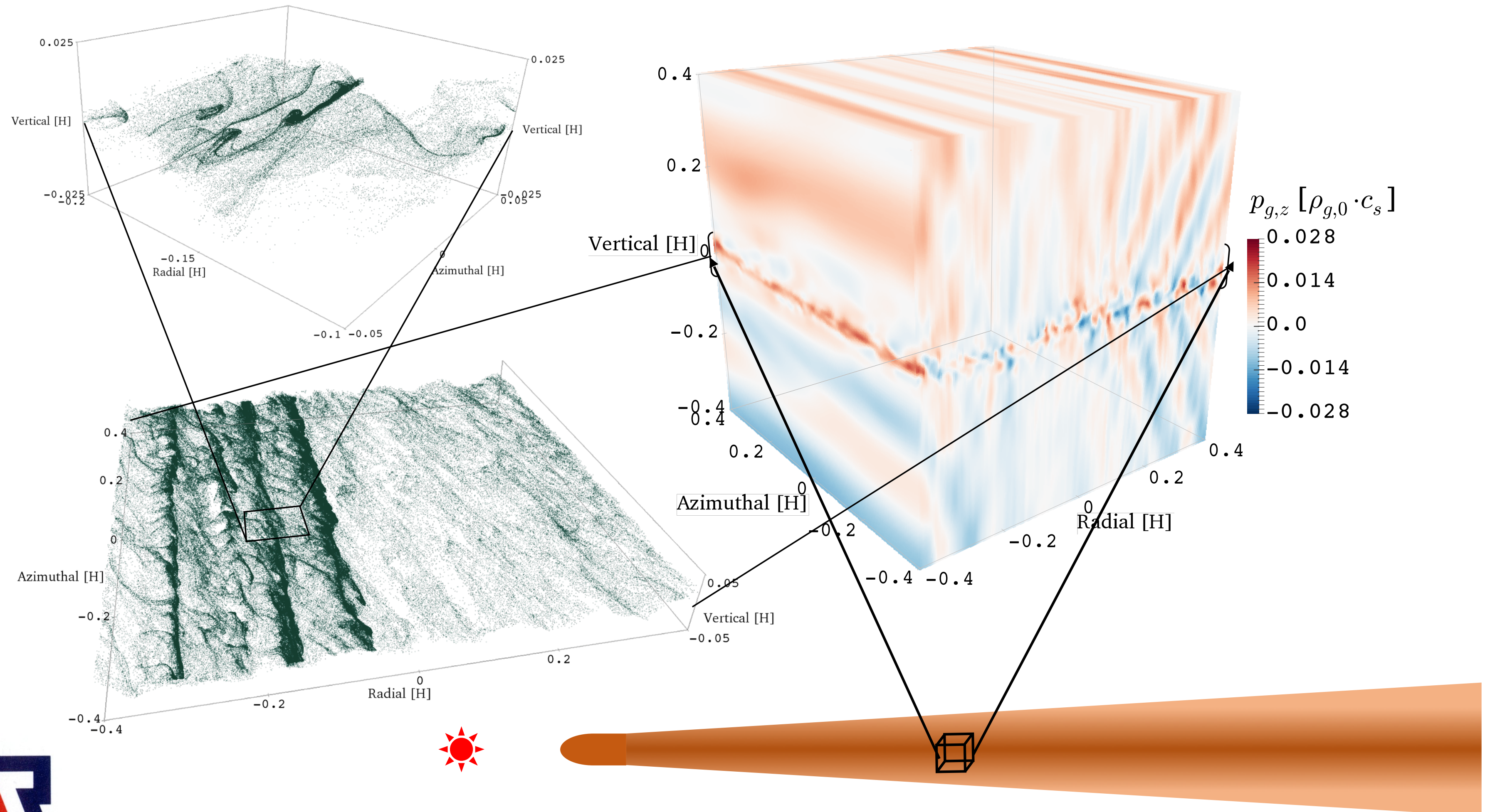
Planetesimal Formation in the ALMA Era

Andrew Youdin

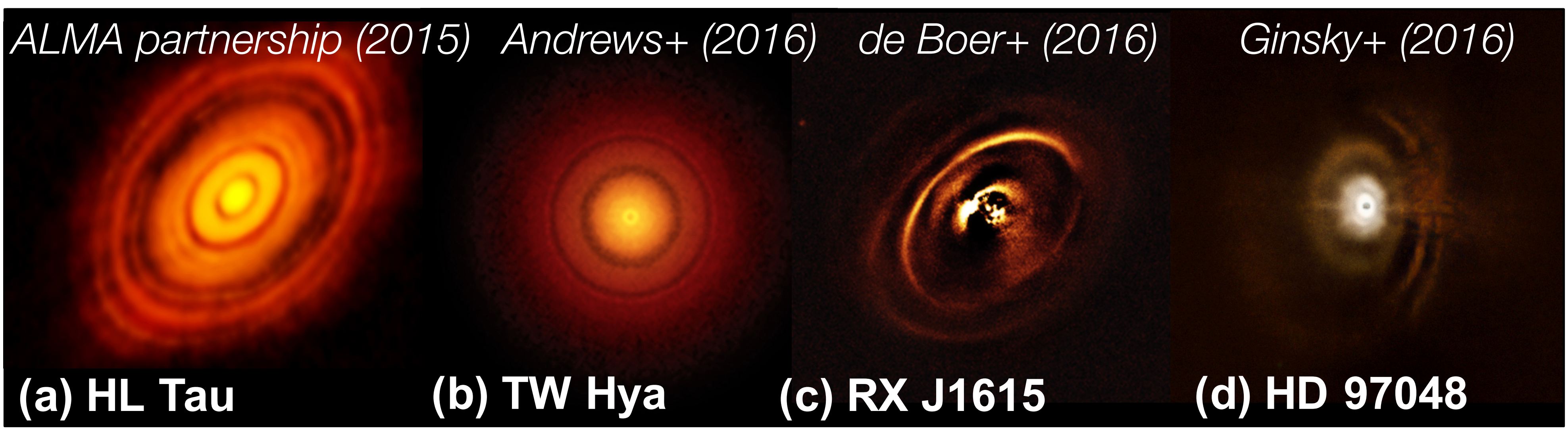


***Rixin Li**, AY & Simon (2018)*

An Unsolved Problem In Planet Formation

- Do imaged structures in disks indicate:
  - dust traps that seed planet formation?
  - (and/)or the effects of already formed planets?

ALMA & SPHERE images (*reproduced in Pinilla & Youdin 2017*)

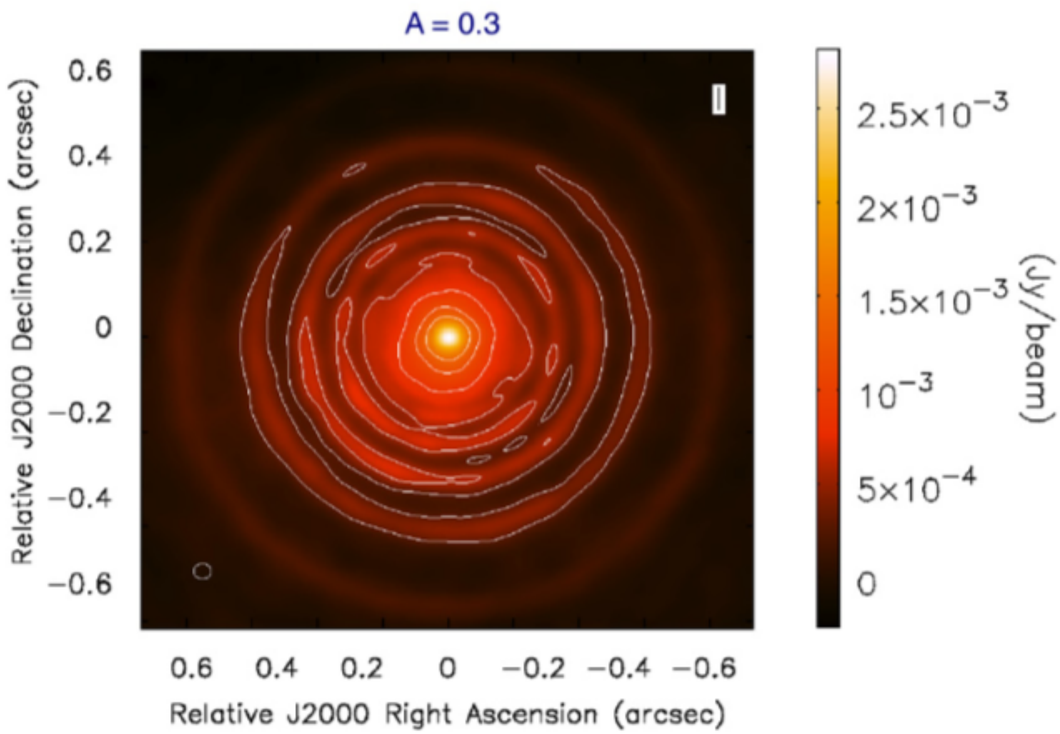


These Rings Were Predicted Theoretically!!! By Pinilla et al. (2012)

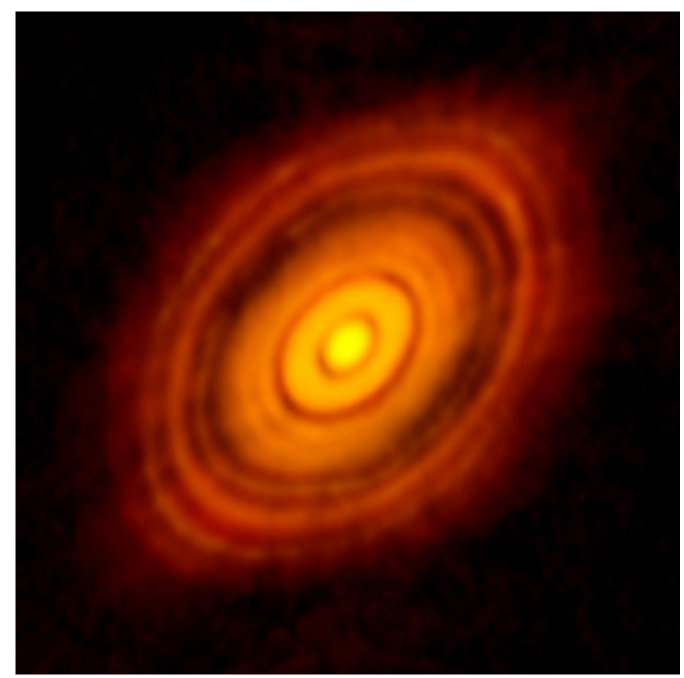
Trapping dust particles in the outer regions of protoplanetary disks

P. Pinilla[1,2], T. Birnstiel[3,4], L. Ricci[5,6], C. P. Dullemond[1,2], A. L. Uribe[2], L. Testi[6,7], and A. Natta[7]

Results. We present the conditions required to trap dust particles and the corresponding calculations predicting the spectral slope in the mm-wavelength range, to compare with current observations. Finally, we present simulated images using different antenna configurations of ALMA at different frequencies, to show that the ring structures will be detectable at the distances of either the Taurus Auriga or Ophiucus star-forming regions.

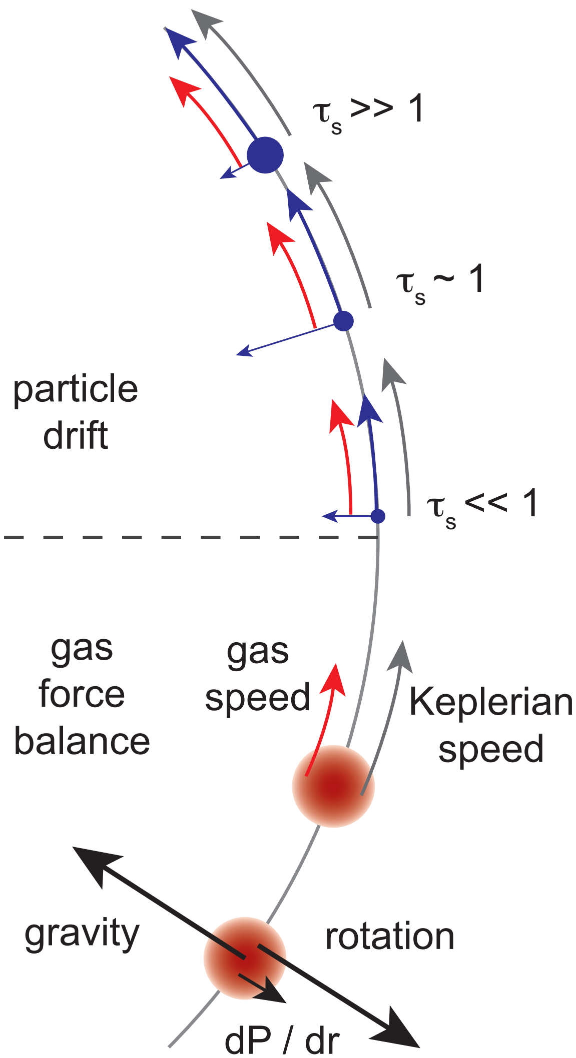


Pinilla et al. (2012)



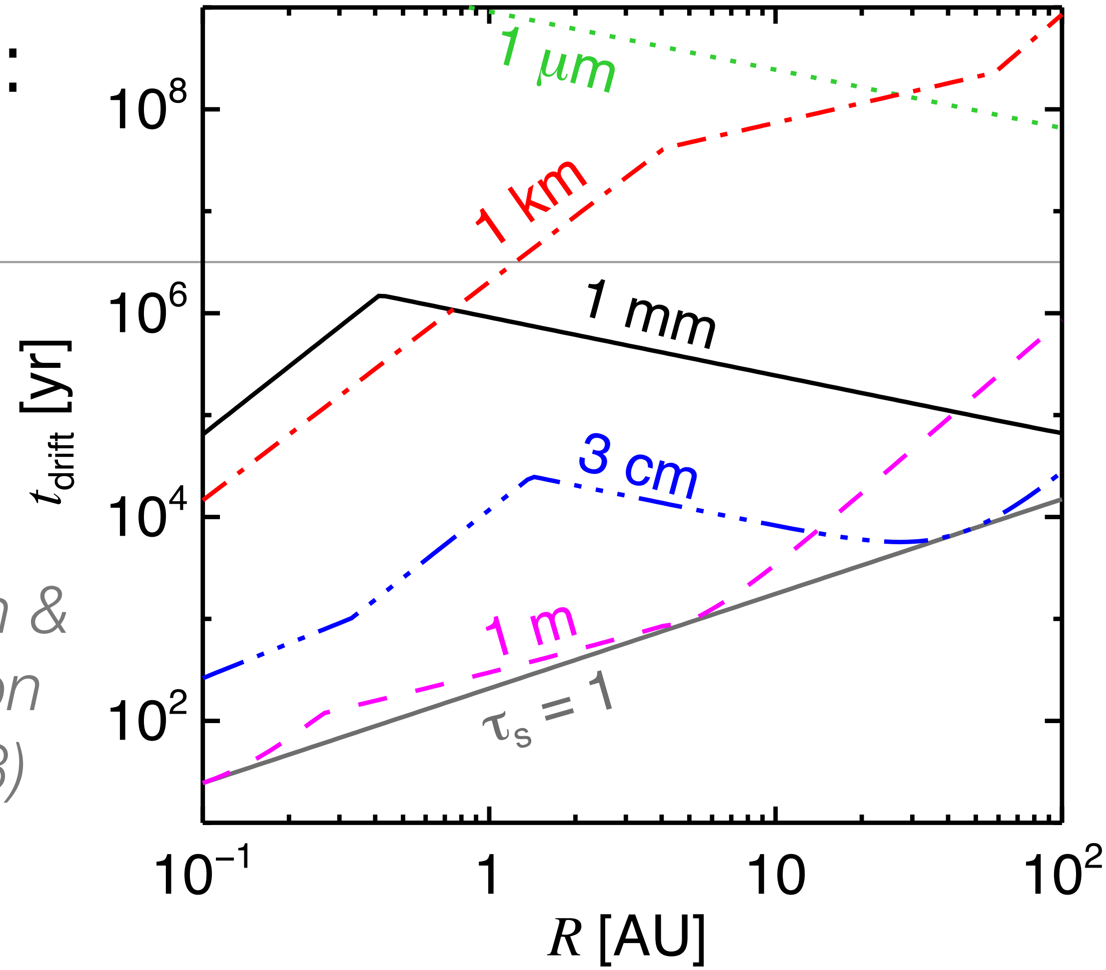
ALMA Partnership (2015)

The radial drift problem: or "meter-size barrier"



Armitage (2015)

Youdin & Kenyon (2013)



- Observed **mm-dust lifetimes** require dust traps and/or collisional grinding.
- Bypassing this meter-size barrier is the key problem in **planetesimal formation**.

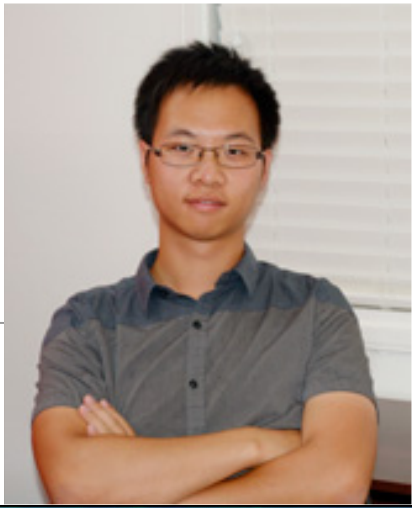
(Main) Planetesimal Formation Options: Overcoming the Meter-Size Barrier

- Rapid **Coagulation**
  - Implausible at ~meter-sizes, as demonstrated by experiments *(Blum 2018)*
- **Gravitational Collapse** of Dust Layer *(Goldreich & Ward 1973; AY & Shu 2002)*
  - May require **particle concentration**
    - **Gas traps**, i.e. vortices or pressure bumps *(Whipple 1972)*, possible "chicken vs. egg" problem
    - **Streaming Instability**: Radial drift as a feature not a bug *(AY & Goodman 2005; Johansen & AY 2007)*
    - **Secular GI**: particle self-gravity + gas drag could slowly collect dust in rings *(Ward 1976; AY 2011; Takahashi & Inutsuka 2014, 2016); Li & AY [in prep])*

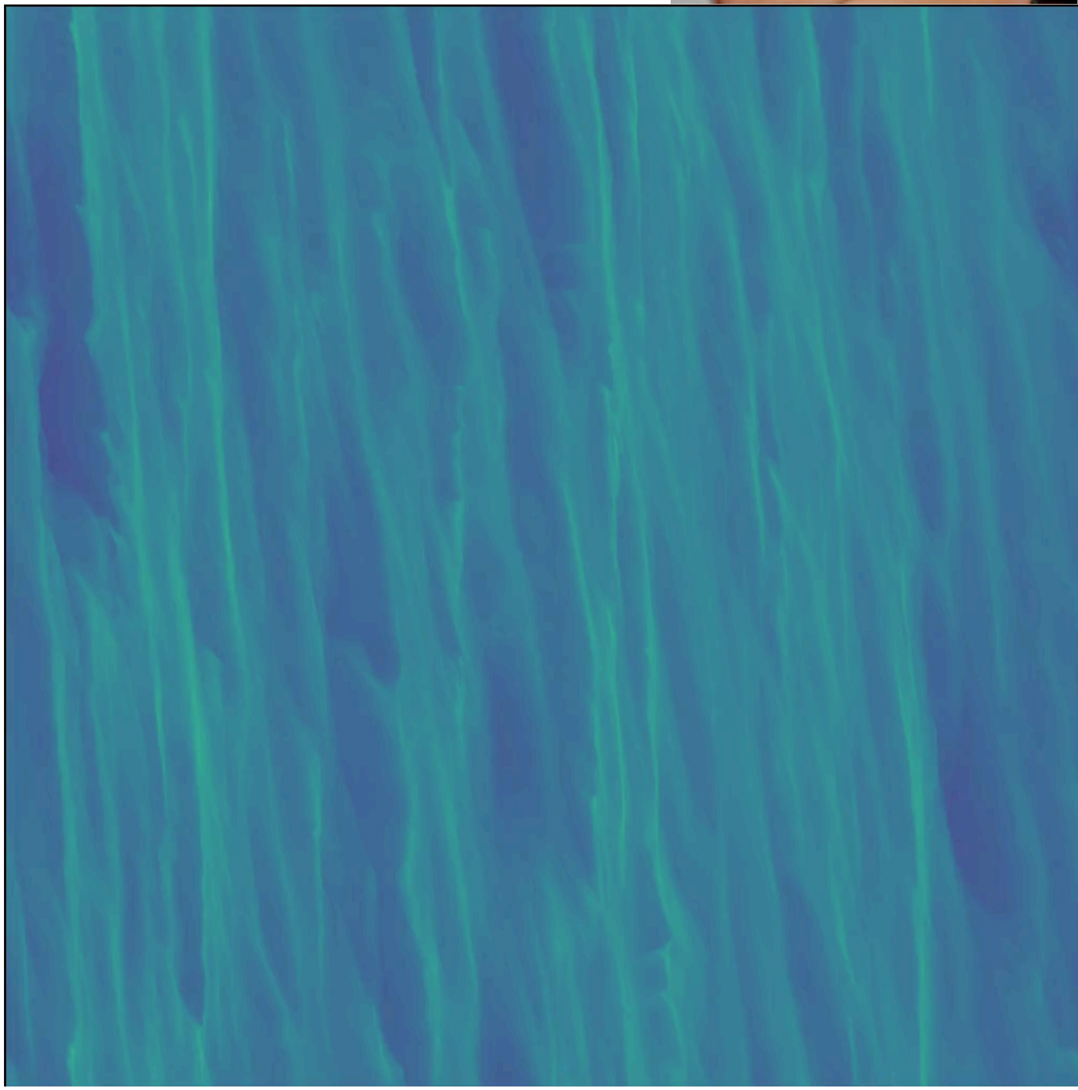
What is the Streaming Instability?

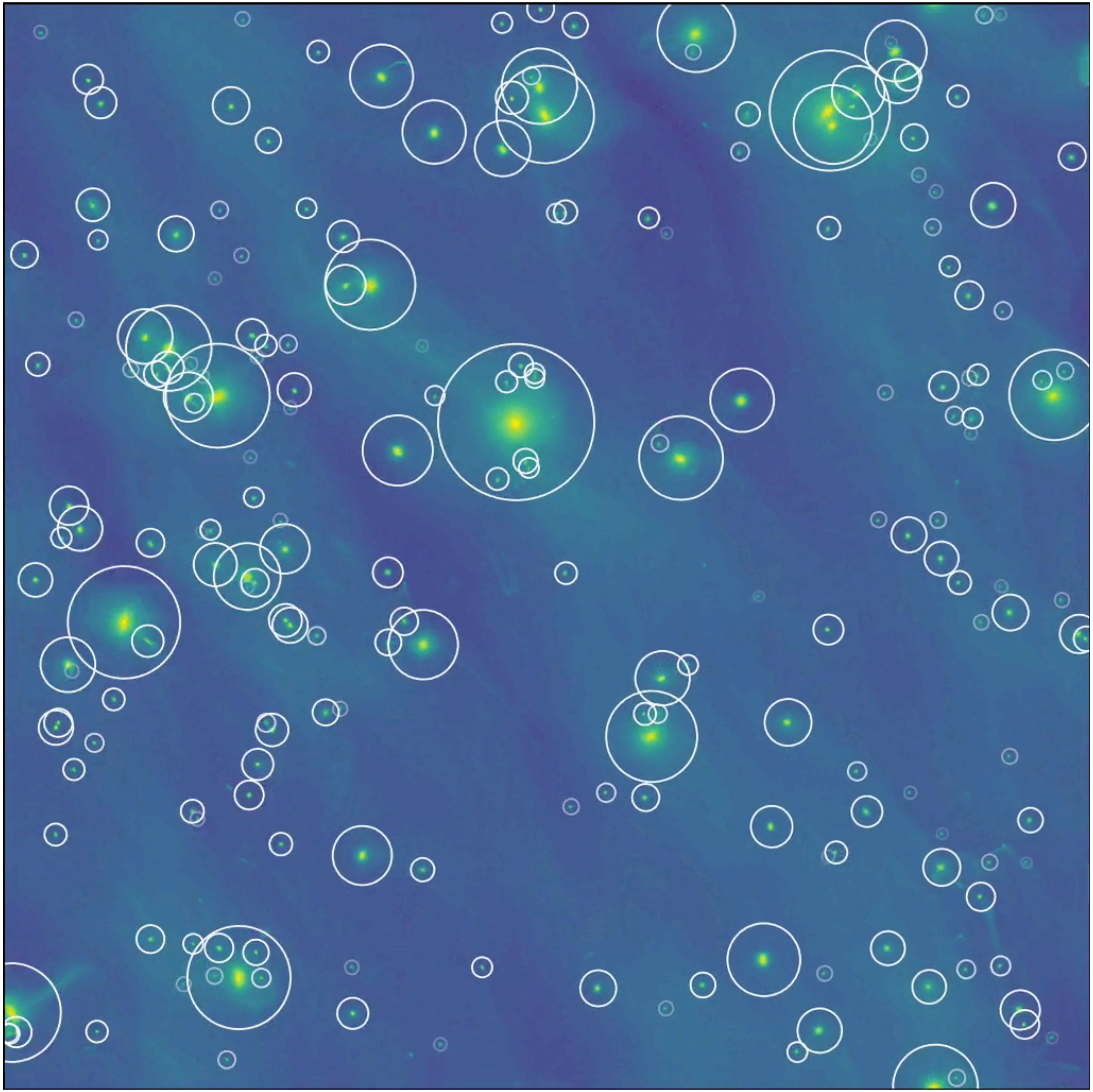
- A mechanism to aerodynamically concentrate pebbles and boulders in disks
  - Must include: two-way drag forces (solids/gas) & radial pressure gradients
- Linear growth discovered analytically *(AY & Goodman 2005)*
  - New analytic insights *(Squire & Hopkins 2017, Lin & AY 2017)*
- Strong, non-linear particle clumping in simulations IF enough pebbles or boulders in disk *(Johansen & AY 2007, Johansen et al. 2009)*
  - Self-gravity causes clumps to fragment into planetesimals
- Lots of work on resulting size distributions *(Simon et al. 2017)* and binary KBOs *(Nesvorný et al. 2010)*

Gravitational Collapse of Streaming Instability Clumps

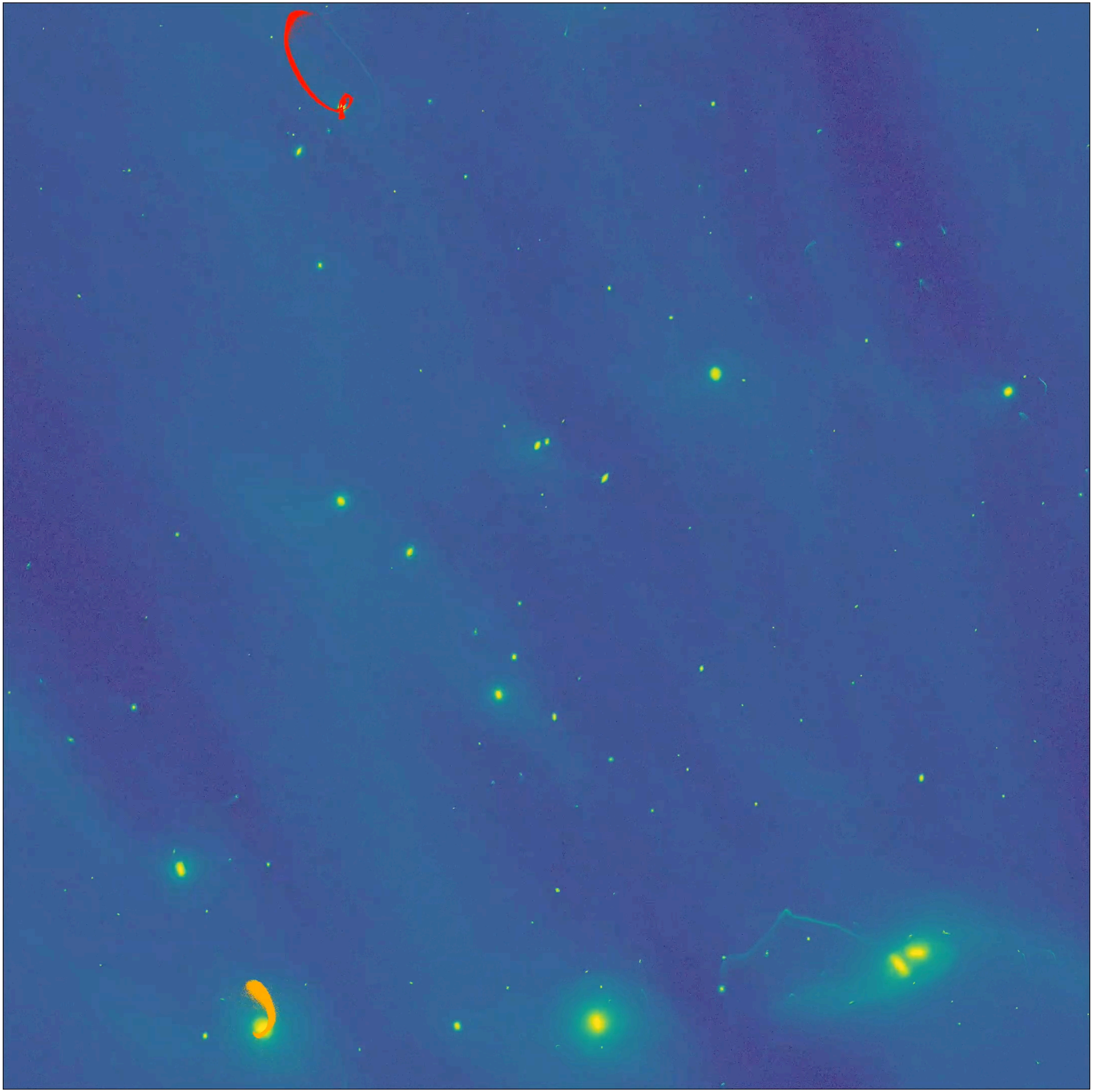


- **Simulation**: Athena w/ particles (Bai & Stone, 2010, Li et al. 2018)
- **Clump finding algorithm**: `PLAN`, by Rixin Li *https://github.com/astroboylrx/PLAN*
  - Based on HOP algorithm *(Eisenstein & Hut1998)*
- **Visualization**: particle density in x (radial) - y (azimuthal) plane, with circled Hill radii





At later times, these planetesimal formation simulations come to resemble galaxy mergers



Conclusions

- Unclear to what extent **planet formation** has already proceeded in observed **protoplanetary disks**.
    - High resolution **ALMA & scattered light images** raise the stakes, but do not yet answer the question.
- One option: rapid **planetesimal formation**, triggered by streaming instabilities, kicks starts the formation of ice and gas **giant planets that cause observed disk structure**.
    - Another option: planet formation proceeds more slowly. **Disk rings** are the **cause***, not the effect, of **planet formation**.
        - * : (in turn caused by MHD or secular particle gravitational instability)