Dust growth during the protostellar collapse

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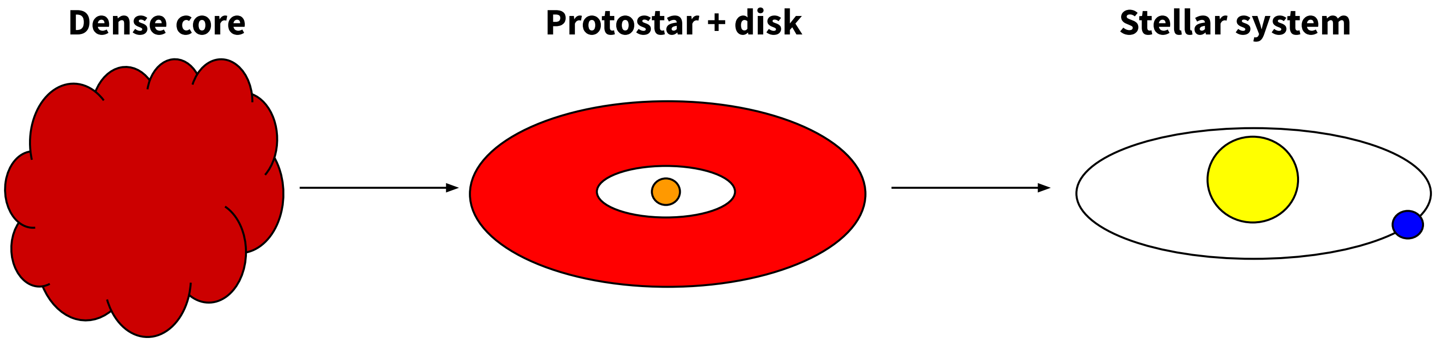
The angular momentum in star formation



Angular momentum

≈ 10^{21} cm^{2} s^{-1} → ≈ 10^{18} cm^{2} s^{-1}

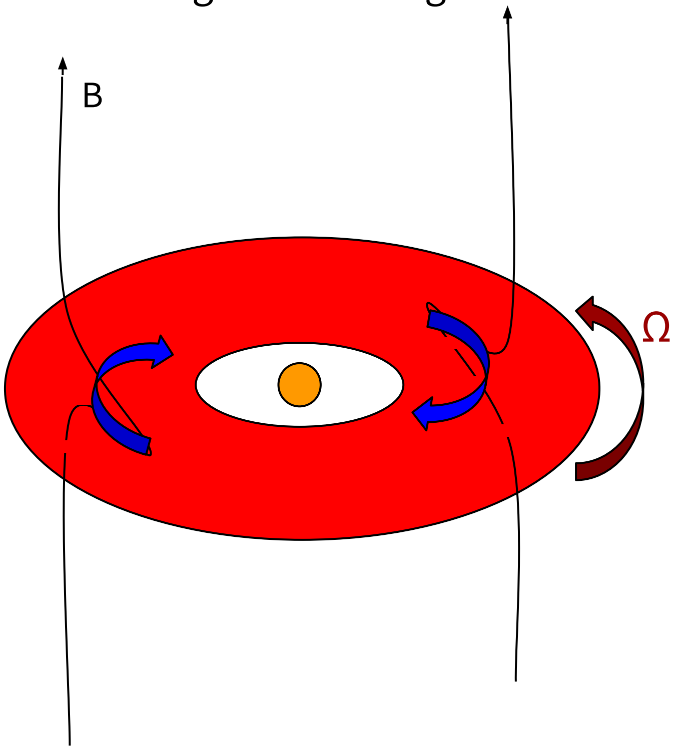
Most angular momentum is removed during star formation

Outline

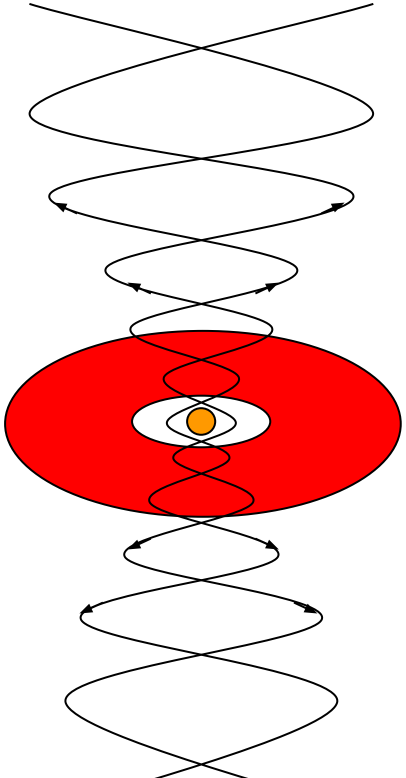
- **Angular momentum is not conserved during star formation.**

Removal of angular momentum by magnetic fields

Magnetic braking



Outflow



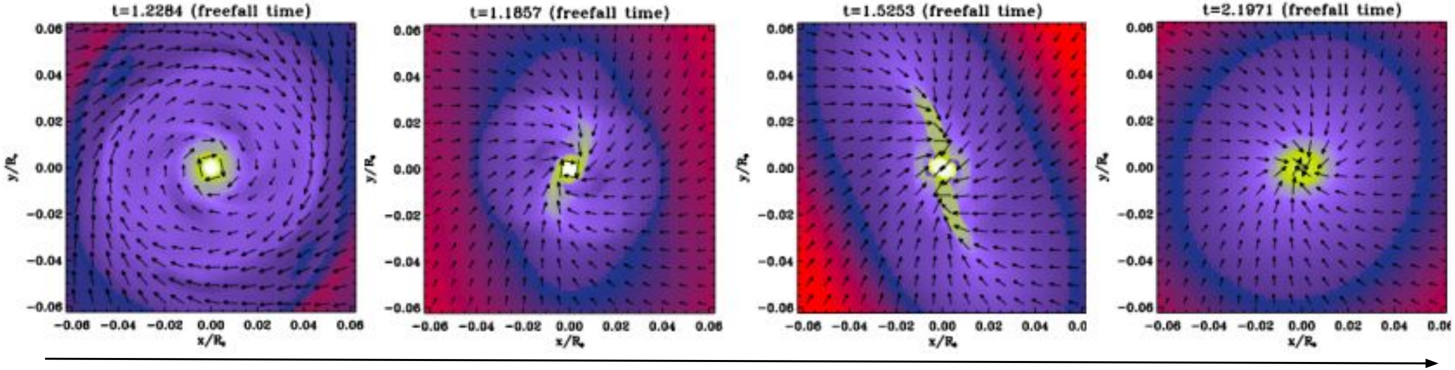
Outline

- Angular momentum is not conserved during star formation.
- **Magnetic fields explain the loss of AM.**

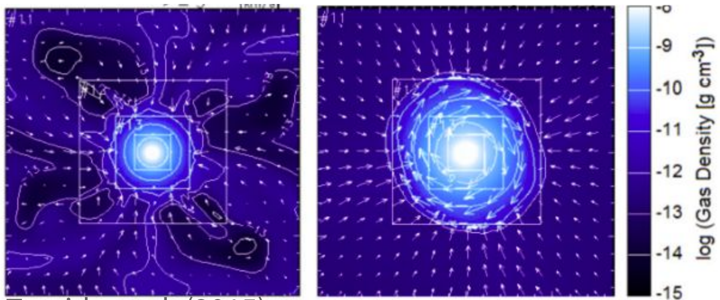
MagnetoHydroDynamics (MHD) in star formation

Ideal MHD = no magnetic dissipation, perfect coupling between the gas and the field.
→ Leads to a *magnetic braking catastrophe.*

Hennebelle & Teyssier (2008)



Ideal MHD / Non-ideal MHD



Tomida et al. (2015)

- Magnetic braking weakened by the **ambipolar** and **Ohmic diffusions**.
- Magnetic braking weakened or strengthened with the **Hall effect**.

Non-ideal MHD necessary in star formation calculations.

Outline

❖ Angular momentum is not conserved during star formation.

❖ Magnetic fields explain the loss of AM.

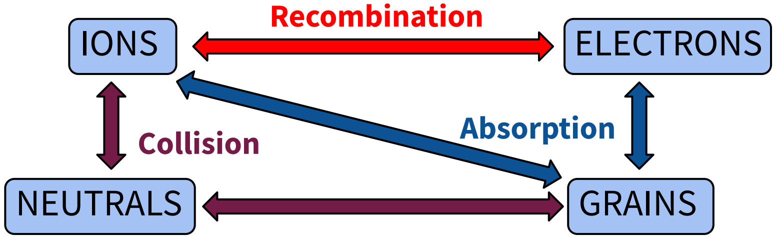
❖ **Ideal MHD prevents disk formation**
→ Non ideal MHD necessary.

Non-Ideal MHD - resistivities

Ohmic diffusion = decoupling of **electrons** and magnetic field
Hall effect = decoupling of **ions** and magnetic field
Ambipolar diffusion = decoupling of **neutrals** and magnetic field

} Weaken / alter magnetic braking

We know how to calculate / implement them.
BUT we need to calculate their strength = **resistivities**



How do particles interact with each other ?

- Ions, neutrals : Number ? Mass ?
- Electrons : Number ? Recombination ?
- Grains : Size ? Number ? Mass ? Charge ? → Grain **size-distribution**
- …

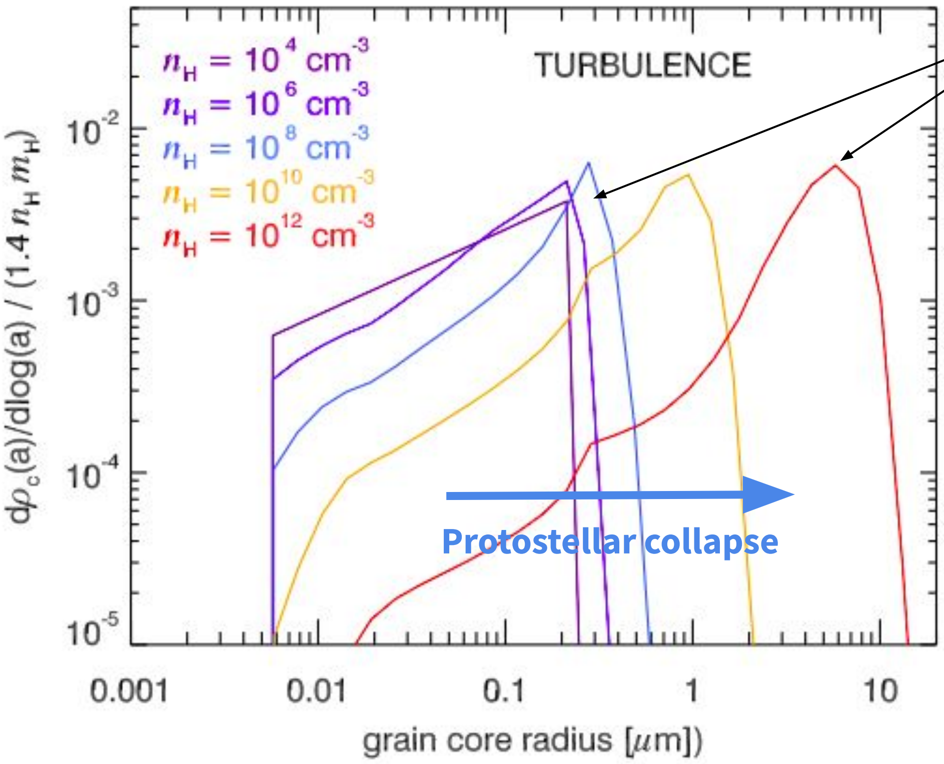
} Chemistry

Outline

- ❖ Angular momentum is not conserved during star formation.
- ❖ Magnetic fields explain the loss of AM.
- ❖ Ideal MHD prevents disk formation → Non ideal MHD necessary.
- ❖ **Magnetic resistivities are difficult to calculate (chemistry, grains…).**

Grain growth

Guillet et al. (2020) in a one-zone model



Growth by coagulation

Grain size important for :

- Chemistry
- Ionization
- Radiative transfer
- Observations
- Cooling
- Planet formation

Grain coagulation computationally expensive

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- **Grain growth is important but expensive.**

Grain coagulation

Smoluchowsky equation of coagulation

Smoluchowsky (1916)

$$\begin{aligned}\frac{\mathrm{d}\rho(m,t)}{\mathrm{d}t} = &-\int_0^{\infty} mK(m,m')n(m,t)n(m',t)\mathrm{d}m' \\ &+\frac{1}{2}\int_0^{m} mK(m-m',m')n(m-m',t)n(m',t)\mathrm{d}m' \\ &+\frac{\rho(m,t)}{n_{\mathrm{H}}}\frac{\mathrm{d}n_{\mathrm{H}}}{\mathrm{d}t},\end{aligned}$$

After some clever manipulations →

Marchand et al. (2021)

$$\frac{\mathrm{d}X(a,\chi)}{\mathrm{d}\chi} = C_2 I(a,X,\chi).$$

$$\chi = \int_0^t n_{\mathrm{H}}^{\frac{3}{4}} T^{-\frac{1}{4}} \mathrm{d}t.$$

Grain quantity

Independent from environment

Summary of relevant grain history

For every kernel K= f(grain)*g(gas)

Coagulation is a 1D process parametrized by χ

= Different environments alter the coagulation speed, not its outcome.

= The coagulated size-distribution is entirely determined by the initial distribution and χ

How to use

1. Pre-calculate the distributions as a function of χ → Use Ishinisan (Marchand et al. 2021)
2. Calculate χ in your hydro simulation
3. Read the size-distribution from the table
4. Do physics

Mathematically exact and self-consistent

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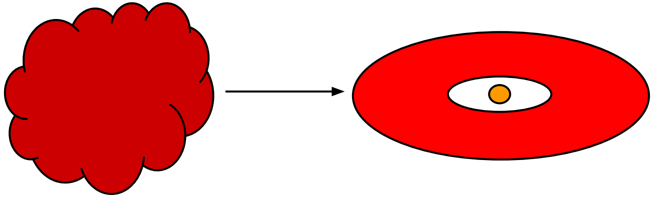
- Grain growth is important but expensive.
- **Grain coagulation is a 1D process parametrized by χ.**

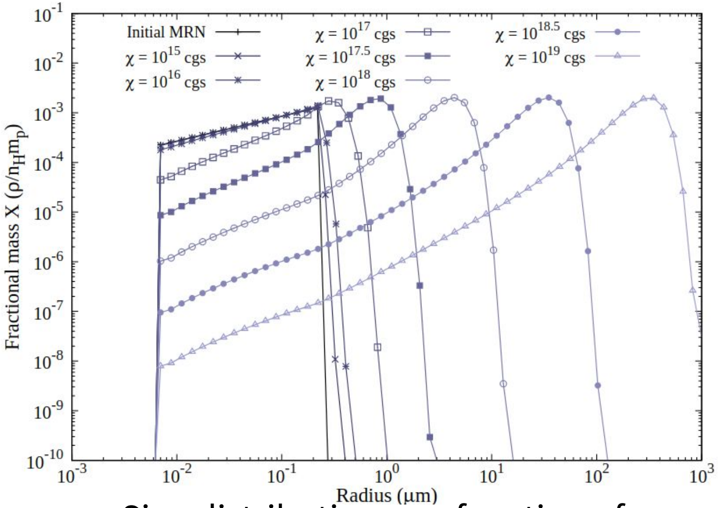
Protostellar collapse : simulation

Marchand et al. (submitted)

Simulation with **RAMSES** (Teyssier 2002) : 3D with full non-ideal MHD effects.

Collapse of a dense core → disk formation.





Size-distribution as a function of χ

Starting size-distribution : **MRN** (Mathis et al. 1977)

Dust-to-gas mass ratio : 1%.

χ calculated as a passive scalar in every cell.

Coagulation pre-calculated with Ishinisan.

Resistivities computed on-the-fly

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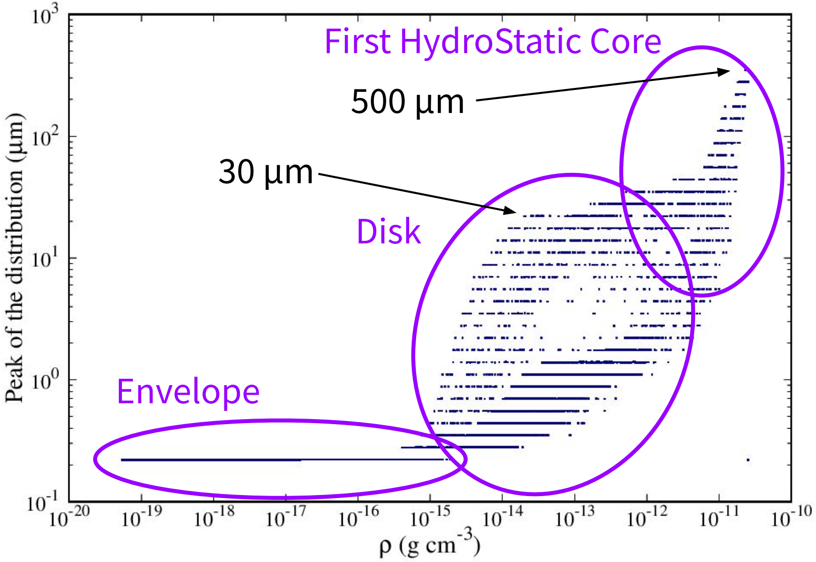
- ❖ Grain coagulation is a 1D process parametrized by χ.

Grain coagulation in protostellar collapse

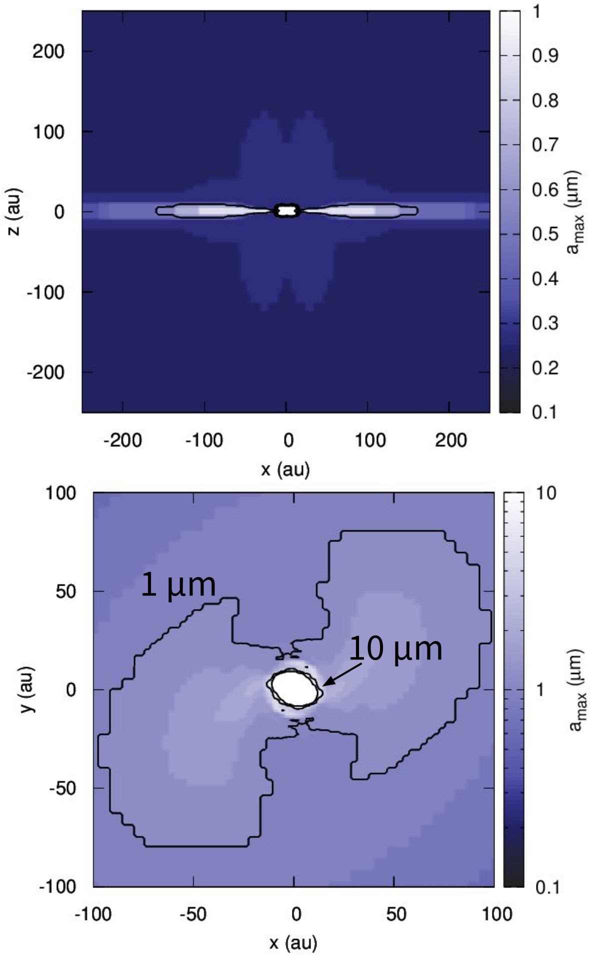
Marchand et al. (submitted)

Peak of the size-distribution in the simulation



Large grains concentrated in the high-density regions

Grains grow to > 10 µm very fast (disk < 1000 yr) !



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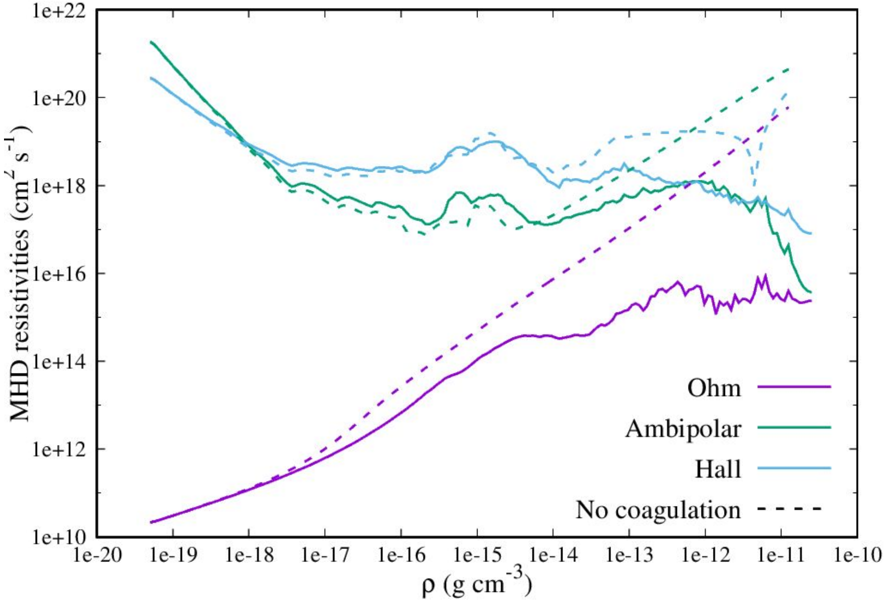
- Grain growth is important but expensive.
- Grain coagulation is a 1D process parametrized by χ.
- **Grains grow rapidly in the disk :**
  > 10 µm in < 1000 years !

Grain coagulation : impact on resistivities

Marchand et al. (submitted)

Resistivities as a function of density in simulations with/without coagulation



Grain coagulation :

→ Small grains disappear,

→ Larger, less numerous grains,

→ Lower grain surface area,

→ Lower electron / ion absorption

→ More “free” electrons / ions

→ **Lower resistivities**

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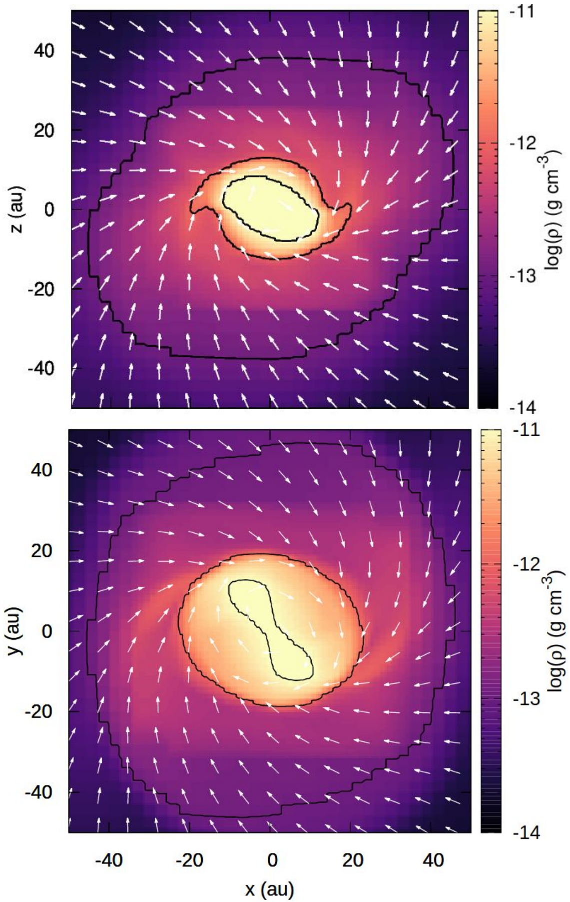
- Grain growth is important but expensive.
- Grain coagulation is a 1D process parametrized by χ.
- Grains grow rapidly in the disk :
  > 10 µm in < 1000 years !
- **Magnetic resistivities highly impacted by grain growth.**

Grain coagulation : impact on the disk

Marchand et al. (submitted)



With coagulation :
Low resistivities → Higher magnetic braking
→ **Smaller disk**

Without coagulation :
High resistivities → Lower magnetic braking
→ **Larger disk**

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- Grain growth is important but expensive.
- Grain coagulation is a 1D process parametrized by χ.
- Grains grow rapidly in the disk :
  > 10 μm in < 1000 years !
- Magnetic resistivities highly impacted by grain growth.
- **Lower resistivities due to growth,**
  → Stronger magnetic braking,
  → Smaller disks !

Summary

- Angular momentum is not conserved during star formation.
- Magnetic fields explain the loss of AM.
- Ideal MHD prevents disk formation. → Non ideal MHD necessary.
- Magnetic resistivities are difficult to calculate (chemistry, grains…).
- Grain growth is important but expensive.
- Grain coagulation is a 1D process parametrized by χ.
- **Grains grow rapidly in the disk : > 10-100 µm in < 1000 years !**
- **Magnetic resistivities highly impacted by grain growth.**
- Lower resistivities due to grain growth → Stronger magnetic braking → Smaller disks !

Thank you !

Grain ionization

Marchand et al. (2021,2022) Inspired from Draine & Sutin (1987)

- Equilibrium of ion/electron flux on grains

$$\epsilon = \frac{1-\psi}{\Theta e^{\psi}}$$

- Charge neutrality

$$n_\mathrm{i} + n_\mathrm{s} - n_\mathrm{e} + \sum n_k Z_k = 0$$

- Recombination/ionization equilibrium for ions

$$\zeta(n_\mathrm{H} - n_\mathrm{s,0} - n_\mathrm{i}) + k_\mathrm{s,i}(n_\mathrm{H} - n_\mathrm{s,0} - n_\mathrm{i})n_\mathrm{s}$$
$$= \langle\sigma v\rangle_\mathrm{ie} n_\mathrm{e} n_\mathrm{i} + n_\mathrm{i} v_\mathrm{i} \sum n_k \pi a_k^2 J_k + k_\mathrm{i,s}(n_\mathrm{s,0} - n_\mathrm{s})n_\mathrm{i}$$

- Recombination/ionization equilibrium for ions (with thermal ionization)

$$\zeta(n_\mathrm{s,0} - n_\mathrm{s}) + \left(\frac{dn_\mathrm{s}}{dt}\right)_{\substack{thermal\\ ionization}} + k_\mathrm{i,s}(n_\mathrm{s,0} - n_\mathrm{s})n_\mathrm{i}$$
$$= \langle\sigma v\rangle_\mathrm{se} n_\mathrm{e} n_\mathrm{s} + n_\mathrm{s} v_\mathrm{s} \sum n_k \pi a_k^2 J_k + k_\mathrm{s,i}(n_\mathrm{H} - n_\mathrm{s,0} - n_\mathrm{i})n_\mathrm{s}$$

4 equations
4 unknowns ψ, ε, n_i, n_s

Get:
- Ions number n_i, n_s
- Electrons number n_e
- Every grain charge Z_k

(arbitrary size-dist.)

~ 3-4 iterations of Newton-Raphson