What molecular-cloud collapse can teach us about initial conditions for planet formation in disks

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Content

- **Introduction:**

  - Disks around Class 0 YSOs – observational evidence;

  - Simulations of molecular cloud collapse: how to get disks forming?

- **New insights:**

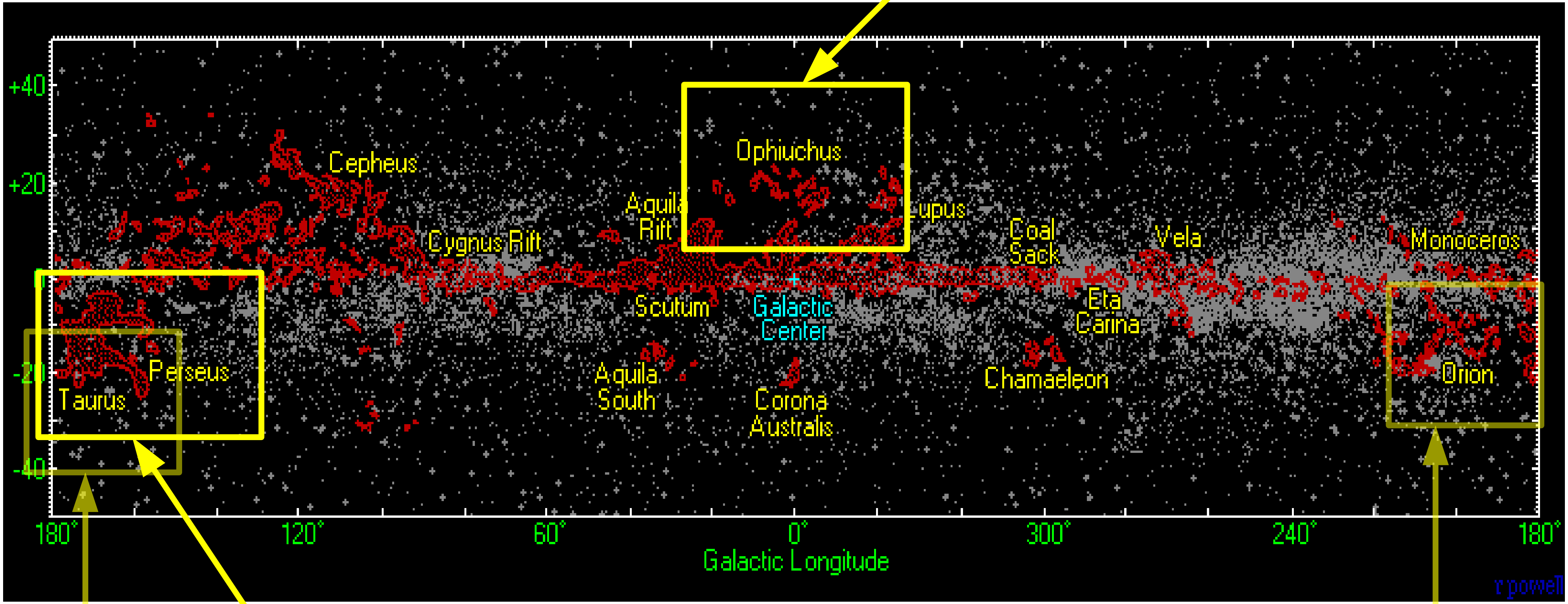
  - Chemo-dynamical model of collapsing cloud with RAMSES

  - Focus on magnetic diffusivities in collapsing clouds

- **What do we learn from collapse about later disk's conditions?**

Observational evidence for Class 0 disks: „nearby“ within 500 pc

Ophiuchus (131pc) & Serpent (225-500pc):
Total 298 YSOs



Taurus(140pc):
Total 296 YSOs

Perseus(d>500pc): total 387 YSOs

Orion (500pc):
Total 3838 YSOs

Observational evidence for Class 0 disks:“nearby“ within 500 pc

Over 4800 'nearby' YSOs are out there.

BUT....

Number of known Class 0 YSOs with <u>rotationally-supported</u> disks:

4 !

	M_central	M_disk	M_env	R_disk
L 1527 **VLA 1623A** **RCrA IRS7B** **HH212 MMS**	$0.2M_\odot$	$0.02M_\odot$	$1M_\odot$	50AU - 150AU

(Tobin+ 2012, Murillo+ 2013, Codella+ 2014, Lindberg+ 2014)

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And with ALMA+VLA?

2 ! more candidates :

L 1448 IRS2
Rer-emb-14

(Perseus cloud, *Tobin+ 2015*)

WHY.... ?

Observational evidence for Class 0 disks:“nearby“ within 500 pc

What are the reasons for pausity of detected disk structures?

- **Collapse is a <u>very short event</u>** in the life of star, low detecting probability.
  Perseus: only 38 out of 387 YSOs are Class 0 !

- **Compact emission** is seen in **many** of Class 0 objects (tracing dust) **R < 100 AU.**
  What could it be?
  - anything compact.

- **Lack of good kinematic data,** to detect the rotation.

- **Distance matters**.
  If L1527 would be in Perseus, disk wouldn't be resolved!

Theory of star formation: do we get disks out of collapse simulations?

It's complicated...........

a) Collapse and fragmenting of massive clouds => multiple star formation

b) Collapse of isolated cloud (apply up to 50% of low mass YSOs)

Without B-field (HD):

$$r_{\rm d,hydro} \simeq \frac{\Omega_0^2 R_0^4}{4\pi/3\rho_0 R_0^3 G} = 3\beta R_0$$
$$= 106\ {\rm au}\ \frac{\beta}{0.02}\left(\frac{M}{0.1\ M_\odot}\right)^{1/3}\left(\frac{\rho_0}{10^{-18}\ {\rm g\ cm^{-3}}}\right)^{-1/3}$$

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With B-field, Ideal MHD: *no disks - magnetic braking catastrophe*

Solutions: misaligned rotation axes and magnetic field directions (Joos et al. 2012),
or applying the external turbulence (Seifried et al. 2013).

Problem: *we know Ideal MHD does not apply in collapsing clouds.*

Theory of star and disk formation: resent RMHD simulations with ohmic and ambipolar diffusivities

MHD simulations with Ohmic dissipation

Dapp & Basu 2010

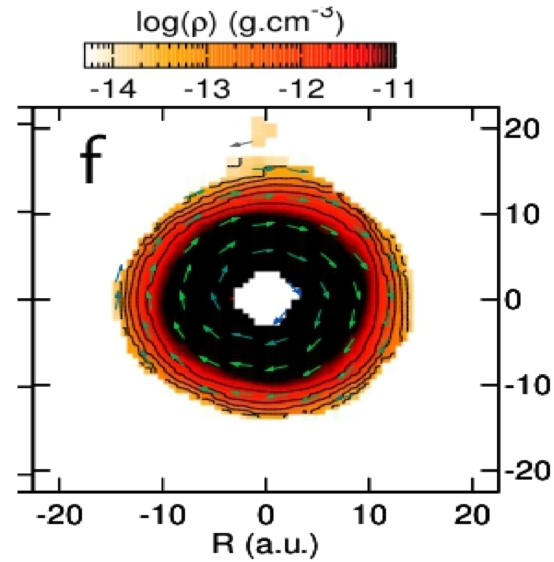
MHD simulations, Ohmic+Ambipolar dif.
of 1 M☼ core , T=10K, ~1.d+4AU domain...

-Tomida+ 2012
- Masson+ 2016
- Tsukamoto+2015a

Results: disk with R ≈1 AU, R≤ 5AU, R < 20 AU

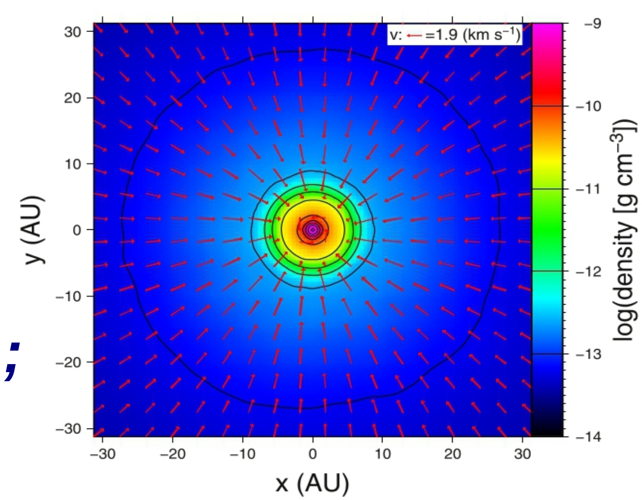
Differences come from:

- different inputs to adopted chemistry / ionization ;
- numerical issues.



Masson+ 2016

Tsukamoto+ 2015a

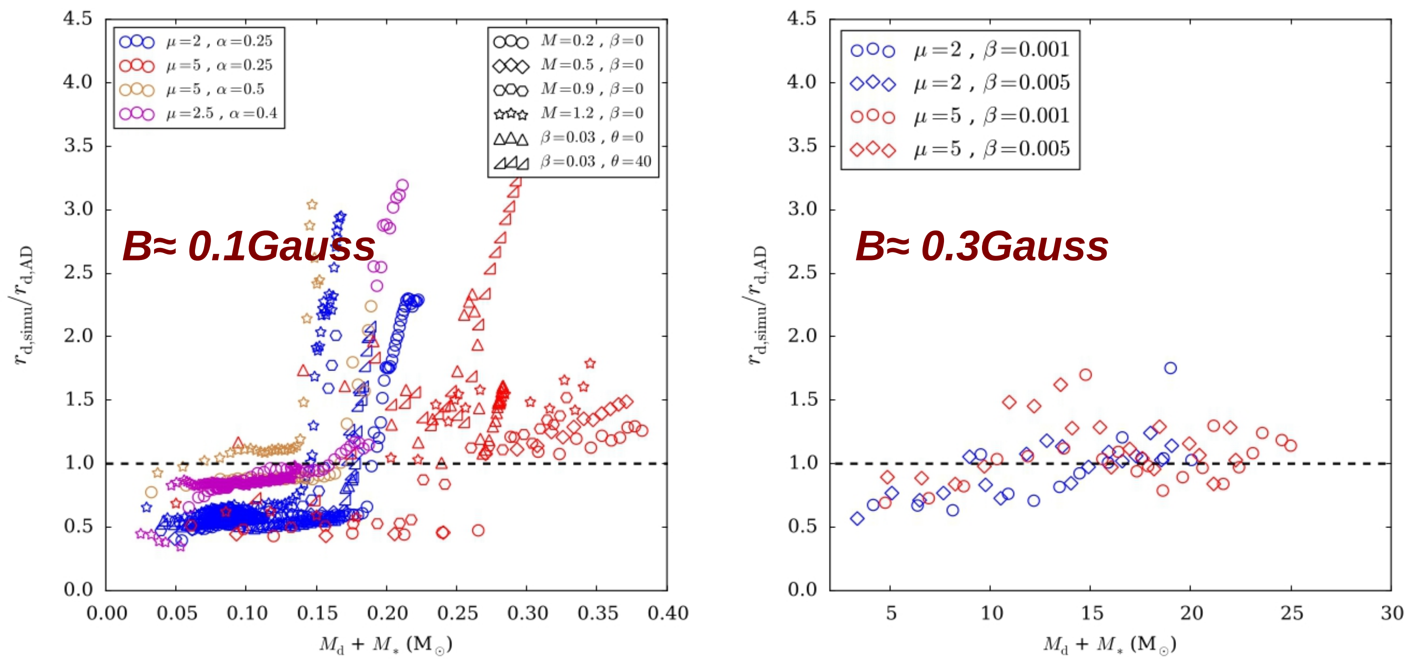


Theory of star and disk formation: resent R-MHD simulations with ambipolar diffusion

Credit:
Hennebelle et al 2016

A survey over large range of R-MHD simu- lations (RAMSES)

Ambipolar diffusion



Claim:

$$r_{\rm d,AD} \simeq 18 \text{ au} \times \delta^{2/9} \left(\frac{\eta_{\rm AD}}{0.1 \text{ s}}\right)^{2/9} \left(\frac{B_z}{0.1 \text{ G}}\right)^{-4/9} \left(\frac{M_{\rm d}+M_*}{0.1\, M_\odot}\right)^{1/3}. \quad (13)$$

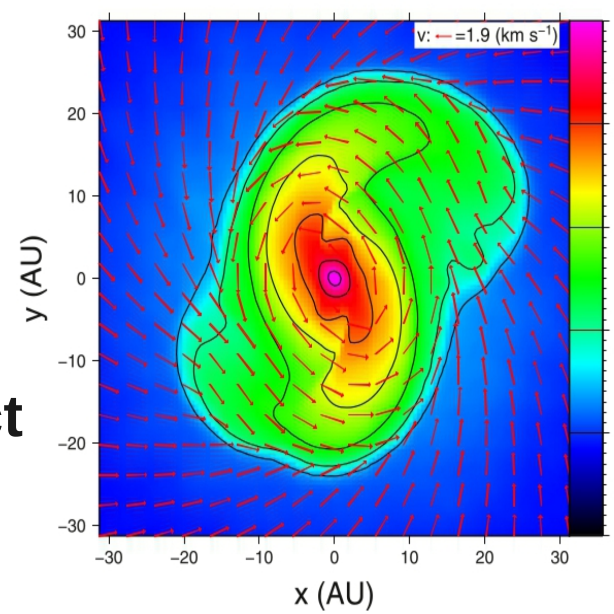
To compare with pure HD case:

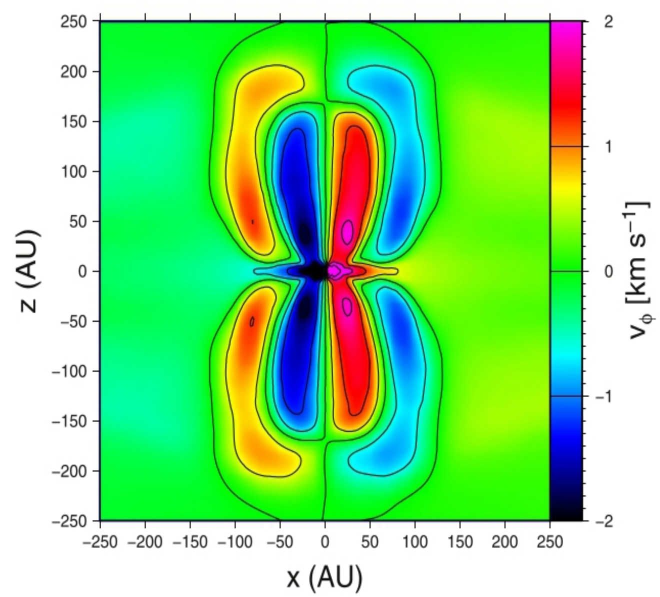
$$r_{\rm d,hydro} \simeq \frac{\Omega_0^2 R_0^4}{4\pi/3 \rho_0 R_0^3 G} = 3\beta R_0 = 106 \text{ au} \frac{\beta}{0.02} \left(\frac{M}{0.1\, M_\odot}\right)^{1/3} \left(\frac{\rho_0}{10^{-18} \text{ g cm}^{-3}}\right)^{-1/3}, \quad (14)$$

Theory of star and disk formation: resent simulations with Hall Effect – on top of ambipolar and Ohmic diff.

Credit:
Tsukamoto 2015b

SPH simulations
AmbipolarD + Hall Effect
of 1 M☼ core ,
R=3x10³AU , μ=4, T=10K





Results:
Anti-parallel to rotation Hall current leads to x10 larger disk compared with ambipolar-only case!

Warning:
Background model with AD produces the disk of only 1 AU! - in contradiction to Masson et al 2016 ; Hennebelle et al 2016; Tomida 2013, 2015

Chemo-dynamical model of collapsing cloud:

Codes: RAMSES (AMR , R-MHD) + PDS code (chemistry) merged;

Basic grid: 64^3,
10 levels of mesh refinement

Domain:

4.d+4 AU, 1 $M_{\odot}$, T=10K
E_th/E_grav=0.44
n_c = 4.4d+5 cm^{-3}

Aims *Part I:*

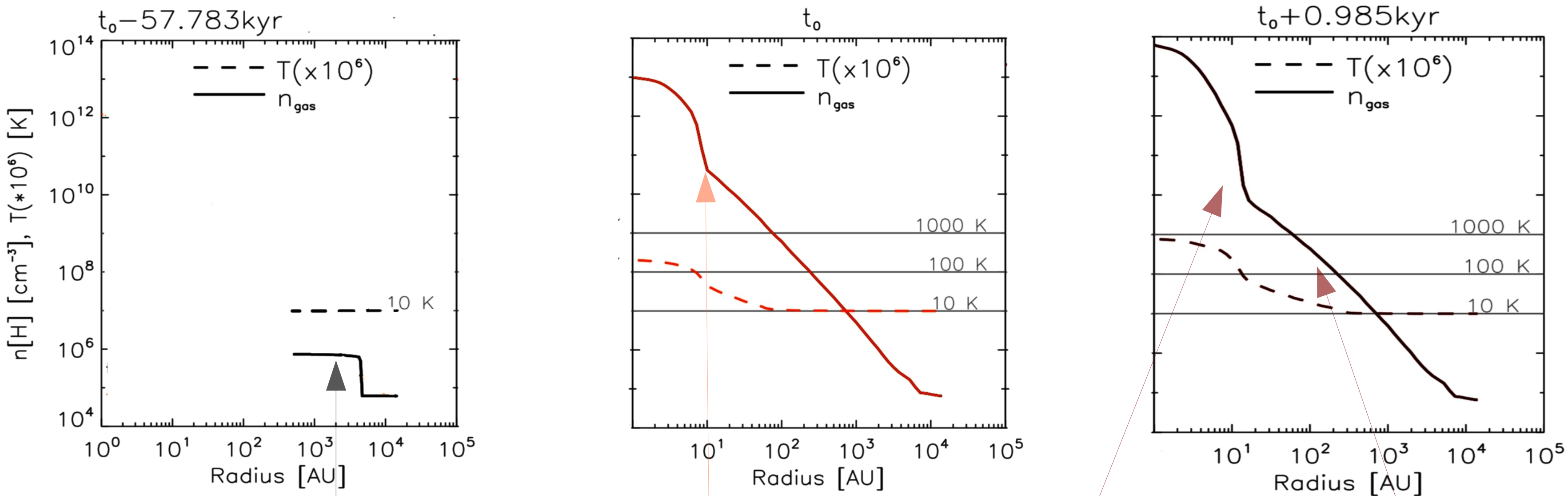
Parameter study (core size, free-fall time, dust size) for chemistry, published in arXiv:1605.08032;

Part II:

How the magnetic dissipation depends on mean dust size in the cloud?

Chemo-dynamical model of collapsing cloud:

Q1: How magnetic dissipation changes with radius during the collapse?



Initial condition,

T = 10 K
n_c = 4.4 x 10^5 /cm^3

In FHSC: *T>100K,*
processed ices on grains

Disk formation site (outside FHSC):
10K < T < 100K
Partly unprocessed ices

FHSC (First Hydro-Static Core)
R~ 8-10 AU , T_c= 210 K, n_c=10^13 /cm^3

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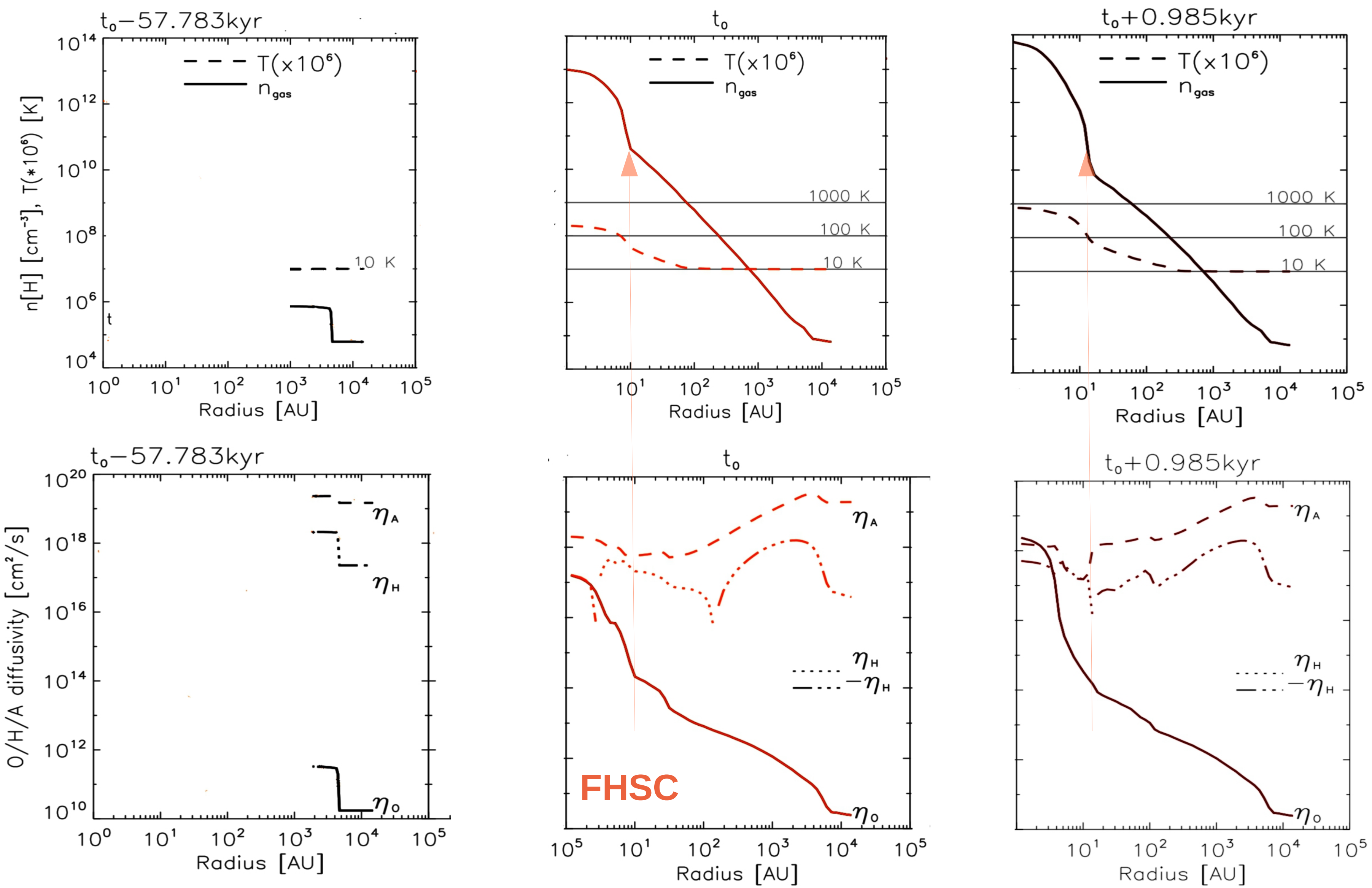


Chemo-dynamical model of collapsing cloud:

Q1: How magnetic dissipation changes with radius during the collapse?

<u>As collapse proceeds:</u>

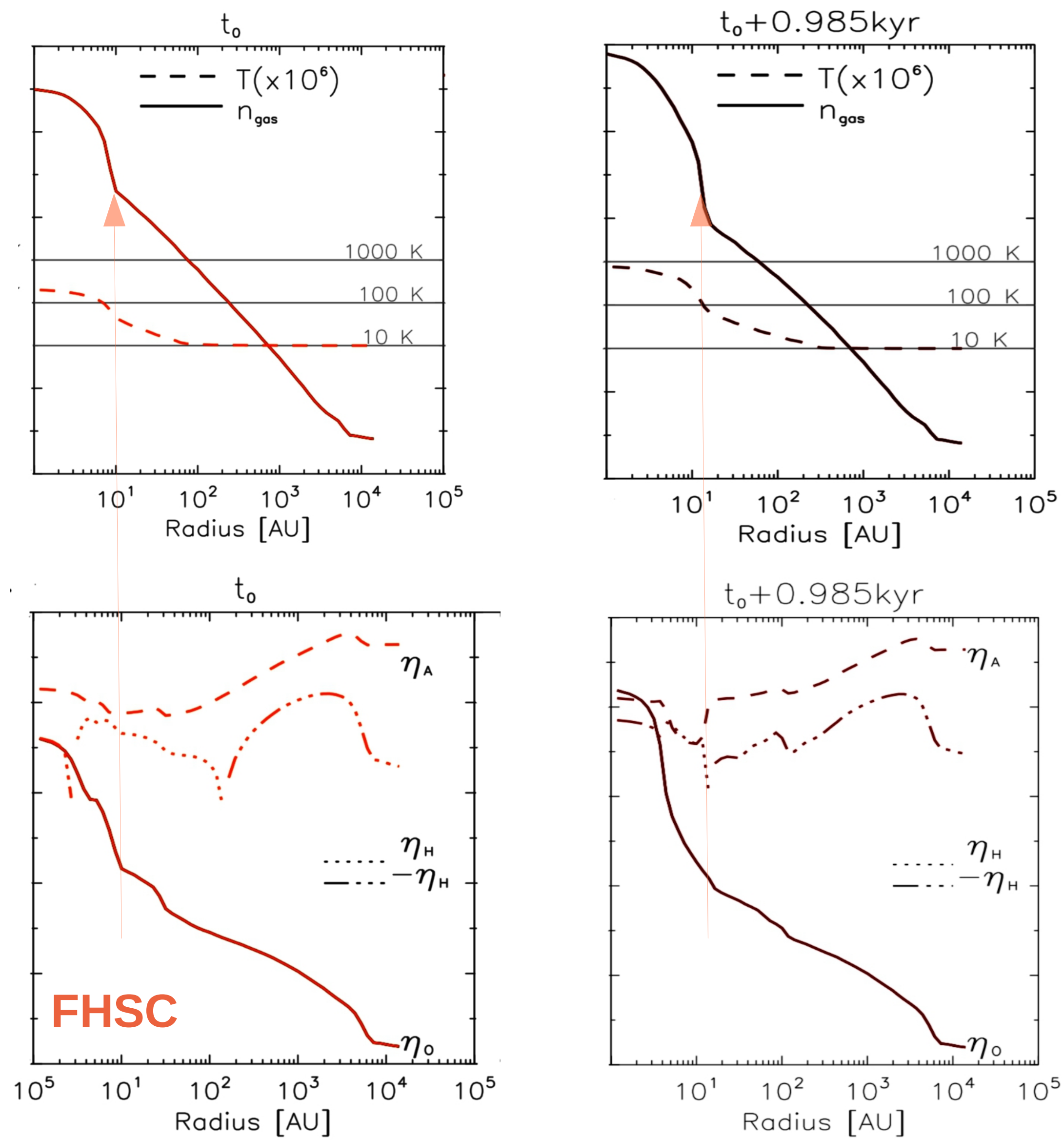
1. η_A > η_H > η_O ;

2. η_H has a reversal, which travels inside with time;

3. η_O is important only within 2-3 AU.

***t*< *t_0* is the longest phase of collapse.**

Following plots show always moment ***t_0.***



Chemo-dynamical model of collapsing cloud:

Q2: what happens if dust mean size changes from cloud to cloud?

$$\eta_{\rm O} = \frac{c^2}{4\pi\sigma_{\rm O}}, \; \eta_{\rm H} = \frac{c^2\sigma_{\rm H}}{4\pi\sigma_\perp^2} \text{ and } \eta_{\rm A} = \frac{c^2\sigma_{\rm P}}{4\pi\sigma_\perp^2} - \eta_{\rm O}, \quad \sigma_{\rm O} = \frac{ec}{B}\sum_x n_x|q_x|b_x,$$

$$\sigma_{\rm H} = -\frac{ec}{B}\sum_x \frac{n_x q_x b_x^2}{1+b_x^2},$$

Can charged dust be important?

$$\sigma_{\rm P} = \frac{ec}{B}\sum_x \frac{n_x|q_x|b_x}{1+b_x^2},$$

Charged species:	type	Coupling parameter ***b***
	1) electrons	» 1
	2) ions,	≤ 1
	3) negatively charged dust,	« 1
	4) positively charged dust	« 1

Chemo-dynamical model of collapsing cloud:

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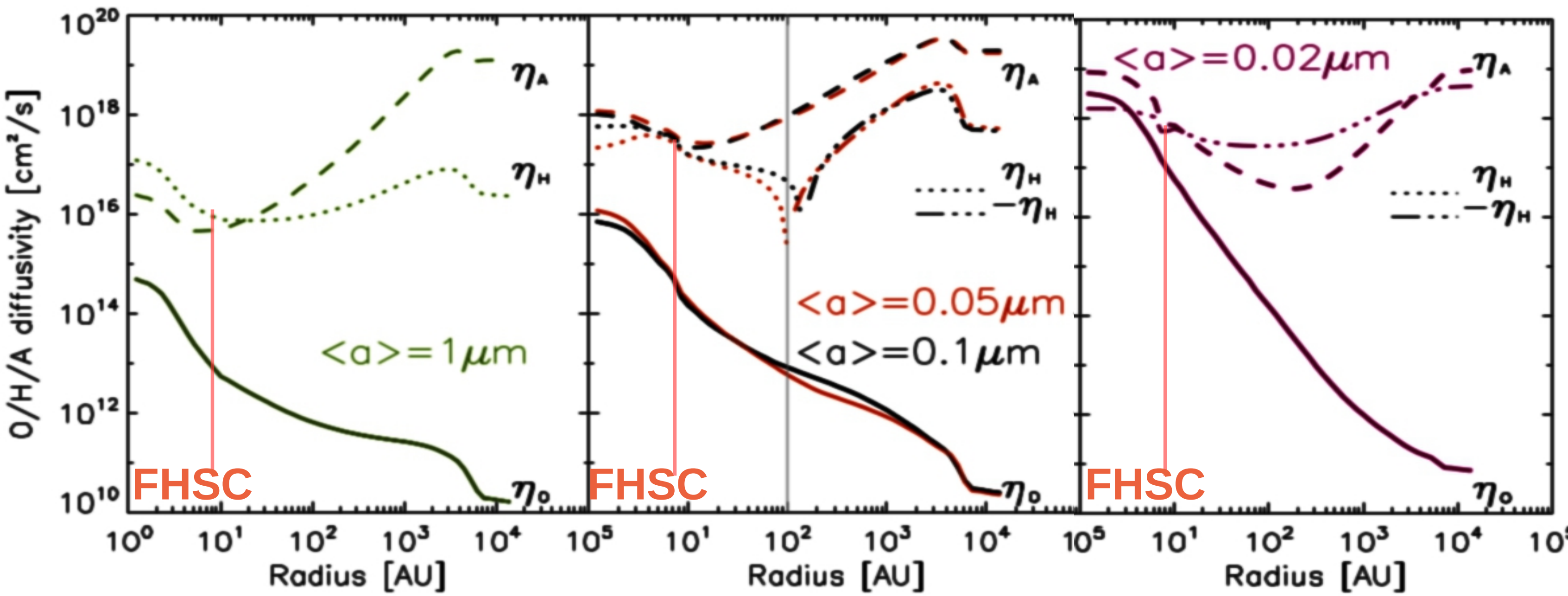
t_0



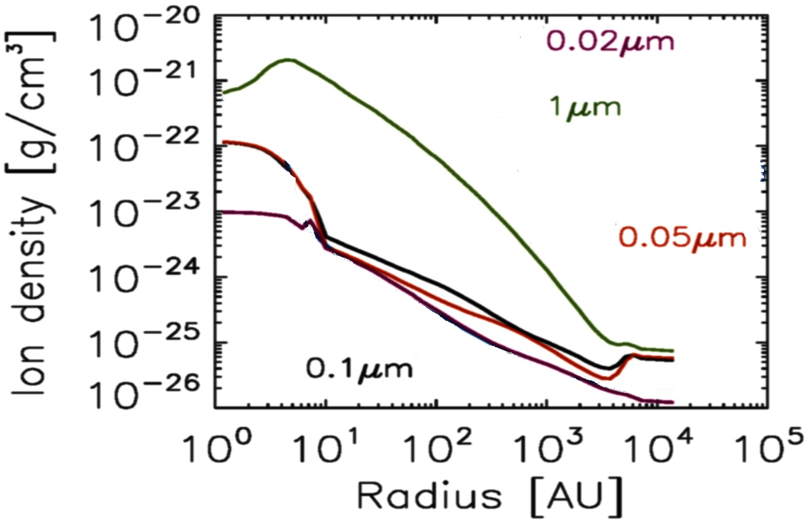
Large dust:
- η_H dominates inside if FHSC
- η_A dominates outside FHSC

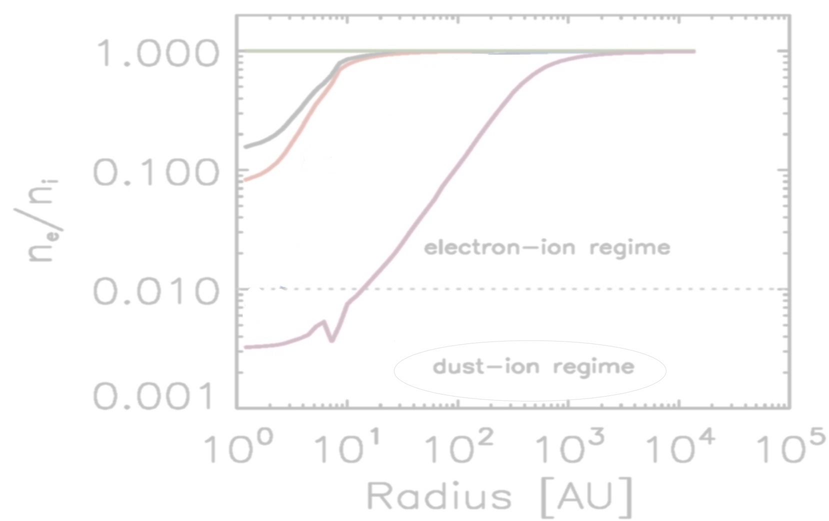
Intermediate dust sizes:
- η_A dominates at all radii,
- η_H has ***sign reversal***

Tiny dust:
- η_H dominates large radial domain outside of FHSC, always negative!

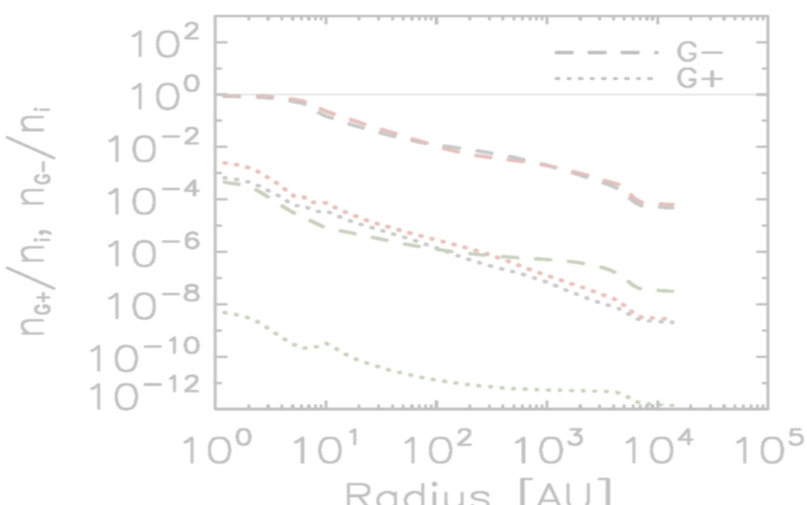
Chemo-dynamical model of collapsing cloud:

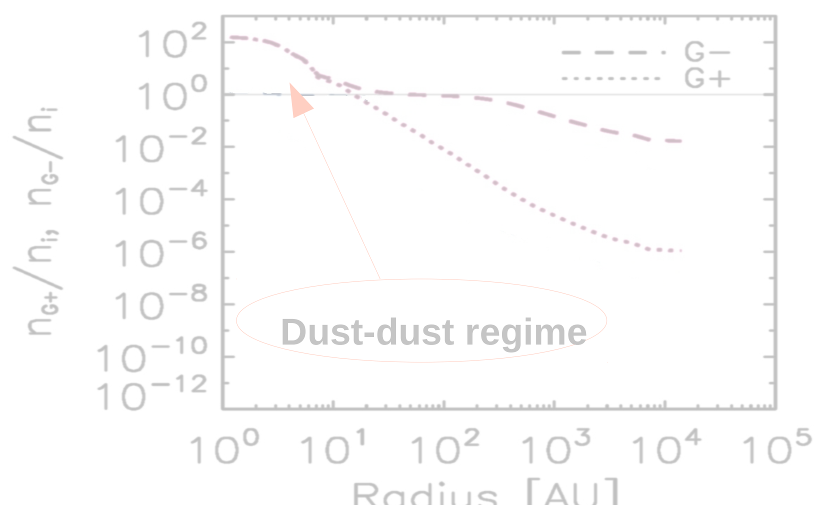
Q3: which charged species dominate if dust size changes?





Dust size affects chemistry, i.e. number and population of ions !





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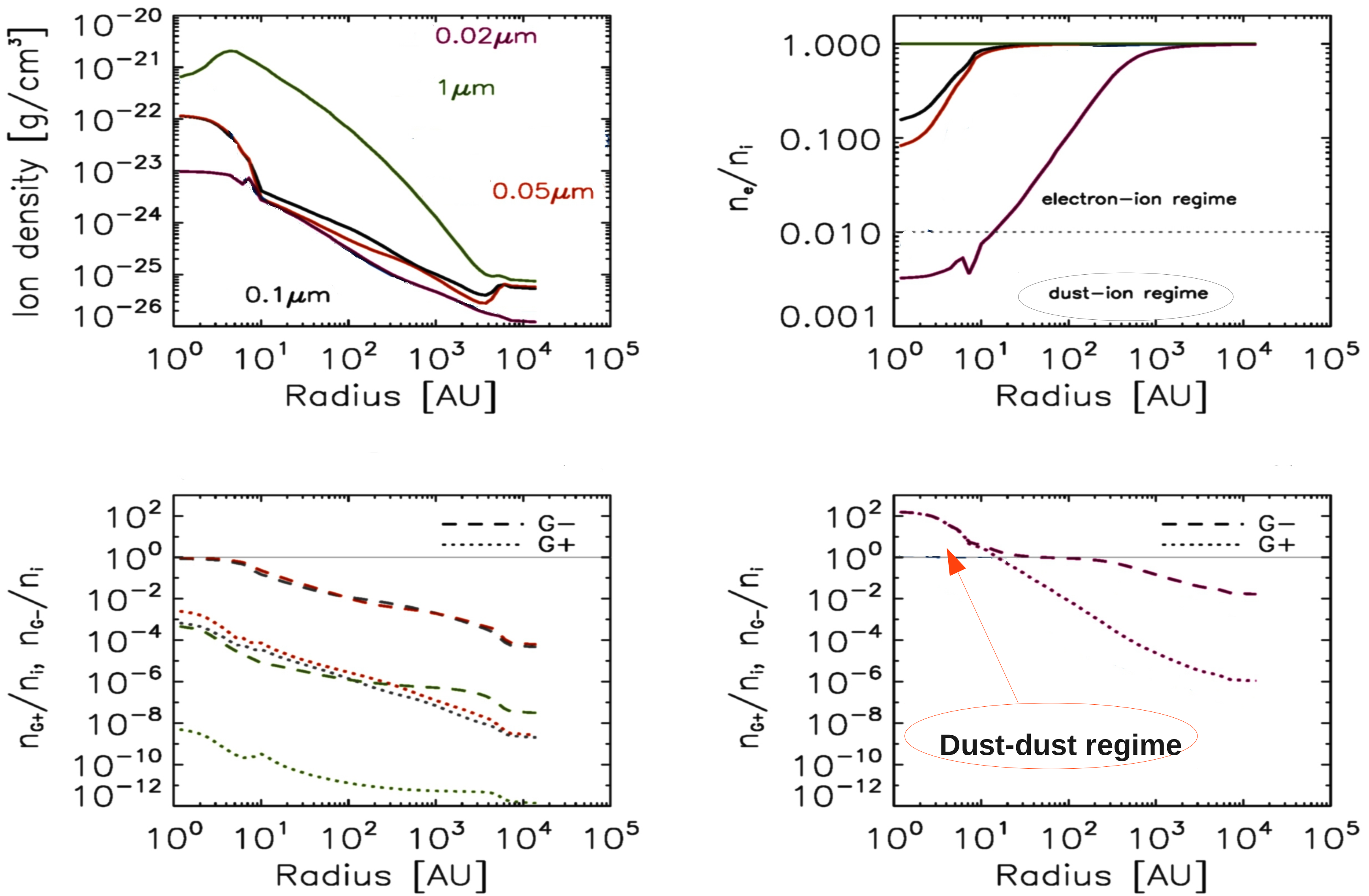

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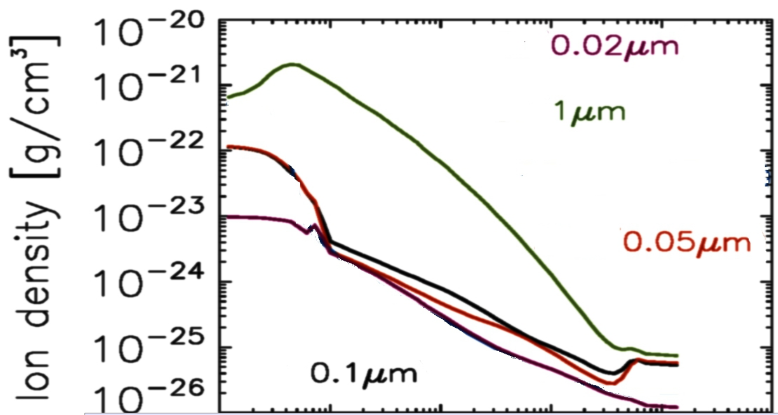
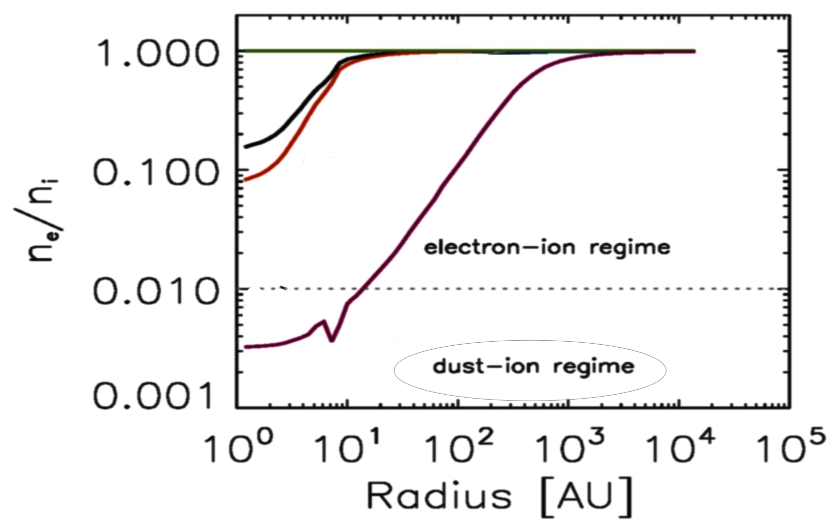
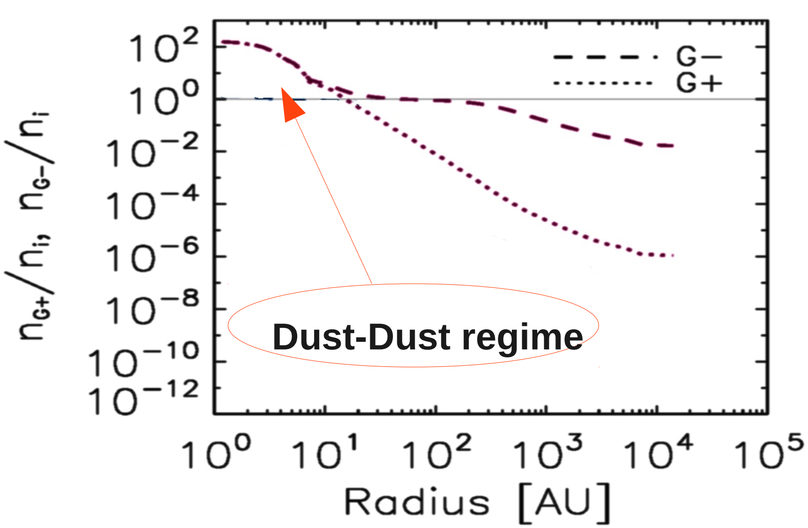




To take away:

1) **ions are the dominant charged species**
Exception: clouds with dust mean size < 0.02μm

2) The location of Hall effect's sign reversal ***does not*** correlate with n_i/n(G-) or n_e/n_i



Chemo-dynamical model of collapsing cloud:

Q4: what causes the reversal of Hall Effect sign ?

$$\sigma_{\mathrm{H}} = \frac{ec}{B}\left(-\frac{n_{\mathrm{e}}}{1+b_{\mathrm{e}}^2} + \frac{n_{\mathrm{i}}}{1+b_{\mathrm{i}}^2} + \frac{n_{\mathrm{G+}} - n_{\mathrm{G-}}}{1+b_{\mathrm{G}}^2}\right)$$

(using values for ***b_x*** coupling parameters)

$$n_{\mathrm{G-}}^{\mathrm{th}} = \frac{n_{\mathrm{i}}}{b_{\mathrm{i}}^2} - \frac{n_{\mathrm{e}}}{b_{\mathrm{e}}^2} + n_{\mathrm{G+}} \cong \frac{n_{\mathrm{i}}}{b_{\mathrm{i}}^2} + n_{\mathrm{G+}}$$

<u>Reversal:</u>

The Hall effect becomes negative, when the number of negative charge carries, weighted over coupling parameter b^2 , is dominating the number of b^2 -weighted positive carriers.

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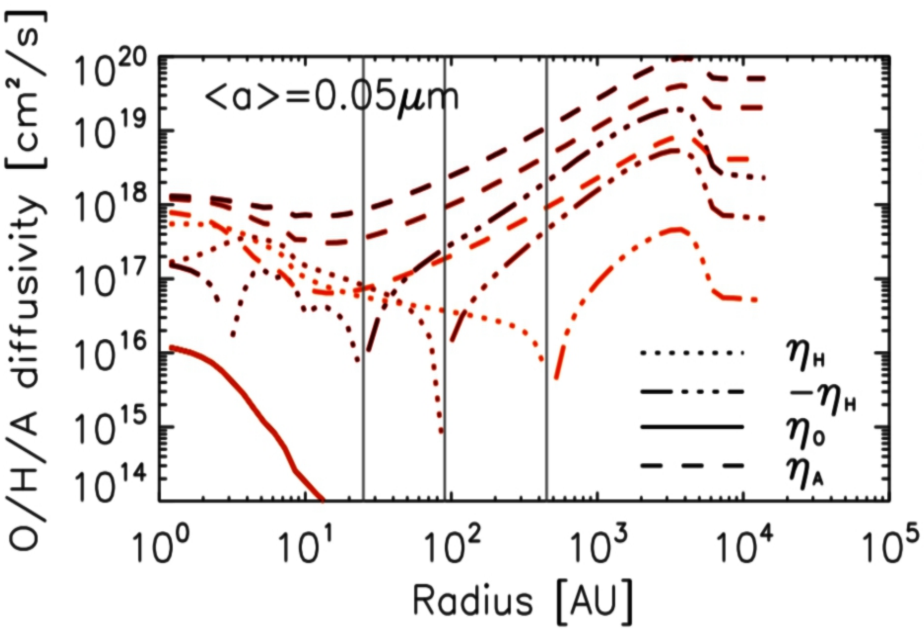

Color coding: μ=2, μ=5, μ=25

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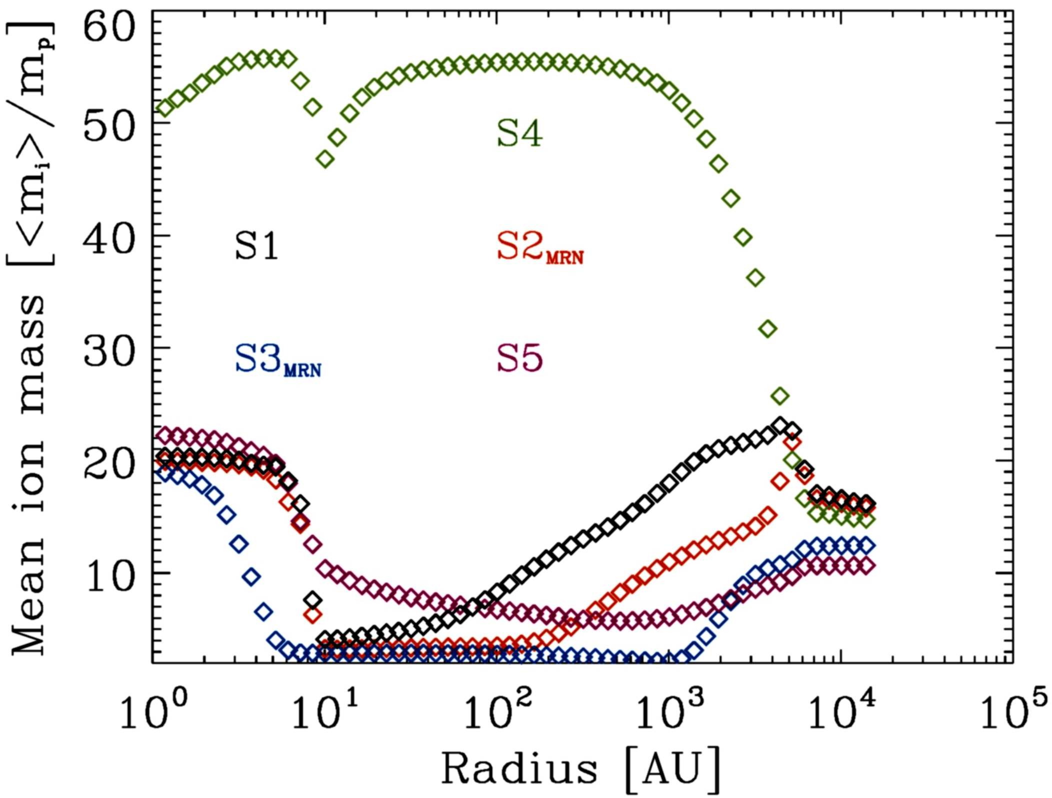
Q5: can we skip doing chemistry and use „representative“ ions for AD?



Mean ion mass can variate strongly, depending on dust size *and* radius !

Answer: **Better not!**

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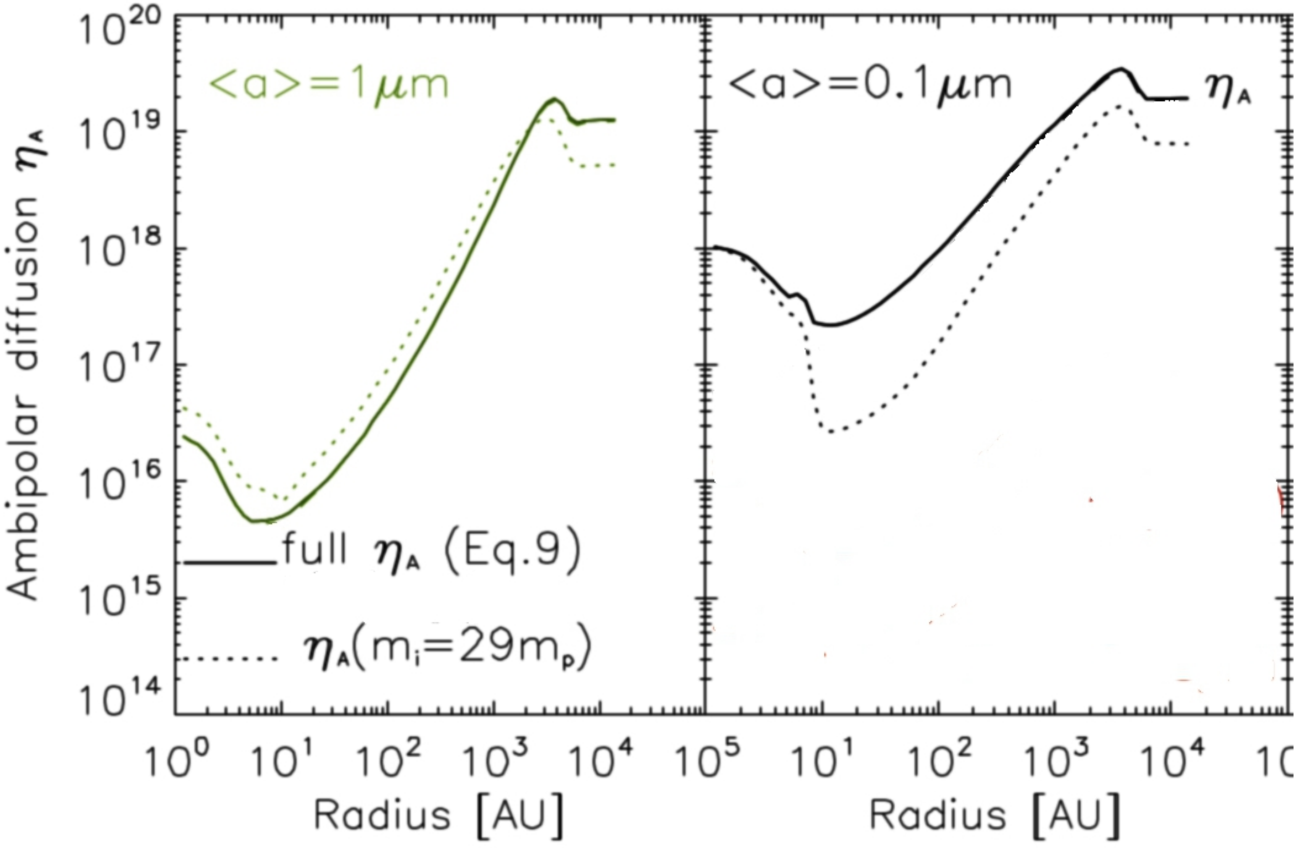

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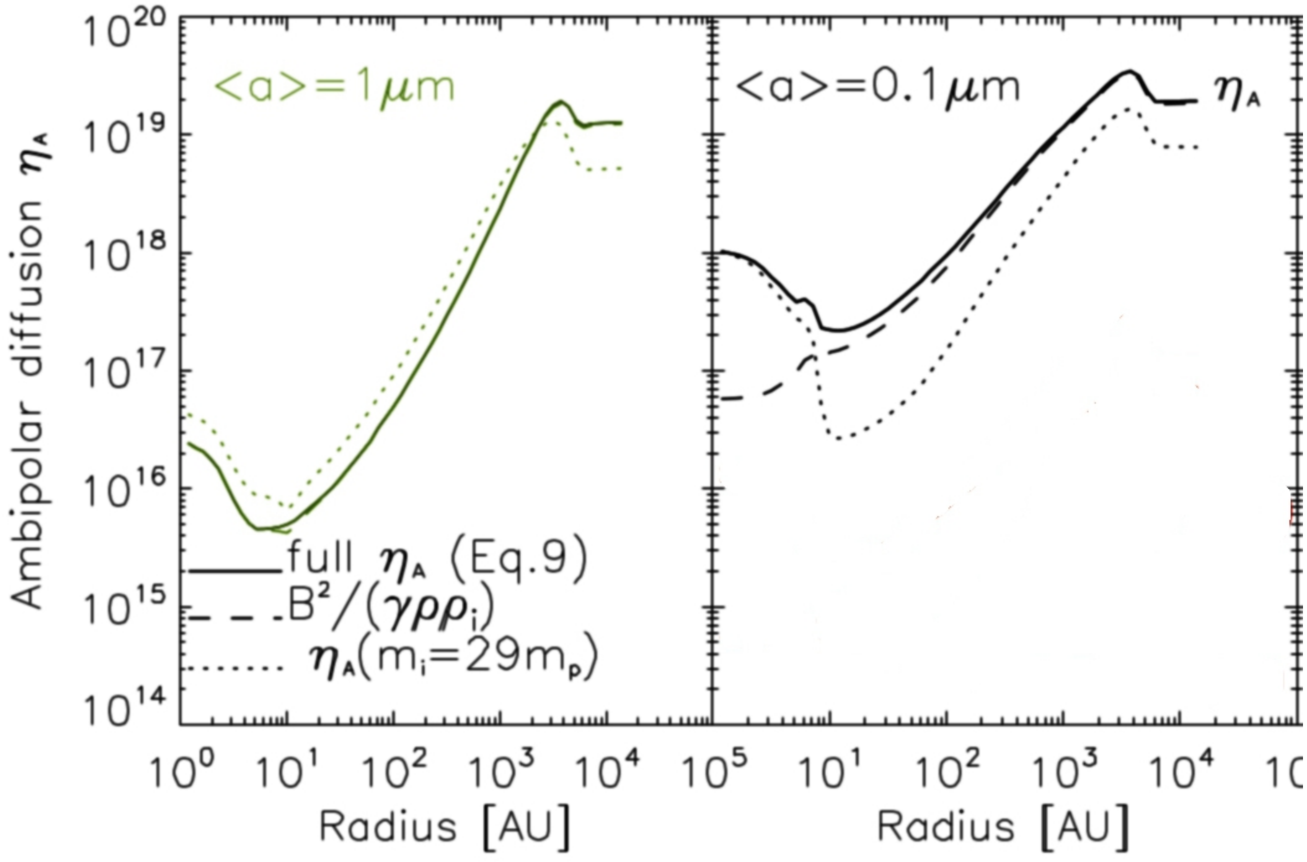

Mean ion mass can variate strongly, depending on dust size <u>*and*</u> radius !

Simplified (ions-only) AD formula as well as „representative“ ion approach are OK <u>*only*</u> for dust grains ≥ 1 μm

<u>Answer:</u> **Better not!**

Conclusions to the chemo-dynamical modelling of the collapsing clouds:

- Relative importance of ambipolar diffusion vs. Hall effect depends on both the dust properties and magnetization of gas in the cloud;

- The reversal of Hall term sign is a race between number of negatively charged dust and number of ions, weightened by coupling parameters;

- Only for mean dust sizes $\leq 0.02\mu m$ Hall effect is negative and dominates over the cloud;

- Only for mean dust sizes $\geq 1\mu m$, the molecular cloud can be treated as AD-dominated AND doen't need chemistry *or* dust („representative“ ion is enough)

Warning: tested for 1 solar mass clouds

What can we take from Class 0 studies to choose initial conditions for PPDisks?

- The most of Class 0 disks are *probably* small (R < 100AU), larger disks are exceptional.

  (stay tuned, search for better resolved Class 0)

- Hall effect is expected to magnify „tiny disk" to „large disk" when antiparallel to rotation – whereas it can reverse sign as a function of dust properties and (mildly) of cloud magnetization;

  (stay tuned, more A+O+H collapse simulations will come)

- **AD *(if alone)*** delivers very reliably **disks of 18 AU**, with radially constant **B field of 0.1 Gauss** as initial condition – and **gravitationally unstable!**

  (those will probably stay undetectable for long time)

- ***We propose: dust size measurements*** *for Class 0 objects with disks (or disk candidates) to* ***probe the link between Hall effect and disk size!***