Polluting white dwarfs with 2nd-generation asteroids formed in AGB outflows

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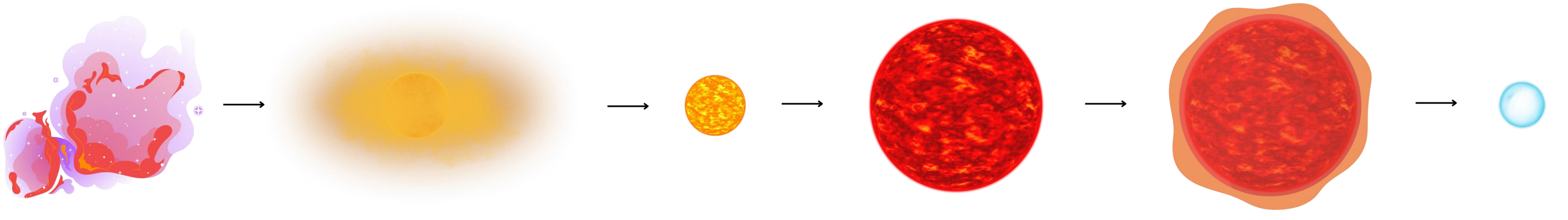
Evolution of low and intermediate mass stars



STELLAR NEBULA

PROTOSTAR
1st planetesimal formation

MAIN SEQUENCE

RED GIANT

ASYMPTOTIC RED GIANT
2nd planetesimal formation?

WHITE DWARF

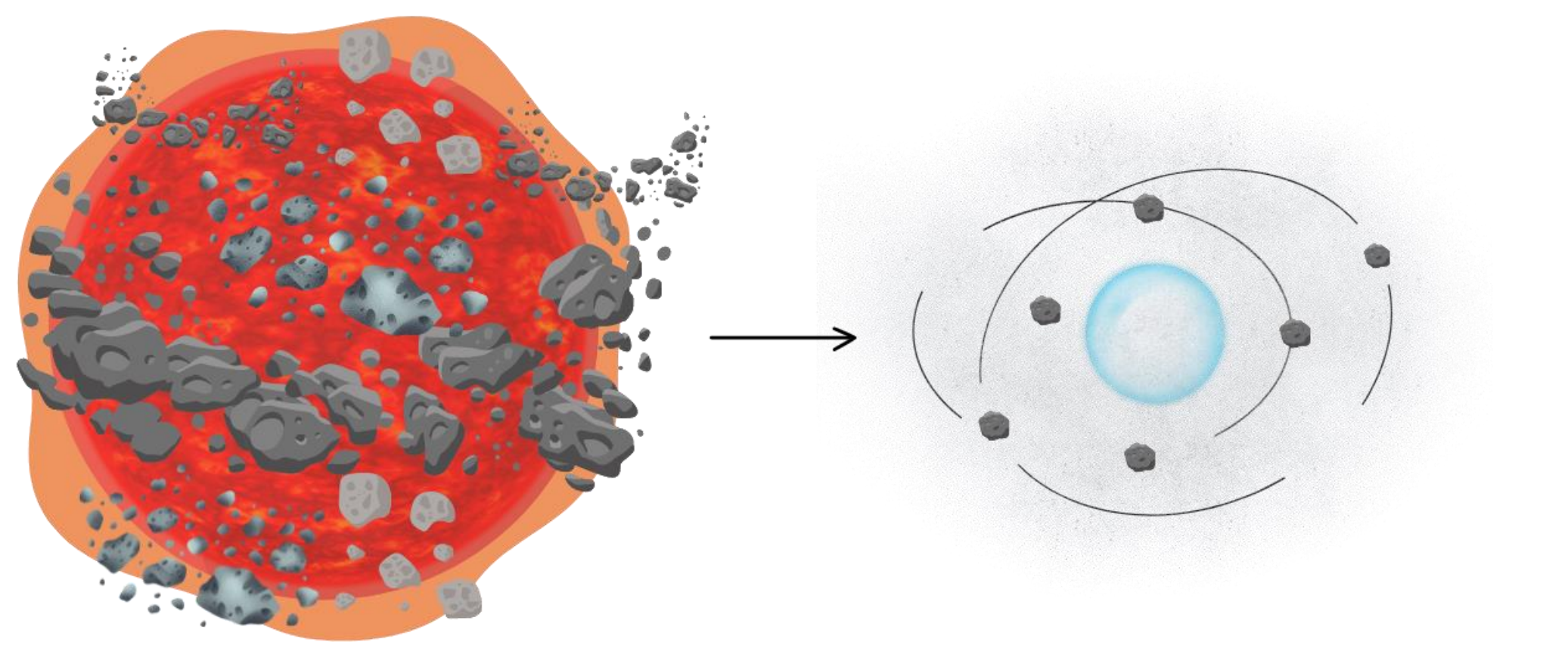
Background

White dwarfs, WD are degenerate cores of < $8M_\odot$ stars. Metals sink in their *H/He* atmospheres fast compared to their lifetimes *(few days-1,000 years vs. billions of years)*

White dwarf pollution refers to the presence of metals in their atmospheres: up to **50% of all white dwarfs are polluted** [Koester+ 2014]

- Long WD lifetimes vs. short metal sinking timescales → **accretion is ongoing**
- **Current pollution picture:** white dwarfs feed on disrupted asteroids, scattered inwards by distant massive planets *(1st generation planetary systems)*. **Scattering planets** have to be **more massive than ~ Neptune** to send asteroids on star-grazing orbits, overcoming the effects of General Relativity [Pichierri+ 2017]
- **The pollution picture is unlikely complete** because
  - the detected **pollution is volatile-poor** → ***why not from comets?***
  - **giant planets are not frequent** around A and F stars (white dwarf progenitors) [Vigan+ 2021] and were even less frequent in the past, when the progenitors were evolving, in lower-metallicity environments

Proposed pollution mechanism



2nd generation asteroids form in AGB envelopes

… and later pollute WD's via collisional grinding or tidal disruption

Table 1

Quantity	Standard AGB values
Mass loss rate, $\dot{M}$	10^{-6} $M_\odot$/year
Stellar radius, R_*	300 $R_\odot$
Outflow velocity, v_{out}	10 km/s
Dust sublimation front, R	2 R_*
Condensation temperature, T	1,000 K
Stellar outflow composition	73% H, 25% He, 2% other
Dust solid density, ρ_s	3 g/cc (silicates)
Velocity of large-scale turbulence	2 km/s

Habing & Olofsson 2004; Hofner & Olofsson 2018

Formation of asteroids in AGB outflows

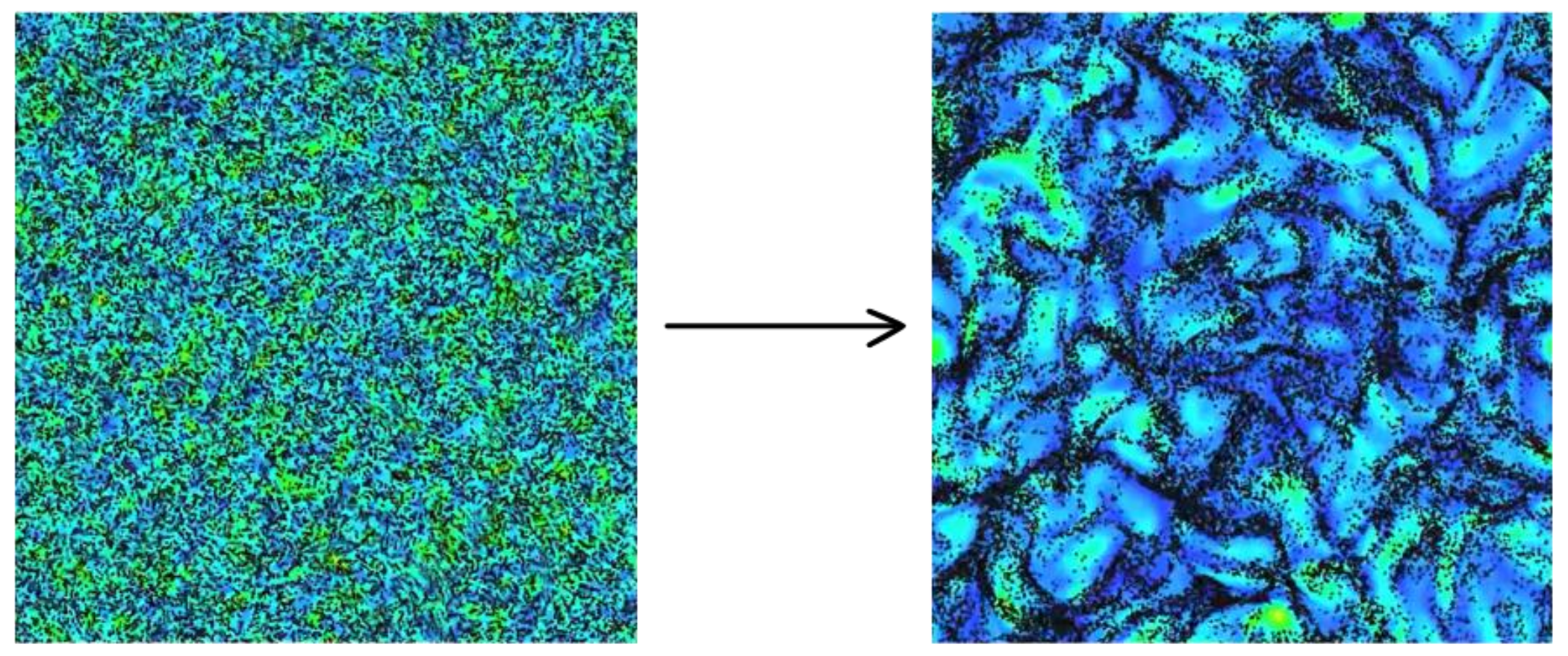
Asymptotic Giant Branch, AGB is a post-main-sequence evolutionary stage of < $8M_\odot$ stars, when they lose most of their mass via turbulent outflows, becoming white dwarfs

- As seen in experiments and numerical simulations, **small eddies** tend to effectively **concentrate dust of specific sizes** in void spaces

Colors show gas vorticity, black points show dust grains

Video

Credits: Phil Hopkins' research group



Dust is homogeneously suspended in gas at *t = 0*

After some time, the turbulence efficiently concentrates dust

- For Kolmogorov-like turbulence, spherically symmetric outflows and standard AGB values (Table 1), we can calculate this **specific grain size s_{conc}** by equating dust aerodynamic (Epstein) stopping time to the eddy turnover time –

$$s_{conc} \sim \frac{\rho_{gas}}{\rho_s} H Re^{-0.5} \sim 0.01 - 0.1\ \mu m$$

ρ_{gas} – local gas density
ρ_s – solid density of dust
H – gas density scale height
Re – Reynolds number

Observations: dust grains in AGB outflows are submicron [Ohnaka+ 2016]

- Kolmogorov prescription gives the **characteristic size of forming dust clumps** and **their lifetimes** – these values are ~ the eddy size and turnover timescale at Kolmogorov microscales

$$l_{clump} \sim H Re^{-3/4} \sim 100\ km$$
$$\tau_{clump} \sim H {c_s}^{-1} Re^{-0.5} \sim 1\ hr$$

c_s – local speed of sound

- For the **gravitational collapse of the dust clumps, 2 requirement must be met** – (1) self-gravity overcomes the local stellar gravity and (2) turbulent diffusion. Simple calculations demonstrate that this is feasible: the maximal concentration factor of dust is $c_{max} \sim 64 Re^{3/4} \sim 10^8$ [Desch & Cuzzi 2000], rising the local dust volumetric density to the local Roche density *($\sim 10^{-7}$ g/cm^3)* and suppressing turbulence (ratio of gas turbulent energy to dust self-gravity is ~ *1*)
- This problem requires further investigation – **turbulent concentration can be a process that seeds planetesimal formation**, when a separate process takes the system to gravitational instability
- One of such processes is **the growth of dust grains via coagulation**. The dust-growth timescales for *0.01-0.1 μm* grains are short compared to the clump lifetimes

$$\tau_{grow} \sim (n\, \sigma\, \delta v)^{-1} \sim 0.5 - 5\ s \ll \tau_{clump}$$

n – number density of dust grains
σ – grains' cross-section
δv – grains' velocity dispersion (eddy velocity at Kolmogorov microscale)

- Growing, **dust decouples from gas** and can **stay on bound orbits** around the star. Adding the aerodynamic (Epstein) drag term to the 2-body-problem equations gives the grain size $s_{decouple}$ at which the decoupling occurs –

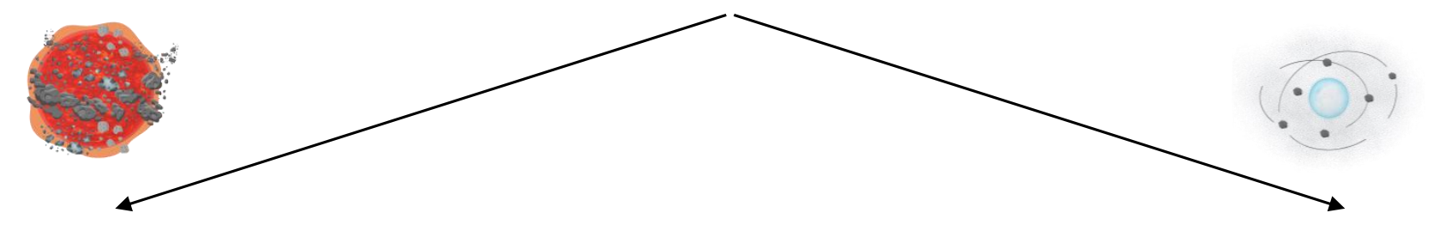
$$s_{decouple} \sim \frac{c_s}{v_{out}} \frac{\rho_{gas}}{\rho_s} 2R \sim 0.1\ mm$$

v_{out} – outflow velocity

To our knowledge, no observations focused on **sub-mm – cm dust around AGB stars**

- **Future work:** **hydrodynamical simulations of dust-gas mixtures around AGB stars with GIZMO**, a multi-purpose fluid dynamics + gravity code [Hopkins 2015]. Recent simulations [Steinwandel+ 2022] demonstrated the gas-dust interactions in AGB outflows create regions with substantial concentration of dust
- If only 0.01% dust collapses into planetesimals, their cumulative mass would be worth of **10,000 main asteroid belts** (assuming $1M_\odot$ is processed in AGB outflows)

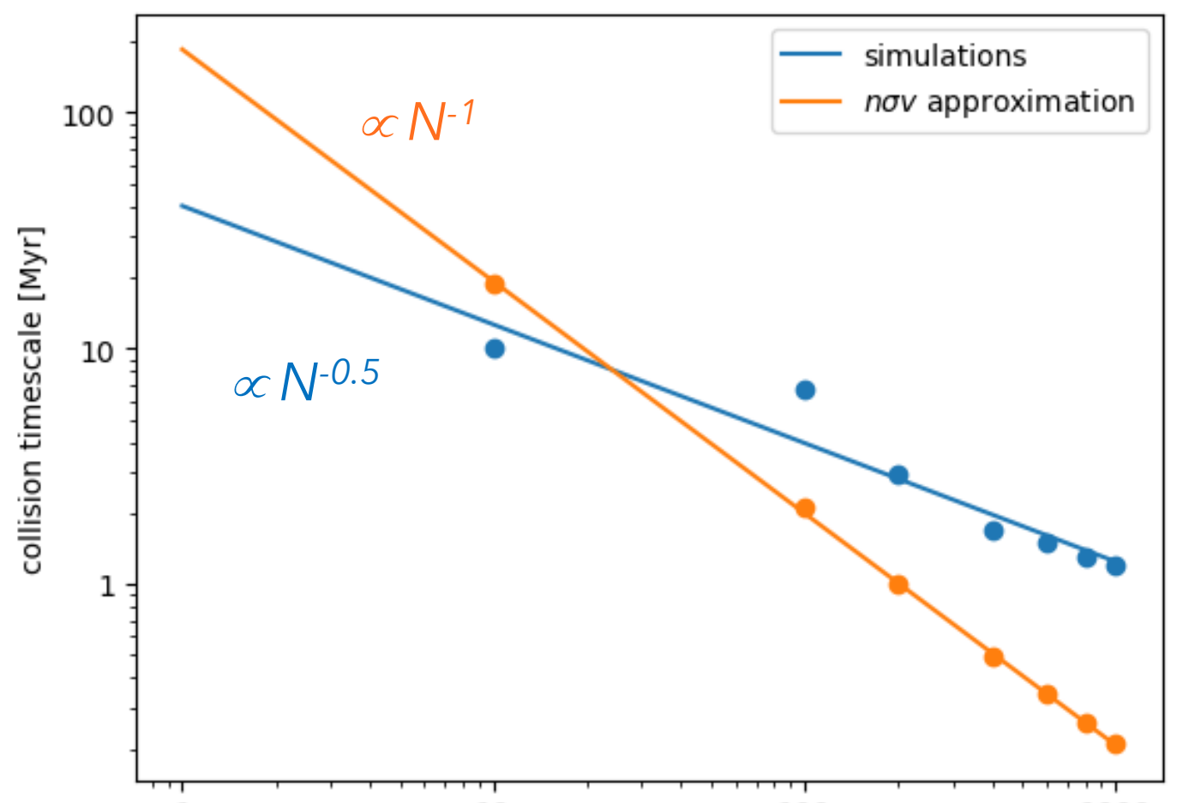
Dynamics of 2nd-generation planetesimals



AGB: planetesimals are **on bound orbits vs. ejected** to the interstellar medium, becoming 'Omuamua's **(future work)**

WD: planetesimal spherical halo/disk **evolves collisionally**, the resulting dust pollutes WD via **Poynting-Robertson drag**

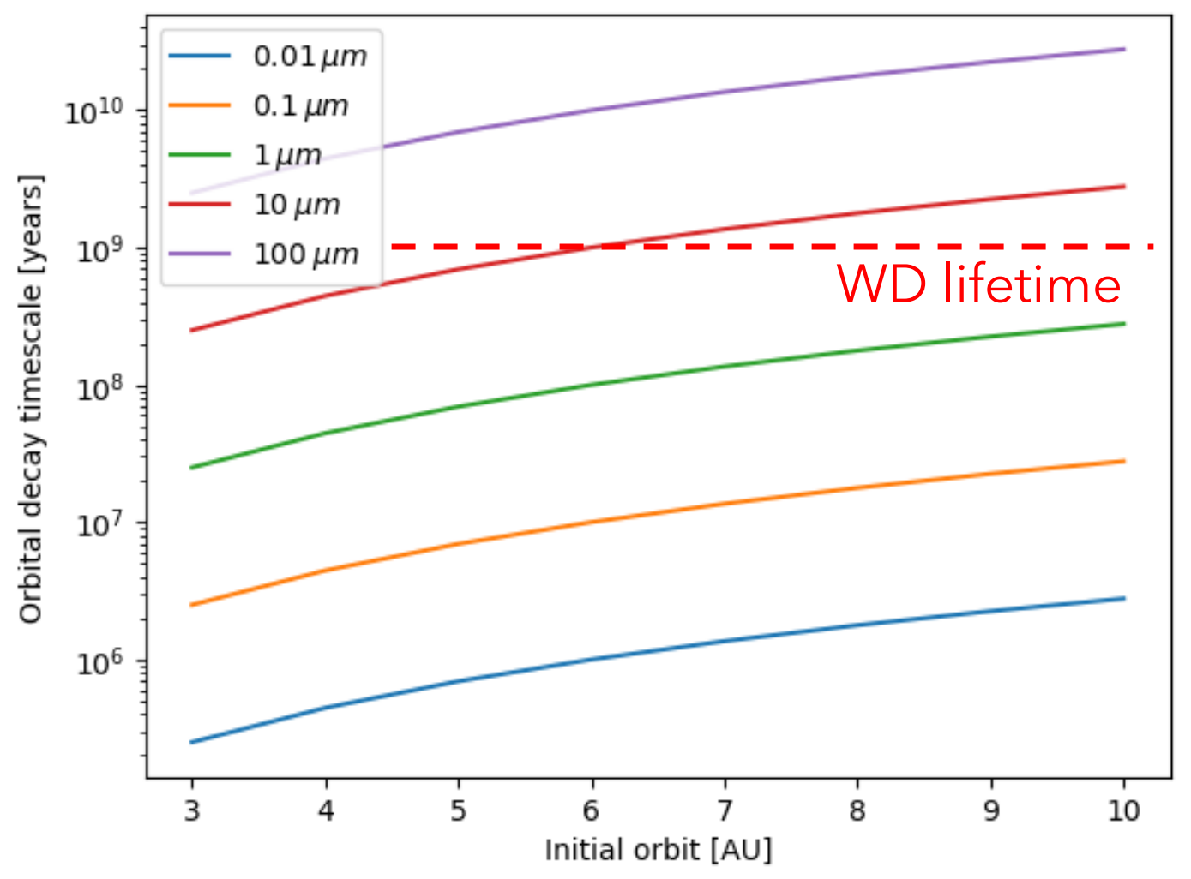
- N-body simulations of 2D WD systems in MERCURY [Chambers 1999] showed that **collisions among planetesimals can occur during WD lifetimes**



Collision rate = proxy for collisional dust production. Interestingly, the $n\sigma v$ approach, often employed for similar problems, tends to overestimate the collision frequency

Future work: N-body simulations of 3D WD systems (WD + spherical halo of planetesimals)

- Poynting-Robertson drag can cause **orbital decay of dust** from a range of orbits



For perfectly absorbing grains and circular orbits, **the orbital decay timescale τ_{PR}** is

$$\tau_{PR} \sim \frac{a^2 \pi c^2 m}{L\sigma}$$

a – orbital radius
c – speed of light
m – grain mass
L – WD luminosity (blackbody at 10,000 K)

- **Future work:** Touma+ 2019 investigated the dynamics of spherical halos of stars with black holes at the center, showing that stars can achieve high-eccentricity orbits in such systems – ***similar mechanism at play in polluted WD systems?***