DUST BUSTERS
Dust and gas in planet forming discs

On the secular evolution of the ratio between gas and dust radii in protoplanetary discs:

TESTING THE EFFICIENCY OF RADIAL DRIFT

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Special thanks: Richard Booth, Marco Tazzari and Alice Somigliana

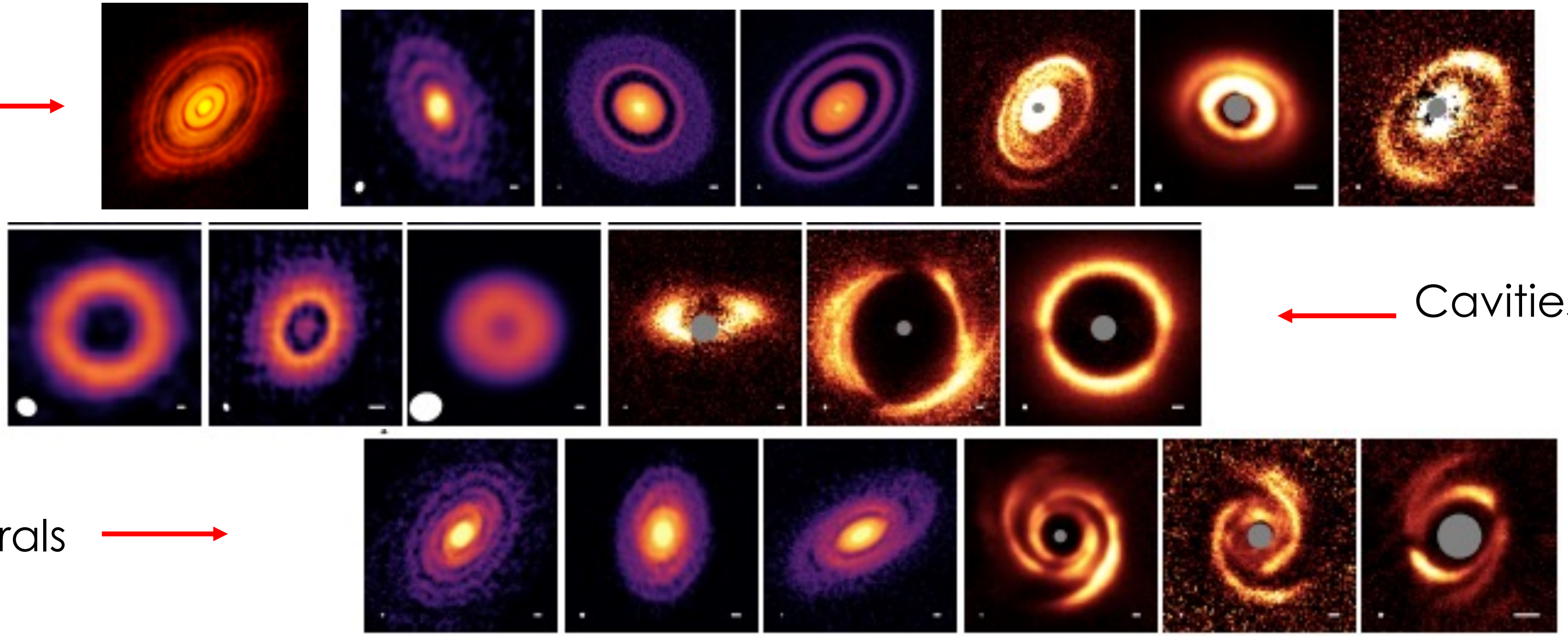
Protoplanetary discs observations

Many observed bright targets are showing *substructures* in high resolution images of the dust continuum and in scattered light:

ALMA partnership, Nov. 2014

Rings

Gaps



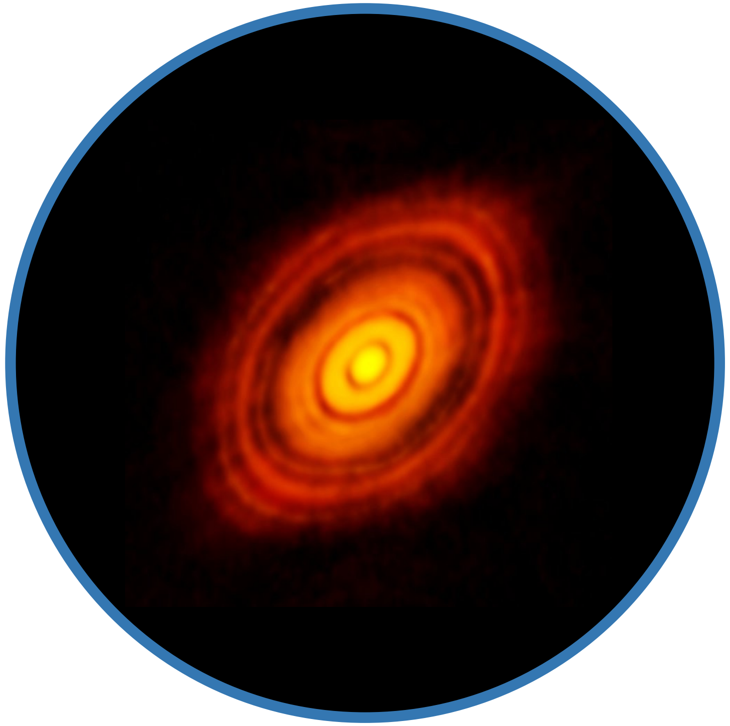
Cavities

Spirals

From: Andrews et al. 2020, many other works on these sources

Substructures

ALMA partnership, Nov. 2014



Dust grains *trapped* in a pressure maxima
(Pinilla et al. 2012, Dullemond et al. 2018, Rosotti et al. 2020 +…)

Induced *without* a pressure maxima, e.g. due to different opacity in different positions, snowlines
(Stammler et al. 2017, ..)

Substructures

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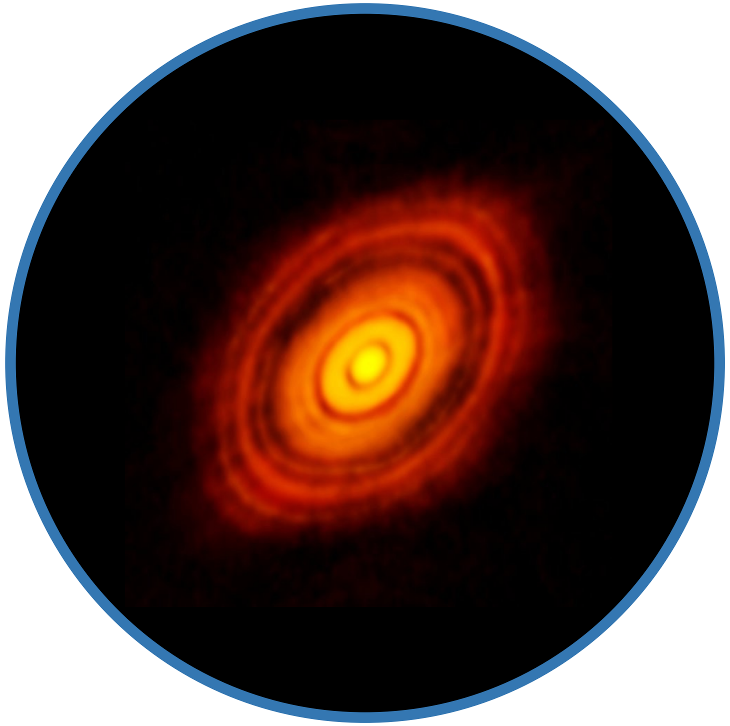

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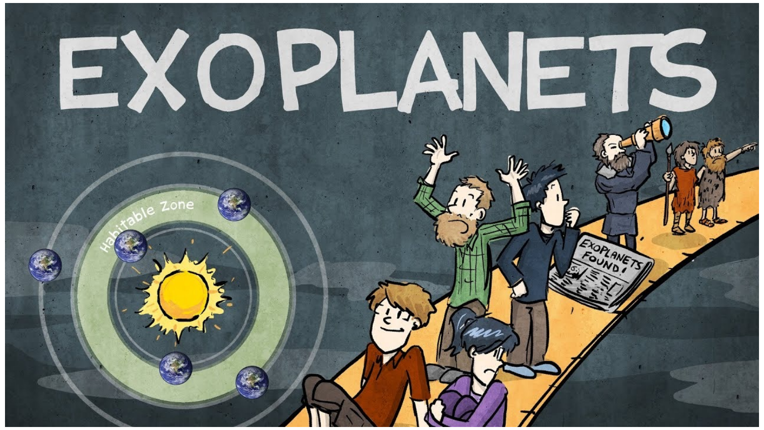

From: PhDcomics.com

Not only bright discs…

Try to study how fast an inhabitant of planet Earth runs the 100 m:

From Wikipedia

Not only bright discs...

Try to study how fast an inhabitant of planet Earth runs the 100 m:

Area	Men				Women			
	Time (s)	Wind (m/s)	Athlete	Nation	Time (s)	Wind (m/s)	Athlete	Nation
Africa (*records*)	**9.77**	+1.2	Ferdinand Omanyala	Kenya	**10.78**	+1.6 −0.3	Murielle Ahouré Marie-Josée Ta Lou	Ivory Coast
Asia (*records*)	**9.83**	+0.9	Su Bingtian	China	**10.79**	0.0	Li Xuemei	China
Europe (*records*)	**9.80**	+0.1	Marcell Jacobs	Italy	**10.73**	+2.0	Christine Arron	France
North, Central America and Caribbean (*records*)	**9.58 WR**	+0.9	Usain Bolt	Jamaica	**10.49 WR**	0.0[a]	Florence Griffith-Joyner	United States
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Vs.

Average researcher (trained): 12-14 ''

Average researcher (untrained): 15-20 ''

From Wikipedia and PHDcomics.com

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Demographic studies!!!!!

A large amount of information

Surveys of star forming regions investigate how disc properties vary with age and are a test-bed for disc evolution theories

Lupus

Ansdell et al. 2016,2018
Tazzari et al. 2017,2020,2021
Hendler et al. 2020,
Sanchis et al. 2021

Young
1-3 Myr

Taurus

Long et al. 2019
Kurtovich et al. 2021

Young
1-2 Myr

Upper Sco

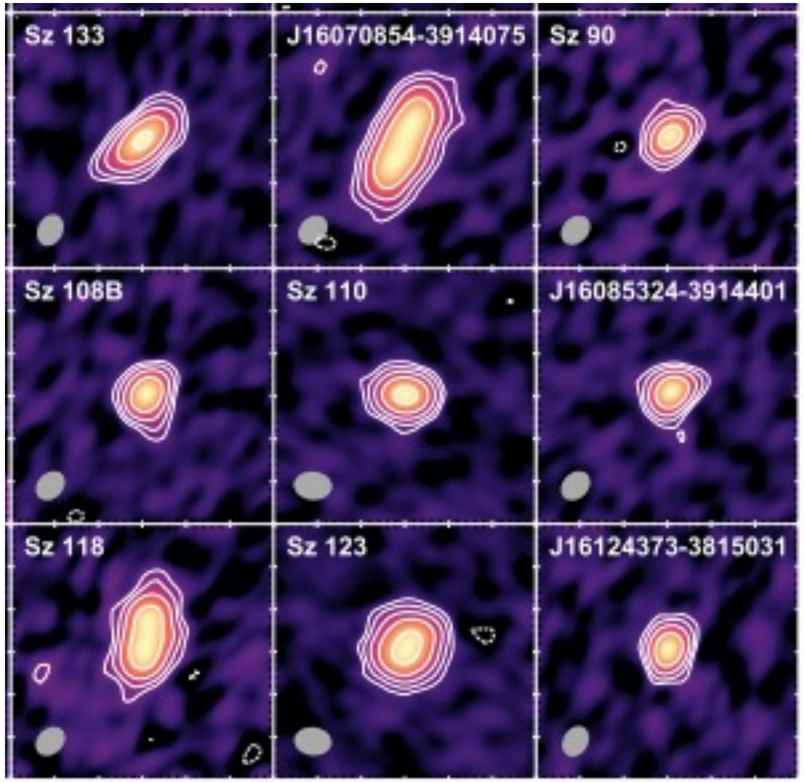
Barenfeld 2016,
Hendler 2017

Old
5-10 Myr

- Lower resolution
- "High" statistics
- Masses
- Dust disc radii
- Gas disc radii

A large amount of information (II)

Surveys of star forming regions investigate how disc properties vary with age and are a test-bed for disc evolution theories



Tazzari et al. 2020, Lupus survey: continuum 3 mm (3''x3'')

- dust disc radii 10 - 80 au

Unresolved substructures or smooth?

A large amount of information (II)

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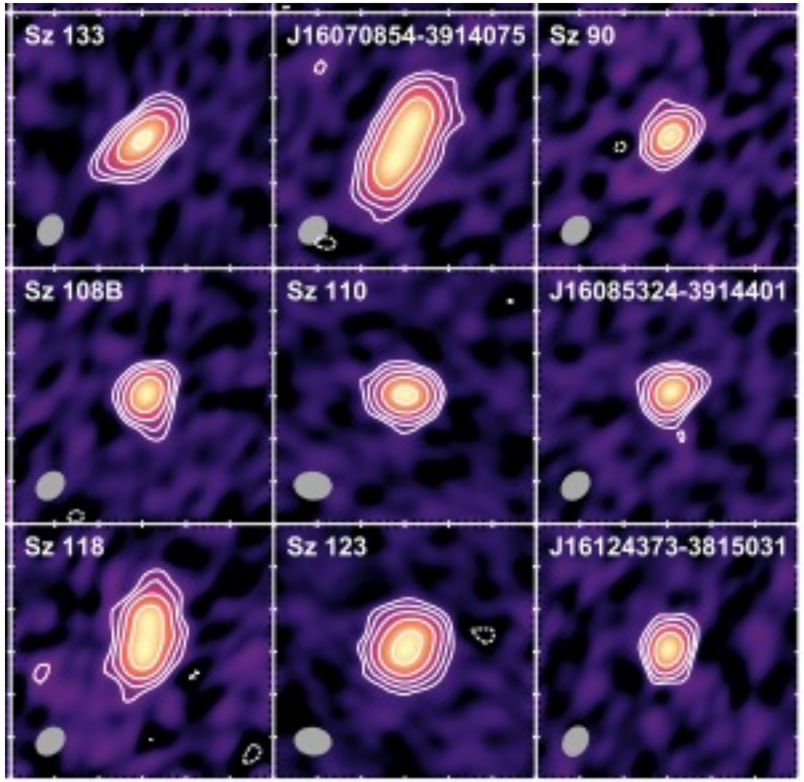

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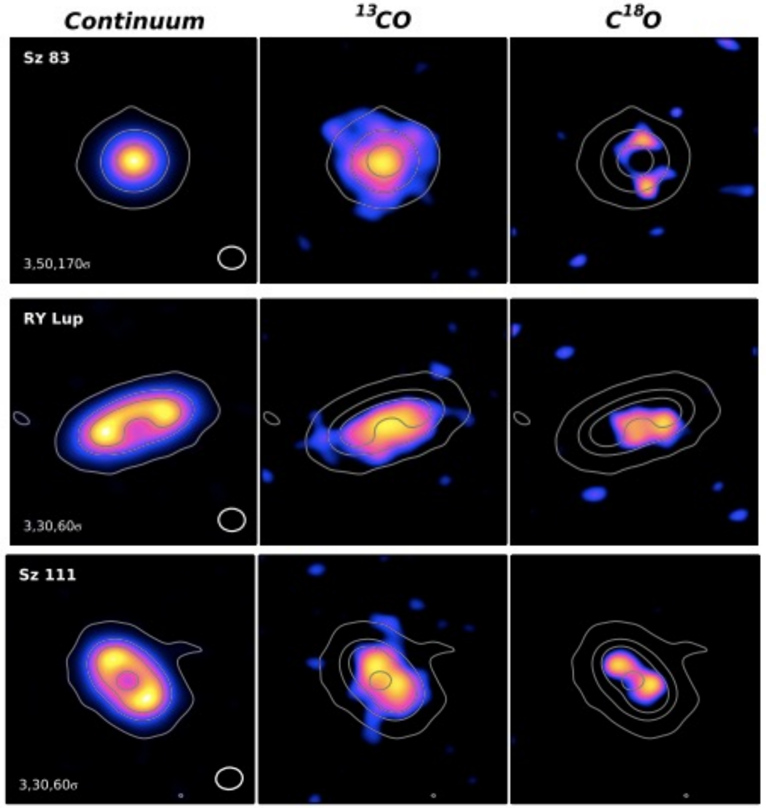
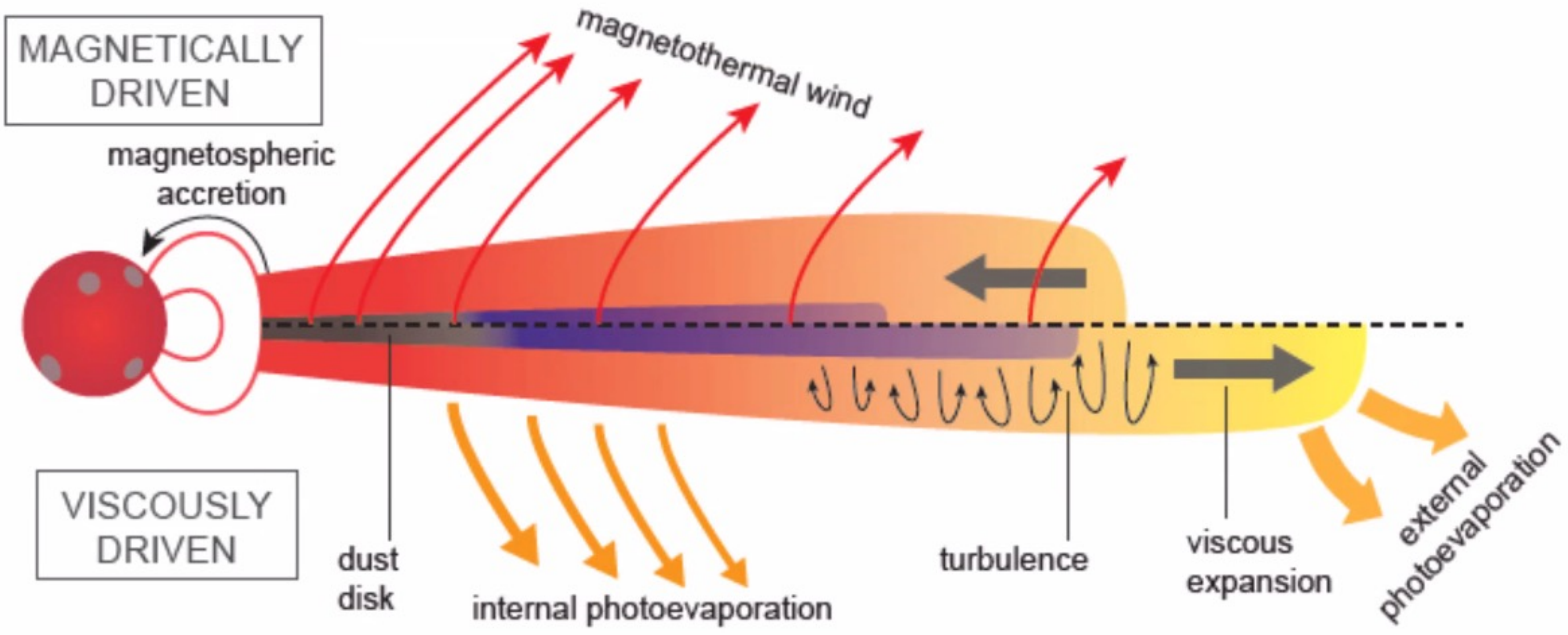


Ansdell et al. 2016, cycle 2 Lupus: CO isotopologues and 0,890 mm, (3''x3'')

- dust disc radii 10 - 80 au
- Gas disc radii (more difficult, time consuming, missing data) 20-200 au

Unresolved substructures or smooth?

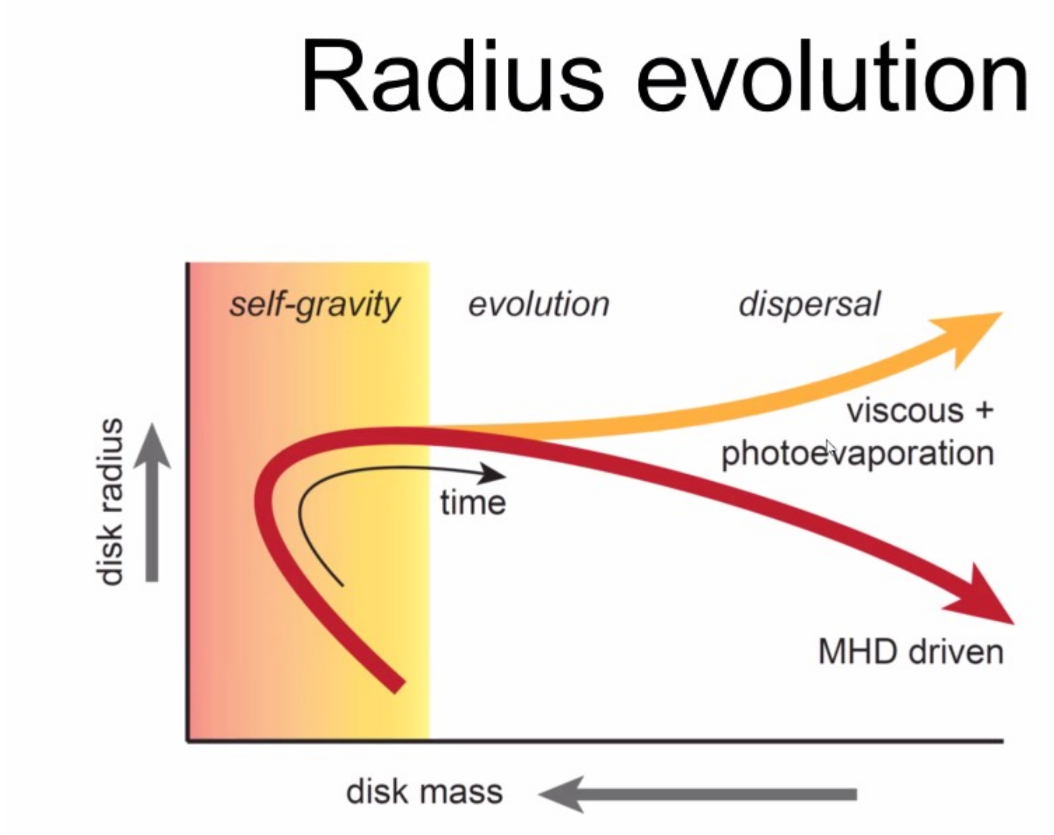
The big debate



Giovanni Rosotti's talk

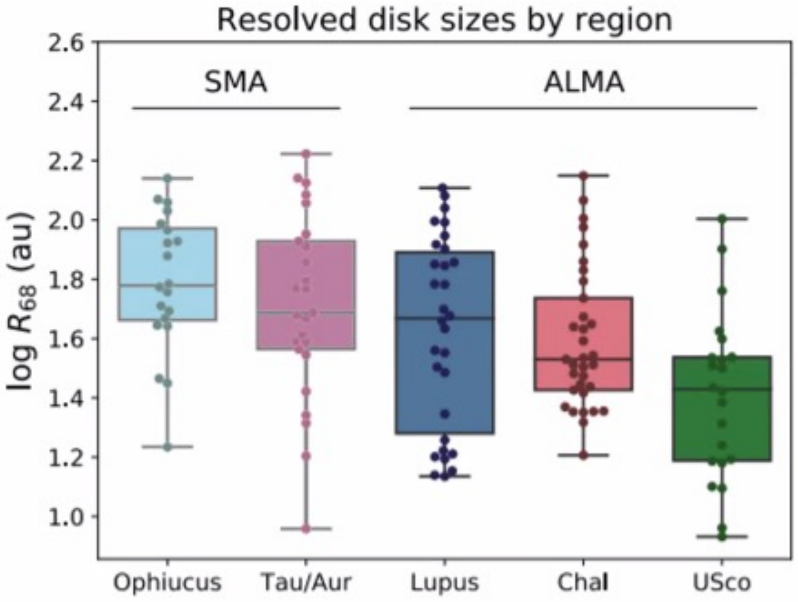
The global evolution of discs

To understand which is the mechanism that is governing disc evolution we need to find a tracer that is sensitive to the global evolution of the disc.

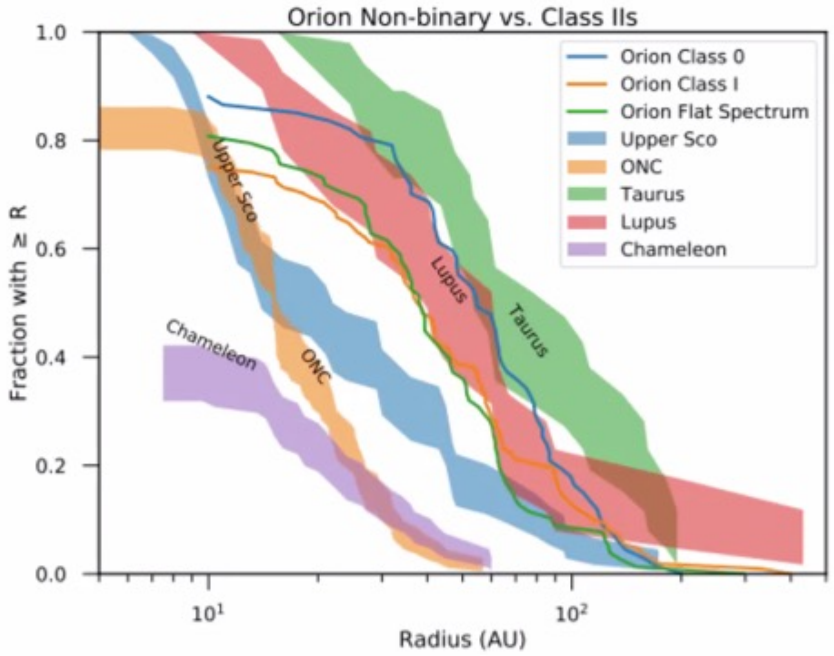


Giovanni Rosotti's talk

Dust radii



Hendler+ 2020

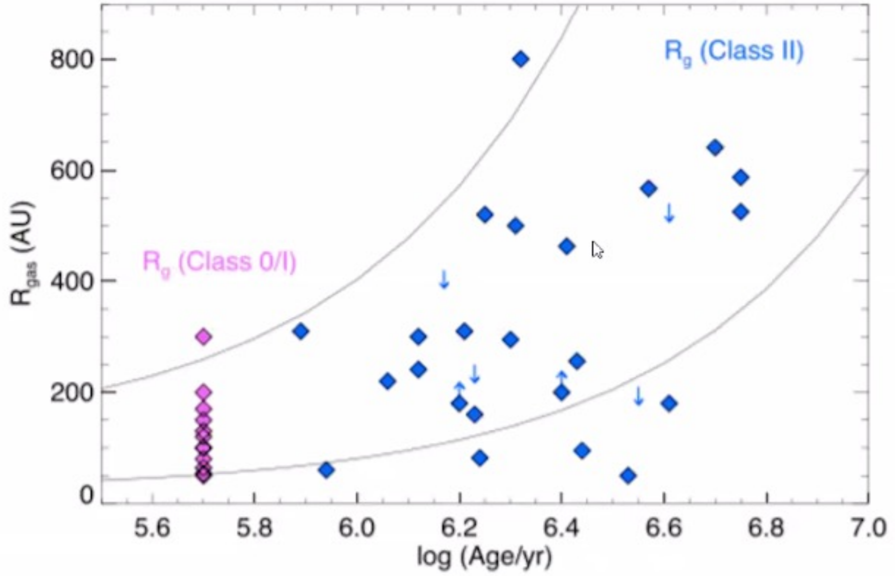


Tobin+ 2020

Class 0/I unclear but otherwise shrinking observed

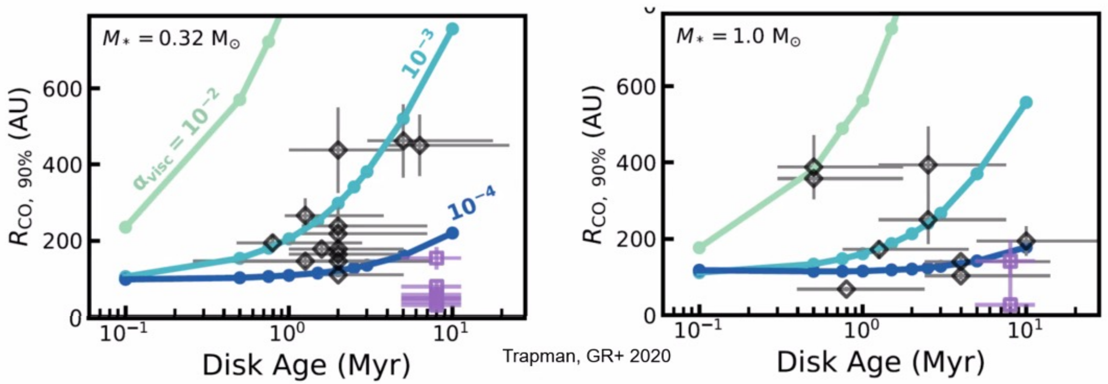
Giovanni Rosotti's talk

Evidence of viscous spreading?



Najita & Bergin 2018

Tentative evidence, but inhomogeneous sample



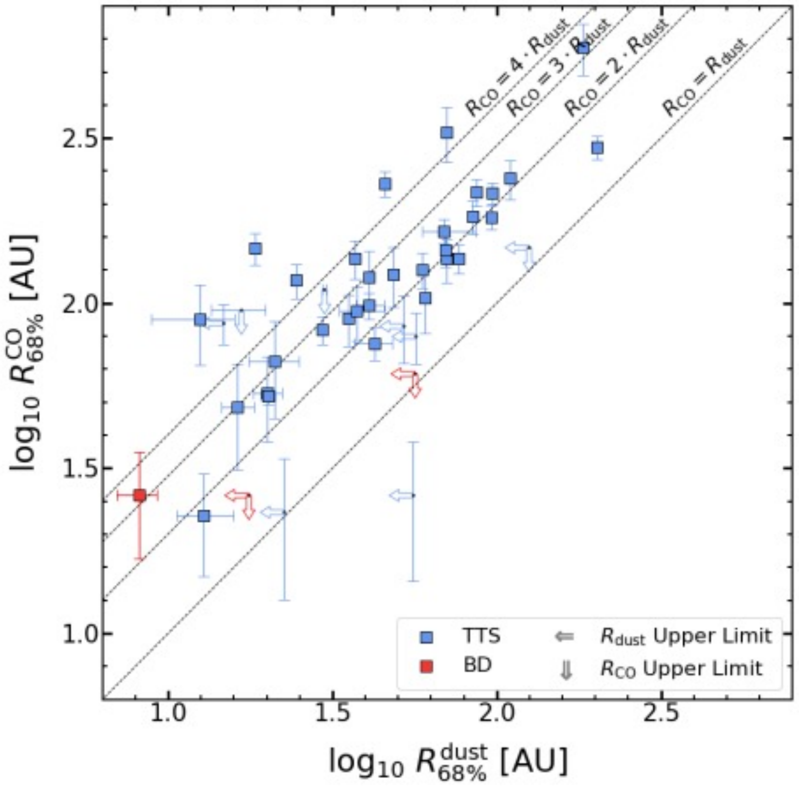
Trapman, GR+ 2020

Excludes discs are highly viscous: observed discs are not large enough
Data too sparse to confirm/reject that disc size increases with time

Giovanni Rosotti's talk

A large amount of information (III)

Surveys of star forming regions investigate how disc properties vary with age and are a test for disc evolution theories



Sanchis et al. 2021

- Rco/Rdust 2-4 in Lupus
- 15% of the population Rco/Rd > 4

Lupus population evolve similarly and is in the same evolutionary stage?

What can we learn from dust radii?

R_{dust}

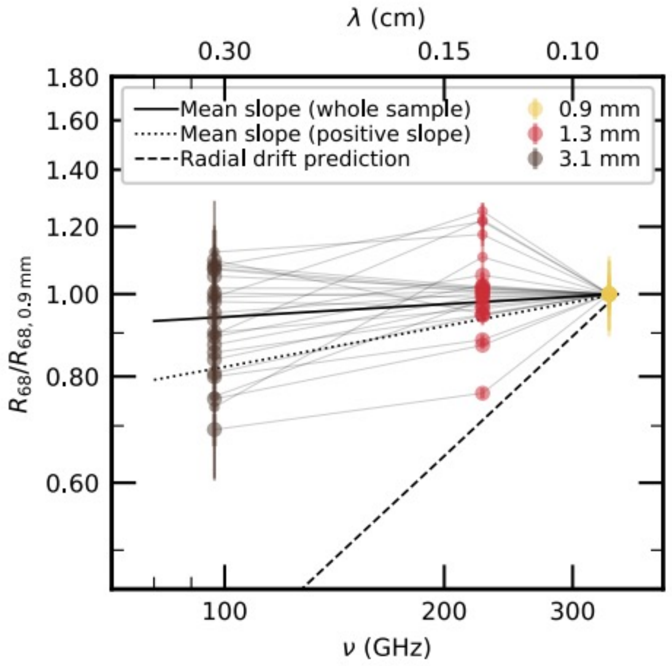
- The value of the radius depends on the dust opacity (large grains) (Rosotti et al. 2019)

- Lupus discs have nearly identical dust radius if observed at different wavelengths
(Tazzari et al. 2021, see Marco's talk)

- Smooth and compact models reproduce observed dust flux-Mdust relation. (Thripathi et al. 2018, Rosotti et al. 2019 a,b)

- Substructures can be common only in bright discs (Banzatti et al. 2020, van der Marel & Muldersl 2021)

Lupus: Marco Tazzari's talk



- Nearly identical radii
- R_{3mm} is ~90% $R_{0.9mm}$

Disc evolution: dust

Decoupled dust feels the gas like a headwind: lose energy and angular momentum

- Large grains drifts towards the star (Weidenschilling 1977)

Open question: understand the role of radial drift

- Removes large grains
- Fast *shrinking* of the dust disc radii, eventually disc disappearing (timescale few 10^5 yr) (Appelgren et al. 2020)
- Substructures can slow down radial drift due to dust trapping (e.g., Pinilla et al. 2012), but are not observed in compact discs surveys (e.g., Sanchis et al. 2021)

Physical question: how much dust drifts in discs?

Do we really have a problem with radial drift?

Initial condition

t_0

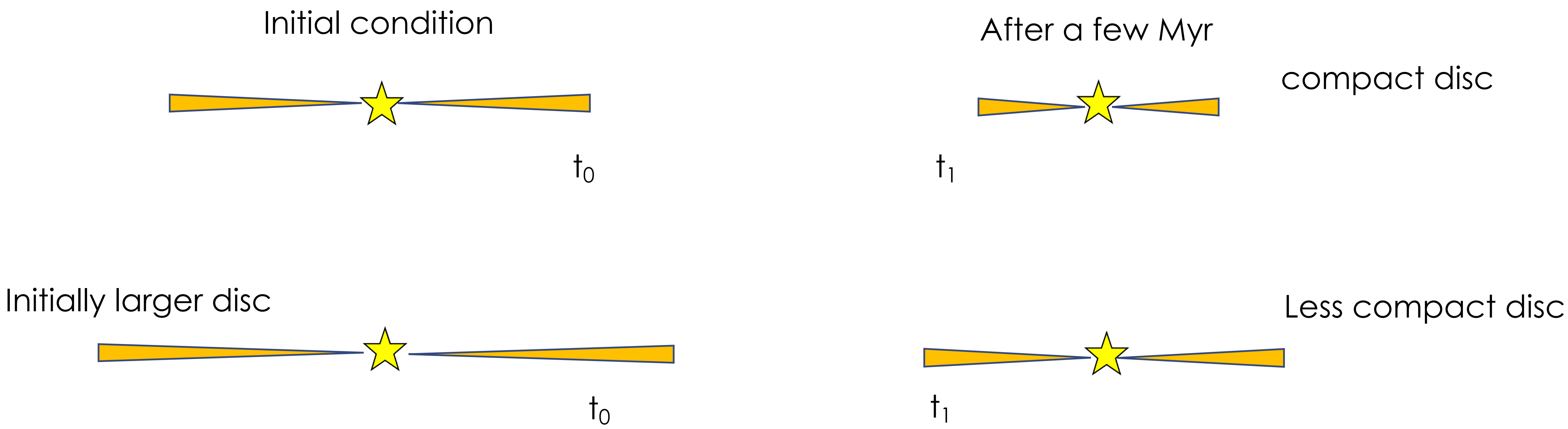
After a few Myr

compact disc
(radial drift)

t_1

Physical question: how much dust drifts in discs?

Do we really have a problem with radial drift?



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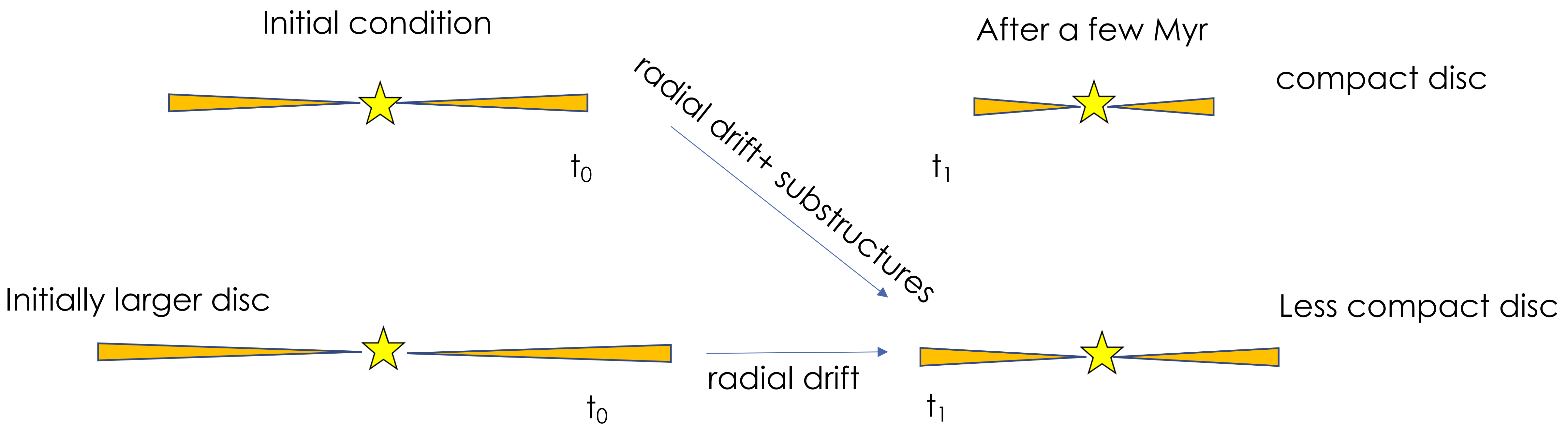


Studying only dust radii we cannot solve this question

What can we learn with gas radii?

Gas dominates in mass. The physical process governing its evolution is linked to the mechanism driving the accretion on the star:

What do we observe?

Gas disc size as

a function of the time R_{CO}

Enviromental evolution of CO

Photodissociation, freeze-out, grain surface chemistry (see i.e. Trapman et al. 2020):

Rco

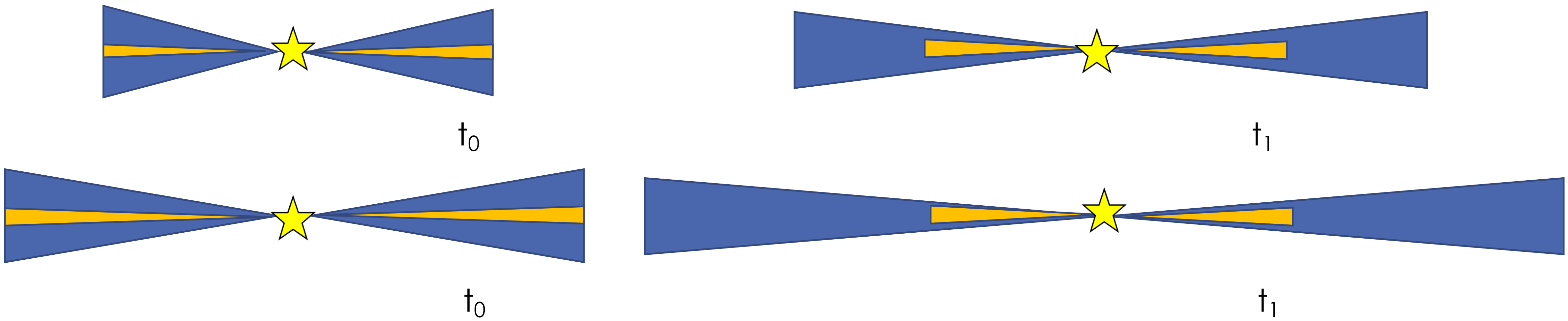
Gas radius (see i.e. Trapman et al. 2020): where CO is photodissociated

Viscous spreading

Not so easy to "measure" (see i.e. Trapman et al. 2020)

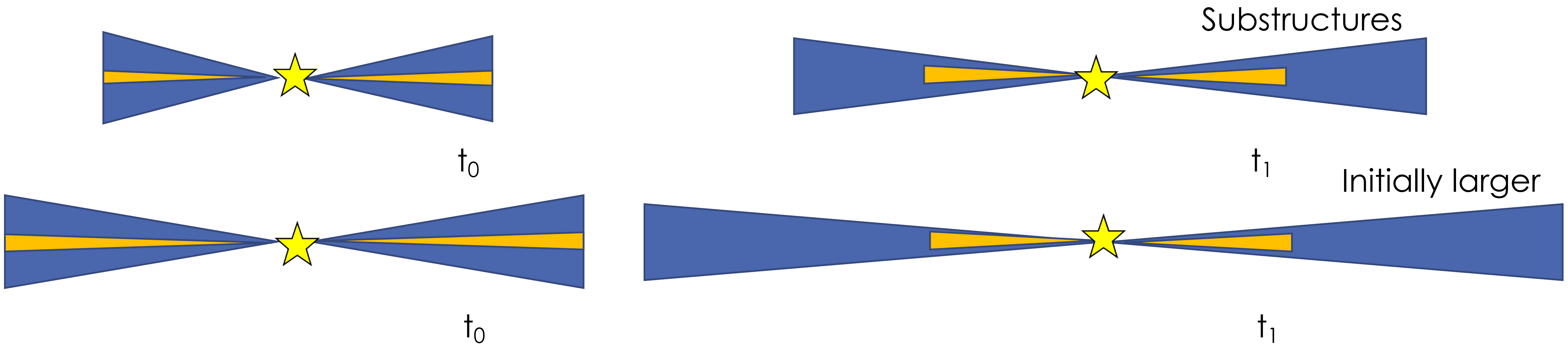
Physical question: how much dust drifts in discs?

- We can use the secular evolution of the ratio between the dust and gas radii, Rco/Rdust, capable to break the degeneracy



Physical question: how much dust drifts in discs?

- We can use the secular evolution of the ratio between the dust and gas radii, Rco/Rdust, capable to break the degeneracy
- Follow up of Rosotti et al. 2019a,b (only dust sizes) testing how much dust drifts in synthetic population of discs with respect to the gas evolution



Toci et al. 2021

Our models

1D synthetic discs composed by gas and dust

- Gas: viscous evolution
- 2 populations of dust (large and small grains) implemented as Birnstiel et al. 2012

  → different dust to gas ratio each timestep (initially 100) NEW!
- Dust feedback considered (Laibe & Price 2014)
- Population evolved from 0-3 Myr
- Synthetic emission of CO lines with RADMC3D (Dullemond et al. 2012)
- Continuum 850 micron flux computed as in Rosotti et al. 2019 a,b $S_b(R) = B_\nu(T(R))[1 - \exp(-\kappa_\nu \Sigma_d)]$

B_ν planck function
k_ν opacity

Rco
Gas radius: 68% of the flux

Rdust
Dust radius: 68% of the flux

Toci et al. 2021

Initial conditions

Suite of models to probe the parameter space (No montecarlo), fixed stellar mass 1Msun

Initial scale radius R_c

R_c = 10, 30, 80 au

Poor constrained
Recent surveys:
discs initially compact
Maury et al. 2019
Tobin et al. 2020

Initial disc mass M_0

M_0=0.01,0.03,0.1 Msun

Determines CO self-shielding
Trapman et al. 2019
Difficult to measure
Miotello et al. 2017

Viscosity α

$\alpha = 10^{-4}, 10^{-3}, 10^{-2}$

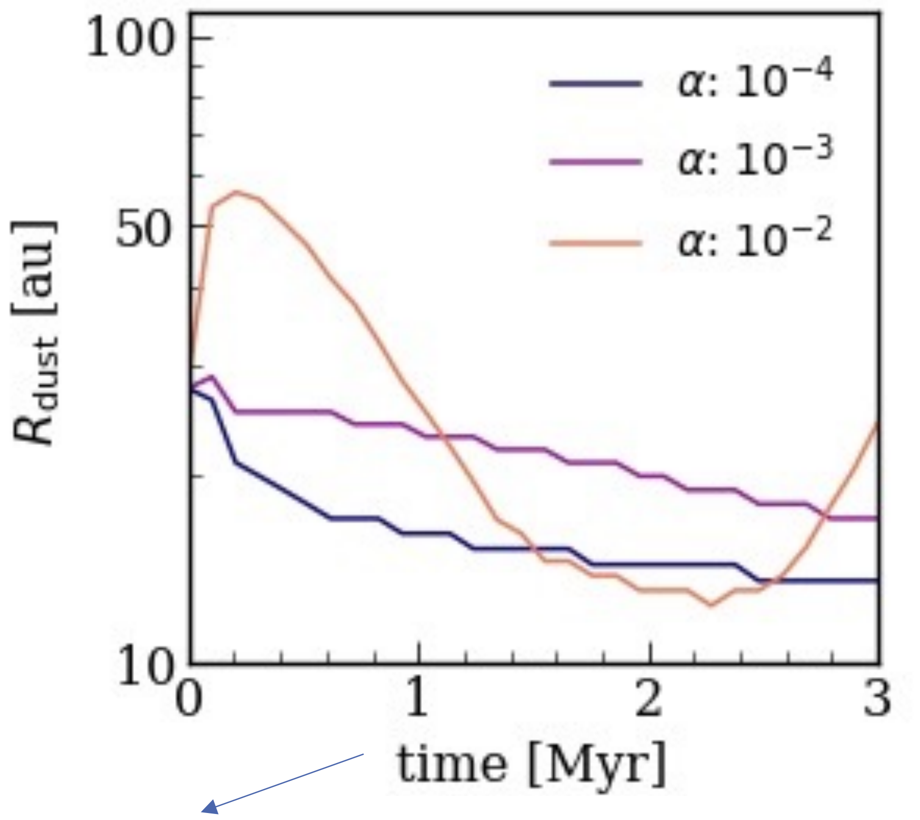
Controls mass accretion rates
and viscous spreading
Trapman et al. 2020,
Flaherty et al. 2017, 2020

Coming soon: Initial conditions for populations of discs (Somigliana + 2021)

Toci et al. 2021

This work Rdust

Reference case: M_0=0.1 Msun, R_c=10 au



From Rosotti et al. 2019 a,b!

Dust radius R_{dust}

α = 10^{-4}, 10^{-3}

- Dust radii decreases with time: radial drift is at play: dust radii becomes 20 -10 au after 1 Myr

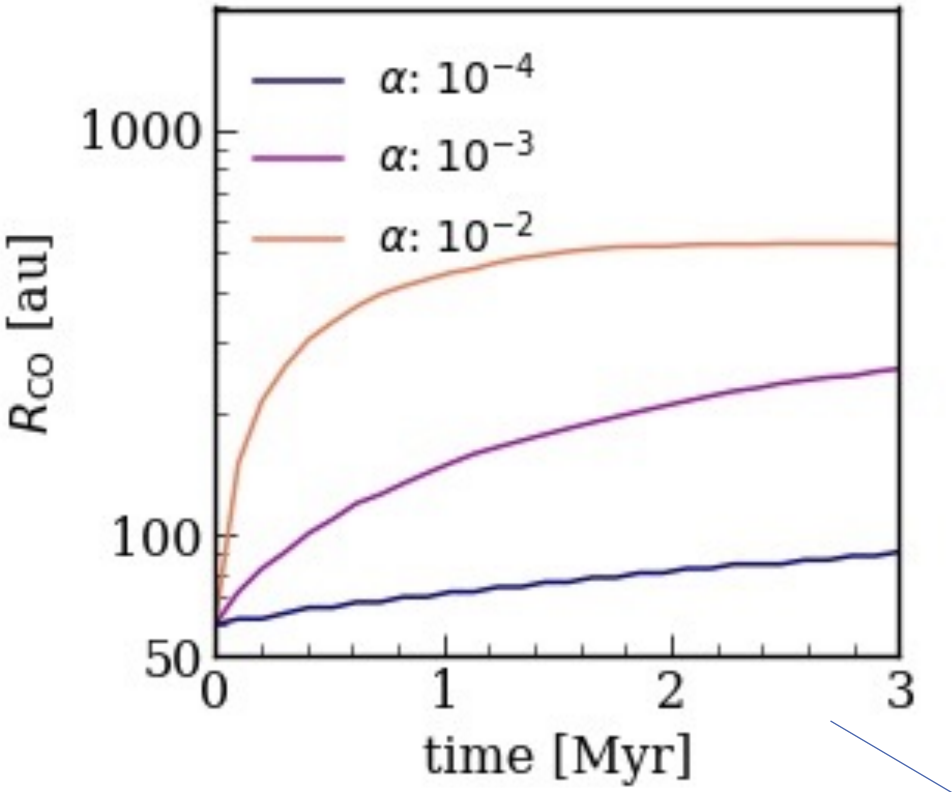
α = 10^{-2}

- Two phases of expansion: due to viscous spreading (grains still grow) and due to the opacity cliff

Toci et al. 2021

This work Rco

Reference case: M_0=0.1 Msun, R_c=10 au



In agreement with
Trapman et al. 2019,2020

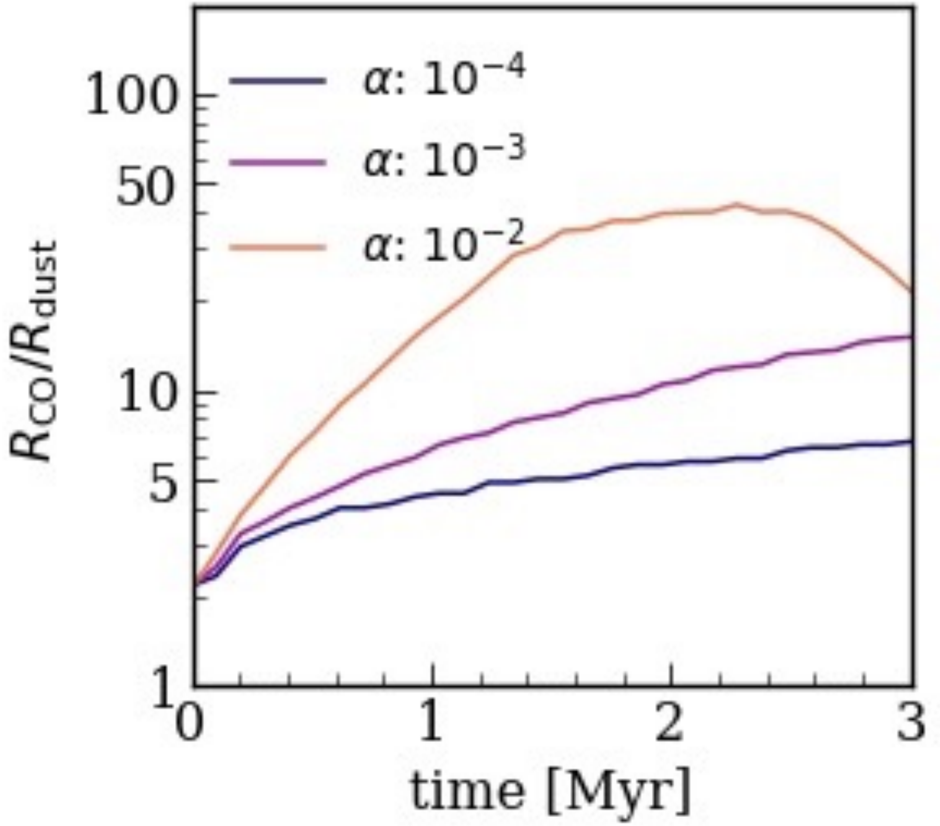
Gas radius R_{CO}

- viscous spreading at play, but not so easy to see after 1 Myr …
  initial faster growing for larger values of α
- Very large values for high viscosity α
- Surface density decreases →
  enhancement of the CO photodissociation

Toci et al. 2021

This work Rco/Rdust

Reference case: M_0=0.1 Msun, R_c=10 au



Ratio R_{CO}/R_{dust}

- Value of the viscosity crucial
- Starts with a relatively high value (2)

α = 10^{-4}, 10^{-3}

- Monothonically increases to >4

α = 10^{-2}

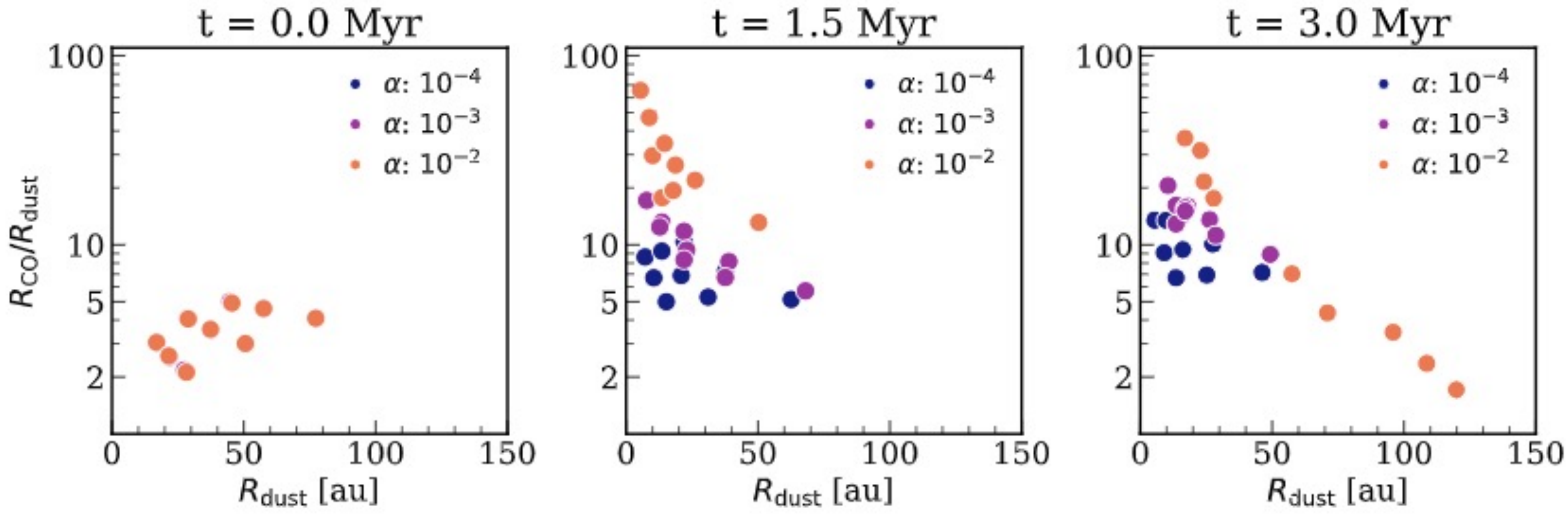
- Grows to 50 then decreases to 20

… in any case *larger* than 4

Toci et al. 2021

Secular evolution

How our models would appear if observed at a certain time?



Linear span:
no age spreading,
no montecarlo

Note that we cannot cover the other parts of the plot (according to observations)

Toci et al. 2021

Secular evolution

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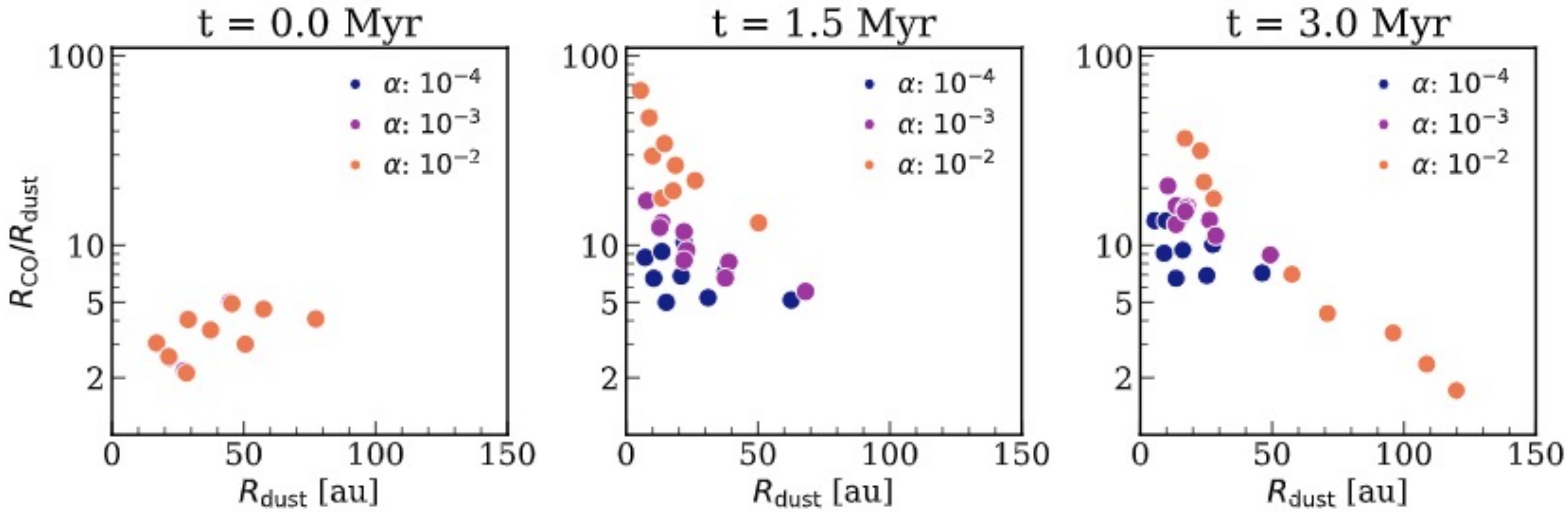

Rdust < 60
Very large gas radii for all the values of the viscosity

Toci et al. 2021

Secular evolution

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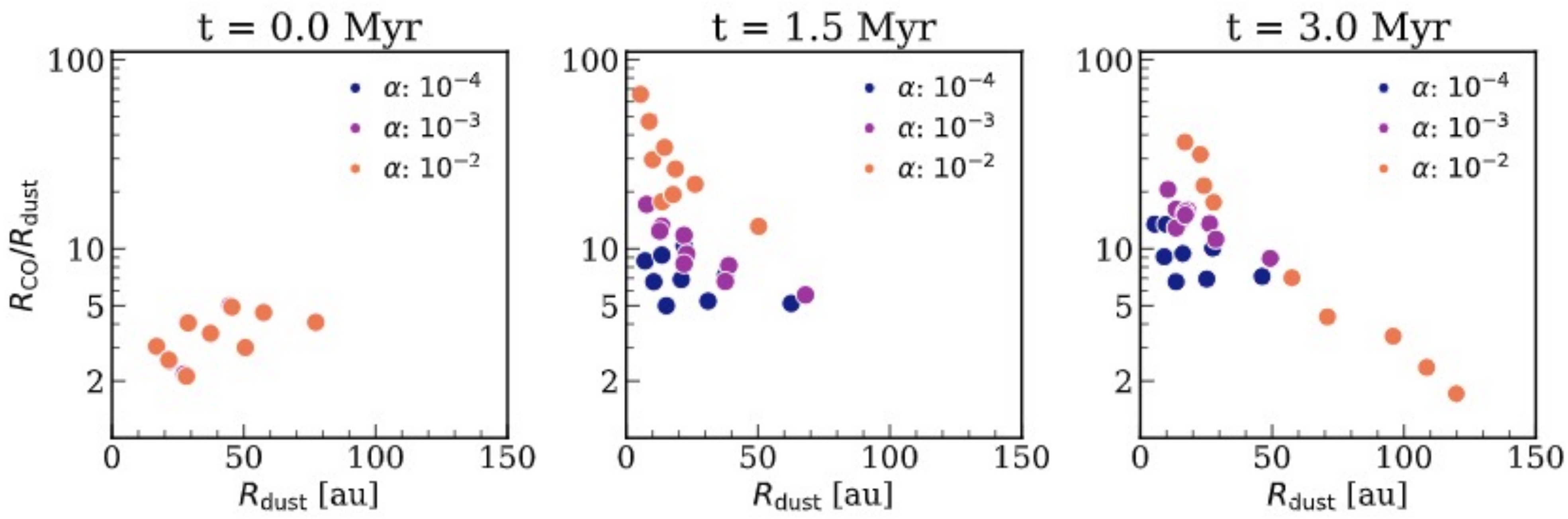
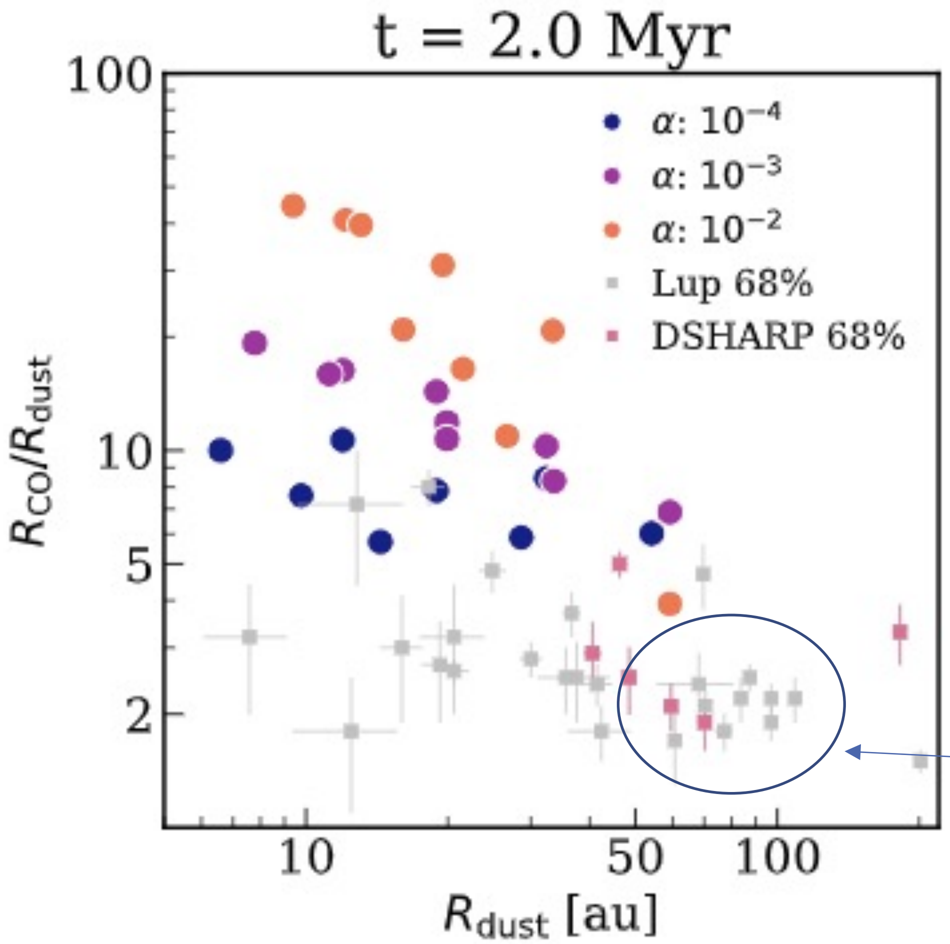


Rdust < 60
Very large gas radii for all small and intermedie values of the viscosity
Rdust > 60
Very large dust radii high value of viscosity (opacity cliff)

Toci et al. 2021

Comparison with observations (Lupus)



Our models do not reproduce the observed ratio of R_{CO} / R_{dust} in Lupus survey

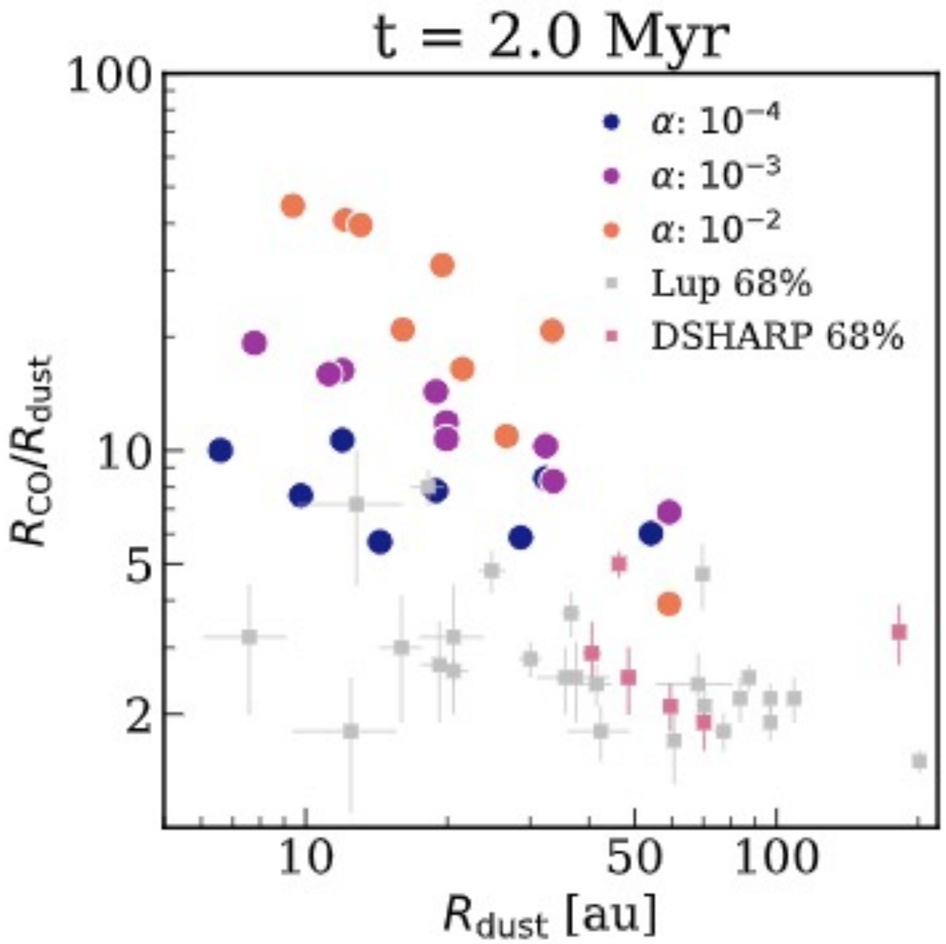
- Too large (>2-3 times) R_{CO} / R_{dust}
- Dust disc radii R_{dust} too small

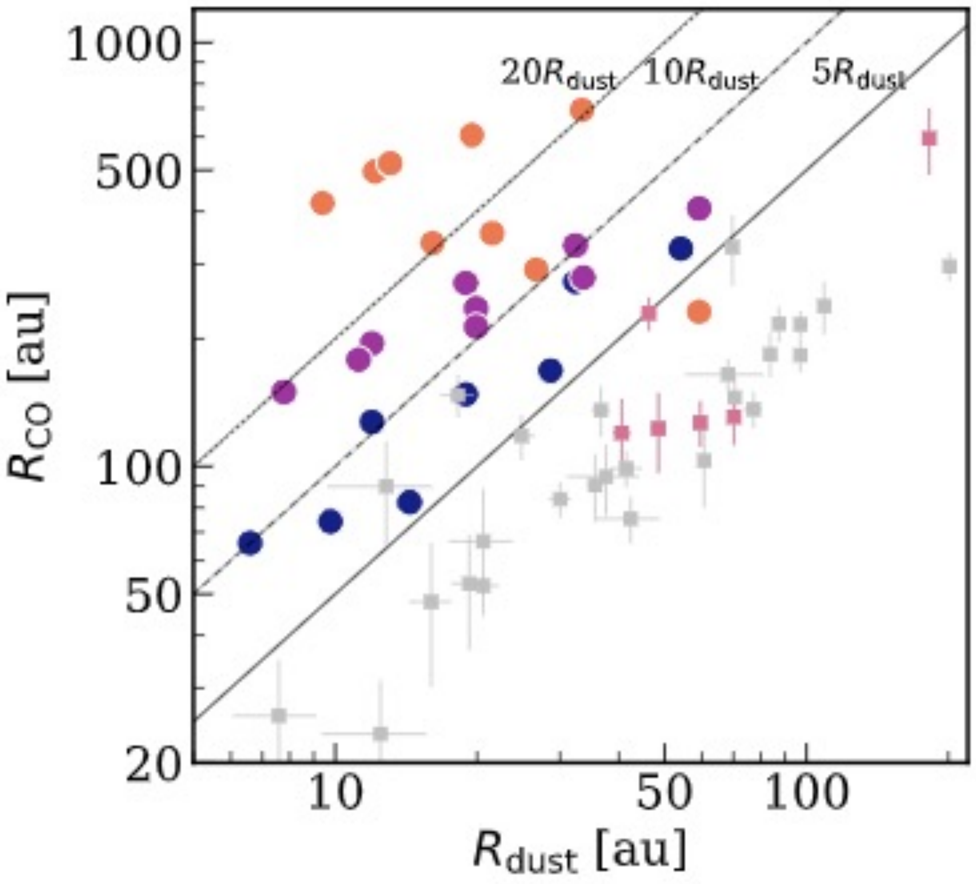
Discs with substructures

Toci et al. 2021

Comparison with observations (Lupus)

Gas sizes almost ok, dust sizes too small!





Toci et al. 2021

Possible solutions: slower growth?

1) R_{dust} is too *small: <u>less efficient radial drift</u>?*

Explore different dust growth timescale in the 2 population model of Birnstiel et al. 2012, as Booth & Owen 2020 and Sellek et al. 2020:

$$t_g = \frac{a}{\dot{a}} = f_{\mathrm{grow}} \left(\frac{\Sigma_g}{\Sigma_d \Omega} \right)$$

f_{grow}=1 → all the collision results in growth

f_{grow}=100 → 1% of the collision results in growth

Toci et al. 2021

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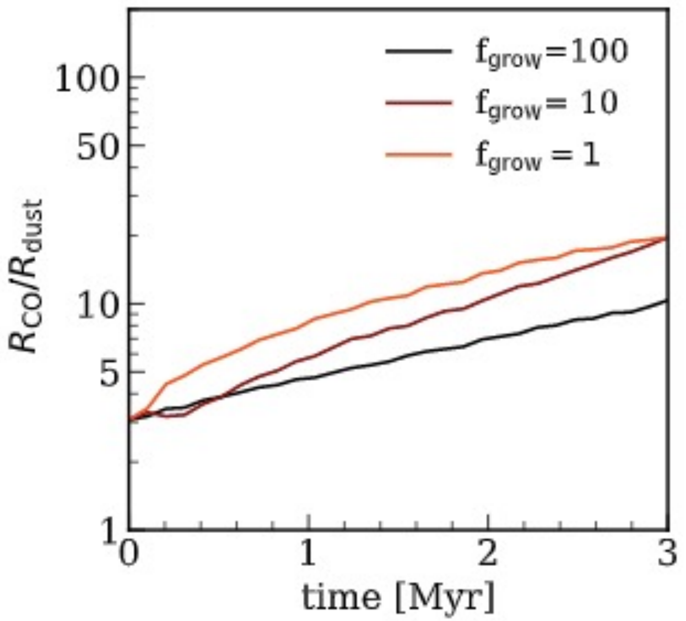

Needs f_{grow}=100 (= block dust evolution)
→ very strong dependence on the initial conditions

Leads to a final disc mass f_{grow} times larger, problems to explain Upper Sco masses (Sellek et al. 2020)

Toci et al. 2021

Possible solutions: MHD winds?

2) R_{CO} is too *large*: *MHD winds?*

If angular momentum of gas is removed due to disc—wind interactions discs sizes should not grow with time (Suzuki 2016, Bai 2016)

- Reduce the values of R_{CO} / R_{dust}

- Strong constraint on the efficiency of disc winds (needs to remove a large fraction of the disc mass)

- Not solving the R_{dust} problem: still needs a way to slow down radial drift

Toci et al. 2021

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- Reduce the values of R_{CO} / R_{dust}

- Strong constraint on the efficiency of disc winds (needs to remove a large fraction of the disc mass)

Future work is coming (Alice's Ph.D. project, B. Tabone's paper, ..)

- Not solving the R_{dust} problem: still needs a way to slow down radial drift

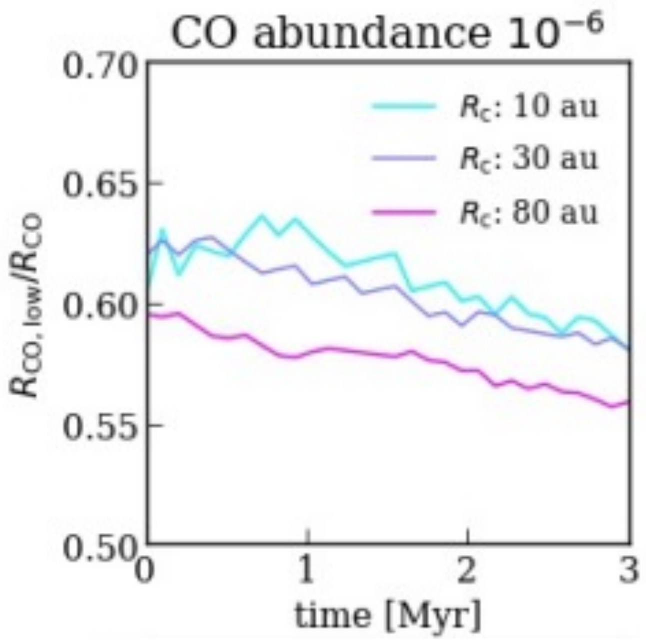
Toci et al. 2021

Possible solutions: Different chemical evolution?

3) R_{CO} is too *large*: *Different CO abundances?*

10 -100 times lower abundance of CO found by several authors (Favre et al. 2013) (Turbulent mixing)

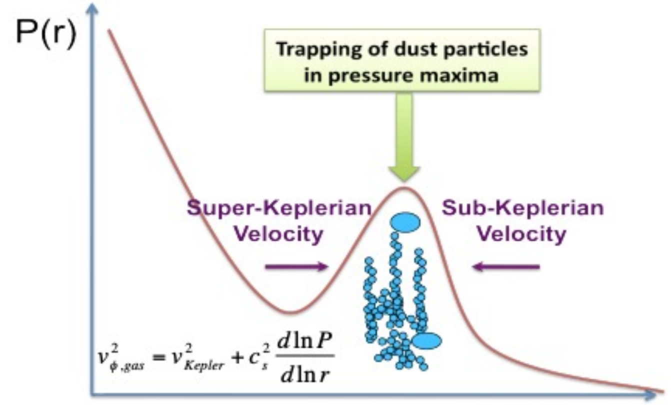
- Abundances of 10^{-6} reduce the values of R_{CO} / R_{dust}
- Allows initially larger discs Rc=30-50 au
- Not solving the R_{dust} problem: still needs a way to slow down radial drift (less stringent)



Toci et al. 2021

Possible solutions: Substructures!

4) Dust traps collecting the dust at pressure maxima
(Whipple 1972, Pinilla et al. 2012, + ...)



e.g. Klahr & Henning (1997) ; Fromang & Nelson (2005); Johansen et al. (2009); Pinilla et al. (2012a)

- Increase the values of R_{dust} withouth changing R_{CO}
- Reduce the values of R_{CO} / R_{dust}
- No requirements for initial conditions or disc evolution

Unresolved substructures can be at play also in compact and faint discs, undetected

- *All* the mechanisms that creates substructures where dust is trapped can be at play! (e.g., Planets Lin & Papaloizou 1979 ..)

Toci et al. 2021

Possible solutions: Substructures!

4) Dust traps collecting the dust at pressure maxima
(Whipple 1972, Pinilla et al. 2012, + …)

- Increase the values of R_{dust} withouth changing R_{CO}

- Reduce the values of R_{CO} / R_{dust}

- No requirements for initial conditions or disc evolution

Future work is coming (A. Zormpas paper, …)

Unresolved substructures can be at play also in compact and faint discs, undetected

- *All* the mechanisms that creates substructures where dust is trapped can be at play! (e.g., Planets Lin & Papaloizou 1979 ..)

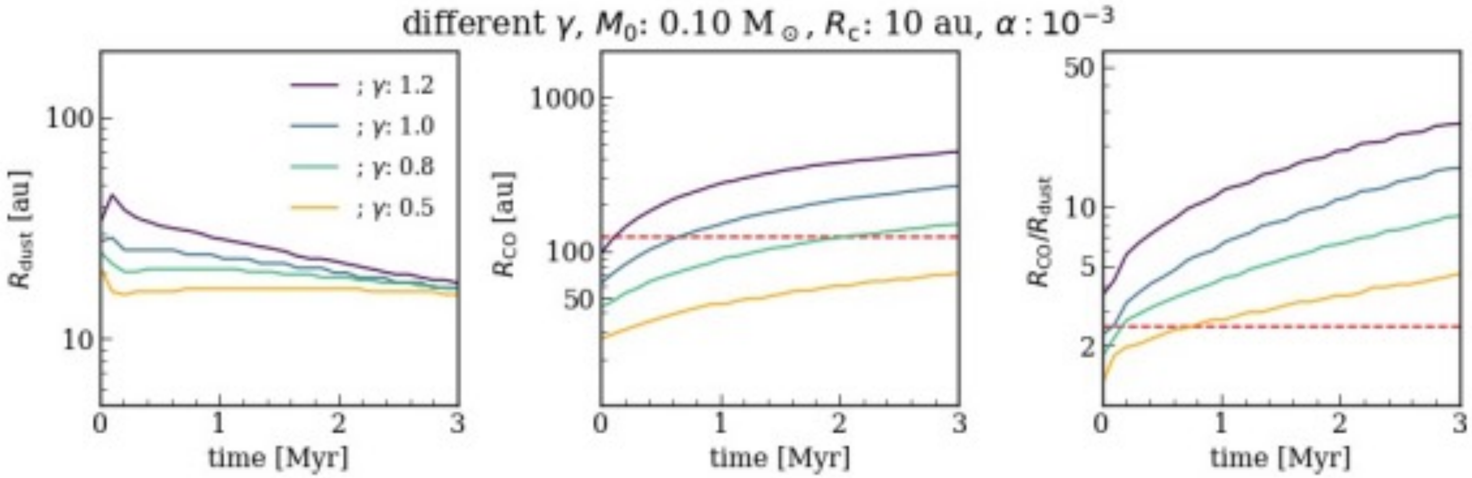
Toci et al. 2021

Possible solutions: Different viscosity law?

5) R_{CO} is too *large*: *effect of the shape of the surface density in the outer part of the disc?*

Affects both the dust and gas sizes → it is difficult to probe the outer part of discs

$$\nu = \nu_c (R/Rc)^{\gamma}$$



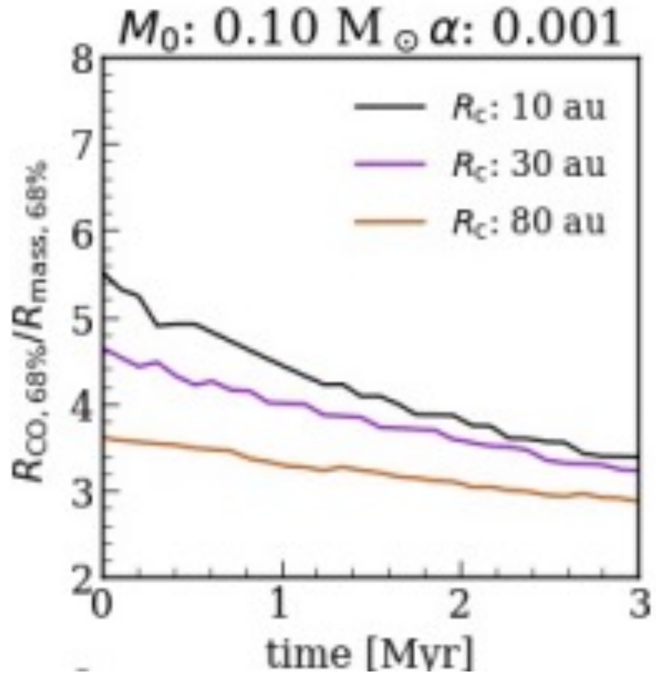
- Not solving the R_{dust} problem: still needs a way to slow down radial drift (less stringent)

Can we trust CO?

Toci et al. 2021

R_{CO} depends on the mass distribution in the outer part in the disc

- Not a good tracer for mass
- Not a good tracer for viscous spreading
- Not a good tracer for the scale radius of the disc



→ Explore other tracers as 13CO (but we need to improve our knowledge of the thermochemistry of discs)

Conclusions

We modelled the secular evolution of R_{CO} / R_{dust} to test the efficiency of radial drift

- First models with dust growth + gas evolution
- Our results for dust and gas are in agreement with previous works (Rosotti et al. 2019, Trapman et al. 2019,2020)
- The values of R_{dust} are too small with respect to the observed values, leading to R_{CO} / R_{dust} values too large for all the values of the viscosity
- To solve this inconsistency unresolved substructures should be present in almost all the discs

Future work

- Proper polulation synthesis
  (coming soon…. Somigliana et al. 2021)
- Analytical prescriptions for the gas size (Toci+ in prep, Trapman+ in prep)
- Enviromental effects
- Different tracers
- Add substructures

Thank you!