Grain growth from sub-micron to pebble-sized grains

Taurus B212/213 filament (@450 pc) as seen by Herschel

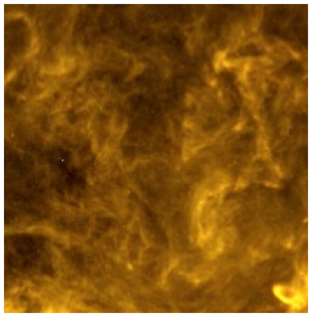
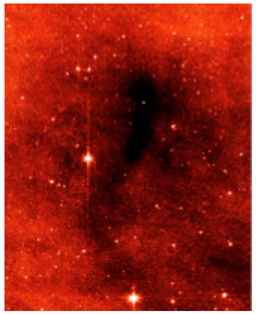
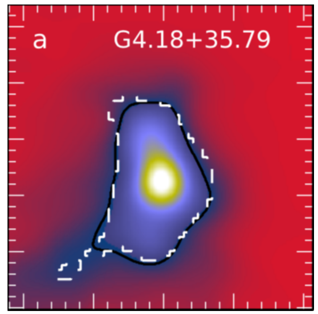
V. Guillet

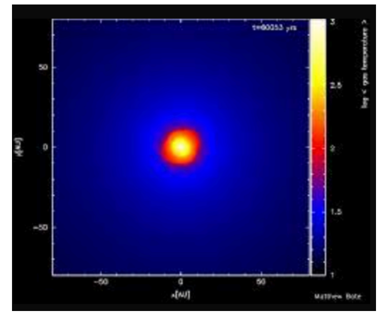
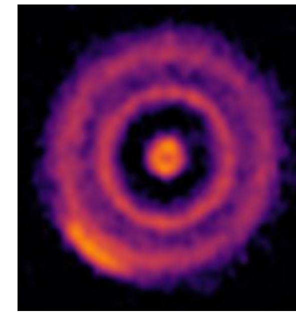
Université Paris-Saclay, IAS, Université de Montpellier, LUPM

Collaborators: A. Marcowith (LUPM), P. Henebelle (AIM), P. Marchand (IRAP), U. Lebreuilly (AIM)

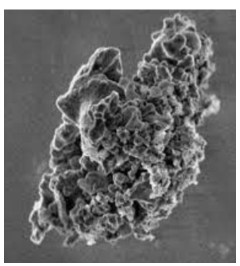
Problematics : grain growth from ISM grains to planetesimals

How to make grains grow as long as gravitationnal force between grains remains negligible ?

Diffuse ISM → prestellar core →prestellar disks →protoplanetary disks



x 10^5 in size

- Bouncing barrier
- Fragmentation barrier
- Radial drift barrier

x 10^5 in size

ISM dust
~ 0.1 µm

Peeble-size dust
~ 1 cm

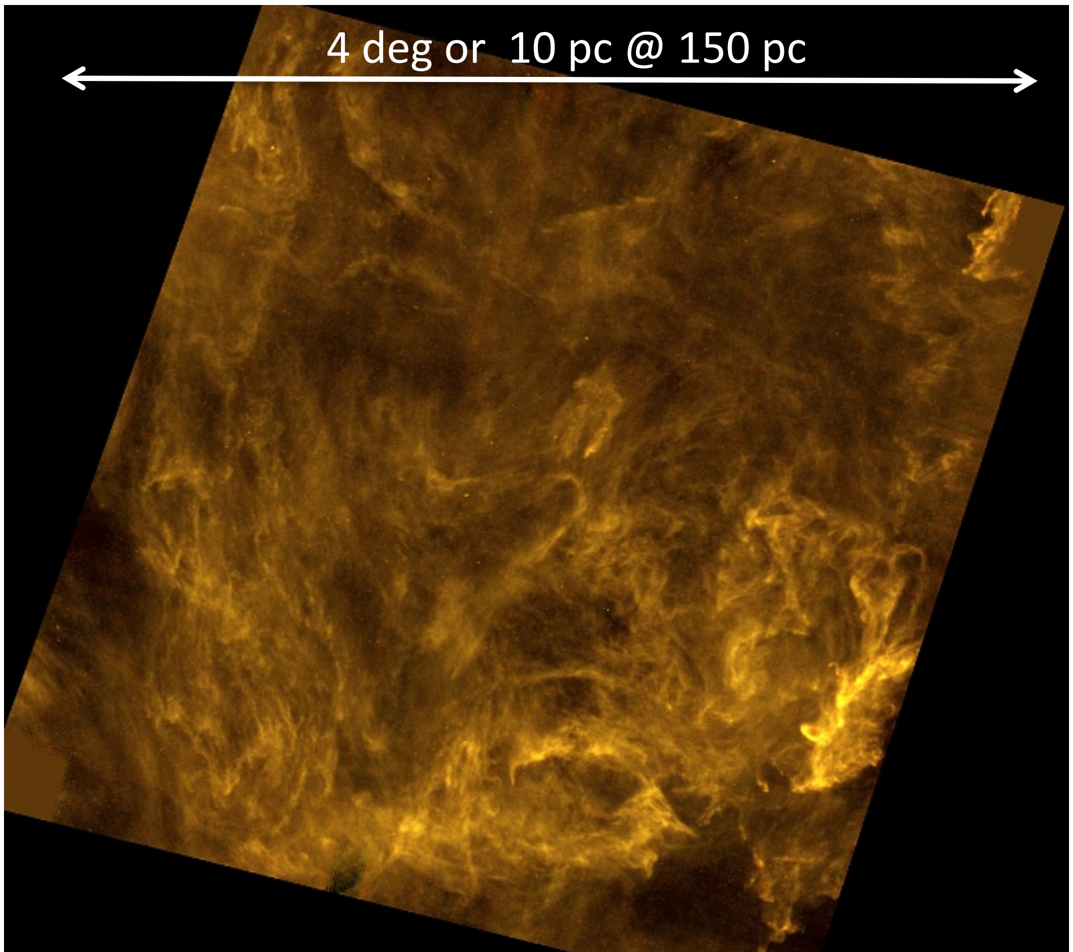
Planetesimals
> 1 km

Outline

1. The observational context
   a) The diffuse interstellar medium (ISM)
   b) Observational constraints on grains sizes
   c) Observational evidence for the evolution of dust optical properties in the ISM
   d) Observational evidence for grain growth in the dense ISM
2. The dust microphysics
   a) The initial dust size distribution
   b) Dust evolution processes
   c) Grain charging
   d) Grain coupling
   e) Grain dynamics
3. The governing equations
   a) The Smoluchowski equation
   b) The ionization equilibrium equation
4. Modeling and simulation results for grain growth in core collapse
5. Subtilities
   a) Electrostatic effects between charged grains
   b) Feedback of grain growth on MHD resistivities

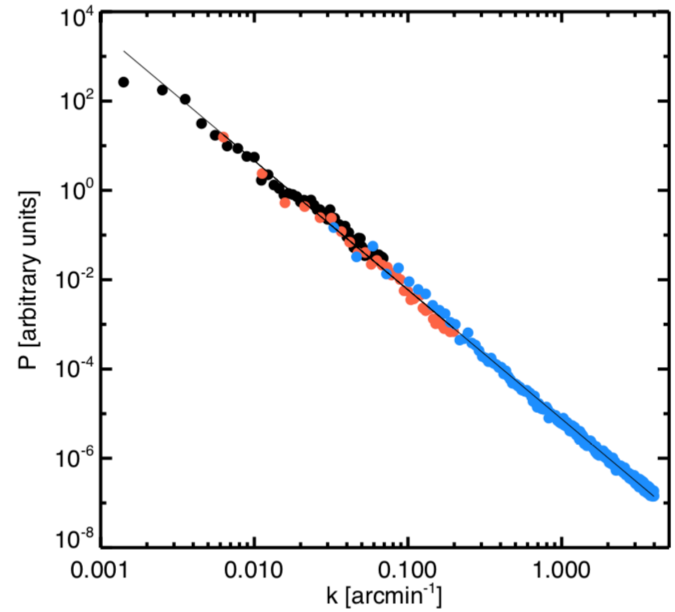
1. The observational context : a) The diffuse Interstellar Medium (ISM)

The diffuse ISM is a **turbulent** medium



Herschel 250 µm, Polaris flare (d < 150 pc), Miville-Deschênes+2010

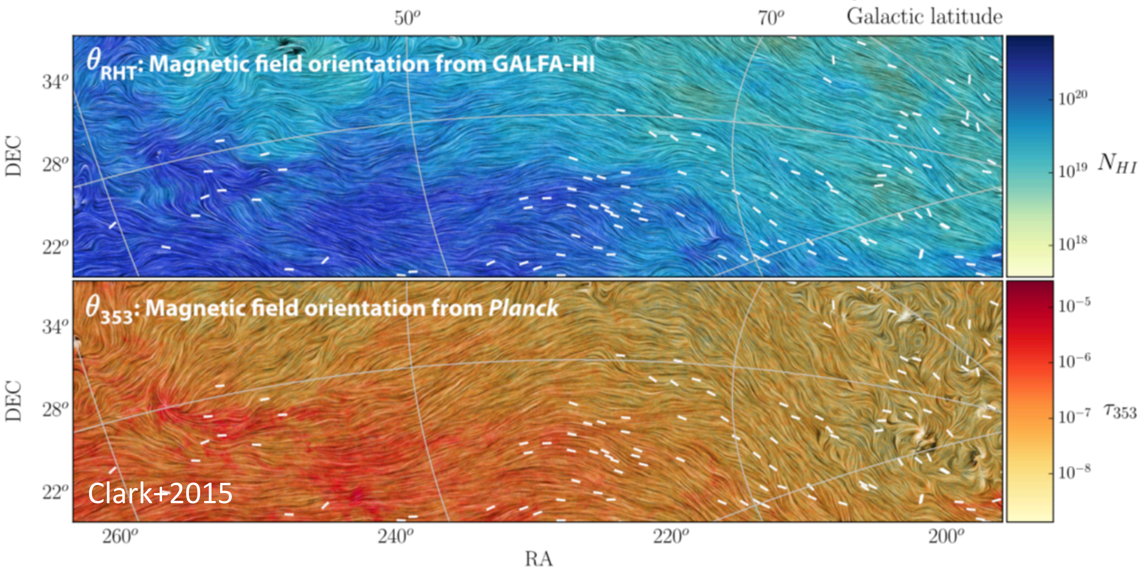
Interstellar Turbulence in cirrus (Miville-Deschênes+2016)

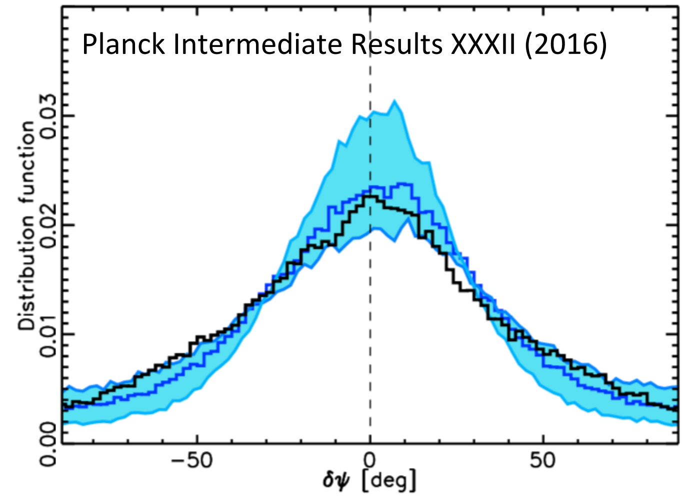


- Turbulent cascade with index -2.7 to - 2.9 ± 0.1
- No sign of dissipation down to 0.01 pc scale
- Filament typical width ~ 0.1 pc.

1. The observational context : a) The diffuse Interstellar Medium (ISM)

The diffuse ISM is a **turbulent and magnetized** medium



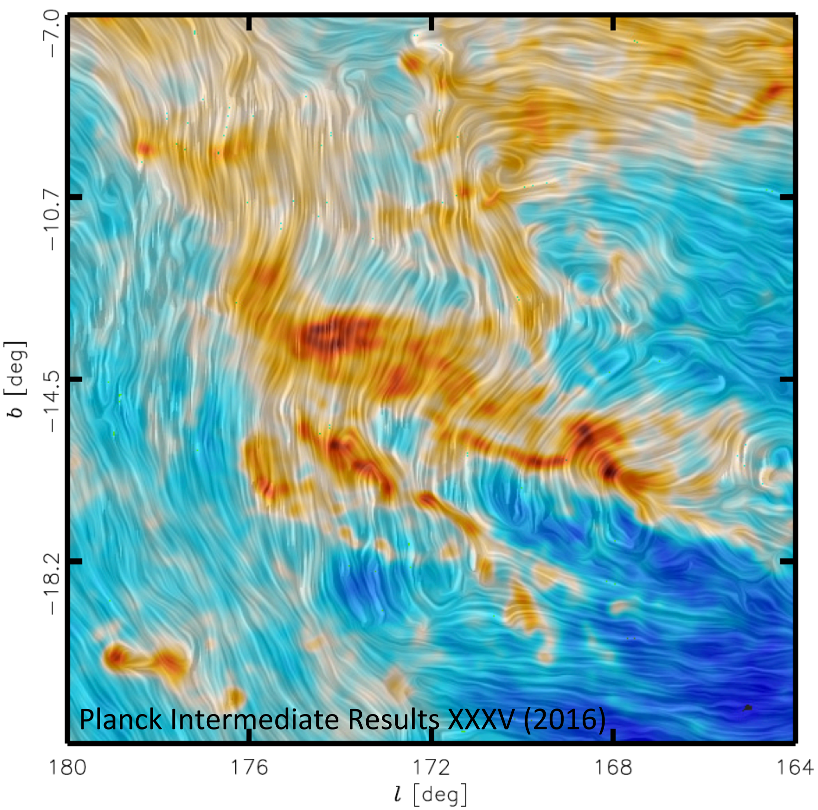


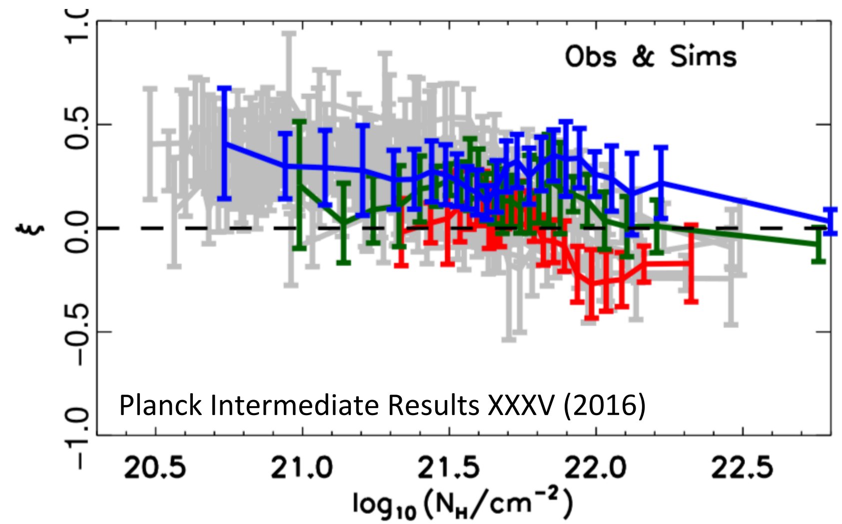
Histogram of difference in position angles between filaments and B-field

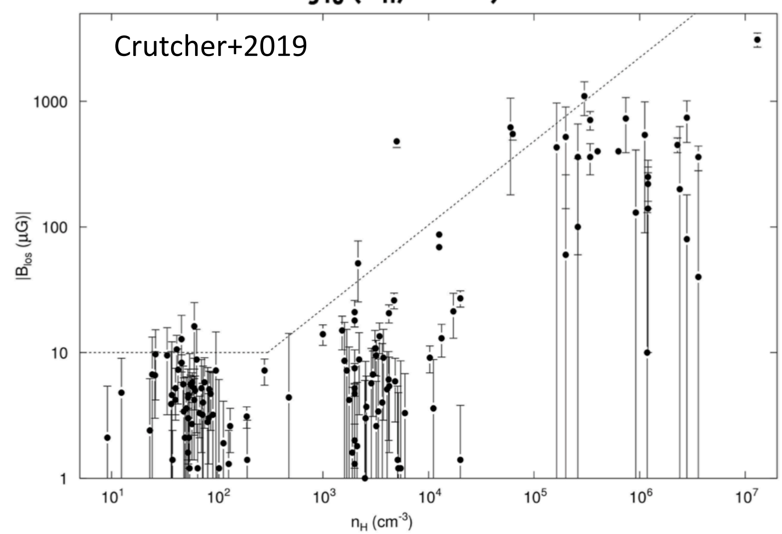
- HI filaments are well aligned with the magnetic-field
- Dispersion in angles filaments vs B-field can be explained by projection effects with a turbulent magnetic field
    - Ordered (large-scale) component of the B-field is uniform
    - B-field close to equipartition : $B_{random} \approx B_{ordered}$
    - Multiple components on each line of sight

1. The observational context : a) The diffuse Interstellar Medium (ISM)

The diffuse ISM is a **turbulent and magnetized** medium







- Alignment of filaments with the magnetic field tend to change from being parallel at low N_H to being perpendicular at high N_H (Planck IR XXXV 2016)
- Magnetic field intensity tends to increase with the density (Zeeman measures, Crutcher+2010,+2019)

1. The observational context : a) The diffuse Interstellar Medium (ISM)

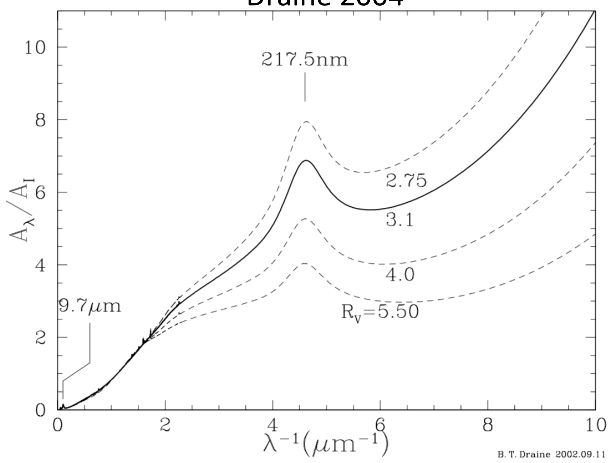
The diffuse ISM is a **turbulent**, **magnetized**, **weakly-ionised** medium

- The ISM includes different phases in approximate pressure equilibrium ($nT \sim 3000\ cm^{-3}.K$) :
  - Phases in the diffuse ISM : Cold Neutral Medium (30 cm-3, 100 K), Warm Neutral Medium (0.2 cm-3, 8000 K) + unstable phase in between (bi-stability)
  - Other phases : Warm Ionized Medium (SN-shocked, 10^4 K), Hot Ionized Medium (« Coronal », 10^6 K)
- The Cold Neutral Medium (CNM) phase of the ISM
  - 1-2% in volume of the ISM, but ~ 90% of its mass
  - Mainly molecular (H_2), with a rich chemistry protected from UV
  - Mesuring the ionisation degree in the diffuse ISM is difficult (e.g. Caselli+2002)
  - Ionisation of the gas dominated by C^+, not H^+ : IP(C) = 11.3 eV < IP(H) = 13.6 eV

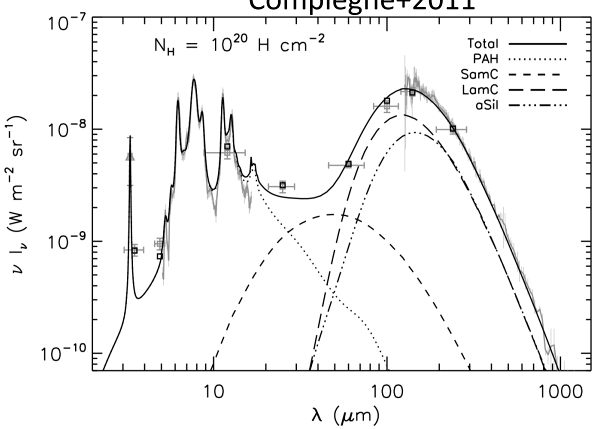
    => **ionisation degree $X_i = n_i / n_H \sim 10^{-4}$!**
- The ionisation degree decreases with increasing density (e.g. in filaments and cores)
  - Screening of the starlight UV-field by dust grains
  - Cosmic-rays (CRs) tends to become the dominant ionization process (ionisation rate ζ, s^{-1})
  - Recombination of ions with electrons scales faster with the density ($\sim n^2$) than ionisation by CRs ($\sim \zeta n$)
- A low ionisation degree allow for the gas to decouple from the magnetic field at certain scales.
  - Streaming of gas with respect to ions and B-field is named « ambipolar diffusion »
  - This process should happen below a certain scale L_{AD} and dissipate energy in ions/neutral collisions
    - From theory : $10 < L_{AD} < 1000$ ua (Stanimirović & Zweibel 2018)
    - From observations: $L_{AD} < 0.01$ pc (no dissipation observed above that scale) (NB: 1 pc ~ 200 000 ua)
    - Not observed yet, but key ingredient in the modeling of the star formation process.

1. The observational context : b) Observational constraints on grain size

Draine 2004



Compiegne+2011



Dust thermal emission characterized by temperature T and spectral index β, with β close to 2.

1) The starlight extinction curve provides constraints on grain size *a*

- Extinction = Absorption + Scattering
- Scattering efficiency is a strong function of *a*/λ, and peaks when 2π*a* ~ λ.
- A dust model is needed: a_{max} ~ 0.3 - 0.5 µm for the diffuse ISM (Rv = 3.1)
- The polarization curve in extinction can also be used.

2) The presence of NIR aromatic bands (« PAHs », from 3.3 to 12.7 µm) indicate the presence of carbon nano-particles (*a* < 1 nm)

- Only nanoparticles can reach the high temperatures needed to emit in the NIR (by absorbing a single UV photon).

3) when *a* << λ, it is impossible to derive *a* from the dust spectral energy distribution (SED) of grains emitting at thermal equilibrium

- Rayleigh regime (*a* << λ): Q_{abs} ~ *a* => σ Q_{abs} ~ a^3 ~ grain (total) volume
- Same for total or polarized emission

4) When *a* ~ λ, it may be possible to derive *a* from the SED

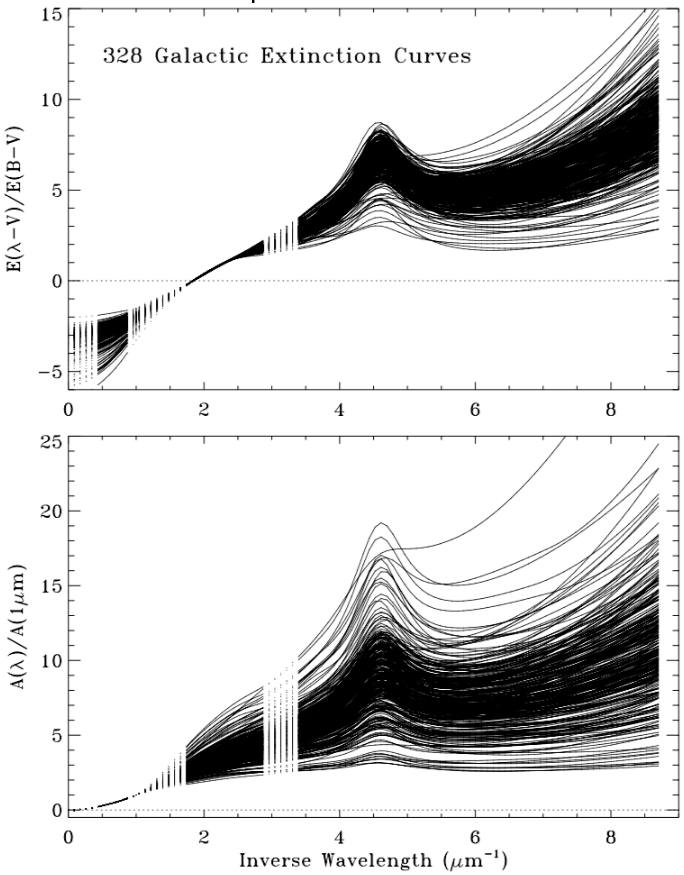
- Mie regime (*a* ~ λ): Q_{abs} strong function of *a*/λ => β is affected
- for λ in the FIR-submm, this necessitates *a* in 100 µm - 1mm
- Analysis possible in total intensity (Galametz+2019) and polarized intensity for grains aligned with the magnetic field (Guillet+2020)
- Beware of radiation transfer effects (optical thick case).

1. The observational context : c) Observational constraints on dust evolution

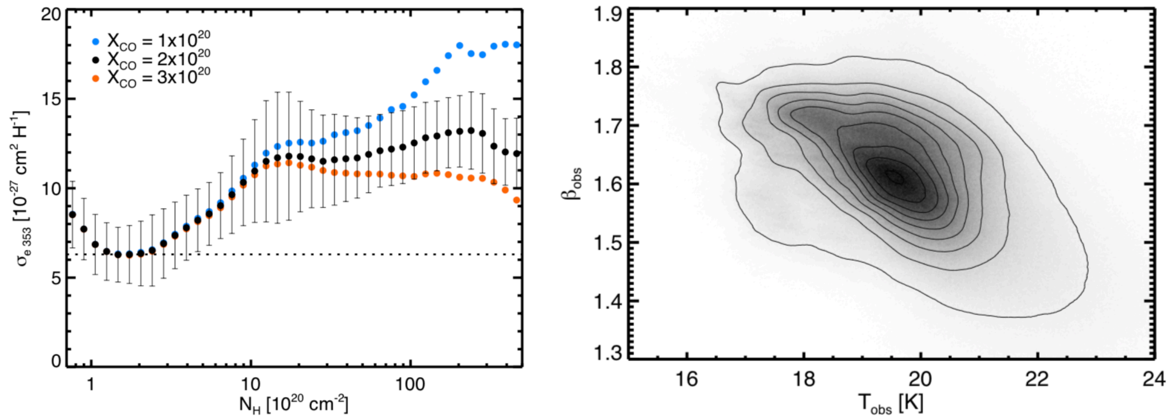
Dust properties vary (even in the diffuse ISM) ⇔ dust « evolution »

- Observables : extinction curve, spectral index, emissivity
- Related dust properties : size distribution, composition, Q(λ) factors (absorption, scattering & emission coefficients), shape, porosity/fractal dimension.

Fitzpatrick & Mass 2007



Planck 2013 Results XI.



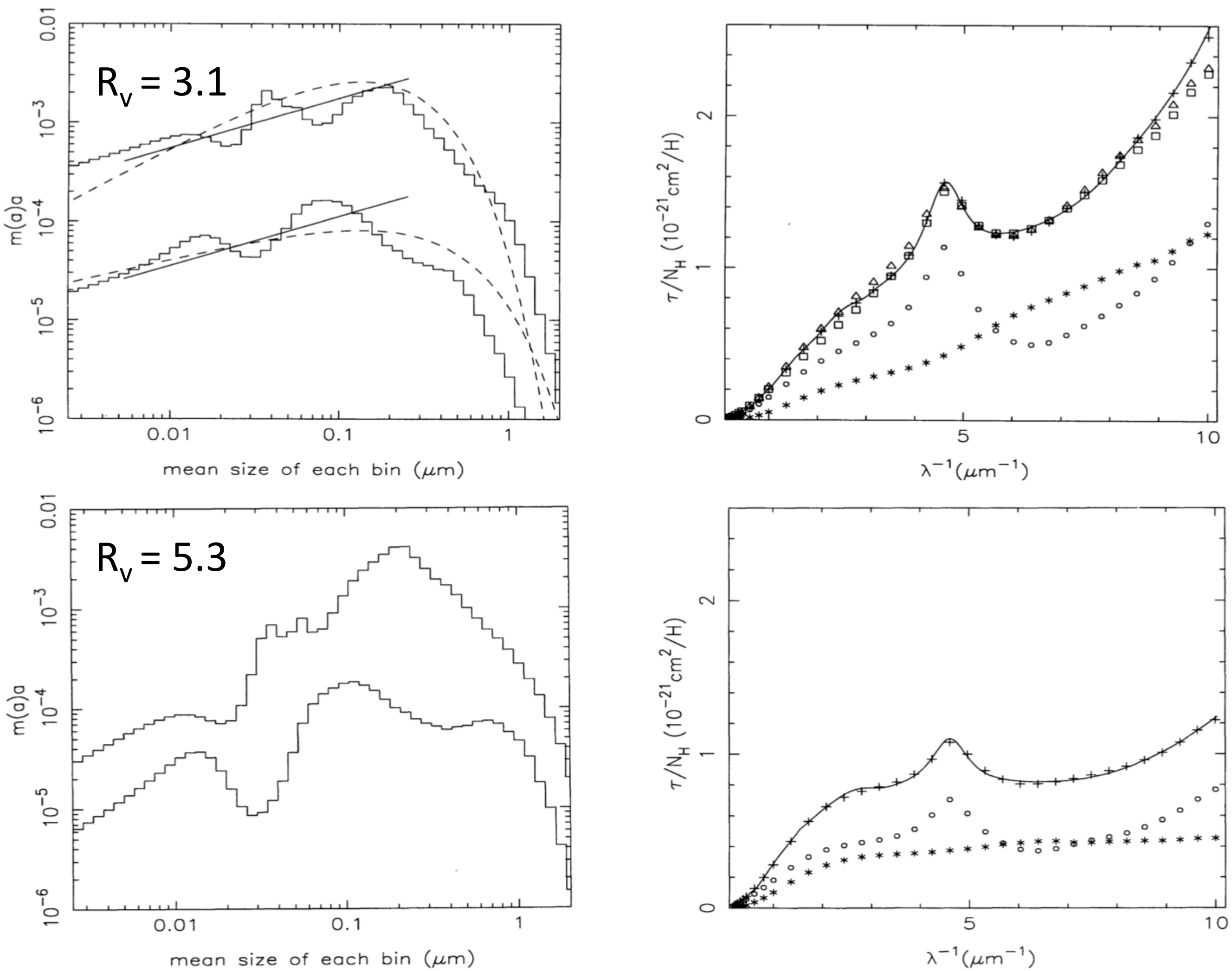
- The emissivity of dust grains σ_e increase with N_H.

$$\tau_{353} = \frac{I_{353}}{B_{353}(T_{obs})} = \sigma_{e\,353}\, N_H$$

- β anticorrelates with T

1. The observational context : d) Observational evidence for grain growth

1. From the variations in the extinction curve (Kim, Martin & Hendry 1994)



1. The observational context : d) Observational evidence for grain growth

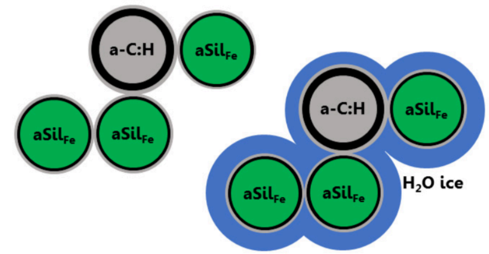
2. The observed increase in emissivity can be explained by grain-grain coagulation and mantle accretion (Koehler+2015)

3. The detection of scattering @3.6 µm toward dense cores (Pagani+2010). Depending on the dust model used:
   - Requires *a* = 0.5 − 1.5 µm (Steinaecker+2015) with astrosilicates.
   - Requires *a* ~ 0.7 µm (Ysard+2015, THEMIS) through the accretion of aliphatic-rich C-H mantles.

4. Maximal polarization fraction
   - Depends on the grain size in the Radiative Torque Theory. The observed polarization fraction can constrain the grain size (e.g. Valdivia+2019).

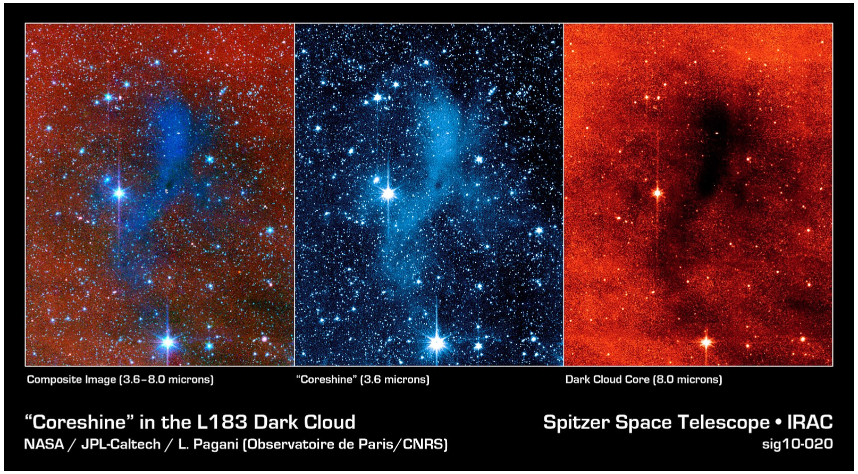
5. Polarization patterns
   - Self-scattering of dust thermal emission by mm grains (Kataoka+2015)

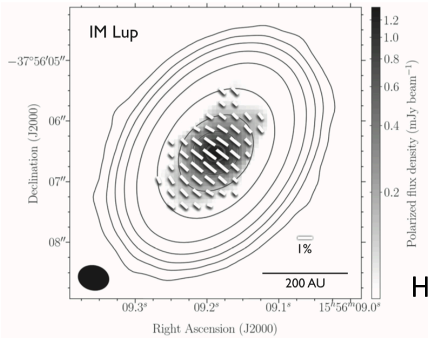
NB: all interpretations are not so direct and must go through a model.



The THEMIS framework (Jones+2013)

Pagani+2010



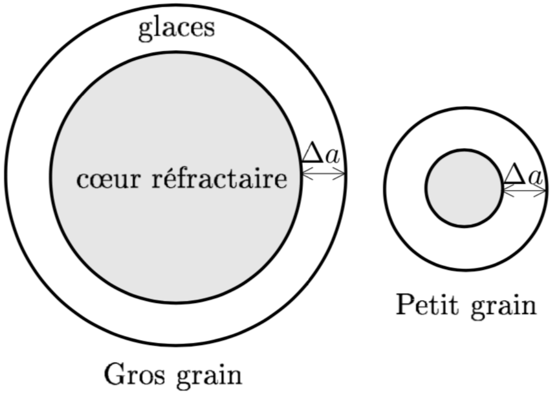


Hull+2018

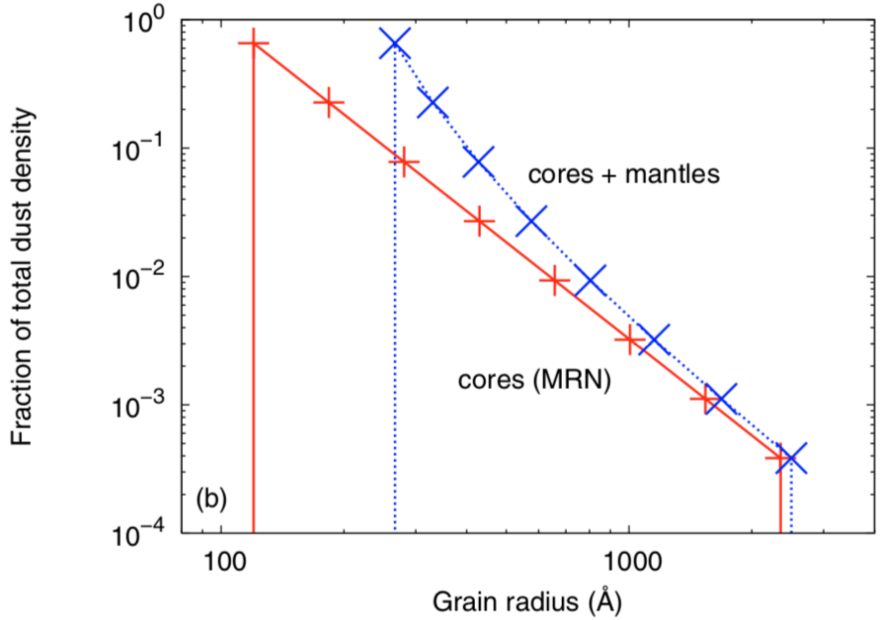
2. The dust microphysics : a) the initial dust size distribution

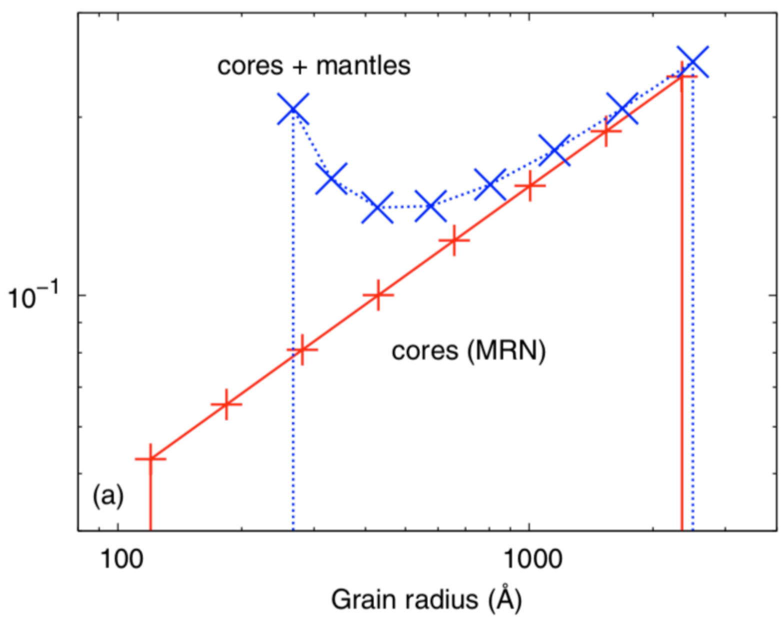
The widely-used MRN (Mathis, Rumpl & Nordsieck 1977) size distribution

$$\frac{\mathrm{d}n(a)}{\mathrm{d}a} = \kappa\, a^{\alpha}$$



with $\alpha = -3.5$, $a_{min} = 5$ nm, $a_{max} = 250$ nm



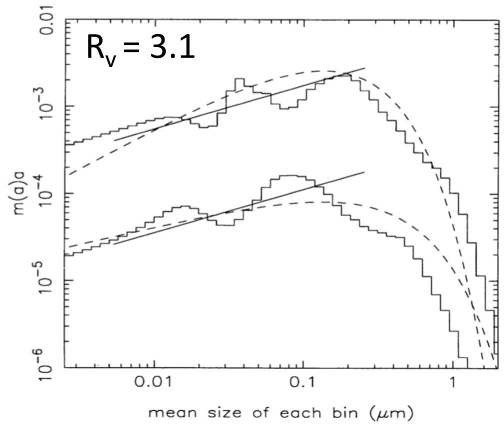


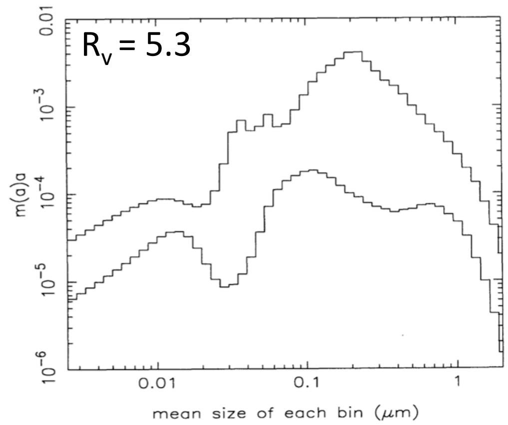
2. The dust microphysics : a) the initial dust size distribution

What do you start with ?

- MRN from diffuse ISM (R_v=3.1)?
- Already evolved (R_v = 5.3)?

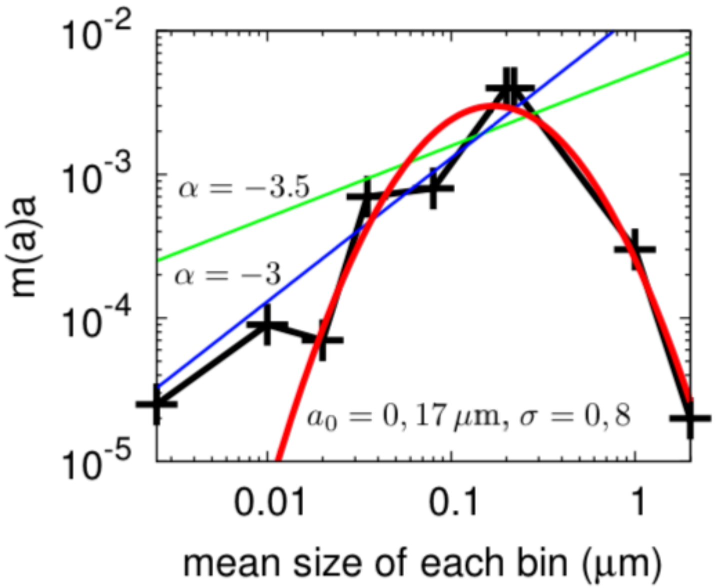
The abundance of small grains is very different





How do you model it ?

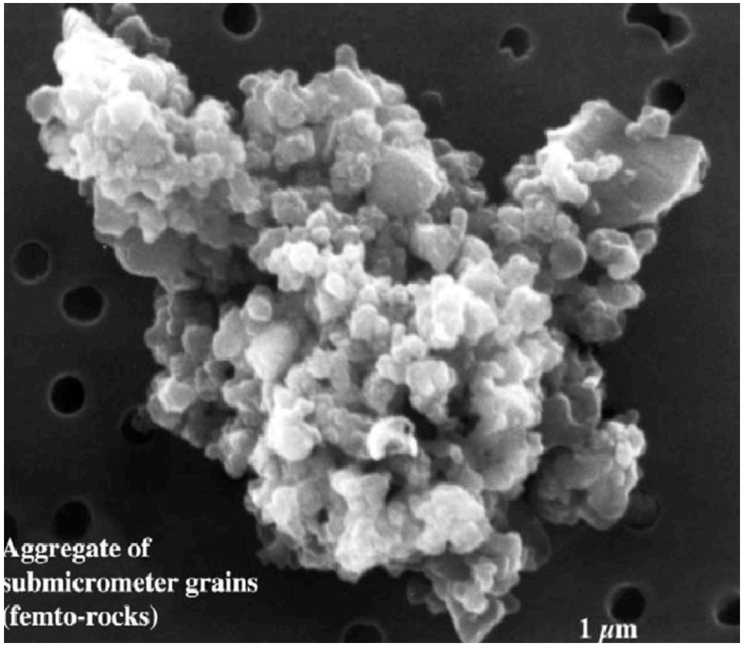
- Is it a power-law ?
- Is it a log-normal ?



2. The dust microphysics : a) initial dust size distribution

How does your dust grain initially (in the diffuse ISM) look like ?

Rocks (sand)



Aggregate ?

Contraint from X-ray halos :

- porosity of diffuse dust grains < 55 % (Heng & Draine 2009) ⇔ not very porous.

2. The dust microphysics : b) dust evolution processes for rocks

Impact ↑ velocity (km/s)

Gas – Grain

sputtering

T > 5.10 K
V > 30 km/s

vaporization

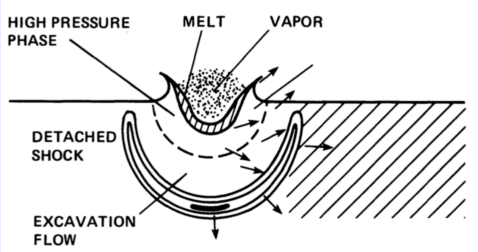
20 km/s

adsorption

0 km/s

Grain – Grain

Physics of shock propagating through solids
See Tielens+1994, Jones+1994,Jones+1996



Fragmentation

1-2 km/s

Ices / organicsrebound

rebound

coagulation

Destruction & formation

Total dust mass decreases/increases

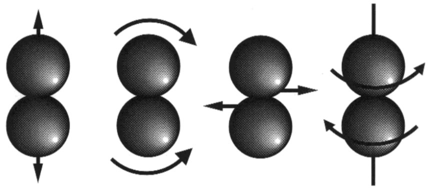
Size redistribution

Total dust mass is conserved

2. The dust microphysics : b) dust evolution processes for aggregates

From the pionner study of Dominik & Tielens (1997):

- Pull-off, roll, slide, torsion

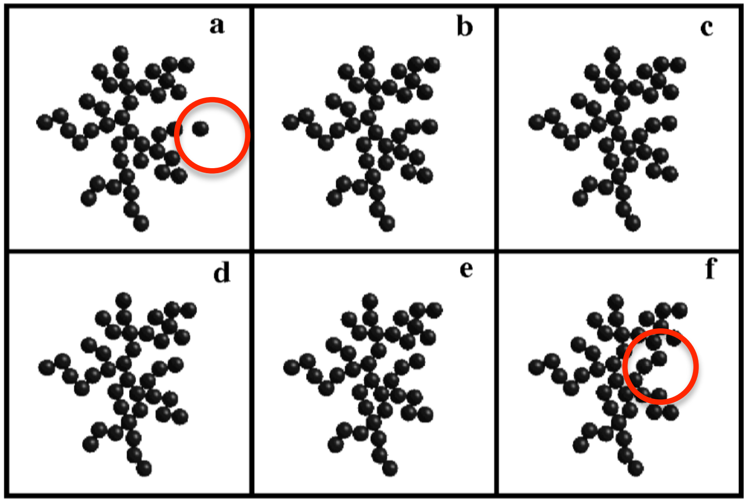


Outcome of the collision :

- Merge, with or without restructuring
- Merge with or without loosing monomers
- Catastrophic disruption

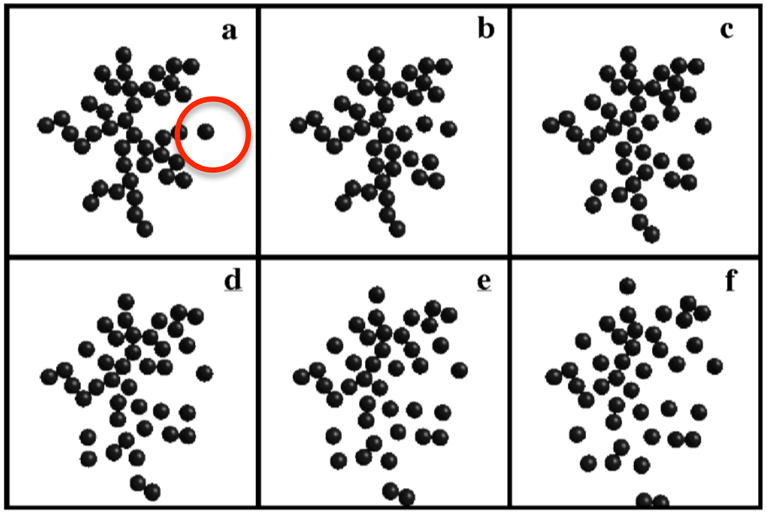
Different time steps during the collision

V_{impact} = 20 m/s



Water ice monomers (0.1 µm)

V_{impact} = 200 m/s

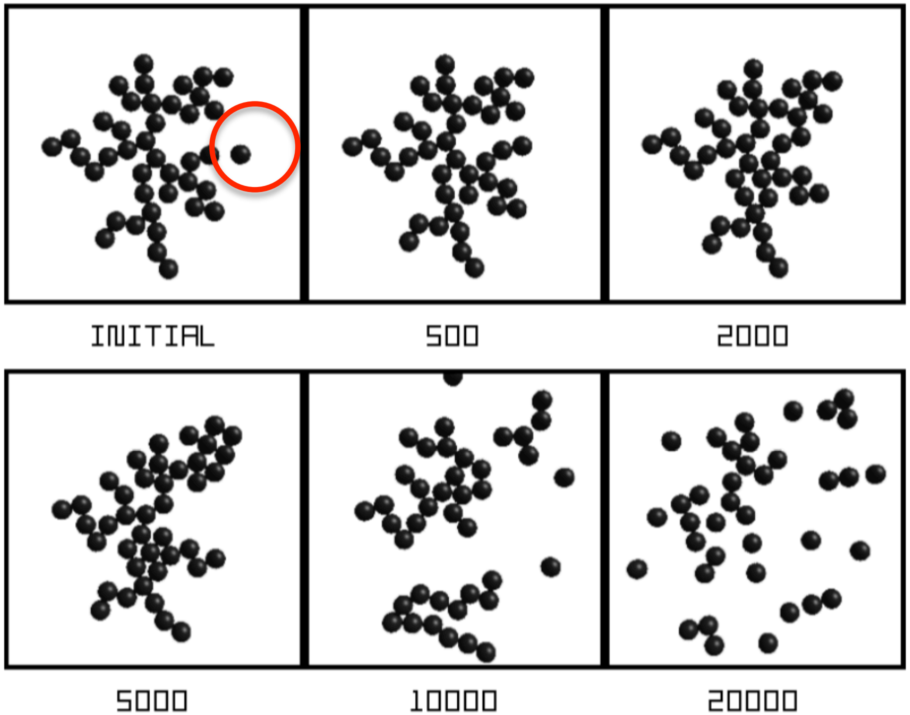


Water ice monomers (0.1 µm)

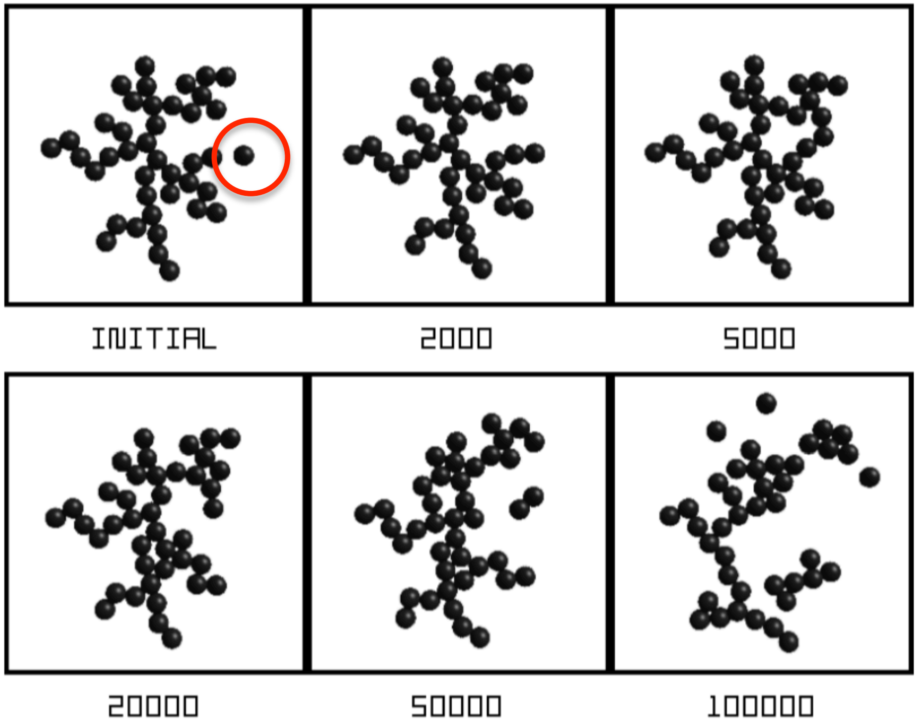
2. The dust microphysics : b) dust evolution processes for aggregates

The size of the monomer is a critical parameter for the outcome of the collision :

Varying the impact velocity from 5 m/s to 200 m/s.



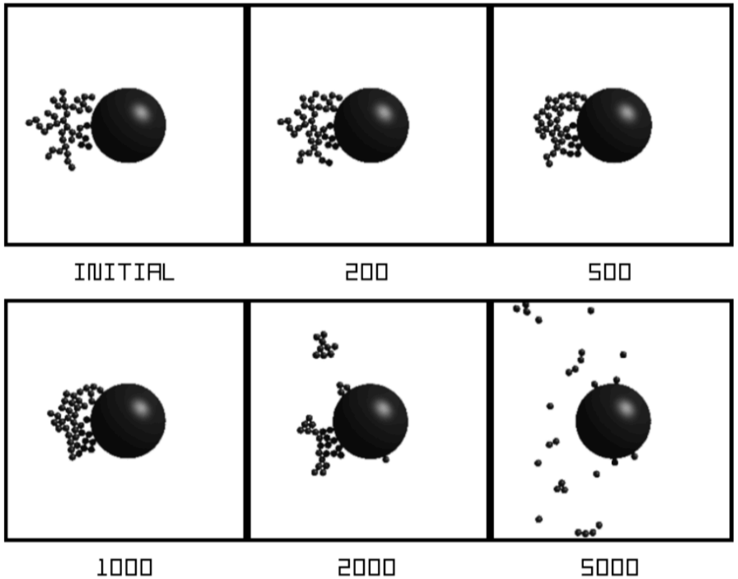
Monomers : water ice grains a = 0.1 μm



Monomers : water ice grains a = 0.01 μm

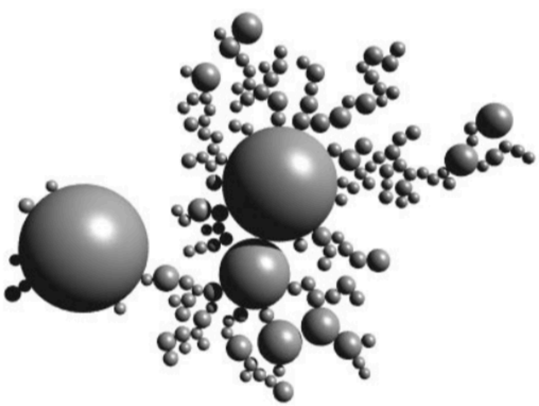
2. The dust microphysics : b) dust evolution processes for aggregates

With a size distribution of monomers

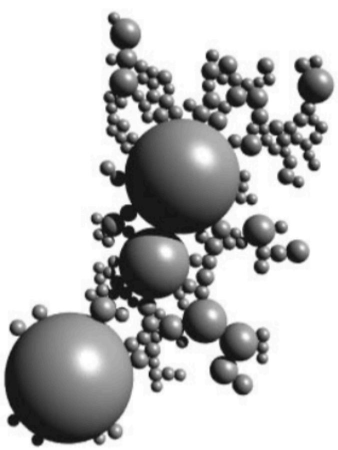


Effect of the impact velocity (keeping every else identical) on the build-up of aggregates :

No compaction with low impact velocity



Strong compaction with high impact velocity



2. The dust microphysics : b) dust evolution processes for aggregates

https://4d2u.nao.ac.jp/t/var/download/DustGrowth_e.html

4D2U Project (Wada, K. etal 2023)

2. The dust microphysics : b) dust evolution processes for aggregates

Since 2000, extensive laboratory experiments on outcome of collisions between aggregates

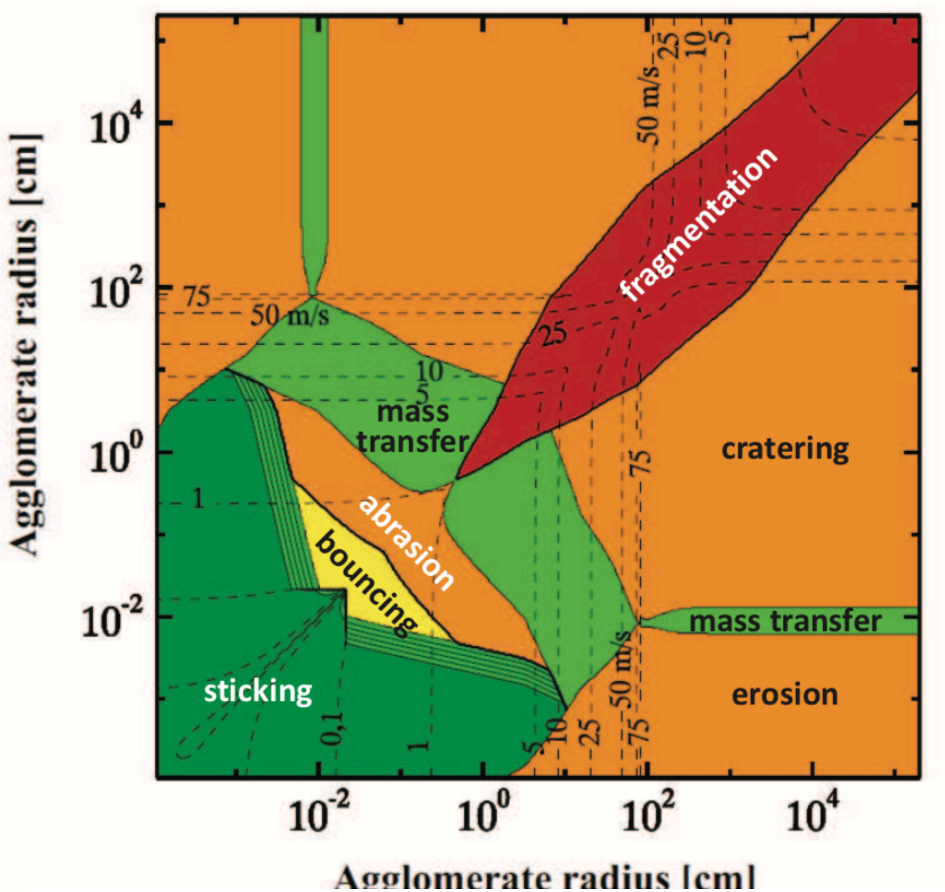


Fig. 1 Example of the latest collision model under development at TU Braunschweig for SiO_2 monomer particles with 0.75 μm radius, a minimum mass solar nebula model at 1 AU in the midplane, and a turbulence strength of $\alpha = 10^{-3}$, respectively. Collisional outcomes are marked in colour and labelled. Dashed contours mark the mean collision velocities in units of m s^{-1}. Image credit: Kothe and Blum (in prep.).

Experiences in:

- Drop towers (Blum+2014)
- Suborbital rockets (Brisset+2017)
- Space

Blum (2018)
Model based on lab experiments

2. The dust microphysics : b) dust evolution processes for aggregates

Ormel+2009 : Recipe for the outcome of a collision for aggregate composed of a single type of monomer

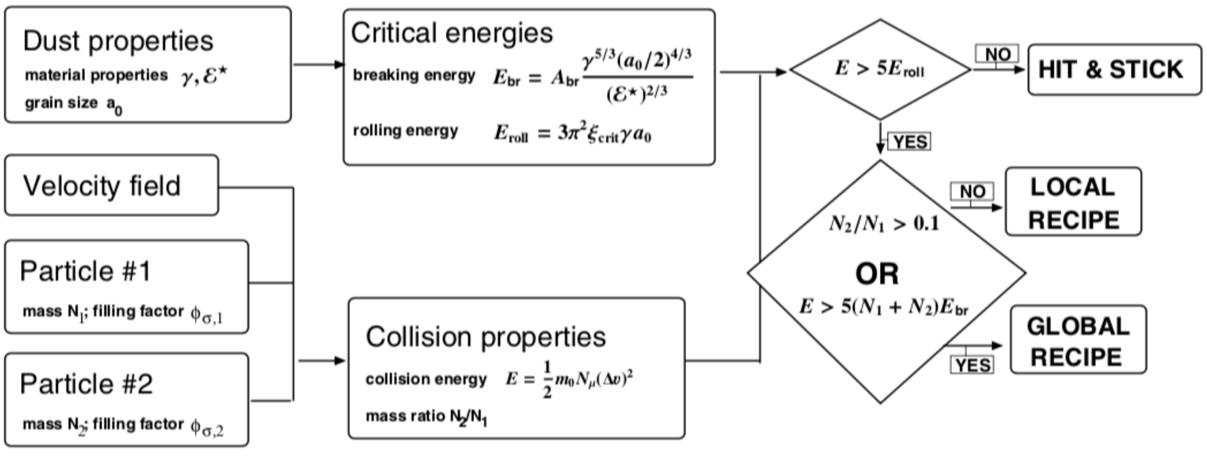
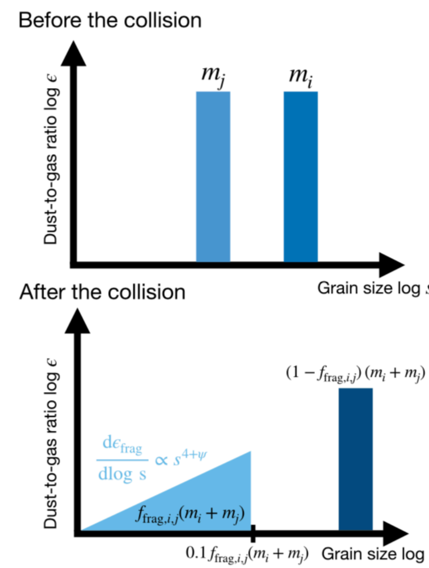


Fig. 2. Schematic decision chain employed to distinguish between the hit-and-stick, global, and local recipes.



Lebreuilly+2023

- hit-and-stick: (low collision energies) the internal structure of the aggregate is preserved;
- local: only a small part of the aggregate is affected by the collision, as in, e.g., erosion. The mass ratio between the two particles is large;
- Global: the collision outcome results in a major change to the structure or size of the target aggregate. Relevant for equal-size particles or at large energies.

Take home message: the physics of rocks and aggregates is different for thresholds

- Collision in **rocks** involves **velocities** (through shocks propagating into both solids)
- Collision in **aggregates** involves **energies** (using reduced mass)

2. The dust microphysics : c) grain charging

In a magnetized ISM, grains are coupled

- to the gas through collisions with gas atoms and molecules.
- to the B-field owing to their charge

Dust grains charging processes (e.g. Draine & Sutin 1985, Weingartner & Draine 2001)

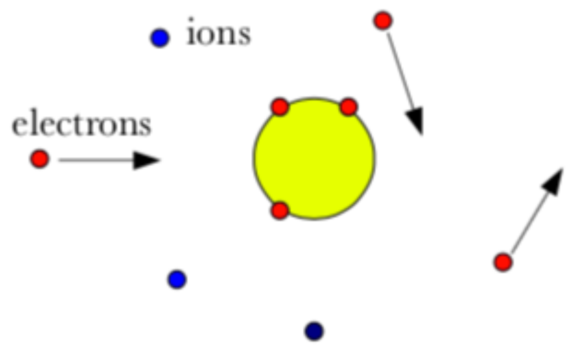
1. Attachment of free electrons onto the grain surface
2. Recombinaison of ions (> 0) on the grain surface
3. Photoelectric effect by UV photons
4. Secondary electron emission (T >> 10^5 K, Draine & Salpeter 1979).

In the absence of UV photons, the electron current is stronger than the ion current because the thermal velocity of electrons is > 40 times higher than that of ions

➔ grain charge is negative

Grain charging is a stochastic random process

➔ grain charge fluctuates



2. The dust microphysics : c) grain charging

We model grain charging like the charge of a spherical capacitor of radius *a* by an electric current (Spitzer 1941, Draine & Sutin 1985)

$$Ze = C\phi_{\rm s} = a\,\phi_{\rm s}$$
$$\psi = \frac{e\,\phi_{\rm s}}{kT}\,.$$

- Φ_s is the electric potential of the surface of the grain
- C the capacity of the grain
- ψ the ratio of the electrostatic energy of the grain to the thermal energy of ions and electrons.

Mean grain charge Q = <Z> e in the absence of photoelectric effect

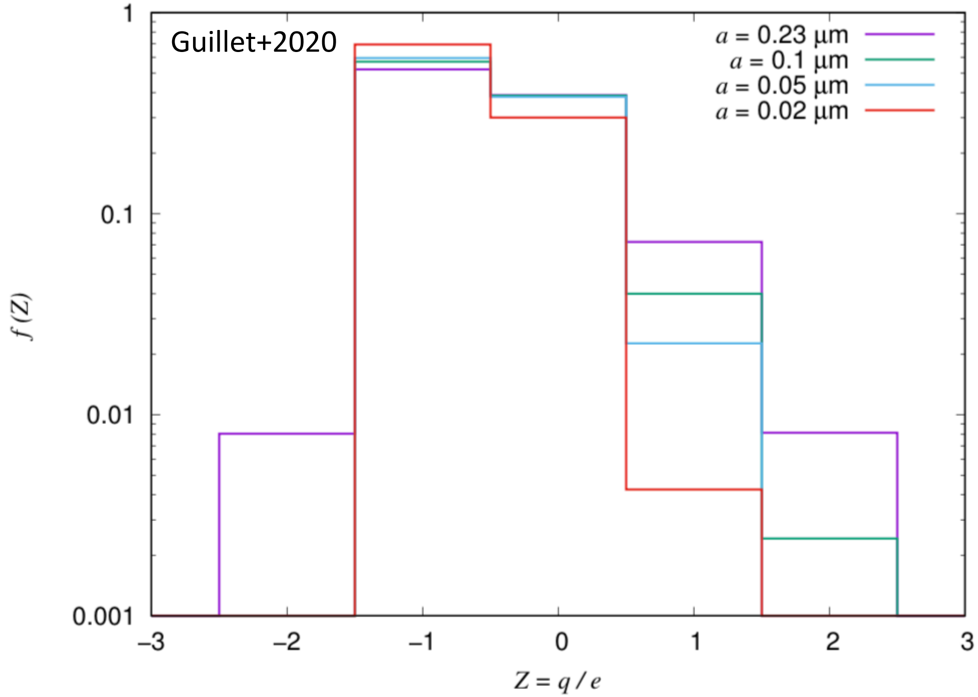
$$\langle Z\rangle = \psi\tau\,,$$
$$1-\psi = \sqrt{\frac{m_{\rm i}}{m_{\rm e}}}\,{\rm e}^{\psi}$$
$$\tau = \frac{akT}{e^2}\,,$$

<u>Take home messages</u> : the mean grain charge is

- Negative in the absence of UV photons
- <u>proportional to the grain radius and gas temperature</u>
- Z ≈ -1 for submicron grains at 10 K, Z =-10,000 for 100 µm grains at 500 K !
- Ψ = -2.5 for a H^+-dominated plasma, -3.7 for a heavy ion (25 m_H) plasma.

2. The dust microphysics : c) grain charging

Grain charge distribution in a cold cloud (T = 10 K, $\zeta = 5.10^{-17}\ s^{-1}$, $n_H = 10^4\ cm^{-3}$, Guillet+2020).

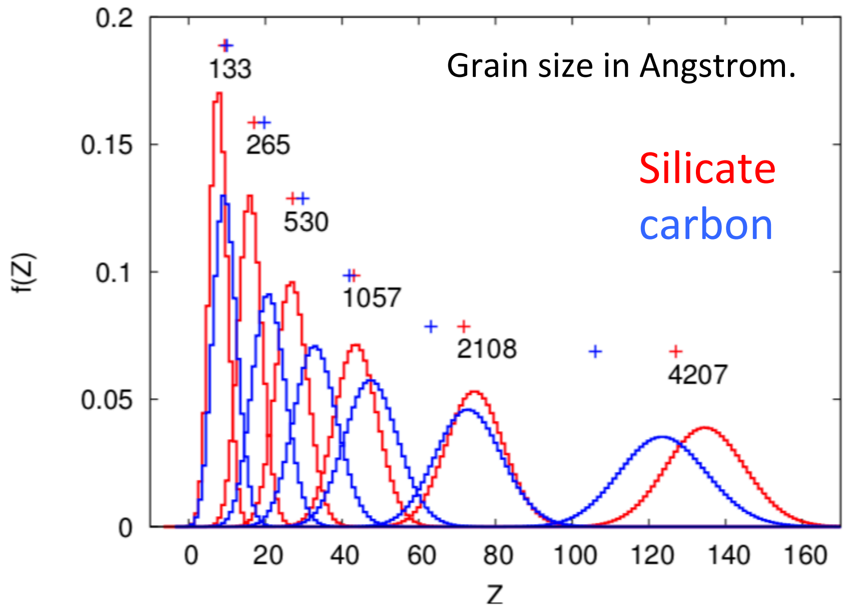


The mean grain charge is close to Z = -1, and slightly increases with the grain radius

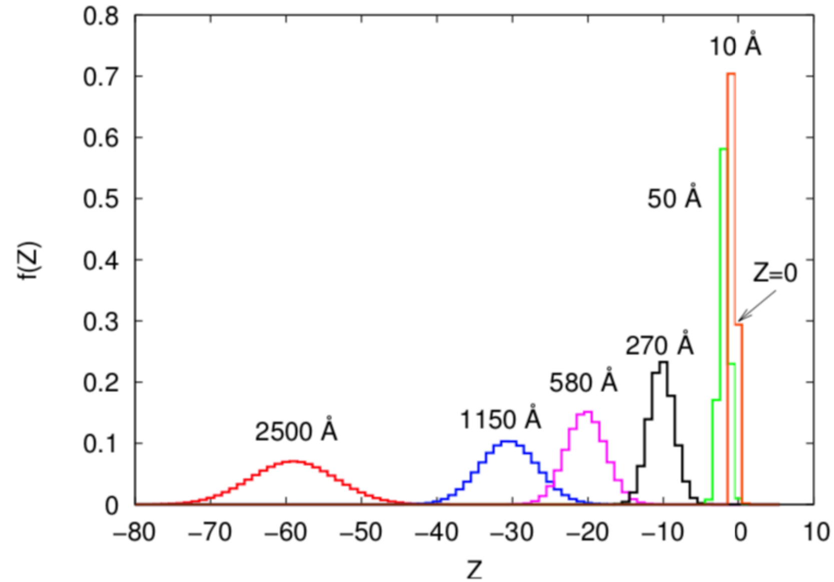
Take home message : There is no such thing like a « neutral grain » : grain charge fluctuates, grains become neutral, and charged again. One can rarely consider neutral and charged grains as independent fluids.

2. The dust microphysics : c) grain charging

Grain charge distribution in the diffuse ISM (CNM : $G_0 = 1$, $n_H = 30\ cm^{-3}$, $n_e = 1{,}49.10^{-2}\ cm^{-3}$, T = 100 K).



Grain charge distribution in a shocked (V_s = 20 km/s) molecular gas ($n_{H0} = 10^6\ cm^{-3}$) screened from the ISRF.



- Large grains at high Z : we can ignore charge fluctuations and discreteness, and assume a mean fixed charge (function of local conditions).
- Small grains or low temperatures : we can not ignore charge fluctuations and charge discreteness

2. The dust microphysics : d) grain coupling

Characteriscal timescales for charged grains (years)

- Coupling with the magnetic field, assuming Z = -1 and b = 1 in $B = b\sqrt{\frac{n_\mathrm{H}}{1\,\mathrm{cm}^3}}\ \mu G$

$$\tau_\mathrm{gir} = \frac{mc}{|Z|eB} \simeq 0,25\left(\frac{a}{0.01\,\mu\mathrm{m}}\right)^3\left(\frac{n_\mathrm{H}}{10^4\,\mathrm{cm}^{-3}}\right)^{-1/2}$$

- Coupling with the gas, calculated with $V_{grain} = V_n$ and $\kappa = 128k_B/(9\pi m_n)$ (McKee+87)

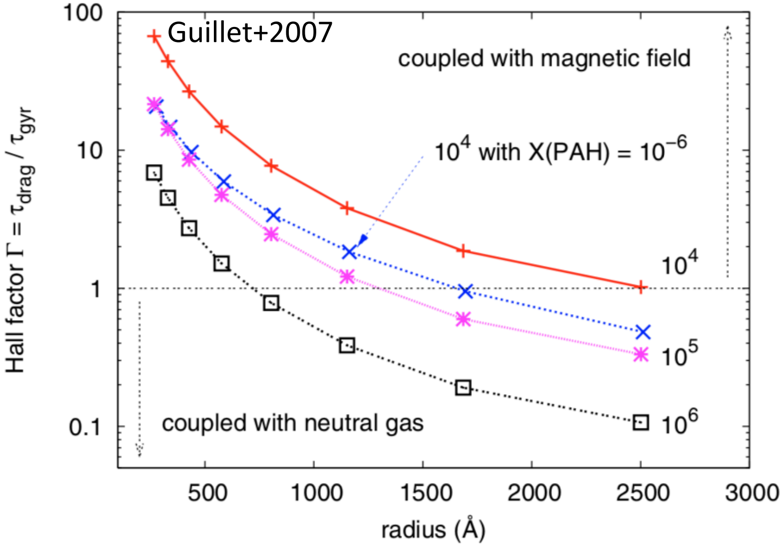
$$\tau_\mathrm{drag} = \frac{m}{\rho_\mathrm{n}\sigma\sqrt{(\mathbf{V}_\mathrm{n}-\mathbf{V})^2+\kappa T_\mathrm{n}}} \simeq 125\left(\frac{a}{0.01\,\mu\mathrm{m}}\right)\left(\frac{n_\mathrm{H}}{10^4\,\mathrm{cm}^{-3}}\right)^{-1}\left(\frac{T}{10\,\mathrm{K}}\right)^{-1/2}$$

- Charge fluctuation timescale (Yan, Lazarian & Draine 2004, Guillet+2020) :

$$\tau_Z = \frac{\mathrm{Var}(Z)}{\sum_Z f(Z)\times\left(J_e(Z)+J_i(Z)+J_\mathrm{pe}(Z)\right)}$$

Hall factor :

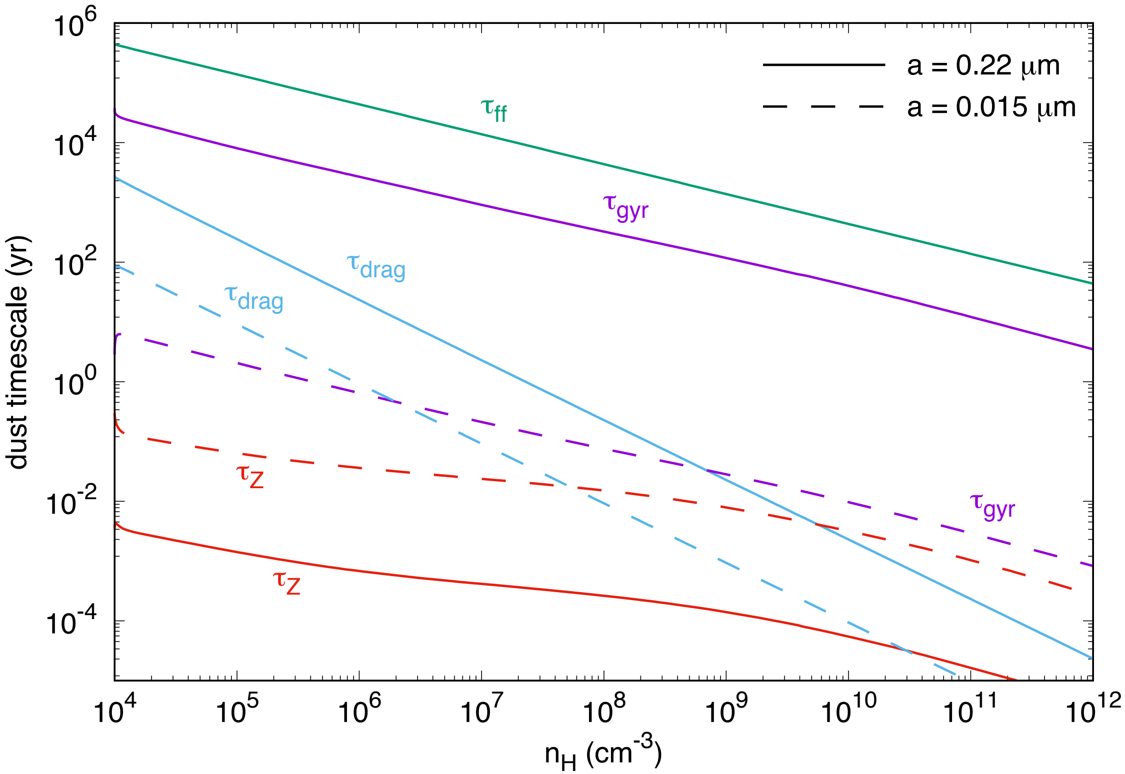
$$\Gamma = \frac{\tau_\mathrm{drag}}{\tau_\mathrm{gir}} \simeq 500\left(\frac{a}{0.01\,\mu\mathrm{m}}\right)^{-2}\left(\frac{n_\mathrm{H}}{10^4\,\mathrm{cm}^{-3}}\right)^{-1/2}\left(\frac{T}{10\,\mathrm{K}}\right)^{-1/2}$$



2. The dust microphysics : d) grain coupling

Evolution of characteristical timescales with density and grain size (Guillet+2020)

- Large grains are coupled to the gas.
- Small grains are strongly coupled to the magnetic field.
- High densities tend to decouple grains from the magnetic field.
- Charge fluctuations can be ignored for a > 1 nm

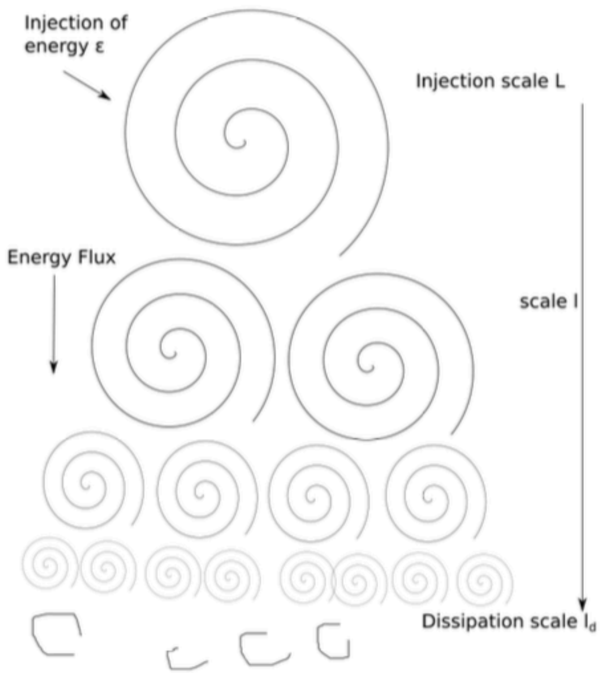


2. The dust microphysics : e) grain dynamics

To follow grain growth, one must determine the expression for the **relative (collisional) velocities** between grains of different sizes.

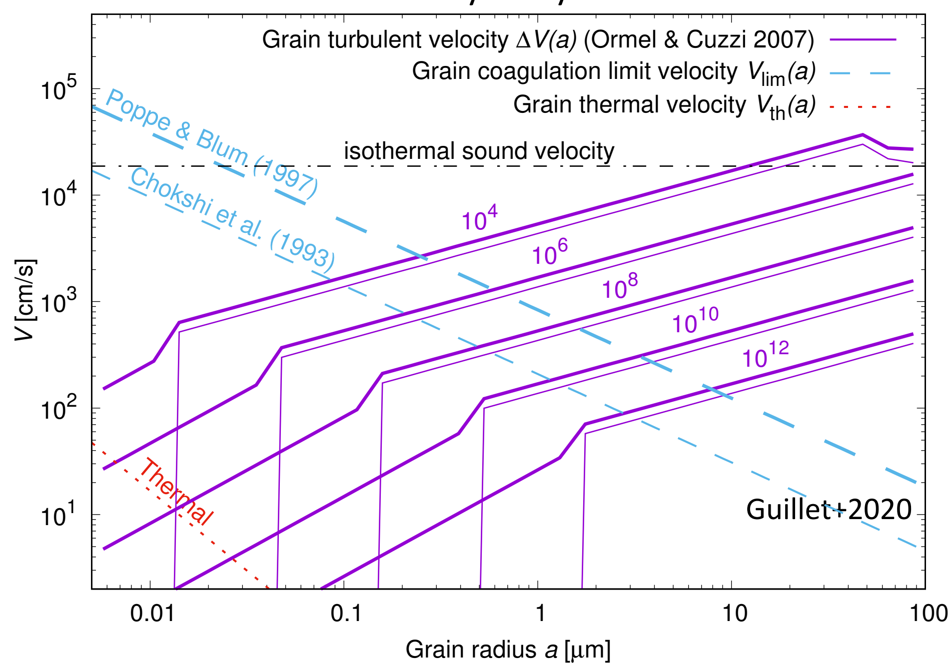
1. Grain thermal velocities : V ~ sqrt($2k_BT/m$)
2. Grain acceleration by turbulence = f(St) (Stokes number St = t_{drag}/t_{dyn})

- **Hydro : Long history from Voelk+1980 to Ormel & Cuzzi 2007**
- MHD : few studies: Yan, Lazarian & Draine 2004 (analytic), Moseley, Teyssier & Draine 2022 (numerical)



The Kolmogorov Cascade

Predictions for hydrodynamical turbulence



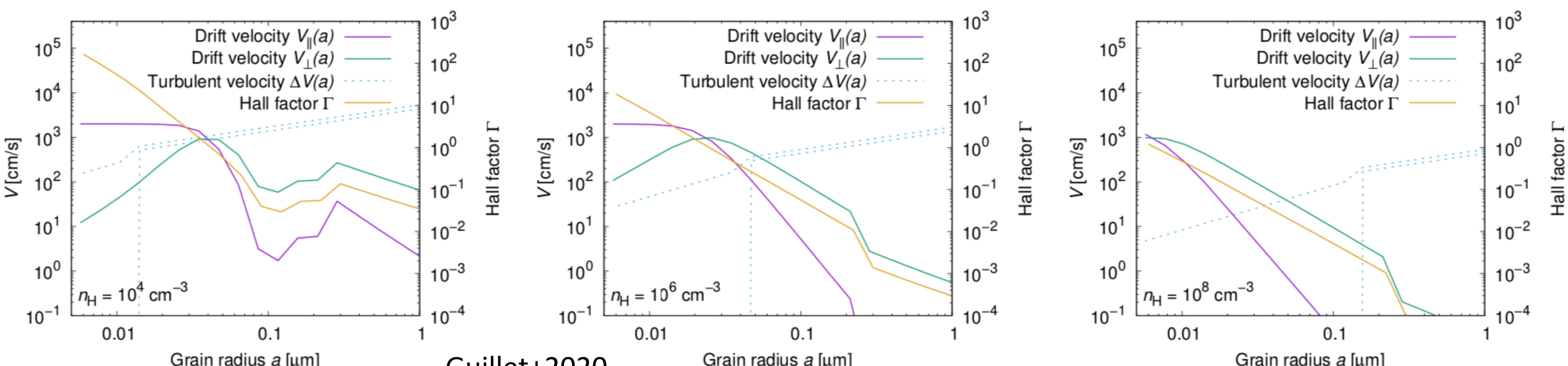
2. The dust microphysics : e) grain dynamics

3. Drift velocities generated by ambipolar diffusion (Guillet+2020, Lebreuilly+2023)

- We note V_{AD} the differentiel velocity between ions and neutral due to ambipolar diffusion. V_{AD} decreases with the gas density.
- If Γ >> 1, dust follow ions. If Γ << 1, dust follow the gas.
- If Γ ~ 1, dust fluid dynamics is intermediate between that of ions (magnetic field) and that of neutral gas

$$|\boldsymbol{V}_{\mathrm{n}} - \boldsymbol{v}_k| \simeq \frac{\Gamma_k^2}{1+\Gamma_k^2} V_{\mathrm{AD}}$$

➔ Ambipolar diffusion creates relative velocities between small and large grains in the enveloppe, in a much more efficient way than turbulence or brownian motion.



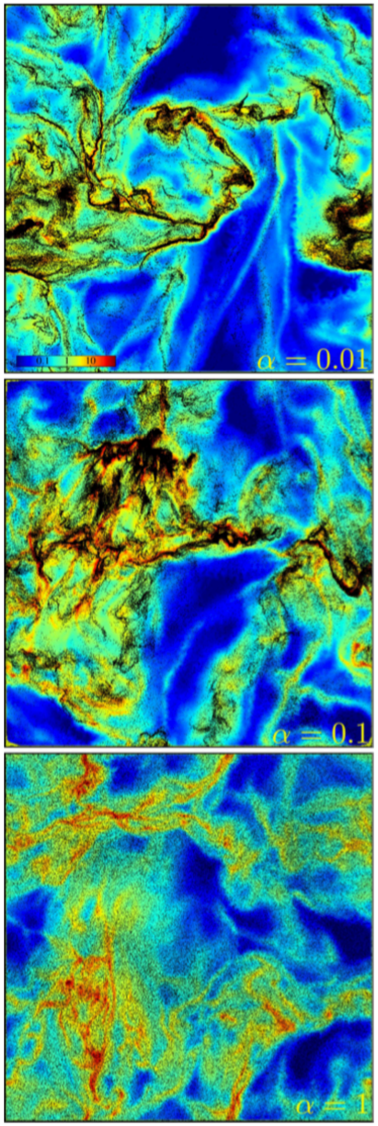
Guillet+2020

2. The dust microphysics : e) grain dynamics

Simulations of dust dynamics in molecular clouds

- Hopkins & Lee 2016 : dynamics of neutral grains in highly supersonic MHD turbulence
  - For a < 0.01 µm, the dust-to-gas ratio varies by factor 1000 on small scales
  - Strong clustering of dust grains.
  - For a > 1 µm, grains are never tightly coupled to the gas.
- Lee, Hopkins & Squire 2017 : same simulations, with charged grains (i.e. add the Lorentz Force)
  - For a < 0.1 µm, the Lorentz force suppress the dust-to-gas ratio fluctuations.
  - For a > 1 µm, no effect of the Lorentz force.
- Commercon + 2023 : (neutral) dust dynamics in turbulent molecular cloud
  - Dust-to-gas ratio should not vary beyond a factor 2 in high-density regions

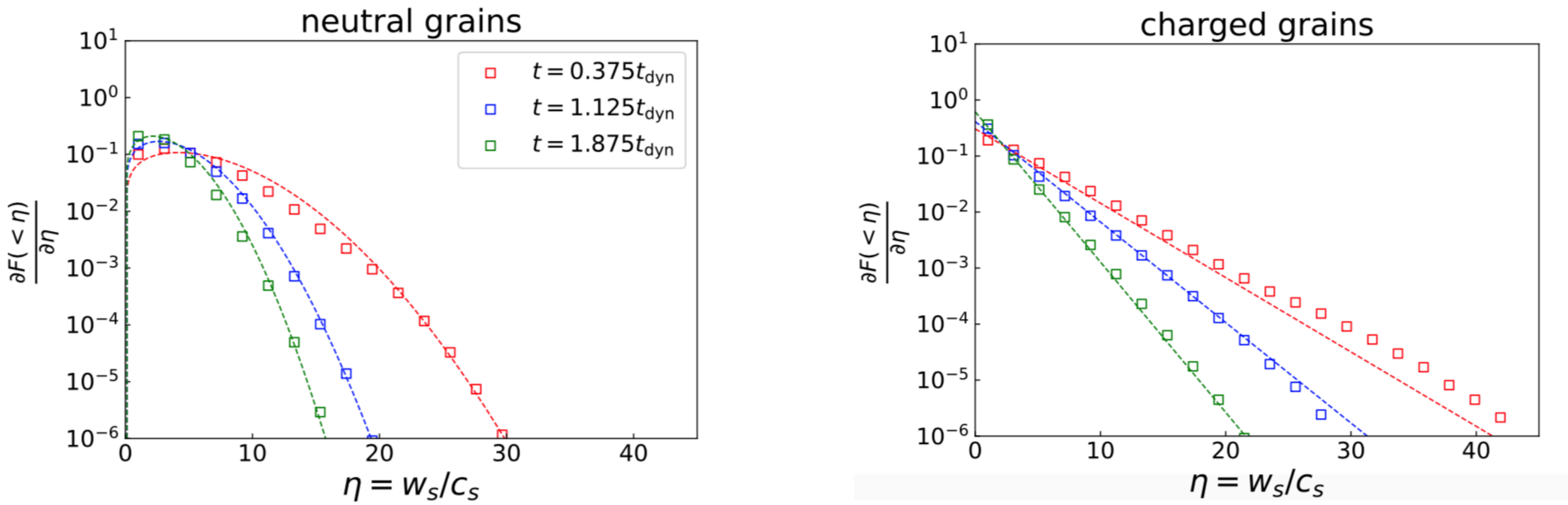
Hopkins & Lee 2016



2. The dust microphysics : e) grain dynamics

Simulations of dust stochastic acceleration in decaying MHD turbulence

Moseley, Teyssier & Draine (2022)



NB: effect on grain-grain coagulation and shattering is not straightforward because of drift velocities and clustering.

3. The governing equations : a) The Smoluchowski equation

Grain-grain coagulation obeys to the coagulation equation (Smoluchowski 1916)

- Integral form (Mizuno, Markiewicz & Volk 1988)

$$\frac{\partial}{\partial t} \varrho(m,t) = -\int_0^\infty m\,\alpha(m,m')\,\varrho(m,t)\,\varrho(m',t)\,dm' + \frac{1}{2}\int_0^m m\,\alpha(m-m',m')\,\varrho(m-m',t)\,\varrho(m',t)\,dm'$$

$$\alpha(m,m') = \frac{(\sigma v)_{m,m'}}{m\,m'}$$

- Discrete form (Lebreuilly+2023)

$$S_{k,\text{growth}} = \sum_{i+j\to k} K_{i,j}(m_i+m_j)\,n_j n_i - n_k m_k \sum_i^{\mathcal{N}} K_{k,i} n_i,$$

$$K_{i,j} = \sqrt{\frac{8}{3\pi}}\pi(s_i+s_j)^2\Delta v_{i,j}$$

The Smoluchowski equation has self-similar solutions (e.g. Manon & Pego 2004)

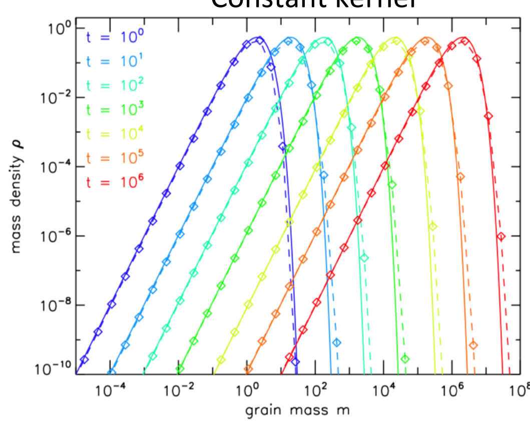
- The constant kernel : $K_{ij} = C^{te}$
- The additive kernel : $K_{ij} = m_i + m_j$

This can help checking your numerical code.

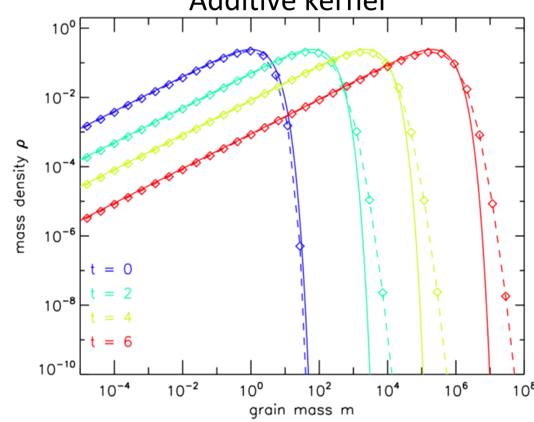
- The mutiplicative kernel : $K_{ij} = m_i\, m_j$

Also called « gelation » : all mass concentrates into one single particle at a finite time.

Constant kernel



Additive kernel



3. The governing equations : a) The Smoluchowski equation

An interesting numerical trick to follow grain growth (Marchand+2021)

If the kernel can be expressed in a product of two separeted quantities (as is the case for Ormel & Cuzzi 2007)

$$K(m, m') = C g_{\text{local}} h(m, m')$$

g_{local} contains the dependence on the local physical conditions (n_H, B, T etc..)
h(m,m') only depends on the dust properties (size, density etc..)

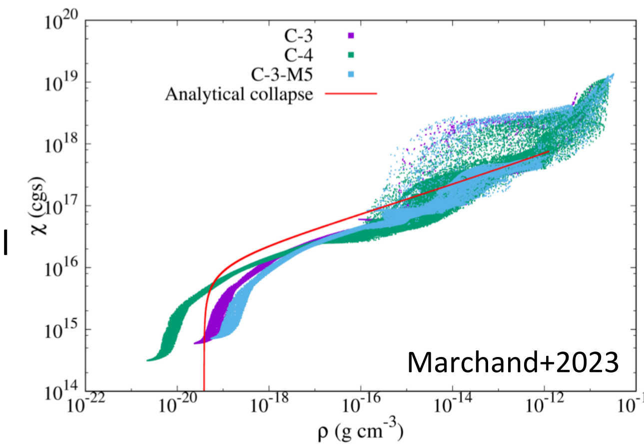
Then instead of following the evolution of the size distribution, it is easier to follow the single parameter **χ**

$$d\chi = g_{\text{local}} n_{\text{H}} dt.$$

$$\frac{dX(a,\chi)}{d\chi} = CI(a, X, \chi) \qquad n(a) = n_{\text{H}} X(a, t)$$

$$I(a, X, t) = -\int_0^\infty h(m, m') X(m, t) X(m', t) dm' + \frac{1}{2}\int_0^m h(m - m', m') X(m - m', t) X(m', t) dm'$$

- Useful for 3D MHD simulations of grain growth : integrate χ in each cell
- Does not work with fragmentation
- Assumes that dust is tightly coupled with the gas.



3. The governing equations : b) The ionization equilibrium equation

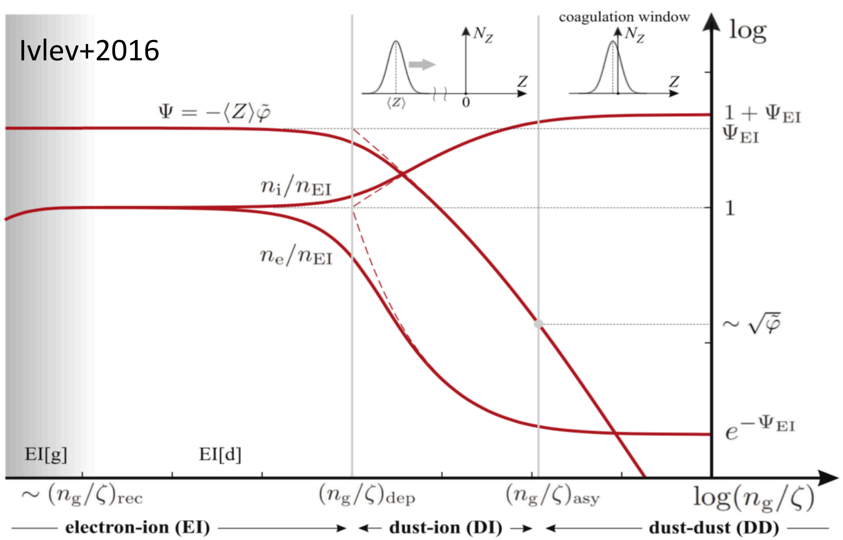
References: Ivlev+2016, Marchand+2021:

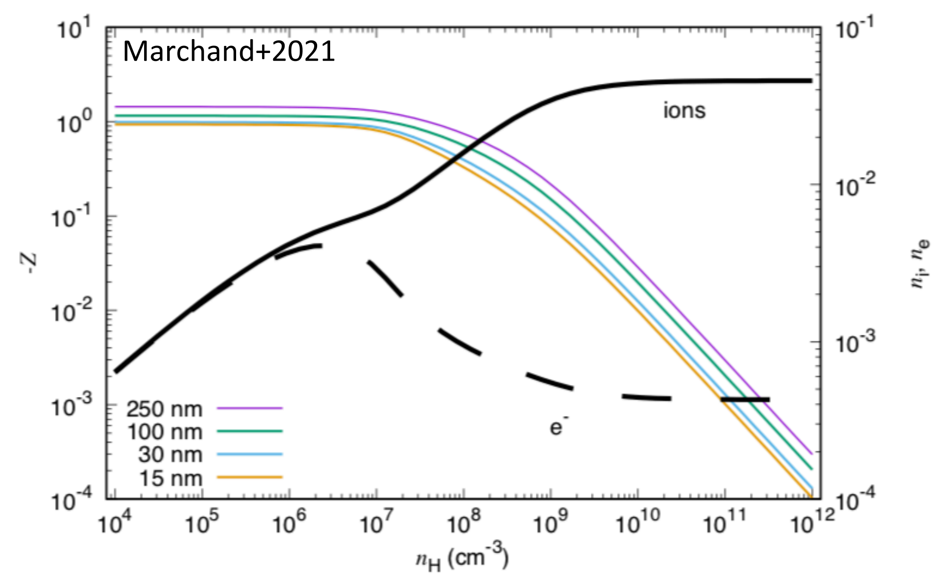
- Ionization equilibrium: ionisation rate = recombination rate of e^- with ions (in the gas phase) + recombination rate of ions onto negatively chared grains.

$$\zeta n_{\rm H} = \langle \sigma v \rangle_{\rm ie} n_{\rm i} n_{\rm e} + n_{\rm i} v_{\rm i} \sum_k \langle \tilde{J}(\tau_k) \rangle n_k \pi a_k^2$$

- Low density : electrons – ions plasma : $n_e \sim n_i \sim \mathrm{sqrt}(\zeta n_H)$
- Intermediate density : dust – ion plasma : $n_e < n_i$ (dust grains deplete electrons from the gas phase)
- High density : dust-dust plasma : $n_e / n_i = \mathrm{sqrt}(m_e/m_i)$, n_e and n_i independent of n_H, mean grain charge $\langle Z \rangle = 0$

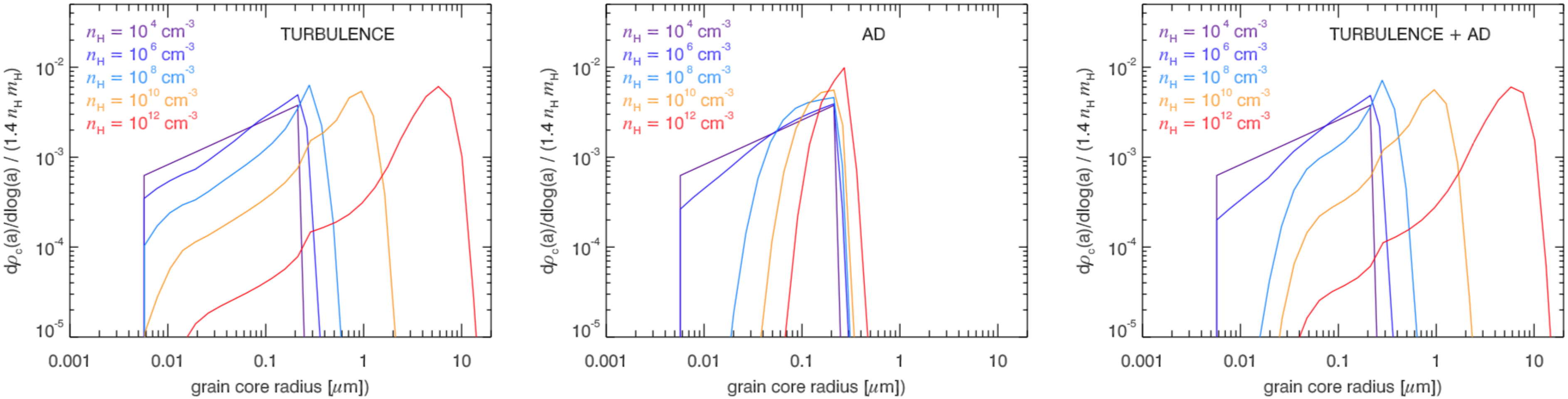
Marchand+2021: numerical method to derive n_e and n_i knowing n_H, ζ and the dust size distribution.





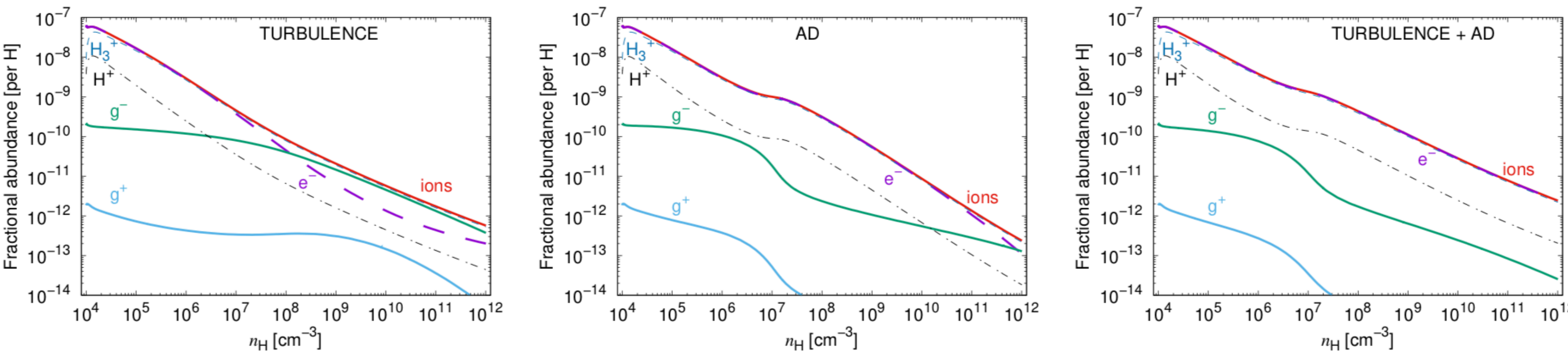
4. Modeling and simulation results for grain growth in core collapse

A simple model (Guillet+2020) for core collapse with coagulation



See also :

- Silsbee+2020: removal of small grains by ambipolar diffusion
- Silsbee+2022 : coagulation can **NOT** form 100 µm grains in the collapsing envelop.



4. Modeling and simulation results for grain growth in core collapse

Simulations of grain growth during core collapse

Marchand+2023: 3D MHD simulation of collapse with coagulation and feedback on MHD resistivities

- Coagulation is inefficient at growing large grains in the enveloppe. Fragmentation can be ignored.
- Grains grow in size extremely rapidly from the pseudo-disk (> 10^{-15} g/cm3) to the disk (> 10^{-13} g/cm3), up to 100 µm in a 1000 yrs-old disk.
- Feedback on MHD resistivities is strong, and impact on disk dynamics significant.

Lebreuilly+2023 : MHD simulation of collapse in spherical geometry, with coagulation and fragmentation and feedback on MHD resistivities

- Grains grow up to 10 µm through turbulence in the enveloppe (which, in this spherical simulation, includes the densities characteristic for the pseudo-disk), and to > 100 µm in the first hydrostatic core.
- Fragmentation is important for silicate grains, unimportant for icy grains.
- MHD resistivities are strongly affected by grain growth
- Ambipolar diffusion deplete small grains in the enveloppe.

Bate (2022) : 3D SPH code for radiation hydrodynamical calculation with coagulation

- Grains do not grow in the enveloppe of the core, only small grains start to deplete.
- Large (> 100 µm) dust grains only begin to grow significantly within the first hydrostatic core or pre-stellar disc, but they do so very quickly. Grain growth is driven by brownian motion.

NB : distinct modeling of the Reynolds number with the density (Marchand+2023), affects the importance of turbulence in grain growth.

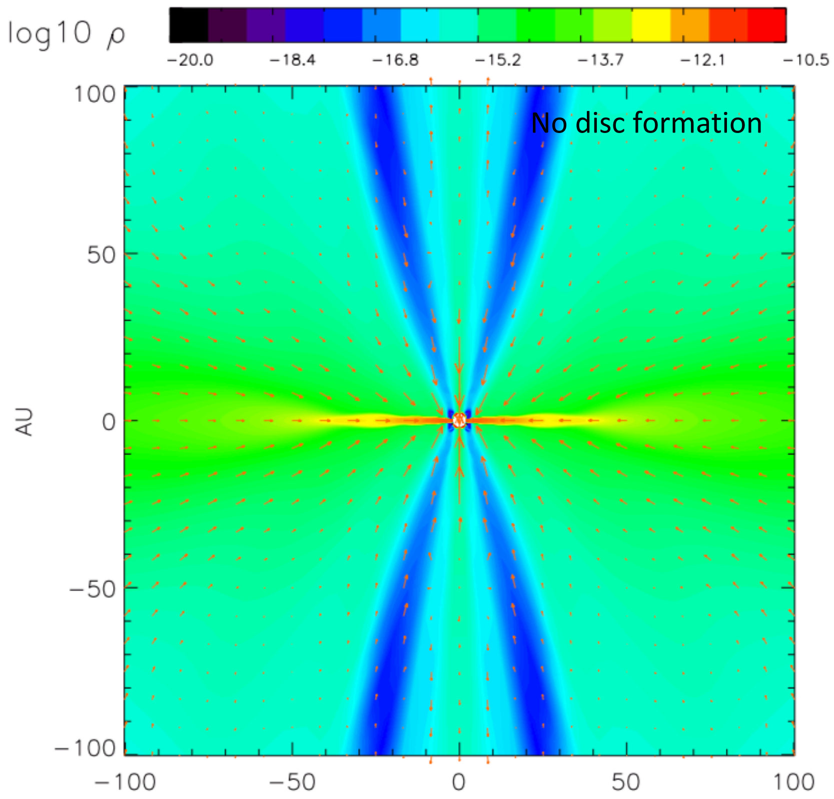
5. Subtilities : b) Feedback of grain growth on MHD resistivities

Zhao+2016 : Protostellar disc formation enabled by removal of small dust grains

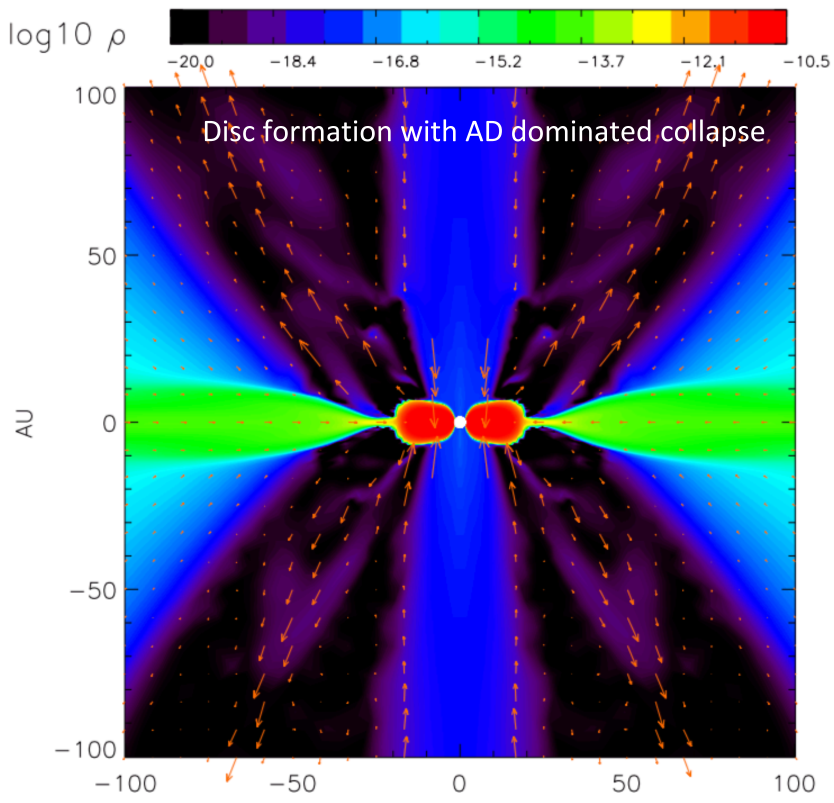
- The size distribution of grains affects the MHD resistivities (Ohmic, Hall, Ambipolar diffusion)
- With a MRN size distribution, resistivities are too low

➔ magnetic breaking preventing the formation of a disc

MRN (no coagulation)



Truncated-MRN (a_{min} = 0.1 μm no coagulation)



5. Subtilities : b) Feedback of grain growth on MHD resistivities

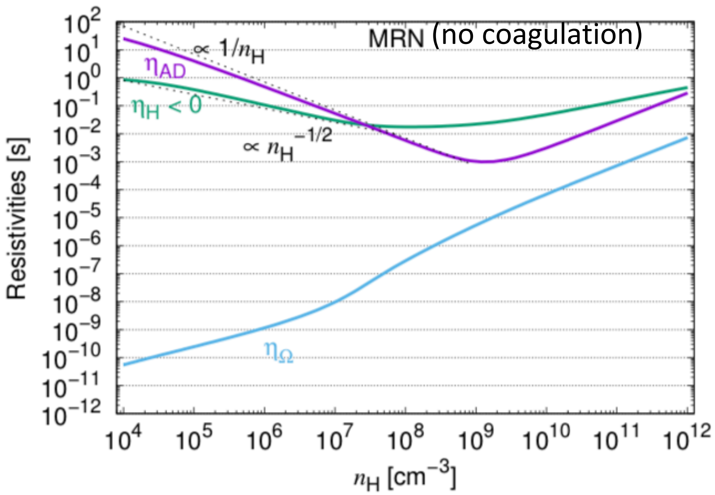
The conductivity of a given fluid (ions, electrons, dust grains) : $\sigma_j = n_j \frac{q_j^2}{m_j} \tau_j$

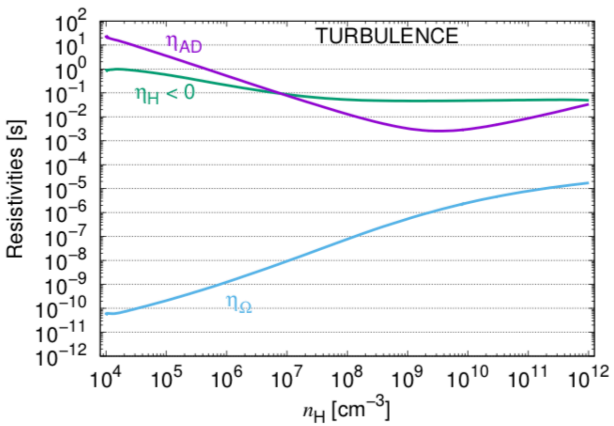
Conductivities (Siemens) Resistivities (Ω)

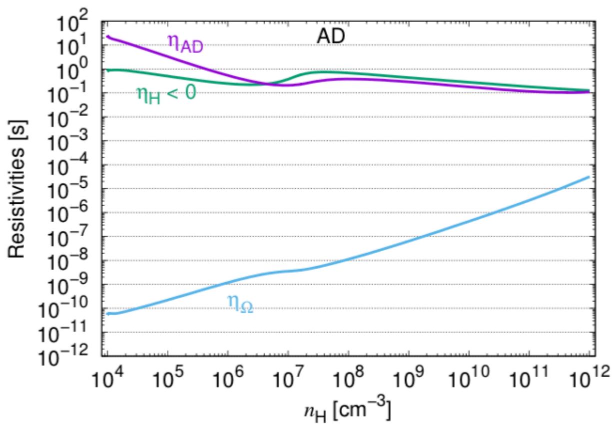
$$\sigma_{\rm par} = \sum_j \sigma_j, \qquad \eta_{\rm O} = \frac{1}{\sigma_{\rm par}},$$

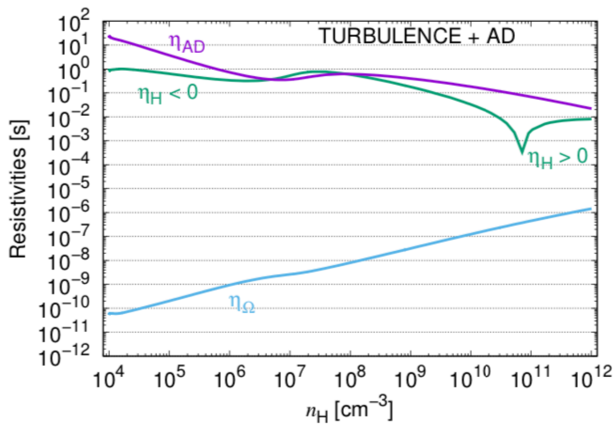
$$\sigma_{\rm perp} = \sum_j \sigma_j \frac{1}{1+\Gamma_j^2}, \qquad \eta_{\rm AD} = \frac{\sigma_{\rm perp}}{\sigma_{\rm perp}^2 + \sigma_{\rm H}^2} - \frac{1}{\sigma_{\rm par}},$$

$$\sigma_{\rm H} = -\sum_j \sigma_j \frac{\Gamma_j}{1+\Gamma_j^2}. \qquad \eta_{\rm H} = \frac{\sigma_{\rm H}}{\sigma_{\rm perp}^2 + \sigma_{\rm H}^2}.$$









5. Subtilities : b) Electrostatic effects between charged grains

Ivlev, Morfill & Konopka (2002), Akimkin+2023

The charge distribution of grains generates electrostatic attraction and repulsion. This enhance or decrease their collisional cross-section.

Both grains interact through their charge/charge (and also charge/induced-dipole).

- Electrostatic potential energy:

$$U_{\rm ch}(r) = \frac{QQ'}{r},$$

- Effective potential energy (ρ impact parameter, ε_r impact energy, m_* reduced mass)

$$U_{\rm eff}(r,\rho) = \mathcal{E}_r(\rho/r)^2 + U_{\rm ch}(r) \qquad \mathcal{E}_{\rm r} = \frac{1}{2} m_* v_{\rm r}^2$$

- Collisional cross-section

$$\sigma_{\rm ch} = \pi(a+a')^2(1-\mathcal{E}_{\rm ch}/\mathcal{E}_{\rm r}), \qquad \mathcal{E}_{\rm ch} \equiv U_{\rm ch}(a+a') = QQ'/(a+a')$$

Can be attractive or repulsive. **Only significant if ε_{ch} >> ε_r, i.e. for small impact velocities (brownian motion).**

Akimkin+2023 : in the presence of effective fragmentation of pebbles, if velocities are brownian (inner disk), electrostatic repulsion can maintain the presence of small grains and prevent the (re-)building-up of larger grains.

Summary & conclusions on grain growth from sub-micron to pebble sizes

- Grain growth is driven by the competition between coagulation and fragmentation
  - Coagulation is well-modelled, unlike fragmentation.
  - The irruption of fragmentation can have dramatic consequences on MHD resistivities by producing large quantities of small grains
  - The physics of collisions between aggregates must be used.
- Modeling the size-dependence of (random and systematic) velocities:
  - In the cloud envelop : Current models are based on simple models of grain acceleration in hydrodynamical turbulence. Simulations are starting to characterize the acceleration of charged grains in MHD turbulence. Possible contribution of ambipolar diffusion.
  - In the disk : brownian motions drive grain-grain coagulation
- Grain charge is important
  - For dust dynamics and dust (de-)coupling with the gas
  - For the ionisation equilibrium and the resulting MHD resistivities (➔magnetic breaking)
  - To enhance or limit coagulation by electrostatic effects in the disk if brownian motions are dominating.
- Results on grain growth in core collapse
  - In the envelop : coagulation is inefficient at growing up grains before entering the pseudo-disk stage. But it can remove small grains and therefore increase AD resitivity, allowing for the formation of a large disk. Fragmentation is not significant in the enveloppe.
  - In the pseudo-disk and in the disk : Grain growth is rapid (up to 10 μm in the pseudo-disk and 100 μm in the first hydrostatic core), driven by brownian motion. Fragmentation may come back significantly in the disk when large grains collide.