Seeding planetesimals in circumstellar discs

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Proplanetary discs - Grishin, Perets & Avni (2019), MNRAS, 487, 3324
WD discs - Grishin & Veras (2019), MNRAS, 489, 168

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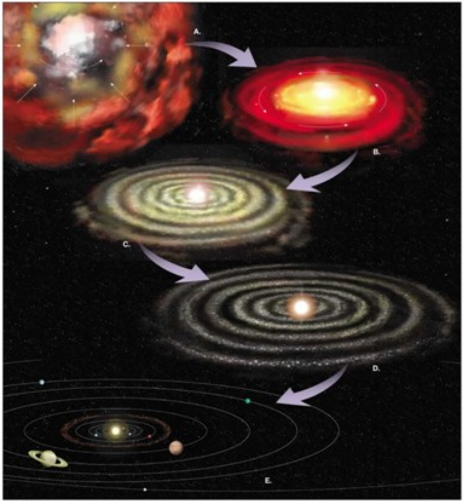
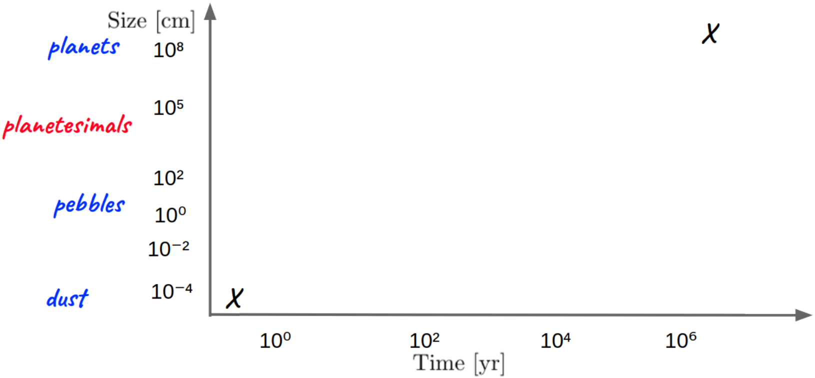
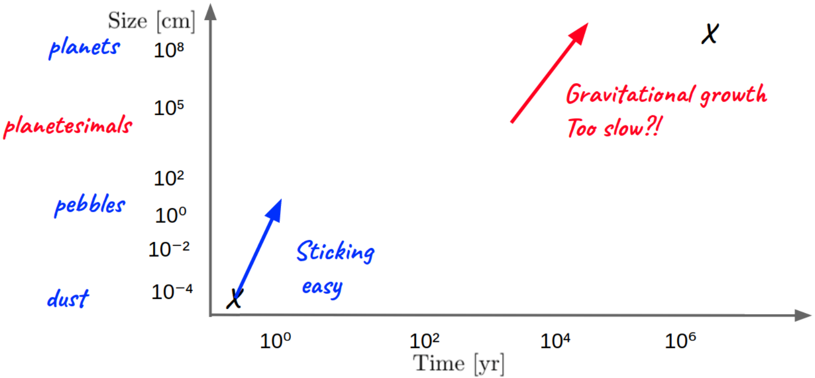
Planets form from a protoplanetary disc of gas and dust



Planets should form fast



Different scales are affected by different physical processes



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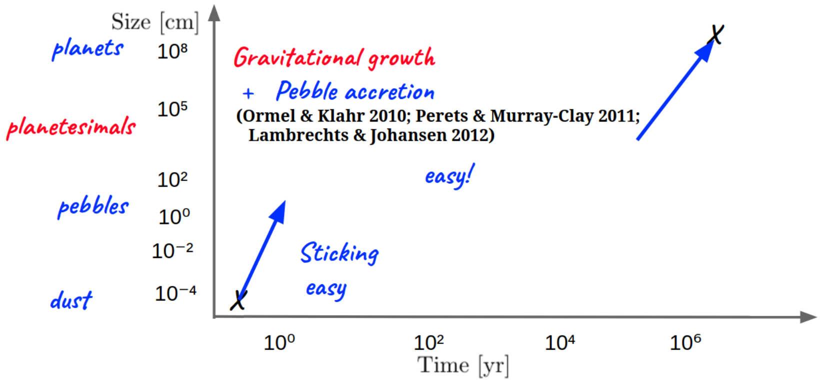
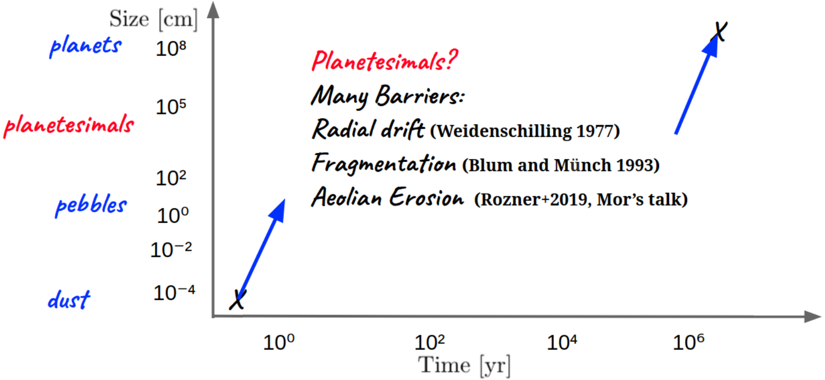
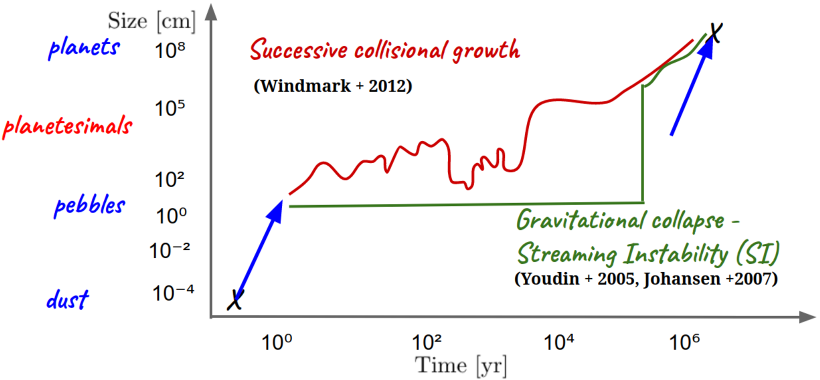


Formation of planetesimals is the hardest phase



Several models have been suggested to form planetesimals



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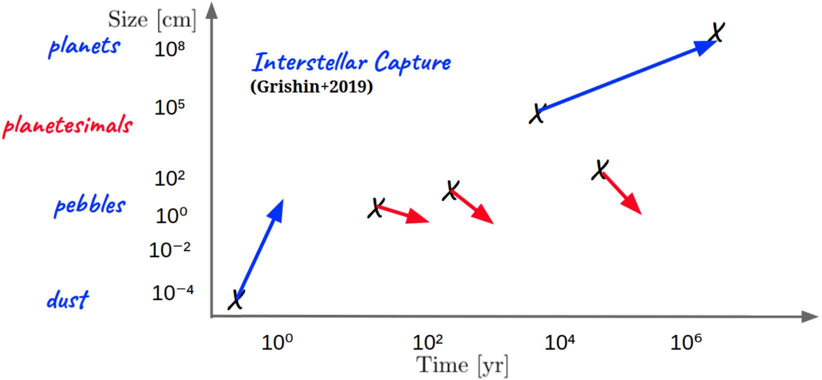
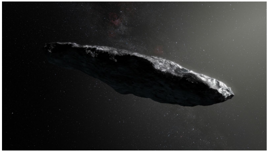


Last stages of planet formation are inefficient

- Many ejections in our own Solar System:
  - Nice model, Grant Tack and late heavy bombardment (Gomes+2005, Walsh+2011 Nature)
  - **At least $\gtrsim M_\oplus$ is ejected** (Dones+1999; Melosh 2003)
- Mass Function: $dN_{\rm eject}/dm \propto m^{-p}$
  - $p = 5/3$ (SI, Simon+2016) or $p = 11/6$ (collisional, Dohnanyi 1969, Raymond+2018)

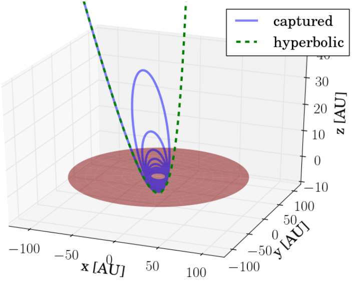


Expected number density $n = 0.2\ \mathrm{au}^{-3}$, ~ 50 times denser than the nominal estimate (Do+ 2018)

'Oumuamua's are efficiently captured in young systems (Grishin+2019)

- Gas drag: $F \propto C_D R_p^2 \rho_g v_{\rm rel}^2$
- Energy loss during passage $\Delta E \sim F \cdot (v_{\rm rel} t_{\rm cross}) \sim C_D R_p^2 \Sigma_g v_{\rm rel}^2$
- Capture if $\Delta E \gtrsim E_k \implies R_p \lesssim C_D \frac{\Sigma_g}{\rho_p} \left(1 + \frac{v_{\rm esc}^2}{v_\infty^2}\right)$

- $\Theta_s(v_\infty, r) \equiv \frac{v_{\rm esc}^2}{v_\infty^2} = 2\frac{GM_\star}{r v_\infty^2}$ - Safronov number
- $\Theta_s \ll 1$ geometric
- $\Theta \gg 1$ gravitational focusing
- At 1 AU: $v_{\rm esc} \sim 40$ km/s $\implies$ $R_p \sim 50$ m



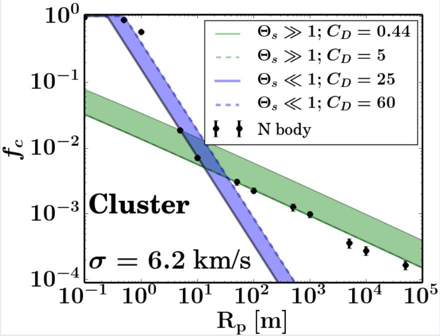
The capture fractions are estimated by a probabilistic model (Grishin+2019)

- Protoplanetary disk structure: MMSN (Chaing, Goldreich 1997, Grishin, Perets 2015): $\Sigma_g = 2 \cdot 10^3 \left(\frac{r}{AU}\right)^{-3/2} \ \mathrm{g \cdot cm^{-2}}$
- Distribution functions: Maxwellian velocity, dispersion σ, uniform area for impact parameter b
- $f_V(v_\infty) \propto v_\infty^2 \exp(-v_\infty^2/2\sigma^2)$; $f_B(b) \propto b/b_{\max}^2$
- Geometric Scattering $\Theta_s \ll 1$
  - $f_c(R_p) \propto b_{\max}^{-2} R_p^{-4/3}$
  - **Underestimates** the capture fraction
- Gravitational focusing $\Theta_s \gg 1$
  - $f_c(R_p) \propto \sigma^{-14/5} b_{\max}^{-2} R_p^{-2/5}$

Monte Carlo simulations well fitted by grav. focusing regime (Grishin+2019)

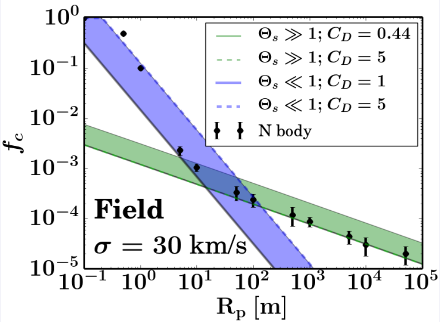
Cluster

- Focused ($\Theta_s \gg 1$) for $R_p \gtrsim 10$ m



Field

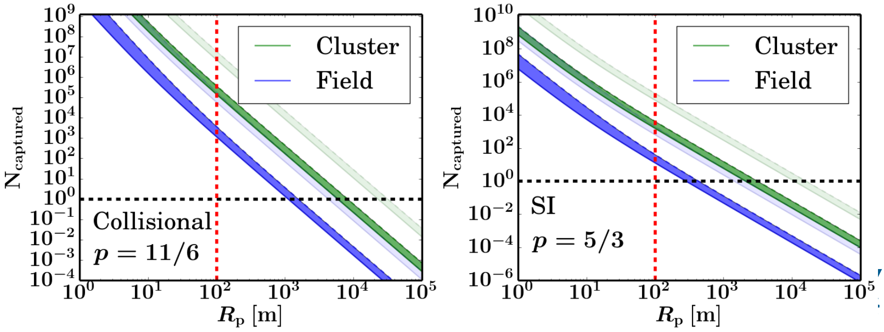
- Geometric ($\Theta_s \ll 1$) up to $R_p \lesssim 100$ m



Young planetary systems can capture many large planetesimals (Grishin+2019)

$$N_{\mathrm{captured}}(R_p) = n_\star N_{\mathrm{eject}}(R_p) \cdot \pi b_{\mathrm{max}}^2 \cdot \sigma \cdot t_{\mathrm{typ}} \cdot f_c(R_p); \;\; \frac{dN}{dm} \propto m^{-p}$$

	$n_\star$ [pc^{-3}]	t_{typ}[Myr]	σ [km/s]
Field	0.1	3	40
Cluster	$750/\pi N_\star^{1/2}$	0.3	6.2

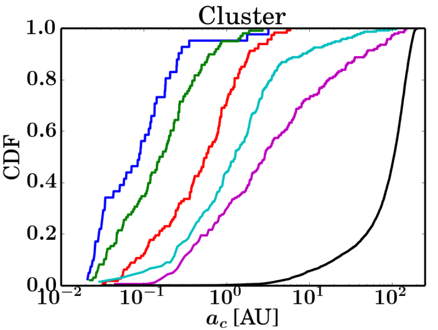


Larger planetesimals require progressevely closer approach for capture (Grishin+2019)

- ~ 1 km planetesimals captured within $a_c \lesssim 2$ AU
- ~ 1 m pebbles captured everywhere in the disc

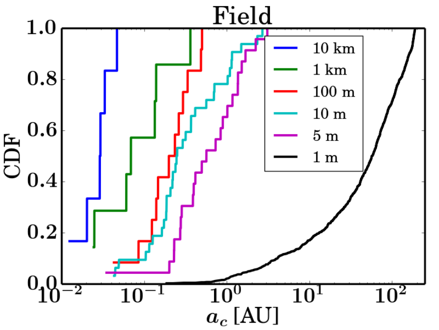
Cluster: ~ 100 m 'Oumuamua's:

- capture within $a_c \lesssim 5$ AU



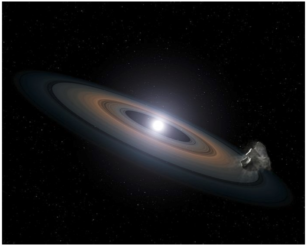
Field: ~ 100 m 'Oumuamua's:

- capture within $a_c \lesssim 0.5$ AU



WDs show signs of gas, debris discs around them and metal pollution

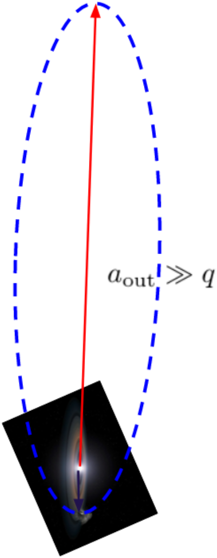
- 25-50% of WDs show signs of metal pollution (Veras 2016)
  - attributed to accreting planetesimals
- Over 40 discs around WDs are known (Farihi 2016)
  - 20% have both gas as well as dust (Gänsicke+ 2006; Dennihy+ 2018)
  - Condensation is stalled due to unknown process (Metzger+2012)
- Viscous spreading should expand the disc beyond the Roche limit (Metzger+2012, Kenyon & Bromley 2017)



Intact planetesimal inside the debris disc of SDSS J1228+1040 is a puzzle (Manser+2019)

WDs show signs of gas, debris discs around them and metal pollution (Grishin & Veras, 2019)

- Similar gas-assisted capture can work for scaled-down WD discs
  - very low rates for ISM material
  - Exo-KBO and exo-Oort cloud comets are easily captured after 1 orbit
- Effective loss-cone calculation due to Galactic tides (Heisler & Tremaine 1986) leads to loss rate of $\dot{m} \sim 10^{18}\ \mathrm{g\ yr^{-1}}$ for $q = R_{\mathrm{Roche}} \approx R_{\odot}$
  - $\sim$1% of the Oort cloud is lost within $\sim$1 Gyr, similar to Alcock+1986
  - loss rate **linear in closest approach** q (Grishin & Veras, 2019)
- If the disc extends further than $q \gg R_{\mathrm{Roche}}$, many planeteisimals are captured rather than disrupted



Prospects for Planet formation and planets around WDs

- Metre barrier potentially resolved by inserting few 'seeds'
  - Small number of large planetesimals is enough for planet formation (Ormel and Kobayashi 2012)
  - Newly captured planetesimals are targets for pebble accretion (Ormel, Klahr 2010; Lambrechts, Johansen 2012)
  - **Does not explain** the first generation of planetesimals (chicken and egg), likely to be formed by a rare event (e.g. SI)
  - Most probable mechanism for lithopanspermia (Adams & Spergel 2005)
- Discs around evolved stars can capture ISM and exo-Oort planetesimals
  - Can lead to second generation planet formation
  - Captures planeteismals around WDs
  - Possibly **higher rate** than direct break-up at $R_{\rm roche}$, maybe relevant for the formation of SDSS J1228+1040b

Summary

- We found an analytical model for capture of planetesimals in Protoplanetary discs
- Thousands of 'Oumuamua-like objects and a few $\gtrsim 1$km ones are likely to be captured
- Potential doorway to overcome the metre barrier, planetesimal formation and lithopanspermia
- First generation is still a rare events, but planet formation is not in isolation
- Same capture occurs on discs around evolved stars
- Could lead to second generation planet foration and bringing rocky material to the WD debris disc before break-up

Aerodynamic gas drag is the main interaction with small planetsimals

Aerodynamic Gas Drag

(Weidenschilling 1977; Perets, Murray-Clay 2011)

- $F_d = -\frac{1}{2} C_D(Re) A \rho_g v_{rel}^2$
  - C_D - Drag coefficient
  - $Re = 2R_p v_{rel}/c_s\lambda$ - Reynolds number
    - R_p- planetesimal size; c_s - sound speed; λ- mean free path
  - A - Cross section
  - v_{rel} - relative velocity

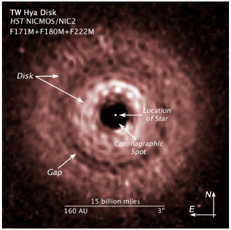
Different drag regimes

- Epstein regime: $C_D \propto Re^{-1}$ $(R_p \ll \lambda)$
- Ram pressure regime: $C_D \approx 0.44$ $(R_p \gg \lambda)$
- Stokes regime: $C_D \propto Re^{-3/5}$

Protoplanetary disks are abundant around young stars

Compelling evidence for protoplanetary disks

- Spectral Energy Distribution
- Direct Observations (ALMA Partnership: 2015, 2016)
- ~ 3 Myr disk lifetimes (Haisch+2003; Mamajek+2009)
- Disks are abundant around young stars



The ejected planetesimals can encounter other planetary systems

Encounters during disk lifetime$= N_{ejected} n_\star \cdot (\pi b_{max}^2)\langle\sigma\rangle t_{disk}$,

- $N_{ejected}(m > m_{min}) \sim (m_{min}/M_\oplus)^{-2/3}$ (Adams and Spergel 2005)
- $t_{disk} = 3\mathrm{Myr}$

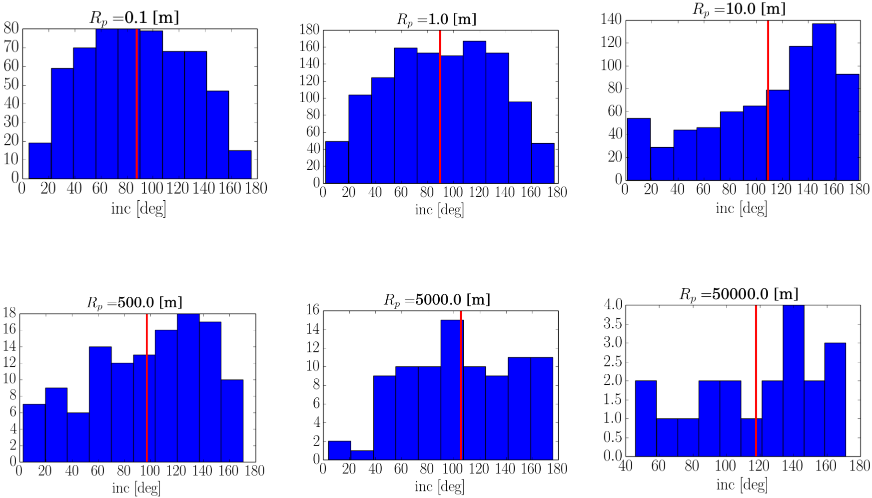
Field (Nordström 2004; Adams and Spergel 2005)

- $\langle\sigma\rangle = 30\mathrm{km/s}$ - dominated by star's relative velocities
- $b_{max} = 50\mathrm{AU}$
- $n_\star^f \sim 0.1pc^{-3}$
- $R_{\mathbf{enc}} \sim \mathbf{10^{-2}\ yr^{-1}}$

Cluster (Lada and Lada 2003; Adams and Spergel 2005)

- $\langle\sigma\rangle = 6.2 \pm 2.7\mathrm{km/s}$ - dominated by planeteismal's escape velocity
- $b_{max} = 120\mathrm{AU}$
- $n_\star^c \sim 750/\pi N_\star^{1/2}\ \mathrm{pc}^{-3}$
  - $N_\star$ - number of stars
- $R_{\mathbf{enc}} \sim \mathbf{1\ yr^{-1}}$

back up: Capture comes with a variety of disk inclinations



back up: The encounter fractions are estimated by a probabilistic model

- Dist. functions:

$$f_V(v) = \sqrt{\frac{2}{\pi}}\frac{v^2}{\sigma^3}\exp\left(-\frac{v^2}{2\sigma^2}\right);\; v \in [0,\infty];\; f(b) = \frac{2b}{b_{max}^2};\; b \in [0, b_{max}]$$

- Joint dist. function of rand. var. $x \equiv \left(\frac{b}{b_{max}}\right)^{\alpha}\left(\frac{v_\infty}{\sigma}\right)^2$ is

$$f_X(x) = 2^{2-2/\alpha}\frac{1}{\alpha\sqrt{\pi}}x^{(2-\alpha)/\alpha}\Gamma\left(\frac{3\alpha-4}{2\alpha}, \frac{x}{2}\right)$$

Geometric Scattering

$\Theta_s \ll 1 \implies \alpha = 2$

- $f_X(x) = \frac{1}{\sqrt{\pi}}\Gamma(1, x/2) = \mathrm{erfc}\left(\sqrt{x/2}\right)$
- $P(x < x_{max}) = x_{max} = 5.5 \cdot 10^{-6}\left(\frac{\sigma}{6.2 km/s}\right)^{-2}\left(\frac{b_{max}}{234\mathrm{AU}}\right)^{-2}\left(\frac{R_p}{1\mathrm{km}}\right)^{-1}$
- $x_{max} = \frac{2GM}{b_{max}^2\sigma^2}\frac{3C_D\Sigma_{g,0}}{4\rho_p R_p}$

Gravitational focusing

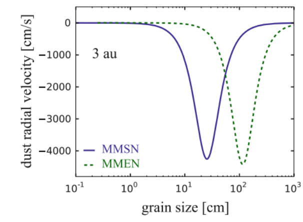
$\Theta_s \gg 1 \implies \alpha = 4/3$

- $f_X(x) = \frac{3}{\sqrt{8\pi}}x^{1/2}\Gamma(0, x/2) = -\frac{3}{\sqrt{8\pi}}x^{1/2}\mathrm{Ei}(-x/2)$
- $P(x < x_{max}) \propto x_{max}^{3/2} = 1.09 \cdot 10^{-3}\left(\frac{\sigma}{6.2 km/s}\right)^{-3}\left(\frac{b_{max}}{234\mathrm{AU}}\right)^{-2}\left(\frac{R_p}{1\mathrm{km}}\right)^{-1/2}$
- $x_{max} = \left(\frac{6C_D\Sigma_0}{\rho_p R_p}\right)^{1/3}\frac{GM}{\sigma^2 b_{max}}\left(\frac{b_{max}}{\mathrm{AU}}\right)^{-1/3}$

back up: Planet formation is inefficient

Radial drift and pebble accretion

- Short drift times: $t_{drift} \sim 10^{3-4}\mathrm{y}$ for $\sim 1\mathrm{m}$ pebbles (Youdin 2010; Pessah and Gressel 2017)
- Efficient **pebble accretion** onto planetesimals (Ormel, Klahr 2010; Lambrechts, Johansen 2012)
- first planetesimal formation from **streaming instability** (Youdin, Goodman, 2005; Johansen+2007 *Nature*)



Planet formation spans from μ-sized grains to $10^3\mathrm{km}$ planets

Ejection of large planetesimals

- Planet planet scattering (Juric, Tremaine 2008); Secular chaos (Wu, Lithwick 2011; Grishin+2018)
- Many ejections in our own Solar System:
  - Nice model and late heavy bombardment (Gomes+2005, Nature)
- At least $\gtrsim M_{\odot}$ is ejected (Dones+1999; Melosh 2003) with mass function $dN/dm \propto m^{-5/3}$ (Napier 2004)