The Formation of Planetesimals

and Large Cores

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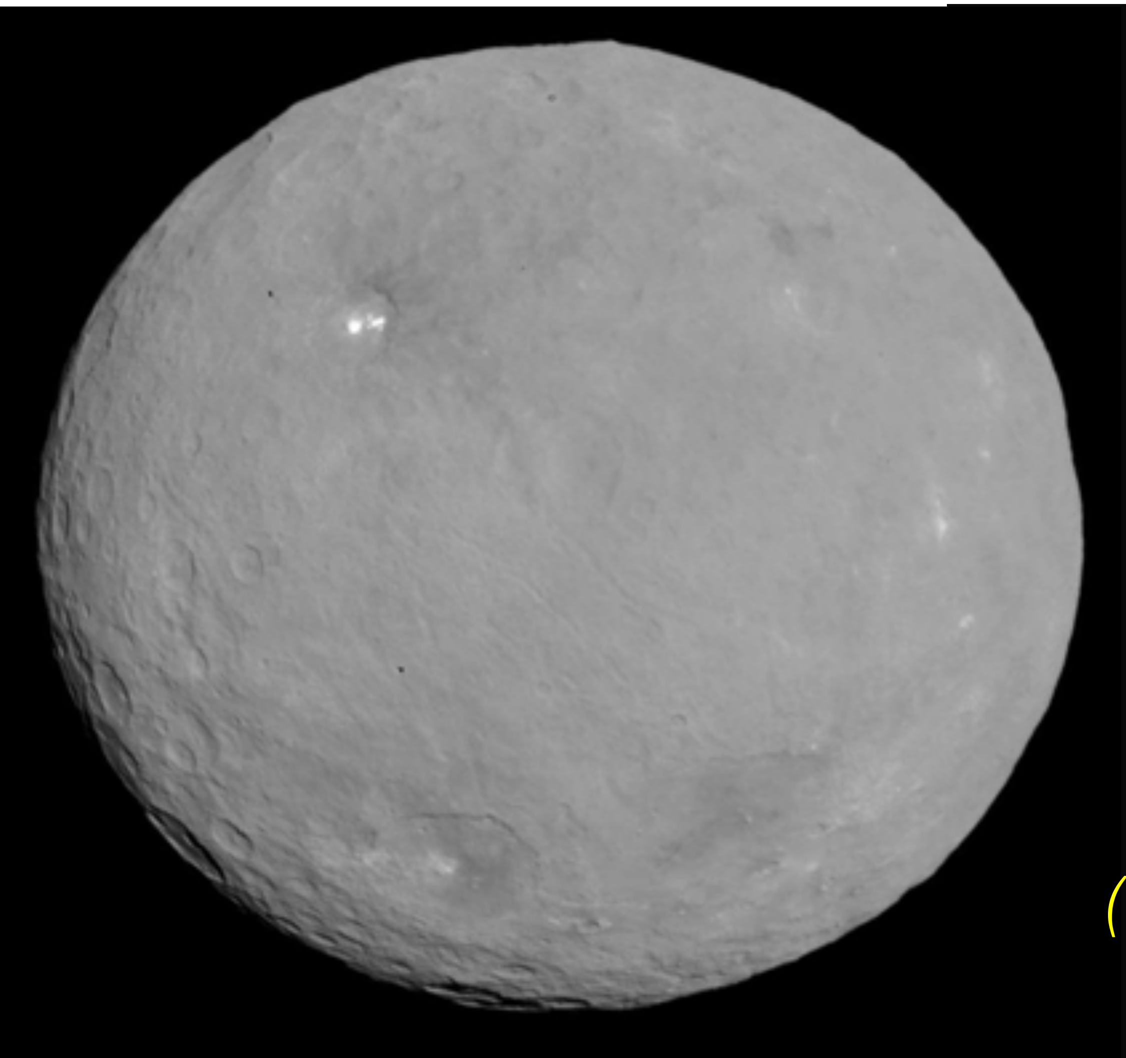
STEWARD OBSERVATORY

THE UNIVERSITY OF ARIZONA

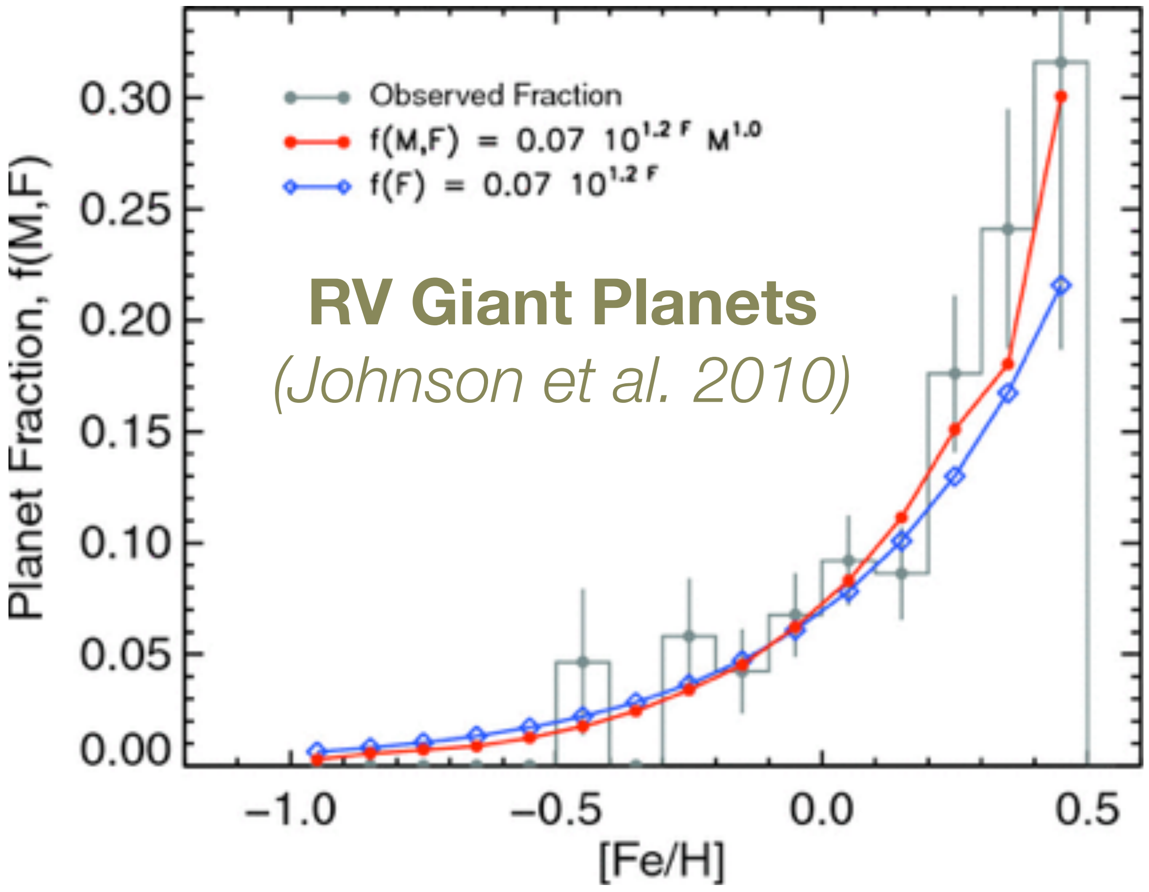
TAP

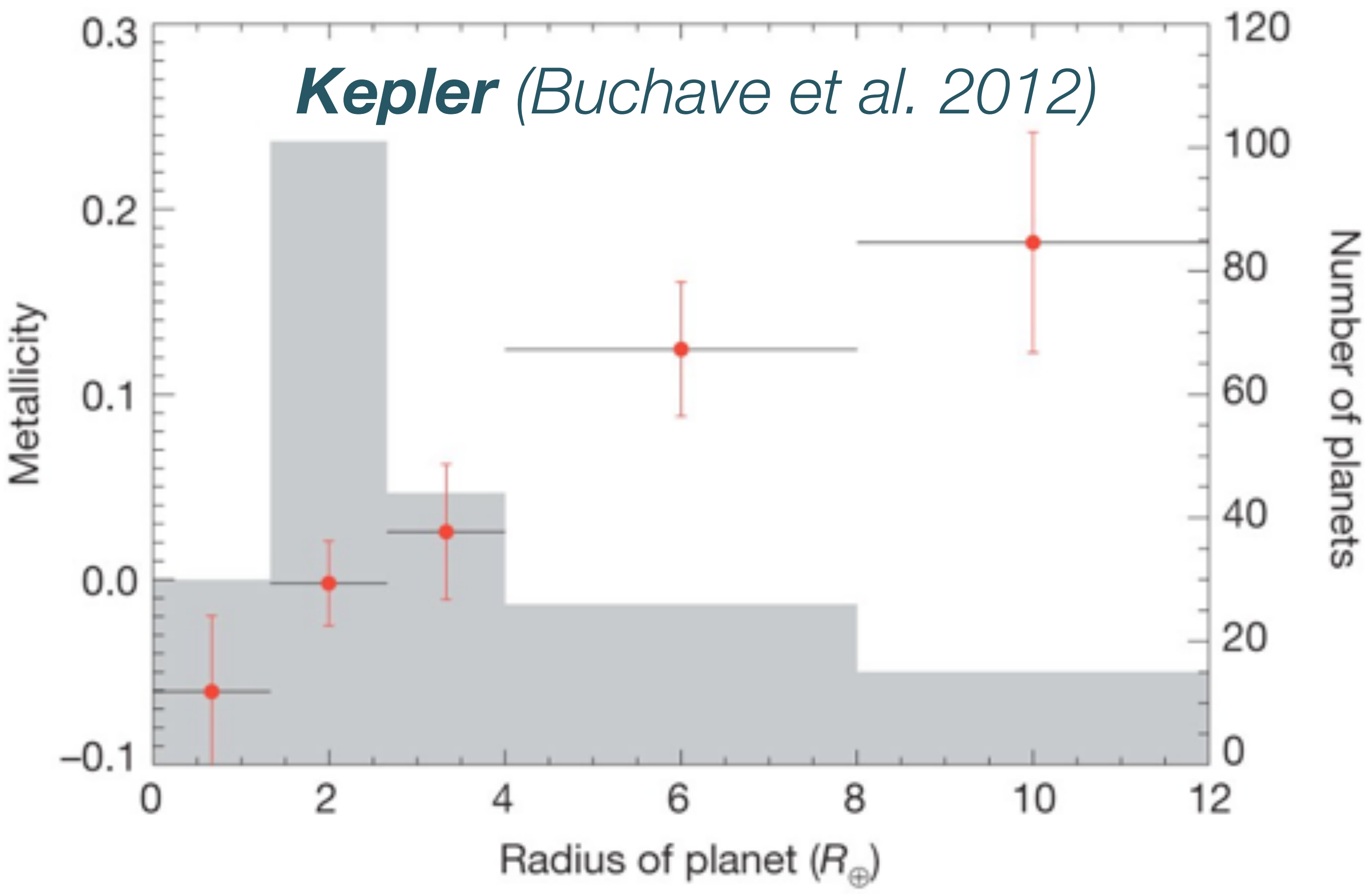
THEORETICAL ASTROPHYSICS PROGRAM



(Youdin & Kenyon, 1206:0738)

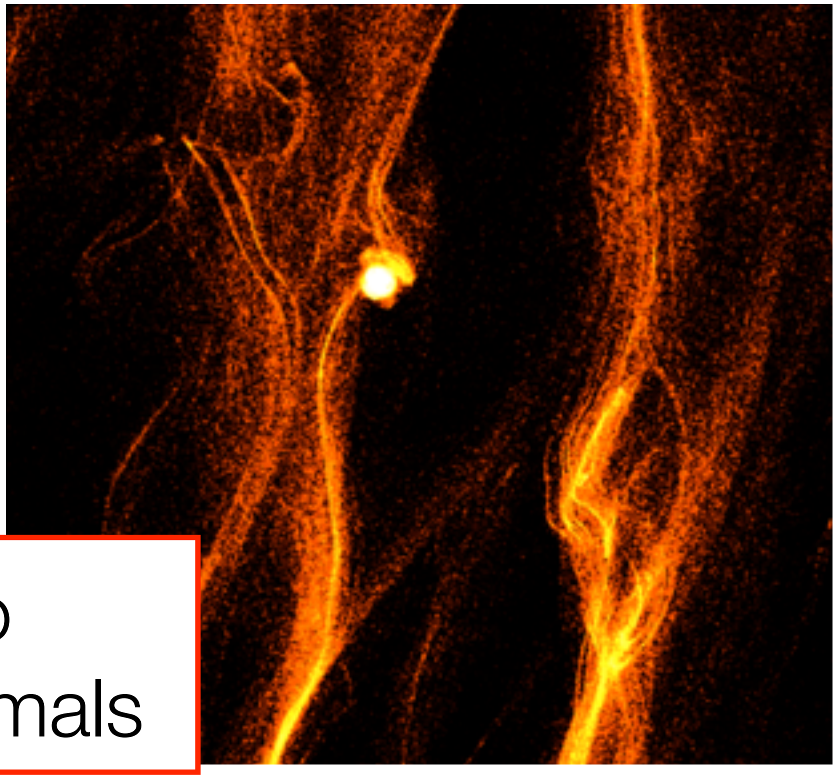
Giant Planets are More Common Around Metal Rich Stars





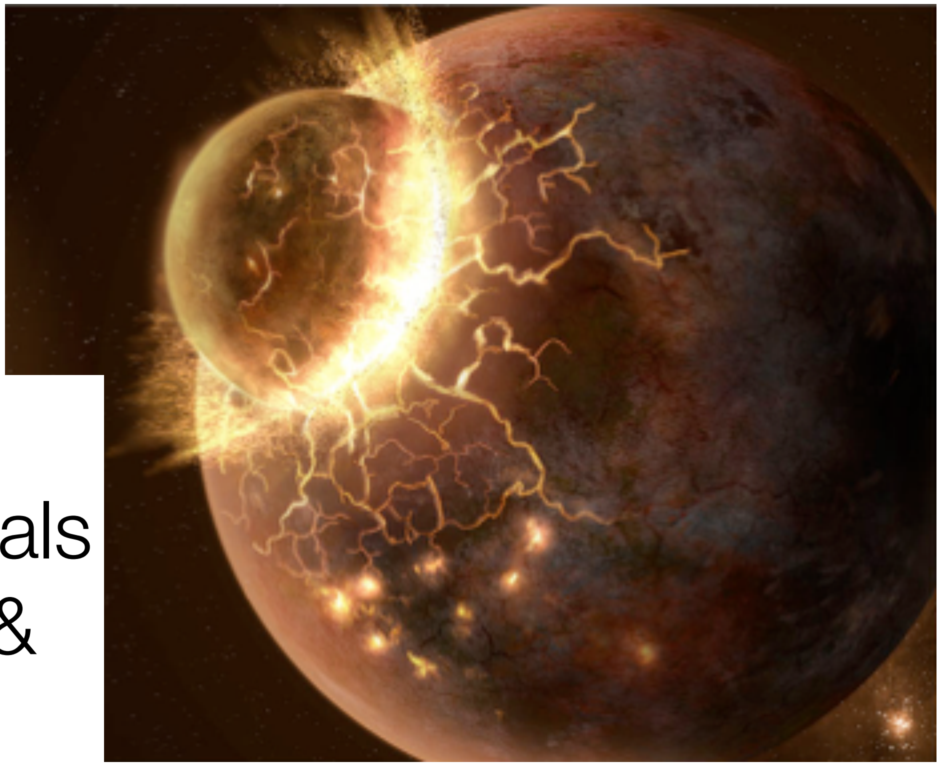
Formation of Solid Planetesimals Holds the Key!

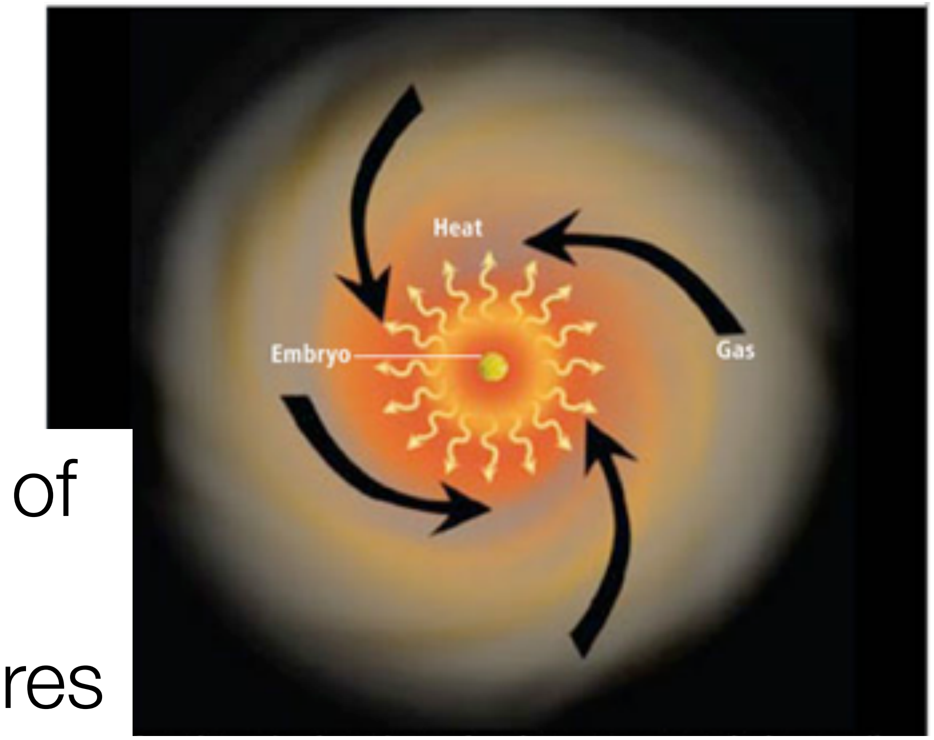
Four Stages of Planet Formation:
The Core Accretion Model



1. Dust to Planetesimals

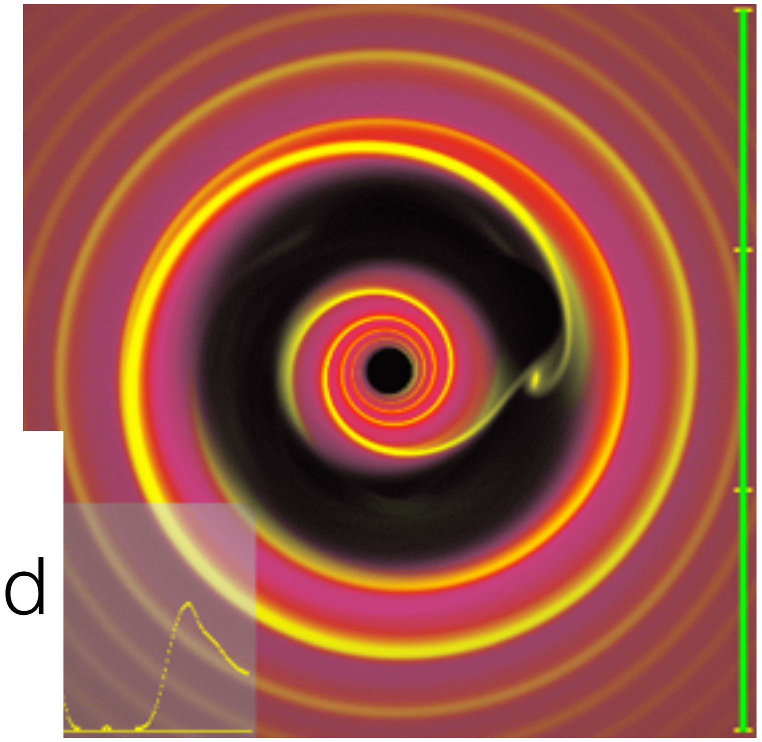
2. From Planetesimals to Planets & Cores





3. Growth of Gas Giant Atmospheres

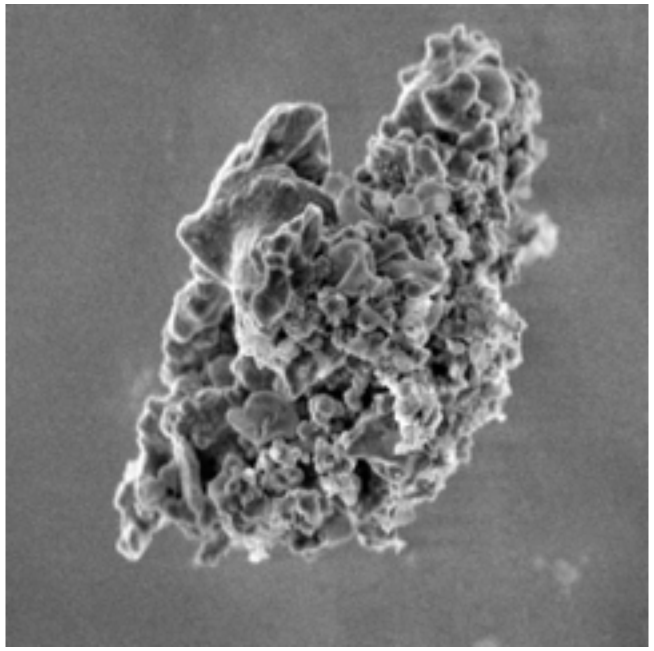
4. Planet Migration and Scattering



Credits: A. Johansen, F. Sulehria, D. Lin, P. Armitage

Planetesimal Formation Spans Many Orders of Magnitude and Different Processes

μm dust



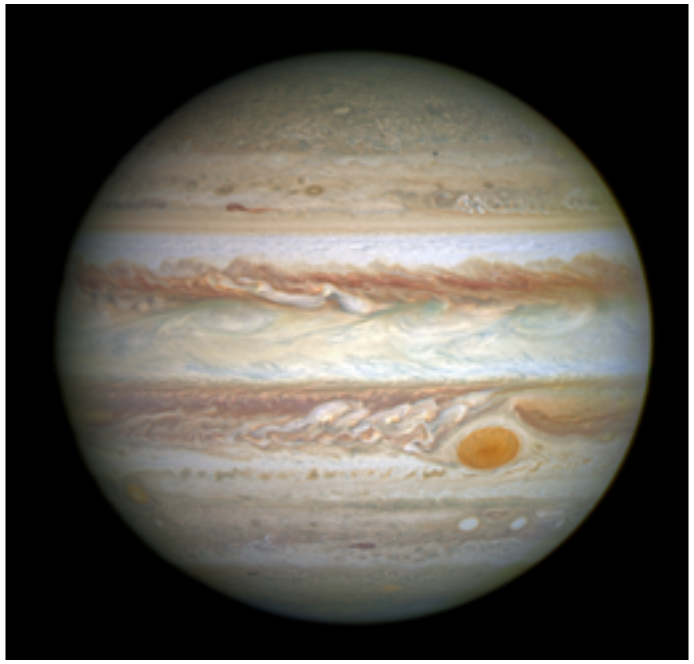
50 km planetesimal

mass growth

$\times 10^{33}$

50 km planetesimal

M_{Jup} Giant Planet



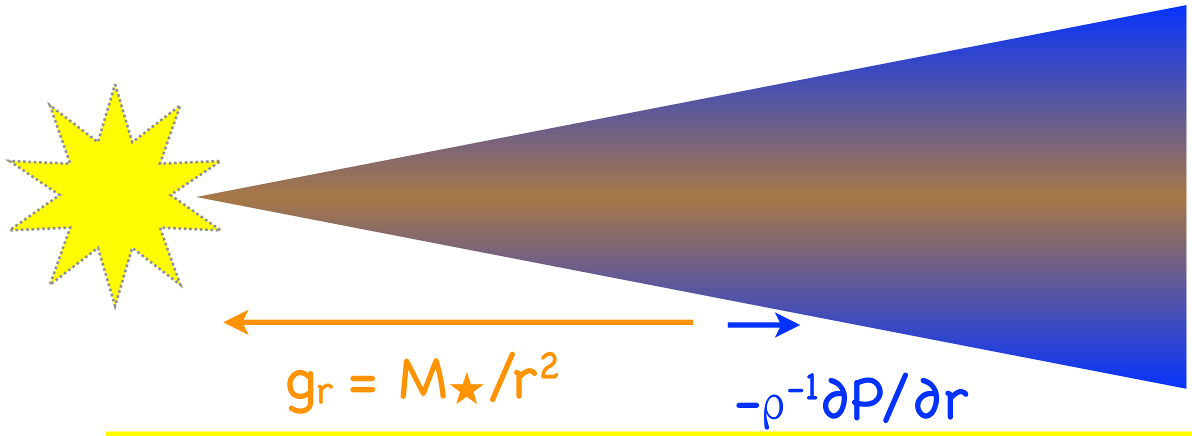
mass growth

$\times 10^{9}$

Key Aspects of Planetesimal Formation: Starting Small in a Gas Disk

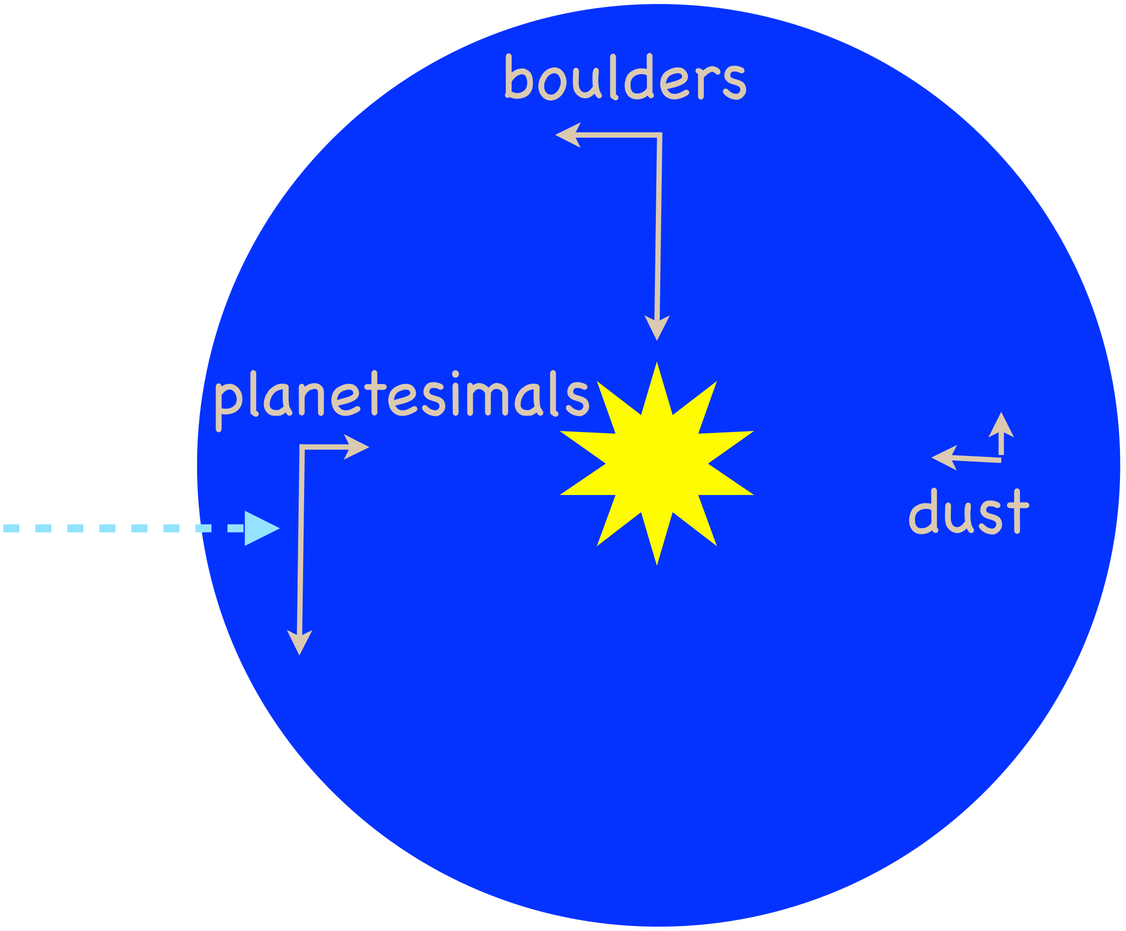
- Surface gravity is weak
- Sticking is important for dust growth
- Aerodynamic gas drag is crucial
  - Radial drift introduces a “meter-size” barrier
- Resolution: particle concentration and gravitational collapse

Radial Drift Timescale Constraints (aka the “Meter-Size Barrier”)



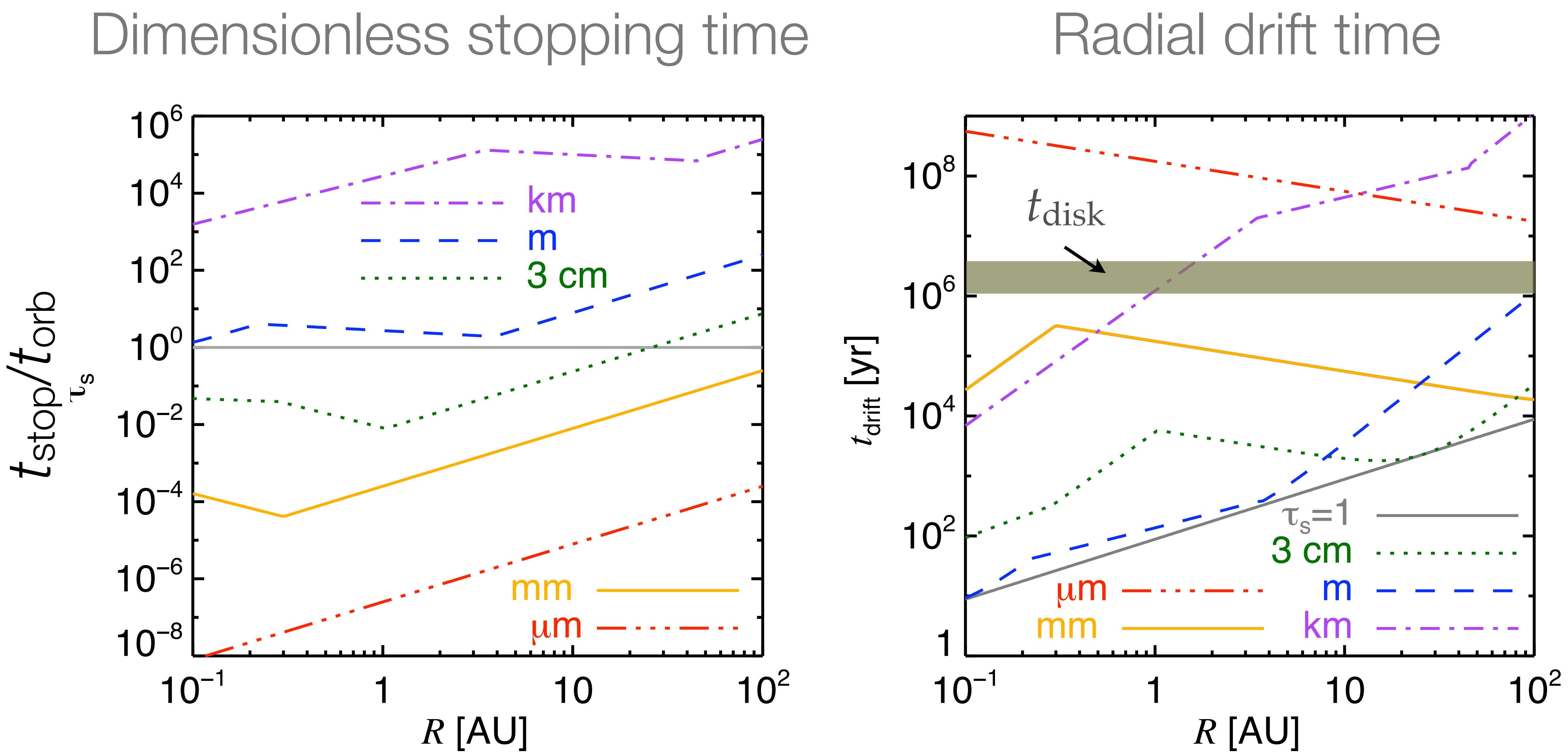
sub-Keplerian gas rotation

optimal coupling gives
fastest drift:
1 AU/(50 m/s) ~ 100 yr



max 50 m/s headwind

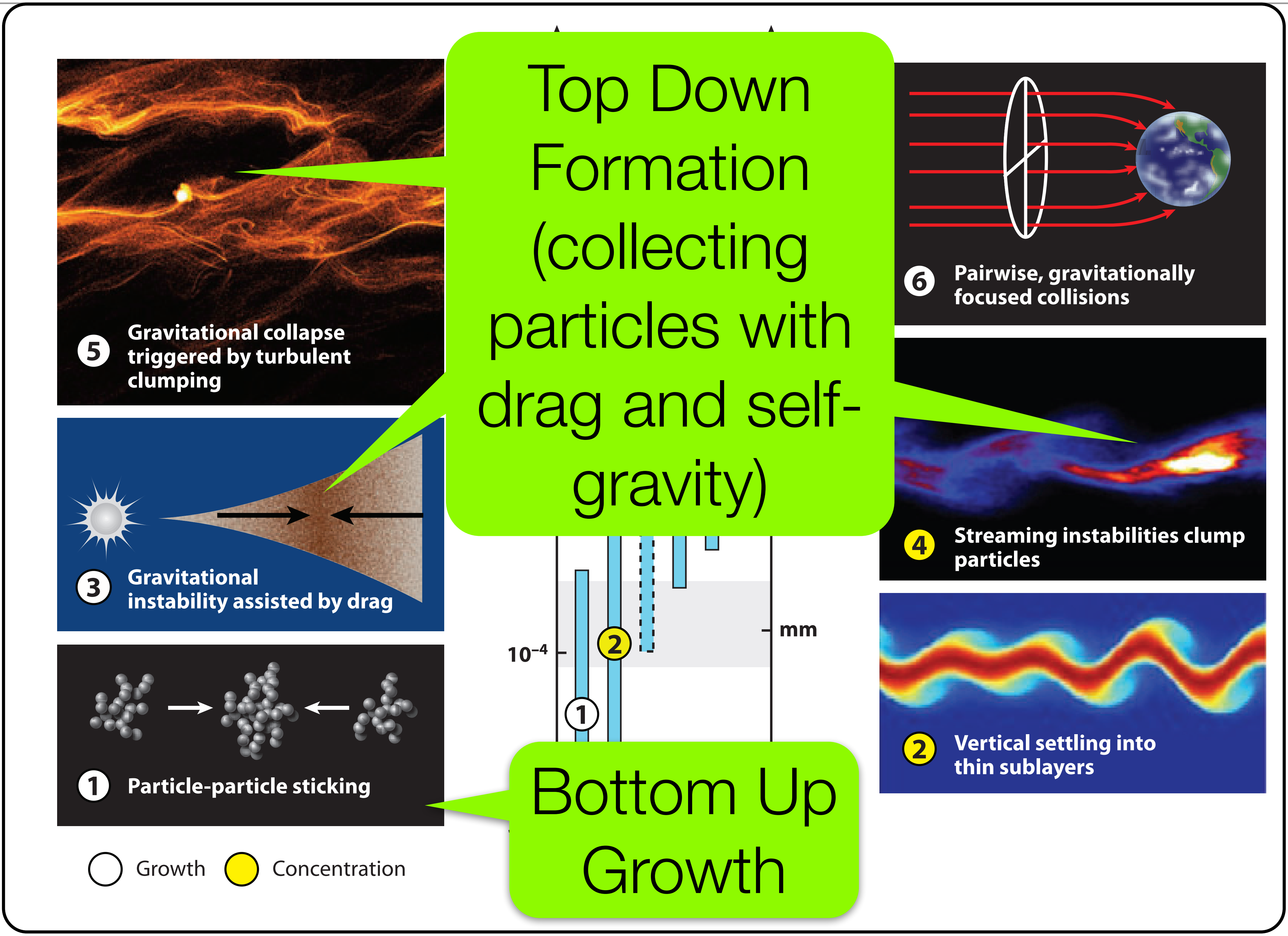
Drag Forces in a “Minimum Mass” Disk Model



Youdin (2010)

Climbing the size ladder

Chiang & Youdin (2010, AREPS)



Top Down Formation (collecting particles with drag and self-gravity)

Bottom Up Growth

Growth by Sticking

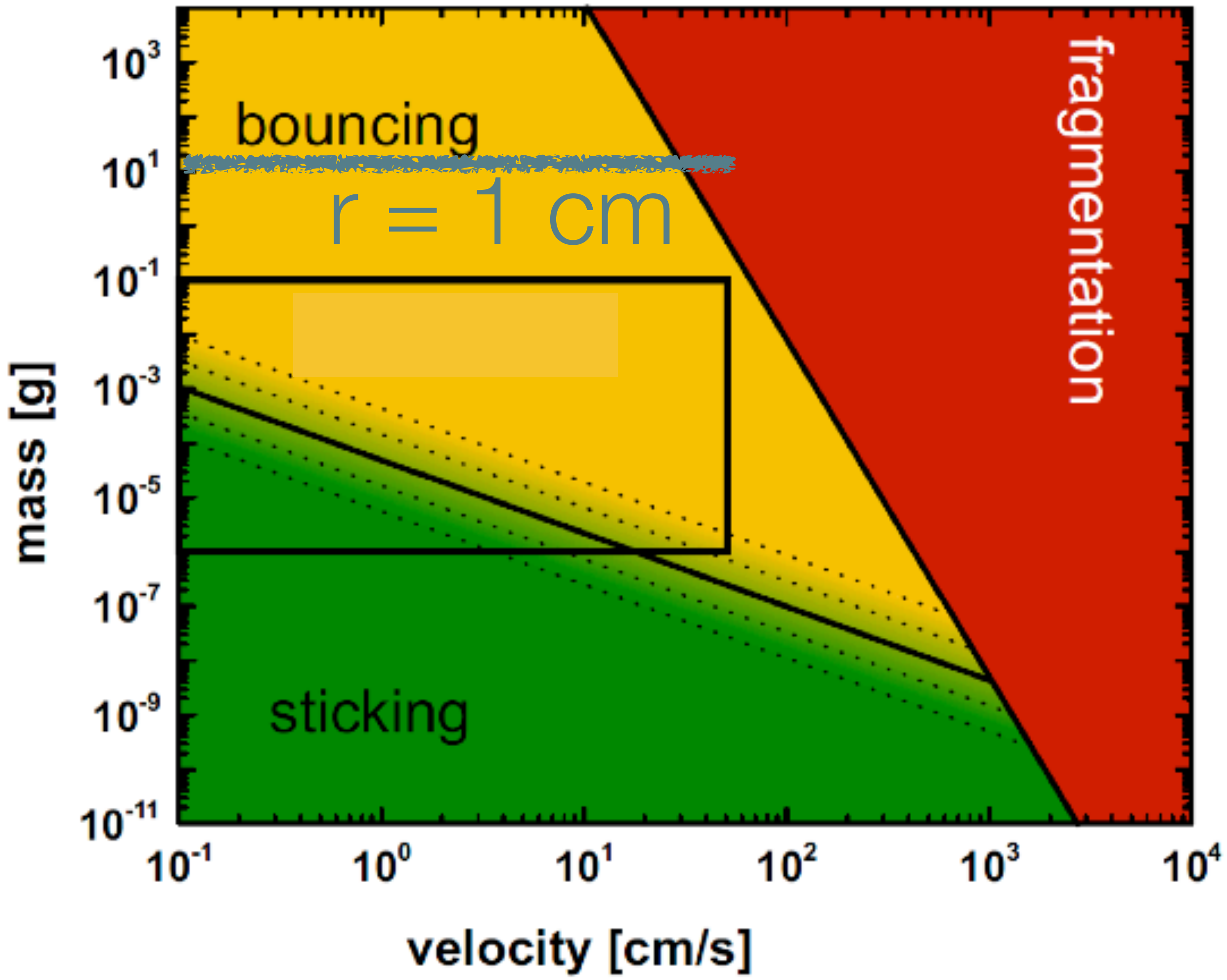
inefficient growth

from mm—km

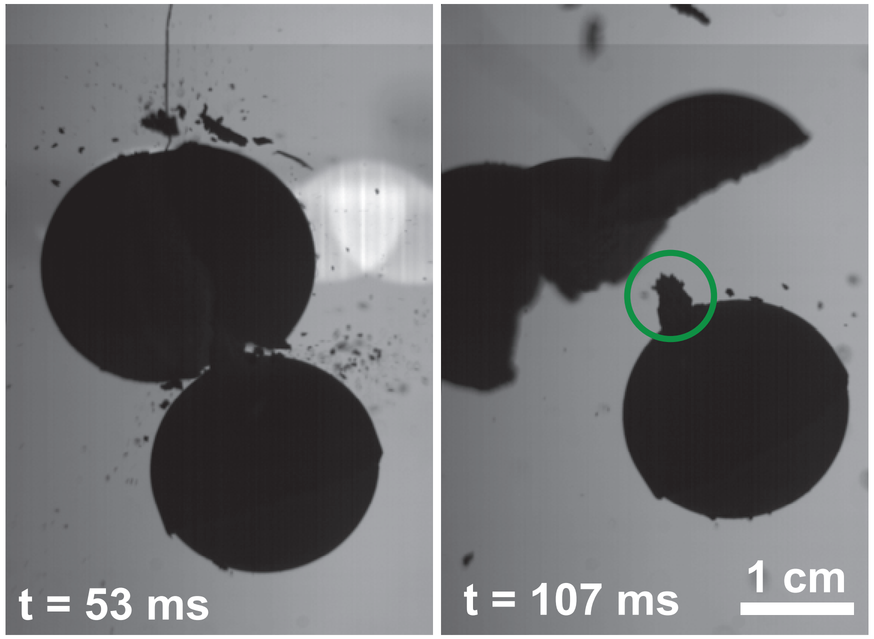
compounds

meter-size barrier

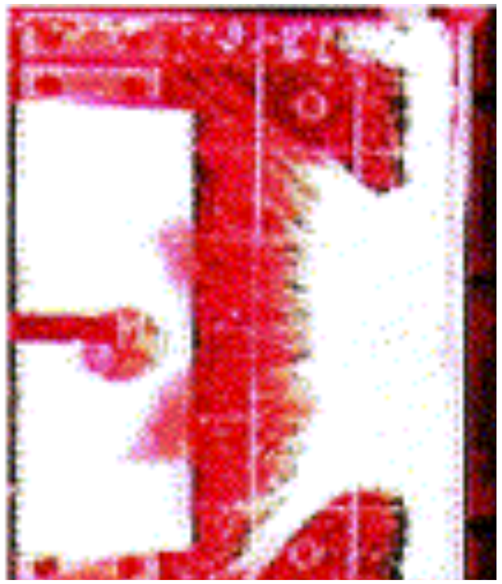
Many Outcomes
(Guttler et al. 2010)



Fragmentation
(Blum & Meunch 1993)



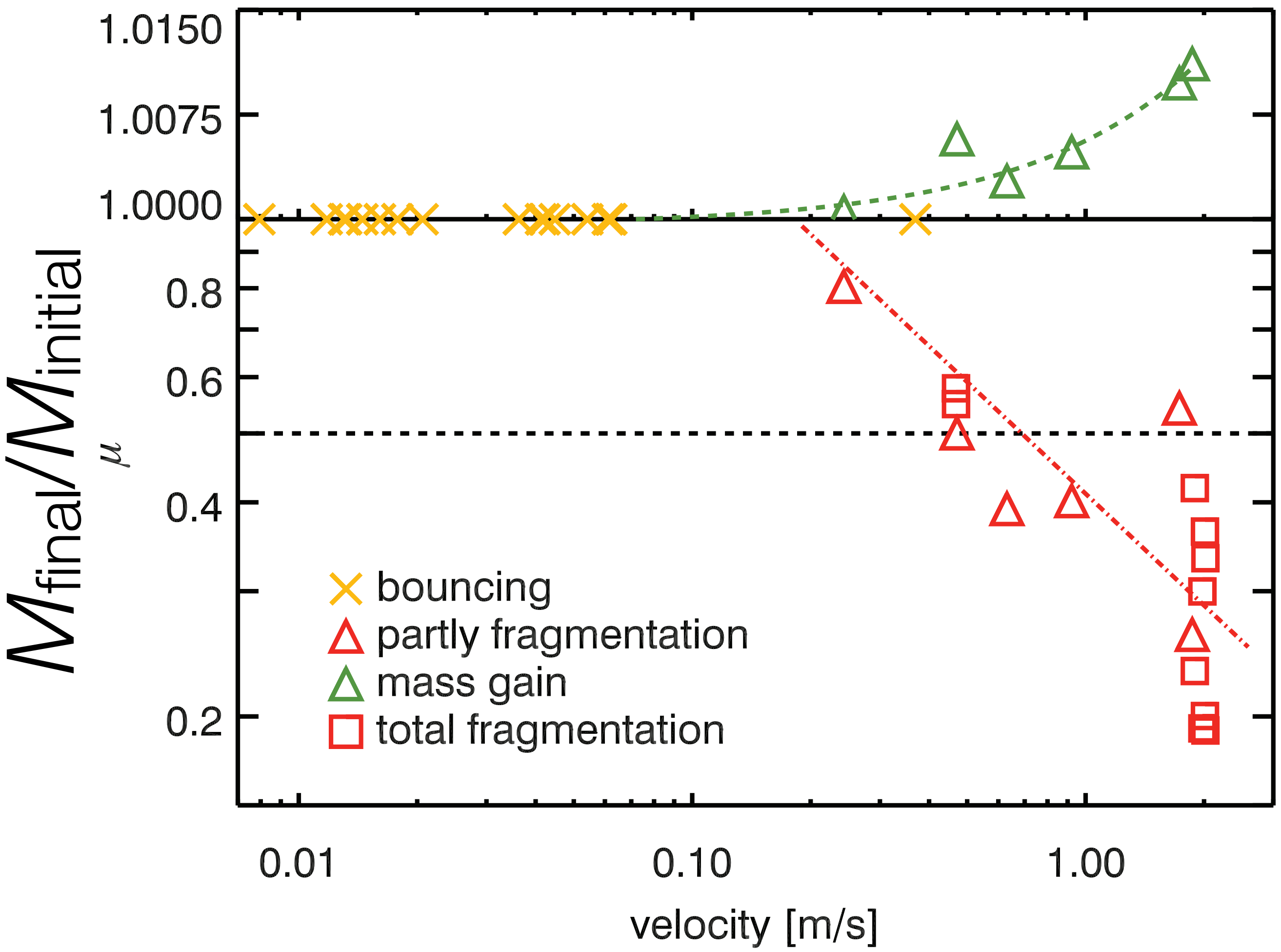
Mass Transfer
(Beitz et al. 2011)

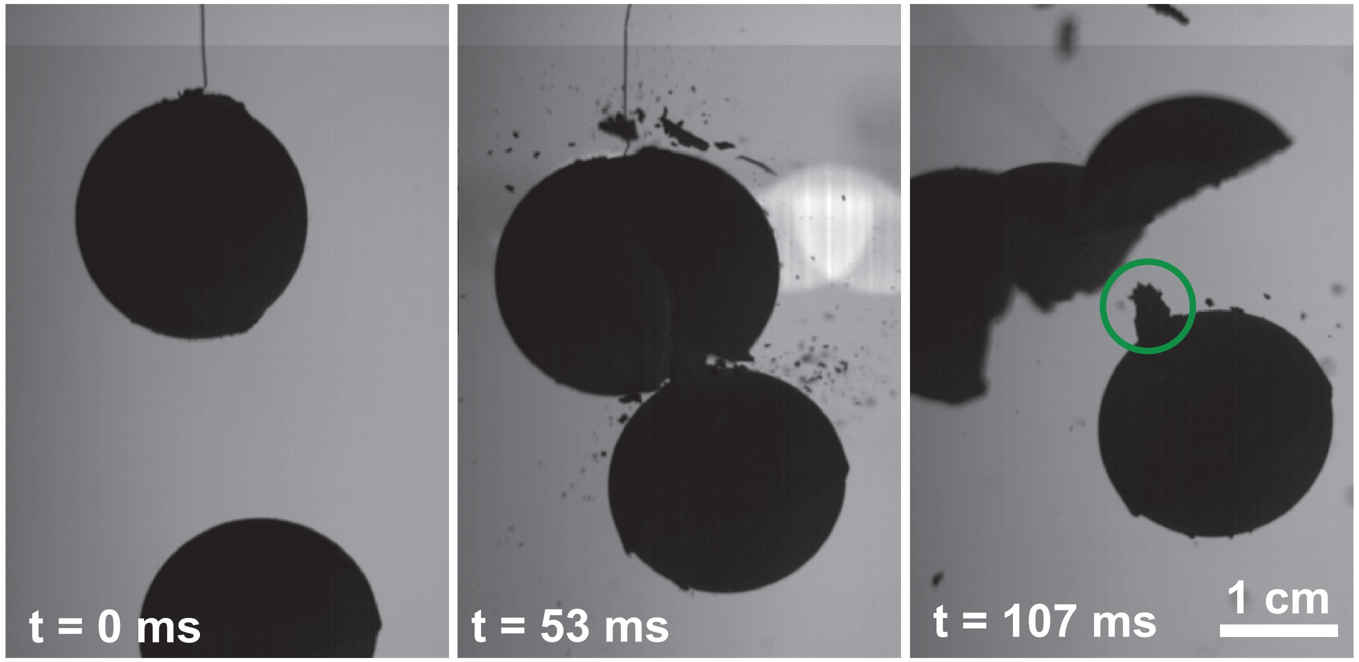


Erosion
(Colwell 2003)

The cm-size barrier of bouncing and fragmentation

Mass transfer overwhelmed by fragmentation





compare to:
drift speeds ~ 50 m/s
turbulent speeds ~

$$10\sqrt{\frac{\alpha}{10^{-4}}}\ \mathrm{m/s}$$

Three modes of particle concentration

1. Static

2. Passively Dynamic

3. Spontaneous

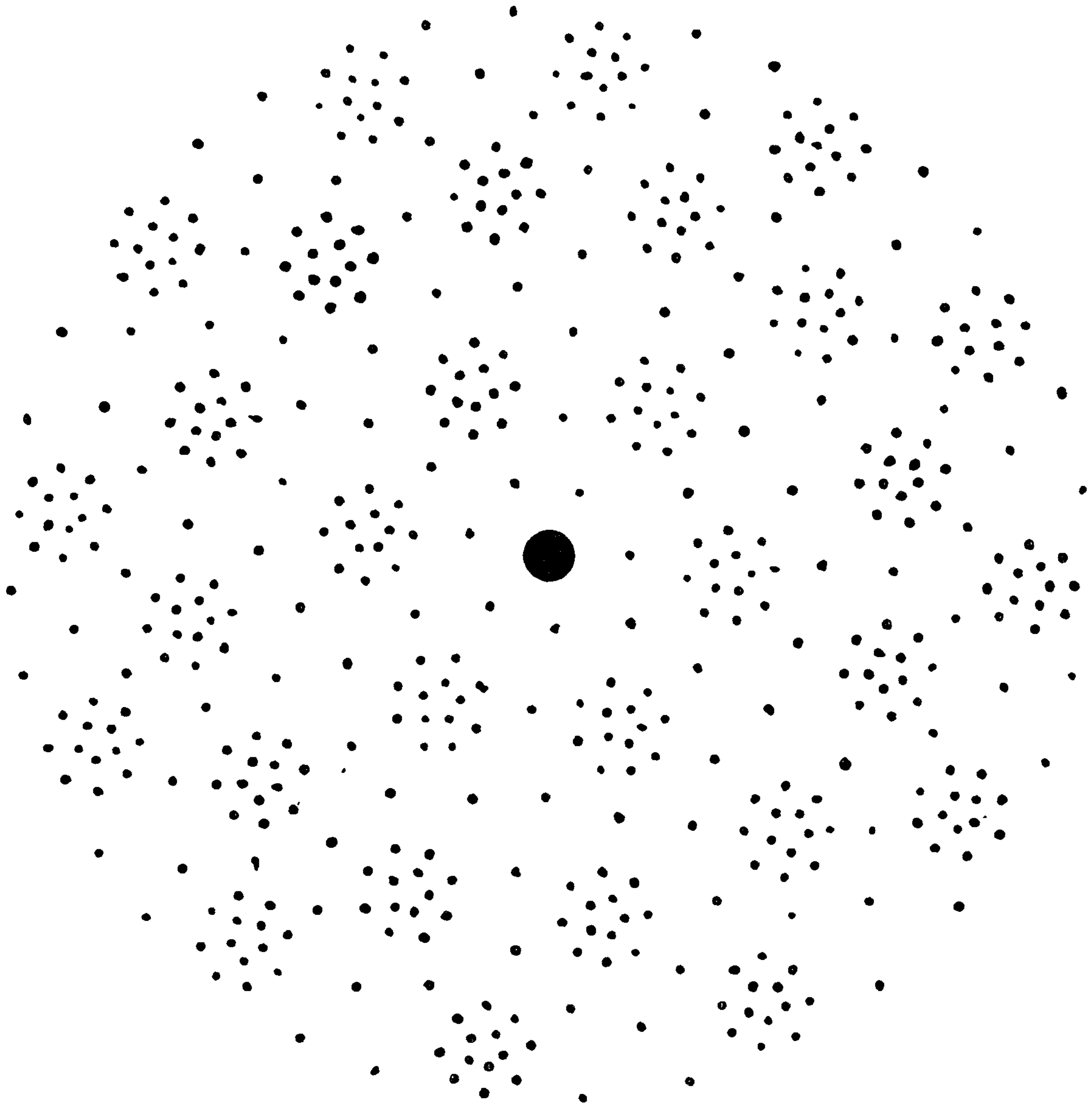


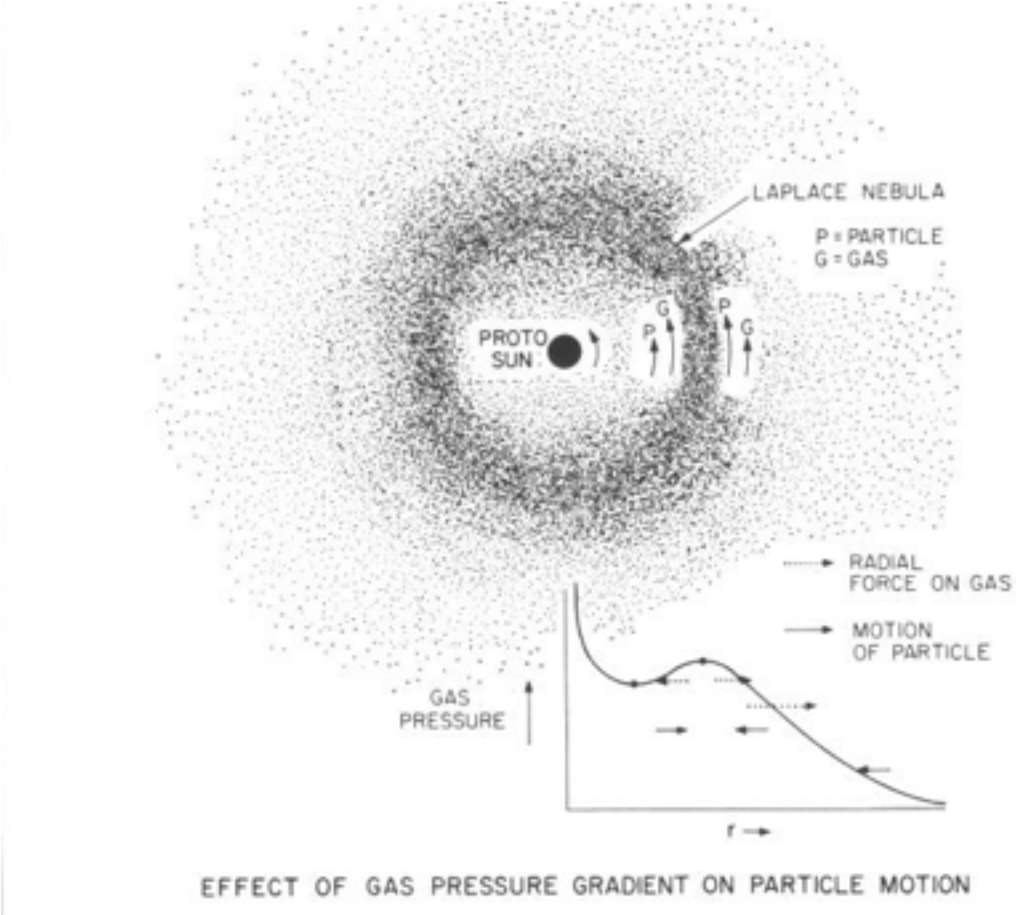
FIG. 3.

"local condensations"

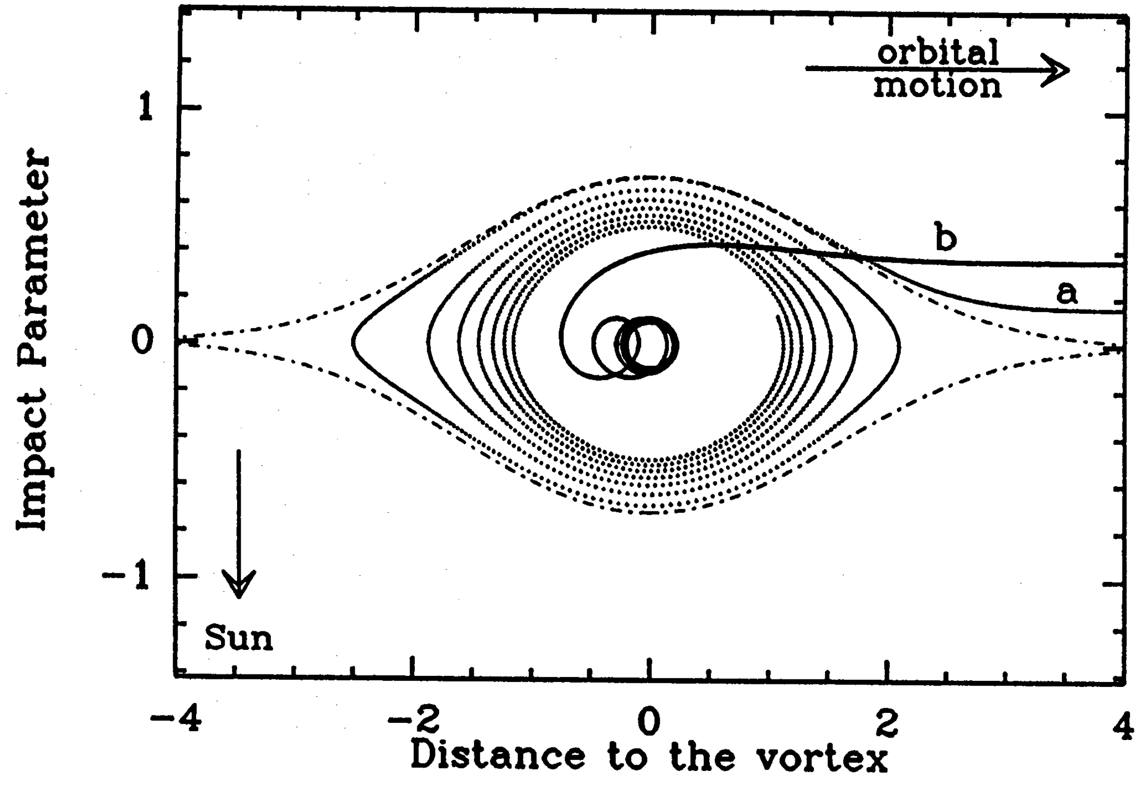
(Edgeworth 1943)

1. Static Concentration:
Particles collect in long-lived pressure maxima.

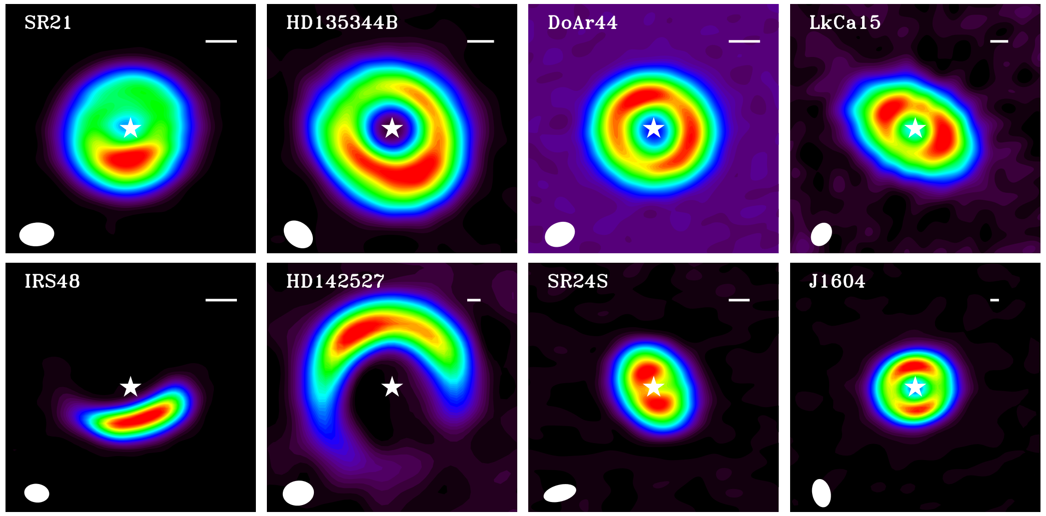
Ring *(Whipple 1972)*



Vortex *(Barge & Sommeria 1995)*



sources: dead zone boundaries, snow lines, zonal flows, spiral arms and more



Seen by ALMA?!
(van Dishoeck et al. 2015)

2. Passively Dynamic, i.e. Turbulent Concentration:

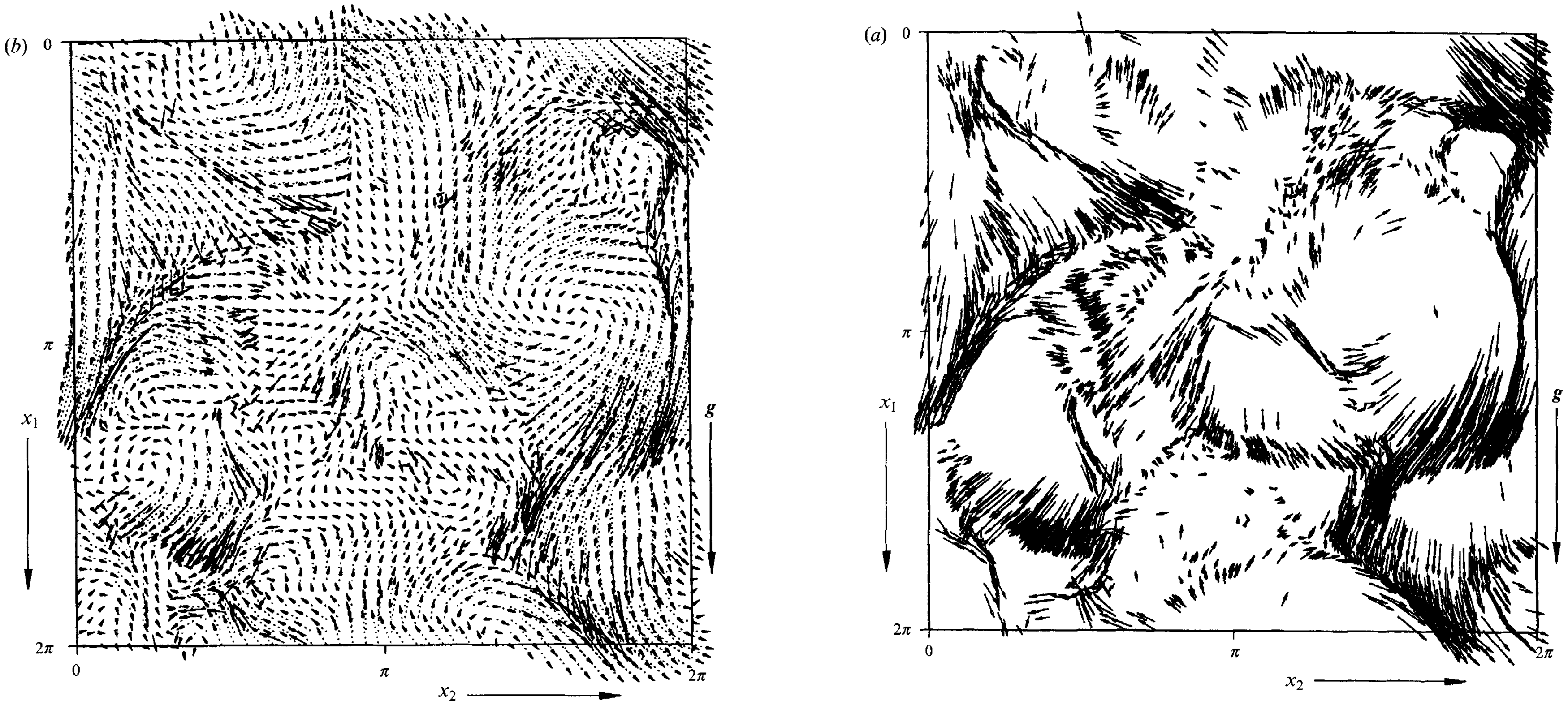
Particles concentrate briefly by interacting with eddies.

“dust devils” are dynamic, but a different effect

(credit: Joseph Brauer)

2. Passively Dynamic, i.e. Turbulent Concentration:

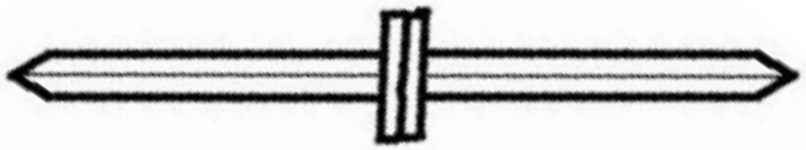
Particles concentrate briefly when expelled from eddies.



(Wang & Maxey 1993)

Are concentrations long-lived and massive enough to form planetesimals?

(Cuzzi et al. 2008; Pan et al. 2011; Hopkins 2014)



3. Spontaneous: Particles trigger their own concentration via the streaming instability

(credit: Martine Maes)

The streaming instability:
Complex behavior from simple ingredients

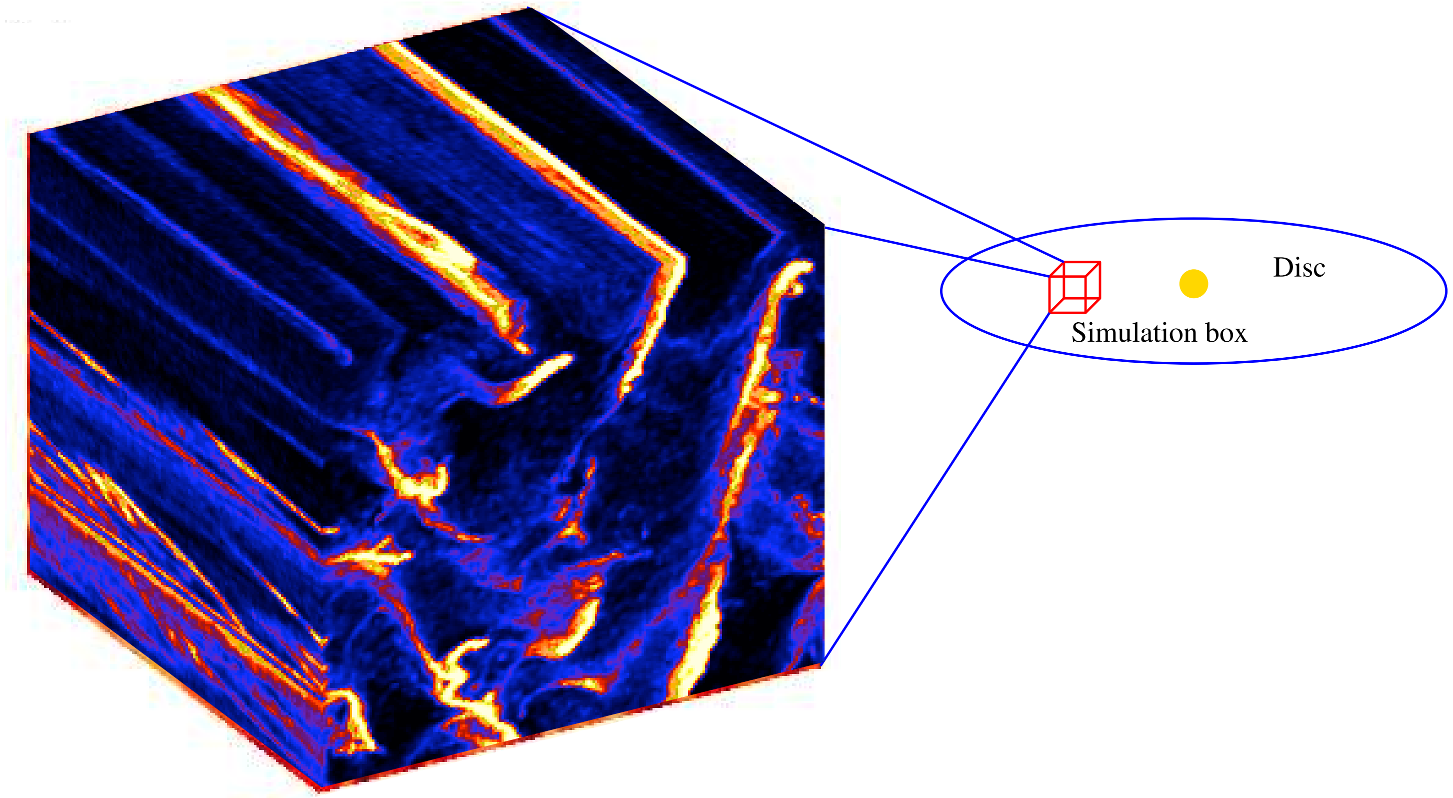
Two-way drag forces &
Radial pressure gradient
(Youdin & Goodman 2005)

$$\frac{\partial \rho_p}{\partial t} + \nabla\cdot(\rho_p \boldsymbol{V}_p) = 0,$$

$$\nabla\cdot\boldsymbol{V}_g = 0,$$

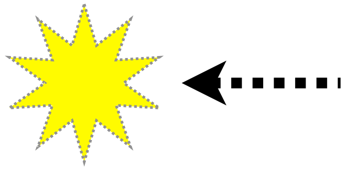
$$\frac{\partial \boldsymbol{V}_p}{\partial t} + \boldsymbol{V}_p\cdot\nabla\boldsymbol{V}_p = -\Omega_{\mathrm{K}}^2\boldsymbol{r} \boxed{-\frac{\boldsymbol{V}_p - \boldsymbol{V}_g}{t_{\mathrm{stop}}}},$$

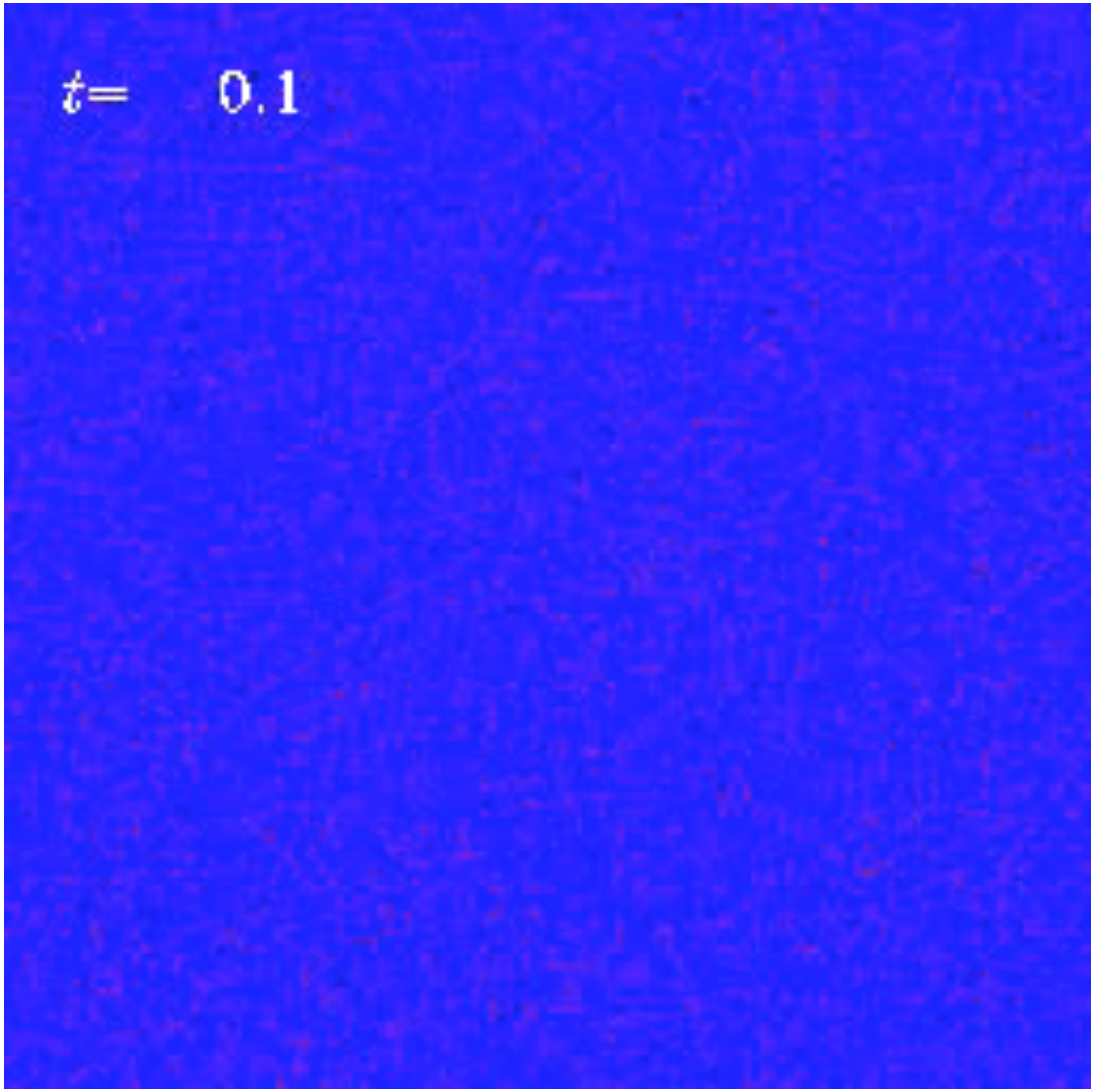
$$\frac{\partial \boldsymbol{V}_g}{\partial t} + \boldsymbol{V}_g\cdot\nabla\boldsymbol{V}_g = -\Omega_{\mathrm{K}}^2\boldsymbol{r} + \boxed{\frac{\rho_p}{\rho_g}\frac{\boldsymbol{V}_p - \boldsymbol{V}_g}{t_{\mathrm{stop}}}} - \boxed{\frac{\nabla P}{\rho_g}},$$



Local box simulations of
gas & “super”-particles
(Youdin & Johansen 2005, Johansen et al. 2007, etc; Bai & Stone 2010)

Particles trigger their own concentration via the streaming instability





feeds off of
radial drift
(Johansen & Youdin 2007)

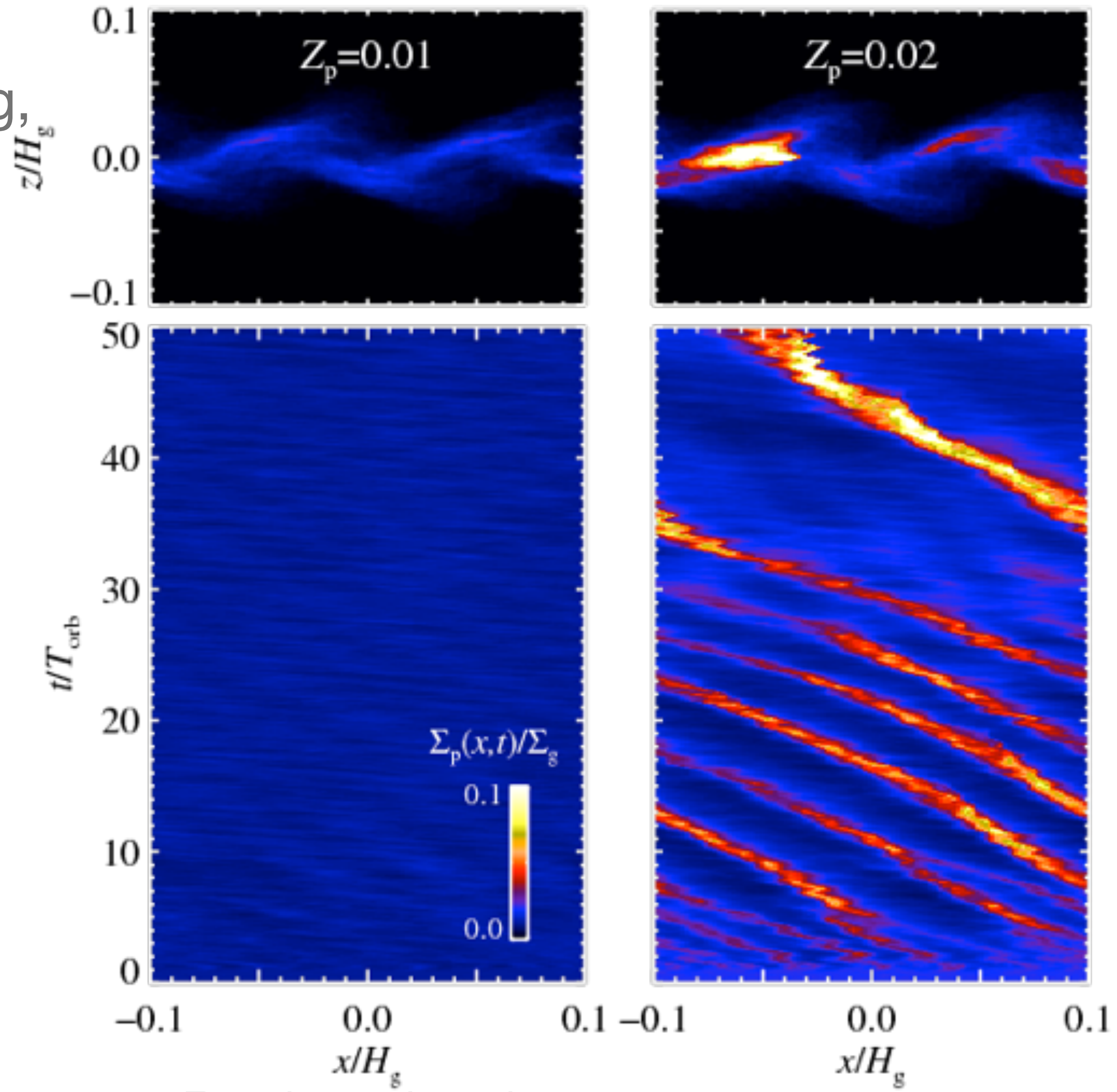
Conditions for strong particle concentration

(Johansen, Youdin & Mac Low 2009)

1. Particle sizes near optimal coupling, $\tau_s \approx 0.1\text{-}1.0$
2. Particle-gas ratio, $Z \gtrsim 1\%$
    - varies w/ radial pressure gradient *(Bai & Stone, 2010b)*
    - exoplanet-metallicity correlation?

- Role of box size and boundary conditions? *See poster by Rixin Li*

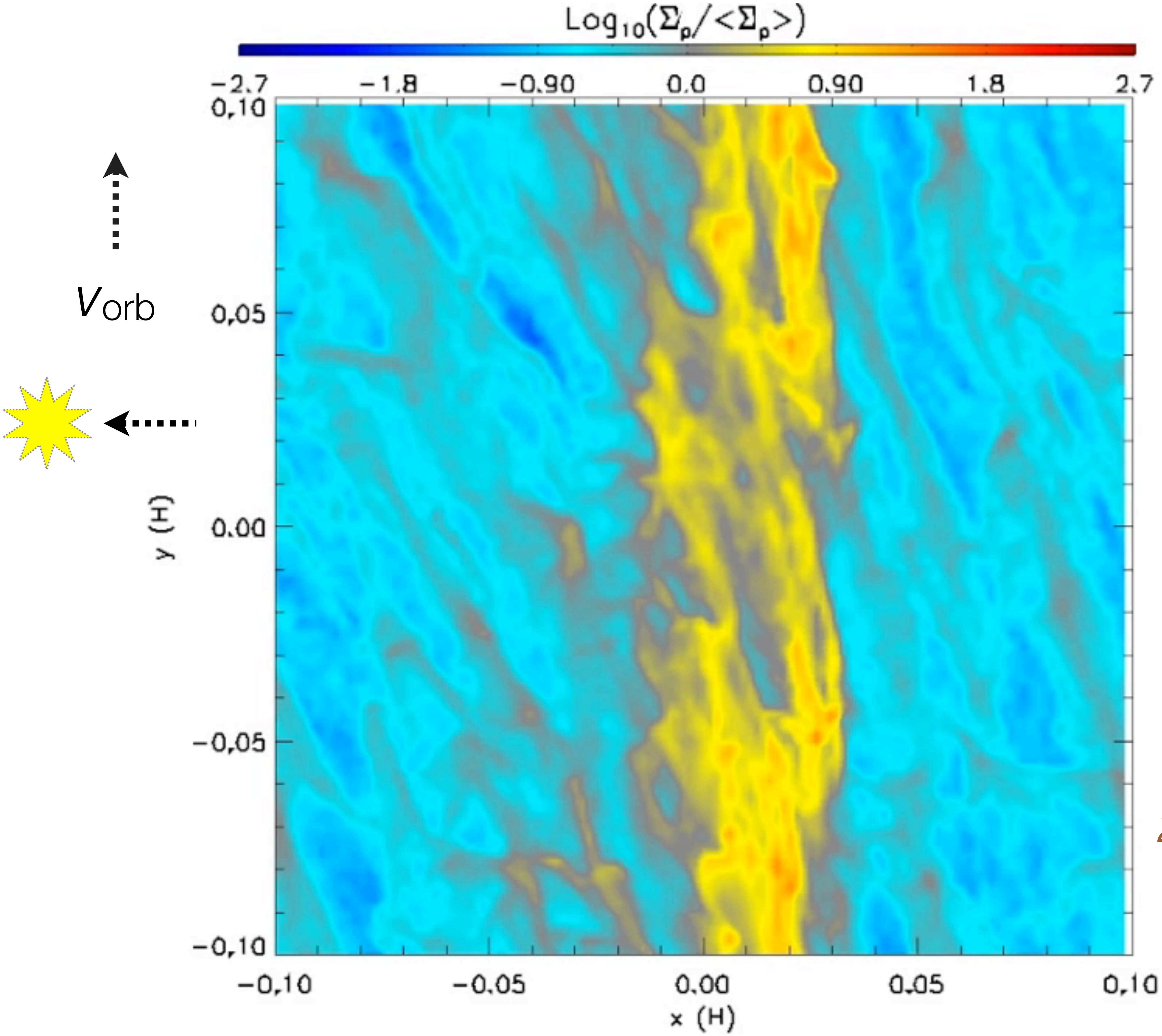
"Sub-Solar:" weak clumping *"Super-Solar:" strong clumping*



Particle density:
radius vs. height *(top)*
radius vs. time *(bottom)*

τ_s = 0.1-0.4,
3-12 cm @ 5 AU

Streaming Inst. triggering planetesimal formation



Gravitational collapse from ~few cm-sizes into ~100 km, planetesimals

(Simon et al., in prep; also Johansen, Youdin & MacLow 2009; Johansen et al 2007, 2012)

The bouncing and fragmentation barriers remain

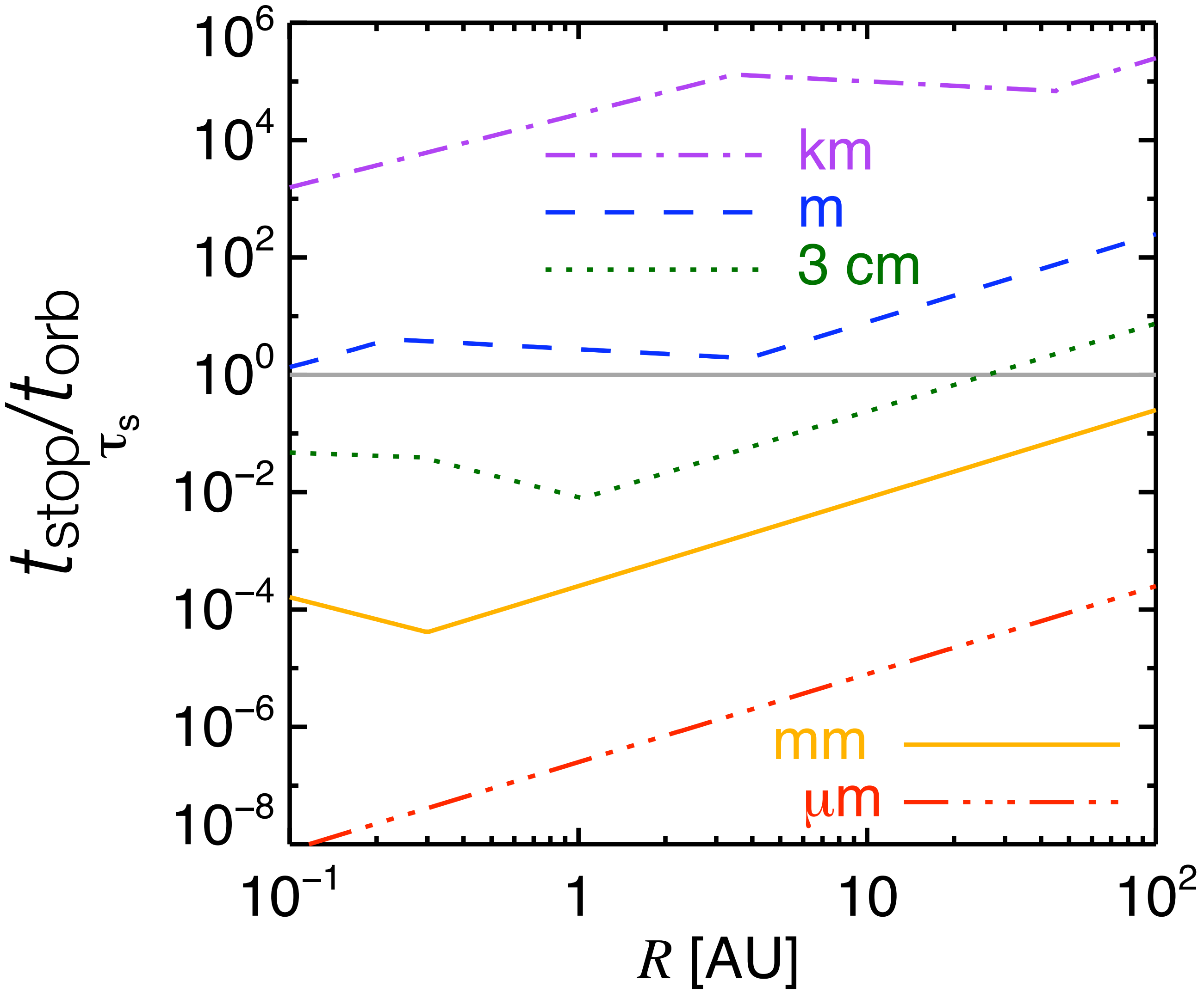
- What if particles don't grow large enough, to $\tau_s \approx 0.1\text{-}1.0$?

  A. Less gas

  B. Look at interplay with other mechanisms

  - pressure bumps
  - direct gravitational instability *(Safronov '69, Goldreich & Ward '73)*

Goal:
~10 cm @ 1 AU,
~mm @ 30 AU



Slow "secular" gravitational instabilities collect small particles into wide rings

- Current studies analytic
  (Ward 1976; Youdin 2005, 2011; Shariff & Cuzzi 2011, Takahashi & Inutsuka 2014)

- Long time and length scales

  - Opportunity to explain observed disk structures

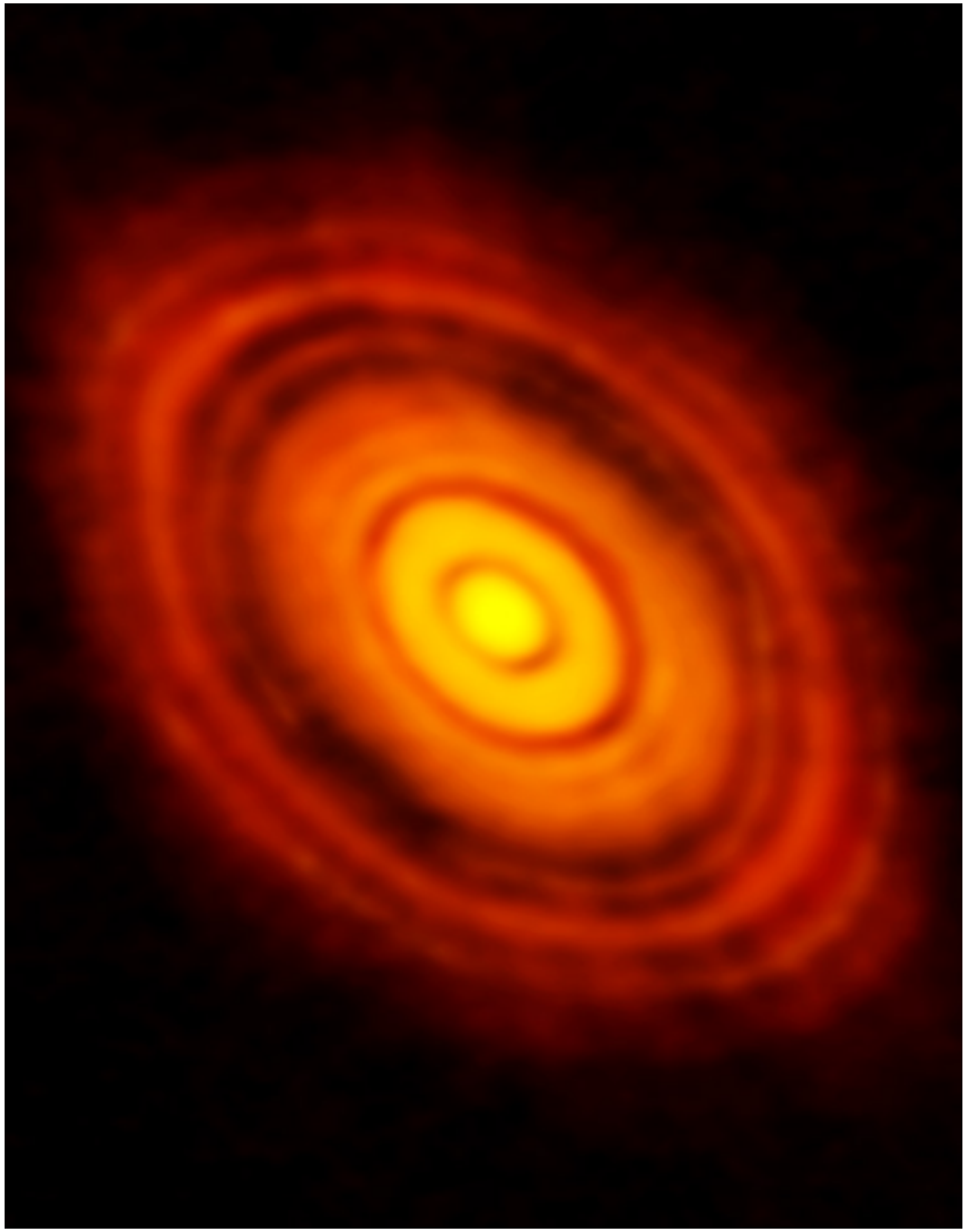


image: ALMA

SS evidence for Gravitational Collapse

KBO binary colors match!

(Benecchi et al. 2009, Nesvorny, Youdin & Richardson 2010)

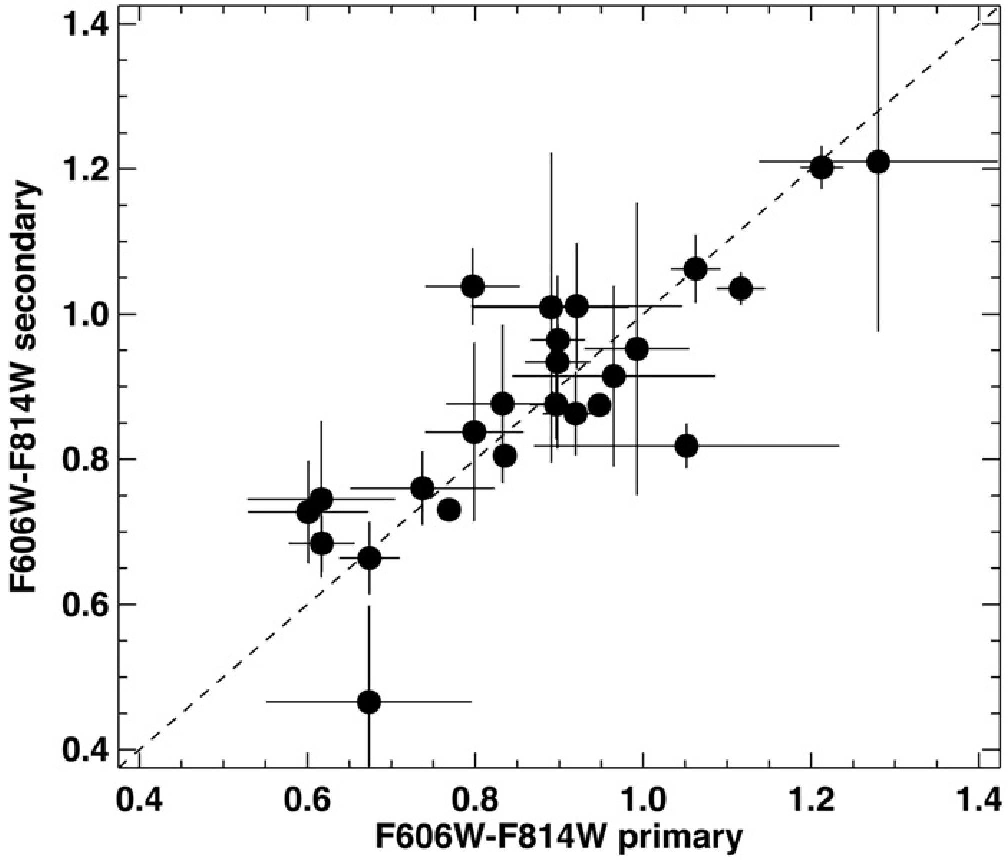
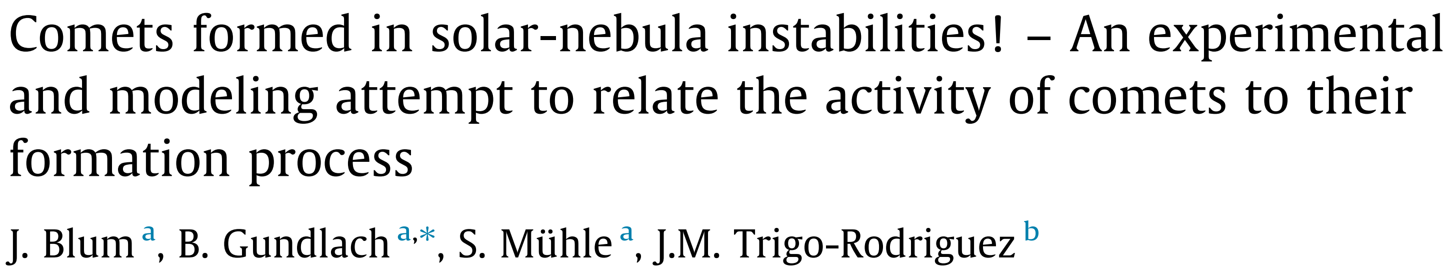


image: John Laborde

Comets have tails!

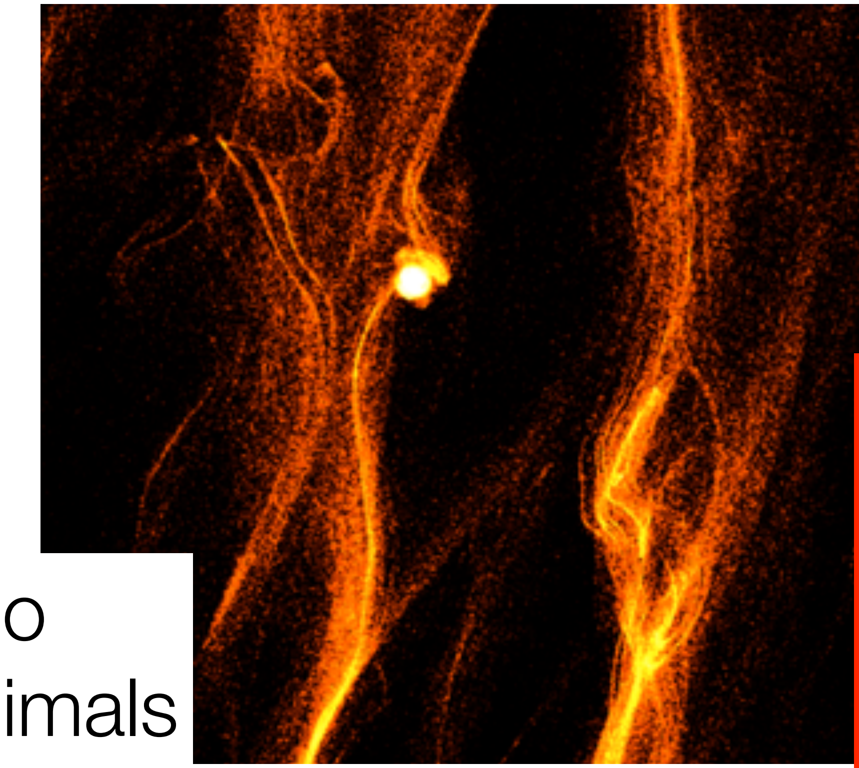
(Blum et al. 2014)



Comets formed in solar-nebula instabilities! – An experimental and modeling attempt to relate the activity of comets to their formation process

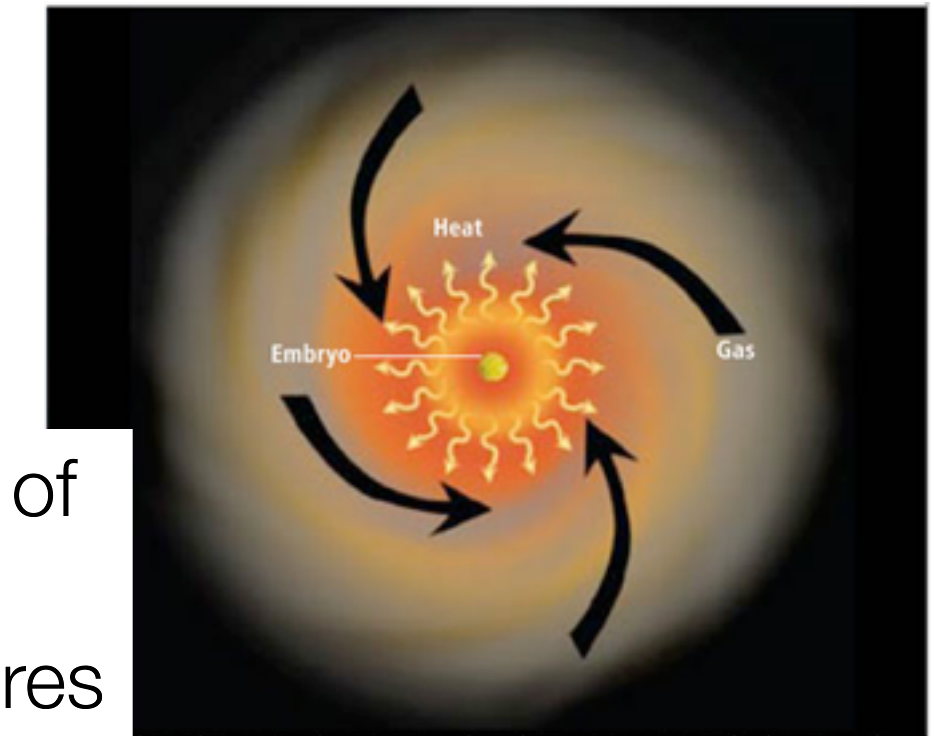
J. Blum [a], B. Gundlach [a,*], S. Mühle [a], J.M. Trigo-Rodriguez [b]

Four Stages of Planet Formation: The Core Accretion Model

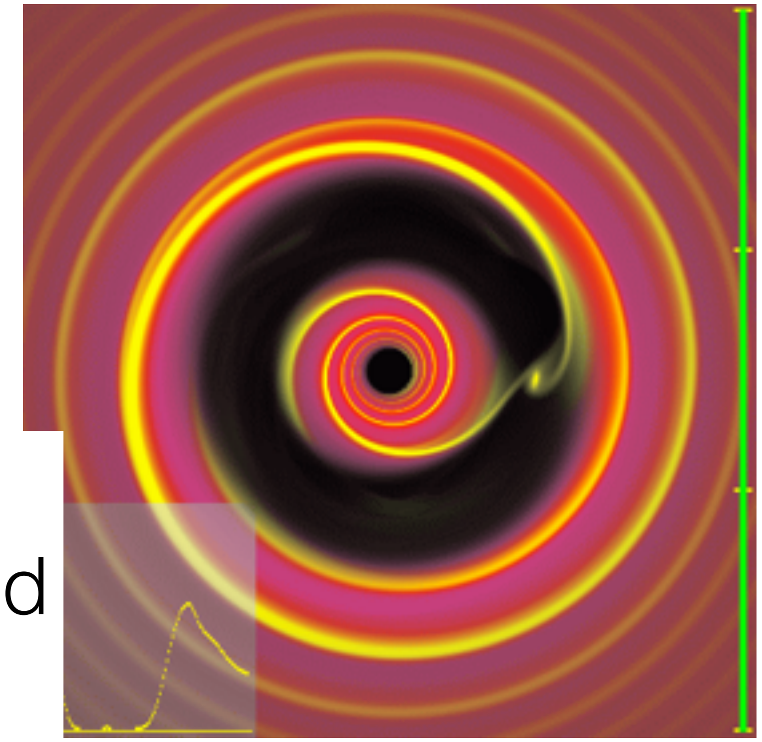


1. Dust to Planetesimals

2. From Planetesimals to Planets & Cores



3. Growth of Gas Giant Atmospheres



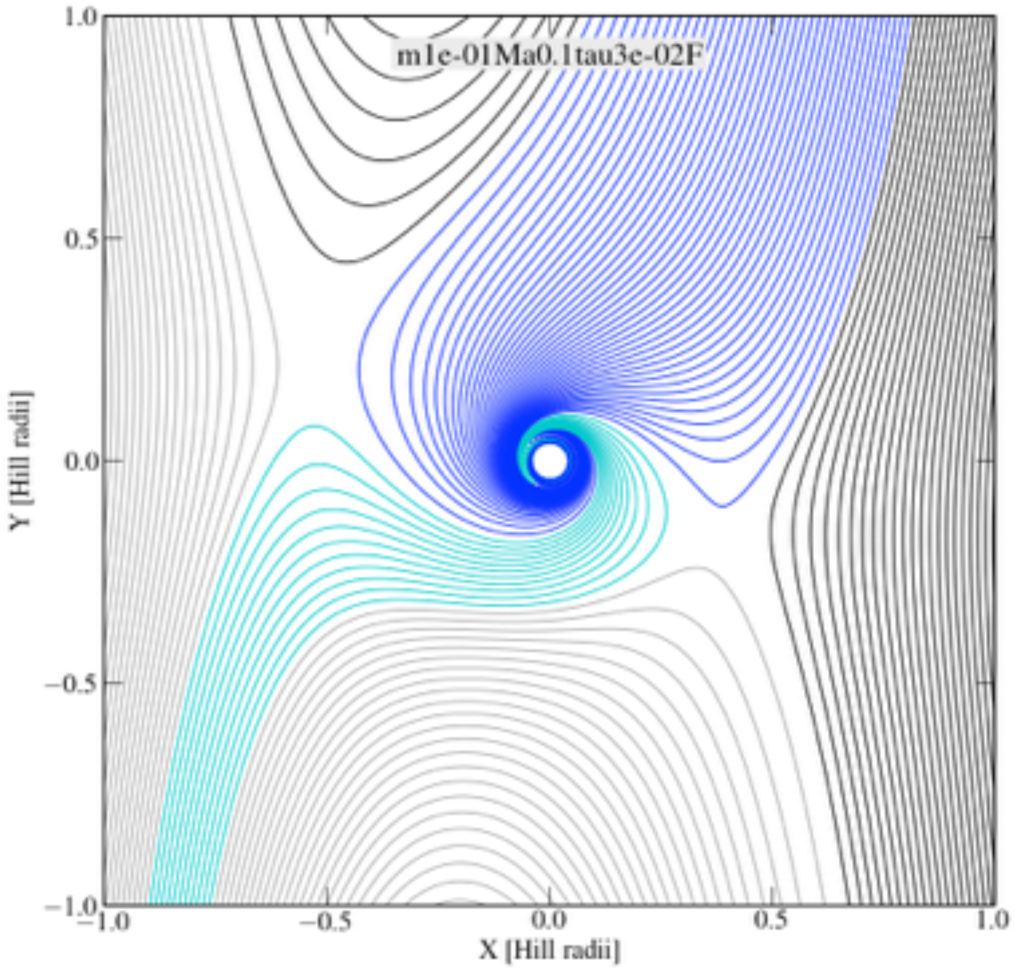
4. Planet Migration and Scattering

Credits: A. Johansen, F. Sulehria, D. Lin, P. Armitage

Options for growing terrestrial planets and cores

1. Giant impacts

2. Aerodynamically assisted “pebble accretion”

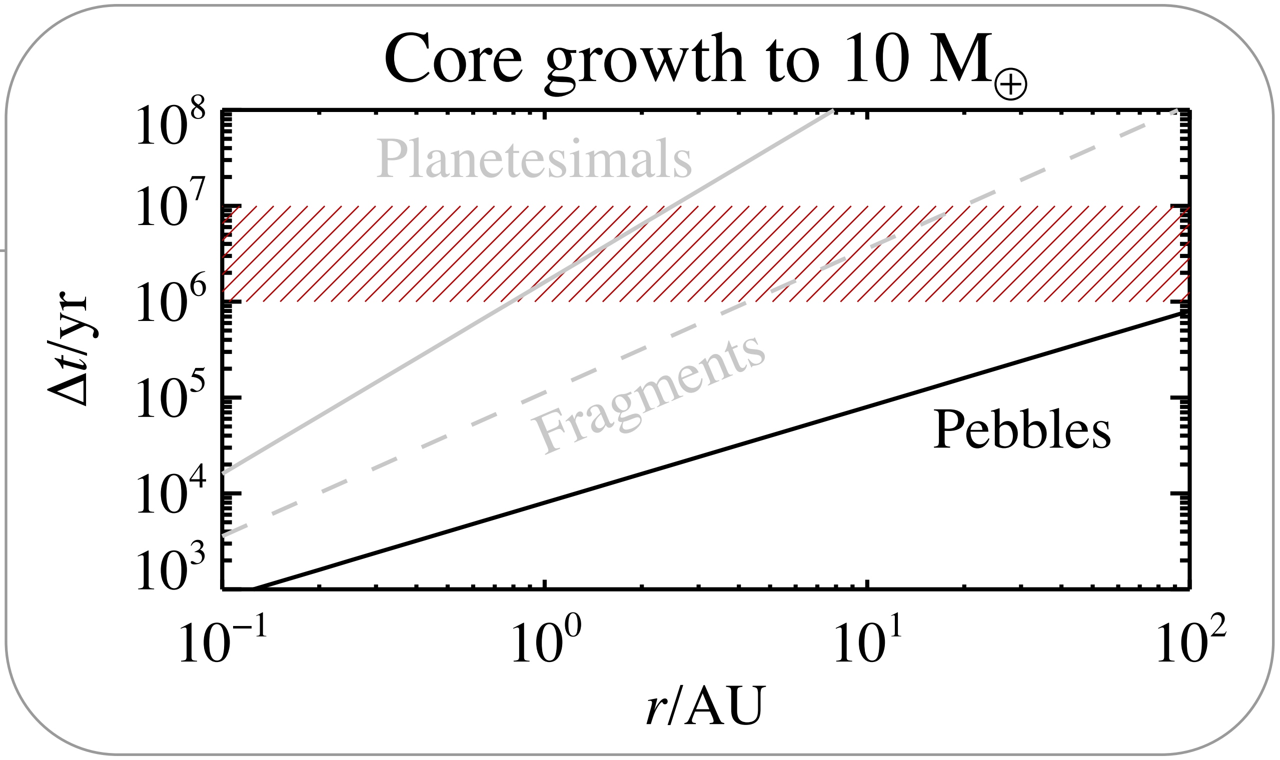


Ormel & Youdin (unpublished)

Key Issues in Terrestrial Planet & Core Growth

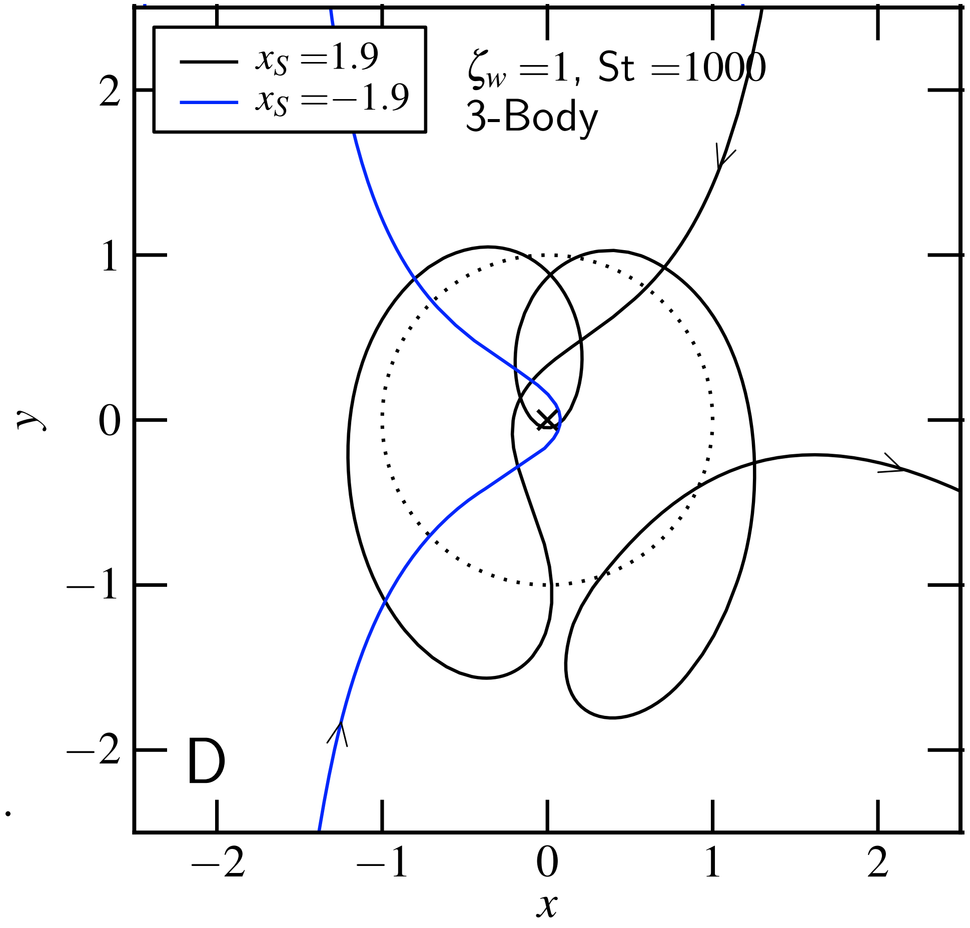
1. Timescale
   - Potentially faster for aerodynamic pebbles
2. Availability of Mass
   - Planetesimal accretion stalls at “isolation mass”
   - Radial drift overcomes isolation

Lambrechts & Johansen (2012)



$$m_{iso} = \frac{(2\pi B\Sigma)^{3/2}}{(3\mathrm{M}_\star)^{1/2}}a^3 \approx 0.08\left(\frac{B}{7}\right)^{3/2}\left(\frac{FZ_{\rm rel}}{0.33}\right)^{3/2}\left(\frac{\mathrm{M}_\star}{\mathrm{M}_\odot}\right)^{-1/2}\left(\frac{a}{\mathrm{AU}}\right)^{3/4}\ \mathrm{M}_\oplus\ .$$

Youdin & Kenyon (2012)



The problem w/ weak drag

Ormel & Klahr (2012)

Summary

color me bad
image?

- Planetesimal formation
  - Starts with dust coagulation
  - Ends with gravitational collapse
  - Streaming instability and other particle concentration mechanisms bridge the “meter-size barrier”
- Terrestrial planet and core formation
  - New: an early phase of aerodynamic pebble accretion