Making planets from small grains and big data

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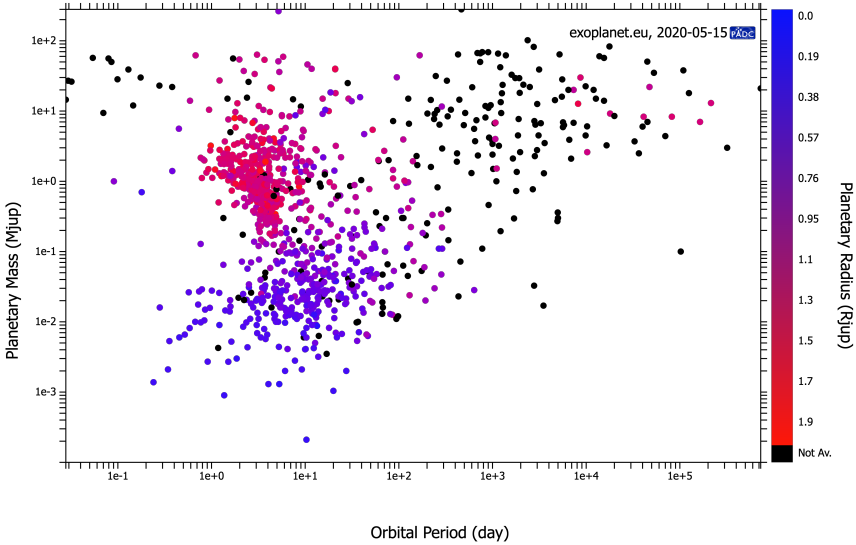
Diversity of planetary systems

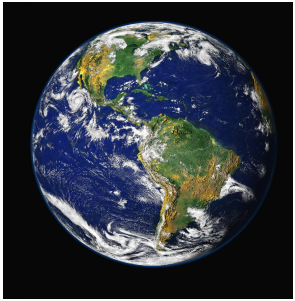


- $>$ 4000 extra-solar planets detected
- $>$ 3000 planetary systems
- Wide range of orbital configurations

The big question

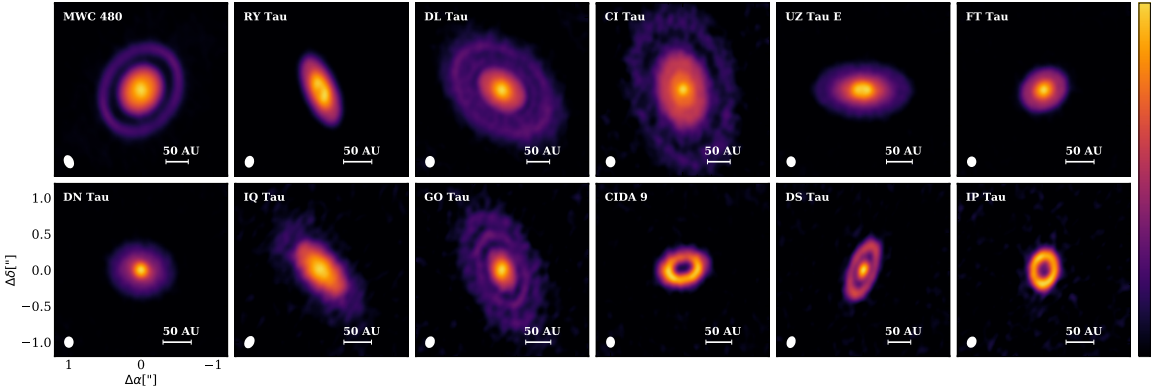
$\sim 10^{-6}\mathbf{m}$

?



$\sim 10^{7}\mathbf{m}$

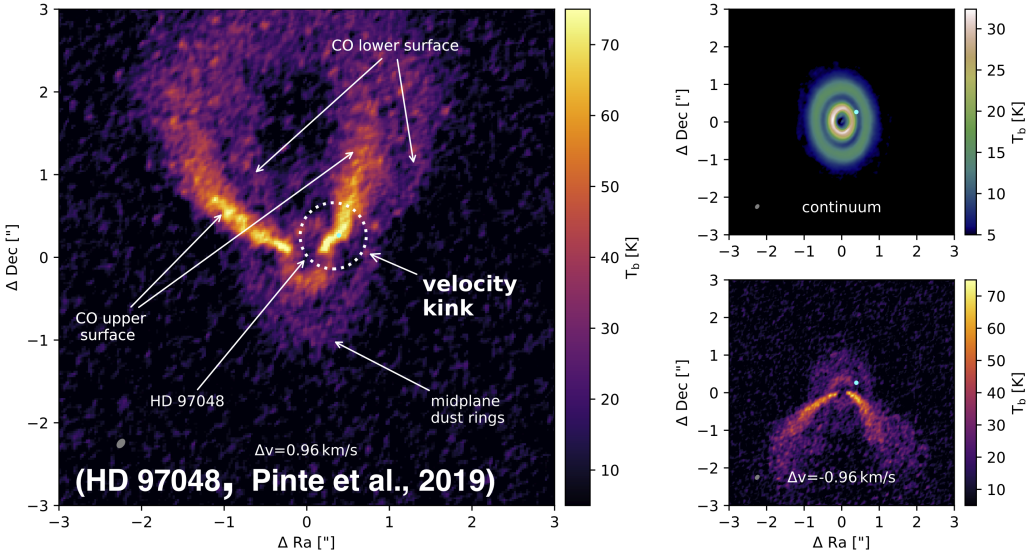
Protoplanetary disks in the era of ALMA



(Long et al 2018)

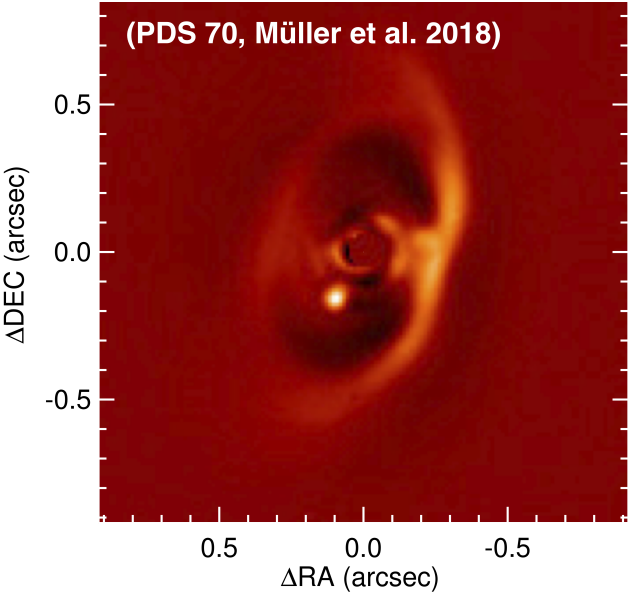
- Rings and gaps: signposts of disk-planet interaction?

Planet-forming disks



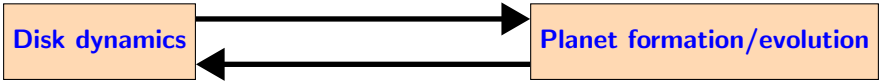
- Kinematic detection of planets

Planet-forming disks



- First planet detected inside protoplanetary disk gap

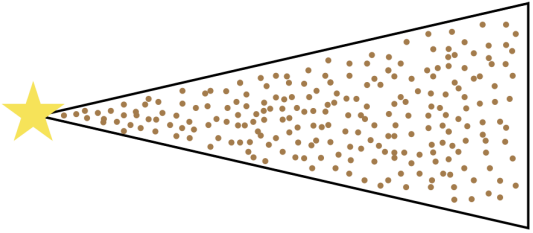
The disk-planet connection



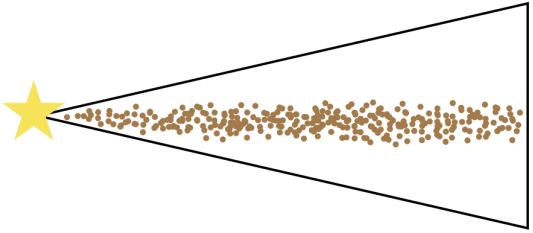
- How do protoplanetary disks accrete onto their stars?
- What are the sources of turbulence in protoplanetary disks?
- Origin of rings, gaps, asymmetries?
- Dust dynamics
  - How do planetesimals form from tiny dust grains?
  - Dust-gas interaction
  - Interpreting observations of PPDs, inferring disk structure/conditions

From dust to planets

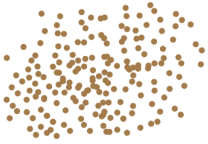
well-mixed dust in young disk



dust settles to disk midplane



dust grains



μm $\xrightarrow[\text{sticking}]{}$ mm – cm

Streaming instability?

Secular GI?

planetesimals

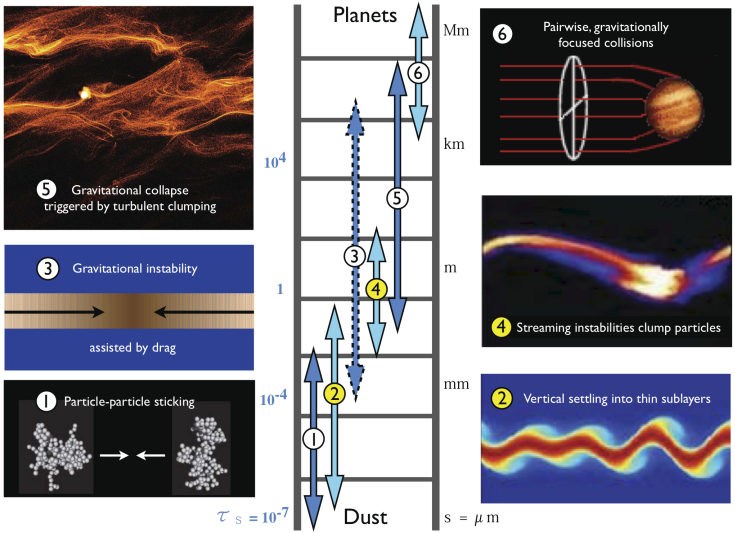
$\sim$ km

gravity/pebble accretion

protoplanet

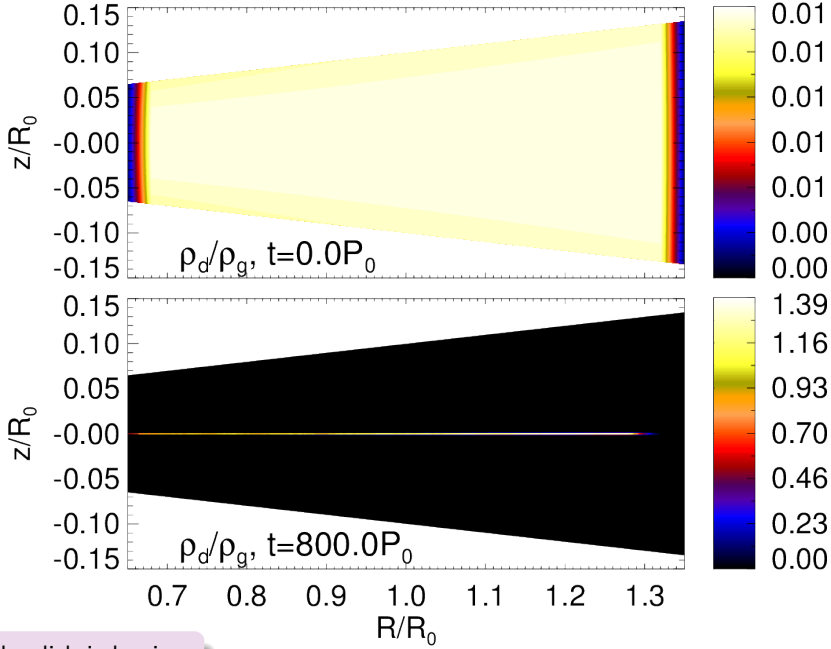
$\gtrsim 10^3$km

Importance of dust



- Planets form from the solids (at least in core accretion)
- Need to understand how dust grains evolve in the gaseous disk

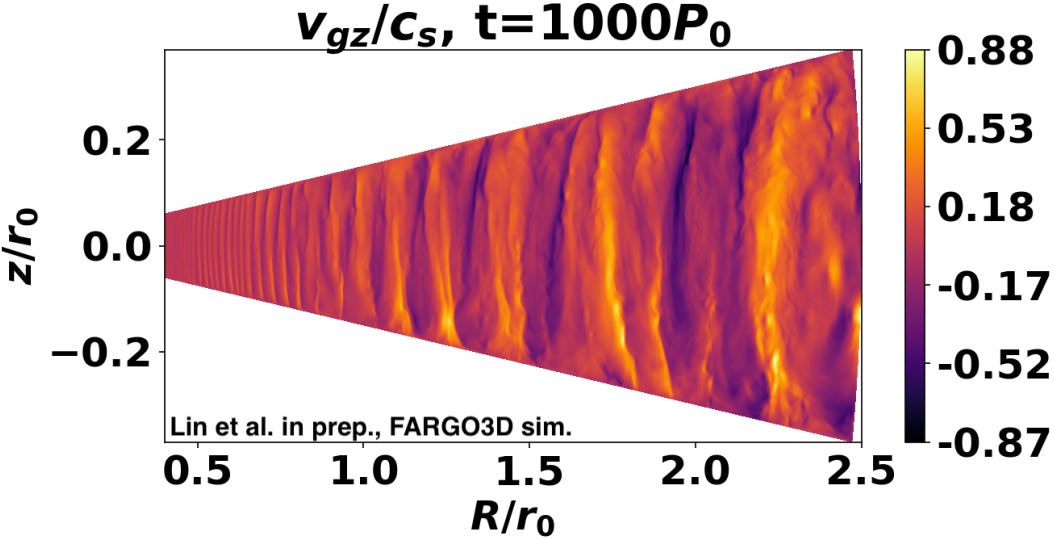
The first step: dust settling



- Yes... if the disk is laminar

Hydrodynamic turbulence

Vertical shear instability (Nelson et al., 2013)



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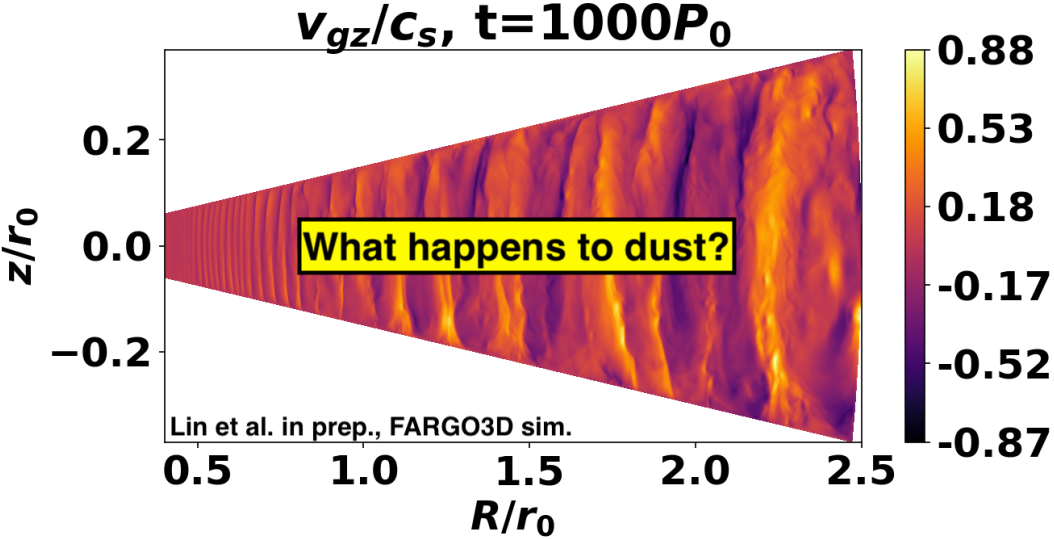
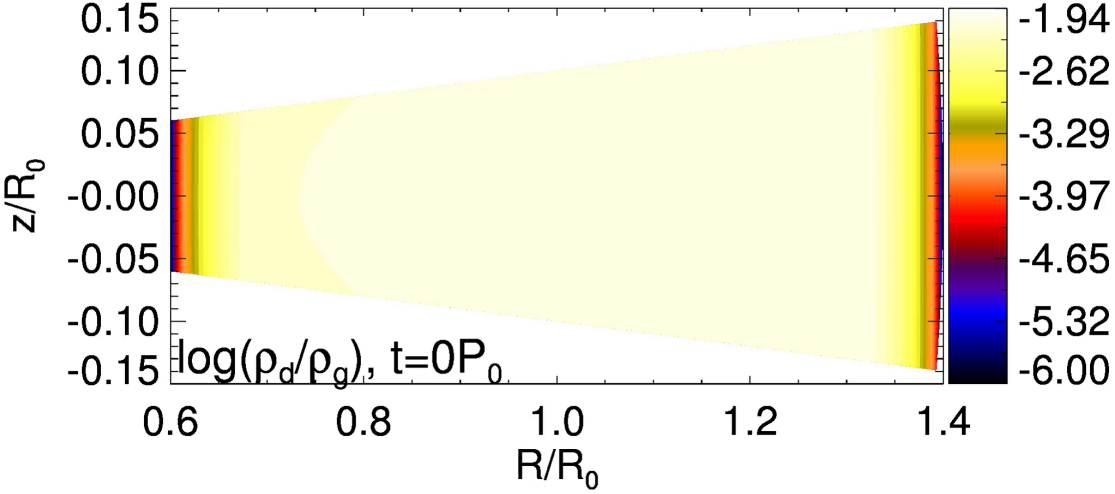
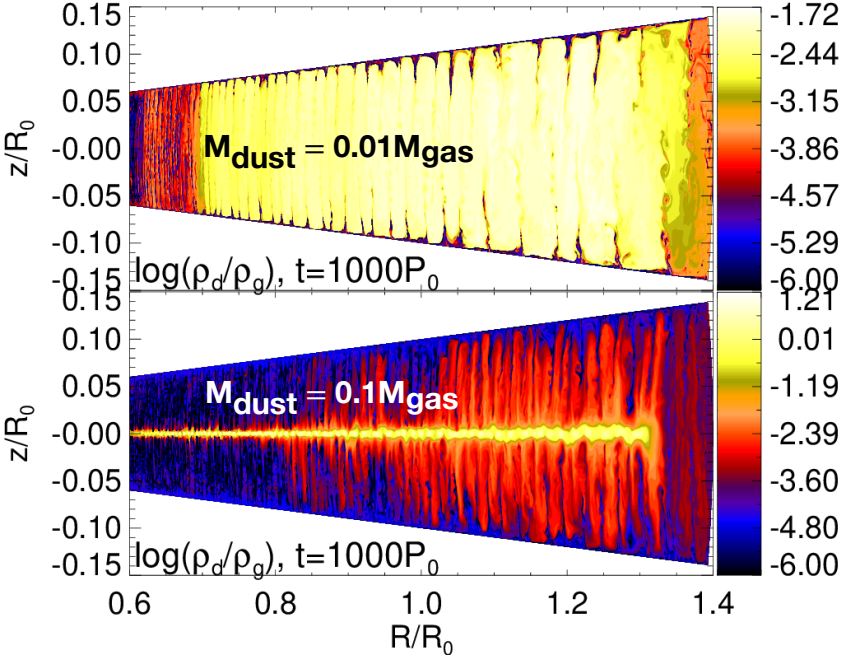


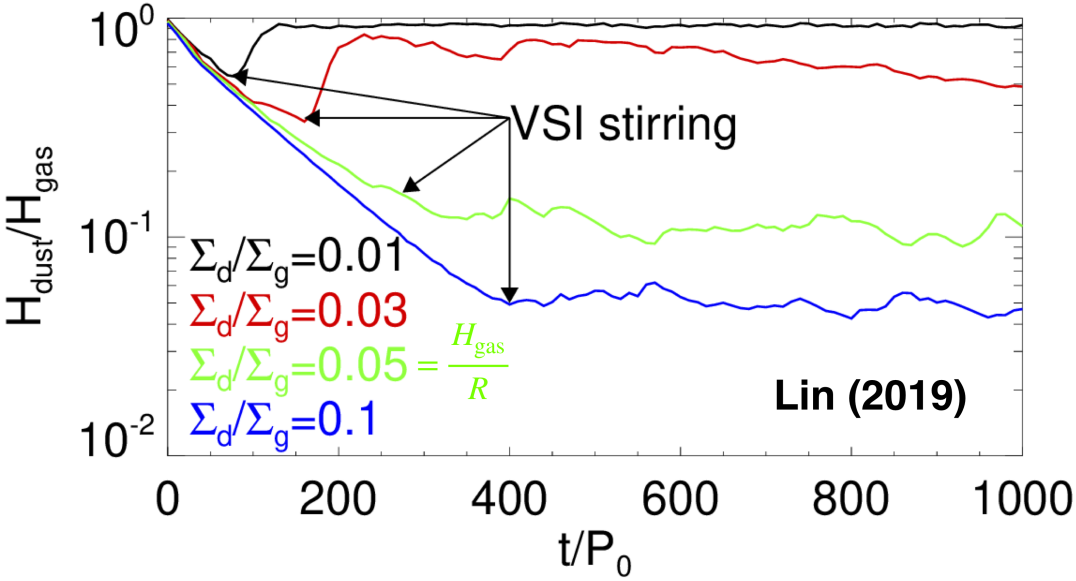
Lifting dust particles by the VSI



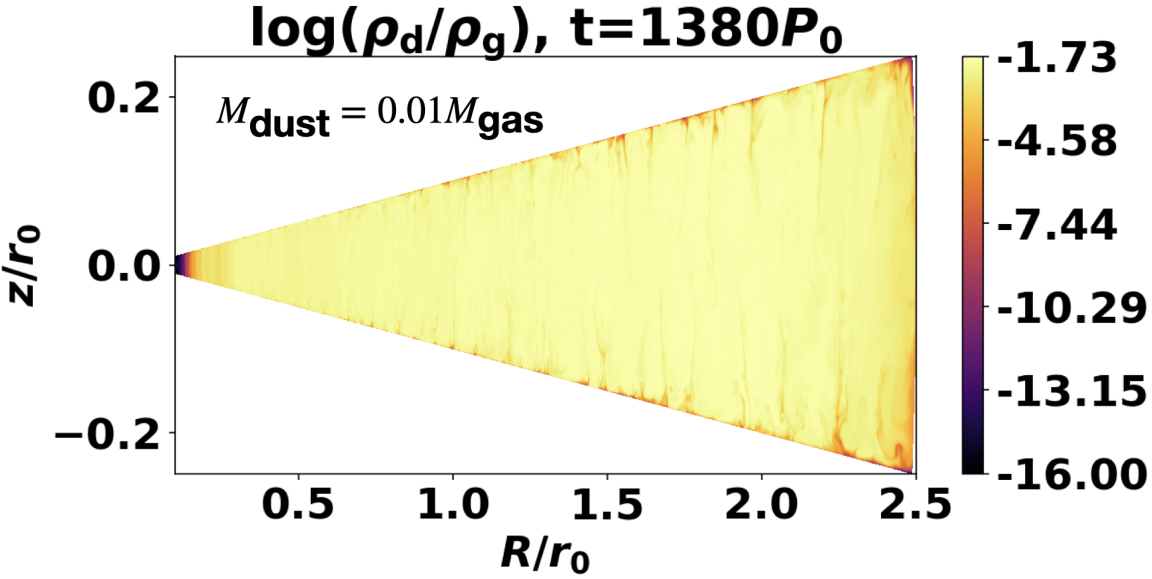
Effect of metallicity (Lin, 2019; one-fluid approx.)



More dust can settle further



New: full two-fluid treatment with FARGO3D



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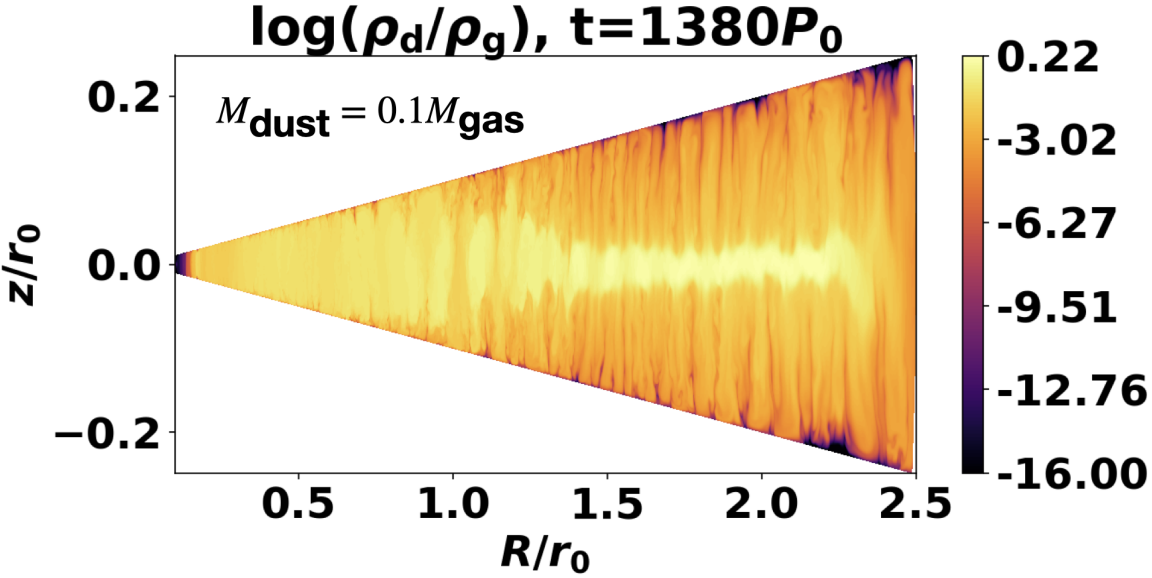
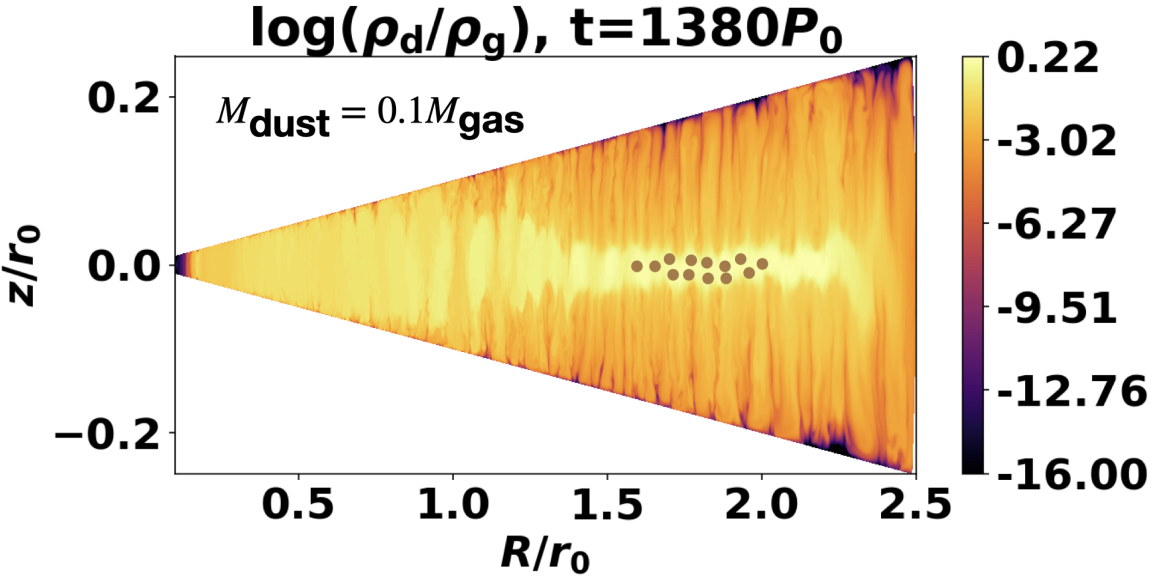


Planetesimal formation in turbulent dust layers?



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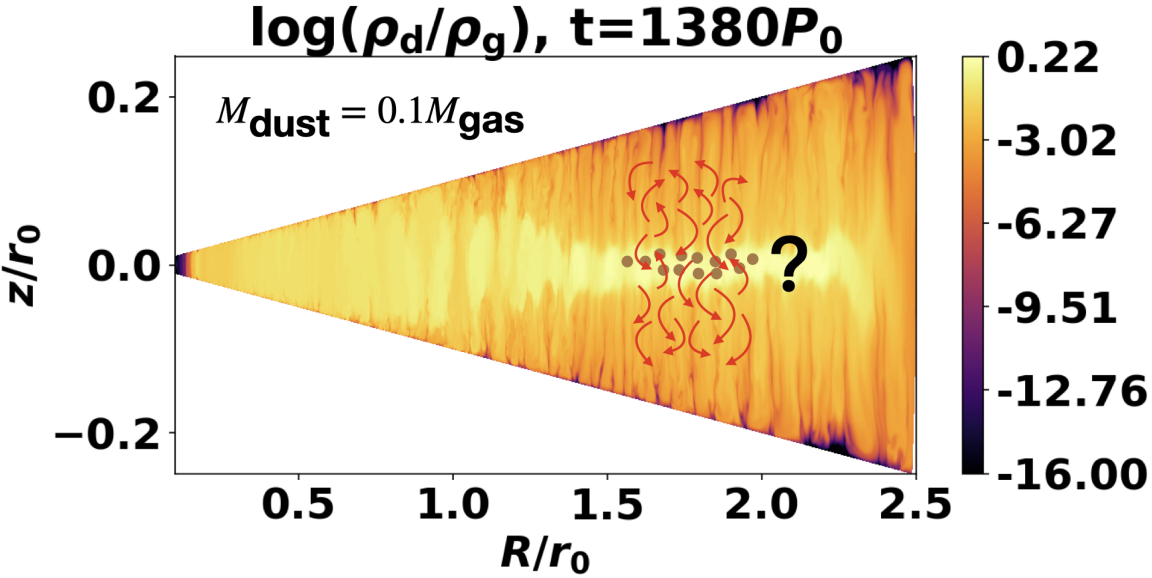
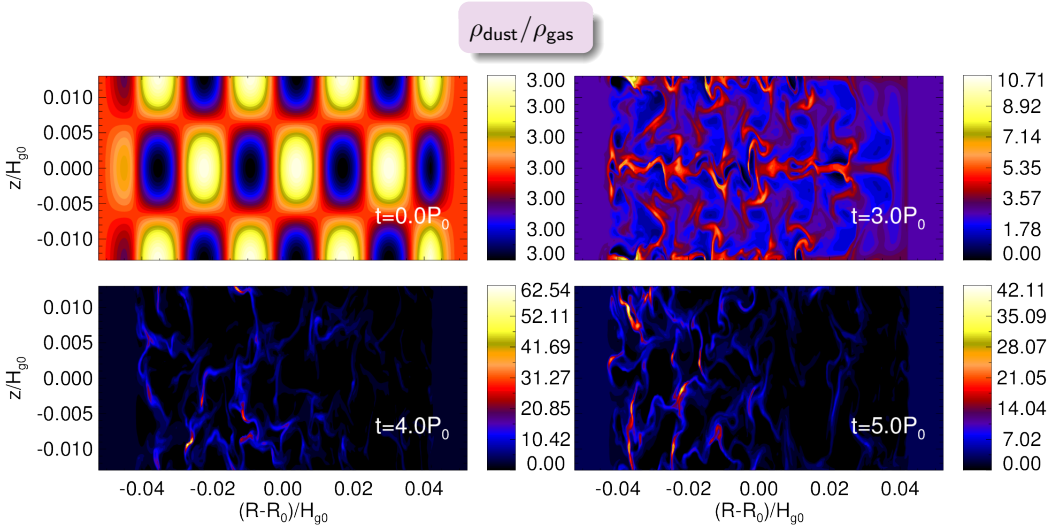
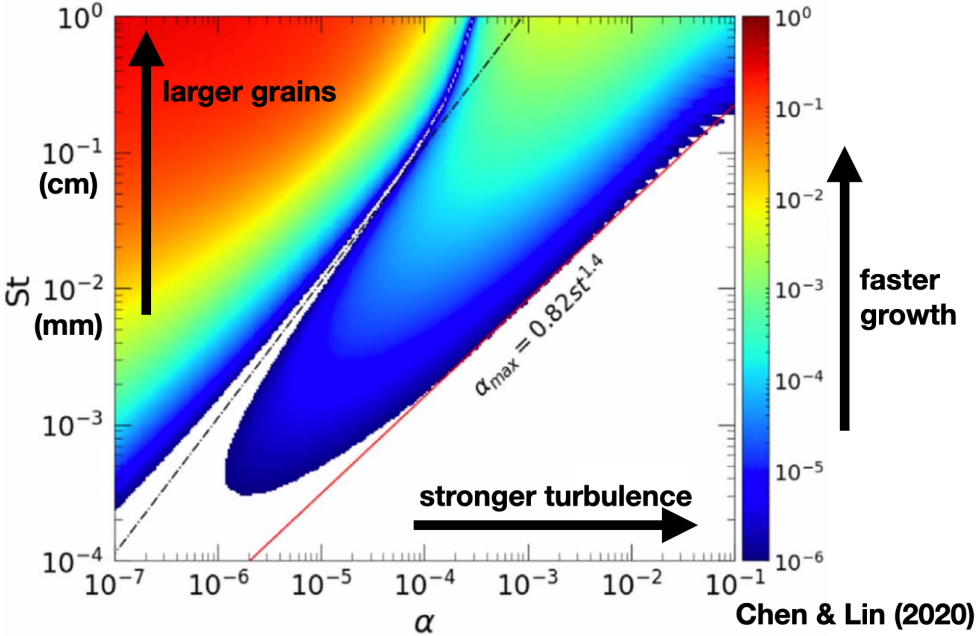


Interlude: efficient treaming instability in laminar disks

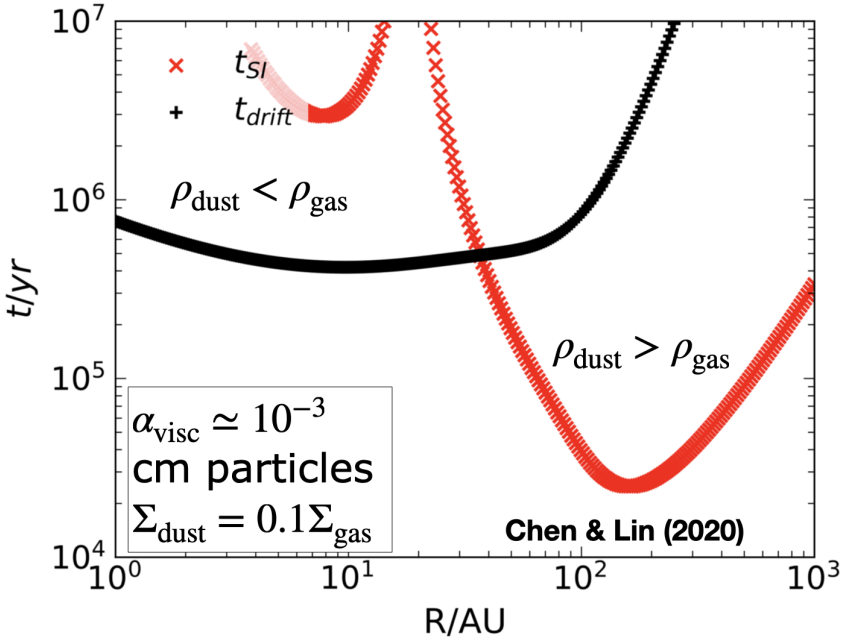


Streaming instability is easily killed by viscosity

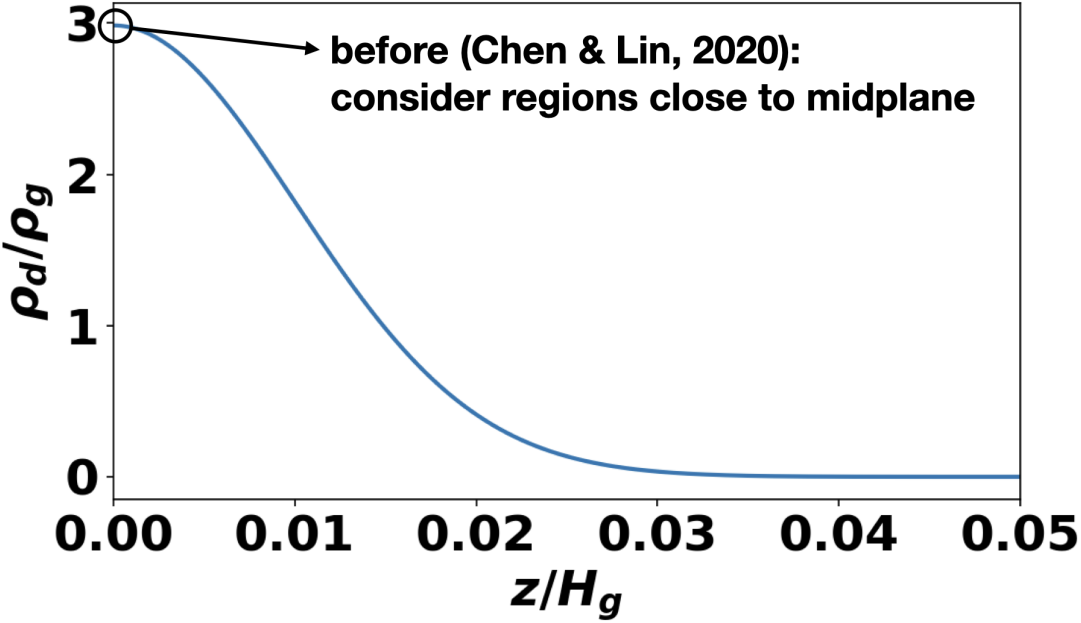


Chen & Lin (2020)

Streaming instability in a MMSN-like disk



A technical caveat



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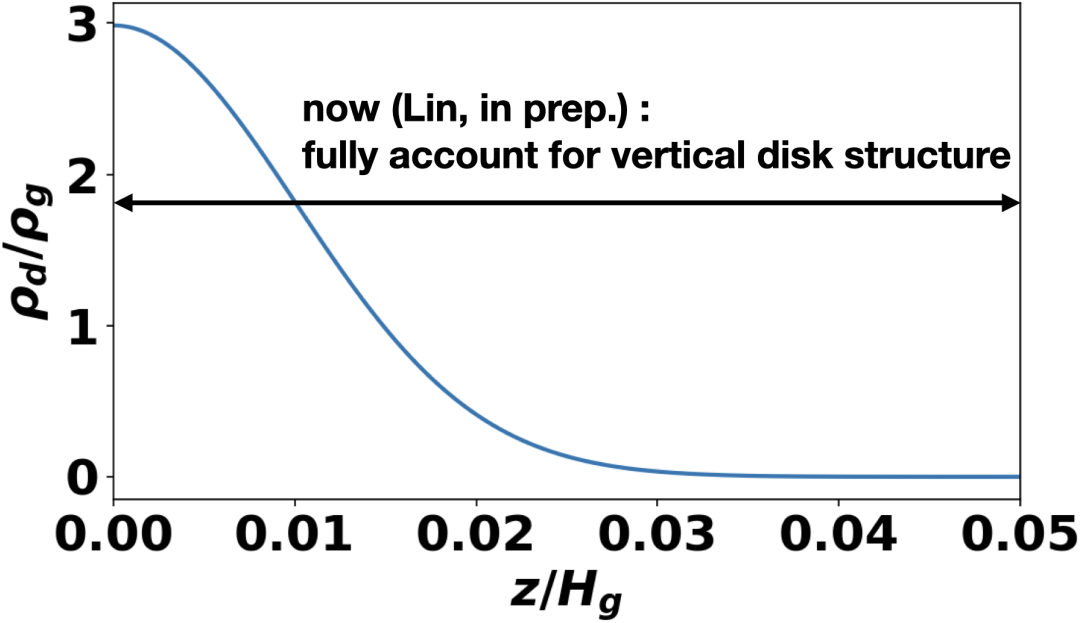
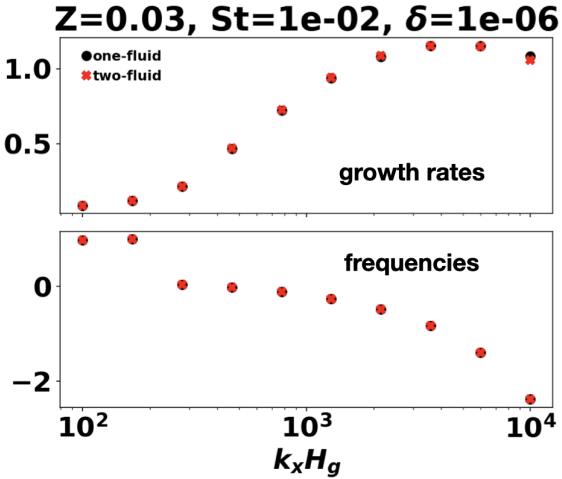
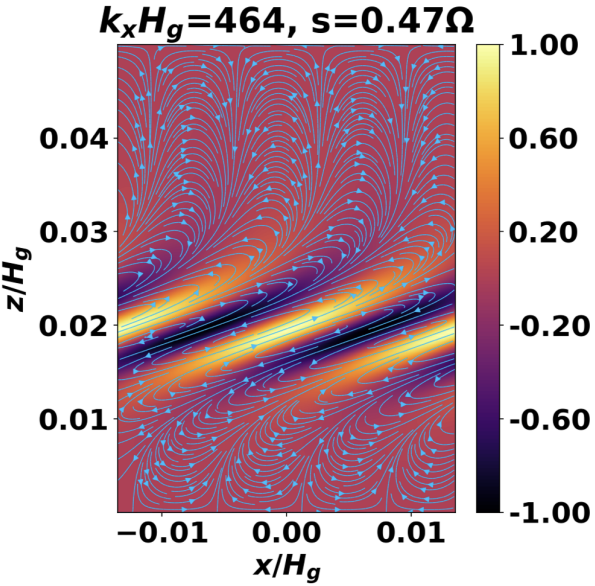
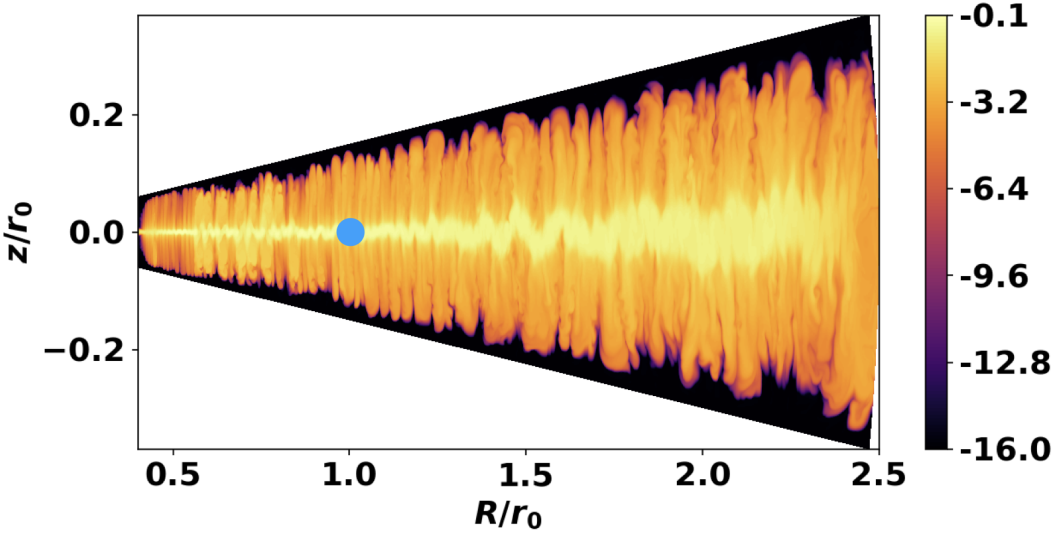


Stratified streaming instability (or is it?)





Anyway, let's assume planets form



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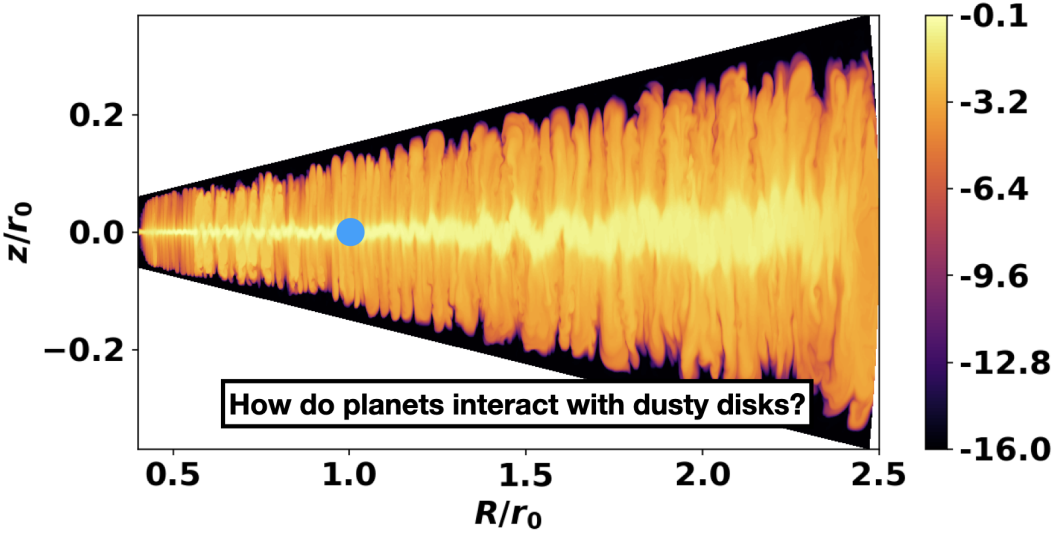
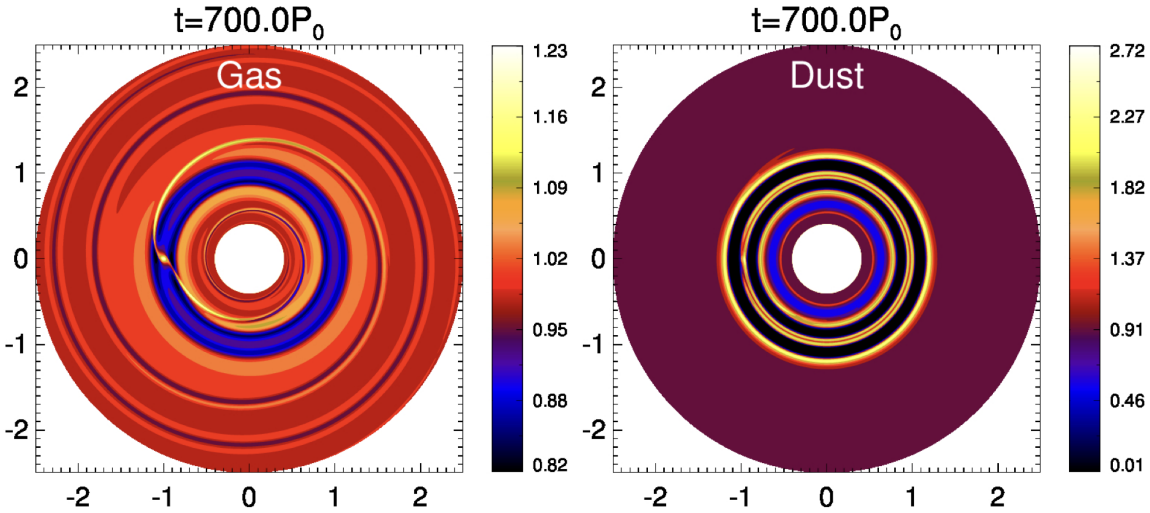
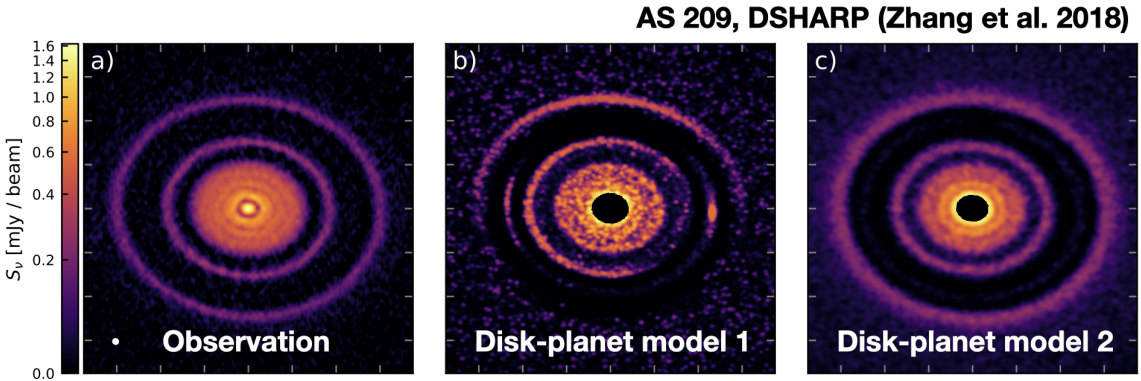


Planet gaps and dust rings

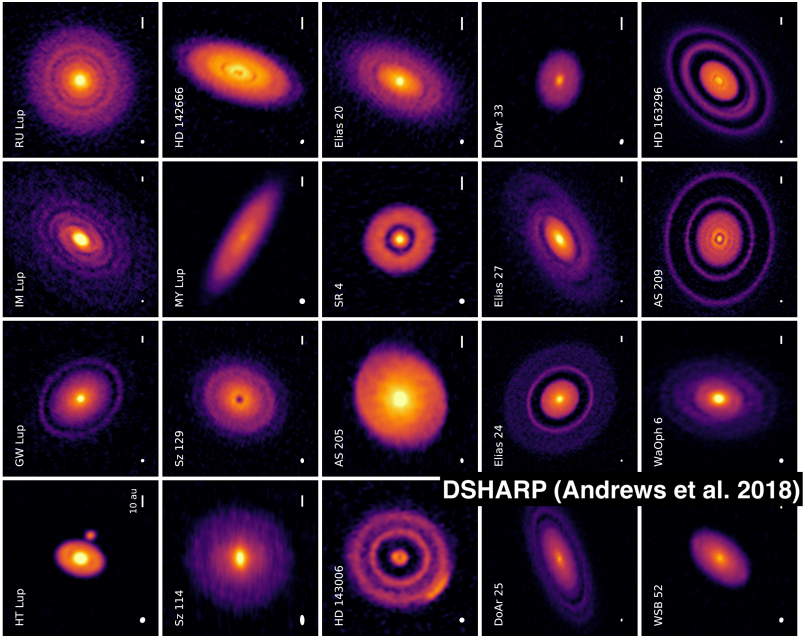


Chen & Lin (2018), one-fluid approx.

Are observed dust gaps made by planets?



Interpreting big data



DSHARP (Andrews et al. 2018)

Empirical relations between gap morphology and planets

- Lodatol et al. (2019): $\text{gap width} \propto (\text{planet mass})^{1/3}$
- Kanagawa et al. (2018): $\text{gap width} = F\,(\text{planet mass}, \text{viscosity}, \text{temperature})$

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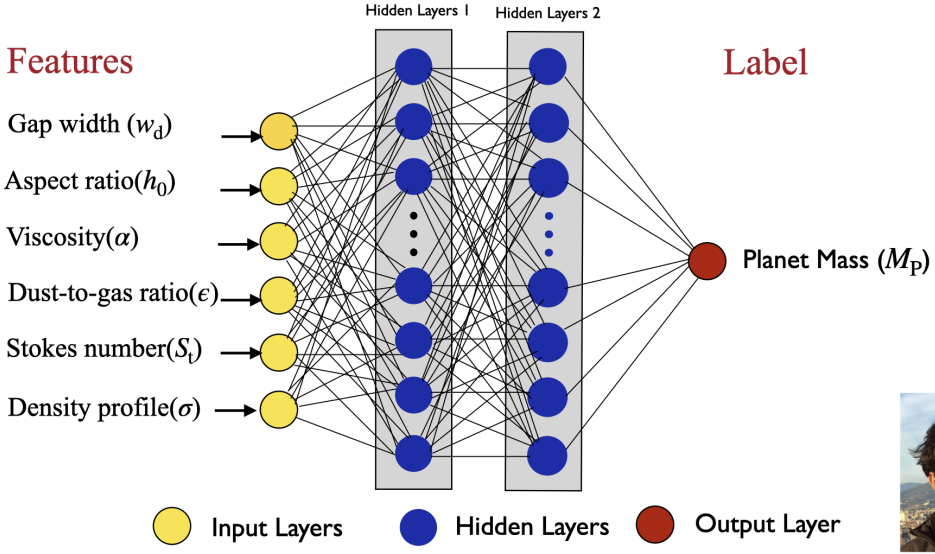
How do we add more physics to describe planet gaps more accurately?

(dust abundance, particle size, disk profiles, etc.)

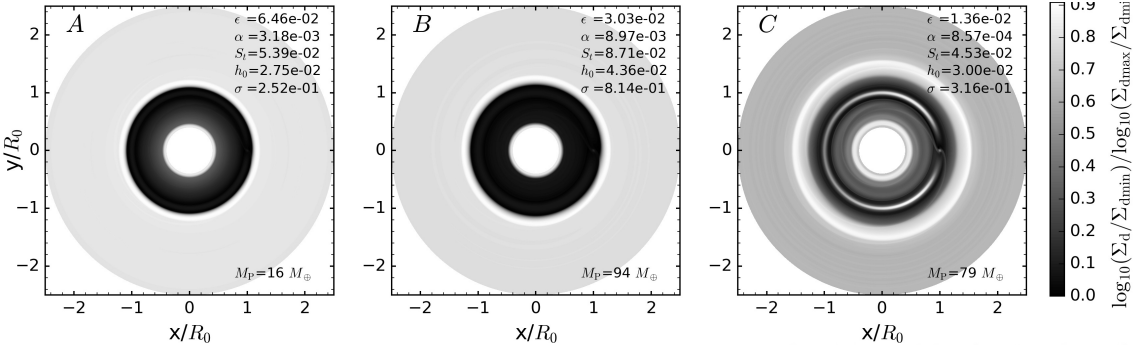
Teaching disk-planet interaction to a machine

Artificial Deep Neural Network



(Sayantan Auddy & Lin, submitted)

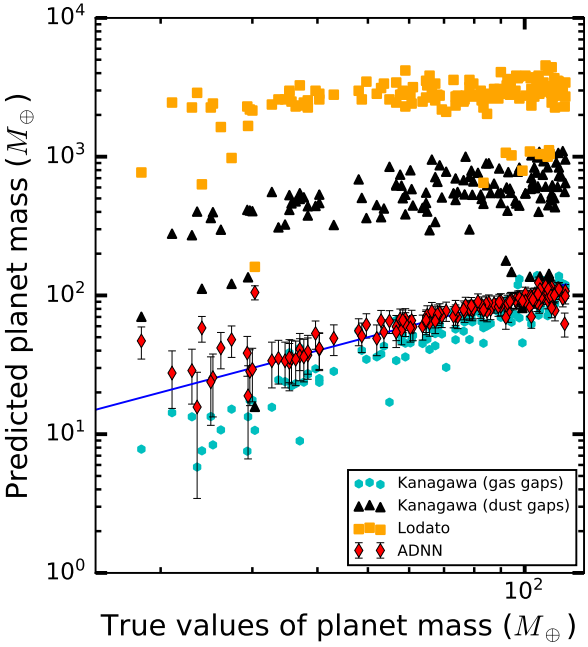
Teaching disk-planet interaction to a machine



Auddy & Lin (submitted)

- Ran $\sim$ 1200 FARGO3D simulations, once and for all
- Use TENSORFLOW to train the ADNN to model gap profiles

Man vs. machine



(Auddy & Lin, submitted)

Planets in the HL Tau disk

- Explicit hydro. sims.
  (Dong et al., 2015; Dipierro et al. 2015; Jin et al., 2016)

  $M_p = 0.2\text{–}0.35 M_J,\ 0.17\text{–}0.27 M_J,\ 0.2\text{–}0.55 M_J$

- Artificial Deep Neural Network
  (Auddy & Lin, submitted)

  $M_p = 0.24 M_J,\ 0.21 M_J,\ 0.2 M_J$

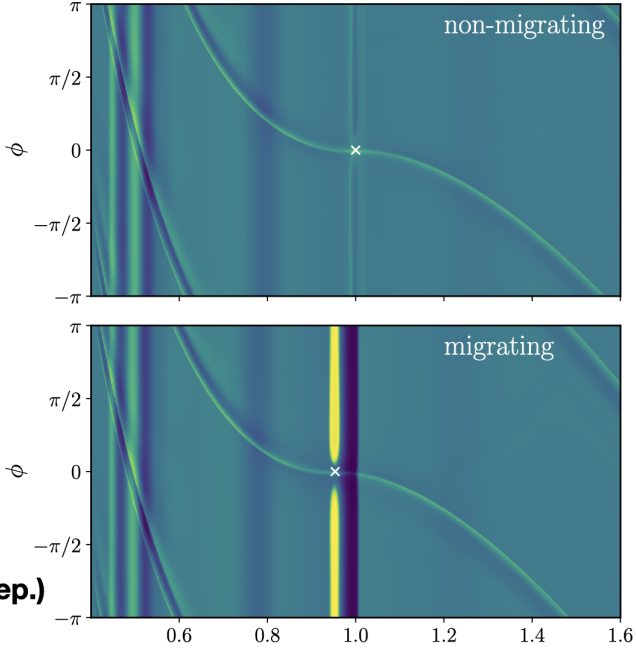
Two simulation caveats

- Planet on fixed orbits
- 2D disks

Migrating planets in dusty disks

$\Sigma_{\mathbf{dust}} = 0.01\Sigma_{\mathbf{gas}}$

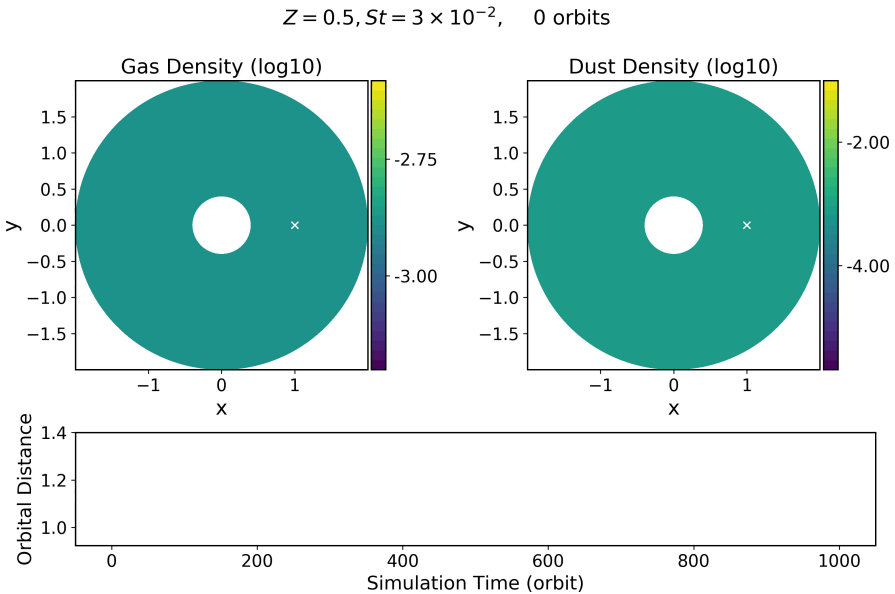
$\mathbf{St} = 0.03$



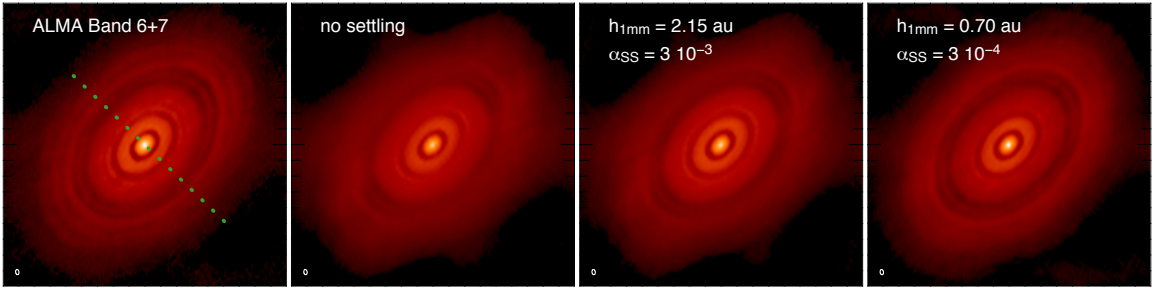
(He-Feng Hsieh & Lin, in prep.)

Can dusty vortices stop planet migration?

Hsieh & Lin, in prep.



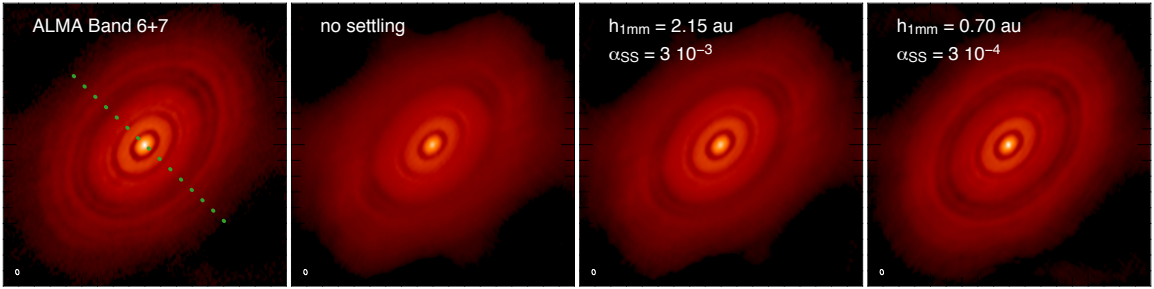
Are dust gaps opened by planets?



(Pinte et al. 2016)

- Well-defined rings ⇒ settled dust

Are dust gaps opened by planets?



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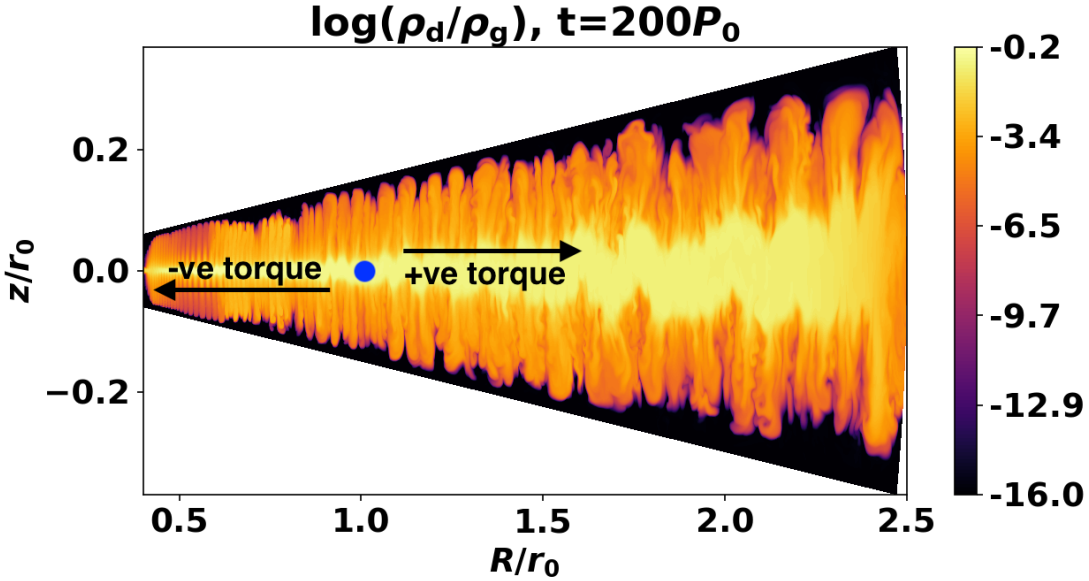
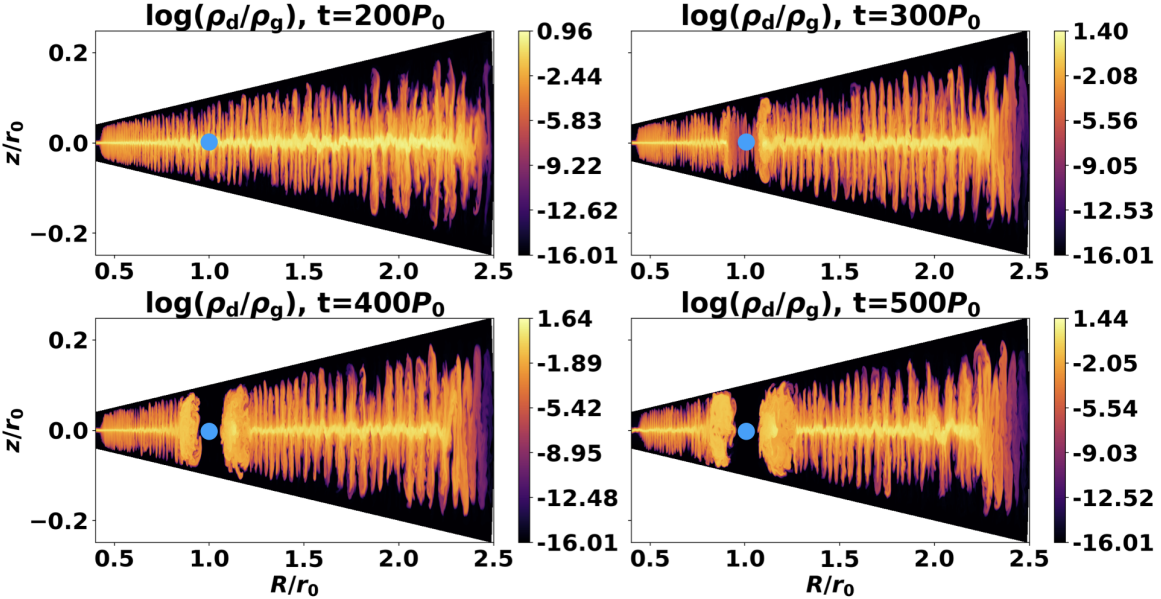
Is dust settling compatible with gap opening?

Gap opening in 3D, dusty disks



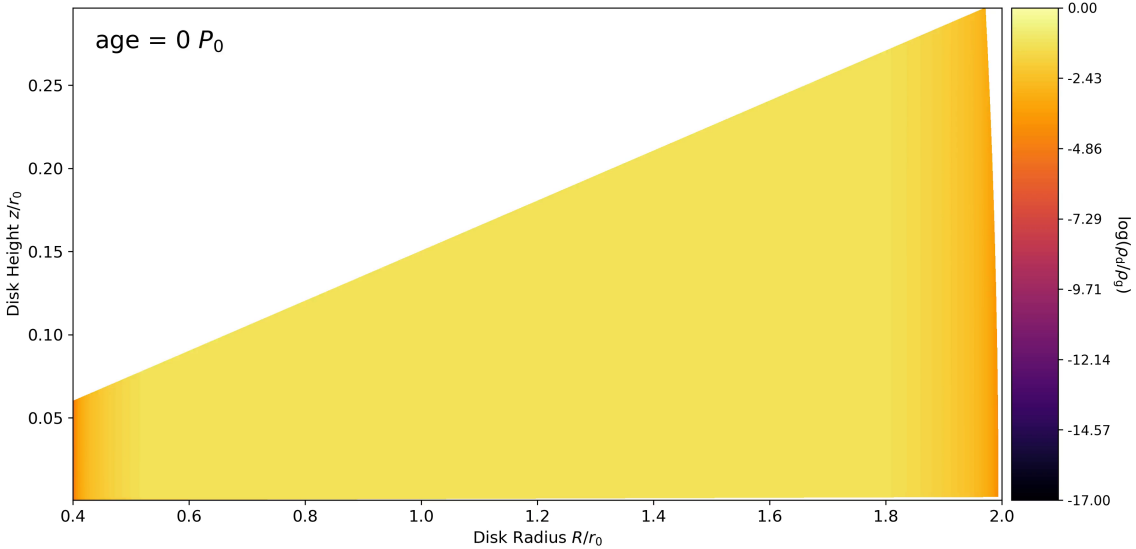
Fake planet-disk simulations

(Lin et al., in prep.)

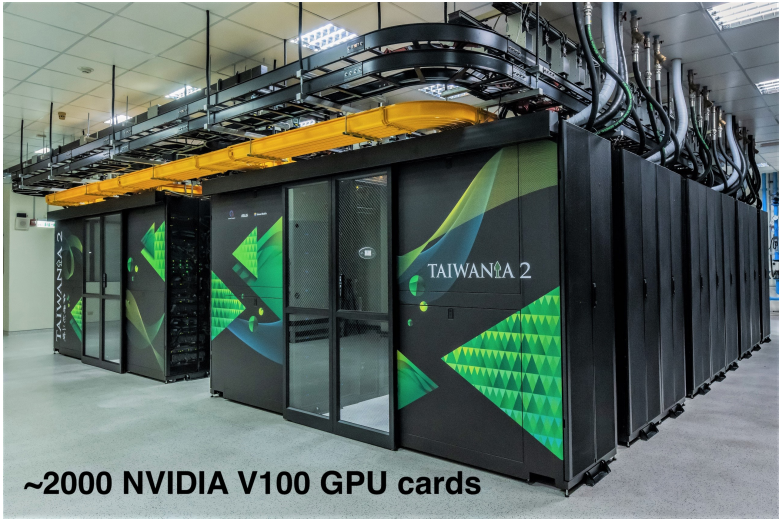


Full 3D simulations

(Jiaqing Bi, Lin, & Dong, in prep.)



Taiwan Computing Cloud



https://www.twcc.ai/
https://www.nchc.org.tw/

Summary

- Dust settling depends on solid abundance (Lin, 2019)
- Planetesimal formation is sensitive to turbulence (Chen & Lin, 2020)
- Machine learning may replace hydrodynamic simulations (Auddy & Lin, submitted)
- Planet migration can be chaotic in dusty disks (Hsieh & Lin, in prep.)
- Dust settling may be difficult around gap-opening planets (Bi, Lin, & Dong, in prep.)

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Thank you

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