Electric Charging of Dust Aggregates and its Effect on Dust Coagulation in Protoplanetary Disks

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Ref.) Okuzumi (2009), ApJ, 698, 1122

Outline

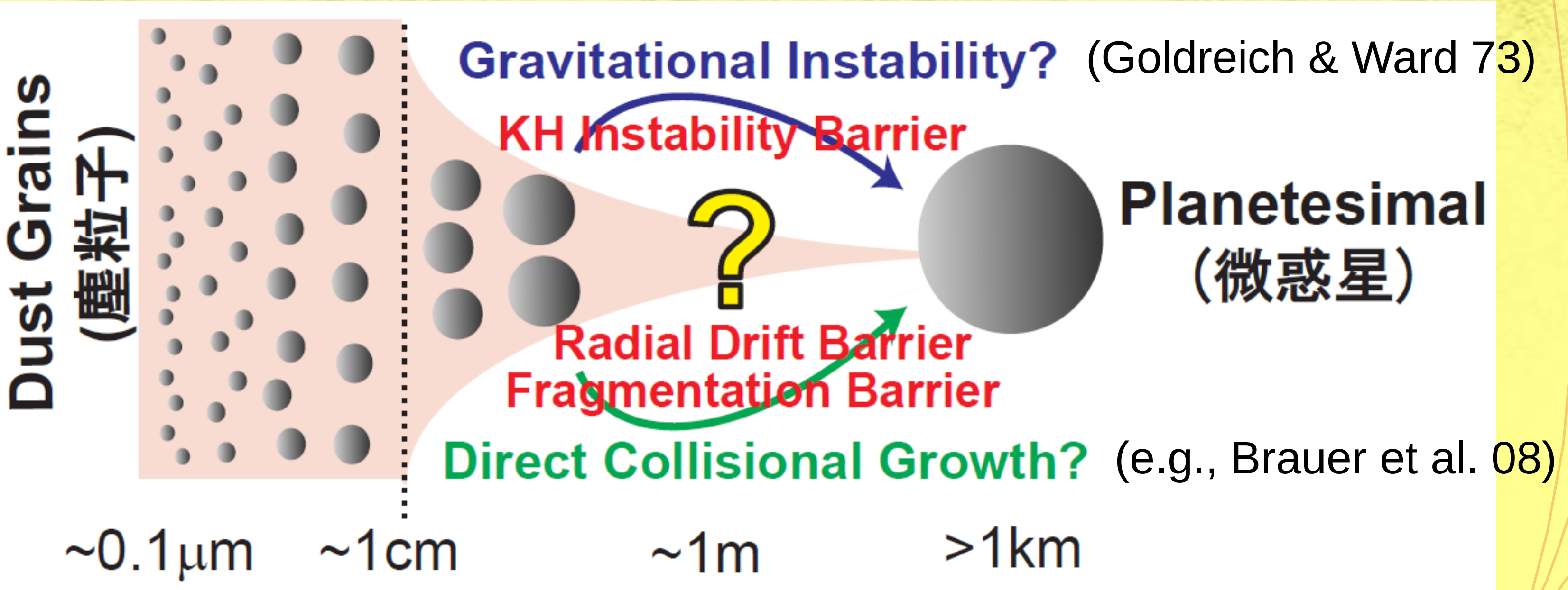
❑ Introduction: Dust charging in protoplanetary disks
  ✓ Dust is an “MRI killer”

❑ Evolution of dust charge & gas ionization states
  🡐 Analytical solutions

❑ “Electric barrier” against dust growth
  ✓ Without turbulence, uniform (orderly) dust growth is likely to stall at its very early stage.

❑ Coagulation simulation with porosity evolution
  ➔ Bimodal growth induced by the electric barrier

Dust Coagulation: The First Step toward Planet Formation



(Goldreich & Ward 73)

(e.g., Brauer et al. 08)

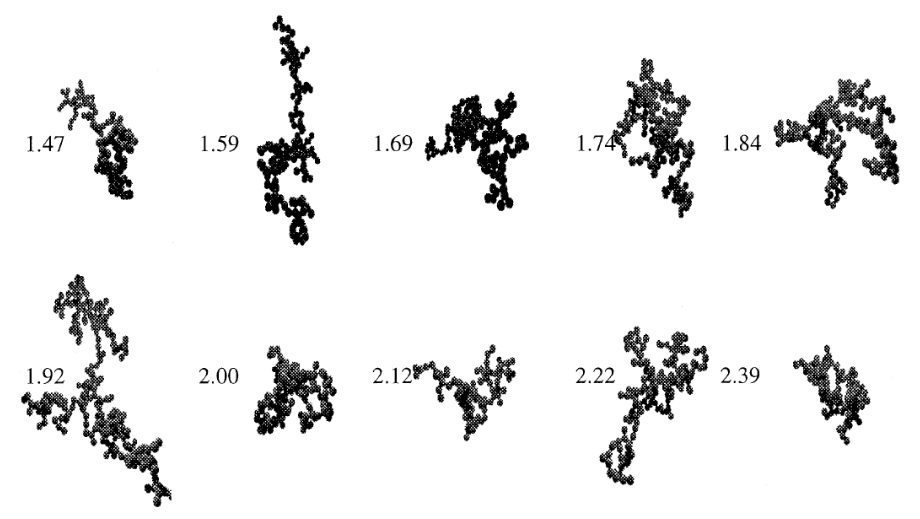
One way to go further:
More “realistic” modeling of dust aggregates

Porosity Evolution of Aggregates

"Classical" dust model:
compact sphere (ρ=const)

Experimental: Wurm & Blum 98; Blum+ 98
Statistical: Ormel+ 07; Zsom & Dullemond 08
N-body: Kempf+ 99; Wada+ 07,08; Suyama+08

In reality, aggregates can be very porous!



An N-body result of thermal coagulation
(Kempf et al. 1999)

Low-velocity collision
➔ Merger w/o restructuring
➔ Fractal Structure: **D ≈ 2**

$$\mathbf{a \approx a_0 N^{1/2}}$$

✓ Fractal growth lasts
until porous size reaches 0.1-10cm (Blum 04, Suyama+ 08)

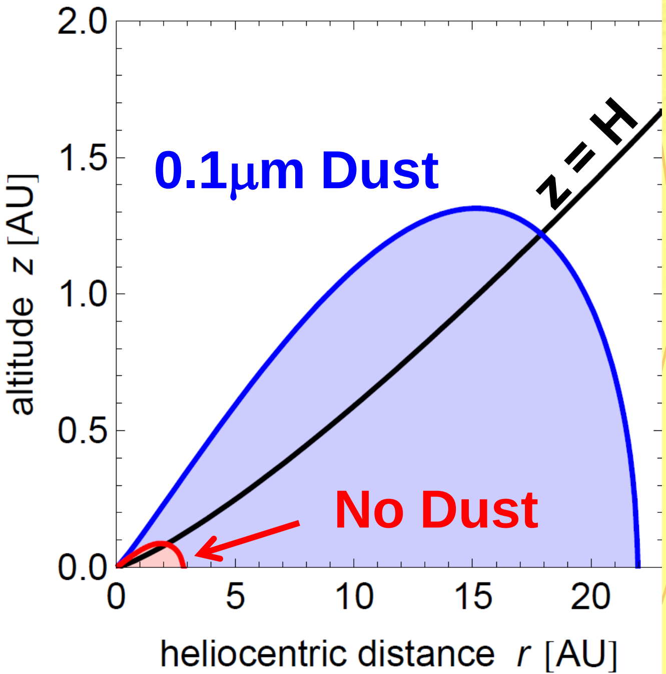
High porosity ➔ Large surface area
➔ Strong coupling to gas, Efficient ion & electron capturing

Another Key: Dust Charging

- ❑ MRI provides disk turbulence which may cause:
  - ✓ Fragmentation of large aggregates
  - ✓ Stirring-up of small aggregates/ fragments
- ❑ Small grains/aggregates greatly reduces x_e by negative charging
  - ➔ Wide "dead zone" (Sano+ 00)

Dust = "MRI Killer"

Location of the Dead Zone
MMSM+CR+XR+RA



Dust Growth & Settling ⇆ MRI-driven Turbulence
Interact via Dust Charging

Question:

What's the role of the electrostatic interaction of aggregates in their collisional growth?

1: How the dust charge state (& gas ionization state) evolve with dust growth?

2: How the dust charging feed back to the growth?

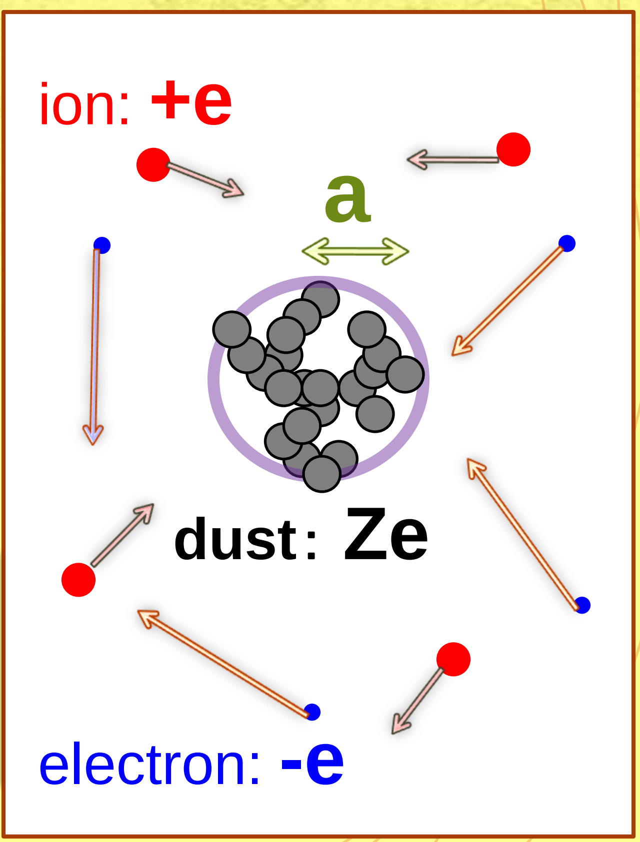
Step 0: Dust Charging in Neutral Plasmas

Thermal velocity: Electron >> Ion

Negatively Charged

Charge Equilibrium Condition: $$-\frac{Ze^2}{a} \sim k_B T$$

$$Z \sim -\frac{a k_B T}{e^2} \sim \left(\frac{a}{0.1\mu\mathrm{m}}\right)\left(\frac{T}{100\mathrm{K}}\right)$$



☐ An exact solution exists for spherical bodies (Spitzer 1941)
☐ Roughly holds for fluffy aggregates (Matthews & Hyde 2008)

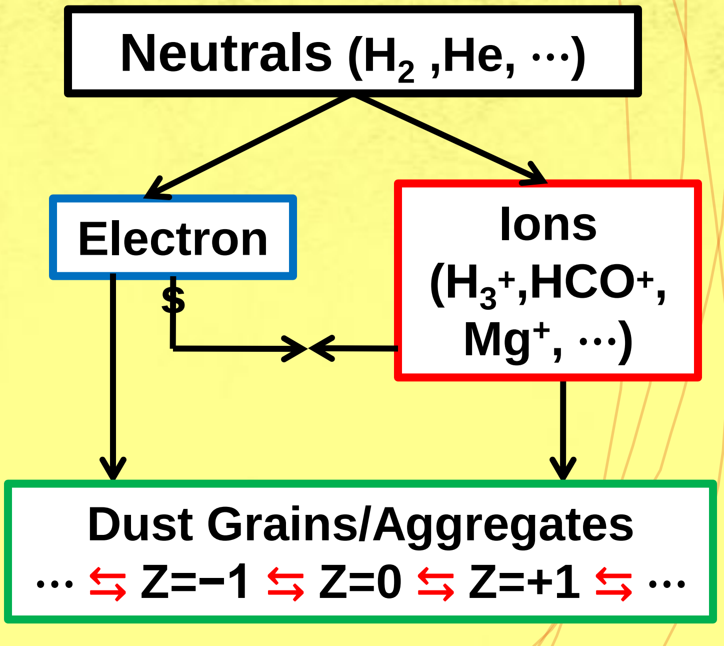
Step 1: Charge State in Weakly Ionized Gas

⋆ Dust charge state : $n_d(Z)$
⋆ Gas ionization state : n_i & n_e

Must be computed **consistently**

❑ Previous Work (Sano+ 00, Ilgner & Nelson 06)
- Solved charge transfer numerically
- Heavy to compute

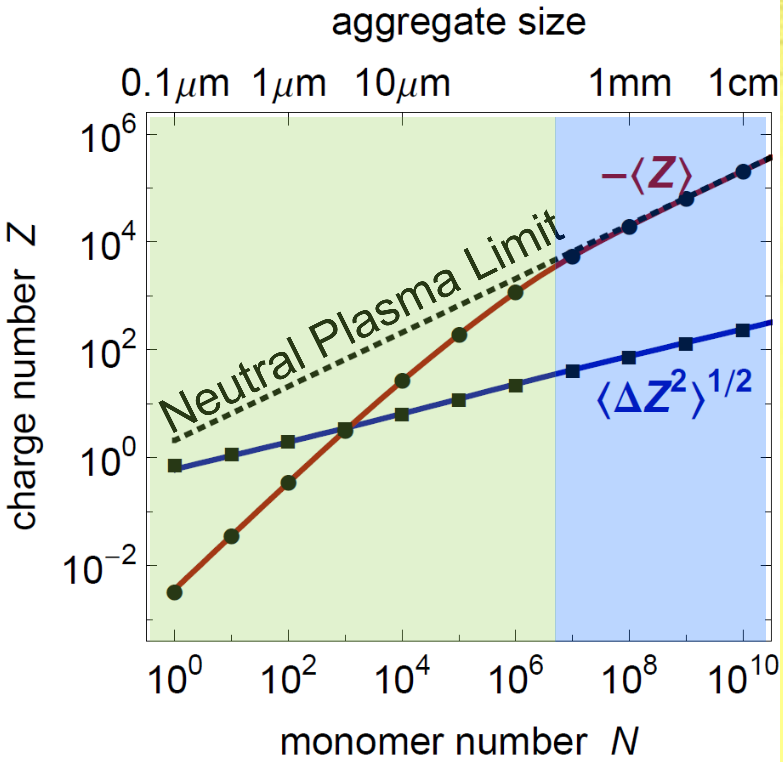
❑ This Work: solves charge transfer as analytically as possible
- ✓ Single eq. for a “master” parameter
- ✓ Arbitrary size & porosity distribution
- ✓ Agrees with numerical solutions very well (see next slide)
- ✓ Enables coupled simulation of dust growth/settling & MRI turbulence



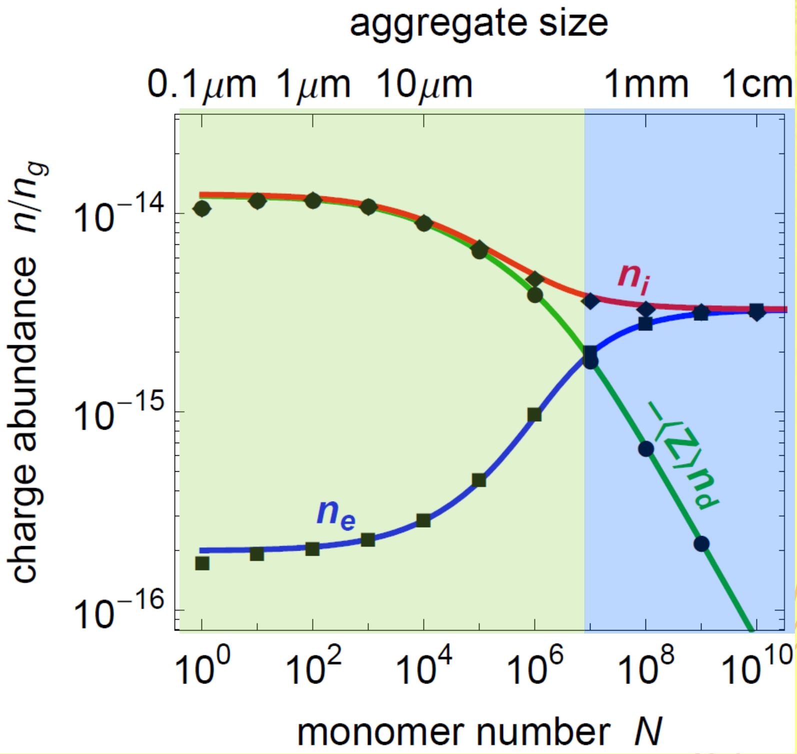
Co-Evolution of Dust Charge & Gas Ionization States

Example: r = 5AU, z = H, **fractal growth (D=2) : $a \approx a_0 N^{1/2}$**

Evolution of Dust Charge State



Evolution of Gas Ionization State



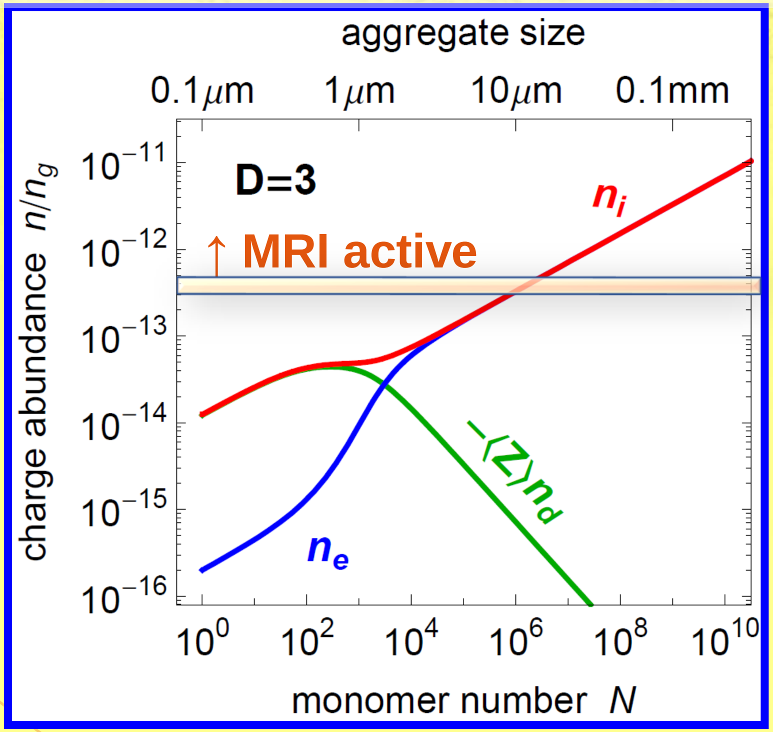
Small Dust ➔ Ion-Dust Plasma (IDP) : $n_i \approx -\langle Z \rangle n_d$, $\boxed{-\frac{\langle Z \rangle e^2}{a} \ll k_B T}$

Large Dust ➔ Ion-Electron Plasma (IEP) : $n_i \approx n_e$, $\boxed{-\frac{\langle Z \rangle e^2}{a} \sim k_B T}$

Fractal Dust Maintains a Wide Dead Zone

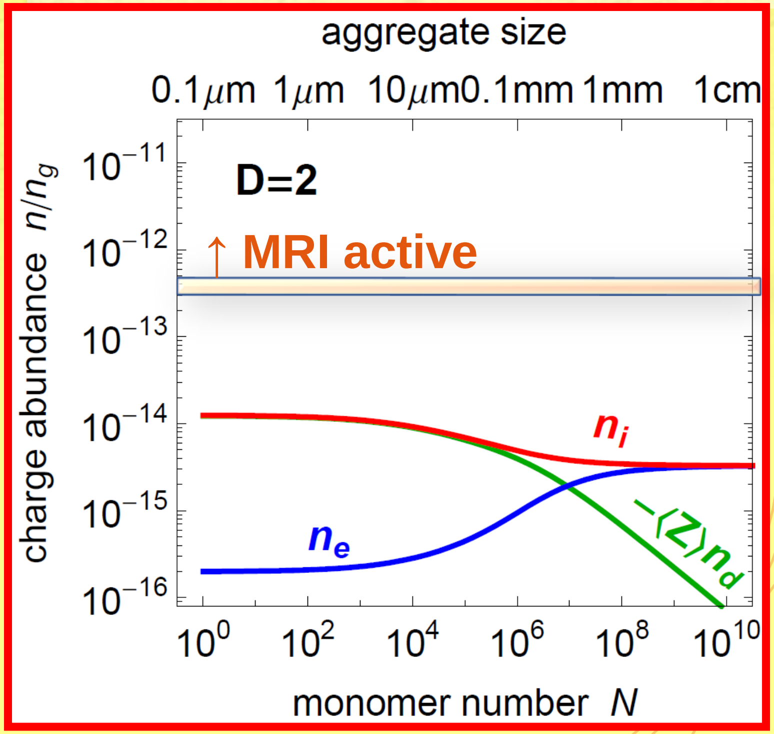
D≤2 → Total surface area σn_d conserved → n_e kept low

Compact (D=3) Dust Model



MRI active for size a>10μm

Fractal (D=2) Dust Model



MRI inactive for all sizes!!

→ Dead zone is maintained until aggregates are compressed (a~cm)

Step 2: A Simple Estimation of the Effect of Electrostatic Repulsion on Dust Growth

$$E_{\mathrm{kin}} = \frac{1}{2}\mu v_{\mathrm{rel}}^2$$

Relative Kinetic Energy

$$E_{\mathrm{el}} = \frac{ZZ'e^2}{a+a'}$$

"Electric Energy" before Contact

Collisional Cross Section: $\sigma_{\mathrm{eff}} = \pi(a+a')^2\left(1 - \boxed{\frac{E_{\mathrm{el}}}{E_{\mathrm{kin}}}}\right)$ ➡

Growth Possible if

$$E_{\mathrm{kin}} > E_{\mathrm{el}}$$

- ✓ Dust Motion : Brownian Motion + Sedimentation + Turbulence
- ✓ Growth Mode: Monodisperse(=uniform) & Fractal (D=2)

  ← valid for early evolutionary stages (a < 1cm)
- ✓ Disk Model: MMSN + Ionization sources

  (cosmic ray + X-ray + radionuclides)

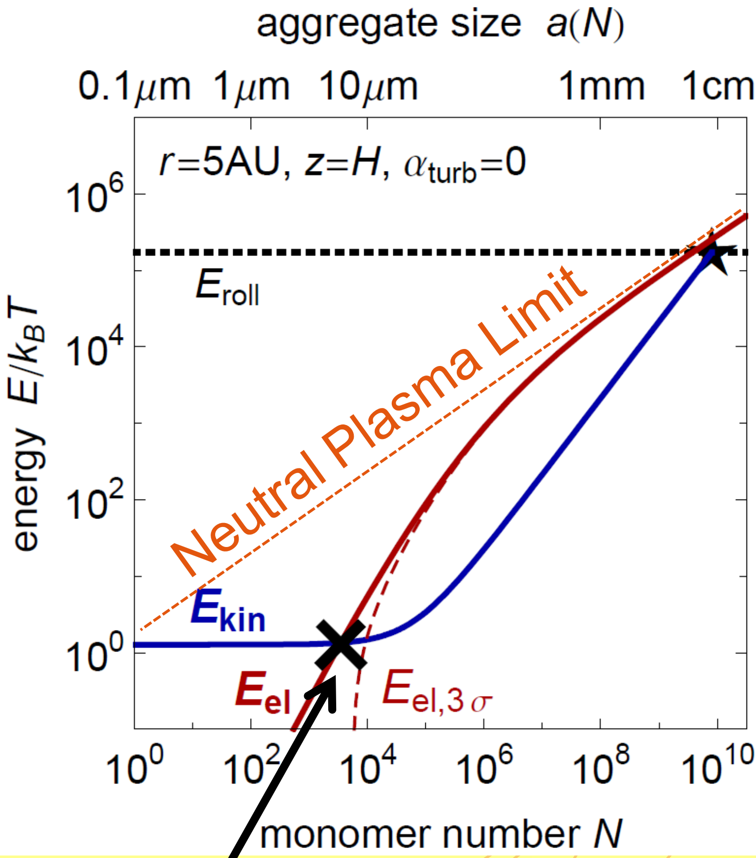
Kinetic Energy vs Electrostatic Energy

Example: r = 5AU, z = H, no turbulence

E_{el} : $Z_1 = Z_2 = \langle Z \rangle$

$E_{el,3\sigma}$: $Z_1 = \langle Z \rangle$, $Z_2 = \langle Z \rangle + \underline{3\langle \Delta Z^2 \rangle^{1/2}}$

Both E_{el} & $E_{el,3\sigma}$ quickly converge to the neutral plasma limit, exceeding E_{kin} much before collisional compaction (★) begins!

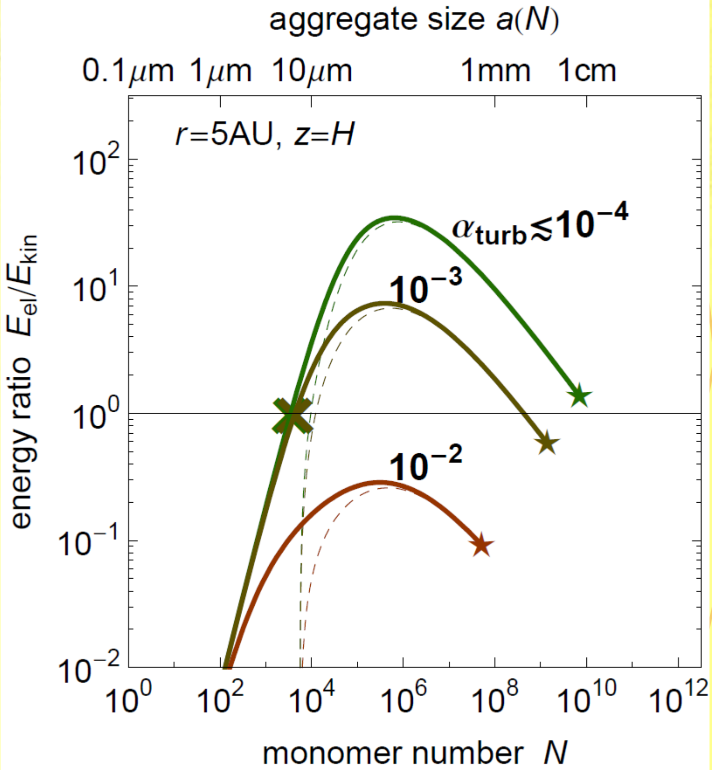


Uniform growth stalls at size as small as 10μm !

Effect of Turbulence

- ☐ Disk turbulence enhances the collisional velocity Δv. (see, e.g., Ormel & Cuzzi 07)
- ☐ The electric barrier ($E_{el}>E_{kin}$) is removed for **$\alpha \gtrsim 10^{-2}$**.

➔ If MRI turbulence is present, dust is likely to overcome the electric barrier.



But…

Disk Turbulence: a Friend or Foe?

At later stages, such strong turbulence is very likely to cause collisional fragmentation of aggregates!!

- **$\Delta v \sim \alpha^{1/2} c_s \sim$ 100m/s for $t_{fric} \sim T_k$ & $\alpha \sim 10^{-2}$**
  (Ormel & Cuzzi 07)
- Collision of aggregates results in fragmentation for **$\Delta v >$ 30-60** m/s
  (Wada+ 08,09(submitted))

Laminar → **Electric barrier at early growth stages**
Turbulent → **Fragmentation barrier at late stages**

Summary up to here

- ❑ Evolution of dust charge & gas ionization states with dust growth is investigated analytically.
  - ✓ Fractal growth (valid for size < cm) tends to maintain a large dead zone.

- ❑ “Electric barrier” against dust growth:
  - ✓ Without turbulence, uniform (orderly) dust growth is likely to stall at its very early stage.
  - ✓ With turbulence, dust can overcome the barrier, but then suffers from collisional fragmentation.

A Possible Path to Evolve: Bimodal Growth

Small “field” aggregates (mass **m)**
Large “test” aggregates (mass **M)**

$$M \gg m$$
$$n(M) \ll n(m)$$

➡ Test aggregates can collide with “frozen” field aggregates if $(\Delta v)_{Mm} > (\Delta v)_{mm}$

- ☐ Brownian-motion dom. → $(\Delta v)_{Mm} < (\Delta v)_{mm}$
- ☐ Sedimentation-dom. → $(\Delta v)_{Mm} \gtrsim (\Delta v)_{mm}$

A small fraction of massive aggregates are allowed to continue growing even if the growth of the others has “frozen out.”

Step 3: Simulation of Porous Dust Coagulation

- Extended Smoluchowski Equations:

  Evolve mass DF n(M) & mass-volume rel. V(M) consistently

- Porosity change 🡐 Empirical formula from N-body simulations

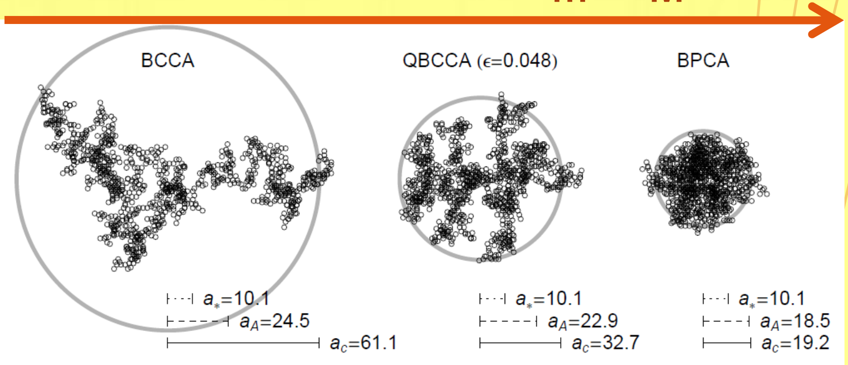
(Okuzumi, Tanaka, & Sakagami, coming soon!)

$$\partial_t n_M = \int_0^{M/2} \underline{K^{M',V_{M'}}_{M-M',V_{M-M'}}} n_{M'} n_{M-M'} dM' - n_M \int_0^{\infty} \underline{K^{M,V_M}_{M',V_{M'}}} n_{M'} dM'$$

$$\partial_t V_M = \int_0^{M/2} [\underline{V_{1+2}(V_{M'}, V_{M-M'})} - V_M] \times \underline{K^{M',V_{M'}}_{M-M',V_{M-M'}}} n_{M'} n_{M-M'} dM'$$

$V_{1+2}(V_m,V_M)$: volume of collisional outcome

Decreasing V_m/V_M



Small Size Ratio

⇓

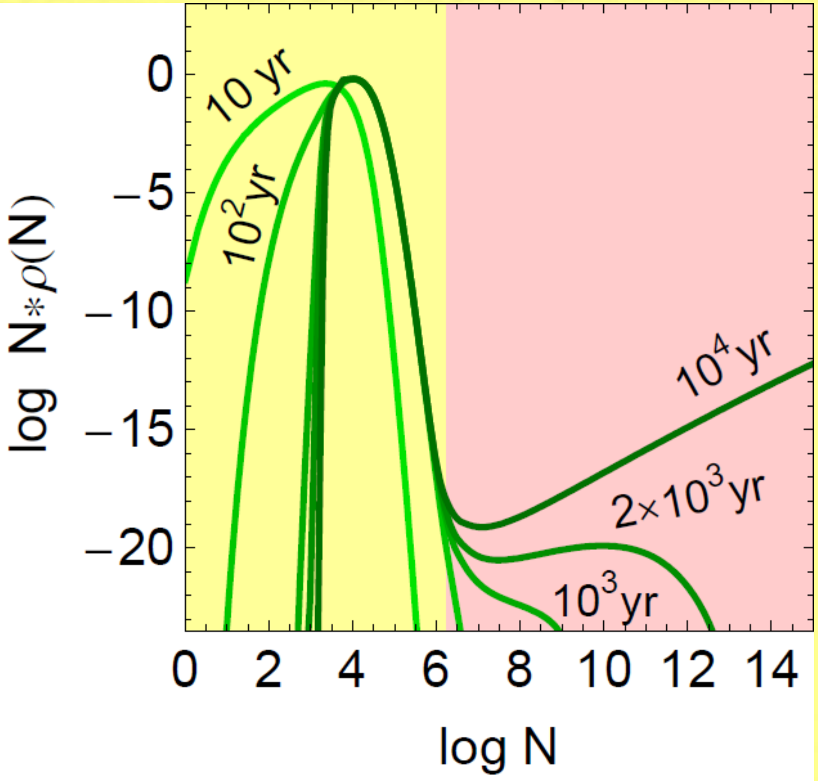
Small Porosity Increase

Result

r = 5AU, z = H, α =0, Ionization Rate = 0.1 x(X-ray Ionization)

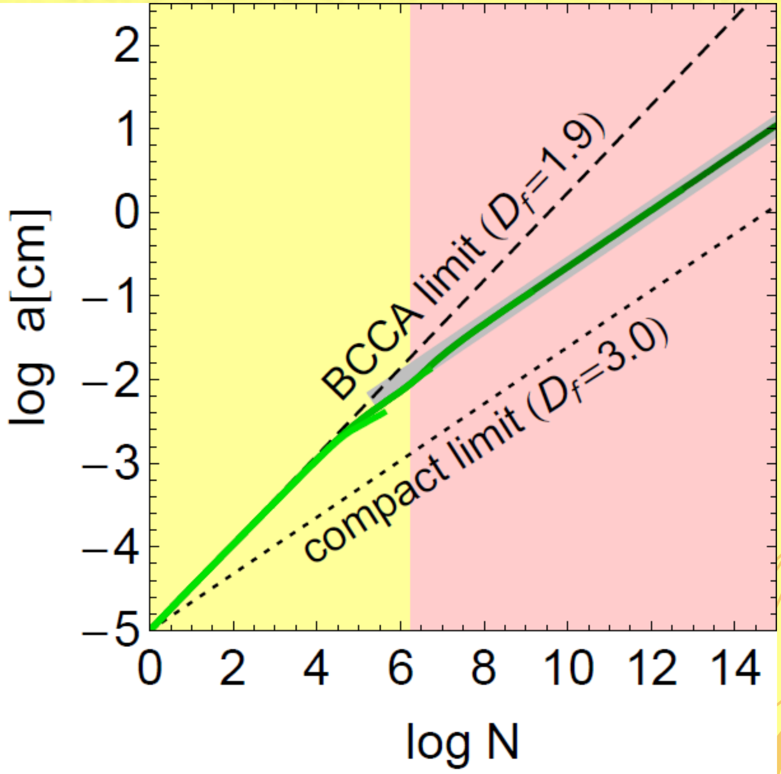
Mass Spectrum

Brownian dom. ↔ Sedimentation dom.



Mass-Radius Relation

Brownian dom. ↔ Sedimentation dom.



Summary

- ☐ Evolution of dust charge & gas ionization states with dust growth is investigated analytically.
  - ✓ Fractal growth (valid for size < cm) tends to maintain a large dead zone.

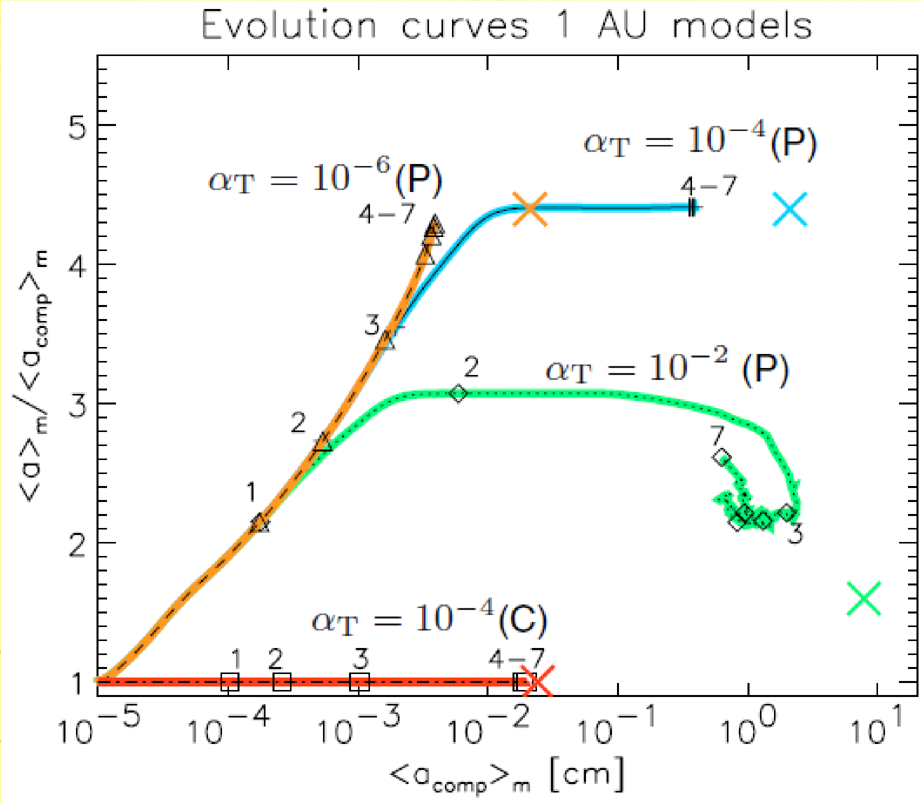
- ☐ "Electric barrier" against dust growth
  - ✓ Fractal growth is likely to stall in the absence of strong turbulence

- ☐ Bimodal growth induced by the electric barrier is confirmed by a coagulation simulation including porosity evolution.

Code Check: Comparison with a Full-2D Method

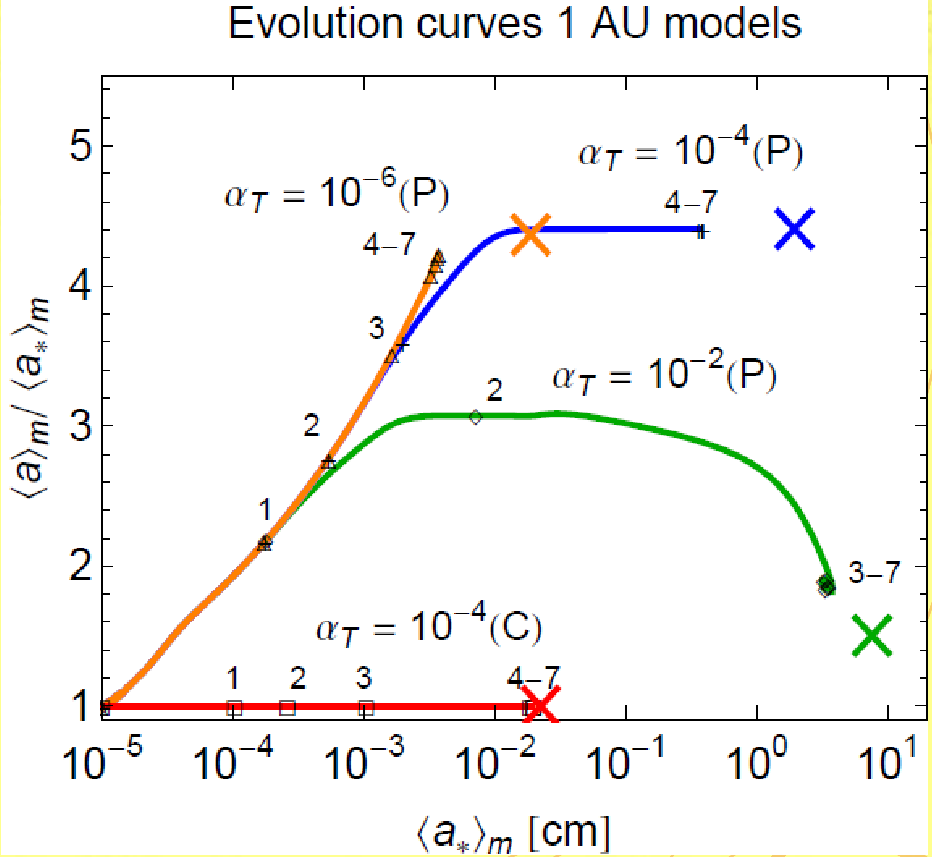
VAM reproduces full-2D results in surprisingly good accuracy

Full-2D Monte Carlo Method (Ormel+ 07)



CPU Time: 2 Hours

Volume-Averaging Method



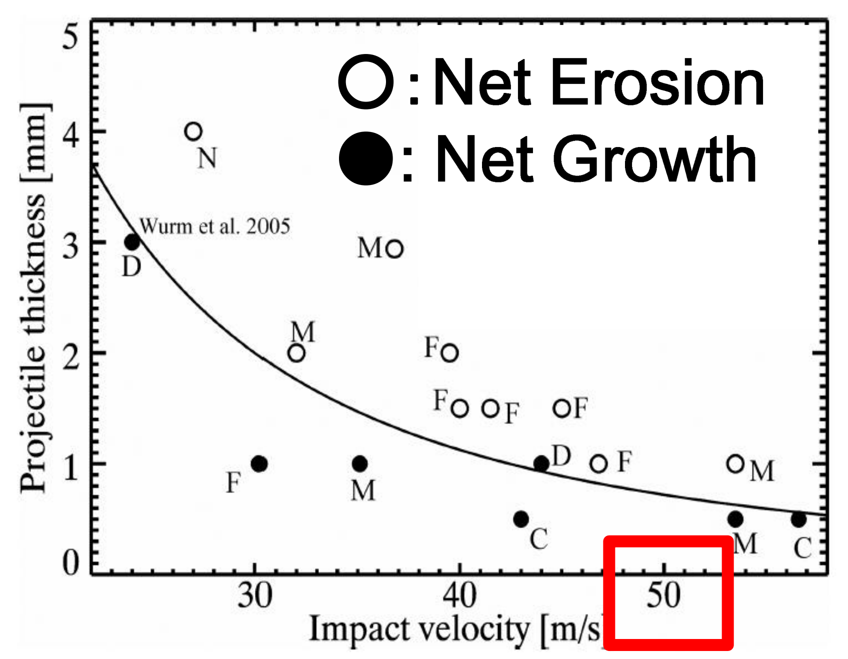
CPU Time: 1 Min

Is Bimodal Growth Favorable for Planetesimal Formation?

Recent Lab Experiment
(Teiser & Wurm 08)

Collision of large (1-10cm) target and small(<mm) projectile

➔Target can achieve net growth even if v_{imp}>50cm!!



Teiser & Wurm (2008)

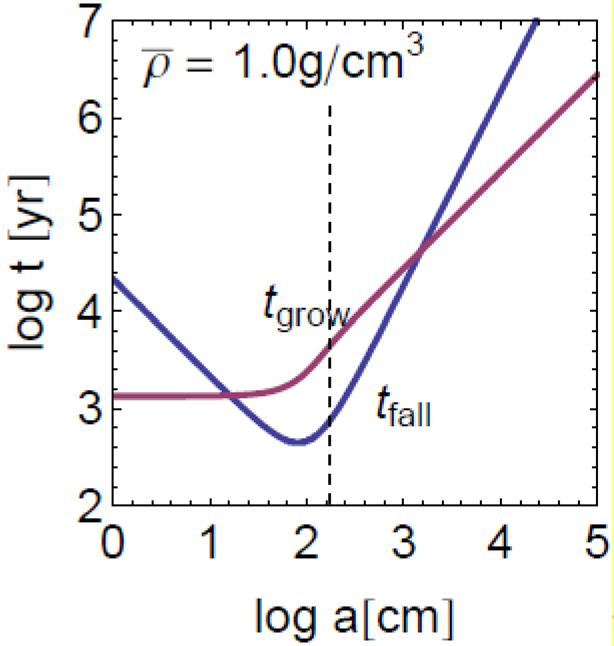
Bimodal growth might overcome the fragmentation barrier!

Porous Dust Can Overcome the Radial Drift Barrier

r = 5AU, z = 0

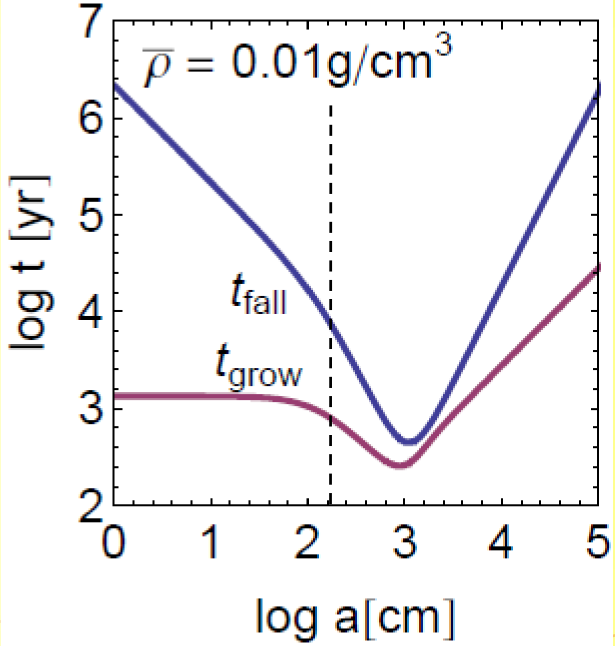
Compact Dust Model
(Porosity = 0%)

Epstein Stokes



Porous Dust Model
(Porosity = 99%)

Epstein Stokes



$$t_{\rm stop} \propto \frac{ma}{\sigma} \propto \bar{\rho} a^2$$

$$\boxed{t_{\rm stop} \sim \Omega_{\rm K}^{-1} \Rightarrow a_c \propto \bar{\rho}^{-1/2}}$$

$$\left\{ \begin{array}{c} \sigma \propto \bar{\rho}^{-1} \\ m \propto \bar{\rho} a_c^3 \propto \bar{\rho}^{-1/2} \end{array} \right.$$

$$\boxed{\frac{\dot{m}}{m} \propto \frac{\sigma}{m} \propto \bar{\rho}^{-1/2}}$$