A Comparative Study of Streaming Instability

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PFITS+ (Planet Formation in the Southwest)

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Simulating Physics in Celestial Environments (SPiCE2)

Lyon - Mar 16-20, 2026

21 Coauthors

Planet Formation in the Southwest Plus (PFITS+) Collaboration

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- Iowa State University (ISU)
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    - Prakruti Sudarshan
    - Hossam Aly
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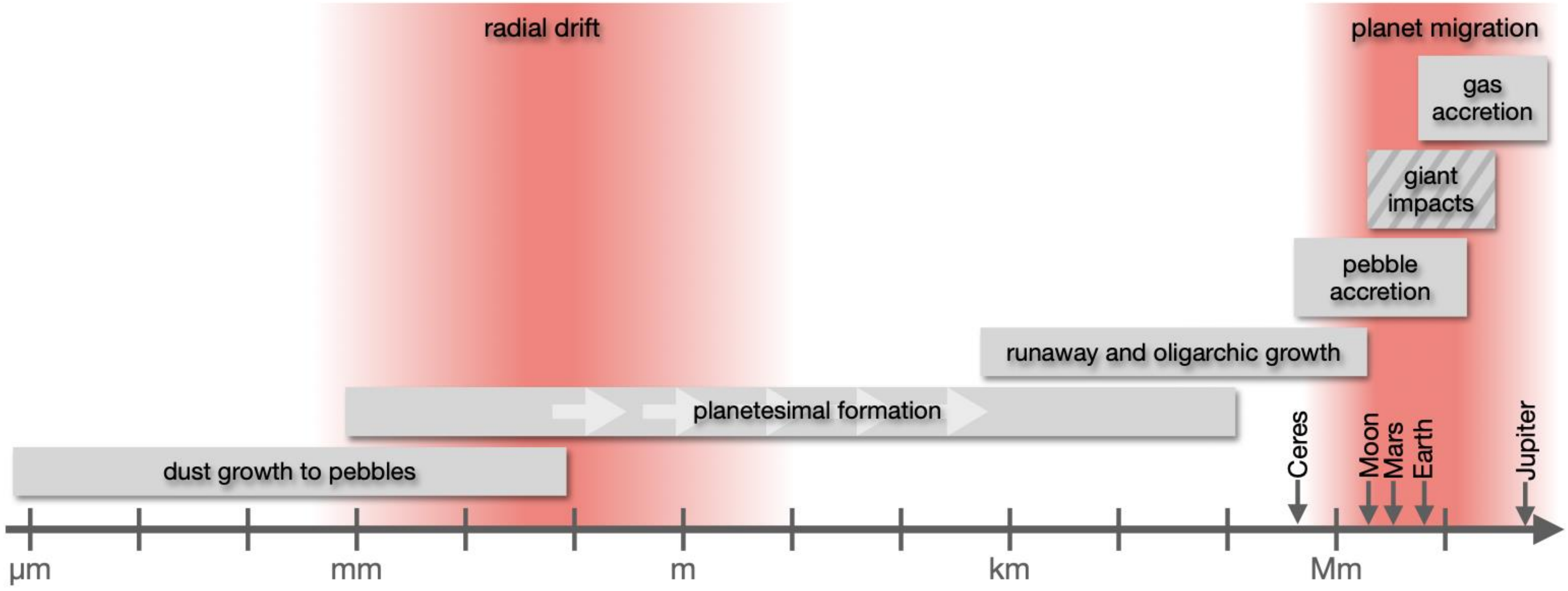
Planet Formation Ladder



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Drazkowska et al. (2023; Protostars and Planets VII)

Linear Analysis

Youdin & Goodman (2005)

Parameter Dependence

Youdin & Johansen (2007)

Nonlinear Evolution

Johansen & Youdin (2007)
Bai & Stone (2010)
Benitez-Llambay et al. (2019)

Physical Mechanism

Lin & Youdin (2017)

Magnan et al. (2024)

Resonant Drag Instability

Squire & Hopkins (2018a)
Squire & Hopkins (2018b)
Hopkins & Squire (2018)

<u>Nonlinear saturation</u>
less understood due to resolution demands and method dependence

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Problem: Run BA

- Johansen & Youdin (2007)
  - (Stokes number) $\tau_\mathrm{s} \equiv \Omega_\mathrm{K} t_\mathrm{s} = 1$
  - Dust-to-gas ratio $\epsilon \equiv \dfrac{\langle \rho_\mathrm{p} \rangle}{\rho_{\mathrm{g},0}} = 0.2$
- Grid resolutions
  - 512^2
    - $n_\mathrm{p} = 1, 9$ (> 260K, 2.3M particles)
  - 1024^2
    - $n_\mathrm{p} = 1$ (> 1M particles)

TABLE 1

Run Parameters

Run	τ_s	ϵ	$L_x \times L_y \times L_z$	$N_x \times N_y \times N_z$	N_p	Δt
AA	0.1	0.2	4.0 × 4.0 × 4.0	256 × 1 × 256	...	2000.0
AB	0.1	1.0	2.0 × 2.0 × 2.0	256 × 1 × 256	1.6×10^6	50.0
AC	0.1	3.0	2.0 × 2.0 × 2.0	256 × 1 × 256	1.6×10^6	50.0
BA	1.0	0.2	40.0 × 40.0 × 40.0	256 × 1 × 256	1.6×10^6	500.0
BB	1.0	1.0	20.0 × 20.0 × 20.0	256 × 1 × 256	1.6×10^6	250.0
BC	1.0	3.0	20.0 × 20.0 × 20.0	256 × 1 × 256	1.6×10^6	250.0
AB-3D	0.1	1.0	2.0 × 2.0 × 2.0	128 × 128 × 128	2.0×10^7	35.0
BA-3D	1.0	0.2	40.0 × 40.0 × 40.0	128 × 128 × 128	2.0×10^7	300.0

Note.—Columns give, from left to right, name of run, friction time, solids-to-gas ratio, box size in units of ηr, grid resolution, number of particles, and total run time in units of Ω^{-1}.

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PROTOPLANETARY DISK TURBULENCE DRIVEN BY THE STREAMING INSTABILITY: NONLINEAR SATURATION AND PARTICLE CONCENTRATION

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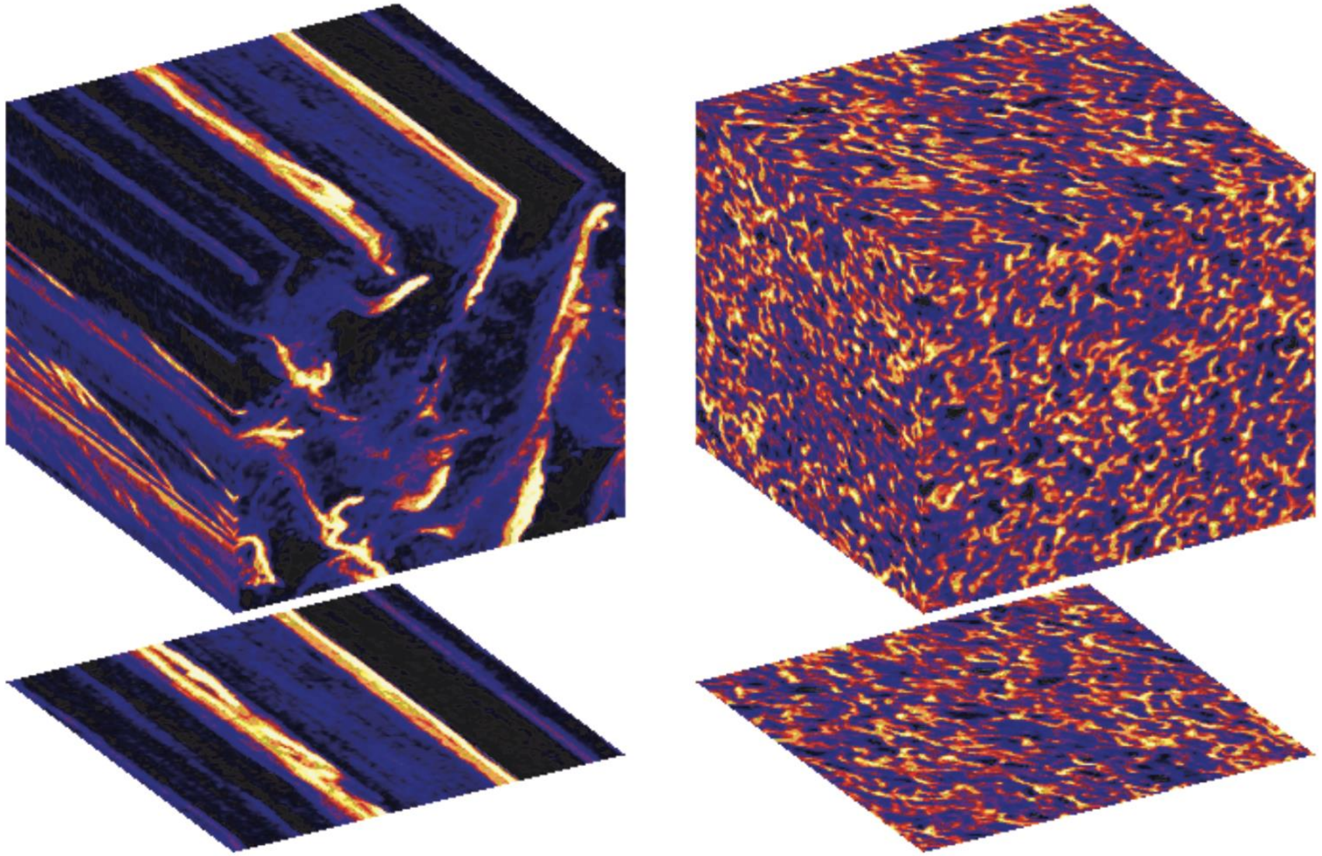

Fig. 9.—Saturated streaming turbulence for run BA-3D ($\epsilon = 0.2$, $\tau_s = 1.0$, *left*) and run AB-3D ($\epsilon = 1.0$, $\tau_s = 0.1$, *right*). The boxes are oriented with the radial x-axis to the right and slightly up, the azimuthal y-axis to the left and up, and the vertical z-axis directly up. The contours show the particle density at the sides of the simulation box after the streaming turbulence has saturated. The axisymmetry of the marginally coupled particles witnesses the smearing effect of Keplerian shear on the relatively long-lived clumps. The tightly coupled particles drive rapid fluctuations that develop fully nonaxisymmetric density patterns. [*This figure is available as an mpeg animation in the electronic edition of the Journal.*]

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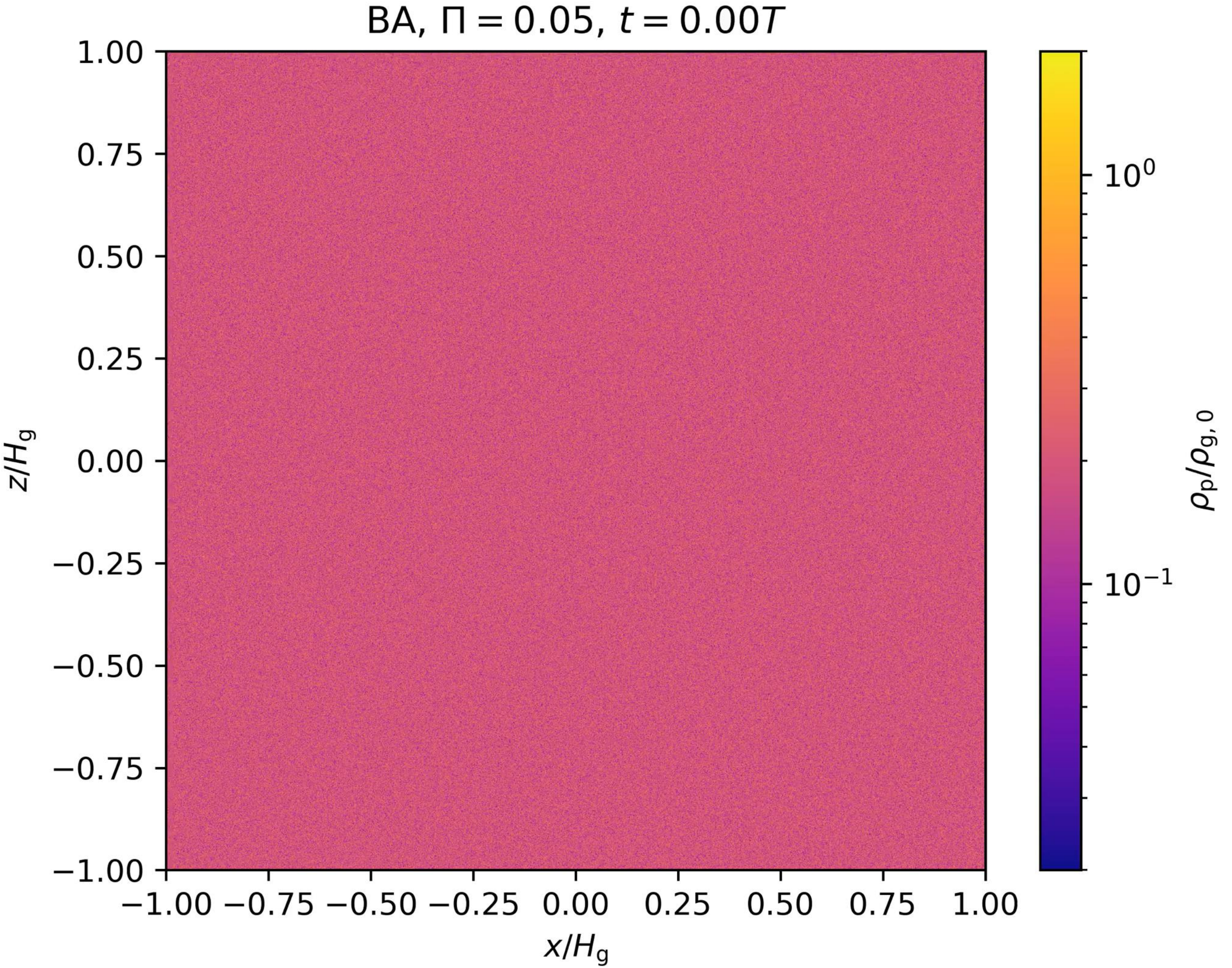
Baronett+ 24

2048^2



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Codes and Numerical Methods

Table 2. Codes

Code	Section	Dust	Equations	Riemann Solver		Reconstruction		Time	
				Gas	Dust	Gas	Dust	Integrator	Order
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Athena	2.2.2	Particles[a]	(2), (14)	HLLC[c]	...	PPM[h]	...	CTU[m]	2nd
Athena++	2.2.3	Particles	(7), (15), (16)	HLLE[d]	...	PPM[i]	...	VL2[n]	2nd
		Fluid[b]	(2), (21)	Roe[e]	Custom[f]	PPM	PLM	VL2	2nd
Idefix	2.2.5	Fluid	(2), (21)	HLLC	HLL	PLM[j]-VLFL[k]	PLM-VLFL	TVD[o]-RK2[p]	2nd
LA-COMPASS	2.2.6	Fluid	(2), (21)	HLLE	HLLE	PLM	PLM	TR-BDF2[q]	2nd
PLUTO	2.2.8	Particles	(2), (14)	Roe	...	PPM	...	RK2	2nd
		Fluid	(2), (21)	Roe	Exact[g]	PLM-MC[l]	PLM-MC	RK2	2nd
FARGO3D	2.2.4	Fluid	(2), (21)	...	...	PLM-VLFL	PLM-VLFL	Euler	1st
Pencil	2.2.7	Particles	(7), (15), (16)	...	...	...	...	RK4	4th

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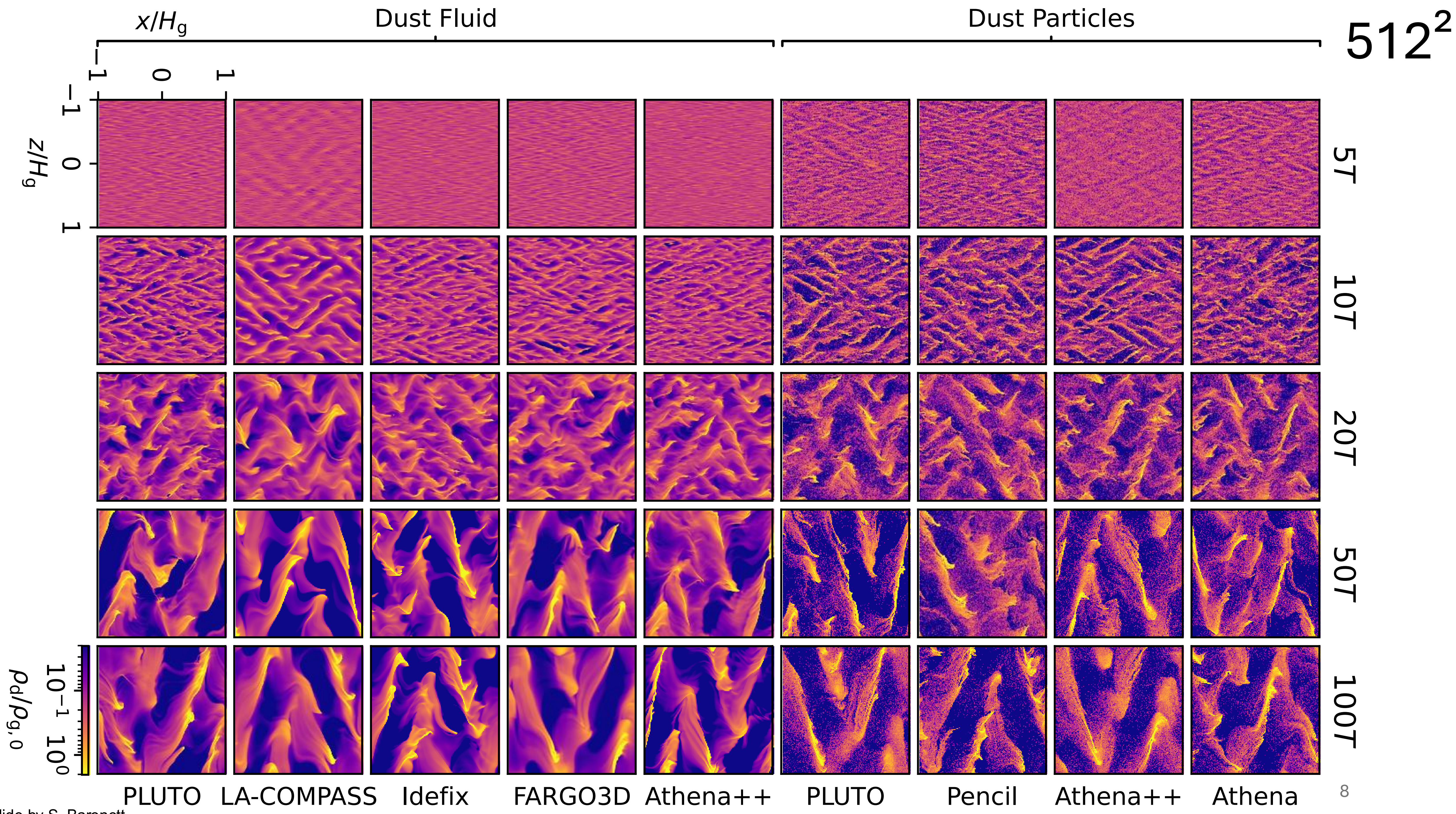

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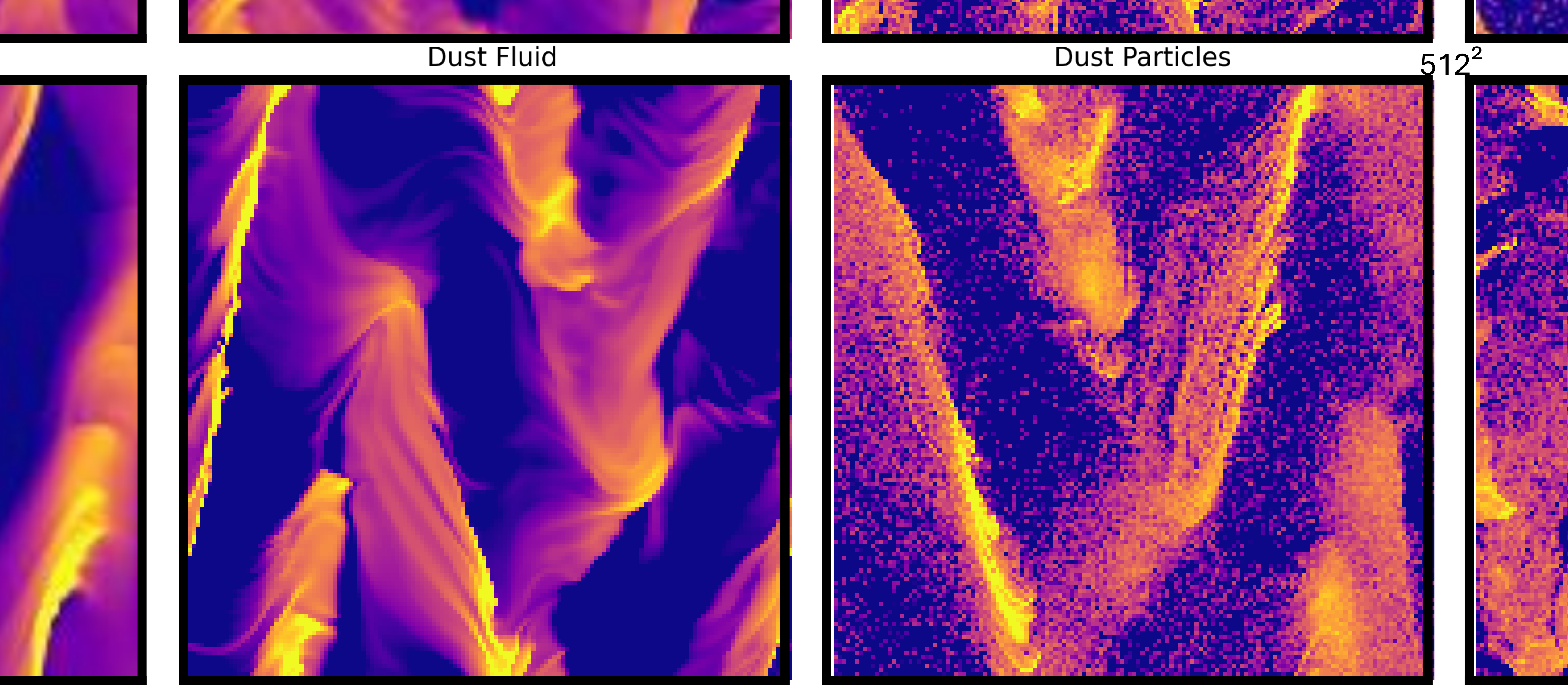
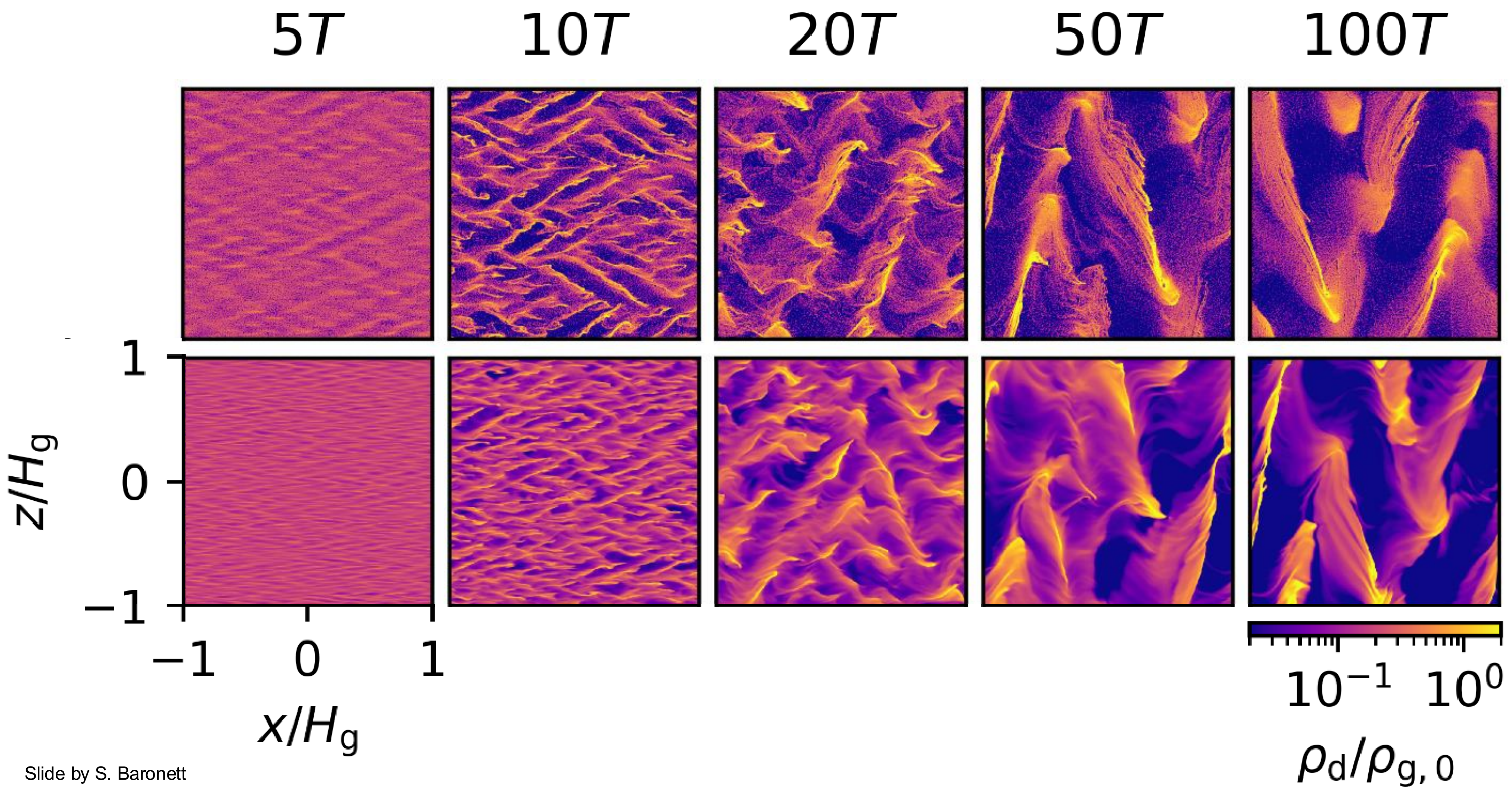


3D Athena++ PLUTO

Athena++ (512^2 Fiducial Grid Resolution)



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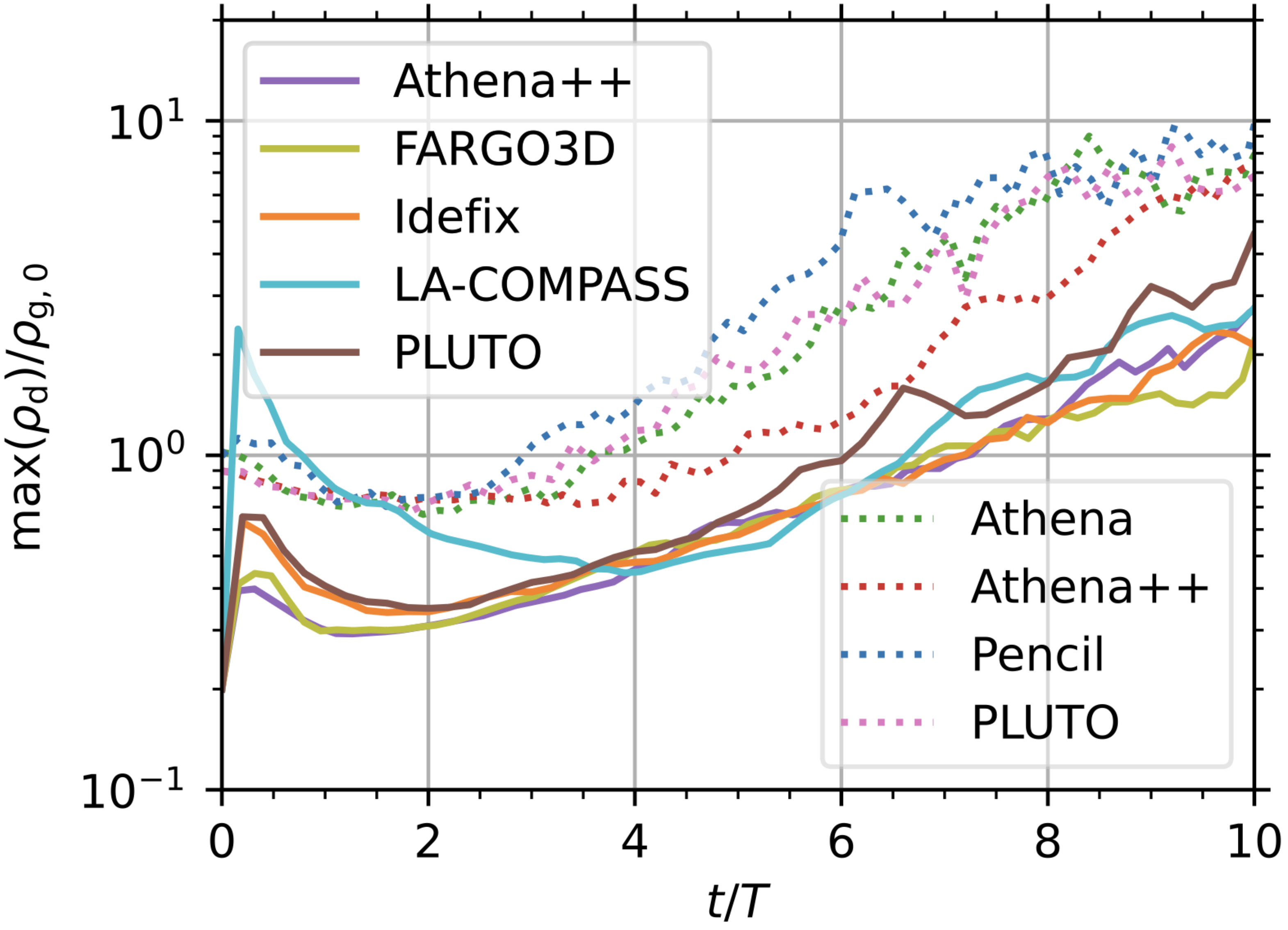
Fiducial Grid Resolution (512^2)



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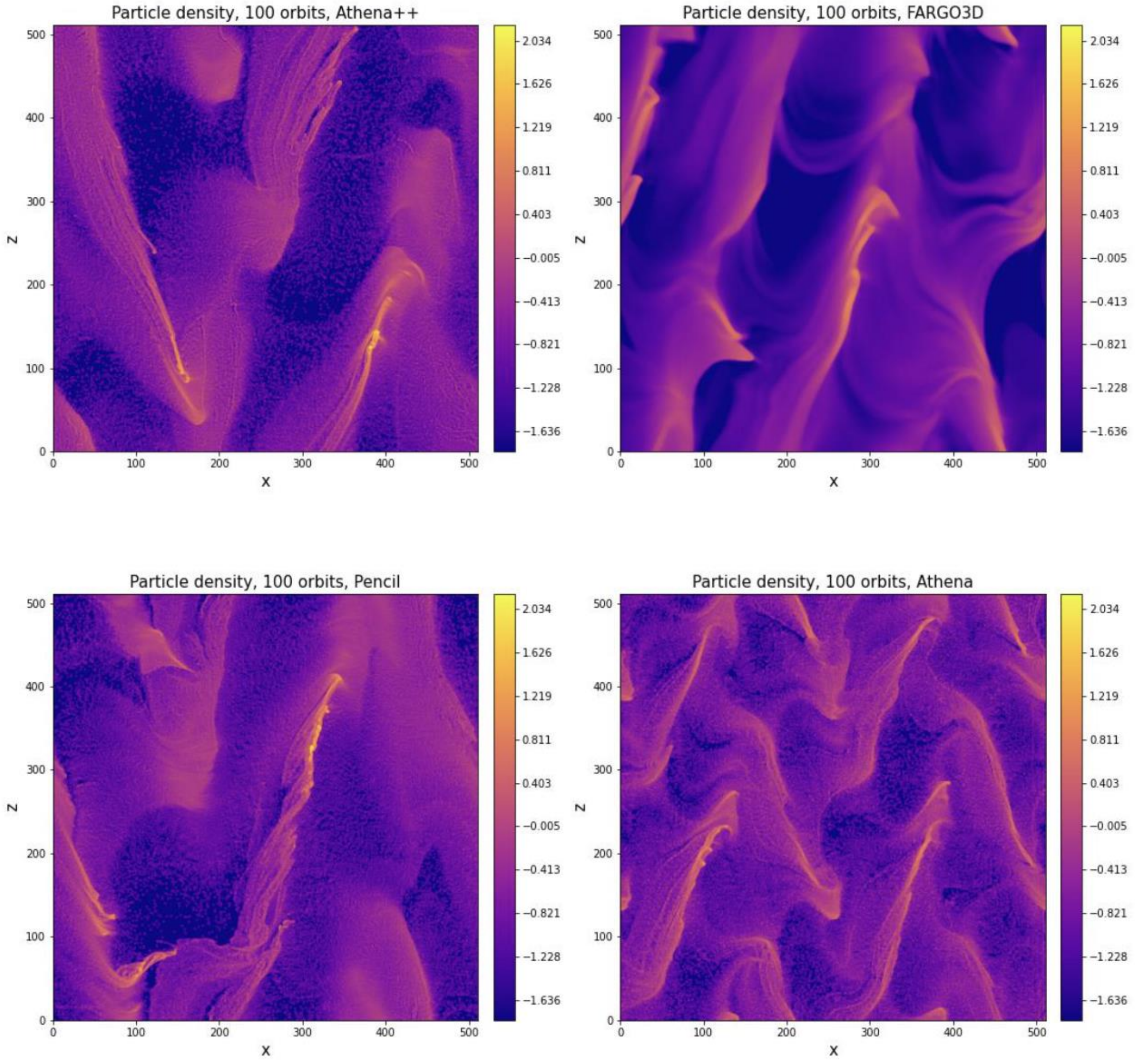
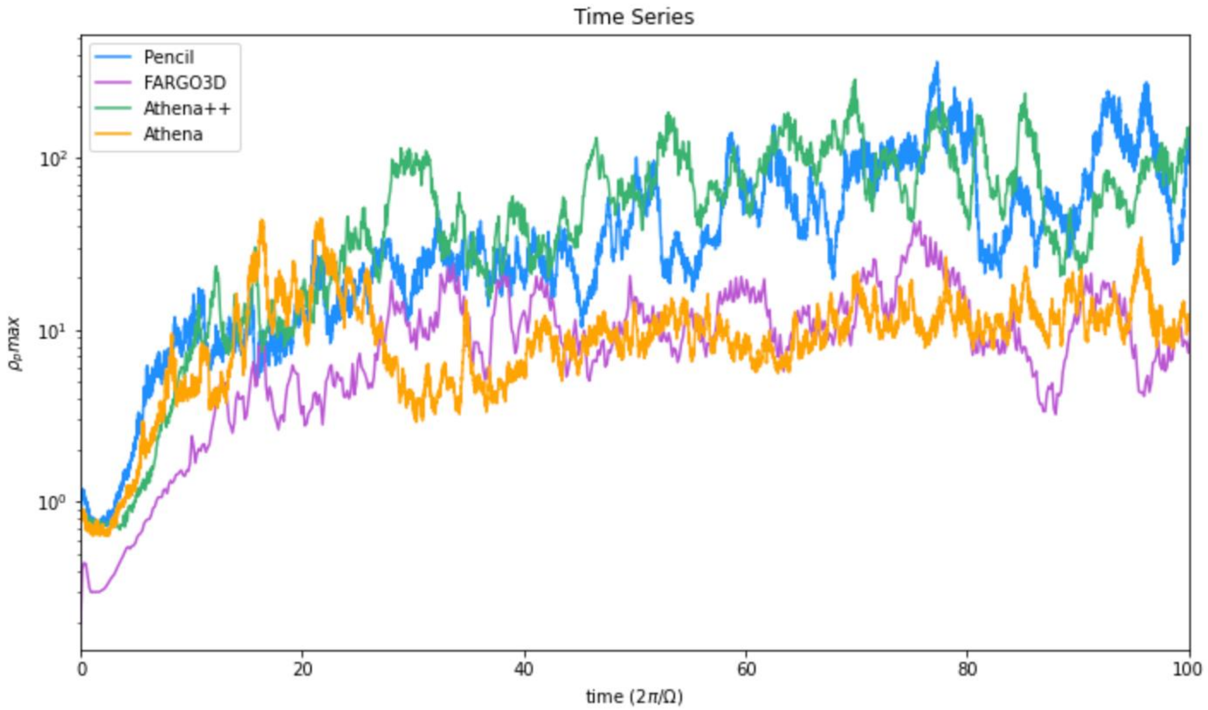
Blast from the past… (2023)
First version of this plot





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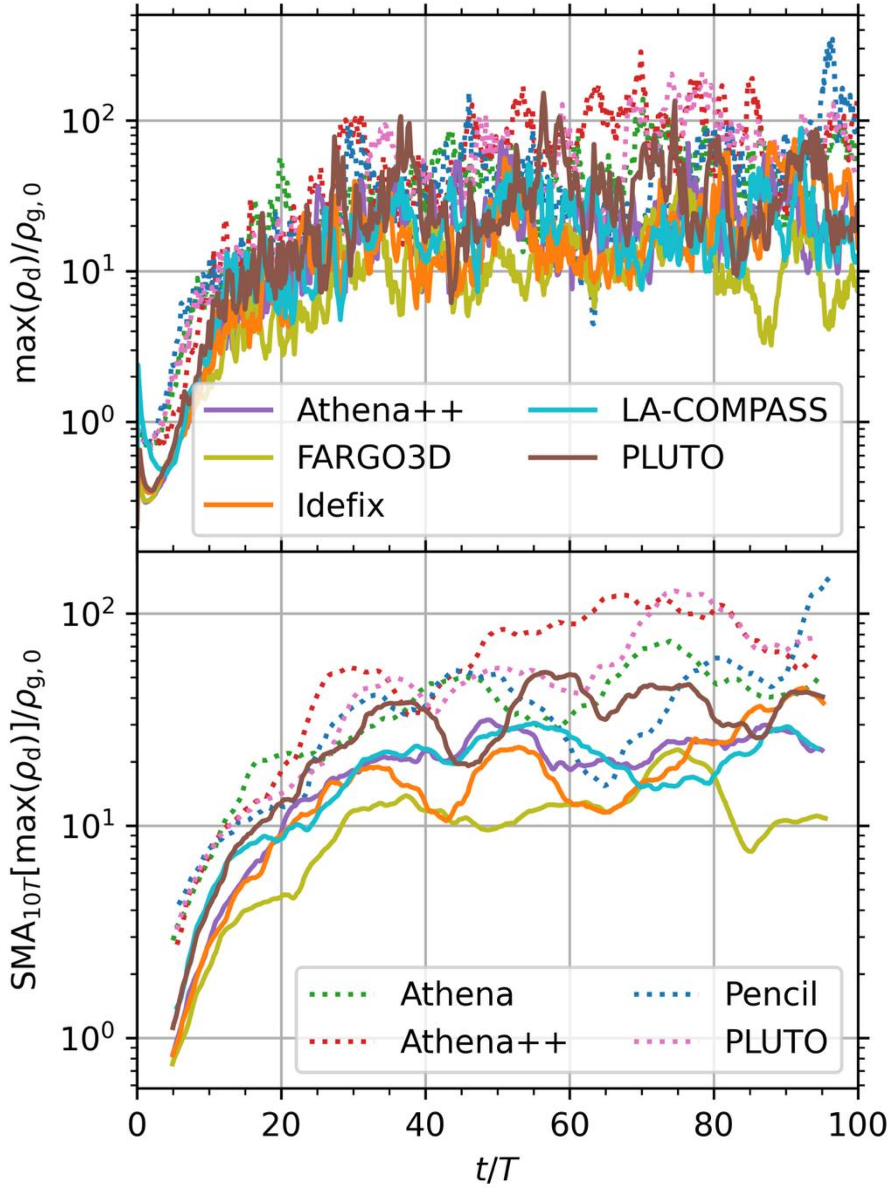
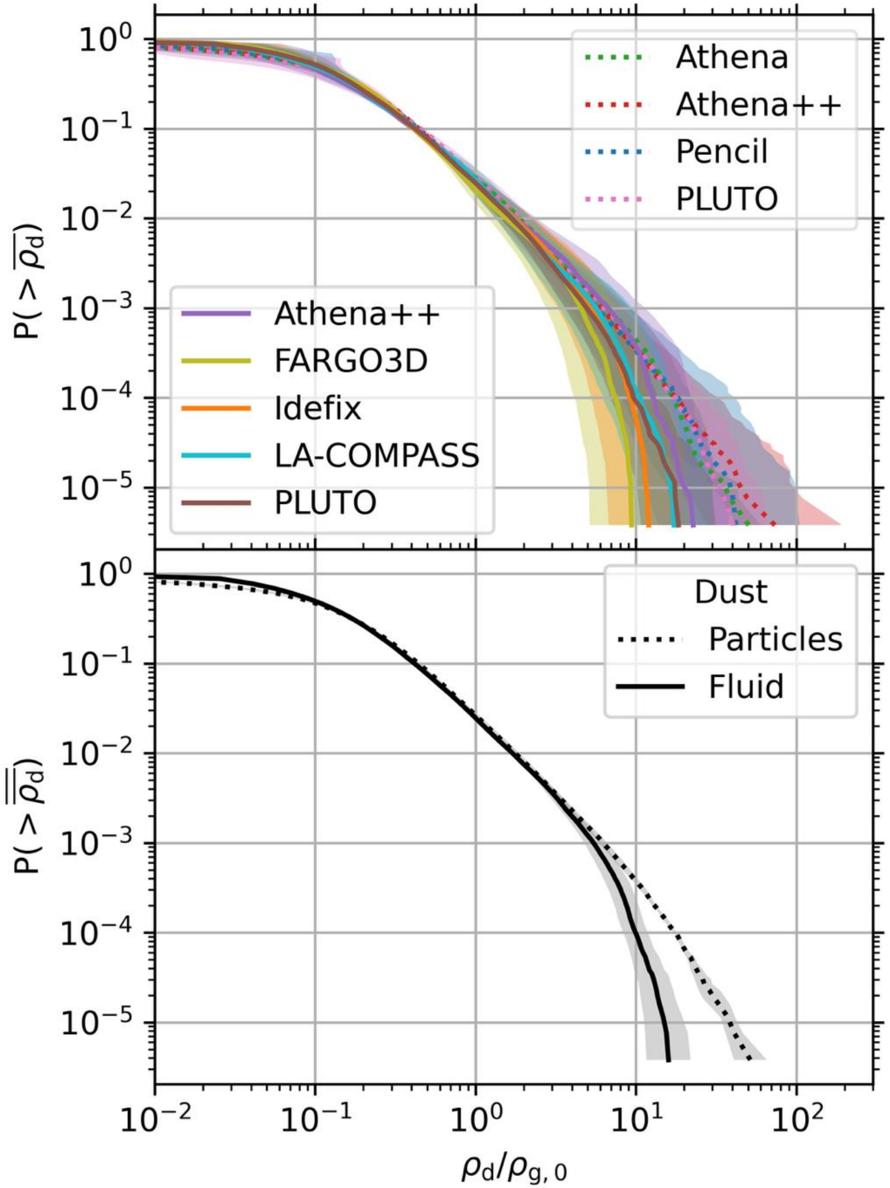
Fiducial Grid Resolution (512^2)





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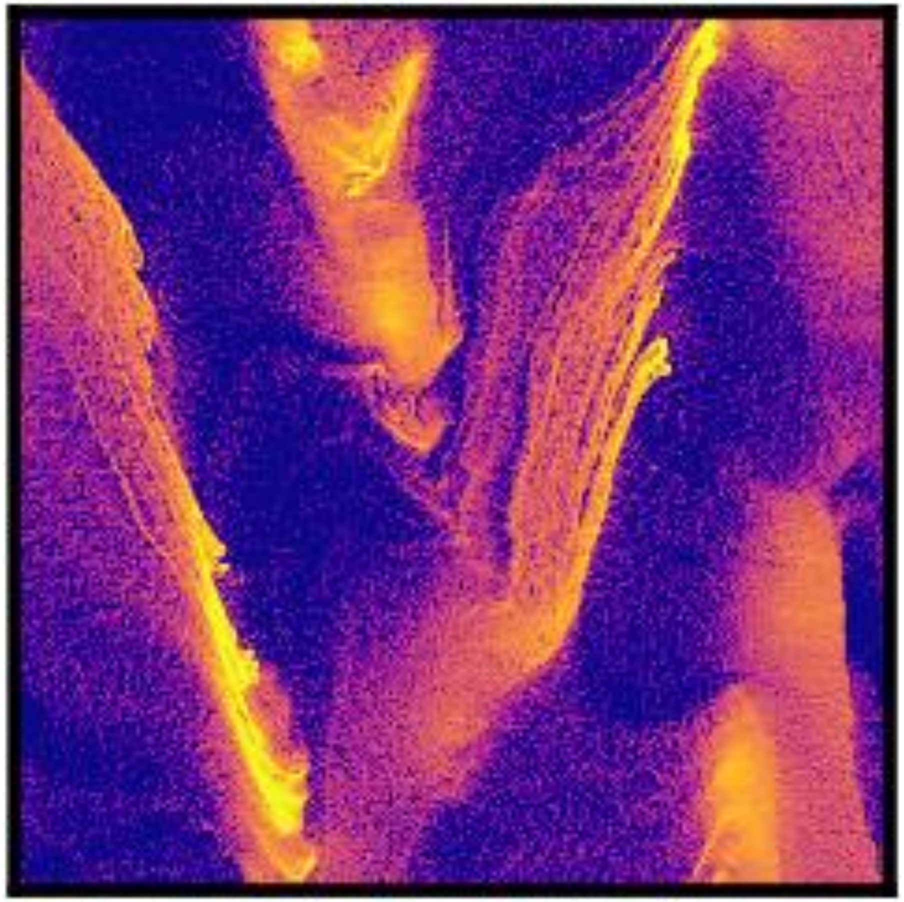
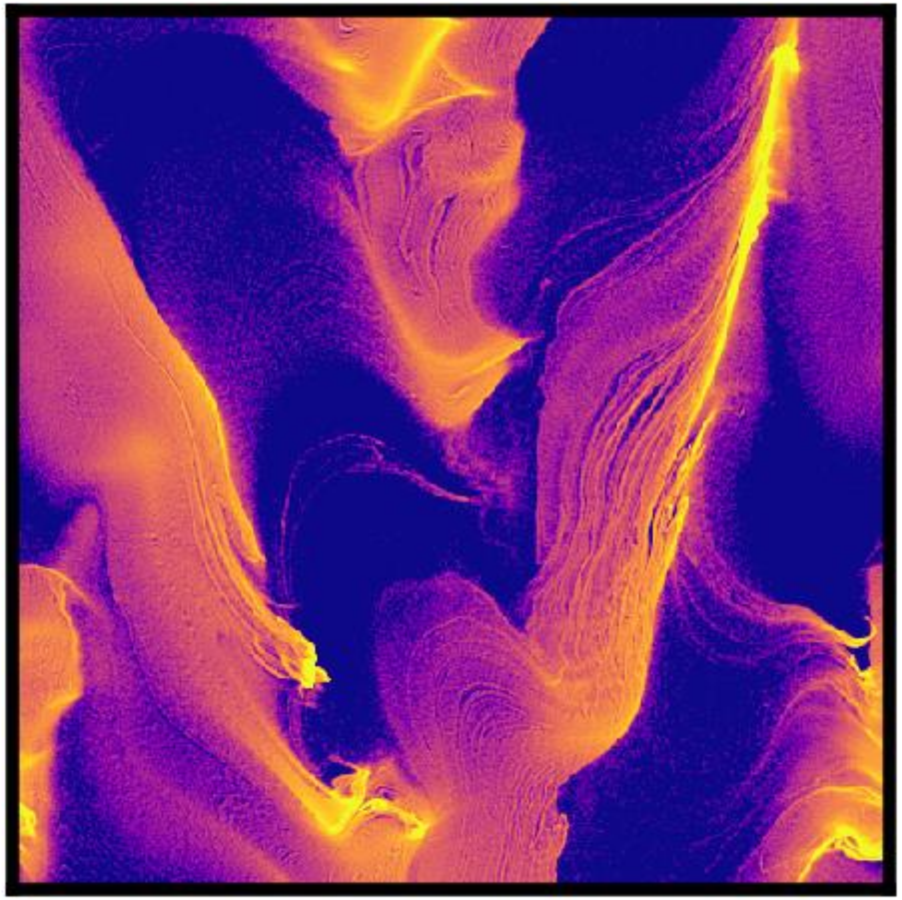
Higher Particle Resolution (512^2 grid): PLUTO



$n_{\mathrm{p}} = 1$



$n_{\mathrm{p}} = 9$

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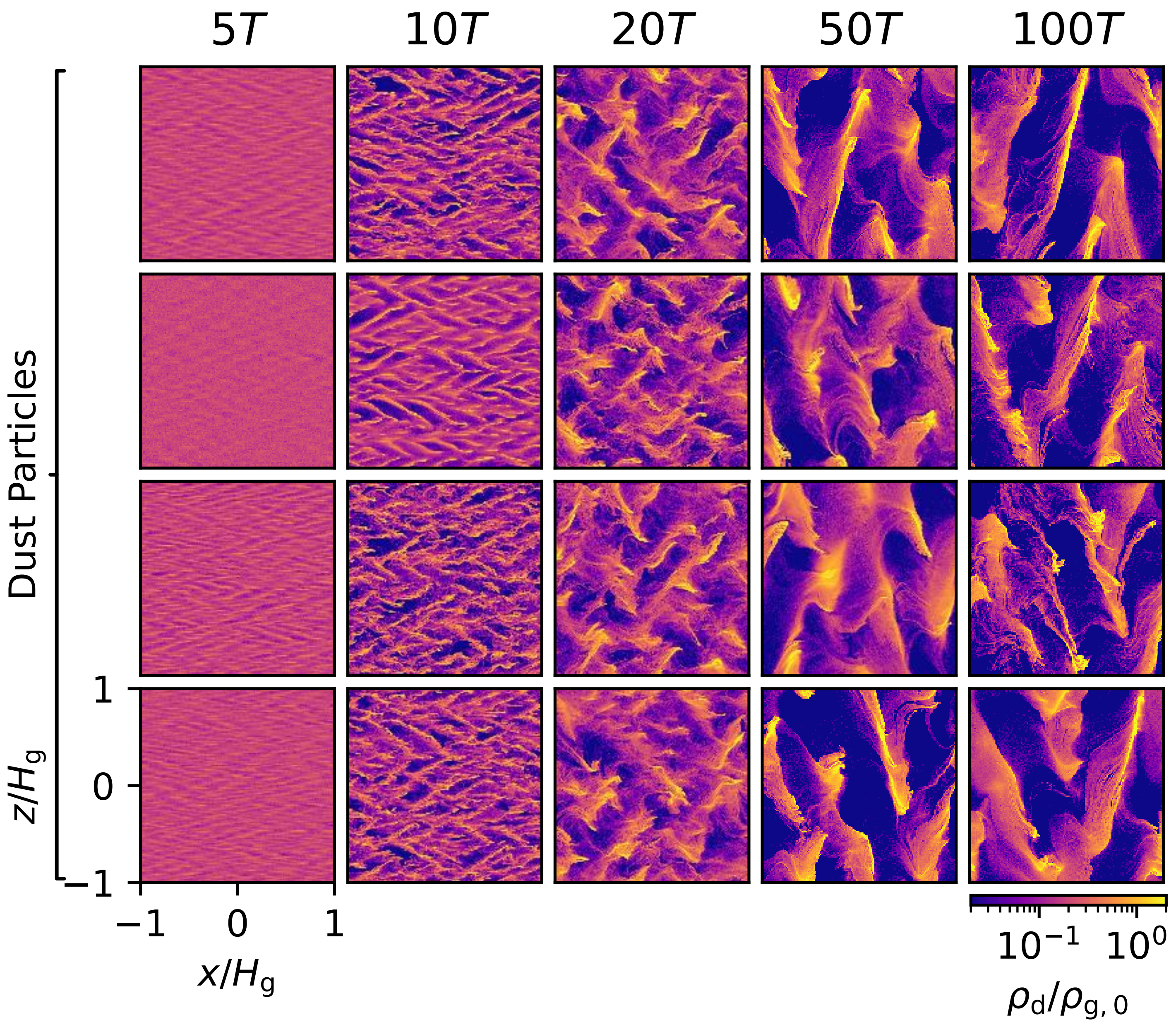
Higher Particle Resolution (512^2 grid)



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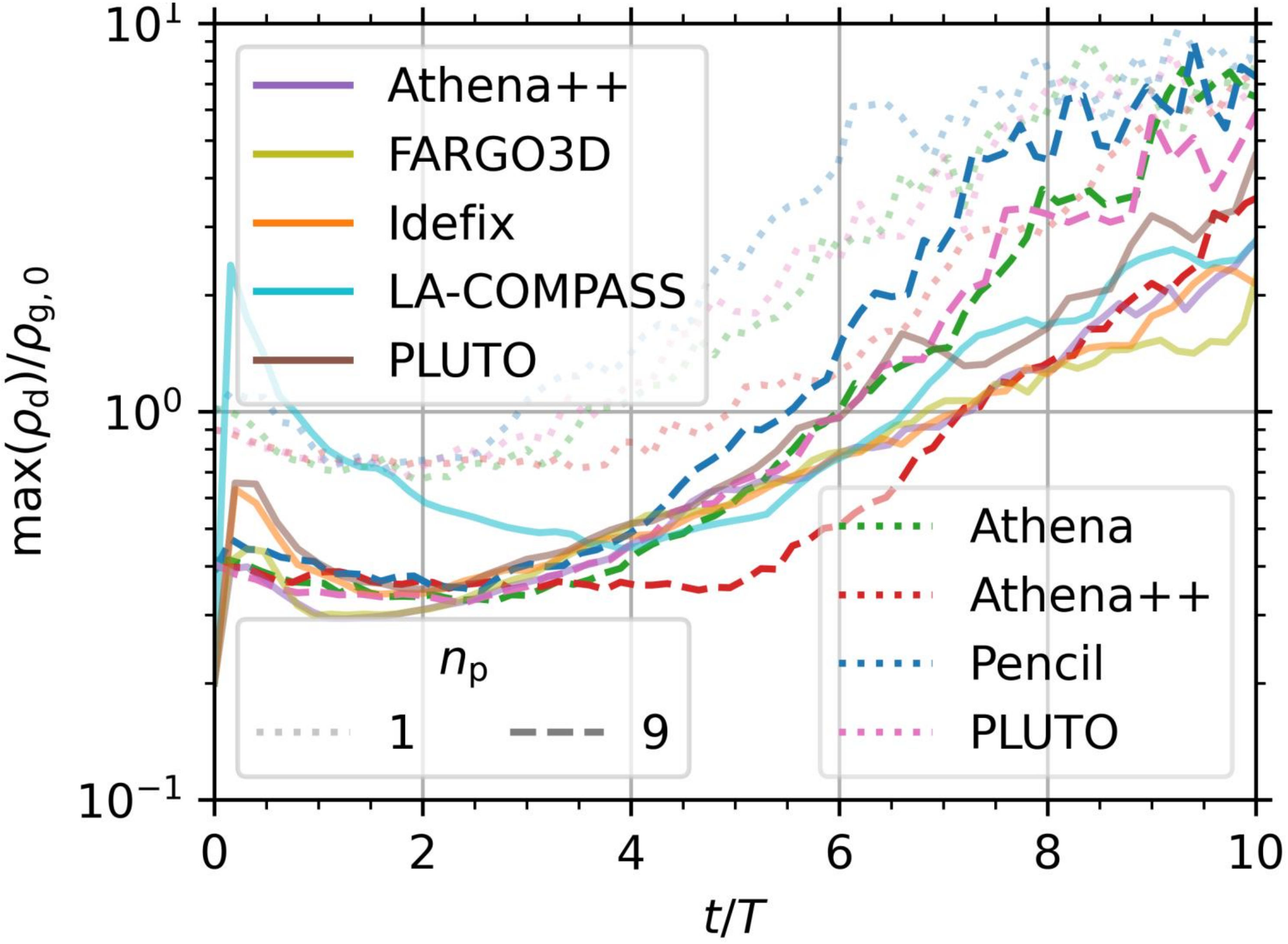
Higher Particle Resolution (512^2 grid)



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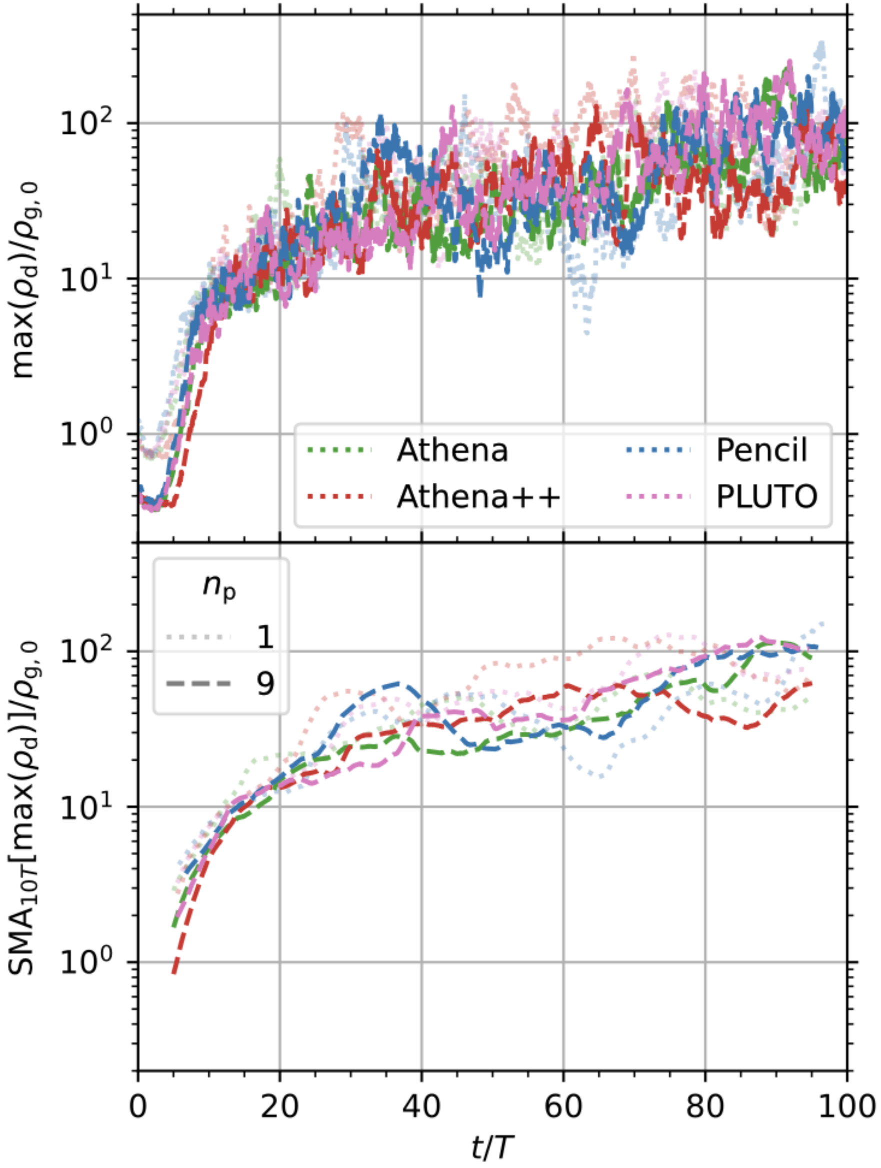
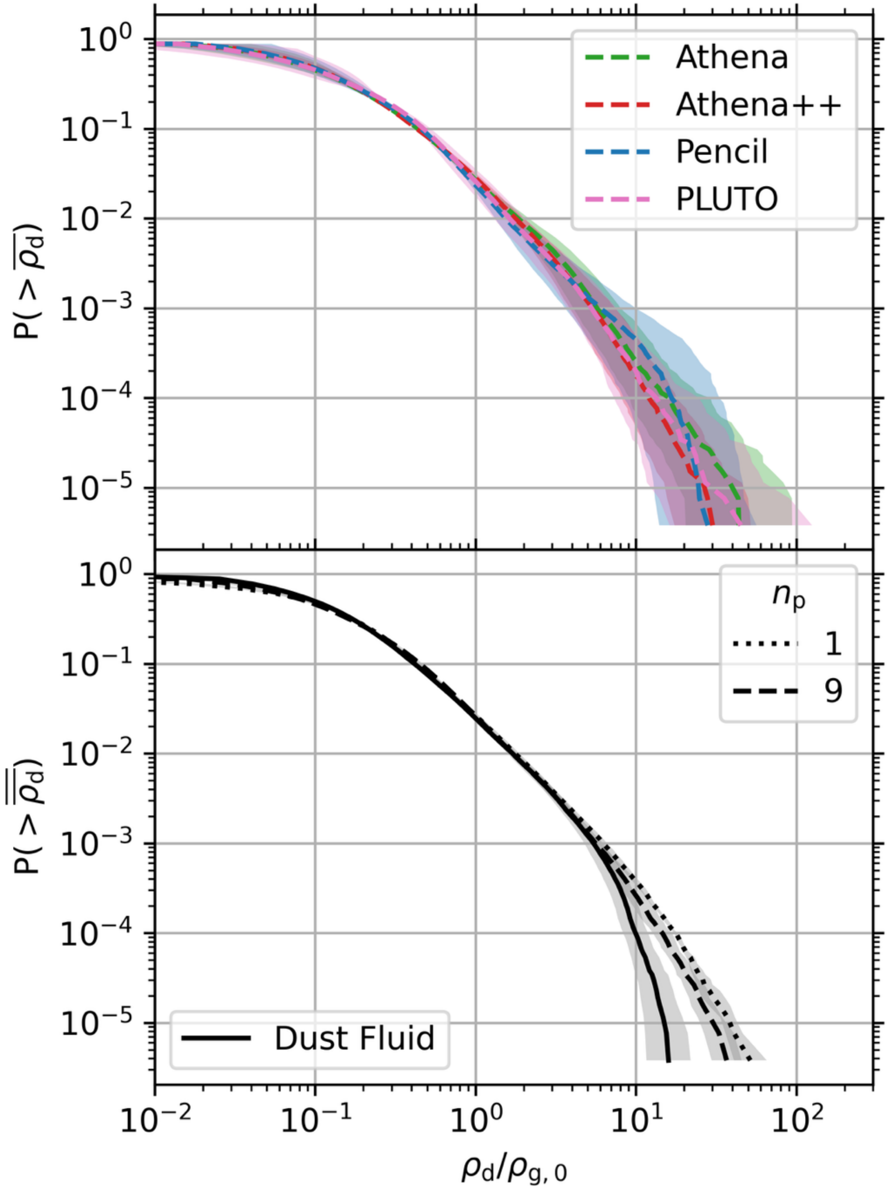
Higher Particle Resolution (512^2 grid)





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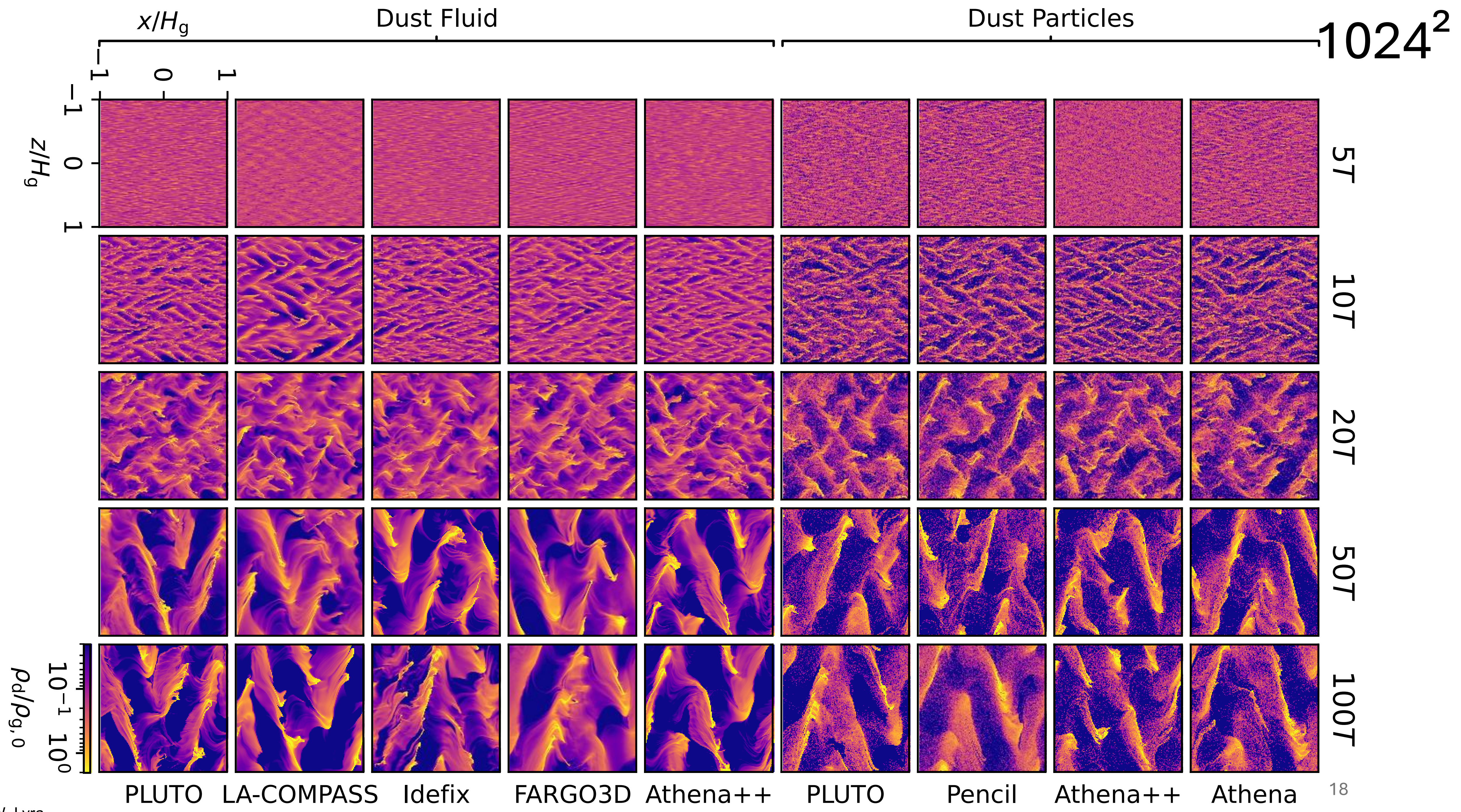

x/H_g
Dust Fluid
Dust Particles
1024^2
−1
0
1
z/H_g
5T
10T
20T
50T
100T
$\rho_\mathrm{d}/\rho_{\mathrm{g},0}$
10^{-1}
10^0
PLUTO
LA-COMPASS
Idefix
FARGO3D
Athena++
PLUTO
Pencil
Athena++
Athena

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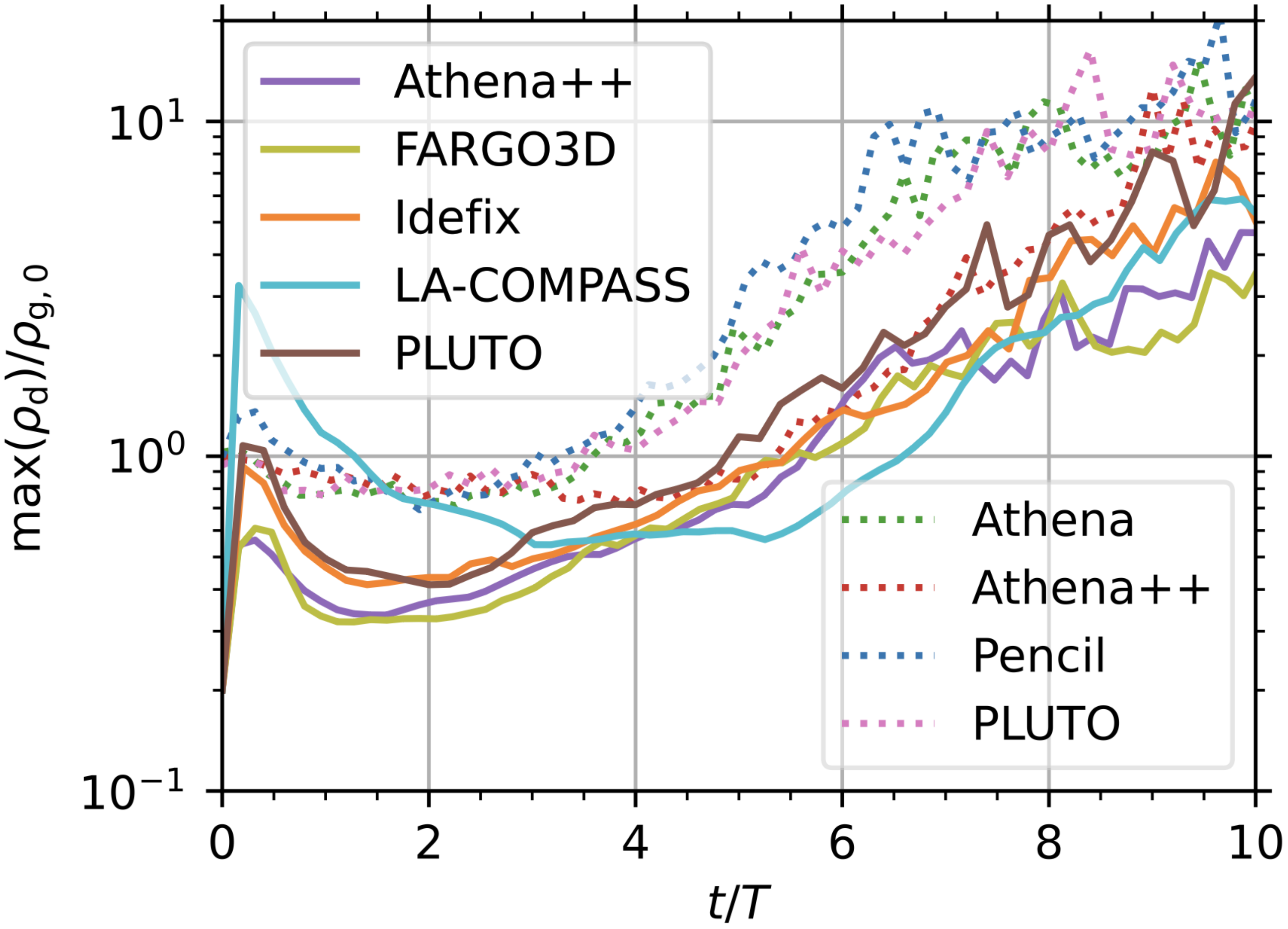
Higher Grid Resolution (1024^2)



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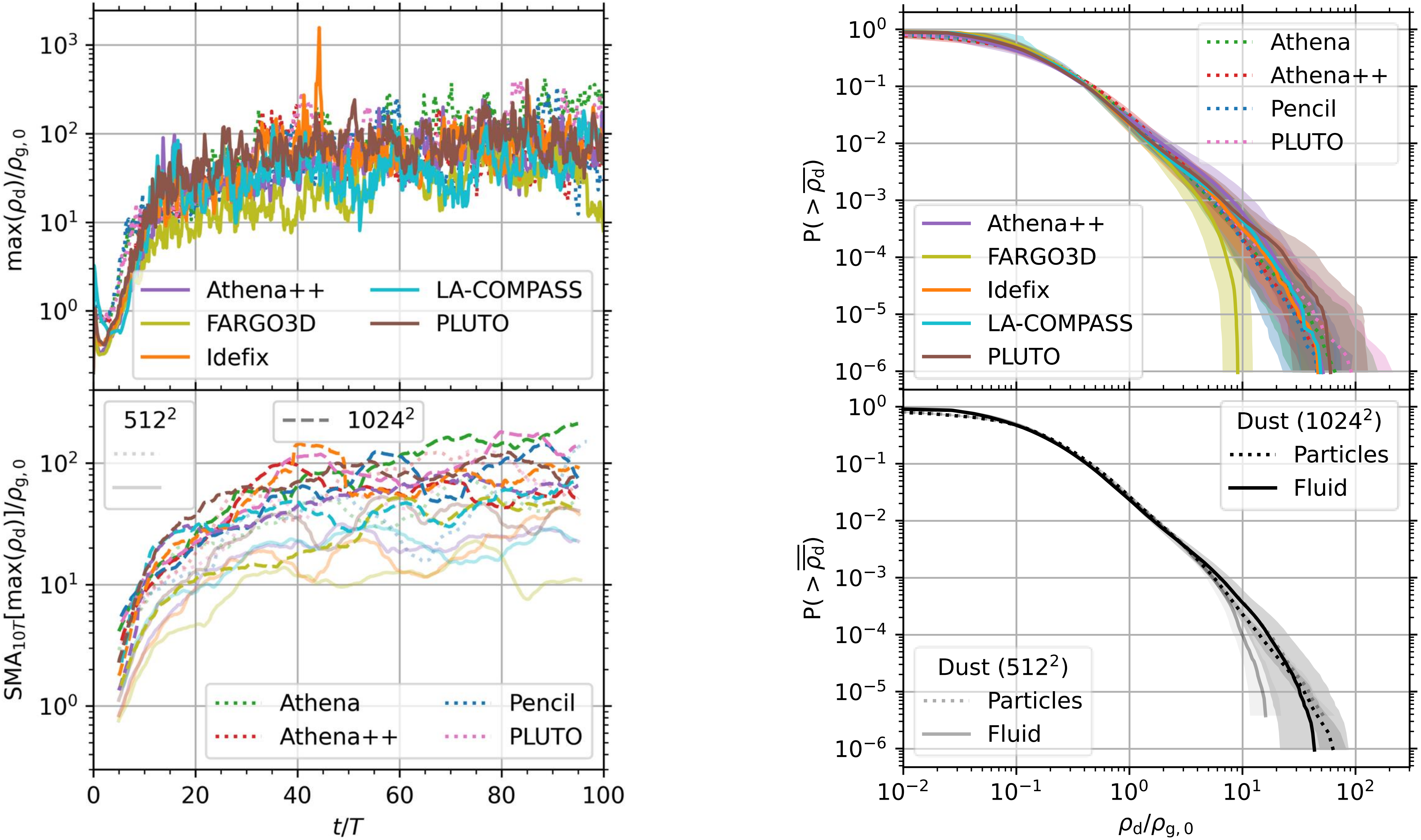
Higher Grid Resolution (1024^2)



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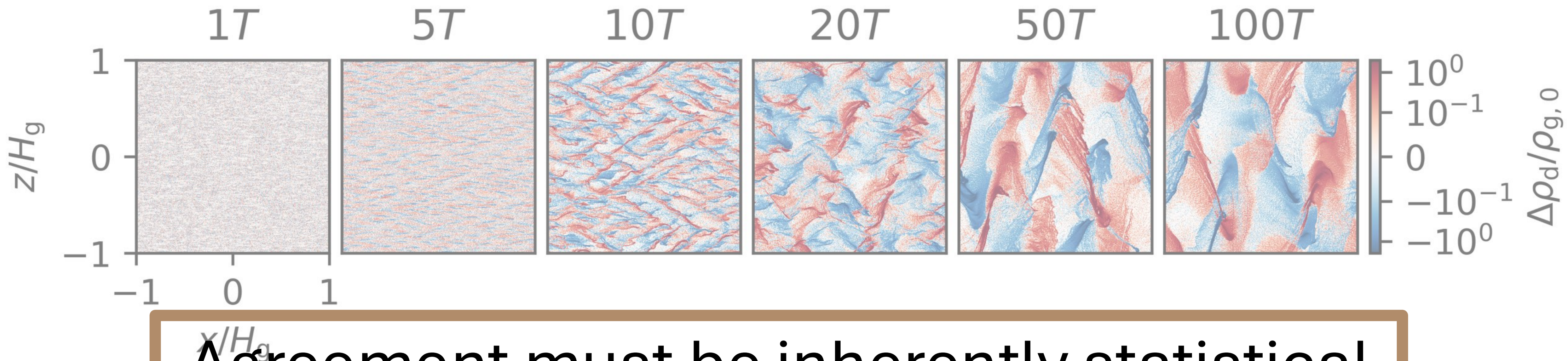
Stochasticity: Athena++ vs. PLUTO particles



Agreement must be inherently statistical

Code	Method	Dust	Flux Integration		Reconstruction		Time	
			Gas	Dust	Gas	Dust	Integrator	Order
Athena++	FV	Particles	HLLE[f]	···	PPM	···	VL2[q]	2nd
PLUTO	FV	Particles	Roe	···	PPM	···	RK2	2nd

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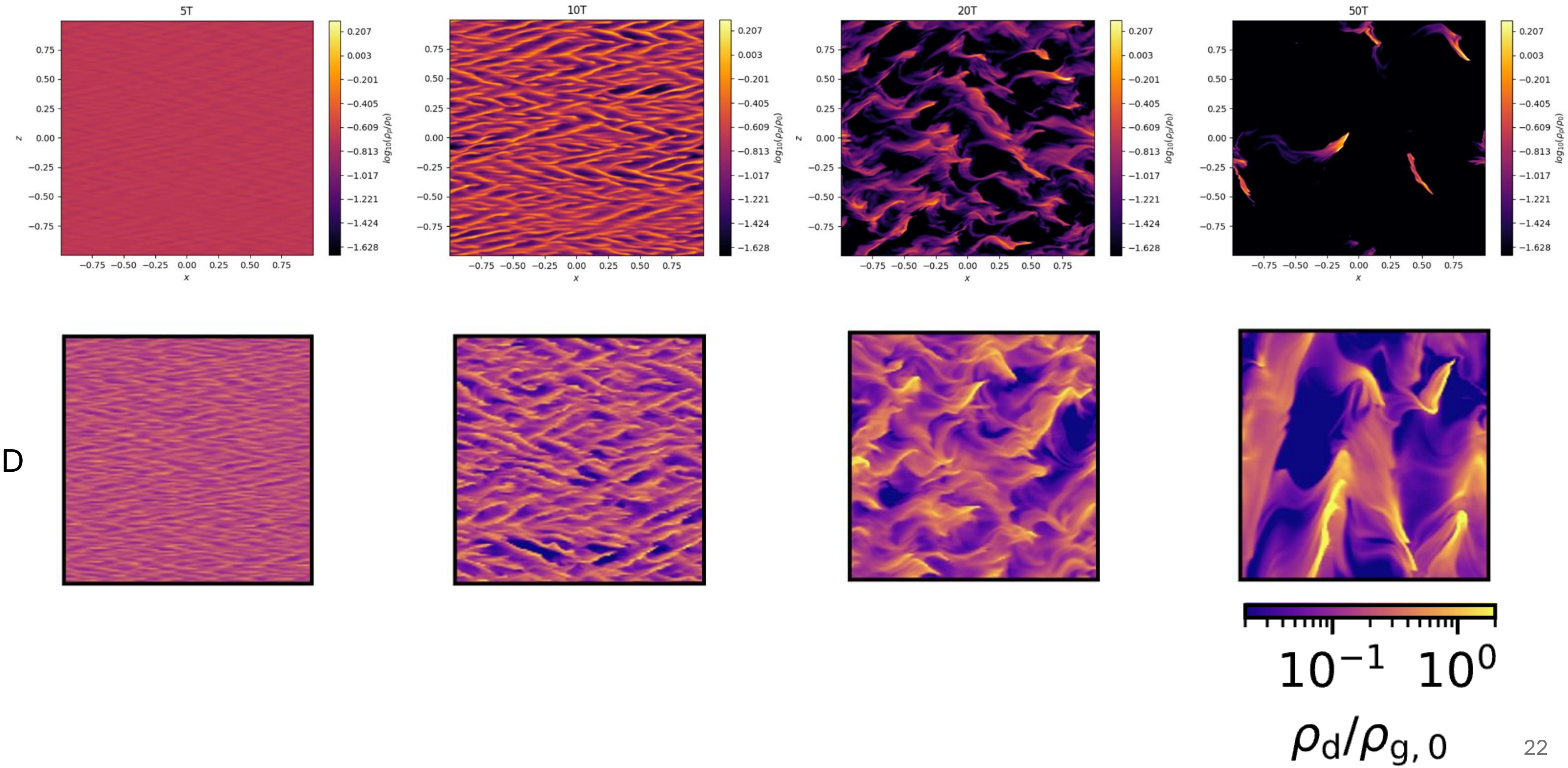
Non-conservative dust fluid

Pencil

FARGO3D



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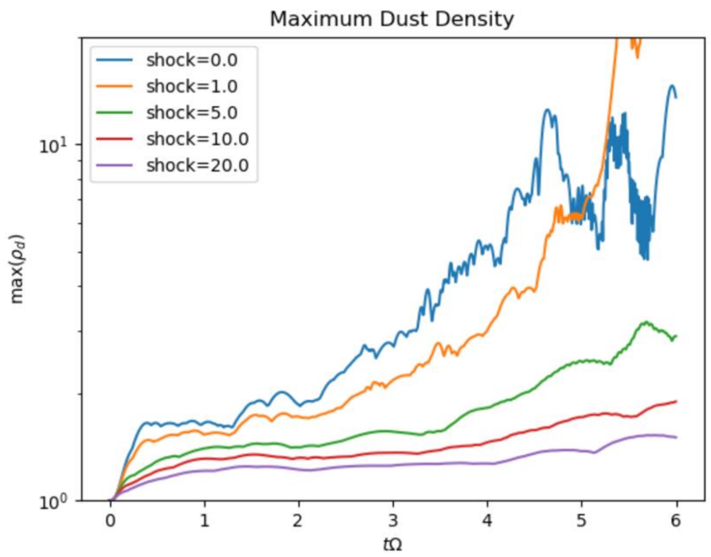
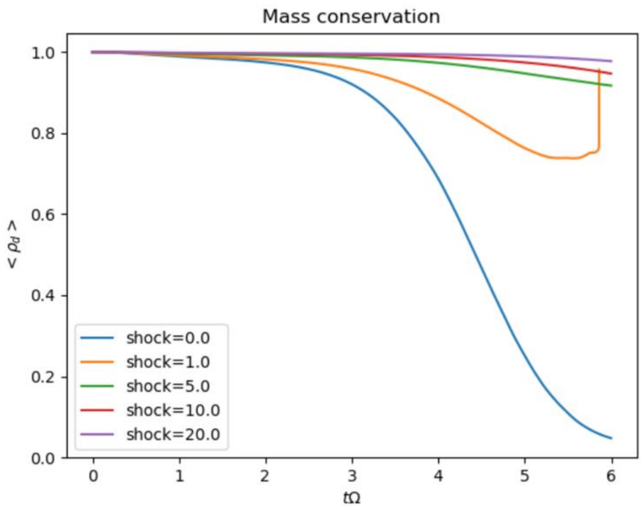
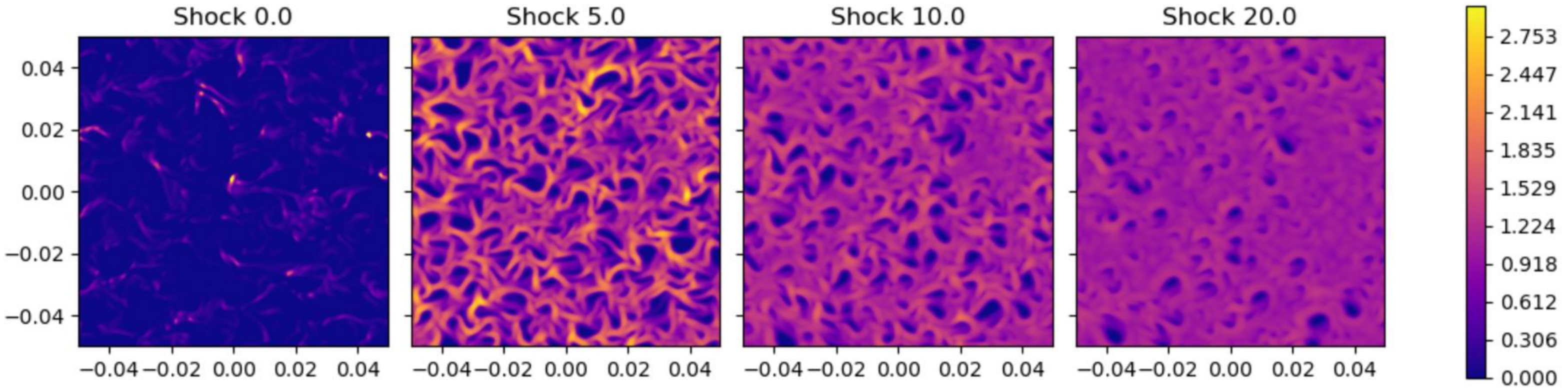
Non-conservative dust fluid

Run AB with shock viscosity







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Dust Models

- High densities matter for **planetesimal formation thresholds**
  - At 1024^2, particle–fluid differences **shrink (~50% gap)**
  - Dust fluid sims should use a higher minimum grid resolution ($> 256^2/H^2$)
- Particle methods
  - Trades fluid grid errors for **interpolation errors, reduced with better kernels**
  - **Load-balancing** issues for performance
- Fluid methods
  - **No stream crossing** (cf. moment-method radiation transport)
  - May crash under steep gradients (finite-difference Pencil code)
- Neither model clearly superior among results
  - **Advanced fluid models** emerging (Binkert 2023; Lynch & Laibe 2024)

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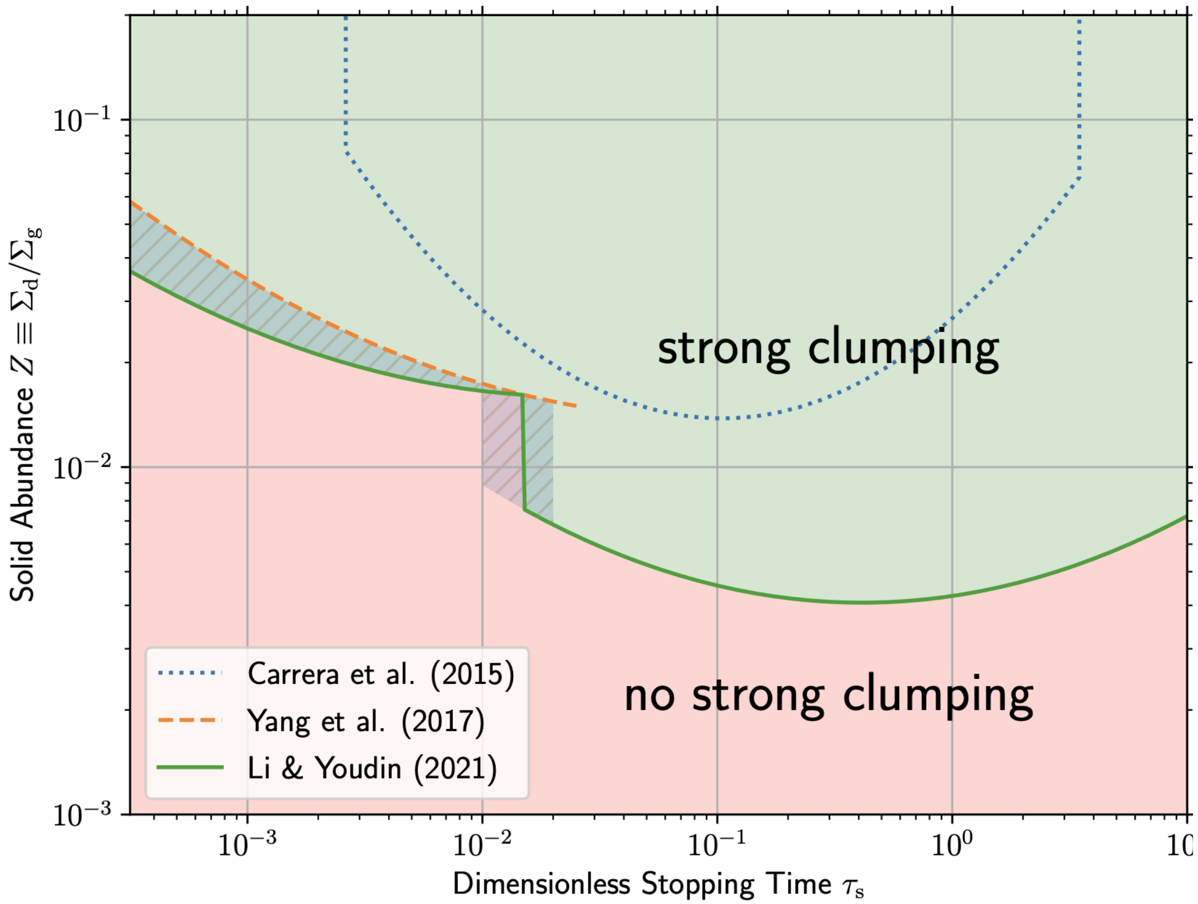
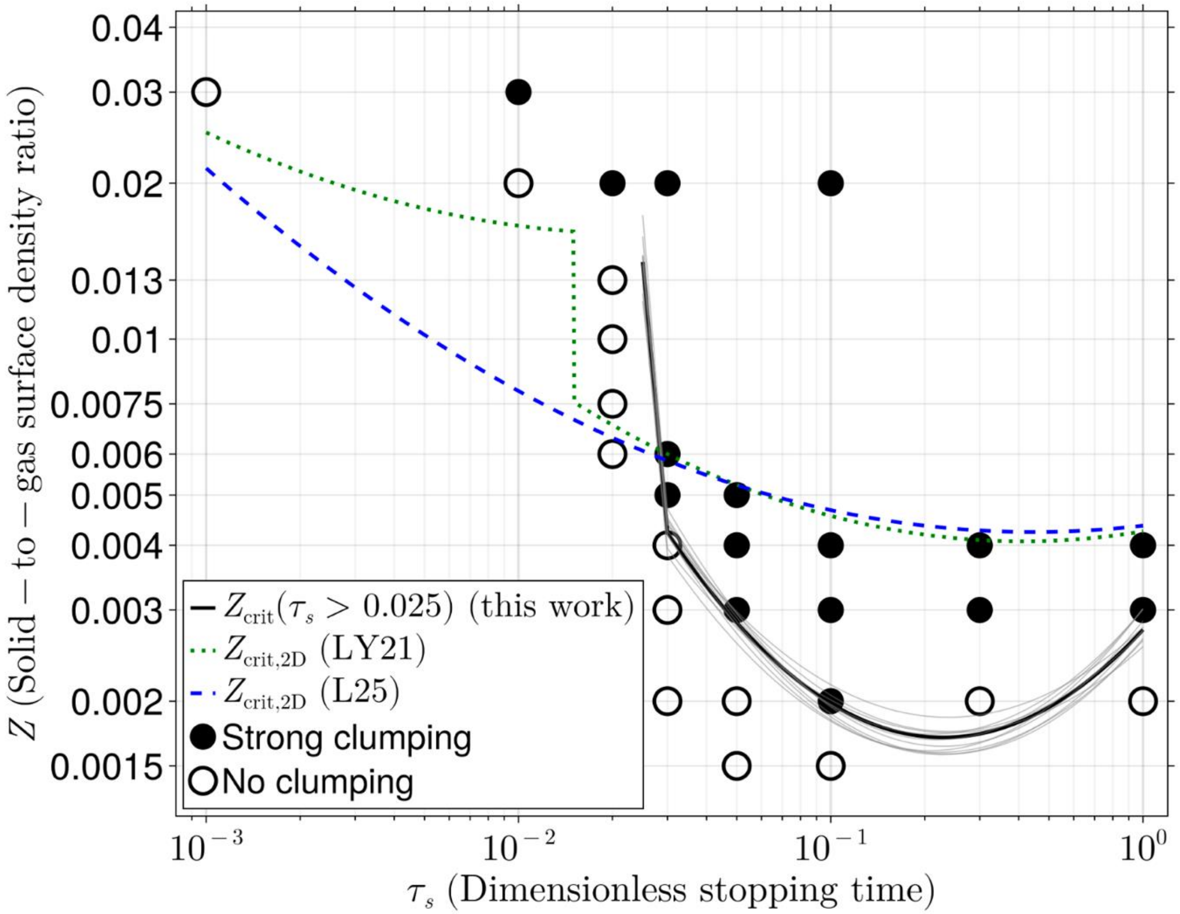
Follow-up: Clumping Boundary



Lesur et al (2023, Protostars & Planets VII, Chapter 13)



Lim et al. (2025)

Planets in the Desert - A Streaming Instability Code Comparison

Dust/Gas Drag Instability Code Comparison Project

The project was initiated after the Building Blocks of Planets 2020 conference. The goal is to perform and compare simulations of the dust and gas drag instabilities in accretion disks. We aim to have a broad number of different methods and codes, including fluid and particle descriptions.

pfitsplus.github.io/research/meetings/

PFITS+
Planet Formation in the Southwest +

Team | Meetings | Code Comparisons | Talks | Research | News

Meetings

RESEARCH OVERVIEW

AREAS OF INTEREST

- Protoplanetary Disks
- Planet Formation
- Fluid Dynamics

SOFTWARE DEVELOPMENT

- Athena
- Athena++
- Pencil Code

MEETINGS

- 2026 June 8–12

CODE COMPARISONS

3rd PFITS+ Meeting on Hydrodynamics of Circumstellar Disks and Planet Formation

On this page

2026 June 8–12

The goal of the meeting is to bring together researchers to discuss current and future research on planet formation with a focus on hydrodynamical instabilities and computational astrophysics. Topics to be covered:

- Vertical shear instability
- Convective overstability
- Rossby wave instability
- Streaming instabilities
- Non-ideal MHD instabilities

The workshop is the third in the PFITS+ (Planet Formation in the Southwest Plus) series: the first meeting was held in June, 2022, in Las Cruces, NM; the second in Tucson AZ, in Nov., 2023.

Venue

SETI institute, Mountain View, CA.

Conclusions

- All codes capture the same SI progression:
  growth → filaments → turbulence

- **Dust model** is the main source of variation;
  - particles reach higher densities than fluids
    - (hint of convergence?)

- **Convergence** improves at higher resolution
  - **Fluids** need finer grids
  - **Particles** face higher cost from load-imbalance

- Agreement inherently **statistical.**

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