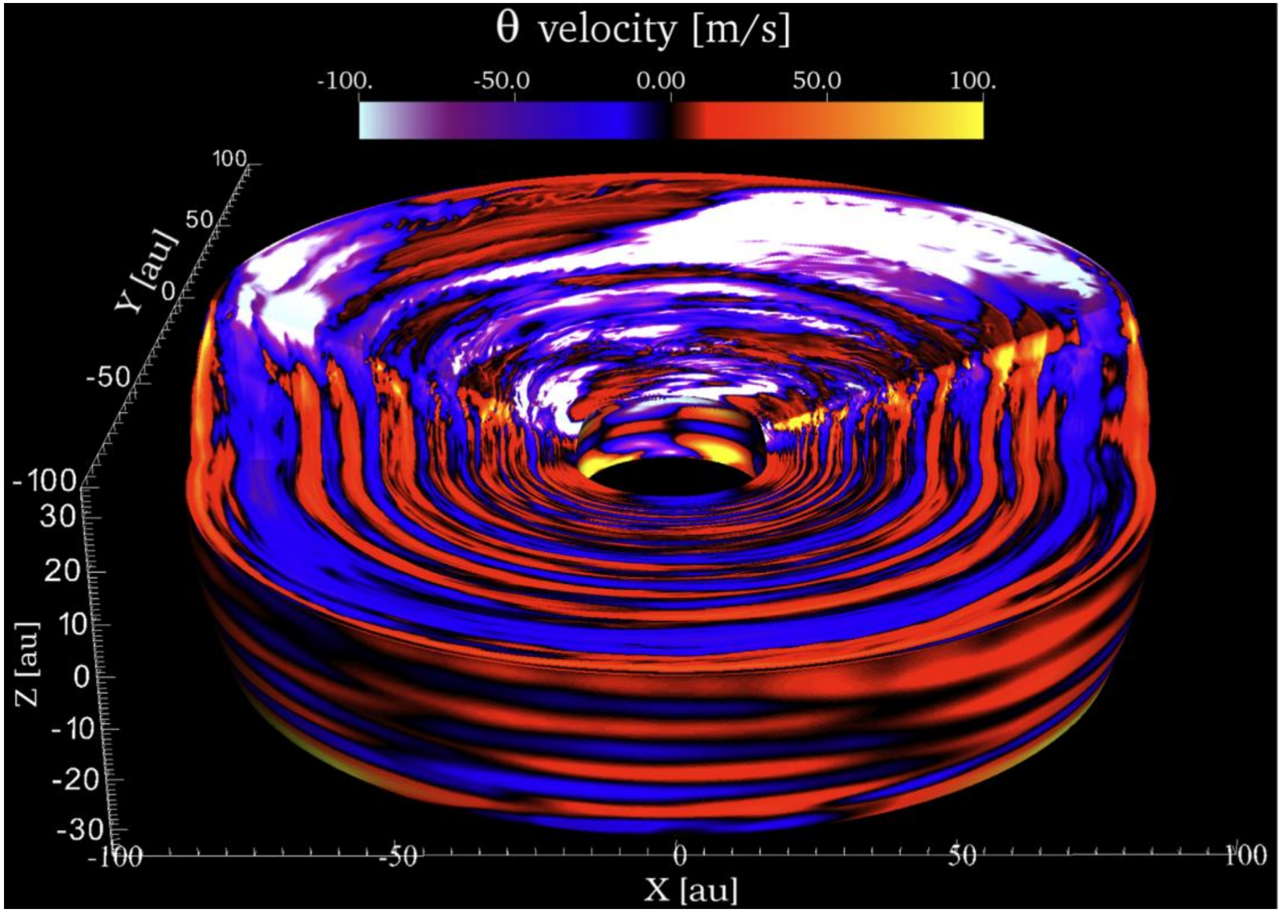
1000 orbits

8M CPU hours

Flock et al (2011)

Simulations

Global hydro & MHD models
Vertical Shear Instability



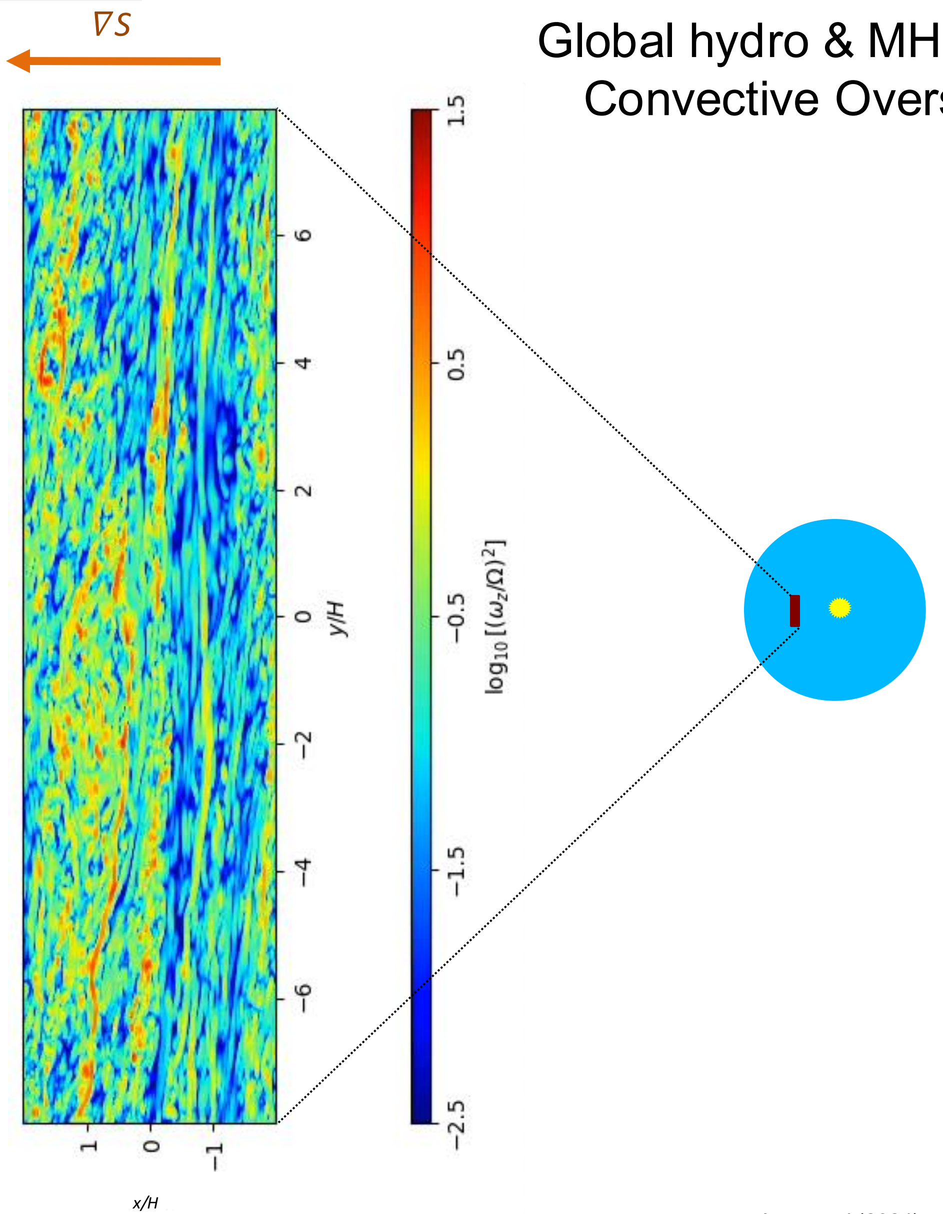
Resolution
1024 x 512 x 2044

1000 orbits

Flock et al (2020)

Simulations

Global hydro & MHD models
Convective Overstability



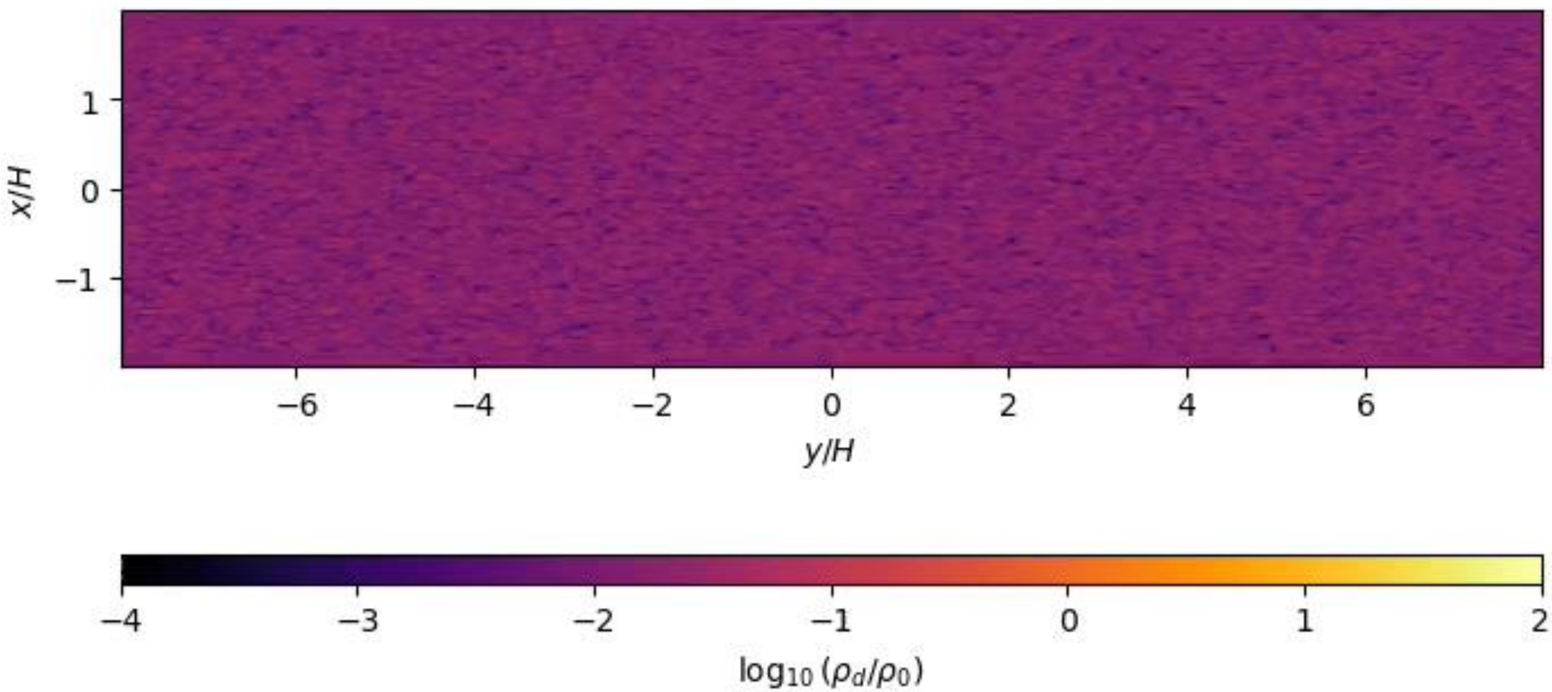
Resolution
512^3

400 orbits

Lyra et al (2024)

Simulations

Dust and grains



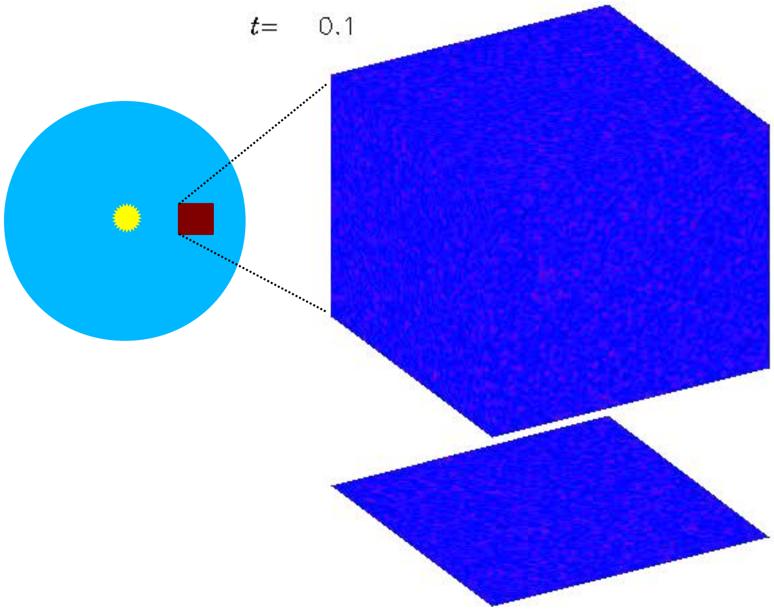
Resolution
512^3

Lyra et al. (2024)

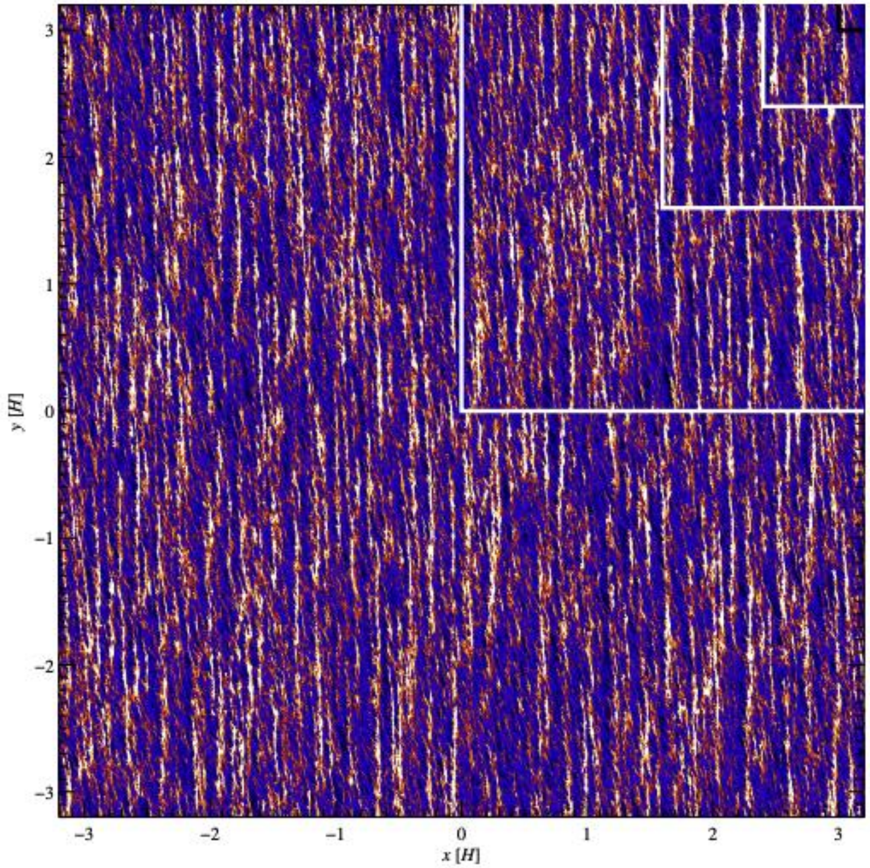
Simulations

Streaming Instability

Resolution
2048 x 2048 x 128



Johansen & Youdin (2007)



Schafer et al. (2024)

Simulations

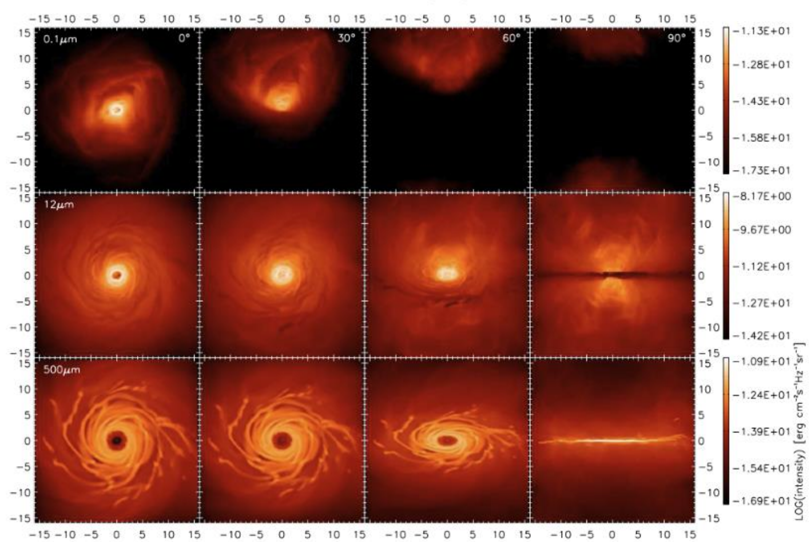
Radiative Transfer - Postprocessing

Main
Description
Features
Download
User guide
Discussion forum
Gallery
Publications
Contributions
Contact

Gallery

Synthetic observations of 3-D hydrodynamics model of an AGN torus

The unification principle of active galactic nuclei (AGN) says that the difference between type 1 and type 2 AGN is simply a viewing-angle issue. Some viewing angles allow direct sight of the central engine, while others have this central engine obscured by the dust and gas in the circumnuclear environment. Shown here is the 3-D hydrodynamics model of such an AGN torus by M. Schartmann, K. Wada, M.A. Prieto, A. Burkhardt and K.W.R. Tristram (2014) MNRAS, 445, 3878.

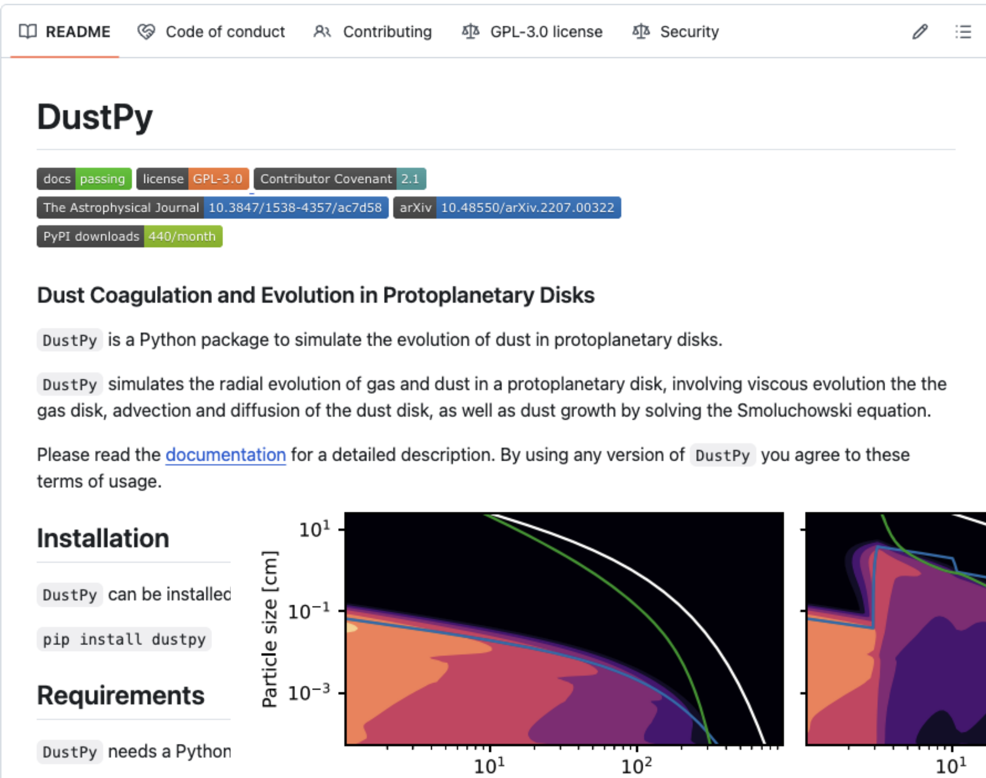


And here is a movie of a similar model by K. Wada, M. Schartmann and R. Meijerink (2016) ApJ, 828, L19: (click on the image to download the movie)

Dullemond et al. (2012)

Simulations

Coagulation


README | Code of conduct | Contributing | GPL-3.0 license | Security

DustPy

docs passing | license GPL-3.0 | Contributor Covenant 2.1
The Astrophysical Journal 10.3847/1538-4357/ac7d58 | arXiv 10.48550/arXiv.2207.00322
PyPI downloads 440/month

Dust Coagulation and Evolution in Protoplanetary Disks

`DustPy` is a Python package to simulate the evolution of dust in protoplanetary disks.

`DustPy` simulates the radial evolution of gas and dust in a protoplanetary disk, involving viscous evolution the the gas disk, advection and diffusion of the dust disk, as well as dust growth by solving the Smoluchowski equation.

Please read the documentation for a detailed description. By using any version of `DustPy` you agree to these terms of usage.

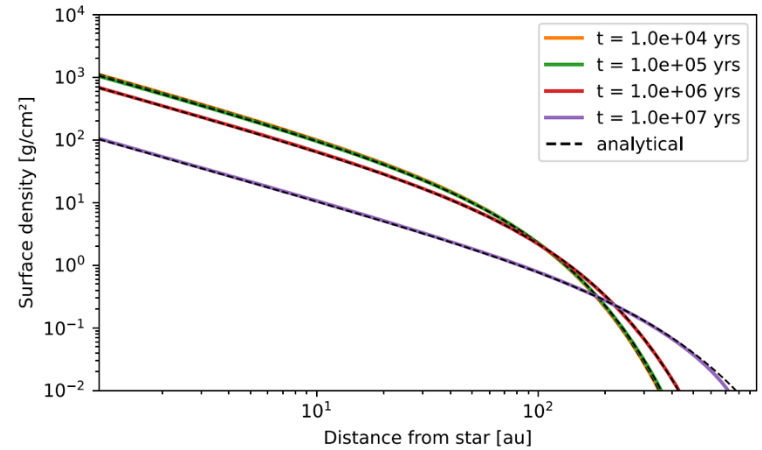
Installation

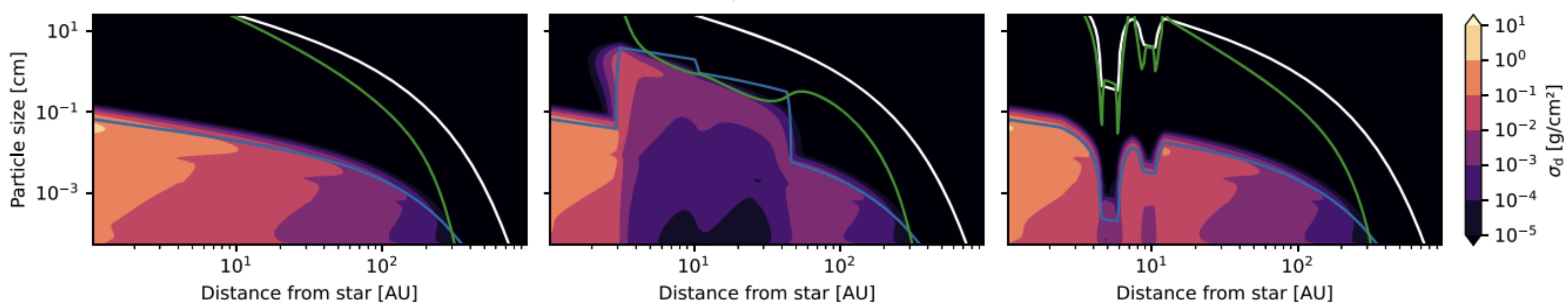
`DustPy` can be installed

```
pip install dustpy
```

Requirements

`DustPy` needs a Python

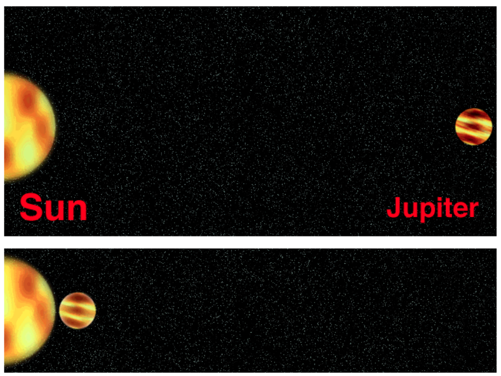




Stammler & Birnstiel (2022)

Simulations

Planet Migration – The need for multiphysics



Mon. Not. R. Astron. Soc. 387, 1063–1079 (2008) doi:10.1111/j.1365-2966.2008.13339.x

Numerical simulations of type III planetary migration – III. Outward migration of massive planets

A. Pepliński,[1★] P. Artymowicz[2] and G. Mellema[1]
[1]Stockholm University, AlbaNova University Centre, SE-106 91 Stockholm, Sweden
[2]University of Toronto at Scarborough, 1265 Military Trail, Toronto, Ontario M1C 1A4, Canada

nature
Explore content About the journal Publish with us
nature > letters > article
Letter | Published: 01 April 2015

Planet heating prevents inward migration of planetary cores

Pablo Benítez-Llambay, Frédéric Masset, Gloria Koenigsberger & Judit Szulágyi

Nature 520, 63–65 (2015) | Cite this article

A&A 459, L17–L20 (2006)
DOI: 10.1051/0004-6361:20066304
© ESO 2006
Astronomy & Astrophysics
Letter to the Editor

Halting type I planet migration in non-isothermal disks

S.-J. Paardekooper[1] and G. Mellema[2,1]
[1] Leiden Observatory, Postbus 9513, 2300 RA Leiden, The Netherlands
e-mail: paardeko@strw.leidenuniv.nl
[2] Stockholm Observatory, AlbaNova University Center, Stockholm University, 106 91 Stockholm, Sweden
e-mail: garrelt@astro.su.se

Received 28 August 2006 / Accepted 20 September 2006

TYPE I PLANETARY MIGRATION IN A SELF-GRAVITATING DISK

C. Baruteau and F. Masset[1]
Laboratoire AIM, CEA/DSM-CNRS-Université Paris Diderot, DAPNIA/Service d'Astrophysique, CEA-Saclay, 91191 Gif/Yvette Cedex, France; clement.baruteau@cea.fr, fmasset@cea.fr
Received 2007 September 20; accepted 2008 January 9

ABSTRACT

We investigate the tidal interaction between a low-mass planet and a self-gravitating protoplanetary disk by means of two-dimensional hydrodynamic simulations. We first show that considering a planet as freely migrating in a disk without self-gravity leads to a significant overestimate of the migration rate. The overestimate can reach a factor of 2 for a disk having 3 times the surface density of the minimum mass solar nebula. Unbiased drift rates may be obtained only by considering a planet and a disk orbiting within the same gravitational potential. In the second part, the disk self-gravity is taken into account. We confirm that the disk gravity enhances the differential Lindblad torque with respect to the situation where neither the planet nor the disk feels the disk gravity. This enhancement only depends on the Toomre parameter at the planet location. It is typically 1 order of magnitude smaller than the spurious one induced by assuming a planet migrating in a disk without self-gravity. We confirm that the torque enhancement due to the disk gravity can be entirely accounted for by a shift of Lindblad resonances and can be reproduced by the use of an anisotropic pressure tensor. We do not find any significant impact of the disk gravity on the corotation torque.

Subject headings: accretion, accretion disks — hydrodynamics — methods: numerical — planetary systems: formation — planetary systems: protoplanetary disks

Monthly Notices of the Royal Astronomical Society
MNRAS 484, 728–748 (2019) doi:10.1093/mnras/stz023
Advance Access publication 2019 January 05

Migrating super-Earths in low-viscosity discs: unveiling the roles of feedback, vortices, and laminar accretion flows

Colin P. McNally,[1★] Richard P. Nelson,[1] Sijme-Jan Paardekooper[1,2] and Pablo Benítez-Llambay[3]
[1]Astronomy Unit, School of Physics and Astronomy, Queen Mary University of London, London E1 4NS, UK
[2]DAMTP, University of Cambridge, Wilberforce Road, Cambridge CB3 0WA, UK
[3]Niels Bohr International Academy, Niels Bohr Institute, Blegdamsvej 17, DK-2100 Copenhagen Ø, Denmark

The Astrophysical Journal, 986:199 (11pp), 2025 June 20 https://doi.org/10.3847/1538-4357/add92a

Quantifying the Impact of the Dust Torque on the Migration of Low-mass Planets. II. The Role of Pebble Accretion in Planet Growth within a Global Planet Formation Model

Octavio M. Guilera[1], Pablo Benitez-Llambay[2], Marcelo M. Miller Bertolami[1], and Martin E. Pessah[3]
[1] Instituto de Astrofísica de La Plata (IALP), CCT La Plata-CONICET-UNLP, Paseo del Bosque S/N, La Plata, Argentina; oguilera@fcaglp.unlp.edu.ar
[2] Facultad de Ingeniería y Ciencias, Universidad Adolfo Ibáñez, Av. Diagonal las Torres 2640, Peñalolén, Chile
[3] Niels Bohr International Academy, Niels Bohr Institute, Blegdamsvej 17, DK-2100 Copenhagen Ø, Denmark
Received 2025 January 24; revised 2025 May 9; accepted 2025 May 13; published 2025 June 18

Mon. Not. R. Astron. Soc. 318, 18–36 (2000)

The migration and growth of protoplanets in protostellar discs

Richard P. Nelson,[1★] John C. B. Papaloizou,[1] Frédéric Masset[1] and Willy Kley[2,3]
[1]Astronomy Unit, Queen Mary & Westfield College, Mile End Road, London E1 4NS
[2]Theoretisch-Physikalisches Institut, Universität Jena, Max-Wien-Platz 1, D-07743 Jena, Germany
[3]Max-Planck-Institut für Astronomie, Königstuhl 17, D-69117 Heidelberg, Germany

Monthly Notices of the Royal Astronomical Society
MNRAS 477, 4596–4614 (2018) doi:10.1093/mnras/sty905
Advance Access publication 2018 April 14

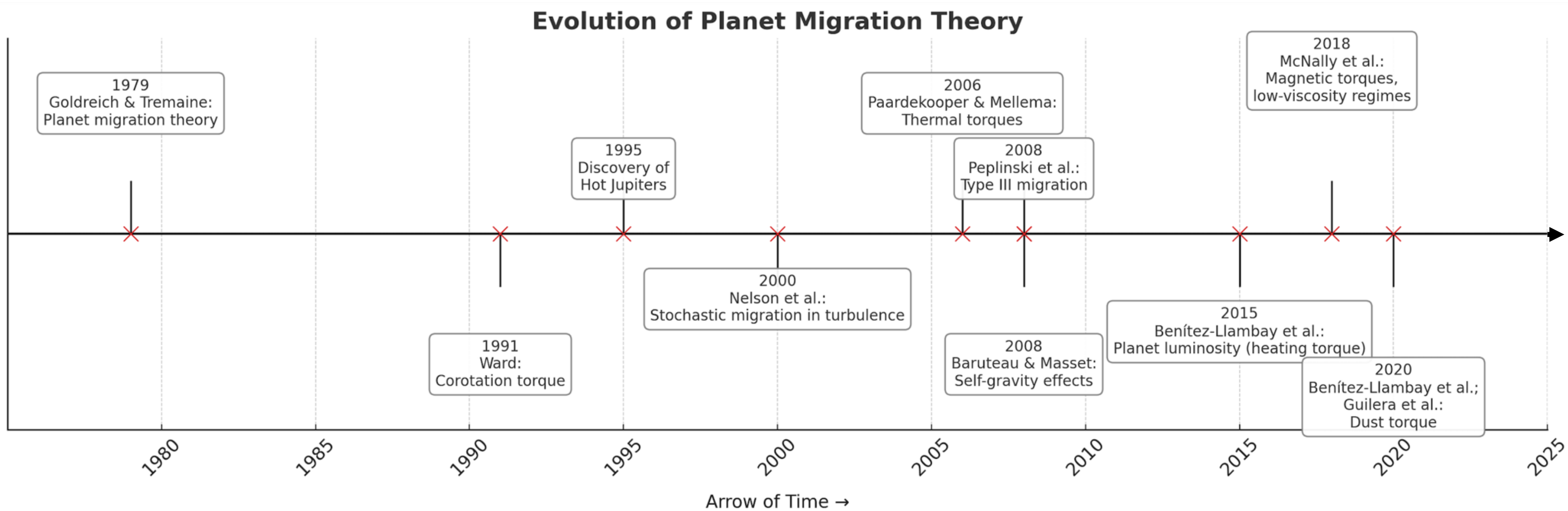
Low-mass planet migration in magnetically torqued dead zones – II. Flow-locked and runaway migration, and a torque prescription

Colin P. McNally,[1,2★] Richard P. Nelson[1,2] and Sijme-Jan Paardekooper[1,3]
[1]Astronomy Unit, School of Physics and Astronomy, Queen Mary University of London, London E1 4NS, UK
[2]Kavli Institute for Theoretical Physics, University of California Santa Barbara, CA 93106, USA
[3]DAMTP, University of Cambridge, Wilberforce Road, Cambridge CB3 0WA, UK

Accepted 2018 April 6. Received 2018 April 6; in original form 2018 March 1

Simulations

Planet Migration – The need for multiphysics



W. Lyra

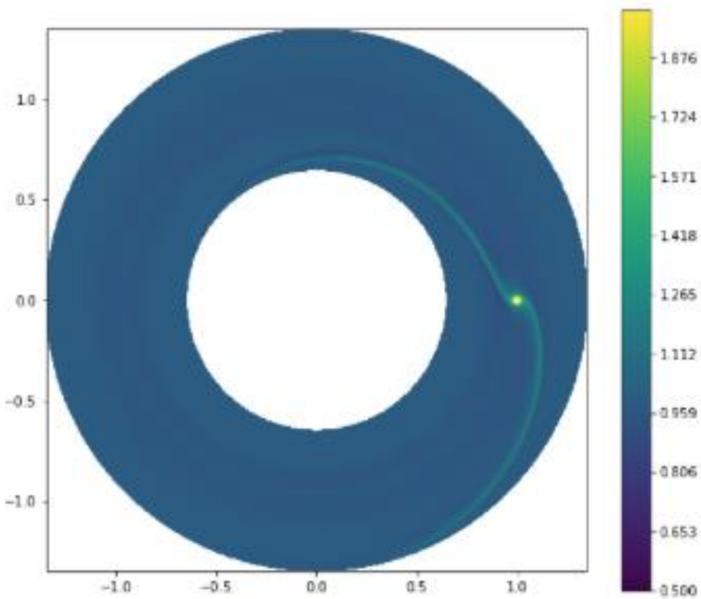
Simulations

Planet Migration – The need for multiphysics

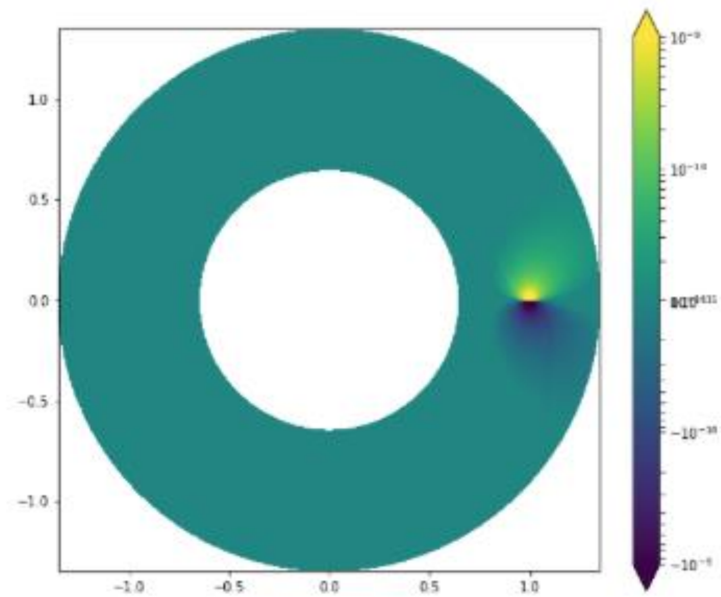
Migration Torques

$$\mathbf{\Gamma} = r_p G m_p \iint \Sigma \frac{r^2}{|\boldsymbol{r} - \boldsymbol{r_p}|^3} \sin\phi \, dr d\phi$$

Density



Torque



The planet generates a non-axisymmetric wake
Non-zero torque

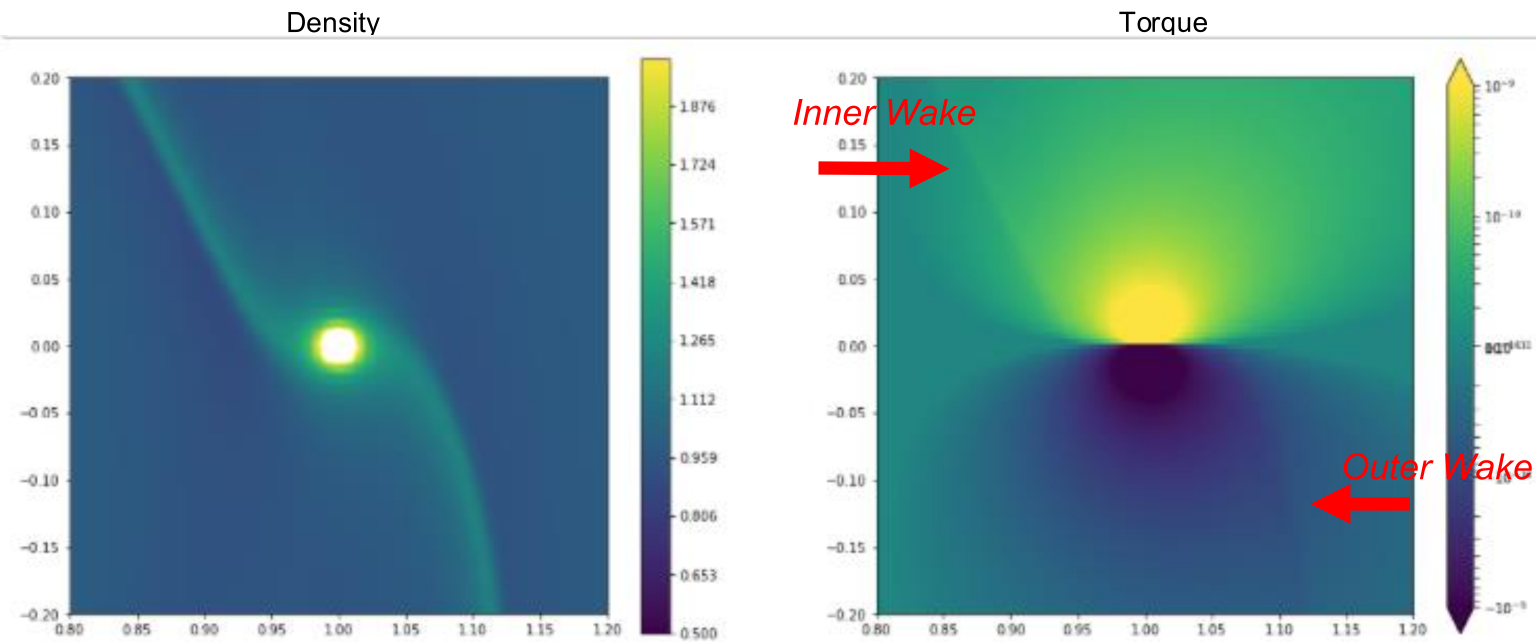
W. Lyra

Simulations

Planet Migration – The need for multiphysics

Migration Torques

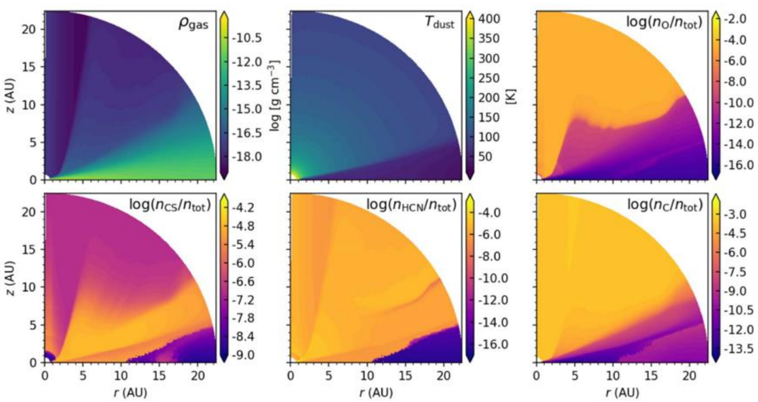
$$\mathbf{\Gamma} = r_p G m_p \iint \Sigma \frac{r^2}{|\boldsymbol{r} - \boldsymbol{r_p}|^3} \sin\phi \, dr d\phi$$

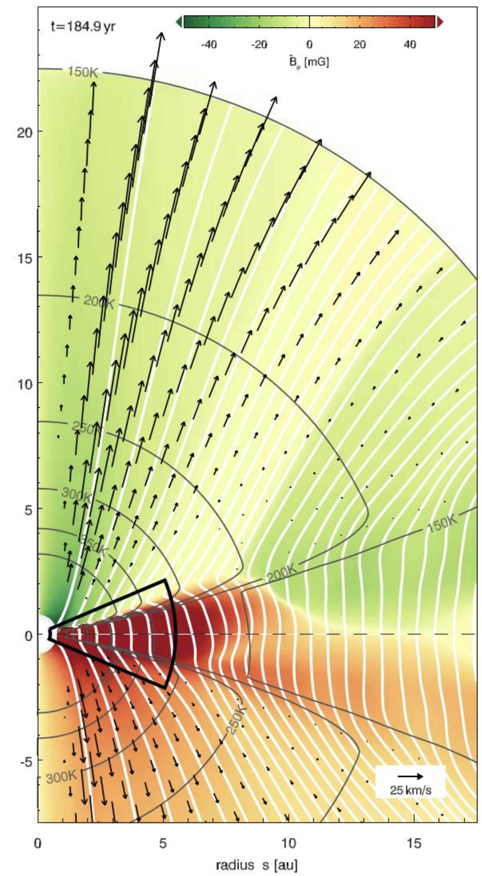


The planet generates a non-axisymmetric wake
Non-zero torque

Features of Next-Gen models

Non-ideal MHD and Radiative Transfer





$$\partial_t \rho + \nabla \cdot (\rho \boldsymbol{v}) = 0,$$

$$\partial_t (\rho \boldsymbol{v}) + \nabla \cdot \mathcal{F}_{\rm m} = \boldsymbol{\mathcal{S}}_{\rm m},$$

$$\partial_t \boldsymbol{B} - \nabla \times (\boldsymbol{v} \times \boldsymbol{B} + \boldsymbol{E}_{\rm d}) = \boldsymbol{0},$$

$$\partial_t e + \nabla \cdot \boldsymbol{\mathcal{F}}_{\rm e} = \mathcal{S}_{\rm e} + \boldsymbol{\mathcal{S}}_{\rm m} \cdot \boldsymbol{v} + \nabla \cdot (\boldsymbol{E}_{\rm d} \times \boldsymbol{B}),$$

$$\partial_t \epsilon + \nabla \cdot (\epsilon \boldsymbol{v}) + p \nabla \cdot \boldsymbol{v} = \mathcal{S}_{\rm e} + \eta_\Omega \, |\nabla \times \boldsymbol{B}|^2 + \eta_{\rm A} \, |\hat{\boldsymbol{e}}_b \times \nabla \times \boldsymbol{B}|^2, \quad (5)$$

$$\frac{c}{\hat{c}} \partial_t \mathcal{E} + \nabla \cdot (\mathcal{E} \boldsymbol{v}) = c\rho \, \kappa_{\rm P} (a_{\rm R} T^4 - \mathcal{E}) - \nabla \cdot \boldsymbol{\mathcal{F}}_{\rm r} - \mathcal{P}_{\rm r} \colon \nabla \boldsymbol{v}, \quad (6)$$

$$\mathcal{F}_{\rm m} = \rho \boldsymbol{v}\boldsymbol{v} + p^\star \mathbb{I} - \boldsymbol{B}\boldsymbol{B},$$
$$\boldsymbol{\mathcal{F}}_{\rm e} = (e + p^\star)\boldsymbol{v} - (\boldsymbol{v} \cdot \boldsymbol{B})\boldsymbol{B},$$
$$\boldsymbol{\mathcal{S}}_{\rm m} = -\rho \nabla \Phi + \rho \kappa_{\rm R} \, c^{-1} \, \boldsymbol{\mathcal{F}}_{\rm r},$$
$$\mathcal{S}_{\rm e} = -c\rho \, \kappa_{\rm P} (a_{\rm R} T^4 - \mathcal{E}) + \mathcal{Q}^+_{\rm irr} + \mathcal{Q}^{+/-}_{\rm pdr},$$

$$\boldsymbol{E}_\Omega \equiv -\eta_\Omega (\nabla \times \boldsymbol{B}), \quad \text{and}$$

$$\boldsymbol{E}_{\rm A} \equiv +\eta_{\rm A} [(\nabla \times \boldsymbol{B}) \times \hat{\boldsymbol{e}}_b \,] \times \hat{\boldsymbol{e}}_b,$$

$$\boldsymbol{\mathcal{F}}_{\rm r} = -\lambda(R) \frac{c}{\rho \kappa_{\rm R}} \nabla \, \mathcal{E},$$

$$\mathcal{P}_{\rm r} \equiv \left[\frac{1}{2}(1 - f_{\rm edd}) \mathbb{I} + \frac{1}{2}(3 f_{\rm edd} - 1) \hat{\boldsymbol{n}}\hat{\boldsymbol{n}} \right] \mathcal{E},$$

$$\boldsymbol{\mathcal{F}}_{\rm r,irr}(r) \equiv F(r_\star) \, (r_\star / r)^2 \, \exp(-\tau_\star(r) \hat{\boldsymbol{r}}$$

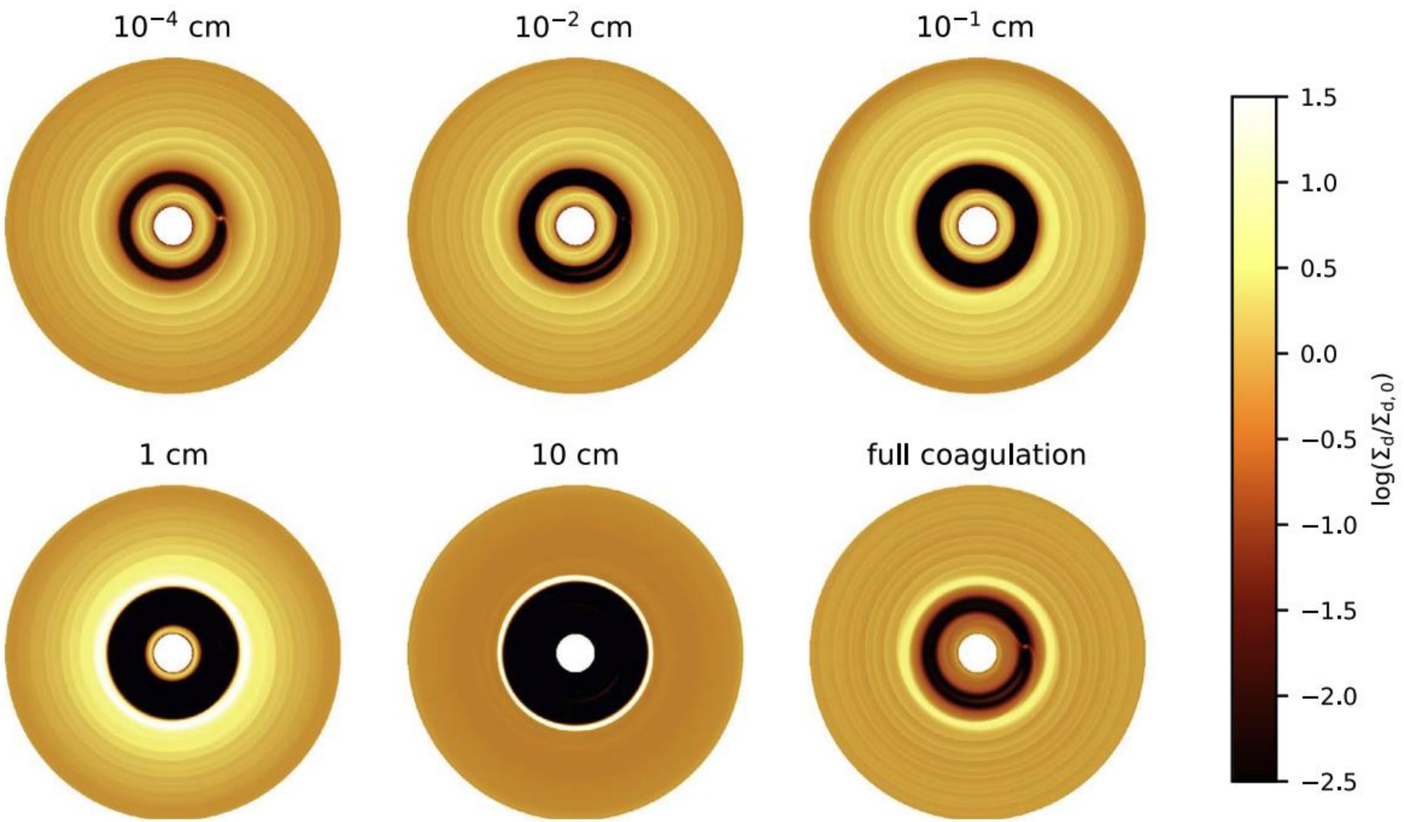
$$\mathcal{Q}^+_{\rm irr}(r, \theta) \equiv -\nabla \cdot \boldsymbol{\mathcal{F}}_{\rm r,irr}(r, \theta).$$

$$\mathcal{Q}^+_{\rm irr}(r_i) \equiv \frac{3 \, \rho \kappa_{\rm P}}{r^3_{i+\frac{1}{2}} - r^3_{i-\frac{1}{2}}} \int_{r_{i-\frac{1}{2}}}^{r_{i+\frac{1}{2}}} \hat{\boldsymbol{r}} \cdot \boldsymbol{\mathcal{F}}_{\rm r,irr}(r') r'^2 dr'.$$

Gressel et al. (2020)

Features of Next-Gen models

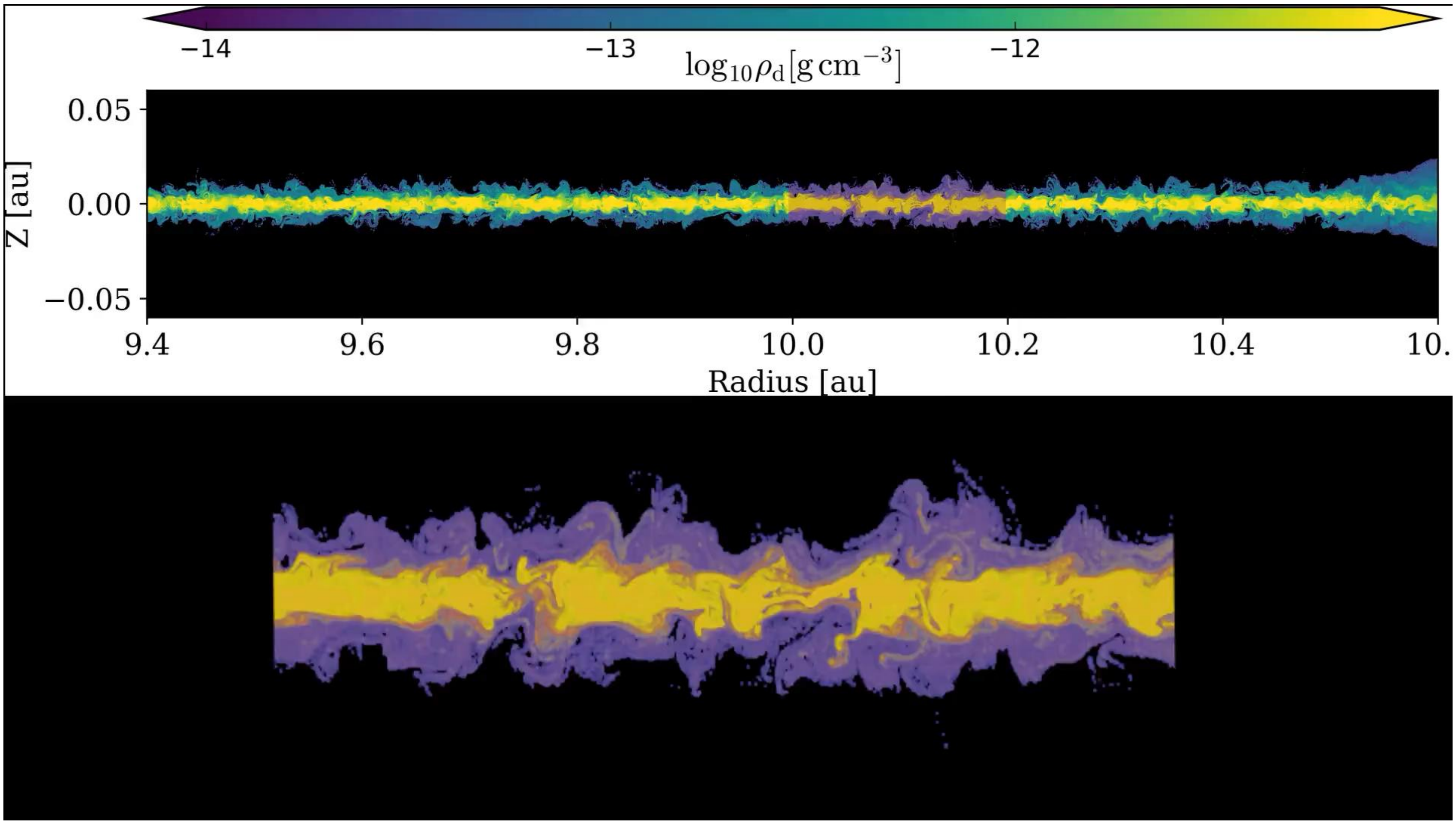
Dust coagulation and Hydrodynamics



Drazkowska et al. (2019)

Features of Next-Gen models

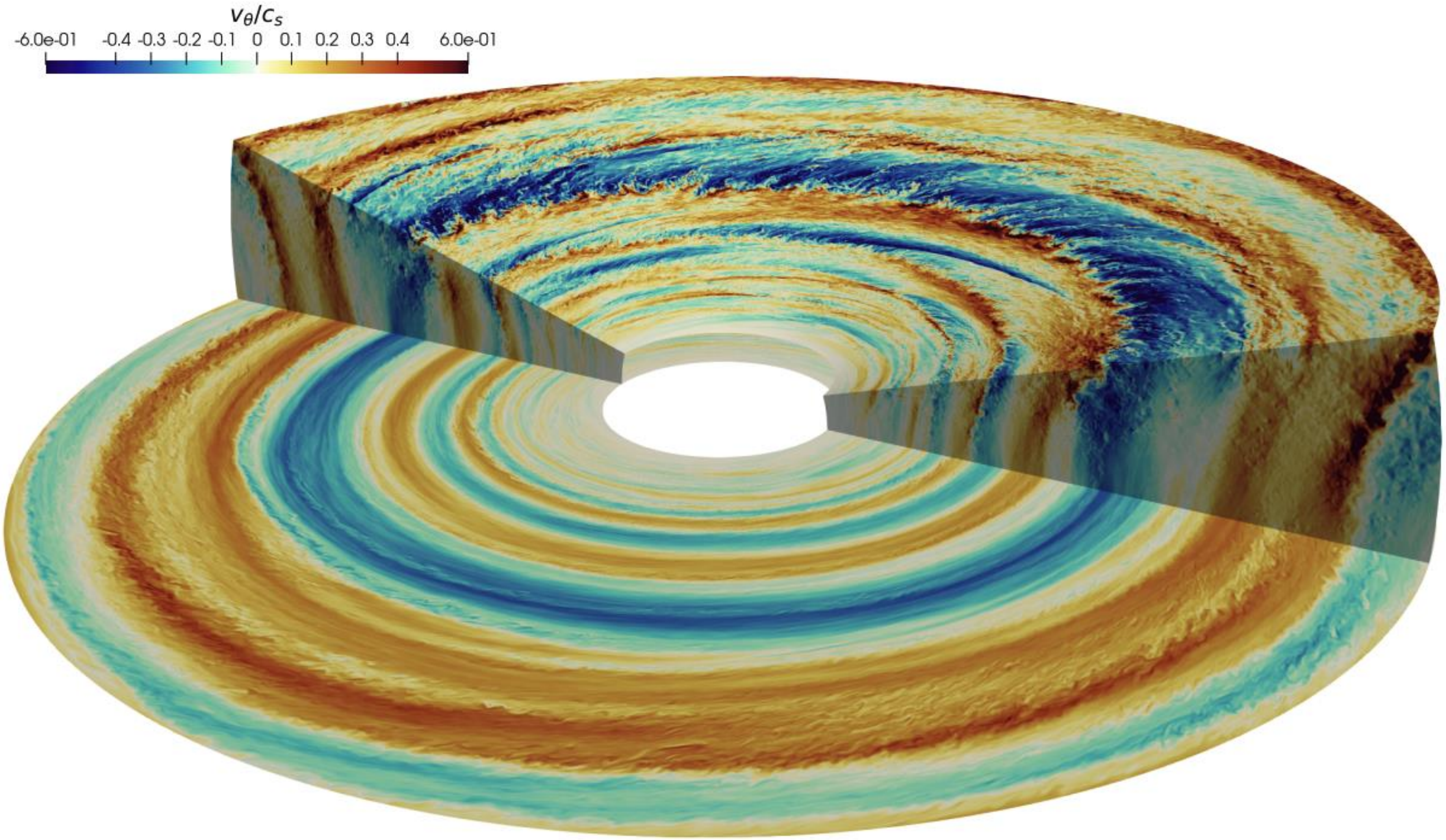
Multiscale for dust grains – Global streaming instability



Flock et al. (2021)

Features of Next-Gen models

High-resolution 3D

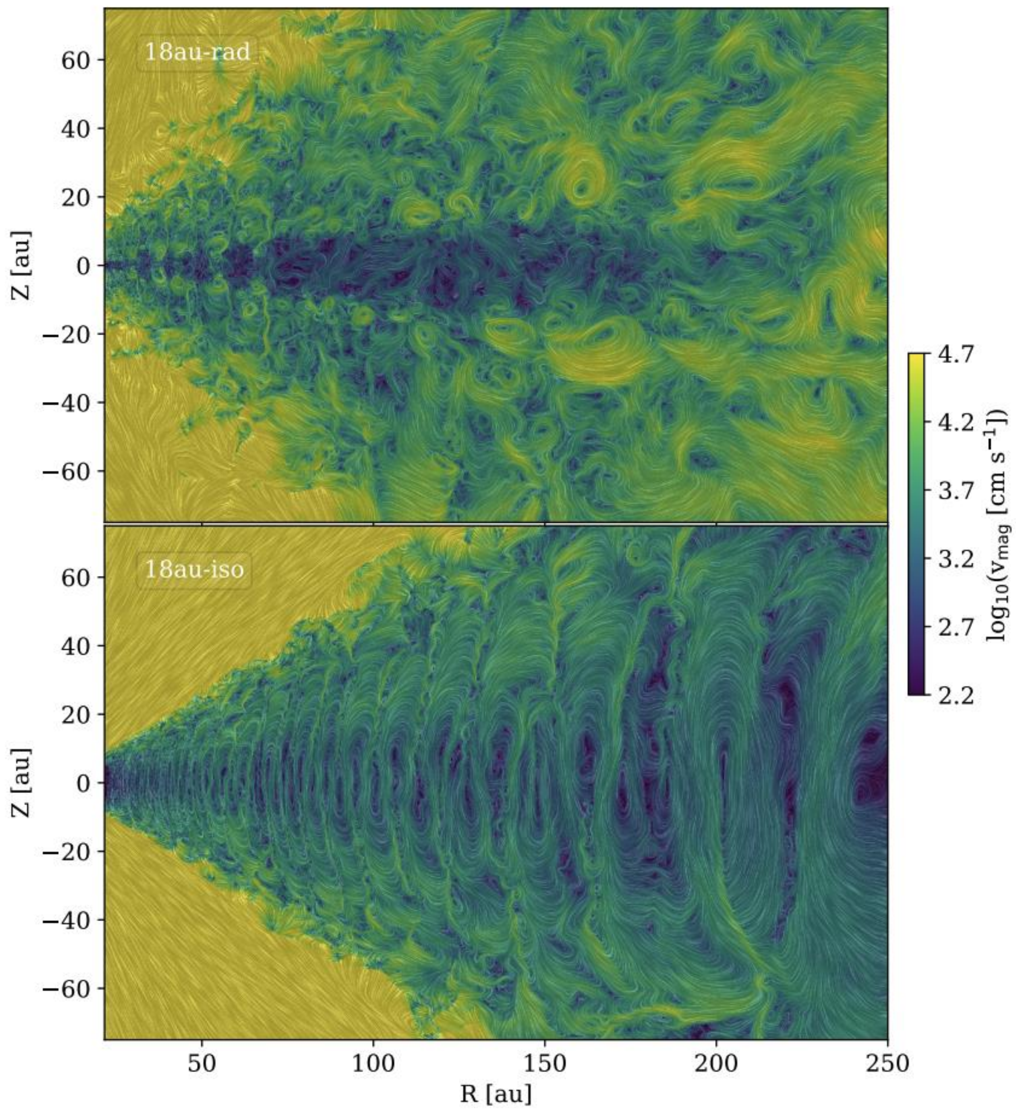


Resolution 3872 x 2000 x 12544
(Equivalent resolution ~ 4597 ^{3})
~200 points per H

Lesur et al. (2025)

Features of Next-Gen models

On-the-fly detailed radiative transfer



Time-dependent implicit on-the-fly Radiative Transfer in Athena++ (Jiang, 2021)

$$\frac{\partial \boldsymbol{I}}{\partial \boldsymbol{t}} + \boldsymbol{c}\boldsymbol{n} \cdot \boldsymbol{\nabla} \boldsymbol{I} = \boldsymbol{c}(\eta - \chi \boldsymbol{I}),$$

Still isothermal, Newton cooling, and FLD widely used in the community

W. Lyra

Features of Next-Gen models

GPU Exascale

GPU-exascale ready astrophysics codes

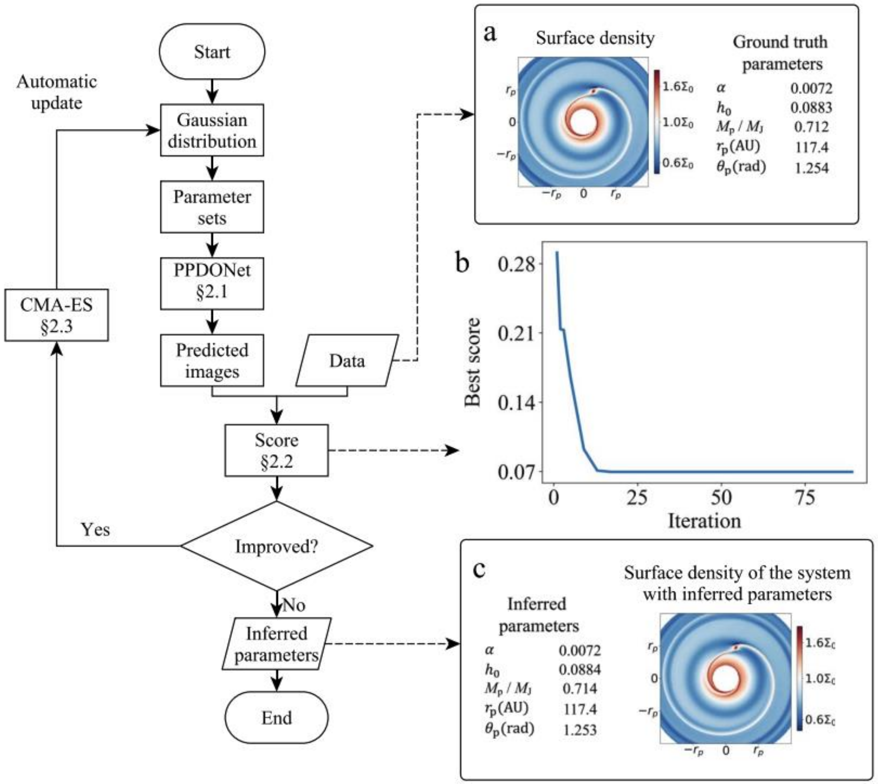
- *AthenaK (Jim Stone)*
- *Idefix (Geoffroy Lesur)*

Features of Next-Gen models

Machine-learning

AEGIS: Advanced Emulator for Giant Impact Simulations (Timpe et al. 2020)
Planetary masses from gaps (Auddy & Lin 2020)
Key parameters in planet-disk systems (Shunyuan et al. 2024)

- Parameter space exploration
- Pattern Recognition
- Inverse Problems



Shunyuan et al. (2024)

Features of Next-Gen models

Machine-learning

ML could be used for sub-grid physics

PNAS

Deep learning to represent subgrid processes in climate models

Stephan Rasp[a,b,1], Michael S. Pritchard[b], and Pierre Gentine[c,d]

[a]Meteorological Institute, Ludwig-Maximilian-University, 80333 Munich, Germany; [b]Department of Earth System Science, University of California, Irvine, CA 92697; [c]Department of Earth and Environmental Engineering, Earth Institute, Columbia University, New York, NY 10027; and [d]Data Science Institute, Columbia University, New York, NY 10027

Edited by Isaac M. Held, Geophysical Fluid Dynamics Laboratory, National Oceanic and Atmospheric Administration, Princeton, NJ, and approved August 8, 2018 (received for review June 14, 2018)

Features of Next-Gen models

Machine-learning

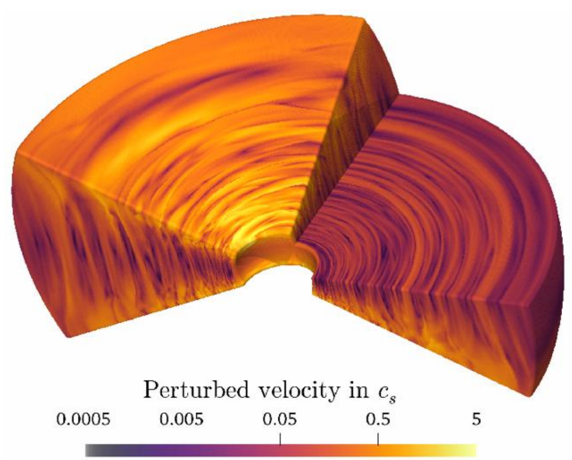
ML could be used for sub-grid physics

ML emulators for bridging scales:

High-res local sims (4096^3 boxes, lab experiments)	Machine Learning Training (Neural nets, Gaussian Processes)	Emulator in Global Disk Model (AU-scale)

Sub-grid processes

Turbulent dissipation and angular momentum transport



Barraza-Alfaro et al. (2021)

Features of Next-Gen models

Machine-learning

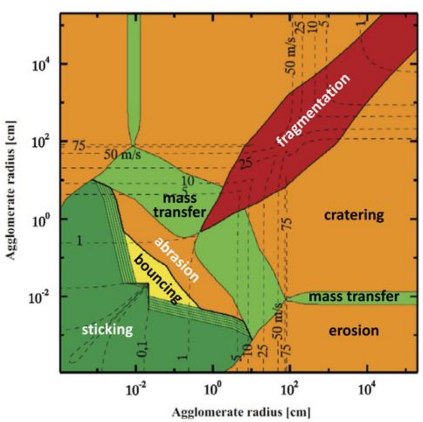
ML could be used for sub-grid physics

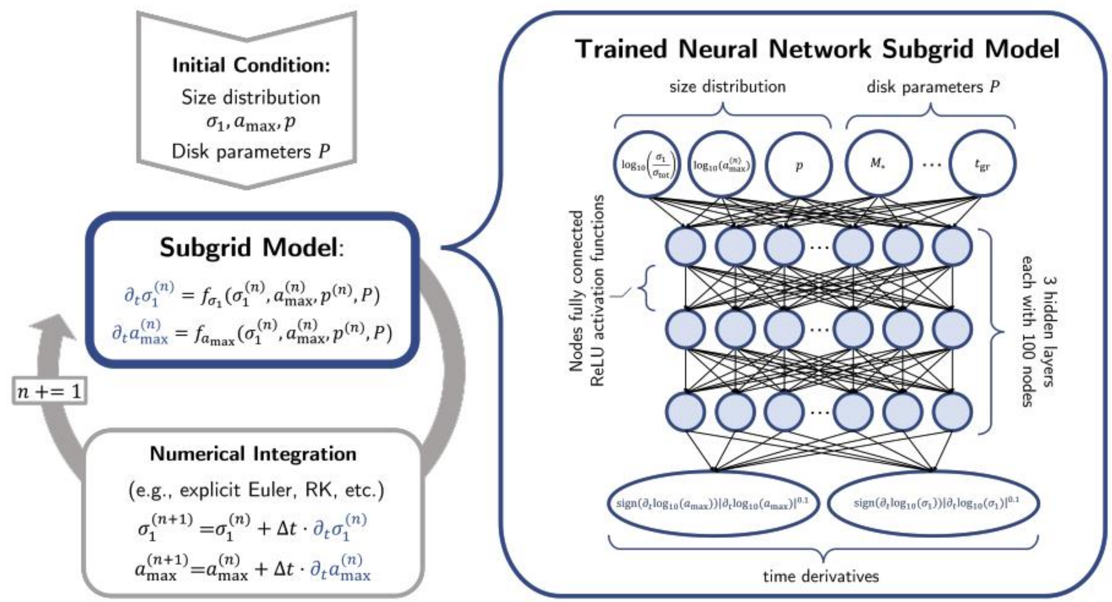
ML emulators for bridging scales:

High-res local sims (4096^3 boxes, lab experiments)	Machine Learning Training (Neural nets, Gaussian Processes)	Emulator in Global Disk Model (AU-scale)

Sub-grid processes

Dust coagulation,
fragmentation,
and porosity evolution





Blum (2018), Pfeil et al. (2022)

Features of Next-Gen models

Machine-learning

ML could be used for sub-grid physics

ML emulators for bridging scales:

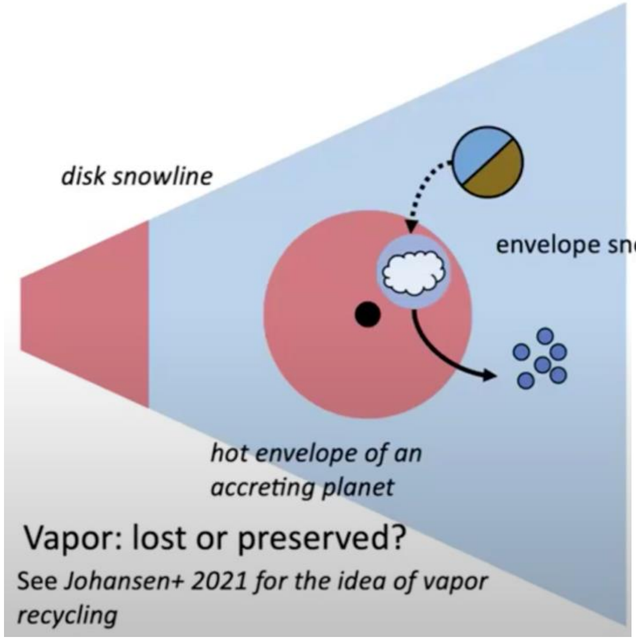
High-res local sims (4096^3 boxes, lab experiments)

Machine Learning Training (Neural nets, Gaussian Processes)

Emulator in Global Disk Model (AU-scale)

Sub-grid processes

Pebble accretion and processing in planetary atmospheres;



Johansen et al (2021)

Features of Next-Gen models

Machine-learning

ML could be used for sub-grid physics

ML emulators for bridging scales:

High-res local sims (4096^3 boxes, lab experiments)	Machine Learning Training (Neural nets, Gaussian Processes)	Emulator in Global Disk Model (AU-scale)

Sub-grid processes

Chemistry and opacity

A&A, 682, A79 (2024)
https://doi.org/10.1051/0004-6361/202348221

Astronomy & Astrophysics

Harnessing machine learning for accurate treatment of overlapping opacity species in general circulation models

Aaron David Schneider[1,2], Paul Mollière[3], Gilles Louppe[4], Ludmila Carone[5], Uffe Gråe Jørgensen[1], Leen Decin[2], and Christiane Helling[5]

[1] Centre for ExoLife Sciences, Niels Bohr Institute, Øster Voldgade 5, 1350 Copenhagen, Denmark
e-mail: aaron.schneider@nbi.ku.dk
[2] Institute of Astronomy, KU Leuven, Celestijnenlaan 200D, 3001 Leuven, Belgium
[3] Max-Planck-Institut für Astronomie, Königstuhl 17, 69117 Heidelberg, Germany
[4] Montefiore Institute, University of Liège, Liège, Belgium
[5] Space Research Institute, Austrian Academy of Sciences, Schmiedlstrasse 6, 8042 Graz, Austria

Received 10 October 2023 / Accepted 1 December 2023

Schneider et al (2024)

Features of Next-Gen models

Prepare for ngVLA

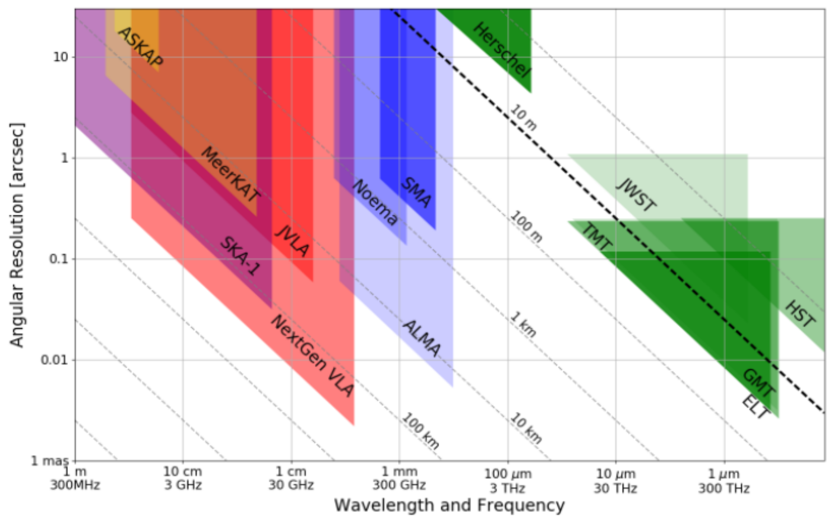
After ~15 years of ALMA…

Nearly all nearby disks observed at <0.1” (< 20-30AU) show substructures.

3 main types of substructures
- Crescent-shaped
- Spiral arms
- Rings/Gaps

Features of Next-Gen models

Prepare for ngVLA



NRAO

Features of Next-Gen models

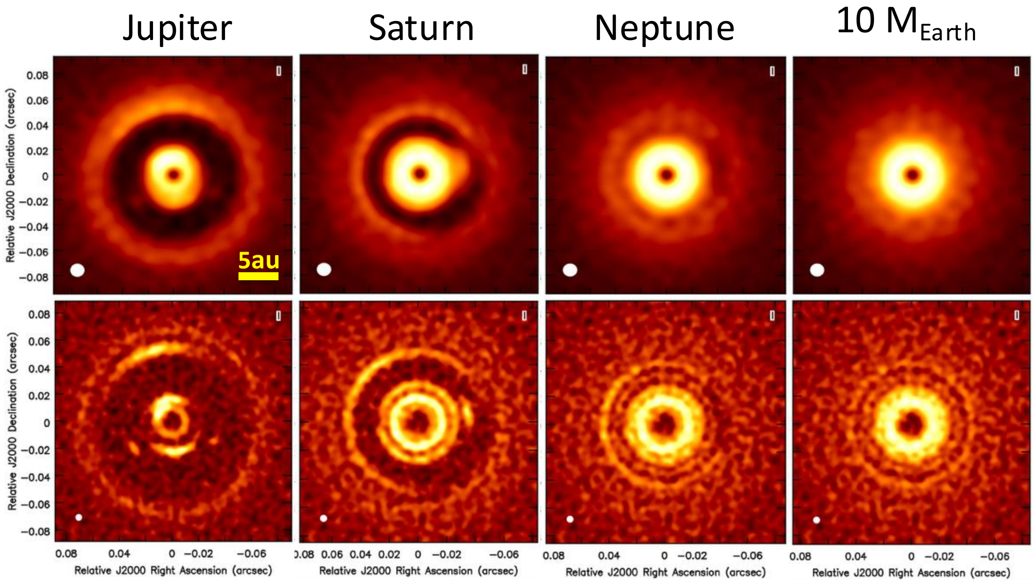
Prepare for ngVLA

Planets at 5AU

ALMA @ 0.87mm

ngVLA @ 3mm

5 mas = 0.7 AU
rms = 5×10^{-7} Jy/beam



Ricci et al. 2018

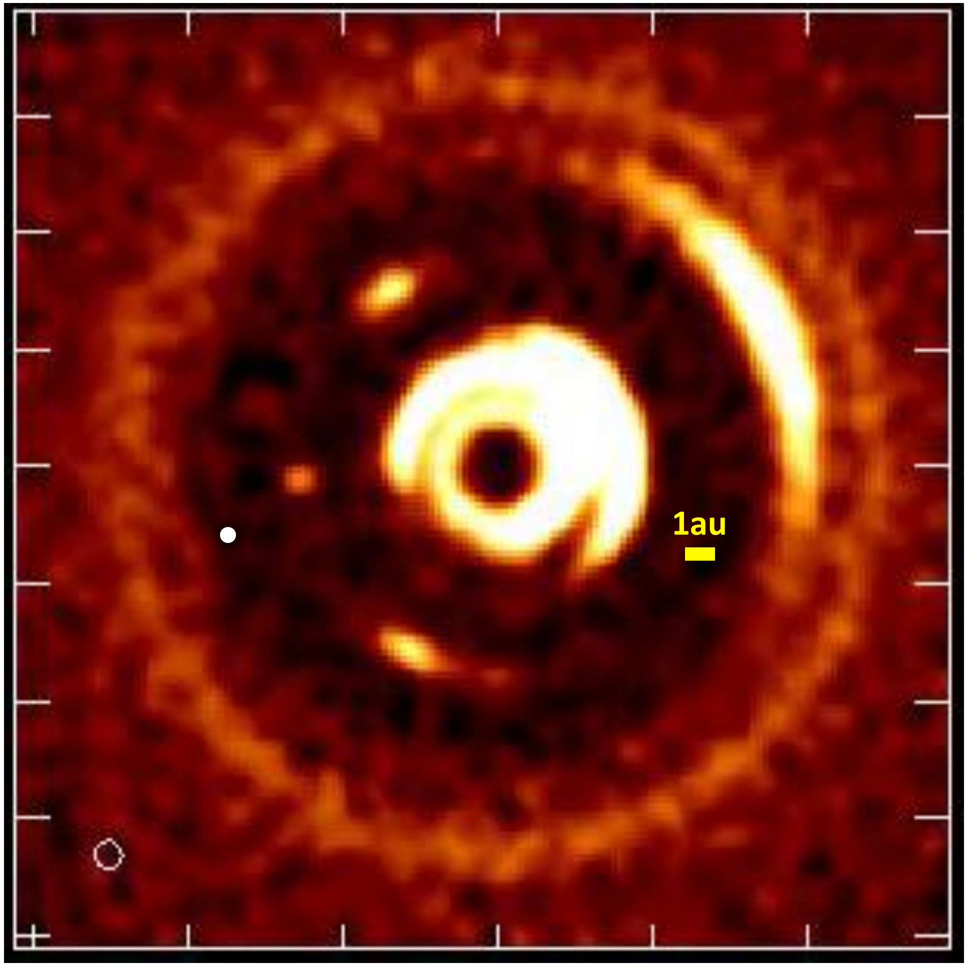
ngVLA identifies gaps/substructures down to ~5-10 M_{Earth}

W. Lyra

Features of Next-Gen models

ngVLA: Proper motions

Jupiter at 5 AU



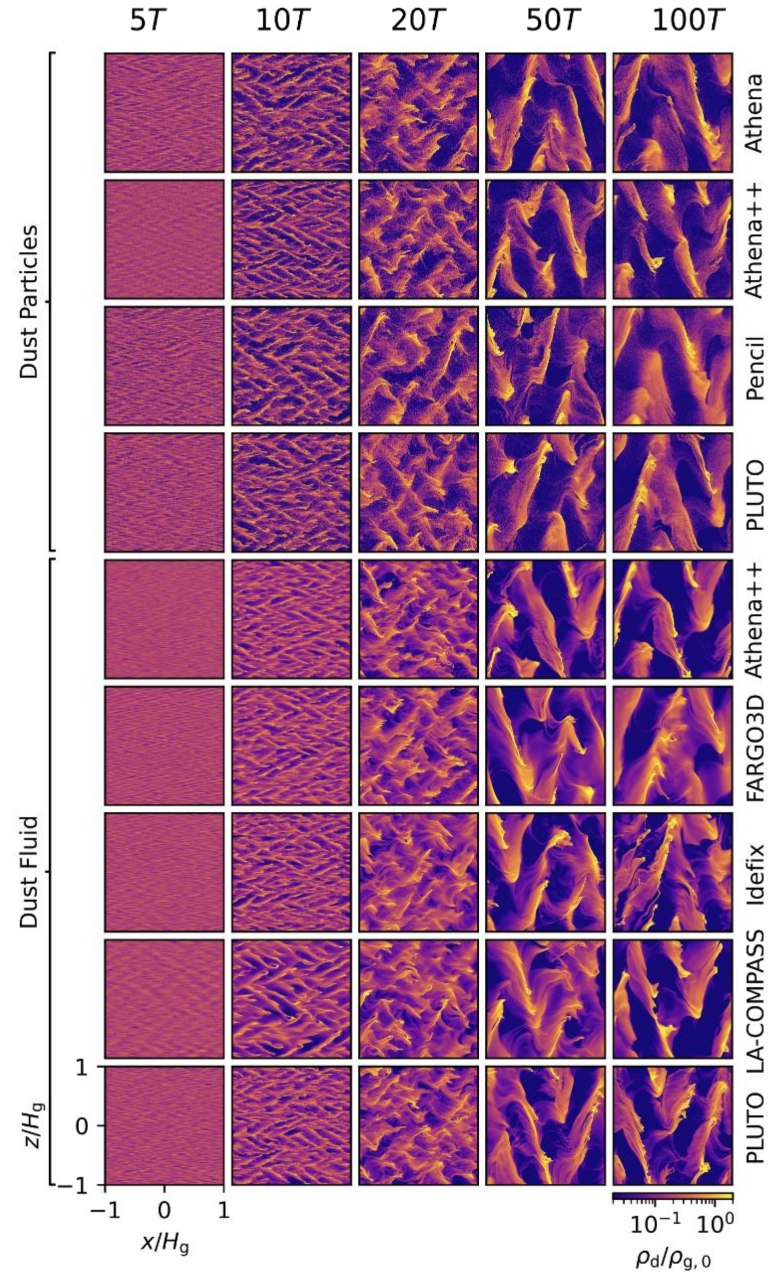
Ricci et al. 2018

Draft version September 29, 2025
Typeset using LaTeX **twocolumn** style in AASTeX7.0.1

Streaming Instability Code Comparison

Stanley A. Baronett [1,2,*] Wladimir Lyra [3] Hossam Aly [4] Olivia Brouillette [3] Victoria I. De Cun,[3]
Mario Flock [5] Pinghui Huang (黄平辉) [6,7] Leonardo Krapp [8] Geoffroy Lesur [9]
Shengtai Li (李胜台) [10] Jeonghoon Lim (임정훈) [11] Sijme-Jan Paardekooper [4] Jacob B. Simon [11]
Prakruti Sudarshan [5] and Chao-Chin Yang (楊朝欽) [12]

[1] Nevada Center for Astrophysics, University of Nevada, Las Vegas, Box 454002, Las Vegas, NV 89154, USA
[2] Department of Physics and Astronomy, University of Nevada, Las Vegas (UNLV), Box 454002, Las Vegas, NV 89154, USA
[3] Department of Astronomy, New Mexico State University, PO Box 30001 MSC 4500, Las Cruces, NM 88001, USA
[4] Faculty of Aerospace Engineering, Delft University of Technology, Kluyverweg 1, 2629 HS Delft, The Netherlands
[5] Max-Planck-Institut für Astronomie, Königstuhl 17, 69117 Heidelberg, Germany
[6] CAS Key Laboratory of Planetary Sciences, Purple Mountain Observatory, Chinese Academy of Sciences, Nanjing 210023, People's Republic of China
[7] Department of Physics and Astronomy, University of Victoria, Victoria, BC, V8P 5C2, Canada
[8] Departamento de Astronomía, Facultad de Ciencias Físicas y Matemáticas Universidad de Concepción, Av. Esteban Iturra s/n Barrio Universitario, Casilla 160-C, Chile
[9] Université Grenoble Alpes, CNRS, IPAG, 38000 Grenoble, France
[10] Los Alamos National Laboratory, Los Alamos, NM 87545, USA
[11] Department of Physics and Astronomy, Iowa State University, Ames, IA, 50010, USA
[12] Department of Physics and Astronomy, The University of Alabama, Box 870324, Tuscaloosa, AL 35487-0324, USA



Baronett & Lyra +, in prep

Roadmap (for next 5 years?)

- Develop a community code?
- Build modular, open, interoperable codes (several post-processing codes exist, they should talk to each other and be included in hydrodynamics)
- Optimize for GPU / exascale computing
- Develop community benchmark problems
- Pipelines for synthetic observations with sophisticated physics
- Support ML emulators

Conclusions

- Next-gen models must be
  - multiphysics, multiscale, high-res 3D, modular and scalable
- Community benchmarks & open GPU-ready codes are essential